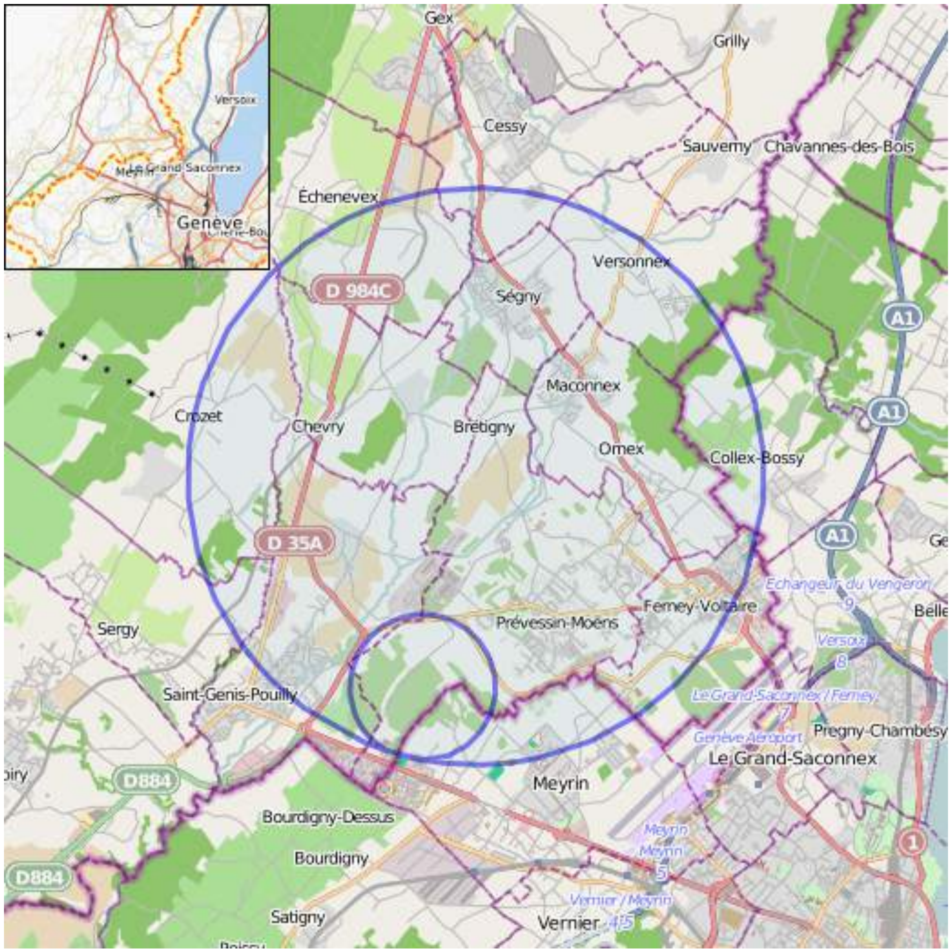
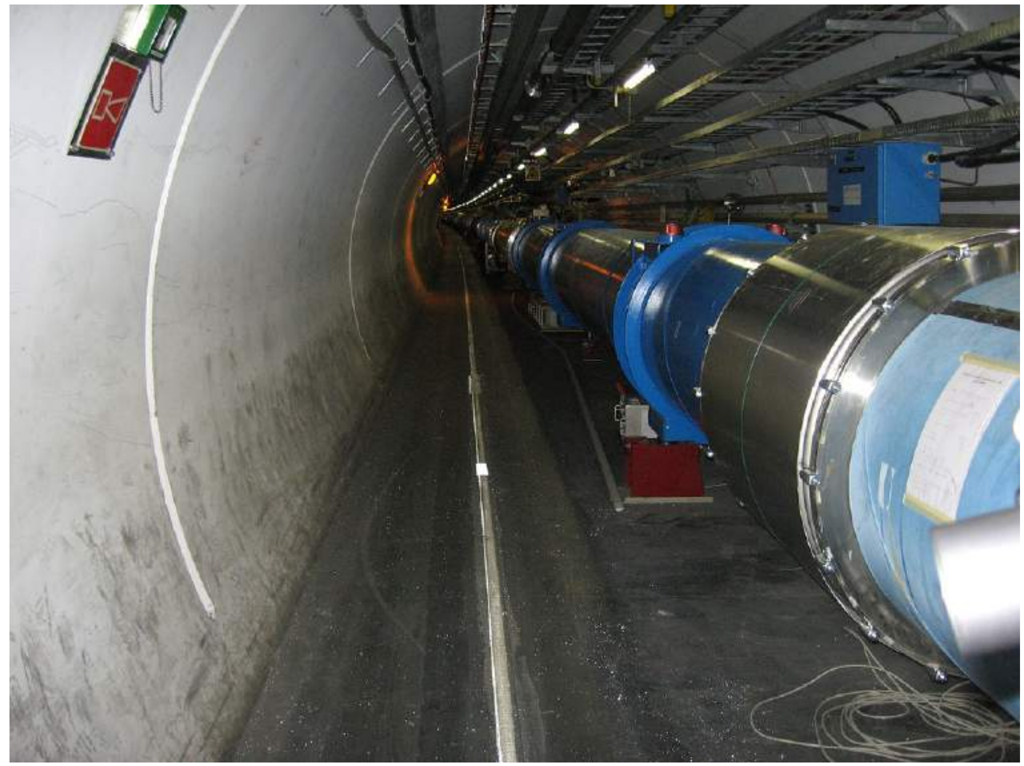
Big Bang nucleosynthesis

