Abstract

Cosmological implications of asymmetry between particles and antiparticles are reviewed. Three possible mechanisms of CP-violation in cosmology are described. General features of kinetics of generation of cosmological charge asymmetry are discussed in detail. In particular, the cyclic balance condition, which plays the same role in time non-invariant theory as detailed balance does in T-invariant case, is derived. Several scenarios of baryogenesis are described with an emphasis on CP-violation mechanisms. Production of cosmic antimatter and a possibility of its “living” in our neighborhood is discussed.

1 Introduction

In these three lectures I am going to discuss the cosmological impact of the asymmetry between particles and antiparticles and the role that C and CP violations play in creating the universe in the present suitable for life form. Seemingly, the breaking of C and CP symmetries are necessary for our existence but this happens to be true only in the simplest versions of the theory. There are realistic and natural scenarios according to which charge asymmetric universe can be created even in the case of C and CP conserving fundamental interactions. We will consider different possible mechanisms of breaking of C and CP symmetries in cosmology, some of which are the usual ones created by complex couplings or mass matrices, while the others may be operative only in the early universe and disappear today. Different models of creation of cosmological baryon, or any other charge asymmetry will be presented. A special attention will be paid to physical kinetics in the case of a broken time reversal invariance and to some general properties of elementary processes leading to a generation of cosmological charge asymmetry.

The generally accepted mechanism of generation of a cosmological charge asymmetry is based on three famous Sakharov’s conditions [1]:
1. Non-conservation of (baryonic) charge.
2. Breaking of symmetry between particles and antiparticles, both C and CP.
3. Deviation from thermal equilibrium.

We will see in what follows that none of these conditions is obligatory [2] but in the simplest versions of the baryogenesis scenarios they are usually assumed to be fulfilled.

As is known from different pieces of astronomical data, the universe, at least in our neighborhood, is strongly charge asymmetric: it is populated only with particles, while antiparticles are practically absent. A small number of the observed antiprotons or positrons in cosmic rays can be explained by their secondary origin through particle collisions or maybe by annihilation of dark matter. Any macroscopically large antimatter domains or objects (anti-stars, anti-planets or gaseous clouds of antimatter), if exist, should be
quite rare. As we see in what follows, there are plenty of baryogenesis scenarios which predict either charge symmetric universe at very large scales or, even more surprising, an admixture of antimatter in our vicinity with rather large amount but still compatible with observational restrictions.

The content of these lectures is the following. In sec. 2 we will see that the baryon asymmetry of the universe was certainly generated dynamically and was not a result of a charge asymmetric initial state. In sec. 3 the Sakharov conditions are considered. Kinetic equations with broken detailed balance and, possibly, without CPT are analyzed in sec. 4. General features of the observed baryon asymmetry and possible existence of cosmological antimatter are discussed in sec. 5. Three mechanisms of C and CP violation which may be operative in cosmology are presented in sec. 6. In secs. 7 and 8 two most conservative scenarios of baryogenesis: electroweak and heavy particle decays are respectively described. In sec. 9 several more speculative models of baryogenesis are presented. In particular, creation of cosmic antimatter and testable consequences of these models are discussed.

2 Dynamical or accidental?

The first question to address is whether the observed predominance of matter over antimatter is dynamical or accidental? The former should be generated by some physical processes in the early universe starting from a rather arbitrary initial state, while the latter could be created by proper initial conditions? Such a question could be sensible a quarter of century ago, but now with established inflationary cosmology, the answer may be only that any cosmological charge asymmetry should have been generated dynamically [2, 3].

First of all I would like to stress that inflation is practically an “experimental” fact. We do not know any other way to create the universe with the observed properties (for review on inflation see e.g. [4]). Inflationary cosmology naturally explains:

1. Flatness of the present-day universe, $\Omega = \rho/\rho_c = 1$, here $\rho$ is the average cosmological mass/energy density and $\rho_c = 3H^2m_{Pl}^2/8\pi$ is the critical energy density. Without inflation the adjustment of $\Omega$ should be at the level $10^{-60}$ at the Planck era or about $10^{-15}$ during primordial nucleosynthesis.

2. The well known problems of homogeneity, isotropy, and horizon, which created headache in frameworks of the old Friedman cosmology, are uniquely and beautifully solved.

3. Inflation presents a natural mechanism of generation of small density perturbations with practically flat spectrum in agreement with observations. The only known competing mechanism of creation of density perturbations by topological defects seems to be ruled out by the angular spectrum of the Cosmic Microwave background radiation (CMBR) [5]. (Maybe better to say that topological defects cannot be the dominant source of density perturbations.)

To fulfill all these jobs inflation should last at least 70 Hubble times. During this period the energy density must remain (approximately) constant, otherwise expansion would not be an exponential one but only a power law. Indeed the Hubble parameter is:

$$\dot{a}/a = H \sim \sqrt{\rho}/m_{Pl} \quad (1)$$
The scale factor would rise exponentially if \( \rho = \text{const} \). On the other hand, if there is a conserved charge the energy density cannot stay constant. The density of any conserved, in particular baryonic, charge scales as

\[
B \sim 1/a^3
\]

and the energy density associated with this charge evolves as

\[
\rho_B \sim 1/a^n,
\]

where \( n = 4 \) for relativistic matter and \( n = 3 \) for non-relativistic matter.

According to observations, the ratio of the baryonic charge density to the number density of photons is

\[
\beta = B/N_\gamma \approx 6 \cdot 10^{-10},
\]

Let us assume now that we go backward in time and reach inflationary era. As we mentioned above, at inflationary period the energy density of matter must be (approximately) constant. For conserved baryons it could be true if baryons were sub-dominant in the energy density. However, it is clear that according to eqs. (3) and (4) the energy density associated with conserved baryonic charge should rise with decreasing time as \( \rho_B \sim \exp(-4Ht) \) and for \( Ht = 4 - 5 \) the sub-dominant baryons would become dominant. Thus the energy density could not be maintained constant and inflation would be destroyed after too short duration, \( Ht \approx 5 \ll 70 \).

Hence successful inflation is incompatible with baryonic charge conservation and baryon asymmetry must be generated dynamically.

### 3 Three Sakharov’s conditions - discussion

#### 3.1 Non-conservation of baryons

In 1967, when Sakharov [1] first presented his work on baryogenesis, a non-conservation of baryonic charge was the weakest point. No theory demanded that and, clearly, there were no experimental data in support of this hypothesis. Today direct experimental proof that baryons are not conserved are still missing but there is great theoretical progress: it is shown that grand unification and even the standard electroweak theory demand nonconservation of baryonic charge. Another very interesting possibility is that gravity itself, most probably, breaks all global charges and, in particular, baryonic charge [6, 7, 8].

The only “experimental piece of data” in favor of non-conservation of \( B \) is our universe: \textit{we exist, ergo baryons are not conserved}. A half of century ago the same piece of knowledge led to the opposite conclusion: \textit{we exist, ergo baryons are conserved}. This surely shows a necessity of a theory for interpretation of even very clear experimental data.

#### 3.2 C and CP violation

In contrast to non-conservation of baryons, the breaking of CP-symmetry, was discovered in 1964 in direct experiment [9]. It was a great surprise to community, despite of parity
violation broken in 1956 \[1]\) and almost simultaneous realization that charge symmetry, C, is also broken. In an attempt to preserve symmetry between matter and antimatter it was suggested \[1]\) that combined parity, CP, i.e. the transformation from particles to mirror reflected antiparticles is a rigorous symmetry of Nature. It happened not to be the case. The particles and antiparticles are really different and after this discovery “life in the universe became possible”. (As we will see in what follows, this is not exactly so because the generation of cosmological charge asymmetry and thus creation of suitable for life universe is possible even without CP-violation in particle physics, but still some asymmetric conditions must be created dynamically even in a charge symmetric theory.\]

A natural question may arise at this stage: if breaking of C-symmetry only may be sufficient for generation of cosmological charge asymmetry? The answer is negative by the following “global” (presented here) and “local” (presented later, eq. (51)) arguments. Let us assume that the universe is initially charge symmetric i.e. she is in C eigenstate:

\[
C|u\rangle = \eta|u\rangle
\]  

(5)

where \(|\eta| = 1\). This means, in particular, that the universe has all zero charges. May some non-zero charge, e.g. \(B\), be generated dynamically if CP is conserved but C is violated?

Let us assume first that even C is conserved. Then it is evident that no charge asymmetry could be created. The formal arguments go as follows. Since C is conserved the operator of C-transformation commutes with the Hamiltonian:

\[
[C, \mathcal{H}] = 0
\]  

(6)

Time evolution of baryonic charge density \(B\) is governed by the equation:

\[
B(t) = \langle u|e^{-i\mathcal{H}t}J_B^0e^{i\mathcal{H}t}|u\rangle.
\]  

(7)

Let us insert now the unity operator \(I = C^{-1}C\) into 4 places above:

\[
B(t) = \langle u|Ie^{-i\mathcal{H}t}I J_B^0 e^{i\mathcal{H}t}I|u\rangle = -B(t) = 0
\]  

(8)

taken that baryonic current is a C-odd operator, \(CJ_B^0C^{-1} = -J_B^0\). Thus in C-conserving theory B or any other charge cannot be generated.

The same arguments with \(CP\) instead of \(C\) leads to the conclusion that with conserved \(CP\) no charge asymmetry could be generated if the universe is an eigenstate of CP:

\[
CP|u\rangle = \eta|u\rangle
\]  

(9)

However, e.g. in a globally rotating universe charge asymmetry might be generated even if CP is conserved: \textit{global rotation could be transformed into baryonic charge}! To this end new interactions, almost surely long range and possibly pathological, are needed.

