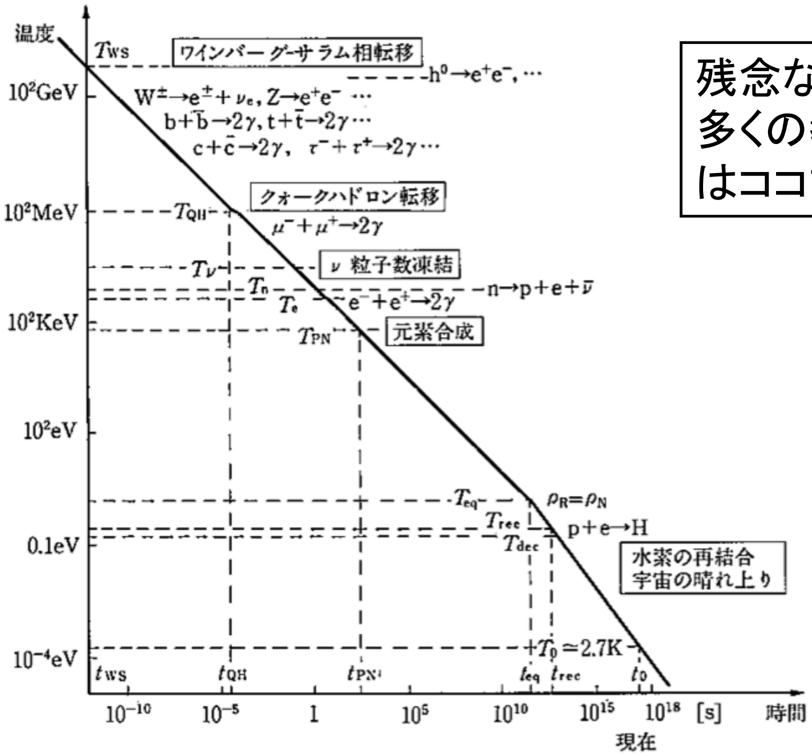
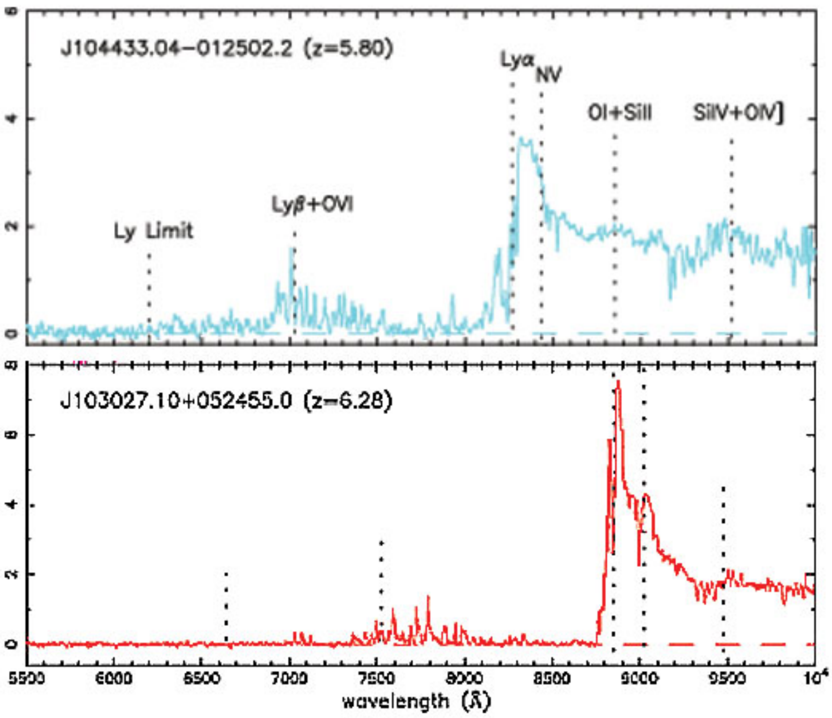
Thermal history