The early universe vs. the Large Hadron Collider

LHC is 27 km in circumference



Accelerates protons to ~13 TeV



Universe: $t \approx 10^{-13}\ \mathrm{s} \left(\frac{E_{\mathrm{mean}}}{10\ \mathrm{TeV}}\right)^{-2}$

LHC Wikipedia

Binding energy per nucleon

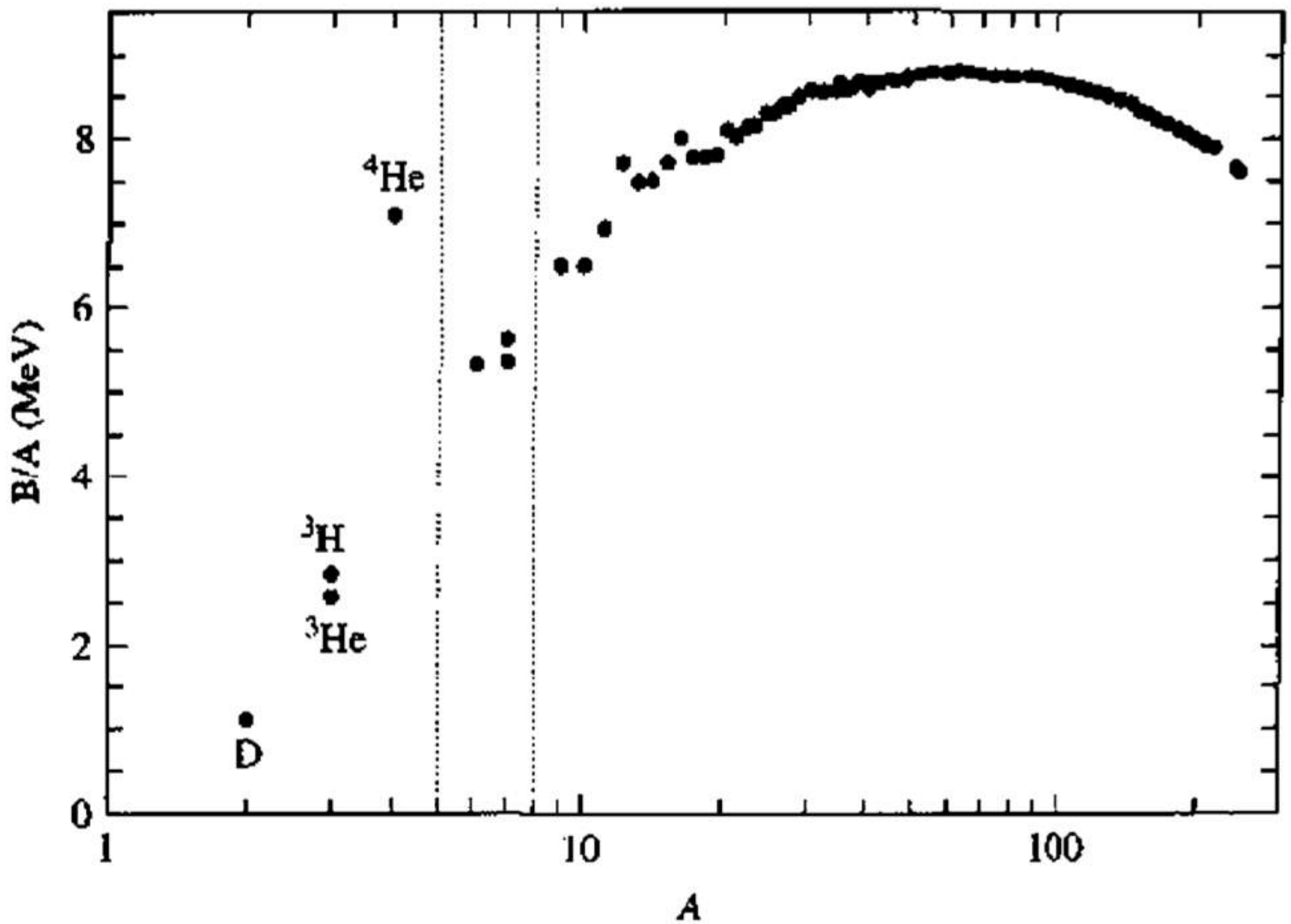


FIGURE 10.1 The binding energy per nucleon (B/A) as a function of the number of nucleons (protons and neutrons) in an atomic nucleus. Note the absence of nuclei at $A = 5$ and $A = 8$.

Forming ^{4}He from lighter elements releases energy,
but low probability of going beyond ^{4}He

