COSMOLOGY AT THE TURN OF CENTURIES

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A brief review of the present-day development of cosmology is presented for mixed physical audience. The universe history is briefly described. Unsolved problems are discussed, in particular, the mystery of the cosmological constant and dark energy, the problems of dark matter, and baryogenesis. A brief discussion of the cosmological role of neutrinos is also presented.

1. Introduction

Probably the most important scientific breakthrough of the last quarter of the previous century was related to tremendous progress in cosmology. From a poor relative of distinguished family of fundamental science characterized by the words prescribed to L. Landau: “always in error but never in doubt”, cosmology turned, or is turning, into an exact science and possibly the most interesting one. It is full of mysteries, unsolved problems, puzzling phenomena and strongly indicates that there exists new physics beyond the standard model.

The stunning development of cosmology is due to a combination of two factors: 1) development of new theoretical methods, application of particle physics and quantum field theory to the early and contemporary universe; 2) new observational technique and devices, much more precise then even recently used ones and exploration of new windows to the universe (electromagnetic radiation in all wave length ranges, gravitational waves, neutrinos, high energy cosmic rays). Taken together they have led to Great Cosmological Revolution which keeps on going, turning into “permanent revolution” almost on Leo Trotsky own terms but, fortunately, not so bloody.

Cosmological parameters are now quite accurately known with even brighter perspectives for the nearest future. One impressive example is the baryon asymmetry of the universe or, better to say, the ratio of the
cosmological number density of baryons to the number density of photons in cosmic microwave background radiation (CMBR). When the first works on the baryon asymmetry were written this ratio was known as $\beta = n_B/n_\gamma = 10^{-9.1\pm1}$. Now it is $\beta = (6 \pm 1) \cdot 10^{-10}$. The progress is striking.

2. Cosmological Parameters

An important indication that cosmology is entering the club of exact sciences is the precision in determination of the values of basic cosmological parameters. The progress of the recent years is achieved, to a large extent, thanks to the measurements of the angular fluctuations of the CMBR and detailed study of large scale structure (LSS) of the universe.

The universe expansion law, $V = Hr$, is usually expressed in terms of the dimensionless Hubble parameter $h = H/100 \text{ km/sec/Mpc}$. According to the present day measurements, it is $h = (0.72 - 0.73) \pm 0.05$. Previously for a long time it’s value was between 1 and 0.5 with unclear systematic arrows.

With this accurate determination of $h$ the critical value of the cosmological energy density becomes

$$\rho_c = \frac{3H^2m_{Pl}^2}{8\pi} = 10^{-29} \text{g/cm}^3 (h/0.73)^2 = 5.62 \text{kev/cm}^3 (h/0.73)^2$$  \hspace{1cm} (1)

The contribution of any form of matter into total cosmological energy density is expressed in terms of the parameter $\Omega_j = \rho_j/\rho_c$; sometimes a more accurately determined quantity is $\Omega_j h^2$.

The total energy density in the universe is quite close to the critical one, $\Omega_{tot} = 1.02 \pm 0.02$ in agreement with inflationary theory. Visible matter (either shining or absorbing light) gives a minor contribution into total mass, $\Omega_{vis} \approx 0.005$ (see e.g. ref.4). The total fraction of baryonic matter is about an order of magnitude larger, $\Omega_{b} = 0.044 \pm 0.004$. The answer to the question where are the unseen 90% of baryons is not completely clear by now. A much larger contribution to $\Omega$ comes from some unknown form of matter, the so called dark matter, while a better word could be “invisible”, $\Omega_{DM} = 0.27 \pm 0.04$. Though unknown what, it is still normal matter, presumably, though not surely, with a normal non-relativistic equation of state with zero pressure $p = 0$ and positive energy (mass) density, $\rho > 0$. Dark matter is believed to posses the usual gravitational interactions.

Much more puzzling, even mysterious, is the dominant contribution to the cosmological energy density, the so called dark energy, with $\Omega_{DE} =$
0.73 ± 0.04. It has negative pressure density,

\[ p = w \rho \]  \hspace{1cm} (2)

with \( w < -0.8 \), so it could be vacuum energy (or, in other words, cosmological constant) for which \( w = -1 \). Its impact on the cosmological expansion is anti-gravitating, i.e. it leads to accelerated expansion\(^5\). This statement follows from the Friedman/Einstein equation for the second time derivative of the cosmological scale factor \( a(t) \):

\[ \frac{\ddot{a}}{a} = -\frac{4\pi G}{3} (\rho + 3p) \]  \hspace{1cm} (3)

and acceleration of the expansion would be positive if \( p < -\rho/3 \), of course under the standard assumption that \( \rho \) is positive. For negative \( \rho \) anti-gravity could be easily created but such theories would possess quite unpleasant pathological features if special care is not taken.

