Abstract

The comparison of the Standard Cosmological Model (SCM) with astronomical observations, i.e. theory versus experiment, and with the Minimal Standard Model (MSM) in particle physics, i.e. theory versus theory, is discussed. The main issue of this talk is whether cosmology indicates new physics beyond the standard \( SU(3) \times SU(2) \times U(1) \) model with minimal particle content. The answer to this question is strongly and definitely "YES". New, yet unknown, physics exists and cosmology presents very weighty arguments in its favor.

1 Cosmological Parameters

1.1 Hubble Expansion Law

The cosmological stage is quite simple and is set by General Relativity and the assumption (well confirmed by the data) of the homogeneous and isotropic matter distribution on cosmological scales. The Einstein equations for this very special but realistic case were solved by Friedmann [1], who found in particular that the universe expands, i.e. distant objects run away in accordance with the law

\[
v = H r
\]

which was later observed by Hubble [2]. Here \( v \) is the velocity of a distant cosmic object (a galaxy or a galactic cluster), \( r \) is the the distance to this object and the coefficient of proportionality \( H \) is the well known Hubble constant. (It is better to say instead the Hubble parameter because, though \( H \) is believed to be independent of space points, its magnitude depends on time.) The proportionality law (1) is quite accurately established but the magnitude of the Hubble parameter is rather poorly known. It is usually parameterized in the form

\[
H = 100 \ h \ \text{km/sec/Mpc}
\]

where the dimensionless parameter \( h \) is crudely bounded by \( 0.5 < h < 1 \). The recent data have a trend towards lower values. The average presented in the review [3] a few months ago is \( h = 0.6 \pm 0.1 \). However the most recent measurement [4] by Hubble Space Telescope (HST) from brightest cluster galaxies gives \( h = 0.89 \pm 0.1 \).

\[1\] Also: ITEP, Bol. Cheremushkinskaya 25, Moscow 113259, Russia.
1.2 Cosmological Matter/Energy Density

The matter (or better to say energy) density in the universe, $\rho$, is characterized by the dimensionless parameter

$$\Omega = \frac{\rho}{\rho_c}$$

where $\rho_c = 3H^2m_{Pl}^2/8\pi = 1.88 \cdot 10^{-29}h^2$ g/cm$^3$ is the critical or closure density. It is usually said that if $\Omega \geq 1$ the universe is open (or spatially flat for the particular value $\Omega = 1$) and will expand forever. If $\Omega < 1$ the universe is closed and the expansion will later change to contraction and the universe will re-collapse. These statements about the ultimate universe fate are true only if vacuum energy or, what is the same, cosmological constant is zero.

Theoretically most favorable value is $\Omega = 1$. It is the only value which does not change with time in the course of the universe evolution. Any initial deviation from unity would evolve with time as a power of scale factor and thus would change by many orders of magnitude from initial moment till present time. In inflationary scenario this initial value is adjusted to 1 with exponentially good precision so that even after the scale factor changes in the course of the normal Friedmann expansion more than by 30 orders of magnitude, the deviation from unity remains very small. Inflationary cosmology predicts $\Omega = 1 \pm 10^{-4}$ on the present day horizon scale. The indicated here possible deviations from unity are not related to the initial non-perfect adjustment of $\Omega$ to unity but could be induced by the local density perturbations. In principle open or closed universe (with $\Omega \neq 1$) might be compatible with inflationary models but at the expense of an unnatural fine-tuning.

There are different contributions into $\Omega$ coming from different forms of matter, $\Omega = \sum_j \Omega_j$. Directly visible matter gives a minor fraction into it:

$$\Omega_{\text{vis}} \leq 0.003h^{-1}$$

Presumably all visible matter consists of usual baryonic stuff which we observe in our surroundings. A large part of baryons is most probably invisible. The cosmic baryon budget is analyzed in ref. [5] where it is concluded that

$$0.007 \geq \Omega_B \leq 0.04$$

There is an independent way to find the density of cosmic baryons based on primordial nucleosynthesis (see below). This method is sensitive to the total baryonic number density and gives:

