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COSMOLOGICAL STANDARD MODEL

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Abstract

A review of the contemporary state of the cosmological standard model is presented. The bulk properties of the model seems to be solid and firmly established but unsolved and possibly serious problems exist. The cosmological data demanding new physics beyond the particle standard model are outlined.

1 Introduction

During the last 2-3 decades of the previous century a symbiotic development of cosmology and elementary particle physics has led to a striking success in both fields. Two standard models have been established: the (minimal) standard model of particle physics, (M)SMPP, and the cosmological standard model, CSM. Though both these models are called "standard", there is an important difference between them. (M)SMPP well agrees with all existing experimental data in particle physics and could last without new physics. On the contrary, the CSM contains many unusual effects and phenomena which do not fit the framework of the MSMPP (and even of the SMPP) and surely demand new, not yet discovered physics.

In what follows the CSM and its relation to the SMPP are discussed. In sec. 2 matter-energy content of the universe is inventoried. Next, in sec 3 brief cosmological history is presented, as we understand it now, and a necessity of new physics is advocated. In sec. 4 basic facts about large scale structure (LSS) of the universe (observations and theory) are presented. A proper list of references would make this paper to go beyond the allocated volume limit and thus only references to reviews are made. In particular, all values of basic cosmological parameters presented below can be found in the new issue of the Particle Data Group [1].

2 Matter-energy inventory.

The contribution of a certain form of matter into cosmological matter-energy density is usually expressed by dimensionless parameter $\Omega_a = \rho_a/\rho_c$, where

$$\rho_c = \frac{3H^2 m_{Pl}^2}{8\pi} = 1.88 \cdot 10^{-29} h^2 \,\frac{\mathrm{g}}{\mathrm{cm}^3} = 10.5\, h^2\, \frac{\mathrm{keV}}{\mathrm{cm}^3} = 3 \cdot 10^{-47} h^2 \mathrm{GeV}^4 \tag{1}$$

is the critical or closure energy density and $h = 0.72 \pm 0.05$. The position of the first acoustic peak in the angular spectrum of CMBR, combined with other astronomical observations, accurately confirms predicted by inflation flatness of the universe, $\Omega_{tot} = 1.02 \pm 0.02$. The usual baryonic matter makes only a tiny fraction of total mass density, $\Omega_b = 0.05 \pm 0.01$ This result is obtained from two *independent* pieces of data: from analysis of cosmological abundances of light elements produced during BBN and from the positions and heights of acoustic peaks of CMBR [1]. Only 10% of all cosmic baryons are observed directly in the form of luminous or light-absorbing matter. It is an intriguing problem where are the remaining 90% of baryons [2].

The total amount of clustered matter, the so called dark matter, observed by its gravitational action, is about 6 times larger than that of baryons: $\Omega_{DM} = 0.30 \pm 0.07$, where Ω_{DM} includes all kinds of non-relativistic gravitating matter with equation of state $p = 0$. Out of these 0.3 approximately 1/6 are normal baryons, while the dominant 0.25-part consists of some unknown new form of matter. It is important that this serious conclusion is based on different independent pieces of astronomical data [3]:

1. Rotational velocities of gas clouds surrounding galaxies show that the amount of gravitating matter is much larger than that of the luminous one with the bulk of dark matter far outside the luminous part of the galaxy. Still the amount of dark matter is not enough to make $\Omega_m = 1$.

2. Peculiar velocities of galaxies superimposed on the cosmological Hubble flow are supposed to be induced by the surrounding matter. Measurements of these velocities are consistent with $\Omega_m \approx 0.3$.

3. Analysis of the equilibrium of hot gas in rich galactic clusters shows that the ratio of baryonic mass to the total mass is about 0.2.

4. Theory of cluster evolution predicts that in the universe with high matter content, $\Omega_m \approx 1$, the number of galactic clusters at $z = 1$ should be several, 3-5 times smaller, than at $z = 0$. Observations show that they are approximately the same, as is predicted by low Ω_m cosmology.

5. Gravitational lensing: light deflection from distant objects shows that the total clustered mass along the path of propagation is consistent with $\Omega_m = 0.3$.

One more argument in favor of non-baryonic dark matter comes from the theory of LSS formation. Small angular fluctuations of CMBR show that the density fluctuations at hydrogen recombination epoch, $z \approx 10^3$, were also small, $\delta\rho/\rho \sim 10^{-4}$. They could rise, due to gravitational instability, at most, as cosmological scale factor. Hence at the present time $\delta\rho/\rho$ might reach only 0.1, while it should be of the order of unity. This conclusion is true for the so called adiabatic density perturbations, in contrast to the isocurvature ones. According to CMBR data [4], the latter are small.