If cosmological charge asymmetry could be generated only in local processes, as in out-of-equilibrium decays of heavy particles, then one can easily see that in CP-invariant situation the partial decay rates are equal for charge conjugated channels and resulting asymmetry is zero - it is discussed in detail below. However, if decaying particles are globally polarized with respect to some fixed axis, then a charge asymmetry may be produced even in CP invariant theory.
Out of the three symmetries, P, C, and T, each of which was believed to be true in the first part of the XX century, only their product, CPT, survived by now. And there is a good reason for that: while breaking of any of these three individual symmetries does not contradict “sacred” physical principles, CPT invariance is the only symmetry with solid theoretical justification, the famous CPT-theorem \[12\]. It can be proved that Lorentz-invariant theory with canonical relation between spin and statistics is automatically invariant with respect to CPT transformation. The situation with C, P, and T transformations demonstrates the validity of the principle “all what is not forbidden is allowed and exists”. At the present time there are no serious data indicating to breaking of CPT-invariance.

A simple consequence of CPT invariance, namely that breaking of CP leads simultaneously to breaking of T is important for kinetics of charge asymmetry generation, as we see in sec. 4.

Despite of CPT-theorem, some models without CPT are considered, e.g. for explanation of neutrino anomalies or just “why not’?” \[13\]. Keeping this in mind we will discuss the generation of cosmological charge asymmetry with broken CPT as well.

### 3.3 Thermal equilibrium

In thermal equilibrium particle number densities in phase space are given by the expressions:

\[
f_{eq} = \left[ \exp \left( \frac{E - \mu}{T} \right) \pm 1 \right]^{-1}
\]

where signs $\pm$ refer to Fermi and Bose statistics and $E = (p^2 + m^2)^{1/2}$ is particle energy. In equilibrium chemical potential for a non-conserved charge must vanish: $\mu = 0$ (see below). Due to CPT-invariance the masses of particles and antiparticles are equal, $m = \bar{m}$ and thus:

\[
n = \bar{n} = \int \frac{d^3p}{(2\pi)^3} f_{eq}
\]

By definition equilibrium distributions are the solutions of the kinetic equation:

\[
\frac{df}{dt} = I_{coll}[f],
\]

which annihilate the collision integral:

\[
I_{coll}[f_{eq}] = 0.
\]

We will check later that $f_{eq}$ presented above, eq. (10), indeed annihilate collision integrals due to conservation of energy:

\[
\sum E_{in} = \sum E_{fin}
\]

and of chemical potentials:

\[
\sum \mu_{in} = \sum \mu_{fin},
\]
While the first condition should be always true, the second one is enforced by reactions if they are fast enough to establish equilibrium. Here sub-indices “in” and “fin” refer respectively to initial and final particles.

Now we can check that chemical potentials of baryons vanish if the processes with non-conservation of B-charge are in equilibrium. It may happen that baryonic charge is conserved or its non-conservation is so weak that equilibrium with respect to reactions with $\Delta B \neq 0$ is never established. In this case baryonic chemical potential would not evolve with time and would remain equal to its initial value. Correspondingly baryonic charge density would be constant in comoving volume (i.e. in volume which expands together with the universe, $V \sim a^3$, where $a(t)$ is the cosmological scale factor).

We assume that complete equilibrium with respect to all reactions is established and check what happens with chemical potentials. First, as is well known, chemical potential of photons in equilibrium is zero. Indeed, the number of photons is not conserved and the following reactions with different number of photons in the final state are possible:

$$ q + \bar{q} \rightarrow 2\gamma, \quad q + \bar{q} \rightarrow 3\gamma \quad (16) $$

In equilibrium:

$$ \mu_q + \mu_{\bar{q}} = 2\mu_\gamma = 3\mu_\gamma = 0 \quad (17) $$

We see, in particular, that in equilibrium chemical potential of particles and antiparticles are opposite:

$$ \mu_q = -\mu_{\bar{q}} \quad (18) $$

If there is an excess of $q$ over $\bar{q}$ or vice versa, it is described by a non-vanishing $\mu_q$. If B-nonconserving processes are in equilibrium, then e.g. the reaction (or any other with different baryonic number in the final and initial states)

$$ q + q + q \leftrightarrow \bar{q} + \bar{q} + \bar{q} \quad (19) $$

leads to $3\mu_q = 3\mu_{\bar{q}}$ and simultaneously the condition (18) is valid. Thus:

$$ \mu_q = \mu_{\bar{q}} = 0. \quad (20) $$

Normally because of large magnitude of the Planck mass, $m_{Pl} \approx 1.2 \cdot 10^{19}$ GeV, the cosmological expansion rate

$$ H = \frac{\dot{a}}{a} \sim \frac{\sqrt{\rho}}{m_{Pl}} \sim \frac{T^2}{m_{Pl}} \quad (21) $$

is much smaller than the reaction rates in the hot primeval plasma and because of that deviations from equilibrium are very weak. (In the equation above $\rho \sim T^4$ is the energy density of cosmological plasma with temperature $T$.) Moreover, for massless particles no deviation from equilibrium is induced by the cosmological expansion. Still for massive particles some deviation from equilibrium always exist, though suppressed by the small ratio:

$$ \frac{H}{\Gamma} \sim \frac{T^2}{m_{Pl}\Gamma} \quad (22) $$
where $\Gamma$ is the rate of processes creating equilibrium. For heavy particle decays $\Gamma \sim \alpha m$, while for two-body reactions with massless or light particles $\Gamma \sim \alpha^2 T$, where $\alpha$ is usually close to 1/100.

In Friedman-Robertson-Walker cosmology kinetic equation has the form:

$$\frac{df}{dt} = (\partial_t + \dot{p} \partial_p) f = (\partial_t - H p \partial_p) f$$  \hspace{1cm} (23)$$

since $\dot{p} = -Hp$. As we mentioned above, in equilibrium $I_{coll}$ must vanish and so must $df/dt$. Let us check if this may be fulfilled for massive particles:

$$(\partial_t - H p \partial_p) f_{eq} \left( \frac{E - \mu(t)}{T(t)} \right) = \left[ -\frac{\dot{T}}{T} \frac{E - \mu}{T} - \frac{\dot{\mu}}{T} - \frac{Hp}{T} \right] f_{eq}'$$  \hspace{1cm} (24)$$

where prime means derivative with respect to the argument of $f_{eq}$. The factor in square brackets vanishes if, firstly,

$$\dot{\mu} = \dot{T}/T = -H,$$  \hspace{1cm} (25)$$

this can be true, and, secondly,

$$E(\dot{T}/T) = -Hp,$$  \hspace{1cm} (26)$$

This can be true only for massless particles for which $E = p$. For example cosmic microwave background radiation (CMBR) has perfect equilibrium spectrum, because photons are massless. Photons were in equilibrium at high temperatures and even when the interactions were switched-off after hydrogen recombination, the equilibrium distribution of photons was not distorted by the cosmological expansion.

The magnitude of deviation from equilibrium for massive particles can be estimated from the kinetic equation with a simplified collision integral

$$Ha \frac{\partial f}{\partial a} = \Gamma (f_{eq} - f)$$  \hspace{1cm} (27)$$

where $a \sim 1/T$ is the cosmological scale factor. This equation can be obtained from eq. (23) after change of variables to $a(t)$ and $y = p/a(t)$ instead of $t$ and $p$ and the substitution into the r.h.s. of eq. (27) the simplified algebraic expression, instead of the exact collision integral. This approximation is reasonably good for small deviations from equilibrium, $f = f_{eq} + \delta f$. In this case it is easy to find:

$$\frac{\delta f}{f_{eq}} \approx \frac{H m^2}{\Gamma E T} \approx \frac{m}{\alpha m_{Pl}}$$  \hspace{1cm} (28)$$

The last estimate is obtained for $\Gamma \sim \alpha m$. The temperature was taken of the order of the mass of the decaying particle, $T \sim m$. For larger $T$ the deviations from equilibrium are small, while for smaller $T \ll m$ the equilibrium distribution is Boltzmann suppressed, $f_{eq} \sim \exp(-m/T)$, and so is $\delta f$, while the relative deviation from equilibrium can be large.
Thus for successful baryogenesis either heavy particles are needed or low decay rate, i.e. small coupling constant, $\alpha \ll 10^{-2}$, i.e. $\alpha$ must be much smaller than the natural value of the gauge coupling constant. Thermal equilibrium can be strongly broken even with light particles ($m \ll m_{Pl}$) in the case of first order phase transitions when two phases coexisted in the primeval plasma.

A new possibility to break thermal equilibrium even without immediate action of massive particles was suggested in ref. [14]. The authors considered two weakly interacting thermal bathes, each being an equilibrium one, but with different temperatures. Such a case could be realized with mirror matter if temperature of mirror world was different from ours. The situation is similar to the breaking of equilibrium between electrons/photons and neutrinos in the standard cosmology after $e^+e^-$-annihilation which led to an increase of $e\gamma$ temperature but leaves neutrino temperature practically unchanged. Residual interactions between $e^\pm$ and neutrinos distorts spectrum of massless neutrinos [15].

