Primordial Nucleosynthesis

- BBN theory
- Observational abundances
- BBN predictions versus data
- Non standard BBN
Some bibliography

During the expansion after the Big Bang, for $1 \text{ s} < t < 3600 \text{ s}$ (1 MeV > $T$ > 0.01 MeV), when the radiation still dominated the energy density, the universe behaved as a nuclear reactor, producing sensible amounts of light nuclei, H, 2H, T, $^3\text{He}$, $^4\text{He}$, $^6\text{Li}$, $^7\text{Li}$, $^{12}\text{C}$, $^{16}\text{O}$...

Key pillar of the Hot Big Bang Model, BBN is an overconstrained scenario. Its theoretical predictions depends on two parameters:

$$t(s) \approx \frac{0.738}{T^2(\text{MeV})}$$

$$\Omega_b h^2 \quad N_{\nu}^{\text{eff}}$$
Why BBN is important?

Primordial Elements Observations

Nuclear Astrophysics

BBN

Nuclear rates

“PDG” and cosmo stuff: \( \tau_n, G_N, \alpha, \nu \) Physics...

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Why BBN is important?

Primordial Elements Observations

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Why BBN is important?

Primordial Elements Observations

Nuclear Astrophysics

BBN

Primordial Elements Observations: $X_i$, $N_\nu$, $\xi_\nu$

Nuclear Astrophysics: Nuclear rates

“PDG” and cosmo stuff: $\tau_n$, $G_N$, $\alpha$, $\nu$ Physics...

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Why BBN is important?

Primordial Elements
Observations

Nuclear Astrophysics
Nuclear rates

BBN

\( X_i \)
\( N_V, \xi_V \)

“PDG” and cosmo stuff:
\( \tau_n, G_N, \eta, \nu \)

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new Particle Physics
\( \nu \) Properties
deviations from FRW

Burles, No., 2000

Barger et al., PL B569 (2003)
History

• 1946, Gamow: nuclear reactions in the early universe might explain the abundances of elements.

• Fermi and Turkevich: lack of stable nuclei with mass 5 and 8 prevents significant production of nuclei more massive than $^7$Li.

• 1964, Peebles, Hoyle and Tayler: $Y_p \approx 0.25$.

• 1967, Wagoner, Fowler and Hoyle: first detailed calculation of light nuclei abundances.

• 1988 & 1992, Kawano, release of a user friendly code.

• ... Schramm, Turner, Steigman, Olive, ...

• 2008, release of a new generation code, PArthENoPE.
May we describe particle distribution in phase space via equilibrium FD or BE distribution functions?

Formally no (but for massless particles), practically yes, to a very good precision. As long as particle interactions are fast with respect to the expansion rate:

$$f = \frac{1}{E-\mu} e^{\frac{T(t)}{e}} \pm 1$$

$$T(t) \approx \left( \frac{1}{\sqrt{\sum g_i}} \frac{1}{t(\text{sec})} \right)^{1/2} \text{MeV}$$

Remember that out-of-equilibrium phases are crucial in the history of the universe. As expansion goes on, interactions maintaining kinetic and chemical equilibrium between species may become less and less efficient: FREEZE OUT.
Neutrino decoupling I

In the early stages of the expansion, neutrinos are kept in kinetic and chemical equilibrium with \( e^\pm, \) n, p via weak processes.

We must solve \( \nu \)-Boltzmann equations to get their momentum distributions.

Neutrino distributions enter the conversion weak rates (only electron-neutrinos), their overall energy density (which determines \( H \)) and pressure.

\[
\rho = \frac{\pi^2 T^4}{15} + \frac{2}{\pi^2} \int \frac{dq q^2 \sqrt{q^2 + m_e^2}}{\exp(E/T) + 1} + \frac{1}{\pi^2} \int dq q^3 f_{\nu_e} + \frac{2}{\pi^2} \int dq q^3 f_{\nu_\mu}
\]

\[
P = \frac{\pi^2 T^4}{45} + \frac{2}{\pi^2} \int \frac{dq q^4}{3\sqrt{q^2 + m_e^2}[\exp(E/T) + 1]} + \frac{1}{3\pi^2} \int dq q^3 f_{\nu_e} + \frac{2}{3\pi^2} \int dq q^3 f_{\nu_\mu}
\]
Neutrino decoupling II