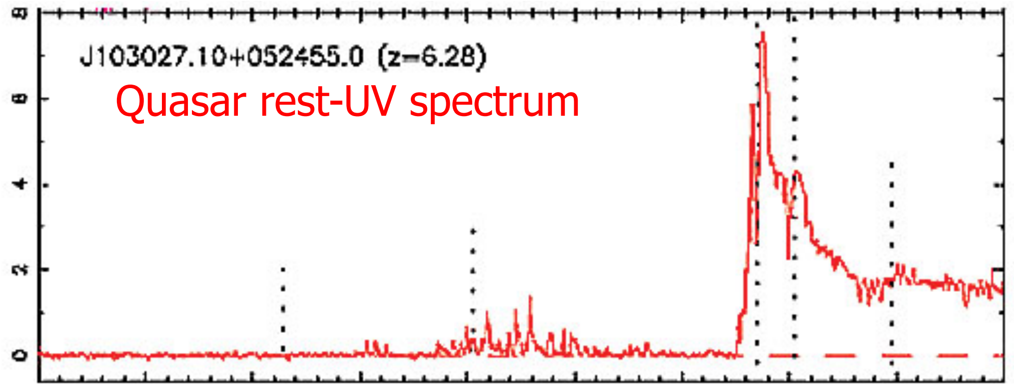


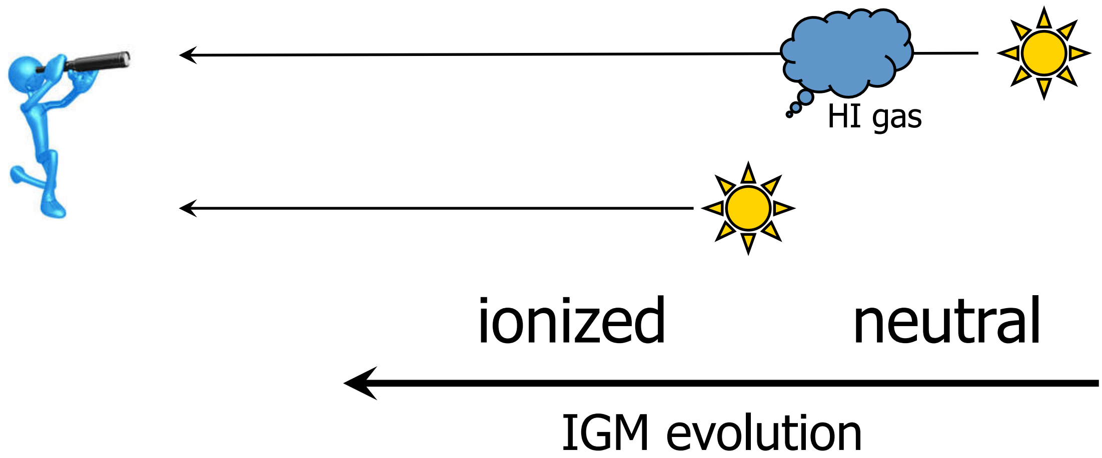
残念ながら
多くの教科書
はココまで

Hydrogen Reionization and Gunn-Peterson Trough

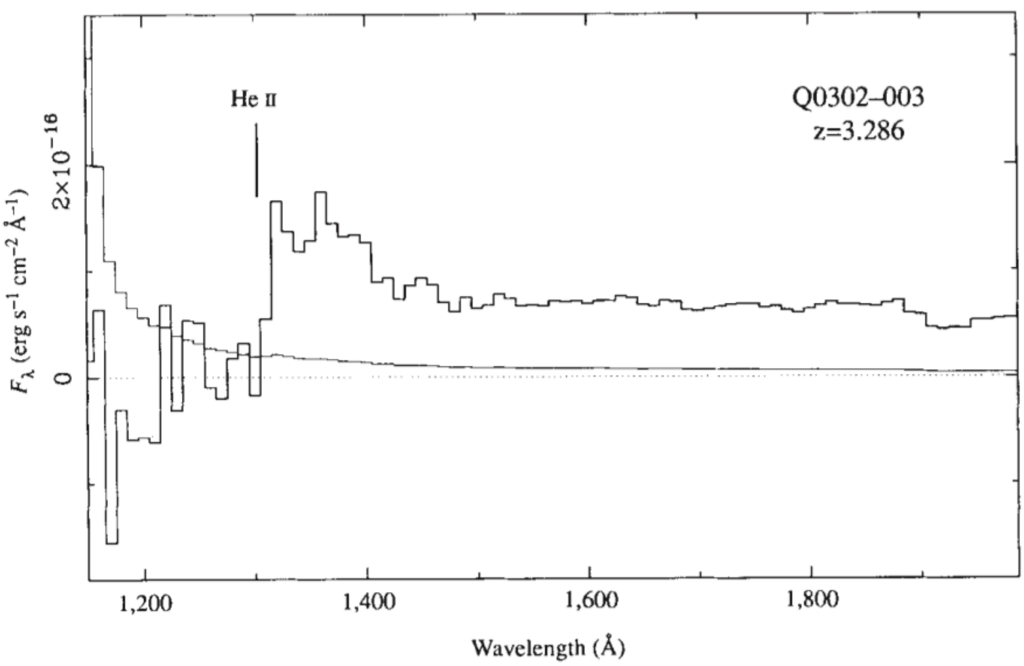


Transmission shortward (blue side) of Lyman-a completely suppressed
- "a trough".





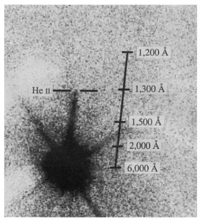
HeII Gunn-Peterson Trough



Jakobsen et al. 1994, Nature

ARTICLES

Detection of intergalactic ionized helium absorption in a high-redshift quasar



