Special Topics in Particle Physics

Big Bang Nucleosynthesis

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Big Bang Nucleosynthesis

At times from around **10^{-2} s through the first several minutes after the Big Bang**, the temperature passed through the range from around **10 to below 10^{-1} MeV**. During this period **protons and neutrons combined to produce a significant amount of ^{4}He**— one quarter of the universe's nuclei by mass—plus smaller amounts of **deuterium (^{2}H), tritium (^{3}H), ^{3}He, ^{6}Li, ^{7}Li, and ^{7}Be**.

Further ***synthesis of nuclei in stars accounts for all of the heavier elements plus only a relatively small (1 to 2%) additional amount of helium***. The predictions of Big Bang Nucleosynthesis (BBN) are found to agree remarkably well with observations and provide **important support of the Big Bang model.**

Big Bang Nucleosynthesis

The two main ingredients of BBN are the equations of cosmology and thermal physics, plus the rates of nuclear reactions. Of crucial importance is the rate of the reaction $\nu_e + n \leftrightarrow e^- + p$, which allows **transformations between neutrons and protons**.

The proton is lighter than the neutron by $\Delta m = m_n - m_p \approx 1.3$ MeV, and as long as this reaction proceeds sufficiently quickly, one finds that the neutron-to-proton ratio is suppressed by the Boltzmann factor $e^{\Delta m/T}$.

At a temperature around 0.7 MeV the reaction is no longer fast enough to keep up and the neutron-to-proton ratio 'freezes out' at a value of around 1/6. To first approximation one can estimate the helium abundance simply by assuming that all of the available neutrons end up in ^{4}He.

The **one free parameter** of BBN is the baryon density Ω_b or, equivalently, the **baryon-to-photon ratio η**. By **comparing the observed abundances of the light elements with those predicted by BBN, the value of η can be estimated**.

The result is of fundamental importance for the dark-matter. → Based on Ω_b we can get the density of dark matter Ω_{DM}.

Ingredients of the Big Bang Nucleosynthesis

To model the synthesis of light nuclei one needs the equations of **cosmology and thermal physics** relevant for **temperatures in the MeV range**.

At this point the **total energy density of the universe is still dominated by radiation** (i.e., relativistic particles), so the pressure and energy density are related by $\boldsymbol{P = \varrho/3}$. This leads to relations for the expansion rate and time as a function of temperature

$$H \sim \frac{T^2}{m_{\mathrm{Pl}}} , \qquad (10.1.1)$$

$$t \sim \frac{m_{\mathrm{Pl}}}{T^2} . \qquad (10.1.2)$$

To use these equations numerically one needs to know the effective number of degrees of freedom. At this point **quarks and gluons have already become bound into protons and neutrons** (at around $T = 200$ MeV), and since the nucleon mass is around $m_{\mathrm{N}} \approx 0.94$ GeV, these are **no longer relativistic**.

Nucleons and antinucleons can remain in thermal equilibrium down to temperatures of around 50 MeV. At temperatures below several tens of MeV the antimatter has essentially disappeared.

At temperatures **in the MeV range, the relativistic particles are photons, e^{-}, ν_e, ν_μ, ν_τ , and their antiparticles**.

Ingredients of the Big Bang Nucleosynthesis

A temperature of $\boldsymbol{T}$ **= 10 MeV is reached at a time** $\boldsymbol{t \approx}$ **0.007 s**. At this temperature, all of the relativistic particles (γ , e^-, ν_e, ν_μ, ν_τ) are in **thermal equilibrium through reactions** of the type

$e^+ + e^- \leftrightarrow \nu + \bar{\nu}$, $e^+ + e^- \leftrightarrow \gamma + \gamma$, etc.

The **number density of the neutrinos**, for example, is given by the equilibrium formula appropriate for relativistic fermions,

$$n_\nu \sim T^3 \,. \qquad (10.2.1)$$

Such a proportionality also holds for the electron density.

Already **at temperatures around 20MeV, essentially all of the antiprotons and antineutrons annihilated.**

The **baryon-to-photon ratio** is a number that one could, in principle, predict, if a complete theory of **baryogenesis** were available. Since this is not the case, however, **the baryon density has to be treated as a free parameter.**

Ingredients of the Big Bang Nucleosynthesis

Since one does not expect any more baryon-number-violating processes at temperatures near the BBN era, **the total number of protons and neutrons in a comoving volume remains constant.** That is, even though protons and neutrons are no longer relativistic, **baryon-number conservation** requires that the sum of their number densities follows

$$n_n + n_p \sim \frac{1}{R^3} \sim T^3 \,. \qquad (10.2.2)$$

At temperatures much greater than the neutron–proton mass difference, $\Delta m = m_n - m_p \approx 1.3$ MeV, one has $\boldsymbol{n_n \approx n_p}$**.**

Although the total baryon number is conserved, **protons and neutrons can be transformed through reactions** like $n + \nu_e \leftrightarrow p + e^-$ and $n + e^+ \leftrightarrow p + \bar{\nu}_e$. A typical Feynman diagram is shown in Fig. 10.1.

