9 Baryogenesis and Nucleosynthesis

- If we go back to the first three minutes of the life of our Universe, this period is when important initial conditions that set the content of the Universe were set.

  At this time the Universe was radiation dominated (i.e. $t < t_{rm}$) so $a(t) \propto t^{1/2}$, and

$$T(t) \approx 10^{10}\,\mathrm{K} \left(\frac{t}{1\mathrm{s}}\right)^{-1/2} \qquad (9\text{-}1)$$

$$E_{Mean}(t) \approx 2.7\, k_B T(t) \approx 3\,\mathrm{MeV} \left(\frac{t}{1\mathrm{s}}\right)^{-1/2} \qquad (9\text{-}2)$$

  - at early enough epochs the photon energies can be greater than baryon rest masses, so acts like a particle accelerator.

  - this epoch is well before last scattering, so we cannot observe what is going on directly.

Baryogenesis

- It doesn't appear that the Universe contains significant amounts of anti-matter. We would, for example, have seen annihilation signals such as spatally clustered photons.

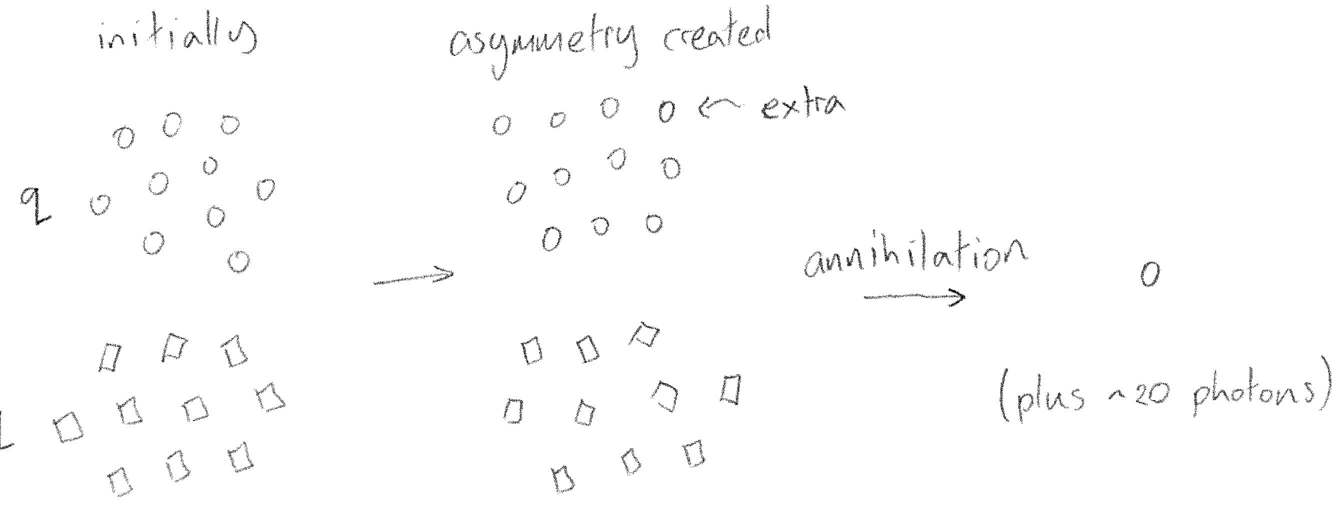
- We do however think there was nearly equal amounts of matter and anti-matter initially, but that they annihilated to leave what we see today.

- The idea is that early enough there was an equilibrium between photons and (anti) quarks via pair production.

$$\gamma + \gamma \rightleftharpoons q + \bar{q} \tag{9.3}$$

and at this point there are equal numbers of quarks antiquarks, and photons. Temperature $k_B T \sim 100$s of MeV.

Somehow (i.e. we don't know how) a small excess of quarks over antiquarks arose, which can explain both the preference for matter, and the very high photon to baryon ratio.



- to get $\eta = \frac{n_{bary}}{n_\gamma}$ the asymmetry needs to be very small, for example only 3 extra quarks per 8×10^8.

q	800 000 003	→	1 (e.g. proton)
$\bar{q}$	800 000 000		0
γ	1600 000 000		1.6×10^9

Nucleosynthesis

- As the Universe contiues to expand and cool, the energy drops below the binding energy of atomic nuclei. The ratio of protons to neutrons is also set, which determines the primordial abundance of Helium (and others). This process is called "nucleosynthesis".

- A few properties of protons and neutrons are relevant here.