In addition to the direct observation of the accelerated expansion by high red-shift supernovae, there is an indirect argument in favor of non-zero vacuum-like energy. Namely with \( \Omega = 1 \) and \( h = 0.73 \) the age of the universe would be about 9 Gyr, while nuclear-chronology and stellar evolution theory give the number 12-14 Gyr. With non-zero vacuum energy, \( \Omega_{\text{vac}} = 0.7 \) the universe needs considerably more time to reach the present-day state and its age would well agree with the data. Theory of large scale structure formation also supports a non-zero value of the vacuum energy.

One more comment is worth making. Different forms of matter/energy density have similar values at the present time: \( \Omega_b = 0.044 \), \( \Omega_m = 0.27 \), \( \Omega_{DE} = 0.73 \), though their physical origin could be quite different and unrelated at least at the level of our present understanding. They may naturally differ by many orders of magnitude. Moreover, densities of non-relativistic matter and dark energy evolve in different ways in the course of the cosmological expansion (see sec. 3). This makes the problem even more profound. At the moment this cosmic coincidence (or cosmic conspiracy) problem is not understood at all.

### 3. Cosmological Constant/Dark Energy

Cosmological constant (or lambda-term) was introduced to equations of general relativity by Einstein in 1918 when he found out that the equations did not admit stationary solution in cosmological situation with homogeneous and isotropic matter source \( T_{\mu\nu} \):

\[ R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R - \Lambda g_{\mu\nu} = 8\pi G_N T_{\mu\nu} \]  \hspace{1cm} (4)
Later, after the Friedman’s cosmological solution and the Hubble’s observation of the universe expansion, Einstein strongly rejected the idea of cosmological constant and considered it as the “biggest blunder” of his life. For a long time after that the majority of the astronomical/cosmological establishment even refused to hear about it, though were were notable exceptions like e.g. Lemaitre, De Sitter, Eddington. The attitude of majority could be characterized by the words written by G. Gamow in his autobiography book “My World Line”: “lambda rises its nasty head again”, after astronomical data indicated an accumulations of quasars near redshift $z = 2$. In a sense Gamow was right because these data were explained without cosmological constant but it seems impossible to avoid non-zero $\Lambda$ today.

According to the contemporary point of view, $\Lambda$-term can be interpreted as the energy-momentum tensor of vacuum and should be positioned in the r.h.s. of the Einstein equation:

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = 8\pi G_N \left(T_{\mu\nu}^{(m)} + \rho_{\text{vac}}g_{\mu\nu}\right)$$  \hspace{1cm} (5)$$

Quantum field theory immediately leads to a very serious trouble. The energy of the ground state is generally non-vanishing and, moreover, for a single species it is infinitely divergent:

$$\rho_{\text{vac}} = g_s \int \frac{d^3p}{(2\pi)^3} \sqrt{p^2 + m^2} = \infty^4$$  \hspace{1cm} (6)$$

Here $m$ is the mass of the field, $g_s$ is the number of spin states of the field and it is assumed that the field in question is a bosonic one. One cannot live in the world with infinitely big vacuum energy, so Zeldovich assumed that bosonic vacuum energy should be compensated by vacuum energy of fermionic fields. Indeed, vacuum energy of fermions is shifted down below zero and is given by exactly the same integral as (6) but with the opposite sign. (This is related to the condition that bosons are quantized with commutators, while fermions are quantized with anti-commutators.) So, if there is a symmetry between bosons and fermions such that for each bosonic state there exists a fermionic state with the same mass and vice versa, then the energy of vacuum fluctuations of bosons and fermions would be exactly compensated, giving zero net result. This assertion was made before the the pioneering works on super-symmetry were published. However, since super-symmetry is broken this compensation is not complete and non-compensated amount of vacuum energy in any softly-broken super-symmetry must be non-vanishing, $\rho_{\text{vac}}^{(\text{susy})} \sim m_{\text{susy}}^4 \geq 10^8$.
GeV$^4$. This is 55 orders of magnitude larger than the cosmological energy density $\rho_c \approx 10^{-47}$ GeV$^4$, eq. (1). Supergravity, i.e. locally realized supersymmetry, allows vanishing vacuum energy even in the broken phase but at the expense of fantastic fine-tuning by more than 120 orders of magnitude. Somewhat smaller contribution but still significant (mismatch by 55 orders of magnitude), and in a sense more troubling, comes from the vacuum condensates in quantum chromodynamics (QCD). It is practically an experimental fact that vacuum in QCD is not empty but filled by quark and gluon condensates with the energy density about $10^{-2} - 10^{-4}$ GeV$^4$. What else “lives” in vacuum and exactly “eats up” all these contributions (with accuracy $10^{-45}$ or maybe even $10^{-120}$) is the biggest mystery in modern physics. The reviews of vacuum energy problem and possible solutions (none is satisfactory at the moment) can be found in refs.\textsuperscript{10}. Another side of the problem emerges from the observed acceleration of the universe: it means that either the vacuum energy-momentum tensor is non-vanishing, $T_{\mu\nu} = \rho_{\text{vac}} g_{\mu\nu} \neq 0$, or there exists something unknown with negative and large by absolute value pressure, $p = w \rho$ with $w < -1/3$. According to the covariant conservation of energy-momentum:

$$\dot{\rho} = -3H(\rho + p),$$

the energy density of matter with the equation of state (2) evolves in the course of expansion as $\rho \sim a^{-3(1-w)}$. In particular, for vacuum energy $\rho = \text{const}$. A puzzling feature is why the energy densities of non-relativistic matter which evolves as $\rho_m \sim a^{-3}$ and dark (vacuum) energy are almost coinciding today, though their cosmological evolution were completely different. This may be explained by the so called quintessence\textsuperscript{11}, that is by a new scalar field with vanishingly small mass and negligible interaction with other matter fields, except for gravity. Equation of motion of this field might have a tracking solution whose energy density closely follows the dominant one, though a fine-tuning is necessary to realize such a solution. On the other hand, even if the problem of coincidence of $\rho_{\text{vac}}$ and $\rho_m$ today, may be solved by the tracking solution, this new field does not explain why the vacuum energy is so close to zero.

A model which in principle could solve both these problems is based on dynamical adjustment of vacuum energy by a new massless scalar\textsuperscript{12}, vector\textsuperscript{13}, or tensor\textsuperscript{14} field coupled to gravity in such a way that this new field is unstable in De Sitter space-time with respect to formation of vacuum condensate whose energy would compensate the source (i.e. the original vacuum energy) in accordance with the general principle of Le Chatelier.
Such models have a generic property that the vacuum energy is compensated, however the compensation is not complete but only down to the terms of the order of the critical energy density at the running time moment $t$. So at each moment there is a non-compensated remnants (dark energy) with $\Omega \sim 1$ with equation of state which may differ very much from the usual ones. Phenomenologically such models describe decaying vacuum energy and contain many of the later suggested “quintessential” ideas. The only, but important, shortcoming is that a realistic cosmological model based on this mechanism has not yet been found.

An important quantity which may lit some light on the physical nature of dark energy is the value of the parameter $w$ which describes the equation of state of dark energy (2). The present-day data agrees with $w = -1$, i.e. dark energy could be the vacuum energy. However, other values of $w$ are not excluded, moreover, it is possible that $w$ is not a constant but a function of time and even that equation of state does not exist, so $p$ cannot be expressed locally through $\rho$.

In a normal field theory the energy dominance condition, $|p| < \rho$ is usually fulfilled. However, dealing with such a strange entity as the dark energy we cannot exclude that $w < -1$. In this quite unusual case the energy density rises(!) in the course of expansion, $\dot{\rho} > 0$ (see eq. (7)). An example of field theory leading to such a regime can be found in ref.\textsuperscript{14}: it is a theory of free massless vector (or tensor) field with the Lagrangian density $L = V_{\mu\nu}V^{\mu\nu}/2$. Such a theory in a curved background is unstable with respect to formation of vacuum condensate of the time component $V_t$ with the energy and pressure densities:

$$\rho_V = \dot{V}_t^2/2 + 3H^2V_t^2/2,$$
$$p_V = \dot{V}_t^2/2 - 3H^2V_t^2/2 - \dot{H}V_t^2 - 2HV_tV_t$$

There is no equation of state $p = p(\rho)$ in this theory but anyhow $\rho_V + p_V$ may be negative and a new type of cosmological singularity:

$$H \sim (t_0 - t)^{-3/2}$$

can be reached in a final time resulting in “tearing apart” the universe\textsuperscript{14}. A different model of negative ($\rho + p$) based on a scalar field with a wrong sign of the kinetic term and a discussion of a similar singularity can be found in ref.\textsuperscript{15}. The pathological properties of such theories probably indicate that a negative $\rho + p$ is impossible, though it is not yet rigorously forbidden.