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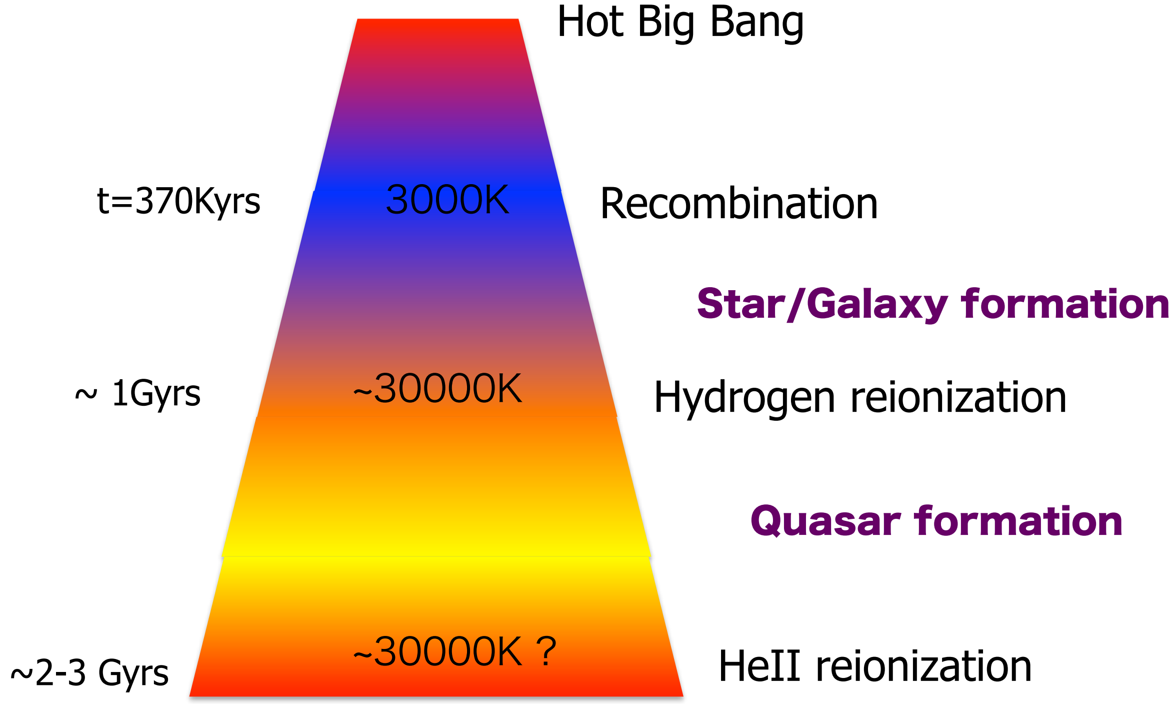
Observations obtained with the recently refurbished Hubble Space Telescope reveal strong absorption arising from singly ionized helium along the line of sight to a high-redshift quasar. The strength of the absorption suggests that it may arise in a diffuse ionized intergalactic medium. The detection also confirms that substantial amounts of helium existed in the early Universe, as predicted by Big Bang nucleosynthesis theory.