  - protons have a lower rest mass than neutrons
  $$Q_n = m_n c^2 - m_p c^2 = 1.29\,\mathrm{MeV} \tag{9.4}$$

  - free neutrons are unstable and decay with a (surprisingly long) half-life τ_n of 880s (15 min).
  $$n \rightarrow p + e^- + \bar{\nu}_e \tag{9.5}$$

  - bound neutrons in an atomic nucleus don't decay

- Consider the Universe at $t = 0.1$ s. The temperature was 3×10^{10} K, and the mean photon energy ≈ 10 MeV. Electrons and positrons created by pair production $\gamma + \gamma \rightleftharpoons e^- + e^+$. Neutrons and protons convert back and forth via

$$\begin{aligned} n + \nu_e &\rightleftharpoons p + e^- \\ n + e^+ &\rightleftharpoons p + \bar{\nu}_e \end{aligned} \tag{9.6}$$

  - all particles are in kinetic equilibrium with energy $k_B T \approx 3\,\mathrm{MeV} \ll m_p c^2$, so are non-relativistic and can be described by a Maxwell-Boltzmann distribution.

the number density of a Maxwell-Boltzmann distribution is

$$n \propto m^{3/2} \exp\left\{-\frac{mc^2}{k_B T}\right\} \qquad (9.7)$$

so (regardless of what the constant of proportionality is)

$$\frac{n_n}{n_p} = \left(\frac{m_n}{m_p}\right)^{3/2} \exp\left\{\frac{-(m_n - m_p)c^2}{k_B T}\right\} \qquad (9.8)$$

the neutron and proton masses are very similar, so the ratio is simply

$$\frac{n_n}{n_p} = \exp\left\{-\frac{Q_n}{k_B T}\right\} \qquad (9.9)$$

- at early times when $k_B T \gg Q_n$, the number of neutrons and protons is very similar, but as the Universe cools protons become strongly favoured.

- <u>if</u> thermal equilibrium was maintained, there would eventually be no neutrons. Obviously, it is not, because expansion decreases the rate at which the reactions in equation (9.6) occur. Just as for photon decoupling, the reactions cease (and the neutron to proton ratio "frozen") when their rate drops below the Hubble parameter. After this time neutrons will still decay however.

- the "freezeout" temperature turns out to be $k_B T_{freeze} = 0.8\,\mathrm{MeV}$ which occurs at $t_{freeze} \sim 1\,\mathrm{s}$. Thus

$$\frac{n_n}{n_p} = \exp\left\{ -\frac{1.29}{0.8} \right\} \approx 0.2 \qquad (9\text{-}10)$$

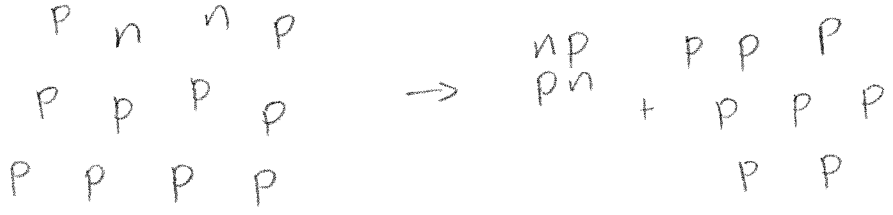
so at times $t_{freeze} < t < \tau_n$ there were five times as many protons as neutrons.

- from this point elements are formed by fusion until all neutrons are in atomic nuclei. e.g.

$$\begin{aligned} p + n &\rightarrow D + \gamma \\ D + p &\rightarrow {}^3He + \gamma \\ {}^3He + D &\rightarrow {}^4He + p \end{aligned} \qquad (9\text{-}11)$$

(some neutrons decay to protons before they become bound).