4 Baryon asymmetry with broken CPT and validity of standard equilibrium distributions in CPT or T violating theories

Evidently, if CPT is broken and masses of particles and antiparticles are unequal, then charge asymmetry can be generated in thermal equilibrium, see e.g. [16]. The difference between the number densities of particles and antiparticles is equal to:

$$\frac{N_B - N_{\bar{B}}}{N_B} = \int \frac{d^3p}{(2\pi)^3} [f_B(p) - f_{\bar{B}}(p)]$$

(29)

If equilibrium distributions maintain the same standard form [10], despite CPT breaking, then neglecting possible chemical potentials, we obtain:

$$\frac{N_B - N_{\bar{B}}}{N_B} \approx \frac{\delta m}{T}, \text{ for } m > T, \text{ but } \delta m < T$$

(30)

and

$$\frac{N_B - N_{\bar{B}}}{N_B} \approx \frac{\delta m}{T} \frac{m}{T} \text{ for, } m < T.$$  

(31)

Two comments are in order here.

1. Care should be taken of electric charge neutrality. Cosmological electric charge asymmetry must be zero or extremely small. For a closed universe even a single excessive electron is not allowed. The condition of vanishing electric charge demands non-zero chemical potentials of protons (quarks) and electrons and the results presented above should be modified in a model dependent way.

2. The results above may be correct only if the equilibrium distributions are not damaged by breaking of CPT and/or T invariance.

Let us first discuss whether the usual equilibrium distributions remain the same if T-invariance is broken. The problem is related to the fact that the annihilation of collision
integrals by the equilibrium functions given by eq. (10) is usually verified under assumption of detailed balance condition which is true because of T-invariance. Now we see what happens if T-invariance is broken. The collision integral has the form:

$$I_{\text{coll}} = \frac{1}{2E_1} \sum_{f_{\text{in}}} \int d\tau_{\text{in}} d\tau_{f_{\text{in}}} \left[ |A_{if}|^2 \Pi f_{\text{in}} \Pi (1 \pm f_{f_{\text{in}}}) - |A_{fi}|^2 \Pi f_{f_{\text{in}}} \Pi (1 \pm f_{\text{in}}) \right],$$  \hspace{1cm} (32)

where particle number 1 is the one whose evolution is studied, integration is taken over the phase space of all particles in the final state, $d\tau_{f_{\text{in}}}$, and all but 1 particles in the initial state, $d\tau_{\text{in}}$, $A_{if}$ and $A_{fi}$ are the amplitudes of initial to final and final to initial reactions respectively; summation is taken over all possible final states.

In T-invariant theory the detailed balance condition is fulfilled:

$$|A_{if}|^2 = |A_{fi}|^2$$  \hspace{1cm} (33)

(after some evident change of variables). Hence the amplitudes can be factored out of the square brackets in eq. (32) and there remains:

$$\left[ \Pi f_{\text{in}} \Pi (1 \pm f_{f_{\text{in}}}) - \Pi f_{f_{\text{in}}} \Pi (1 \pm f_{\text{in}}) \right]$$  \hspace{1cm} (34)

As we have seen above this expression vanishes for $f = f_{eq}$ because of energy conservation (14) and conservation of chemical potentials (15).

If however T-invariance is broken then the detailed balance equality (33) is not fulfilled and one should expect $|A_{if}|^2 \neq |A_{fi}|^2$. A natural suspicion arises in this case if the equilibrium distributions may become different in T-noninvariant world? For the usual equilibrium functions we can rewrite the expression in square brackets of eq. (32) as

$$I_{\text{coll}} \sim \sum_{f_{\text{in}}} \Pi f_{\text{in}} (1 \pm f_{f_{\text{in}}}) \left( |A_{if}|^2 - |A_{fi}|^2 \right)$$  \hspace{1cm} (35)

The last factor is evidently non-vanishing and one is tempted to conclude that if detailed balance condition is invalid, the equilibrium distribution are to be modified.

One should remember, however, that T-violation is observable only if several reaction channels are open. If only one reaction channel is allowed the amplitude of direct and inverse processes may differ only by a phase factor and their absolute values are equal. Now we will show that, though individual terms in sum (35) are non-zero (detailed balance is violated), their sum vanishes and equilibrium distributions remain the same as in the standard T-invariant theory [17, 18].

To see that we will use the unitarity of the scattering matrix, $SS^\dagger = 1$. Separating in the usual way the unity matrix $I$, $S = I + iT$, we find that $T$-matrix, which describes scattering amplitudes, satisfies:

$$i \left( T_{if} - T_{fi}^\dagger \right) = - \sum_n T_{in} T_{nf}^\dagger = - \sum_n T_{in}^\dagger T_{nf}$$  \hspace{1cm} (36)

Here summation over $n$ includes integration over phase space. $T$-matrix differs from the usual scattering amplitude by some simple factor.
If T-invariance is broken, still the unitarity of S-matrix leads, instead of detailed balance, to a new condition:

$$\sum_k \int d\tau_k \left( |A_{ki}|^2 - |A_{ik}|^2 \right) = 0 \quad (37)$$

Here $d\tau_k$ includes Bose/Fermi enhancement/suppression factors. Equation (37) ensures vanishing of $I_{coll}$ for $f = f_{eq}$ and thus, even in the absence of detailed balance, the equilibrium distributions remain the same.

Equation (37) can be called cyclic balance condition [17] because equilibration is now realized not simply by equality of probabilities of direct and inverse reactions but by more complicated cycle of all relevant reactions.

In conclusion of this subsection the following comments may be useful:
1. As is evident from eq. (36), in the lowest order $A_{ij}^* = A_{ji}$ and the effects of T-breaking are unobservable. That’s why several intermediate states are to be taken into account to produce an additional imaginary part of the amplitude created by particle rescattering.
2. Full unitarity is not necessary. Normalization of probability

$$\sum_f w_{if} = 1 \quad (38)$$

plus CPT invariance are sufficient.
3. In the case that CPT is broken, another relation in addition to (38) is needed:

$$\sum_f w_{fi} = 1 \quad (39)$$

(to save the standard equilibrium distributions. 4. If conditions 1-3, specified above, are not true, then small violations of CPT and unitarity could be strongly enhanced in a system relaxing during long time interval and the effects of CPT breaking in kinetics and statistics would be large if simultaneously with CPT equations (38) and/or (39) are broken. Maybe stationary equilibrium distributions do not exist in this case.

5 General features of cosmological baryon asymmetry

Baryons by number are quite rare in the universe. According to the data there is 1 baryon per 2 billions photons in CMBR, see eq. (4). While there are about 400 photons per cm$^3$, there is only 1 proton per 4m$^3$. The number of baryons which are directly observed is even smaller than that, almost by an order of magnitude. Majority of cosmic baryons are invisible [19]. Nevertheless, their total number density is quite well known from two independent pieces of observations: from abundances of light elements created during big bang nucleosynthesis (BBN) [20] and from angular fluctuations of CMBR [21]. Both ways of determination of $\beta$ give similar results and one may speak of another success of the standard cosmological model but there is an inconsistency between abundances of $He^4$ and deuterium which indicate to different values of $\beta$. Deuterium data rather well agree
with $\beta$ found from CMBR, while helium disagrees with the latter by factor two. It is unclear if the data are accurate enough to conclude that there exists a real disagreement, note only that measurements of light elements are done at the red-shifts $z \ll 1$ for helium and $z \sim 1$ for deuterium. On the other hand, the data on the angular fluctuations of CMBR inform us about the universe at $z \approx 10^3$ with $\beta$ effectively averaged over all the sky. Maybe the discrepancy between $^4\text{He}$ and $^2\text{H}$ can be explained by small fluctuations of the baryon number density at relatively small spatial scales. Moreover, according to the observations, the deuterium abundance quite strongly fluctuates from point to point on the sky.

The measured small value of $\beta$ is still huge in comparison with the baryon-to-photon ratio which would be in baryo-symmetric cosmology. In the universe with locally equal numbers of baryons and antibaryons we should expect:

$$\frac{n_B}{n_\gamma} = \frac{n_B}{n_\gamma} \approx 10^{-19}$$

Life in such universe would surely be impossible for us.

Fortunately the universe is not baryo-symmetric at least in our neighborhood. We know for sure that the Galaxy is matter dominated and only a small fraction of antimatter is allowed by observations. We cannot say if distant galaxies are made of matter or antimatter but in all the cases when colliding galaxies or galaxies in the same cloud of intergalactic gas are observed, an absence of noticeable annihilation indicates that such galaxies, as well as the intergalactic gas are dominated by matter (or antimatter). An absence of noticeable gamma ray line from $\pi^0$ decay (the latter would come from $\bar{p} + p \rightarrow \pi^0$) allows to conclude that the nearest rich antimatter region should be away from us at least at 10 Mpc [22].

A much stronger bound, valid for average baryo-symmetric universe was derived in ref. [23]. According to the results of these works the nearest antimatter domain should be at the distance of the order of gigaparsec, i.e. comparable to the present day cosmological horizon. This bound was obtained from the data on the cosmic gamma ray background. Proton-antiproton annihilation should be very efficient on the boundaries between matter and antimatter domains producing energetic photons. Naively one would expect that the annihilation should create an excessive pressure which push matter and antimatter apart. According to ref. [23], the picture is opposite. An excessive pressure is indeed created but at a large distance from the boundaries where the annihilation products slow down. This produces an opposite effect of pushing matter and antimatter towards each other and strongly enhances the annihilation. A study of possible distortions of CMBR spectrum to constraint the amount of antimatter leads to a noticeably weaker bound [24].

It is still an open question if the baryon asymmetry is the same everywhere in the universe, $\beta = \text{const}$, or it may be a function of space points, $\beta = \beta(x)$. In particular, could the universe be charge asymmetric locally but charge symmetric globally, i.e. may her average baryonic charge be zero? As we mentioned above for a globally symmetric universe the characteristic scale, $l_B$, of variation of $\beta$ is close or larger than the present day horizon size. Much more interesting from the point of view of a discovery of cosmological antimatter is the possibility of baryo-asymmetric universe dominated by baryons (or maybe even by antibaryons). In this case astronomically large clouds of antimatter or
compact objects (anti-stars) can be quite close to us, even in our Galaxy. Compact antimatter objects may escape observations even if their mass fraction is quite high. Disperse clouds of antimatter are much better visible.

