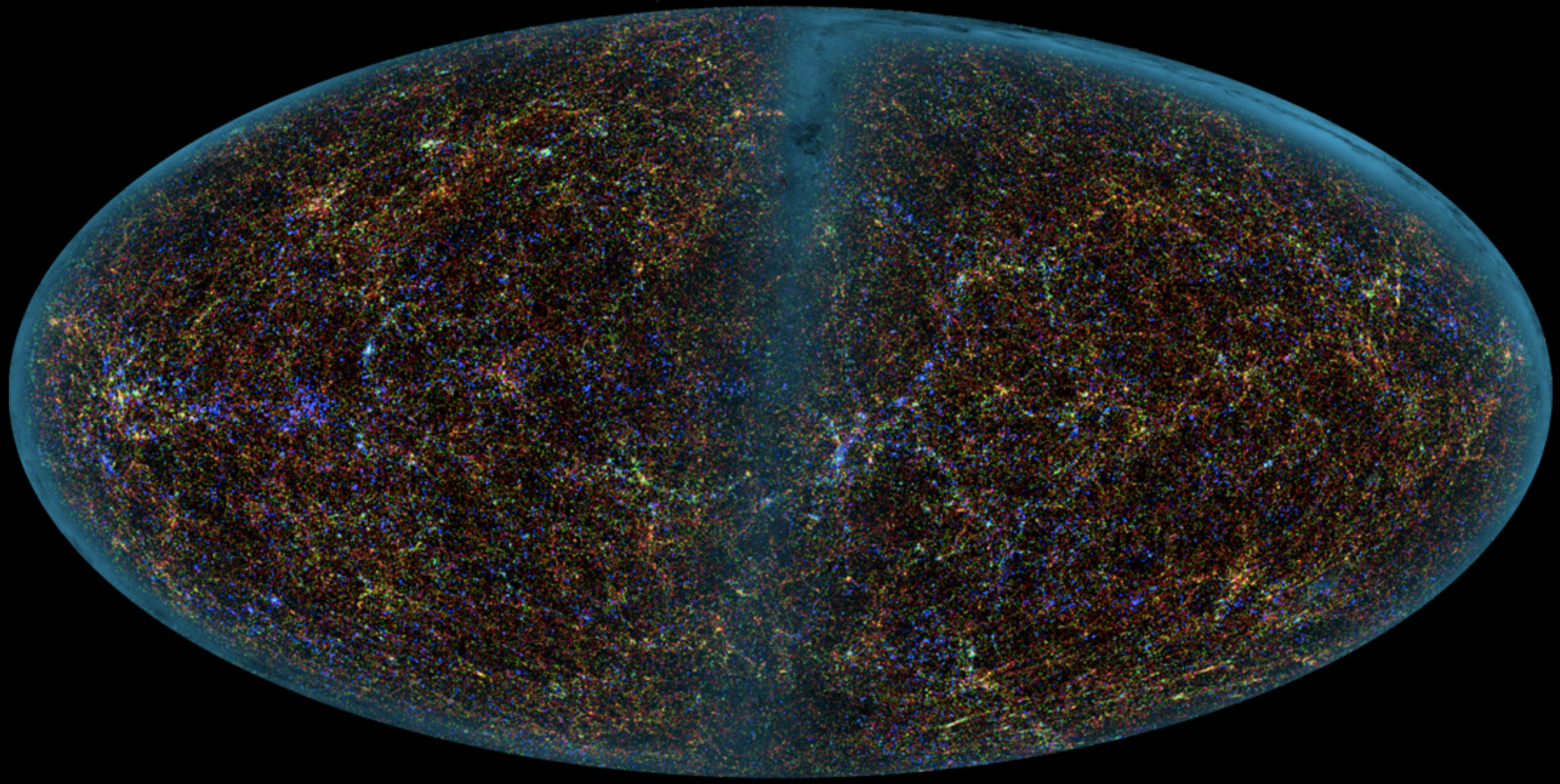
Cosmology

and Large Scale Structure



VOTE!

Today

Empirical Pillars of the Hot Big Bang

Nucleosynthesis (observations)

Homework 4 in one week

5 November 2024

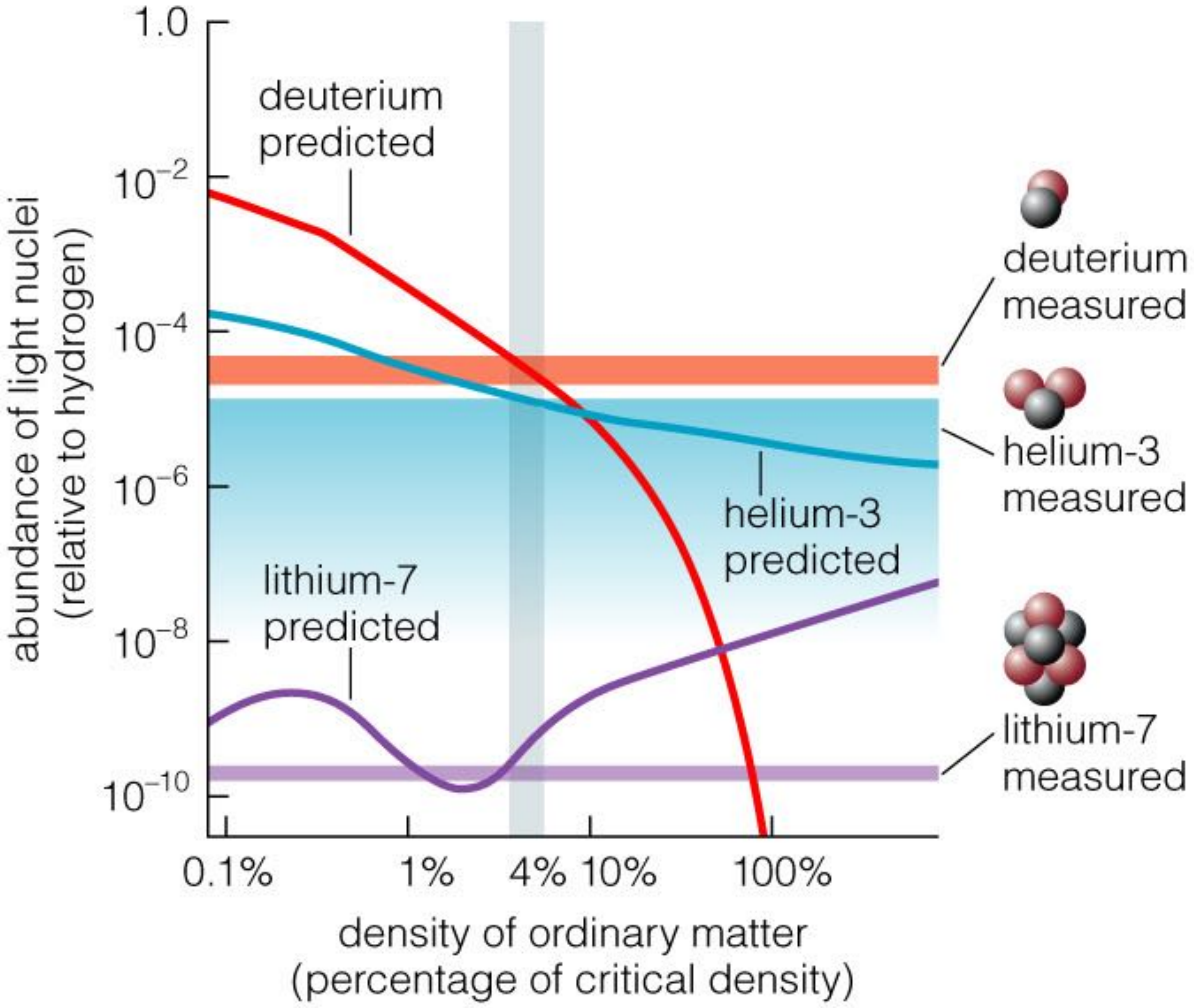
http://astroweb.case.edu/ssm/ASTR328/

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.

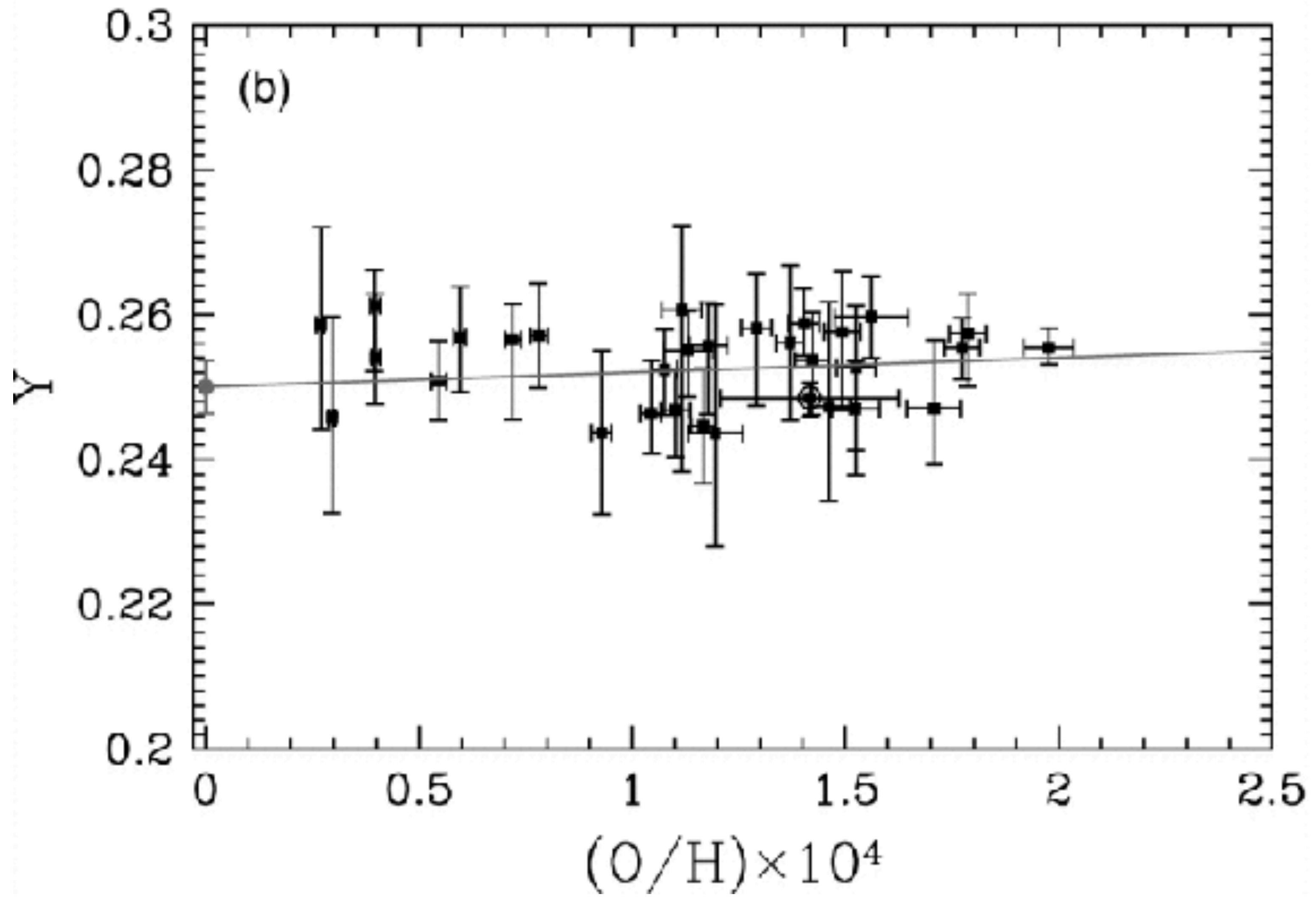
Observationally, it is challenging to measure helium lines with great accuracy, and interpret their abundance as the percent level. It is also challenging to differentiate between primordial helium and stellar helium production

