Evolution of Big Bang Universe

Lecture from the course
« Introduction to cosmoparticle physics »

Thermal History of Universe

The modern expansion of the Universe with relic radiation corresponds to the thermal history of its early hot stages, including:

- very early Universe (t<1s),
- Big Bang Nucleosynthesis (first three minutes),
- beginning of matter dominance and formation of Large Scale structure of Universe and galaxies

Cosmochronology

T~?
Generation of baryon excess

T~100 MeV
Hadronization
(QCD phase transition)

T~10 MeV
$\mu\mu$-annihilation

***T*~1 MeV, *t*~1 s**
n/p freezing out, ν-decoupling

***T*~0.1 MeV, *t*~100 s**
Nucleosynthesis

***T*~1 eV, *t*~30000 yr**
RD->MD

***T*~3000 K,**
***t*~400000 yr**
Recombination

***t*~1 Gyr**
Galaxy formation

t~3 Gyr
Λ-dominance

***t*~10 Gyr**
Modern epoch

Formation of LSS

Very early Universe

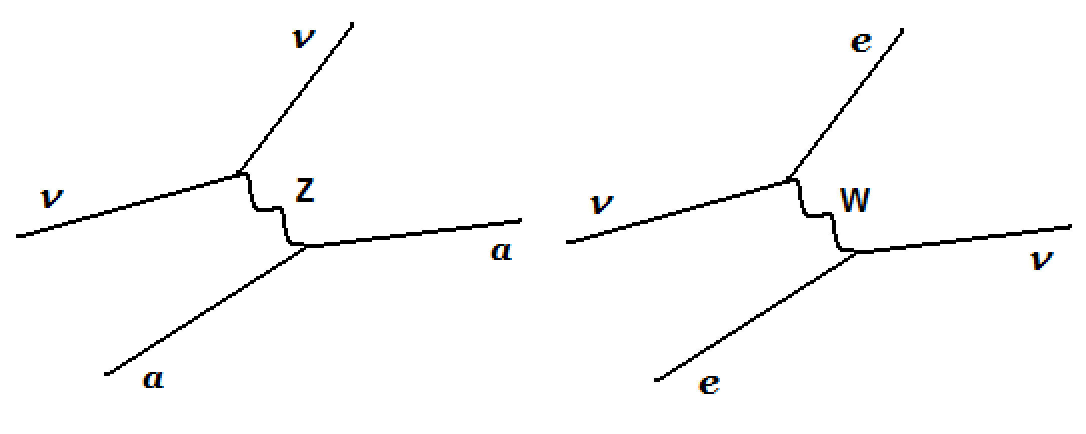
- At $t \ll 1$s temperatures were $T \gg 1$ MeV and all the Standard Model particles were present in equilibrium.
- Gauge nature of SM interactions proves thermodynamical description of particles in approximation of ideal noninteracting relativistic Bose or Fermi gases. QCD proved this description also for hadrons.
- Absence of antimatter in the amounts comparable with matter in the modern Universe corresponds to the excess of baryons (quarks) at T>1GeV

Neutrinos in early Universe

Let us consider conditions of equilibrium of neutrinos at *T* ~ 1 MeV

$$\overset{(\sim)}{\nu}_{e,\mu,\tau}\, a \leftrightarrow \overset{(\sim)}{\nu}_{e,\mu,\tau}\, a, \qquad a = \overset{(\sim)}{\nu}_{e,\mu,\tau}, e^{\pm}$$

$$\nu_e + \tilde{\nu}_e \leftrightarrow e^- + e^+$$



$$\left.\begin{array}{l}\tilde{\nu}_e + p \leftrightarrow e^+ + n \\ \nu_e + n \leftrightarrow e^- + p\end{array}\right\}$$ are not important for ν-equilibrium, because $n_{n,p} << n_{\nu,e}$

Decoupling of neutrinos

Condition of ν-decoupling (it coincides with freezing out of weak reactions) is

$$\boxed{n_a \sigma_{\nu a} \upsilon_{\nu a} = H}$$

$$\varepsilon_{cr} = \frac{3H^2}{8\pi G} = \kappa_\varepsilon \bar{\sigma} T^4 \quad \Rightarrow \quad \left\{ \begin{array}{l} n_a \sim T^3 \qquad \text{- for relativistic species} \\ \sigma_{\nu a} \sim G_F^2 E^2 \sim G_F^2 T^2 \\ \upsilon_{\nu a} \sim 1 \\ H \sim \dfrac{\sqrt{\kappa_\varepsilon} T^2}{m_{Pl}} \end{array} \right.$$

$$\Downarrow$$

$$\boxed{T \equiv T_* \sim \frac{\kappa_\varepsilon^{1/6}}{(G_F^2 m_{Pl})^{1/3}} \approx 1\,\mathrm{MeV}}$$

Accurate calculation gives close result.

