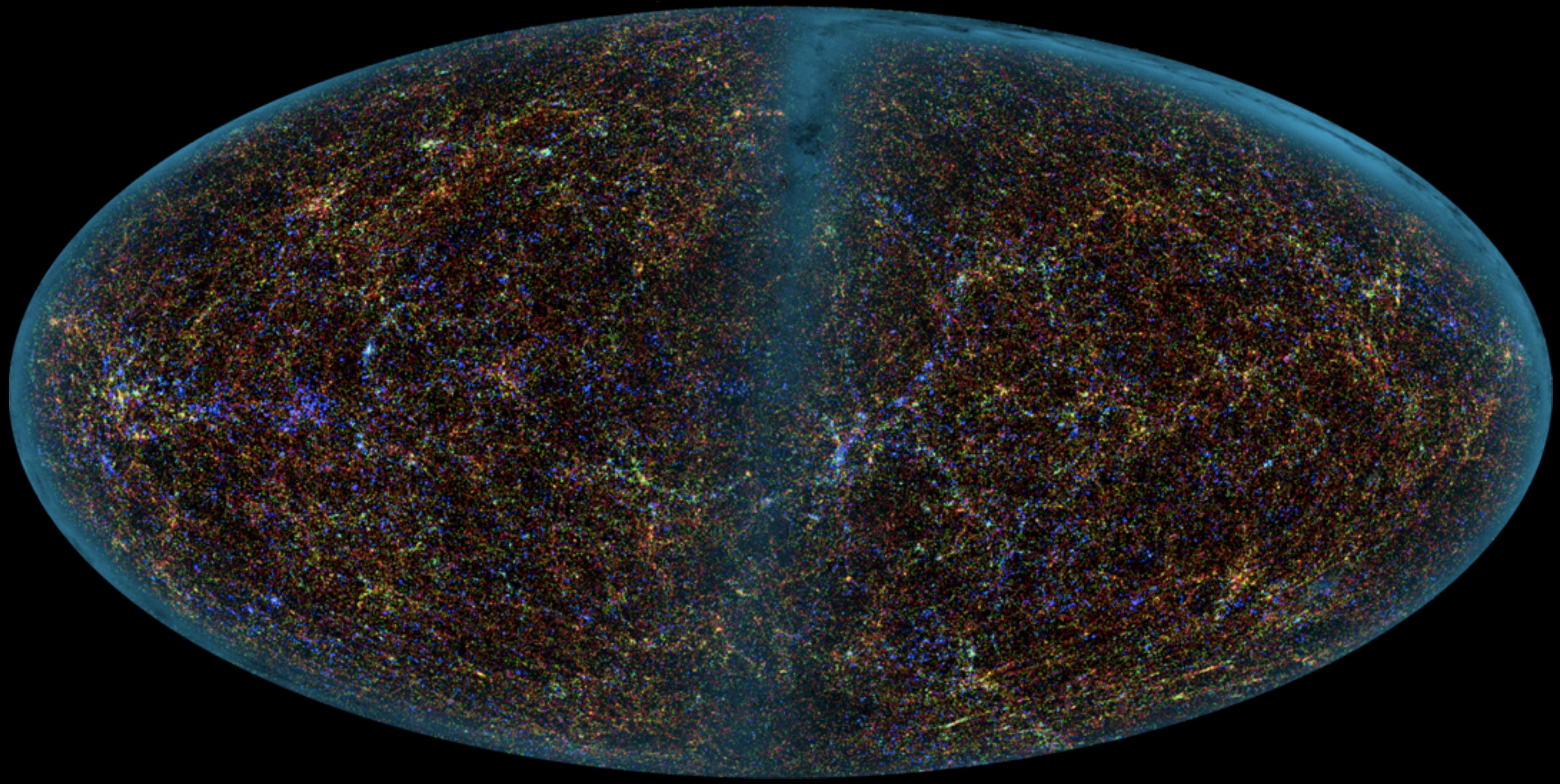
Cosmology

and Large Scale Structure



<u>Today</u>

Empirical Pillars
of the Hot Big Bang

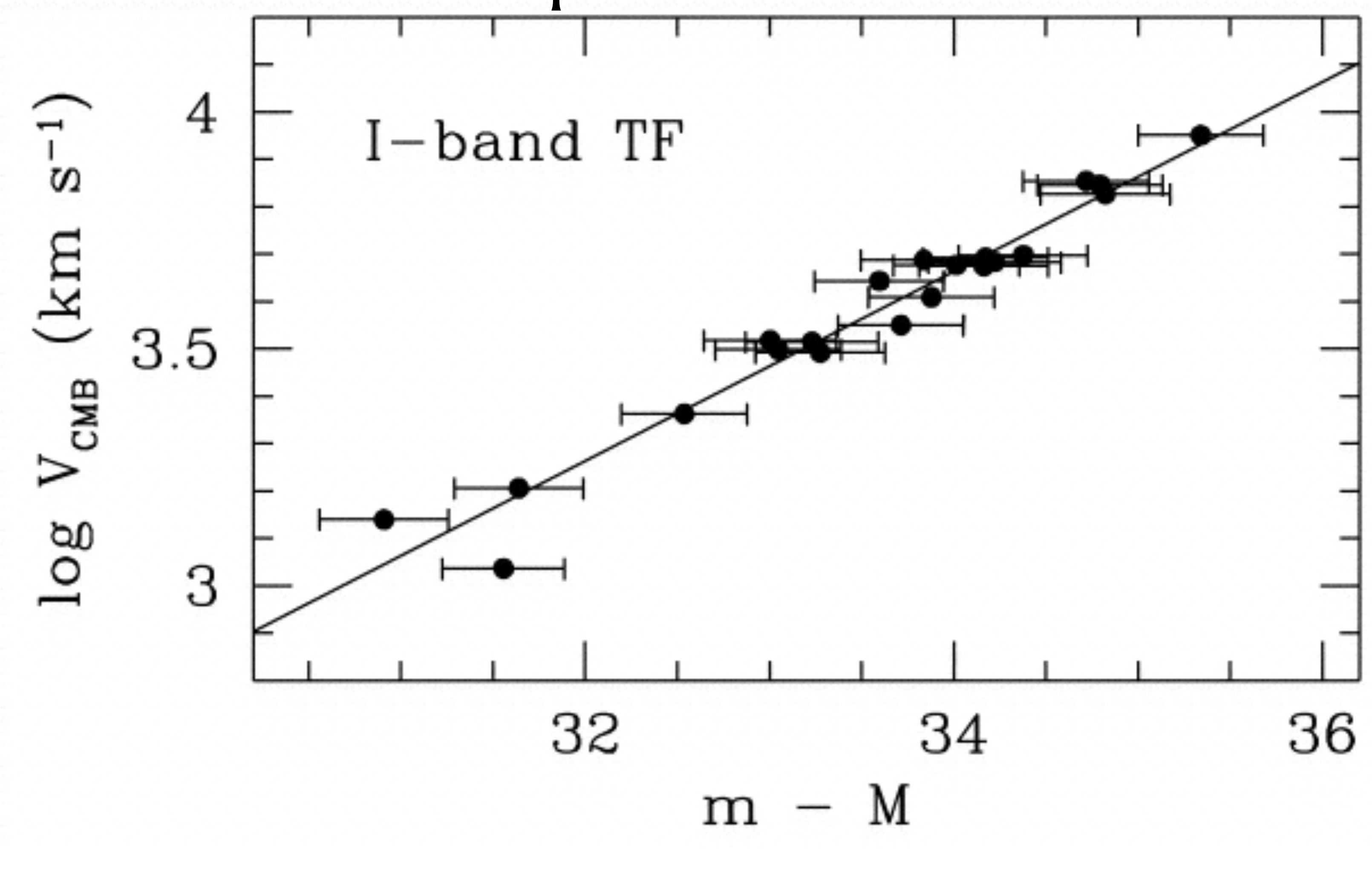
Nucleosynthesis

Expansion dynamics

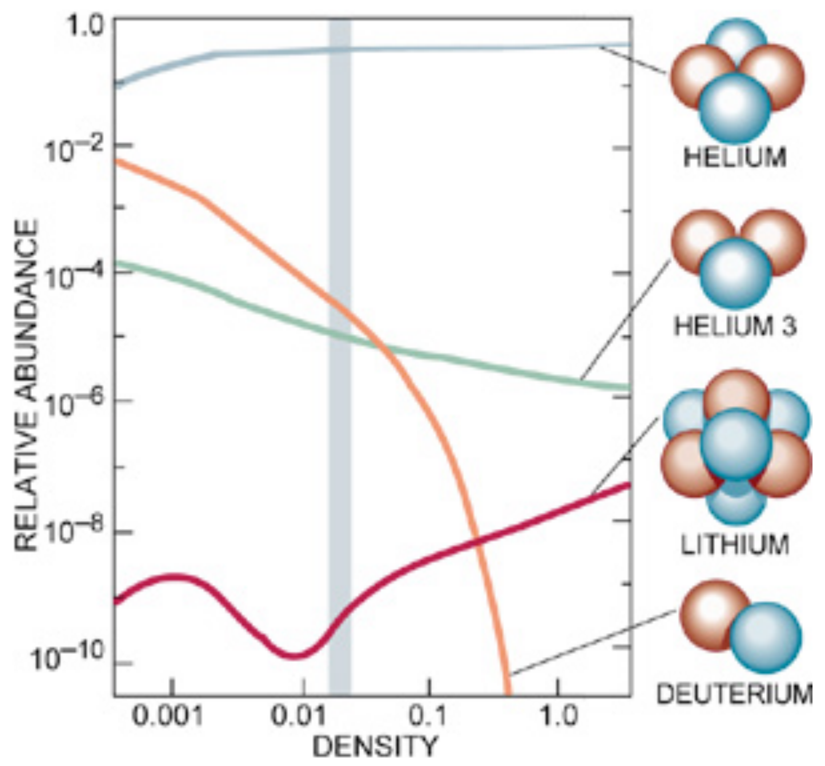
Empirical Pillars of the Hot Big Bang

1. Hubble Expansion — Hubble (1930)
2. Big Bang Nucleosynthesis (BBN) — Alpher, [Bethe], & Gamow (1948) — $\alpha\beta\gamma$ paper
3. Cosmic Microwave Background (CMB) — Penzias & Wilson; Peebles & Dicke (1965)