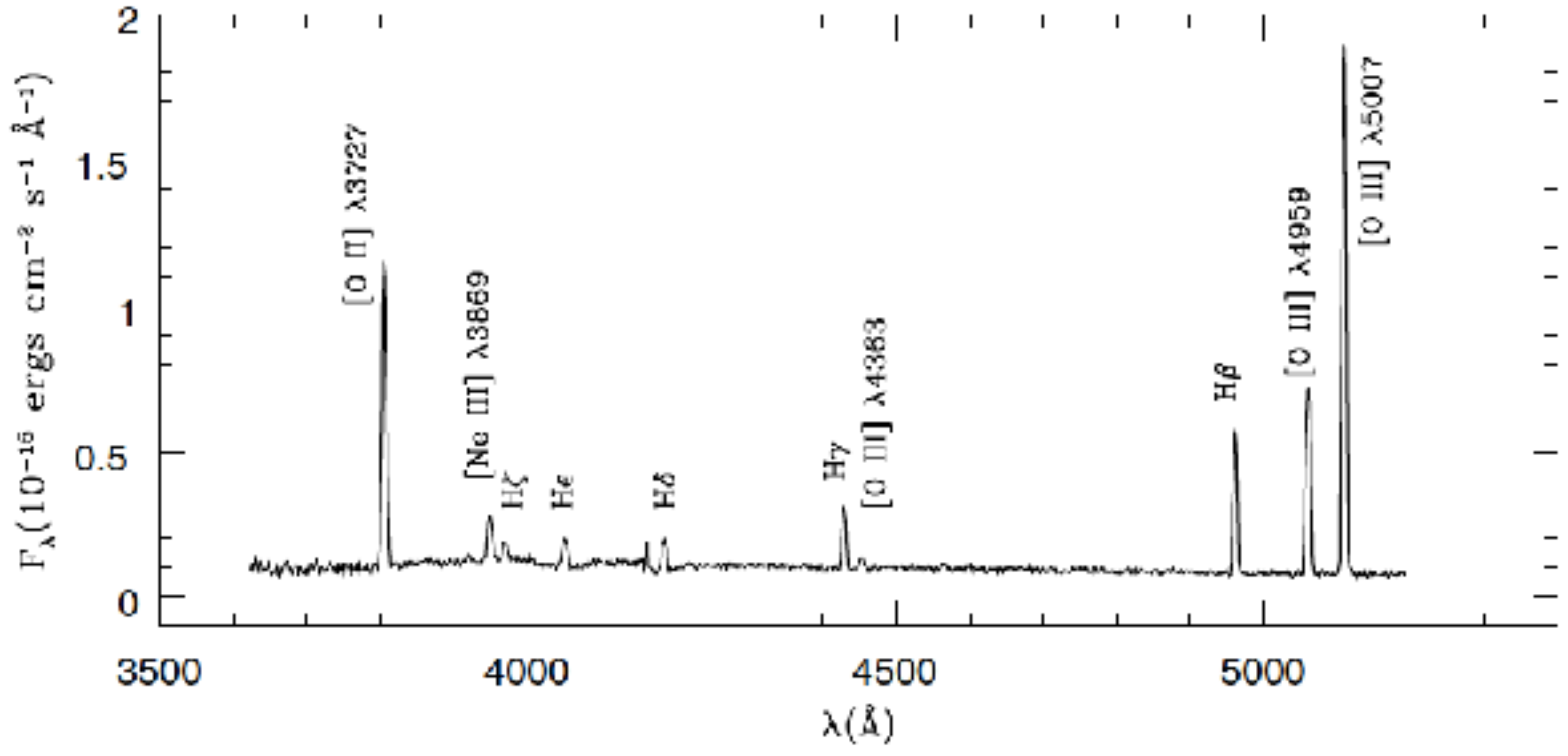


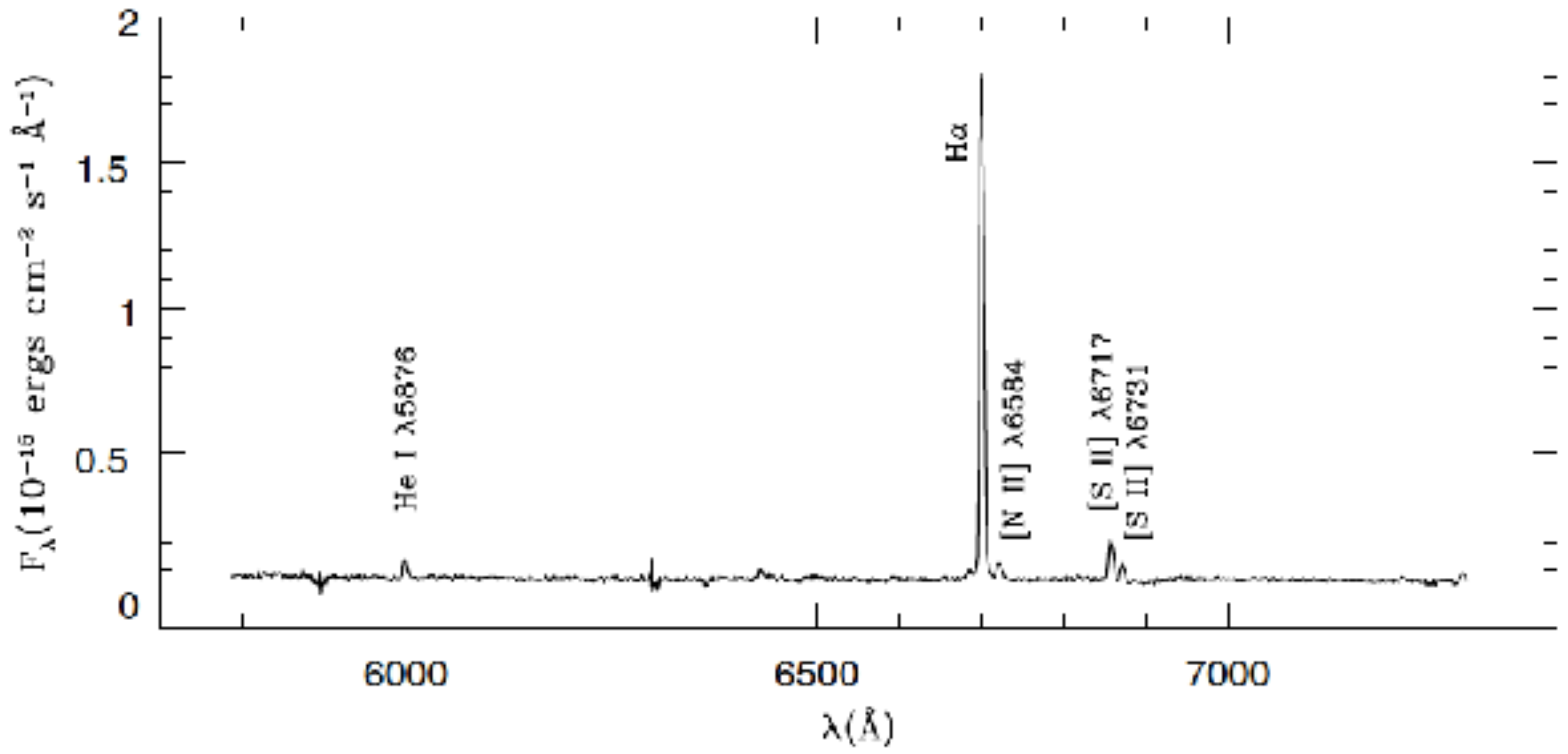
Ω_b

$$Y_P = 0.25 \pm 0.01$$

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

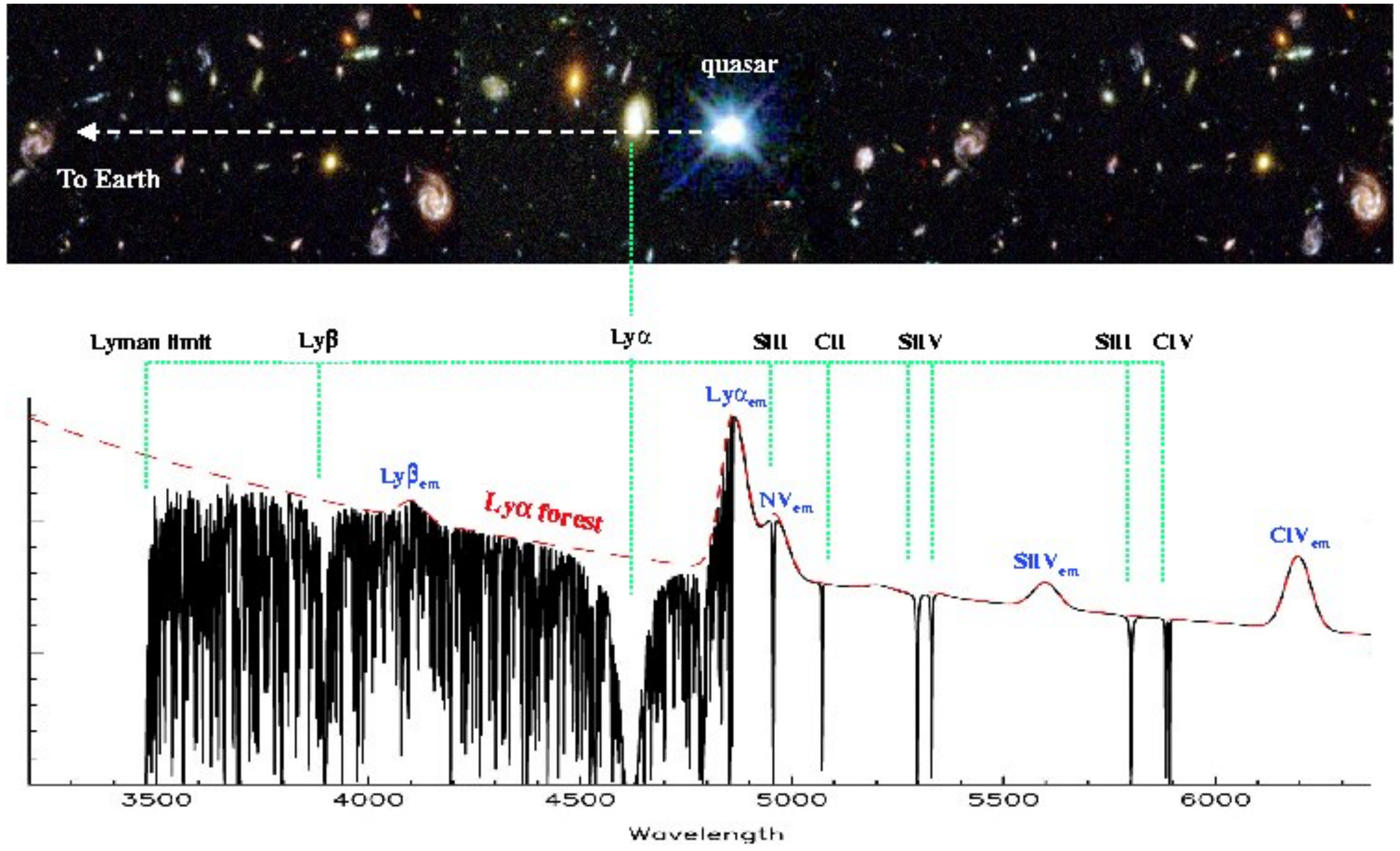






Deuterium

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



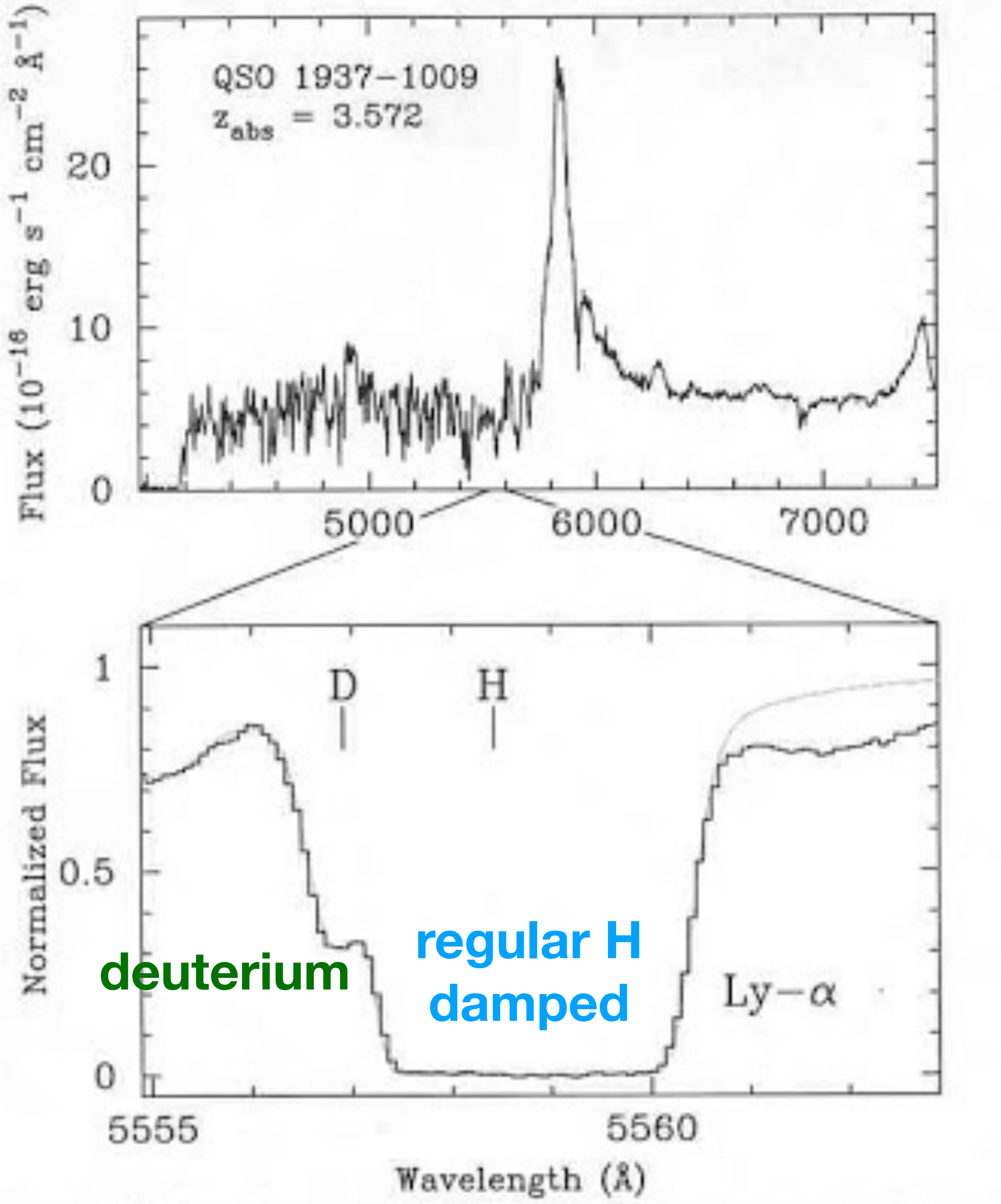
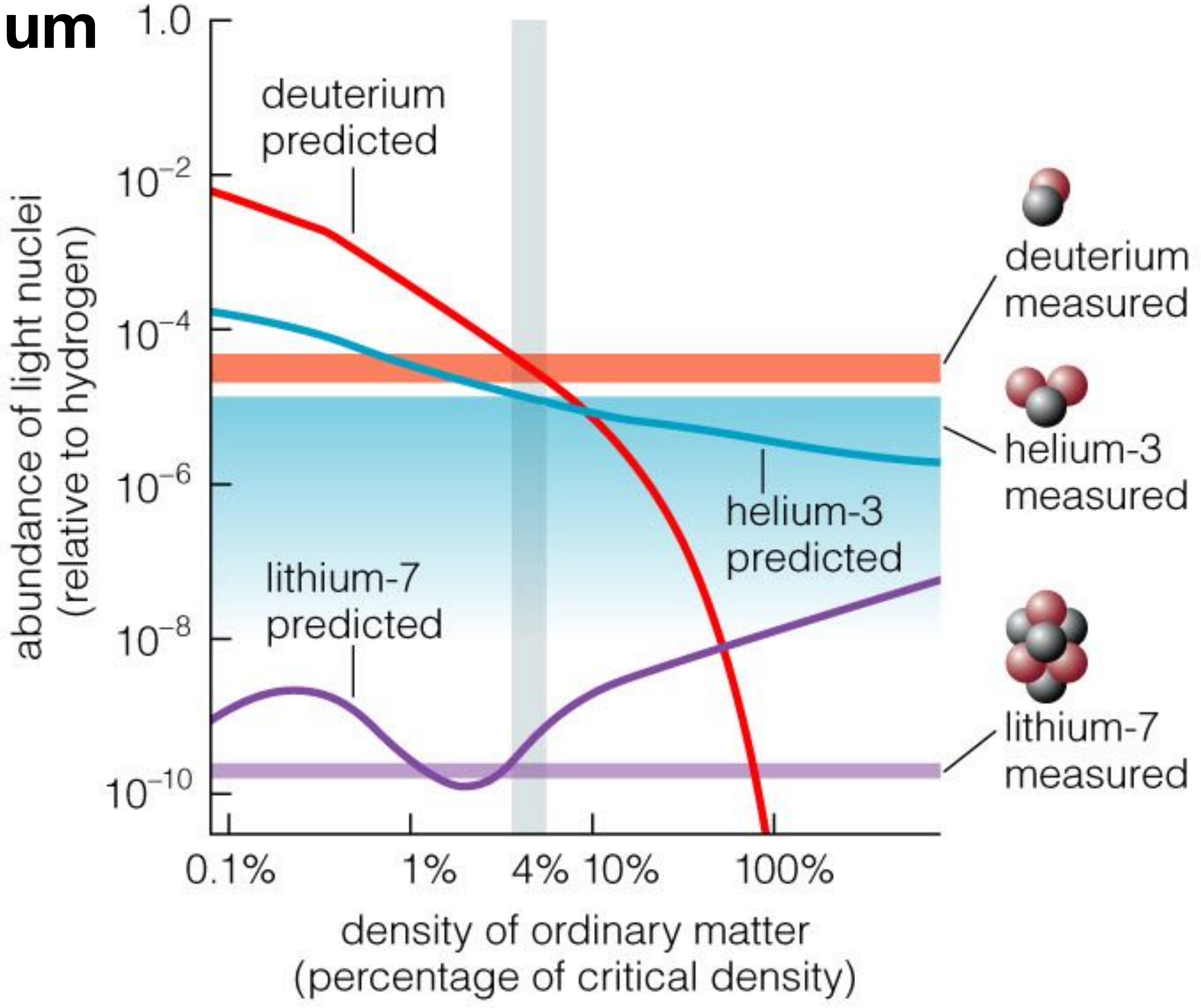
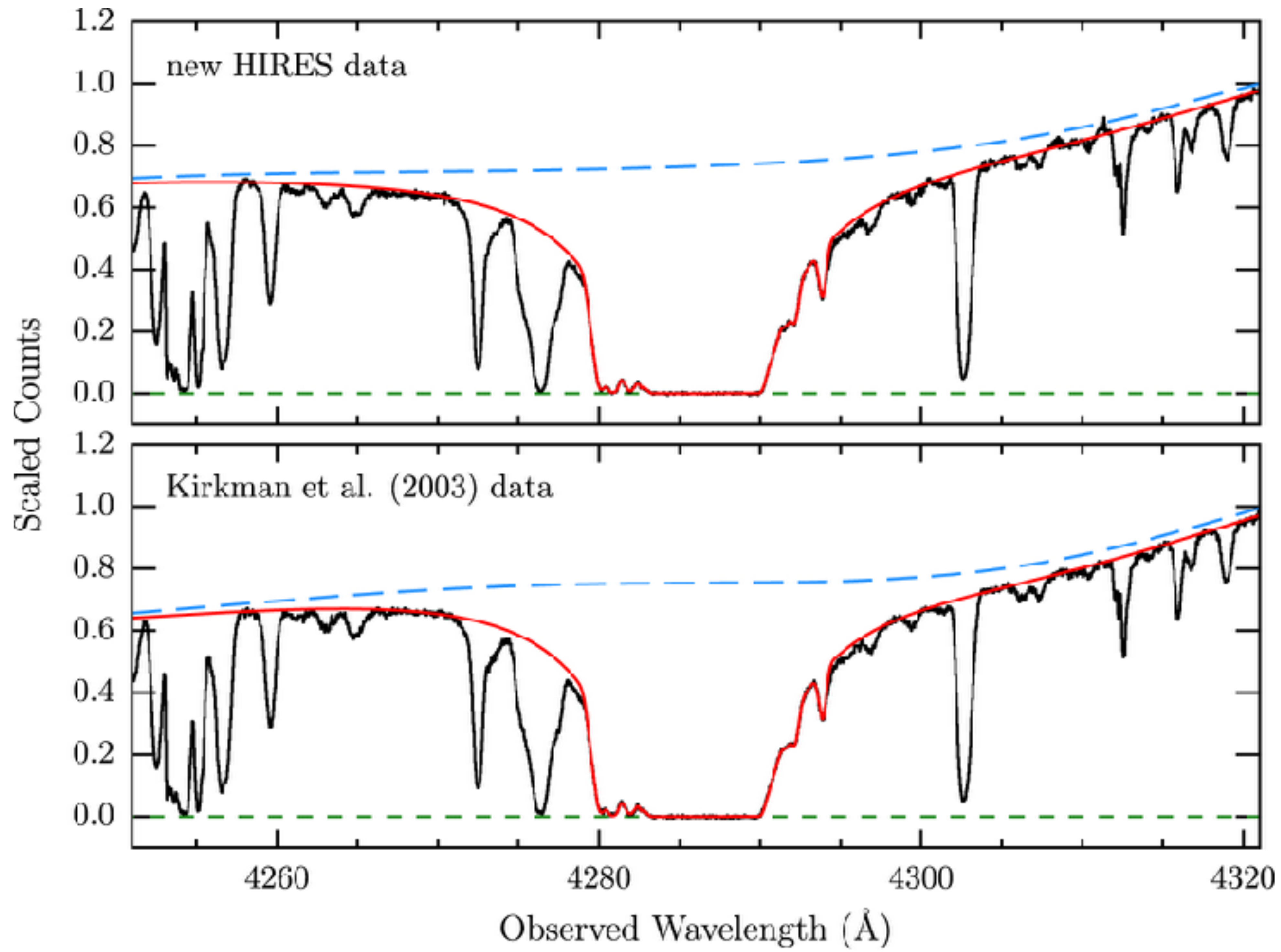


FIG. 3. Spectrum of Q1937-1009; blueward of the characteristic Lyman-α emission line of the quasar is the "forest" of Lyman-α absorption due to the hundreds of intervening gas clouds. The lower panel shows a blowup of the region around the deuterium detection, a cloud at redshift $z = 3.572$, and the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

Many discrete absorbers in the Lyman α forest, but
no broad Gunn-Peterson trough from a neutral IGM

