Primordial Nucleosynthesis in the Precision Cosmology Era

The Annual Review of Nuclear and Particle Science
Gary Steigman (2007)

Galactic Archeology Seminar
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Universität Heidelberg

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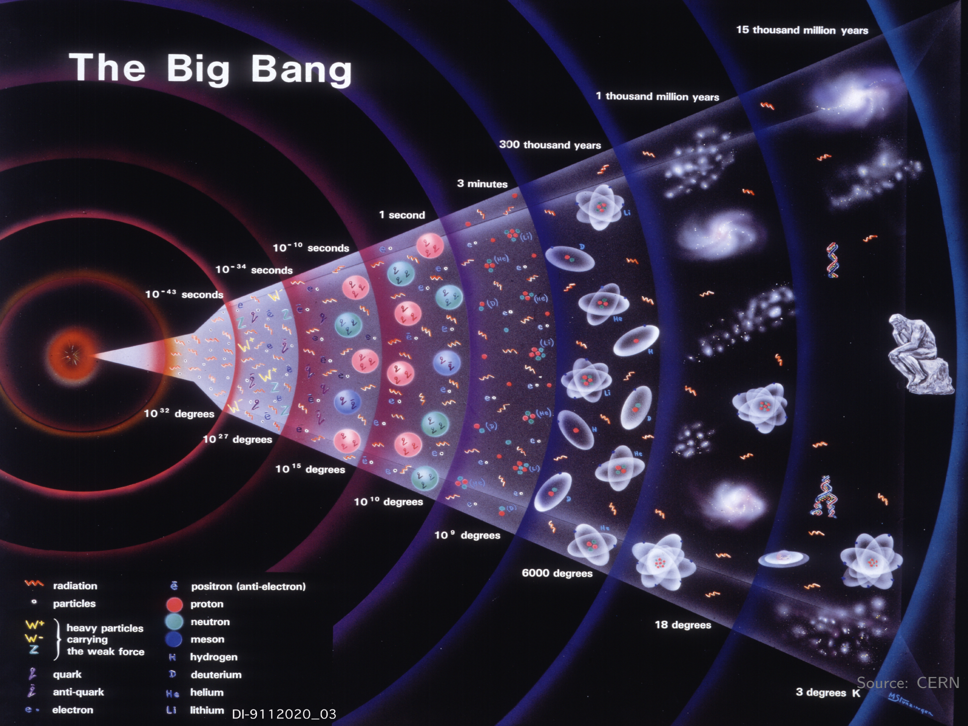
Contents



DI-9112020_03

Source: CERN

Fusion of the first nuclides

Initial neutron to proton ratio

Neutron & Proton equilibrium

- Once stable hadrons can form from the quark gluon plasma in the very early universe, neutrons and protons are in thermal equilibrium by the weak interactions:

$$
\begin{aligned}
p + e^- &\leftrightarrow n + \nu_e \\
n + e^+ &\leftrightarrow p + \bar{\nu}_e
\end{aligned} \tag{1}
$$

- Mass of protons is slightly lower than that of the neutrons

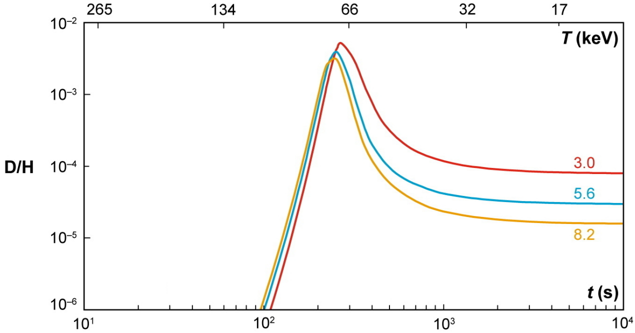
$$n_i/p_i = 1/7 \tag{2}$$

Deuterium evolution

- Deuterium is formed by fusion of a proton and a neutron

$$n + p \leftrightarrow d + \gamma \tag{3}$$

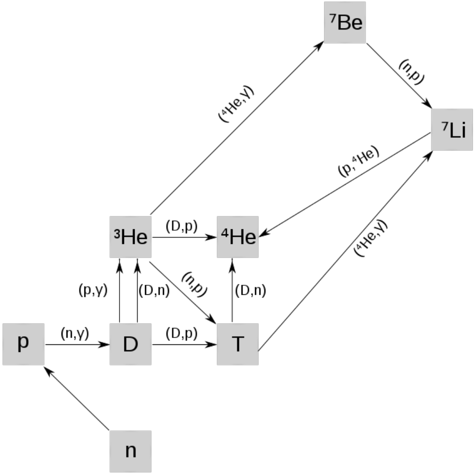
- Significant amounts can only built up when $kT \lesssim 80\,\mathrm{keV}$
- The higher the baryon density $\eta_{10} = 10^{-10}(n_B/n_\gamma)$, the higher the interaction rate