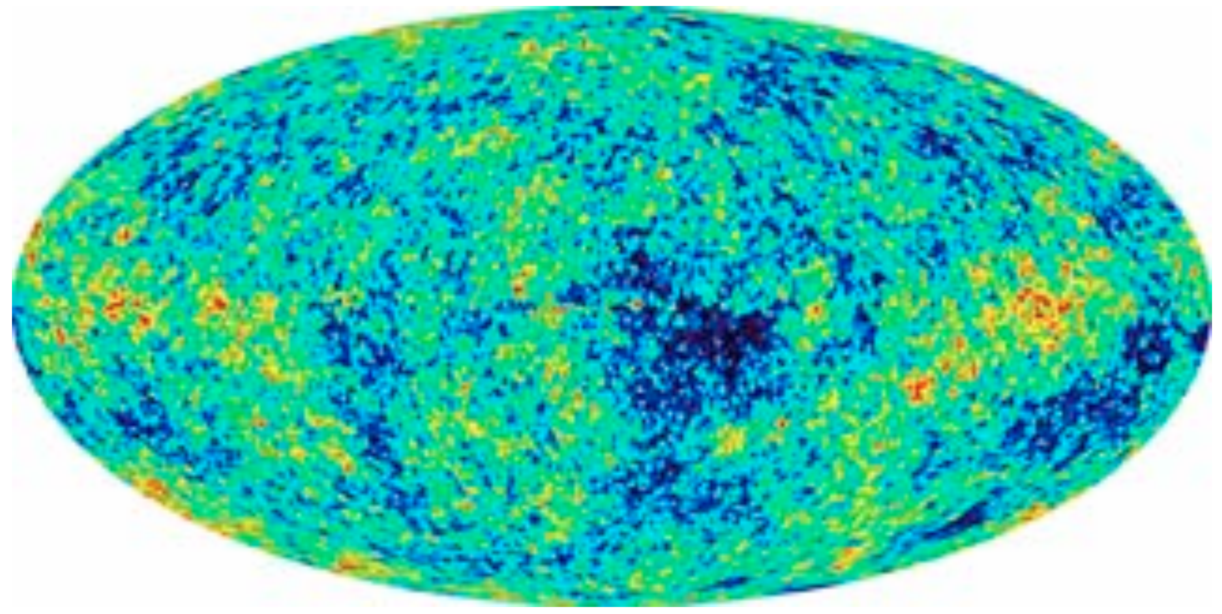
Hubble expansion



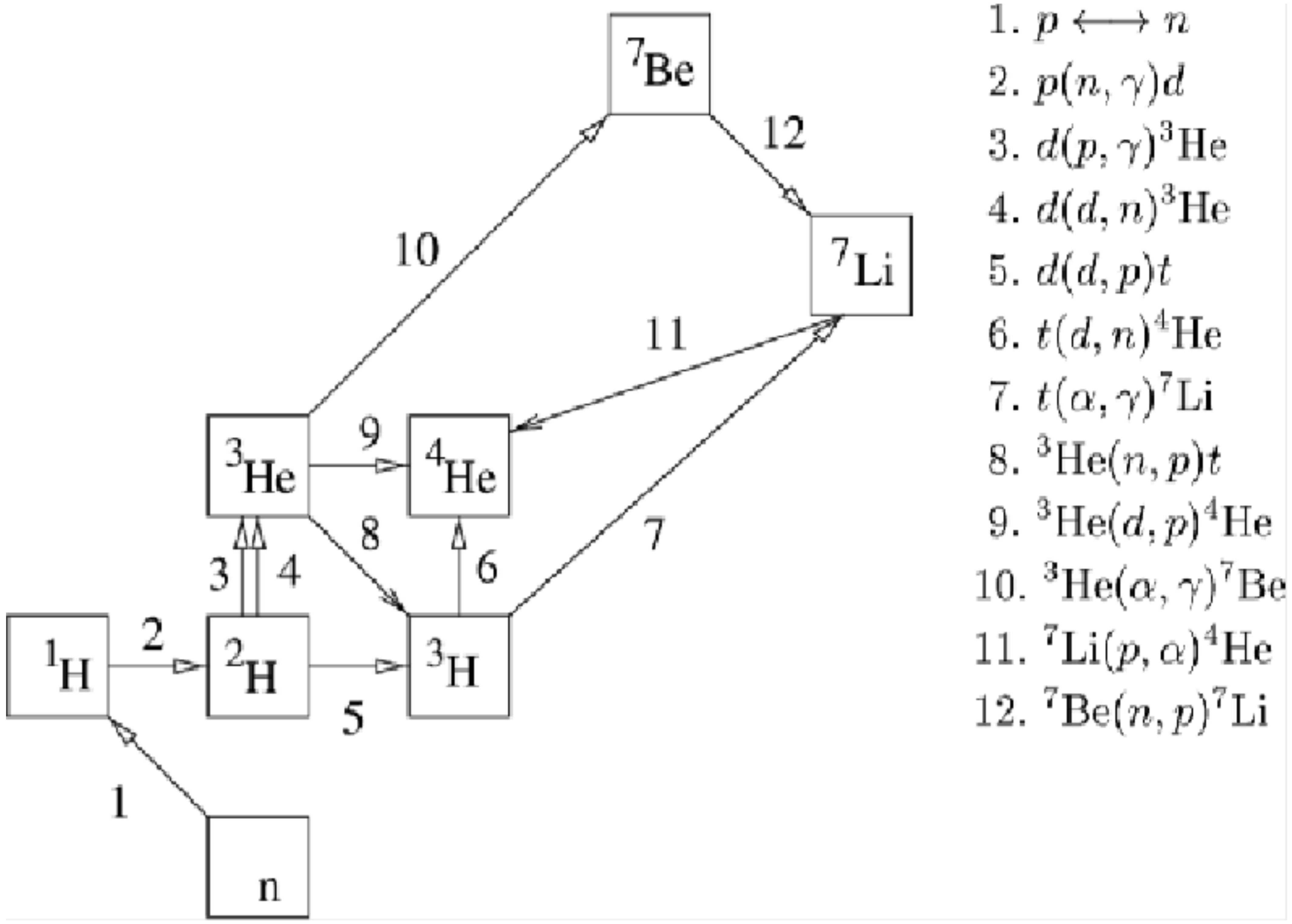
BBN
t ~ 3 minutes



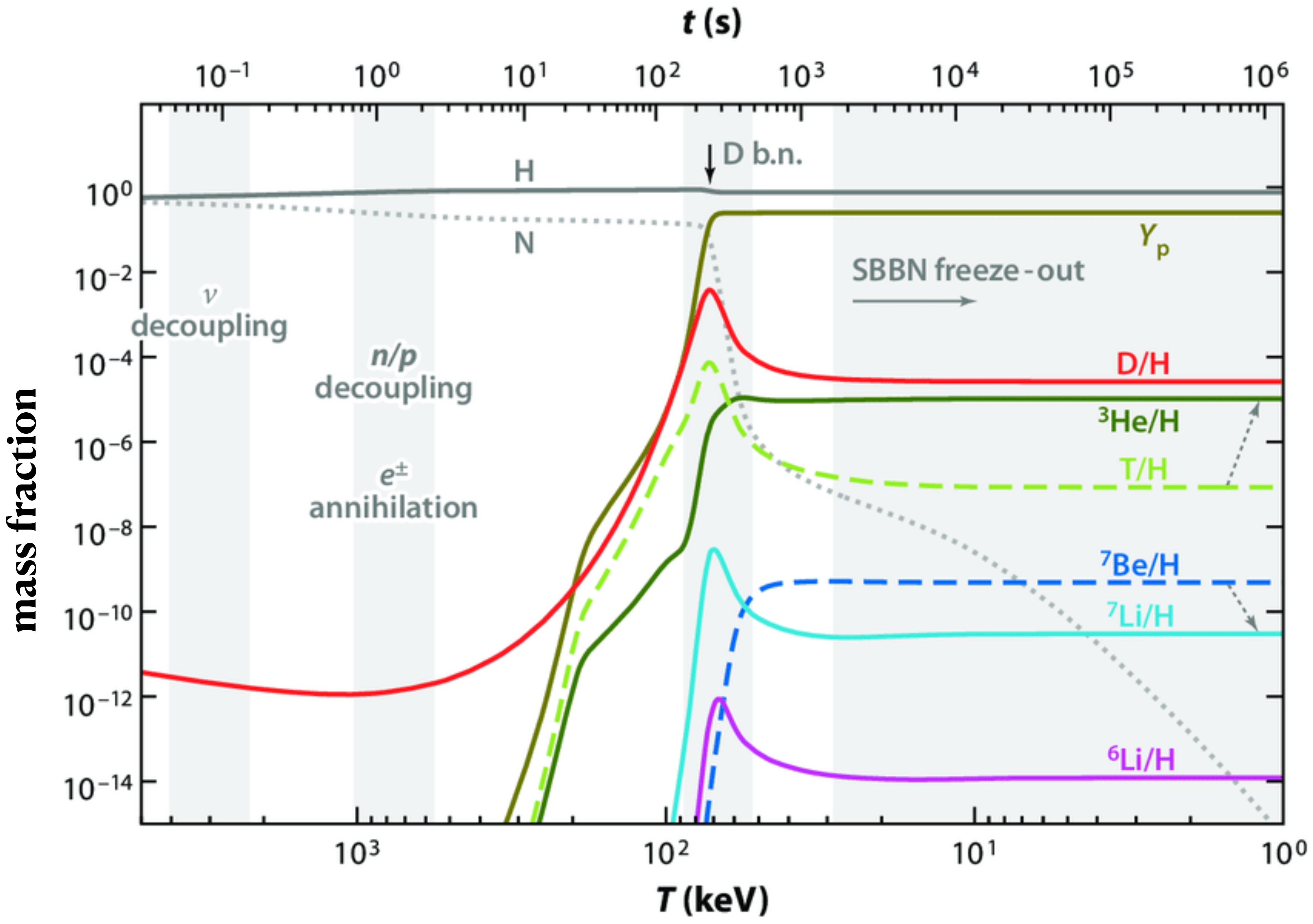
CMB
z = 1090
t = 380,000 yr



Big Bang Nucleosynthesis occurs during the radiation dominated era



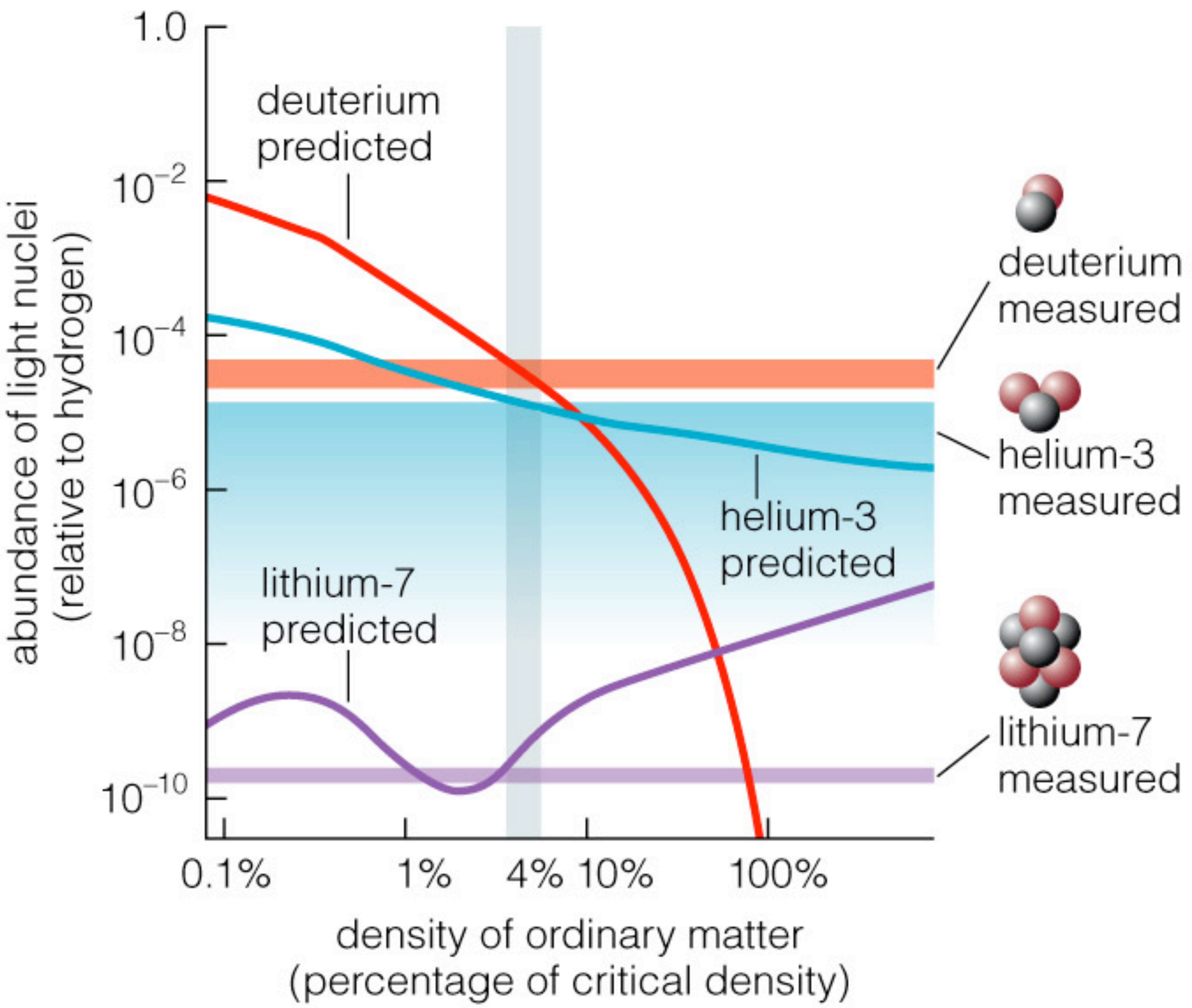
$$a(t) \propto t^{1/2}$$



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

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

$\tau_N = 10.2$ minutes



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

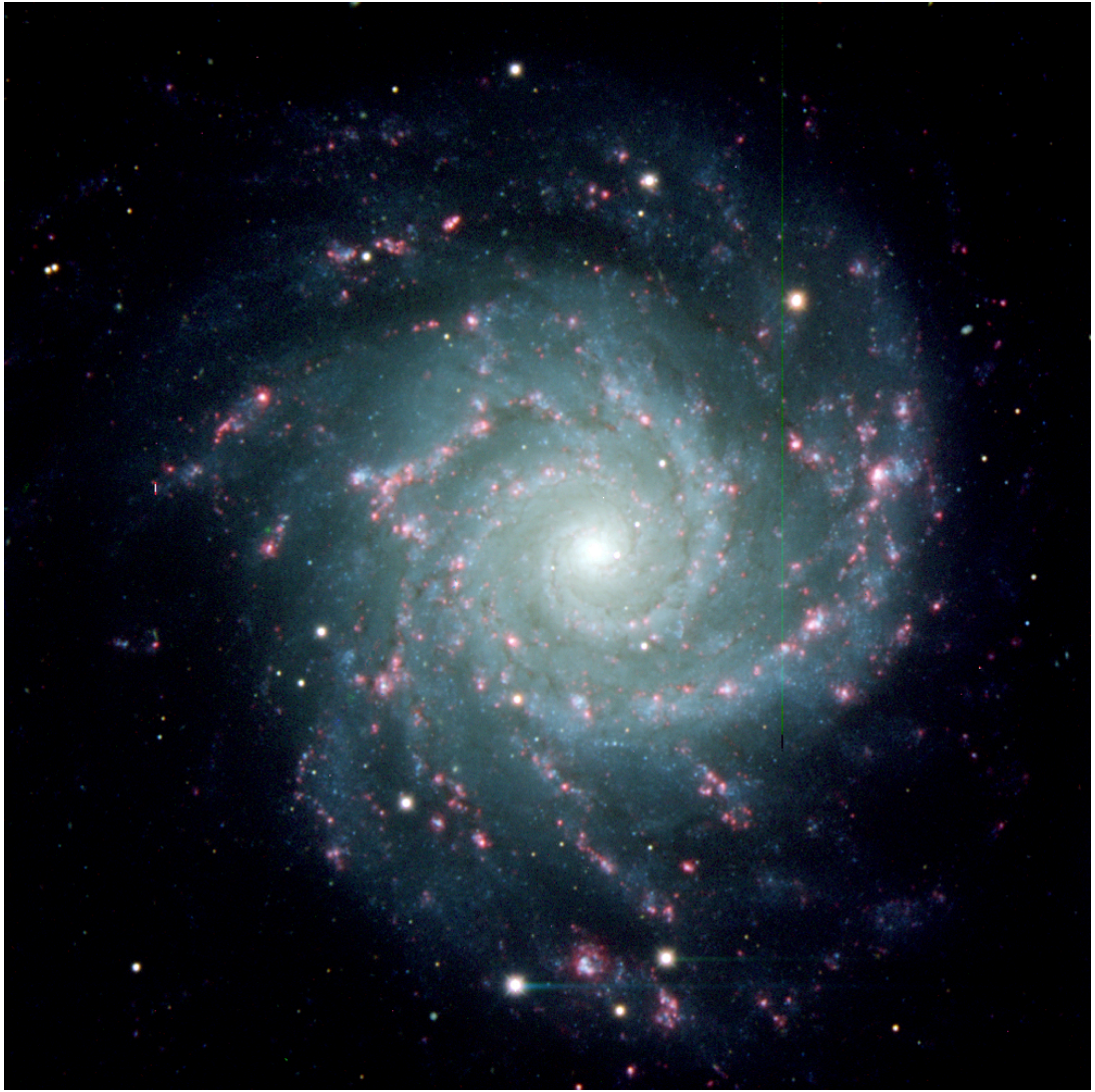
$$\eta = \frac{\Omega_b}{\Omega_r} = \frac{n_b}{n_\gamma} \approx \frac{1}{2 \times 10^9}$$

Helium

NGC 628

Helium is measured in the HII regions of nearby galaxies.