An answer to the above questions and scenarios of creation of relatively rare but astronomically large antimatter domains as well as possibly more abundant compact antimatter objects, which can be not too far from us, depends upon the mechanisms of CP violation realized in cosmology. They are discussed in the following section.

6 Cosmological CP violation

6.1 Explicit CP violation

In majority of baryogenesis scenarios an explicit CP violation in the underlying particle theory is assumed. The latter is realized by an introduction of complex coupling constants into Lagrangian. Hermitian conjugation corresponds to transformation from particles to antiparticles and for complex couplings the charge conjugation symmetry becomes broken. This is the standard way how CP (or C) is broken in particle physics.

This mechanism of CP violation is realized in most popular (though at different periods) scenarios of baryogenesis (they are reviewed e.g. in refs. [2, 25]):
1. GUT baryogenesis.
2. Electroweak baryogenesis.
3. Baryo-thru-lepto-genesis.

In all these models, based on explicit CP-violation, $\beta$ is an universal “cosmological constant” which can be expressed through masses and couplings of fundamental particles. (Not confuse this “baryonic cosmological constant” with the usual cosmological constant which is equivalent to vacuum energy.)

There is no space for cosmic antimatter in this rather dull picture but if these scenarios are combined with other models of cosmological CP-violation a more complicated and interesting pattern may emerge.

CP-violation is introduced into the minimal standard model (MSM) of particle physics, and not only into it, by a complex mass matrix of quarks and leptons. The former is called CKM (Cabibbo-Kobayashi-Mascawa) matrix. The masses become complex because of complex Yukawa coupling constants of Higgs field to fermions, $g_{ij} H \bar{\psi}_i \psi_j$, where $i, j$ are quark flavors and the interaction of Higgs boson with quarks is not necessarily diagonal in the flavor basis. When the Higgs condensate is formed fermions acquire masses $m_{ij} = g_{ij} \langle H \rangle$.

It is evident that CP-violation in MSM is absent for two quark families because any phase in $2 \times 2$ matrix $m_{ij}$ can be rotated away by the phase transformation of quark wave functions,

$$q_i \rightarrow \exp(-i\phi_i) q_i.$$

(41)

The diagonal entries $m_{ii}$ must be real because of hermicity and the only off-diagonal one, $m_{12}$, can be always made real by transformation (41).
At least three quark families are necessary to give rise to observable CP-violation due to complexity of the quark mass matrix. Indeed there can be three phases in the off-diagonal components of $m_{ij}$: $\phi_{ij} = -\phi_{ji}$ with $i, j = 1, 2, 3$. Each of them can be changed by the quark phase rotation as:

$$m_{ij} \rightarrow e^{i(\phi_i - \phi_j)} m_{ij} \equiv e^{i\phi_{ij}} m_{ij}$$  \hspace{1cm} (42)

Here $\phi_{12} + \phi_{23} + \phi_{31} = 0$ and the phase freedom of the quark wave functions allows nullify only two phases out of three independent ones.

This feature demonstrates the necessity of three quark families for CP-breaking and could be an anthropic explanation why these three families are needed. However, as we see below, CP-violation in the standard model is extremely weak at high temperatures and baryogenesis is not efficient enough. If however a workable model of baryogenesis is found based on CP-breaking in the quark sector (with 3 families) we would have an explanation why there are three and not just one quark family in Nature.

If masses of different up or down quarks are equal, CP violating phase can also be rotated away because unit matrix is invariant with respect to unitary transformation between different quarks. If the mass matrix is partly diagonal, i.e. some of off-diagonal entries $m_{ij}$ vanish, CP-violation can be rotated away as well.

Thus, CP-breaking is proportional to the product of the mixing angles and to the mass differences of all down and all up quarks:

$$A_- \sim J (m_t^2 - m_u^2)(m_t^2 - m_c^2)(m_c^2 - m_u^2)(m_b^2 - m_d^2)(m_s^2 - m_d^2)/M_{12}^{12}$$  \hspace{1cm} (43)

where the Jarlskog determinant is $J \approx \sin \theta_{12} \sin \theta_{23} \sin \theta_{31} \sin \delta \approx 3 \times 10^{-5} \sin \delta$ and $\delta$ is a CP-odd phase, while $\theta_{ij}$ are the angles describing the mixing of flavor states in terms of mass eigenstates. The normalizing mass $M$ depends upon the process under consideration. In the case of electroweak baryogenesis, see sec. 7 it is taken of the order of the electroweak scale, $M \sim 100 \text{ GeV}$.

This consideration shows that CP violation could manifest itself only in high orders of perturbation theory with all quarks participating as virtual particles. A diagram of this kind has been studied in ref. [27] where it was argued that CP-violation appears only in the 12th order of perturbation theory. However, in a later paper [28] a lower, but still high order, diagram has been found with logarithmic dependence on the quark masses which leads to similar vanishing of the amplitude when masses are equal but the amplitude is several orders of magnitude larger.

The result above is valid for the Dirac mass matrix, the only type of the mass matrix which is allowed for charged fermions. For neutral fermions, e.g. neutrinos, Majorana mass term is also possible:

$$\mathcal{L}_M = M_{ij} \nu_i \nu_j + \text{h.c.},$$  \hspace{1cm} (44)

where $C$ is the operator of charge conjugation. Now all elements of $M_{ij}$ including the diagonal ones may be complex. One can kill three phases in $M_{ii}$ by 3 phase rotations of $\nu_i$. No freedom is left after that and three phases of $M_{12}, M_{23}, M_{31}$ remain arbitrary. Thus, in the Majorana case there can be three independent CP-odd phases.
If small neutrino masses are generated by the well known seesaw mechanism through mixing of light left-handed neutrinos, $\nu_L$, with heavy right-handed ones, $L_R$, the mass matrix can be written as:

$$\mathcal{L}_M = M L_R C L_R + m \nu_L C L_R = h.c. \quad (45)$$

After diagonalization of this matrix it will be reduced to two $3 \times 3$ matrices in the light and heavy sectors, each having 3 independent CP-odd phases. Evidently the number of CP-odd phases is now six: 3 phases in light $\nu$ sector and 3 phases in heavy $\nu$ sector. The phases which may be measured in neutrino oscillations are not directly related to the phases in heavy $L_R$ decays and low energy measurements cannot teach us about CP-violation at leptogenesis in model independent way.

### 6.2 Spontaneous CP violation

If the Lagrangian is invariant with respect to CP transformation but the ground states are not, we speak about spontaneous symmetry breaking. Such a mechanism for CP violation was suggested in ref. [29] in an attempt to save global symmetry between particles and antiparticles.

A concrete realization of this idea can be achieved with a complex scalar field $\Phi$ acquiring different complex vacuum expectation values:

$$\langle \Phi \rangle = \pm f \quad (46)$$

This can be done if the potential of $\Phi$ has two degenerate minima at $\Phi = \pm f$. It resembles more complicated potential of the electroweak Higgs field but instead of continuous symmetry this potential has only a discrete symmetry with respect to the transformation $\Phi \leftrightarrow -\Phi$.

Such a mechanism of CP violation is locally indistinguishable from the explicit one but globally it leads to charged symmetric universe with domains of opposite but equal by magnitude baryon asymmetry. As we mentioned above in a globally baryo-symmetric universe matter-antimatter domains should be very large with $l_B \sim \text{Gpc}$ to avoid too strong gamma ray background. In the case of spontaneous CP violation there is one more reason to make the domain size very big, even larger than the present day horizon. If so, our chances to observe cosmic antimatter are negligible at least during the next several billion years. The condition of a huge domain size is related to a well known problem of cosmological domain walls [30], which arises if a discrete symmetry is spontaneously broken. The energy of the wall separating two different vacua with opposite signs of CP-violation is so large that even a single wall per horizon volume would destroy the observed isotropy of the universe. This domain wall problem either demands $l_B \gg \text{Gpc}$ or some non-trivial mechanism of wall destruction after baryogenesis.

### 6.3 Stochastic or dynamical CP violation [2]

This mechanism is somewhat similar to spontaneous CP breaking but operates only in the early universe and does not suffer from domain wall problem. It could be especially
good for creation of subdominant antimatter domains or compact objects in our matter dominated universe \cite{31}. Similar versions of dynamical CP-violation have been studied recently in papers \cite{32}.

Let us assume that there exists a complex scalar field $\chi$ by some reason displaced from its equilibrium point, e.g. by quantum fluctuations at inflation. It is known that a massless or light, $m < H$, scalar field is infrared unstable at De Sitter stage and its average value rises with time as \cite{33}:

$$\chi^2 \sim H^3 t.$$  \hspace{1cm} (47)

(see however ref. \cite{34} where it was argued that the coefficient in eq. (47) has an opposite sign but the same absolute value).

When inflation is over, $\chi$ starts to relax down to zero. If this relaxation process is not too fast so that $\chi \neq 0$ during baryogenesis, $\chi$ would act as a CP-violating agent. Its complex amplitude forces time dependent CP-violation into action. In the old universe $\chi$ either vanishes and all CP-violating effects associated with $\chi$ vanishes as well, or $\chi$ may remain nonzero and create the usual explicit CP-violation. As we see in what follows with such a mechanism of CP-violation an inhomogeneous $\beta(x)$ could be easily generated. In particular, domains with $\beta < 0$, that is antimatter domains, might be created. They could be not too far from us and in sufficiently small amount to satisfy the existing constraints. Moreover, if antimatter is mostly confined inside compact stellar type objects, the upper bound on their cosmological mass density could be much less restrictive.