HeII Gunn-Peterson Trough

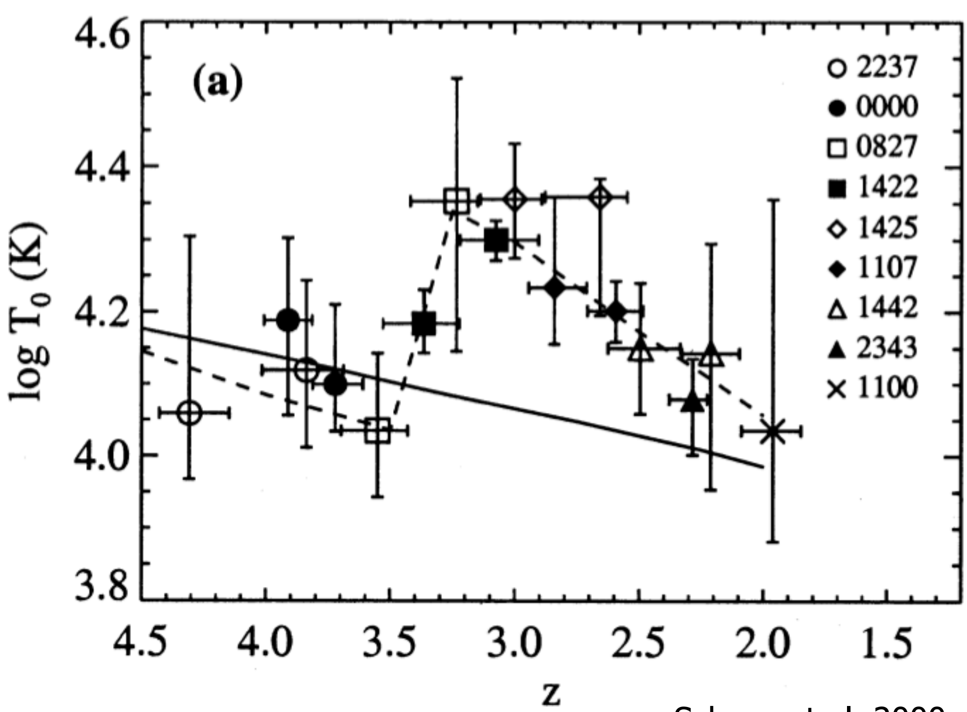
Detection of clear HeII Lyman-a absorption
(at rest 304 Angstrom) at z=3.28
suggests that there were singly-ionized helium,
i.e. HeII was reionized around z~3.

The ionization potential of an HeII is 54.4 eV.
What are the sources of HeII reionization ?

