Primordial Nucleosynthesis

(K&T chapter 4)

Kinetic eqm, nuclear species A(Z) with mass A and charge Z:

$$n_A = g_A \left(\frac{m_A T}{2\pi} \right)^{3/2} \exp\left(\frac{\mu_A - m_A}{T} \right)$$

Chemical eqm:

$$\mu_A = Z\mu_p + (A - Z)\mu_n$$

Binding energy:

$$B_A \equiv Zm_p + (A - Z)m_n - m_A$$

Mass fraction: $X_A \equiv \dfrac{n_A A}{n_N}$ N => all nucleons

Eqm result:

$$n_A = g_A A^{3/2} 2^{-A} \left(\frac{2\pi}{m_N} \right)^{3(A-1)/2} n_p^Z n_n^{(A-Z)} \exp(B_A / T)$$

Binding energies of some light nuclei

${}^{A}Z$	B_A	g_A
${}^{2}H$	2.22 MeV	3
${}^{3}H$	6.92 MeV	2
${}^{3}He$	7.72 MeV	2
${}^{4}He$	28.3 MeV	1
${}^{12}C$	92.2 MeV	1

Phase 1: Nuclear statistical eqm in the early universe

T>> 1MeV

Free protons and neutrons

Eqm maintained by

$$p + e^- \longleftrightarrow n + \nu$$

$$n + e^+ \longleftrightarrow p + \bar{\nu}$$

$$n + \nu_e \rightleftarrows p + e^-$$

$$\frac{n_n}{n_p} = \left(\frac{m_n}{m_p}\right)^{3/2} \exp\left(-\frac{(m_n - m_p)}{T}\right) \approx \exp\left(-\frac{1.29MeV}{T}\right) \approx 1$$

Phase 2: Weak interactions no longer maintain eqm, but do facilitate neutron decay

T<< 1MeV

Free protons and neutrons

$$n \longrightarrow p + e^- + \bar{\nu}$$

Phase 3: Formation of light elements

0.1MeV < T < 0.3MeV

Essentially all n's bind into He (7:1 ratio of p:n ➔He 25% by mass)

