

13 Lecture 13: History of the *Very* Early Universe

“The Universe is full of magical things, patiently waiting for our wits to grow sharper.”

Eden Phillpots

The Big Picture: Today we are going to outline the standard model of the Universe in the first few minutes following the hot Big Bang. These earliest epochs in the evolution of the Universe are still inadequately understood. As we move away from the Big Bang, our understanding of the physical epochs of the Universe becomes increasingly better understood.

Keeping Track of Universe’s History

The different times in the history of the Universe can be tracked by any of the several quantities which change monotonically throughout: age of the Universe t , scale factor a , redshift (as we observe it today) z and temperature of the CMB radiation T (currently measured at ≈ 2.7 K).

From eq. (205)

$$\rho_\gamma = \frac{\pi^2}{15} T_\gamma^4, \quad (257)$$

and the result derived from Friedmann’s second equation that the radiation scales as

$$\rho_\gamma \propto a^{-4}, \quad (258)$$

we obtain that

$$T_\gamma(a) \propto a^{-1}, \quad (259)$$

which, combined with the current measurement of the temperature of the CMB radiation

$$T_{\gamma 0} = T_\gamma(a = 1) \approx 2.7K, \quad (260)$$

yields

$$T_\gamma(a) \approx 2.7a^{-1}. \quad (261)$$

To relate this to the age of the Universe t , one can explicitly solve integrals for $a(t)$ and substitute in eq. (261).

The mutual relationship between the quantities t , z , a and T_γ is given in Table 5.

It is beneficial to relate directly — albeit crudely — the temperature T and the age of the Universe t . This can only be analytically only for matter-dominated or radiation-dominated Universe, as we have done in Lecture 5. (Relating the scale factor a and the age of the Universe t in a more general case when Universe has matter, radiation and the cosmological constant (as vacuum energy) requires solving the integral given in Table 5 for $t(a)$ and inverting it. This can only be done numerically). Therefore, as a rough approximation, let us recall:

1. flat, matter-dominated Universe [eq. (115)]: $a(t) = \left(\frac{3H_0}{2}\right)^{2/3} t^{2/3}$,
2. flat, radiation-dominated Universe [eq. (119)]: $a(t) = (2H_0)^{1/2} t^{1/2}$,

where

$$\begin{aligned} H_0 &= 100h \text{ km sec}^{-1}\text{Mpc}^{-1} = 100h \left(\frac{1000\text{m}}{1\text{km}}\right) \left(\frac{1\text{Mpc}}{3.0856 \times 10^{22}\text{m}}\right) \text{ km sec}^{-1}\text{Mpc}^{-1} \\ H_0 &\approx 3.24h \times 10^{-18}\text{sec}^{-1} \approx 2.3 \times 10^{-18}\text{sec}^{-1}, \end{aligned} \quad (262)$$

with $h \approx 0.72$. Therefore, for the two approximations, we have:

1. flat, matter-dominated Universe: $a(t) = 2.3 \times 10^{-12}t^{2/3}$,
2. flat, radiation-dominated Universe [eq. (119)]: $a(t) = 2.2 \times 10^{-10}t^{1/2}$.

When these are combined with the eq. (261), we obtain:

1. flat, matter-dominated Universe: $T_\gamma(t) \approx 10^{12}t^{-2/3}$ K,
2. flat, radiation-dominated Universe: $T_\gamma(t) \approx 10^{10}t^{-1/2}$ K.

To estimate the age of the Universe in Table 6, we use flat, matter-dominated Universe.

