Hot Big Bang model: early Universe and history of matter

Initial „soup“ with elementary particles and radiation in thermal equilibrium.
Radiation dominated era (recall energy density grows faster than matter density going back in time (~ a^{-4} rather than a^{-3}).
Thermal equilbrium maintained by electroweak interactions between individual particle species and between them and radiation field --- interaction rate **Γ=*n*<vσ>,** where ***n*** is the number density of a type of particles, **σ** the cross section and **v** the relative velocity (**σ** depends on **v** in general).

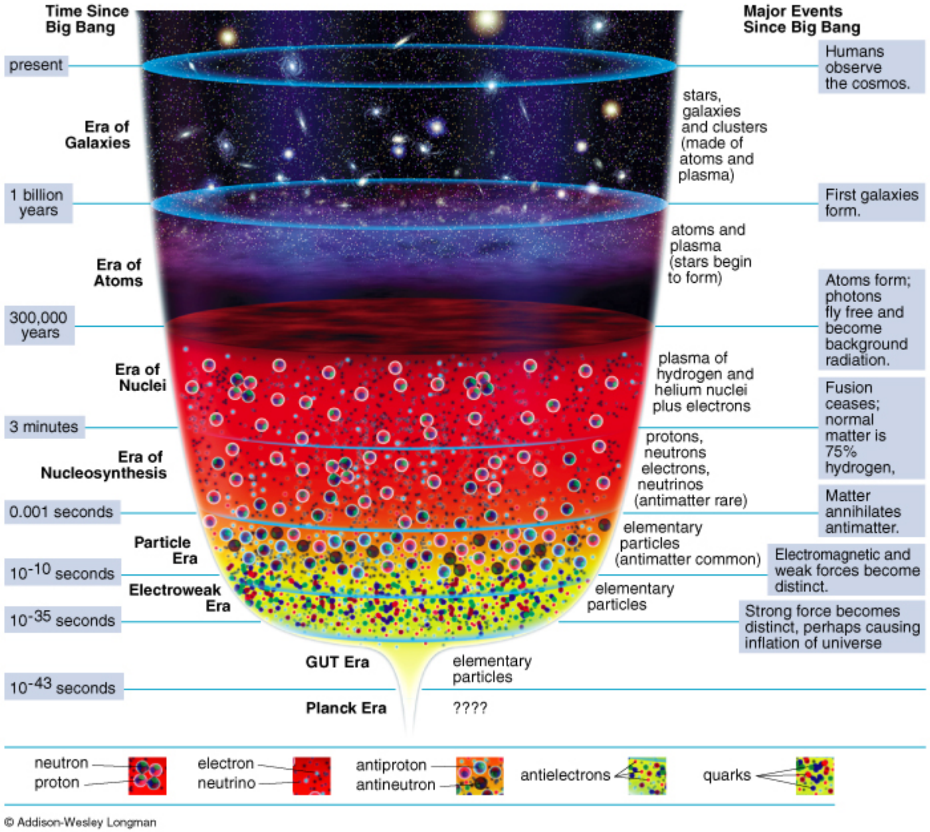
Key concepts:

(1) At any given time particles can be created if their rest mass energy is such that $k_BT >> mc^2$, where T is the temperature of radiation. As the Universe expands T ~ a^{-1} (radiation dominated) so only increasingly lighter particles can be created.
Important example: *pair production from $\gamma + \gamma$ < - -> e- + e+ (requires T > 5.8 x 10^9 K), which Immediately thermalize with electrons via Compton scattering and produce electronic neutrinos via e- + e+ < --> $\nu_e + \bar{\nu}_e$, also in thermal equilibrium with radiation.*
(2) As the Universe expands Γ decreases because *n* and v decrease -→ when Γ < H(t) particle species decouples from photon fluid and *n* „freezes-out“ to the value at first decoupling(subsequently diluted only by expansion of Universe if particle stable).
Present-day elementary particles are „thermal relics“ that have decoupled from photon fluid at different times, some when they were still *relativistic* („hot relics“, $k_BT >> mc^2$, T is temperature of radiation field), some when they were *non-relativistic* ($k_BT << mc^2$,“cold relics“)

In the early Universe the very high temperatures ($T \sim 10^{10}$ K a $t \sim 1$ s) guarantee that all elementary particles are relativistic and in thermal equilibrium with radiation.
The relation between temperature (or energy $E=k_B T$) and time is thus that for
a radiation dominated Universe ($T \sim 1+z$, $t \sim (1 + z)^{-2}$)
In the natural system of units $c = k_B = h/2\pi =1$, one also has the following dimensional relations:

$$[\text{energy}] = [\text{mass}] = [\text{temperature}] = [\text{time}]^{-1} = [\text{length}]^{-1}$$

with the following conversion factors into physical units: 1 MeV = 1.16×10^{10} K = 1.783×10^{-27} g $=5.068 \times 10^{10}$ cm^{-1},, $t \sim$ 10 s



When the Universe was at $t < 10^{-6}$ s it means E >~ 1 GeV (~ 10^{13} K). With LHC we have probed up to 7-8 TeV, now going to 13 TeV after restart (<< E_{gut} ~ 10^{13} Tev)

Various symmetry-breaking phases that decoupled the different interactions (electromagnetic, weak, strong and gravitational) as we know them today. Various theories involve scalar fields and exotic particles (including dark matter candidates) to explain the source and outcome of symmetry breaking.
In order: first GUT transition (strong interaction separates from electroweak one), then electroweak transition (electromagnetic forces and weak forces separate, Higgs boson!).