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

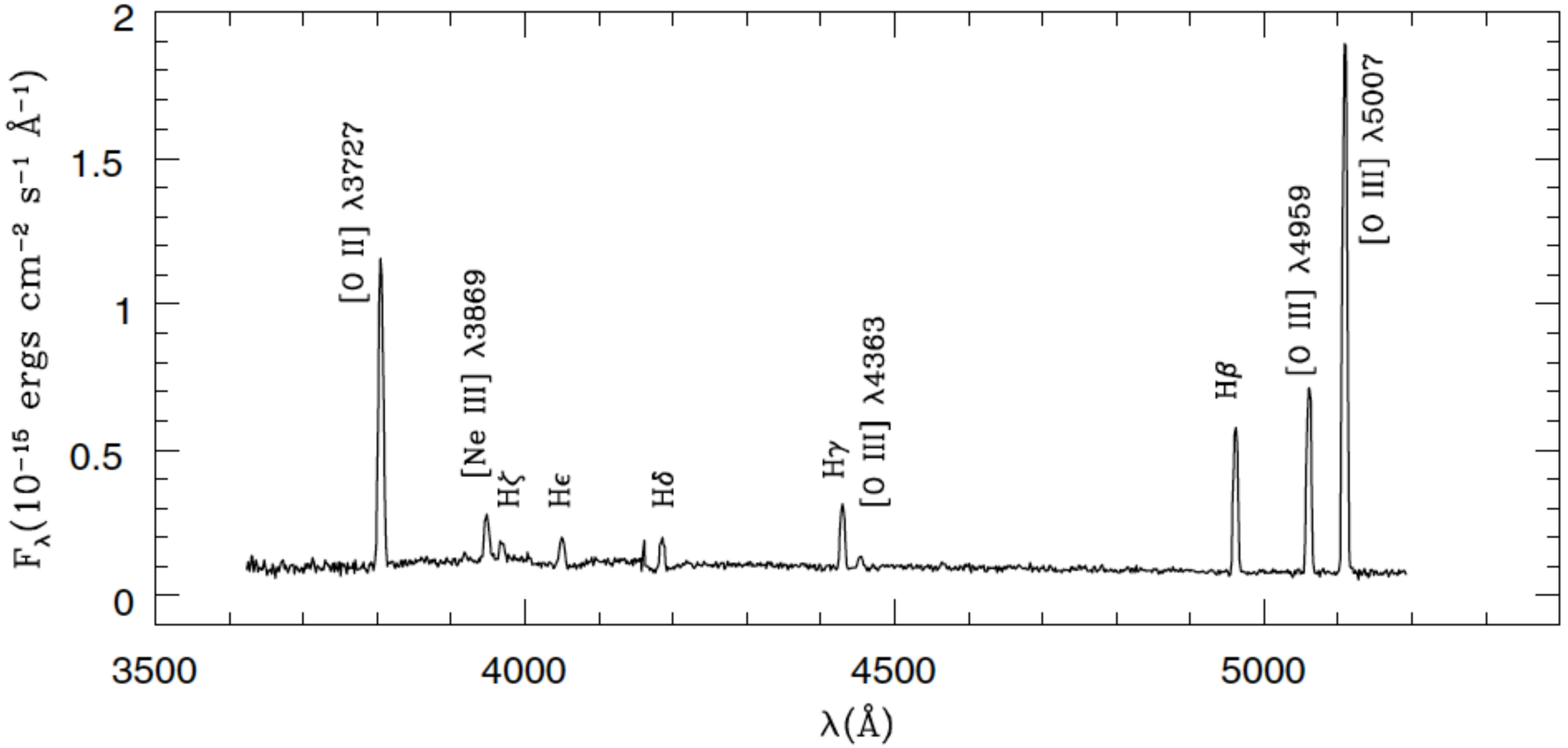


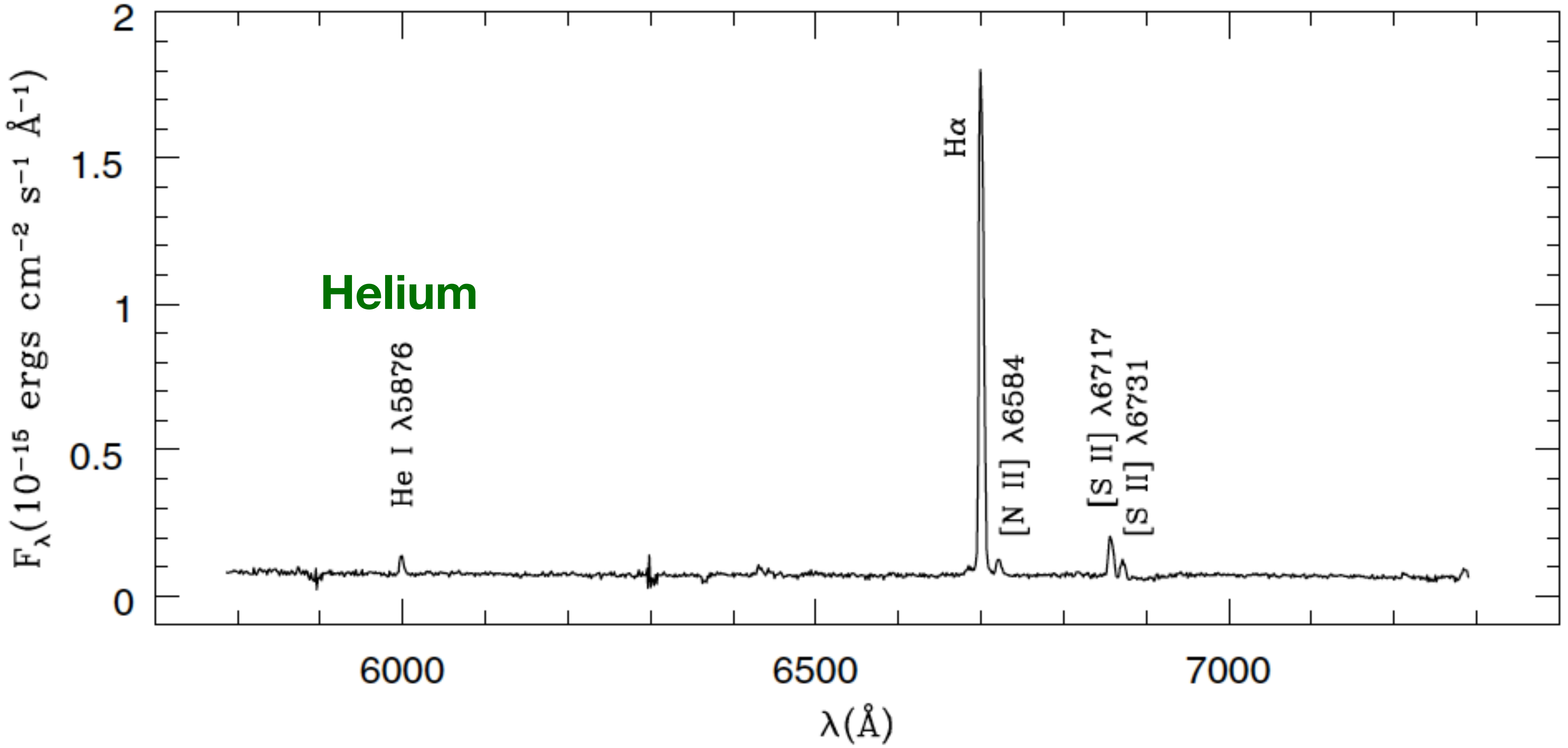
Helium

UGC 12695

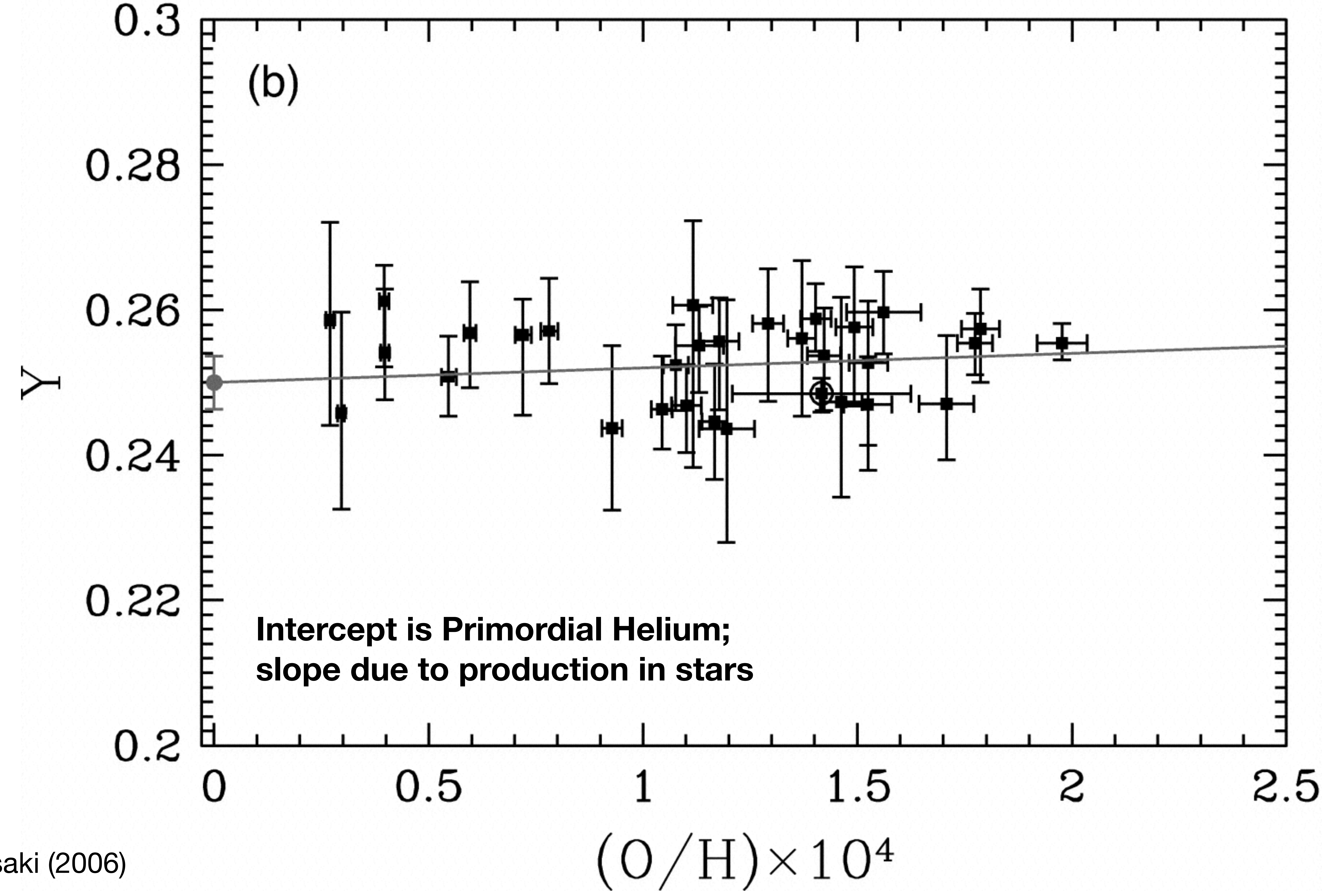
Spectrum of HII region S1(2)

Helium is measured in the HII regions of nearby galaxies.





Helium



Fukugita & Kawasaki (2006)

$$Y_P = 0.25 \pm 0.01$$

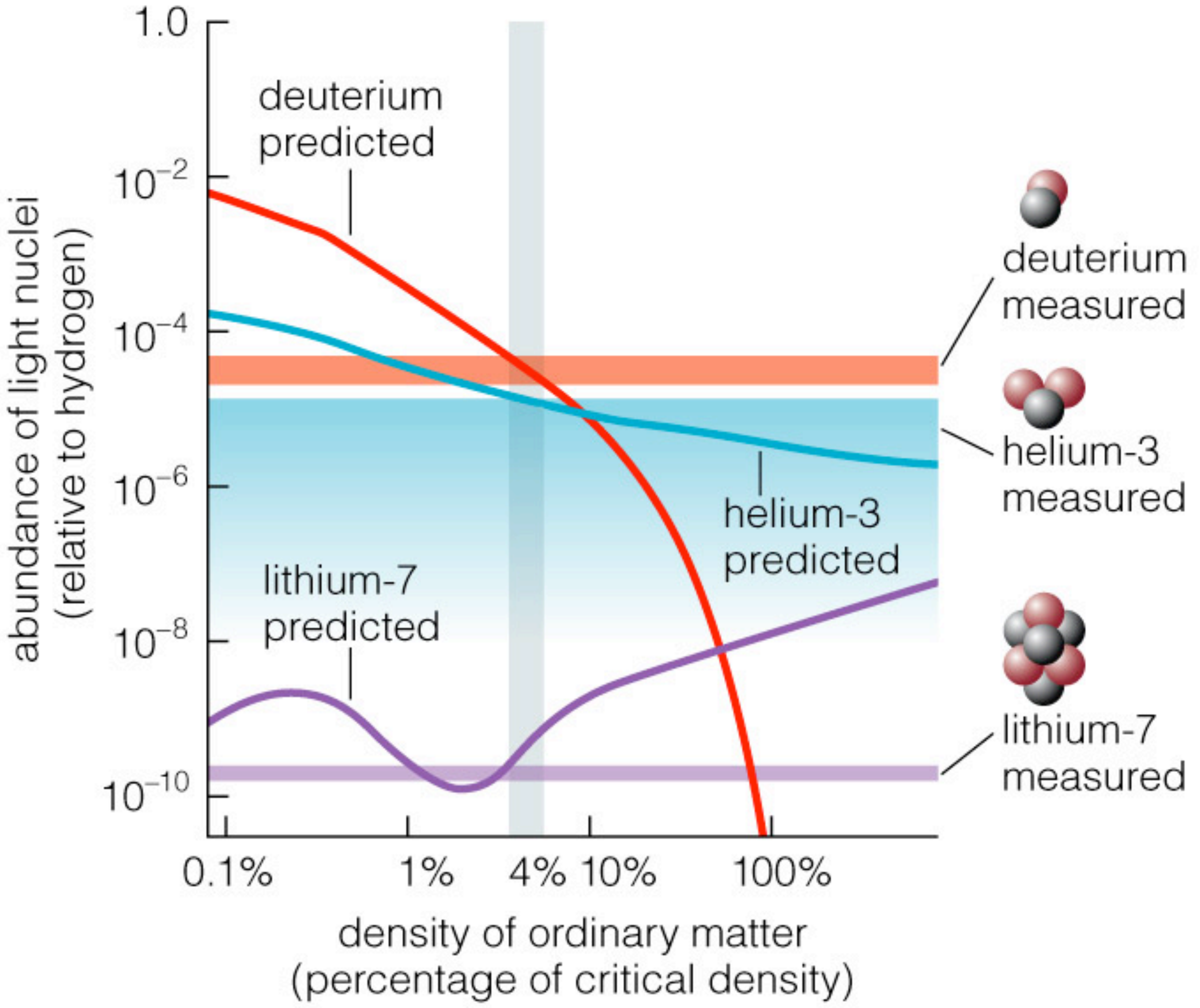
with lots of debate over the 3rd place of decimals!