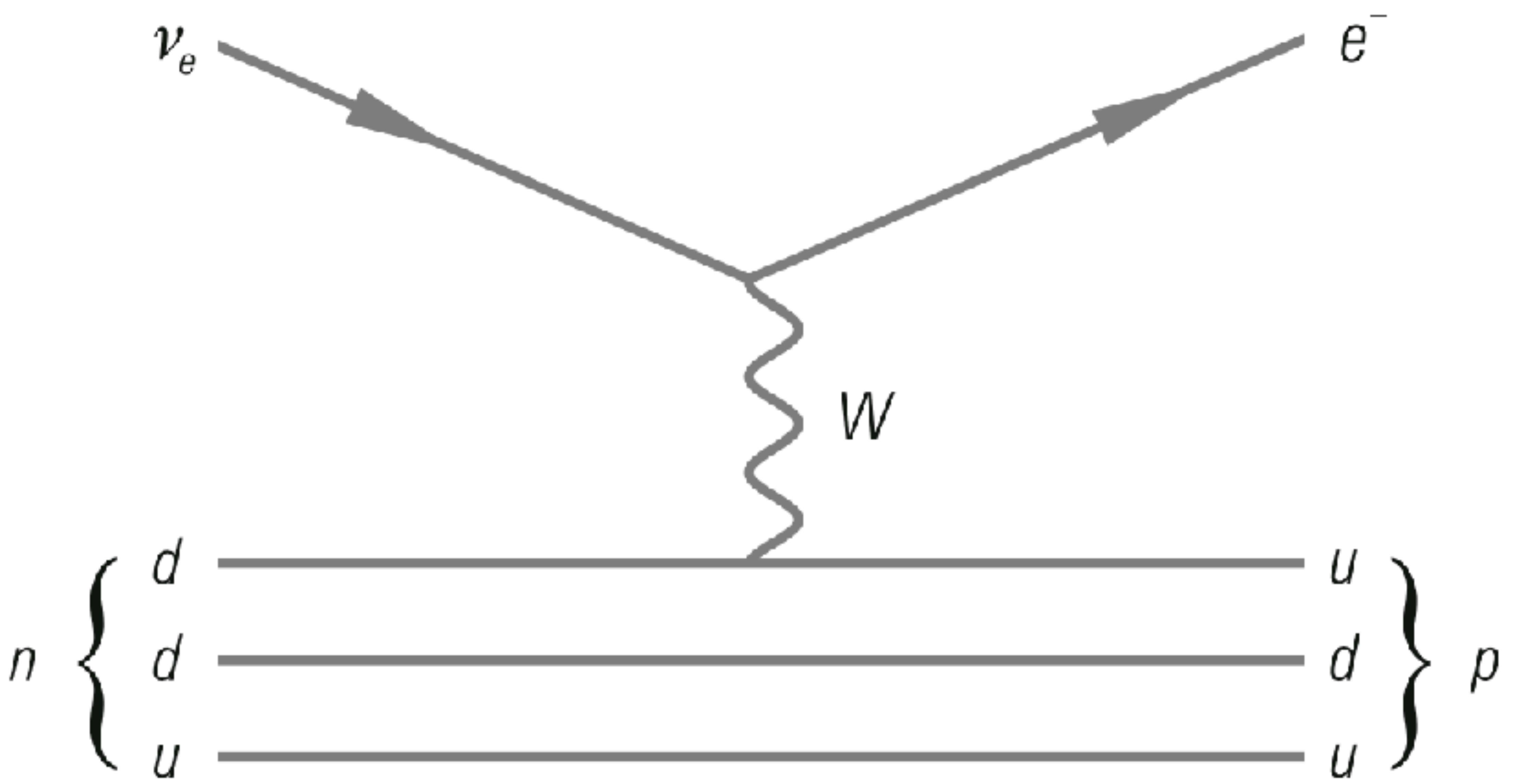


Fig. 10.1 Feynman diagram for the reaction $\nu_e n \leftrightarrow e^- p$

Neutron to proton ratio

The crucial question is **whether these reactions proceed faster than the expansion rate so that thermal equilibrium is maintained.** If this is the case, then the ratio of neutron-to-proton number densities is given by

$$\frac{n_n}{n_p} = \left(\frac{m_n}{m_p}\right)^{3/2} \mathrm{e}^{-(m_n - m_p)/T} \approx \mathrm{e}^{-\Delta m/T} , \qquad (10.3.1)$$

where m_p = 938.272 MeV, m_n =939.565 MeV, and $\Delta m = m_n - m_p$ =1.293MeV.

To find out whether equilibrium is maintained, one needs to **compare the expansion rate *H*** from (10.1.1) **to the reaction rate Γ** . This rate depends on the number density, the cross section, and the velocity, and is given by

$$\Gamma = n\langle \sigma v \rangle \, . \qquad (10.3.2)$$

$$H \sim \frac{T^2}{m_{\mathrm{Pl}}} , \qquad (10.1.1)$$

Neutron to proton ratio

Γ is the reaction rate per neutron for $n + \nu_e \leftrightarrow p + e^-$ where the brackets denote an average of σv over a thermal distribution of velocities. The number density n in (10.3.2) refers to the target particles, i.e., neutrinos, which is therefore given by (10.2.1).

The **cross section** for the reaction $n + \nu_e \leftrightarrow p + e^-$ can be **predicted using the Standard Model of electroweak interactions.** A good approximation one finds for the thermally averaged speed times cross section:

$$\langle \sigma v \rangle \approx G_F^2 T^2 \,. \tag{10.3.3}$$

Here $G_F = 1.166 \times 10^{-5}$ GeV^{-2} is the **Fermi constant,** which **characterizes the strength of weak interactions.**

To find the **reaction rate**, one has to multiply (10.3.3) by the number density n from (10.2.1). But since the main interest here is to get a rough approximation, factors of order unity can be ignored and one can take $n \approx T^3$ to obtain

$$\Gamma(\nu_e n \to e^- p) \approx G_F^2 T^5 \,. \tag{10.3.4}$$

Neutron to proton ratio

A similar expression is found for the inverse reaction $e^- + p \rightarrow \nu_e + n$.
Now the question of **whether this reaction proceeds quickly enough to maintain thermal equilibrium** can be addressed. The point, **where the reaction rate Γ equals the expansion rate H** **, $\Gamma = H$** , determines the decoupling or ***freeze-out temperature T_f*** **.**

Equating the expressions for Γ and H ,

$$G_\mathrm{F}^2 T^5 \sim \frac{T^2}{m_\mathrm{Pl}} , \qquad (10.3.5)$$

and solving for T gives

$$T_\mathrm{f} \sim \left(\frac{1}{G_\mathrm{F}^2 m_\mathrm{Pl}} \right)^{1/3} . \qquad (10.3.6)$$

A careful analysis of the numerical factors including all relevant degrees of freedom gives

$$\boxed{T_\mathrm{f} \approx 0.7\,\mathrm{MeV} . \qquad (10.3.7)}$$

Neutron to proton ratio

At **temperatures below T_f** the reaction $n + \nu_e \leftrightarrow p + e^-$ can **no longer** proceed quickly enough to **maintain the equilibrium number densities**. **The neutron density is said to *freeze out*,** i.e., the path, by which neutrons could be converted to protons, is effectively closed.

If neutrons were stable, this would mean that the number of them in a comoving volume would be constant, i.e., their number density would follow $n_n \sim 1/R^3$. Actually, this is not quite true because **free neutrons can still decay.** But the **neutron has a mean lifetime** $\tau_n \approx 886$ s, **which is relatively long, but not entirely negligible, compared to the time scale of nucleosynthesis.**

Ignoring for the moment the effect of neutron decay, the **neutron-to-proton ratio at the freeze-out temperature is**

$$\frac{n_n}{n_p} = \mathrm{e}^{-(m_n - m_p)/T_\mathrm{f}} \approx \mathrm{e}^{-1.3/0.7} \approx 0.16\,. \qquad (10.3.8)$$

According to (10.1.3), this temperature is reached **at a time $t \approx 1.5$ s**.

In the next five minutes, essentially all of the neutrons become bound into ^{4}He, and thus **the neutron-to-proton ratio at the freeze-out temperature is the dominant factor in determining the amount of helium produced**.

Neutron to proton ratio

To obtain a precise value for the n/p ratio, among others, also the neutron decay must be taken into account.

In addition, it is important to note the fact that in **thermal equilibrium the reaction** $e^+ + e^- \leftrightarrow \gamma + \gamma$ provides **energetic photons**. Therefore, the photon temperature decreases more slowly than one would expect from the normal expansion.

If further neutron decay after decoupling is considered, according to

$$\frac{n_n}{n_p} = \mathrm{e}^{-(m_n - m_p)/T_\mathrm{f}}\, \mathrm{e}^{-t/\tau_n}\,, \tag{10.3.10}$$

one finally obtains for the neutron-to-proton ratio a value of

$$\boxed{\frac{n_n}{n_p} \approx 0.13\,, \qquad (10.3.11)}$$

if one assumes that the **nucleosynthesis is completed after three minutes (t = 180 s).**

Synthesis of light elements

The synthesis of ^{4}He proceeds through a **chain of reactions,** which includes, for example,

$$p\,n \to d\,\gamma\,, \tag{10.4.1}$$

$$d\,p \to {}^3\mathrm{He}\,\gamma\,, \tag{10.4.2}$$

$$d\,{}^3\mathrm{He} \to {}^4\mathrm{He}\,p\,. \tag{10.4.3}$$

The binding energy of deuterium is $E_{\mathrm{bind}} = 2.2$ MeV, so if the temperature is so high that there are many photons with energies higher than this, then the deuterium will be broken apart as soon as it is produced. One might naively expect that the reaction (10.4.1) would begin to be effective as soon as the temperature drops to around 2.2 MeV. In fact this does not happen until a considerably lower temperature. This is because there are so many more photons than baryons, and the photon energy distribution, i.e., the Planck distribution, has a long tail towards high energies.

