Energy composition of the Universe:
time-independent internal symmetry

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Abstract
The energy composition of the Universe, as emerged from the Type Ia supernova ob-
servations and the WMAP data, looks preposterously complex, – but only at the first
glance. In fact, its structure proves to be simple and regular. An analysis in terms of
the Friedmann integral enables to recognize a remarkably simple time-independent
covariant robust recipe of the cosmic mix: the numerical values of the Friedmann
integral for vacuum, dark matter, baryons and radiation are approximately identi-
cal. The identity may be treated as a symmetry relation that unifies cosmic energies
into a regular set, a quartet, with the Friedmann integral as its common genuine
time-independent physical parameter. Such cosmic internal (non-geometrical) sym-
metry exists whenever cosmic energies themselves exist in nature. It is most natural
for a finite Universe suggested by the WMAP data. A link to fundamental theory
may be found under the assumption about a special significance of the electroweak
energy scale in both particle physics and cosmology. A freeze-out model developed
on this basis demonstrates that the physical nature of new symmetry might be due
to the interplay between electroweak physics and gravity at the cosmic age of a few
picoseconds. The big ‘hierarchy number’ of particle physics represents the interplay in the model. This number quantifies the Friedmann integral and gives also a measure to some other basic cosmological figures and phenomena associated with new symmetry. In this way, cosmic internal symmetry provides a common ground for better understanding of old and recent problems that otherwise seem unrelated; the coincidence of the observed cosmic densities, the flatness of the co-moving space, the initial perturbations and their amplitude, the cosmic entropy are among them.

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1 Introduction

It is increasingly evident that the Universe is fairly simple in its overall differential geometry. Indeed, all the bulk of observational data indicates that the co-moving space of the Universe is uniform, isotropic and flat. To be exact, it looks very nearly uniform, isotropic and flat. The cosmological solutions have the simplest form for the case of a perfectly symmetrical flat co-moving space, and these solutions provide a good approximation to the real spacetime of the Universe.

Contrary to this, the energy content of the Universe seems to be preposterously complex, if not absurd. According to the current data on distant Ia type supernovae (Riess et al. 1998, Perlmutter et al. 1999) and cosmic microwave background anisotropy (Bennett et al. 2003, Spergel et al. 2003), the major cosmic energy component is dark: cosmic vacuum (which is also called dark energy) and dark matter comprise together more than 95% (in round numbers) the total cosmic energy. The dark sector ingredients are well measured, but poorly understood. Indeed, the microscopic properties of dark energy and dark matter are unconstrained by cosmological observations and remain quite uncertain. ‘Ordinary’ matter of stars in galaxies and intergalactic gas contributes less than 5%, and its physical origin is almost as unclear as the nature of the dark sector. It is embarrassing that only cosmic microwave background radiation which contributes about 0.005% to cosmic energy is well interpreted in its nature and origin.

In this paper, I review first the key observational figures that constitute the current
concordance dataset based mostly on the WMAP observations (Sec.2). I describe also a new impressive idea of a finite Universe derived by Luminet et al. (2003) from the WMAP data. Then I show that a simple regularity can be recognized behind the list of the cosmic energy ingredients. The new regularity is found in terms of the Friedmann integral which serves as a genuine time-independent characteristic of each of the cosmic energies. The numerical values of the integral estimated with the concordance data for cosmic vacuum, dark matter, baryons and radiation prove to be approximately identical, on the order of magnitude. The new regularity does not depend on time, and it is valid whenever cosmic energies exist in nature. It is a time-independent covariant recipe of the cosmic mix (Sec.3).

This result suggests that there exists a special correspondence among the cosmic energy ingredients which may be treated as internal (non-geometrical) symmetry of the cosmic mix (Sec.4). New symmetry unifies the four energy ingredients into a regular set with a common genuine physical parameter which is the Friedmann integral. The physical nature of cosmic internal symmetry can be clarified under the assumption that the dark sector is well described by ‘simple physics’. The simple physics assumption adopts that dark energy is cosmic vacuum with the perfectly uniform density $\rho_V$ and pressure $p_V$ which are also constant in time. Cosmic vacuum with the equation of state $p_V = -\rho_V c^2$ is equivalent to Einstein’s cosmological constant, as it was first recognized by Gliner (1965).

It is also adopted that dark matter is an ensemble of weakly interacting massive particles (WIMPs) which have not yet registered in laboratory experiments. It is proposed that the WIMP mass is near 1 TeV which is the characteristic electroweak energy scale. Accordingly, a special significance in the framework of simple physics is prescribed to the electroweak-scale physics. I demonstrate that the interplay between gravity and electroweak-scale physics might be responsible for the origin of cosmic internal symmetry (Sec.5). A relation between new symmetry and the concept of macroscopic extra dimensions is discussed (Sec.6). Finally, I show that cosmic internal symmetry can shed a light on some basic features of the real Universe that otherwise seem obscure and unrelated (Sec.7). The results are summarized in Sec.8.
2 The concordance figures

The observed part of the Universe referred to as Metagalaxy extends almost up to the principal observation horizon. The most remote observed objects which are quasars and first galaxies are seen at distances of ten billion light years, or \( \sim 10^{28} \) cm, on the order of magnitude. The present-day horizon radius is of the same order of magnitude:

\[
R_0 = ct_0 = 1.2 \times 10^{28} \text{ cm.} \tag{1}
\]

Here

\[
t_0 = 13.7 \pm 0.2 \text{ Gyr} \tag{2}
\]

is the current age of the Universe measured in the proper time, according to the precision data from the WMAP (Wilkinson Microwave Anisotropy Probe) observations. The WMAP data provide a set of cosmological parameters measured or constrained in observations of the temperature variations in the cosmic microwave background (CMB). Together with the data on cosmological supernovae and the results of other modern cosmological observations, the WMAP data constitute the concordance dataset which is the empirical basis of the current standard cosmological model.

The time rate of the evolution of the Universe as a whole, or the rate of the cosmological expansion, is given by the Hubble constant \( H = \dot{R}/R \), where \( R(t) \) is the cosmological scale factor. According to the WMAP measurements in combination with the Hubble Space Telescope (HST) observations and other studies, the present-day Hubble constant

\[
H_0 = 71 \pm 4 \text{ km/s/Mpc}. \tag{3}
\]

With this Hubble constant, the present-day Hubble radius

\[
R_H(t_0) = c/H_0 = 1.3 \times 10^{28} \text{ cm.} \tag{4}
\]

Note a remarkable, almost exact, coincidence of the two times,

\[
t_0 \simeq 1/H_0, \tag{5}
\]

and the two lengths,

\[
R_0(t_0) \simeq R_H(t_0). \tag{6}
\]
This is an example of a number of cosmic coincidences – some understandable, some entirely mysterious – in modern cosmology.

Alongside with the cosmic age and the Hubble constant, the third major cosmological parameter characterizing the present-day epoch of the cosmic evolution is the dimensionless density parameter \( \Omega \equiv \rho / \rho_c \), where \( \rho \) is the total density of all the cosmic energies and \( \rho_c \equiv \frac{3}{8 \pi G} H^2 \) is the critical density. The value of the present-day density parameter given by the WMAP dataset is

\[
\Omega_0 = 1.02 \pm 0.02. \tag{7}
\]

According to the Friedmann theory, if the co-moving 3D space is flat, the parameter is equal to 1. The fact that \( \Omega_0 \) is exactly 1 or practically 1 today is considered a major piece of observational evidence for the flatness of the observed Universe. In accordance with this, the present-day spacetime of the Universe can be described – with good accuracy – by the simplest form of the metric interval:

\[
ds^2 = c^2 dt^2 - R(t)(dx^2 + dy^2 + dz^2), \tag{8}
\]

where synchronous proper time \( t \) and the Cartesian spatial coordinates are used. The only difference here from the Minkowski spacetime of the Special Relativity is in the time dependent scale factor \( R(t) \) which describes the cosmological expansion. It is the scale factor that makes the 4D spacetime non-trivial with non-zero 4D curvature.

