Primordial Nucleosynthesis: from precision cosmology to fundamental physics

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BBN in few words

During the expansion after the Big Bang, for:

\[ 1 \, \text{s} \lesssim t \lesssim 3600 \, \text{s} \quad (1 \, \text{MeV} \gtrsim T \gtrsim 10 \, \text{keV}) \]

when the radiation was still dominating the energy

The Universe made of n, p, e\(^\pm\), \(\gamma\), \(\nu\) anti- \(\nu\) and \(X\)? behaved as a nuclear reactor,

producing sensible amount of light nuclei,

H, \(^2\text{H}\), \(^3\text{H}\), \(^3\text{He}\), \(^4\text{He}\), \(^6\text{Li}\), \(^7\text{Li}\) \(\ldots\).
What can we learn about fundamental physics from BBN?
Physics Beyond the Standard Model

• **BBN and Neutrino physics**
  - Bounds on electromagnetic interactions of neutrinos
  - Bounds on other exotic interactions of neutrinos
  - Neutrino asymmetry
  - Sterile Neutrinos and BBN

• **Inhomogeneous nucleosynthesis**
  - Baryon inhomogeneous models
  - Matter-antimatter inhomogeneities

• **Constraints on fundamental interactions**
  - Extra-Dimensions and BBN
  - Variation of fundamental constants

• **Massive Particles & BBN**
  - Cascade Nucleosynthesis
  - Catalyzed BBN
- 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 $^7\text{Li}$.
- 1964 Peebles, Hoyle and Tayler: $Y_p \approx 0.25$.
- Schramm, Turner, Steigman, Olive, .......
- 1988 & 1992 Kawano, release of a user friendly code

- 2008 PArthENoPE, our release of a new generation code
website: http://parthenope.na.infn.it/
Prerequisites (The Hot Big Bang)

Einstein equations:
\[ R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi G_N T_{\mu\nu} + \Lambda g_{\mu\nu} \]

FLRW universe: spatial homogeneity and isotropy

Equilibrium vs non equilibrium: Out of equilibrium phases are crucial in the history of the universe.

Thermodynamics would have make everything much boring! Tool: Boltzmann transport equations
They are described by their relative abundances $X_a = n_a / n_B$. With short convenient notations:

$$
\frac{^2H}{H} \equiv \frac{X_{^2H}}{X_p}, \quad \frac{^3He}{H} \equiv \frac{X_{^3He}}{X_p}, \quad Y_p = 4 X_{^4He}, \quad \frac{^7Li}{H} \equiv \frac{X_{^7Li}}{X_p}
$$
BBN set of coupled differential equations

\[ H \equiv \frac{\dot{a}}{a} = \sqrt{\frac{8\pi}{3m_{Pl}^2}} \rho \]

\[ \frac{\dot{n}_B}{n_B} = -3H \]

\[ \dot{\rho} = -3H(\rho + P) \]

\[ n_B \sum_j Z_j X_j = n_{e^-} - n_{e^+} \]

\[ \dot{X}_a = \sum_{b,c,d} N_a \left( \frac{X_c}{N_c} \right)^{N_a - 1} \frac{N_d}{N_d!} - \Gamma_{a+b\rightarrow c+d} \frac{X_a}{N_a!} \frac{X_b}{N_b!} \]

\[ \left( \frac{\partial}{\partial t} - H \left| \vec{p} \right| \frac{\partial}{\partial |\vec{p}|} \right) f_{v_\alpha} \left( |\vec{p}|, t \right) = I_{v_\alpha} \left[ f_{v_e}, f_{\bar{v}_e}, f_{v_x}, f_{\bar{v}_x}, f_{e^-}, f_{e^+} \right] \]

\[ \rho = \rho_\gamma + \rho_e + \rho_v + \rho_B \]

\[ P = P_\gamma + P_e + P_v + P_B \]

**We can solve it separately**

**The neutrinos decoupling**
BBN Input:
- baryon density: \( \eta = \frac{n_B}{n_\gamma} \approx 274 \times 10^{-10} \Omega_b h^2 \)
- energy density in relativistic degrees of freedom historically described as “effective number of neutrinos”, \( N_\nu \), but it can account for:
  1) non instantaneous decoupling effects
  2) non standard neutrino physics
  3) extra relativistic degrees of freedom

\[
\rho_\nu + \rho_X (\ldots) \equiv \frac{N_\nu}{3} \rho_{\nu,0} \equiv N_\nu \frac{7}{8} \left( \frac{4}{11} \right)^{4/3} \rho_\gamma
\]