Ryden

Neutron-to-proton ratio

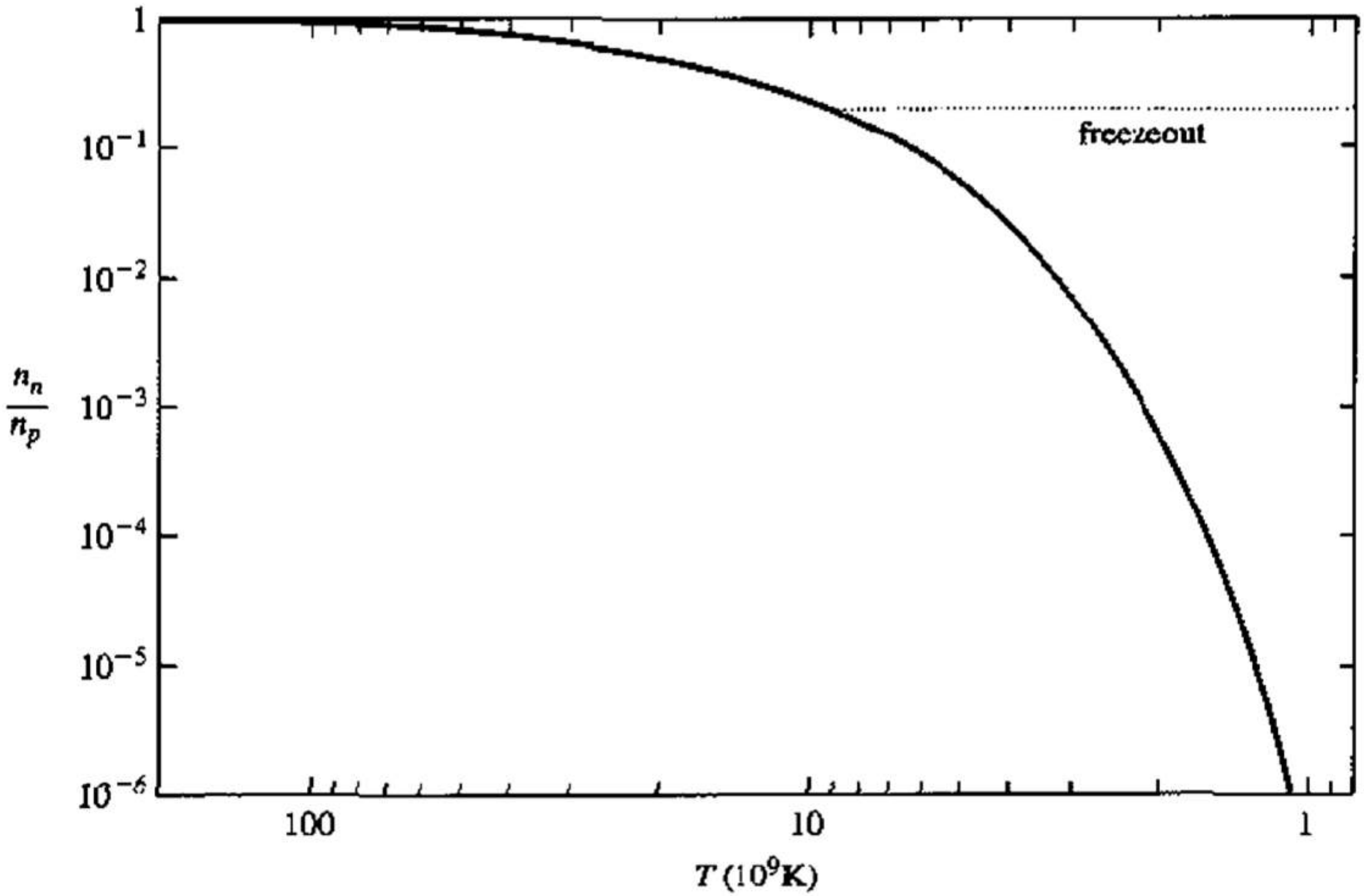


FIGURE 10.2 Neutron-to-proton ratio in the early universe. The solid line assumes equilibrium; the dotted line gives the value after freezeout.