Thermal history of the Universe
- structure formation view -



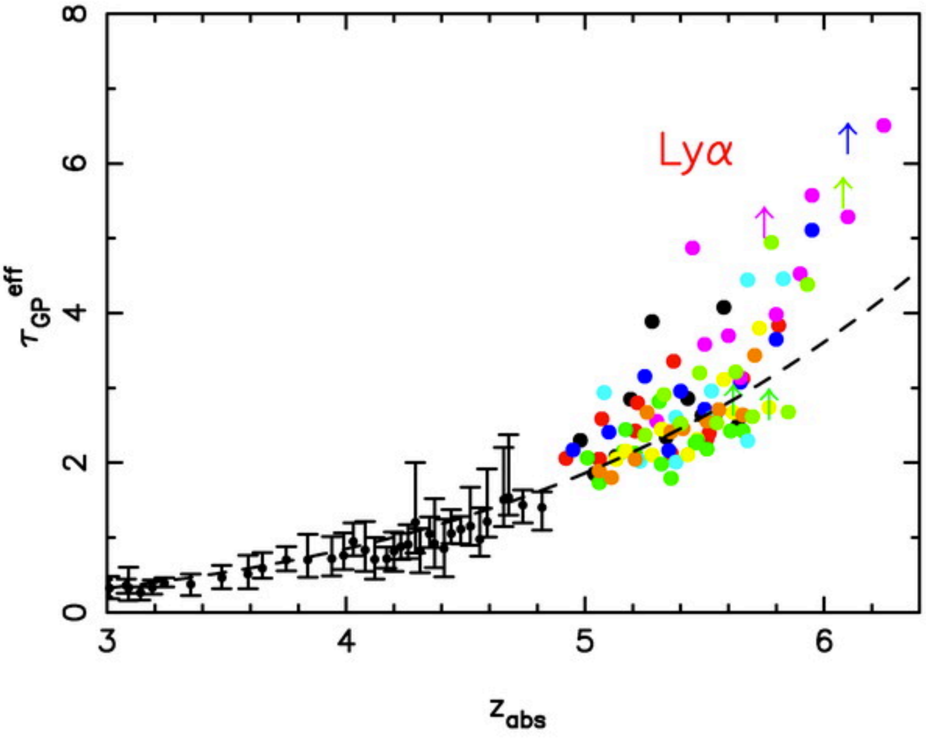
HeII reionization



Schaye et al. 2000, MNRAS

Hydrogen reionization

IGM almost fully ionized at z<6



IGM mostly ionized...

Why, or how ?

$$H + \gamma \rightarrow p + e$$

The ionization potential of an H atom is 13.598 eV. Photons more energetic than this can photo-ionize hydrogen. The residual energy is carried out by detached electrons, which eventually heat up the gas (IGM). Suppose that 1eV per ionization (per H atom) is deposited as heat; this is sufficient to raise the gas temperature to ~10000 K. (Check this value by yourself).