Dynamical C(CP)-violation could create a very interesting/unusual pattern of the cosmological matter-antimatter distribution. For example, if a complex scalar field, $\phi$, oscillated around its equilibrium point at $\phi = 0$ during baryogenesis then it would contribute to CP-odd amplitude in addition to the standard explicit CP-violation term. If the potential of $\phi$ is not strictly harmonic (quadratic) one, then the baryon asymmetry would have a spatially periodic distribution \cite{35}. Depending upon the relative magnitude of explicit and dynamical CP-odd terms there would be either periodic layers of matter and antimatter in the universe separated by voids with a small baryon or antibaryon number density, or some periodic modulation of homogeneous baryonic background. The voids between the matter and antimatter domains may help to loosen the bound of ref. \cite{23} that the nearest domain of antimatter in baryo-symmetric universe should be at the distance above 1 Gpc. On the other hand, such fluctuations in baryon/antibaryon number density would lead to large isocurvature fluctuations which contradict the observed spectrum of angular fluctuations of CMBR at the scales down to tens of Mpc. At smaller scales the bounds from CMBR are weak because of the diffusion (Silk) damping \cite{36} but such scales are restricted, though not so strongly, by the observations of the large scale structure of the universe.

Some more examples with dynamical CP-violation are discussed at the final part of these lectures (see below, secs. 9.3 9.4).
7 Electroweak baryogenesis in the minimal standard model [37]

In the standard electroweak (EW) theory all the necessary ingredients for baryogenesis are present:
1. CP is known to be broken (but very weakly, see sec. 6.1).
2. Baryonic charge is non-conserved because of chiral anomaly [38]. At zero T baryon nonconservation is exponentially suppressed, as \( \exp(-2\pi/\alpha) \), because baryon nonconservation proceeds through barrier penetration between different vacua. At high T it might be possible to go over the barrier, but abundant formation of specific classical field configuration, sphalerons, is necessary. Classical field configurations are those whose size is much larger than their Compton wave length and quantum production of such objects, which are coherent at very large distances, is not well understood, see e.g. discussion in ref. [39].
3. Thermal equilibrium is absent during the phase transition between the phases with unbroken EW symmetry at high T and broken one at low T if the phase transition is first order. However, a heavy Higgs renders the first order phase transition improbable. Another possible source of deviation from equilibrium due to massive particles is weak: \( \sim m_{EW}/m_{Pl} \sim 10^{-16} \). However it could be large in TeV-scale gravity.

CP-odd amplitude in MSM is estimated above, eq. (43). At high temperatures near EW phase transition the characteristic mass should be of the order of the EW energy scale, \( M \sim 100 \text{ GeV} \), and thus

\[
A_- \approx 5 \cdot 10^{-19}.
\]  

Such a smallness of CP violation at high temperatures makes hopeless generation of the observed baryon asymmetry in the frameworks of MSM.

The result [48] is rather surprising because at \( T = 0 \) the effects of CP are non-negligible. Naively one might expect that CP-odd effects in a decay of a heavy quark should not be much different at high and low T because the propagators, which determine the normalizing mass \( M \) in the amplitude of decay “know” the mass of the decaying particle and not its energy. However, this is not the case because of the temperature corrections to the mass, or better to say to the dispersion relation, \( E = E(p,T) \). The largest corrections come from QCD because of the largest coupling constant. This effect leads to a large denominators of the propagators which enters the CP-odd amplitude and thus leads to a large \( M \sim 100 \text{ GeV} \), while in the numerators there are still “Higgs masses” or, better to say, small Yukawa coupling constants. Attempts to modify quark dispersion relation at high T [41] were proved to be unsuccessful [11].

Surprisingly a much larger amplitude of CP-violation found in ref. [28] at zero temperature gives the same result as eq. (48) at high T.

Thus it seems that MSM is unable to explain the observed cosmological baryon asymmetry and physics beyond the standard model is necessary. The standard CP-odd effects may be strongly amplified if Yukawa coupling constants change with time in such a way that they are much larger at high T. Such a mechanism is suggested in ref. [12]. The first order phase transition, which is necessary to break thermal equilibrium, still remains
problematic but with a low value of the Planck mass at EW scale one can manage with second order phase transition as well.

8 Baryogenesis through heavy particle decays

The original idea of this type of baryogenesis stems from the pioneering works \cite{1,43}. A large list of literature can be found e.g. in the reviews \cite{2,16}. From particle physics perspective, two most conservative models of this kind are GUT baryogenesis and baryothru-leptogenesis.

Before going to more detailed discussion of these two models we describe some general features of generation of cosmological charge asymmetry by decay of heavy particles. Let us consider the decays of a heavy boson $X$ (it can be e.g. gauge or Higgs boson of grand unification) into two decay channels with different baryon numbers:

$$X \rightarrow qq, \quad X \rightarrow q\bar{l},$$

$$\bar{X} \rightarrow q\bar{q}, \quad \bar{X} \rightarrow \bar{q}l.$$ (49)

The widths of the charge conjugated channels would be different only in higher orders of perturbation theory when rescattering with baryonic charge non-conservation in the final state is taken into account (see conclusion to sec. \cite{1}):

$$\Gamma_{X\rightarrow qq} = (1 + \Delta_q)\Gamma_q, \quad \Gamma_{X\rightarrow q\bar{l}} = (1 - \Delta_l)\Gamma_l,$$

$$\Gamma_{\bar{X}\rightarrow q\bar{q}} = (1 - \Delta_q)\Gamma_q, \quad \Gamma_{\bar{X}\rightarrow \bar{q}l} = (1 + \Delta_l)\Gamma_l.$$ (50)

Here $\Delta_{q,l}$ are non-zero due to CP violation and if other channels of $X$-decays are negligible, then $\Gamma_q\Delta_q = \Gamma_l\Delta_l$ to ensure the equality of the total decay widths of $X$ and $\bar{X}$ which follows from CPT invariance.

As we have already mentioned, particles and antiparticles can have different decay rates into charge conjugated channels, if both C and CP are broken. If only C is broken, but CP is OK, then partial widths, summed over spins, are the same:

$$\Gamma (X \rightarrow f, \sigma) = \left(\bar{X} \rightarrow \bar{f}, -\sigma\right)$$ (51)

Thus to break equality of the partial decay widths both C and CP should be broken.

If the initial state is populated only by $X$ and $\bar{X}$ bosons in equal amount and if only their decays are essential and all other processes can be neglected, the baryon asymmetry generated by these decays would be evidently proportional to $\left(2/3\right)(2\Delta_q - \Delta_l)$.

Such an initial state could be realized if by some reason inflaton quickly decayed into $X$ and $\bar{X}$ and not into anything else. In reality, more probable is high temperature cosmic plasma which is rather close to thermal equilibrium. At this stage we may ask the question how baryon asymmetry which is generated in the decays of $X$ and $\bar{X}$ would be equilibrated down to zero? What processes are responsible for that? A usual (and incorrect) answer is that the inverse decay, $qq \rightarrow X$, and similar ones do the job. However using CPT, one finds:

$$\Gamma_{q\bar{q}\rightarrow X} = (1 + \Delta_q)\Gamma_q, \quad \Gamma_{q\bar{l}\rightarrow \bar{X}} = (1 - \Delta_l)\Gamma_l,$$

$$\Gamma_{qq\rightarrow X} = (1 - \Delta_q)\Gamma_q, \quad \Gamma_{q\bar{l}\rightarrow \bar{X}} = (1 + \Delta_l)\Gamma_l.$$ (52)
Thus direct and inverse decays produce the same sign of baryon asymmetry! It can be shown that destruction of the baryon asymmetry is achieved by baryon non-conserving $qq$ and/or $ql$ scattering with exchange of $X$ and $\bar{X}$ bosons.

Let us comment a little more on the necessity of rescattering for the generation of the baryon asymmetry. From the unitarity condition \[2 \Im m T_{ii}[\lambda] = - \int d\tau_i |T_{if}|^2 - \int d\tau_f |T_{ff}|^2\] follows that if only two reaction channels $i$ and $f$ are open then:

\[2 \Im m T_{ii}[\lambda] = - \int d\tau_i |T_{if}|^2 - \int d\tau_f |T_{ff}|^2\]

By CPT transformation:

\[T_{ii}[\lambda] = T_{\bar{i}i}[\bar{\lambda}]\]

and after summing over polarization we find $\Gamma_{if} = \Gamma_{\bar{i}f}$. Hence to destroy the equality of partial widths of charge conjugated processes, $\Gamma_{if} = \Gamma_{\bar{i}f}$, at least three reaction channels must be open.

\[i \leftrightarrow f, \quad i \leftrightarrow k, \quad k \leftrightarrow f.\]

Let us discuss now some concrete examples.

Grand unified theories (GUT) naturally violate baryonic number conservation because quarks and leptons are put into the same multiplet of the symmetry group. The mass of the gauge bosons of grand unification, $m_X \sim 10^{16}$ GeV, is high enough to ensure sufficiently large deviation from equilibrium, see eq. (28). CP-violation can be easily unsuppressed at grand unification scale, $T \sim m_X$. So far so good, but such high temperatures may never be accessible in the universe after inflation but even if the universe was hot enough with $T > m_X$ or X-bosons could be produced out of equilibrium, one should take care of overabundant production of gravitinos [44]. The latter of course could be dangerous only if supergravity is realized.