We search for solutions of the system of integro-differential equations having a distortion with respect to the equilibrium form.

\[ f_{\nu_\alpha}(x, y) = \frac{1}{e^{y-\xi_\alpha} + 1} (1 + \delta f_{\nu_\alpha}(x, y)) \]

where the initial conditions are fixed by thermodynamical equilibrium (satisfied for \( T > 10 \text{ MeV} \)).

\[ x_{in} = \frac{m_e}{10 \text{ MeV}} \approx 20 \right \Rightarrow \delta f_{\nu_\alpha}(20, y) = 0 \]

The asymptotic distribution functions are not perfectly thermodynamical distributions.
BBN in four steps

1. initial conditions \( T > 1 \text{ MeV} \)
2. \( n/p \) ratio freeze out \( T \approx 1 \text{ MeV} \)
3. D bottleneck \( T \approx 0.1 \text{ MeV} \)
4. nuclear chain \( 0.1 \text{ MeV} > T > 0.01 \text{ MeV} \)
Initial conditions

Notations:

\[ n_A = \frac{N_A}{V}; \quad \eta = \frac{n_B}{n_\gamma} \approx 274 \times 10^{-10} \Omega_B h^2 \]

\[ X_A = \frac{n_A}{n_B} \quad Y_p \approx 4 \frac{n_{4\text{He}}}{n_B} \]

For large temperatures all nuclear species are kept in chemical equilibrium (Nuclear Statistical Equilibrium, NSE).

\[ n_A = g_A \left( \frac{m_A T}{2\pi} \right)^{3/2} e^{-\frac{m_A + \mu_A}{T}} \]

\[ m_A = Z m_p + (A-Z)m_n - B_A \]

\[ \mu_A = Z \mu_p + (A-Z)\mu_n \]

\[ \eta = \frac{n_B}{n_\gamma} = \frac{\rho_B}{m_B n_\gamma} = \frac{\rho_B}{\rho_c m_B n_\gamma} = \Omega_B \frac{\rho_c}{m_B n_\gamma} \]

\[ \frac{n_A}{n_B} = \left( \frac{2\xi(3)}{\sqrt{\pi}} \right)^{A-1} \frac{g_A}{2} A^{3/2} \left( \frac{T}{m_N} \right)^{3(A-1)/2} \eta^{A-1} \left( \frac{n_p}{n_B} \right)^Z \left( \frac{n_n}{n_B} \right)^{A-Z} e^{B_A/T} \]

\[ B_A = \text{binding energy} \]
### Binding energy

<table>
<thead>
<tr>
<th>nucleus</th>
<th>( B_A ) (MeV)</th>
<th>( \frac{B_A}{A} ) (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>2.23</td>
<td>1.1</td>
</tr>
<tr>
<td>(^3\text{H})</td>
<td>6.92</td>
<td>2.3</td>
</tr>
<tr>
<td>(^3\text{He})</td>
<td>7.72</td>
<td>2.6</td>
</tr>
<tr>
<td>(^4\text{He})</td>
<td>28.30</td>
<td>7.1</td>
</tr>
<tr>
<td>(^6\text{Li})</td>
<td>31.99</td>
<td>5.3</td>
</tr>
<tr>
<td>(^7\text{Li})</td>
<td>39.25</td>
<td>5.6</td>
</tr>
<tr>
<td>(^7\text{Be})</td>
<td>37.60</td>
<td>5.4</td>
</tr>
<tr>
<td>(^{12}\text{C})</td>
<td>92.2</td>
<td>7.7</td>
</tr>
</tbody>
</table>
n/p ratio freeze-out

The density ratio of n and p is kept in chemical equilibrium by weak processes:

\[ \nu_e + n \leftrightarrow e^- + p \]
\[ \bar{\nu}_e + p \leftrightarrow n + e^+ \]
\[ \bar{\nu}_e + e^- + p \leftrightarrow n \]

\[ \frac{n_n}{n_p} = \exp\left( -\frac{m_n - m_p}{T} \right) \]

All other nuclei abundances are negligible for T>1 MeV.

\[ \Gamma \equiv \langle \sigma v \rangle n > H(t) \quad \text{equilibrium} \]

\[ \Gamma \equiv \langle \sigma v \rangle n \leq H(t) \quad \text{freeze out} \]
Weak rates

As for purely leptonic weak interactions, also $n \leftrightarrow p$ processes freeze out at $T \approx 1$ MeV.