Output: \( X_a (\eta, N_\nu) \)
BBN in four steps

i) Initial conditions \( T > 1 \text{ MeV} \)

ii) n/p ratio freeze out \( T \approx 1 \text{ MeV} \)

iii) Deuterium bottleneck \( T \approx 0.1 \text{ MeV} \)

iv) Nuclear chain \( 0.1 \text{ MeV} > T > 0.01 \text{ MeV} \)
**Time - Temperature\(^{-1}\) evolution**

\[ \eta, N_v \text{ fixed} \]

- Mass Fraction
- Time
- Temperature (10\(^9\) K)
- Elements: n, p, \(^7\)Li, \(^7\)Be, D, \(^4\)He, \(^3\)H, \(^3\)He, \(^6\)Li
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 $^4\text{He}(^3\text{H},\gamma)^7\text{Li}$, $^7\text{Li}(\text{p},^4\text{He})^4\text{He}$; for larger $\eta$, $^7\text{Li}$ starts growing due to larger $^7\text{Be}$ production, leading to $^7\text{Li}$ via electron capture: $^4\text{He}(^3\text{He},\gamma)^7\text{Be}(\text{e}^-,\nu_e)^7\text{Li}$.
Dependence on relativistic d.o.f. $\equiv N_\nu$

When $N_\nu$ increases:

- $^2$H, $^7$Li only slightly affected
- $^4$He a larger value for $N_\nu \rightarrow$ a larger expansion rate $H(\rho_\nu + \rho_\gamma + \rho_e + \rho_b)$

This implies an earlier freeze out (larger $T$) of the n/p ratio, and so a larger value for $Y_P$. More neutrons $\rightarrow$ more $^4$He.

$$\frac{n}{p} = \exp\left(\frac{m_p - m_n}{T}\right)$$
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.

The main net., but \( \sim 100 \) reac. are involved

Once D 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 \(^7\text{Be}\).
Uncertainties
From nuclear rates ultimately propagate onto the final errors on the nuclides.
For two body collisions, like $i + j \rightarrow k + l$, the nuclear reaction rates enter the eq. via

$$\Gamma_{ij \rightarrow kl} = \langle \sigma_{ij \rightarrow kl} \nu \rangle$$

Where the average is over the nuclei distributions

$$\langle \sigma_{ij \rightarrow kl} \nu \rangle \propto T^{-3/2} \int_0^\infty dE \sigma_{ij \rightarrow kl}(E) E e^{-E/T}$$
For $\omega_b=0.0224$

<table>
<thead>
<tr>
<th>nuclide $i$</th>
<th>central value</th>
<th>$\sigma_{\omega_b}$</th>
<th>$\sigma_{ii}$</th>
<th>rate</th>
<th>$\delta\sigma^2/\sigma^2$(%)</th>
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<tr>
<td>$^2\text{H}/\text{H}(10^{-5})$</td>
<td>2.58</td>
<td>$+0.19_{-0.16}$</td>
<td>$\pm0.04$</td>
<td>$R_2$</td>
<td>49</td>
</tr>
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<td></td>
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<td></td>
<td>$R_3$</td>
<td>37</td>
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<td></td>
<td></td>
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<td></td>
<td>$R_4$</td>
<td>14</td>
</tr>
<tr>
<td>$^3\text{He}/\text{H}(10^{-5})$</td>
<td>1.03</td>
<td>$+0.02_{-0.03}$</td>
<td>$\pm0.03$</td>
<td>$R_7$</td>
<td>80.7</td>
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<td>$R_2$</td>
<td>16.8</td>
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<td>$Y_p$</td>
<td>0.2479</td>
<td>$+0.00004_{-0.00004}$</td>
<td>$\pm0.0002$</td>
<td>$R_0$</td>
<td>98.5</td>
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<tr>
<td>$^6\text{Li}/\text{H}(10^{-14})$</td>
<td>1.1</td>
<td>$\pm0.1$</td>
<td>$+1.7_{-1.1}$</td>
<td>$R_{13}$</td>
<td>$\sim100$</td>
</tr>
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</table>
ASTROPHYSICAL OBSERVATIONS
Main problem

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

1) Observations in systems negligibly contaminated by stellar evolution;

2) Carefull account for galactic chemical evolution.
Deuterium

It is commonly believed that there are no astrophysical sources of deuterium. Since it is destroyed by stellar evolution processes and non-thermal production channels have been constrained to be negligible, any astrophysical observation can provide a lower bound for the primordial abundance.