$$\Omega_{NS}^B = (0.7 - 3) \cdot 10^{-2}h^{-2} = (0.7 - 12)\%$$

If the Hubble constant is at the lower end of the permitted interval, $h = 0.5$, the fraction of invisible baryons is rather large, $\Omega_{\text{vis}}/\Omega_B \leq 0.21$, while for the large $H$,
\( h = 1 \), the fraction of invisible baryons is much smaller, \( \Omega_{\text{vis}}/\Omega_B \leq 0.43 \), and it is easier to conceal them in the universe. Still the question remains where are all these invisible baryons. Cold baryonic gas could be observed by absorption lines in quasars. Hot gas would produce an unacceptable distortion of the cosmic microwave background or emit too much X-rays. As was recently shown in ref. [6], \( \Omega_B > 0.1 \) would result in production of too many X-ray bright clusters. Dust would be seen by observation in infrared range.

A good hiding place for invisible baryons are compact objects such as white dwarfs or black holes. A large fraction of white dwarfs is difficult to explain with the standard theory of stellar evolution. Too many black holes which were produced as result of stellar collapse are excluded because of accompanying enrichment of the interstellar space by heavier elements. To overcome this difficulty the black holes should be primordial but, if so, they could equally well, or even most probably, consist of non-baryonic matter. A direct search of compact objects by gravitational micro-lensing in our Galaxy and galactic halo, the so called MACHO’s, is in process. More than a hundred of such objects have been already observed (for a recent review see e.g. ref. [7]). There are indication that masses of these MACHO’s are quite large, \( m > 0.3 m_\odot \), where \( m_\odot \) is the Solar mass. That heavy compact objects, if they are made of normal matter, should be luminous, practically normal stars. The absence of light from these objects is quite mysterious. If e.g they are white dwarfs then their age must be bigger than 18 Gyr which is not compatible with the measured value of the Hubble parameter if cosmological constant is zero (see below).

Anyhow the baryonic mass fraction of the universe is quite small. One can safely conclude that \( \Omega_B < 0.1 \) so that the cosmic mass/energy density is dominated by a non-baryonic (dark) matter. This conclusion is supported both by direct observations and by the theory of large scale structure formation.

It is known for already quite a long time that masses of galaxies and their clusters are not concentrated inside the luminous central part but are spread over a much larger distances where no matter is directly seen. This is observed by the velocity of gas around the luminous centers up to distances almost 10 times larger than the galactic radius. The velocity \( v(r) \) remains constant with increasing distance. It means that the mass density is non-zero even outside the galactic radius. It falls down as \( \rho_m \sim 1/r^2 \) and the total mass inside radius \( r \) is not a constant as one would normally expect but rises as \( m(r) \sim r \). A large sample of these flat rotational curves can be found in ref. [8]. The analysis of the mass-to-light ratio found from galactic rotational curves up to the scales of 100 kpc permits to conclude that \( \Omega_{DM} \geq 0.1 \). The same analysis made for galactic clusters at the scales of several Mpc leads to the conclusion that \( \Omega_{DM} \geq 0.2 \). Different methods and results of the determination of \( \Omega \) are reviewed in refs. [8, 9]. Different estimates vary in the region 0.2-0.4, while larger values are
not excluded. Possibly safe bounds are

\[ \Omega_m \geq 0.3, \]
\[ \Omega_\Lambda \leq 0.7. \]  

(7)  
(8)

Here \( \Omega_m \) describes the mass fraction of the normal matter, both baryonic and non-baryonic, while \( \Omega_\Lambda \) describes contribution of vacuum energy density into total cosmological energy/mass density. The flat universe with \( \Omega_{tot} = \Omega_m + \Omega_\Lambda = 1 \) is not excluded.