Synthesis of light elements

The **nucleon-to-photon ratio** is at this point essentially the same as the **baryon-to-photon ratio η** = n_b/n_γ , which is around 10^{-9}. One can estimate roughly when **deuterium production** can begin to proceed by finding the temperature, where the number of photons with energies greater than 2.2MeV is equal to the number of nucleons. For a nucleon-to-photon ratio of 10^{-9}, this occurs at $\boldsymbol{T = 0.086}$ **MeV**, which is reached at a time of $\boldsymbol{t \approx 3}$ **min**. Over the next several minutes, essentially all of the neutrons, except those that decay, are processed into ^{4}He.

The abundance of ^{4}He is usually quoted by giving its mass fraction,

$$Y_P = \frac{\text{mass of } ^4\text{He}}{\text{mass of all nuclei}} = \frac{m_{\text{He}} n_{\text{He}}}{m_{\text{N}}(n_n + n_p)}, \qquad (10.4.4)$$

where the neutron and proton masses have both been approximated by the nucleon mass, $m_N \approx m_n \approx m_p \approx 0.94$ GeV. There are four nucleons in ^{4}He, so, neglecting the binding energy, one has $m_{He} \approx 4m_N$. Furthermore, there are two neutrons per ^{4}He nucleus, so if one assumes that all of the neutrons end up in ^{4}He, one has $\boldsymbol{n_{He} = n_n/2}$. The next most common nucleus, **deuterium**, ends up with an **abundance four to five orders of magnitude smaller than that of hydrogen**.

Synthesis of light elements

The ^{4}He mass fraction is therefore

$$Y_P = \frac{4m_N(n_n/2)}{m_N(n_n+n_p)} = \frac{2(n_n/n_p)}{1+n_n/n_p}$$
$$\approx \frac{2\times 0.13}{1+0.13} \approx 0.23\,. \qquad (10.4.5)$$

This rough estimate turns out to agree quite well with more detailed calculations. **23% ^{4}He mass fraction means that the number fraction of ^{4}He is about 6% with respect to hydrogen.**

The fact that the universe finally ends up containing around **one quarter ^{4}He by mass** can be seen as the result of **a number of coincidences**. For example, mean lifetimes for weak decays can vary over many orders of magnitude. The fact that the mean neutron lifetime turns out to be 885.7s is a complicated consequence of the rather close neutron and proton masses combined with strong and weak interaction physics.

If τ_n were less, then essentially all of the neutrons would decay before they could be bound up into deuterium, and the chain of nuclear reactions could not have started.

Synthesis of light elements

The exact **value of the decoupling temperature** is also a complicated mixture of effects, being **sensitive to** the degrees of freedom, which depends on the **number of relativistic particle species in thermal equilibrium → the number of neutrino types**.

If, for example, **the decoupling temperature T_f had been not 0.7 MeV but, say, 0.1 MeV**, then the **neutron-to-proton ratio would have been** $e^{-1.3/0.1} \approx 2 \times 10^{-6}$, and **essentially no helium would have formed.**

On the other hand, if it had been at a temperature **much higher than $m_n - m_p$**, then there would have been **equal amounts of protons and neutrons**. Then the entire **universe would have been made of helium.** Usual **hydrogen-burning stars would be impossible**, and the universe would certainly be a very different place.

Nucleosynthesis

A detailed **modeling of nucleosynthesis** uses a system of differential equations involving all of the **abundances and reaction rates**. The rates of nuclear reactions are **parameterizations of experimental data.**

An **example of predicted mass fractions** versus temperature and time is shown in Fig. 10.2.