Weak interactions freeze out at T~10^{10} K (t~1 s) → n_n/n_p~0.2

Ryden

Deuterium-to-neutron ratio

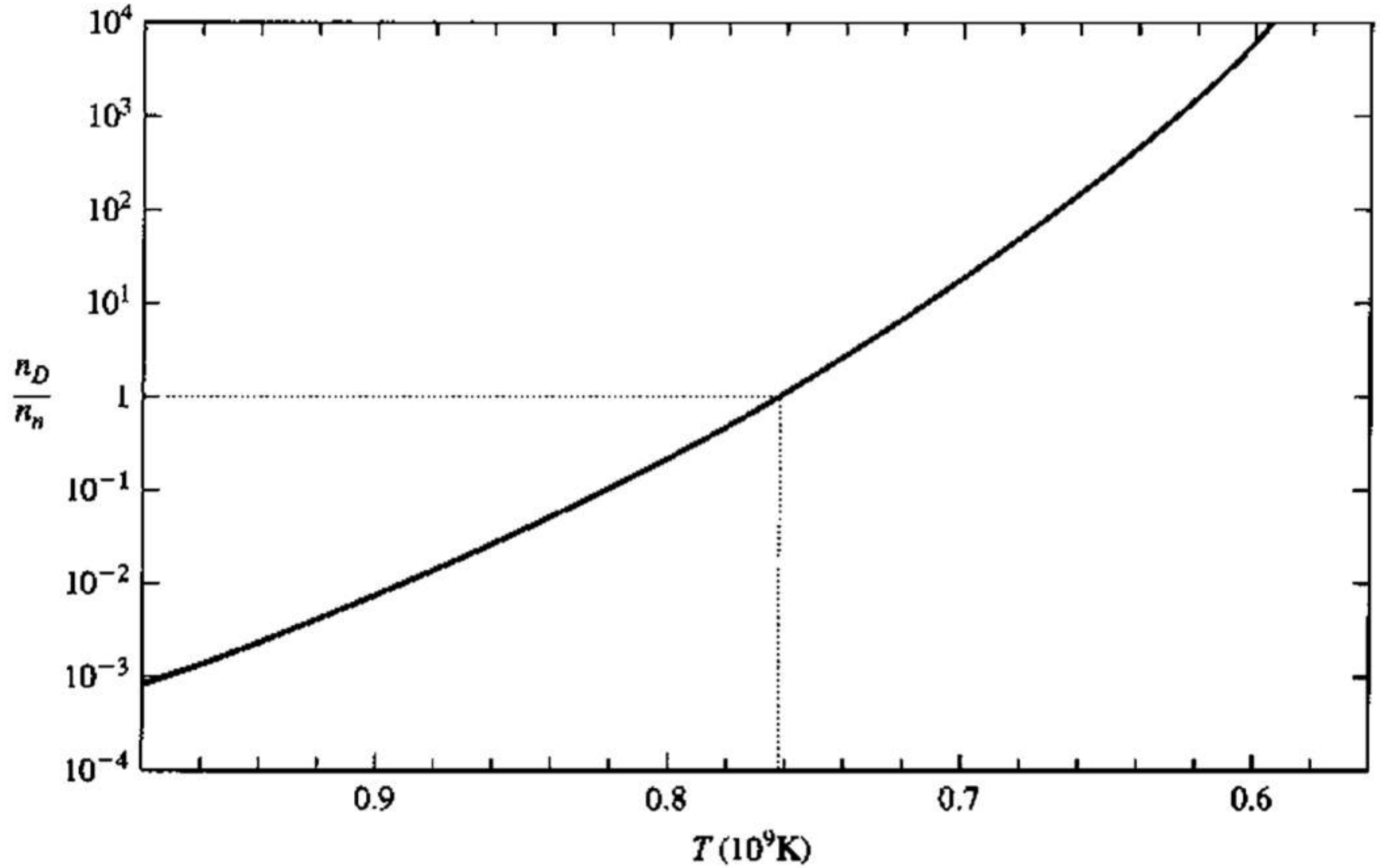


FIGURE 10.3 The deuterium-to-neutron ratio during the epoch of deuterium synthesis. The nucleosynthetic equivalent of the Saha equation (equation (10.27)) is assumed to hold true.

After freeze out, n's bind to p's and form D — half done by T~8×10^8 K (t~200 s)

Ryden

Many rapid, strong force-mediated reactions once D present

$$\mathrm{D + p \rightarrow {}^3He + \gamma}$$
