Heavier Elements, I

Once deuterium present:

nucleosynthesis of lighter elements:

$$\begin{aligned} \mathrm{D}+\mathrm{D} &\longrightarrow \mathrm{T}+\mathrm{p} \\ \mathrm{D}+\mathrm{n} &\longrightarrow \mathrm{T}+\gamma \\ \mathrm{D}+\mathrm{p} &\longrightarrow {}^{3}\mathrm{He}+\gamma \\ \mathrm{D}+\mathrm{D} &\longrightarrow {}^{3}\mathrm{He}+\mathrm{n} \\ {}^{3}\mathrm{He}+\mathrm{n} &\longrightarrow \mathrm{T}+\mathrm{p} \end{aligned} \tag{6.93}$$

production of ^{4}He:

$$\begin{aligned} \mathrm{D}+\mathrm{D} &\longrightarrow {}^{4}\mathrm{He}+\gamma \\ \mathrm{D}+{}^{3}\mathrm{He} &\longrightarrow {}^{4}\mathrm{He}+\mathrm{p} \\ \mathrm{T}+\mathrm{D} &\longrightarrow {}^{4}\mathrm{He}+\mathrm{n} \\ {}^{3}\mathrm{He}+{}^{3}\mathrm{He} &\longrightarrow {}^{4}\mathrm{He}+2\mathrm{p} \\ \mathrm{T}+\mathrm{p} &\longrightarrow {}^{4}\mathrm{He}+\gamma \\ {}^{3}\mathrm{He}+\mathrm{n} &\longrightarrow {}^{4}\mathrm{He}+\gamma \end{aligned} \tag{6.94}$$

Heavier Elements, II

Element gap at $A = 5$ can be overcome to produce Lithium:

$$\begin{aligned} {}^{3}\mathrm{He}+{}^{4}\mathrm{He} &\longrightarrow {}^{7}\mathrm{Be}+\gamma \\ {}^{7}\mathrm{Be} &\longrightarrow {}^{7}\mathrm{Li}+\mathrm{e}^{+}+\nu_{\mathrm{e}} \\ \mathrm{T}+{}^{4}\mathrm{He} &\longrightarrow {}^{7}\mathrm{Li}+\mathrm{e}^{+}+\nu_{\mathrm{e}} \end{aligned} \tag{6.95}$$

Gap at $A = 8$ prohibits production of heavier isotopes.

$\Longrightarrow$ Major product of BBN: ^{4}He.

Mass fraction of ^{4}He can be estimated assuming all neutrons incorporated into ^{4}He
$\Longrightarrow$ number density of H=number of remaining protons, i.e., mass fraction

$$X = \frac{n_{\mathrm{p}} - n_{\mathrm{n}}}{n_{\mathrm{p}} + n_{\mathrm{n}}} \tag{6.96}$$

and

$$Y = 1 - \frac{n_{\mathrm{p}} - n_{\mathrm{n}}}{n_{\mathrm{p}} + n_{\mathrm{n}}} = 2\left(1 + \frac{n_{\mathrm{p}}}{n_{\mathrm{n}}}\right)^{-1} \tag{6.97}$$

Because of neutron decay, at $k_{\mathrm{B}}T = 0.8\,\mathrm{MeV}$: $n_{\mathrm{n}}/n_{\mathrm{p}} = 1/7$, such that

BBN predicts primordial He-abundance of $Y = 0.25$.

Remarkable Things

Note the following coincidences:

1. Freeze out of nucleons simultaneous to freeze out of neutrinos.
2. . . . and parallel to electron-positron annihilation.
3. Expansion is slow enough that neutrons can be bound to nuclei.

$\Longrightarrow$ Long chain of coincidences makes our current universe possible!