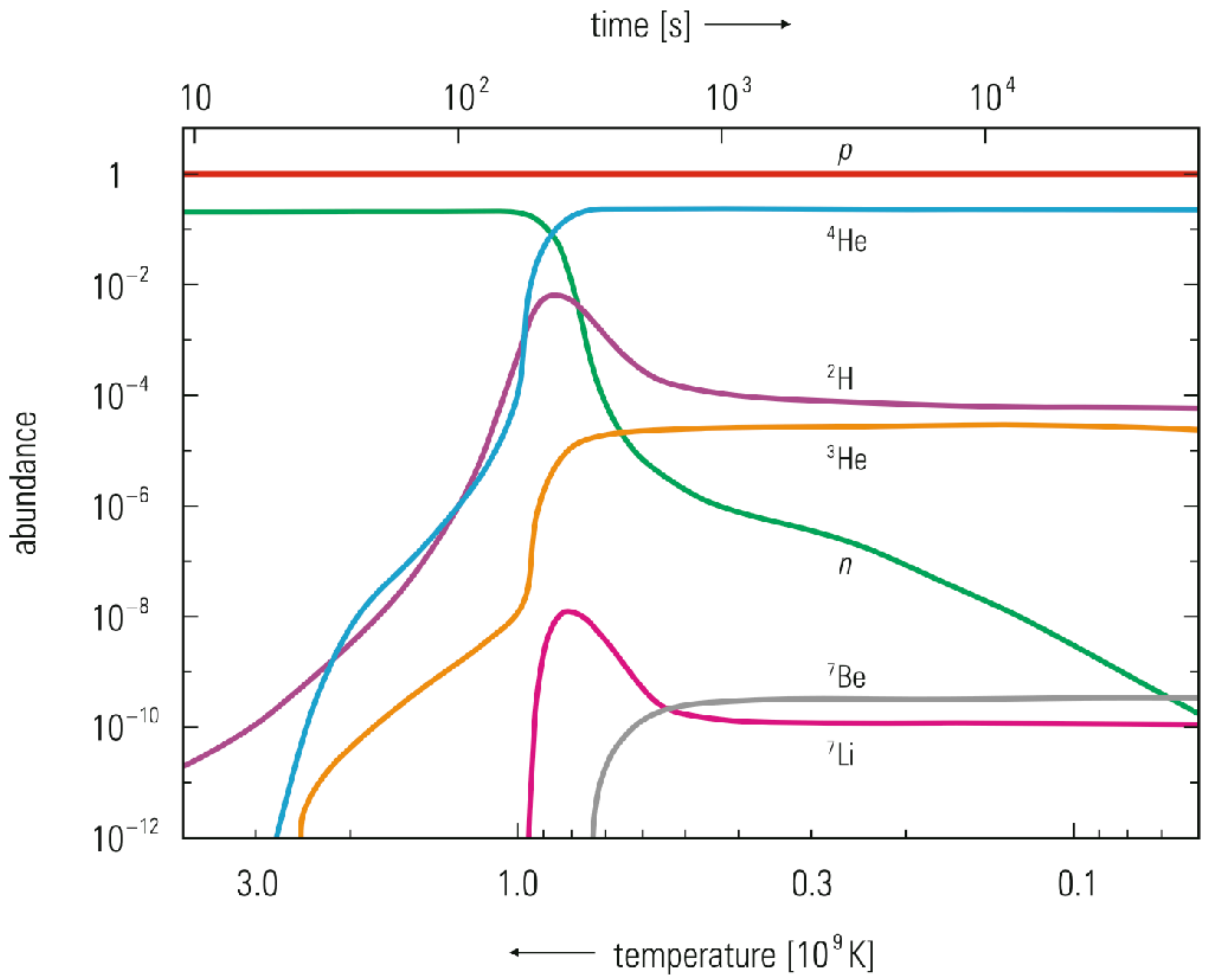


Fig. 10.2 Evolution of the elemental abundance in the primordial nucleosynthesis. ^{4}He is usually given as mass fraction, while for all the other elements the values are given as number fractions, i.e., a mass fraction of 25% ^{4}He corresponds to a number fraction of about 6% (four nucleons form a helium nucleus). The mass fraction of hydrogen is around 75% and its number fraction about 94%. This also implies that all other isotopes are extremely rare [183]

Nucleosynthesis

Around $t \approx$ **1000 s**, the temperature has dropped to $T \approx$ **0.03 MeV**. At this point the kinetic energies of nuclei are too low **to overcome the Coulomb barriers and the fusion processes stop**. So, in the early universe heavy elements cannot be produced because **after about several minutes the temperatures are insufficient to fuse heavier nuclei.**

In order to compare the predictions of Big Bang Nucleosynthesis with observations, one **needs to measure the *primordial* abundances of the light elements**.

However, **abundances change as a result of *stellar* nucleosynthesis**. For example, helium is produced in stars and deuterium is broken apart.

To obtain the most accurate measurement of the ^{4}He mass fraction, for example, one tries to find **regions of hot ionized gas from 'metal-poor' galaxies**, i.e., those, where relatively small amounts of heavier elements have been produced through stellar burning of hydrogen. For standard, **normal stars like our Sun the helium mass fraction from stellar hydrogen burning is on the order of 1 to 2%**. In the determination of the primordial helium abundance this is naturally taken into account.

Nucleosynthesis

A recent survey of data concludes for the **primordial ^{4}He mass fraction**

$$Y_P = 0.238 \pm 0.002 \pm 0.005\,, \qquad (10.5.1)$$

where the first error is statistical and the second reflects systematic uncertainties.

In contrast to the **^{4}He content** of the universe, which is traditionally **given as a mass fraction**, the abundances of the **other primordial elements are presented as number fractions,** e.g., $n_{^7Li}/n_p \equiv n_{^7Li}/n_\mathrm{H}$ for ^{7}Li.

The best determinations of the **^{7}Li abundance come from hot metal-poor stars from the galactic halo**. As with ^{4}He, one extrapolates to zero metallicity to find the primordial value. Recent data give a **lithium-to-hydrogen ratio of**

$$n_{^7\mathrm{Li}}/n_\mathrm{H} = 1.23 \times 10^{-10}\,. \qquad (10.5.2)$$

The systematic uncertainty on this value is quite large, corresponding to the range from about 1 to 2 × $\mathbf{10^{-10}}$.

Nucleosynthesis

Although **deuterium** is produced by the first reaction **in hydrogen-burning stars** through

$p + p \rightarrow d + e^{+} + \nu_e$, it is **quickly processed further into heavier nuclei**. Essentially, no net deuterium production takes place in stars and any present would be quickly fused into helium.

So, **to measure the primordial deuterium abundance, one needs to find gas clouds at high redshift,** hence far away and far back in time, that have never been part of stars. These produce **absorption spectra** in the spectra of **distant quasars.** The **hydrogen Lyman-α line at λ = 121.6 nm** appears at very high redshift ($z \geq 3$) in the visible part of the spectrum. **The corresponding line from deuterium has a small isotopic shift to shorter wavelengths.** Comparison of the two components gives an **estimate of the deuterium-to-hydrogen ratio** n_d/n_p. A recent measurement finds

$$\boxed{n_d/n_p = (3.40 \pm 0.25) \times 10^{-5}\,. \qquad (10.5.3)}$$

Nucleosynthesis

A measurement of the **primordial ^{3}He abundance** is even more complicated. Estimations suggest a range of

$$n_{^3\mathrm{He}}/n_\mathrm{H} = 2 \times 10^{-5}\text{–}3 \times 10^{-4}\,. \tag{10.5.4}$$

Other sources favour a slightly lower value of 1×10^{-5}. However, presently the measured ^{3}He abundance **does not allow to effectively test the Big Bang nucleosynthesis.**

Finally, **the predicted abundances of light nuclei are compared to measurements**. The predictions **depend, however, on the baryon density n_b or,** equivalently, on $\boldsymbol{\eta} = n_b/n_\gamma$. The predicted mass fraction of ^{4}He as well as the numbers relative to hydrogen for D, ^{3}He, and ^{7}Li are shown as a function of η in Fig. 10.3

Nucleosynthesis

The **deuterium fraction D/H decreases for increasing η** because a higher baryon density means that **deuterium is processed more completely into helium**. Since the resulting prediction for D/H depends quite sensitively on the baryon density, **the measured D/H provides the most accurate determination of η**.

The measured, n_d/n_p =(3.40 ± 0.25) × 10^{-5}, gives the range of allowed η values, which are shown by the vertical band in Fig. 10.3. This corresponds to