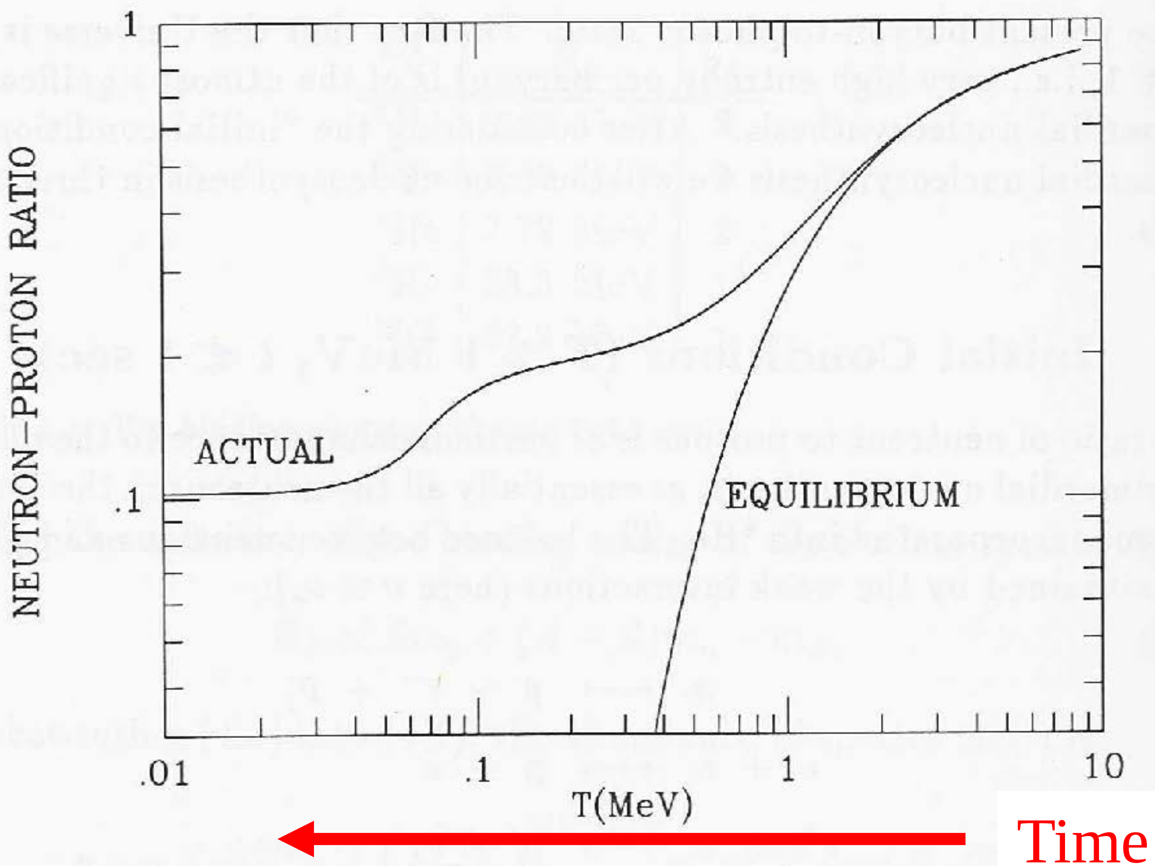
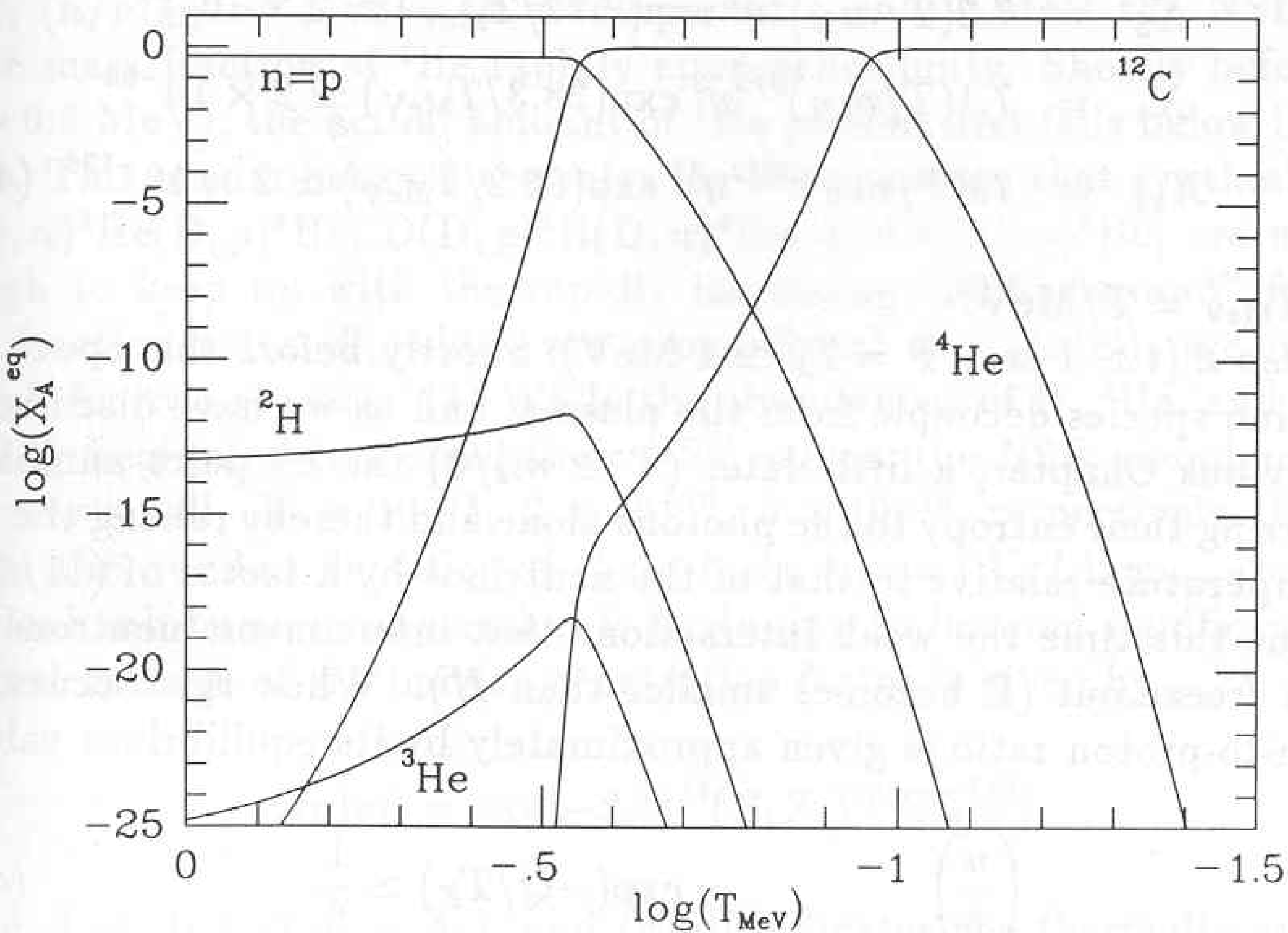
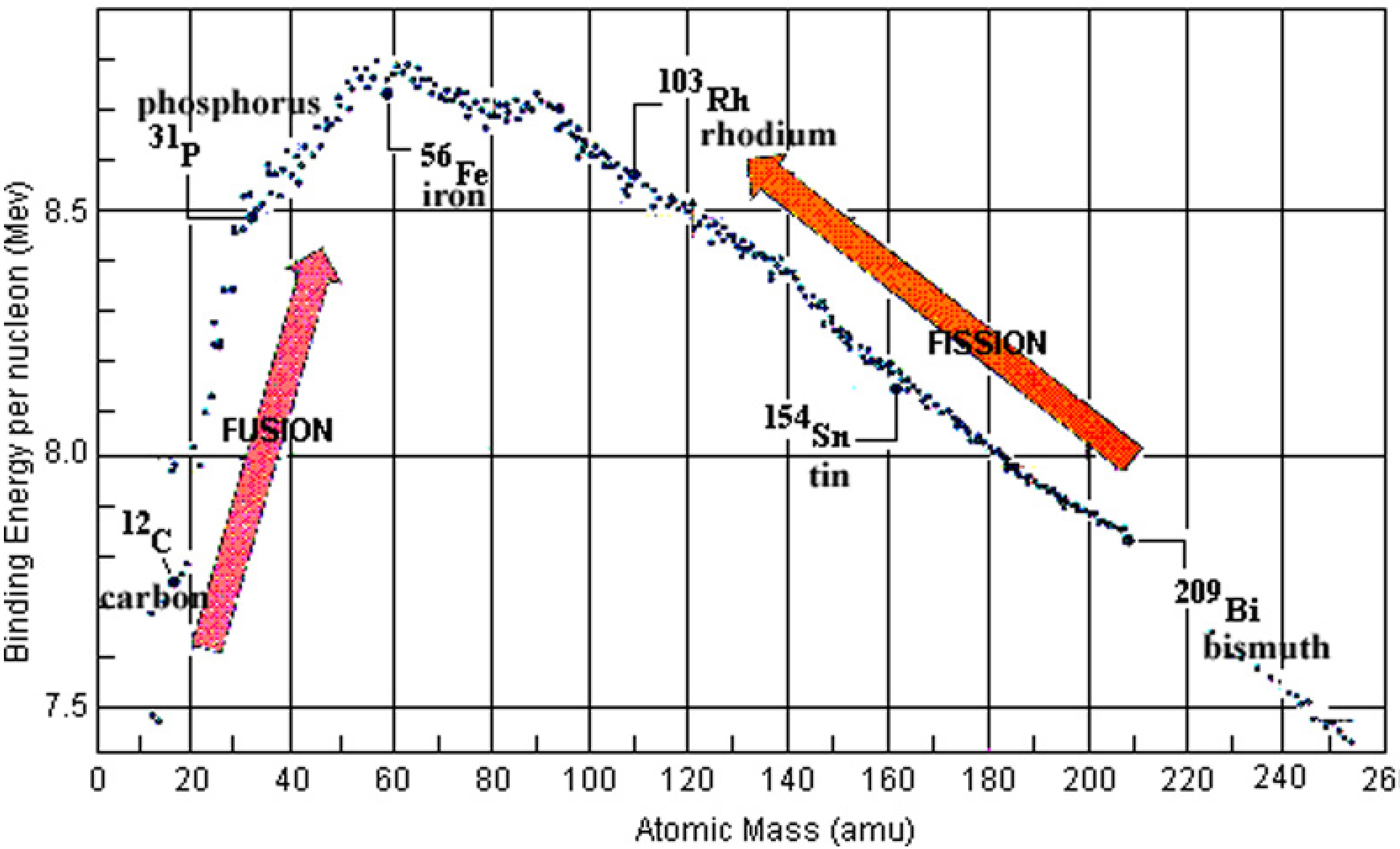


Fig. 4.1: The equilibrium and actual values of the neutron to proton ratio.