Detailed Calculations, I

1. Generally, BBN operates as a function of the entropy per baryon, η.
   Remember that the entropy density for a baryon is

$$s = \frac{7}{8}\frac{2\pi^2}{45} g k_{\mathrm{B}} \left(\frac{k_{\mathrm{B}}T}{\hbar c}\right)^3 = \frac{7}{8}\frac{2\pi^4}{45\,\zeta(3)} k_{\mathrm{B}}\, n \tag{6.73}$$

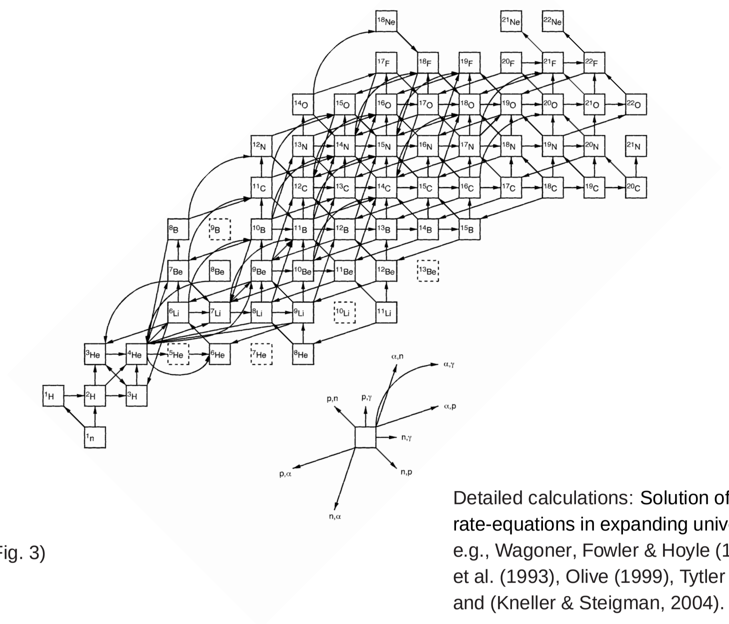
   and therefore the entropy per baryon is

$$\eta = \frac{n_{\mathrm{CMBR}}}{n_{\mathrm{baryons}}} \tag{6.98}$$

   Note that η is related to Ω in baryons, Ω_{B}:

$$\Omega_{\mathrm{B}} = 3.67 \times 10^{7} \cdot \eta \tag{6.99}$$

   (since η, Ω determine expansion behavior)
   $\Longrightarrow$ Perform computations as function of η!
2. Since Y is set by $n_{\mathrm{p}}/n_{\mathrm{n}}$
   $\Longrightarrow$ He abundance is relatively independent from η

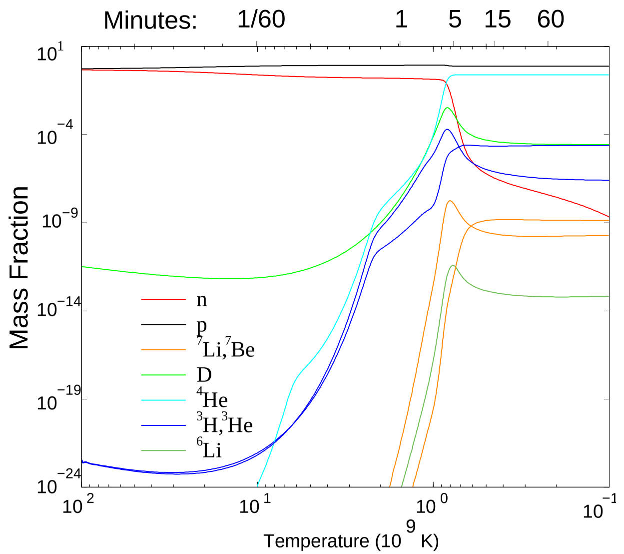


(Olive, 1999, Fig. 3)

