The nuclear big-bang

How far can we go backwards?

How far we know the physics involved?

What is the evidence today to what happened at the beginning

The first seconds

The size of the observed Universe (the distance to the horizon) is:

$$l_{horizon} = ct_{universe}$$

The distance to the horizon increases with time.

Today

The age of the Universe is 15 billion years and we see inside the horizon 10^{12} galaxies.

When the Universe was 10 years old

The horizon contained only $10^{11}M_{sun}$=mass in one galaxy

When the Universe was few seconds old

The horizon contained 1Msun. The observer at this time could see only one solar mass.

When the Universe was 10^{-23} second old

The horizon contained one nucleus. The size of the horizon was like the size of a nucleus, 10^{-13} cm.

The Universe contained the same mass as today but information could reach only to a distance of the size of a nucleus.

The reason for this behavior is the dependence of the density on time. The radius of the horizon is ct and the mass inside the horizon is:

$$M_{horizon} \propto \rho t^3$$

If $\rho \propto t^{-n}$ and n < 3 than the mass in the horizon increases with t

The first seconds

As we reach to smaller and smaller times, the influence of gravity increases. As a sufficiently high density the gravitational force can form particles from the vacuum - the strong gravitational field will turn into mass particles (with non zero rest mass)

How far can we go towards the singularity?

The expansion of the Universe is described by: $H(t) = \frac{\dot{R}(t)}{R(t)} = \frac{1}{2t}$

The behavior of R(t) in all exploding models is given by

$$\dot{R}^2(t) = 8\pi G\rho(t)R^2(t)/3$$

Under these conditions the matter behaves like radiation and hence

$\rho_{rad} = \frac{\varepsilon_{rad}}{c^2} = \frac{aT^4}{c^2}$ where $a = \frac{8\pi^5 k_B^4}{15c^3h^3}$ The Stefan-Boltzmann constant

Hence the equation for the temperature is:

$$\dot{T}^2 = \left(\frac{8\pi G a}{3c^2}\right) T^6$$

and the solution is:

$$T(t) = \left(\frac{32\pi G a}{3c^2}\right)^{-1/4} t^{-1/2}$$

Whenever the frequency ω of a particle is equal to the rate of expansion of the Universe we have to take into account Quantum Theory

When

$$\hbar\omega = particle\ \ energy = kT = particle\ \ energy\ \ in\ \ the\ Universe$$

or

$$\omega = \frac{k_B T}{\hbar} = \frac{k_B}{\hbar}\left(\frac{3c^2}{32\pi G a}\right)^{1/4} t^{-1/2}$$

At this moment, General Relativity (the theory of gravity and large scale structure) and Quantum Theory (the theory of elementary particles behavior) should merge.

This happens when: $\omega \approx H(t)$

or $$t < t_Q = \frac{\hbar^2}{4k_B^2}\left(\frac{32\pi G a}{3c^2}\right)^{1/2} = \pi\left(\frac{hG}{45c^5}\right)^{1/2} \cong 10^{-43}\,\mathrm{sec}$$

The temperature at this moment is: $T_Q \cong 5\times10^{31}\,\mathrm{K}$

And the distance to the horizon is: $l_{horizon} = ct_Q = 3\times10^{-33}\,cm$

Another point of view: $\Delta p \Delta x \approx h$ But: $\Delta x = \underbrace{ct}_{l_{horizon}}$

$$\Delta p = \frac{E}{c} \cong \frac{k_B T}{c} = \frac{energy\ \ per\ \ particle}{c}$$

$$ct \cong \frac{h}{\Delta p} = \frac{hc}{k_B T}$$

Substitute T as a function of time and find for which t there is an equality to get:

The Planck time $t_Q \approx \left(\frac{hG}{c^5}\right)^{1/2}$

The unification of GR and QT is not yet known. The Friedmann equations for the expansion of the Universe are not valid for

$t < t_Q$.

How does the Universe look under such extreme conditions?

At $t = t_Q$ $\rho = 10^{93} g/cc, T = 5\times 10^{31} K$

The energy per particle is: $\left(\frac{\hbar c^5}{G}\right)^{1/2} = 1.2\times 10^{19} GeV$

Our knowledge of elementary particles reaches hardly 10GeV!