Relic neutrinos

After decoupling, number of neutrinos (in comoving volume) does not change.

So, today we must have:

$$n_{\nu\bar{\nu}}^{(\mathrm{mod})} = n_{\nu\bar{\nu}}^{(*)} \cdot \left(\frac{a_*}{a_{\mathrm{mod}}} \right)^3$$

To find the ratio between the scale factors, corresponding to the moments $T=T_*\sim 1\,\mathrm{MeV}$ and $T=T_{\mathrm{mod}}=2.7\ \mathrm{K}$, we need to relate a and T (photon temperature).

It can be done with the help of the law of entropy conservation.

Existence of gas of relic neutrinos is the inevitable consequence of a hot stages with $T>1\,\mathrm{MeV}$

Abundance of relic neutrinos

Entropy conservation (being valid under supposition of absence of any entropy production (irreversible processes) during period of question) reads

$$S_* = S_{\text{mod}}$$

After decoupling, neutrinos behave as a close system, therefore

$$\begin{cases} \cancel{S_{\nu\bar\nu}^{(*)}} + S_{e^\pm}^{(*)} + S_\gamma^{(*)} = \cancel{S_{\nu\bar\nu}^{(\text{mod})}} + S_\gamma^{(\text{mod})} \\ S_{\nu\bar\nu}^{(*)} = S_{\nu\bar\nu}^{(\text{mod})} \end{cases}$$

In modern epoch relic photons and neutrinos are assumed to give dominant contribution into entropy (baryons, dark matter, light of stars are much less).

$$S \equiv s \cdot V \propto s \cdot a^3 \propto \kappa_s T^3 \cdot a^3$$

$$\left(1(\gamma) + \frac{7}{8} 2(e^\pm)\right) \cdot T_*^3 \cdot a_*^3 = 1(\gamma) \cdot T_{\text{mod}}^3 \cdot a_{\text{mod}}^3 \quad \Rightarrow \quad \left(\frac{a_*}{a_{\text{mod}}}\right)^3 = \frac{4}{11} \frac{T_{\text{mod}}^3}{T_*^3}$$

$$n_{\nu\bar\nu}^{(\text{mod})} = \frac{4}{11} \frac{T_{\text{mod}}^3}{T_*^3} n_{\nu\bar\nu}^{(*)} = \frac{4}{11} \frac{T_{\text{mod}}^3}{T_*^3} \frac{3}{4} n_\gamma^{(*)} = \frac{3}{11} n_\gamma^{(\text{mod})}$$

for one neutrino species

$$\boxed{n_{\nu\bar\nu}^{(\text{mod})} = \frac{3}{11} n_\gamma^{(\text{mod})} \approx 110\,\text{cm}^{-3}}$$

Using formally thermodynamic relations, we can define the temperature of relic neutrinos as:

$$n_{\nu\bar\nu}^{(\text{mod})} = \frac{3}{4} n_\gamma (T_{\nu\bar\nu}^{(\text{mod})}) = \frac{3}{11} n_\gamma^{(\text{mod})}$$

$$T_{\nu\bar\nu}^{(\text{mod})} = \sqrt[3]{\frac{4}{11}} \cdot T_\gamma^{(\text{mod})} \approx 2\,\text{K}$$

Neutron to proton ratio

The ratio between the numbers of neutrons and protons in early Universe is regulated by reactions

$$\tilde{\nu}_e + p \leftrightarrow e^+ + n$$

$$\nu_e + n \leftrightarrow e^- + p$$

which are frozen out together with other weak interaction processes (as was obtained) at

$$T_* \sim \frac{\kappa_\varepsilon^{1/6}}{(G_F^2 m_{Pl})^{1/3}} \approx 1\,\mathrm{MeV}$$

This corresponds to

t_*~1 s

Note, that processes of n-p transformation due to π-mesons are suppressed at *T*~1 MeV because of large π-meson mass.