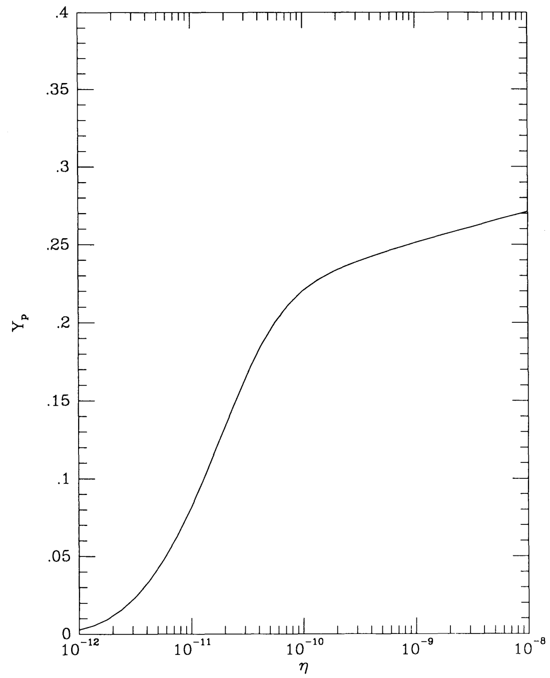
Detailed calculations: Solution of rate-equations in expanding universe, see, e.g., Wagoner, Fowler & Hoyle (1967), Thomas et al. (1993), Olive (1999), Tytler et al. (2000), and (Kneller & Steigman, 2004).

6–39

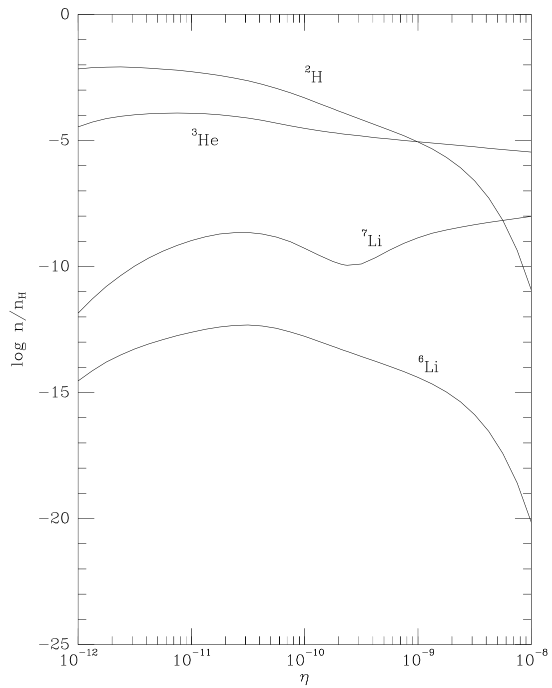
Detailed Calculations, III



Build-up of abundances as function of time for $\eta = 5.1 \times 10^{-10}$ (Burles, Nollett & Turner, 1999, Fig. 3), remember: $\eta = n_{\mathrm{CMBR}}/n_{\mathrm{baryons}}$

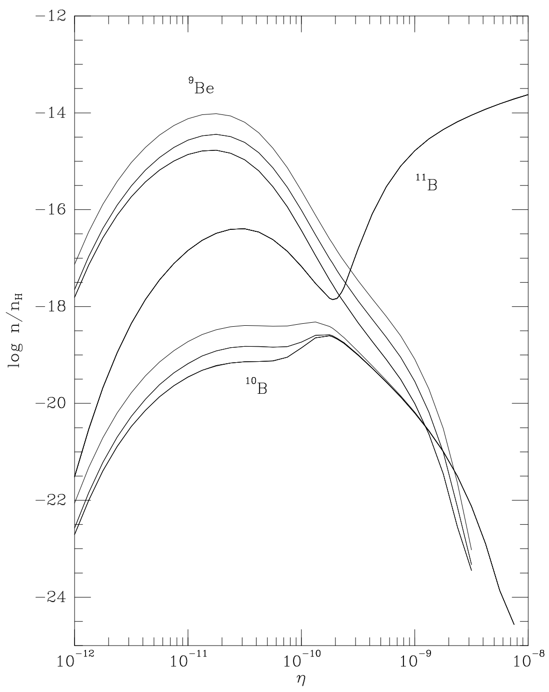


He abundance as function of η (Thomas et al., 1993, Fig. 3a)



Light-element abundances as function of η (Olive, 1999, Fig. 4)

Confrontation with WMAP



Intermediate mass abundances as function of η (Olive, 1999, Fig. 5)

As we will see later: fluctuations in cosmic microwave background allow for a tight determination of cosmological parameters.

