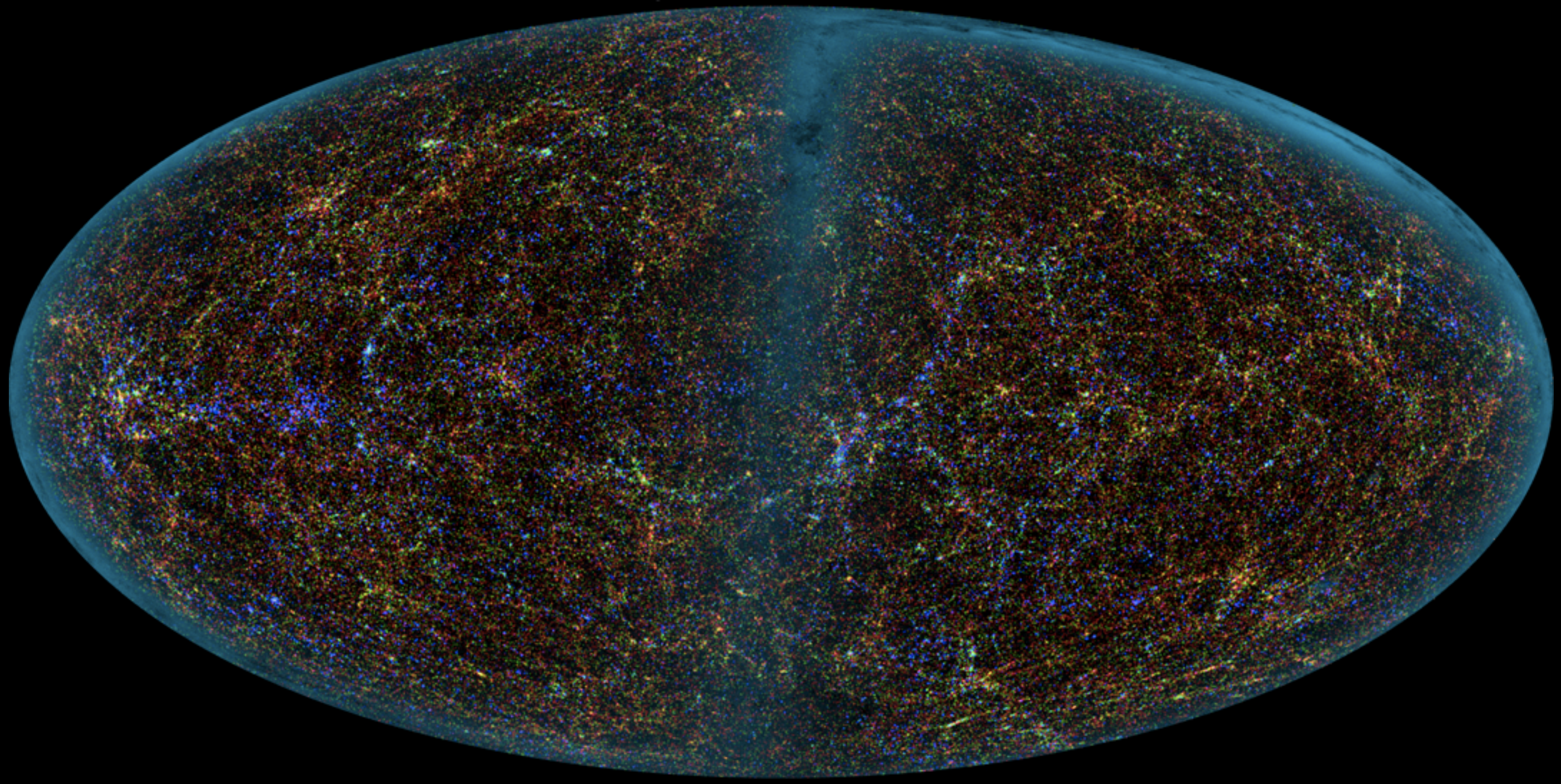
Cosmology

and Large Scale Structure



<u>Today</u>
Empirical Pillars
of the Hot Big Bang

Nucleosynthesis
(observations)

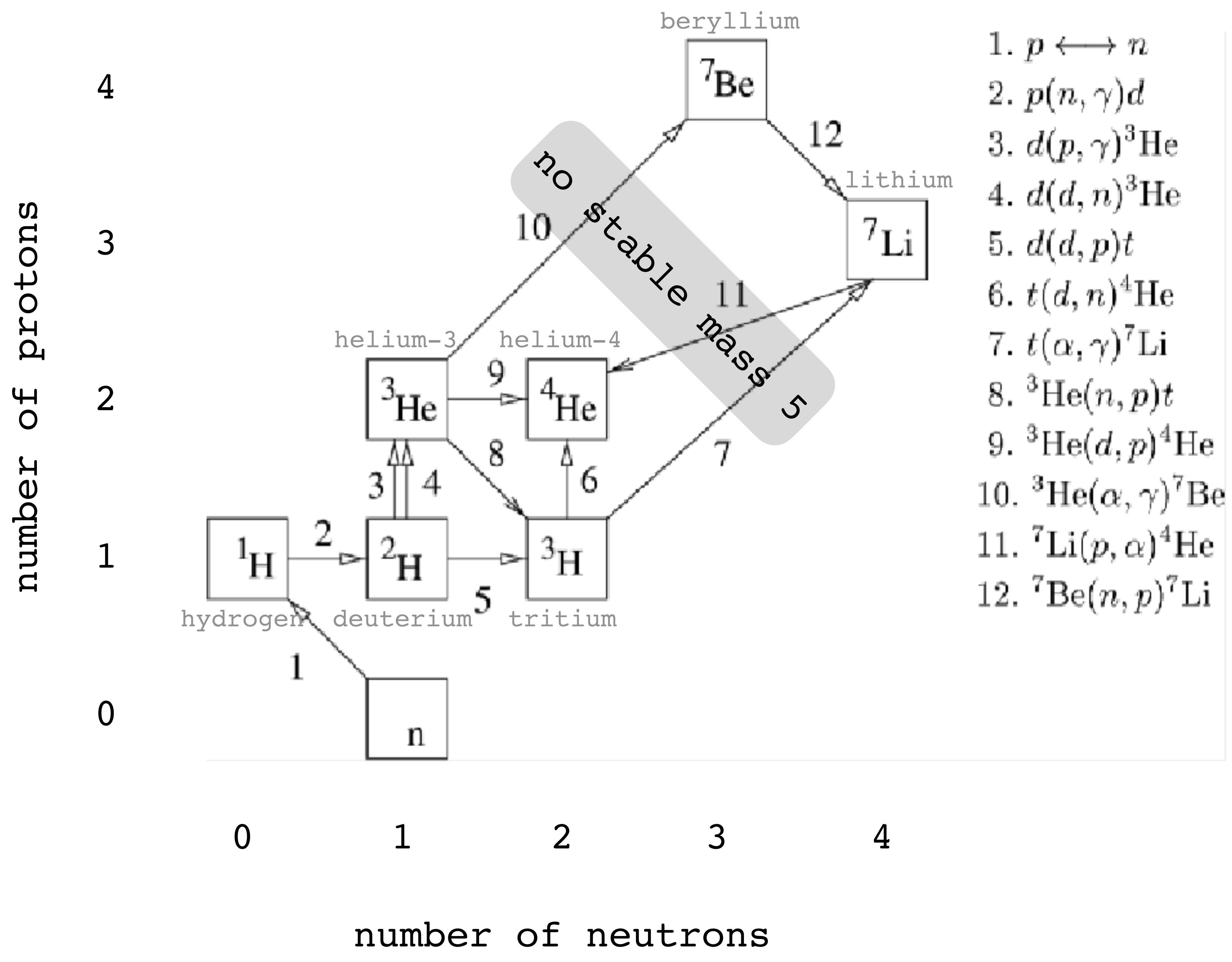
Homework 4 due next time

8 November 2022

http://astroweb.case.edu/ssm/ASTR328/

Big Bang Nucleosynthesis occurs during the radiation dominated era

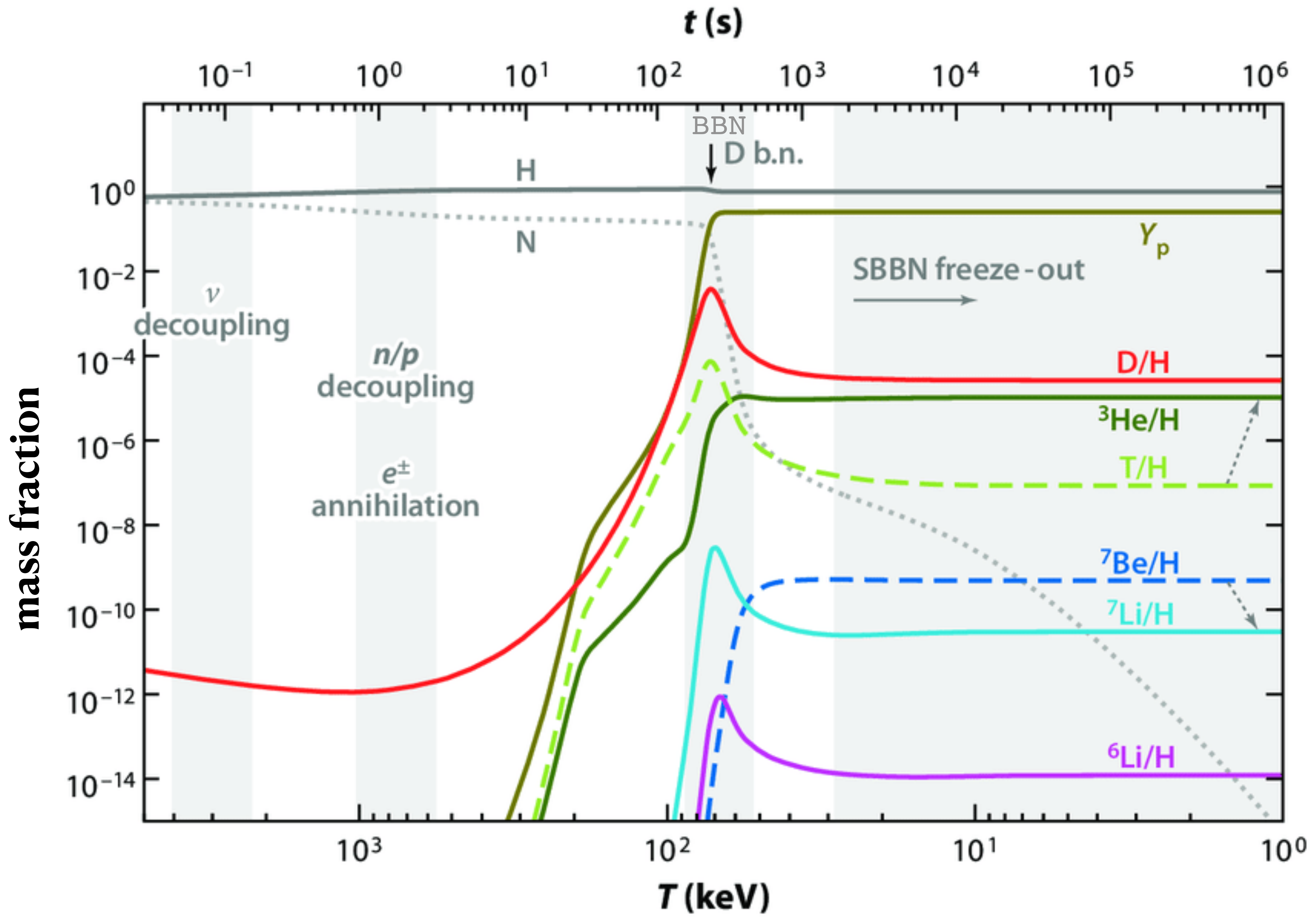
Solve nuclear reaction chain as the universe expands and cools.
Must also keep track of neutron decay!



1. $p \longleftrightarrow n$
2. $p(n,\gamma)d$
3. $d(p,\gamma)^3\mathrm{He}$
4. $d(d,n)^3\mathrm{He}$
5. $d(d,p)t$
6. $t(d,n)^4\mathrm{He}$
7. $t(\alpha,\gamma)^7\mathrm{Li}$
8. $^3\mathrm{He}(n,p)t$
9. $^3\mathrm{He}(d,p)^4\mathrm{He}$
10. $^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$
11. $^7\mathrm{Li}(p,\alpha)^4\mathrm{He}$
12. $^7\mathrm{Be}(n,p)^7\mathrm{Li}$

^{4}He is energetically favored; forms a bottleneck.
There are no stable mass 5 or 8 nuclei.
^{6}Li omitted from illustration. Very rare.

$$a(t) \propto t^{1/2}$$



$$T(a)\ ;\ \rho_m(a)\ ;\ \rho_r(a)$$

$$\tau_N = 10.2 \text{ minutes}$$

still a little uncertain

$$\frac{n_N}{n_{Ni}} = e^{-\frac{t}{\tau_N}}$$

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There is just one variable, the baryon density, but many potential constraints:
the abundance relative to H, log(X/H), of X = ²H, ³He, ⁴He, ⁶Li, and ⁷Li.
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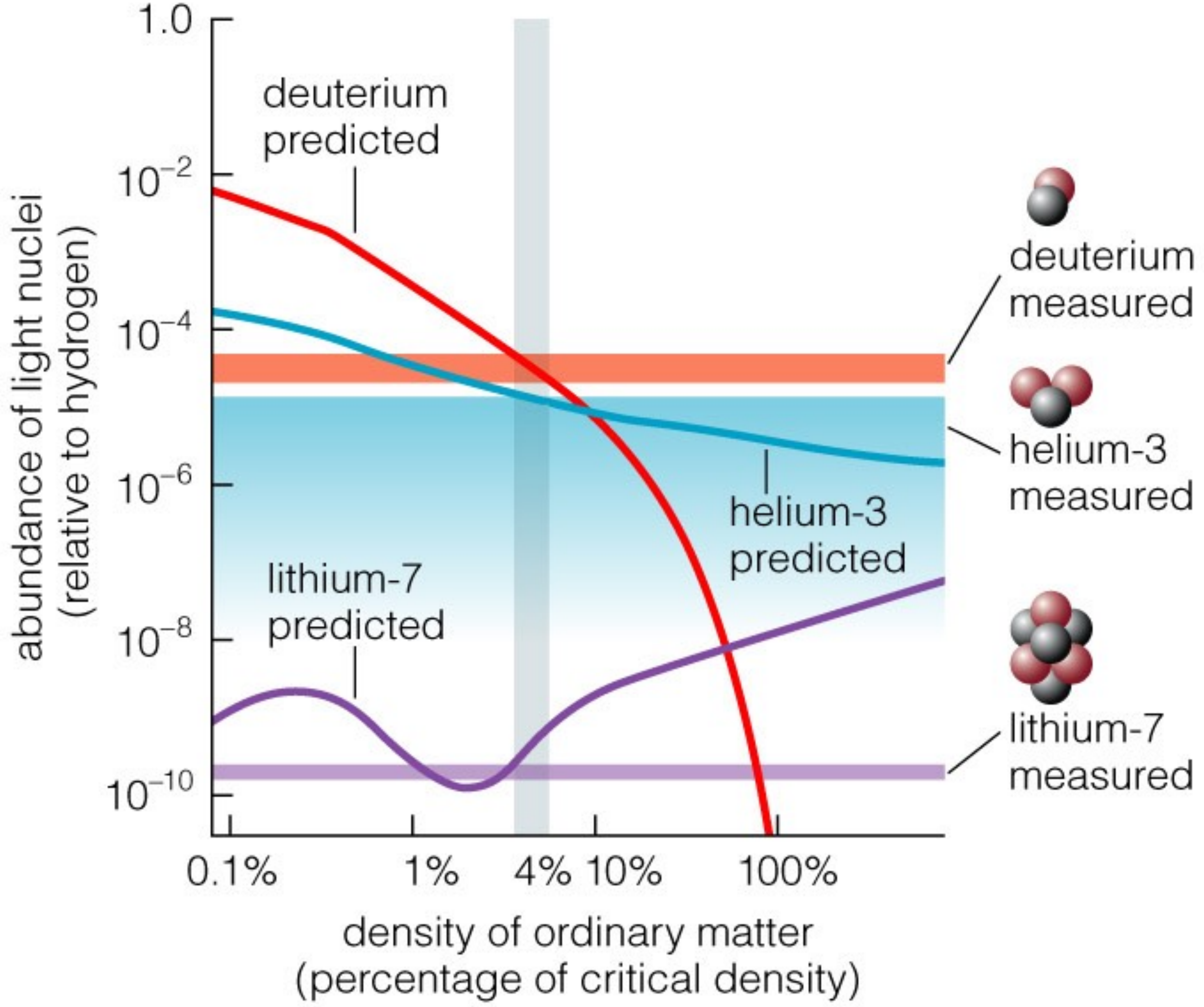
log(X/H)



Ω_b

BBN gets the abundances of deuterium, helium, and lithium right if the mass density is about 4% of the critical density.