$$\mathrm{D + n \rightarrow {}^3H + \gamma}$$

$$\mathrm{D + D \rightarrow {}^4He + \gamma}$$
$$\mathrm{D + D \rightarrow {}^3H + p}$$
$$\mathrm{D + D \rightarrow {}^3He + n}$$

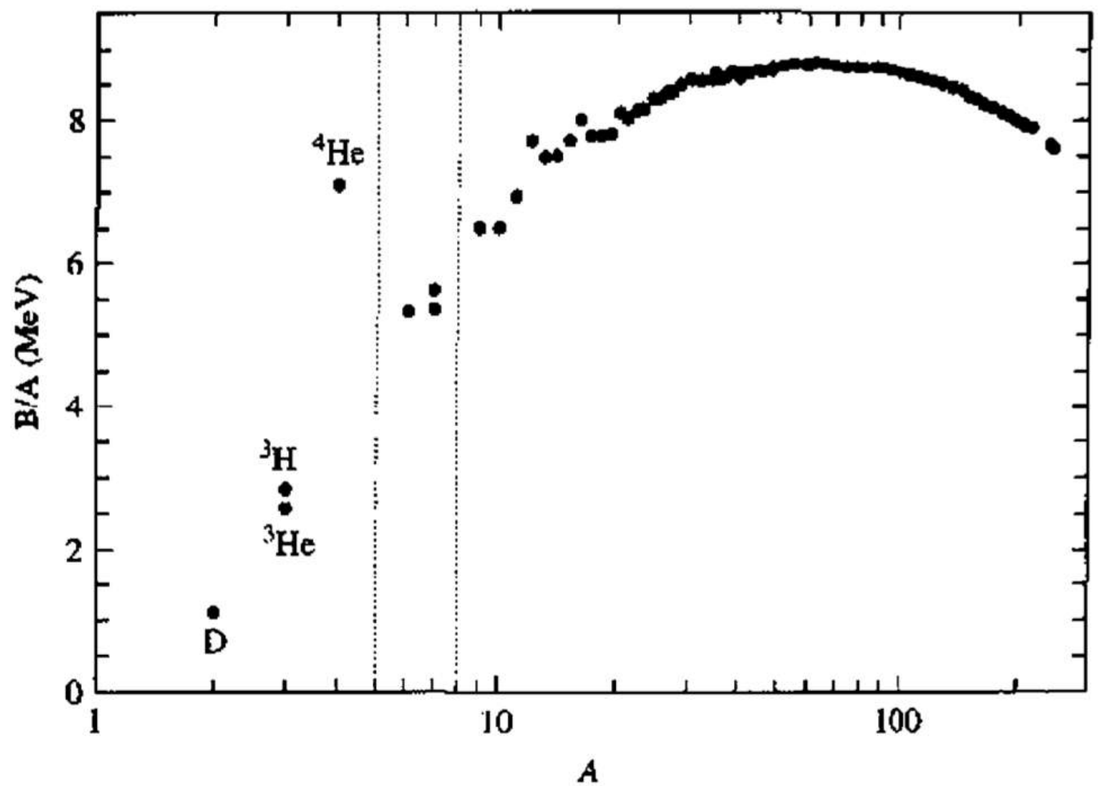
$$\mathrm{{}^3H + p \rightarrow {}^4He + \gamma}$$
$$\mathrm{{}^3He + n \rightarrow {}^4He + \gamma}$$
$$\mathrm{{}^3H + D \rightarrow {}^4He + n}$$
$$\mathrm{{}^3He + D \rightarrow {}^4He + p}$$

efficient ^{4}He production

Roadblock at ^{4}He

Large B/A (costs energy to fuse)

