Lecture 13. The Early Universe

13.0. Review relevant results from earlier in the course

13.1. The Universe as a Particle Physics laboratory

To test theories of fundamental particle physics, there is continuing effort to build accelerators capable of accelerating particles to ever higher energies. The new generation of particle accelerators, such as the LHC, is able to reach energies of several hundred GeV or even TeV. The thermal energies of particles immediately after the Big Bang were much higher, and thus the early Universe can be exploited to study physics at much higher energies.

The typical thermal energy of a particle in *relativistic* plasma of temperature T is $3kT$ where k is the Boltzmann constant), and is related to the energy units used in particle physics by

$$\frac{T}{K} = \left(\frac{E}{\mathrm{GeV}}\right) \frac{10^9 \times (1.6 \times 10^{-19})}{3 \times (1.38 \times 10^{-23})} \quad \rightarrow \quad T = \left(\frac{E}{\mathrm{GeV}}\right) 3.9 \times 10^{12}\ \mathrm{K}. \tag{1}$$

The total thermal energy density of the plasma depends on the number of species of relativistic particles present,

$$\rho_{\rm rel} c^2 = \frac{g_*(T)}{2} \frac{4\sigma T^4}{c}. \tag{2}$$

Here σ is the Stefan constant and $g_*(T)$ counts the **number of effective bosonic degrees of freedom**,

$$g_*(T) = \sum_{\rm bosons} g_{\rm boson} + \frac{7}{8} \sum_{\rm fermions} g_{\rm fermion}, \tag{3}$$

where the sum extends over all species of bosons and fermions that have rest mass $mc^2 \ll 3kT$ and so are (ultra-)relativistic. For photons $g_{\rm boson} = 2$ as they come in two discrete polarisation states. For electrons and positrons $g_{\rm fermion} = 2$ as they come in two spin states. For neutrinos and anti-neutrinos $g_{\rm fermion} = 1$, since only left-handed neutrino and right-handed anti-neutrino exist in the Standard Model. The factor of 7/8 arises from the difference between the Bose-Einstein and Fermi-Dirac energy distributions.

13.2. The Standard Model

In the **Standard Model** of Particle Physics, in addition to the familiar u and d quarks, electrons and neutrinos there are two more generations of particles.

Quarks				**Leptons**			
Symbol	Mass GeV/c^2	Symbol	Mass GeV/c^2	Symbol	Mass eV/c^2	Symbol	Mass MeV/c^2
u	0.002	d	0.005	ν_e	≈ 0	e	0.511
c	1.3	s	0.1	ν_μ	≈ 0	μ	106
t	173	b	4.2	ν_τ	≈ 0	τ	1777

1) These are *all* spin-1/2 fermions.

2) There is an anti-particle for each of these particle, e.g., e^+ (positron) and $\bar{\nu}_e$ (anti-electron neutrino).

In addition, there are the boson particles that mediate each of the four forces:

• The photon, γ, which mediates the electromagnetic (EM) force.

• The $W^{\pm}$ and Z^0 bosons, which mediate the weak interactions ($M_{W^{\pm}} = 80.6\,\mathrm{GeV}/c^2$ and $M_{Z^0} = 91.2\,\mathrm{GeV}/c^2$).

• The gluons which mediate the strong nuclear force. Gluons are massless.

• The Standard Model does not include gravity. Other theories consider gravity as mediated by gravitons, which are massless spin-2 particles.

Finally, we have the Higgs boson, which is often called the God particle, because it is believed to give masses to most massive fundamental particles. The Higgs particle has a mass of about 125 Gev/c^2. Its discovery at CERN won the 2013 Nobel Prize of Physics for the theorists who first hypothesised its existence.

The *quark-hadron phase transition*, a.k.a. Quantum Chromodynamics (QCD) phase transition, happens when the energy is ~200MeV. The strong interaction has a property known as the asymptotic freedom: when quarks are very close to each other, they interact weakly, while their interaction becomes stronger as they move further apart. At early times (when $kT > 200$ MeV), quarks are so close to each other that they are free, and form a quark-gluon plasma. At lower energies, quarks tend to become less dense, however the increasingly stronger interaction stops them from getting farther than the typical proton size from each other. Instead, they are confined to form *hadrons*, including *baryons* (such as protons and neutrons), which contain three quarks, and *mesons* (e.g., pions), which contain a quark-antiquark pair. This is known as *colour confinement*.