Understanding the problem of vacuum energy compensation may have a noticeable impact on cosmology (and quite probably on fundamentals...
of quantum field theory). The mechanism that ensures this compensation may change the standard picture of the cosmological evolution. However, at the moment there is no strong demands for such changes. On the other hand, some discrepancies which may exist in big bang nucleosynthesis (see below sec. 5.4) or possibly in the formation of large scale structure could be cured by the dark energy. A related strong challenge is to understand what is the dark energy and a very important information about it can be obtained through a more accurate measuring of $w$ in the future.

4. Dark Matter

Second most important unsolved problem in cosmology (which may also have a strong impact on particle physics and field theory) is the problem of dark matter. The latter, most probably, consists from normal but yet undiscovered particles or fields. There are many (maybe, too many) possibilities discussed in the literature and at the moment we do not know which one of these hypothetical objects plays the role of dominant matter constituent of our world, or maybe there are even several of them. For a recent review see e.g. the lectures\textsuperscript{16}

Though the dark matter is not observed directly its existence seems to be firmly established. First, the total fraction of non-relativistic matter in the universe is $\sim 0.3$, while the amount of baryonic contribution is about 0.05 (see sec. 2). The latter is determined by two independent methods: by measurements of angular fluctuations of CMBR and by observations of abundances of light elements produced at BBN.

Another argument in favor of cosmological domination of non-baryonic matter is based on the theory of large scale structure formation. Structures in baryo-dominated universe can only be formed after hydrogen recombination which took place at $T \approx 3000$ K, i.e. at red-shift $z_{rec} = 10^3$ when the matter became electrically neutral. Before that period a large light pressure experienced by electrons (and as a result, by protons) prevented them from gravitational clusterization. After recombination, initially small density perturbations, $\delta \rho/\rho$ rose as the cosmological scale factor and hence could increase only by the factor $z_{rec} = 10^3$. On the other hand, the measured angular fluctuations of CMBR temperature are quite small, $\delta T/T < (a$ few)$ \times 10^{-5}$. Hence it follows under the standard assumption of adiabatic density perturbations (this assumption is now confirmed by CMBR data) that the latter should be also small at recombination, $\delta \rho/\rho < 10^{-4}$. Hence they should remain small at the present epoch, even after amplification by
3 orders of magnitude. So one could conclude that there should be some other form of matter which does not interact with light and which started to form structures long before recombination. On the other hand, much larger density perturbations at small scales are not formally excluded by observations and they might allow an efficient structure formation in purely baryonic universe. Still, the combined data are very much against structure formation without dark matter. In particular, inflation predicts flat spectrum of perturbations with spectral index $n = 1$. From observations follows $n = 0.93 \pm 0.03$. If this spectral behavior remains true at small scales then larger density perturbations, mentioned above, would not be present.

Most probably cosmological dark matter consists of cold relics from Big Bang. It is the so called cold dark matter (CDM). Two most popular candidates for the latter are the lightest supersymmetric particle (which could be as heavy as a few hundreds GeV) and axions (which would be extremely light, about $10^{-5}$ eV). However, such simple forms of dark matter meet serious problems in description of details of large scale structure. There are several troubling features. In particular, CDM cosmology predicts dark halos with steep cusps\cite{17}, while observations indicate that halos have a constant density cores (see e.g. ref\cite{18}). Theory also predicts too many, by factor 5, galactic satellites\cite{19}. Comparison\cite{21} of galactic cluster abundances at high $(z > 0.5)$ and low redshifts is compatible with the theory of cluster evolution for a very low cosmological matter density, $\Omega_m \approx 0.17$, which is much smaller than the value, $\sim 0.3$, obtained by other methods. And at last, the galaxies in CDM simulations have considerably smaller angular momenta, than those observed (see the paper\cite{20} and references therein). All these inconsistencies could be either prescribed to shortcomings of numerical simulations and, in particular, to neglecting some essential physical processes, or, more probably, to a real crisis in cold dark matter cosmology.

Several new forms of dark matter were suggested to overcome the CDM problems: warm dark matter (WDM), self-interacting dark matter and, in particular, long discussed mirror or shadow matter (which is a special case of self-interacting dark matter), decaying cold dark matter, etc. Models with non-canonical forms of the spectrum of primordial fluctuations and models with mixed adiabatic and isocurvature fluctuations were also considered. (For a recent review and a list of references see the papers\cite{22}.) It seems that a simple canonical model with one form of dark matter and flat (inflationary) spectrum of perturbations does not satisfactorily describe details of cosmic large scale structure and some deviations from the standard scenario seem
to be necessary. It makes the situation more complicated and more interesting. It is worth mentioning that models with several forms of dark matter, e.g. mixed CDM+WDM, make the problem of cosmic conspiracy even more profound because, in addition to similar magnitudes of $\Omega_b$, $\Omega_m$, and $\Omega_{DE}$ one has to explain close contributions to $\Omega$ of several new forms of DM.