When the temperature is sufficiently high so that $h\nu \geq 2mc^2$ particles with mass *m* can form.

$$two \ \ photons \leftrightarrows particle \ \ anti \ \ particle$$

Examples:

$$e^- + e^+ \leftrightarrows 2\gamma$$

$$p + \overline{p} \leftrightarrows 2\gamma$$

In a reaction in thermodynamic equilibrium the concentration are determined by the chemical potentials:

$$2m_e c^2 + \mu_- + \mu_+ = 2\mu_\gamma$$

Chemical potential e^-

Chemical potential e^+

Chemical potential γ

Twice the rest mass of the particles

The solution of the equation for the chemical potentials is:

$$n = n^- = n^+ = 1.803 \frac{m^3 c^3}{\pi^2 \hbar^3} \left(\frac{k_B T}{mc^2} \right)^3 = 1.507 \times 10^{28} \left(\frac{T}{10^9 K} \right)^3$$

What is the ratio of energy in forms of kinetic energy of particles and the radiation field?

$$\frac{nk_BT}{aT^4} = \frac{1.803m^3c^3}{\pi^2\hbar^3}\left(\frac{kT}{mc^2}\right)^3\frac{k_BT}{aT^4} = constant = \frac{7}{4}$$

Whenever the temperature rise to above $2mc^2$ new pairs of particles and anti-particles are formed and more energy is in the form of matter anti-matter.

The appearance of a new elementary particles leads to energy absorption form the radiation field. Every new particle can be observed as a resonance in a more complex structure. With every new particle there is a new degree of freedom. The energy always spreads between all degrees of freedom.

If the number of resonances or particles (degrees of freedom) increases sufficiently fast- could we have a situation in which the Universe decreases but the temperature does not rise?

The present theory of elementary particles predicts a finite number of particles. Hence, the temperature in the past was high and

$$T \to \infty \quad for \quad t \to 0$$

Is it possible to check how high was the temperature in the past?

When $T \geq 10^{13} K$ (energy of 10^9eV) quarks should appear.

The quarks compose the elementary particles. Quarks have charges 1/3 and 2/3 but always combine to form charge 1.

So far no free quark was discovered and it may be that in principle no free quarks exists.

But at sufficiently high T, when $h\nu \sim k_B T \geq m_Q c^2$ pairs of quarks and anti-quarks appeared.

When the T was high the dominant reaction was:

$$2\gamma \rightarrow Q + \overline{Q}$$

But as T decreases all (or most?) quarks annihilated in the inverse reaction

$$Q + \overline{Q} \rightarrow 2\gamma$$

In principle, at high T all particles are in the form of particle anti-particle and as T decreases they annihilate and transfer the energy back to the radiation field.

Is it possible that a minute fraction of quarks did not annihilate and was left free?

The complete reply depends on the not yet fully known interaction between quarks and other particles.

If the force between quarks is extremely small, then as the density of quarks falls down there is a finite chance that some quarks survive the annihilation

The estimate today is that the quark abundance today is smaller than 1 in 10^9 hydrogen atoms and this quantity is constant as the Universe expands. $(X(Au)=10^{-9} X(H))$

A quark can annihilate only by a collision with another quark and the probability for this to happen is very small. Hence, today the life time of a free quark > the age of the Universe.

In spite of the fact that a fractional charge helps the discovery of quarks, no free quarks have been found and the upper limit for their abundance is below 10^{-20} (in sea water)

If free quarks exist and the large separation between them did not prevent annihilation, then the fact that no quarks were discovered may mean that T in the Universe was not higher than 10^9 eV and we will have to look for a new cosmology to replace the Hot Bing Bang.

The charge symmetry in the Universe

In the first second, when T was very high the Universe was almost symmetric with respect to the charge.

If the Universe were completely symmetric all the matter would have annihilated with the anti-matter and the Universe today would contain only radiation.

Are there in the Universe galaxies made of anti-matter? Probably not!

a) the galaxies formed only after the annihilation of the light particles.

b) how a galaxy made of anti-matter survives and does not annihilate with matter.

At present we still do not know why the Universe is not symmetric.

Is there some charge symmetry violation?

The Nuclear Bang

All heavy particles undergo annihilation a short time after the beginning. This era is called therefore the Hadronic era.

The Hadronic era (in which the strong force dominates) is followed by the Leptonic era (in which the weak force acts)

The appearance of the neutrons

At T > 10^{10}K all particles are in equilibrium with the radiation and among themselves.