$$\boxed{\eta = (5.1 \pm 0.5) \times 10^{-10}\,. \qquad (10.5.5)}$$

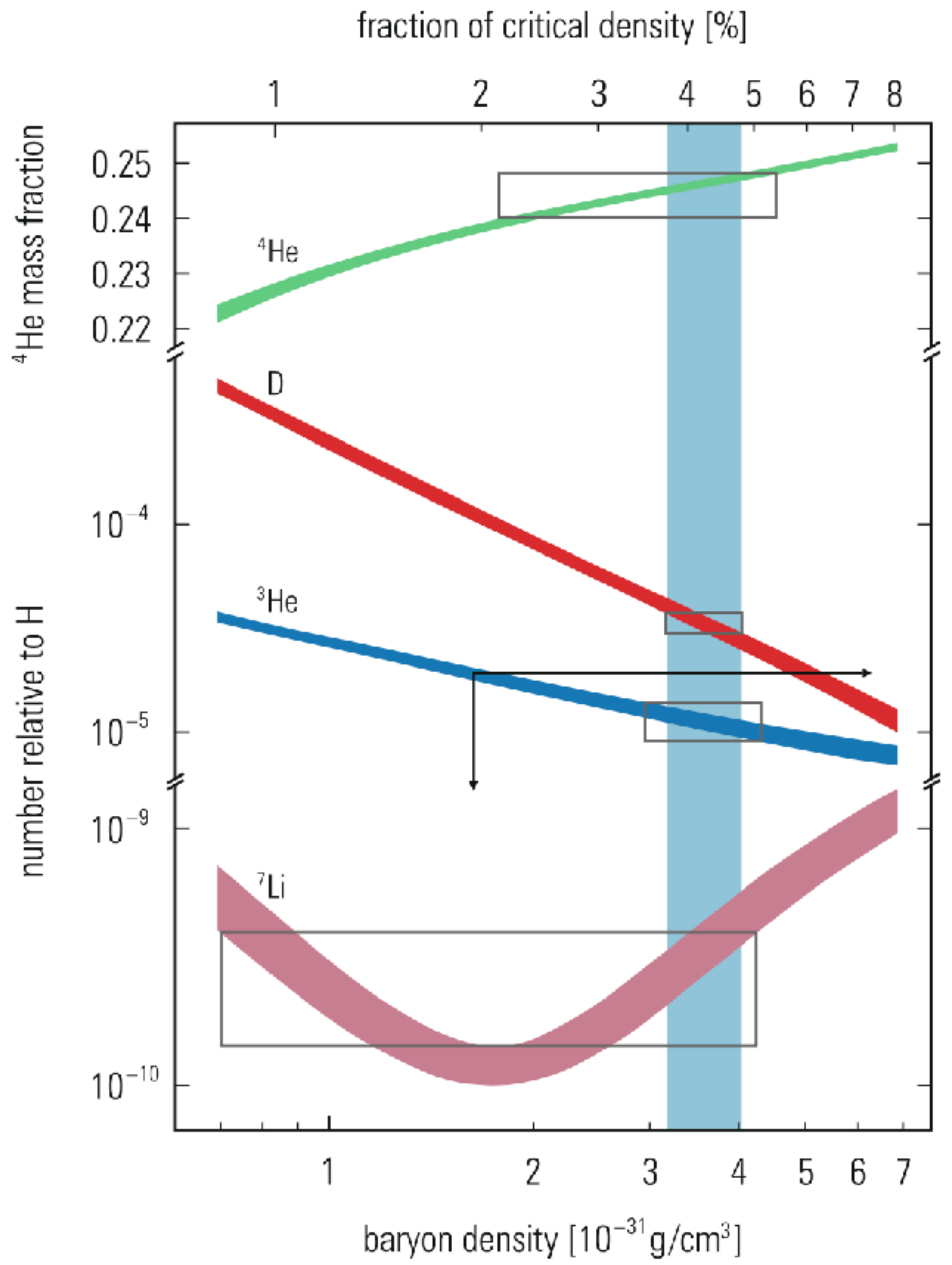


Fig. 10.3 Predictions for the abundance of ^{4}He, D, ^{3}He, and ^{7}Li in their dependence on the baryon density. The ^{4}He fraction is traditionally given as mass fraction. For the other primordial elements their number ratio relative to hydrogen is shown (the *vertical scale* is *broken* at $Y_P = 0.22$ and at $\approx 10^{-6}$). The *rectangles* for the number fractions of the primordial isotopes represent the added statistical and systematic errors. The trend for possible uncertainties of the ^{3}He fraction is indicated [188]

Nucleosynthesis

The **boxes** in Fig. 10.3 **indicate the measured abundances** of ^{4}He and ^{7}Li. The size of the boxes shows the measurement uncertainty.

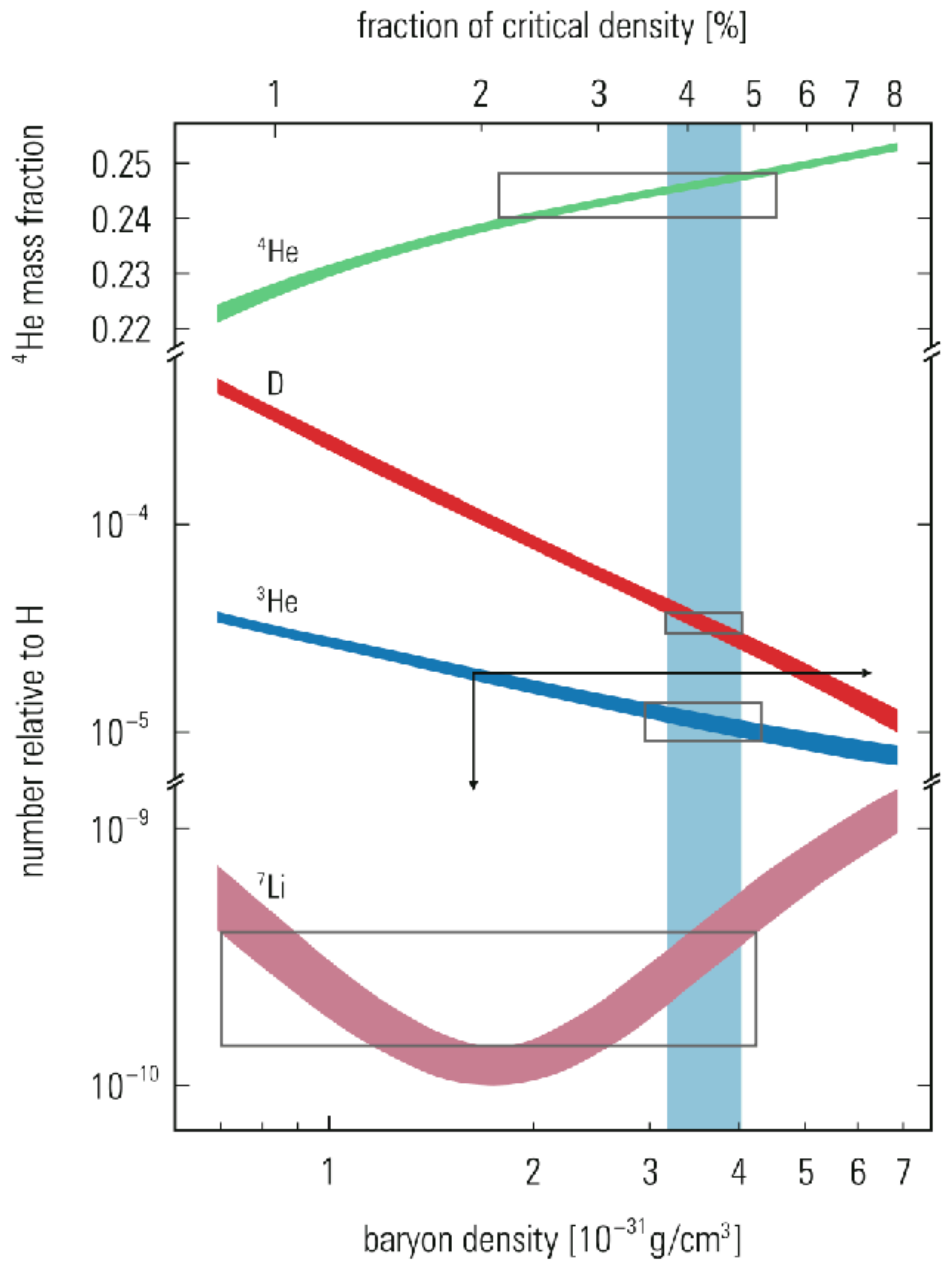
These **measurements agree remarkably well with the predictions**.

The **value of η** = n_b/n_γ **determines the baryon density,** since the **photon density is well-known from** the measured **CMB temperature**, $T = 2.725$ K, and $n_\gamma \sim T^3$.