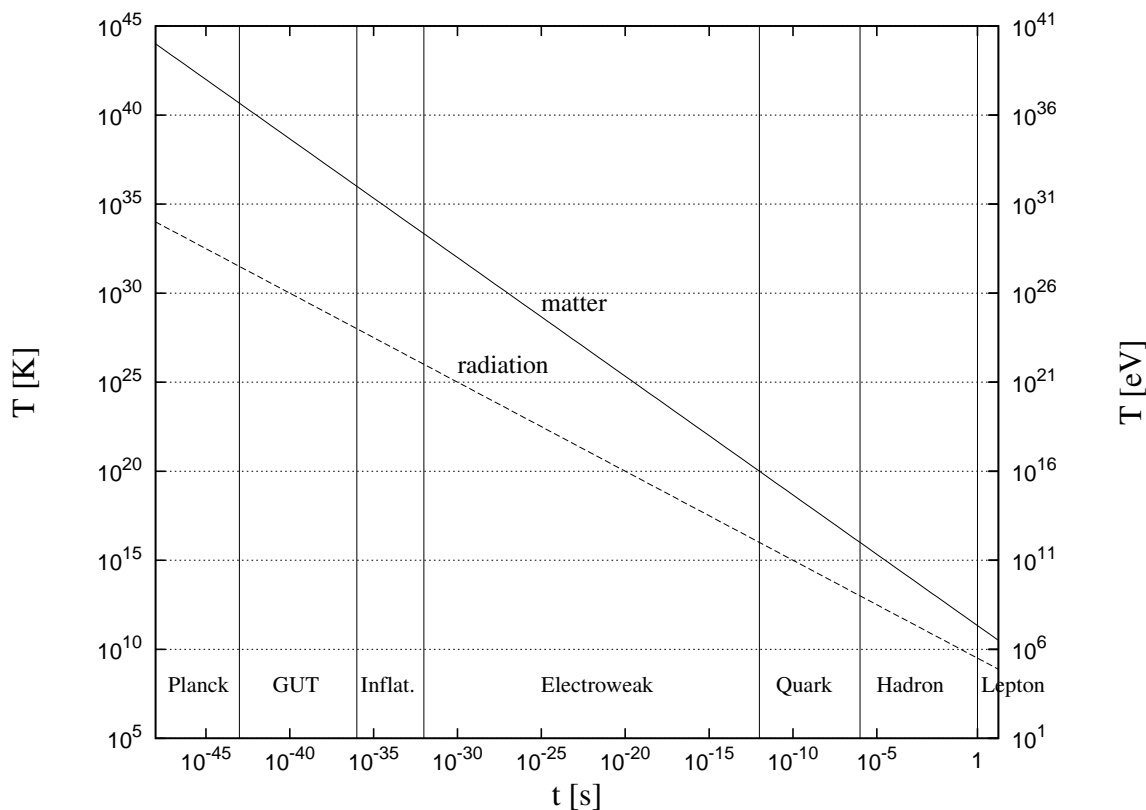


Figure 23: The temperature (given in both K and eV) of the Universe (T) versus the age of the Universe (t) based on matter-dominated (solid line) and radiation-dominated (dashed line) approximations. The epochs in the earliest history of the Universe are outlined. [We approximated $1 \text{ eV} \approx 10^4 \text{ K}$ ($=11605 \text{ K}$)].

Table 5: Relationship between the scale of the Universe (a), age of the Universe (t), redshift as observed from here today (z) and the temperature of the CMB radiation T_γ .

Quantity		Dependence on scale a	Dependence on redshift z
age	t	$t(a) = \frac{1}{H_0} \int_0^a \frac{\tilde{a} d\tilde{a}}{\sqrt{\Omega_{m0}\tilde{a} + \Omega_{r0} + \Omega_{de0}\tilde{a}^4}}$	$t(z) = \frac{1}{H_0} \int_z^\infty \frac{d\tilde{z}}{\sqrt{\Omega_{m0}(1+\tilde{z})^5 + \Omega_{r0}(1+\tilde{z})^6 + \Omega_{de0}(1+\tilde{z})^2}}$
redshift	z	$z(a) = \frac{1}{a} - 1$	-
scale	a	-	$a(z) = \frac{1}{1+z}$
temperature	T_γ	$T_\gamma(a) = 2.7a^{-1}$	$T_\gamma(z) = 2.7(z+1)$

The Big Bang: $t = 0$ s

Extrapolation of the expansion of the Universe backwards in time using general relativity yields an infinite density and temperature at a finite time in the past. This singularity signals the breakdown of GR. How closely we can extrapolate towards the singularity is debated — certainly not earlier than the Planck epoch. The early hot, dense phase is itself referred to as “the Big Bang”, and is considered the “birth” of our Universe — The Beginning.

The discussion about the nature, cause and origin of the Big Bang itself is untestable and as such quickly enters the waters of metaphysics and theology.