EQM





Binding Energy per nucleon (Mev)
Atomic Mass (amu)
8.5
8.0
7.5
0
20
40
60
80
100
120
140
160
180
200
220
240
260
phosphorus
31P
56Fe
iron
103Rh
rhodium
FUSION
FISSION
154Sn
tin
12C
carbon
209Bi
bismuth

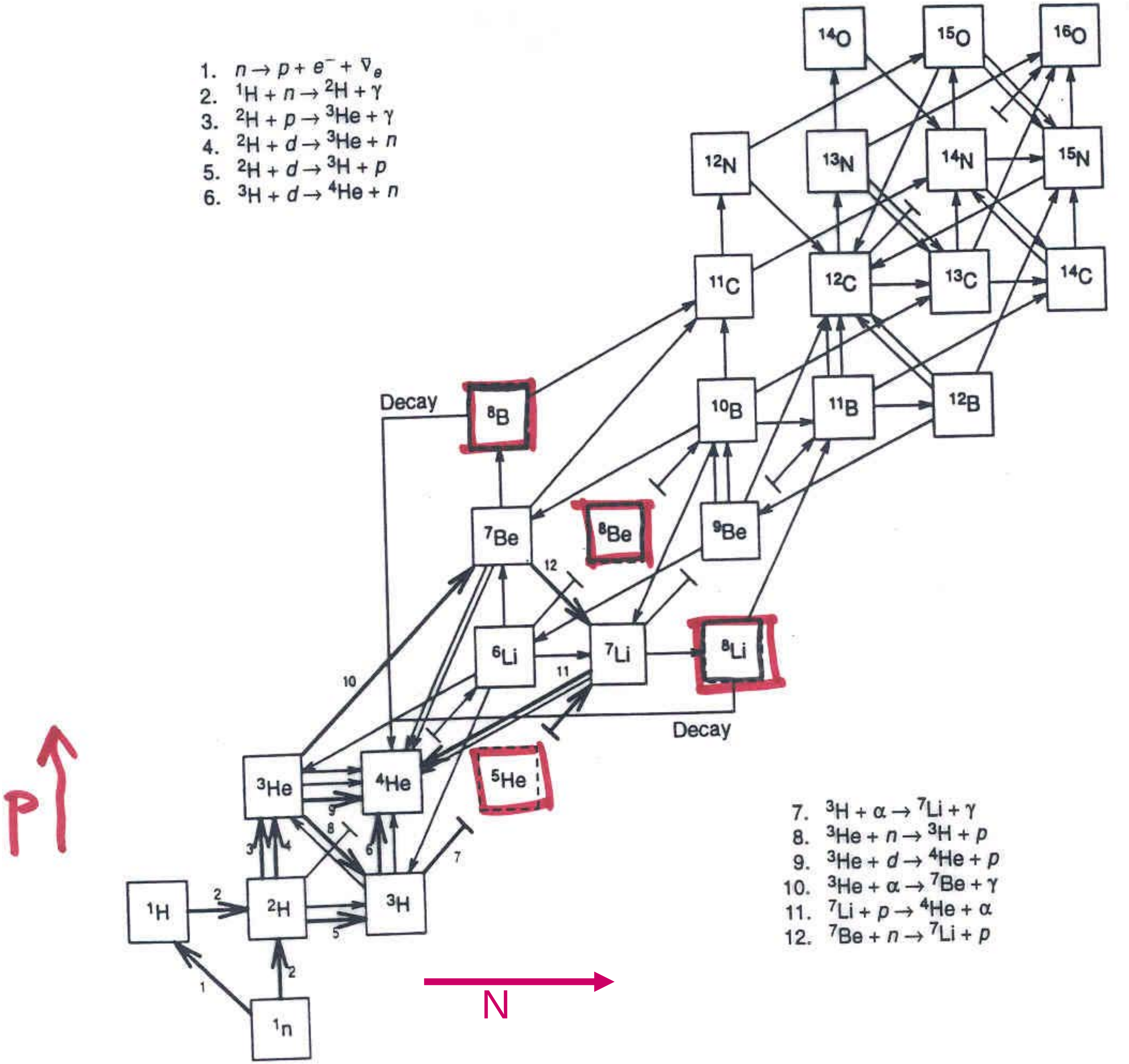
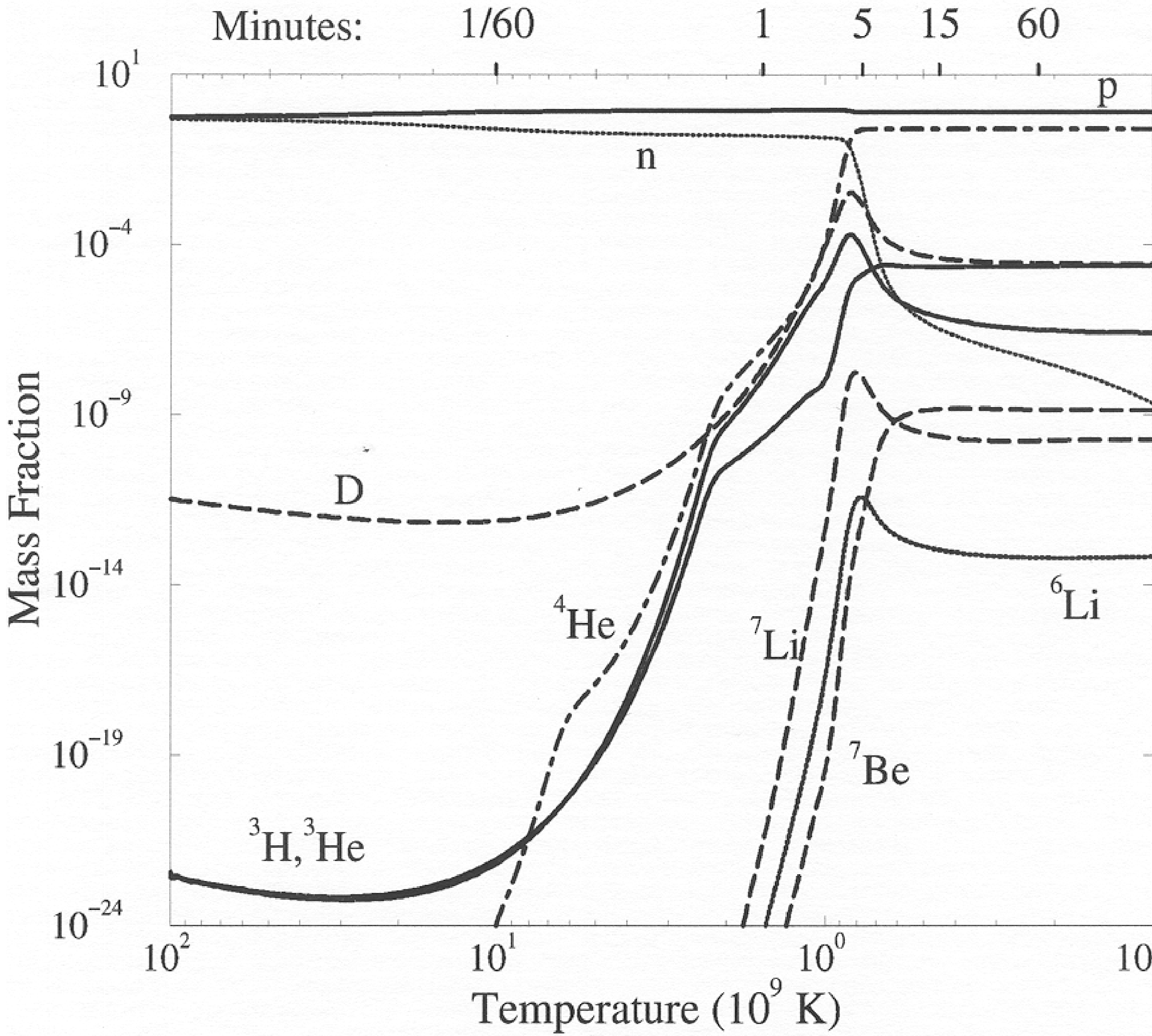