Depends on the absolute scale through the Hubble constant, so often phrased as

$$\omega_b = \Omega_b h^2$$

where

$$h = \frac{H_0}{100}$$

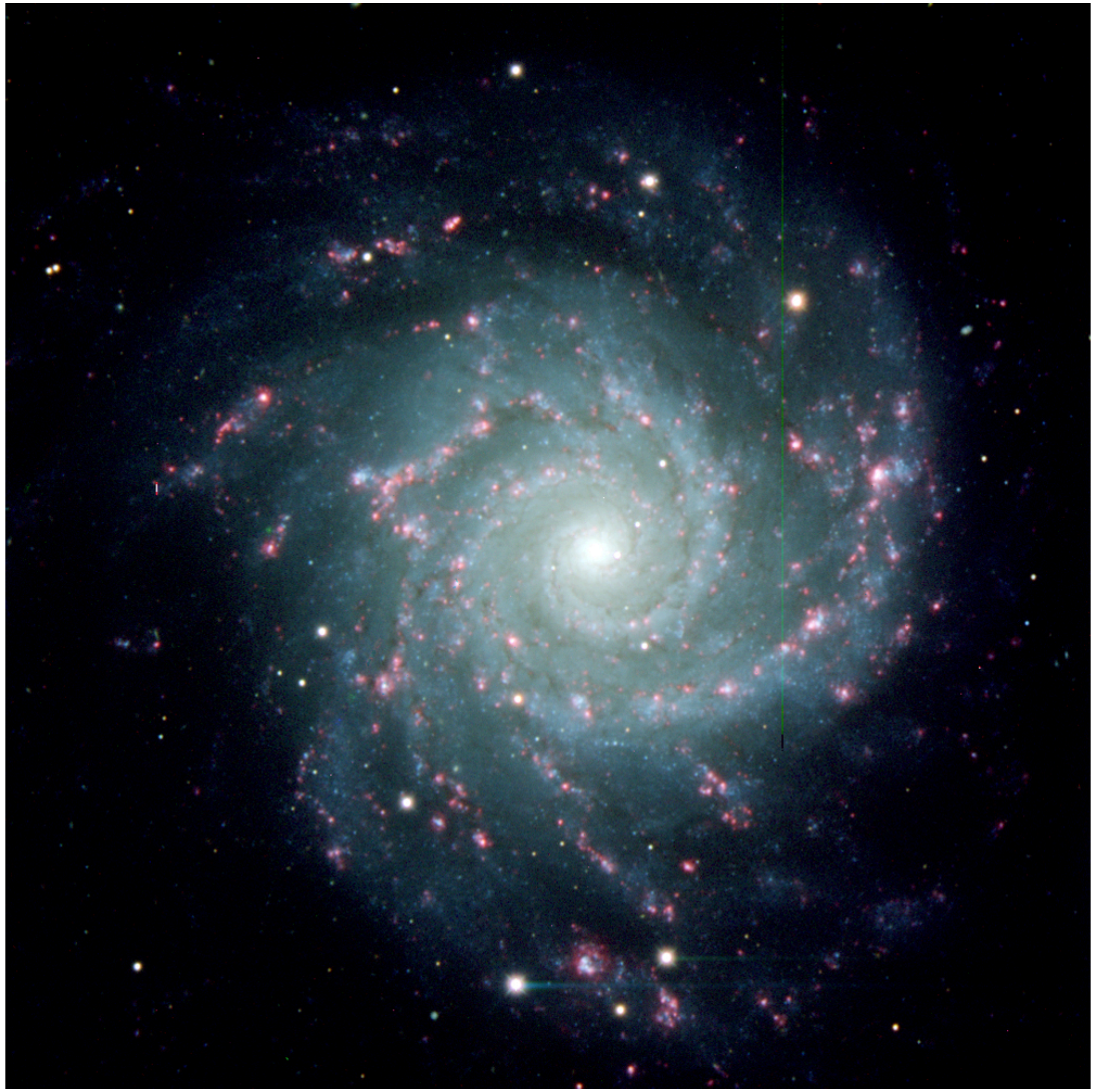
or in terms of the baryon-to-photon ratio

$$\eta = \frac{\Omega_b}{\Omega_r} = \frac{n_b}{n_\gamma} \approx \frac{1}{2 \times 10^9}$$

Helium

Helium is measured in the HII regions of nearby galaxies.

NGC 628



Pink spots are HII regions - interstellar gas ionized by the UV light of hot stars

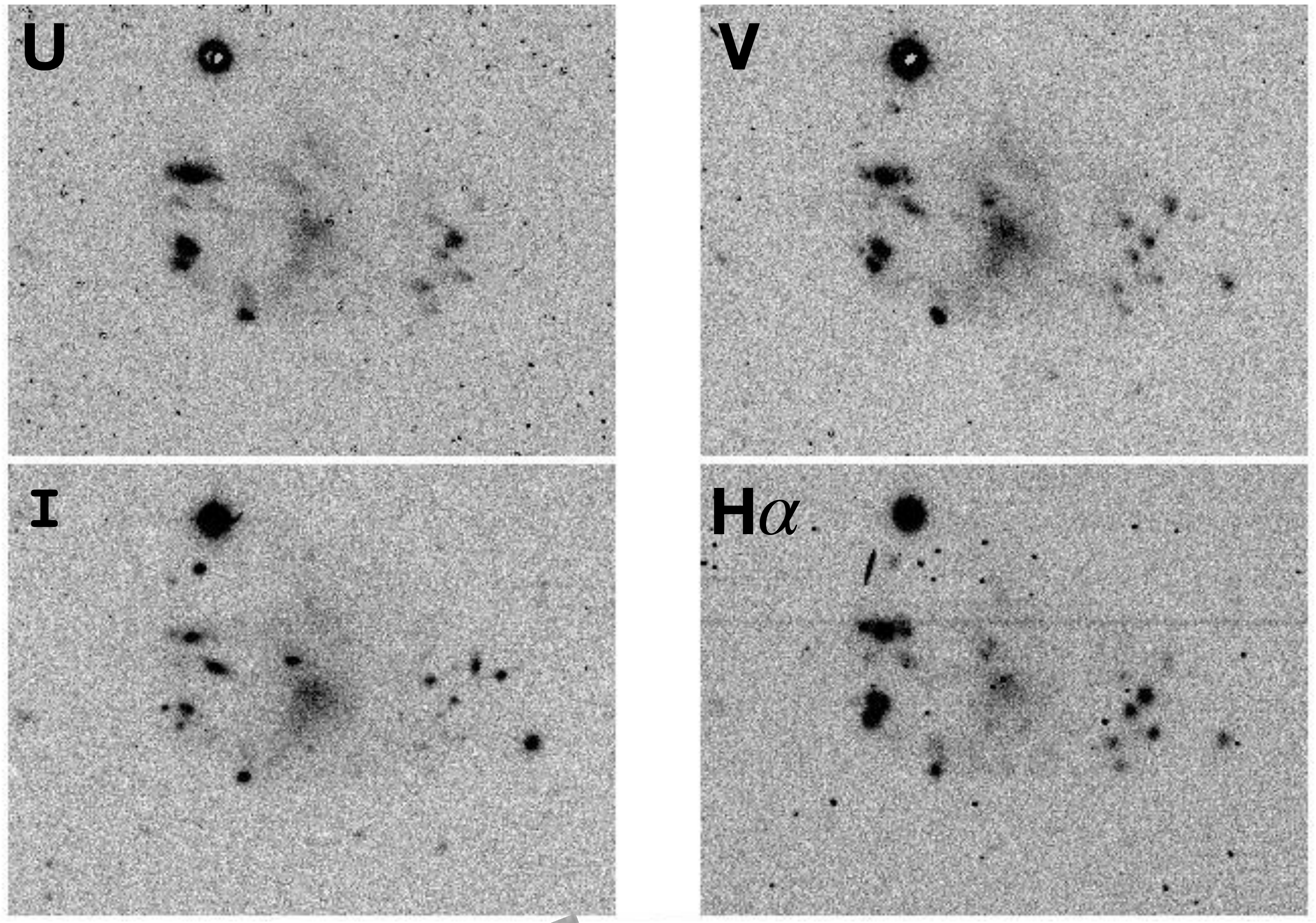
I Zw 18

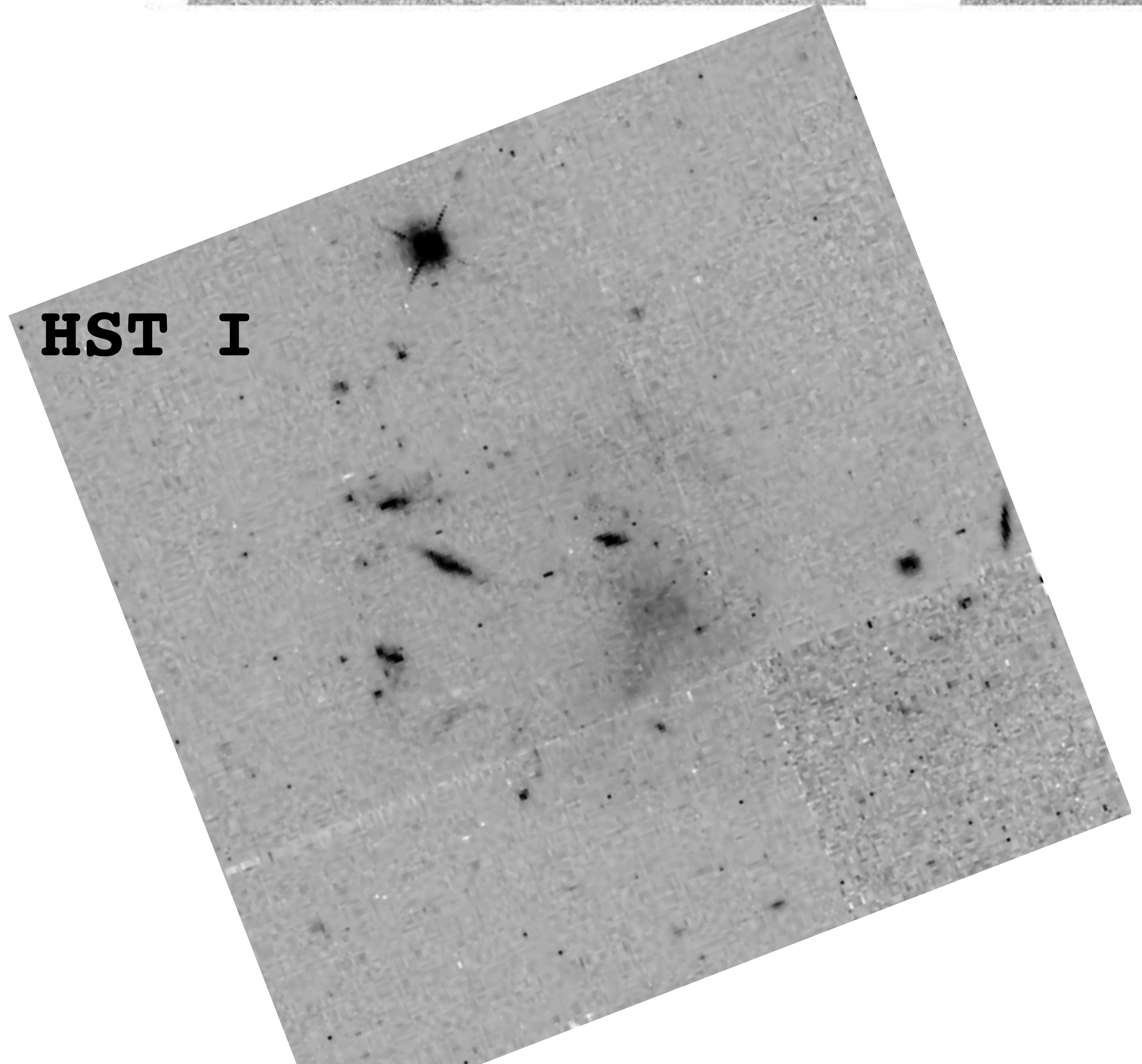
Prefer not to use mature spiral galaxies whose primordial helium abundance has been polluted by stellar production. Instead, seek out very metal poor dwarfs, like I Zw 18.