Photo-ionization is photo-heating

Hydrogen reionization

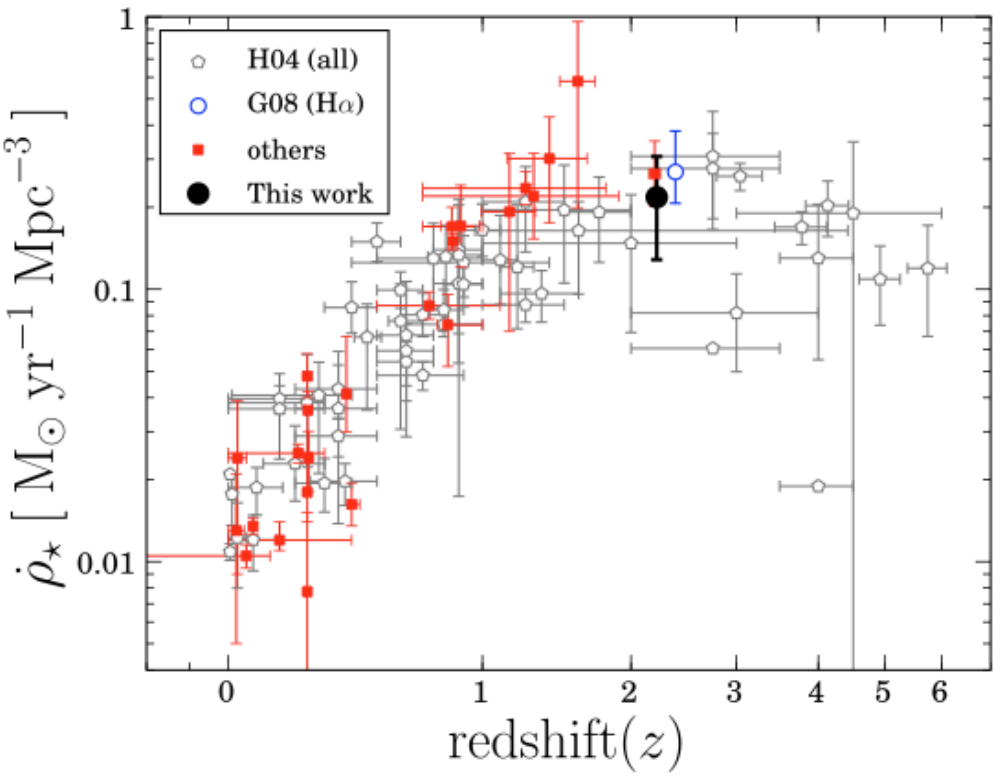
How many photons are needed to completely reionize the universe ?

Step1) Derive the hydrogen number density assuming $\Omega_{baryon} = 0.045$. Use $\rho_{critical} = 3H_0^2/8\pi G$, and $X_H = 0.76$

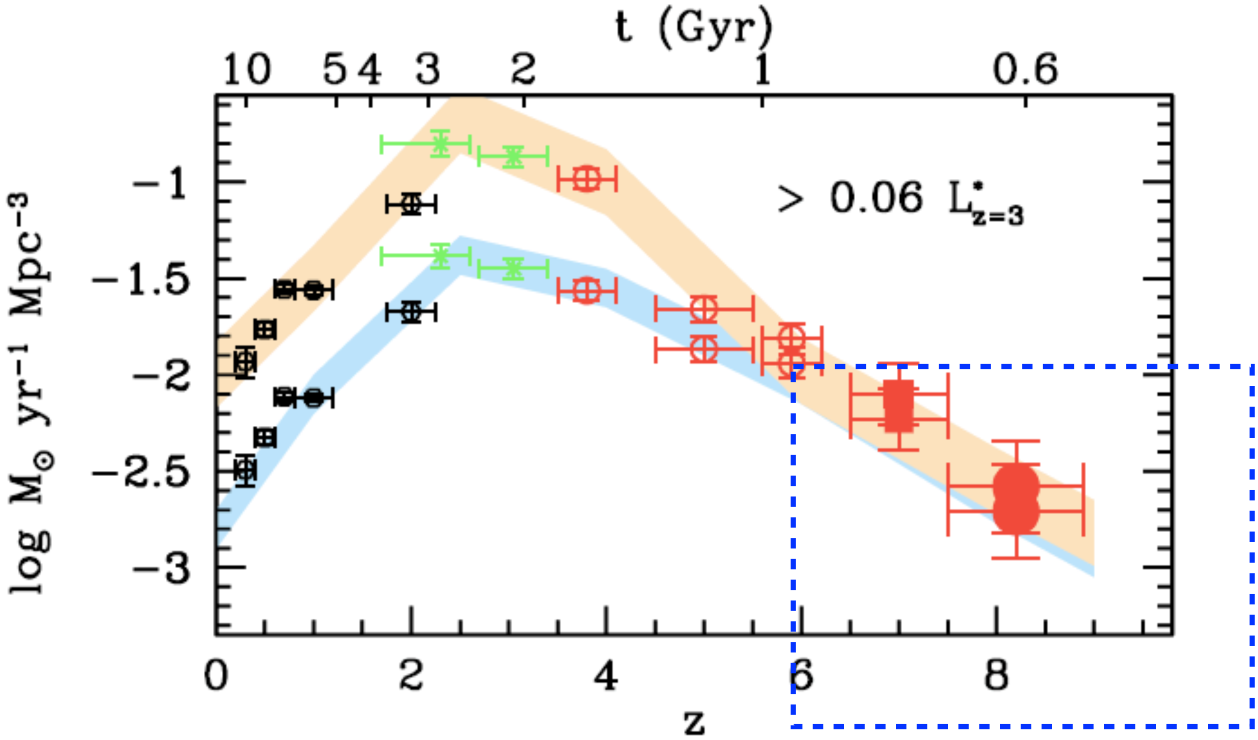
Step2) Ask yourself how many stars (per $[1\text{Mpc}]^3$) can do it.