Fig. 2. The nuclear reaction network used for big-bang nucleosynthesis; the most important reactions are numbered and have bold arrows. The broken boxes for mass 5 and 8 indicate that all nuclides of this mass are very unstable.


Minutes:
1/60
1
5
15
60
10^1
10^{-4}
10^{-9}
10^{-14}
10^{-19}
10^{-24}
Mass Fraction
p
n
D
^{4}He
^{7}Li
^{6}Li
^{7}Be
^{3}H, ^{3}He
10^2
10^1
10^0
10^{-1}
Temperature (10^9 K)

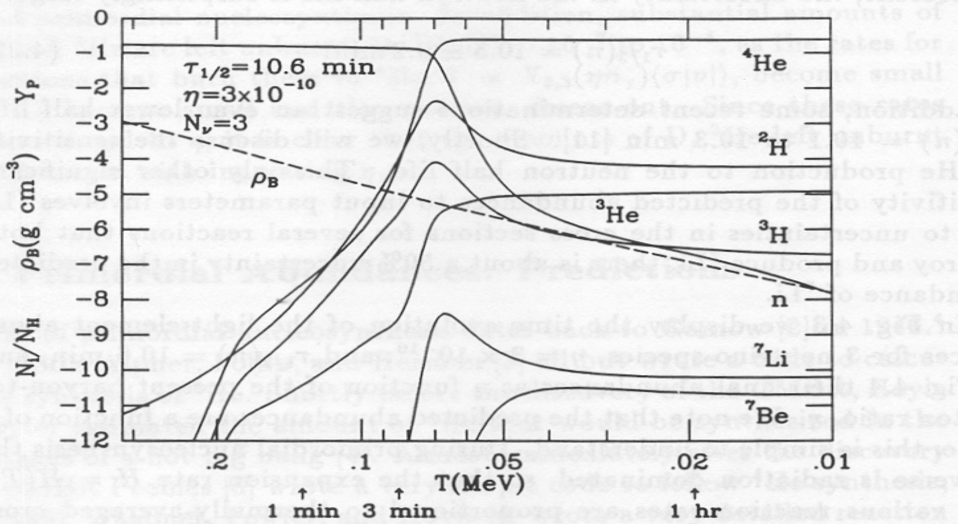
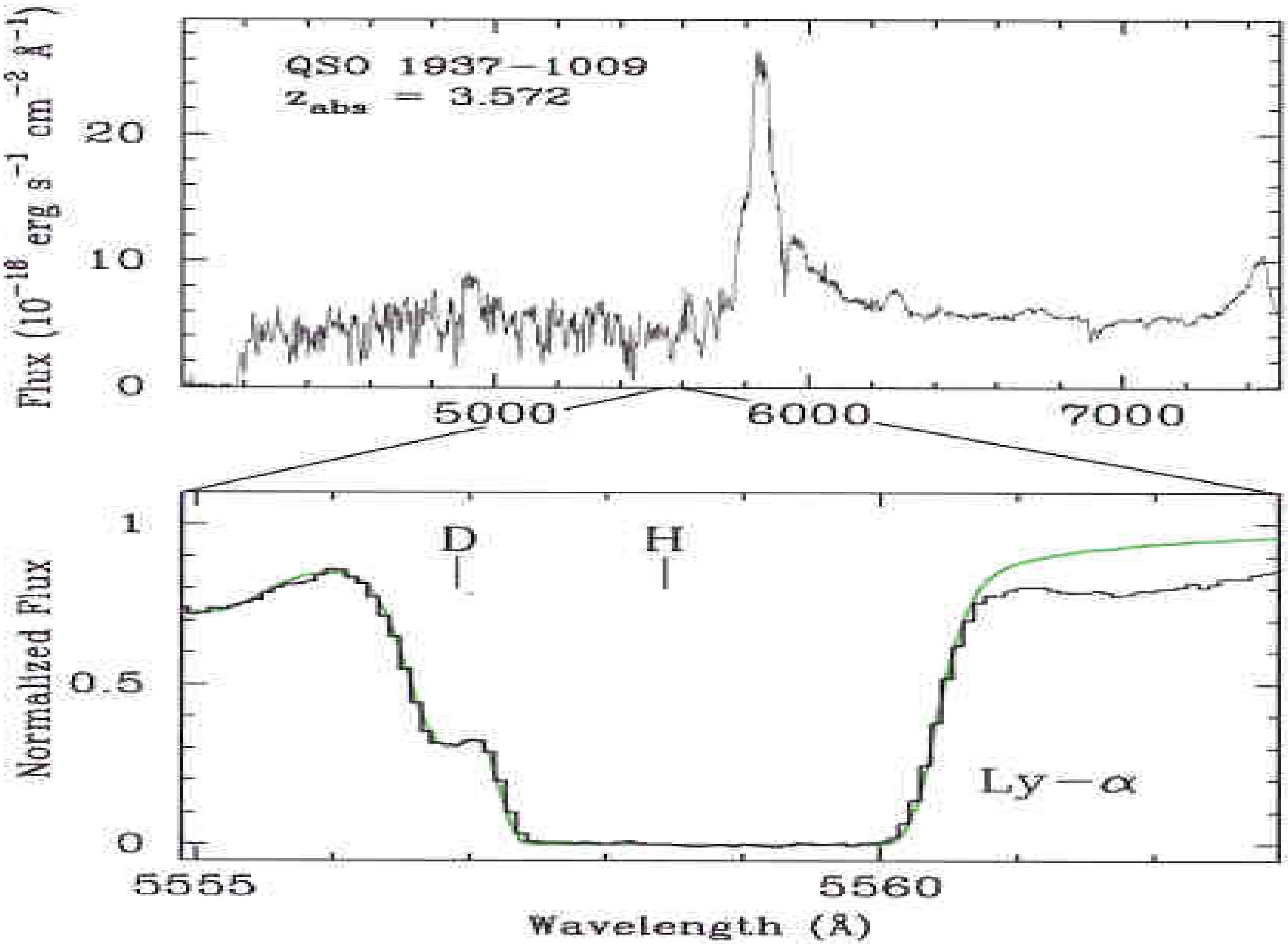