At the present time baryo-thru-leptogenesis [45] is probably the most popular scenario of creation of baryo-asymmetric universe. The process proceeds in two steps. First, lepton asymmetry is generated in decays of a heavy Majorana neutrino, $N$, which was postulated for realization of the seesaw mechanism. Evidently the decays of $N$ do not conserve leptonic charge. At the next step, during the electroweak stage, the lepton asymmetry is transformed into baryon asymmetry by C and CP conserving sphaleron processes in thermal equilibrium. Sphalerons do not conserve baryonic, $B$, and leptonic, $L$, charges individually but they conserve $(B-L)$. Thus initial $L$ would be redistributed in equilibrium in almost equal shares between $B$ and $L$. For reviews of this scenario see refs. [26].

This mechanism looks very attractive. Leptonic and baryonic charges are naturally nonconserved. Heavy particles (Majorana neutrinos) to break thermal equilibrium are present. Three CP-odd phases of order unity might be there. However, the magnitude of the asymmetry $\beta$ is just of the right size if the situation is most favorable. Any deviation from the most favorable case would destroy the successful prediction of the model.

As we mentioned above, the deviation from thermal equilibrium is given by eq. (28). The magnitude of the lepton asymmetry can be estimated as

\[\beta_L \sim \frac{\delta f}{f} \frac{\Delta \Gamma}{\Gamma} \sim \frac{m}{m_{Pl}}\]
where $\Delta \Gamma$ is the difference of the $L$-violating decay widths of charge conjugated channels. Some small numerical coefficients, which should be present in eq. (56), would make the result even smaller. Subsequent entropy dilution due to annihilation of massive particles in the course of cosmological expansion and cooling down could diminish this result by about $1/10-1/100$. Taken all together, for successful lepto/baryo- genesis the mass of the decaying heavy Majorana lepton should be noticeably larger than $10^{10}$ GeV (or $m_{PL} \ll 10^{19}$ GeV at high energies). An additional entropy generation by possible, especially first order, phase transitions would make the final baryon asymmetry considerably smaller.

An interesting suggestion has been put forward in ref. [46]. It was assumed that there exist new heavy scalars decaying into right-handed neutrinos and left-handed leptons (charged or neutral). By assumption, leptonic charge is conserved in these decays and the total cosmological lepton asymmetry remains zero till electroweak sphalerons start to operate. Sphalerons would distribute leptonic charge density of right-handed leptons into almost equal shares between leptonic and baryonic asymmetries as is described above. On the other hand lepton asymmetry of right-handed, sterile neutrinos would remain untouched and unnoticed. In the concrete realization of the model the “natural” value of the neutrino mass due to loop diagram with an exchange of the hypothetical heavy scalars and the charged tau-lepton should lead to too large value of neutrino mass, so some fine-tuning at the level of 0.01-0.001 is necessary. Possibly in other realization of this idea this shortcoming could be avoided.

9 Some more models of baryogenesis

There are plenty of more speculative scenarios of baryogenesis, than the “conservative” ones presented above, but who knows, maybe one of these speculative scenarios happens to be true. It is rather difficult to exclude or confirm one or other scenario because they all need to explain only one number, $\beta$. However, if $\beta$ is not just a number but a function of space points, which creates some specific isocurvature perturbations and even some domains or objects of antimatter (if $\beta$ somewhere becomes negative), the odds to discover the truth become much higher. Another good chance to check the baryogenesis scenario arises if it predicts a certain form of dark matter which is correlated with generation of baryon asymmetry. All scenarios presented above do not present any natural explanation of the close values of the energy density of baryons and that of dark matter:

$$\rho_B/\rho_{DM} \approx 0.2 \quad \text{(57)}$$

Most probably this coincidence is not accidental - these two numbers may easily differ by many orders of magnitude. It is desirable that a realistic scenario of baryogenesis is able not only to present the right value of $\beta$ but also to explain the magnitude of the ratio (57). However, maybe our knowledge of particle physics is not good enough for that.

Below we consider scenarios of baryogenesis which may have, though not necessarily, some of the features described above.
9.1 Baryogenesis through evaporation of primordial black holes

This model does not demand B-nonconservation at particle physics level. If a conserved charge does not create any long-range field, as e.g. electric charge does, then such a charge could disappear inside a black hole (BH) without trace. If by some reason black holes prefer to capture predominantly antibaryons then in external space an excess of baryons over antibaryons would be generated. These black holes could be heavy enough to survive till our time, \( t_u \approx 10 \text{ Gyr} \). Another possibility discussed in refs. [6, 7] is that the process of BH evaporation [47] could be baryo-asymmetric and small black holes in the process of their evaporation would enrich the universe with baryons. Such black holes could either disappear completely or evolve down to stable (?) Planck mass remnants but in all these cases the universe outside black holes would have a non-vanishing baryon asymmetry and the equal amount of antibaryonic charge would be buried inside black holes which either completely disappeared or survived and became cosmological dark matter.

At first sight thermal evaporation of black holes cannot create any charge asymmetry by the same reason as charge asymmetry is not generated in thermal equilibrium. However the spectrum of particles radiated by black holes is not black but gray due to propagation of the produced particles in the gravitational field of black holes [48]. Moreover, interactions among the produced particles are also essential. These two facts allow black holes to create an excess of matter over antimatter in external space. As a possible “realistic” model let us consider the following [7, 49]. Let us assume that there exists a heavy \( A \)-meson which may decay into two charge conjugated channels with unequal probabilities (due to C and CP violation):

\[
A \rightarrow H + \bar{L} \quad \text{and} \quad A \rightarrow \bar{H} + L \tag{58}
\]

where \( H \) and \( L \) are respectively heavy and light baryons, e.g. \( t \) and \( u \) quarks.

If the temperature of a black hole is larger than or comparable to the mass of \( A \)-boson the latter would be abundantly produced at the horizon and decay while propagating in the gravitational field of BH. There is a non-zero probability of back capture of the decay products by BH and evidently the back-capture of the heavy baryons, \( H \) and \( \bar{H} \), is larger than that of the light ones, \( L \) and \( \bar{L} \). As a result a net baryon asymmetry could be created outside black holes. According to ref. [49] the baryon asymmetry may have the proper magnitude compatible with observations.

If at the moment of BH formation, which presumably took place at radiation dominated (RD) stage, primordial black holes contributed a very small fraction, \( \epsilon \), to the total cosmological energy density, then at red-shift \( z = 1/\epsilon \) after formation, black holes would dominate cosmological energy density if their life time happened to be larger than the time interval necessary for this red-shift, \( t_{MD} = t_{in}/\epsilon^2 \). Note, that the black hole formation might take place at some earlier matter dominated (MD) stage which turned into RD stage later. In this case the estimated time would be somewhat different but the scenario would still be viable. Black hole evaporation at \( \tau_{BH} > t_{MD} \) would recreate radiation dominated universe but now with non-vanishing baryon asymmetry. Here \( \tau_{BH} \) is the life-time of BH with respect to evaporation.

Now for the convenience of listeners I present some order of magnitude expressions for the quantities describing BH evaporation. Numerical coefficients of order unity (or
sometimes $4\pi$) are omitted. Precise expressions can be found in any modern text-book on BH physics, e.g. [50]. For a Schwarzschild black hole the essential dimensional parameter is its gravitational radius:

$$r_g = \frac{M_{BH}}{m_{Pl}^2}$$  \hspace{1cm} (59)

The black hole temperature, just on dimensional grounds, is the inverse gravitational radius:

$$T_{BH} \sim \frac{1}{r_g} \sim \frac{m_{Pl}^2}{M_{BH}}$$  \hspace{1cm} (60)

The luminosity can be easily estimated integrating black body radiation emitted by the object of size $r_g$:

$$L_{BH} \sim T_{BH}^4 r_g^2 \sim \frac{m_{Pl}^4}{M_{BH}^2}$$  \hspace{1cm} (61)

Knowing the BH mass and luminosity it is straightforward to estimate its life-time:

$$\tau_{BH} \sim \frac{M_{BH}^3}{m_{Pl}^4}$$  \hspace{1cm} (62)

Black holes with the mass of the order of $M_{BH} = 10^{15} g$ would have radius approximately $10^{-13}$ cm and temperature about 100 MeV. They could survive to the present time, $\tau_{BH} \approx t_U \approx 10$ Gyr.

According to the calculations of ref. [49] the mass of heavy decaying particles should be in the interval $m \sim 10^{10} - 10^6$ GeV to create the observed cosmological baryon asymmetry.

Let us consider the following example. Assume that primordial BH were created when temperature of the universe was about $10^{14}$ GeV. It corresponds to the universe age $t_U \approx 10^{-34}$ sec. The mass inside horizon at that moment was

$$M_h \approx 10^{38} g (t/\text{sec}) \approx 10^4 g.$$  \hspace{1cm} (63)

Black holes with such masses might be in principle created. Their temperature and life time would be respectively:

$$T_{BH} = 10^{10} \text{GeV}$$ \hspace{1cm} (64)
$$\tau_{BH} \sim 10^{-16} \text{ sec},$$ \hspace{1cm} (65)

During this time the universe would cool down to $T \sim 10^5$ GeV and the red-shift from the moment when horizon mass was equal to $M_{BH}$, would be about $z \sim 10^{10}$.

If the black hole production efficiency was such that only in 1 per $10^{10}$ horizon volume a black hole was created, then their mass fraction at production was $10^{-10}$ and at the moment of their evaporation they would dominate cosmological energy density and could create the observed baryon asymmetry. As we mentioned above the Planck mass remnants of such primordial BH could be cosmological dark matter, see e.g. [51].