### 1.3 Universe Age

If one knows the present-day values of the Hubble parameter \( H_0 \) and contributions to \( \Omega \) from different forms of matter one can calculate the universe age:

\[ t_U = \int_0^1 \frac{dx}{(1 - \Omega_{tot} + \Omega_m x^{-1} + \Omega_{rel} x^{-2} + \Omega_\Lambda x^2)^{1/2}} \]  

(9)

It is assumed normally \( \Omega_{rel} = 0, \Omega_\Lambda = 0 \) and the universe age is approximately given by the expression

\[ t_u \approx \frac{9.8 \, h^{-1} \text{Gyr}}{1 + \sqrt{\Omega/2}} \]  

(10)

Nuclear chronology gives universe age in the interval 11-17 Gyr. The estimate of the universe age from the ages of old globular clusters before spring 1997 gave \[ t_U = 14 \pm 2 \text{ Gyr} \]. Recent observations made by astronomical satellite Hipparcos showed that the distances to globular clusters are systematically 5-10\% larger so that the stars in fact are brighter and younger. With these new data the universe age found from globular clusters becomes somewhat smaller:

\[ t_U = 12 \pm 2 \text{ Gyr} \]  

(11)

The smaller universe age and possibly low Hubble constant, \( h = 0.6 \), are compatible with flat universe \( \Omega_{tot} = 1 \) without cosmological constant. So possibly the age crisis which existed for larger \( t_U \) and high \( H_0 \) is over. Still one should keep in mind that the data are not yet conclusive.

### 2 A Few Problems

Though the simple isotropic homogeneous cosmology quite well describes the universe at large, there are a few disturbing points for which no natural explanation is known.
1. **Ω-conspiracy.** Inflationary cosmology naturally predicts that Ω is very close to 1 but it remains unclear why contributions to Ω from different forms of matter are of the same order of magnitude. As we mentioned above, baryonic contribution is at the level of 1%. The dynamically measured Ω is somewhere in the range 0.3-1. The theory of structure formation requests at least two different forms of dark matter: hot dark matter (HDM) and cold dark matter (CDM) with \( \Omega_{HDM} = 0.2 - 0.3 \) and \( \Omega_{CDM} \approx 0.7 \) respectively. The contributions of different forms of matter may differ by many orders of magnitude and their approximate equality looks quite mysterious.

2. **Cosmological constant.** Observations do not exclude that cosmological constant is non-vanishing. The contribution of the corresponding vacuum energy into Ω can be as large as \( \Omega_\Lambda \sim 0.7 \). Moreover the theory of structure formation with just one form of dark matter (CDM) favors non-zero Λ of this order of magnitude. In the course of the universe expansion the energy densities of all normal forms of matter drops down with the scale factor either as \( 1/a^3 \) for non-relativistic matter or \( 1/a^4 \) for relativistic matter while the contribution from Λ stays constant. It is another mystery why exactly today these contributions happened to have similar magnitudes. Astronomers mostly prefer vanishing cosmological constant following Einstein who considered introduction of Λ as the greatest blunder of his life. However there is no consensus with regard to the value of Λ and for example Le Maitre and Eddington believed that cosmological constant could be non-zero.

3. **Vacuum energy.** Though astronomers discuss if Λ is identically zero or essential on cosmological scales, with corresponding energy density of the order of \( \rho_{\text{vac}} \sim \rho_c \approx 10^{-47} \text{GeV}^4 \), from the point of view of particle physicists it should be many orders of magnitude, 50-100, larger than the astronomical upper bound. There are several contributions into vacuum energy each of which is by far bigger than the permitted upper bound (for the recent discussion see e.g. refs. [11, 12]). In particular there is the quite well known contribution to vacuum energy from quark and gluon condensates which give \( \rho_{\text{vac}} \approx 10^{45} \rho_c \). There must exist some other contribution to \( \rho_{\text{vac}} \) which cancels out the quark-gluon contribution with the fantastic precision better than one part per \( 10^{45} \). This is one of the most striking problems of the modern fundamental physics. To my mind the best solution of this problem is the so called adjustment mechanism when there exists a new field which is unstable in the De Sitter space-time and which vacuum condensate induced by the curvature of space-time automatically cancels down any initial vacuum energy [13, 14]. Though no satisfactory model of this kind yet has been found, one can conclude that they possibly possess
a common feature that the vacuum energy is not completely compensated but only down to the terms of the order of \( \rho_c \sim m_p^2 / t^2 \). If this is indeed realized then the non-compensated part of vacuum energy always gives a contribution to \( \Omega \) of order of unity.