Deuterium

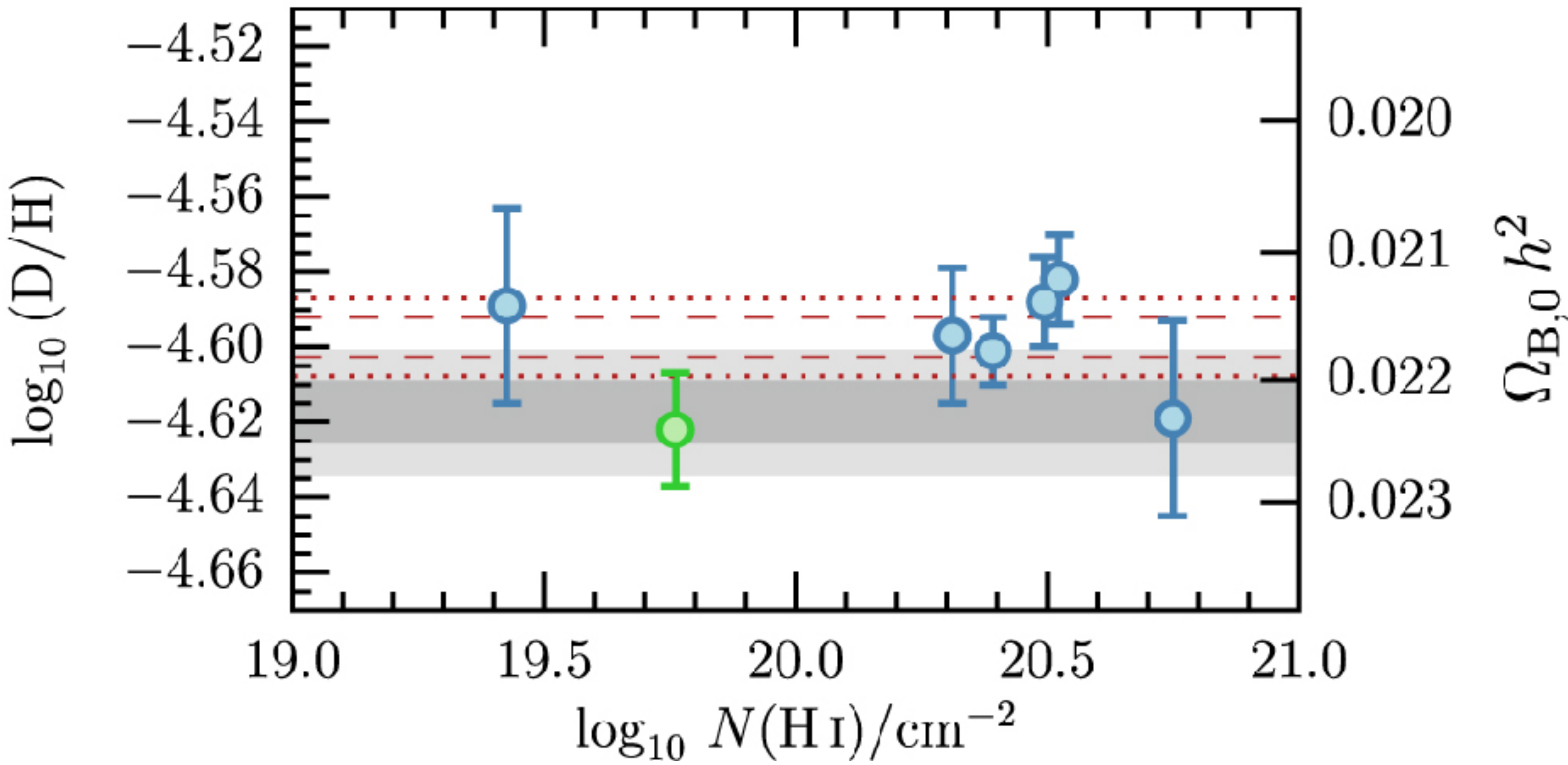




Deuterium is a good baryometer because D/H varies sensitively with the baryon density.

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.

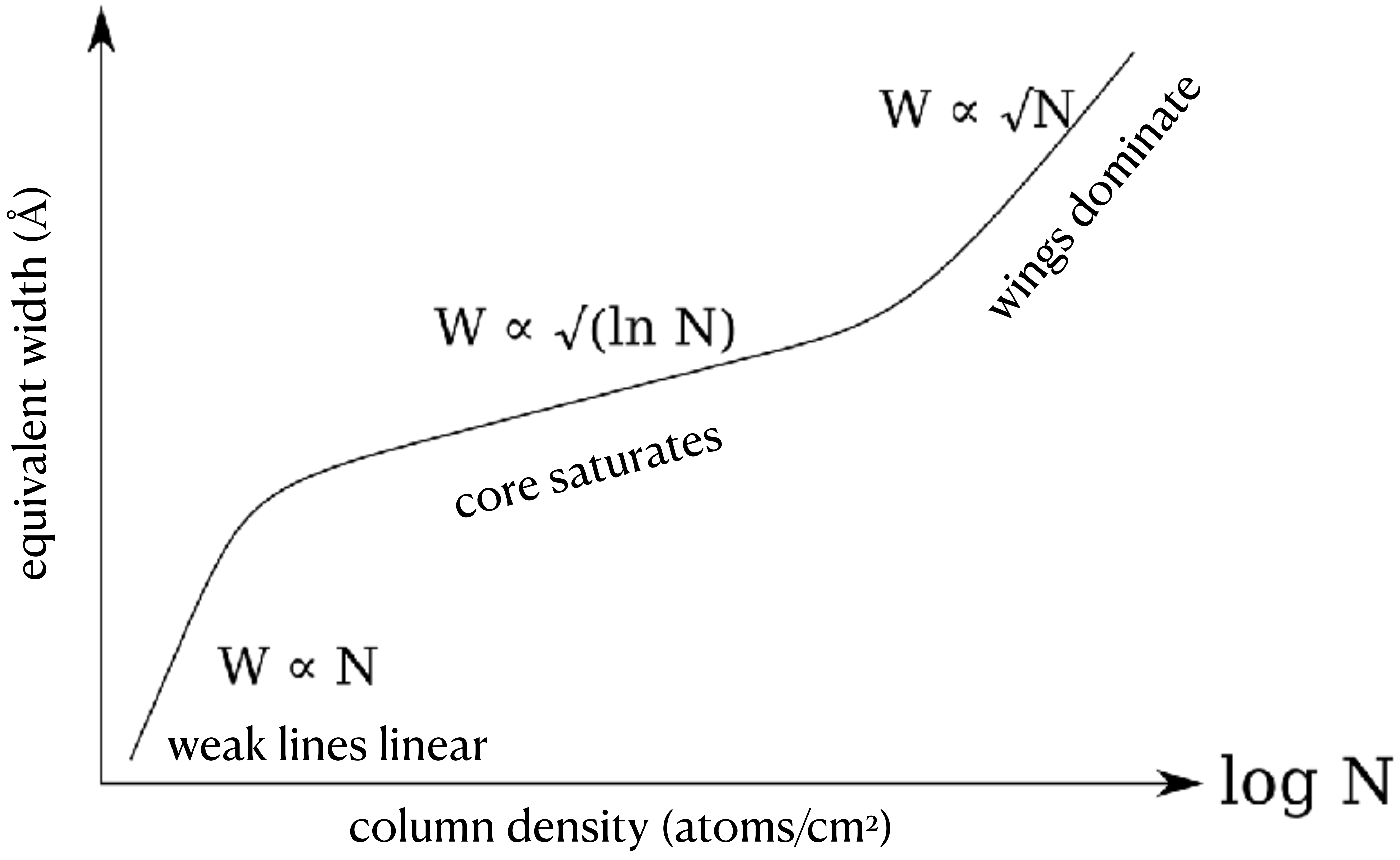


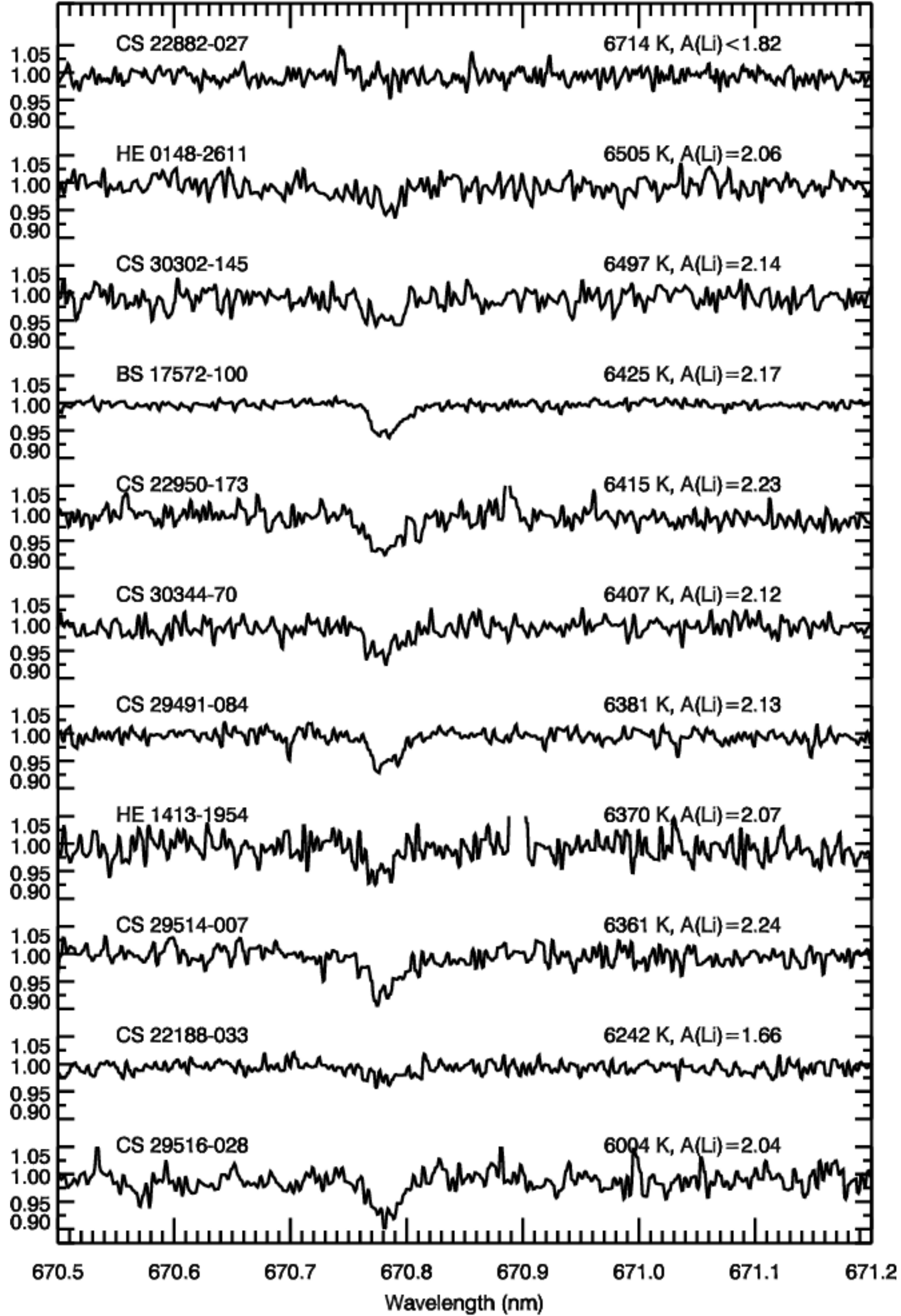
Lithium

Stellar spectra
showing Lithium absorption

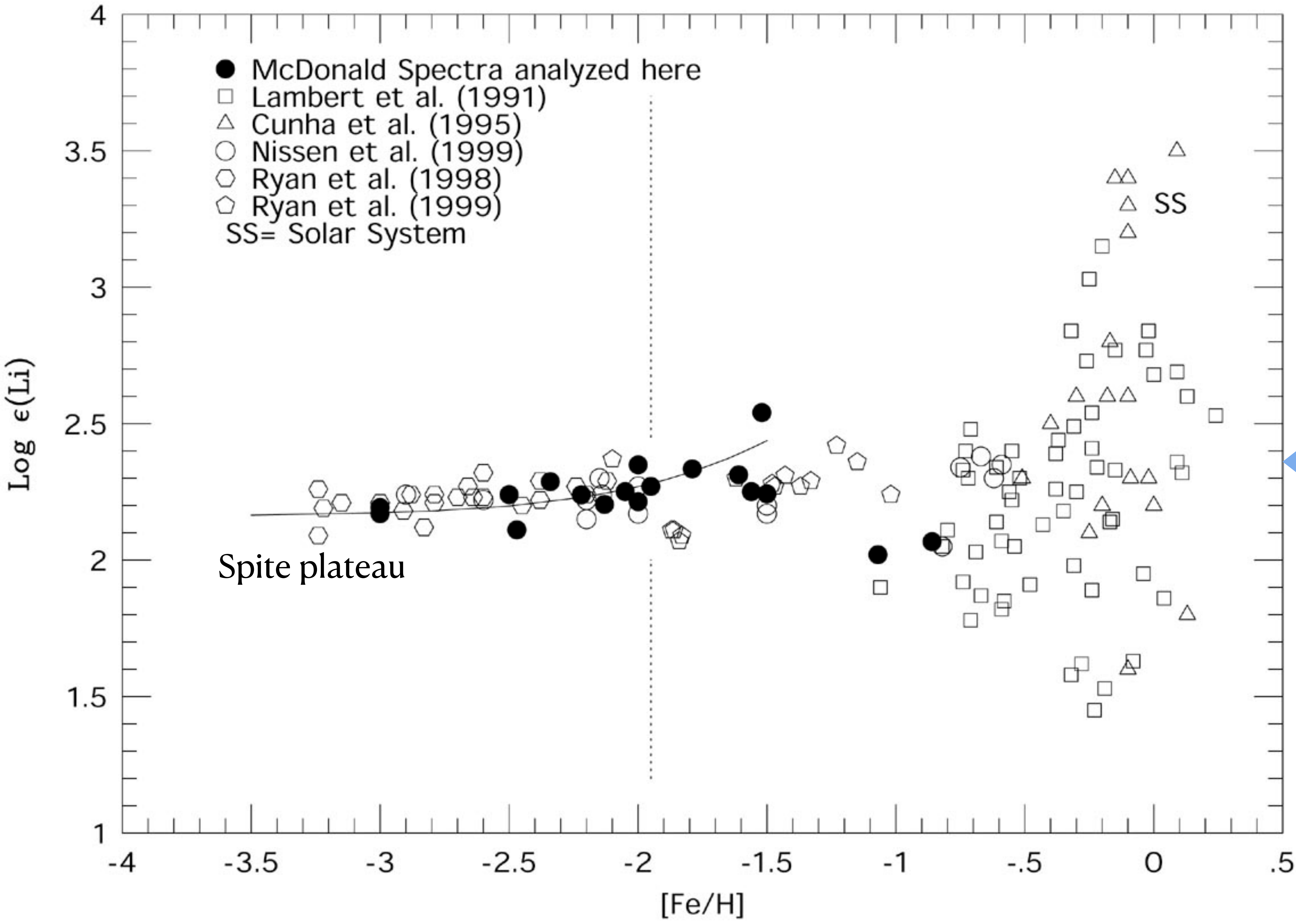
Lithium is measured in old, metal poor stars for which there is hope that the surface abundance is little altered from the primordial abundance - the Spite plateau.