Fig. 4.3: The development of primordial nucleosynthesis. The dashed line is the baryon density, and the solid lines are the mass fraction of ^{4}He, and the number abundance (relative to H) for the other light elements.



QSO 1937−1009
z_{abs} = 3.572
Flux (10^{-18} erg s^{-1} cm^{-2} Å^{-1})
0
10
20
5000
6000
7000
Normalized Flux
1
0.5
0
D
H
Ly−α
5555
5560
Wavelength (Å)

Measurements of primordial Helium

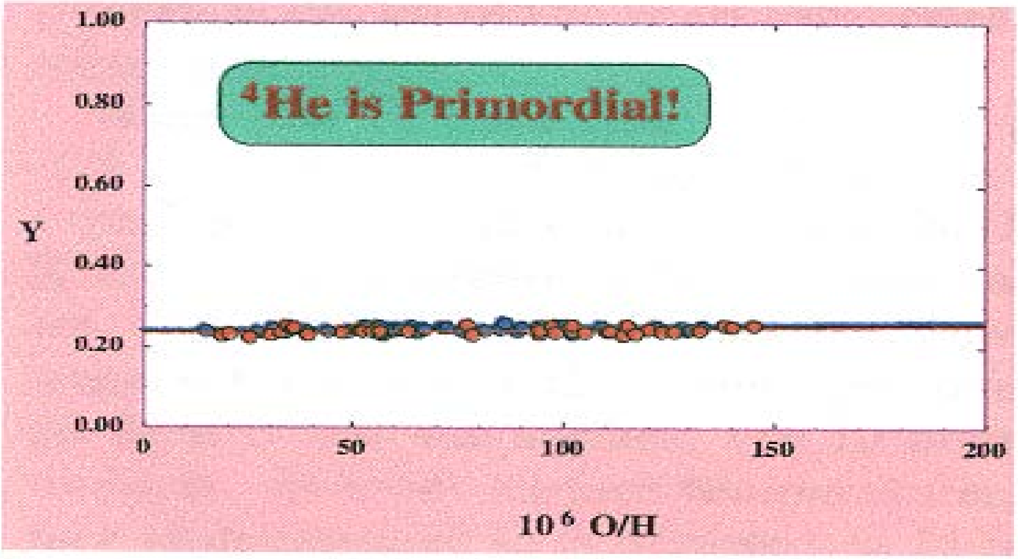


Figure 2. The ^{4}He mass fraction as determined in extragalactic H II regions as a function of O/H.

Figure from K. Olive in the proceedings of the Texas Symposium astro-ph/9903309

Nitrogen is not primordial

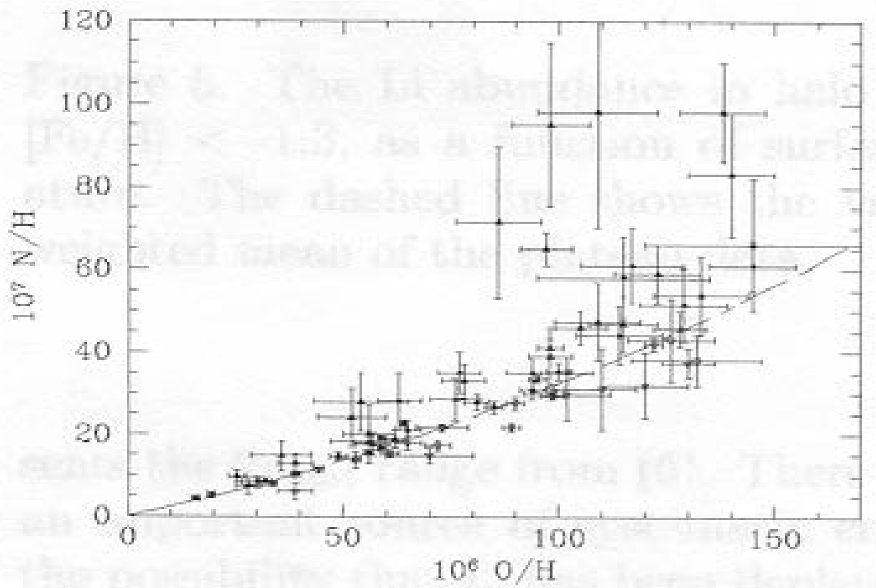


Figure 3. The Nitrogen and Oxygen abundances in the same extragalactic HII regions with observed ^{4}He shown in Figure 2.