3 Cosmic Microwave Background

Cosmic microwave background (CMB) is one of the pillars supporting Big Bang cosmology. It has a perfect Planckian spectrum \(^{[14]}\) with the temperature \( T = 2.728 \pm 0.001 \) K. It is very uniform. There is a noticeable dipole component in the angular distribution of the radiation which corresponds to \( \Delta T = 3.35 \) mK. This dipole is most probably related to our motion with respect to the preferable cosmic frame where microwave radiation is at rest. The measured value of the quadrupole, which describes an inherent anisotropy of CMB is about \( 10 \mu K \). Angular distribution of CMB is measured in terms of spherical harmonics up to \( l \sim 1000 \). It could be one of the most powerful tools for determination of cosmological parameters, \( \Omega, H, \Lambda \). The position and the magnitude of the so called acoustic peaks in the angular distribution depends upon the values of these parameters. The planned cosmic missions MAP and PLANCK will be able to determine these parameters with the accuracy of 10% and 1% respectively. This is a considerable improvement in comparison with the present day 50-100% accuracy. Even with the present date data the maximum in the angular distribution around \( l = 100 - 200 \) is already observed. It is an interesting possibility if the position of this maximum corresponds to the observed 100 Mpc scale in the large scale structure of the universe \(^{[15]}\).

4 History of the Universe

I. **Beginning** is unknown. Several possibilities are considered:

1. Creation from nothing.
2. Perpetually oscillating universe.
3. Eternal chaotic inflation.
4. Pre-big-bang string cosmology.

Discussion of these possibilities is outside the scope and volume of the this talk. At the present stage there is no way to distinguish between these possibilities but what is quite certain a description of the universe creation definitely needs new physics.
II. **Inflationary stage.** During this stage the universe expanded exponentially, \( a \sim \exp(H_I t) \), with a constant (time-independent) \( H_I \). This simple assumption perfectly solved all initial value problems of the Friedmann cosmology \(^{[10]}\) if \( H_I t > 60 \). During this stage the universe is dominated by the vacuum-like matter with the equation of state

\[
\rho + p = 0
\]  

(12)

Because of the covariant conservation of the energy-momentum tensor,

\[
\dot{\rho} = -3H(\rho + p)
\]  

(13)

it follows that the energy density remains constant in the course of expansion. This surprising result means that all the matter in the universe, all universe mass might be created from microscopically small initial piece of matter which approximately satisfied equation (12).

One can ask if inflation is a necessity or the universe can reach the present stage without inflationary period. The no-go theorem is not proved but there is no known way to create our suitable for life universe without inflation. In this sense inflation is an experimental fact. We do not see any other possibility to solve simultaneously the following problems:

1. **Flatness.** The present day value of parameter \( \Omega \) is rather close to 1. It means that during primordial nucleosynthesis when light elements \(^2\)H, \(^3\)He, \(^4\)He, and \(^7\)Li\) were synthesized in good agreement with observations, \( \Omega \) should be close to 1 with the precision of \( 10^{-15} \). At the "initial" Planck epoch the adjustment must be much better, about \( 10^{-60} \). No other model except inflation naturally gives such a fine-tuning.

2. **Homogeneity, isotropy, horizon.** The universe looks the same in any direction from us though in the old Friedmann cosmology different parts of the universe could not be in causal contact. Such similarity means that expansion regime must be different in the past so that the regions which seem to be out of contact in fact came from the same microscopically small piece of space with the same initial conditions. Exponential expansion could easily achieve that.

3. **Initial push.** We see that the universe expands but the origin of the initial push which created this expansion remained mysterious in the Friedmann cosmology. Inflation naturally explains that because the particular equation of state \(^{[12]}\) gives rise to gravitational repulsion (anti-gravity). It is possible only for infinitely large objects for which the Gauss theorem cannot be applied. For such objects the source of gravity is \( (\rho + 3p) \) and with \( p = -\rho \) it induces anti-gravity for normal positively definite energy density.
4. **Density fluctuations.** Though the universe is very smooth on large scales, at smaller scales it has a very rich structure, stars, galaxies, galactic clusters, etc (?). For their creation some initially small density perturbations must exist, which later on rose up due to gravitational instability and evolved into the observed structure. Of course quantum or thermal fluctuations existed in the early universe but their wave length was by far too small to be cosmologically interesting. Inflation could amplify initially small quantum fluctuations (maybe a little too much) and to stretch their initially microscopic wave length up to astronomical scales. This solves the problem of generation of density perturbations. The perturbations have a specific spectrum (flat spectrum) and this can be tested by measurement of angular distribution of CMB.