5. Main events in cosmological evolution

Here we will briefly discuss the history of the universe and physical phenomena necessary for creation of the present state of the world where we can live.

5.1. Before beginning

Nothing is known about the universe prior for a certain temporal moment. So we cannot extend our history infinitely backward in time. It may be so because theory of quantum gravity is yet missing and there is no way to describe the state of the universe when the characteristic curvature and energy density had Planckian magnitudes. Possibly even time and space in our classical understanding did not exist “at that time”. There are some attempts to go beyond Planck scales or, better to say, before Big Bang exploring e.g. string cosmology\textsuperscript{23}. However, it is difficult to say if this or any other continuation through big-bang was indeed realized. Another possibility of periodically oscillating universe between big bang and big crunch was suggested ages ago (a list of the early papers and discussion can be found in the books\textsuperscript{24}) and was recently revitalized\textsuperscript{25} as an alternative to inflation. Such models have an evident difficulty: in contraction phase already evolved large inhomogeneities become even larger and catastrophic formation of black holes during contraction phase may endanger the scenario. A recent discussion of behavior of perturbations in oscillating or bouncing universe can be found in the papers\textsuperscript{26}.

5.2. Inflation

The earliest period of the universe evolution whose existence seems to be on firm grounds is the inflationary epoch. Today one could even say that inflation is an experimental fact. After the original suggestion by Guth\textsuperscript{3} and first realistic models\textsuperscript{27} there appeared billions of papers on the subject; for recent reviews one can address ref.\textsuperscript{28}
During relatively short inflationary period, when the universes exponentially expanded, $a(t) \sim \exp(H_I t)$, the proper initial conditions for creation of the present-day universe have been secured. During this period the cosmological energy density was, by assumption, dominated by a slow varying scalar field, inflaton, with the vacuum-like energy-momentum tensor, $T_{\mu\nu} \approx g_{\mu\nu}\rho_I$. As we have already mentioned above, such energy-momentum tensor creates cosmological gravitational repulsion and hence it explains the origin of the observed today expansion. If inflation was sufficiently long, $H_I \Delta t_I \geq 70$, then the universe would be flat, $\Omega = 1 \pm 10^{-4}$ in accordance with observations (in fact the necessary duration of inflation depends upon the temperature of the universe heating and might be somewhat smaller than 70 Hubble times). The universe would be almost homogeneous and isotropic on large scales. This explains why CMBR coming from different directions has almost the same temperature - one should keep in mind that without inflation the regions on the sky separated by more than one degree would never communicate to each other. Simultaneously with the “smoothing down” the universe, inflaton created small density perturbations but at astronomically large scales which much later became seeds of large scale structure formation. In non-inflationary cosmology no reasonable mechanism of creation of density perturbations was known and the problem of their generation at astronomically large scale remained a great mystery.

A unique explanation of these previously unexplainable features would be enough to consider inflation as an established fact. Moreover, there are some quantitative predictions of inflationary scenario supported by the astronomical data. First is of course a prediction of flat universe, $\Omega = 1$. Second is a prediction of flat (Harrison-Zeldovich$^{29}$) spectrum of perturbations with spectral index $n = 1$. In fact inflationary spectrum usually slightly deviates from the flat one, depending upon the concrete model of inflation (for a review see e.g. ref.$^{30}$). According to the recent WMAP data (fifth paper in ref.$^{1}$), the index deviates from unity, $n = 0.93\pm0.03$. It could be a worrying sign but maybe the deviation is not significant taking into account possible statistical and systematical errors. On the other hand, as argued in ref.$^{31}$, the graceful exit from inflation demands $0.92 < n < 0.97$ and the WMAP data can be considered as confirmation of simple inflationary scenarios. However, even if the spectral index happened to be outside these bounds, it would not mean that inflation is excluded. There could be e.g. some other forms of perturbations, in particular, isocurvature ones (see e.g. the review$^{32}$ for possible mechanisms and recent papers$^{33}$ and references therein) which would have a different spectrum and which may
explain a noticeable deviation of $n$ from unity.