The EM and Weak interactions in the Standard Model are unified in the sense that at energies much greater than the masses of the $W^{\pm}$ and Z^0 the two forces have the same strength. The theory is said to have a *hidden symmetry*, i.e., the EM and weak interactions would be totally symmetric were it not for the fact that something has given $W^{\pm}$ and Z^0 mass, and broken this symmetry.

13.3 Beyond the Standard Model

At laboratory energies, the coupling constant of QCD is much greater than that for the EM and weak interactions. However, each has a slow dependence on energy. By extrapolation, it has been predicted that all three will become equal at an energy $E > 10^{15}$ GeV ($T > 10^{28}$ K). Above this energy, it is expected that all three forces are symmetric and are aspects of some **Grand Unified Theory** (GUT).

The most popular GUTs involve the idea of **supersymmetry**. In supersymmetric models, every fermion of the Standard Model has a boson supersymmetric partner, and every boson has a fermion supersymmetric partner. These hypothetical particles are presumed much more massive than their more familiar partners which explains why they take no part in low energy particle interactions. The supersymmetric partners of the fermions are named by prefixing the corresponding fermions with an "*s*", while the supersymmetric partners of the bosons are named by appending "*ino*" to the corresponding bosons.

Examples

Leptons → Sleptons
Quarks → Squarks

Photon → Photino
Higgs → Higgsino
Graviton → Gravitino
W → Wino

13.4 Quantum Gravity

There is no fully consistent quantum theory of gravity yet. But we could estimate the energy scale at which quantum gravity effects will become important.

Consider the dimensionless combination

$$\alpha_{\rm G} = GM^2/\hbar c,$$

which is formed from the gravitation constant, G, some fundamental mass, M, (perhaps the mass of a proton), and the fundamental constants of quantum mechanics ($\hbar$) and relativity (c). If we plug in the proton mass, we find this number is tiny

$$\alpha_{\rm G} = 5.9 \times 10^{-39},$$

which is why quantum gravitational effects are completely negligible at laboratory energies.

However at high (relativistic) energies it is appropriate to replace M using $E = Mc^2$. Then

$$\alpha_{\rm G} = GE^2/\hbar c^5$$

and $\alpha_{\rm G} = 1$ when $E = E_{\rm planck}$ which is defined by

$$E_{\rm planck} \equiv \left(\frac{\hbar c^5}{G}\right)^{1/2} = 1.22 \times 10^{19}\ {\rm GeV} \qquad (\textbf{The Planck Energy}). \tag{4}$$

At the Planck energy and above, quantum gravitational effects become important. We don't yet have any theory to describe this regime.

13.5. The thermal history of the Universe

We have seen that at high redshift the temperature of the universe was higher

$$T \propto (1+z). \tag{5}$$

Hence, the typical thermal energy of particles increases as we go back to very early times in the universe. As the universe cools down, the physical processes that operate change, and it goes through several distinct eras. See Figures 1 and 2 for a sketch of the descriptive text.

Planck Era: At $T > 10^{32}$K (the Planck temperature) gravitational interactions operate on the same scale as the other fundamental forces. General Relativity is not a good description