An unnatural feature of inflationary scenarios is that the scalar field (inflaton) which drives inflation should have a tiny coupling to other field as well as a tiny constant of self-interaction, \( \lambda < 10^{-14} \). Such a field does not exist in the minimal standard model and for the realization of inflation a new scalar field is necessary.

### III. End of Inflation

A very important period in the history of the universe is the transition from inflationary stage to the "normal" Friedmann stage. During inflation the inflaton field, \( \phi \), remains (almost) constant. This ensures validity of equation of state (12). After some period the temporal evolution of \( \phi \) becomes non-negligible. Generically \( \phi(t) \) begins to oscillate around minimum of its potential energy and, as any oscillating field, starts to produce elementary particles which thermalize and form primeval cosmic plasma. A simplified theory of universe heating was considered in refs. [17, 18, 19]. The particle production was treated perturbatively and it was shown that the transition of energy from inflaton field proceeded slowly so that the temperature of heating was rather small. The non-perturbative approach to heating was put forward in refs. [20, 21]. It was noticed there that the inflaton decay in principle could be parametrically excited and, if this is the case, the process of heating would proceed much faster and efficiently than in the naive theory. However as was argued in ref. [20] the universe expansion and re-scattering of the produced quanta destroy the resonance and it became ineffective. Recently the problem was re-addressed in ref. [22] and in a large number of subsequent papers where is was shown that parametric resonance might be excited and the heating possibly proceeded quite fast. In particular, in such a case the decay of inflaton might produce super-heavy intermediate bosons of grand unification and this would permit baryogenesis at GUT scale.

### IV. Baryogenesis.

The universe in our neighborhood consists predominantly of matter. Antiprotons and positrons observed in cosmic rays most probably have a secondary origin. It is normally assumed that all visible universe is built of the same kind of matter as our Galaxy. It is a very interesting question if there may exist a
considerable amount of (primordial) antimatter in the universe. And, if ”yes”, how far away could be these antimatter domains. This problem was addressed recently in refs. [23, 24] where it was argued that the smoothness of CMB does not permit antimatter domains to be closer than a Gygaparsec. However some rather exotic models of baryogenesis [25] may produce regions of abundant antimatter not so far away.

The asymmetry between matter and antimatter in the universe may be either explained by asymmetric initial conditions ensuring dominance of matter over antimatter or by a dynamical generation of the asymmetry from initially symmetric or even arbitrary initial state. This generation of charge (or baryonic) asymmetry is called baryogenesis. Baryogenesis can be realized if the following three natural conditions are fulfilled [26]:

1. Non-conservation of baryonic charge.
2. Breaking of C- and CP-invariance.
3. Deviation from thermal equilibrium.

If inflation existed, then baryogenesis is a necessity. It can be shown that with any initial conditions conservation of baryonic charge is not compatible with inflation [27].

A natural frameworks for baryogenesis are presented by grand unification theories (GUT). In all such theories baryons are not conserved. Deviation from thermal equilibrium induced by the universe expansion is quite significant. Though nothing is known about CP-violation at GUT scale, it is easy to believe that once CP is broken in low energy physics it is also broken at high energies. With possible efficient universe heating after inflation by excitation of parametric resonance in inflaton decay GUT baryogenesis may still be a viable possibility.