Helium

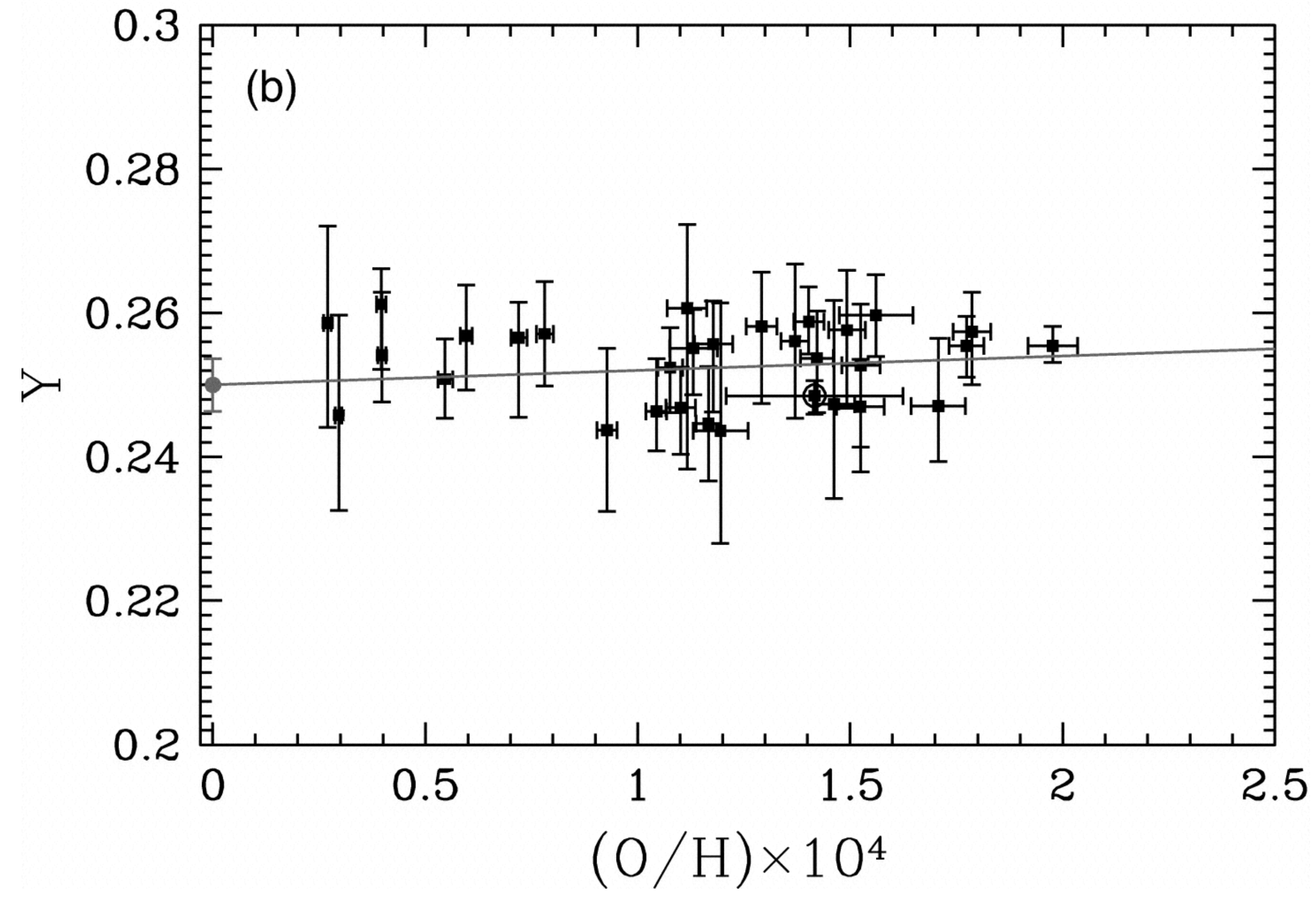
Helium is a poor baryometer because it varies little with the baryon density.

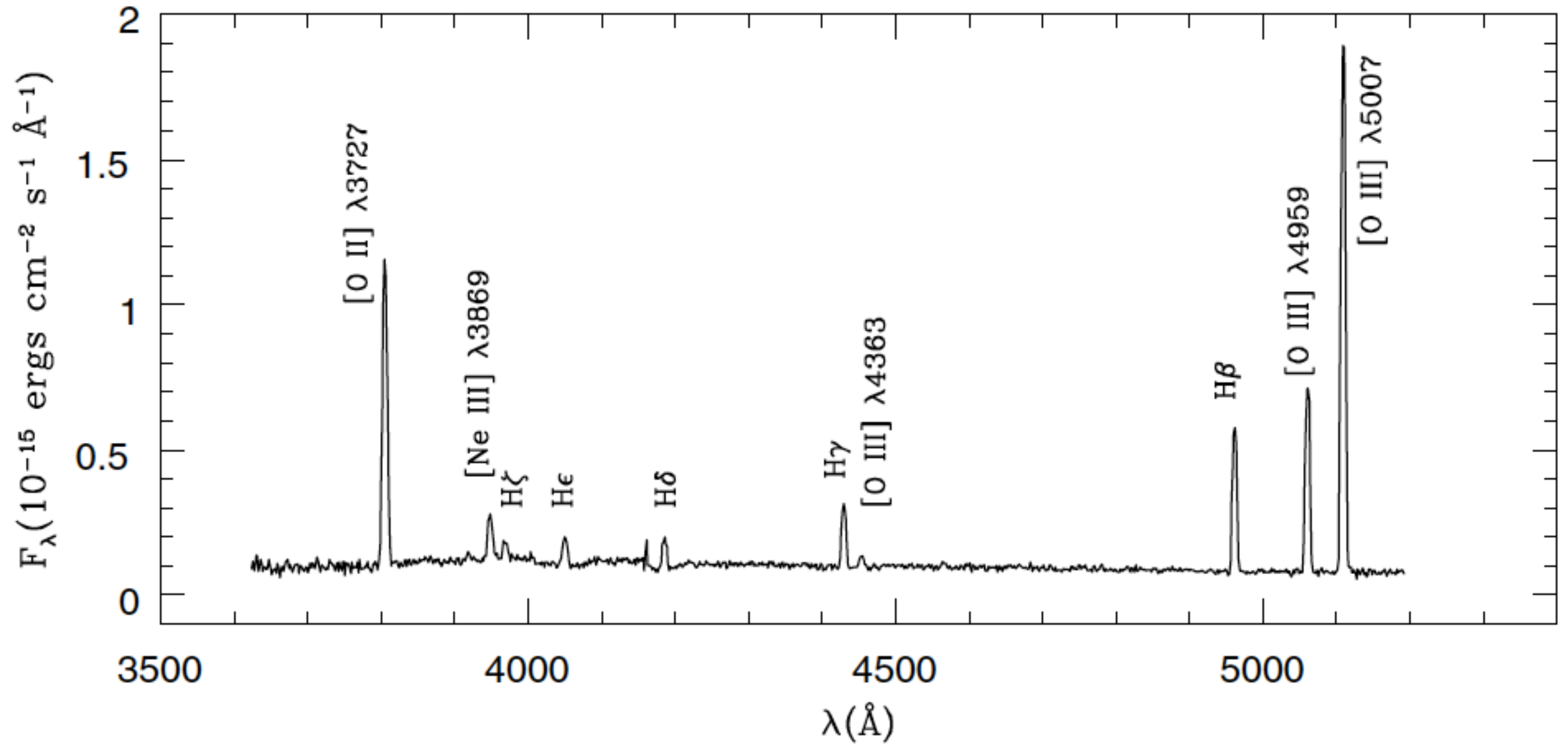
However, it is a strong corroboration of BBN that the abundance is that required.

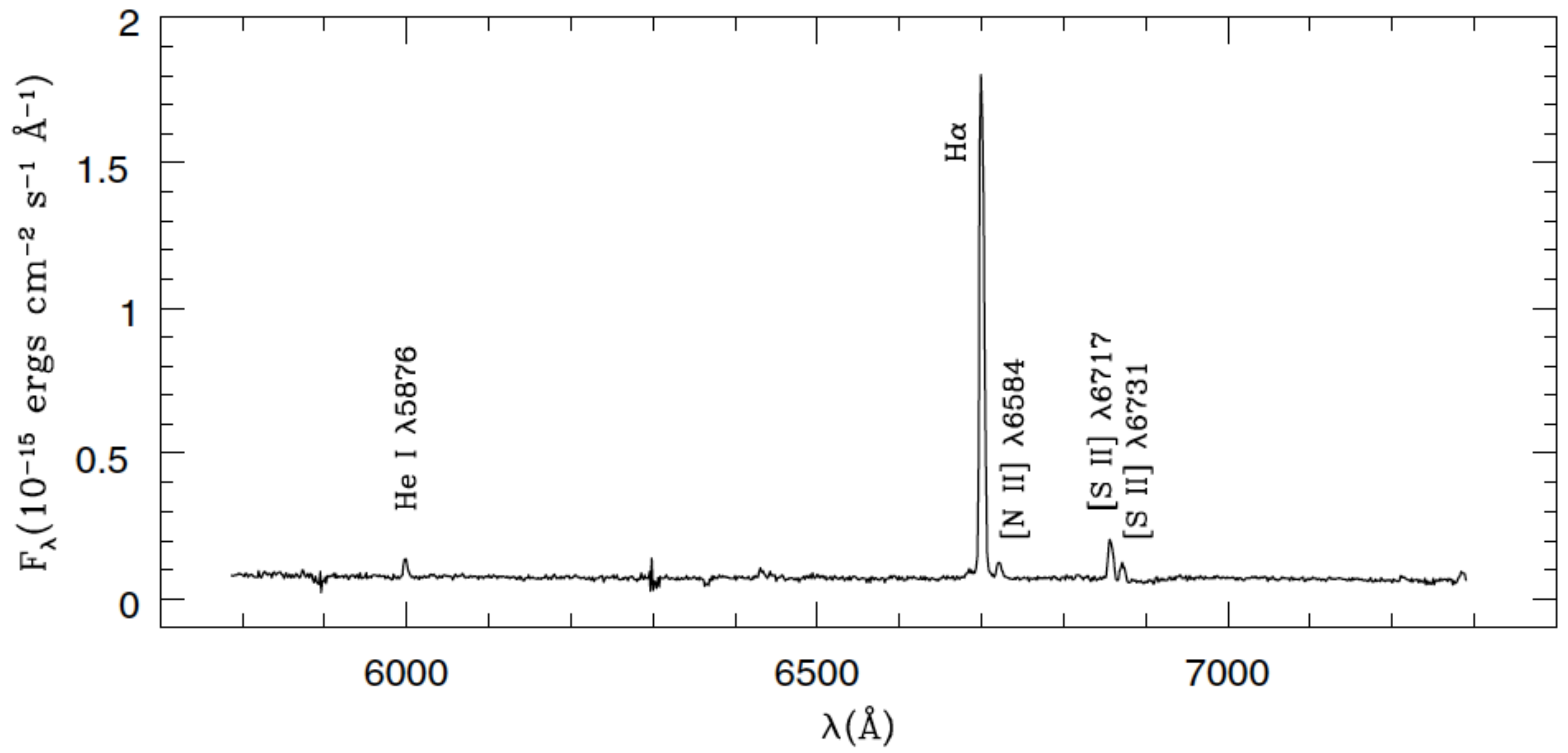
Observationally, it is challenging to measure helium lines with great accuracy, and interpret their abundance as the percent level. It is also challenging to differentiate between primordial helium and stellar helium production