The present-day energy content of the Universe is characterized by four major components. The concordance dataset provides the current densities of cosmic vacuum (V), dark (D) matter, baryons (B) and radiation (R):

\[
\Omega_V = 0.66 \pm 0.07; \tag{9}
\]

\[
\Omega_D = 0.29 \pm 0.07; \tag{10}
\]

\[
\Omega_B h^2 = 0.022 \pm 0.001; \tag{11}
\]

\[
\Omega_R h^2 = 4.7 \alpha \times 10^{-5}, \ 1 < \alpha < 10. \tag{12}
\]

Here \( h \) is the Hubble constant \( H_0 \) measured in the units 100 km/s/Mpc. Factor \( \alpha \) accounts non-CMB contributions (neutrinos, gravitons etc.) to the density of cosmic relativistic matter.
The present-day energy densities are given by Eqs. 9-12 in the units of the present-day critical density:

\[ \rho_c(t_0) = \left( \frac{3}{8\pi G} \right) H_0^2 = 0.94 \times 10^{-29} \text{ g/cm}^3, \]  
(13)

Note that the two major cosmic energies, vacuum and dark matter, have comparable densities that differ in not more than a half order of magnitude:

\[ \frac{\Omega_V}{\Omega_D} = 2.6. \]  
(14)

This is one more cosmic coincidence that characterizes the present epoch of the cosmic evolution: the time dependent density of dark matter occurs near the time independent vacuum density. Moreover, the two other densities, baryonic and radiation ones, are also not too far, on the order of magnitude, from the dominant energies. Within four orders of magnitude, all the four energy densities are coincident at present. Why are the densities coincident now? This is what is referred to as the ‘cosmic density coincidence’ problem (see Sec. 8). The density coincidence is clearly a part of a more general problem concerning the physical nature and origin of the cosmic energies.

One of the most drastic implications from the WMAP data is the evidence for a finite Universe (Luminet et al. 2003). The insight into the global structure of the Universe is provided by the power spectrum of the cosmic microwave background anisotropy at the lowest harmonics, or the largest spatial scales. In particular, the quadrupole is only about one-seventh as strong as would be expected in an infinite flat space. A similar effect (while not so dramatic) is observed also for the octopole. The lack of power on the largest scales indicates most probably that the space is not big enough to support them. According to Luminet et al. (2003), the current size of the 3D co-moving volume

\[ R_U(t_0) = (1.03 - 0.82)R_0(t_0). \]  
(15)

It is very near the current horizon radius or the Hubble radius, so that an approximate identity, \( R_0 \approx H^{-1} \approx R_U \), takes place at the present Universe.

A special model – the Poincaré dodecahedral space of positive spatial curvature with the density parameter \( \Omega \approx 1.013 > 1 \) – is demonstrated to reproduce the observed shape of the spectrum better than do models of an infinite space (Luminet et al. 2003; Luminet
2005, Aurich et al. 2004). The figure for the density parameter is compatible with the WMAP limitations $\Omega = 1.02 \pm 0.02$ (see Eq.7). The idea of a finite Universe – even independently of the special model with its rigid geometry and fixed parameters – can be verified by further analysis of the WMAP data and the upcoming Planck data. If confirmed, this is a major discovery about the nature of the Universe (Ellis 2003).

### 3 Recipe of cosmic mix

The list of the energy ingredients (Eqs.9-12) can be rewritten in terms of the Friedmann integral (hereafter FINT) which is a constant genuine physical characteristic of each of the cosmic energies. The FINT enables one to eliminate the effect of cosmological expansion from the description of the cosmic energy composition. Historically, the quantity appeared in Friedmann’s first paper on cosmological expansion (Friedmann 1922) where the length-dimension constant $A$ was introduced to represent non-relativistic matter in the dynamical equation for the cosmological scale factor.

The FINT comes from the Friedmann ‘thermodynamical’ equation which is applied to each of the energy ingredients individually:

$$\frac{\dot{\rho}}{\rho(1+w)} = -3\frac{\dot{R}}{R}. \tag{16}$$

Here the constant pressure-to-density ratio $w = p/\rho = -1, 0, 0, 1/3$ for vacuum, dark matter, baryons and radiation, respectively; $R(t)$ is the cosmological scale factor. The integral of the equation may be given in the form

$$A = [\kappa \rho R^{3(1+w)}]^{\frac{1}{1+3w}}, \tag{17}$$

where $\kappa = \frac{8\pi G}{3c^2}$ and $G$ is the gravitational constant.

Because of their origin from Eq.16 as constants of integration, the values of the FINT for vacuum, dark matter, baryons and radiation are completely independent of each other a priori and not restricted by any theory constraints (except for trivial ones).

In the Friedmann dynamical equation, the four FINT values $A_V, A_D, A_B, A_R$ represent vacuum, dark matter, baryons and radiation, respectively:

$$\dot{R}/c^2 = (A_V/R)^{-2} + A_D/R + A_B/R + (A_R/R)^2 - K. \tag{18}$$
Here \( K \) is the constant which is zero in a model of a flat 3D space. In models of a non-zero 3D curvature, the scale factor \( R(t) \) is usually identified with the curvature radius \( a(t) \), and then \( K = 1, -1 \), in Eq.18. In a finite-size Universe with positive spatial curvature (as in the model by Luminet et al. 2003), the scale factor \( R(t) \) is most naturally identified with the finite size \( R_U(t) \) of the 3D space; in this case, \( K = (R/a)^2 = \text{Const} > 0 \).

It is seen from Eq.17, that the value of the FINT for vacuum does not depend on the scale factor and its normalization; this is a universal constant which is the same in any cosmological model and in any reference frame:

\[
A_V = (\kappa \rho_V)^{-1/2} \simeq \Omega_V^{-1/2} c/H \simeq 1 \times 10^{28} \text{ cm.} \tag{19}
\]

We see now a new remarkable cosmic coincidence – the universal constant length \( A_V \) turns out to be very near the present-day values of the lengths \( R_0, R_H \) and \( R_U \):

\[
R_0(t_0) \sim R_0(t_0) \sim R_U(t_0) \sim A_V. \tag{20}
\]

This triple coincidence is not too mysterious, as we will see in Sec.7.

The FINT values for non-vacuum energies depend on the scale factor and its normalization explicitly. If the Universe is really finite in size, we may use the most natural scale-factor normalization to the size of the cosmic space:

\[
R(t) = R_U(t) \simeq A_V (1 + z)^{-1}. \tag{21}
\]

With this normalization, the FINT non-vacuum values have a clear physical sense. Indeed, the values \( A_D \) and \( A_B \) are determined by the total masses of dark matter, \( M_D \), and the total mass of baryons, \( M_B \), respectively:

\[
A_D = 2\kappa M_D, \quad A_B = 2\kappa M_B. \tag{22}
\]

The FINT value for radiation is determined by the total number of the CMB photons (and other possible relativistic particles), \( N_R \), in the finite-size Universe:

\[
A_R \simeq (\kappa h c)^{1/2} N_R^{2/3}, \tag{23}
\]

where \( h = h/2\pi \), and \( h \) is the Planck constant.
The normalization of Eq.21 may be used as well, if the co-moving space is infinite; in this case, it may be considered as the normalization to the size of the Metagalaxy. Then the constant total figures $M_D$, $M_D$ and $N_R$ will be related to the whole visible space. The quantitative results for the FINT (see below) will be the same in both cases, since the size of the Metagalaxy is near both $c t_0$ and $A_V$, at the present epoch.