Another beautiful possibility is baryogenesis on electroweak scale [28]. Electroweak interactions are known to break baryonic charge conservation [29] by non-perturbative effects related to quantum chiral anomaly and quantum barrier penetration. It is also well known that both C and CP are broken by electroweak interactions. Deviation from thermal equilibrium is more difficult to realize at electroweak scale than at GUT scale but even this is possible if electroweak phase transition is first order. It may be so for sufficiently light Higgs bosons. Thus all conditions for baryogenesis exist even in the minimal standard model of particle physics. However all attempts to find a satisfactory scenario which may explain the observed baryon-to-photon ratio, \( n_B/n_\gamma \approx 3 \times 10^{-10} \), have failed. The minimal electroweak model gives roughly 5-10 orders of magnitude smaller result. Possibly a low energy supersymmetric extension of MSM is in a better shape and could explain the observed baryon asymmetry. One essential point about general applicability of electroweak approach

9
to baryogenesis is that it is usually assumed that particular field configurations which realize baryonic charge non-conservation (so called sphalerons \[30\]) are abundant in primeval plasma. It is assumed that their number density at high temperatures is the equilibrium one. Strictly speaking it is not known. There is no reliable analytic way to estimate the production rate of sphalerons. The only available possibility now are lattice calculations. Unfortunately they are not accurate enough and the results of different authors \[31, 32\] disagree.

Anyhow, baryogenesis is a necessary feature of modern cosmology and it could generate observable asymmetry only in an extension of MSM. These could be either a low energy supersymmetric extension or high energy SUSY or GUT but definitely new fields and new interactions absent in MSM are necessary.

V. Primordial Nucleosynthesis The discussed above phenomena in the early universe lay to some extend in terra incognita where our knowledge of fundamental physics is non-complete or even absent. Primordial nucleosynthesis takes place at low energies or temperatures, from $\sim 1$ MeV down to 100 keV, in the time interval from 1 sec to 200 sec. Everything at this stage is quite well known from direct nuclear physics experiments and the predictions of the theory of light element formation in the early universe are quite robust. During this stage the following light elements were produced: $^4He$ (25\% by mass), $^2H$ ($2 \cdot 10^{-5} - 2 \cdot 10^{-4}$ by number, relative to hydrogen) and similar amount of $^3He$, and $^7Li$ (a few $\times 10^{-10}$ by number). The predictions of the theory are in a good agreement with observations, though they span 10 orders of magnitude in relative abundances.

Primordial nucleosynthesis serves as a good ”cleaner” for different exotic possibilities in particle physics. It permits to put an upper bound on the number of extra neutrino species or other particles which were abundant during nucleosynthesis. The present day limit on extra neutrino species or other abundant at nucleosynthesis particles is $\delta N_\nu < 1$ (for the recent review see e.g. ref. \[33\]). It permits in particular to put an upper bound on the possible mass of tau-neutrino, $m_{\nu_\tau} < 1$ MeV (the recent most accurate calculations of the influence of massive $\nu_\tau$ and the list of appropriate references can be found in paper \[34\]).

Two years ago the accuracy of the bounds derived from primordial nucleosynthesis was believed to be considerably better than now but recent conflicting data on primordial deuterium abundance created some confusion. Several groups \[35, 36, 37, 38, 39, 40\] have reported measurements of the deuterium abundance in Lyman-limit absorption line systems with red-shifts $0.48 < z < 3.5$ on the line of sight to quasars; these are believed to give essentially the primordial value. Surprisingly some groups have claimed a high value, $D/H \approx 2 \cdot 10^{-4}$ on the basis of ground-based data taken with the Keck telescope, but this result is now thought to be due to various errors \[37\] and the best value available from two “clean” systems is $3 \cdot 10^{-5}$ \[39\]. However, Webb et al \[40\] report a high deuterium abundance, $D/H \approx 2 \cdot 10^{-4}$, in an apparently clean
system with \( z = 0.7 \) observed with the Hubble Space Telescope, as well as a low one in another system with \( z = 0.5 \), raising the possibility that there might be real spatial variations in primordial \( D/H \). If the effect is indeed real (which it is perhaps too early to judge), its significance is difficult to overestimate. It would strongly change our approach to primordial nucleosynthesis and possibly to the physics of the early universe. In the literature there are two explanations of the possible spatial variation of deuterium: either by non-homogeneous baryogenesis \([11, 12]\) or by large and spatially varying leptonic chemical potentials \([13]\). In the first case one should either expect too large variation of the CMB temperature \([12]\) or variation of deuterium on very small scales \([11]\) which is possibly forbidden by observation. In the case of large and varying lepton asymmetry the model \([13]\) predicts a very large mass fraction of primordial \(^4\)He (up to 50-60\%) in deuterium-rich regions. Surprisingly this is not excluded by the data.