The electrons and protons are in equilibrium with the radiation during the Leptonic era. The dominant reactions are

$$e^+ + e^- \leftrightarrow 2\gamma$$

$$p^+ + p^- \leftrightarrow 2\gamma$$

But there is a small leakage to

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

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

At this time the Universe is still opaque to radiation (the mean free path of a photon is extremely small). At

$$T = \frac{m_e c^2}{k_B} = 5 \times 10^9\, K$$

the formation of electron-positron pairs ceases

Approximately at this temperature the creation and destruction of neutron ceases and the number of neutron freezes. When in thermodynamic equilibrium

$$\frac{n_{neutrons}}{n_{protons}} = e^{-(m_n - m_p)c^2 / k_B T}$$

The mass difference between the proton and the neutron is 1.3MeV.

As the neutron abundance freezes at about 10^{10}K, one can substitute this temperature into the above equation to get $n_n/n_p \sim e^{-1.5} = 0.2$

Helium formation

The formation of Helium is determined by the reaction

He formation $n + p \leftrightarrow d + \gamma$ *Deuterium destruction*

At high T and ρ, we have equilibrium

$$\frac{X_n X_p}{X_d} = \frac{4}{3}\frac{(2\pi kT)^{3/2}}{h^3 n}\left(\frac{m_n m_p}{m_d}\right)^{3/2} e^{-B/kT}$$

where $X_n = \frac{N_n}{N}$ and $n = \frac{N}{V}$ N is the total number of nucleons in the volume V. B is the deuterium binding energy.

We use now the parameters of the Universe to obtain the dependence of the density and temperature on time.

From the connection $n = n_0 R_0^3 / R^3(t)$

we write for the present day value of n $n_0 = 1.12 \times 10^{-5} \Omega h^2 cm^{-3}$

(here h is the Hubble constant in units of 100km/Mpc/sec)

We define $\Omega = \frac{n_0}{n_c}$ and observations today tell us that $10^{-2} \leq \Omega \leq 1$

From the Friedmann eq. it now follows that

$$n = \left(\frac{T}{2.7K} \right)^3 n_0$$

$$n = 5.70 \times 10^{20} \left(\frac{T}{10^9 K} \right)^3 \left(\Omega h^2 \right) cm^{-3}$$

Summing all relations yields:

$$\left(\frac{X_n X_p}{X_d}\right) = \exp\left(29.23 - 25.82/T_9 - \frac{3}{2}\ln T_9 - \ln(\Omega h^2)\right) \qquad T_9 = \frac{T}{10^9 K}$$

As the Universe expands and the temperature decreases the equilibrium shifts from n and p to D. This occurs at about T_9~1.

The transition temperature is not sensitive to the Universe parameters.

We find that at: $T_9 \cong 0.8$ $\qquad \frac{n}{n+p} \sim 0.12$

If all the neutrons react with protons then the Helium mass fraction is:

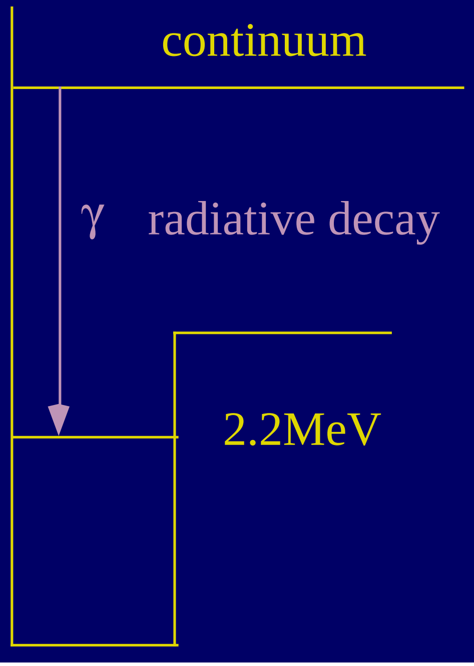
$$Y = \frac{2n}{n+p} \sim 0.24$$

This is the He abundance that results from equilibrium.

He formation takes place when the Universe is few minutes old. Since the life time of a free neutron is 11 minutes any delay in T or ρ would results in no He in the Universe!

If, for example, the parameters of the Universe are the same but the binding energy of Deterium would have been much smaller, the Deuterium would require a significantly lower T, or later time, and hence all n would have decayed leading to a Universe with only Hydrogen.