With the data of Eqs.10-12 and the normalization of Eq.21, the FINT non-vacuum values are

$$A_D = \kappa \rho_D R^3 \simeq \Omega_D R^3 H^2 \simeq \Omega_D c / H \simeq 3 \times 10^{27} \, \text{cm}. \quad (24)$$

$$A_B = \kappa \rho_B R^3 \simeq \Omega_B R^3 H^2 \simeq \Omega_B c / H \simeq 3 \times 10^{26} \, \text{cm}. \quad (25)$$

$$A_R = (\kappa \rho_R)^{1/2} R^2 \simeq (\Omega_R \alpha)^{1/2} c / H \simeq 1 \times 10^{26} \, \text{cm}, \quad (\alpha \simeq 1). \quad (26)$$

Eqs.20,24-26 give a time-independent recipe of the cosmic mix. The recipe proves to be simple – all the FINT values are nearly identical, on the order of magnitude:

$$A_V \sim A_D \sim A_B \sim A_R \sim 10^{27\pm 1} \, \text{cm} \sim 10^{60\pm 1} M_{Pl}^{-1}. \quad (27)$$

Here the ‘natural units’ are used in which the speed of light, the Boltzmann constant and the Planck constant are all equal to unity: $c = k = \hbar = 1$. The Planck mass $M_{Pl} = G^{-1/2} \simeq 1.2 \times 10^{19} \, \text{GeV}$. Though the FINT identity of Eq.27 is found with the data on the present (special) epoch of cosmic evolution, it is valid for all the epochs whenever the four energies exist in nature.

The FINT identity for radiation and ‘ordinary matter’ was first found (Chernin 1968) soon after the CMB discovery. With the discovery of dark matter and cosmic vacuum, the identity was extended to all the four energies (Chernin 2001) (in these two works – contrary to the present one, – a normalization of the scale factor to the curvature radius was used).

The result of Eqs.20, 24-26 may be rewritten as a set of four dimensionless constant quantities defined as follows:

$$\text{mix} \equiv 10 A / A_V. \quad (28)$$
With the figures above, we have:

\[ \text{mix} \simeq [10, 3, 0.3, 0.1], \]  

where the four dimensionless numbers relate to vacuum, dark matter, baryons and radiation, respectively. These (somewhat ‘rounded up’) numbers are all of the order-of-unity, if one agrees, as usual, that a number between 0.1 and 10 is of the unity order.

4 Cosmic internal symmetry

According to one of the most general definitions, any symmetry describes a similarity of objects in a set (Weyl 1951). If symmetry does not concern spacetime relations, it is referred to as internal symmetry – in contrast to geometrical symmetries. A typical example of internal symmetry is symmetry between the proton and the neutron: the particles differ in mass, electric charge, life-time, etc., but they constitute a set which is a hadron doublet with a common constant value (1/2) of isotopic spin.

In the same way, the FINT identity of Eq.27 describes the similarity of the four cosmic energy ingredients. This similarity may be referred to as ‘cosmic internal symmetry’ (hereafter COINS). The energy ingredients are obviously different in many respects, and it is most essential that one of them is vacuum, while the three others are non-vacuum energies. Despite this and other differences, the four energies constitute a regular set – a quartet – with the Friedmann integral \( A \) as its common (approximately identical for all the members) genuine constant physical parameter.

Briefly, some major features of new symmetry:

1. COINS is time-independent symmetry in the evolving Universe. It exists at least since the earliest epoch of the cosmic history which can be traced with the current observational data – this is the epoch of the Big Bang Nucleosynthesis. The FINT for baryons exists since the epoch of \( \sim 1 \) GeV temperatures, redshifts \( \sim 10^{12} \) and the cosmic age \( \sim 10^{-6} \) sec when baryons became non-relativistic. In the future, it exists until the decay of the proton, i.e. to the cosmic age of \( \geq 10^{32} \) years. It means that the FINT for baryons is the same over 45 decades of the cosmic time. The FINTs for vacuum and radiation are constant even for longer times: they are practically eternal.
The FINT for dark matter exists for all the cosmic past when the dark matter particles are non-relativistic; it is since the cosmic age of a few picoseconds, if the exist are ‘weakly interacting massive particles’ (WIMPs) with a mass near 1 TeV (see below).

2. COINS is covariant symmetry, since it is formulated in terms of the FINT which is determined by the scalar (invariant) quantities \(M_D, M_B, N_R, \rho_V\). The FINT is associated with the four-dimensional Riemann invariant, \(\mathcal{R} = 8\pi G(\rho - 3p)\). In the limit of infinite time \(\mathcal{R} \rightarrow 32\pi G\rho_V = 12/A_V^2\), \(t \rightarrow \infty\). If cosmic matter is initially generated in the form of massless particles (and the particles acquire mass later via, say, the Higgs mechanism), the invariant is the same in the opposite time limit as well: \(RI \rightarrow 12/A_V^2\), \(t \rightarrow 0\). Identified in the co-moving space, COINS exists in any other spatial sections and in the 4D spacetime as a whole.

3. COINS is not exact, but approximate symmetry, since the four FINT values differ within two orders of magnitude. At fundamental level, its violation might be related to, for instance, fundamental particle-antiparticle asymmetry which is most probably involved in baryogenesis.

4. COINS implies that there is a correspondence between the total dark matter mass, the total baryonic mass and the total number \(N_R\) of relativistic particles (the CMB photons):

\[
N_R^{2/3} \sim M_D/M_{Pl} \sim M_B/M_{Pl}.
\]

5. COINS implies also that there is a consistency of extensive cosmic quantities \(M_D, M_B, N_R\) and the intensive quantity \(\rho_V\):

\[
\rho_V \sim (M_{Pl}/M_D)^2 M_{Pl}^4 \sim (M_{Pl}/M_B)^2 M_{Pl}^4 \sim N_R^{-4/3} M_{Pl}^4.
\]

6. Due to COINS, the Friedmann dynamical equation (Eq.18) contains not four empirical energy parameters, but (as it was said in the section above) in fact only one universal empirical parameter \(A\) which is the Friedmann integral common for all the four energy ingredients – in the first and main approximation.
5 Gravity-electroweak interplay

What is the physical nature of new symmetry? It is obvious that the real understanding of the problem is hardly possible now because the origin of cosmic vacuum, dark matter and baryons is yet completely unknown. However there is a reasonable approach to the problem: this is the assumption that the cosmic energy ingredients are well described by ‘simple physics’. A simple physics approach adopted here assumes that dark energy is vacuum with constant density and $w = -1$ (as above). Also dark matter is WIMPs which are stable or long-living thermal relics of the early Universe. Under these (and some other – see below) assumptions, a model can be developed that describes how, in principle, COINS might originate in the early Universe.