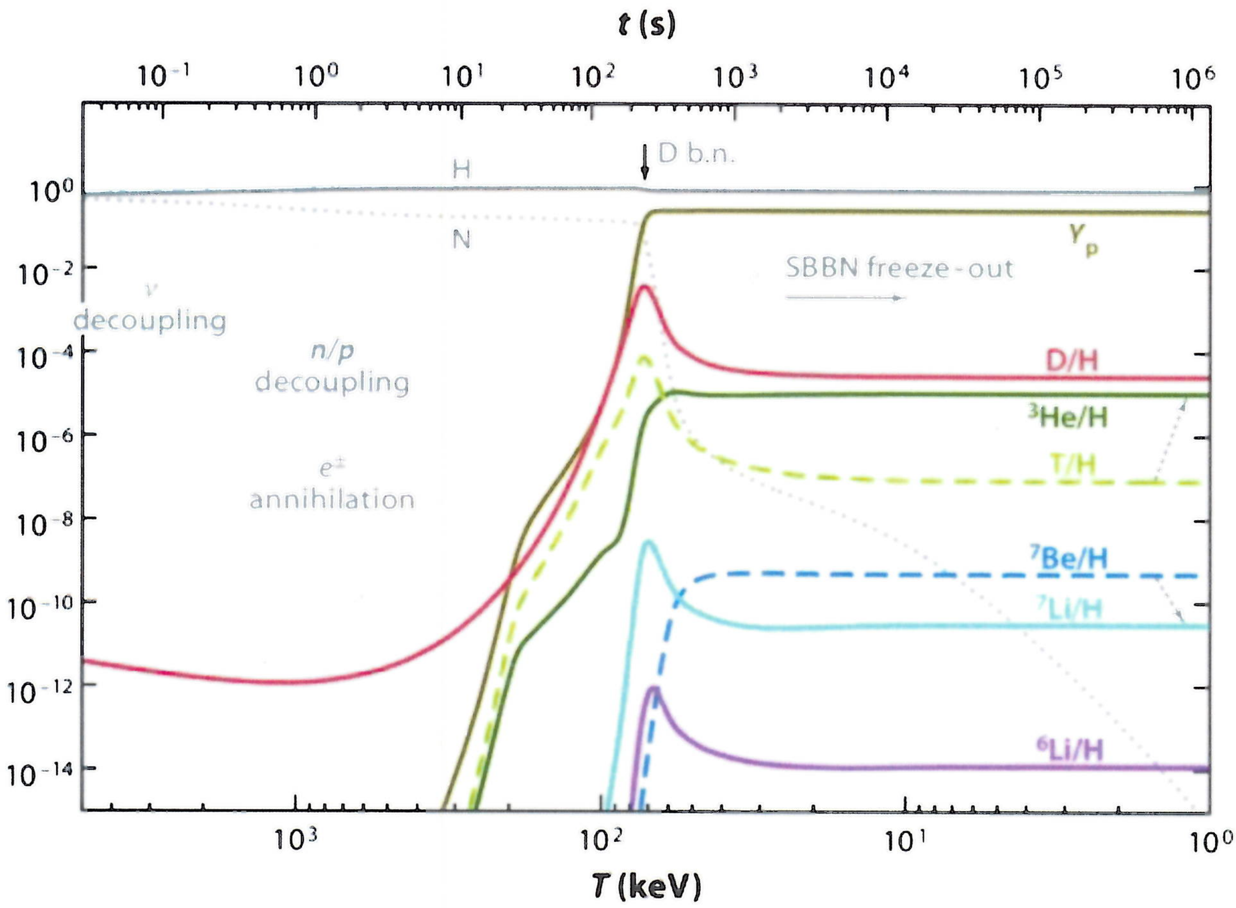
- The neutron to proton ratio allows the maximum fraction of ^4He (known as $Y_p = \rho(^4He)/\rho_{bary}$), to be predicted, as well as abundances of heavier elements (e.g. ^7Li). For example, with $n_n/n_p = 0.2$, the maximum value of $Y_p = 1/3$.



$$Y_p = \frac{4}{12} = \frac{1}{3}$$

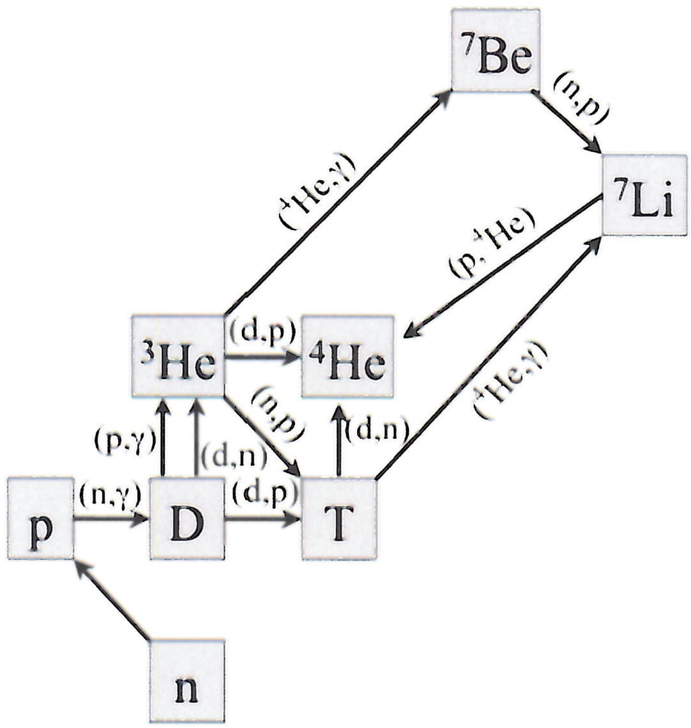
the observed value of $Y_p = 0.24$ is lower because not all neutrons are in ^4He, and some decay while the fusion in equation (9-11) is happening.