The value of **η can be converted into** a prediction for the **energy density of baryons** divided by the critical density,

$$\Omega_b = \frac{\varrho_b}{\varrho_c} \,. \qquad (10.5.6)$$

The critical density is $\varrho_c = 3H_0^2/8\pi G$ *(This is based on cosmology models).*



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Nucleosynthesis

The **baryons today are non-relativistic**, so their energy density is simply the number of nucleons per unit volume times the mass of a nucleon, i.e., $\varrho_b = n_b m_N$, where $m_N \approx 0.94$ GeV. Putting these ingredients together gives

$$\Omega_b = 3.67 \times 10^7 \times \eta h^{-2}\,, \qquad (10.5.7)$$

where h is defined by $H_0 = 100\, h$ km s^{-1} Mpc^{-1}. Using $h = 0.71^{+0.04}$ and η from (10.5.5) gives

$$\boxed{\Omega_b = 0.036 \pm 0.005\,, \qquad (10.5.8)}$$

where the uncertainty originates both from that of the Hubble constant and also from that of η.

Recently η and Ω_b have been measured to higher accuracy using the temperature variations in the cosmic microwave background radiation as determined by the WMAP and mainly **Planck satellites**, leading to $\Omega_b = 0.0483 \pm 0.0004$.

The values from the BBN and CMB studies are consistent with each other and, taken together, provide a convincing confirmation of the Big Bang model.

Neutrino families

In this section it will be shown how **the comparison of the measured and predicted ^{4}He mass fractions can result in constraints on the particle content of the universe at BBN temperatures**.

For example, **the Standard Model has $N_\nu = 3$**, but one can ask whether additional families exist. It will be seen that BBN was able to **constrain N_ν to be quite close to three**—a number of years earlier than **accelerator experiments** were able to determine the same quantity to **high precision using electron–positron collisions** at energies near the Z resonance.

Once the parameter **η has been determined**, the predicted **^{4}He mass fraction is fixed** to a narrow range of values close to $Y_P = 0.24$, which is in good **agreement with the measured abundance**. The prediction **depended, however, on the effective number of degrees of freedom**.

The number of effective degrees of freedom ***g* describes the expansion rate according** to

$$H \sim \frac{T^2}{m_{\mathrm{Pl}}}, \tag{10.6.1}$$

where the constant of proportionality for (10.6.1) contains this factor g. **The effective number of degrees of freedom therefore also has an impact on the freeze-out temperature.**

Neutrino families

The freeze-out temperature is larger for higher values of g, and also with N_ν, since **g increases with N_ν** .

At T_f the neutron-to-proton ratio freezes out to $n_n / n_p = e^{-(m_n - m_p)/T_f}$.

If this occurs at a **higher temperature, then the ratio is higher**, i.e., **there are more neutrons available** to make helium, and the helium abundance will come out higher.

A higher freeze-out temperature **also corresponds to earlier times after the Big Bang**, up to which protons and neutrons are in equilibrium, thus they are still quite numerous.

Neutrino families

Figure 10.4 shows the **predicted helium abundance as a function of the baryon density.**

The three diagonal bands show the predicted Y_P **for different values of an equivalent number of neutrino families** $N_\nu = 3.0, 3.2,$ and 3.4.

Of course, this no longer represents the (integer) number of neutrino flavours but rather an effective parameter. The data are **consistent with $N_\nu = 3$** and are clearly incompatible with values much higher than this.

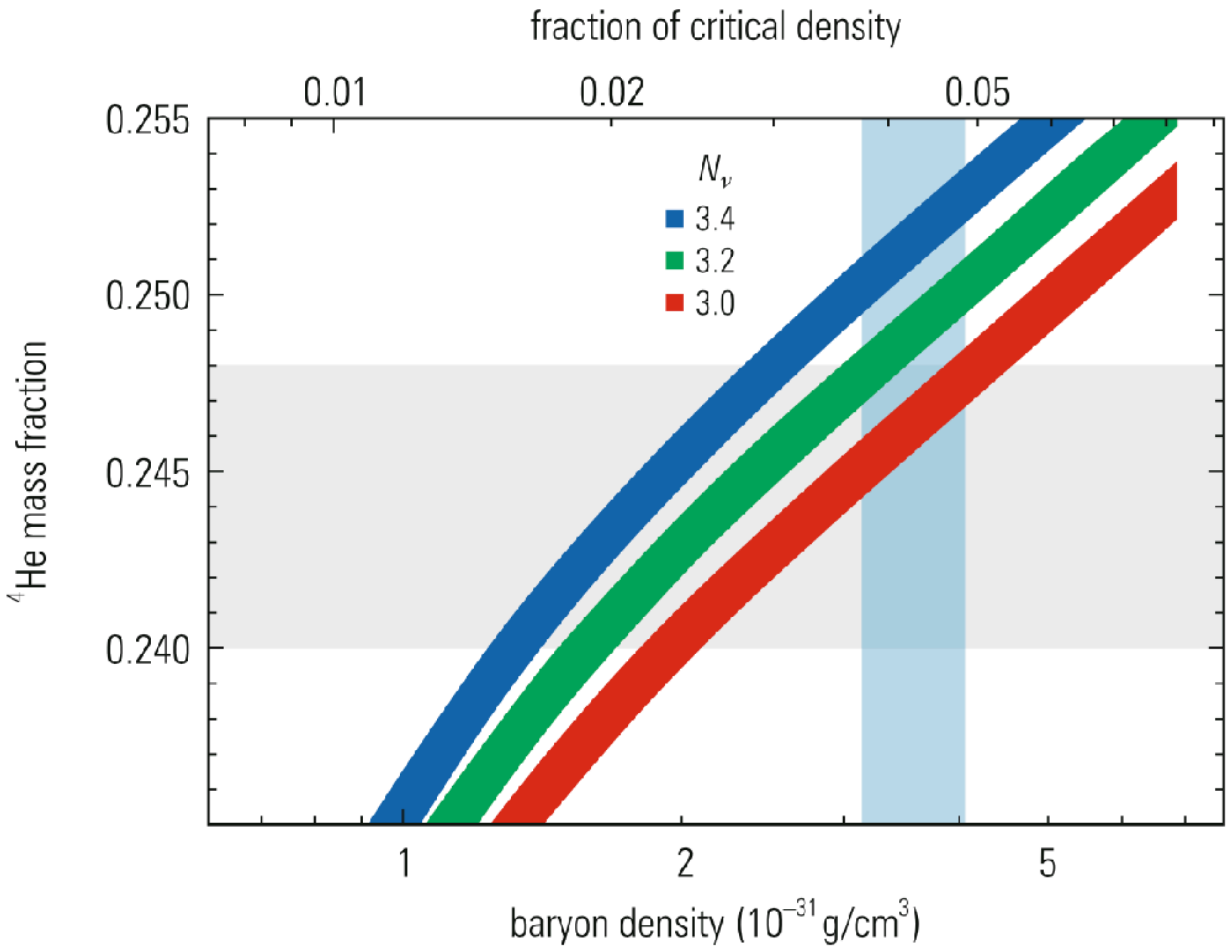

Fig. 10.4 The predicted ^{4}He mass fraction as a function of η for different values of N_{eff} [184, 189, 190]

Neutrino families

Figure 10.5 shows the **expected number of neutrino generations as a function of the baryon density.**

