Discovering internal symmetry in cosmology

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Abstract

Internal (non-geometric) symmetry is recognized and studied as a new phenomenon in cosmology. Symmetry relates cosmic vacuum to non-vacuum forms of cosmic energies, which are dark matter, baryons, and radiation. It is argued that the origin and physical nature of cosmic internal symmetry are due to the interplay between gravity and electroweak scale physics in the early universe. The time-independent characteristic number associated with this symmetry is found in terms of the Planck energy and the electroweak energy scale. Cosmic internal symmetry provides a framework which suggests a consistent solution to both the ‘cosmic coincidence problem’ and the ‘naturalness problem’ that have been considered as the most severe challenge to current concepts in cosmology and fundamental physics.

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1 Introduction

The mystery of the cosmological constant, or cosmic vacuum, is probably the most pressing obstacle to significant improving both fundamental cosmological theories and the models of elementary particle physics. The problem arises because in the standard framework of low energy physics, there appears to be no natural explanation for vanishing or extreme smallness of the vacuum density. Why is it $10^{-123} M_{Pl}^4$? There is another aspect of the problem: why is the vacuum density comparable to the present matter density in the universe? In seeking to resolve this problem, one naturally wonders if the real world may somehow be interpreted in terms of symmetry that can relate vacuum to matter.

This must obviously be symmetry of non-geometric nature, like internal symmetry which is widely used in particle physics. Such a symmetry is not related to space-time and refer to a correspondence in the properties of elementary particles and their families. For instance, there is internal symmetry between neutron and proton, which reveals in the fact they behave similarly in strong interactions. These two particles constitute together a family (doublet) of particles, and the family is characterized by a quantum number called isospin, or isotopic spin, which is equal to 1/2, in this case. Isospin is also attributed to other hadrons, and total isospin is conserved when particles undergo strong interaction. Internal symmetries are obviously useful in classifying particles and in leading to some selection rules in particle transformations.

In cosmology, a special correspondence can be recognized, as I will show below, in genuine physical properties of the components of cosmic medium. These components, which are often called now the forms of cosmic energy, are vacuum (V), cold dark (D) matter, baryons (B) and radiation (R), or ultra-relativistic energy, which includes the cosmic microwave background (CMB) photons and other possible light or massless particles (neutrinos, gravitons, etc.) of cosmological origin. This ‘cosmic family’ of energy forms can be characterized by a time-independent number, called the Friedmann number hereafter, which is the same, numerically, for each of the energy forms.

This new phenomenon may indeed be identified as a kind of symmetry, if one uses a universal operational definition of symmetry by Weyl (1951). According to Weyl (1951),
symmetry exists, if there is an object which remains unchanged after being affected by different operations. The numerical value of the Friedmann number may be considered as an object of this kind, since it remains unchanged being calculated for each of the energy forms in a unified manner. The evaluations of the characteristic number for different energy forms (at any moment of time) constitute a set of operations that can be performed without changing the object.

This cosmic internal symmetry is associated with a conservation of the Friedmann number, which remains constant during all the time when the cosmic energy forms exist in nature.

Cosmic internal symmetry is not perfect; the Friedmann number is not exactly, but only approximately, on the order of magnitude, the same, for the four energy forms. As Okun (1988) mentions, the concept of symmetry is closely related to the idea of beauty, and the true supreme beauty needs some slight symmetry breaking to acquire a mysterious and attractive quality of non-finito...

The origin and physical nature of cosmic internal symmetry are argued to be due to the interplay between electroweak-scale physics and gravity in the early universe. This enables to found the characteristic number in terms of the Planck energy scale and the electroweak energy scale.

Since cosmic internal symmetry relates vacuum to non-vacuum forms of cosmic energy, it can really provide a framework which suggests a consistent solution to both aspects of cosmic vacuum problem mentioned above.

Historically, internal symmetry between baryons and radiation was first recognized soon after the discovery of the CMB (Chernin 1968).