It is unknown at the present time what makes the dark matter. There are many possible candidates, we will mention only a few [5]:

1. The lightest supersymmetric particle, which would be stable if R-parity is conserved. The mass of such particles in natural model is about $10^2 - 10^3$ GeV.

2. Axion, its mass should be very small, about 10^{-5} eV, but since cosmological axions might be produced at QCD phase transition at rest, they would be non-relativistic and good for structure formation.

3. Primordial black holes or early formed star-like objects. They should be formed before BBN, otherwise successful predictions for light element abundances would be destroyed.

4. Mirror matter, a new world of particles which are connected to ours only through gravity and, possibly, through some other weak interaction. In contrast to mentioned above forms of DM mirror matter could be self-interacting and its cosmological evolution and cooling would be different.

Whatever dark matter particles could be, they, at least, have normal gravitational (inter)action by which their existence is detected. Really astonishing fact is that the bulk of matter in the universe, about 70%, anti-gravitates creating accelerated cosmological expansion. This unknown form of cosmological energy density is called *dark energy*. It is normally assumed that the energy density is positive, $\rho > 0$, and, to drive gravitational repulsion the pressure density should be negative and larger by absolute value than $\rho/3$. One should bear in mind, however, that with positive ρ gravitational repulsion (anti-gravity) may be created only in infinitely large systems; any finite object always gravitates. According to the combined astronomical data [1] the fraction of dark energy in the universe is $\Omega_{DE} \approx 0.7$ with equation of state determined by $w_{DE} = -0.98 \pm 0.12$. Thus cosmological dark energy can be just vacuum energy with $w = -1$ or something quite close to it. Several sets of astronomical data support these results:

1. Direct observations of cosmological acceleration [6, 7]. To do that one needs to measure the universe expansion law at high red-shifts. This is done with type Ia supernovae which are possibly the standard candles, i.e. astronomical objects with known luminosity. Their observations at $z \sim 1$ show that they are systematically dimmer than would be expected for normal decelerated expansion and a possible conclusion is that the universe expands with acceleration. Dimness of supernovae at large distances cold be explained by additional light absorption on the way by the so called gray dust. However, the effect of accelerated expansion must have maximum around $z = 0.7$; for larger z the normal matter should dominate and supernovae would be brighter. This is exactly what was observed [7] and it is a very strong argument in favor of "accelerated" interpretation of the data.

2. Angular spectrum of CMBR shows a prominent acoustic peak at $l = 200$. This corresponds to geometrically flat universe i.e. $\Omega_{tot} = 1$. Since $\Omega_m = 0.3$, this result implies that there is 0.7 in unknown form of energy. Moreover, a slight decrease of multipoles from l=5 to l=20 is in agreement with evolution of perturbations in a universe with non-zero vacuum energy.

3. LSS is well described in the theory with $\Omega_{vac} = 0.7$ and $\Omega_m = 0.3$. This is the best fit model at the present time.
4. If $\Omega_{vac} = 0$ and $\Omega_m = 1$ then the universe age would be too short to be compatible with the age of globular clusters and nuclear chronology. However, if $\Omega_{vac} = 0.7$ the universe age is in a perfect agreement with the data.

Probably the most natural assumption about dark energy is that it is simply vacuum energy. The energy momentum tensor of the latter is proportional to the metric tensor, $T_{\mu\nu}^{(vac)} = g_{\mu\nu}\rho_{vac}$ and, evidently, $p = -\rho$. Quantum field theory claims many contributions into vacuum energy, thus a non-zero result is quite natural. The only problem is that these contributions are huge in comparison with the observed value. For example, the well known QCD vacuum energy created by quark or gluon condensates is about 10^{-2} GeV^2 which overshoots cosmological energy density by 45 orders of magnitude. Other estimated contribution into ρ_{vac} are much larger, up to 120 orders of magnitude. How these almost infinitely large contributions are tuned or adjusted down to the observed value is one of the most serious problems of fundamental physics [8].

Except for vacuum energy, the dark energy could be either created by a new very light or even massless field or might be mimicked by modification of gravity at large distances. Neither of these two approaches addresses a problem of mismatch of theoretical expectations and the observed value of cosmological energy density by 50-100 orders of magnitude. In principle both problems could be solved by adjustment mechanism, when a new field did both jobs: compensate vacuum energy down to the terms of the order of critical energy density, m_{Pl}^2/t^2, with non-compensated remnant being the dark energy. Unfortunately at the moment there is no realistic model of adjustment.

There is one more strange fact about cosmological matter. Mass density of baryons is determined by the process of baryogenesis which, to the best of our knowledge, is unrelated to the creation of most popular forms of dark matter. Hence the energy densities of these two could be easily different by several (many) orders of magnitude. In reality they differ only by factor 5. This probably means that the two processes are physically connected and this is yet to be discovered.