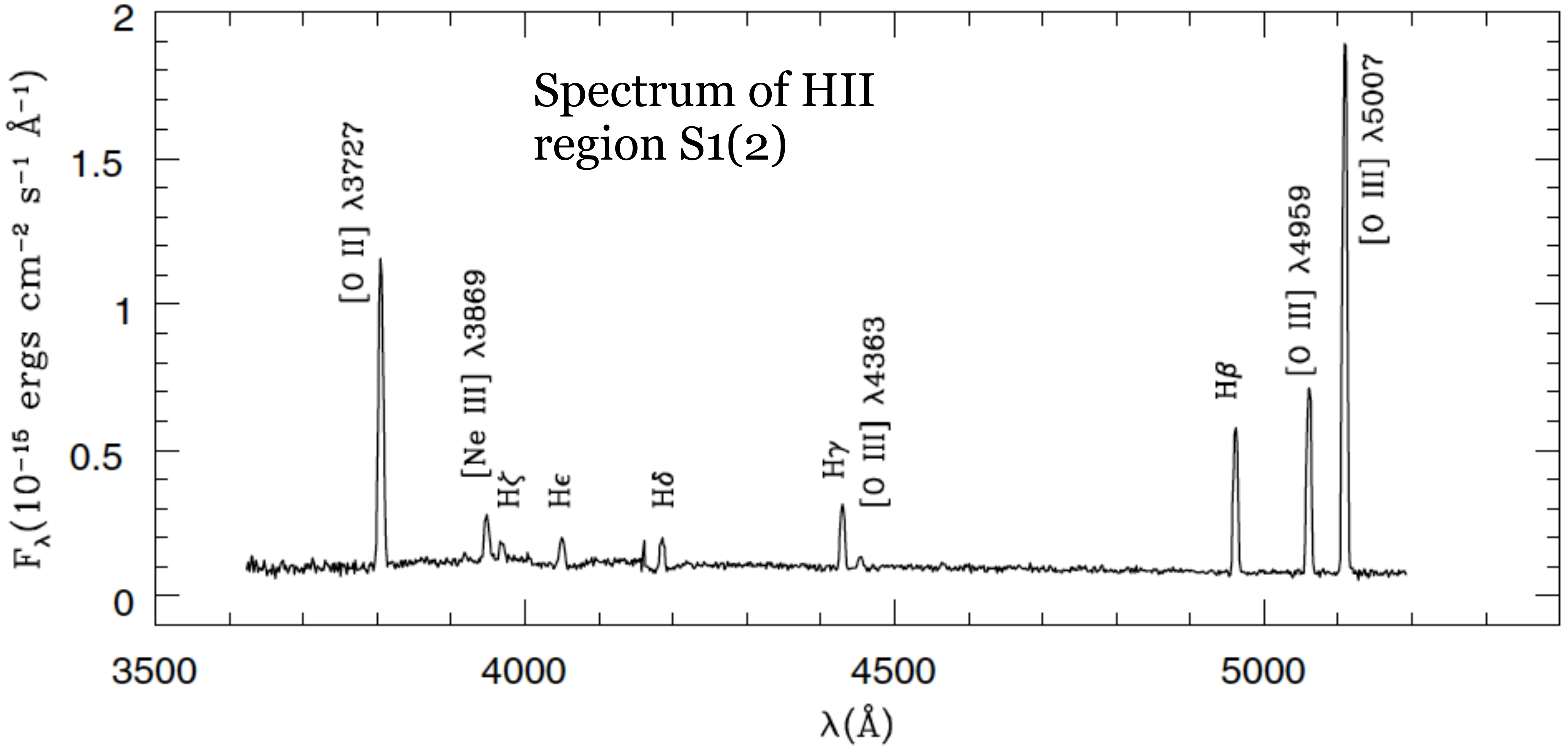
Helium

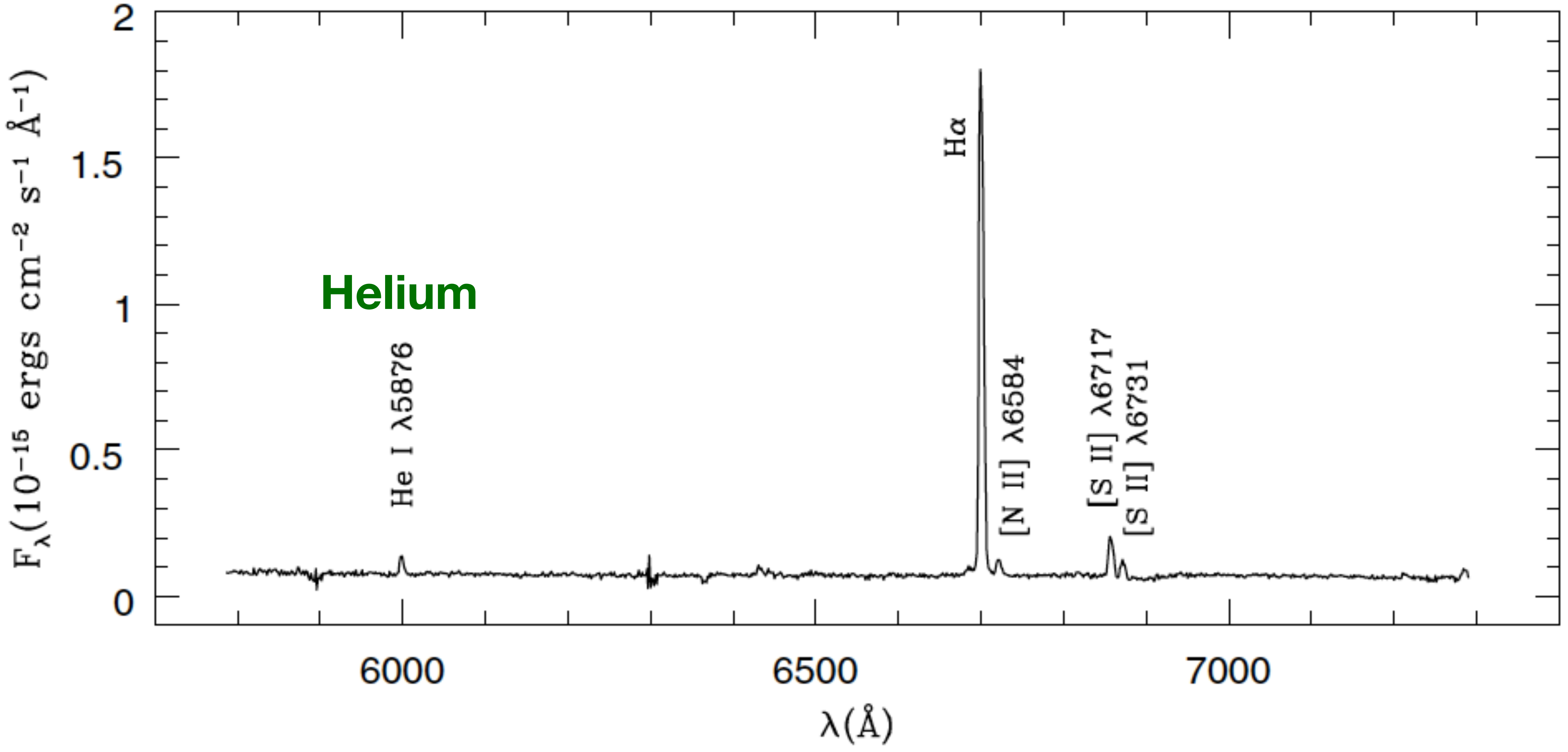
Helium is measured in the HII regions of nearby galaxies.

UGC 12695

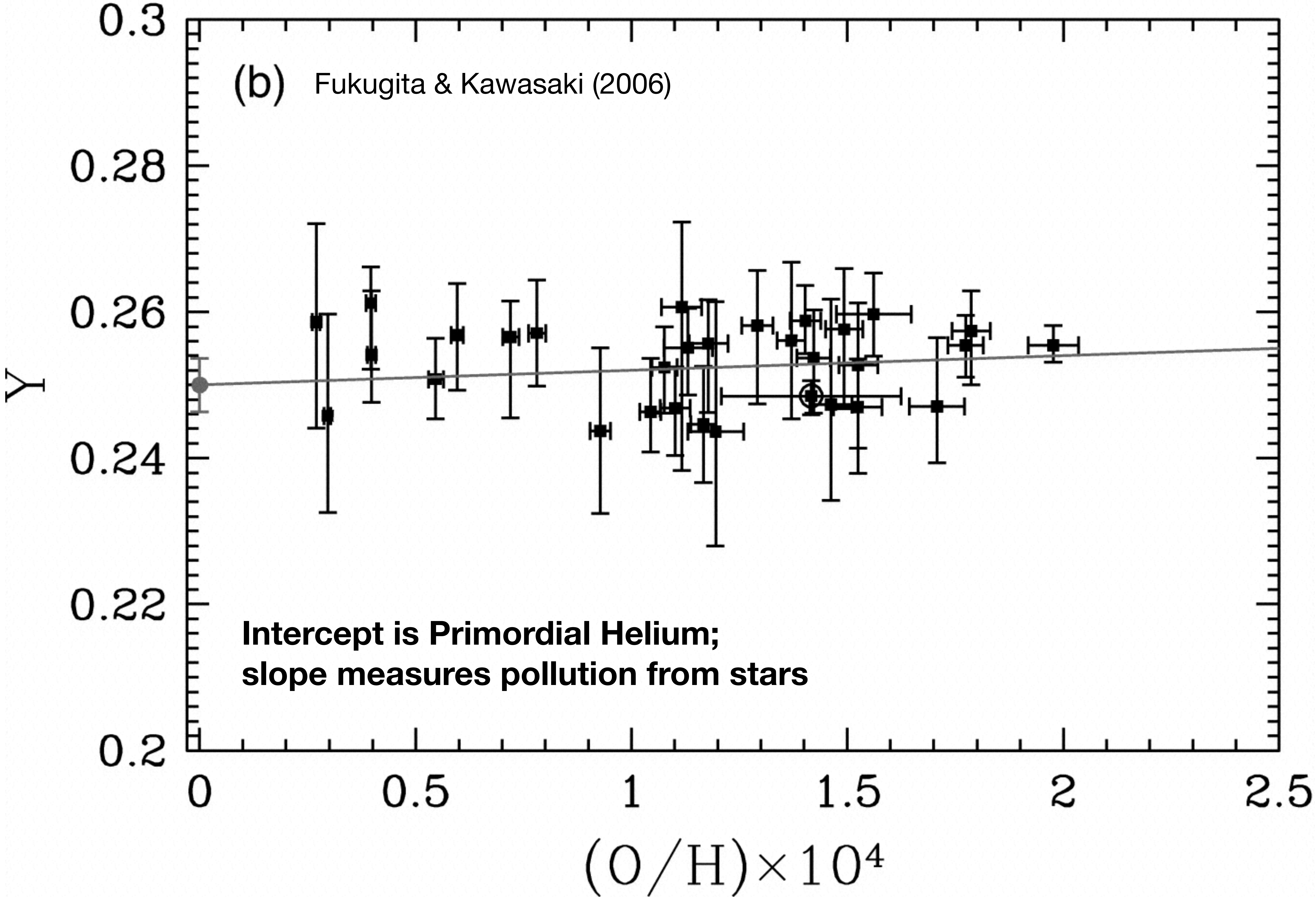








Helium



Fukugita & Kawasaki (2006)

Intercept is Primordial Helium;
slope measures pollution from stars

$$Y_P = 0.25 \pm 0.01$$

with lots of debate over the 3rd place of decimals!

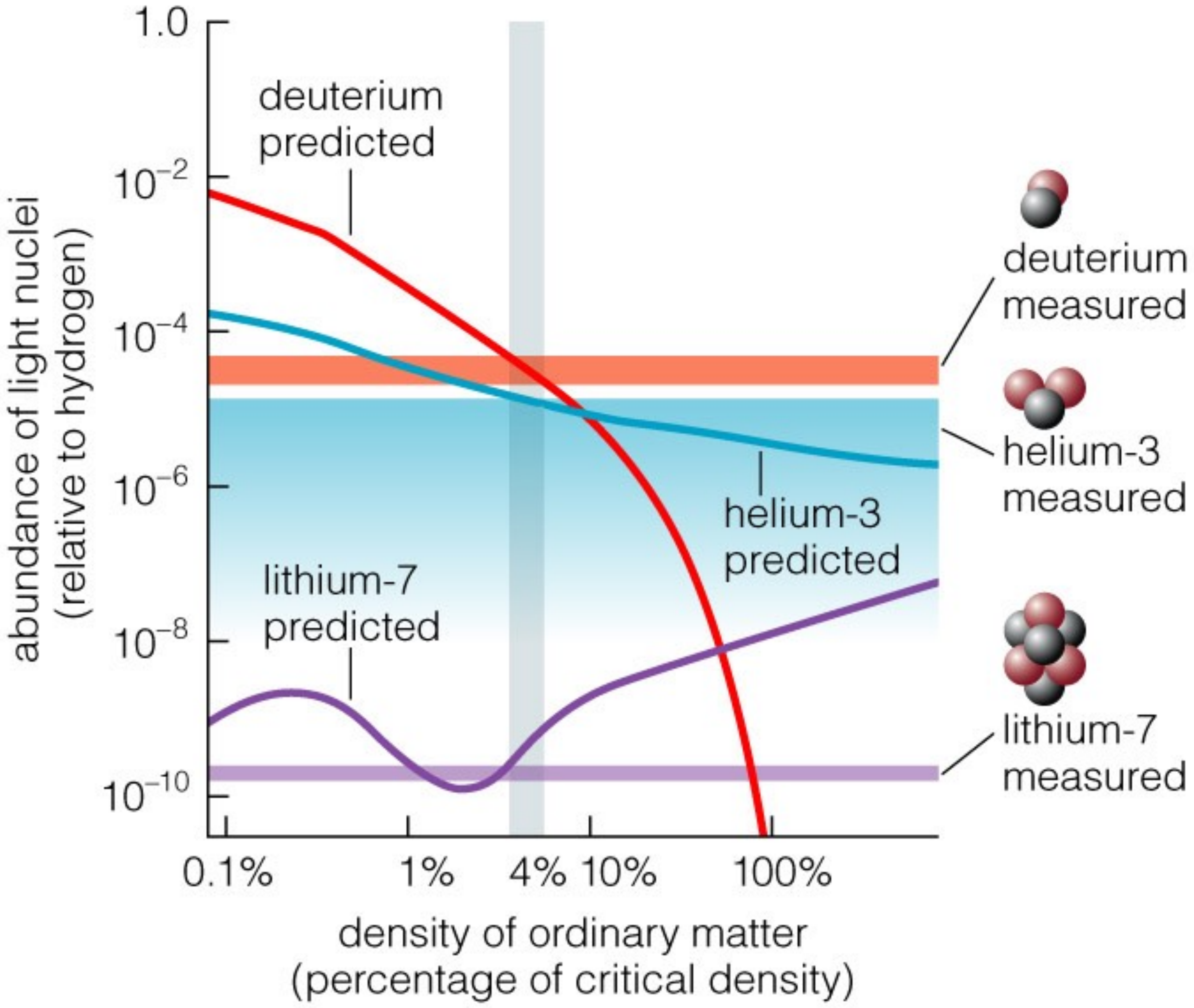
Kuzio de Naray et al. (2004)