Freezing out of n/p ratio

The ratio between the numbers of *n* and *p* (of two energetic states of nucleon) is defined by thermodynamic relation while $T>T_*$

$$\frac{n_n}{n_p} = \exp\left(-\frac{\Delta m}{T}\right), \qquad \Delta m \equiv m_n - m_p = 1.29\,\mathrm{MeV}$$

After $T=T_*$ this ratio is frozen out at the magnitude

$$\boxed{\frac{n_n}{n_p} = \exp\left(-\frac{\Delta m}{T_*}\right) \sim \frac{1}{6}}$$

Afterwards, neutrons decay gradually until they are combined with protons into nuclei.

Formation of deuterium

In order a simplest composite nucleus (deuteron) were synthesized in primordial plasma, the rate of reaction

$$p + n \to \mathrm{D} + \gamma$$

might become higher than that of back reaction (photo-disintegration of deuteron)

$$\gamma + \mathrm{D} \to p + n$$

The last rate exponentially falls down when the temperature becomes below the binding energy of deuteron, E_{D}=2.2 MeV, because photons from only a tiny tail of thermal distribution can do it.

So

$$n_\gamma(>E_{\mathrm{D}}) \sim n_\gamma \cdot (E_{\mathrm{D}}/T)^2 \exp(-E_{\mathrm{D}}/T) \equiv n_\gamma \cdot f(>E_{\mathrm{D}})$$

$$\Gamma_{np\to\mathrm{D}\gamma} = \Gamma_{\mathrm{D}\gamma\to np},$$

$$\Gamma_{np\to\mathrm{D}\gamma} = n_{n,p}\left\langle \sigma_{np\to\mathrm{D}\gamma} v_{np} \right\rangle \sim \eta_B n_\gamma \cdot \langle \sigma v \rangle,$$

$$\Gamma_{\mathrm{D}\gamma\to np} = n_\gamma(>E_{\mathrm{D}})\left\langle \sigma_{\mathrm{D}\gamma\to np} v_{\mathrm{D}\gamma} \right\rangle \sim f(>E_{\mathrm{D}}) n_\gamma \cdot \langle \sigma v \rangle.$$

$$\Rightarrow \boxed{T \equiv T_{\mathrm{D}} \sim E_{\mathrm{D}} / \ln\left(\frac{400}{\eta_B}\right) \approx 0.1\,\mathrm{MeV}}$$

$\boxed{t_{\mathrm{D}} \sim 100\ \mathrm{s}}$

Here $\eta_B = n_B/n\gamma \sim 0.6 \times 10^{-9}$.

Big Bang nucleosynthesis

During period between $t_* \div t_D$, about 10% of neutrons decay, so

$$\boxed{\frac{n_n}{n_p} \equiv \frac{n}{p} \sim \frac{1}{7}}$$

This ratio defines total modern number of neutrons.

Virtually all the neutrons hit into helium-4 nuclei in the result of the successive chain of nuclei reactions (BBN)

$$n + \mathrm{D} \to \mathrm{T} + \gamma \qquad p + \mathrm{T} \to {}^4\mathrm{He} + \gamma \qquad \mathrm{T} + {}^4\mathrm{He} \to {}^7\mathrm{Li} + \gamma$$

$$\mathrm{D} + \mathrm{D} \to \mathrm{T} + p \qquad \mathrm{D} + \mathrm{T} \to {}^4\mathrm{He} + n$$

$$p + \mathrm{D} \to {}^3\mathrm{He} + \gamma \qquad n + {}^3\mathrm{He} \to {}^4\mathrm{He} + \gamma \qquad \ldots\ldots\ldots$$

$$\mathrm{D} + \mathrm{D} \to {}^3\mathrm{He} + n \qquad \mathrm{D} + {}^3\mathrm{He} \to {}^4\mathrm{He} + p$$