So as a whole inflation is a great success. It is observationally confirmed and theoretically beautiful. Now we have to fix some details: what is the inflaton, in which potential it evolves, are there gravitational waves generated at inflationary stage, etc. This is of course highly non-trivial, especially because there could be some other sources of perturbations, except for the inflaton. The measurements of CMBR angular spectrum and polarization gives some hopes to progress in this direction. Existence of inflation means in particular that there should be new physics beyond the standard model (SM) because there is no space for the inflaton in the frameworks of SM.

5.3. Baryogenesis

Predominance of matter over antimatter was one of the biggest cosmological puzzles of the first two thirds of the XX century. Its solution was outlined by Sakharov in 1967 and is now commonly accepted. The mechanism is based on three conditions: 1) Non-conservation of baryonic charge; 2) Breaking of C and CP symmetries; 3) Deviation from thermal equilibrium in primeval plasma. All these three conditions are known to be true either from experiment or because they are well justified theoretically. Moreover, the existence of the charge asymmetric universe itself is a strong indication to non-conservation of baryons, otherwise inflation would not be possible.

The time and temperature interval where baryogenesis took place strongly depends on concrete model and may vary in a very wide range from GUT or even almost Planck scales down to a fraction of GeV. For the reviews and more recent quotations see refs. There are many models of baryogenesis considered in the literature. Possibly an incomplete list includes:

1. Baryogenesis in out-of-equilibrium heavy particle decays.
2. Electroweak baryogenesis.
3. Baryogenesis by supersymmetric baryonic charge condensate.
4. Spontaneous baryogenesis.
5. Baryo-through-lepto-genesis.
6. Baryogenesis in black hole evaporation.
7. Baryogenesis by topological defects (domain walls, cosmic strings, magnetic monopoles).

The problem is to understand what of the above is indeed realized and how it can be verified. The second part is non-trivial because usually a model of
baryogenesis has to explain only one number the ratio of baryonic charge
number density to the number density of photons in CMBR, $\beta = 6 \cdot 10^{-10}$, and there could be many models giving the same baryon asymmetry. It seems established that electro-weak baryogenesis, which might proceed in the frameworks of the standard model, is not efficient enough to produce the observed asymmetry. All other models demand new physics. So the baryon asymmetry of the universe is another cosmological fact that indicates to existence of physics beyond the standard model.

There are plenty of models of baryogenesis which simultaneously with excess of matter over antimatter in our neighborhood predict that there could be astronomically large domains of antimatter and maybe even not too far from us. Such models are discussed in ref.42. In this connection expected BESS, Pamela, or AMS experiments searching for cosmic antinuclei $^4$He or heavier ones would be of primary importance (for a review see e.g. ref.43).

5.4. **Big Bang Nucleosynthesis**

Big bang nucleosynthesis (BBN) took place in a relatively old and cold universe in the temperature interval from a few MeV down to 60-70 keV and time in the range from roughly 1 sec up to 300 sec. Physical processes involved are well known: they include low energy weak interactions and low energy nuclear physics. In contrast to phenomena considered in the previous subsections when we were in *terra incognita* and had to use our imagination based on reasonable theoretical models, now we are on firm grounds of well established physics.

The only unknown parameter that enters theoretical calculations of the light element abundances is the ratio of baryon-to-photon number densities, $\beta = n_B/n_\gamma$, which a few years ago was found from BBN itself. Now can be independently determined from CMBR. A reasonable concordance of the two values of $\beta$ shows that the theory is in a good shape and that there was no influx of photons into the cosmic plasma between neutrino decoupling at $T \approx 1$ MeV and hydrogen recombination at red-shift $z \approx 10^3$ or $T \approx 0.26$ eV. The accurate Bose-Einstein shape of the CMBR spectrum indicates the same but in a slightly shorter temperature interval, roughly speaking, starting from the red-shift $10^7$ (see e.g. the reviews$^{44,45}$).

During those several minutes the following light elements have been produced: deuterium ($\sim 3 \cdot 10^{-5}$, relative to hydrogen by number), helium-3 (about the same number as $^2$H), helium-4 (23-24% by mass), and a little of
7Li (a few $\times 10^{-10}$). Accuracy of calculations is mostly determined by the uncertainties in the nuclear interaction rates and is quite good. According to the analysis of ref. 46, the theoretical accuracy is at the level $\leq 0.1\%$ for $^4\text{He}$, better than 10\% for $^2\text{H}$ and is about 20-30\% for $^7\text{Li}$. Anyhow, in all the cases theoretical uncertainty is much smaller than the observational precision. The latter suffers from two serious problems: systematic errors and poorly understood evolutionary effects. They are reviewed e.g. in refs. 47. Despite existing uncertainties, theory reasonably well agrees with observations. However, there are indications to possible discrepancies. The results of different groups measuring deuterium at high redshifts, which may be a primordial one, are in noticeable disagreement with each other. Moreover, the measured abundances of $^4\text{He}$ and $^2\text{H}$ seem to correspond to somewhat different values of $\beta$. It is not clear if these discrepancies are serious and indicate some unusual physics (degeneracy of cosmic neutrinos, non-negligible role of dark energy at BBN, some new particles present at BBN, etc) or after a while all measurements will come to an agreement between themselves and with the value of $\beta$ inferred from CMBR. Hopefully it will not take more than a decade.