Figure from K. Olive in the proceedings of the Texas Symposium astro-ph/9903309

BBN Predictions and Observations

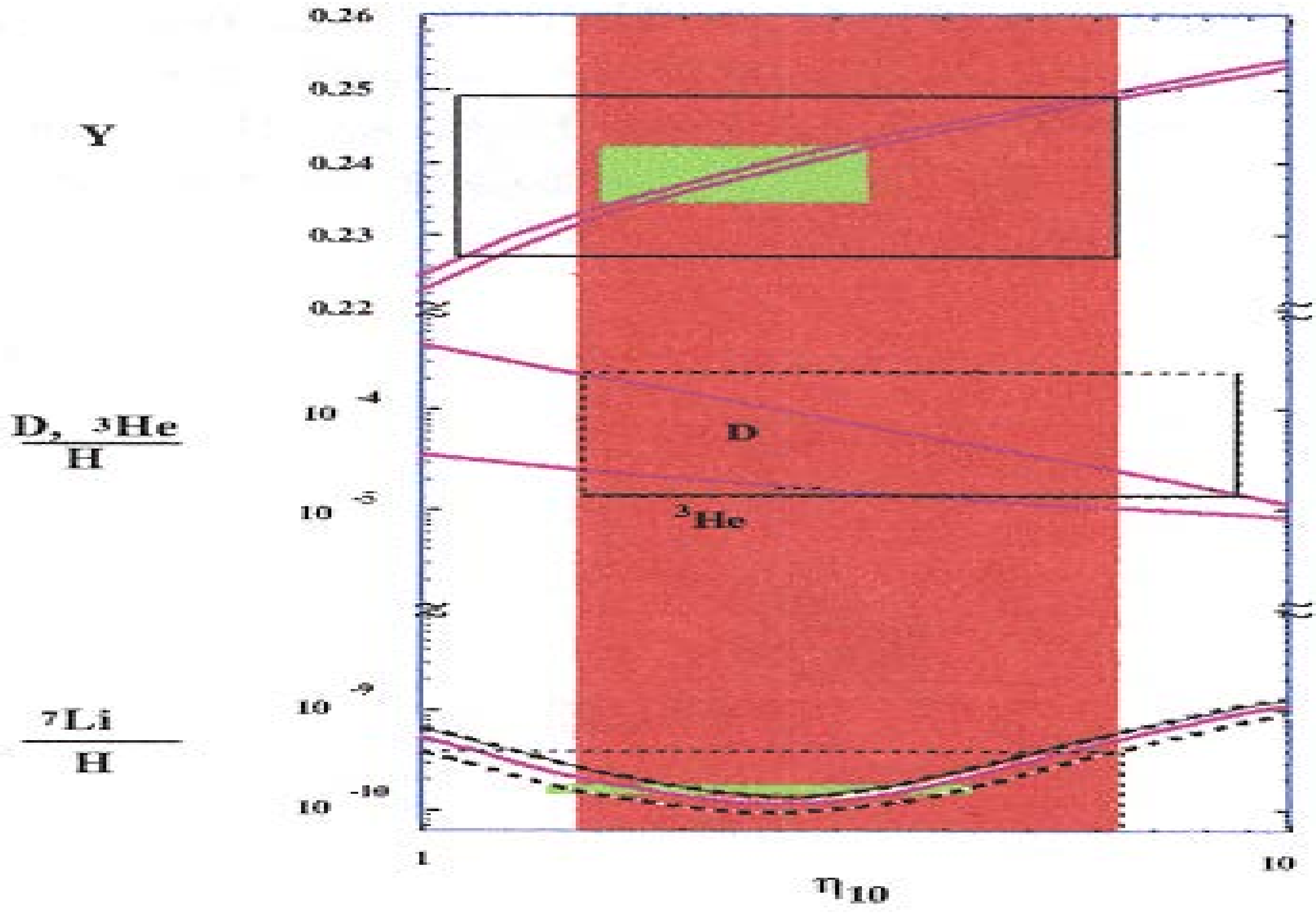
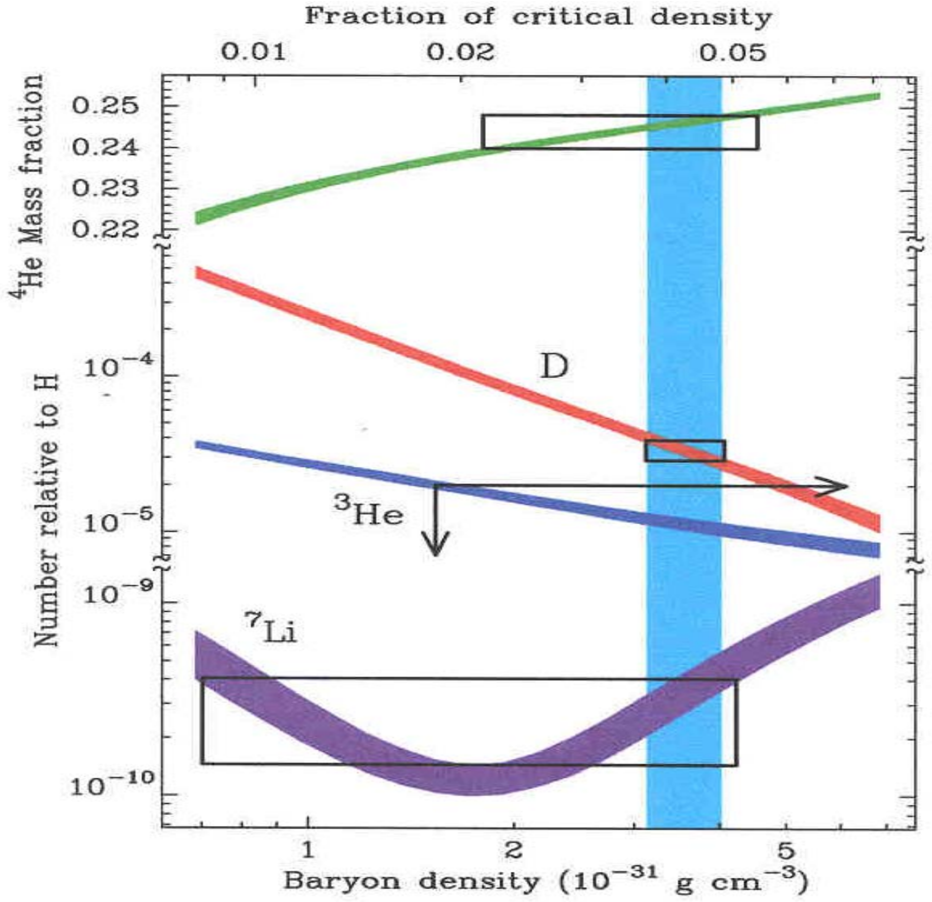