No stable A=5 or A=8 nuclei (can't produce stable elements by fusion with free p or other ^{4}He)



Small amounts of stable Li, Be isotopes produced via relatively rare reactions:

$$^4\mathrm{He} + \mathrm{D} \rightarrow {}^6\mathrm{Li} + \gamma$$

$$^4\mathrm{He} + {}^3\mathrm{H} \rightarrow {}^7\mathrm{Li} + \gamma$$

$$^4\mathrm{He} + {}^3\mathrm{He} \rightarrow {}^7\mathrm{Be} + \gamma$$

equilibrium abundances reached by $T \sim 4\times10^8$ K ($t\sim$10 mins) — end of BBN

Beyond deuterium

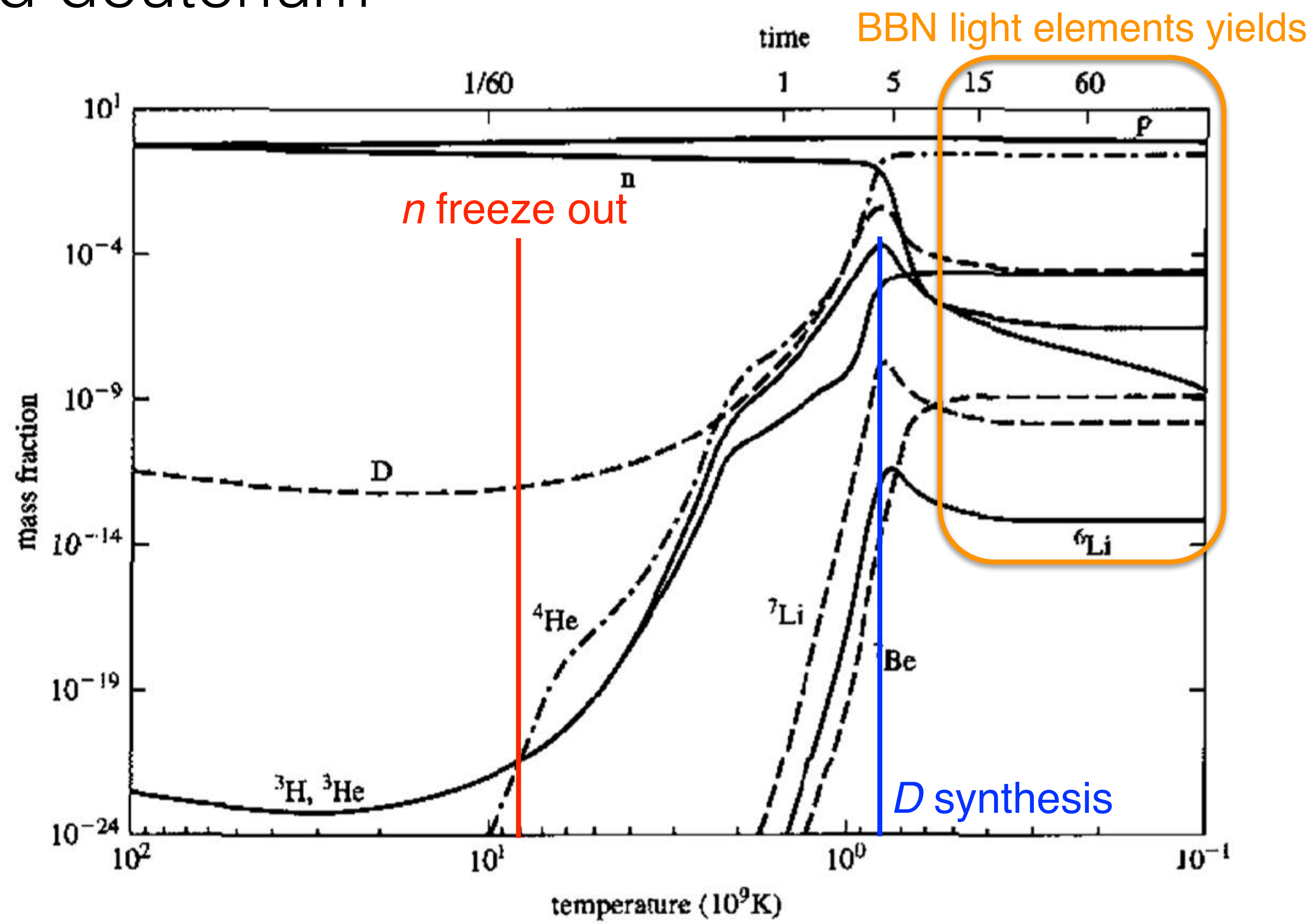


FIGURE 10.4 Mass fraction of nuclei as a function of time during the epoch of nucleosynthesis. A baryon-to-photon ratio of $\eta = 5.1 \times 10^{-10}$ is assumed.

Solving full reaction network gives abundances of each isotope vs. T, for given η

Ryden

Baryon density from BBN vs. CMB

Observed light element abundances constrain η

higher $\eta \Rightarrow$ higher T_{nuc}, i.e. D synthesis starts earlier

$\Rightarrow$ BBN more efficient at producing ^{4}He, leaving less D, ^{3}He behind