The model addresses physical processes at the epoch of electroweak-scale temperatures, $T \sim M_{EW} \sim 1$ TeV. A reason for that is the special significance of the electroweak energy scale in fundamental physics (Okun 1985, Rubakov 1999, Weinberg 2000). At the epoch of TeV temperatures, the cosmic age, $t_{EW}$, is about a few picoseconds, and the horizon radius, $R_{EW}$ is of a fraction of 1 mm.

Two major factors are involved in the model: electroweak-scale physics and gravity which controls the rate of the cosmological expansion. They are represented in the model by two fundamental constants which are the electroweak energy/mass $M_{EW}$ and the Planck mass $M_{Pl} = G^{-1/2}$. The model describes the COINS origin as a result of the interplay between gravity and electroweak physics. The gravity-electroweak interplay reveals itself in the WIMP freeze-out at the $M_{EW}$ temperatures.

The cosmological freeze-out kinetics is well-known (see Zeldovich & Novikov 1982, Dolgov et al. 1988, Kolb & Turner 1990). In a simple version suggested by Arkani-Hamed et al. (2000), the WIMPs freeze out when the temperature $T$ falls to the particle mass $m$ and the expansion rate $1/t$ wins over the annihilation rate, $\sigma n$. Here the annihilation cross-section $\sigma \sim m^{-2}$ and $n$ is the number density of particles. Accordingly, at that moment,

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

The approximate cosmological relation $t \sim (G\rho_R)$ is also used for the early radiation
domination epoch.

Introducing the FINT values for dark matter, $A_D$, and for radiation, $A_R$ and putting $\rho_D \sim mn$, one finds:

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

(33)

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

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

(34)

where $R(t) \sim A_V(1 + z)^{-1}$ is the scale factor (normalized as in Eq.28), and $z$ is the redshift, at the freeze-out epoch. The system of Eqs.32-34 describes the freeze-out kinetics in terms of the FINT values $A_D, A_R, A_V$.

If the system has a solution in terms of $M_{Pl}$ and $M_{EW}$ only, the vacuum density must be (Arkani-Hamed et al. 2000)

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

(35)

With this density, the vacuum integral is

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

(36)

Arguing along this line, one might expect that the mass of the particle must be identified with $M_{EW}$ (the other mass $M_{Pl}$ is enormously large for this) and the redshift $z$ at the freeze-out epoch is a simple combination of the two energy scales:

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

(37)

Then one has the solution of the system:

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

(38)

Thus, the equality of the three FINT values appears as an outcome of the interplay between gravity and electroweak-scale physics which controls the freeze-out kinetics. The model gives also the Friedmann integral in terms of the two fundamental energy scales $M_{Pl}$ and $M_{EW}$.

To refine the quantitative estimates, one may introduce, as usual, a ‘reduced Planck scale’ $\bar{M}_{Pl} = 0.1 M_{Pl}$ which takes into account the effective number of the degrees of
freedom that must be included in the freeze-out kinetics and also factors like \(8\pi/3\) or \(32\pi/3\) in exact cosmological formulas (see Zeldovich & Novikov 1982, Kolb & Turner 1990). Then one gets:

\[
A \sim (\bar{M}_{Pl}/M_{EW})^4 M_{Pl}^{-1} \sim 10^{60} M_{Pl}^{-1}.
\]

(39)

A quantitative agreement with the empirical result of Eq.27 is quite satisfactory here.

The big dimensionless ratio

\[
X = \bar{M}_{Pl}/M_{EW} \sim 10^{15}
\]

(40)

that enters the result is known as the hierarchy number, in particle physics. It characterizes the huge gap between the two fundamental energies. The nature of the gap is not well understood, and this is considered as one of the most difficult problems in fundamental theory (see more about this in Sec.5 below).

Note that the freeze-out model is not complete: it does not account for the FINT value for baryons. It may, however, be assumed, that baryons can be included in a more general model of gravity-electroweak interplay, that assumes that baryogenesis takes place at the electroweak temperatures. Electroweak baryogenesis was proposed by Kuzmin et al. (1985); see also Dolgov (1992) and Rubakov (1999) for a critical review of the problem.

Moreover, the gravity-electroweak interplay might also be responsible for the origin of cosmic vacuum via supersymmetry violation at TeV temperatures (see Zeldovich 1968, Dolgov 2004 and references therein). If so, the epoch of electroweak energies is the real beginning of the evolution described by the current standard cosmological model. At that epoch, cosmic energies come into existence due to a common physical process. Their common origin in the ‘Electroweak Big Bang’ might guarantee, in particular, the internal mutual correspondence among them which manifests itself as COINS, at phenomenological level.
6 COINS and extra dimensions

As is seen from the results of the section above, the hierarchy number $X$ provides COINS (and associated phenomena – see the next section) with a common quantitative measure. It may be expected that if the hierarchy problem is resolved in fundamental physics, it gives a new insight into the nature of COINS and the cosmic energy origin.

Presently, the hierarchy problem is completely open. There is however an interesting recent approach to its understanding that may be useful for cosmology. Arkani-Hamed et al. (1998) proposed an idea of macroscopic extra dimensions to eliminate the energy hierarchy of fundamental theory. The idea assumes that there exist finite (compactified) macroscopic spatial extra dimensions in space. In a finite Universe, the extra dimensions constitute, together with the 3D space, a close multi-dimensional space. This multi-dimensional space is treated as the ‘true space of nature’.

It is also assumed that there is one and only one ‘truly fundamental’ energy scale $M_\ast$ in nature, and that this scale is close to the electroweak scale $M_{EW}$. As for the Planck scale, it is reduced to a combination of the scale $M_\ast$ and the size $R_\ast$ of the compact macroscopic extra dimensions of the true space:

$$M_{Pl} \sim (M_\ast R_\ast)^{n/2} M_\ast.$$  \hfill (41)

Here $n$ is the number of the extra dimensions, which are proposed to be of the same size. Together with the Planck mass, the gravitational constant in three-dimensional space, $G = M_{Pl}^{-2}$, looses its fundamentality and is reduced to a combination of the two truly fundamental constants $M_\ast$ and $R_\ast$.

It is reasonably argued that the case $n = 2$ is the most appropriate one; if so, the size of two extra dimensions is in the millimeter (or submillimeter) range:

$$R_\ast \sim 0.1 \text{ cm}, \quad n = 2.$$  \hfill (42)

It is clear that when the hierarchy number, $X = M_{Pl}/M_{EW}$, is replaced with the product

$$X = M_\ast R_\ast,$$  \hfill (43)
this is not elimination of the hierarchy, but its re-formulation in the new terms of $M_*$ and $R_*$.  

In the multi-dimensional space, all the physical fields, except gravity, are assumed to be confined in the three-dimensional space, or brane. The multi-dimensional physics affects the brane via gravity, and therefore cosmology must be re-formulated in terms of the true fundamental constants. In particular, one has from Eq.38 for the FINT:

$$A \sim (M_* R_*)^{(3/2)n} M_*^{-1}. \quad (44)$$

In the case of two extra dimensions:

$$A \sim (M_* R_*)^2 R_*, \quad n = 2. \quad (45)$$

Then the vacuum density

$$\rho_V \sim (M_* R_*)^{-2n} M_*^4, \quad (46)$$

and in the case of two extra dimensions:

$$\rho_V \sim R_*^{-4}; \quad n = 2. \quad (47)$$

This is a surprising result: the vacuum density proves to be expressed via the size of the extra dimensions alone. The new relation is free from any signs of the hierarchy effect (Chernin 2002b). In this important case, the hierarchy is really eliminated from the multi-dimensional physics.