The Planck Epoch: $0 < t \leq 10^{-43}$ s

The Planck epoch is the earliest period of time in the history of the Universe, spanning the brief time immediately following the Big Bang during which the quantum effects of gravity were significant.

In order to compute the time-scale over which quantum effects dominate (barring the existence of branes which would circumvent them), we use dimensional analysis:

effects	constant	value	units
Relativity	c	3×10^{10}	$\frac{\text{cm}}{\text{s}}$
Quantum mechanics	h	6.63×10^{-27}	$\text{g} \frac{\text{cm}^2}{\text{s}}$
Gravitation	G	6.67×10^{-8}	$\frac{\text{cm}^3}{\text{gs}^2}$

We need to find the way to combine the constants above to obtain the the relevant time scale:

$$c^A h^B G^D = s,$$

$$\implies \left(\frac{\text{cm}}{\text{s}}\right)^A \left(\text{g} \frac{\text{cm}^2}{\text{s}}\right)^B \left(\frac{\text{cm}^3}{\text{gs}^2}\right)^D = s,$$

[cm] :	A	+2B	+3D	= 0
[g] :		+B	-D	= 0
[s] :	-A	-B	-2D	= 1

$$\text{Solution } A = -\frac{5}{2} \quad B = \frac{1}{2} \quad D = \frac{1}{2} \implies t_P = c^{\frac{5}{2}} h^{\frac{1}{2}} G^{\frac{1}{2}},$$

The time scale for quantum gravity, *the Planck time* t_P , is therefore

$$t_P \equiv \sqrt{\frac{hG}{c^5}}, \tag{263}$$

which numerically is equal to

$$t_P = \left[\frac{(6.63 \times 10^{-27})(6.67 \times 10^{-8})}{(3 \times 10^{10})^5} \right]^{1/2} \approx 10^{-43} \text{s}. \tag{264}$$

If the supersymmetry is correct, then during this time the four fundamental forces — electromagnetism, weak force, strong force and gravity — all have the same strength, so they are possibly unified into one fundamental force. Our understanding of this early epoch is still quite tenuous, awaiting a happy marriage of quantum mechanics and relativistic gravity.

Grand Unification Epoch: $10^{-43}\text{s} \leq t \leq 10^{-36}\text{s}$

Assuming the existence of a Grand Unification Theory (GUT), the Grand Unification Epoch was the period in the evolution of the early Universe following the Planck epoch, in which the temperature of the Universe was comparable to the characteristic temperatures of GUTs. If the grand unification energy is taken to be 10^{15} GeV, this corresponds to temperatures higher than 10^{27} K. During this period, three of the four fundamental interactions — electromagnetism, the strong interaction, and the weak interaction — were unified as the electronuclear force. Gravity had separated from the electronuclear force at the end of the Planck era. During the Grand Unification Epoch, physical characteristics such as mass, charge, flavor and color charge were meaningless.

The Grand Unification Epoch ended at approximately 10^{-36}s after the Big Bang. At this point, the strong force separated from the other fundamental forces.

Inflationary Epoch: $10^{-36}\text{s} \leq t \leq 10^{-32}\text{s}$

The Inflationary Epoch was the period in the evolution of the early Universe when, according to inflation theory, the Universe underwent an extremely rapid exponential expansion. This rapid expansion increased the linear dimensions of the early Universe by a factor of at least 10^{26} (and possibly a much larger factor), and so increased its volume by a factor of at least 10^{78} . At this time, the strong force started to separate from the electroweak interaction.

The expansion is thought to have been triggered by the phase transition that marked the end of the preceding Grand Unification Epoch at approximately 10^{-36}s after the Big Bang. One of the theoretical products of this phase transition was a scalar field called the inflation field. As this field settled into its lowest energy state throughout the Universe, it generated a repulsive force that led to a rapid expansion of the fabric of spacetime. This expansion explains various properties of the current Universe that are difficult to account for without the Inflationary Epoch (flat Universe, horizon problem, magnetic monopoles).

The rapid expansion of spacetime meant that elementary particles remaining from the Grand Unification Epoch were now distributed very thinly across the Universe. However, the huge potential energy of the inflation field was released at the end of the Inflationary Epoch, repopulating the universe with a dense, hot mixture of quarks, anti-quarks and gluons as it entered the Electroweak Epoch.