5.5. Large scale structure formation

During an initial period of the universe life-time (but after inflation) the universe was very smooth, practically homogeneous and isotropic. It remained such between the epoch of inflation and the end of radiation domination (RD) era. This period lasted roughly speaking about 100,000 years or until red-shift $z_{eq} \approx 10^4$. Small density perturbations generated at inflation were almost frozen during RD period and were practically unnoticeable. However, their importance at matter dominated (MD) regime is difficult to overestimate. At MD-stage these small density perturbations became unstable with respect to gravitational attraction, they started to rise forming seeds from which astronomical large scale structures such as galaxies, their clusters and superclusters evolved. Development of such huge objects, their temporary evolution, and power spectrum primarily depend upon the form of primordial density perturbations and properties of dark matter. In particular, detailed study of the large scale structure at different scales can help to establish essential properties of dark matter particles prior to their possible discovery in direct experiments. To some extent this subject is discussed in sec. 4.

An interpretation of the astronomical data and conclusion about prop-
Properties of DM-particles depend upon the hypothesis about the perturbation spectrum. Usually the spectrum of primordial density perturbations is taken in one parameter power law form with an arbitrary spectral index $n$. Such shape is justified for the flat spectrum (with $n = 1$) which is scale free and on dimensional grounds this is the only possible form of the spectrum. In the case that a dimensional parameter exists, any function of this parameter, and not only a power law, is a priori allowed. Though, as is mentioned above, the nearly flat spectrum is supported by inflation and quite well agrees with the data, noticeable deviations from this type of spectrum are possible. Such deviations would be very interesting for physics of the early universe and, in particular, for possible mechanisms of creation of density fluctuations but simultaneously it would make it more difficult to obtain conclusions about DM-particles from the LSS data.

5.6. Future of the universe

In Friedman cosmology with the normal matter content the ultimate fate of the universe is completely determined by the spatial curvature: for flat (zero curvature) and open (negative curvature) geometry the universe will expand forever, while closed universe (positive curvature) will stop expanding and will recollapse to big crunch. One can see that from the Friedman equation:

$$H^2 \equiv \left( \frac{\dot{a}}{a} \right)^2 = \frac{8\pi\rho}{3m_P^2} - \frac{k}{a^2}$$

(11)

where the sign of the constant $k$ determines the sign of curvature. The energy density $\rho$ of any normal matter with positive pressure drops in the course of expansion faster than $1/a^3$, the limiting case corresponds to non-relativistic matter with $p = 0$. Hence the curvature term will dominate at large $a(t)$ and determine the universe destiny.

If the parameter $w$ connecting pressure and energy densities, eq. (2), may be negative, then for $w < -1/3$ the pressure density which evolves as $\rho \sim a^{-3(1+w)}$, would decrease slower than $k/a^2$ so initially inessential curvature term would always remain such and expansion would never stop in any geometry. Thus in a distant future only gravitationally binded objects will continue to exist, while distant galaxies will disappear from the sky. It would not create a big difference for a naked eye if stellar luminosity remains the same during some billion years. Unfortunately this is not so because the Sun and other stars will exhaust their nuclear fuel and the world will fall into (almost) complete darkness and cold which may be
slightly lit up and heated by possible proton decay. For the proton lifetime $\tau_p \sim 10^{33}$ years the solar luminosity generated by the decay will be 20 orders of magnitude smaller than the present-day solar luminosity. In this epoch the Earth will be much stronger “illuminated” and heated by her own decaying protons. Nevertheless, life will hardly be possible in such uncomfortable conditions. The only chance for survival could be catalysis of proton decay by e.g. magnetic monopoles if they exist. The consumption of the whole solar mass will allow to maintain life on the Earth for about $10^{30} - 10^{32}$ years, if other civilizations do not interfere.