Ω_b





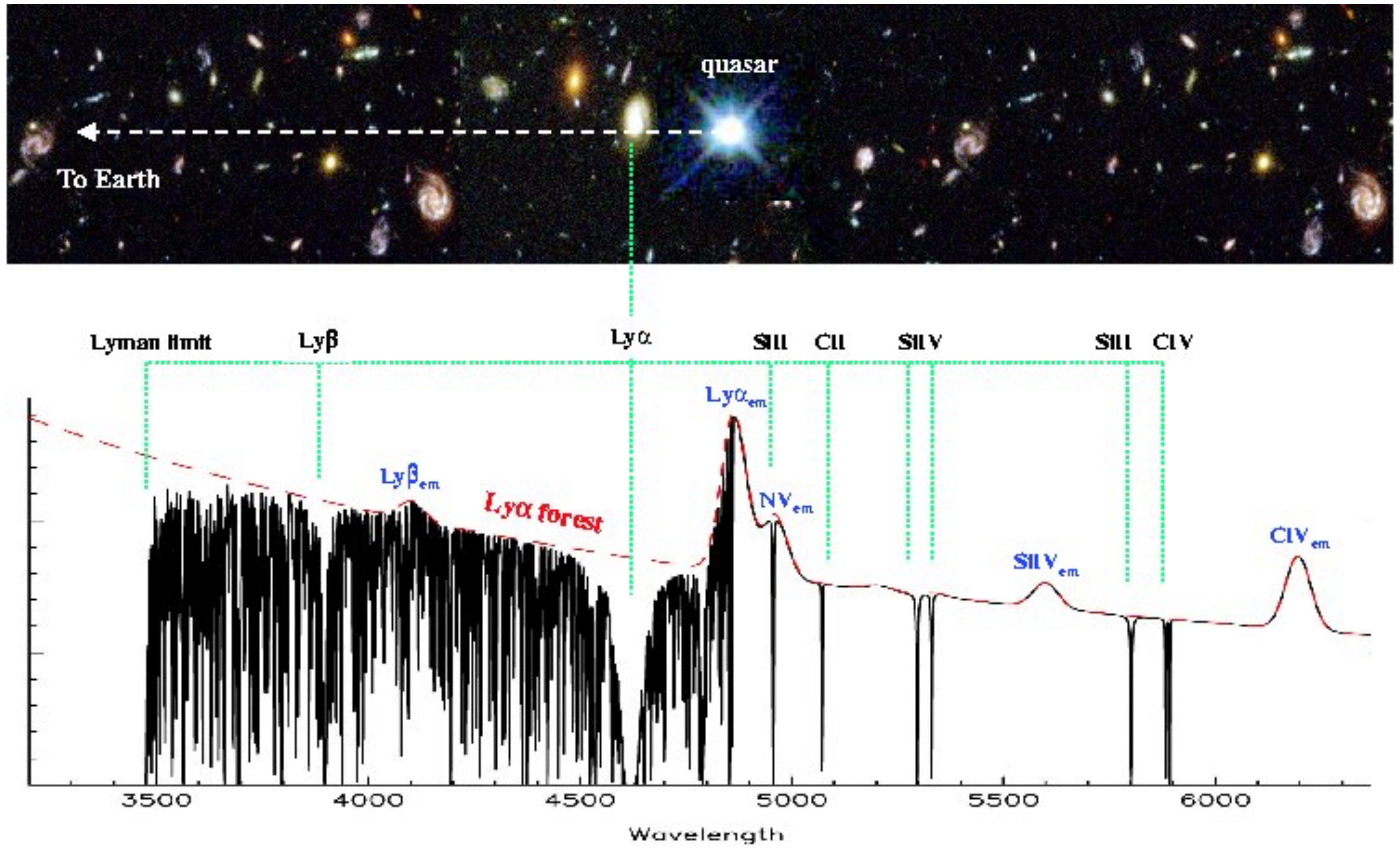


$$Y_P = 0.25 \pm 0.01$$

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

Deuterium

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



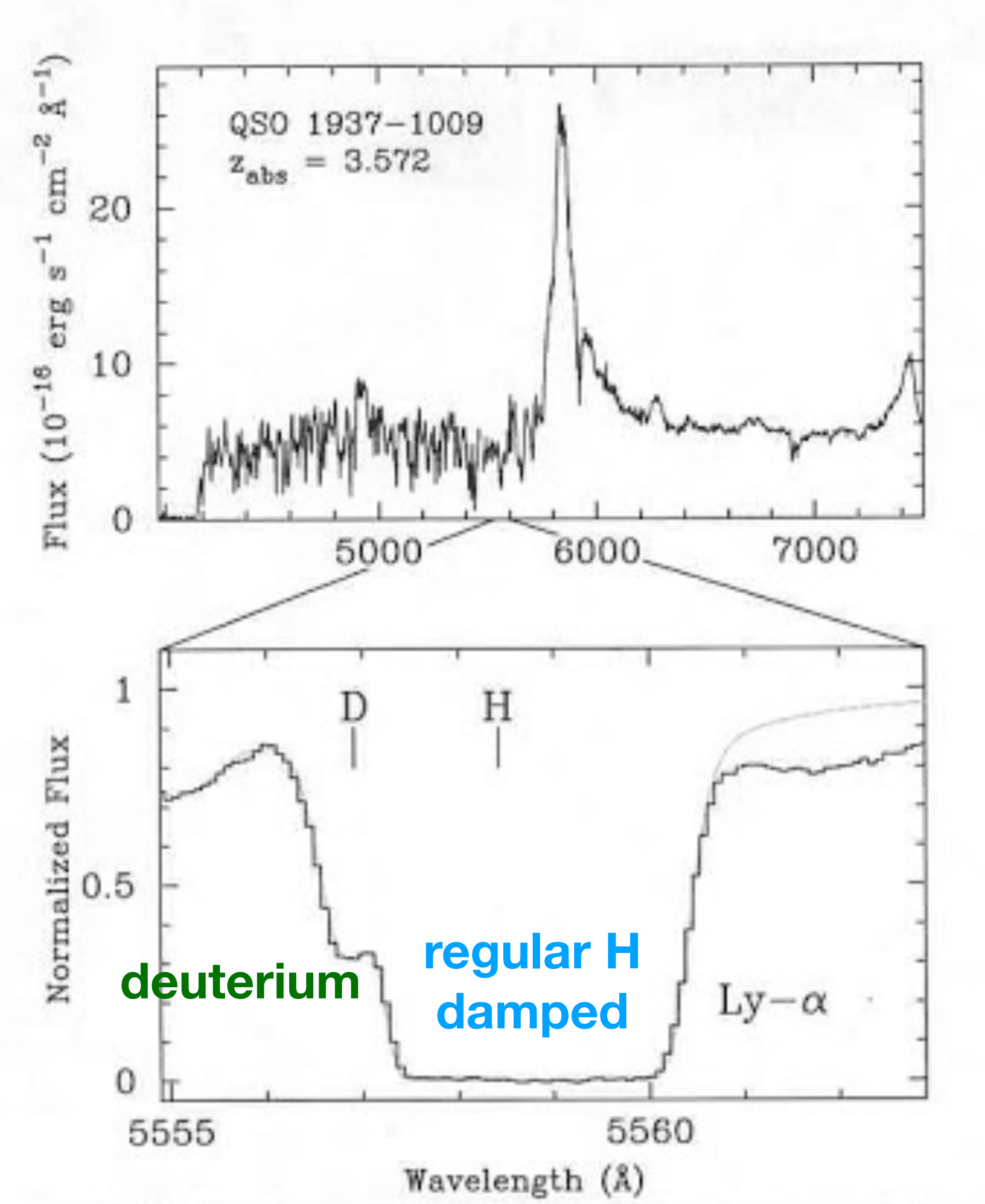


FIG. 3. Spectrum of Q1937-1009; blueward of the characteristic Lyman-α emission line of the quasar is the "forest" of Lyman-α absorption due to the hundreds of intervening gas clouds. The lower panel shows a blowup of the region around the deuterium detection, a cloud at redshift $z = 3.572$, and the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