Best results so far from Wilkinson Microwave Anisotropy Probe (WMAP; see Spergel et al. 2007):

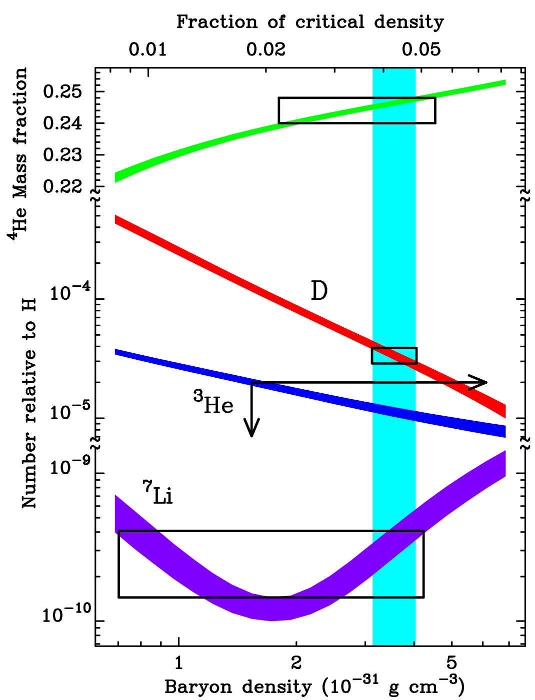
$$\Omega_b h^2 = 0.02233^{+0.00072}_{-0.00091} \quad (6.100)$$

With the most modern BBN calculations (Kneller & Steigman, 2004), this gives (Molaro, 2007):

Element	SBBN+WMAP
Y_p	$0.2482^{+0.0004}_{-0.0003}$
^{3}He/H	$(10.5 \pm 0.6) \times 10^{-6}$
D/H	$(25.7^{+1.7}_{-1.3}) \times 10^{-6}$
Li/H	$(4.41^{+0.3}_{-0.4}) \times 10^{-10}$

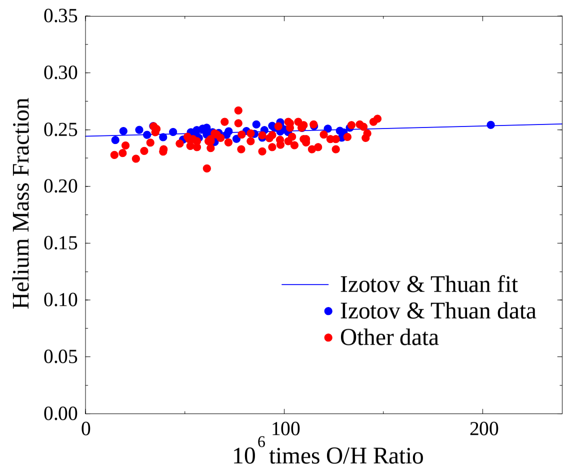
$\Longrightarrow$ Can use WMAP parameters and BBN theory to compare BBN theory with measurements

^{4}He



BBN observations strongly constrain Ω_{Baryons}.

(Burles, Nollett & Turner, 1999, Fig. 1)



(Burles, Nollett & Turner, 1999, Fig. 4)

^{4}He produced in stars

$\Longrightarrow$ extrapolate to zero metallicity in systems of low metallicity (i.e., minimize stellar processing).

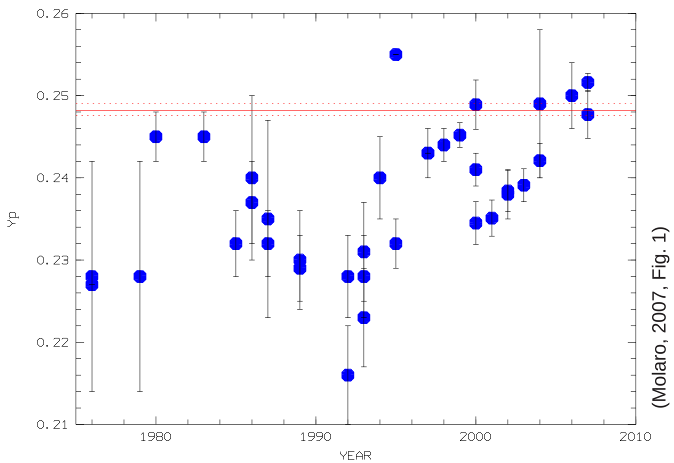
Best determination from He II $\longrightarrow$ He I recombination lines in H II regions (metallicity $\sim 20\%$ solar).