Helium-4 evolution

Nucelar fusion processes

- The starting point for all subsequent fusions is Deuterium
- Deuterium fusion is a slow reaction
- Deuterium is immediately converted to ^{3}He and tritium
- no stable mass-5 nuclides $\rightarrow$ bottleneck at ^{4}He

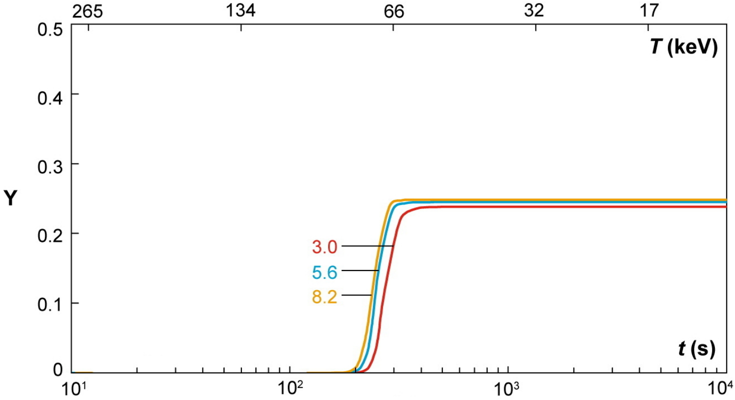


Source: https://en.wikipedia.org/wiki/Big_Bang_nucleosynthesis

Helium-4 evolution

Time dependence

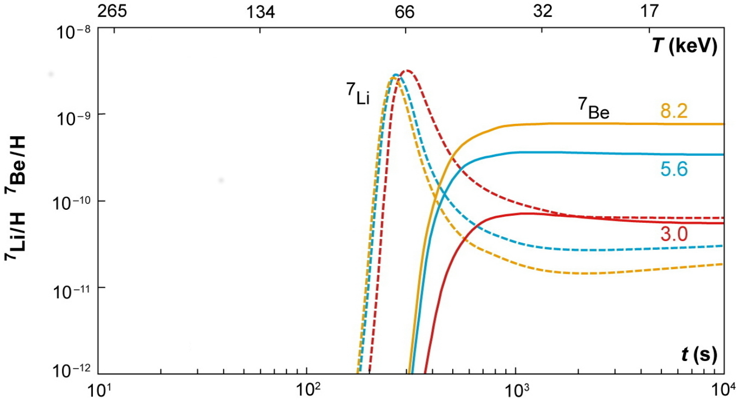
- All available neutrons are incorporated in ^{4}He $\rightarrow$ insensitive to baryon abundance η_{10}
- ^{4}He fusion requires deuterium



Lithium-7 and Beryllium-7 evolution

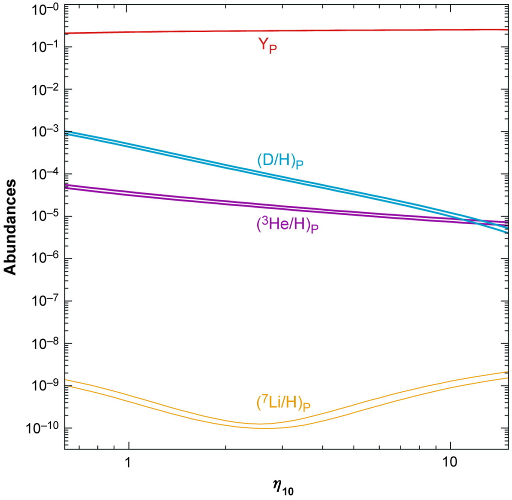
Time dependence

- No stable mass-5 nuclide → larger gap from ^{4}He to ^{7}Li
- ^{7}Li decays into ^{4}He more easily at higher density
- ^{7}Be is more efficiently fused at higher density



Primordial abundances

- Fusion processes can be cast in differential equation
- They only depend on η_{10}
- Higher density leads to faster fusion of Deuterium and ^{3}He
- ^{4}He abundance (Y) is only limited by available neutrons
- ^{7}Li fusion is more effective at lower η_{10}, but vice versa for ^{7}Be



Observations of the relic nuclides

Deuterium - The Baryometer of Choice

Evolution after the Big Bang Nuceleosynthesis

- Deuterium is burned away in the collapse of prestellar gas
- Deuterium in stars is immediately fused into ^{3}He