Helium

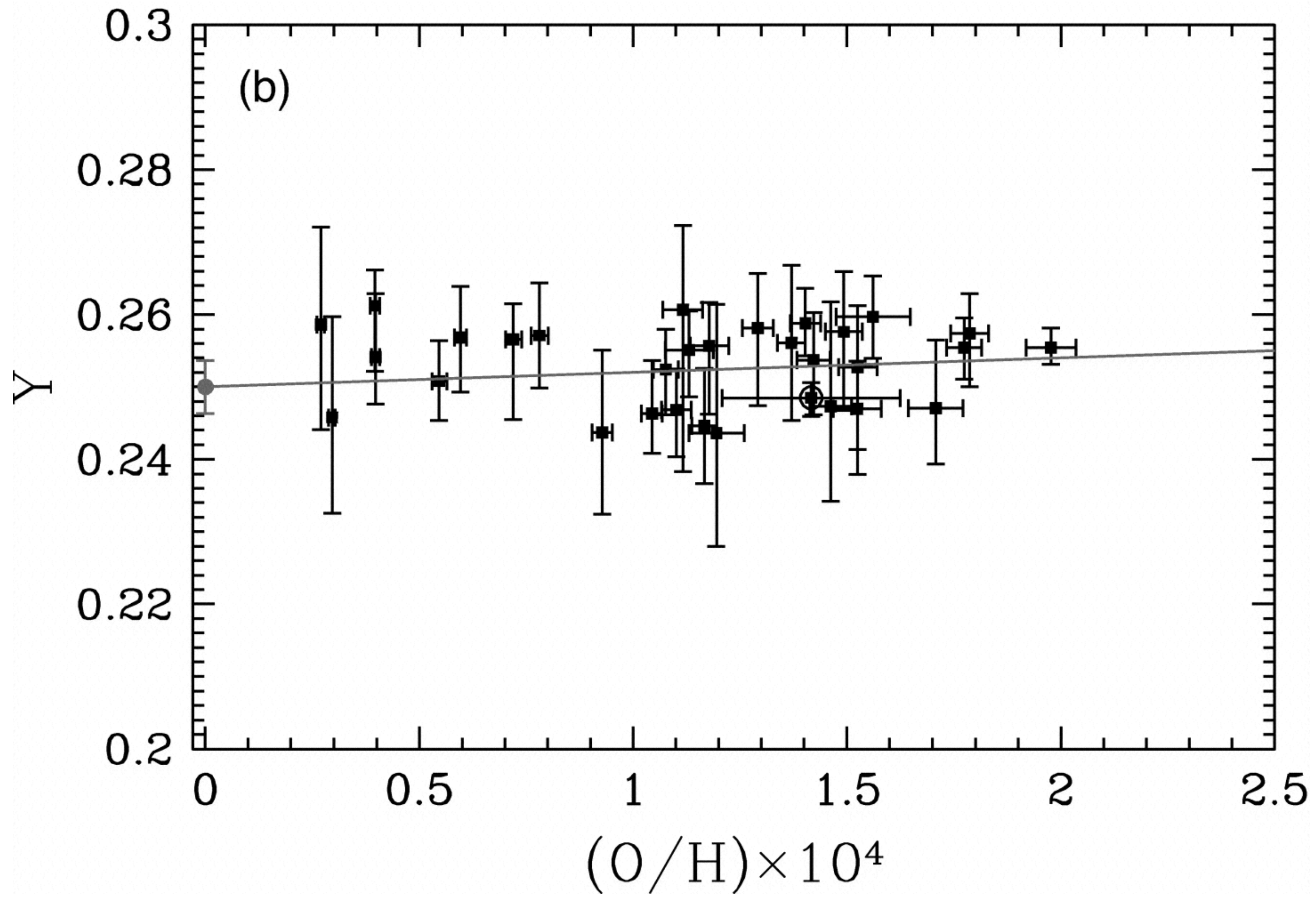
Helium is a poor baryometer because it varies little with the baryon density - we need a measurement accurate to the third place of decimals to constrain the baryon density.

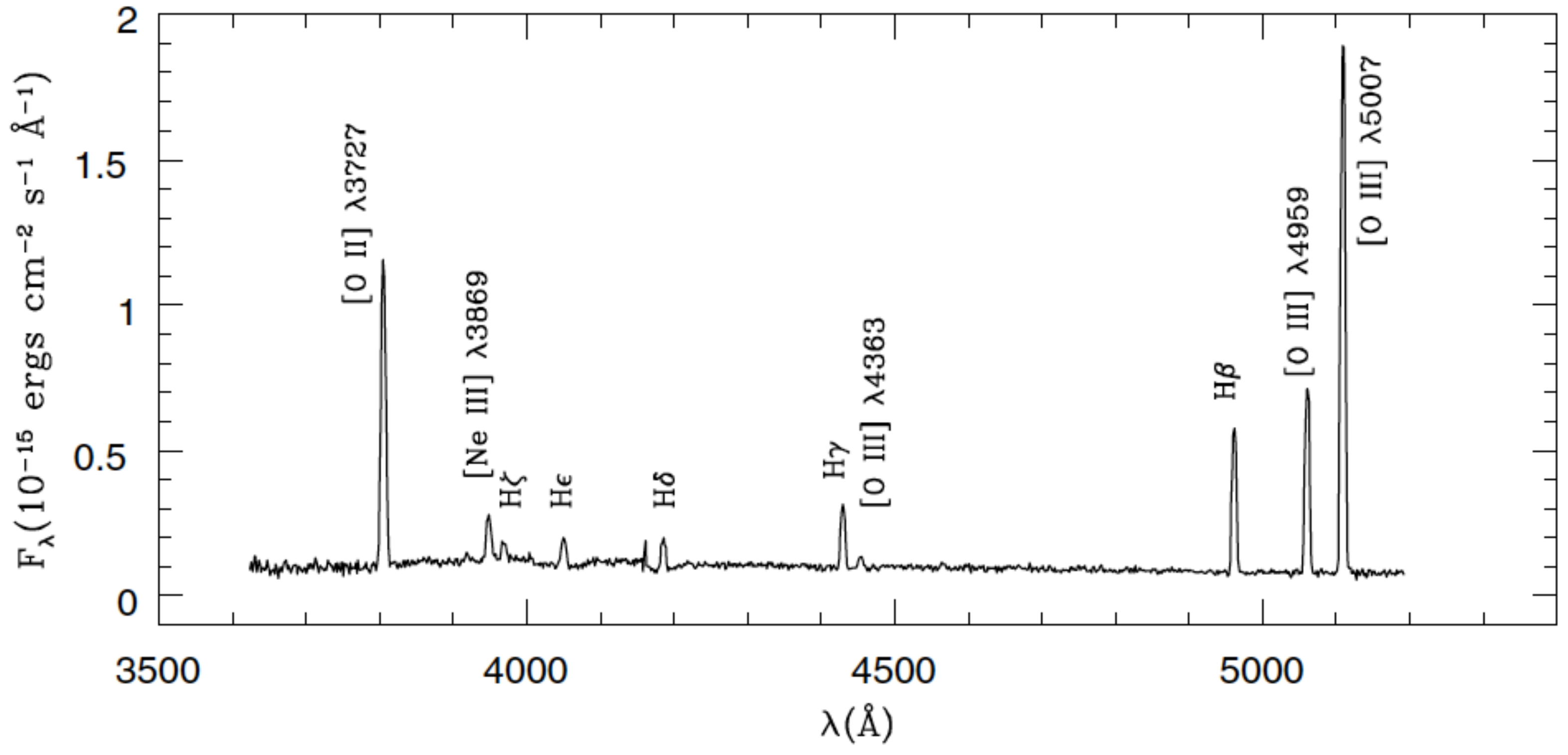
However, simply having a mass fraction of 1/4 it is strong corroboration of BBN.

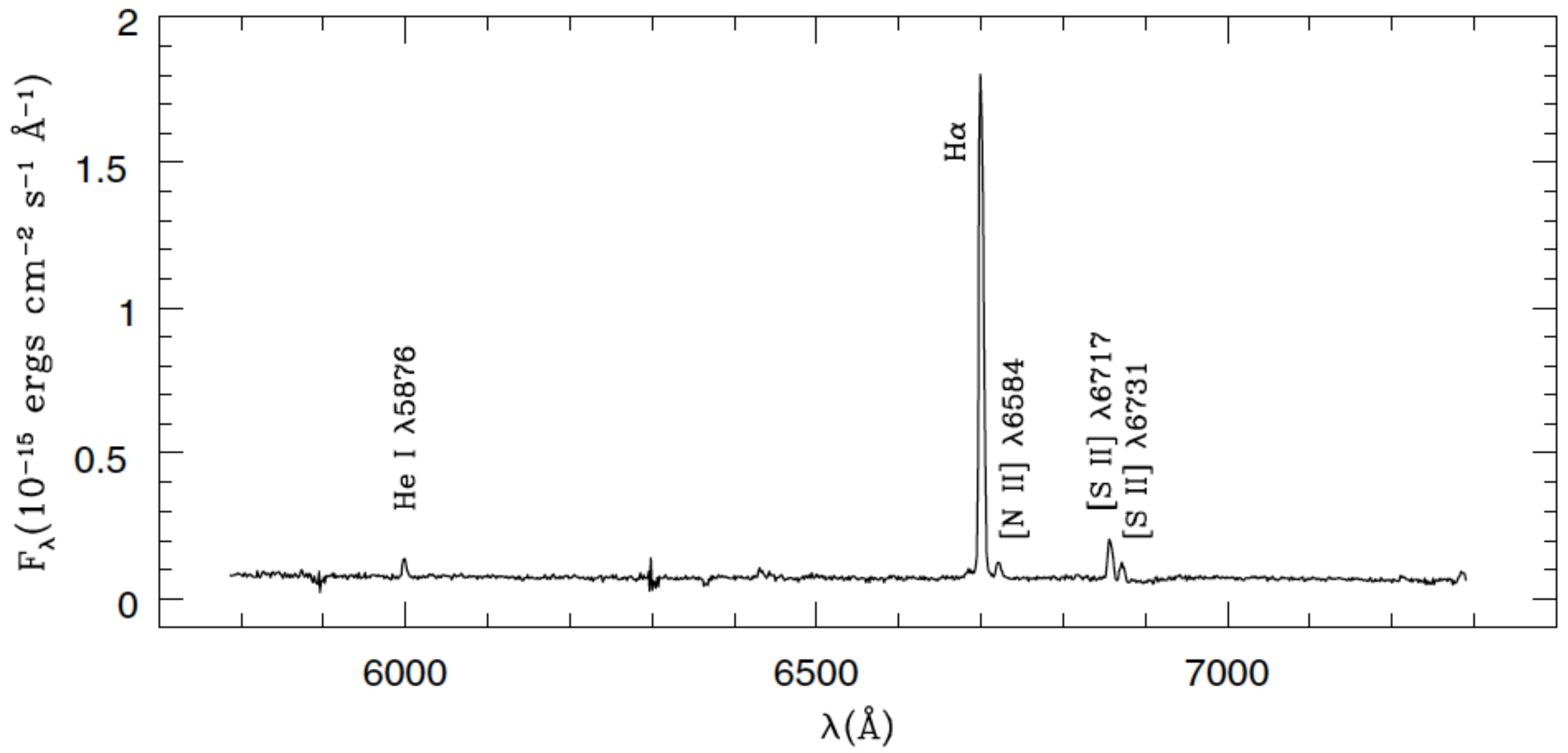
Observationally, it is challenging to measure helium lines with great accuracy, and interpret their abundance as the percent level. It is also challenging to differentiate between primordial helium and stellar helium production



Ω_b





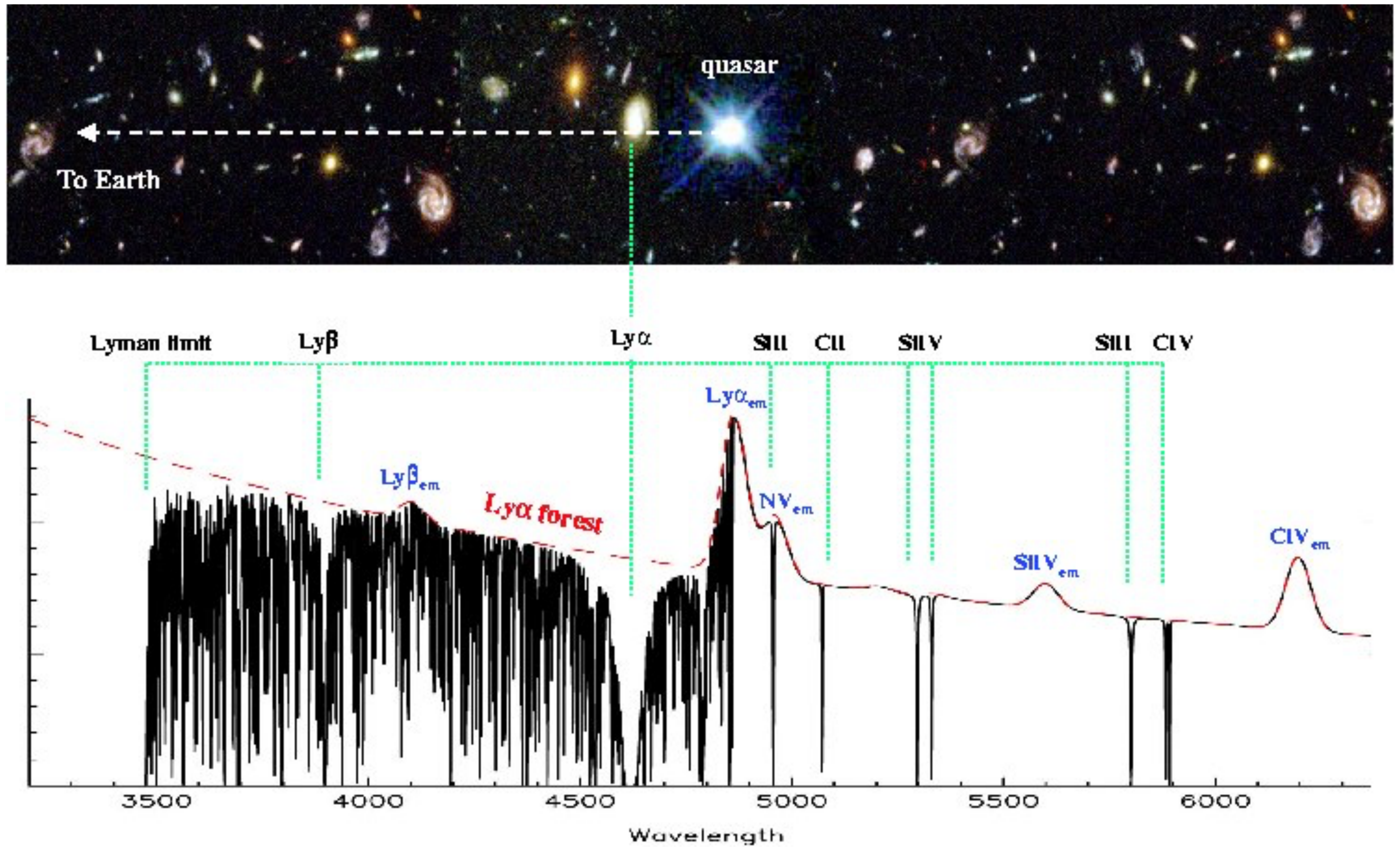


$$Y_P = 0.25 \pm 0.01$$

with lots of debate over the 3rd place of decimals!