A 20 Msun Population I star can emit UV photons at a rate $N = 8 \times 10^{47}$ /sec. How many such massive stars are needed ? Is it ever possible to form that many stars within 1 Gyrs ?

Cosmic star formation history



Cosmic star formation history



Star formation,
helium abundance,
and Big Bang Nucleosynthesis

Helium production

In cosmology text books, we learn (*simply read)* that hydrogen and helium were produced by Big Bang during “the first three minutes”, without thinking *why* it is needed.

It was not so, historically. All the elements other than hydrogen were thought to be formed in stars.

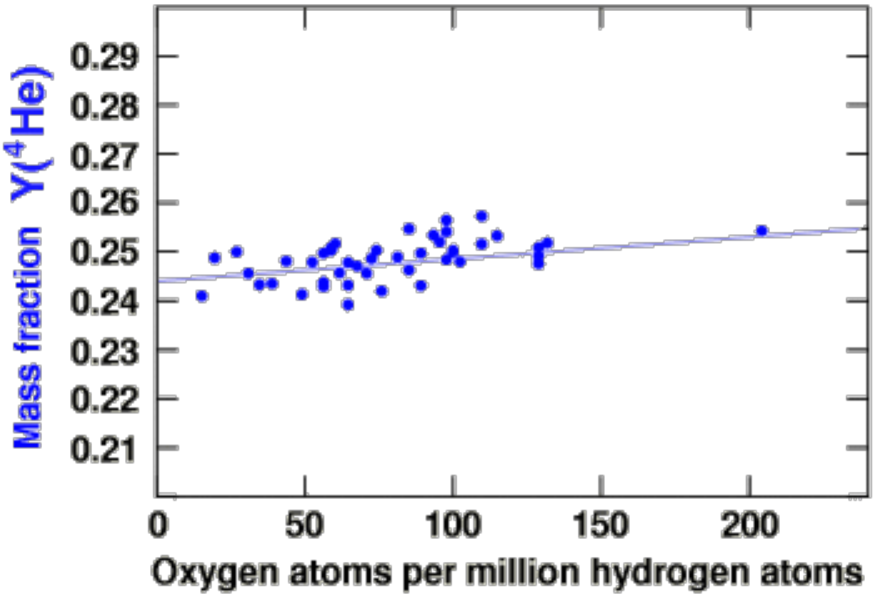
But it quickly turned out it wouldn’t work....

Hydrogen burning in stars

The net result of hydrogen burning is the fusion of four H nuclei into one ^{4}He nucleus. The difference in binding energy is 26.731 MeV, hence ~ 7MeV per H. (Not all this energy is emitted as photons from the surface, though. Think about “Where does the rest go ?”)