2 Friedmann integrals

There are four major energy forms in modern cosmological models, and cosmic vacuum is one of them. As is well-known, the initial idea of cosmic vacuum – in the form of cosmological constant – was suggested by Einstein in 1917, and after the discovery of the cosmological expansion, he discarded this idea. But actually Einstein believed that
the ultimate fate of the cosmological constant could have to be determined by physical experiments and astronomical observations which would directly examine the effects of cosmic vacuum in the real universe. We know now that observational data have recently provided strong evidence in favor of cosmological constant. The crucial argument has come from the observations of high-redshift supernovae (Riess et al. 1998, Perlmutter et al. 1999), and this has been also supported by considerations concerning the cosmic age, the large-scale structure, the CMB anisotropy in combination with cluster dynamics, the dynamics of the Hubble local flow, etc. (see Cohn 1998, Carol 2000, Bahcall et al. 2000, Sahni & Starobinsky 2000, Chernin 2001 and references therein).

The density of cosmic vacuum has proven to be larger than the total density of all non-vacuum forms of cosmic energy, which are dark matter, baryons, and radiation. The best fit concordant with the bulk of all observational evidence today (see the references above) is provided by the following figures for the densities of the forms of energy measured in the units of the critical density:

\[
\begin{align*}
\Omega_V &= 0.7 \pm 0.1, \\
\Omega_D &= 0.3 \pm 0.1, \\
\Omega_B &= 0.02 \pm 0.01, \\
\Omega_R &= 0.6\alpha \times 10^{-4},
\end{align*}
\] (1)

where \(1 < \alpha < 10^{-30}\) is a dimensionless constant factor that accounts for non-CMB contributions to the relativistic energy. With the Hubble constant \(h_{100} = 0.65 \pm 0.10\), the figures lead to either an open cosmological model or a spatially flat model.

Note that the accuracy in these figures seems to be somewhat overestimated here; perhaps a more reasonable estimate for the observation error may be ±0.2 (if not ±0.3), rather than the formal figure ±0.1. Anyway this is not essential for my discussion now: the cosmic phenomenon I study is measured at the level of orders of magnitude, not tens percent, so my considerations are not affected by these details.

Let us turn now to the Friedmann general solution written for the four cosmic energies of Eq.1:

\[
\int da(A_V^{-2}a^2 + 2A_D a^{-1} + 2A_B a^{-1} + A_R^2 a^{-2} - K)^{-1/2} = t,
\] (2)

were \(a(t)\) is the curvature radius and/or a scale factor of the model, \(K = 1, 0, -1\), accordingly to the sign of the spatial curvature.

Quantities \(A_D, A_B, A_R\) are constants that come as integrals from the Friedmann
‘thermodynamic’ equation which is equivalent to energy and entropy conservation relation of dark matter, baryons, and radiation, respectively, in a co-moving volume:

\[ A = \left( \frac{1 + 3w^2}{2} \right)^2 \kappa \rho_0^3 (1 + w) \left[ \frac{1}{1 + 3w} \right]^{\frac{1}{1 + 3w}}. \] (3)

Here \( w = p/\rho \) is the constant pressure-to-density ratio for a given energy form; \( w = 0, 0, 1/3 \) for dark matter, baryons and radiation, respectively; \( \kappa = 8\pi G/3 = (8\pi/3)M_{Pl}^2 \); the Planck energy \( M_{Pl} = 1.2 \times 10^{19} \) GeV.

It is interesting that the integral for vacuum, \( A_V \) in Eq.(1), is also given by the same general relation of Eq.(3), if one puts there \( w = -1 \), though the interpretation in terms of particles does not obviously work for vacuum. It indicates that the physical sense of all the four constants cannot be simply reduced to the energy and entropy conservation or number-of-particle conservation, generally. In any case, the existence of the integrals means that there is no energy exchange among all the four forms of cosmic energy.