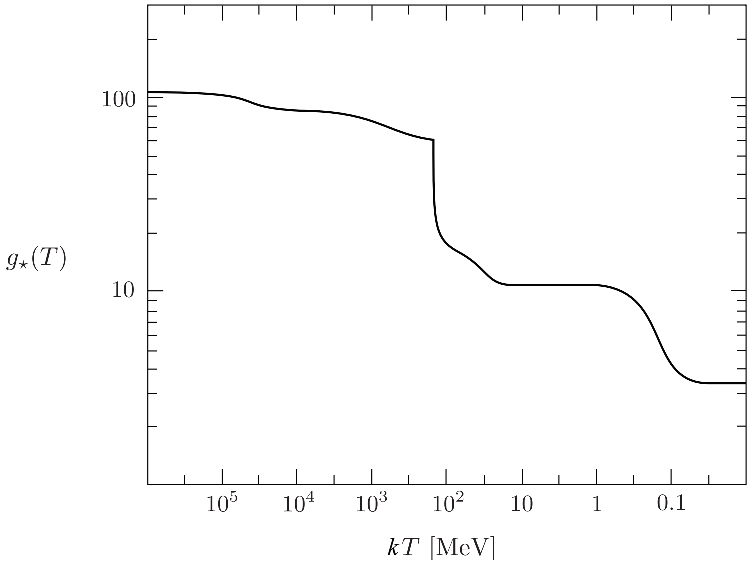

Figure 1: The dependence of $g_*(T)$ as a function of the quantity kT (result from exact calculation according to the standard model of particle physics).

of gravity anymore, and one needs a theory of **quantum gravity**. Currently nothing can be calculated about the detailed behaviour of the universe at this stage.

Quark Era: ($10^{32} > T > 10^{12}$K) Gravity can now be described by GR. The universe is full of quarks (of all flavours) and leptons. Above 10^{28}K, a GUT is needed to explain the quark and lepton interactions as weak, strong and EM forces are unified. The process of **baryogenesis** probably occurs around 10^{28}K, and a very small excess of quarks over anti-quarks (3 parts in 10^9) is established. Also at $\sim 10^{28}$K, the universe undergoes the GUT phase transition and the electroweak force becomes separated from the strong force of QCD. At 10^{12}K, the quark hadron phase transition is believed to occur when colour confinement becomes dominant and quarks are bound into baryons, anti-baryons and mesons of all energetically possible varieties.

Lepton Era: ($10^{12} > T > 10^{10}$K) The universe is now a plasma of free $e^{\pm}$, n, p, γ, ν, and , all strongly coupled by weak and EM interactions and thus in good thermodynamic equilibrium. Late in this era, the neutrinos decouple, but the remaining particles remain strongly coupled by the EM interaction.

Photon Dominated Era: ($10^{10} > T > 16,500$K) This begins with electrons and positrons annihilating ($T < 1$ MeV$/c^2$ needed for this) to produce more photons and so injecting energy into the photon background, but not the decoupled neutrino background. This annihilation gives rise to the factor $(4/11)^{4/3}$ in the formula for the energy density in relativistic particles. Between 10^{10}K and 10^9K, nuclear synthesis of light elements occurs (see next lecture).

Matter Dominated Era: ($16,500 > T > 3$K) This era begins when the energy density in matter first exceeds that in relativistic particles (such as photons). It results in a change in