The Deuterium structure, only one bound state and no excited states. The depth of the potential is much deeper than the energy level.



As the temperature continues to decrease, the reaction moves out of equilibrium and a full rate equation is needed.

$$R = [n][p] < \sigma v >$$

At the relevant energies (~100KeV) $\sigma \propto \frac{1}{v}$

So that $\langle \sigma v \rangle = 4.55 \times 10^{-20} cm^3 / \sec$ independent of T

We find then $\eta = \langle \sigma v \rangle n^* t^* = 4000(\Omega h^2)$

where n* and t* are the density and the age of the Universe at that moment

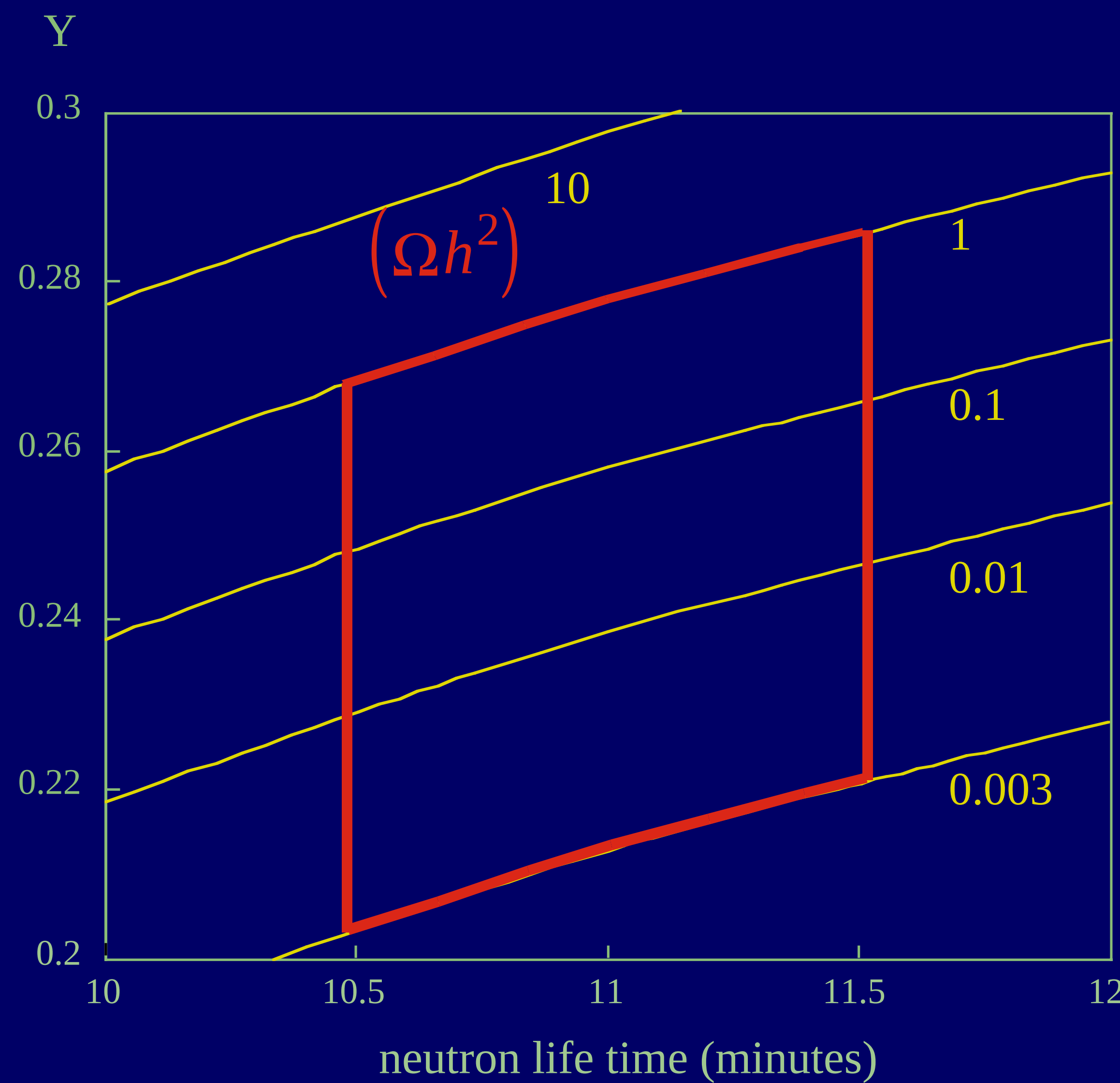
If η>>1 all neutrons form deuterium

If η<<1 the neutrons decay and leave only Hydrogen

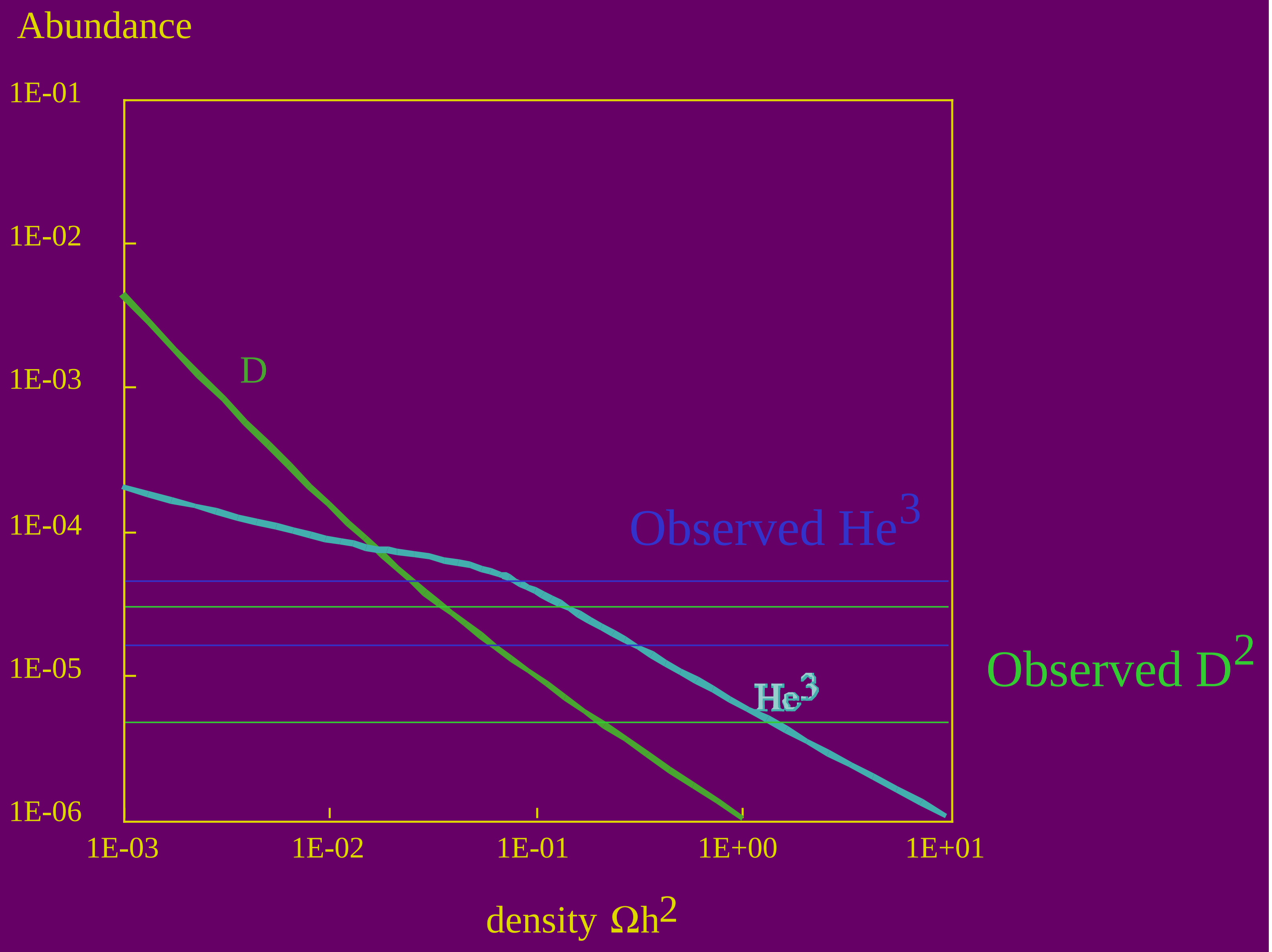
Observations of He

The amount of He^4 is not sensitive to the parameters of the hot BB model.