Figure from K. Olive in the proceedings of the Texas Symposium astro-ph/9903309

Big Bang Nucleosynthesis: Predictions and observations



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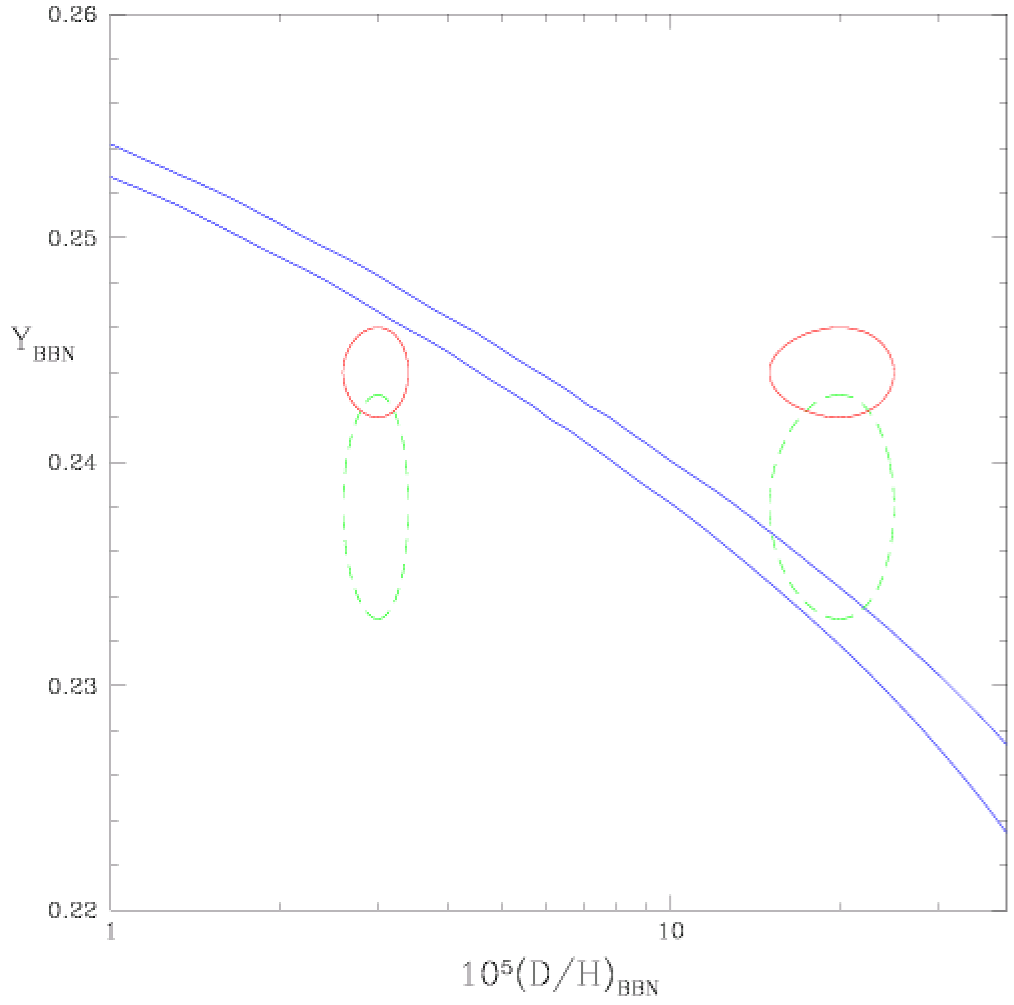


Around 2001(astro-ph/0102152): Conflicting data

WMAP

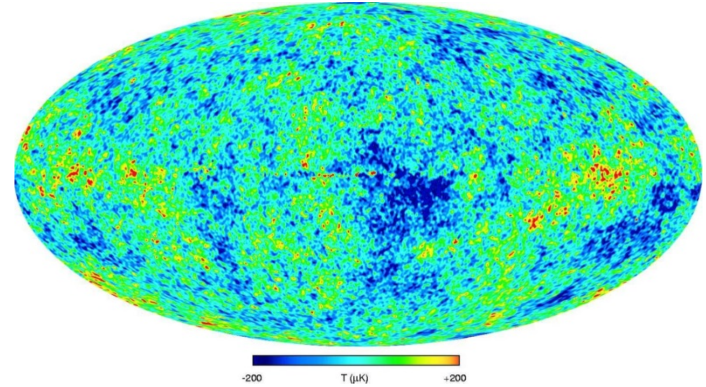
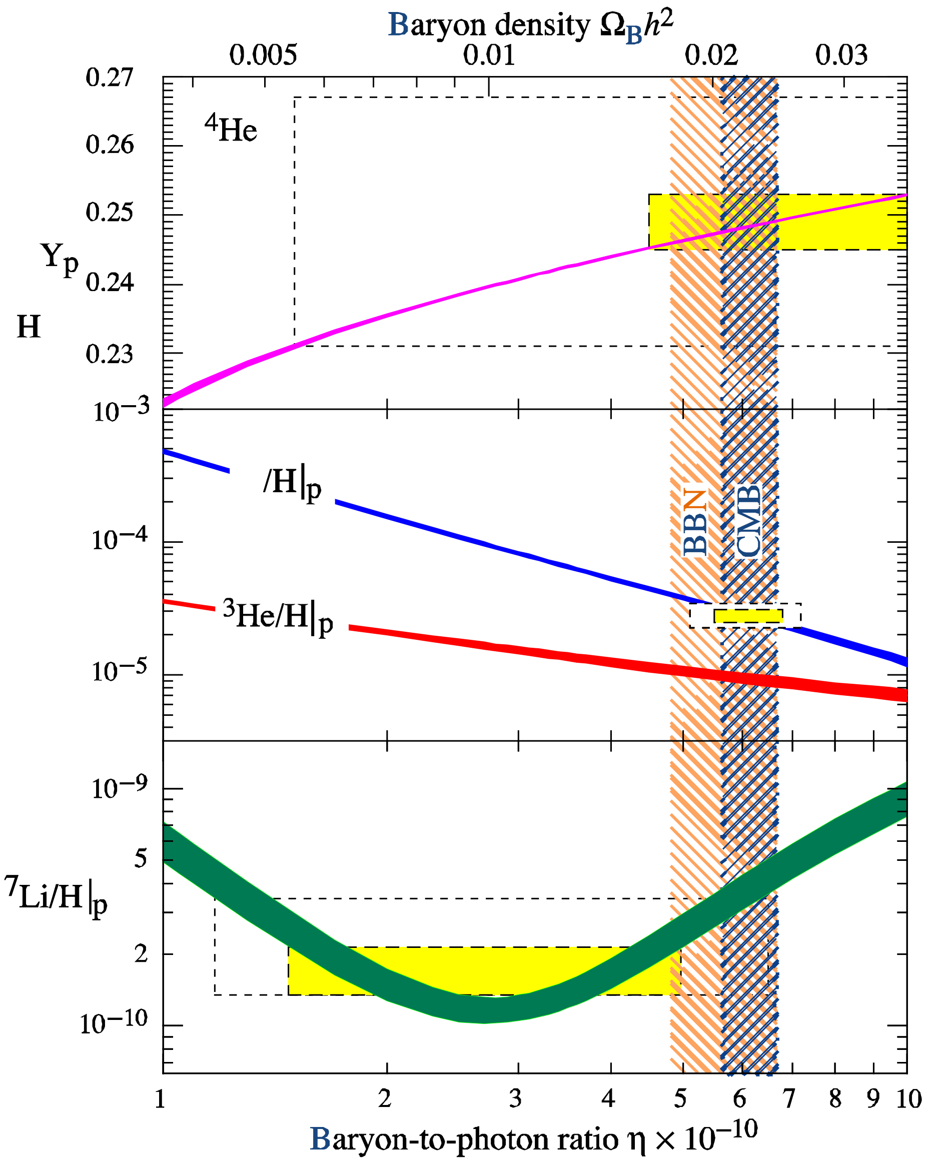