In the standard calculation the thermal averaged weak rates are evaluated at tree level with V-A theory and in the infinite nucleon mass limit (Born approximation). Example:

$$\Gamma(n \rightarrow p + e^- + \bar{\nu}_e) = \frac{G_F^2 (c_V^2 + 3c_A^2)}{2\pi^3} \int dp_e p_e^2 E_{\nu}^2 \Theta(E_{\nu}) f(E_{\nu}) f(E_e)$$

$G_F$, $c_V$ and $c_A$ are well know from muon decay, $0^+ \rightarrow 0^+$ beta decays and neutron beta decay angular distribution,

$$G_F = 1.16639 \times 10^{-5} \text{ GeV}^{-2} \quad c_V = 0.9751 \pm 0.0006$$

$$c_A / c_V = 1.2601 \pm 0.0025$$
(a) $\nu_e + n \rightarrow e^- + p$
(b) $e^- + p \rightarrow \nu_e + n$
(c) $e^+ + n \rightarrow \nu^- + p$
(d) $\nu^- + p \rightarrow e^+ + n$
(e) $n \rightarrow e^- + \nu_e + p$
(f) $e^- + \nu_e + p \rightarrow n$
Improving precision

How good is the Born approximation?

A possible check is the calculation of the neutron lifetime in vacuum

\[ \tau_n(\text{Born}) = 961 \text{ sec} \]

\[ \tau_n(\text{exp}) = (885.7 \pm 0.8) \text{ sec} \]

Very bad!

To improve the precision in n/p ratio, and eventually in \(^4\text{He}\) abundance at percent level, it is necessary to consider:

- QED radiative effects \(O(\alpha)\)
- finite nucleon mass \(O(m_e/m_N)\)
- QED plasma corrections \(O(\alpha T/m_e)\)
The goodness of QED expansion

Up to the first order in $\alpha$

$\tau_n(\text{Born}) = 961 \text{ sec}$

$\rightarrow \tau_n(\text{th}) = 893.9 \text{ sec}$

to be compared with

$\tau_n(\text{exp}) = (885.7 \pm 0.8) \text{ sec}$

Thus QED corrections, up to order $\alpha$, reduces of 7% the neutron lifetime. Another 0.9% is needed, maybe provided by second order corrections?
Helium mass fraction

Using weak rates and solving the set of Boltzmann equation for $n$ and $p$ densities:

\[ X_n \approx (1 + \exp( (m_n-m_p)/T))^{-1} \approx 0.150 \]

This ratio slightly decreases due to neutron decay:

\[ X_n \rightarrow X_n \exp(-t/\tau_n) \approx 0.122 \]

A first rough estimate: Since basically all neutrons are eventually captured in $^4$He nuclei (largest gain in energy), neglecting all other nuclei:

\[ Y_p = \frac{4n_{^4He}}{n_B} = \frac{4n/2}{n+p} = \frac{2n/p}{1+n/p} \approx 2 \cdot 0.122 = 0.244 \]

This rough estimate turns out to be rather accurate indeed!
Deuterium formation is crucial for triggering the complicated nuclear reaction chain.

\[ 2 \text{n} + 2 \text{p} \rightarrow ^4\text{He} \]

disfavoured (low density)
Toward $^4\text{He}$

$^4\text{He} + \beta^- \rightarrow ^{7}\text{Be} + e^-$

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Nuclear chain

Once $^2\text{H}$ is produced, $^4\text{He}$ is rapidly formed, along with small fractions of $^3\text{H}$, $^3\text{He}$, $^6\text{Li}$, $^7\text{Li}$ and $^7\text{Be}$.