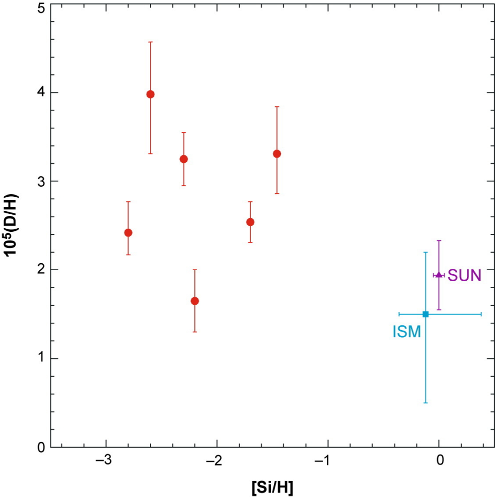
→ Deuterium is only destroyed

→ Ideal to determine lower boundary of the relic abundance

Deuterium - The Baryometer of Choice

High redshift observations as function of metallicity

- Observation of neutral gas absorption lines
- Few datapoints due to difficulties in the observation
- Expected plateau is masked by dispersion
- Value determined $10^5(\mathrm{D/H}) = 2.68^{+0.27}_{-0.25}$



Observations of the relic nuclides
Helium-3

Evolution after the Big Bang Nucleosynthesis

- ^{3}He is both produced and destroyed in stars

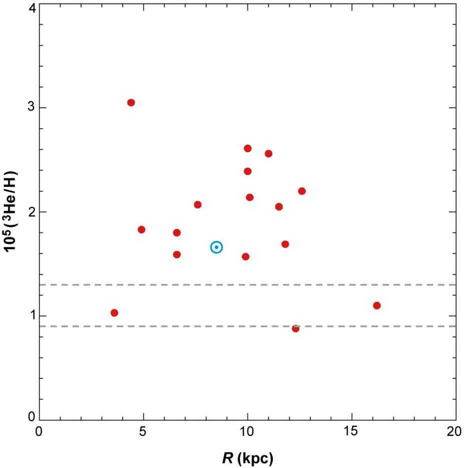
→ Evolution dependent on stellar and galactic models

- Net production or destruction should create correlation to metallicity

Helium-3

HII observations

- Observation of spin flip transition in HII regions
- Limited to our galaxy due to its low intensity
- No correlation to the galaxy's metallicities gradient
- Most metal poor regions give an upper limit for the primordial ^{3}He abundance $10^5(^3\mathrm{He/H}) = 1.1 \pm 0.2$



Observation of the relic nuclides

Helium-4

Post Big Bang Nucleosynthesis evolution

- Significant production in stars
- Correlation between metallicity and ^{4}He abundance

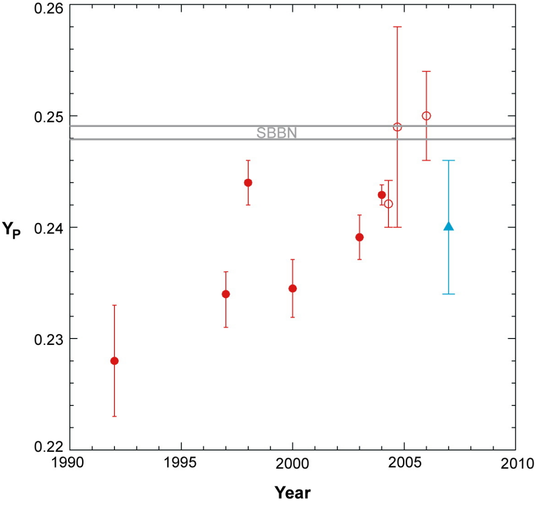
→ High redshift observations

→ Extrapolation to zero metallicity

Helium-4

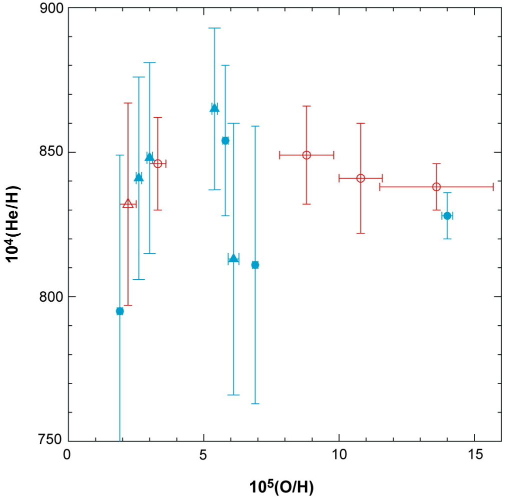
Observations over time

- Observations of extragalactic HII regions
- Large number of objects reduces statistical error
- Sample of observationally inferred primordial ^{4}He over the years
- Blue: Value adopted $Y_P = 0.240 \pm 0.006$.