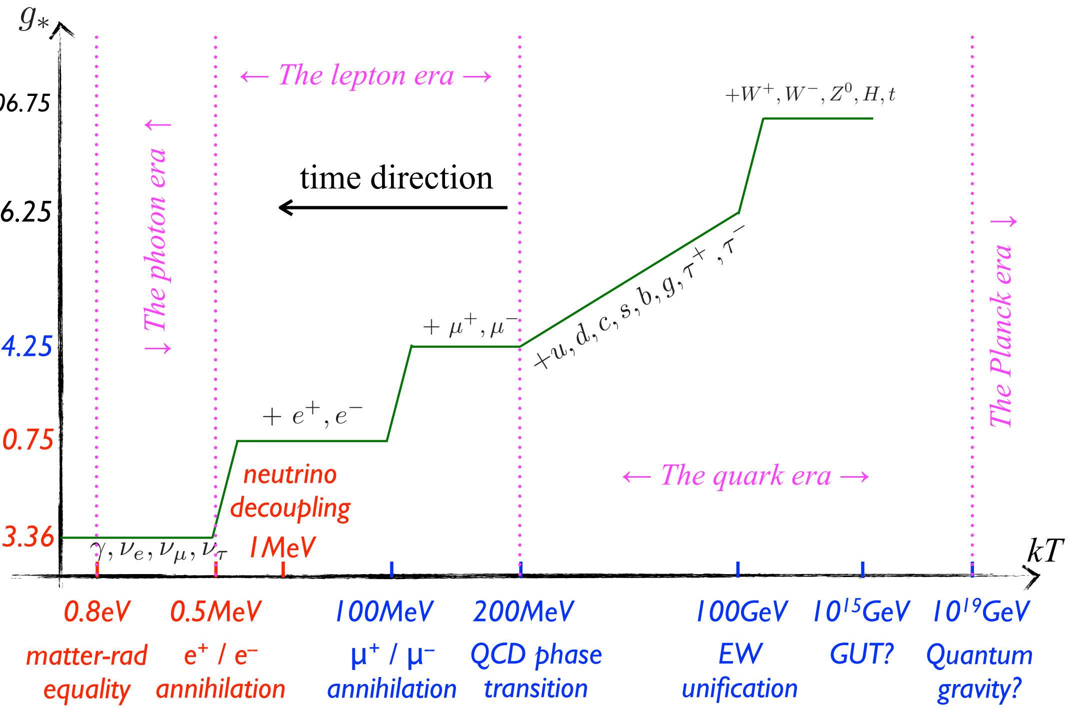

Figure 2: A simplified cartoon version of Figure 1 with the key sub-eras of the radiation-dominated era and the key events in the early Universe marked.

the expansion law of the universe, as we have learned in Lecture 8. At $T \approx 3000$K atoms form and the photon background decouples from the now neutral matter. The photon background simply adiabatic cools to form the CMB. The matter begins to clump and start forming the rich structure observed in the present day universe.

Baryogenesis:

The universe does not contain large amounts of anti-matter. The baryon-to-photon ratio today is estimated to be

$$\frac{n_B}{n_\gamma} \approx 10^{-9} \tag{6}$$

At early times ($T > 10^{15}$K) the thermal equilibrium generates about the same number of q-q̄ pairs as photons, and hence we conclude that at this points there must be an excess of quarks over anti-quarks of about 3 parts in 10^9.

GUT can give rise to mechanisms of generating this excess of quarks, but research so far is still inconclusive.

Key Takeaway Points of Lecture 13

• The energy density in the *radiation-dominated era* can be written as

$$\rho_{\rm rel} c^2 = \frac{g_*(T)}{2} \frac{4\sigma T^4}{c},$$

where $g_*(T)$ is the *number of effective bosonic degrees of freedom*,

$$g_*(T) = \sum_{\rm bosons} g_{\rm boson} + \frac{7}{8} \sum_{\rm fermions} g_{\rm fermion},$$

and accounts for contributions from all *relativistic* fundamental particle species.

• Therefore, knowing the relativistic species, one can calculate the expansion rate $H(a)$ in the radiation-dominated era using the Friedmann equation, and consequently the time or the age of Universe, $t = 1/(2H)$, at a given temperature T.

• This is possible given the Standard Model of Particle Physics, which describes the fundamental particles and three (out of the four) fundamental forces through which they interact with each other.

• Depending on which particle species dominates the energy density, the radiation-dominated era can be divided into (from early to late times) four sub-eras – Planck era, quark era, lepton era and photon era. Some key events of each sub-era are described.

Lecture 13 Examples

13.1 At the end of the quark era, the temperature of the Universe is $T \sim 10^{12}$ K, and the energy density of the relativistic plasma is

$$\epsilon = \frac{g_*}{2}\frac{4\sigma T^4}{c}.$$

Assuming that the effective number of bosonic degrees of freedom, g_*, is 100, estimate the age of the Universe at this time.

13.2 A universe contains three species of active neutrinos all with zero mass, which decoupled from other matter species when the photon temperature T_γ was given by $kT_\gamma = 1$ MeV. The annihilation of electrons and positrons happened when $kT_\gamma = 0.5$ MeV, and the annihilation of other particles all happened at $kT_\gamma \gg 2$ MeV. At the present day, the temperatures of photons and neutrinos (T_ν) satisfy $T_\nu = (4/11)^{1/3} T_\gamma$.

Assume instantaneous neutrino decoupling and e^--e^+ annihilation, find the ratio of T_ν/T_γ at the following values of T_γ: (i) $kT_\gamma = 0.3$ MeV, (ii) $kT_\gamma = 0.8$ MeV, (iii) $kT_\gamma = 1.2$ MeV.