Electroweak Epoch: $10^{-32}\text{s} \leq t \leq 10^{-12}\text{s}$

The Electroweak Epoch was the period in the evolution of the early Universe when the temperature of the Universe was high enough to merge electromagnetism and the weak interaction into a single electroweak interaction ($\approx 100\text{GeV} \approx 10^{15}\text{K}$). At approximately 10^{-32}s after the Big Bang the potential energy of the inflation field that had driven the inflation of the Universe during the Inflationary Epoch was released, filling the Universe with a dense, hot quark-gluon plasma (*reheating*). Particle interactions in this phase were energetic enough to create large numbers of exotic particles, including W and Z bosons and Higgs bosons. As the Universe expanded and cooled, interactions became less energetic and when the Universe was about 10^{-12}s old, W and Z bosons ceased to be created. The remaining W and Z bosons decayed quickly, and the weak interaction became a short-range force in the following Quark Epoch.

After the Inflationary Epoch, the physics of the Electroweak Epoch is less speculative and better understood than for previous periods of the early Universe. The existence of W and Z bosons has been demonstrated, and other predictions of electroweak theory have been experimentally verified.

Quark Epoch: $10^{-12}\text{s} \leq t \leq 10^{-6}\text{s}$

The Quark Epoch was the period in the evolution of the early Universe when the fundamental interactions of gravitation, electromagnetism, the strong interaction and the weak interaction had taken their present forms, but the temperature of the Universe was still too high to allow quarks to bind together to form hadrons. The Quark Epoch began approximately 10^{-12}s after the Big Bang, when the preceding Electroweak Epoch ended as the electroweak interaction separated into the weak interaction and electromagnetism. During the Quark Epoch the Universe was filled with a dense, hot quark-gluon plasma, containing quarks, gluons and leptons. Collisions between particles were too energetic to allow quarks to combine into mesons or baryons. The Quark Epoch ended when the Universe was about 10^{-6}s old, when the average energy of particle interactions had fallen below the binding energy of hadrons. The following period, when quarks became confined within hadrons, is known as the Hadron Epoch.

Hadron Epoch: $10^{-6}\text{s} \leq t \leq 1\text{ s}$

The Hadron Epoch was the period in the evolution of the early Universe during which the mass of the Universe was dominated by hadrons. It started approximately 10^{-6}s after the Big Bang, when the temperature of the Universe had fallen sufficiently to allow the quarks from the preceding Quark Epoch to bind together into hadrons. Initially, the temperature was high enough to allow the creation of hadron/anti-hadron pairs, which kept matter and anti-matter in thermal equilibrium. However, as the temperature of the Universe continued to fall, hadron/anti-hadron pairs were no longer produced. Most of the hadrons and anti-hadrons were then eliminated in annihilation reactions, leaving a small residue of hadrons. The elimination of anti-hadrons was completed by one second after the Big Bang, when the following Lepton Epoch began.

Lepton Epoch: $1\text{ s} \leq t \leq 3\text{ min}$

From the time t_P of quantum gravity up to the lepton era, the physics of the Universe is dominated by *very high* temperatures ($> 10^{12}\text{ K}$) and therefore by high-energy particle physics.

• **Muon annihilation:**

At sufficiently high temperatures, there is a *pair production*:

$$\begin{aligned} \gamma + \gamma &\rightarrow \mu^+ + \mu^-, \\ \Rightarrow \text{photon energy} &\rightarrow \text{muon mass.} \end{aligned} \quad (265)$$

This can persist only as long as $kT \approx 2m_\mu c^2$:

$$T \geq \frac{2m_\mu c^2}{k} = \frac{2(200m_e)c^2}{k} = \frac{2(2009.1 \times 10^{-28})(3 \times 10^{10})^2}{1.38 \times 10^{-16}} = 2 \times 10^{12}\text{K}. \quad (266)$$

Therefore, *muons annihilate at* $T \approx 10^{12}\text{K}$.

• **Electron/positron annihilation:**

The argument used for muon annihilation applies to electron-positron pair production

$$T \geq \frac{2m_e c^2}{k} \approx 10^{10}\text{K}, \quad (267)$$

so, *electrons and positrons annihilate at* $T \approx 10^{10}\text{K}$.