All the story may end much faster if $p < -\rho$ and the universe will evolve to catastrophic expansion singularity (10) in 10-100 Gyr. In this case not only astronomically large objects but even atoms and elementary particles may be destroyed. However this conclusion is model dependent and an inhomogeneous component of the dark energy field $V(t, x)$ may stop the catastrophe.

6. Neutrinos in cosmology

The universe is filled with neutrinos - 55 neutrinos and the same number of antineutrinos per cm$^3$ for each neutrino flavor - and though they are very light and weakly interacting their sheer number makes them cosmologically important. Knowing the number density of cosmic neutrinos one can immediately deduce an upper limit on their mass:

$$\sum_a m_{\nu_a} < 94 \text{ eV } \Omega_m h^2 = 15 \text{ eV}$$

(12)

where $\Omega_m = 0.3$ and $h^2 = 0.5$ have been substituted and the sum is taken over all neutrino species, $a = e, \mu, \tau$.

Since neutrinos were relativistic during a large part of the universe history, their long free streaming path would suppress structure formation in neutrino dominated universe at the scales below $M = 10^{17} M_\odot (m_\nu/\text{eV})^{-2}$ where $M_\odot$ is the solar mass. Hence massive neutrinos cannot be the dominant dark matter particles and their mass density should be below $\Omega_{\nu} < 0.1$. Correspondingly $\sum_a m_{\nu_a} < 5 \text{ eV}$ (further discussion and references to this and other subjects discussed below can be found in the review). More detailed studies of the large scale structure together with WMAP data on angular fluctuations of CMBR allowed to improve this limit down to $\sum_a m_{\nu_a} < 0.7 \text{ eV}$. Already today astronomy is able to constraint $m_\nu$ with better accuracy than direct experiment. Future Planck mission and more
data on LSS will possibly push this limit down to $\sim 0.1$ eV or will measure the neutrino mass. This would be a unique example when the mass of an elementary particle is determined by telescopes.

Apart from LSS, neutrinos can be traced through BBN and CMBR. BBN permits to constrain the number of neutrino families. Keeping in mind the existing accuracy in extracting primordial abundances of $^2$H and $^4$He from observations (see sec. 5.4) one can impose the upper limit on the number of additional neutrino families, $\Delta N_\nu < 0.3 - 0.5$ with justified expectations to strengthen this limit down to about 0.1 in the near future. At the present time the CMBR data are not competitive with the upper limit obtained from BBN. Still the analysis of the CMBR data indicates, independently from BBN, that cosmological relic neutrinos indeed exist and the number of families is confined between: $1 < N_\nu < 6$. One may hope for a drastic improvement of this result if the expected sensitivity of the Planck mission at per cent level is achieved, so that it may register even non-equilibrium corrections to the energy spectrum of relic neutrinos at the level of 3%. These corrections are predicted to result from non-equilibrium $e^+e^-$ annihilation in the primeval plasma and deviations from ideal gas approximation at the epoch when the universe was about 1 sec old (see discussion and references in the review).

Consideration of BBN permits also to derive bounds on mixing between active and possible sterile neutrinos, on the magnitude of cosmological charge asymmetry, on magnetic moment of neutrinos, etc.

7. Conclusion

Great progress in cosmology at the end of the previous century helped to understand the universe much better and simultaneously led to discovery of many new puzzles, problems, and even mysteries. Today cosmology tells us that fundamental physics is not completed and there surely exist new phenomena outside well established known physics. We need to discover much more to understand the observed features of the universe.

To start, the greatest mystery of (almost) complete cancellation of vacuum energy is not (or cannot be) resolved in the frameworks of known physics. The next, possibly not so striking, question about the nature of dark energy also remains unanswered.

As for dark matter, it may possibly be explained by some extension of the realm of the existing particles by addition either stable lightest supersymmetric particle or axion. There are some more good candidates for
dark matter particles or objects but it is not yet established which one of them makes dark matter. Moreover, the CDM crisis (see sec. 4) possibly demand either several forms of DM, thus deepening the cosmic conspiracy puzzle, or particles with rather strange properties unexpected in simple, theoretically motivated generalizations of the standard model.

Baryogenesis might in principle operate based on the existing minimal standard model of particle physics but the latter is not sufficiently productive to create the observed baryon asymmetry of the universe. Hence new particles or fields are necessary.

Hopefully joint efforts of experimentalists and theoreticians will help to resolve some or, in further perspective, all these problems but new mysteries and discoveries are waiting for us on the way and this is what makes cosmology so interesting now. To conclude, cosmology had very productive period during last quarter of the previous century, it is in the process of exciting development today, and bright future with many new discoveries is coming.

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