Result: Linear correlation He vs. O

$\Longrightarrow$ extrapolate to zero oxygen to obtain primordial abundances.

Result: $Y = 0.234 \pm 0.005$ (Olive, 1999).

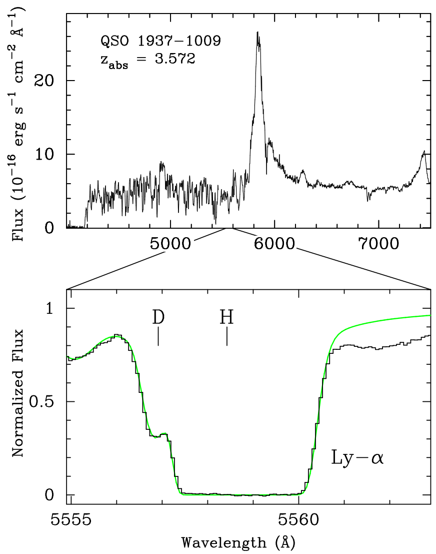
WMAP BBN and He



(Molaro, 2007, Fig. 1)

After improving He recombination physics and intrinsic absorption, He abundances are now in agreement with BBN prediction using Ω_B from WMAP.

Deuterium, I



Stars destroy D in fusion processes

$\Longrightarrow$ use as non-processed material as possible!

Lyα forest: absorption of quasar light by intervening material

$\Longrightarrow$ Some absorption lines in the Lyα forest show asymmetric line structure caused by primordial deuterium.

Remember the Balmer formula:

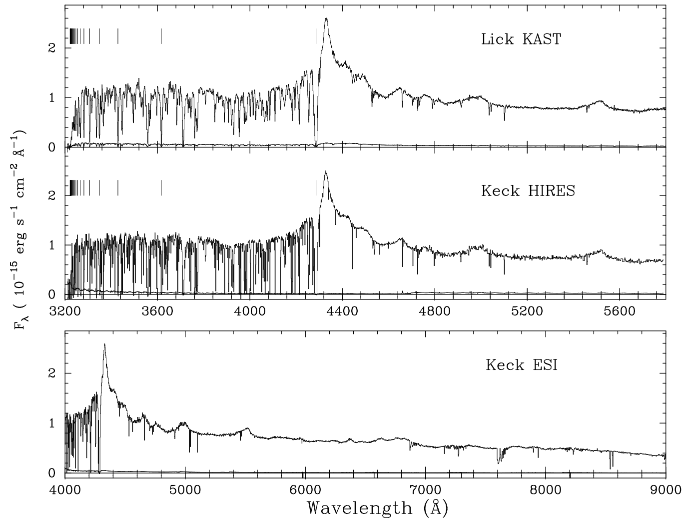
$$\frac{1}{\lambda_{n,m}} = R_H\left(\frac{1}{m} - \frac{1}{n}\right) \quad (6.101)$$

with with Rydberg constant

$$R_H = \frac{m_e m_p}{m_e + m_p}\frac{e^4}{8\pi\epsilon_0^2 h^3} \quad (6.102)$$

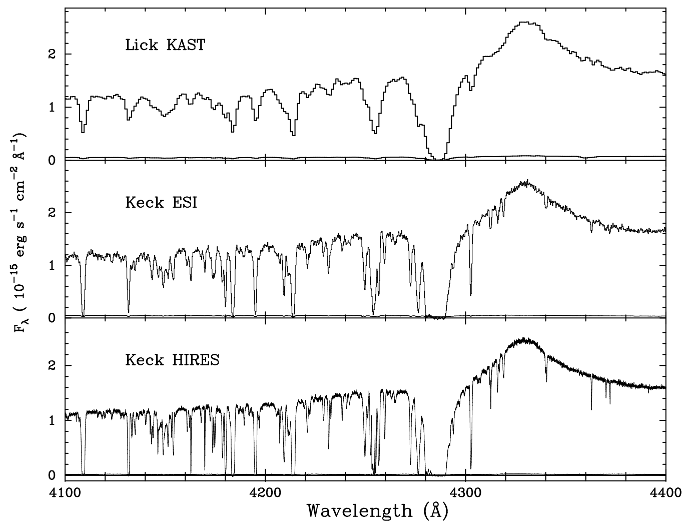
(QSO 1937−1009; top: 3 m Lick, bottom: Keck; Burles, Nollett & Turner, 1999, Fig. 2)