Deuterium

D/H in absorption along the line of sight to high redshift QSOs



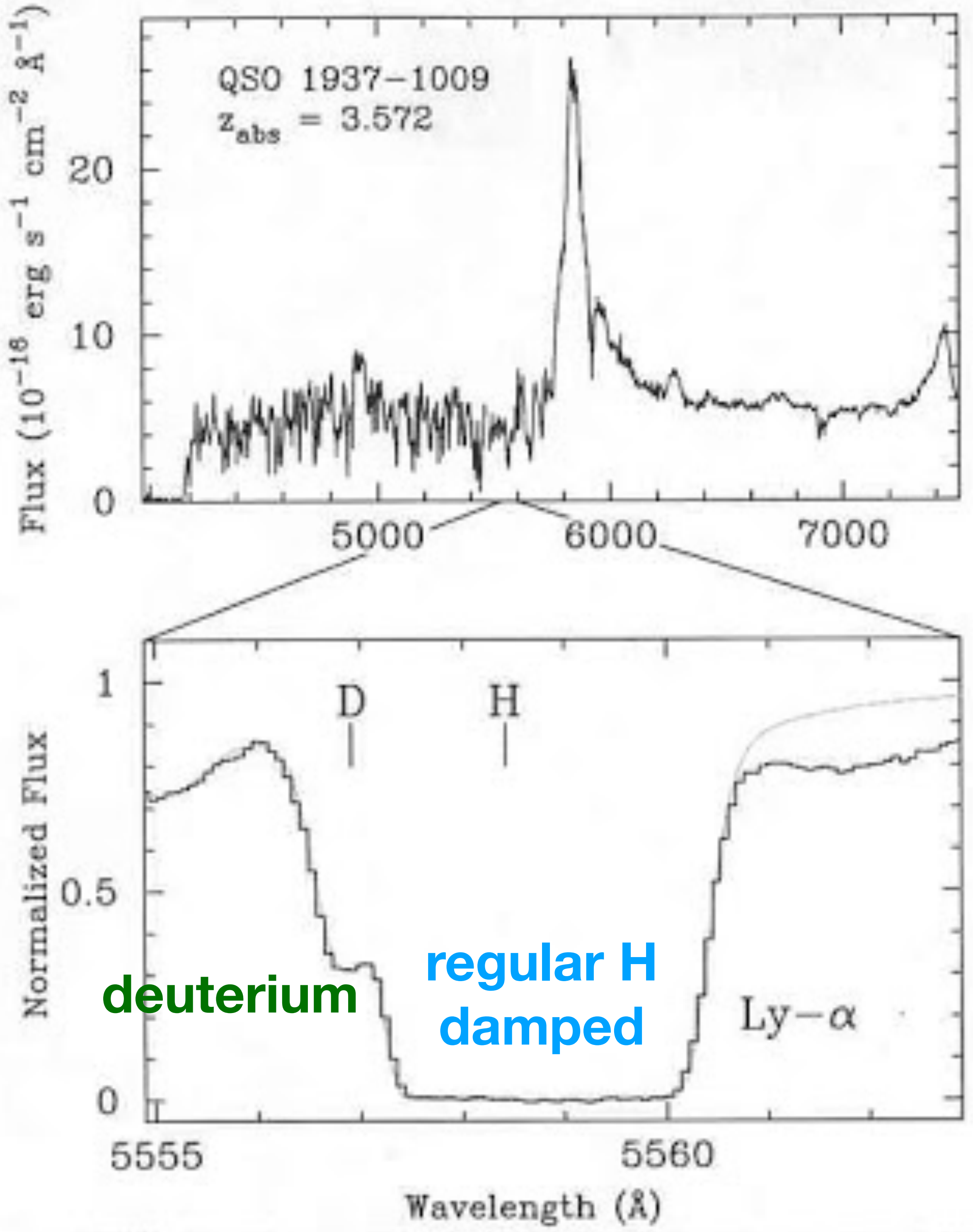
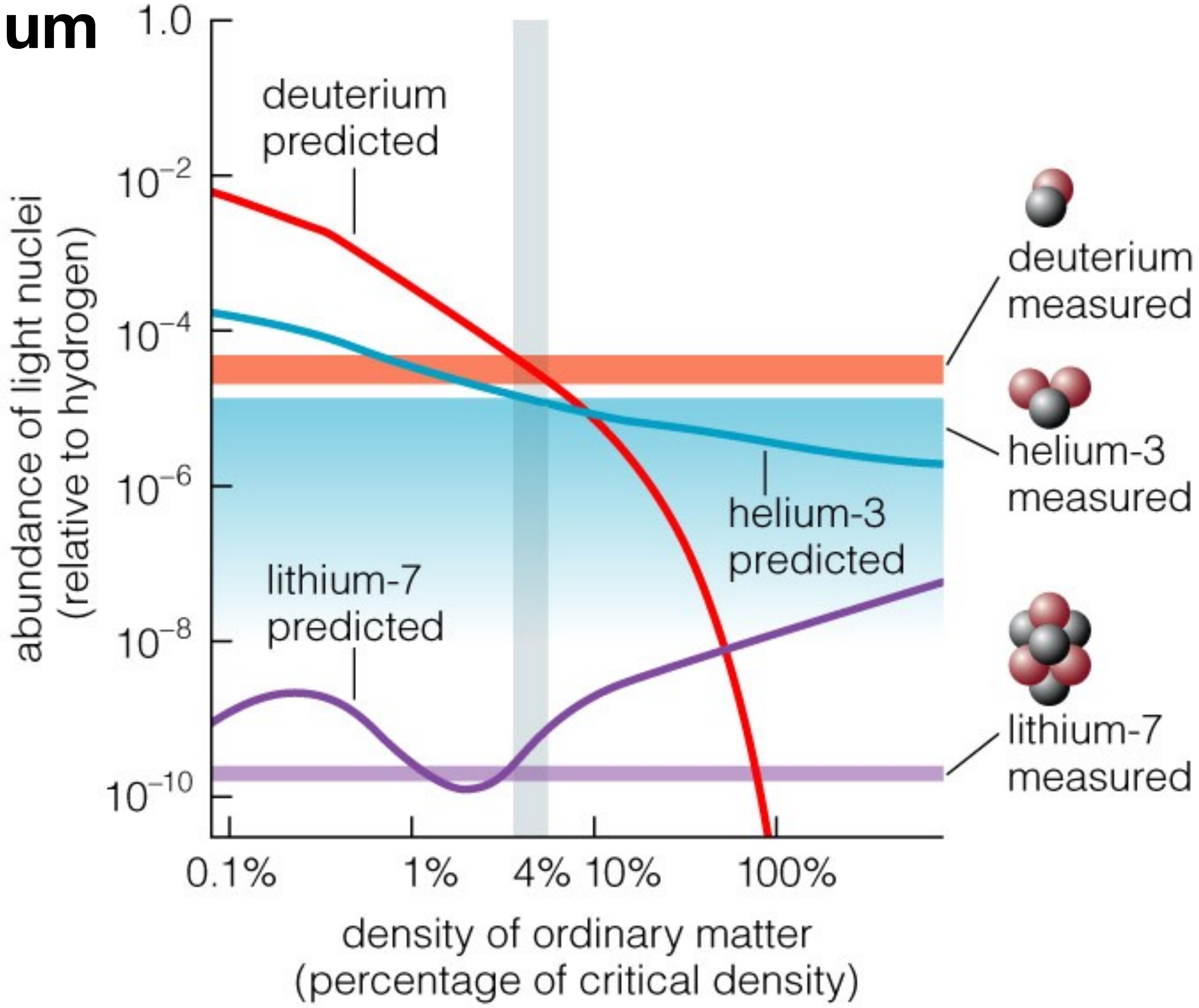
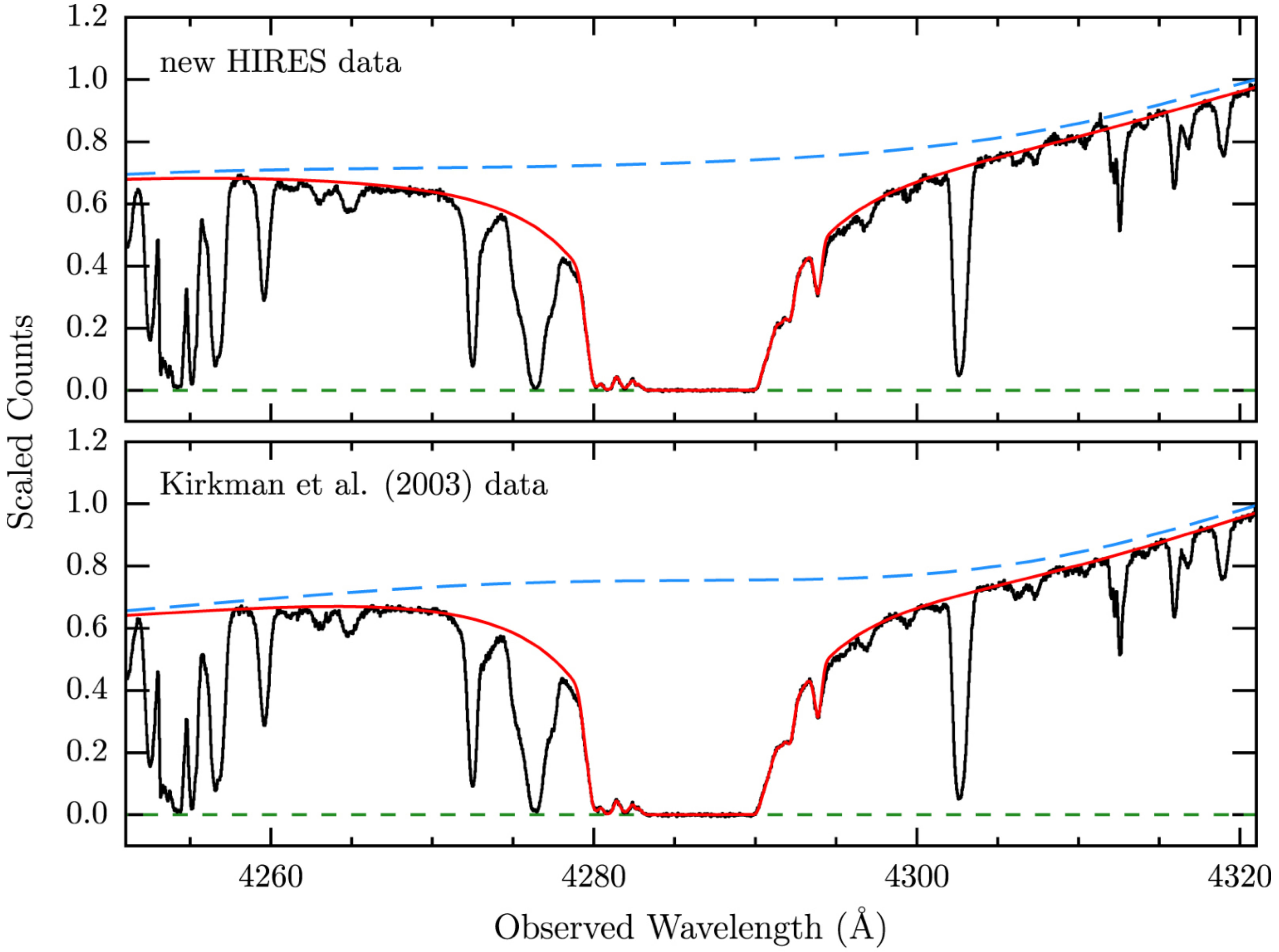


FIG. 3. Spectrum of Q1937-1009; blueward of the characteristic Lyman-α emission line of the quasar is the "forest" of Lyman-α absorption due to the hundreds of intervening gas clouds. The lower panel shows a blowup of the region around the deuterium detection, a cloud at redshift $z = 3.572$, and the model fit.

Deuterium

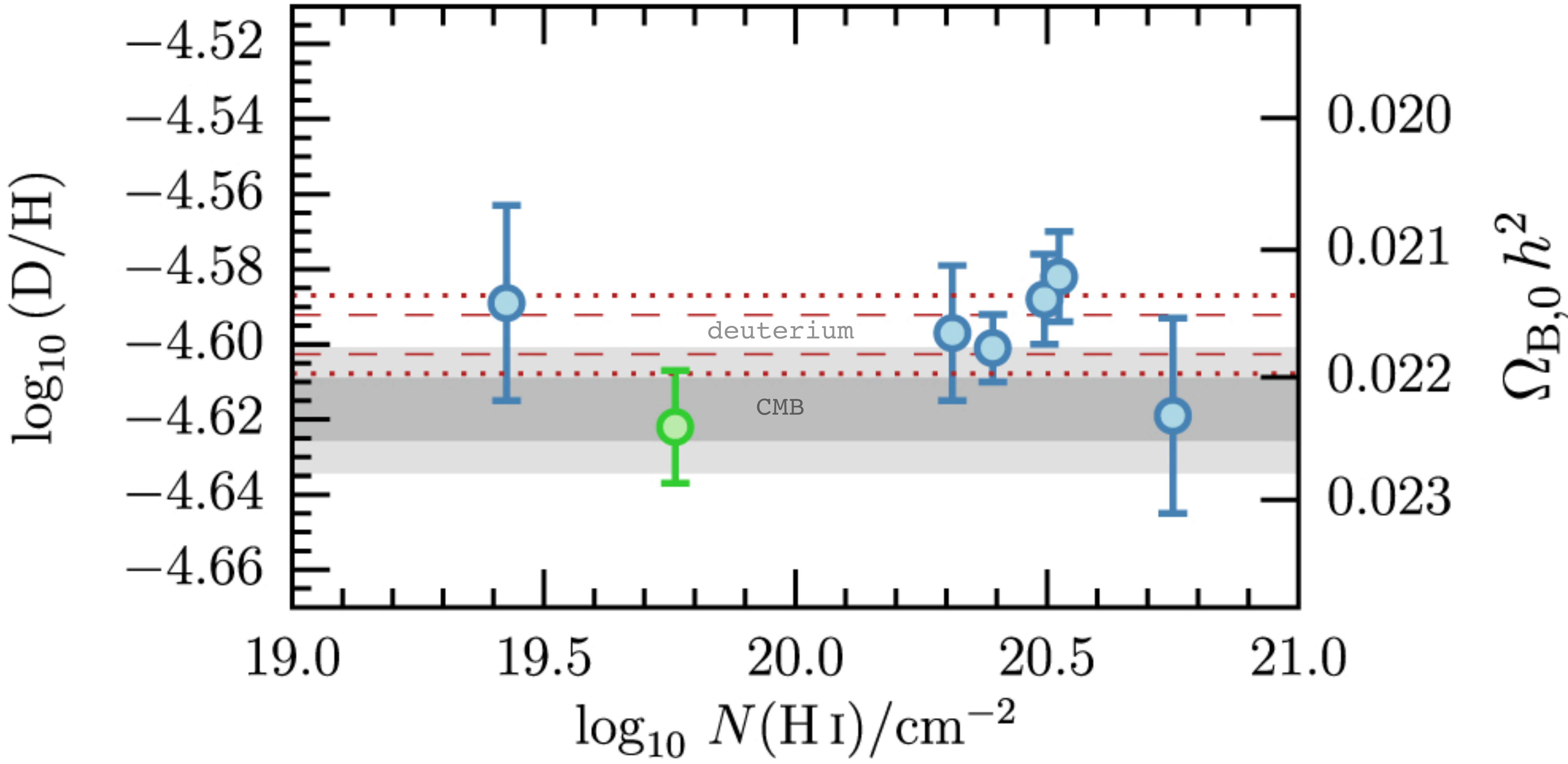




Deuterium is a good baryometer because D/H varies sensitively with the baryon density.