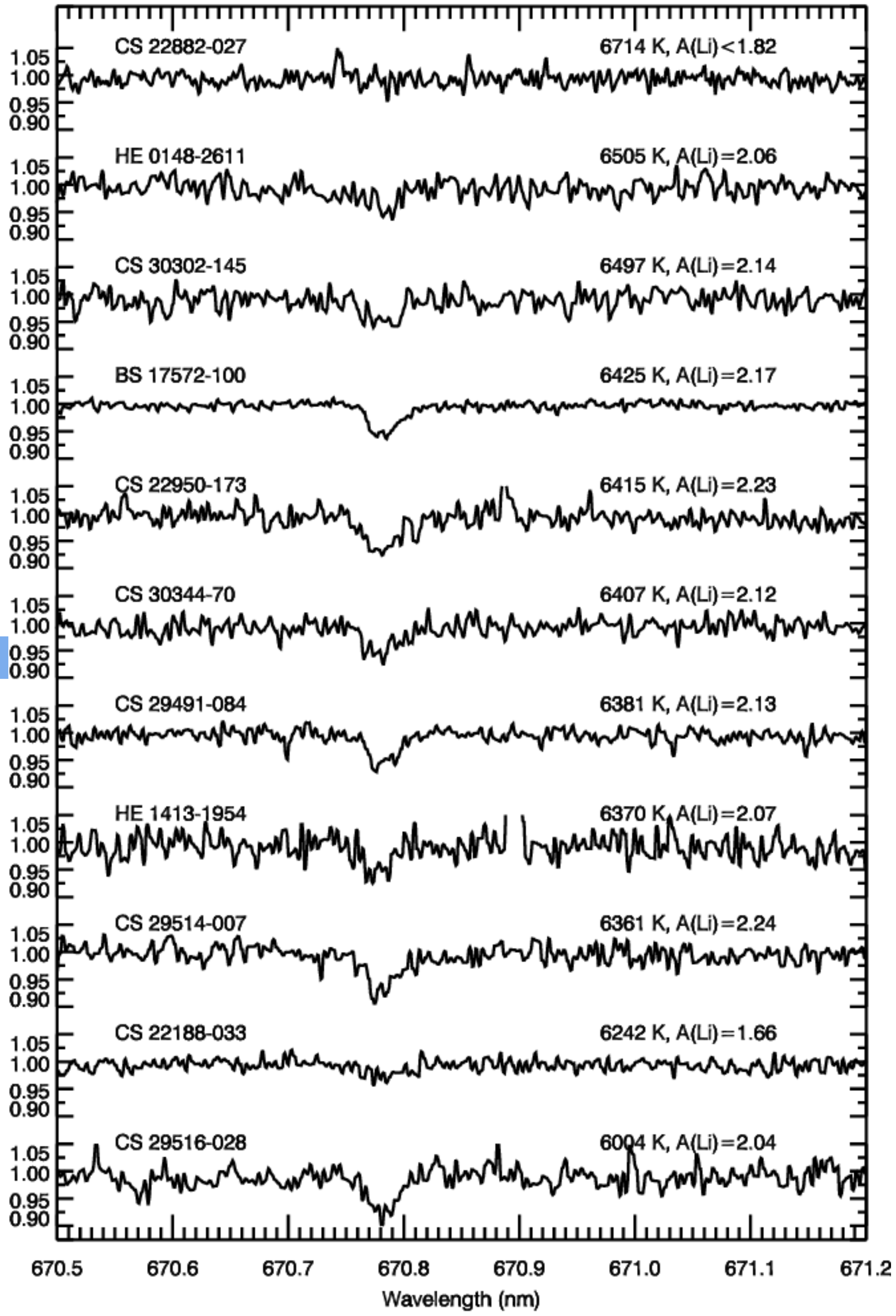
curve of growth





Lithium

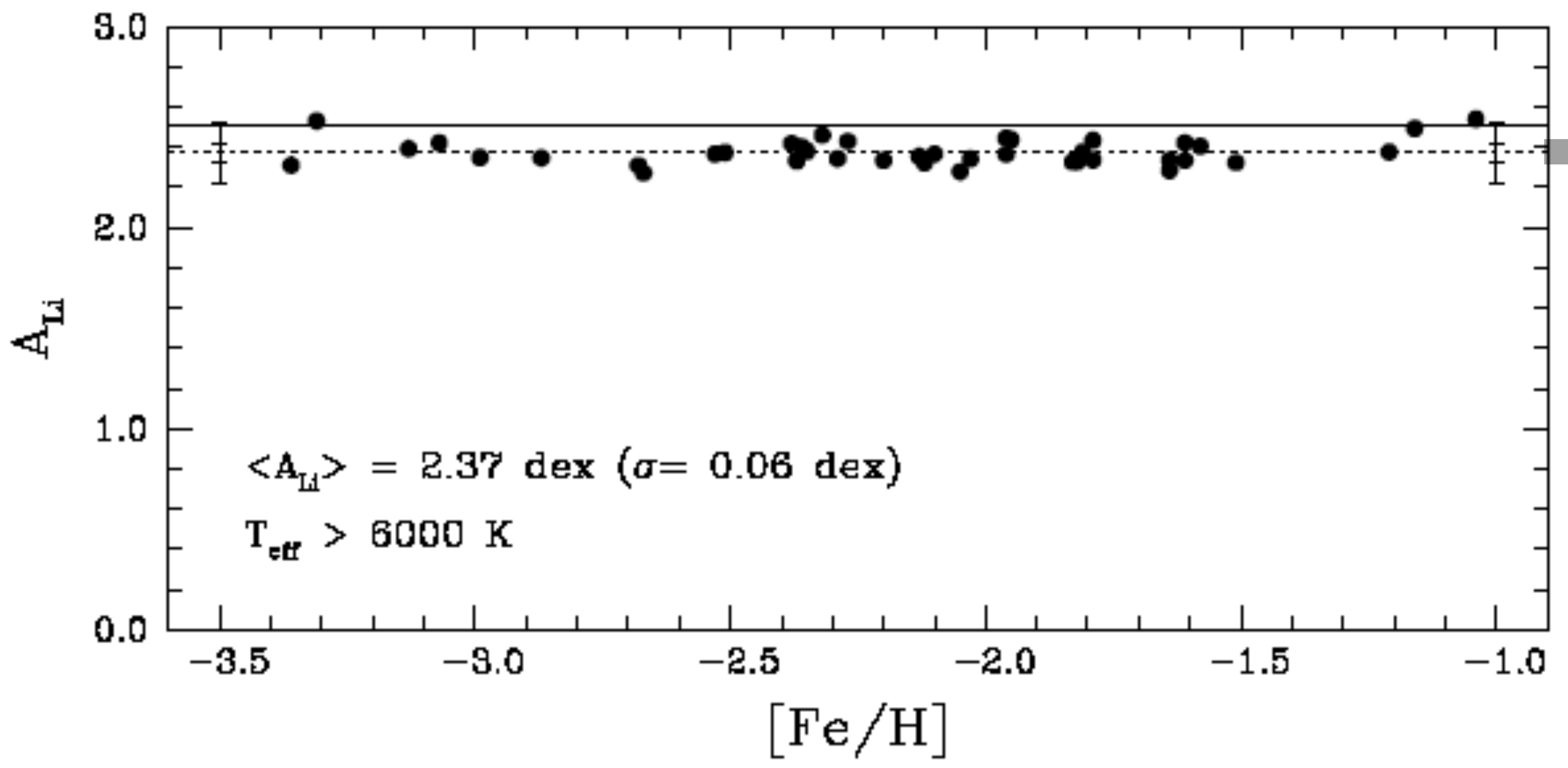

McDonald Spectra analyzed here
Lambert et al. (1991)
Cunha et al. (1995)
Nissen et al. (1999)
Ryan et al. (1998)
Ryan et al. (1999)
SS= Solar System
SS
Spite plateau
Log ϵ(Li)
[Fe/H]
4
3.5
3
2.5
2
1.5
1
-4
-3.5
-3
-2.5
-2
-1.5
-1
-.5
0
.5