If baryon asymmetry could be generated via evaporation of a classical (in contrast to quantum) black holes, then it is natural to expect that baryonic charge might be non-conserved also in decay of small quantum black holes. Expressed in other words it means that gravity breaks all global symmetries and at the Planck scale the effects should be
unsuppressed. First this observation was done in ref. [8] where it was stated that proton must decay due to transformation into a virtual black hole which subsequently decays into, say, positron and meson. We can very crudely estimate the proton life-time as follows (it differs from the original Zeldovich estimate into much larger direction). The probability that one quark would collapse into a virtual black hole is proportional to the volume of such black hole, i.e. to \( r_0^3 \sim m_q^3/m_{Pl}^6 \). However, because of charge and color conservation this black hole must be stable. Thus to force proton to decay, two quarks in proton should enter inside horizon and to form “two-quark” black hole which may decay into antiquark and lepton. The probability of such process is further suppressed by a power of \((m_q/m_{Pl})^n\). It is unclear what should be substituted here instead of effective quark mass, its bare (current) mass, \( m_q \approx 5 \) MeV, or its constituent mass, \( m_q \approx 300 \) MeV. Possibly in the first factor the bare mass (mass at small distances) should be substituted, while the second factor might contain the constituent mass. Even with the constituent mass the proton life-time with respect to such gravitational decay would be huge:

\[
\tau(p \rightarrow e^+ \pi^0) \sim \left( \frac{r_0^3 m_q^4}{m_{Pl}^6} \right)^{-1} = \frac{m_{Pl}^{6+n}}{m_p^{7+n}} \approx 10^{90} \text{sec}(m_{Pl}/m_p)^n
\]  

(66)

What happens, however, if TeV gravity is realized, i.e. \( m_{Pl} \sim \) TeV? If in the estimate above one should substitute small bare quark mass then the proton life-time even for \( n = 2 \) would be \( \sim 10^{44} \) sec which is completely safe. However, heavy quarks, e.g. \( t \)-quark may noticeably decay into \( 2\bar{q} + l \). A discussion of heavy particle decay and a list of literature can be found in the lecture [52].

### 9.2 Baryon asymmetry with conserved baryonic charge

Though it was claimed in the previous section that baryonic charge is conserved in the process of large (classical) black hole evaporation, strictly speaking, it was not so. If the final result of black hole evaporation would be a stable Planck mass remnant, one might say that the compensating amount of (anti)baryonic charge is stored in these remnants. Probably in quantum world these particles should be indistinguishable, despite different baryonic charges, and we must admit that at quantum level baryonic charge is not conserved, though it is formally conserved in particle physics Lagrangian. Moreover, proton decay through formation of a virtual black hole surely demonstrates the non-conservation of baryons.

Now we consider a model of baryogenesis where baryons are really conserved [53], see also [2]. This model is somewhat similar to the one discussed above but without black holes. Their role now plays a sterile (or weakly interacting with our world) new baryon \( Q \). Baryon asymmetry can be e.g. generated in decays of some heavy boson:

\[
A \rightarrow q + \bar{Q}, \quad \bar{A} \rightarrow Q + \bar{q}
\]

(67)

with different partial widths of charge conjugated channels. It would lead to equal but opposite signs of baryon asymmetries in ours and in (hidden) \( Q \) sector. A nice feature of this model is that \( Q \)-baryons could make dark matter if their mass is 5 times larger than \( m_p \). So we have a unique mechanism of baryogenesis and DM creation. Unfortunately there is no indication from particle physics to such a new baryon.
The scenario reminds generation of large lepton asymmetry in the sector of active neutrinos through resonance oscillations between active and hypothetical sterile neutrinos [55]. Leptonic charge is assumed to be conserved but the probability of transformation of active neutrinos into sterile partners is different from the similar process for antiparticles. This process goes without an explicit CP-violation in neutrino mass matrix. The necessary breaking of symmetry between particles and antiparticles is induced by the charge asymmetry of the cosmic plasma and corresponding charge asymmetric terms in the neutrino refraction index.

The similar scenario may operate at high temperatures if there exist heavy neutrinos, one of which being sterile with respect to our world but unstable, decaying into sterile sector. Since by assumption the cosmological plasma at this stage was charge symmetric, one needs CP-violation. The latter may be introduced directly into neutrino mass matrix. As we have seen above there is plenty of space for CP-odd phases, see the end of sec. 6.1. Now lepton asymmetry in active neutrino sector could be generated by heavy neutrino oscillations. Due to conservation of the total leptonic charge equal and opposite asymmetry would be created in the sector of heavy sterile neutrinos. Later leptonic charge of active neutrinos would be transformed into baryonic charge by electro-weak processes as it happens in baryo-thru-leptogenesis scenario, sec. 7. This is another example of generation of baryon asymmetry with conserved charges.

A few months after this School a paper [54] has appeared with somewhat similar idea that the difference of baryonic and leptonic charges, \((B - L)\), is globally conserved, while the observed charge asymmetry in the standard particle sector is compensated by \((B - L)\) stored in dark energy sector.

### 9.3 Spontaneous baryogenesis

If a global symmetry, \(U(1)\), related to baryonic or some other charge which is not orthogonal to baryonic one, is spontaneously broken, the spontaneous baryogenesis scenario [56] could be realized. As usually spontaneous symmetry breaking is described by the Higgs mechanism. A scalar field \(\phi\) with nonzero baryonic charge acquires a vacuum expectation value because its potential energy reaches minimum at non-zero \(\phi\).

\[
U(\phi) = \lambda(|\phi|^2 - \eta^2)^2, \tag{68}\]

Though the potential is invariant with respect to \(U(1)\) phase rotation, \(\phi \to \exp(i\theta)\phi\), an accidentally chosen ground state, \(\langle \phi \rangle \exp(i\theta_0)\eta\), is not. Spontaneous breaking of a global symmetry leads to appearance of a massless scalar field, Goldstone boson, proportional to the phase of \(\phi\)

\[
\phi = [\eta + \zeta(x)]\exp[i\theta(x)] \tag{69}\]

The Lagrangian of the Goldstone field, \(\theta(x)\), has the form

\[
\mathcal{L} = \eta^2(\partial\theta)^2 + \partial_\mu \theta j^B_\mu - V(\theta) + i\bar{Q}\gamma_\mu \partial_\mu Q + i\bar{L}\gamma_\mu \partial_\mu L + (g\eta\bar{Q}L + h.c.). \tag{70}\]

The potential \(V(\theta)\) may be nonzero due to some other physical effects. If \(V'' \neq 0\) the field \(\theta\) would be massive, but usually light. In this case it is called pseudogoldstone boson.
In the homogeneous situation the second term in eq. (70) looks like chemical potential, \( \dot{\theta} n_N \), but in reality it is not, because the coupling is derivative and the corresponding term in the Lagrangian (70), \( \partial_\mu \dot{\theta} j_\mu^B \), does not coincide with that in the Hamiltonian [57].

If \( V(\theta) = 0 \), i.e. purely Goldstone case, we can integrate the equation of motion:

\[
2 \eta^2 \partial^2 \theta = - \partial_\mu j_\mu^B
\]  

(71)

and obtain:

\[
\Delta n_B = - \eta^2 \Delta \dot{\theta},
\]  

(72)

where \( \Delta \) means the difference between the running values and the initial ones. Thus, non-zero baryon asymmetry may exist in thermal equilibrium and without explicit CP-violation. The latter is created by initial \( \dot{\theta} \neq 0 \). This is an example of dynamical CP violation in cosmology discussed in sec. [33].

In realistic situation \( \dot{\theta} \) is small, because kinetic energy is normally red-shifted away in the course of expansion, and hence the pseudogoldstone case could be more efficient for creation of the baryon asymmetry. The equation of motion in the pseudogoldstone case has the form:

\[
\eta^2 \ddot{\theta} + 3 H \dot{\theta} + V'(\theta) = \partial_\mu j_\mu^B.
\]  

(73)

where the second term proportional to the Hubble parameter \( H \) appears because of the cosmological expansion, this is the so called Hubble friction term, \( j_\mu^B = \bar{\psi} \gamma_\mu \psi \) is the baryonic currents of fermions (quarks) and the potential is expanded near minimum (which is taken to be at \( \theta = \pi \)) as:

\[
V(\theta) \approx -1 + m_\theta^2 \eta^2 (\theta - \pi)^2 / 2
\]  

(74)

where \( m_\theta \) is the mass of the pseudogoldstone field.

Initially, at inflation, \( \theta \) should be uniformly distributed in the interval \([0, 2\pi]\), so at the end of inflation it would typically have the value of order unity. When the universe expansion slowed down so that \( H \) becomes smaller than the mass of \( \theta \), the field started to evolve down to the equilibrium point of the potential oscillating around it. The value of the baryon asymmetry which was generated on the way is not so easy to calculate as in the purely Goldstone case. To this end the equation of motion of fermions has to be solved. The equation for the quantum operators of the baryonic Dirac field reads:

\[
(i \partial + m) \psi = -g \eta l + (\partial_\mu \theta) \gamma_\mu \psi
\]  

(75)

One can find the solution of this equation in one-loop approximation for \( \psi \) in external classical field \( \theta \) and substitute \( \bar{\psi} \psi = F(\theta) \) into equation of motion for \( \theta \) [33]. The solution oscillates with alternating baryonic number. Because of these oscillations the net result for the baryon asymmetry is not linear in \( \theta \) but cubic [58]:

\[
n_B \sim \eta^2 \Gamma_{\Delta B} (\Delta \theta)^3.
\]  

(76)

where \( \Gamma_{\Delta B} \) is the decay rate of \( \theta \) into baryons and \( \Delta \theta \) is the difference between initial value of \( \theta \) and the equilibrium one at the minimum of the potential \( V(\theta) \).
9.4 Baryogenesis from super-partner baryonic condensate

As is well known, supersymmetry (SUSY) predicts existence of scalar superpartners of baryons which have non-zero baryon number. Self-potential of such scalars can typically have flat directions along which potential energy does not change. Moreover, baryonic charge is naturally non-conserved. Some more detail about SUSY are presented in the lecture by A. Masiero at this School.