→ can solve for implied Ω_b

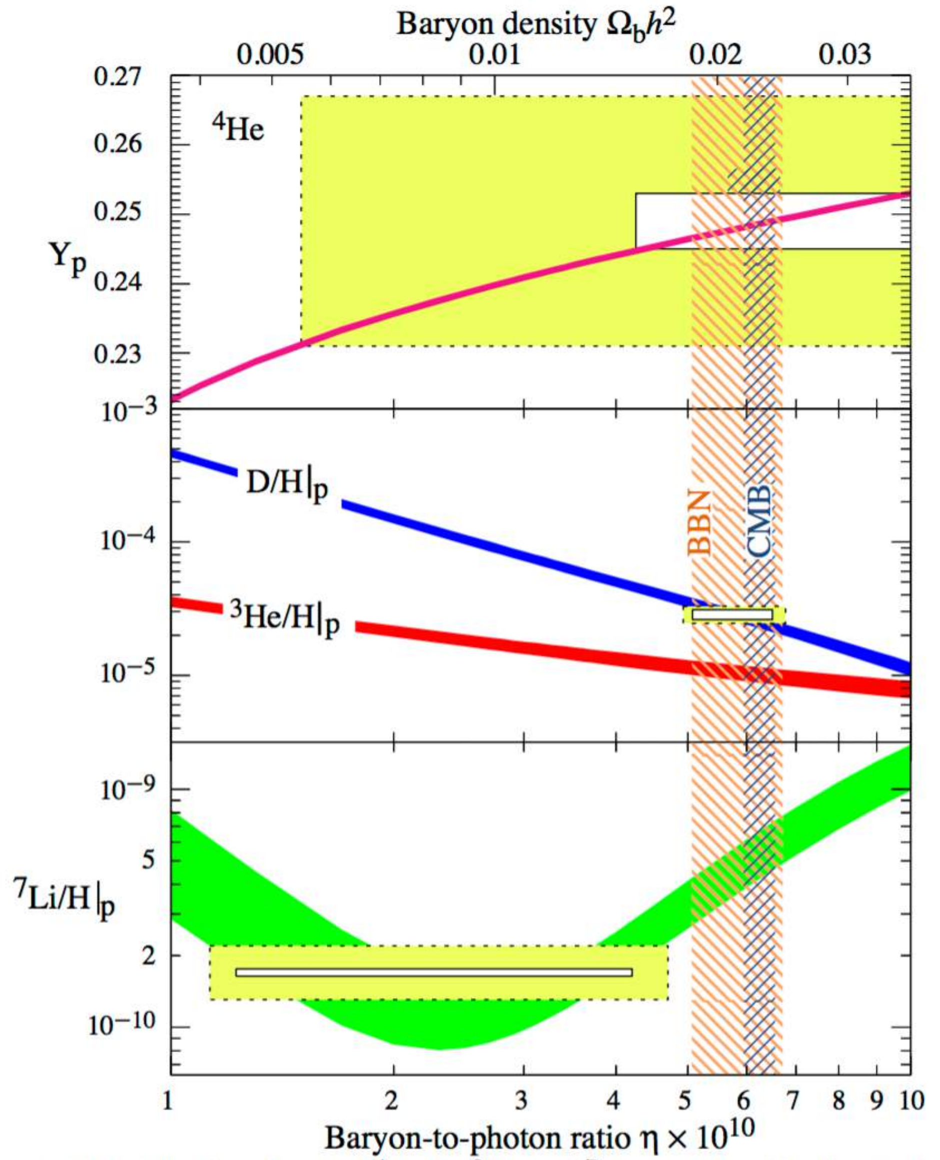


Figure 20.1: The abundances of ^{4}He, D, ^{3}He, and ^{7}Li as predicted by the standard model of Big-Bang nucleosynthesis [14] – the bands show the 95% CL range. Boxes indicate the observed light element abundances (smaller boxes: $\pm 2\sigma$ statistical errors; larger boxes: $\pm 2\sigma$ statistical *and* systematic errors). The narrow vertical band indicates the CMB measure of the cosmic baryon density, while the wider band indicates the BBN concordance range (both at 95% CL).

Particle Data Group

Expressing BBN η constraint in terms of Ω_b

$$\Omega_{\rm b,0} = \frac{n_{\rm b,0} m_{\rm p}}{\rho_{\rm crit,0}}$$

CMB temperature