Deuterium, II



(Kirkman et al., 2003, Fig. 1): Lyman forest against three QSOs

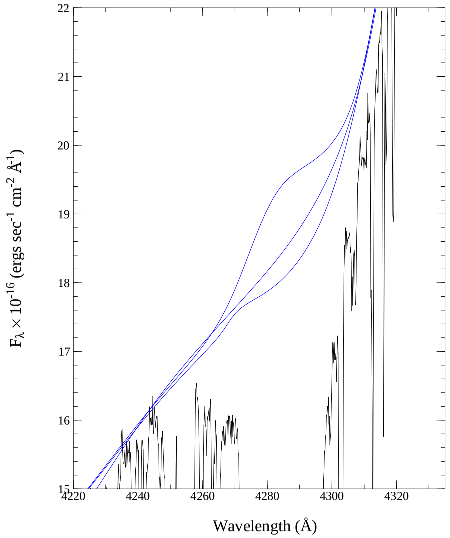
Deuterium, III



(Kirkman et al., 2003, Fig. 2): use absorption close to 4285 Å to measure D/H

6–50

Deuterium, IV



To measure abundances, measure column from the optical depth:

$$\tau(\lambda) = n\sigma(\lambda)\ell = N\sigma(\lambda) \quad (6.103)$$

where σ: absorption cross section of line, N: column density. This can be measured from

$$I_{\text{obs}}(\lambda) = I_{\text{cont}}(\lambda)\mathrm{e}^{-\tau(\lambda)} \quad (6.104)$$

$\Longrightarrow$ Need to know the continuum, I_{cont}

Very difficult to do in Lyα forest (see Figure)

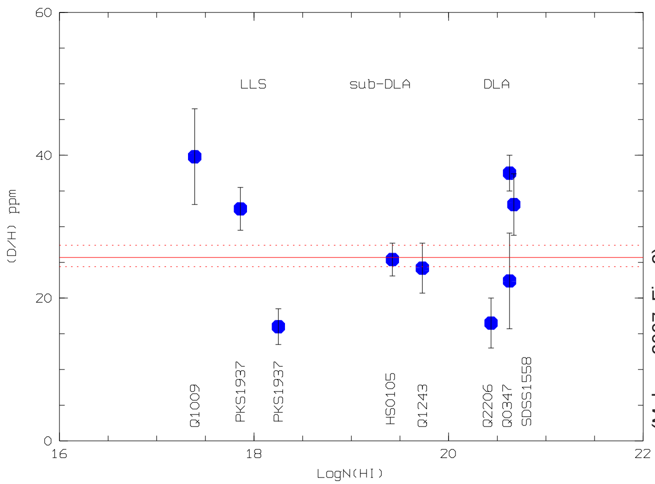
Currently best result for D/H (Kirkman et al., 2003):

$$\text{D/H} = 2.78^{+0.44}_{-0.38} \times 10^{-5}$$

Corresponding to $\eta = 5.9 \pm 0.5 \times 10^{-10}$ or $\Omega_{\text{B}}h^2 = 0.0214$ ($\pm 9.3\%$).

6–51

WMAP BBN and D



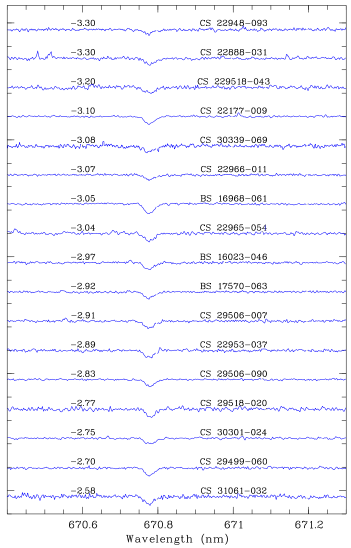
(Molaro, 2007, Fig. 2)

Measured deuterium abundances agree with WMAP predictions

Although there are issues with Milky Way deuterium abundances...