To conclude, primordial nucleosynthesis is quite well described by the standard well known physics but if spatial variation of primordial deuterium indeed exists, a new physics seems necessary for an explanation of the phenomenon.

VI. Structure Formation. The early universe was quite homogeneous as a result of inflation; it is well confirmed by the isotropy of CMB. At the present day we observe evolved large scale structure. By assumption this structure was formed as a result of gravitational instability from initially small density perturbations. This is the basic point of the theory of large scale structure formation and it seems that (almost?) everybody agrees with it.

Initial density perturbations most probably were generated during inflationary stage. Their spectrum is an important input in calculations of the structure formation. It is usually assumed that the original spectrum is flat (without any particular scale) as follows from simple inflationary models. However other forms of spectrum are possible and this may introduce a lot of freedom into theory, though this possibility is not very popular.

Another important input parameter is the chemical composition of the universe. Structure formation is very much suppressed in the universe which consists only of the usual matter, that is of baryons and electrons. When the temperature of primeval plasma was above 3000 K the matter was ionized and structure formation was suppressed due to a large radiation pressure. The structure could be formed only after hydrogen recombination at or below red-shift \( z = 10^3 \). In such a case there is too little time for formation of evolved structures. So a new form (or several different forms) of matter which is (are) not strongly coupled to radiation is (are) very desirable (or maybe necessary). To this end we also need new physics. Particle physics has several possible candidates on the role dark matter particles but it is unknown which one indeed plays this role. Possibly a comparison of calculations of structure formation with detailed future astronomical data will permit to deduce
some properties of dark matter and to single out the right particles.

5 Conclusion

It seems quite well established that the universe during its evolution went through epochs of inflation, baryogenesis, nucleosynthesis, and structure formation. Without them it would be simply impossible to create the observed world. Surprisingly physical processes during practically all these epochs demand an extension of the Minimal Standard Model. Moreover there are some cosmological puzzles which may need new physics for their resolution. Let us compare Standard Cosmological Model with Minimal Standard Model of particle physics summarizing discussion of the previous sections:

1. Inflation. Does not exist in MSM. Needs a new scalar field with mass $m < 10^{13}$ GeV and small coupling of self-interaction, $\lambda < 10^{-14}$.

2. Baryogenesis. Possible in MSM but too weak. For successful realization needs supersymmetric extension of MSM (though there may be some serious problems), GUT’s or some other new physics at high energies.

3. Nucleosynthesis. In a good agreement with MSM. A possible trouble is a spatial variation of primordial deuterium. If confirmed, it may indicate on a very serious problem in both MSM and SCM.

4. Structure formation. MSM does not produce primordial fluctuations on astronomical scales. To this end one needs inflation or topological defects, though the latter seem to be excluded now.

5. Dark matter. It is seen by its gravitational action and is necessary for structure formation. The only possible candidate in MSM is massive neutrino (or neutrinos), but the observed structure cannot be described with this form of dark matter only. New particles are necessary: lightest supersymmetric particle (if R-parity is conserved and it is stable), axion, majoron, shadow world particles, etc. One of the most interesting challenges is to find what is the nature of dark matter particles constituting 90% or more of the total mass of the universe.

6. Vacuum energy. The discrepancy between theoretical expectations and observations is 50-100 orders of magnitude (!). There is no satisfactory solution to this problem even with any kind of new physics.

7. Conspiracy of $\Omega_j$. Close values of $\Omega_j$ for different forms of matter. There is no explanation for that in MSM. Possibly it can be found in unified theories.
There are some more unsolved problems which are not related to cosmology on large scales but still present a serious theoretical challenge. It is not known if they can be solved in the frameworks of the usual physics but of course these attempts should be done first. Among them are γ-bursters, magnetic fields in galaxies, cosmic rays of extremely high energies, non-luminous heavy MACHO’s and possibly some more.

Thus even though MSM is in very good agreement with practically all direct experiments we still can be sure that New Physics exists. With the new generation of telescopes, with new more sophisticated technology we should expect that new discoveries and more mysteries are on the way.

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