The integral for pressure-free matter appeared in the Friedmann cosmology papers and was denoted as \( A \) (see Eq.(8) of his 1922 paper). The integrals of Eq.(3) will be below referred to as the Friedmann integrals.

The Friedmann integrals \( A_V, A_D, A_B, A_R \) given by Eq.(3) are genuine constant characteristics for the respective forms of energy during all the time when each of the energies exists. Each of the energies is represented in Eq.(2) by its corresponding integral independently from other components. Being constants of integration, the integrals are completely arbitrary, in the sense that the Friedmann equations provide no limitations on them, except for trivial ones. From the view point of physics, the integrals are determined by ‘initial conditions’ at the epoch of the origin of the forms of energy in the early Universe; at that time, each of the energies acquires its own integral as a natural quantitative characteristic, which is then kept constant in time. At each moment of time, the Friedmann integrals can be estimated numerically for the corresponding values of the energy densities and the function \( a(t) \). Empirically, the integrals are evaluated for the present-day figures of these values.
3 Symmetry

For the present vacuum domination epoch, one has from Eq.2 a well-known particular solution that describes the expansion controlled by vacuum only:

\[ a(t) = A_V f(t), \quad f(t) = \sinh(t/A_V), \exp(t/A_V), \cosh(t/A_V), \]

(4)

for open, spatially flat and close models, respectively. The present-day \( t = t_0 \simeq 15 \pm 2 \) Gyr value of \( a(t) \) estimated with the use of this solution and the observed Hubble constant is approximately \( a(t_0) \sim A_V \), for all the three models.

Now the numerical evaluation of the four Friedmann integrals can easily be made with the figures of Eq.(1) and with \( a \sim A_V \):

\[ A_V = (\kappa \rho_A)^{-1/2} \sim 10^{42} \text{GeV}^{-1} \sim 10^{61} M_{Pl}^{-1}, \]

(5)

\[ A_D = \frac{1}{4} \kappa \rho_D a^3 \sim 10^{41} \text{GeV}^{-1} \sim 10^{60} M_{Pl}^{-1}, \]

(6)

\[ A_B = \frac{1}{4} \kappa \rho_B a^3 \sim 10^{40} \text{GeV}^{-1} \sim 10^{59} M_{Pl}^{-1}, \]

(7)

\[ A_R = (\kappa \rho_R)^{1/2} a^2 \sim 10^{40} \text{GeV}^{-1} \sim 10^{59} M_{Pl}^{-1}. \]

(8)

The integrals (that have the dimension of the length) are evaluated for the open model with \( a(t_0) \sim A_V \). It is easy to see that the evaluation for the flat (with the scale factor normalized as in Eq.(4)) and close models gives rise to similar results, on the order of magnitude. In the estimation of \( A_R \), a conservative value \( \alpha = 10 \) is adopted.

As one sees from the set of the relations above, the numerical values of the four integrals have proven to be close to each other within two orders of magnitude, and this result may be summarized in a compact formula (Chernin 2001b):

\[ A_V \sim A_D \sim A_B \sim A_R \sim 10^{60 \pm 1} M_{Pl}^{-1}. \]

(9)

If this is not a numerical accident, the coincidence of the four Friedmann integrals presents a new epoch-independent phenomenon in cosmology.

The four Friedmann integrals exist in the Universe since the epoch at which the four major forms of energy came to existence themselves, e.g. at least after \( t \sim 1 \) sec, and will exist until the decay of the protons at \( t \geq 10^{31-32} \) yrs or/and the decay of the particles
of dark matter. In the beginning of this time interval, the vacuum density is about forty
orders of magnitude less than the density of R-energy that dominates at that epoch;
but the constants $A_A$ and $A_R$ are as close at $t \sim 1$ sec as they are in Eq.(9). In future,
the scale factor will change in orders of orders (!) of magnitude during the life-time of
the proton, and so the densities of D-, B-, and R-energies, as well as the ratios of these
densities to the vacuum density, will change enormously. But the four constant numbers
of Eq.(9) will remain the same keeping their near-coincidence for all this future time.