$^7\text{Be}$ eventually gives $^7\text{Li}$ by electron capture

$$e^- + ^7\text{Be} \rightarrow \nu_e + ^7\text{Li}$$

Though both $^{12}\text{C}$ and $^{16}\text{O}$ have larger binding energy than $^4\text{He}$, they are not produced in sensible amounts since:

i) no tightly bound isotopes with $A=5, 8$

ii) Coulomb barrier starts to be significant

iii) low baryon density suppresses triple $\alpha$ processes

(@ 0.1 MeV baryon density $\approx$ air density)
Deuterium production

Two competing processes:

\[ p+n \rightarrow \gamma+^2H \quad \text{fusion} \]
\[ \gamma+^2H \rightarrow n+p \quad \text{photo-dissociation} \]

poorly known experimentally, theoretical calculation
D synthesis & destruction

\[ T_9 = T(K)/10^9 \]
Deuterium bottleneck

One would expect that when $T$ just drops below $B_D = 2.23$ MeV, photodissociation processes become ineffective. However: too many photons!!

$$\frac{X_D}{X_n X_p} = \frac{12 \zeta(3)}{\sqrt{\pi}} \left( \frac{T}{m_p} \right)^{3/2} \eta \exp\left(\frac{B_D}{T}\right)$$

Deuterium formation starts (rapidly leading to $^4$He) only when $\eta \exp(\frac{B_D}{T^*}) \approx 1$.

Since $\eta \approx 10^{-10}$, $T^* \approx 0.1$ MeV.
BBN differential equations

How to evaluate nuclei yields? BBN code: solving a set of coupled differential equations.

\[ \dot{a} = \sqrt{\frac{8\pi}{3m_{Pl}^2}} (\rho_\gamma + \rho_{e^\pm} + \rho_b + \rho_v) \]

\[ \frac{\dot{n}_b}{n_b} = -3 \frac{\dot{a}}{a} \]

\[ \dot{T} = \Phi(t, X_a) \]

\[ Q_{\text{lepton}}(\mu_e, T) = -Q_{\text{baryon}}(X_a) \]

\[ \dot{X}_a = \sum_{b,c,d} N_a \left( \Gamma(c + d \rightarrow a + b) \frac{(X_c)^{N_c}}{N_c!} \frac{(X_d)^{N_d}}{N_d!} \right. \]

\[ -\Gamma(a + b \rightarrow c + d) \frac{(X_a)^{N_a}}{N_a!} \frac{(X_b)^{N_b}}{N_b!} \]

\( \rho_v = \) energy density of relativistic species (contains \( N_{\text{eff}} \))

\( \mu_e = \) electron chemical potential
Boltzmann equations

Nuclear processes during BBN proceed in an environment very different with respect to the stellar plasmas, where stellar nucleosynthesis takes place. In stars the plasma is dense and species are mostly in chemical equilibrium. For BBN we have a hot and low density plasma with a significant population of free neutrons, which expands and cools down very rapidly, resulting in peculiar “out of equilibrium” nucleosynthetic yields. So, we need Boltzmann equations.

For a nuclide $a$, interacting via $a+b \leftrightarrow c+d$,

$$\frac{dn_a}{dt} + 3Hn_a = -\int d\Pi_T (2\pi)^4$$

$$\delta^{(4)}(p_a + p_b - p_c - p_d)|M|_{Tot}^2(f_a f_b - f_c f_d)$$

Since

$$\frac{1}{n_B} \left( \frac{dn_a}{dt} + 3Hn_a \right) = \frac{dX_a}{dt}$$
Nuclide evolution

we get

\[ n_B \frac{dX_a}{dt} = - \int d\Pi_T (2\pi)^4 \delta^{(4)}(p_a + p_b - p_c - p_d)|M|^2_{Tot}(f_a f_b - f_c f_d) \]