**Galactic measurements**

Far-Ultraviolet Spectroscopic Explorer (FUSE) has provided several Galactic $^2\text{H}/\text{H}$ measurements, but the picture is puzzling:

- In the Local Bubble (a cavity in the ISM of the Orion Arm < 100 pc from sun we are travelling through) $D$ is almost constant
  $$^2\text{H}/\text{H} = (1.56 \pm 0.04) \times 10^{-5}$$
- beyond this bound an unexpected scatter of a factor $\sim 2$ on $^2\text{H}/\text{H}$ is observed and a correlation with heavy elements $\rightarrow$ stellar astration (?)
- The measurements in the Jupiter atm. By Infrared Space Observatory indicate a value for the protosolar cloud of
  $$^2\text{H}/\text{H}_{\text{psc}} = (2.1 \pm 0.4) \times 10^{-5}$$
**High redshift measurements**

The astrophysical environments which seem most appropriate are the hydrogen-rich clouds absorbing the light of background QSO’s at high redshifts.

To apply the method one must require:

(i) neutral hydrogen column density in the range

\[17 < \log \left[ N(\text{H}_i)/\text{cm}^{-2} \right] < 21;\]

(H\(_i\) regions are interstellar cloud made of neutral atomic hydrogen)

(ii) low metallicity \([\text{M/H}]\) to reduce the chances of deuterium astration;

(iii) low internal velocity dispersion of the atoms of the clouds, allowing the isotope shift of only 81.6 km/s to be resolved.

Only a small bunch (~ 14) of QAS’s pass the first exam!
Observation of Lyman absorption lines in gas clouds in QAS’s at high red-shift \((z \approx 2 - 3)\) with low metallicity

\[
C/H \approx 0.01 - 0.001 \ (C/H)_{\text{Solar}}
\]
The best 8 QAS’s in Galactic coordinates

- Q 1243+3047 (Z=2.5)
- SDSS 1558-0031 (Z=2.7)
- PKS 1937-1009 (Z=3.6)
- HS 0105+1619 (Z=2.5)
- Q 2206-199 (Z=2.1)
- Q 0347-3819 (Z=3.0)
- Q 1009+2956 (Z=2.5)
- Q 0913+072 (Z=2.6)

Galactic coordinates are used to locate these QAS's.
Our determination $^2H/H = (2.87^{+0.22}_{-0.21}) \times 10^{-5}$

Combining measurements with asymmetric errors!

$$\chi_i^2(\mu) = \left( \frac{\bar{x}_i - \mu}{\sigma_i} \right)^2 \left( 1 - 2A_i \left( \frac{\bar{x}_i - \mu}{\sigma_i} \right) + 5A_i^2 \left( \frac{\bar{x}_i - \mu}{\sigma_i} \right)^2 \right) \sigma_i \equiv \frac{\sigma_i^+ + \sigma_i^-}{2} \quad A_i \equiv \frac{\sigma_i^+ - \sigma_i^-}{\sigma_i^+ + \sigma_i^-}$$
$^4$He evolution can be simply understood in terms of nuclear stellar processes which through successive generations of stars have burned hydrogen into $^4$He and heavier elements, hence increasing the $^4$He abundance above its primordial value. Since the history of stellar processing can be tagged by measuring the metallicity ($Z$) of the particular astrophysical environment, the primordial value of $^4$He mass fraction $Y_p$ can be derived by extrapolating the $Y_p$ - O/H and $Y_p$ - N/H correlations to $O/H$ and $N/H \to 0$.

- Observation of ionized gas ($\text{He II} \rightarrow \text{He I}$ recombination lines in $H_{\text{II}}$ regions) in Blue Compact Galaxies (BCGs) which are the least chemically evolved known galaxies.
- $Y_p$ in different galaxies plotted as function of $O$ and $N$ abundances.
- Regression to “zero metallicity”

![Graph showing $^4$He mass fraction vs. $O/H$ and $N/H$ ratios with data points and fitted lines.]
Different analyses

i) Izotov et al. 04 reported the estimate $Y_p=0.2421 \pm 0.0021$

ii) Olive et al 04 quoted the value $Y_p=0.249 \pm 0.009$. A small sample size used and large uncertainties affecting analysis are responsible in this case for the very large error.