Helium-4
Metallicity correlation

- Analysis HII regions of two different groups (corresponding to different symbols)
- No support for correlation between ^{4}He and metallicity
- Systematic errors require more attention



Observations of the relic nuclides

Lithium-7

Post Big Bang Nucleosynthesis evolution

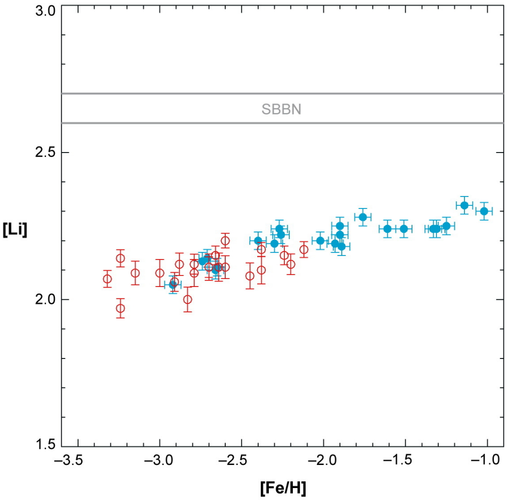
- Burned away in the interior of stars
- Some ^{7}Li may survive in the outer and cooler layers
- Net production by certain convective stars
- Production by spallation processes

$\Rightarrow$ Evolution is complex and not fully understood

Lithium-7

Missing Lithium

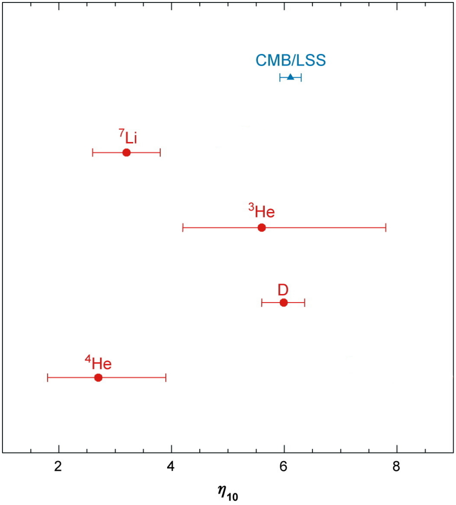
- Analysis of metal poor halo stars
- [Li] $= 12 + log(Li/H)$
- Overall increase with metallicity
- No discernible ^{7}Li plateau
- Clear gap between SBBN prediction and measured values



Baryon density constraints from observations

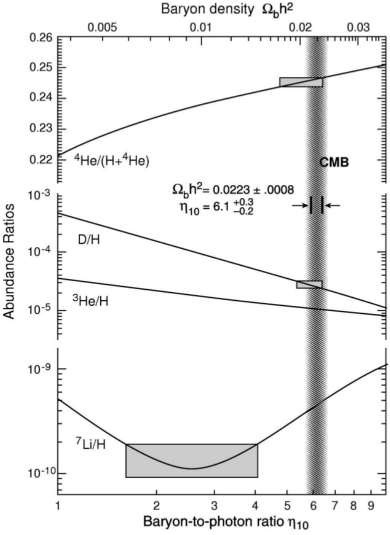
Results in 2007

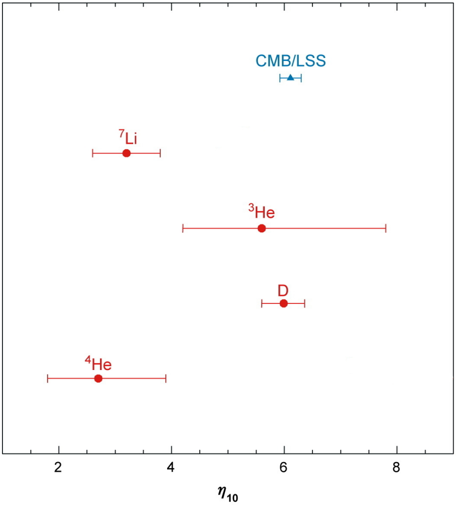
- Values determined by observations and corresponding baryon density
- Best constraint by CMB measurements
- ^{3}He and D are in excellent agreement
- ^{7}Li and ^{4}He are both outside the 1σ range



Baryon density constraits from observations

Comparison to current values





Cosmology lecture of M.Bartelmann WS17/18

Summary

Theory

- Expansion rate and Temperature of the universe are well understood
- Big Bang Nucleosynthesis fusion processes only depend on η_{10}
- Value for η_{10} can be determined from CMB

$\Rightarrow$ Theoretical abundances can be computed

Observation

- Both ^{4}He and Deuterium observation confirm CMB measurement
- ^{3}He is no longer used
- ^{7}Li abundance is too low