Observation of HII regions

Weak dependence on metallicity (O abundance) indicating other source(s) than stars.



Galaxies are not He factory

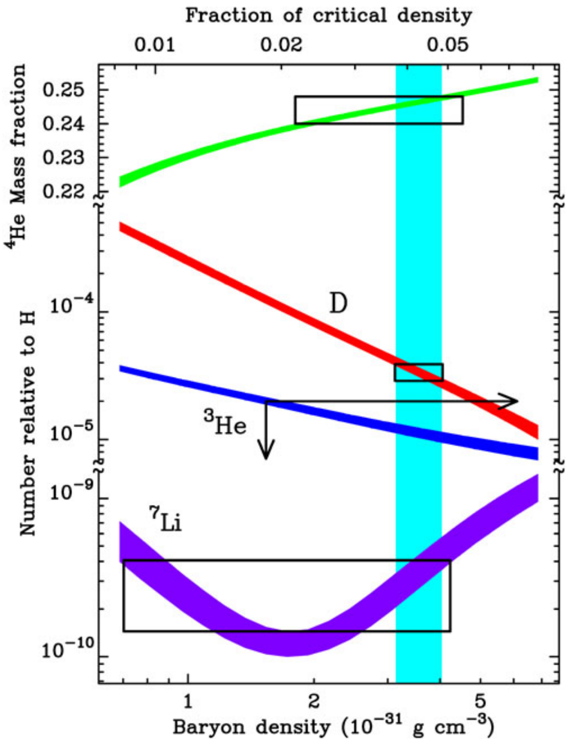
One can calculate light-to-helium production ratio as follows: Let's take a galaxy with $L \sim 10^{11}\ L_{sun}$. Over a cosmological time of 10 Gyrs, it releases a total energy of ~ 7.5×10^{73} eV.

Its stellar mass would be ~ a few $\times 10^{11}\ M_{sun}$. Then it contains ~ 2×10^{68} hydrogen nuclei.

This gives a mean energy output of 0.3 MeV per hydrogen nuclei. This is way too small compared with 7MeV per hydrogen burning.

Galaxies (stars) are luminous, but not as much as it should, in order to produce helium to ~ 25% in mass. <u>There must be another He factory.</u>

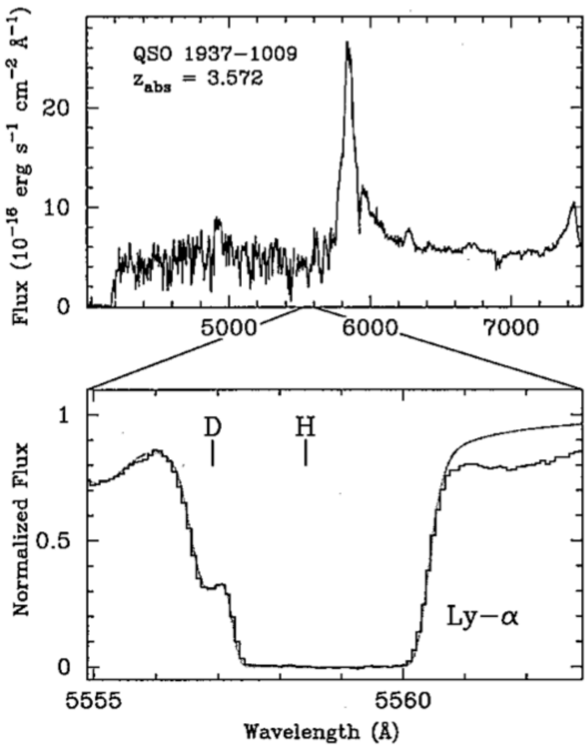
BBN prediction



Helium abundance relatively insensitive to the baryon density.

Lithium abundance is another, ***highly interesting*** mystery.

Deuterium



D/H ratio measured from QSO absorption lines.

D Lyman-α is centered at slightly blueward of H Lyman-α.