Sterrewacht Leiden

Origins & Evolution of the Universe

an introduction to cosmology – Fall 2014

Did you register for the exam?

The lepton era

At $T \approx 200$-300 MeV the quark-hadron transition binds quarks into hadrons

- protons/neutrons made of 3 u,d quarks
- mesons in particular π^+, π^0, π^-

In this hadron era pion-pion reactions are very important and the equation-of-state of the hadron fluid is very complicated.

Once the pions disappear (≈10μs after the Big Bang) the lepton era starts. It lasts until the e^+e^- pairs annihilate (≈1s after the Big Bang)

The lepton era

At the start of the lepton era the Universe comprises

- photons
- small excess of non-relativistic baryons
- leptons & anti-leptons

$e^+ \, e^- \, \nu_e \, \bar{\nu}_e$

$\mu^+ \, \mu^- \, \nu_\mu \, \bar{\nu}_\mu$

$\tau^+ \, \tau^- \, \nu_\tau \, \bar{\nu}_\tau$ most likely already annihilated, but neutrinos remain

Statistical equilibrium distributions

A relativistic particle species in thermal equilibrium follows a Fermi-Direct(+) or Bose-Einstein(-) distribution:

$$n(T) = \int_0^\infty \frac{g}{2\pi^2\hbar^3c^3}\frac{E^2dE}{e^{E/k_BT} \pm 1} \simeq 0.1216 \binom{3/4}{1} g \left(\frac{k_BT}{\hbar c}\right)^3$$

The energy density is given by:

$$\rho(T)c^2 = \int_0^\infty \frac{g}{2\pi^2\hbar^3c^3}\frac{E^3dE}{e^{E/k_BT} \pm 1} = \binom{7/8}{1} \frac{g}{2}\sigma_r T^4$$

The total energy density $\rho(T)c^2=(g^*\sigma_r/2)T^4$.

Entropy conservation

Important events during the lepton era are:

- annihilation of muons at $T<10^{12}$K (early-on)
- annihilation of electrons at $T<5x10^9$K (at the end)
- nucleosynthesis

These represent transitions where a particle species disappears. However, entropy is conserved for components still in thermal equilibrium (reactions are reversible):

g^*T^3=constant: as a species annihilate g^* falls and T rises a bit.

Neutrino background

At the start of the lepton era the neutrinos are still in thermal equilibrium through weak force interactions.

The cross section for such weak interactions depends on temperature: $\sigma_w \approx 10^{-47} m^2 \times (kT/MeV)^2$.

Neutrinos decouple at $T_W \approx 3 \times 10^{10}$K but remain relativistic.

After the electrons and anti-electrons annihilate the radiation era starts.

Neutrino background

Assuming that neutrinos have a negligible rest mass, the energy density of the neutrino background is

$$\rho_{0\nu} c^2 = 2 N_\nu g \frac{7}{8} \frac{\sigma_r T_\nu^4}{2} \simeq N_\nu 10^{-34} \mathrm{g\,cm}^{-3} c^2$$

Compared to photons: $$\frac{\rho_\nu}{\rho_\gamma} = \frac{7}{8} \left(\frac{4}{11} \right)^{4/3} N_\nu$$

The number of neutrino families N_ν is almost certainly 3.

Timeline up to the radiation era

Unkown physics

Planck time	10^{-43}s	10^{19}GeV 10^{32}K	Quantum Gravity ???
GUT transition	10^{-35}s	10^{15}GeV 10^{28}K	baryon asymmetry frozen in; mag.monopoles
Inflation	???	???	>60 e-foldings monopoles diluted, curvature removed
Electroweak transition	10^{-9}s	100GeV 10^{15}K	separate strong, weak, e/m forces
quark-hadron transition	10^{-4}s	200-300MeV 2-3 10^{12}K	quarks condense into mesons and hadrons. Hadron era starts
pion decay	few 10^{-4}s	130MeV 1.4 10^{12}K	Hadron era ends. Lepton era begins.
muon-antimuon decay	few 10^{-4}s	130MeV 1.4 10^{12}K	leaves electrons, neutrinos, photons, + a few baryons
neutrinos decouple	0.1s	3MeV 3.10^{10}K	Temperatures continue to decrease as a^{-1}
e^+-e^- annihilation	4s	0.5MeV 5.10^{9}K	End of lepton era. Heating of radiation

Big Bang Nucleosynthesis

Towards the end of the lepton era nuclear physics begins to take place in the (trace) heavy particles, protons & neutrons.

Atmospheres of main-sequence stars consist of ≈25% ^{4}He by mass (or 6% by number). We observe only a small trend with age and metallicity: must be close to the primordial abundance.

Abundance of ^{4}He: $Y \approx 0.25$; $^3He \approx 10^{-3} Y$; $^2H = D \approx 0.02Y$

Observational challenge: the observed abundances are affected by late-time affects: pollution due to stellar nuclear reactions, but also cosmic-ray bombardments).

Big Bang Nucleosynthesis