6–52

Lithium



Lithium lines (Li doublet at 6707 Å) are visible in some stars

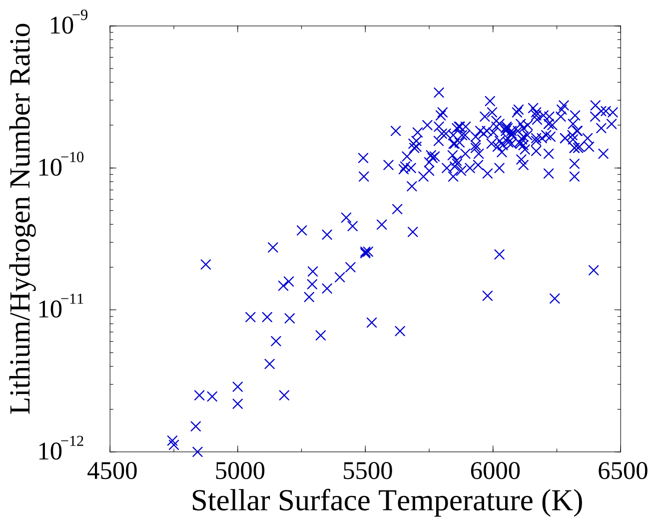
$\Longrightarrow$ allow measurement of Li abundance

Li line as a function of [Fe/H]

(Bonifacio et al., 2007, Fig. 1)

6–53

Lithium



Spite & Spite (1982): Old halo stars with very low [Fe/H]) show primordial Lithium abundance,

^{7}Li/H $= 1.6 \times 10^{-10}$

"Spite plateau"

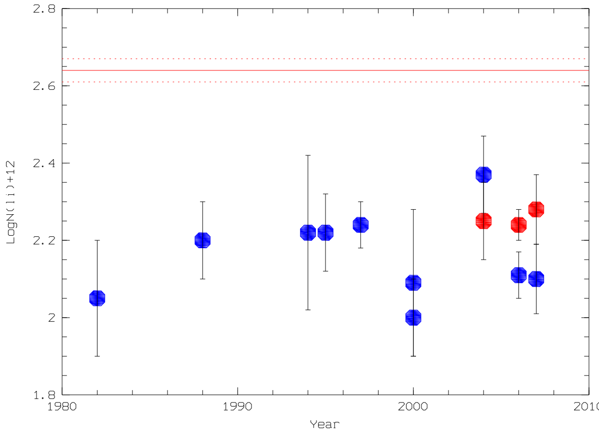
Lower temperature stars: outer convection zone

$\Longrightarrow$ Li burning destroys Li.

Cannot use galactic objects since spallation of heavier nuclei by cosmic rays produces Li (up to 10× primordial!).

(Burles, Nollett & Turner, 1999, Fig. 5)

WMAP BBN and Li, I

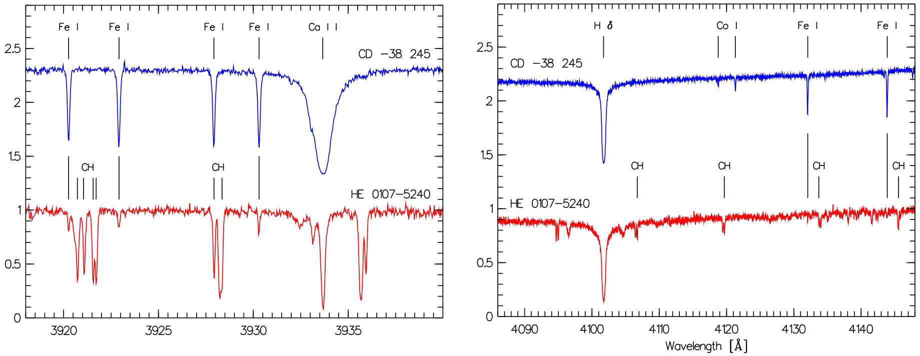


(Molaro, 2007, Fig. 3)

Lithium has a big problem!