iii) Fukugita et al. 06, based on a reanalysis of a sample of 33 H\textsubscript{II} regions from i) determined a value of $Y_p=0.250 \pm 0.004$

iv) Peimbert et al 07, present a new $^4\text{He}$ mass fraction determination, yielding $Y_p=0.2477 \pm 0.0029$. This result is based on new atomic physics computations together with observations and photoionization models of metal-poor extragalactic H\textsubscript{II} regions.
All recent estimates are dominated by systematics. We 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

$$Y_p = 0.247 \pm 0.002_{\text{stat}} \pm 0.004_{\text{syst}}$$

Finally, CMB anisotropies are sensitive to the reionization history, and thus to fraction of baryons in the form of $^4\text{He}$. Present data only allow a marginal detection of a non-zero $Y_p$, and even with PLANCK the error bars from CMB will be larger than the present systematic spread of the astrophysical determinations.
In stellar interior it can be either produced by $^2$H-burning or destroyed in the hotter regions → all the $^3$He nuclides surviving the stellar evolution phase contribute to the chemical composition of the InterStellar Medium (ISM). Stellar and galactic evolution models are necessary to track back the primordial $^3$He abundance from the post-BBN data, at least in the regions where stellar matter is present.

**Terrestrial measurements**

- From balloon measurements $^3$He/$^4$He $\sim 10^{-6}$
- From continental rock $^3$He/$^4$He $\sim 10^{-8}$

Large spread of values, confirm the idea that the terrestrial He has no cosmological nature. Most of it is $^4$He produced by the radioactive decay of elements such as uranium and thorium. No natural radioactive decay produces $^3$He, hence its observed terrestrial traces can be ascribed to unusual processes such as the testing of nuclear weapons or the infusion of extraterrestrial material.
**In the Solar System**

The most accurate value was measured in Jupiter's atmosphere by the Galileo Probe. Support the idea of a conversion of D initially present in the outer parts of the Sun into $^3$He via nuclear reactions.

- ProtoSolar Material (PSM) $^{3}\text{He}/^{4}\text{He} = (1.66 \pm 0.05) \times 10^{-4}$
- Meteoritic gases $^{3}\text{He}/^{4}\text{He} = (1.5 \pm 0.3) \times 10^{-4}$

**In the Local ISM**

By counting the helium ions in the solar wind, the Ulysses spacecraft has measured

- LISM $^{3}\text{He}/^{4}\text{He} = (2.48^{+0.68}_{-0.62}) \times 10^{-4}$ note that $^{4}\text{He}/\text{H} \sim 0.1$

not inconsistent with the idea that $^3\text{He}$ at our galaxy location might have grown in the last 4.6 billion years since the birth of the Sun.
Only one spectral transition allows detection of $^3\text{He}$, namely the 3.46 cm spin-flip transition of $^3\text{He}^+$, the analog of the widely used 21-cm line of hydrogen. A powerful tool for the isotope identification, as there is no corresponding transition in $^4\text{He}^+$. The emission is quite weak, hence $^3\text{He}$ has been observed outside the solar system only in a few HII regions and Planetary Nebula in the Galaxy. The values found in PN result one order of magnitude larger than in PSM and LISM $^3\text{He}/\text{H} = (2 - 5) \times 10^{-4}$ confirming a net stellar production of $^3\text{He}$ in at least some stars. From the expected correlation between metallicity of the particular galactic environment and its distance from the center of galaxy, one would expect a gradient in $^3\text{He}$ abundance versus metallicity and/or distance.
No $^3$He dependence on environment metallicity, as predicted by chemical evolution models of Galaxy. Known as $^3$He problem. Thus a conservative approach: $^3$He/H < $(1.1 \pm 0.2) \times 10^{-5}$. In alternative, by using $^2$H/H estimate and the theoretical stability of ratio $(^2$H+$^3$He)/H = $(3.6 \pm 0.5) \times 10^{-5} \implies ^3$He/H = $(0.7 \pm 0.5) \times 10^{-5}$.
Lithium's two stable isotopes, $^6$Li and $^7$Li, continue to puzzle astrophysicists and cosmologists. Spite & Spite (1982) showed that the lithium abundance in the warmest metal-poor dwarfs was independent of metallicity for $[\text{Fe/H}] < -1.5$. This is commonly called the Spite plateau and may be the lithium abundance in pre-Galactic gas provided by the BBN.