In terms of the Friedmann integrals, none of the energy forms, vacuum including,
looks preferable. While they are very different in their observational appearance and time
behaviour, all of them are characterized by the same (approximately) genuine constant
quantity $A \sim A_V \sim A_D \sim A_B \sim A_R$, which will be called the Friedmann number. The
equality of the energy forms, in terms of the Friedmann integrals, indicates the existence
of a special kind symmetry that relates vacuum to non-vacuum forms of cosmic energy.

It is clear that such a symmetry does not concern space-time, in contrast to, say,
isotropy of the 3D space of the Friedmann model or 4D space-time of the de Sitter model.
In this sense, this non-geometric symmetry is similar to internal symmetries in particle
physics, for instance to symmetry between neutron and proton (mentioned in Sec.1).

This cosmic internal symmetry can also be described in a more formal way. Indeed,
the Friedmann number is a mathematical object that appears the same (approximately)
being evaluated for each of the four energies. In this formulation, new symmetry satisfies
the general operational definition of symmetry by Weyl (1951); the evaluations of the
number for each of the energy forms constitute a set of operations that can be performed
without changing the object.

This symmetry is not perfect, and its accuracy is within a few percent, on logarithmic
scale, according to Eqs.(5-9).

Cosmic internal symmetry is associated with a conservation law, since the Friedmann
number is an epoch-independent constant.

To conclude this empirical part of my discussion, let me note that, historically, in-
ternal symmetry between two forms of cosmic energy, namely baryons and radiation,
was first recognized (Chernin 1968) soon after the discovery of the CMB. The sig-
nificance of this (even partial) symmetry is obvious from the fact that the relation
\[ A_B \sim A_R \sim 10^{59} M_{Pl}^{-3} \]
enables alone to quantify such things as the baryon-antibaryon asymmetry of the Universe, the entropy per baryon, the light-element production in the nucleosynthesis, the epoch of hydrogen recombination, the present-day temperature of CMB, etc.

4 Vacuum energy scale

In any fundamental unified theory, the physical nature of cosmic internal symmetry would have to be explained, and the value of the Friedmann number would have to be calculable. This seems to be a rather remote goal. Nevertheless, one may try to identify a clue physical factor that might determine both symmetry and numerical value of the number.

Let me start this theory part of the discussion with some remarks on the physical nature of cosmic vacuum. If one assume that the vacuum energy is completely due to zero oscillations of quantum fields (as it was suggested not once since the 1930-s – see, for instance, a review in Dolgov et al. 1988), the vacuum density is given by an integral over all frequencies of the zero oscillations. As is clear, this would give infinite value for the density. One may cut off the range of the frequencies, introducing a maximal frequency \( \omega_V \); then the integral takes a form: \( \rho_V \sim \omega_V^4 \) (as it can be seen, for instance, from dimension considerations). With the observed vacuum density, one finds that the cut-off frequency \( \omega_V \sim 10^{-31} M_{Pl} \).

Then one may try to put this maximal frequency into the cosmological context and compare it with the rate of cosmological expansion in the early Universe \( 1/t \sim (G\rho)^{1/2} \); here \( \rho \sim \rho_R \sim T^4 \), and \( T \) is the temperature of radiation which dominates at that times. From this, one finds that \( \omega_V \sim 1/t \) at the epoch, when \( T \sim 10^{-16} M_{Pl} \simeq 1 \text{ TeV} \). The latter value is close to the electroweak energy scale \( M_{EW} \), and therefore \( \omega_V \sim M_{EW}^2/M_{Pl} \).