Temperature sensitivity might have been underestimated, also rotational mixing, diffusion, and differences between 1D- and 3D-radiative transfer in stellar atmosphere models might play a role. However, no convincing solution has been proposed as of today.

Outlook: Population III, I

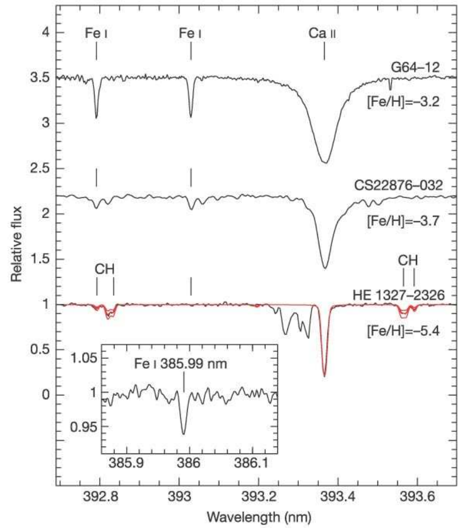


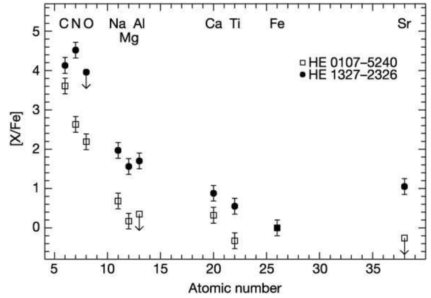
(HE0107−5240, metallicity 1/200000 solar; after Christlieb et al., 2002, Fig. 1)

Earliest stars should only have H, He, i.e., $Z = 0 \Longrightarrow$ detection of such stars would enable the *direct* measure of primordial abundances.

"population III star", formed either from primordial gas cloud (and got some elements later through accretion from ISM), or from debris from type II SN explosion.

Outlook: Population III, II





(Frebel et al., 2005, Fig. 2)

Lowest metallicity known: HE1327−2326, with Fe-abundance of 1/250000 solar

(Frebel et al., 2005, Fig. 1)

Summary

Summary: History of the universe after its first 0.01 s (after Islam, 1992, Ch. 7, see also Weinberg, The first three minutes).

$t = 0.01\,\mathrm{s}$ $T = 10^{11}\,\mathbf{K}$ $\rho \sim 4 \times 10^{11}\,\mathbf{g\,cm^{-3}}$

Main constituents: γ, ν, $\bar{\nu}$, e^--e^+ pairs.

No nuclei (instable). n and p in thermal balance.

$t = 0.1\,\mathrm{s}$ $T = 3 \times 10^{10}\,\mathbf{K}$ $\rho \sim 3 \times 10^{7}\,\mathbf{g\,cm^{-3}}$

Main constituents: γ, ν, $\bar{\nu}$, e^--e^+ pairs. No nuclei.

$n + \nu \leftrightarrow p + e^-$: mass difference becomes important, 40% n, 60% p (by mass).

Summary

$t = 1.1$ **s** — $T = 10^{10}$ **K** — $\rho \sim 10^5$ **g cm**$^{-3}$

Neutrinos decouple, e^--e^+ pairs start to annihilate. No nuclei.

25% n, 75% p

$t = 13$ **s** — $T = 3 \times 10^9$ **K** — $\rho \sim 10^5$ **g cm**$^{-3}$

Reheating of photons, pairs annihilate, ν fully decoupled, deuterium still cannot form.

17% n, 83% p

$t = 3$ **min** — $T = 10^9$ **K** — $\rho \sim 10^5$ **g cm**$^{-3}$

Pairs are gone, neutron decay becomes important, start of nucleosynthesis

14% n, 86% p

Summary

$t = 35$ **min** — $T = 3 \times 10^8$ **K** — $\rho \sim 0.1$ **g cm**$^{-3}$

game over

Next important event: $t \sim 300000$ years: Interaction CMB/matter stops ("last scattering", recombination).

Before we look at this, we look at
the first 0.01 s: the very early universe

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