According to the idea of extra dimensions, all we observe in three-dimensional space are shadows of the true multi-dimensional entities. In particular, it may be assumed that true vacuum exists in the multi-dimensional space, and the observed cosmic vacuum is not more than its 3D projection to the cosmological brane. This is possible, only if vacuum is due to gravity alone and not related to the fields of matter. In this case, the true vacuum is defined in the multi-dimensional space, and its density $\rho_{V5} \sim R_*^{-6}$, for two extra dimensions. This ‘true vacuum’ is also free from the hierarchy effect.

But if the observed vacuum density is due to supersymmetry violation (Zeldovich 1968), vacuum is confined in the brane – together with fermionic and bosonic fields of
matter. In such a case, a real sense of the relation between the vacuum density and the extra-dimension size would be not obvious.

Thus, taking the relations of this section at face, one may conclude that the basic cosmological parameter $F_{\text{INT}}$ and also $\rho_V$ have roots in the extra-dimension physics, – if extra dimensions really exist.

It is expected that the idea of macroscopic extra-dimensions will be directly tested with the Big Hadron Collider and in submillimeter laboratory experiments in the coming several years – perhaps, at the same time when the Planck mission will test the compactness of the finite 3D space on cosmological scales.

7 COINS related figures and phenomena

Cosmic internal symmetry offers a productive common ground for better understanding of a number of cosmological problems that otherwise seem unrelated. The problems concern a wide range of basic figures and phenomena.

7.1 Cosmic density coincidence

According to the WMAP results and all the concordance data (Sec.2), the densities of the two energies in the dark sector of the cosmic mix, $\rho_V$ and $\rho_D$, are nearly coincident at the present epoch. Why should we observe them to be so nearly equivalent right now? While the vacuum density (or the cosmological constant) is by definition time independent, the dark matter density is diluted as $R^{-3}$ as the Universe expands. Despite the evolution of $R(t)$ over many orders of magnitude, we appear to live at an epoch during which the two energy densities are roughly the same. This is the ‘cosmic coincidence’ problem which is commonly considered as a severe challenge to the current cosmological concepts (see, for instance, Chernin, 2002, and references therein).

Note that the idea of quintessence was initially introduced in an attempt to eliminate the problem. However it is now clear that quintessence can hardly be useful because the pressure-to-density ratio has recently been found to lie between -1.2 and -0.9 (Perlmutter et al. 2003), which seemingly rules out the idea. Contrary to this, COINS suggests a
natural solution to the problem without any additional assumptions.

In a broader view, all the four energy densities, the two dark ones and the two others, are of nearly the same order of magnitude. Their coincidence is temporary and therefore accidental, in this sense. The ‘eternal’ coincidence of the FINT values is really behind it.

Indeed, taking the approximate identity of the Friedmann integrals as a basic relation, one has for the four densities:

\[ \rho_V \sim (M_{Pl}/A)^2, \quad \rho_D \sim A/R^3M_{Pl}^2, \quad \rho_B \sim A/R^3M_{Pl}^2, \quad \rho_R \sim A^2/R^4M_{Pl}^2. \]  

(48)

It is seen from these equations that the four densities must become identical (approximately) and equal to \( \sim (M_{Pl}/A)^2 \), when \( R(t_0) \sim A \).

Thus, the four cosmic densities are near coincident because of COINS and the special character of the moment of observation at which the size of the finite Universe and/or the size of the Metagalaxy are equal to the Friedmann integral.

In fact, all the coincidences that take place at the present epoch (Sec.2) are due to the only equality \( R(t_0) \sim A \). It follows from this equality that \( \rho_V \sim \rho_D(t_0) \) (see Eq.48); but this means that the present epoch is the epoch of transition from the matter domination to the vacuum domination. At this epoch, the solution for the matter domination, \( R(t) \propto t^2/3 \), and the solution for the vacuum domination, \( R(t) \propto \exp(ct/A_V) \), are both valid, in a rough approximation. We have from the first and second of them, correspondingly:

\[ H(t_0) \simeq 2/(3t_0); \quad H(t_0) \simeq c/A_V. \]  

(49)

Then the equality \( t_0 \sim H(t_0)^{-1} \) comes from these two relations directly. For a finite space, we have also from this that \( R_U \sim ct \) at present.

The fact that the size of the finite space is near the Hubble radius at present is sometimes treated as a strange accident or unnatural tuning in the finite-space model by Luminet et al. (2003). As we see now, this is not the case. Actually when the size of the space reaches the universal constant \( A_V \), the size turns to be necessarily and naturally near the Hubble radius. This consideration eliminates a critical argument against the model.
Another question is why we happen to live at such a special epoch. This is among the matters that are effectively discussed on the basis of the Anthropic Principle (see, for instance, Weinberg 1987).

7.2 The Dicke problem

The geometry of the co-moving space looks nearly flat in observations, and the cosmological expansion proceeds in a nearly parabolic regime. The both is quantified by the density parameter $\Omega(t)$ which is measured to be near unity (see Sec.2). Why this is so? The question is known as the ‘flatness problem’ that was first recognized by Dicke (1970) who mentioned that the Universe must be extremely finely tuned to yield the observed balance between the total energy density of the Universe and the critical density.

In the 1970-s, the observational constraints on $\Omega(t_0)$ were much weaker than now, and it was considered that this quantity was between 0.1 and 10. Such an apparently wide range implies a very narrow range at earlier epochs. It was estimated that the density balance quantified by $\Omega$ must be tuned with the accuracy $\sim 10^{-16}$ or $\sim 10^{-60}$, if it is fixed at the epoch of the Big Bang Nucleosynthesis (BBN) or at the Planck epoch, respectively. Such a fine tuning in the ‘initial conditions’ for the cosmological expansion was reasonably considered by Dicke as unacceptable (see, for instance, Chernin 2003 for more references).

COINS shows the Dicke problem in quite different light. Indeed, the correspondence between vacuum and dark matter described by the symmetry relation $A_V \sim A_D$ puts a strong upper limit to any deviations from the flatness in possible models with non-zero spatial curvature. The deviations are measured by the quantity $|\Omega(t) - 1|$, and, as is seen from the Friedmann equation of Sec.3, this quantity goes to zero in both limits $t \to 0$ and $t \to \infty$. At earlier epoch, the deviations are restricted by the matter gravity, and at the later epoch, they are restricted by the vacuum antigravity. The extreme deviation takes place in the era when gravity and antigravity balance each other. The corresponding redshift

$$1 + z = 1 + z_V \simeq (2A_V/A_D)^{1/3} \simeq 1.$$  (50)
At that time, 
\[ \Omega(z_V) - 1 \simeq \left[ 1 \pm \frac{1}{2} \left( \frac{A_{V}}{A_D} \right)^{2/3}(R/a)^2 \right]^{-1} - 1 \simeq \pm \frac{1}{2}(A_{V}/A_D)^{2/3}(A_{V}/a_0)^2 . \] (51)

Here \( R(t) \) is the scale factor normalized as \( R(t) = A_{V}(1 + z)^{-1} \) (see Eq.21), and \( a_0 \) is the present-day space curvature radius.

As we see, there is the upper limit for any possible nonflatness at the present, in the past and future of the Universe:
\[ |\Omega(z) - 1| \leq |\Omega(z_V) - 1| \simeq \frac{1}{2}(A_{V}/A_D)^{2/3}(A_{V}/a_0)^2 . \] (52)

Nonflatness is quantified by the constant parameter \( y \equiv \frac{1}{2}(A_{V}/A_D)^{2/3}(A_{V}/a_0)^2 \simeq (A_{V}/a_0)^2 \) which might be fixed by initial conditions at the TeV temperature epoch, at the BBN epoch, at the Planck epoch or at any other epoch equally, because the parameter is time-independent. The parameter is also normalization-independent.