The very metal-poor stars in the halo of the Galaxy or in similarly metal poor galactic globular cluster (GGC) thus represent ideal targets for probing the primordial abundance of lithium.
Several technical and conceptual difficulties have been responsible for quite a long tale of $^7\text{Li}$ determinations:

$$[ ^7\text{Li}/H ] = 12 + \log_{10}( ^7\text{Li}/H )$$

1. (Bonifacio et al. 97) $[ ^7\text{Li}/H ] = 2.24 \pm 0.01$
2. (Ryan et al. 99, 00) $[ ^7\text{Li}/H ] = 2.09^{+0.19}_{-0.13}$
3. (Bonifacio et al. 02) $[ ^7\text{Li}/H ] = 2.34 \pm 0.06$
4. (Melendez et al. 04) $[ ^7\text{Li}/H ] = 2.37 \pm 0.05$
5. (Charbonnel et al. 05) $[ ^7\text{Li}/H ] = 2.21 \pm 0.09$
6. (Asplund et al. 06) $[ ^7\text{Li}/H ] = 2.095 \pm 0.055$
7. (Korn et al. 06) $[ ^7\text{Li}/H ] = 2.54 \pm 0.10$
It is unclear how to combine the different determinations in a single estimate, or if the value measured is truly indicative of a primordial yield.

A conservative approach (similar to the one used for $^4\text{He}$) is to quote the simple (un-weighted) average and half-width of the above distribution of data as best estimate of the average and "systematic“ error on $^7\text{Li}/\text{H}$, obtaining

$$
\left[\frac{^7\text{Li}}{\text{H}}\right] = 2.27 \pm 0.23 \implies \left(\frac{^7\text{Li}}{\text{H}}\right) = \left(1.86^{+1.30}_{-1.10}\right) \times 10^{-10}
$$
We have a substantial disagreement, as a factor 1.5 – 2, between BBN prediction and observations. What could be the reason?

i) a factor 1.5 - 2 lower value of $\eta$ at the BBN time with respect to the best fit deduced from CMB data is excluded by the agreement between D observations and CMB value of $\eta$, and also by the inferred upper limit of the primordial $^3$He abundance.

ii) underestimated errors in the adopted nuclear reaction rates are now excluded: the laboratory measurements of the crucial $^3$He($\alpha,\gamma$)$^7$Be cross section, its inferred rate from solar neutrino data and the measurement of the proposed alternative channel for $^7$Be destruction $^7$Be($d; p$)$^2\alpha$

iii) Systematic errors in the analysis, although in principle still possible, seem very unlikely. 3D model atmospheres did not result in a significant upward revision of results obtained from more primitive 1D atmospheres.
Perhaps, and more likely, the lithium abundance of very metal-poor stars is not the one of the primordial gas.

Even assuming some diffusion and turbulent mixing mechanism to explain the $^7\text{Li}$ problem, still an issue remains with $^6\text{Li}$. The presence of the fragile $^6\text{Li}$ isotope, which is produced during BBN at the level of $^6\text{Li}/\text{H} \sim 10^{-15} - 10^{-14}$, has been recently confirmed in a few metal-poor halo stars, with some hint of a plateau vs. metallicity with abundance as high as $^6\text{Li}/\text{H} \sim 6 \times 10^{-16}$.

A great help in solving this issue might come from detecting lithium in a different environment!
BBN, BARYON FRACTION AND NEUTRINOS
Abundances dependence on $\omega_b$ ($N_\gamma=3$)
Likelihood analysis

- Run a BBN code (PArthENoPE) to get $Y_P(N_\nu, \eta)$, $X_D(N_\nu, \eta)$

- Construct for each abundance the likelihood function:

$$
L_i(N_\nu, \eta) = \frac{1}{2\pi\sigma_i^{th}(N_\nu, \eta)\sigma_i^{ex}} \int dx \exp\left(-\frac{(x - Y_i^{th}(N_\nu, \eta))^2}{2\sigma_i^{th}(N_\nu, \eta)^2}\right) \exp\left(-\frac{(x - Y_i^{ex})^2}{2\sigma_i^{ex2}}\right)
$$

- Define a total likelihood function $L = L_{4\text{He}} L_D$

- Plot the 68%, 95% and 99% cl contours in the $(N_\nu, \eta)$ plane.