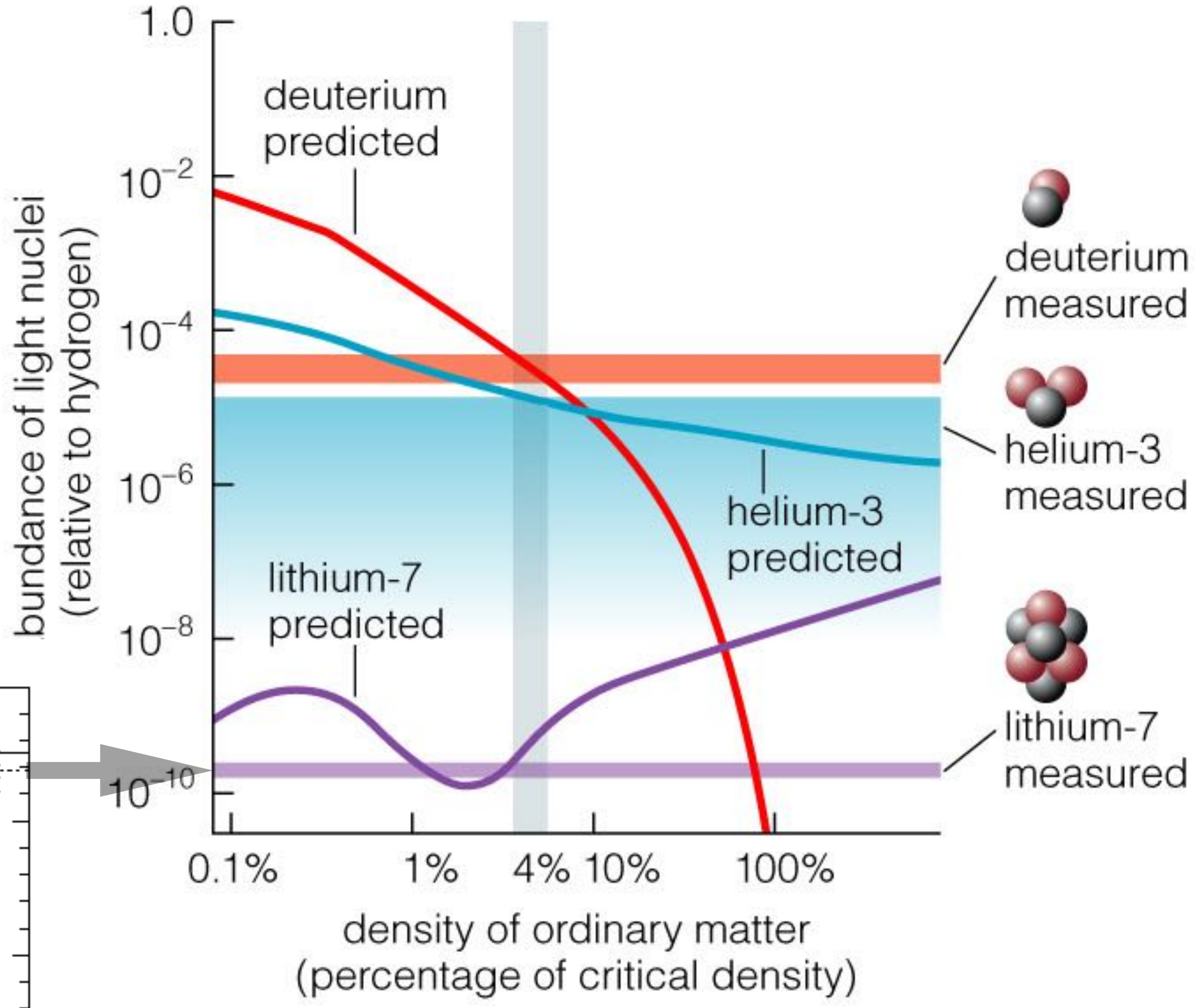

CS 22882-027
6714 K, A(Li)<1.82
HE 0148-2611
6505 K, A(Li)=2.06
CS 30302-145
6497 K, A(Li)=2.14
BS 17572-100
6425 K, A(Li)=2.17
CS 22950-173
6415 K, A(Li)=2.23
CS 30344-70
6407 K, A(Li)=2.12
CS 29491-084
6381 K, A(Li)=2.13
HE 1413-1954
6370 K, A(Li)=2.07
CS 29514-007
6361 K, A(Li)=2.24
CS 22188-033
6242 K, A(Li)=1.66
CS 29516-028
6004 K, A(Li)=2.04
1.05
1.00
0.95
0.90
670.5
670.6
670.7
670.8
670.9
671.0
671.1
671.2
Wavelength (nm)

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.



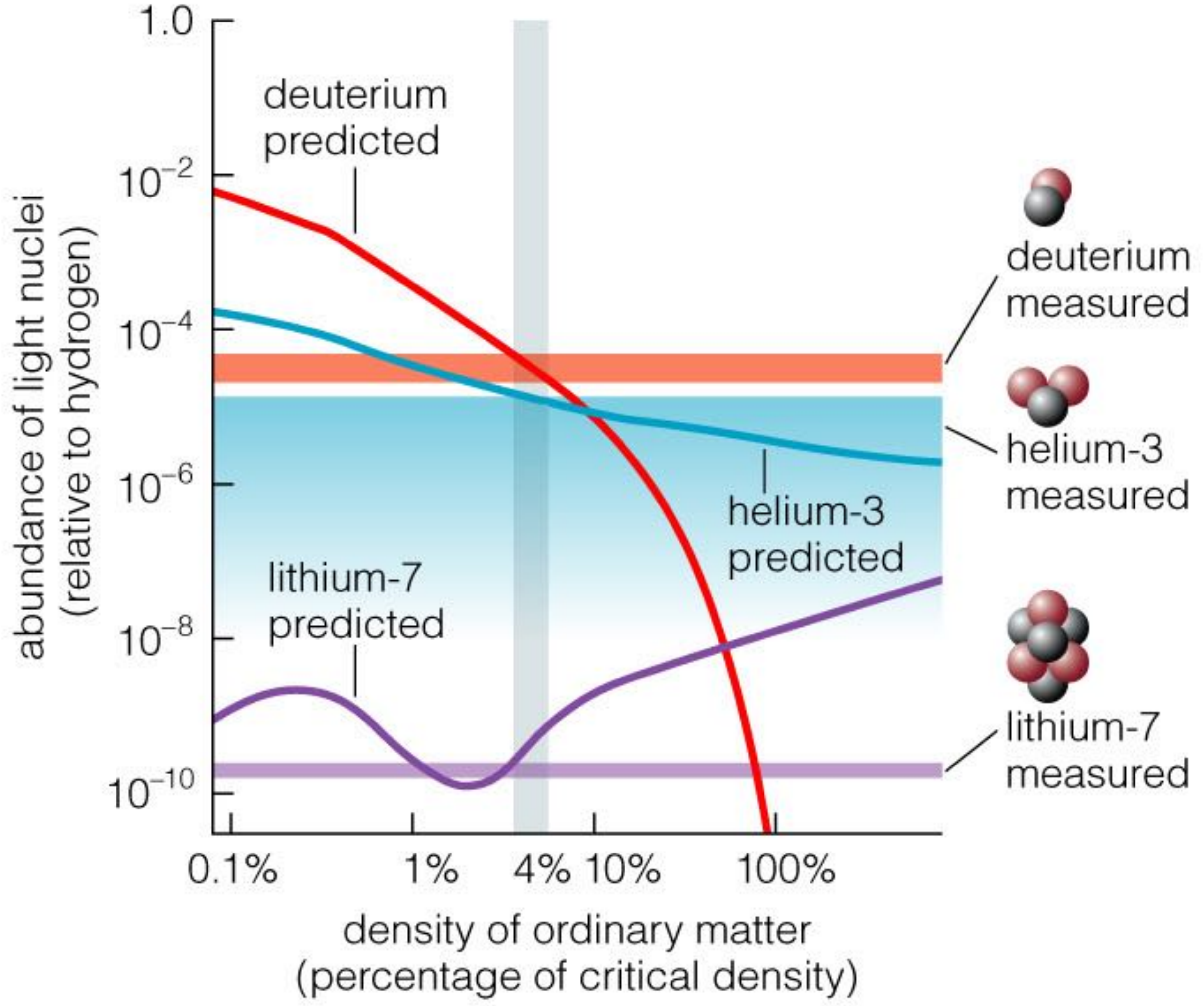


Ω_b

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.

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

$$\omega_b = 0.0224 \pm 0.0001 \qquad \text{(Planck 2018)}$$

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

TERRY P. WALKER,[1,2] GARY STEIGMAN,[2,3] DAVID N. SCHRAMM,[4] KEITH A. OLIVE,[5] AND HO-SHIK KANG[2]

Received 1990 December 17; accepted 1991 January 17

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, $2.8 \le \eta_{10} \le 4.0$ ($\eta_{10} \equiv 10^{10} n_B/n_\gamma$), 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 $\Omega_{TOT} = 1$ and would require that the universe be dominated by nonbaryonic matter. An upper bound to the primordial mass fraction of ^{4}He, $Y_p \le 0.240$, constrains the number of light (equivalent) neutrinos to $N_\nu \le 3.3$, in excellent agreement with the LEP and SLC collider results. Alternatively, for $N_\nu = 3$, we bound the predicted primordial abundance of ^{4}He: $0.236 \le Y_p \le 0.243$ (for $882 \le \tau_n \le 896$ s).

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

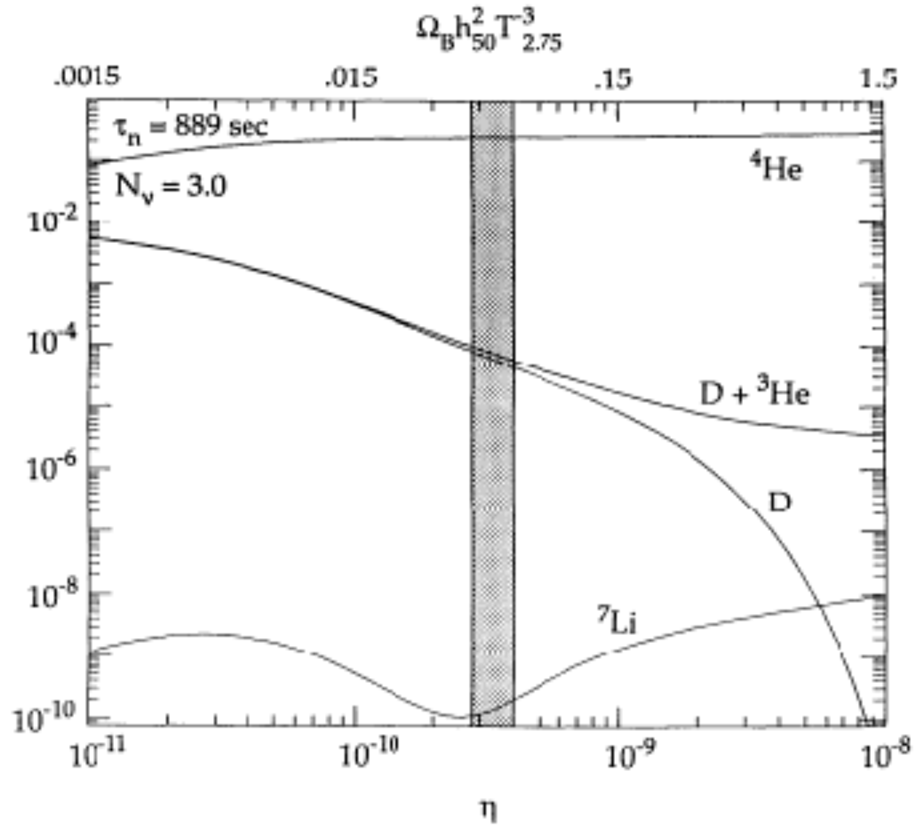


FIG. 12.—Predicted abundances (by number) of D, D + ^{3}He, and ^{7}Li, and the ^{4}He mass fraction as a function of η for $N_\nu = 3$ and $\tau_n = 889$ s for $0.1 \le \eta_{10} \le 100$. The vertical band delimits the range of η consistent with the observations.

Since $N_\nu > 3$ (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 $\tau_n \ge 882$, we see from equation (4) that