• **Decoupling of electron neutrinos:**

Assuming the matter-dominated Universe, we crudely estimate electron number density:

$$\begin{aligned} \rho &= \rho_0 \left(\frac{a_0}{a}\right)^3 = \frac{\rho_0}{(2.3 \times 10^{-12} t^{2/3})^3} \approx \frac{10^{-29}}{10^{-35} t^2} = 10^6 t^{-2}, \\ n_e &= \frac{\rho}{m_e} \approx \frac{10^6 t^{-2}}{9.1 \times 10^{-28}} \approx \frac{10^{33}}{t^2}. \end{aligned} \tag{268}$$

The neutrino scattering cross-section is $\sigma_\nu \approx 10^{-44} \text{cm}^2$, so the time between scatterings is

$$t_\nu \approx \frac{1}{n_e \sigma_\nu c}. \tag{269}$$

Scatterings will become “scarce” when

$$t_\nu \approx \frac{1}{\frac{10^{33}}{t_\nu^2} \sigma_\nu c} = 10^{33} \sigma_\nu c = (10^{33}) (10^{-44}) (3 \times 10^{10}) \approx 0.3 \text{ s}. \tag{270}$$

Therefore, *electron neutrinos decouple from the Universe* at about $t \approx 1 \text{ s}$.

Table 6: Early history of the Big Bang Universe, up to the Big Bang Nucleosynthesis. Temperature estimates are based on the crude matter-dominated Universe approximation: $T(t) \approx 10^{12} t^{-2/3} \text{ K}$.

Epoch	Temperature	Characteristics
Big Bang 0 s	$\infty \text{ K}$ $\infty \text{ eV}$	singularity (vacuum fluctuation?)
Planck $0 \text{ s} < t \leq 10^{-43} \text{ s}$	$> 10^{40} \text{ K}$ $> 10^{36} \text{ eV}$	quantum gravity
Grand Unification $10^{-43} \text{ s} \leq t \leq 10^{-36} \text{ s}$	$10^{36} - 10^{40} \text{ K}$ $10^{26} - 10^{32} \text{ eV}$	gravity freezes out the “grand unified force” (GUT)
Inflationary $10^{-36} \text{ s} \leq t \leq 10^{-32} \text{ s}$	$10^{33} - 10^{36} \text{ K}$ $10^{29} - 10^{32} \text{ eV}$	inflation begins strong force freezes out
Electroweak $10^{-32} \text{ s} \leq t \leq 10^{-12} \text{ s}$	$10^{20} - 10^{33} \text{ K}$ $10^{16} - 10^{29} \text{ eV}$	weak force freezes out 4 distinct forces (EM dominates) baryogenesis: baryons and antibaryons annihilate
Quark $10^{-12} \text{ s} \leq t \leq 10^{-6} \text{ s}$	$10^{16} - 10^{20} \text{ K}$ $10^{12} - 10^{16} \text{ eV}$	Universe contains hot quark-gluon plasma: quarks, gluons and leptons
Hadron $10^{-6} \text{ s} \leq t \leq 1 \text{ s}$	$10^{12} - 10^{16} \text{ K}$ $10^8 - 10^{12} \text{ eV}$	quarks and gluons bind into hadrons
Lepton $1 \text{ s} \leq t \leq 3 \text{ min}$	$10^{10} - 10^{12} \text{ K}$ $10^6 - 10^8 \text{ eV}$	Universe contains photons (γ), muons (μ^\pm), electrons/positrons (e^\pm), and neutrinos ($\nu, \bar{\nu}$); nucleons n and p in equal numbers
1 s	$\leq 10^{12} \text{ K}$ $\leq 10^8 \text{ eV}$	μ^+ and μ^- annihilate; ν and $\bar{\nu}$ decouple; e^\pm, γ and nucleons remain. Reactions: $e^+ + n \rightleftharpoons p + \nu_e$ $e^- + p \rightleftharpoons n + \nu_e$ $n \rightarrow p + e^- + \bar{\nu}_e$
100 s	$10^{10} \text{ K}, 10^6 \text{ eV}$	e^+ and e^- annihilate