To determine the effective number of neutrino generations from cosmological considerations one uses the relation between the baryon density of the universe and helium isotope ratio, the deuterium-to-hydrogen ratio and the results from the Big Bang blackbody radiation as well as the primordial nucleosynthesis. These results clearly **favour a value of N_{eff} =3. With these cosmological data N_{eff} = 4 is strongly disfavoured.**

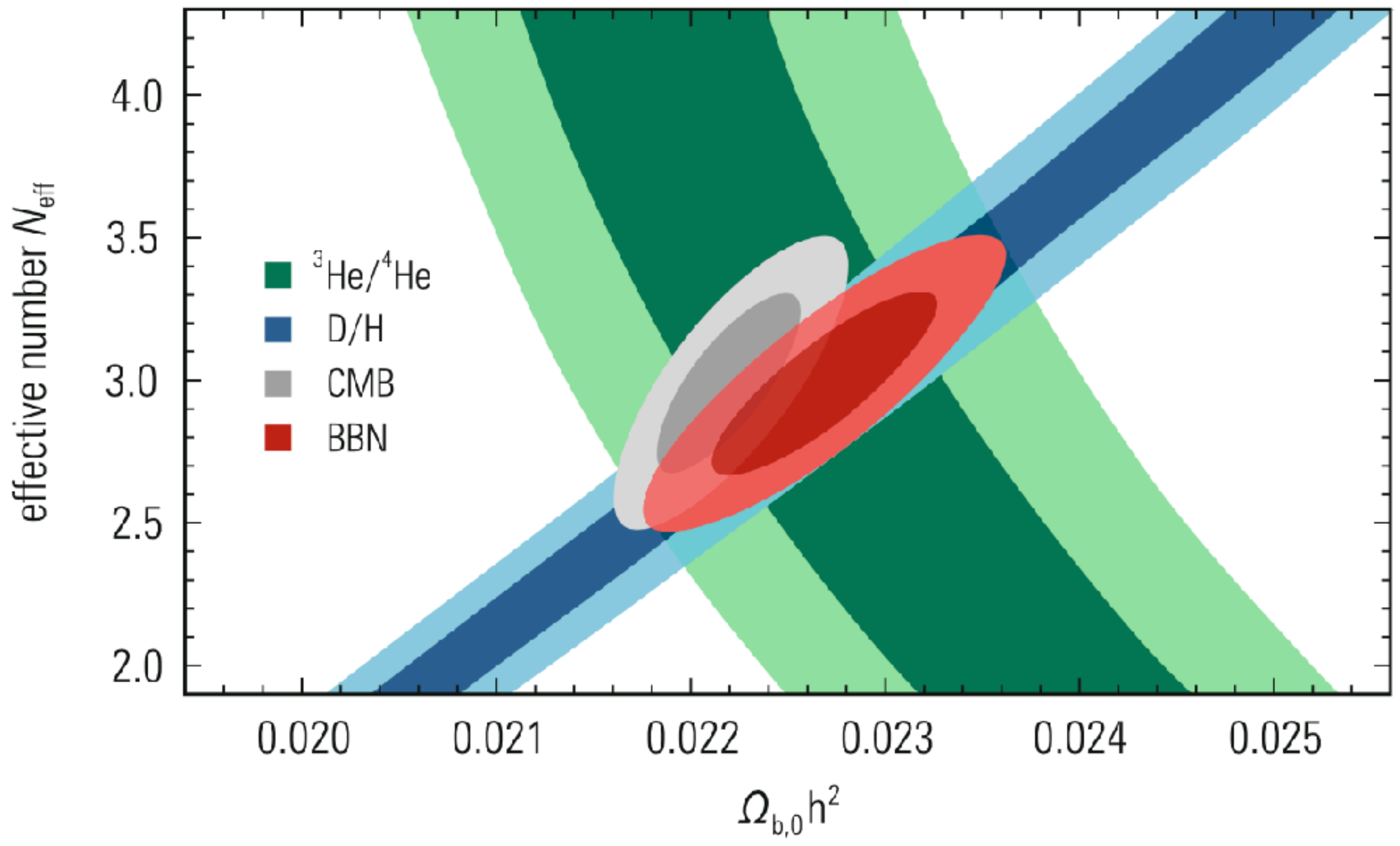

Fig. 10.5 Dependence of the effective number of neutrino generations N_{eff} on the baryon density, the helium isotope ratio, the deuterium-to-hydrogen ratio, and the results from measurements of the cosmic blackbody radiation and the Big Bang nucleosynthesis. The *shaded and dark contours* for the D/H and $^3He/^4He$ ratio represent the 68% and 95% confidence levels, respectively. The measurements of the blackbody radiation (CMB) are from the Planck satellite. The *red contours* show the confidence limits for the combined D/H and $^3He/^4He$ ratio (BBN). $\Omega_{b,0}$ is the cosmic baryon density and h is the Hubble constant in units of 100 km/(s Mpc) [191]

Neutrino families

The **deuterium-to-hydrogen ratio and the CMB data** can also be used to determine the number of neutrino families**.** The results of this analysis are shown in Fig. 10.6.

These data clearly **favour N_{eff} = 3 and exclude N_{eff} = 4**.

Even as early as 1990 a number on the neutrino generations had been derived from the helium abundance, indicating that very likely only three or at most four neutrino generations would exist. The **modern cosmological results** confirm these with **N_{eff} = 3.046.**