As a toy model possessing these properties we can take the scalar partner of baryons, $\chi$ with the potential:

$$U_{\chi}(\chi) = \lambda |\chi|^4 (1 - \cos 4\theta),$$

where $\chi = |\chi| \exp(i\theta)$. There are four flat directions in this potential along $\cos 4\theta = 1$. The potential breaks symmetry with respect to phase rotation $\chi \rightarrow \chi \exp(i\alpha)$. This leads to nonconservation of baryonic charge of $\chi$. Due to infrared instability of massless fields in De Sitter space-time, see eq. (47), such bosons may condense along flat directions of the potential. To be more accurate, only colorless and electrically neutral combination of the fields may condense. When these flat directions acquired a non-zero curvature (mass) and the universe expansion rate becomes smaller than the mass, $H < m_\chi$, the field would evolve down to equilibrium. During this relaxation down to $\chi = 0$ the field $\chi$ decays into quarks, most probably with conserved $B$, and released the baryonic charge stored in the condensate into the baryonic charge of quarks. This is an essence of the Affleck and Dine scenario of baryogenesis [59].

In addition to the quartic potential (77) the mass term can be added:

$$U_m(\chi) = m^2 |\chi|^4 [1 - \cos (2\theta + 2\alpha)],$$

Here $\alpha$ is some arbitrary phase. If $\alpha \neq 0$, C and CP are explicitly broken.

"Initially" (at inflation) $\chi$ is away from the origin and when inflation is over, $\chi$ starts to evolve down to the equilibrium point, $\chi = 0$, according to its equation of motion which for homogeneous $\chi$ coincides with equation of motion of point-like particle in Newtonian mechanics:

$$\ddot{\chi} + 3H \dot{\chi} + U'(\chi) = 0.$$  \hspace{1cm} (79)

Baryonic charge of $\chi$,

$$B_\chi = \dot{\theta}|\chi|^2$$  \hspace{1cm} (80)

is analogous to mechanical angular momentum. When $\chi$ decays, its baryonic charge is transferred to that of quarks in B-conserving process. Thus we can easily visualize the process without explicit solution of the equations of motion.

The B-charge of $\chi$ is accumulated in its “rotational” motion, induced by quantum fluctuations in the orthogonal to valley direction. The space average value of the baryonic charge is evidently zero and as a result a globally charge symmetric universe would be created. The size of domains with definite sign of the baryonic charge density, $l_B$, is determined by the size of the region with a definite sign of $\dot{\theta}$. Normally the size of the
region with definite $\dot{\theta}$ is microscopic and this leads to a very small $l_B$. However, if the Hubble parameter at inflation happened to be larger than the second derivative of the potential $U_\lambda$ in the direction orthogonal to the valley, the field motion in orthogonal direction would be frozen during exponential expansion and the size of the domains with a fixed value of $B$ may be large enough.

Situation may be different if $m \neq 0$. In this case initial angular momentum or, what is the same, baryonic charge of $\chi$ could be zero but the rotational motion (or baryonic charge) may be created by a different direction of the valley at low $\chi$. At large $\chi$ the direction of the valley is determined by $U_\lambda(\chi)$, eq. (77), while at small $\chi$ the quadratic part (78) dominates.

If the CP-odd phase in eq. (78) is zero, $\alpha = 0$, but the flat direction of $U_\lambda$, along which $\chi$ condensed, is orthogonal to flat directions of $U_m$, the field $\chi$ would rotate near origin with 50% probability clock-wise or anti-clockwise creating baryonic or antibaryonic universe. If inflation helped, such regions could be sufficiently big. This is an example of baryogenesis without an explicit C(CP)-violation and without domain wall problem.

If the CP-odd phase, $\alpha$, is small but non-vanishing, the rotation of $\chi$ when it approached the $m$-valley would proceed with different probabilities in different directions. Hence both baryonic and antibaryonic regions are possible with a dominance of one of them. Matter and antimatter domain may exist but globally $B \neq 0$ [31, 60]. A different scenario of formation of cosmic domains of antimatter can be found in the paper [61] (and references therein).

A very interesting picture appears if the field $\chi$ is coupled to the inflaton with the general renormalizable coupling [60]:

$$\lambda |\chi|^2 (\Phi - \Phi_1)^2$$

(81)

In this case the “gates” to the valley may be open only for a short time when the inflaton field $\Phi$ was close to $\Phi_1$. Thus the probability of penetration to the valley would be small and $\chi$ would acquire a large baryonic charge condensate, giving $\beta \sim 1$ only in a tiny fraction of space. The bulk of space would have the normal homogeneous baryon asymmetry $\beta = 6 \cdot 10^{-10}$, which could be created by one of the standard mechanisms described above, while high-B regions would be rare. Depending upon the concrete model, the high-B regions may be symmetric with respect to baryons and antibaryons or dominated by one of them.

The mass distribution of the high-B regions was calculated in ref. [60]. It depends upon two unknown constants $C_0$ and $C_1$ and has a simple log-normal form:

$$\frac{dN}{dM} = C_0 \exp \left[ -C_1 \ln^2 \left( \frac{M}{M_0} \right) \right].$$

(82)

The high-B regions could be primordial black holes, in particular quasars, disperse clouds of antimatter, and unusual stars and anti-stars. All may be not too far from us. These black holes may make all or a part of the cosmological dark matter. Such dark matter is similar to normal dark matter with one difference that the masses of DM “particles” are not the same. Their dominant part may have masses close to the solar mass, but on the tail of the distribution very heavy black holes of millions solar masses may exist.
Since they are dispersed over mass, their existence may be compatible with the bounds on MACHOs in different mass intervals [62].

Primordial nucleosynthesis in hi-B domains proceeded with large $n_B/n_\gamma$ and the abundances of the early produced elements would be quite different from the standard BBN [63]. In particular, primordial heavy nuclei and anti-nuclei, up to iron or anti-iron could be formed. An early formation of heavy nuclei may explain evolved chemistry around high redshift quasars. If such hi-B regions were formed in our neighborhood, an observation of heavy anti-nuclei might be plausible.

A different process of formation of high density baryonic bubbles was proposed in ref. [64]. It was argued that during QCD phase transition macroscopically heavy (with mass about $10^7$ g) objects might be formed which consisted either of baryons or antibaryons. Due to CP-violation there could be a small excess of antibaryonic bubbles with respect to baryonic ones and, vice versa, a small excess of free baryons over antibaryons. The latter would be the observed cosmic baryons, while the former could make the cosmological dark matter. Unfortunately no persuasive calculations have been presented (at least till now) to support this picture.

10 Conclusion

Universe existence clearly demonstrates that both CP and B are not conserved. Though models without CP and B breaking can be constructed, they are much less natural. Most probably CP-violation in cosmology is not directly related to CP-violation observed in particle physics. Moreover, there exists a natural mechanism of CP-breaking in the early universe which is untraceable today in direct experiments.

The standard scenarios of baryogenesis can explain one number, the magnitude of the cosmological baryon asymmetry, $\beta = \text{const}$. Due to this it is impossible to distinguish between them and to understand what really happened in the early universe.

There are two ways to resolve this uncertainty. First, to find a testable model of particle physics which allows to express the high energy parameters through the measurable low energy ones. A crucial demand to such a model is the explanation of the close magnitudes of energy densities of baryonic and dark matter. At the present stage it is hardly feasible.

Another possibility is to rely on cosmological good luck. If a non-standard model of baryogenesis is realized, such that $\beta$ is not a constant but a function of space points, $\beta = \beta(x)$, then measuring the corresponding isocurvature perturbations we can hope to select the right baryogenesis scenario. Especially interesting is the case if somewhere $\beta < 0$ i.e. cosmic antimatter is created (see more below). In connection with “good luck” I would like to re-quote quotation from Napoleon presented in one of the lectures by I. Bigi at this School: Napoleon considered being lucky as a necessary condition for his generals. Maybe being lucky to exist, we also have some other portions of good luck, in particular, to understand the universe. Maybe anthropic principle includes good luck?

It is unknown if astronomically large domains of antimatter exist not too far from us, though the universe is most probably globally charge asymmetric at least inside the present day horizon volume. Still some antimatter may be almost at hand with abundant
heavy anti-nuclei.

Stochastic or dynamical CP-breaking leads to a very interesting pattern of distribution of baryonic matter and antimatter. A search for isocurvature fluctuations in the angular spectrum of CMBR and in large scale structure, together with the search for cosmic antimatter and unusual sources of gamma rays from matter-antimatter annihilation is of primary importance for understanding the nature of the cosmological CP-violation.

As for more theoretical conclusions, we should mention that despite breaking of T-invariance and related to it absence of detailed balance, the canonical equilibrium distributions remain true. Most probably they survive even if CPT is broken.

If unitarity and the canonical spin-statistics relation are broken then the usual equilibrium distributions may be broken too and the effects can be accumulated and large. Maybe stationary equilibrium distributions do not exist. However, one should be aware of Pandora’s box of consequences if sacred principles are destroyed. I would like to finish with a quotation from “Brothers Karamazov” by Fedor Mihailovich Dostoevsky: “If there is no God, everything is permitted.”

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