By introducing

\[ \langle \sigma v \rangle_{i+j \rightarrow k+l} \equiv \frac{\Gamma_{i+j \rightarrow k+l}}{n_B} \equiv \frac{1}{n_i n_j} \int d\Pi_T (2\pi)^4 \delta^{(4)}(p_T^{\text{fin}} - p_T^{\text{in}})|M|^2_T f_i f_j \]

one gets the well known form

\[ \frac{d}{dt} X_a \Gamma_{cd \rightarrow ab} X_c X_d - \Gamma_{ab \rightarrow cd} X_a X_b \]
Revision of nuclear chain

1. Nuclear reaction analysis shows differences for reactions

\[ ^2\text{H} + ^2\text{H} \rightarrow \text{n} + ^3\text{He}, \quad ^2\text{H} + ^2\text{H} \rightarrow \text{H} + ^3\text{H}, \quad ^2\text{H} + \text{H} \rightarrow \gamma + ^3\text{He} \]

2. The revision of the key reaction p+n→γ+^2\text{H} has allowed to reduce the theoretical uncertainty

3. Several reactions involving Tritium were missing, like \( ^3\text{He} + ^3\text{H} \rightarrow ^2\text{H} + ^4\text{He} \). They are going to affect the amount of Deuterium
BBN and baryon fraction

How $^2\text{H}$, $^4\text{He}$ and $^7\text{Li}$ depends on $\eta = 274 \times 10^{-10} \Omega_B h^2$? When $\eta$ increases:

$^2\text{H}$: a larger baryon density shifts the onset of $^2\text{H}$ production towards larger temperatures, burning into $^4\text{He}$ is more efficient;

$^4\text{He}$: weakly increasing for more efficient burning;

$^7\text{Li}$: for small $\eta$, $^7\text{Li}$ decreases as a result of the balance of the two processes

$$^4\text{He} + ^3\text{H} \rightarrow \gamma + ^7\text{Li} \quad \text{and} \quad ^7\text{Li} + p \rightarrow ^4\text{He} + ^4\text{He}$$

for larger $\eta$, $^7\text{Li}$ starts growing due to larger $^7\text{Be}$ production, leading to $^7\text{Li}$ via electron capture:

$$^4\text{He} + ^3\text{He} \rightarrow \gamma + ^7\text{Be} \quad \text{and} \quad ^7\text{Be} + e^- \rightarrow \nu_e + ^7\text{Li}$$
How $^2$H, $^4$He and $^7$Li depend on $\eta = 10^{-10} \Omega_B \Omega_c$? When $\eta$ increases:

- $^2$H: a larger baryon density shifts the onset of $^2$H production towards larger temperatures, burning into $^4$He is more efficient;
- $^4$He: weakly increasing for more efficient burning;
- $^7$Li: for small $\eta$, $^7$Li decreases as a result of the balance of the two processes $^4$He$^3$H$\rightarrow$$^7$Li + $^7$Be for larger $\eta$, $^7$Li starts growing due to larger $^7$Be production, leading to $^7$Li via electron capture:

$$^4$$He$^3$He$\rightarrow$$^7$$Be + e^-$$^7$$Be + e^-\rightarrow$$^7$$Li +$$^7$$Li +$$^7$$Li +$$^7$$Li +$$^7$$Li.
Relativistic degrees of freedom are historically described as “effective number of neutrinos”, but they can account for:

- non instantaneous decoupling effects;
- non standard neutrino physics;
- extra relativistic degrees of freedom:

\[
\rho_\nu + \rho_x = N_{\text{eff}} \frac{7}{8} \left( \frac{4}{11} \right)^{4/3} \rho_\gamma
\]

How $^2\text{H}$, $^4\text{He}$ and $^7\text{Li}$ depends on $N_{\text{eff}}$? When $N_{\text{eff}}$ increases:

- $^2\text{H}$, $^7\text{Li}$ only slightly affected;
- $^4\text{He}$ a larger $N_{\text{eff}}$ implies a larger expansion rate, thus an earlier freeze out and a higher value of the n/p ratio: more neutrons $\rightarrow$ more $^4\text{He}$;
BBN code

Inputs:

1. nuclear rates (experimental values extrapolated in the relevant energy range)
2. baryon density ($\eta \sim \Omega_B h^2$)
3. energy density in relativistic degrees of freedom, $N_{\text{eff}}$

Output: $X_a (\eta, N_{\text{eff}})$

All nuclides with $A \leq 7$, stable or weak decaying are included in the code. The only exception is for $^6\text{He}$ decaying in 8 sec in $^6\text{Li}$. 
Main problem:

We cannot observe directly primordial abundances, since stars have changed the chemical composition of the universe.