Before GUT era:

Planck era, defined by smallest possible physical timescale which we can
Probe without a quanum theory of gravity:

Planck time : $(h/2\pi * G/c^5)^{1/2}$

Planck Energy ~ 10^{16} TeV

It is the timescale implied in the natural system of units based on the fundamental constants of nature.

It is obvious that here gravity (G) matters at least as much as quantum processes (h/2p) since they appear with the same powers in the definition of the Planck time ----> (1) need quantum theory of gravity to describe physics at beyond the Planck time as (2) gravity and strong+electroweak forces likely unified at Planck time

Between GUT and Electroweak epoch (10^{-35} s to 10^{-24} s)

(1) Inflation – a phase of rapid exponential expansion caused by the decay of a scalar field. Required to explain flatness of primordial Universe and causality/horizon problem (will see later in course). In some models electroweak phase transition connected with dissipation of energy of scalar field (inflaton) that gives rise to inflation.

(2)Baryogenesis
Pair production reactions imply same amount of particles and antiparticles. However today baryons (three quarks) constitute most of ordinary matter (protons, neutrons), hence much more abundant than antibaryons (otherwise frequent annihilation into photons would produce cosmic gamma ray background much stronger than observed)
--→ *baryon/antibaryon asymmetry*

Baryonic asymmetry parameter $\boldsymbol{\eta = (n_B - n_{\bar{B}} / n\gamma) \sim n_B / n\gamma \sim 10^{-9}}$

Necessary (1) to postulate non-conservation of baryon number (**B = 1/3 (n_q – n_q-)**, n_q and n_q- numbers of quarks and antiquarks, B=1 for baryons) in reactions between particles in early Universe. Admitted by standard model of particle physics (via quantum tunneling).
Also (2) need (large) violation of other symmetries (CP or C) to create (large) asymmetry. Likely requires going beyond standard model (insufficient CP violation). Alternatively, asymmetry has to be already in the initial conditions (fine tuning), but then dilution by inflation!

Note: thermal non-equilibrium to preserve asymmetry (othwerwise annihilation of photons re-introduces symmetry, but this ok in first-order phase transition (eg electroweak)

Particle Era

After Electroweak transition all known elementary particles of Standard Model have been produced. Bosons (W+, W-, Z0, Higgs) cannot be created anymore due to decreased thermal energy of the Universe (T ~ 1/a) plus those created earlier have already decayed.

At $t < 10^{-6}$ s, $E < 1$ GeV, the Universe is thus made of free quarks (not bound into hadrons), leptons and photons in thermal equilbrium.

The following events take place from this point onwards, leading ultimately to the creation of ordinary nuclei and atoms...

1 - Quark-hadron transition, at T ~ 3 x 10^{12} K (t ~ 10^{-5} s). *Energy becomes low enough for quarks to be confined into hadrons.* Once transition complete Universe is filled with pions, protons and neutrons (already non-relativistic), charged leptons (electrons, muons) and their associated neutrinos, all in thermal equilibrium with photons. Tau-neutrinos are already decoupled, previously coupled via electroweak Reactions with tau leptons, and possibly via exotic particles making dark matter.

2. Nucleons era, at T ~ 10^{12} K, t ~ 10^{-4} s. Starts after pions π+ and π- annihilate and π0 decay into photons ---> nucleons become only hadronic particles left.

3. Neutron-Proton asymmetry. As T <~ 10^{11} K neutrons, which are more massive than protons, are produced less efficiently by exp(-Δm/t), where Δm ~ 1.3eV is the mass difference between neutrons and protons. The asymmetry grows until the reaction rates involving proton and neutrons (eg electron/neutrino capture) become negligible After further expansion of the Universe ---> *relative abundance will eventually freeze out*

4. Annihilation of e, e+ pairs and decoupling of neutrinos.
Annihilation becomes predominant over their creation by γ photons as T ~ 5 x 10^9 K (t ~ 4s).Causes decoupling of electron neutrinos, which were kept in thermal equilibrium with the photons via weak reactions with free electrons -→ *neutrino background produced* Since neutrinos and electrons involved in all equilibrium reactions between neutrons and protons **n/p** freezes out (to ~ 1/10). β decay of neutrons does not affect **n/p** because half-time of the decay ~ 10 minutes > 1/H(t) at this stage of the Universe

5. Nucleosynthesis starts. At T ~ 10^9 K (t ~ a few minutes) protons and neutrons begin to synthesize D, He and a few other elements, but products still ionized because T still too high for stable neutral atomic phase (electrons have excess kinetic energy).
So Universe is now plasma of highly ionized atoms (mainly protons and He++), electrons, photons, all in thermal equilibrium, and the decoupled neutrino background.

6. Recombination era. At T ~ 4000 K (t > 10^5 yr), 50% of baryonic matter is in the form of neutral atoms. Because this means the number of free electrons has dropped consistently the Universe becomes transparent to photons (Compton scattering by electrons negligible). These photons that decouple from matter become the CMB radiation (surface of last-scattering at t ~ 300.000 years).
→ ***Matter-Radiation decoupling***
Note this is different from **radiation-matter equivalence** ($\rho_r = \rho_m$), which happens earlier at z ~ 2 x 10^4

Most of the particles, especially atoms, are now non-relativistic because T had decreased substantially due to the expansion, and their total energy density is higher than the sum of radiation and relativistic particles (should also apply to dark matter)
-→ ***beginning of Matter Dominated Era.***