Accordingly, the vacuum energy scale \( M_V \) may be introduced:

\[ M_V \sim \omega_V \sim GM_{EW}^2/l_{Pl} \sim (M_{EW}/M_{Pl})^2 M_{Pl} \sim 10^{-31} M_{Pl}. \]  

(10)

The vacuum energy scale \( M_V \) is much less than the characteristic energy scales in
particle physics; it means that very-low-energy physics is responsible for the nature and structure of cosmic vacuum. According to Eq.(10), this very-low-energy physics is associated with electroweak scale physics and gravity. As is seen from Eq.(10), the energy scale $M_V$ is the gravitational potential energy (in absolute value) of two masses $M_{EW}$ each separated by the distance of the Planck length: $M_V \sim GM_{EW}^2/l_{Pl}$.

With the vacuum energy scale, the vacuum density is

$$
\rho_V \sim M_V^4 \sim (M_{EW}/M_{Pl})^8 M_{Pl}^4.
$$

(11)

Note that the energy scale of Eq.(10) was mentioned by Antoniadis et al. (1998); the relation of Eq.(11) was found also in a field-theoretic model (Arkani-Hamed et al. 2000) – unfortunately, under some arbitrary and rather strong additional assumptions.

5 Interplay between gravity and electroweak scale physics

The considerations above suggest that the electroweak scale physics and also gravity might determined observed density of cosmic vacuum. This ‘electroweak-gravity’ physics may also be the major mediator between vacuum and non-vacuum forms of cosmic energies in the processes that might develop in the early Universe at the epoch of TeV temperatures. If so, the same processes might be behind cosmic internal symmetry.

In a search for theory equations that could connect the Friedmann integrals with each other, let me use a standard freeze-out model to show how – in principle – the interplay between gravity and electroweak scale physics might develop in early universe. In the model, non-relativistic dark matter is considered as thermal relic of early cosmic evolution (see, for instance, the books by Zeldovich and Novikov 1983, Dolgov et al. 1988, Kolb and Turner 1990, and especially a recent work by Arkani-Hamed et al. 2000). In the version discussed below, the model is incomplete: baryonic energy is not included in it, and so baryogenesis at TeV temperatures has to be studied separately (but, perhaps, not independently) of the model. As for vacuum, dark matter and radiation, they will be represented in the model by the corresponding Friedmann integrals $A_V, A_D, A_R$.

According to the model, for stable (or long-living) particles of the mass $m$, the abundance freezes out when the temperature falls to the mass $m$ and the expansion rate
1\/t starts to win over the annihilation rate, $\sigma n$, where the annihilation cross-section $\sigma \sim m^{-2}$. So that at that moment the particle density is

$$n \sim 1/(\sigma t) \sim m^2(G\rho_R).$$

(12)

Using Eq.(3) for $A_D$ and $A_R$ and putting $\rho_D \sim mn$, one finds:

$$A_D \sim a(t)m^3M_{Pl}^{-2}A_R.$$ 

(13)

One also has at that moment $\rho_R \sim m^4$, and because of this

$$A_R \sim a(t)^2m^2M_{Pl}^{-1},$$

(14)

where $a(t) \sim A_V(1+z)^{-1}$, and $z$ is the redshift at the freeze-out epoch; in this way, the vacuum integral comes to the model.

One may specify the underlying fundamental physics, referring to a special significance of the electroweak scale physics, as it was mentioned above, and assume that only two fundamental energy scales are involved in the process, namely $M_{EW}$ and $M_{Pl}$. If so, it is natural to identify the mass $m$ with the electroweak energy scale $M_{EW}$.

The further treatment of the model can be carried out in two different ways.