Strategies:

1. observations in systems negligibly contaminated by stellar evolution
2. careful account for galactic chemical evolution
Deuterium

$^2\text{H}$ is easily destroyed by galactic chemical evolution. Two different classes of measurements.

- $C/H \approx \text{solar value}$
- $C/H \approx 0.01 - 0.001 \left(C/H\right)_{\text{solar}}$

Interstellar and proto-solar observations:

- Observation of Lyman absorption lines by neutral hydrogen (HI) gas clouds placed along the line of sight of Quasar systems at large red-shift ($z \approx 2 - 3$):
  - very few candidates $\rightarrow$ low statistics and possible local effects

$$\left( \frac{^2\text{H}}{\text{H}} \right)_{\text{ISM}} = (1.56 \pm 0.04) \cdot 10^{-5}$$

$$\left( \frac{^2\text{H}}{\text{H}} \right)_{\text{psc}} = (2.1 \pm 0.4) \cdot 10^{-5}$$
Deuterium
Deuterium

\[
\frac{^{2}H}{H} = (2.87^{+0.22}_{-0.21}) \cdot 10^{-5}
\]

our analysis
In stellar interior $^3\text{He}$ can be either produced by $^2\text{H}$-burning or destroyed in the hotter regions. All the $^3\text{He}$ nuclides surviving the stellar evolution phase contribute to the chemical composition of the ISM. Stellar and galactic evolution models are necessary to track back the primordial $^3\text{He}$ abundance from the post-BBN data, at least in the regions where stellar matter is present.

The most accurate value was measured in Jupiter's atmosphere by the Galileo Probe, $^3\text{He}/^4\text{He} = (1.66\pm0.05) \times 10^{-4}$. It supports the idea of a conversion of $^2\text{H}$ initially present in the outer parts of the Sun into $^3\text{He}$ via nuclear reactions. By counting the helium ions in the solar wind, the Ulysses spacecraft has measured $^3\text{He}/^4\text{He} = (2.48^{+0.68}_{-0.62}) \times 10^{-4}$.

The values found in Planetary Nebulas result one order of magnitude larger than in Proto Solar Material and Local Interstellar Medium, $^3\text{He}/H = (2 - 5) \times 10^{-4}$, confirming a net stellar production of $^3\text{He}$ in at least some stars.
No $^3$He dependence on environment metallicity, as predicted by chemical evolution models of Galaxy: known as the $^3$He problem. Thus a conservative approach: $^3$He/H < (1.1 ± 0.2) $10^{-5}$. 
$^4\text{He}$

$^4\text{He}$ evolution can be simply understood in terms of nuclear stellar processes which, through successive generations of stars, have burned H into $^4\text{He}$ and heavier elements, hence increasing the $^4\text{He}$ abundance above its primordial value. Since the history of stellar processing can be tagged by the metallicity ($Z$) of the particular astrophysical environment, $Y_{\text{P}}$ can be derived by extrapolating the $Y_{\text{P}}$-O/H and $Y_{\text{P}}$-N/H correlations to O/H and N/H $\rightarrow$ 0.

- Observation in ionized gas regions (He II $\rightarrow$ HeI recombination lines) in low metallicity environments (BCG), with O abundances 0.02 – 0.2 times those in the sun.

- $Y_{\text{P}}$ in different galaxies plotted as function of O and N abundances.

- regression to “zero metallicity”.