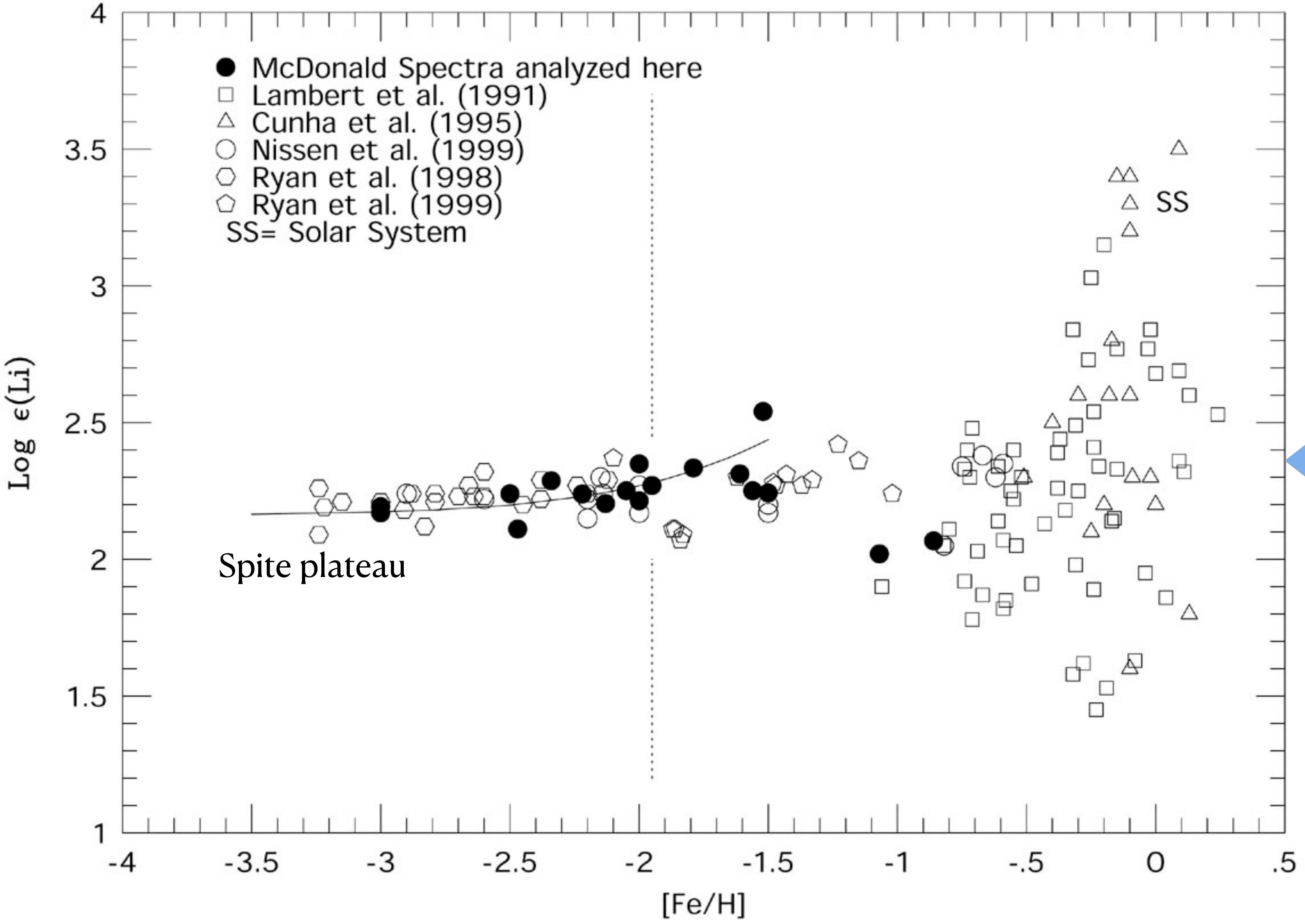
In addition, we also expect the gas observed in absorption at high redshift to be minimally affected by stellar nucleosynthesis subsequent to BBN.

Observationally, it is challenging to estimate the continuum level against which the absorption happens, and to compare a very weak deuterium line to a very strong hydrogen line.

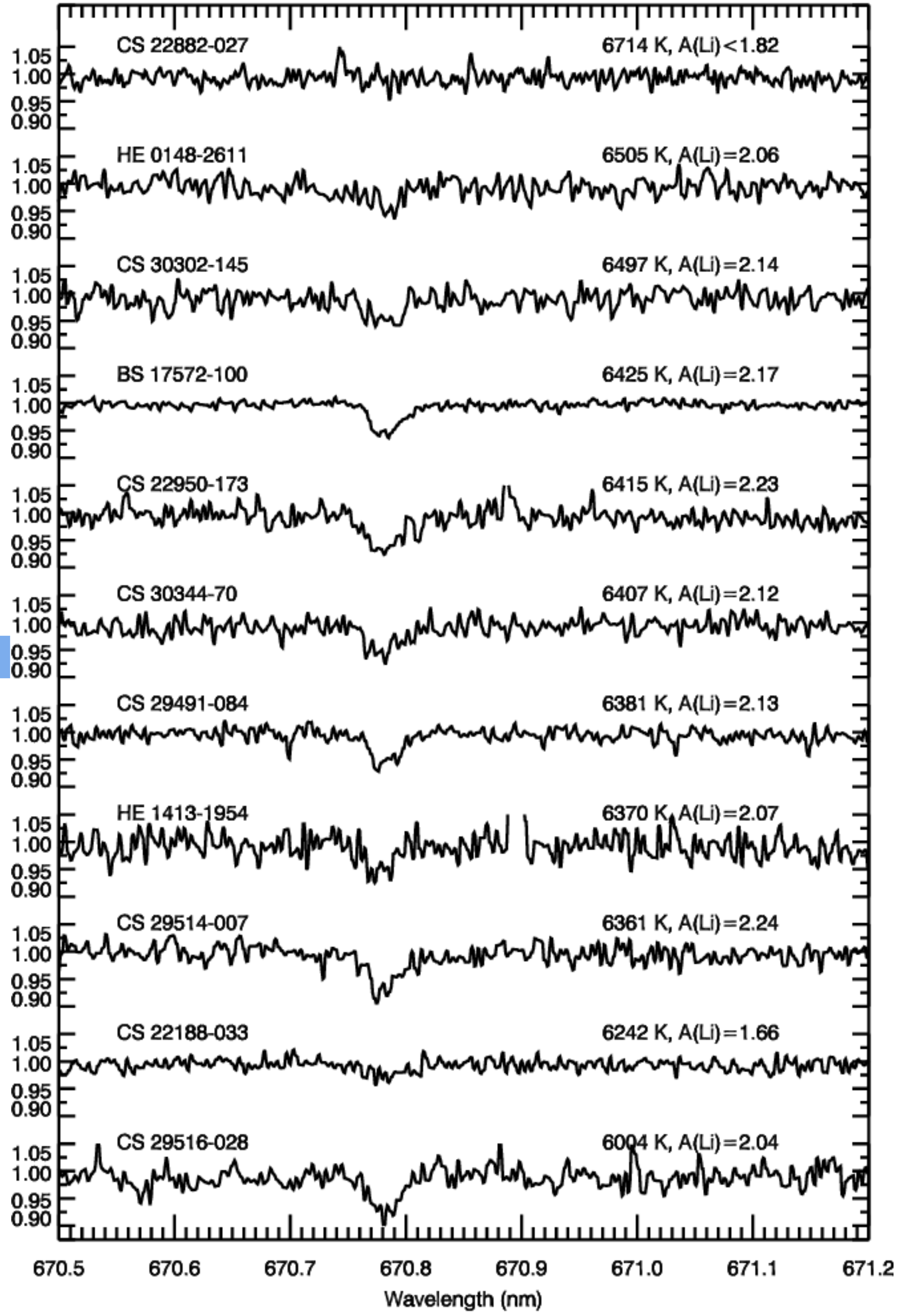


Lithium

Lithium is measured in old, metal poor stars for which there is hope that the surface abundance is little altered from the primordial abundance - the Spite plateau.



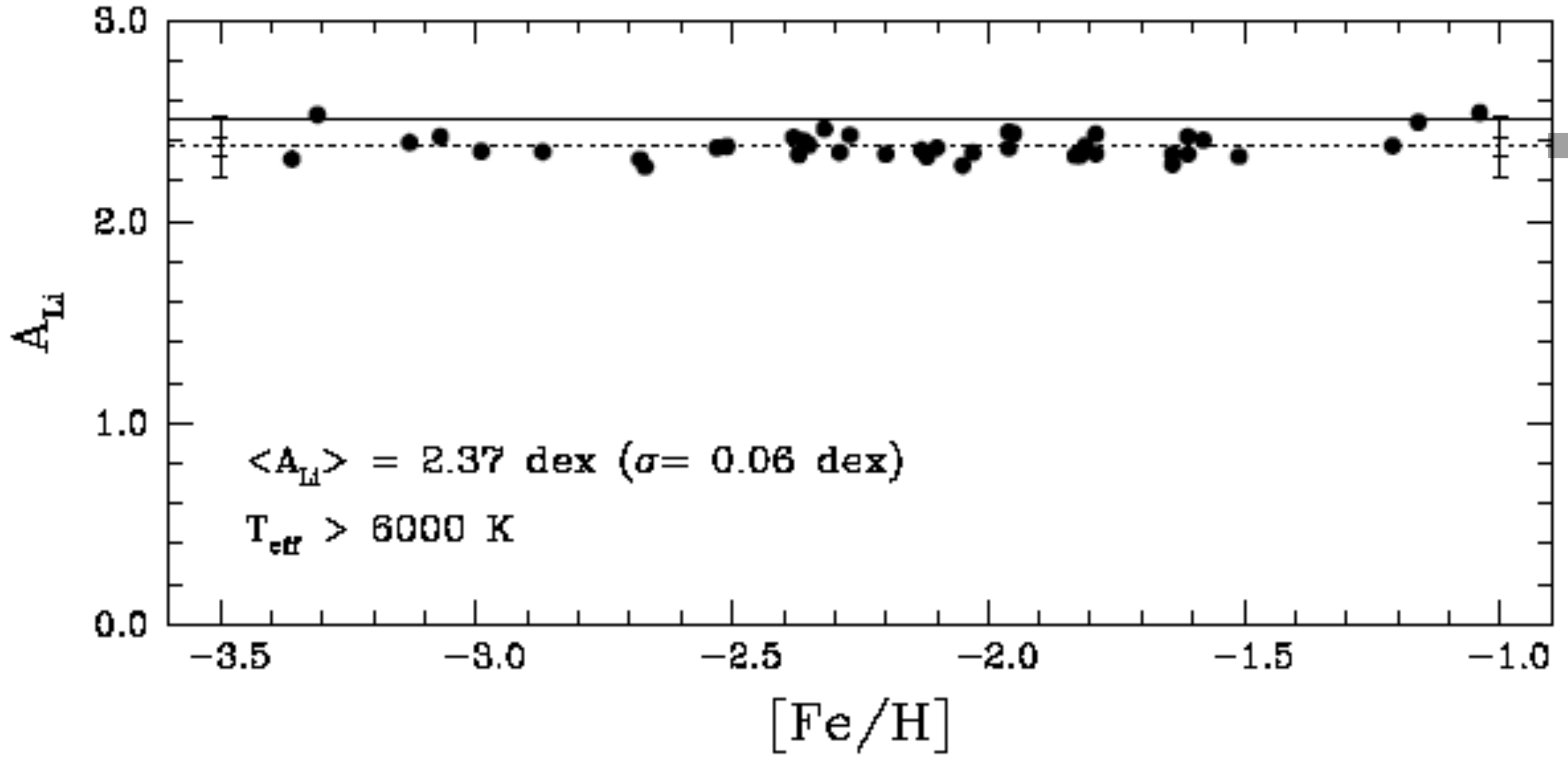
Stellar spectra showing Lithium absorption

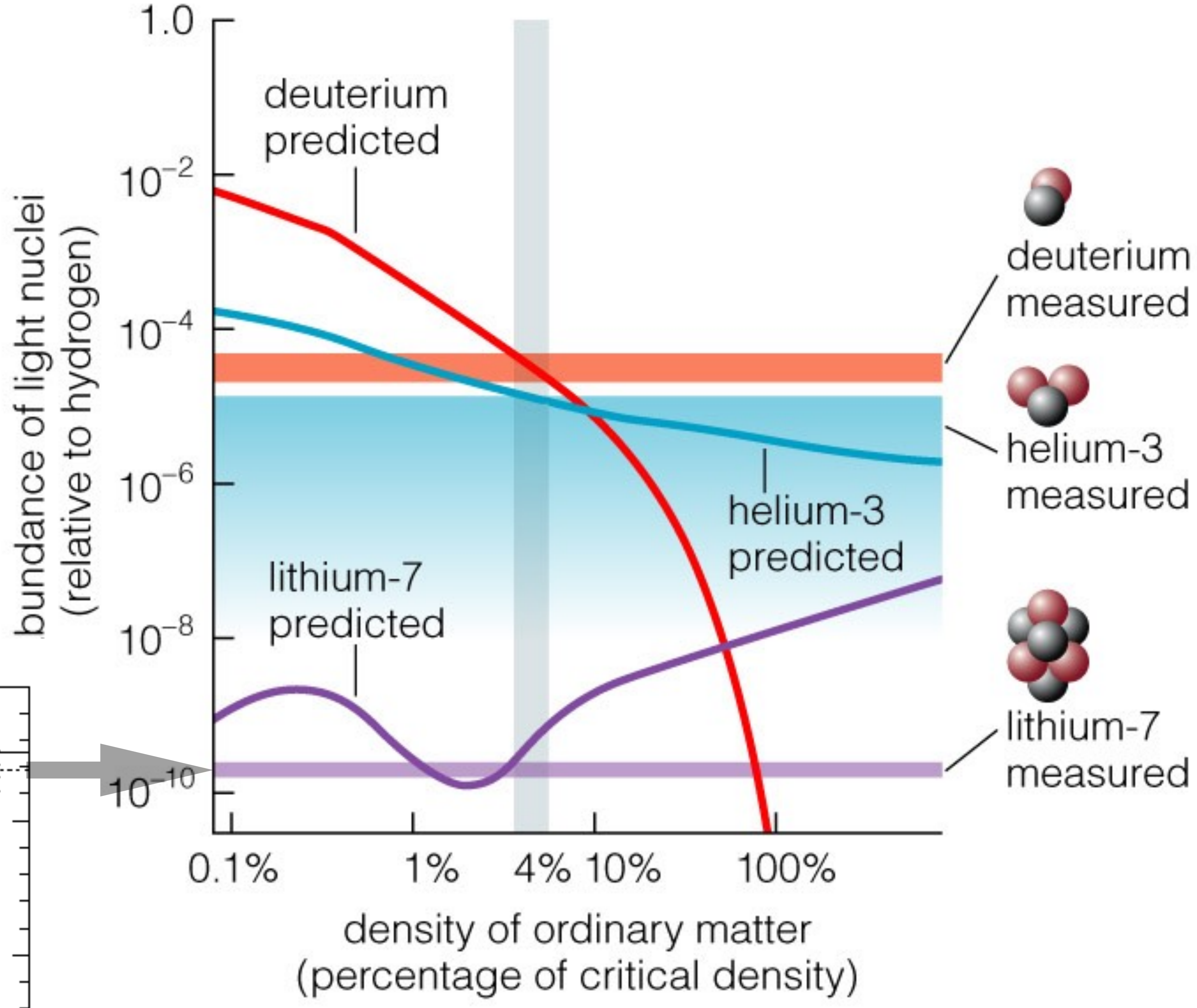


Lithium

Lithium is a challenging as a baryometer because the variation of Li/H with the baryon density is double-valued thanks to the competition between lithium and beryllium.

It is hard to be sure that no astrophysical processes have altered the primordial abundance.