1. One may use the relation for the vacuum density in terms of the two fundamental energy scales, $M_{EW}$ and $M_{Pl}$, as given by Eq.(11). With this density, the vacuum integral is

$$A_V \sim (M_{Pl}/M_{EW})^4M_{Pl}^{-1}.$$ 

(15)

Arguing along this line, one may expect that the redshift $z$ at the freeze-out epoch may be given by a simple combination of the same two mass scales:

$$z \sim M_{Pl}/M_{EW}.$$ 

(16)

Now the model is described by a system of four algebraic Eqs.(13-16) (with $m = M_{EW}$) for the four numbers $A_D, A_R, A_V, z$. The solution of the system is:

$$A_M \sim A_R \sim A_V \sim (M_{Pl}/M_{EW})^4M_{Pl}^{-1}.$$ 

(17)

Thus, in this treatment of the model (Chernin 2001a,c), the coincidence of the three Friedmann integrals appears as a direct result of the freeze-out process mediated by
the electroweak scale physics. This physics determines also the numerical value of the integrals.

2. Treating the same model in another way, one may not use the relation for vacuum density given by Eq. (11), but instead take into account the empirical equality of Eq. (9). Then, turning to Eqs. (13, 14), one can put there \( A_V \sim A_D \sim A_R \sim A \), where, as above, \( m \) is identified with \( M_{EW} \). Now one has the following solution to the equations of the model:

\[
\begin{align*}
    z & \sim \frac{M_{Pl}}{M_{EW}}, \\
    A & \sim \left( \frac{M_{Pl}/M_{EW}}{M_{EW}} \right)^4 M_{Pl}^{-1},
\end{align*}
\]

(18)

(19)

Thus, the model in its second version gives the value of the Friedmann integral \( A \) and the corresponding redshift in terms of two fundamental energy scales. In this case, the expression of Eq. (11) for the vacuum density follows directly as a result of the model.

Following Arkani-Hamed et al. (2000) and another recent work by Kawasaki et al. (2000), one may introduce the ‘gravitational scale’ \( M_G \), or the ‘reduced’ Planck scale \( m_{Pl} \), instead of the standard Planck scale: \( M_G \simeq m_{Pl} \simeq g M_{Pl} \), where \( g \simeq 0.1 - 0.3 \).

The dimensionless factor \( g \) accounts for the fact that the gravity constant \( G \) enters the exact relations in combinations like \( 8\pi G, 6\pi G, \) or \( 32\pi G/3 \). Similarly, a few dimensionless factors, like the effective number of degrees of freedom, etc., may also be included in the model – see again the books mentioned above. With this minor modification, one gets finally:

\[
A \sim g^4 \left( \frac{M_{Pl}/M_{EW}}{M_{EW}} \right)^4 M_{Pl}^{-1} \sim 10^{61\pm1} M_{Pl}^{-1}, \quad w = [-1, 0, 1/3].
\]

(20)

A quantitative agreement with the empirical result of Eq. (9) looks satisfactory here.

Similarly, the vacuum density is \( \rho_A \sim g^8 \left( \frac{M_{Pl}/M_{EW}}{M_{EW}} \right)^8 M_{Pl}^4 \sim 10^{-122\pm2} M_{Pl}^4 \).

The numerical value of the redshift \( z \sim g M_{Pl}/M_{EW} \sim 10^{15} \), and so the temperature at the freeze-out is \( T \sim 1 \text{ TeV} \sim M_{EW} \), which reflects once again the central role of the electroweak energy scale in the physical processes involved in the interplay between vacuum and the non-vacuum forms of cosmic energy.

To summarize the results of the model in its both versions, the freeze out shows how – at least, in principle – the nature of the symmetry of cosmic energy forms can be treated
in terms of fundamental physics. It demonstrate also that the Friedmann number (and therefore the vacuum density) might indeed be calculable in electroweak-gravity physics.

6 Cosmic coincidence problem

There are two problems that have been reasonably recognized as the most severe challenge to the current concepts in cosmology and theoretical physics. These are the cosmic coincidence problem and the naturalness problem. Let me show that cosmic internal symmetry provides a framework, within which a consistent solution to both problems can be suggested. The two problems can be treated as two inter-related ‘secondary’ aspects of a more fundamental phenomenon of symmetry.