$$Y_p \ge 0.227 + 0.010 \ln \eta_{10} , \qquad (30)$$

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

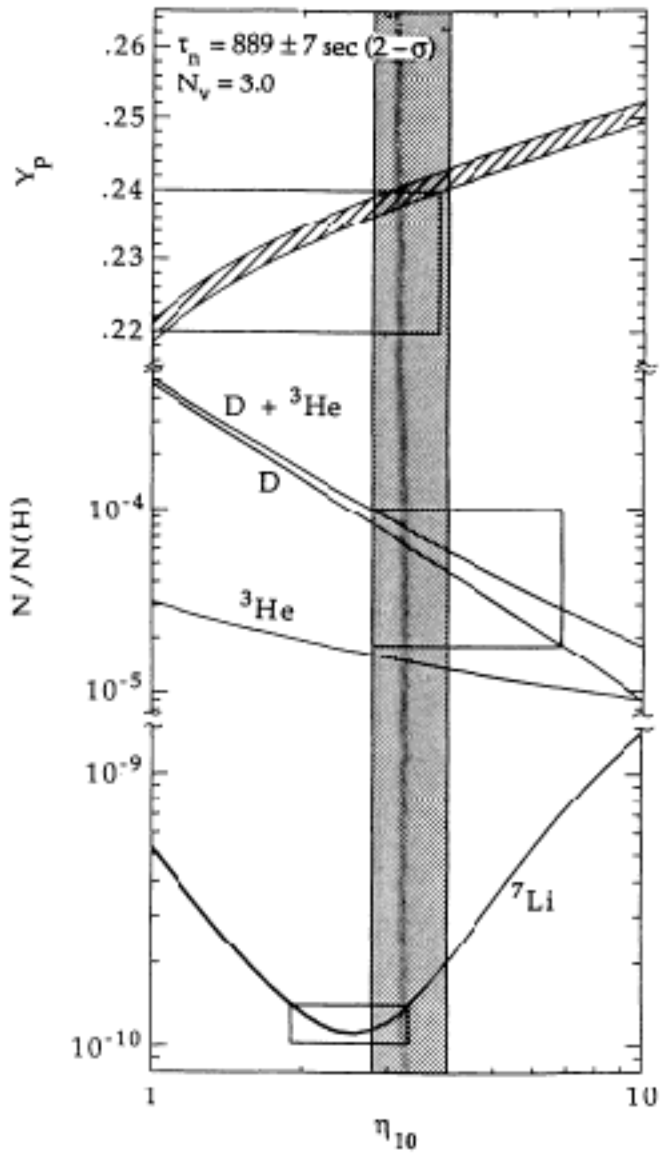
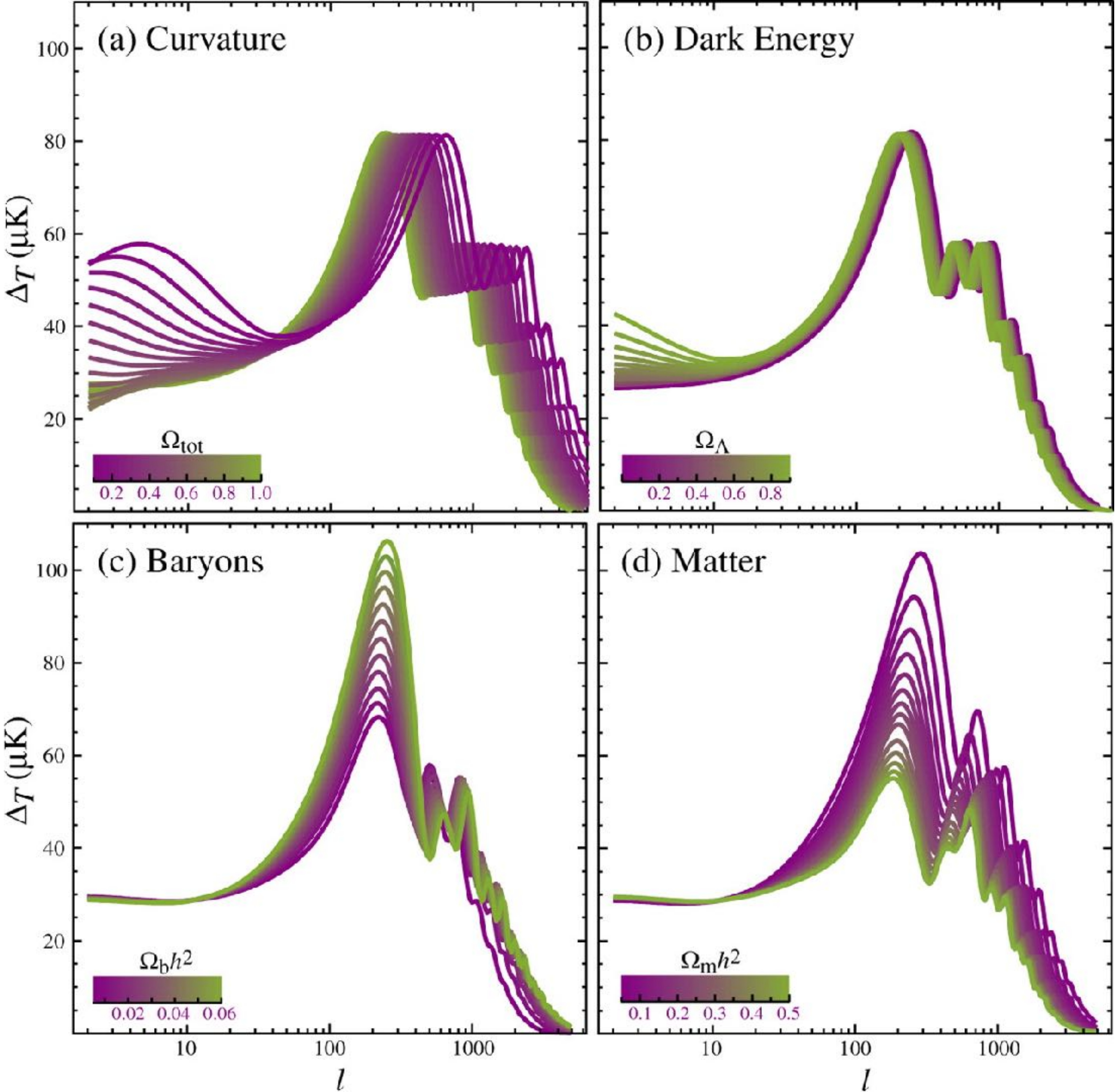


FIG. 13.—Predicted abundances (by number) of D, ^{3}He, D + ^{3}He, and ^{7}Li, and the ^{4}He mass fraction as a function of η for $N_\nu = 3$ and $882 \le \tau_n \le 896$ s. The 95% CL bounds on the abundances (see text) are shown. The vertical band delimits the range of η consistent with the observations.

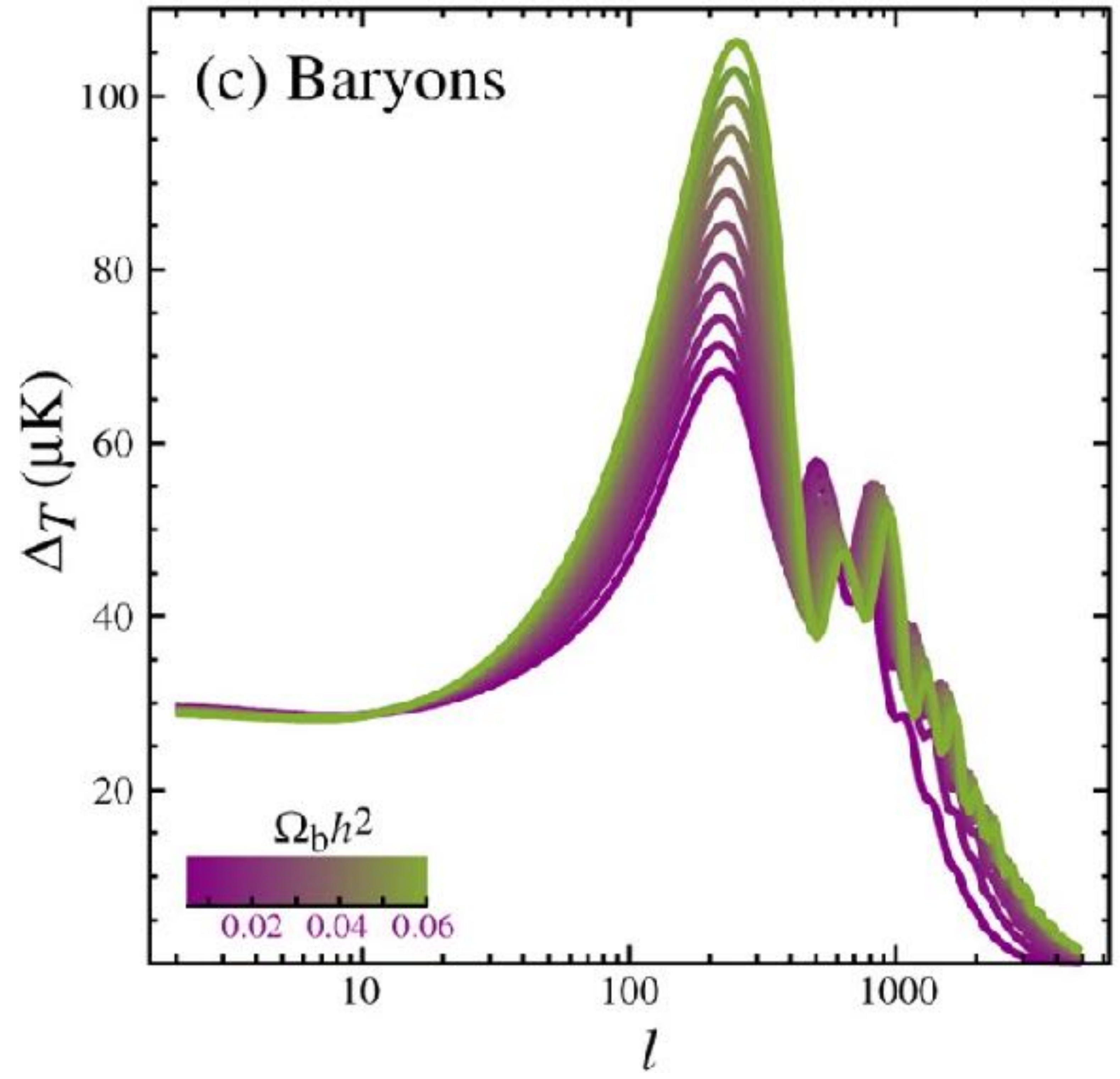
where T is in kelvins. Comparing the baryon mass density

CMB

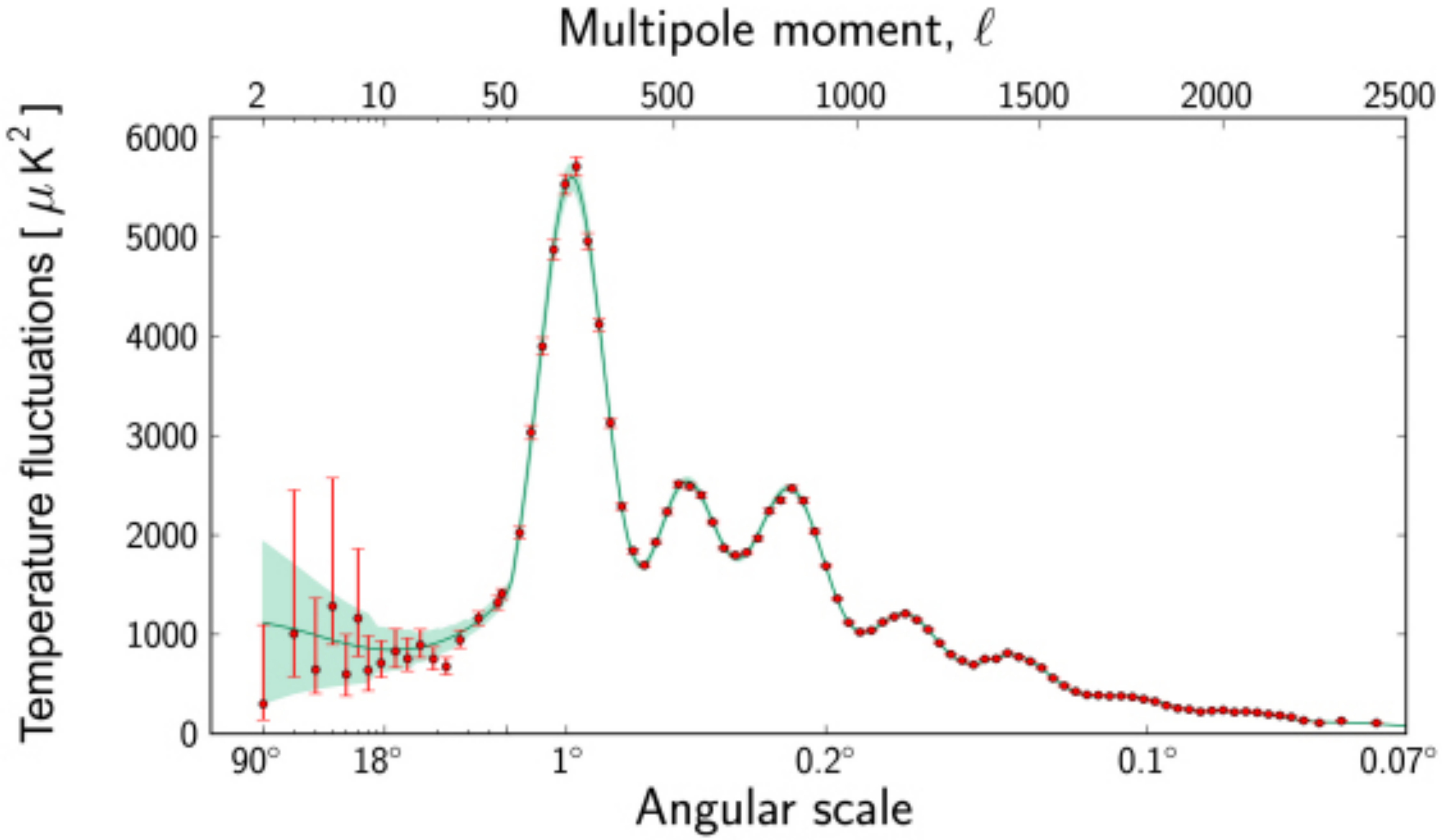


Dodelson & Hu (2004)