The coincidence becomes more impressive if one takes into account that the density of dark energy is almost the same as that of dark matter (they differ by factor 2 only). Moreover, vacuum (or vacuum-like) energy remains constant (or almost constant, if $w \approx -1$), while the energy density of dark matter scales as $1/a^3$. These coincidences are so striking that one may even call them "cosmic conspiracy". The cosmic conspiracy would be much more profound if other forms of DM (e.g. WDM) exist with comparable contributions into Ω (see sec 4).

There are two more known, though sub-dominant, contributions into cosmological matter, CMBR and cosmic neutrino background (CNB). The properties of the former is very accurately studied. The photons have perfect equilibrium thermal spectrum, with $T = 2.725$K and with vanishing chemical potential, $\mu/T < 10^{-4}$. Their number density is $410/\text{cm}^3$. The radiation is almost isotropic with the precision of about 10^{-5}, except for rather large dipole component, $\delta T/T \approx 2 \cdot 10^{-3}$. The latter is believed to be induced by our motion with respect to cosmological rest frame and corresponds to about 600 km/sec. This velocity is probably too fast to be explained by the gravitational action of neighboring clusters of galaxies. If this is true, then some other explanation for a large dipole asymmetry would be necessary (intrinsic dipole?). Some concern creates also a too low value of the quadrupole asymmetry.

As usually in physics, small imperfections are much more interesting than an exact symmetry and the observed small angular fluctuations of CMBR are now one of the most powerful tools for studying universe. Spectrum of angular fluctuations of CMBR, which is now measured up to the multipole number $l = 1000$ allows to determine basis cosmological parameters; Ω_{tot}, Ω_b, Ω_{vac}, h, and the spectrum of primordial density fluctuations. The latter is assumed to have a power law form with $n = 0.97 \pm 0.03$ in good agreement with inflationary prediction. One should keep in mind, however, the problem of degeneracy, i.e. the same spectrum of $\delta T/T$ could be created with different values of cosmological parameters in certain combinations. To resolve the degeneracy other astronomical measurements, especially of the power spectrum at smaller scales, found from distribution of matter at galaxy cluster scales and around, is of primary importance. CMBR measures the spectrum of fluctuations at the scales between the present day horizon size (a few Gpc) down to 10 Mpc, while the study of matter distribution (galaxies, clusters, and superclusters) measures spectrum of fluctuations from galactic scales up to tens Mpc. The fact that the measurements made from different ends agree in the coinciding region is a strong argument in favor of the consistency of the CSM.

After photons of CMBR, neutrinos are the second most abundant particles in the universe (among known ones, since e.g. the number density of cosmic axions might be higher). In the standard model, the number density of neutrinos is $55/\text{cm}^3$ for any type of neutrino and anti-neutrino. If neutrinos were massless they would have practically equilibrium Fermi-Dirac distribution with the present-day temperature $T_\nu \approx 1.95$ K. The observations of neutrino oscillations leads to conclusion that they must be massive with the mass of at least one of them being bigger than 0.05 eV. On the other hand, combined CMBR and LSS data put a stringent upper bound on neutrino mass [4], $\sum_a m_{\nu_a} < 0.7$ eV, where summation is made over all neutrino mass eigenstates. Correspondingly the relative contribution from CNB into total cosmological energy density is bounded by $10^{-3} < \Omega_\nu < 0.15$. Thus, a possible role of neutrinos in LSS formation is rather weak. Neutrinos might play a significant role there only if they do not obey Fermi statistics. In this case they even could form all dark matter in the universe - a thermal part of them would make hot dark matter, while a possible neutrino condensate would make cold dark matter.

3 Brief cosmological history

Observing universe today one can extrapolate this knowledge into the past and reconstruct main events in the universe history. Still it is not known what happened before time-zero or, in other words, how the universe started to evolve or if it existed for ever. There are several hypothesis: creation from nothing, eternal chaotic inflation, oscillating universe, string-motivated pre-big-bang cosmology, and possibly many more. None of them is either confirmed or rejected.

The earliest known period is *inflationary epoch* [9] when the universe expanded exponentially, $a \sim \exp(H_I t)$ with constant H_I. Inflation is practically an experimental fact. Of course one cannot rigorously exclude (unknown) alternatives but inflationary scenario is capable to solve by one blow the long standing problems of horizon, homogeneity and isotropy, to explain the origin of expansion and density perturbations on astronomically large scales. The generic predictions of inflation: $\Omega_{tot} = 1$, (almost) flat spectrum of density perturbations, Gaussian fluctuations of $\delta T/T$ are in a very good agreement with the data. Inflation cannot be realized in the framework of (M)SMPP and demands a new weakly interacting field, inflaton.