The cosmic coincidence problem is seen from Eq.(1): the density of cosmic vacuum is near-coincident with the density of dark matter and also with the densities of the two other forms of non-vacuum energy. Why this is so?

Indeed, the four energy forms are very different in their physical structure, appearance and time behaviour; vacuum produces acceleration of the cosmic expansion, while the three other forms produce deceleration; dark matter is non-luminous, while baryons are visible; dark matter and baryons are non-relativistic, while radiation is ultra-relativistic, etc.

One possible approach to the problem would be to assume that the acceleration of the expansion is produced by non-vacuum energy which has negative pressure and negative effective gravitating density (Peebles and Ratra 1988, Frieman and Waga 1998, Caldwell and Steinhardt 1998, Caldwell et al. 1998, Zlatev et al. 1999, Wang et al. 2000). This energy form, called quintessence, can naturally be realized in some scalar field models in which the field depends on time, and so the density of quintessence is diluted with the expansion. If so, the densities involved in the observed cosmic coincidence are all diluted, which makes them seemingly more similar to each other. Quintessence density might temporarily or even always be comparable to the density of dark matter. Although such an idea may make the closeness of all cosmic densities natural, it does not explain the coincidence that the quintessence field becomes settled with a fi-
nite energy density comparable to the matter energy density just now (see, for instance, Arkani-Hamed et al. 2000, Weinberg 2000).

The analysis of Secs. 2, 3 has led to the recognition of the tetramerous coincidence of time-independent constant numbers – in contrast to the epoch-dependent (and therefore accidental, in this sense) coincidence of the densities. It is clear from the analysis that the cosmic densities are coincident at the present epoch simply because this is the epoch of the transition from the decelerated matter dominated expansion to the accelerated vacuum domination expansion. Because of cosmic internal (and ‘eternal’) symmetry, the densities must be coincident just now, because $a(t) \sim A_V$ at present:

$$\rho_V \sim \frac{M_{Pl}^2}{A_V^4}, \quad \rho_D \sim \frac{A_V^3}{a^3} \frac{M_{Pl}^2}{A_V^4}, \quad \rho_B \sim \frac{A_V^3}{a^3} \frac{M_{Pl}^2}{A_V^4}, \quad \rho_R \sim \frac{A_V^4}{a^3} \frac{M_{Pl}^2}{A_V^4} \quad (21)$$

Another question is why do we happen to live at a transition epoch? This is among the matters that may be discussed with antropic principle (see, for instance, Weinberg 1987, 2000).

Are there any other forms of cosmic energy with the equation of state $p = w \rho$ in the same family of energies characterized by the known A-number?

If yes, their current densities must be

$$\rho \sim (1 + 3w)^{-2}(M_{Pl}/A)^2 \sim (1 + 3w)^{-2} \rho_V. \quad (22)$$

These densities may be both comparable to or very different from the four observed densities. For instance, quintessence, a completely hypothetical form of energy with equation of state $p = w \rho$, where $-1 < w < -1/3$, would be described by the fifth(!) energy term in the Friedmann formula of Eq.(2) and have a density of the order of the observed vacuum density, if $w$ is not too close to -1/3. If $w$ is very close to -1/3, the corresponding density will be much larger, on the order of magnitude, than the observed densities.

Another extreme case is $w \rightarrow \pm \infty$. In this case, the corresponding density would be very low. As it was demonstrated (Chernin et al. 2001), General Relativity allows, in principle, ‘density-free’ energy forms with $w = \pm \infty$. These extreme energy forms do not play in cosmology because of the high space-time symmetry of the models, but they can produce a rather ‘ordinary’ non-uniform space-time with spherical symmetry.
Finally, are any other energy families with different Friedmann numbers possible in cosmology? No way to approach this question is yet seen...