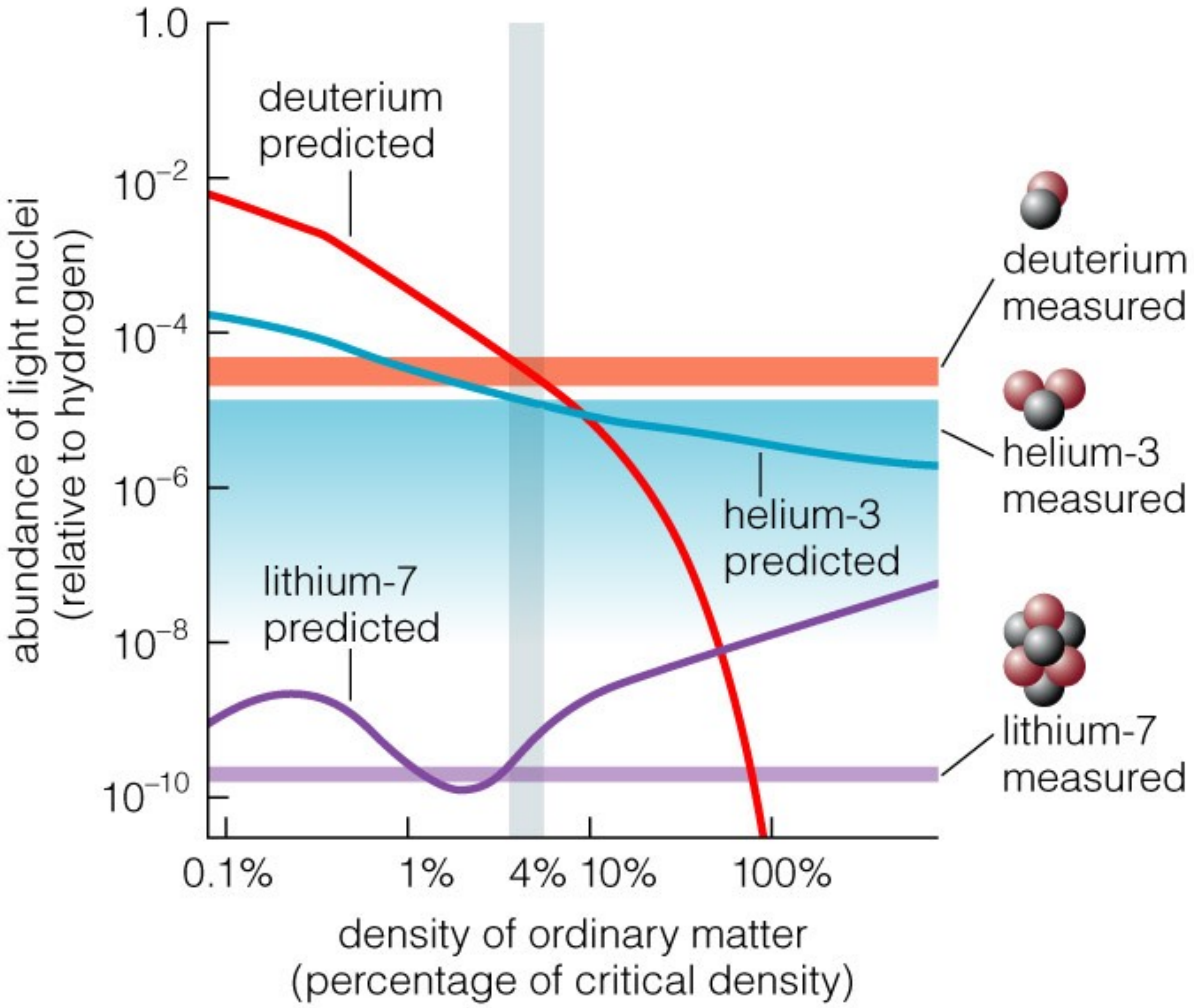


Ω_b

BBN gets the abundances of deuterium, helium, and lithium right if the mass density is about 4% of the critical density.

There is some tension in that lithium prefers a somewhat lower baryon density, but the basic picture is sound.

BBN is one of the most robust aspects of the hot big bang, as each isotope provides independent corroboration.



BBN gets the abundances of deuterium, helium, and lithium right if the mass density is about 4% of the critical density.

$$\omega_b = \Omega_b h^2 = 0.022$$

from deuterium

$$\left[\omega_b = \Omega_b h^2 = 0.019\right]$$

from deuterium prior to CMB constraints

$$\omega_b = \Omega_b h^2 = 0.017$$

from lithium

Consequently, the baryon density is well-known, but far short of the critical density.

$h = \frac{H_0}{100}$ so $\omega_b = 0.02$ and $H_0 = 70$ means $\Omega_b = 0.04$

Walker et al. (1991)

$$\Omega_b h_{50}^2 = 0.05 \pm 0.01 \qquad h_{50} = \frac{H_0}{50}$$

so

$$\omega_b = 0.0125 \pm 0.0025 \qquad h = \frac{H_0}{100}$$

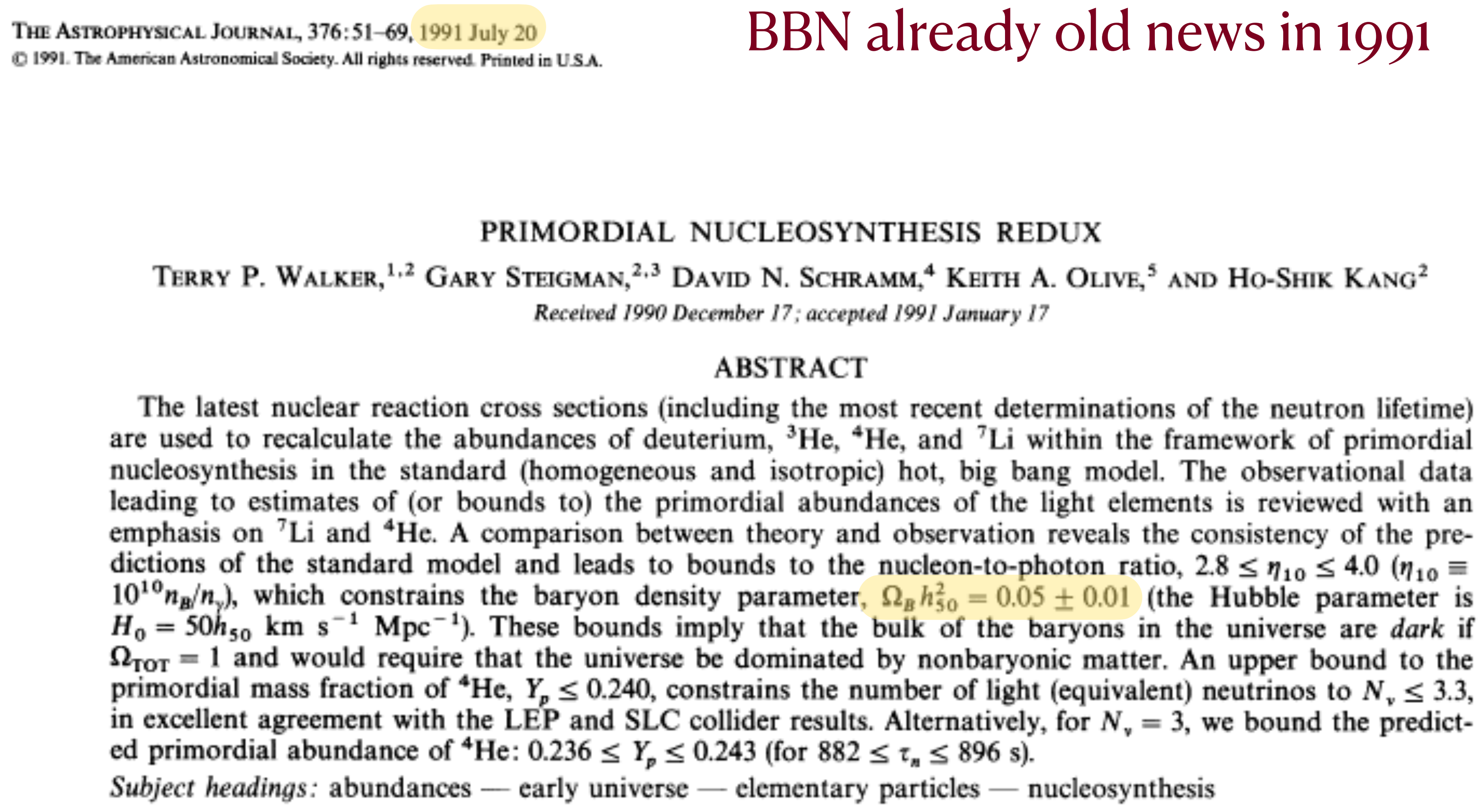
was canonical for many years. Now

$$\omega_b = 0.0224 \pm 0.0001$$

(Planck 2018)

take error bars with a grain of salt!

BBN already old news in 1991



THE ASTROPHYSICAL JOURNAL, 376:51–69, 1991 July 20

PRIMORDIAL NUCLEOSYNTHESIS REDUX

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ABSTRACT

The latest nuclear reaction cross sections (including the most recent determinations of the neutron lifetime) are used to recalculate the abundances of deuterium, ^{3}He, ^{4}He, and ^{7}Li within the framework of primordial nucleosynthesis in the standard (homogeneous and isotropic) hot, big bang model. The observational data leading to estimates of (or bounds to) the primordial abundances of the light elements is reviewed with an emphasis on ^{7}Li and ^{4}He. A comparison between theory and observation reveals the consistency of the predictions of the standard model and leads to bounds to the nucleon-to-photon ratio, $2.8 \leq \eta_{10} \leq 4.0$ ($\eta_{10} \equiv 10^{10} n_B/n_\gamma$), which constrains the baryon density parameter, $\Omega_B h_{50}^2 = 0.05 \pm 0.01$ (the Hubble parameter is $H_0 = 50 h_{50}$ km s^{-1} Mpc^{-1}). These bounds imply that the bulk of the baryons in the universe are *dark* if $\Omega_{\rm TOT} = 1$ and would require that the universe be dominated by nonbaryonic matter. An upper bound to the primordial mass fraction of ^{4}He, $Y_p \leq 0.240$, constrains the number of light (equivalent) neutrinos to $N_\nu \leq 3.3$, in excellent agreement with the LEP and SLC collider results. Alternatively, for $N_\nu = 3$, we bound the predicted primordial abundance of ^{4}He: $0.236 \leq Y_p \leq 0.243$ (for $882 \leq \tau_n \leq 896$ s).

Subject headings: abundances — early universe — elementary particles — nucleosynthesis

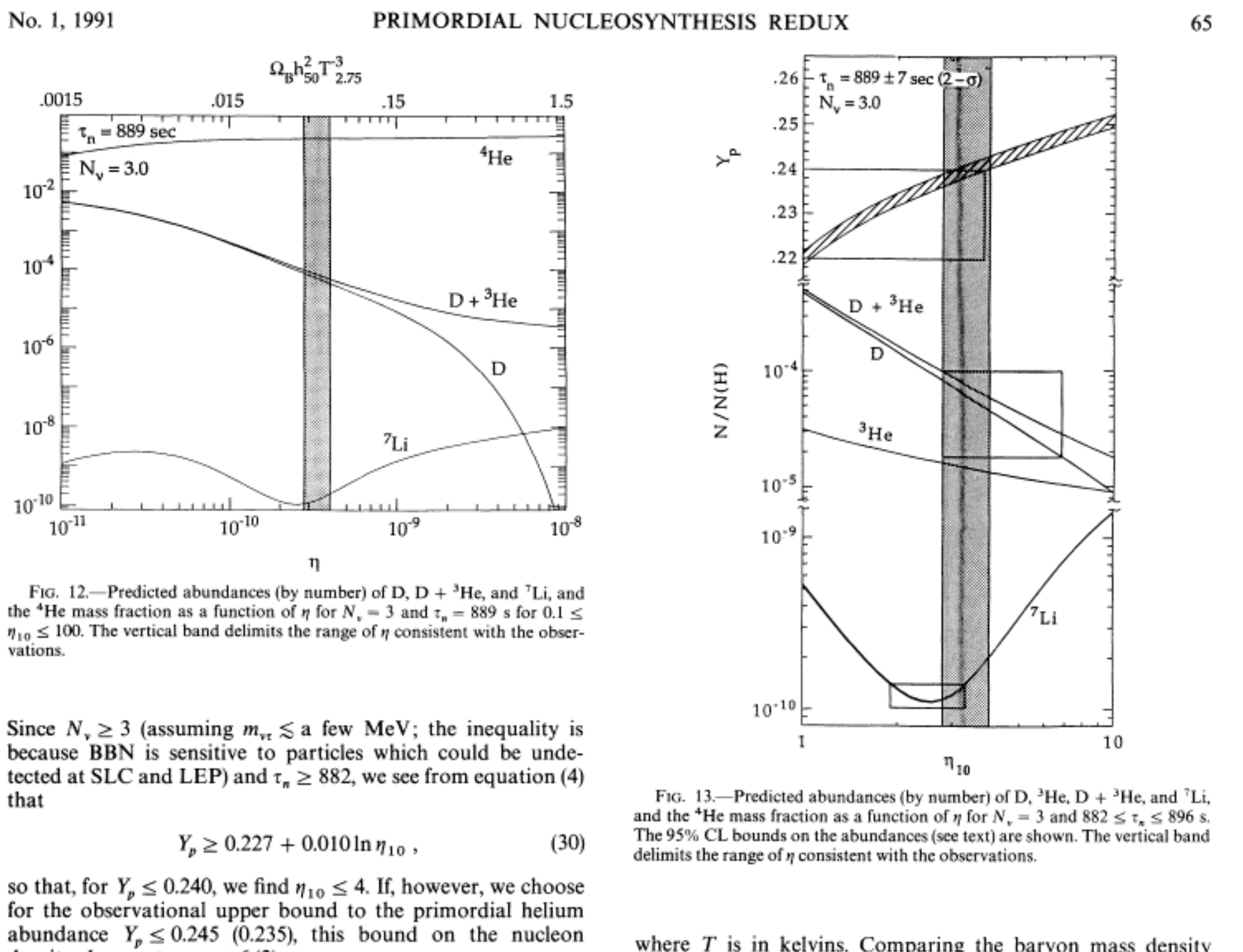


FIG. 12.—Predicted abundances (by number) of D, D + ^{3}He, and ^{7}Li, and the ^{4}He mass fraction as a function of η for $N_\nu = 3$ and $\tau_n = 889$ s for $0.1 \leq \eta_{10} \leq 100$. The vertical band delimits the range of η consistent with the observations.

FIG. 13.—Predicted abundances (by number) of D, ^{3}He, D + ^{3}He, and ^{7}Li, and the ^{4}He mass fraction as a function of η for $N_\nu = 3$ and $882 \leq \tau_n \leq 896$ s. The 95% CL bounds on the abundances (see text) are shown. The vertical band delimits the range of η consistent with the observations.