$$= \frac{8\pi G m_{\rm p}}{3H_0^2}\eta\left[0.243\left(\frac{kT_0}{\hbar c}\right)^3\right]$$

SNe

$n_{\gamma,0}$

$$\approx 0.04 \pm 0.01$$

→ consistent with Ω_b value from acoustic oscillations (CMB power spectrum)

Light element abundances can be measured using QSO absorption, e.g. D

Rest wavelength of D Lyα is 0.3 Å shorter than H Lyα

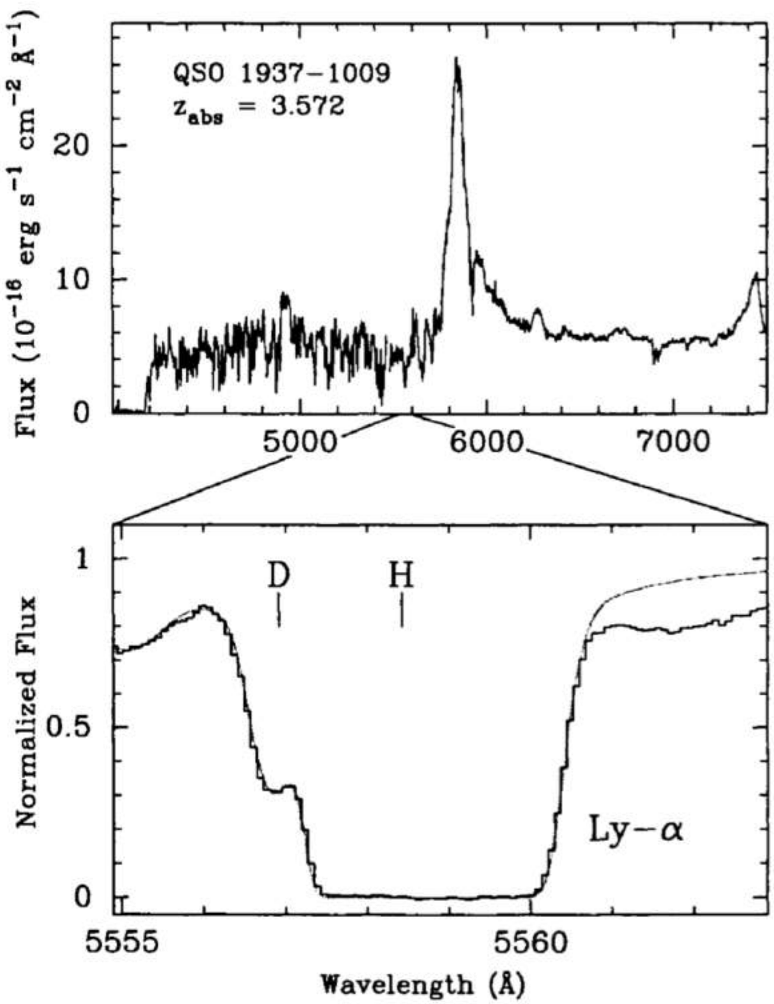


Figure 1.9. Spectrum from a distant QSO (Burles, Nollett, and Turner, 1999). Absorption of photons with rest wavelength 1216 Å corresponding to the $n = 1$ to $n = 2$ state of hydrogen is redshifted up to $1216\,(1 + 3.572)$ Å. Bottom panel provides details of the spectrum in this range, with the the presence of deuterium clearly evident.

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