Any cosmological model of non-zero spatial curvature fits the 1970’s observational constraints, if the parameter \( y = \lesssim 1 \). The modern WMAP constraints are met, if the parameter \( y \lesssim 0.02 \). For the Luminet’s et al. (2003) model with \( \Omega = 1.013 \) we have \( y \simeq 0.1 \). To see the contrast with the fine-tuning argument, one may compare modest numbers like 1 or 0.02-0.01 with the enormous numbers \( 10^{-16} \) and \( 10^{-60} \). A similar result has recently been found in a complementary treatment by Adler and Overduin (2005).

Thus, the balance between vacuum antigravity and dark matter gravity is actually behind the observed near flatness of the 3D co-moving space. This balance is controlled by COINS which rules out any significant deviations from flatness at any time.

Note that no special hypothesis (about, say, an enormous vacuum density, or enormous energy density of inflaton field, at enormously large \( z \)) is required to clarify and eliminate the Dicke fine-tuning problem. The really observed vacuum density and the standard cosmology at modest \( z \) are quite enough to understand why the observed space is nearly flat and the cosmic expansion is nearly parabolic.
7.3 Perturbation amplitude

A fine-tuning problem which is similar to the Dicke argument is well-known in the theory of cosmic structure formation. Indeed, the perturbations must be extremely finely tuned in amplitude to come to the nonlinear regime between the red shifts, say, \( z \simeq 3 - 10 \) (when the oldest galaxies are observed) and \( z = z_N \simeq 1 \) (when the vacuum antigravity terminates the linear perturbation growth – see, for instance, Chernin et al. 2003). Consider, for example, the large-scale adiabatic perturbations which are ever grow before \( z \sim 1 \). Using the standard theory of weak perturbations (Lifshits 1946), we may easily see that, the perturbation generated at the BBN epoch must increase \( 10^{16} - 10^{17} \) times, so that their initial amplitudes must be tuned with the accuracy better than \( 10^{-16} \) to guarantee nonlinearity in the appropriate redshift range. If perturbations are generated at the Planck epoch, the accuracy must be better than \( 10^{-60} \).

The numerical similarity with the Dicke considerations is not purely accidental. It is long known due to Zeldovich (1965) that the correct time rate of the perturbation growth could be obtained in a simple picture in which a perturbation overdensity is treated as a part of a universe of positive curvature on the unperturbed background of a flat space. The relative amplitude of density perturbation is given in this case by the deviation of the density parameter \( \Omega \) from unity:

\[
\delta \equiv \delta \rho/\rho \simeq \Omega(t) - 1.
\]  

It is because of this relation that the perturbation growth resembles the evolution of nonflatness. We will show now that this analogy may help to understand the nature of the initial perturbation amplitude which is a key quantity in the theory of structure formation.

Following Zeldovich (1965), we may generally assume that various perturbation areas are described by models with different curvature parameters \( K > 0, K = 0, K < 0 \) (see Sec.3) and different curvature radii \( a(t) \), but with the same set of the Friedmann integrals as in the background model. If, for instance, \( K = 0 \) in the background model, then areas with \( K > 0 \) and \( K < 0 \) correspond to over-density perturbations and under-density perturbations, respectively. The perturbation areas of various sizes \( r(t) \) develop
independently of each other (even if they spatially overlap), in the linear approximation.

In such a simple example, we will use the parabolic ($K = 0$) solution with the scale-factor normalized as $R(t) \simeq A_V (1 + z)^{-1}$ to describe the unperturbed background expansion. Then an overdensity perturbation may be described by a model with $K > 0$ normalized in the same manner. In accordance with Eq.53 and the results of the subsection above, the density contrast $\delta$ in dark matter reaches its maximum when the redshift $z = z_V \sim 1$. At that time

$$\delta(z_V) \equiv |\delta \rho_D / \rho_D| = |\Omega_{z_V} - 1| \simeq |[1 \pm \frac{1}{2} (\frac{A_V}{A_D})^{2/3} (A_V/a_0)^2]^{-1} - 1|.$$  

(54)

Here $a_0$ is the present-day value of the curvature radius corresponding to a given perturbation area.

The value of the amplitude $\delta(z_V)$ is about unity, $\delta \sim 1$, provided the constant parameter $y = \frac{1}{2} (A_V/A_D)^{2/3} (A_V/a_0)^2 \sim 1$.

No fine tuning of the amplitude is needed, as we see: the order-of-unity constant parameter $y$ guarantees the quantitatively correct perturbation evolution. This parameter may be fixed by the ‘initial conditions’ at any epoch in the past, because the parameter is time independent.

Remind that the result relates to the perturbations which grow all the time in the past when $z \geq z_V$. The spatial scales of these perturbations are large enough: they are ever not less than the Jeans critical length for gravitational instability $R_J(t)$. The Jeans length has maximum at the moment $z = z_*$ when the matter density $\rho_D + \rho_B$ is equal to the radiation density $\rho_R$ (see, for instance, Zeldovich and Novikov 1983). At this moment, $z_* \simeq A_V A_D / A_R^2$, and

$$R_J(t_*) \simeq c t_* \simeq 0.4 A_R^2 / A_D.$$  

(55)

The minimal spatial scale $L(t_*)$ for ever growing perturbations is near the Jeans length, at this moment: $L(t_*) \simeq R_J(t_*)$. At $z = z_V$, this scale is $L(z_V) = R_L(t_*) (1 + z_*) / (1 + z_V) \simeq 0.2 A_V A_R / A_D$.

With this relation, we may estimate the amplitude of the perturbation of the gravitational potential $\Delta$, at this scale. In accordance with the general theory (Lifshits 1946),
we find:
\[ \Delta = \delta(z_V) [L(z_V)/ct_V]^2 \simeq 0.2\delta(z_V)(A_R/A_D)^2, \]  
(56)

where \( t_V = t(z_V) \simeq 0.5A_V/c \).

Since \( \delta(R_L, z_V) \simeq 1 \), the value \( \Delta \) turns out to be expressed in terms of the Friedmann integrals only:
\[ \Delta \simeq 0.2(A_R/A_D)^2 \simeq 10^{-4}. \]
(57)

The general theory indicates that this value does not depend on time: \( \Delta = \text{Const}(t) \). Moreover, this value is scale independent initially, if the initial perturbations have the Harrison-Zeldovich (HZ) spectrum: \( \delta \propto r^{-2} \). The HZ spectrum is in good agreement with the WMAP data (Spergel et al.2003).

Thus, the key quantity of gravitational instability comes in a quite natural and simple way as a universal dimensionless constant of cosmology \( \Delta \). Together with the HZ spectrum, this constant gives a complete quantitative description of the initial adiabatic perturbations that seed the large-scale cosmic structure.

No fine tuning for the amplitude is needed at all. Since the quantity \( \Delta \) is a constant, the initial conditions for the perturbations do not need to be fixed at any specific ‘initial’ moment: we have in fact ‘no-initial conditions’ situation.