\[\frac{^2H}{H} = 2.87^{+0.22}_{-0.21} \times 10^{-5}, \quad Y_p = 0.247 \pm 0.002_{\text{stat}} \pm 0.004_{\text{syst}}\]
• Only $^2\text{H} \rightarrow \Omega_B h^2 = 0.021 \pm 0.002$ at 95% CL
• Only $^4\text{He}$ stat. $\rightarrow \Omega_B h^2 = 0.020^{+0.010}_{-0.006}$ at 95% CL
• WMAP 5-years $\rightarrow \Omega_B h^2 = 0.02273 \pm 0.00062$

The slight tension could affect primordial scalar perturbation spectral index $n_s$ determination ($^2\text{H}$ is a prior)
After marginalization we get

\[ N_\nu = 2.97^{+0.29}_{-0.27} \text{ (95\% CL)} \text{ add. Syst. } 2.4 \leq N_\nu \leq 3.6 \text{ (95\% CL)} \]

\[ \Omega_\text{B} h^2 = 0.021 \pm 0.002 \text{ (95\% CL)} \]
Combining with other observables

Figure 4:
(Left) In blue (solid), the 68% and 95% contours in the $N_\nu - \eta_{10}$ plane derived from a comparison of the observationally-inferred and BBN-predicted primordial abundances of D and $^4$He. In red (dashed), the 68% and 95% contours derived from the combined WMAP 5-year data, small scale CMB data, SNIa, and the HST Key Project prior on $H_0$ along with the LSS matter power spectrum data. (Right) The 68% and 95% joint BBN-CMB-LSS contours in the $N_\nu - \eta_{10}$ plane.
Large neutrino chemical potentials are not forbidden. They affect BBN!

1) chemical potentials contribute to \( N_\nu \) (if no extra d.o.f.)

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

2) a positive electron neutrino chemical potential \( \xi_e \)

(\text{more neutrinos than antineutrinos}) favour \( p \text{~\rightarrow~} p \) with respect to \( p \text{~\rightarrow~} n \) processes.

3) Neutrino oscillations mix \( \xi_e, \xi_\mu, \xi_\tau \). We can take all of them equal.
From $Y_p$

$$\xi_e = 0.004 \pm 0.017_{\text{stat}}(2\sigma) \pm 0.017_{\text{sys}}$$

Even with a sensitivity of $\delta N\sim 0.1$ implies $|\xi| < 0.3$

BBN the best leptometer
According to the recent (arXiv:0808.3137 [astro-ph]) by S. Pastor, T. Pinto and G.G. Raffelt we have a degenerate (fine-tuned) direction, where for some value of $\theta_{13}$ one does not get thermodynamical equilibrium. But Neutrino Asymmetry is back!

FIG. 3: Parameters for the final $\nu_e$ and $\bar{\nu}_e$ spectra as well as the final $\Delta N_{\text{eff}}$ as a function of the initial $\xi_{\nu_e}$. The solid lines correspond to $\theta_{13} = 0$, the dotted lines to $\sin^2 \theta_{13} = 0.04$. In the bottom panel, the dashed line is the surviving $\Delta N_{\text{eff}}$ when the final $\xi_{\nu_e}$ is in the range allowed by BBN.
Some Conclusions

- BBN fixes the baryon abundance $\Omega_B h^2$ mainly through $^2H$
  $\Omega_B h^2 = 0.021 \pm 0.002 (2\sigma)$ 2$\sigma$ agreement with WMAP-5y
- only serious discrepancy with $^7Li$ (a factor 3)
- too much $^6Li$ is found
- Assuming extra dof: $N_\nu = 3.0 \pm 0.3_{\text{stat}} (2\sigma) \pm 0.3_{\text{syst}}$
- Assuming deg. $\nu$'s $\xi = 0.004 \pm 0.017_{\text{stat}} (2\sigma) \pm 0.017_{\text{syst}}$
- Some models invoked to explain the disagreement will be soon tested at LHC
A Planetary Nebula is a glowing shell of gas and plasma formed by certain types of stars when they die.
A HII regions, also known as emission nebula, is a cloud of glowing gas and plasma, sometimes several hundred light-years across, in which star formation is taking place.

NGC 604, a giant HII region in the Triangulum Galaxy.
A **Blue Compact dwarf Galaxy** (BCG galaxy) is a small galaxy which contains large clusters of young, hot, massive stars.

NGC 1705, a nearby example of a blue compact dwarf galaxy.
A **Globular Cluster** is a spherical collection of stars that orbits a galactic core as a satellite.

The Messier 80 globular cluster in the constellation Scorpius