- ^4He very stable and formed rapidly, but heavier elements very rare, primarily because ^8Be has an extremely short lifetime ($10^{-16}\,\mathrm{s}$).



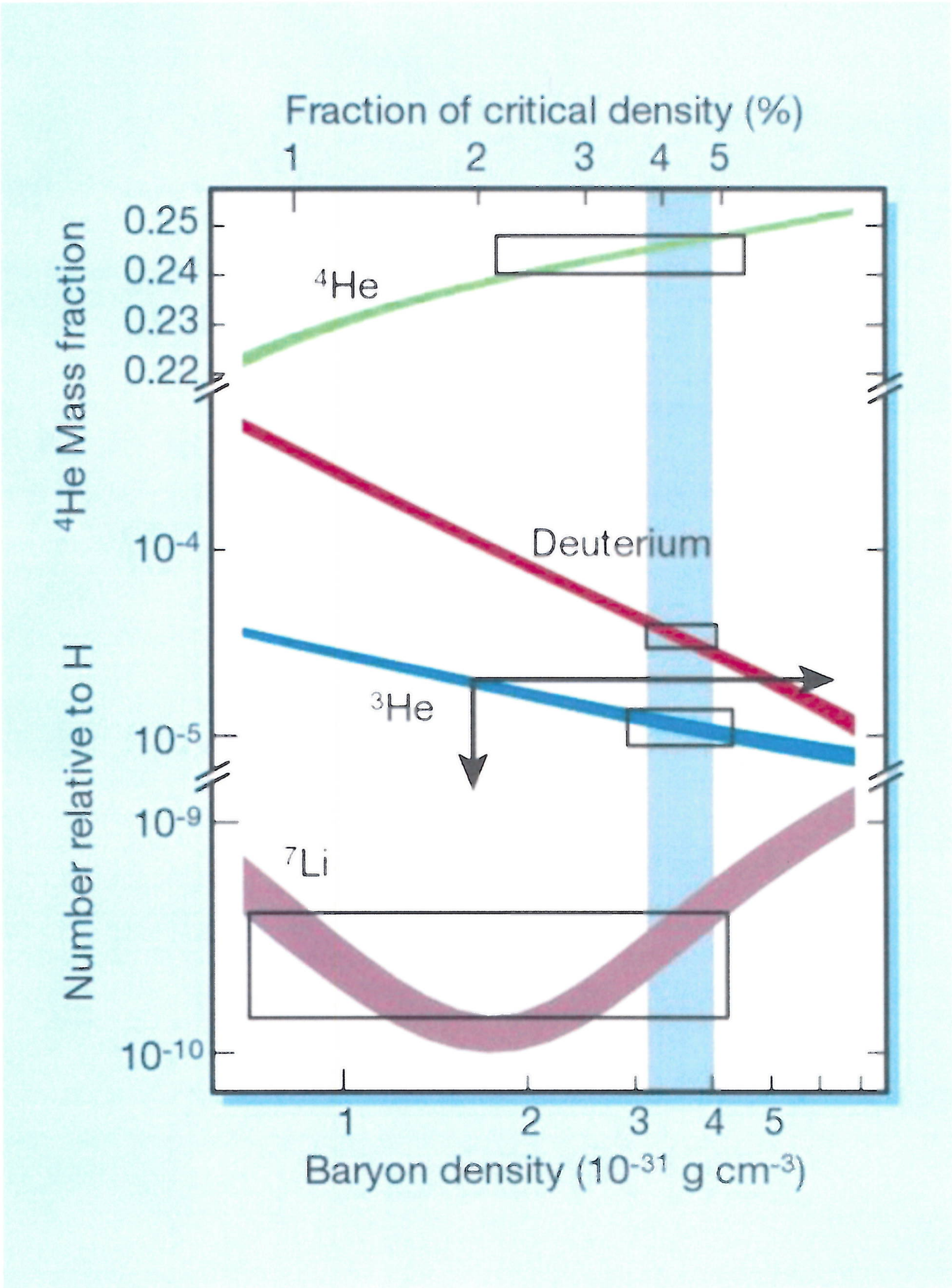
Model for the evolution of Big Bang nucleosynthesis abundances.

Pospelov & Prattler 2010, ARNPS



Standard Big Bang nucleosynthesis reactions.

Nollett & Burles 2000, Phys Rev D, 61, 123505



Observed (in boxes) and expected (vertical band) abundances, showing agreement with theory (lines).

Charbonnel 2002, Nature, 415, 27