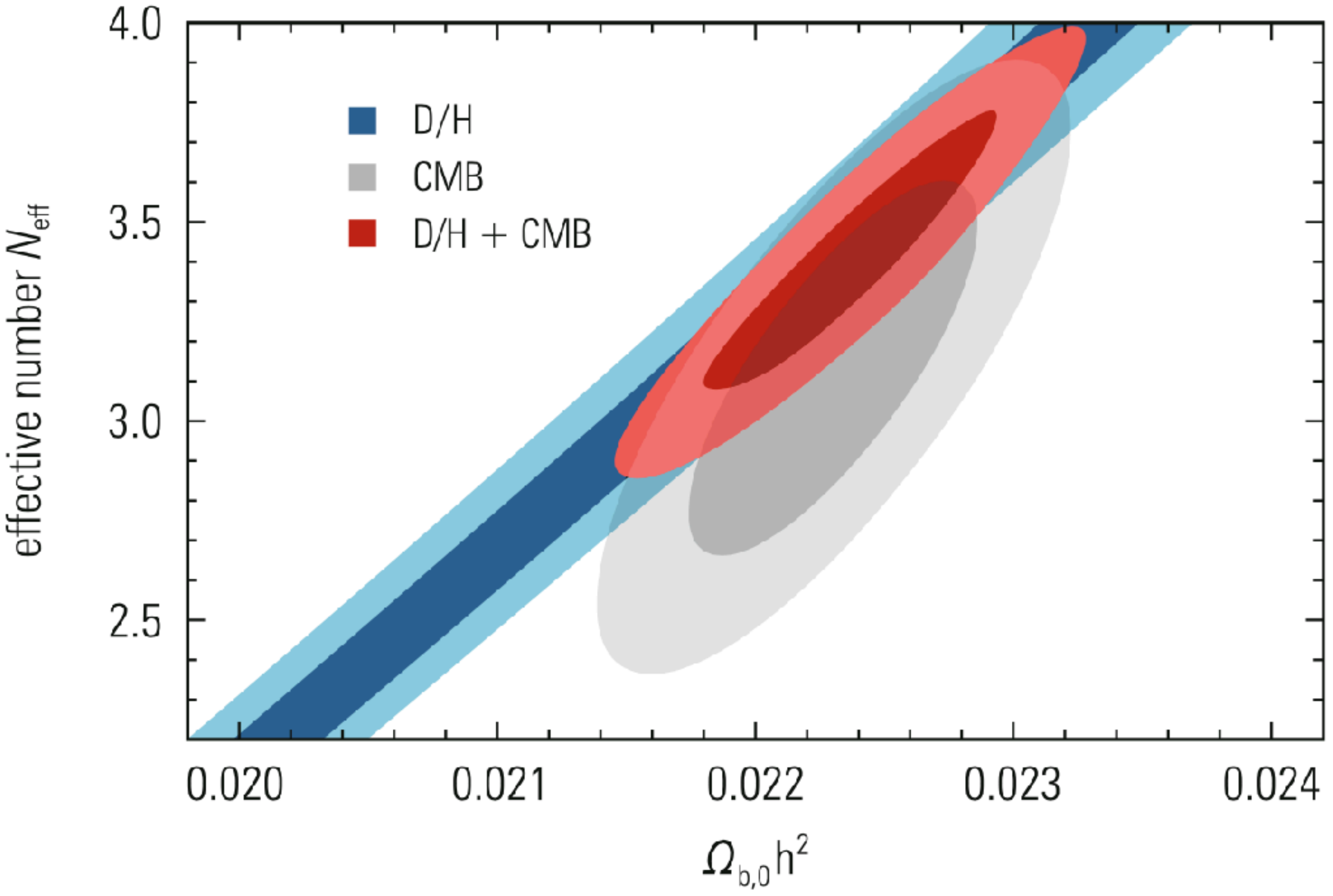

Fig. 10.6 Comparison of the effective number of neutrino generations N_{eff} from the expansion rate with the cosmic baryon density $\Omega_{b,0}h^2$ from Big Bang nucleosynthesis (*blue contours*) and the results from the Cosmological Microwave Background (CMB) (*grey contours*). The *dark and light shades* illustrate the 68% and 95% confidence contours, respectively, for the deuterium/hydrogen (D/H) ratio and the Big Bang nucleosynthesis (CMB) [193]

Neutrino families

$$Z \to \nu_x + \bar{\nu}_x \, .$$

The equivalent number of light neutrino families has also been determined at the **Large Electron–Positron (LEP)** collider from the total width of the ***Z* resonance**, as was shown in Fig. 2.1.

From a combination of data from the LEP experiments one finds

$$N_\nu = 2.9835 \pm 0.0083 \, . \tag{10.6.2}$$

Although this is below 3, it is clear that $\boldsymbol{N_\nu = 3}$ **fits reasonably well and that any other integer value is excluded.**

This number is to be compared to the result from cosmology, given as

$$N_\nu = 3.046 \tag{10.6.3}$$

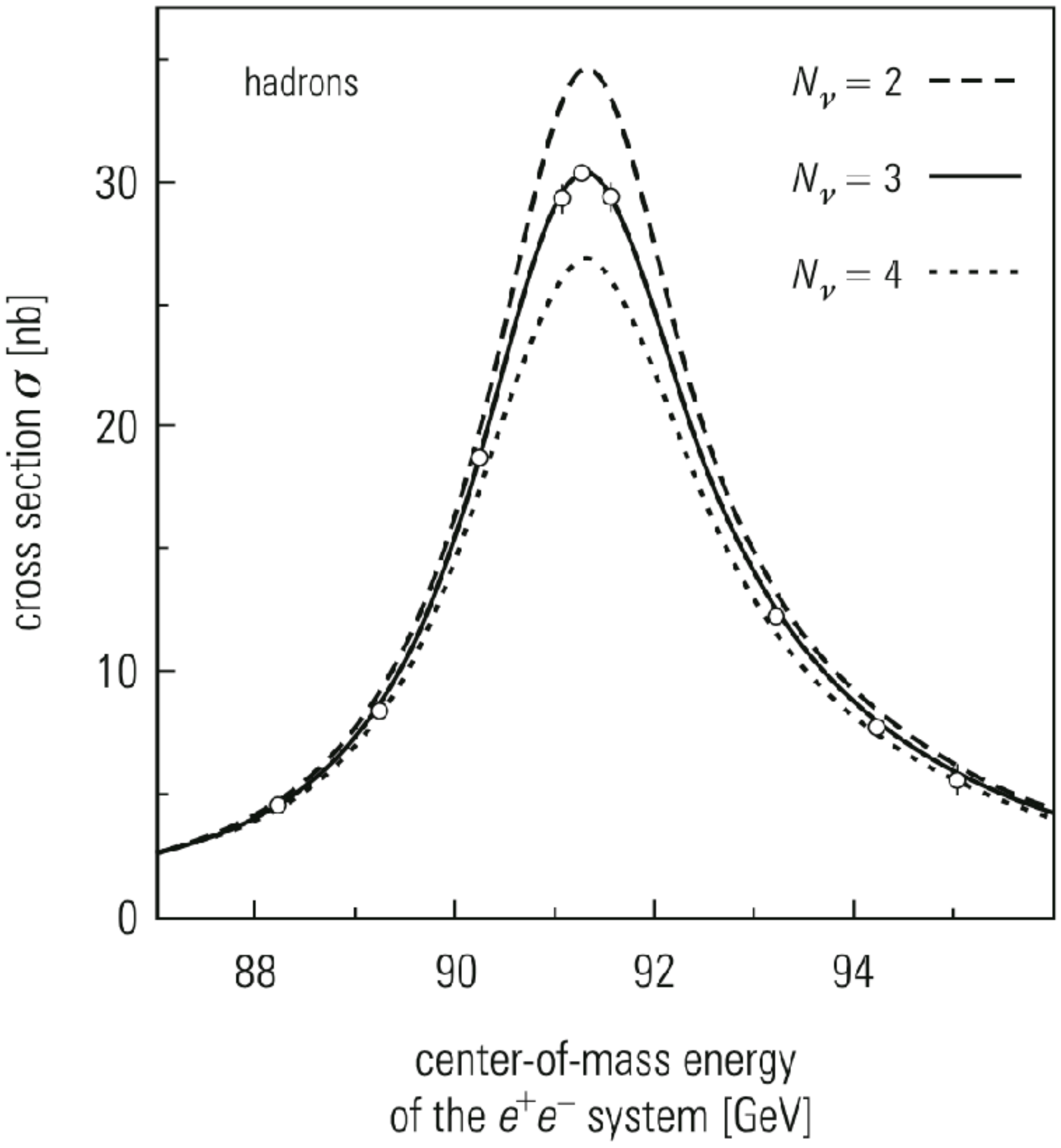

Fig. 2.1 Determination of the number of neutrino generations from Z decay

Neutrino families

The interplay between these two different determinations of N_ν played an important role in alerting particle physicists to the relevance of cosmology. Although the example that has just been discussed is for the number of neutrino families, the same arguments apply to any particles that would contribute to g such as to affect the neutron freeze-out temperature. Thus **the abundances of light elements provide important constraints for any theory involving new particles that would contribute significantly to the energy density during the BBN era.**