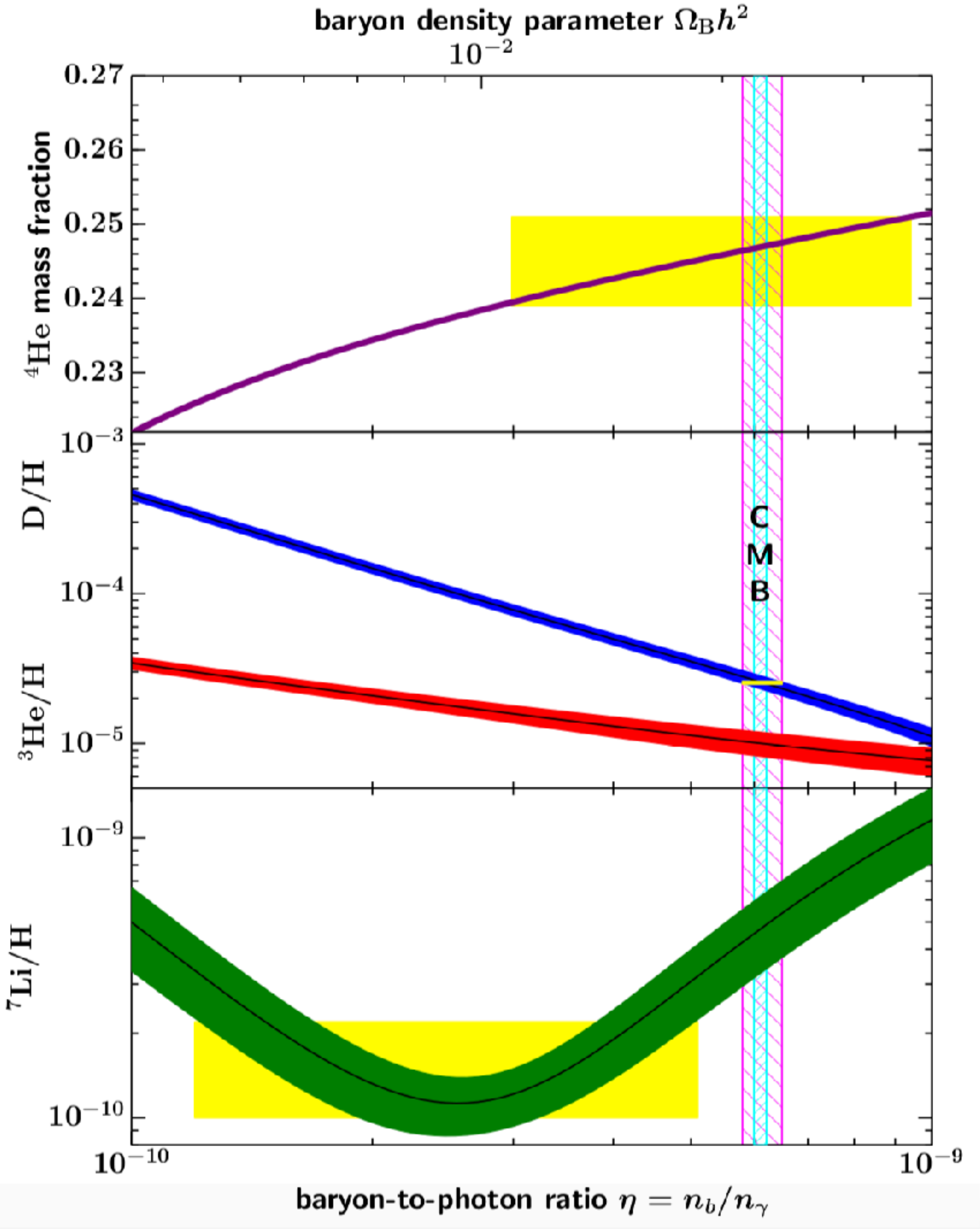
CMB



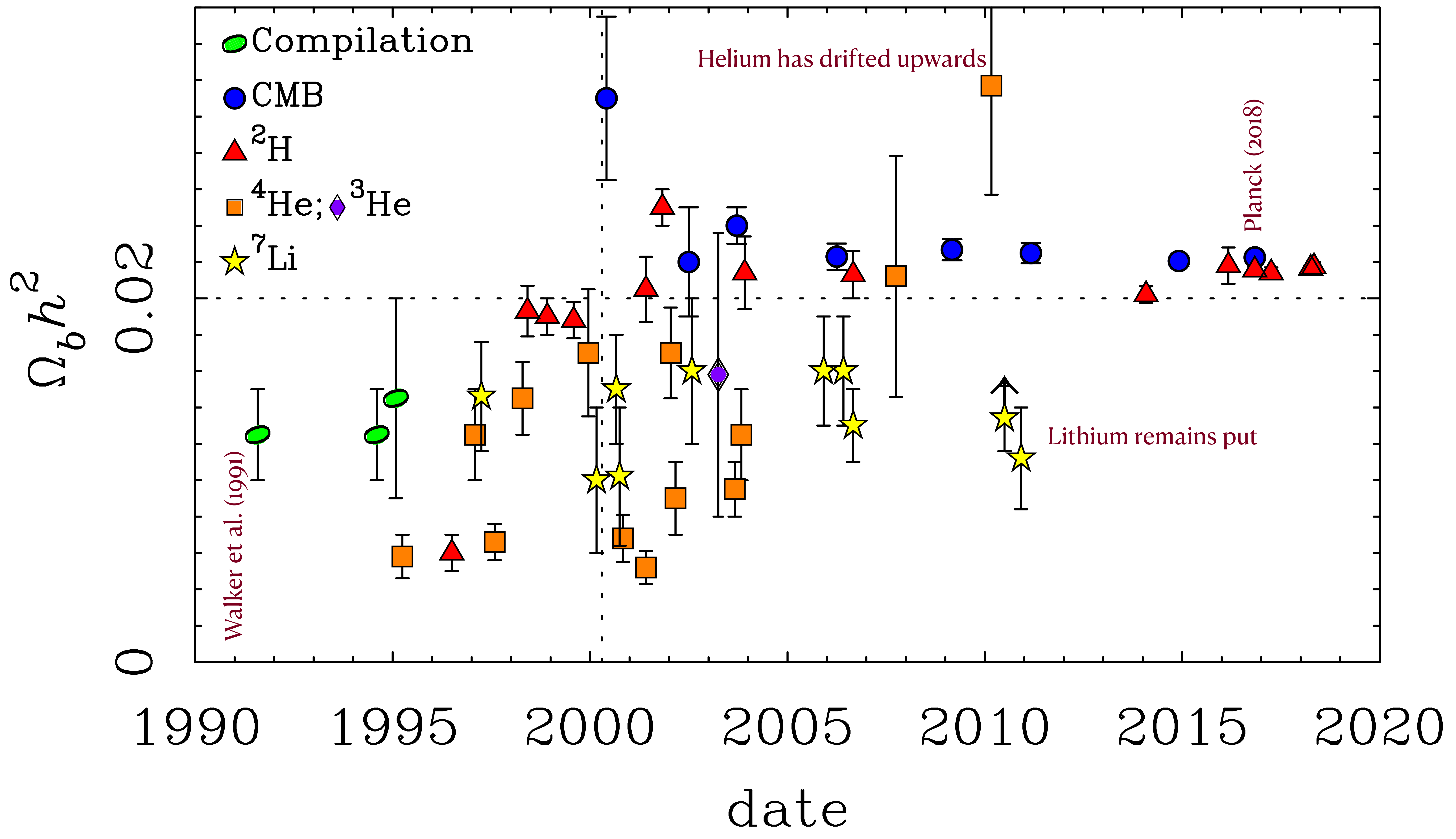
Planck best fit



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



baryon density parameter $\Omega_B h^2$
10^{-2}
^{4}He mass fraction
0.27
0.26
0.25
0.24
0.23
D/H
^{3}He/H
10^{-3}
10^{-4}
10^{-5}
C
M
B
^{7}Li/H
10^{-9}
10^{-10}
10^{-10}
10^{-9}
baryon-to-photon ratio $\eta = n_b/n_\gamma$

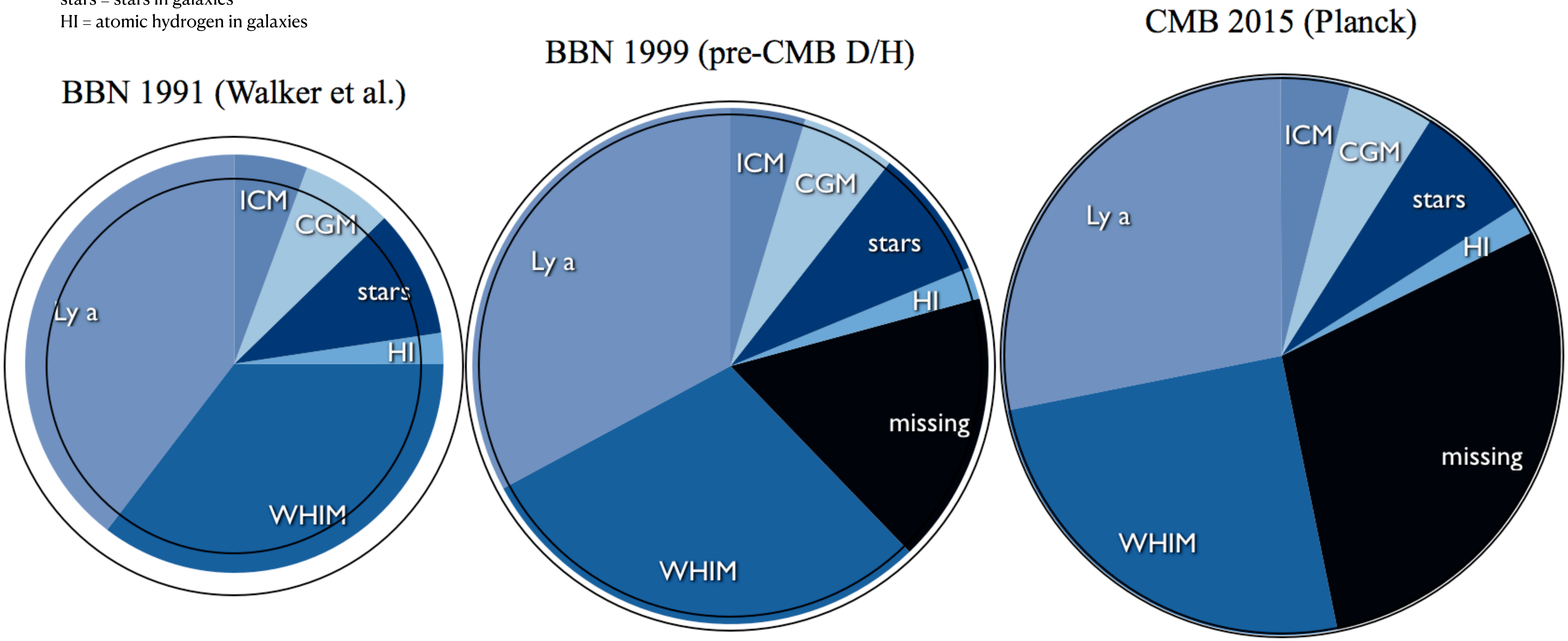


Compilation
CMB
^{2}H
^{4}He; ^{3}He
^{7}Li
Helium has drifted upwards
Planck (2018)
Lithium remains put
Walker et al. (1991)
$\Omega_b h^2$
0.02
0
1990
1995
2000
2005
2010
2015
2020
date

Where are the baryons now? Mostly in the intergalactic medium (IGM) (Shull et al. 2012)

Ly a = Lyman alpha forest (IGM)
WHIM = Warm-Hot Intergalactic Medium
ICM = Intra Cluster Medium (hot gas in clusters)
CGM = CircumGalactic Medium (gas in galaxy halos)
stars = stars in galaxies
HI = atomic hydrogen in galaxies

Stars only about 7% of the baryons expected from BBN - for a long time there seemed to be a missing baryon problem. Perhaps there still is, but chiefly it appeared that way because most normal matter has not condensed into stars.



$\Omega_b h^2 = 0.0125 \pm 0.0025$ $\Omega_b h^2 = 0.019 \pm 0.001$ $\Omega_b h^2 = 0.02230 \pm 0.00023$

There has been more growth in the baryon density than anticipated by the uncertainties, but the basic picture is sound.

But estimates of Ω_m run higher: there's more mass than meets the eye

There is more gravitating mass than Big Bang Nucleosynthesis allows in normal matter.
Need **non-baryonic** dark matter.