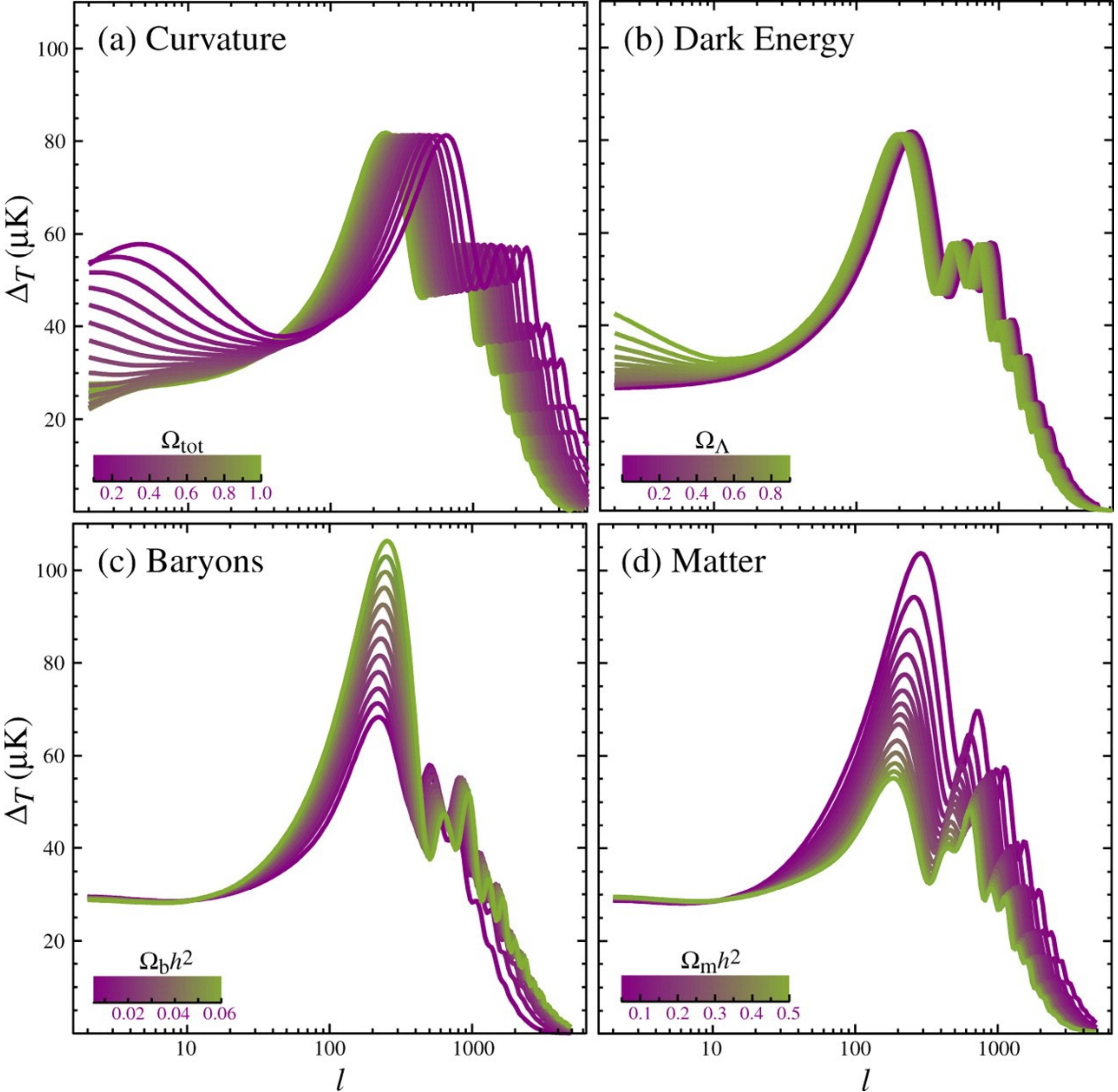
Since $N_\nu \geq 3$ (assuming $m_{\nu\tau} \lesssim$ a few MeV; the inequality is because BBN is sensitive to particles which could be undetected at SLC and LEP) and $\tau_n \geq 882$, we see from equation (4) that

$$Y_p \geq 0.227 + 0.010 \ln \eta_{10}\,, \tag{30}$$

so that, for $Y_p \leq 0.240$, we find $\eta_{10} \leq 4$. If, however, we choose for the observational upper bound to the primordial helium abundance $Y_p \leq 0.245$ (0.235), this bound on the nucleon

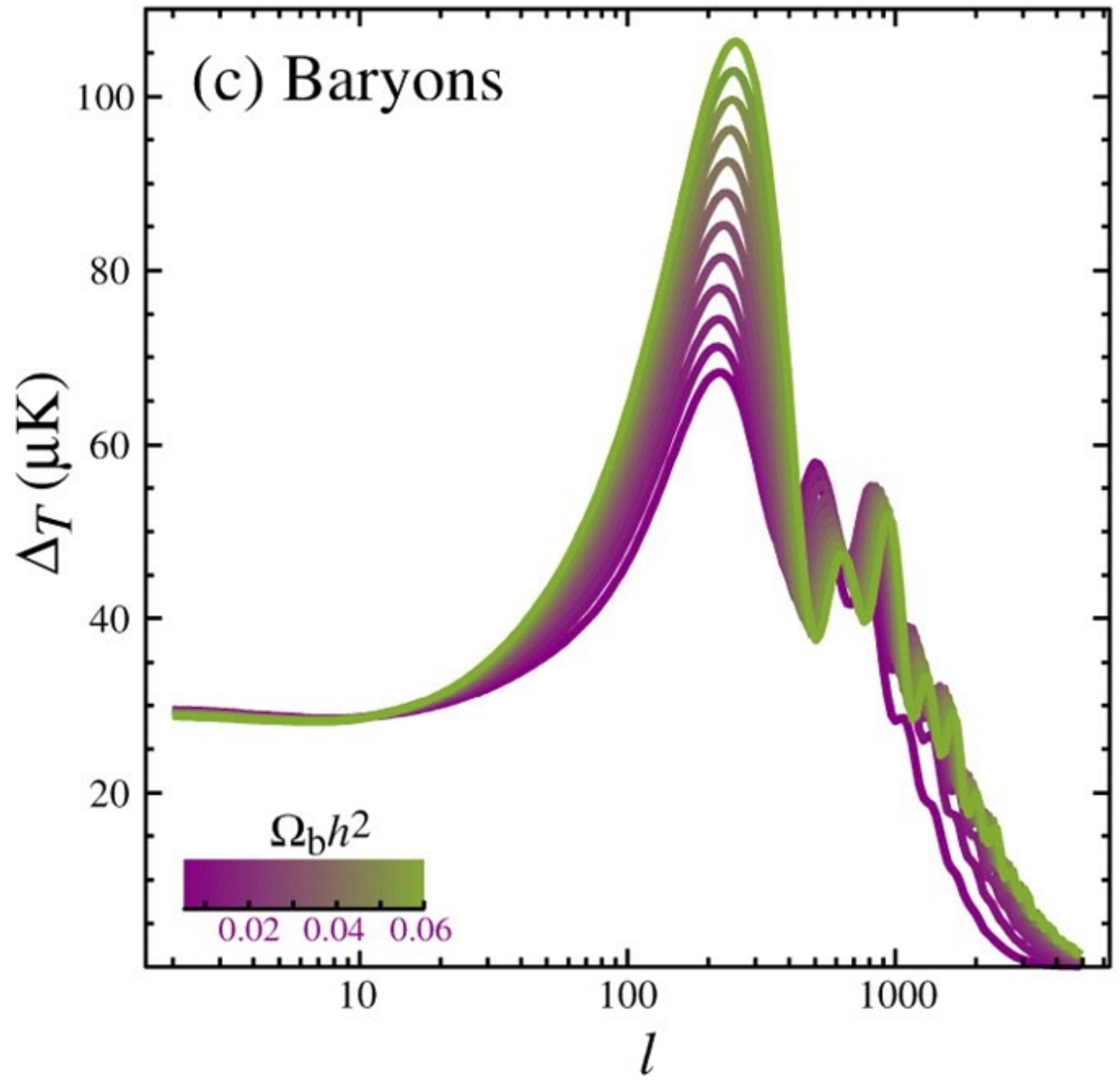
where T is in kelvins. Comparing the baryon mass density

CMB

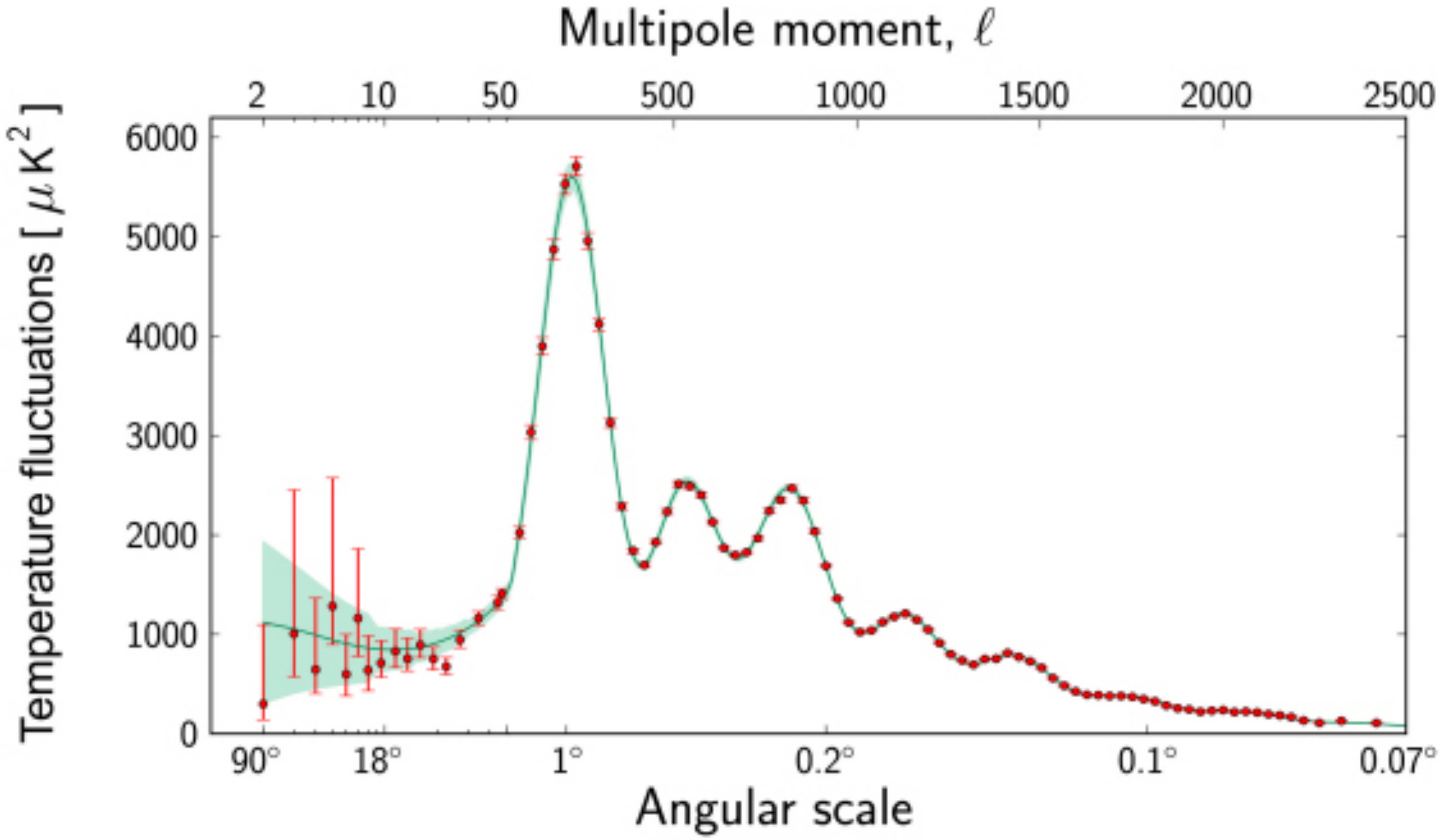


Dodelson & Hu (2004)

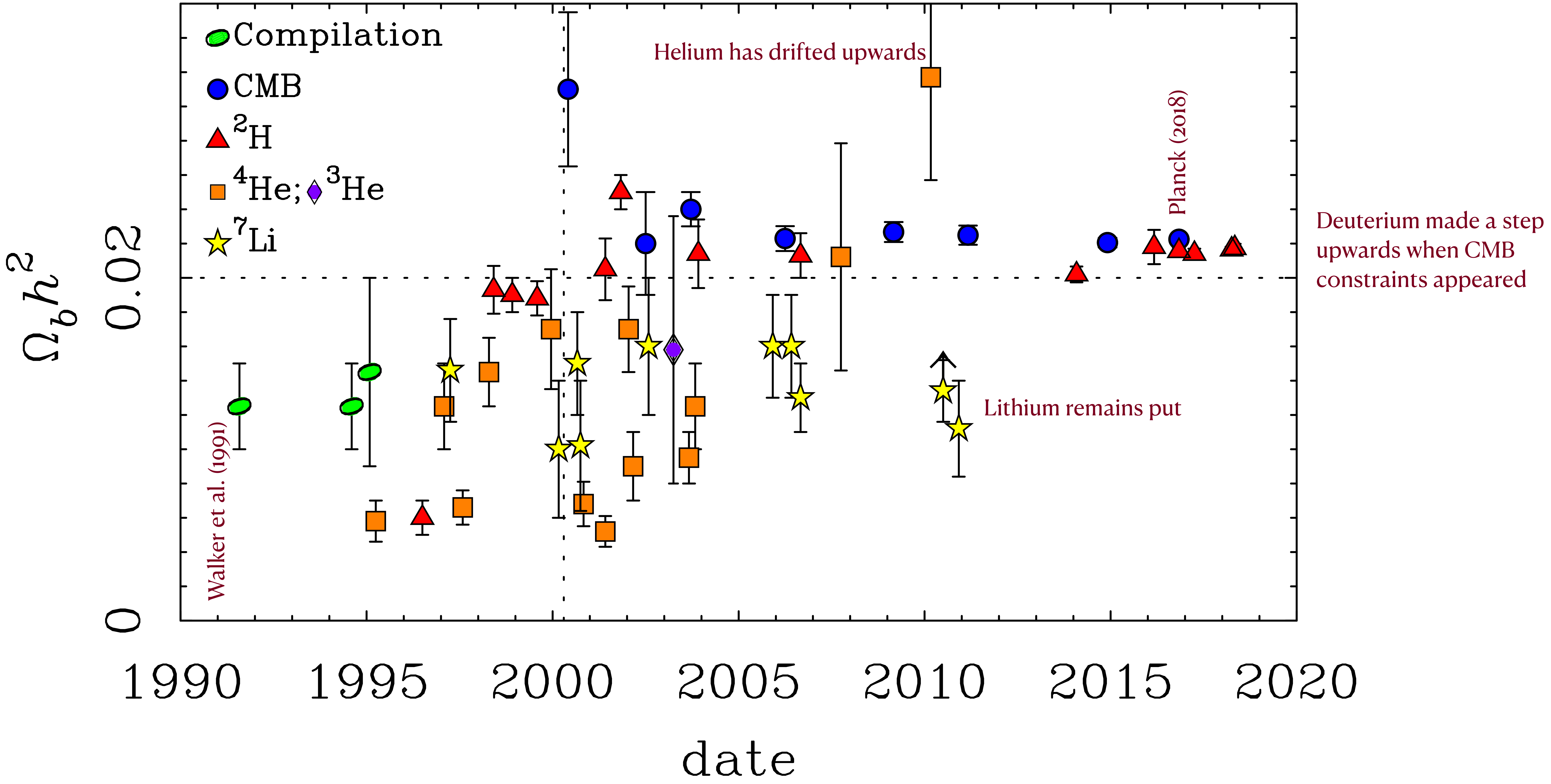
CMB



Planck best fit



$$\Omega_b h^2 = 0.0224 \pm 0.0001$$

Compilation
CMB
^{2}H
^{4}He; ^{3}He
^{7}Li
Helium has drifted upwards
Planck (2018)
Deuterium made a step upwards when CMB constraints appeared
Lithium remains put
Walker et al. (1991)
$\Omega_b h^2$
0.02
0
1990
1995
2000
2005
2010
2015
2020
date