$Y = 0.25 \pm 0.03$



The amount of D^2 and He^3 is sensitive to the parameters of the Universe



The appearance of the primordial fire ball

The nuclear reactions end few minutes after the Big-Bang.

The period between the end of the nuclear reactions and until age of 300,000years is called the radiation era. This is the radiation that will become the 2.7K background radiation as seen today.

The density (and temperature) of matter are too low for nuclear reactions but sufficiently high for photon reactions. The mean free path of a photon is at this time much shorter than the distance to the horizon.

$$ct >> l_{photon} = \sigma_{photon}\rho$$

The Universe is opaque (and the matter in equilibrium with the radiation. $T_{matter}=T_{radiation}$

The decoupling of the radiation from the matter

The processes which cause the opacity of the matter are photon interactions with matter. For example, photo-ionization

$$H + \gamma \leftrightarrow H^{+} + e^{-}$$

absorption in atomic levels, and scattering by electrons.

In particular $\sigma_{photo\_ionization} >> \sigma_{Thomson}$

The abundance of Hydrogen due to photo-ionization in equilibrium between the radiation and the matter is given by the Saha eq. which in this case becomes:

$$\frac{x^2}{(1-x)} = \frac{(2\pi m_e kT)^{3/2}}{nh^3} e^{-157000/kT}$$

Hence, when the temperature decreases to about 6000K the Hydrogen becomes completely neutral and the cross section for photon absorption decreases extremely fast.

At this moment:

- The Universe becomes transparent. The photons cannot ionize the matter any more and they are free to move in the Universe.
- The matter ‘separates’ from the radiation. Each component cools separately.

What happens to the neutrinos?

Many neutrinos are released in the various nuclear reactions. As long as T and ρ are high they are in equilibrium with the matter. But at low density the neutrinos decouple from the matter and each component cools separately.

Today the energy of the meutrino is about 10^{-3} eV and there is no chance to discover these meutrinos in the foreseeable future.

If a neutrino mass will be discovered, than a significant fraction of the dark matter in the Universe must be in the form of neutrinos.

Mass and energy in the Universe

When the temperature is about 30,000K, the mass density equals to the radiation density.

From high T down to 30,000K the radiation density is higher than the matter density. The effective gravity of the radiation is higher than the gravitation due to mass.

When T decreases to below 30,000K the situation reverses and the matter gravity becomes more important.

Today:the density of energy in the radiation field $2\times10^{-13} erg/cm^3$

The equivalent mass density is: $2.2\times10^{34} erg/cm^3$

The Cosmic history

Cosmic time	Redshift	Era	Event
0	Infinite	Singularity	Big-Bang
10^{-43} second	10^{32}	Planck time	Particle creation
10^{-36} second	10^{28}	Inflation	
10^{-4} second	10^{12}	Hadronic Era	$p - \bar{p}$ annihilation
1 second	10^{10}	Leptonic era	$e^{-} - e^{+}$ annihilation
1 minute	10^{9}	Radiation Era	He &D formation-nucleosynthesis
1 week	10^{7}		radiation thermalizes
10,000 years	10^{4}	Matter era	Universe becomes matter dominated

Cosmic time	Redshift	Era	Event
300,000years	1000	Decoupling Era	Universe becomes transparent
1-2 billions	10-30		Galaxy formation begins
2 billion	5		Galaxy clustering begins
3 billion			Our proto galaxy collapses
3.1 billion			The first stars form
4 billion	3		Quasars are born; Pop II stars form
7 billion	1		Pop I stars form
10.2 billion			Our parent interstellar cloud forms
10.3 billion			Collapse of proto solar nebula
10.4 billion			Planets form;rock solidification
10.7 billion			Intense cratering of planets
11.1 billion		Archeozoic Era	Oldest terrestrial rocks

Cosmic time	Era	Event
12 billion		Microscopic life forms
13 billion	Proterozoic Era	Oxygen rich atmosphere forms
14 billion	Paleozoic Era	Macroscopic life forms
14.4 billion		Earliest fossil records
14.55 billion		Early land plants
14.6 billions		Fish
14.7 billion		Ferns
14.75 billion		Conifers;mountains formation
14.8 billion		Reptiles
14.85 billion		Dinosaurs;continental drift
14.95 billion		First mammals
15 billion		Homo sapiens


The end