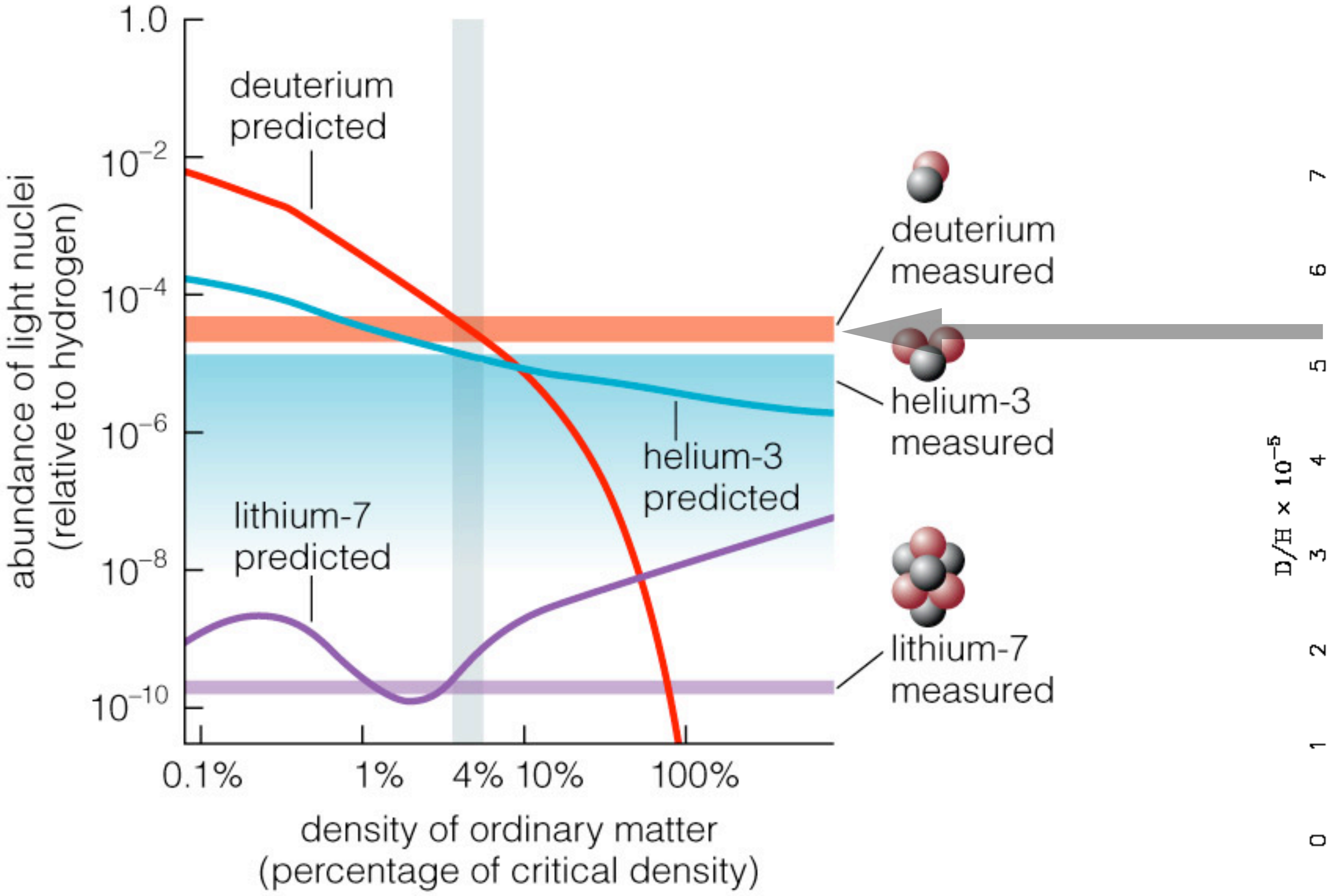
Deuterium

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

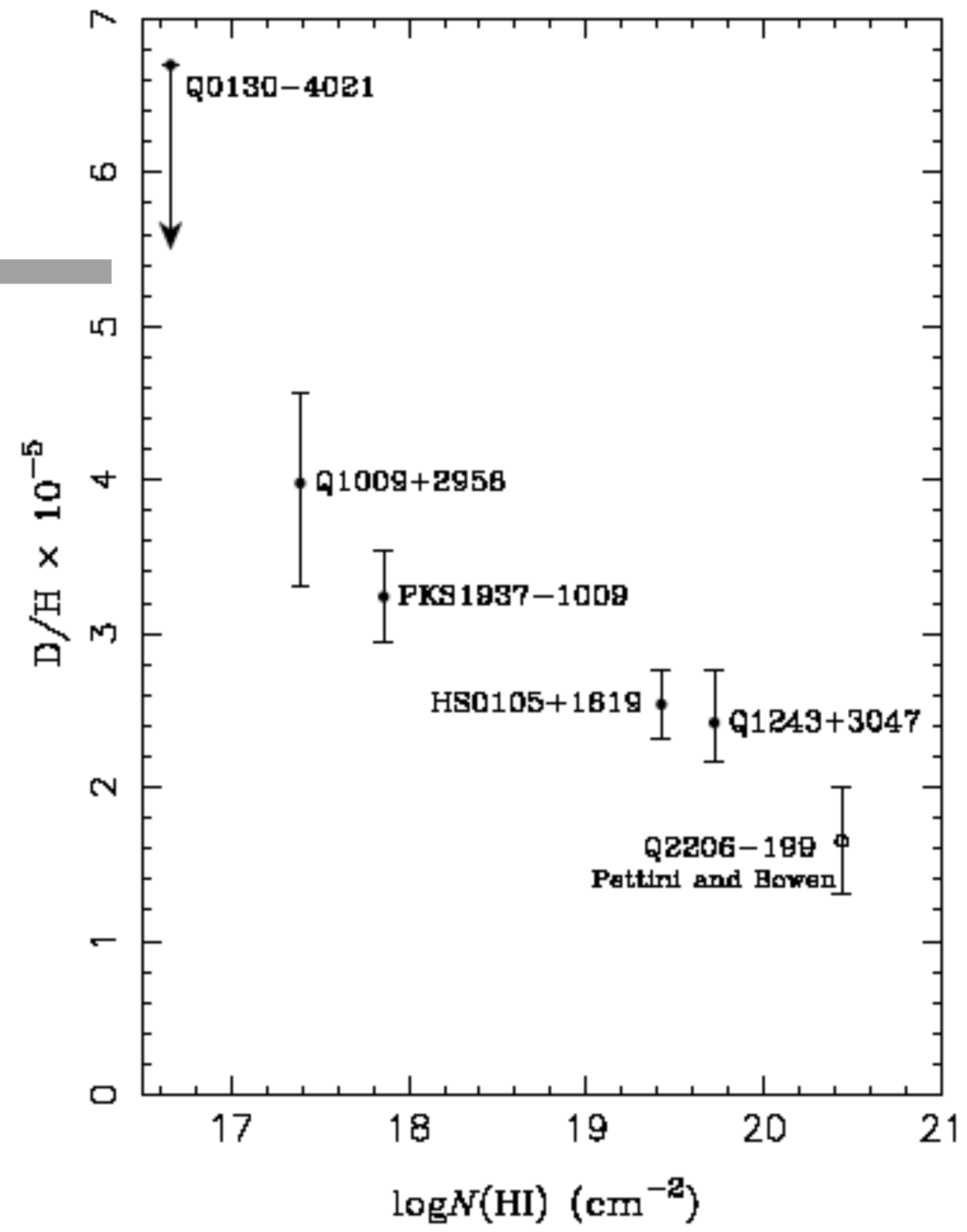
Deuterium is a good baryometer because D/H varies sensitively with the baryon density.

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.