Formation of heavier nuclei is suppressed because of **big Coulomb barrier.**

Primordial chemical elements

All reactions had been going during ~100 s, in the result of which a primordial chemical composition has been established, where the majority of protons and neutrons are distributed between helium-4 and hydrogen:

$$\frac{\rho_{\mathrm{H}}}{\rho_{\mathrm{B}}} \approx \frac{1-n/p}{1+n/p} \approx 0.75$$

$$\frac{\rho_{\mathrm{He}}}{\rho_{\mathrm{B}}} \equiv Y_p \approx \frac{2(n/p)}{1+n/p} \approx 0.25$$

$$\frac{n(\mathrm{D})}{n(\mathrm{H})} \sim 3 \cdot 10^{-5}; \qquad \frac{n(\mathrm{He}^3)}{n(\mathrm{H})} \sim 10^{-5}$$

$$\frac{n(\mathrm{Li}^7)}{n(\mathrm{H})} \sim 10^{-10}; \quad \frac{n(\mathrm{Li}^6)}{n(\mathrm{H})} \sim 10^{-13}; \quad \frac{n(\mathrm{Be}^9)}{n(\mathrm{H})} < 10^{-17}$$

Baryon density in nucleosynthesis

The rates of nuclear reactions are sensitive to the density of all nuclei themselves, being defined by baryon density

$$\eta_B \equiv \frac{n_B}{n_\gamma}$$

As a consequence, prediction of primordial chemical composition depends on η_B. We already were convinced that number of neutrons and, consequently, of ^{4}He depends on moment when D starts to be synthesized what depends on η_B.

Prediction of D is much more sensitive to η_B.

Under conditions in early Universe, amount of D is basically defined by reaction of D and T synthesis into ^{4}He,

$$\mathrm{D} + \mathrm{T} \rightarrow {}^4\mathrm{He} + n$$

which diminishes D, produced during first 100 s, until given reaction will be frozen out.

Density of T is turned out to be proportional to η_B.

Deuterium and baryon density

So, we have

$$\mathrm{D} + \mathrm{T} \rightarrow {}^{4}\mathrm{He} + n$$

$$\frac{dD}{dt} = -D \cdot T \cdot \sigma v$$

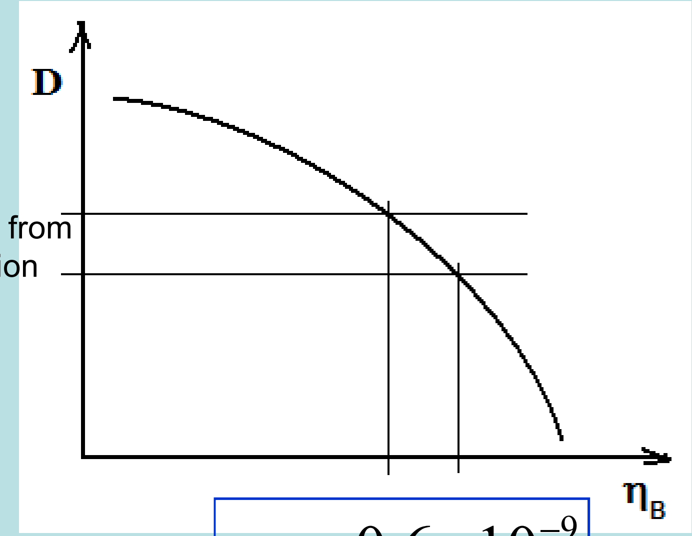
where *D*, *T* are respective number densities