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Most recent estimates:

1. Izotov et al. (2004) reported the estimate $Y_P = 0.2421 \pm 0.0021$

2. Olive et al. (2004) quoted the value $Y_P = 0.249 \pm 0.009$ (small sample size and large uncertainties)

3. Fukugita et al. (2006), based on a reanalysis of a sample of 33 HII regions from 1) determined a value of $Y_P = 0.250 \pm 0.004$

4. Peimbert et al. (2007) presented a new $^4$He mass fraction determination yielding $Y_P = 0.2477 \pm 0.0029$ (new atomic physics computations together with observations and photoionization models of metal-poor extragalactic HII regions)

All recent estimates are dominated by systematics. One can take, as central value of $Y_P$, the average (without weights) of the four determinations, while the systematic error is estimated as the semi-width of the distribution of the four best values, $Y_P = 0.247 \pm 0.002_{\text{stat}} \pm 0.004_{\text{syst}}$. 

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Method: observation of absorption lines in spectra of halo stars of POP II (low heavy element abundances: 0.03 - 0.0003 of solar ones). Very similar abundances of $^7\text{Li}$ (Spite plateau) which should be close to the primordial value. However, possible increase in the abundance of $^7\text{Li}$ with the iron abundance indicates that the $^7\text{Li}$ of the plateau stars is not primordial.

Source of systematics:
1) galactic chemical evolution of Li before star birth from the interstellar medium;
2) presence of anomalous stars in the sample;
3) modelling of the depletion of the initial surface $^7\text{Li}$

$$^7\text{Li}/H = (2.19_{-0.37}^{+0.44}) \cdot 10^{-10}$$

$$^7\text{Li}/H = (2.07_{-0.23}^{+0.36}) \cdot 10^{-10}$$
Likelihood analysis

- run a BBN code to get the abundances;
- construct the relative likelihood function:

\[
L_i(N_{\text{eff}}, \eta) = \frac{1}{2\pi \sigma_i^{th}(N_{\text{eff}}, \eta) \sigma_i^{ex}} \int dx \exp \left( -\frac{(x - Y_i^{th}(N_{\text{eff}}, \eta))^2}{2\sigma_i^{th}(N_{\text{eff}}, \eta)^2} \right) \exp \left( -\frac{(x - Y_i^{ex})^2}{2\sigma_i^{ex^2}} \right)
\]

- define a total likelihood function \( L = L_D L_{4\text{He}} \)
- plot the CL contours in the \((N_{\text{eff}}, \Omega_B h^2)\) plane
Likelihood analysis

Only $^2\text{H}$ cannot fix both $N_{\text{eff}}$ and $\Omega_\text{B} h^2$.

the deuterium likelihood shows a degeneracy
Likelihood analysis

the combined $^2$H-$^4$He likelihood breaks the degeneracy
Degenerate BBN

From the neutrality of the universe

\[ \frac{\mu_e}{T} \leq 10^{-10} \]

but not severe bounds on neutrino-antineutrino asymmetry, \( \xi = \mu \sqrt{T} \).

\[ \rho_v = \frac{7\pi^2}{120} T^4 \quad \text{non degenerate} \]

\[ \rho_v = \frac{6}{\pi^2} T^4 e^\xi \quad \text{slightly degenerate} \]

\[ \rho_v = \frac{1}{8\pi^2} \mu^4 \quad \text{strongly degenerate} \]
BBN and ν chemical potential

How \(^4\)He depends on \(\xi_i\)? When \(\xi_i\) increase:

- \(\xi_i\) contribute to \(N_{\text{eff}}\) giving a larger expansion rate, thus more \(^4\)He

\[
N_{\nu} = 3 + \sum_{i} \left( \frac{30 \xi_i^2}{7 \pi^2} + \frac{15 \xi_i^4}{7 \pi^4} \right) + \ldots
\]

- \(\xi_e\) favours \(n \rightarrow p\) processes with respect to \(p \rightarrow n\) ones, thus less \(^4\)He

These two effects imply a degenerate BBN region in the \((N_{\text{eff}}, \Omega_B h^2)\) plane.

Neutrino oscillations mix \(\xi_e, \xi_\mu, \xi_\tau\): we can take them equal.

From \(Y_P\):

\[
\xi_e = 0.004 \pm 0.009_{\text{stat}} \pm 0.017_{\text{syst}}
\]