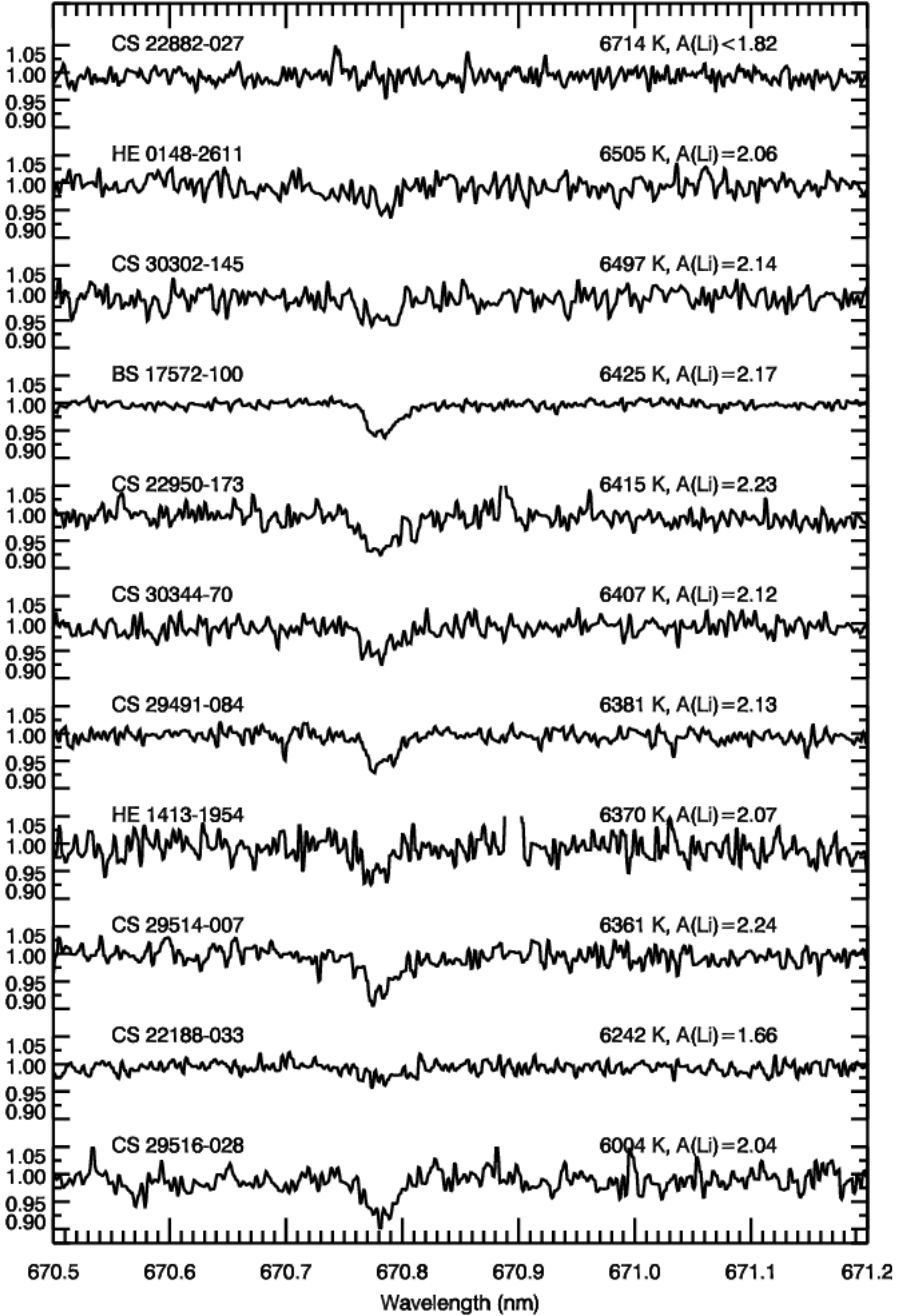
Ω_b



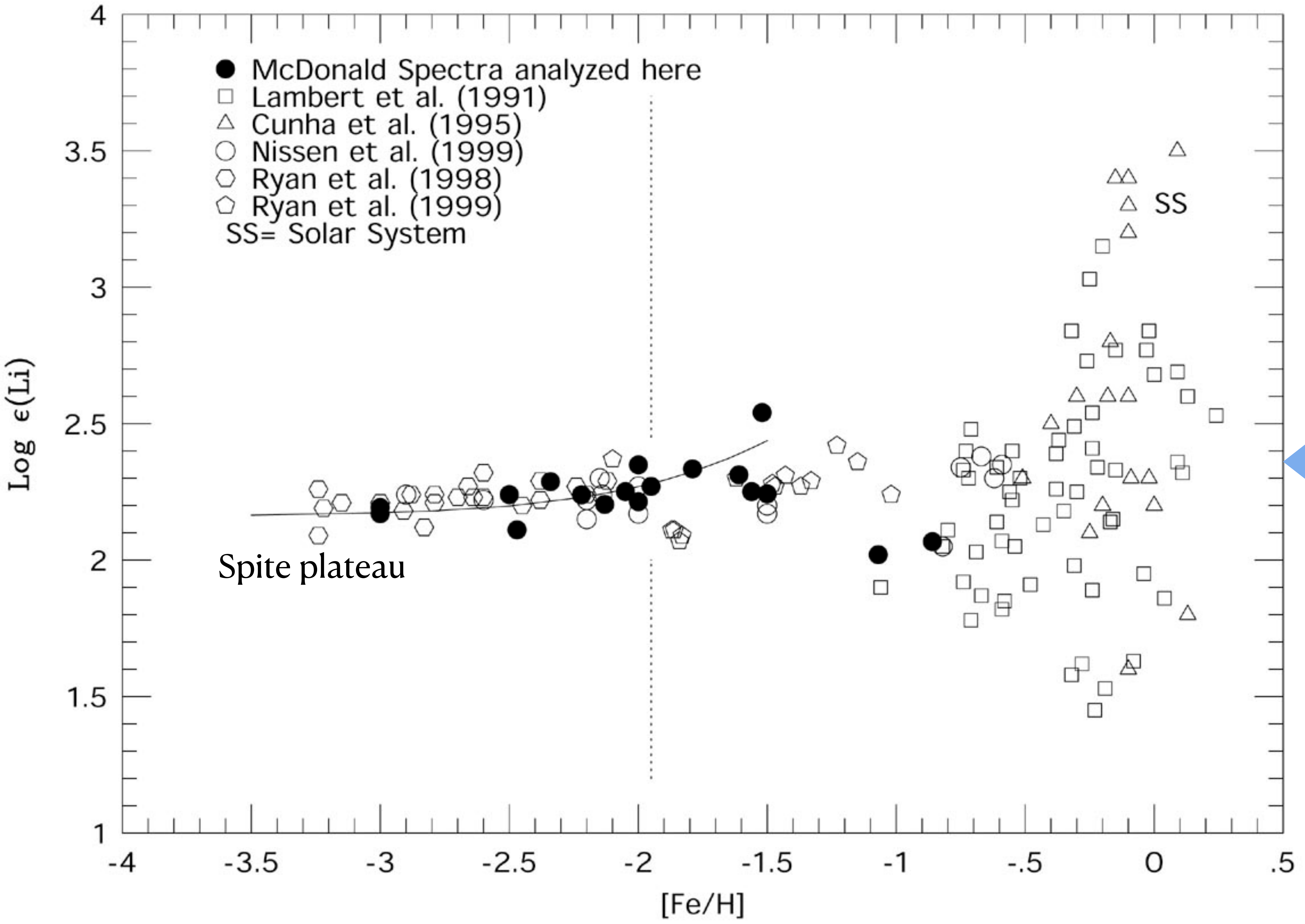
Lithium

Stellar spectra
showing Lithium absorption

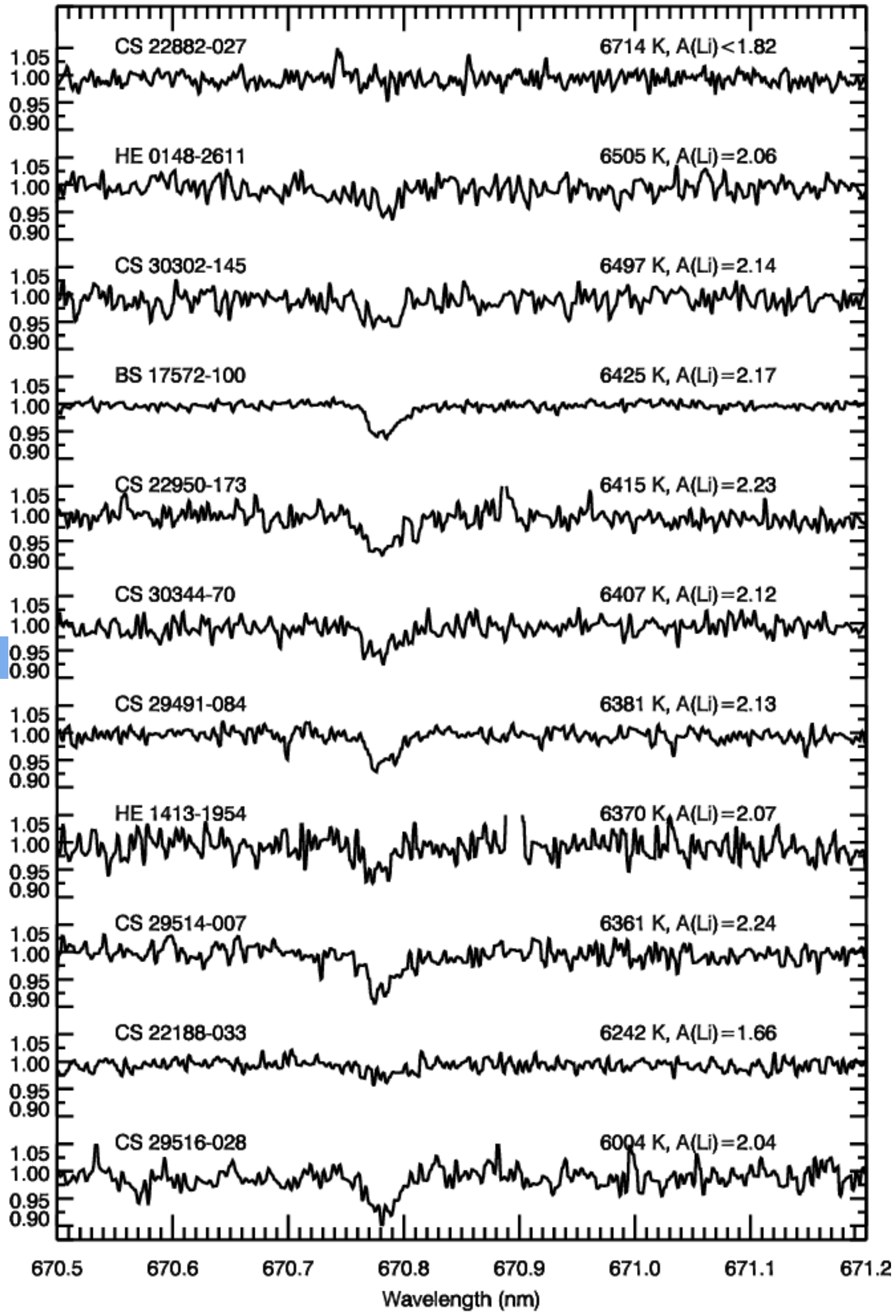
Lithium is measured in old, metal poor stars for which there is hope that the surface abundance is little altered from the primordial abundance - the Spite plateau.



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