$$T \propto \eta_B$$

$$\Downarrow$$

$$D = D_0 \exp(-const \cdot \eta_B)$$

Deduced from observation

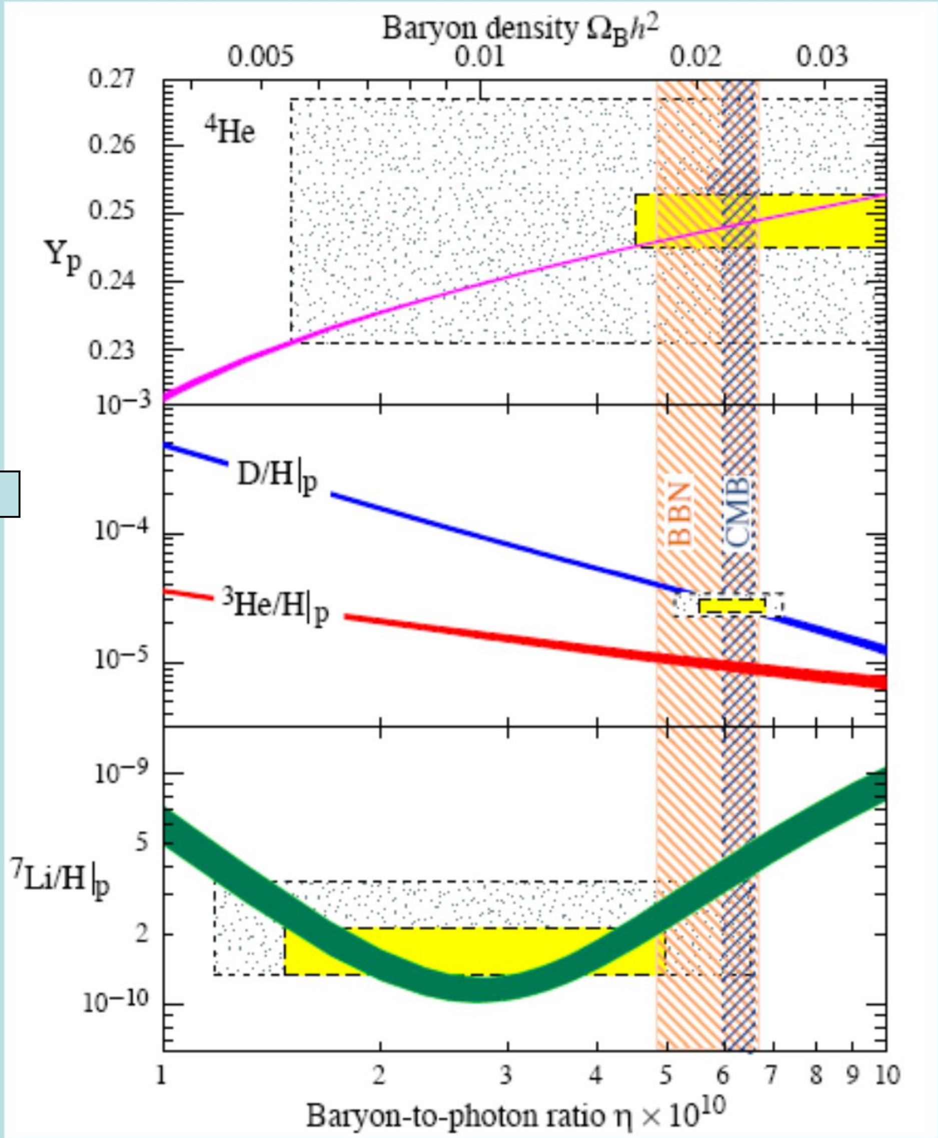


$$\boxed{\eta_\mathrm{B} \approx 0.6 \times 10^{-9}}$$

Estimation of baryon density

Complex analysis of chemical composition of Universe gives

$$\Omega_B \approx 0.044(4)$$



Formation of LSS and galaxies (1)

Large Scale Structure (**LSS**) is supposed to form from small initial perturbations of density (inhomogeneities).

According to the theory of LSS formation,

• inhomogeneities, if they are, are preserved in form of sound waves at RD-stage (for particles being in equilibrium)

$$\boxed{\frac{\delta\rho}{\rho} \approx const}$$

• inhomogeneities grow at MD-stage (for non-relativistic particles), according to Lifshits's theory for expanding Universe, following to a linear law

$$\boxed{\frac{\delta\rho}{\rho} \propto a \propto t^{2/3}} \quad \text{until} \quad \frac{\delta\rho}{\rho} << 1$$

Formation of LSS and galaxies (2)

• when **$\delta\rho/\rho \sim 1$** is reached, evolution of inhomogeneity separates from common cosmological expansion and follows to a non-linear law ("object has been formed");

• no inhomogeneity of the size **>** horizon=ct, if it is, changes;

• no inhomogeneity of the size **<** length of free streaming path of particles survives (they are washed out).

Before recombination, no baryon inhomogeneities could grow since this process is prevented by the pressure of relativistic gas of photons (they exist in form of "sound").

From observational data on an **anisotropy** of CMB we have

$$\boxed{\left.\frac{\delta\rho_B}{\rho_B}\right|_{\text{at recombination}} \sim 3\frac{\delta T}{T} \sim 10^{-4}}$$

Conclusions

- In the very early Universe all the SM particles were present in equilibrium.
- At t~1s neutrinos decoupled from plasma and remained in the Universe in the form of gas of relic neutrinos. Their modern concentration is related to photons by equilibrium and entropy conservation.
- In the first three minutes primordial chemical composition was formed.
- At T~1eV (nonrelativistic)matter dominance started, at which Large scale structure of the Universe was formed