Table 3. "Best" Cosmological Parameters

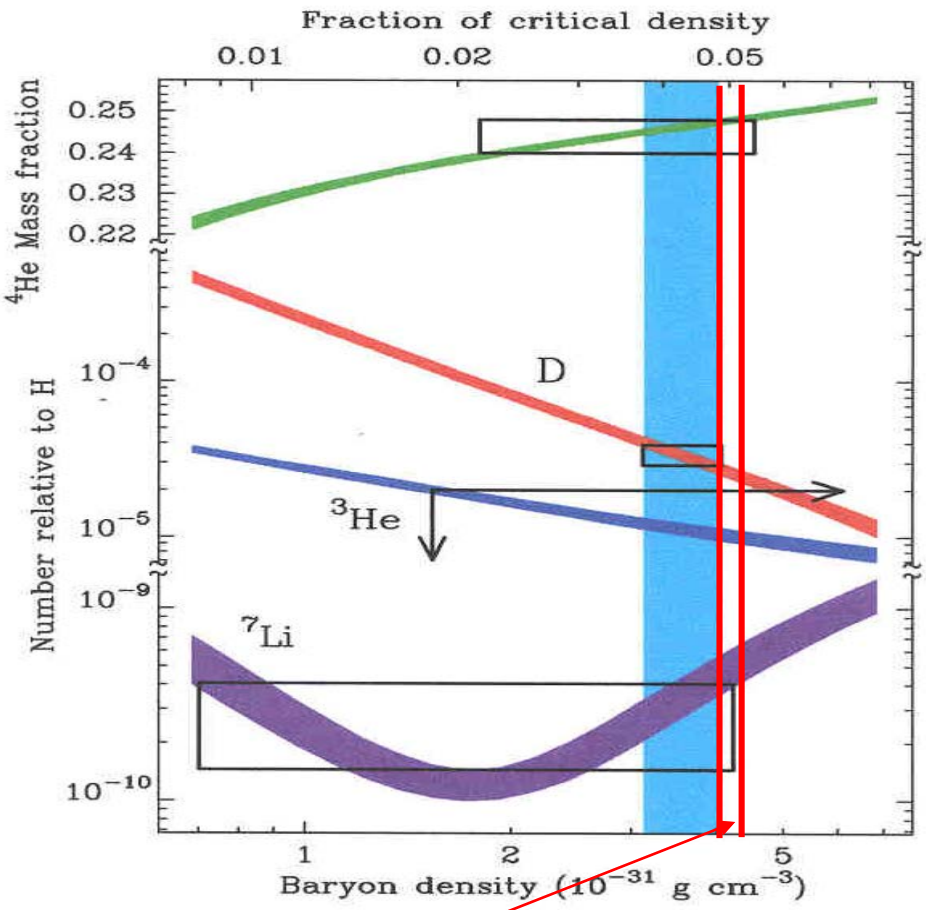
Description	Symbol	Value	+ uncertainty	− uncertainty
Total density	Ω_{tot}	1.02	0.02	0.02
Equation of state of quintessence	w	< -0.78	95% CL	—
Dark energy density	Ω_Λ	0.73	0.04	0.04
Baryon density	$\Omega_b h^2$	0.0224	0.0009	0.0009
Baryon density	Ω_b	0.044	0.004	0.004
Baryon density (cm^{-3})	n_b	2.5×10^{-7}	0.1×10^{-7}	0.1×10^{-7}
Matter density	$\Omega_m h^2$	0.135	0.008	0.009
Matter density	Ω_m	0.27	0.04	0.04
Light neutrino density	$\Omega_\nu h^2$	< 0.0076	95% CL	—

Bennett et al Feb 11 '03



Baryon density $\Omega_B h^2$
0.005
0.01
0.02
0.03
0.27
0.26
0.25
0.24
0.23
Y_p
H
^{4}He
10^{-3}
10^{-4}
10^{-5}
/H|p
^{3}He/H|p
BBN
CMB
10^{-9}
5
2
10^{-10}
^{7}Li/H|p
1
2
3
4
5
6
7
8
9
10
Baryon-to-photon ratio $\eta \times 10^{-10}$

Big Bang Nucleosynthesis:
Predictions and observations



1-sigma WMAP analysis

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