Next important step in the universe history was *baryogenesis* [10]. Inflation ended up with vanishingly small values of all conserved charges and to create the observed today excess of particles over antiparticles baryonic and leptonic charges must be non-conserved. Two other Sakharov's conditions of baryogenesis: breaking of C and CP and deviations from thermal equilibrium can be easily realized in big bang cosmology, allowing generation of the observed asymmetry, $\beta = (n_B - n_{\bar{B}})/n_\gamma = 6 \cdot 10^{-10}$. All three baryogenesis ingredients are present in electroweak interactions of MSMPP, but the magnitude of effect is much smaller than the necessary value. Thus an extension of MSMPP seems necessary. There are many possible scenarios of baryogenesis but we do not yet know which one was realized. It is a difficult problem to choose the correct scenario knowing only one observed number, β. In some models of baryogenesis a noticeable amount of antimatter could be produced in the form of antimatter domains, clouds of dispersed antimatter, or anti-stars and anti-planets. If search for cosmic antimatter is successful we will have a chance to find more about physics of baryogenesis.

Big bang nucleosynthesis (BBN) is already in "terrae cognitae". The underlying physics is low energy weak interactions and nuclear physics. The accuracy of theoretical predictions is a fraction of per cent for ^4He, and about 10% for ^7Li. The main part of theoretical uncertainty comes from the cross-sections of nuclear reactions. Much bigger errors arise in the process of extrapolation of the abundances of light elements produced in the early universe to the contemporary old universe when these elements are observed. Observational determinations of light element abundances are subject to rather large systematic errors and different corrections applied to raw data. Still despite all these uncertainties, there seems to be an inconsistency between measurements of deuterium and helium-4, and, even more, between different measurements of abundances of the same element in different astronomical systems. It is premature to conclude that the standard BBN is in trouble and some non-standard corrections are necessary but still the cloud exists and a resolution of the discrepancies is much needed [11].

At red-shifts about or below 10^4 initially small density perturbations started to rise making seeds for LSS formation, then at $z \approx 10^3$ hydrogen recombined and cosmic matter became practically neutral allowing for formation of baryonic structures and liberation of CMBR which from that moment propagated freely and brought to us information about that period. In more detail LSS formation is discussed in a separate section below.

4 Large scale structure formation

According to the theory, cosmological density perturbations remained frozen (with logarithmic accuracy) till universe became dominated by non-relativistic matter. It happened at approximately $z = 10^4$. After that moment gravitational instability became operative and density contrast begun to rise as cosmological scale factor, $\delta\rho/\rho = (z+1)\,(\delta\rho/\rho)_{in}$. This is the so called linear regime when density perturbations remains small. When $\delta\rho/\rho$ reaches unity, non-linear and much faster rise comes into effect. It is relatively easy to determine the law of evolution of density perturbations in the linear stage, while at non-linear regime numerical simulation methods are used.

The necessary input for the calculations includes an assumption about the spectrum of initial density perturbations. It is usually assumed to be of the power law form and, in particular, flat Harrison-Zeldovich spectrum (supported by inflation). Second important piece of information is the type of perturbations. The latter can be decomposed into two "orthogonal" ones, adiabatic with the same $(\delta\rho/\rho)$ for all types of matter or isocurvature with $\delta\rho = 0$ but varying chemical content. These two types of perturbations evolve independently at initial stage but begin to interact when isocurvature perturbations generate non-zero $\delta\rho$ due to different equations of state in different space points. In the standard model density perturbations are assumed to be adiabatic, in accordance with inflation and in agreement with CMBR data.

One needs also to specify the properties of dark matter particles. From astronomical point of view the latter could either cold (decoupled from cosmic plasma being non-relativistic), warm (semi-relativistic), or hot (relativistic). Correspondingly the characteristic scale of structures formed with WDM is about galactic size and much larger than that for HDM. The dark matter particles have negligible interactions with photons and baryons and between themselves. The last property is not always assumed to be true, as e.g. in scenarios with mirror matter. The standard (reference) model is based on dissipation-less cold dark matter particles (30%) plus uniformly distributed vacuum energy (70%). This model rather well describes general features of the observed structure but there are several troubling signs [12]:

1. Theory predicts cusps in galactic centers which are not observed.
2. The predicted number of galactic satellites is much larger than observed.
3. The calculated angular momenta of galaxies is too small in comparison with the observed ones.

It is unclear if these discrepancies are the results of oversimplified numerical simulations with important physical effects neglected, or some new input is necessary as e.g. warm dark matter.

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