7 Naturalness problem

The observed density of vacuum conflicts drastically with simple field theoretic expectations. Field theoretic arguments may explain why the vacuum density should be either zero or Planckian, but there is no explanation for a non-zero, tiny and positive vacuum density. This is the well-known ‘naturalness problem in theoretical physics’ (Weinberg 1989, Okun 1988).

In the framework of cosmic internal symmetry, the constant characteristic of physical vacuum $A_V$ finds its symmetrical non-vacuum counterparts in the integrals $A_D, A_B, A_R$ which are also constants. In this framework, cosmic vacuum loses its uniqueness and appears among other cosmic energy forms as an ordinary, ‘regular’ member of the family of cosmic energies. Therefore the observed value of the vacuum density is seen quite ‘natural’, because it is this value that yields to cosmic internal symmetry.

On the contrary, the Plank density would look quite ‘unnatural’ in this context, since the corresponding integral would be much smaller (in 60 orders of magnitude) than the three other integrals. Similarly, zero density for vacuum would give infinite integral...

If cosmic internal symmetry is really a phenomenon of fundamental level, one may say that the symmetry implies that the observed density of vacuum $\rho_V \sim \frac{M_{Pl}^2}{A^4}$.

From the theory point of view, the key point is that the characteristic Friedmann number $A$ is calculable within a simple model (Sec.5) in terms of the Planck energy and the electroweak energy scale. As it was demonstrated above: $A \sim (M_{Pl}/M_{EW})^4 M_{Pl}^{-1}$. With this Friedmann number, cosmic internal symmetry sets the vacuum density to its observed value: $\rho_V \sim 10^{-120} M_{Pl}^4$.

Other attempts to solve the naturalness problems are critically reviewed by Sahni & Starobinsky (2000); see also recent works by Weinberg (2000), Guendelmann (1999), Mongan (2001), Kaganovich (2001), Tye et al.(2001).
8 Summary

From the earliest days of natural philosophy, symmetry has furnished insight into the laws of physics and the nature of the universe. Modern cosmology involves notion of symmetry in a fundamental way. Geometric symmetries of cosmological models is the basic element of current knowledge, and the most important recent discovery in cosmology is related to the symmetry of the 4D space-time of the observed universe: if cosmic vacuum dominates in the dynamics of the cosmological expansion, the 4D geometry is described (approximately) by de Sitter model with its perfect 4D isotropy.

The same observational evidence that has led to the conclusion about geometric symmetry suggests also the existence of non-geometric symmetry in the universe. New symmetry is related to not space-time, but to its energy content. This cosmic internal symmetry reveals a special correspondence in the genuine physical properties of physical vacuum and non-vacuum forms of cosmic energies, which are dark matter, baryons and radiation. The four energies look very different from each other and behave differently in space and time, but all of them are characterized by a common genuine physical quantity, called the Friedmann number. The characteristic Friedmann number is eternal, practically. It conserved in time during all the epoch, in which vacuum, dark matter, baryons and radiation are present in nature.

Examining the physical nature of cosmic internal symmetry leads to the conclusion that symmetry might be due to the interplay between gravity and electroweak scale processes developed in the early universe at TeV temperatures. This way the numerical value of the Friedmann number proves to be calculated in terms of the elecroweak energy scale and the Planck energy.

The concept of cosmic internal symmetry demonstrates its productivity in application to the most challenging problems of cosmology and fundamental theory. The cosmic coincidence problem and the naturalness problem are both understood now in the framework of symmetry which is the more fundamental physical phenomenon. Cosmic internal symmetry implies that the observed densities of cosmic energy forms must be nearly coincident at the present epoch, and the vacuum density must be at its observed level since the early stages of the cosmological expansion and practically forever.
Interesting new grounds for further discussion of cosmic internal symmetry can be provided by recent ideas (see, for instance, Maartens 2000) of brane-world scenaria; this issue will be discussed in a separate paper.

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