In the context of the gravity-electroweak interplay (Sec.5), it is especially interesting to estimate the perturbation amplitude at the epoch when the cosmic temperature \( \sim M_{EW} \) and the red shift \( z = z_{EW} \sim X = M_{Pl}/M_{EW} \). With the relations above, we find for the scale \( r = L \):
\[ \delta(z_{EW}, L) \simeq \Omega(z_{EW}) - 1 \simeq [R(t_0)/A_R]^2(1 + z)^{-2} \sim X^{-2} \sim 10^{-30}. \]  
(58)

As we see, the perturbation amplitude at \( z = z_{EW} \) is given in terms of the universal hierarchy number \( X \) alone. In this way, COINS together with the freeze-out physics provide the perturbations with a natural initial amplitude.

We can refine somewhat the quantitative results with the use of the concordance data. It has been long known and confirmed recently by the WMAP data (Spergel et al. 2003), that the largest scale at which the density perturbations have the unity amplitude is \( r_1 \simeq 8h^{-1} \) Mpc, at present. At \( z = z_V \), this scale \( r_1(z_V) \simeq 4 \) Mpc. This
is smaller than $L(z_V)$, which means that the scale $r_1(t)$ is in the range where the HZ spectrum leads to an almost scale-independent amplitude at $z = z_*$:

$$
\delta(r) \propto (1 + 2 \ln R_L/r), \quad r < L, \quad z = z_* .
$$

This spectrum keeps the same shape to the moment $z = z_V$ at which

$$
\delta(r_1) = \delta(R_L)(1 + 2 \ln R_L/R_1) = 1, \quad z = z_V .
$$

It follows from this that

$$
\delta(L) = (1 + 2 \ln L/R_1) \simeq 1/3 .
$$

Incorporating this into our estimate of the potential perturbation amplitude, we have finally:

$$
\Delta \simeq 3 \times 10^{-5}.
$$

The refined estimate contains additional factor 0.3; this difference from the basic result of Eq.57 is obviously not too significant. It is more interesting that the potential perturbation amplitude is just the quantity that is directly measured in the CMB anisotropy observations in the Sachs-Wolfe (SW) range of the angular scales:

$$
(\delta T/T)_{SW} \simeq \frac{1}{3} \Delta \sim 10^{-6} .
$$

The anisotropy amplitude at the level $\delta T/T \simeq 10^{-6}$ has really been measured by COBE and then confirmed by many other observations including the recent WMAP observations (Spergel et al. 2003).

Let us turn again to the flatness problem. The analogy with the perturbation evolution enables us to recognize a new aspect of the phenomenon. The measured figures for $\Omega(t_0)$ have systematically converged to 1 for the last 35 years, since Dicke’s (1970) work. But if $\Omega(t_0)$ is exactly 1, it can hardly be proved observationally. Indeed, an accuracy of measurements may increase significantly, and an observation error $\sigma$ may become very small; but it will be still finite, so that we will anyway have $\Omega(t_0) = 1 \pm \sigma$.

The perturbation analysis above suggests that the perfectly flat co-moving space is hardly real. It is more natural to expect that the initial perturbations extend to the largest scales up to the present-day horizon radius and even beyond it. If so, the
Universe cannot look perfectly flat in observations, and at the largest scales $\sim ct_0$, its spatial geometry should be rather slightly different from the perfectly flat one. A possible quantitative measure of this difference can be obtained from the figures above. With the use of the HZ initial spectrum at the scale $\sim ct_0$, we have:

$$\left( \Omega(t_0) - 1 \right)_{\text{min}} \simeq \delta(r = ct_0) \simeq \Delta \simeq (1 - 3) \times 10^{-5}. \quad (64)$$

The evidence for a positive spatial curvature (Luminet et al. 2003) may mean that in a ‘typical’ case, $\Omega > 1$, and then

$$\left( \Omega(t_0) - 1 \right)_{\text{min}} \simeq +(1 - 3) \times 10^{-5}. \quad (65)$$

This is the minimal possible level of nonflatness in the picture above. The corresponding upper limit of the current curvature radius, $a_{\text{max}} \simeq 3A_V^{2/3}A_D^{4/3}A_R^{-1} \simeq 50A_V$, follows from the equality $y = \Delta$. The values $(\Omega(t_0) - 1)_{\text{min}}$ and $a_{\text{max}}$ describe the Universe in the case when the initial perturbations are the only physical cause of its nonflatness. In principle, this prediction can be tested, if the accuracy of the measurements of the value $\Omega$ reaches the level $\sigma \sim 10^{-5}$ or better.

### 7.4 Cosmic entropy

The number density of the CMB photons $n_R \sim 1000$, at present, and the baryon number density $n_B \sim 10^{-6}$ now. The time-independent ratio, $B = n_R/n_B \sim 10^9$, is referred to as the Big Baryonic Number. It has been long recognized that $B$ represents the cosmic entropy per one baryon which is one of the key cosmological parameter (responsible, in particular, for the BBN outcome). Why this number is so big? This question is known as the ‘cosmic entropy’ problem.

In terms of the FINT, the Big Baryonic Number may be represented as

$$B \sim A_R^{3/2}A_B^{-1}m_BM_{\text{Pl}}^{-1/2}, \quad (66)$$

where $m_B \sim 1$ GeV is the baryon mass.

If one puts $A_R \sim A_B$ and use the expression for the FINT of Sec.5, the Big Baryonic Number turns out to be

$$B \sim (m/M_{\text{Pl}})X^2. \quad (67)$$
This gives numerically $B \sim 10^{11}$ which is not too bad as a rough order-of-magnitude estimate.

The freeze-out physics of Sec.5 suggests that the ‘Big Dark Number’ may also be of interest:

$$D \equiv n_R/n_D \sim 10^{12},$$

where $n_D$ is the number density of dark matter particles and it is assumed again (as in Sec.5) that the WIMP mass $\sim M_{EW}$. In terms of the FINT, one has

$$D \sim A_{R}^{3/2}A_{D}^{-1}M_{EW}M_{Pl}^{-1/2}.$$  \hspace{1cm} (69)

For $A_{R} \sim A_{D}$, this gives $D \sim X \sim 10^{15}$, which is the simplest (and perhaps ‘more fundamental’ than $B$) measure of the cosmic entropy per particle. Numerically, this is not too far from the real figure.

Thus, in the first and main approximation, one may answer the question of this subsection: The cosmic entropy per particle is big because of COINS and the hierarchy phenomenon in fundamental physics. Via cosmic entropy, COINS controls the cosmic light element production in the Big Bang Nucleosynthesis.

### 7.5 The size of a finite space

The gravity-electroweak interplay described in Sec.5 may suggest a guess about the size of the Universe, – if the cosmic space is really finite. In accordance with the considerations of Sec.5, it seems natural to expect that the size of the finite Universe was determined by the same physics as its energy composition. There is no theory that would put the topology of the Universe in relation with its energy content. But if such a relation exists in nature, it might reveal itself in the Electroweak Big Bang. In this case, the equations of this unknown theory might have a simple solution for the value $R_U(t_{EW})$. A natural candidate for this solution may look like

$$R_U(t_{EW}) \sim R_{EW}X,$$  \hspace{1cm} (70)

where $R_{EW} \sim M_{Pl}/M_{EW}^2 \sim 10^{-2}$ cm is the horizon radius at TeV temperatures. Then we have $R_U(t_{EW}) \sim M_{EW}^{-1}X^2$, and so the size of the Universe at present:

$$R_U(t_0) \sim R_{EW}X z_{EW}^2 \sim X^4M_{Pl}^{-1} \sim A \sim 10^{28} \text{ cm}.$$  \hspace{1cm} (71)
Here $z_{EW} \sim X$ is the redshift at $t = t_{EW}$ (see Sec.5).

An additional argument in favour of this guess is provided by the idea of extra dimensions (Sec.6). If the roots of all the phenomena we observe are in fact in the extra dimension physics, it seems reasonable to expect that the 3D brane is compact in volume, like the extra dimensions themselves. Then the 'initial' (at $t = t_{EW}$) size of the Universe might be given in terms of the two truly fundamental constants $R_*$ and $M_* \sim M_{EW}$. So for two extra dimensions, we have:

$$R_U(t_{EW}) \sim R_* X \sim R_*^2 M_*, \quad n = 2. \quad (72)$$

Correspondingly, the present-day size of the Universe

$$R_U(t_0) \sim R_* X^2 \sim R_* (M_* R_*)^2 \sim A \sim 10^{28} \text{ cm}. \quad (73)$$

The estimates of Eqs.71,73 are in good agreement with what the WMAP data – in Luminet’s et al. (2003) interpretation – give for the characteristic length of the compact 3D space.

These considerations point out on an additional important feature of the present epoch: it is the epoch at which all the cosmological distances and lengths are $X$ times larger than they were at the Electroweak Big Bang. Because of the special significance of the hierarchy number $X$ in the fundamental physics and cosmology (Secs.5,6), we may expect that this feature might reveal itself somehow at the phenomenological level. Perhaps the topological effect recognized by Luminet et al. 2003) and the condition $R_U(t_0) \sim r_0(t_0)$ are an observational manifestation of the feature. If so, the topological effect was determined by the gravity-electroweak interplay at the epoch of TeV temperatures.

The big number $X$ provides a common natural quantitative measure to the total figures in the finite Universe. These are the total dark matter mass in the finite Universe

$$M_D \sim X^4 M_{Pl} \sim 10^{60} M_{Pl}; \quad (74)$$

the total number of the TeV dark matter particles WIMPs

$$N_D \sim X^5 \sim 10^{75}; \quad (75)$$
the total number of the CMB photons

\[ N_R \sim X^6 \sim 10^{90}. \]  \hspace{1cm} (76)

In the case of an infinite co-moving space, the figures of Eqs.74-76 are related to the Metagalaxy.

7.6 Naturalness

Finally, let us address the ‘naturalness problem’: Why is the vacuum density \( \rho_V \) at least 120 orders of magnitude smaller than its ‘natural’ value \( \sim M_{Pl}^4 \)? The problem was formulated in this form after the discovery of cosmic vacuum in the supernova observation (Riess et al. 1998, Perlmutter et al. 1999), but it has long been known in a more general form (see for a review Weinberg 1989). COINS provides a new framework for naturalness considerations.

Indeed, due to the COINS symmetry relation \( A_V \sim A_D \sim A_B \sim A_R \), vacuum is now not an isolated and very special type of cosmic energy, but a regular member of the quartet in which all the cosmic energy ingredients are unified by COINS. The real vacuum density looks quite natural in the energy quartet. On the contrary, vacuum with the Planck density would be embarrassingly strange in terms of the FINT: the FINT value for vacuum would be different from the three other FINT values in 60 powers of ten.

In addition, the real vacuum density looks quite natural in the context of two extra dimensions of submillimeter size \( R_* \) (Sec.6): the density is given by the remarkably simple relation \( \rho_V \sim R_*^{-4} \) (Chernin 2002a).

8 Conclusions

The Universe that emerges from the WMAP and other concordance data reveals a new simplicity and symmetry in its energy composition. As we demonstrated in this paper, the list of the cosmic energy ingredients – vacuum (V), dark (D) matter, baryons (B), radiation (R) – looks very simple indeed when it is written in terms of the Friedmann
integral $A$:

$$A_V \sim A_D \sim A_B \sim A_R \sim 10^{60\pm1} M_{Pl}^{-1}. \quad (77)$$

This is the time-independent covariant and robust empirical recipe for the cosmic energy composition.

New internal (non-geometrical) time-independent covariant and robust symmetry is behind this relation: the four energy ingredients constitute a regular set, a quartet, with the same (approximately) values of the Friedmann integral. The integral is the conservation value appropriate to cosmic internal symmetry (COINS). This is a non-exact symmetry, and its violation is within two orders of magnitude, in terms of the Friedmann integral.

Cosmic internal symmetry is a phenomenological manifestation of basic physical processes that determined the ‘initial conditions’ for the observed Universe. A link to fundamental physics may be recognized under the assumption that the energy ingredients are well described by ‘simple physics’. Specifically, it means that dark energy is cosmic vacuum, or the Einstein cosmological constant, and dark matter is weakly interacting stable particles with the mass near the electroweak energy scale $\sim 1$ TeV. Such a conjecture invokes a special significance of the electroweak energy scale in fundamental physics (Okun 1982, 1988, Weinberg 2000). If this is so, the identity of the values of the Friedmann integral results from standard freeze-out kinetics at the early epoch of TeV temperatures. The figure for the integral is given in terms of the dimensionless hierarchy number $X = M_{Pl}/M_{EW} \sim 10^{15}$:

$$A \sim X_4 M_{Pl}^{-1} \sim 10^{60} M_{Pl}^{-1}. \quad (78)$$

This theory value agrees well with the empirical result of Eq.77.

The concept of cosmic internal symmetry provides a productive common ground for better understanding of a number of key problems in cosmology which otherwise seem unrelated. Among them are

1. the problem of cosmic density coincidence: all the four densities are now near the value $(M_{Pl}/A)^2$, on the order of magnitude, because of COINS;

2. Dicke’s problem: the balance between vacuum antigravity and dark matter gravity
is behind the observed near flatness of the 3D co-moving space, and this balance is
controlled by COINS which rules out any significant deviations from flatness now, in the
past and future;

(3) the cosmic entropy problem: the entropy per WIMP $D \sim X$;

(4) the problem of the cosmic size (if the comoving space is finite): its value is $R_U(z) \sim A(1 + z)^{-1}$;

(5) the naturalness problem: due to the COINS, vacuum is not an isolated and very
special type of cosmic energy, but a regular member of the energy quartet with a common
value of the Friedmann integral; in this set, the real vacuum density looks quite natural;

(6) the problem of the perturbation amplitude: the COINS violation gives the uni-
versal time-independent dimensionless amplitude, $\Delta \sim 0.1 (A_R/A_D)^2$, for the cosmic
perturbations.

To summarize, the energy composition of the real Universe looks preposterous only
at the first glance. In fact, its structure proves to be simple and regular. A basic
time-independent covariant symmetry relation of Eq.77 controls the appearance of the
energy composition at any epoch of the cosmic evolution. It determines also a number
of key cosmic parameters and phenomena associated with the energy composition. The
origin of this new symmetry is most probably due to the interplay between gravity and
electroweak-scale physics in the Electroweak Big Bang at the epoch of a few picoseconds.
The microscopic nature of the gravity-electroweak interplay is a new challenge in funda-
mental theory. It is closely related to basic issues in particle physics (and in particular,
to the hierarchy riddle) which may perhaps be clarified with a new generation of big
accelerators, like the Big Hadron Collider (BHC). On the other hand, new space mis-
sions like PLANCK are expected to verify the low-harmonic deficit in the CMB power
spectrum and other possible effects related to the topology of the cosmic space. In com-
bination, the results from physics laboratories and space-based astronomy instruments
may provide a new reliable basis for further studies of COINS as well as other major
features of the observed Universe.

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