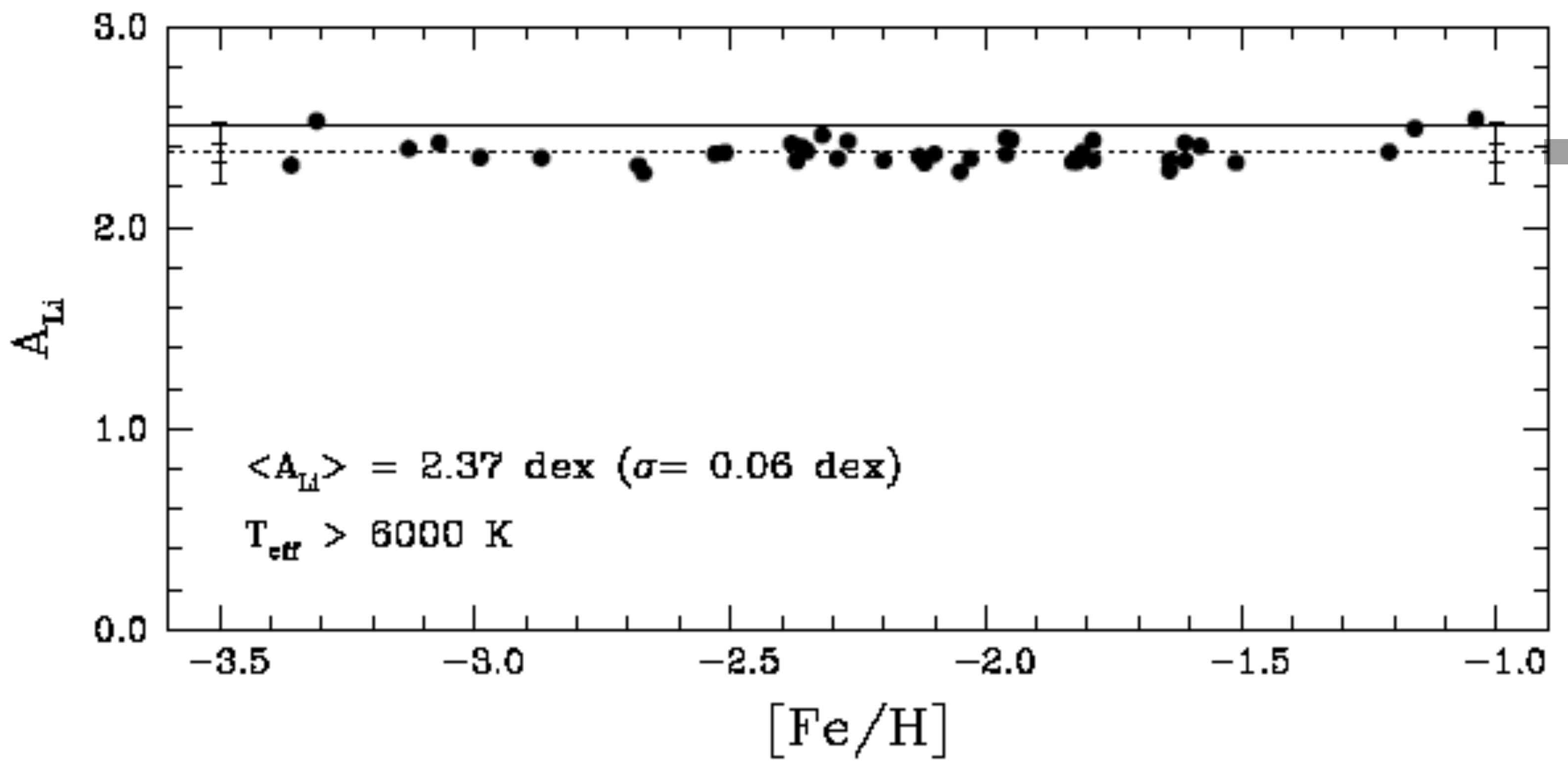


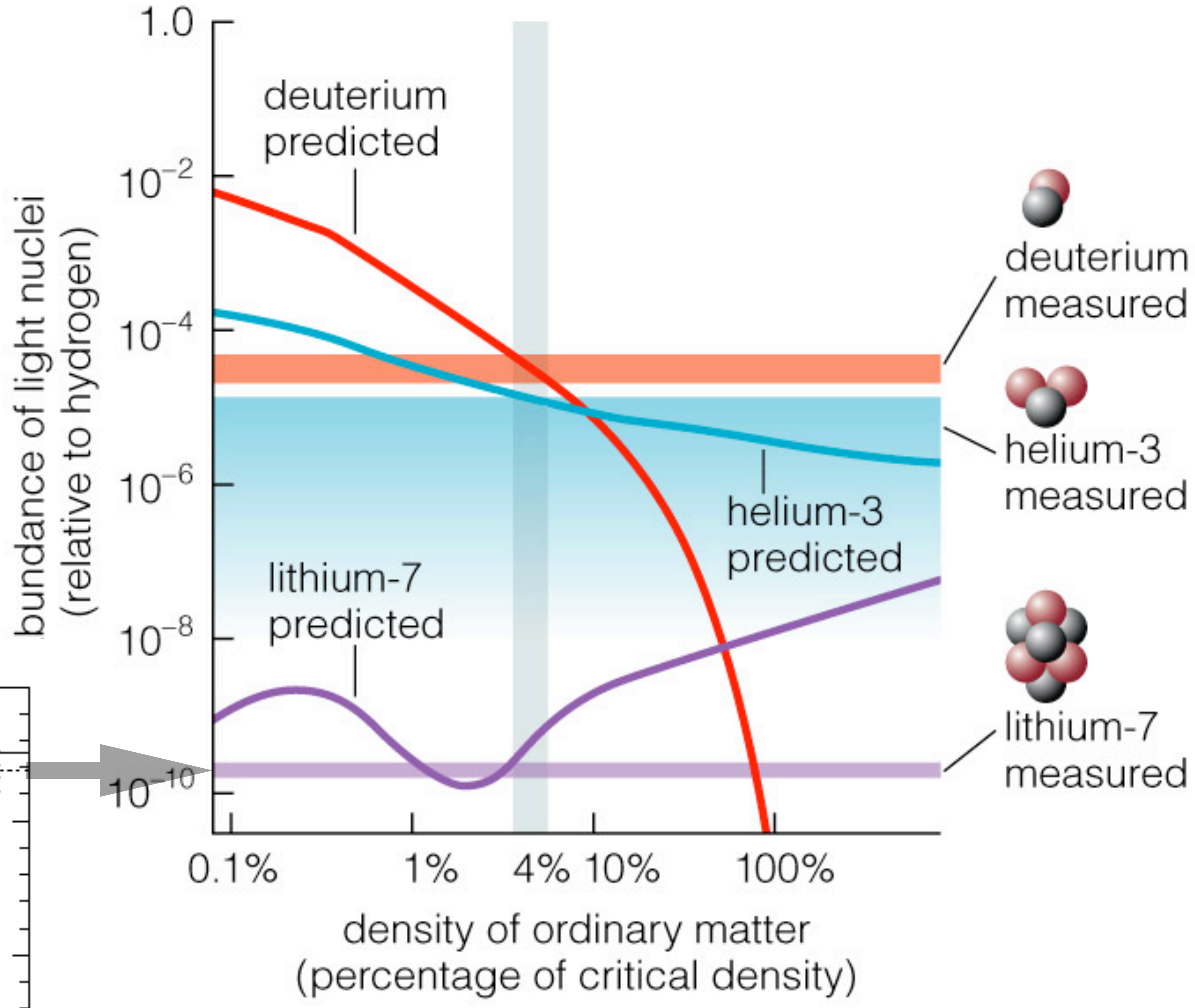
CS 22882-027
6714 K, A(Li)<1.82
HE 0148-2611
6505 K, A(Li)=2.06
CS 30302-145
6497 K, A(Li)=2.14
BS 17572-100
6425 K, A(Li)=2.17
CS 22950-173
6415 K, A(Li)=2.23
CS 30344-70
6407 K, A(Li)=2.12
CS 29491-084
6381 K, A(Li)=2.13
HE 1413-1954
6370 K, A(Li)=2.07
CS 29514-007
6361 K, A(Li)=2.24
CS 22188-033
6242 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.



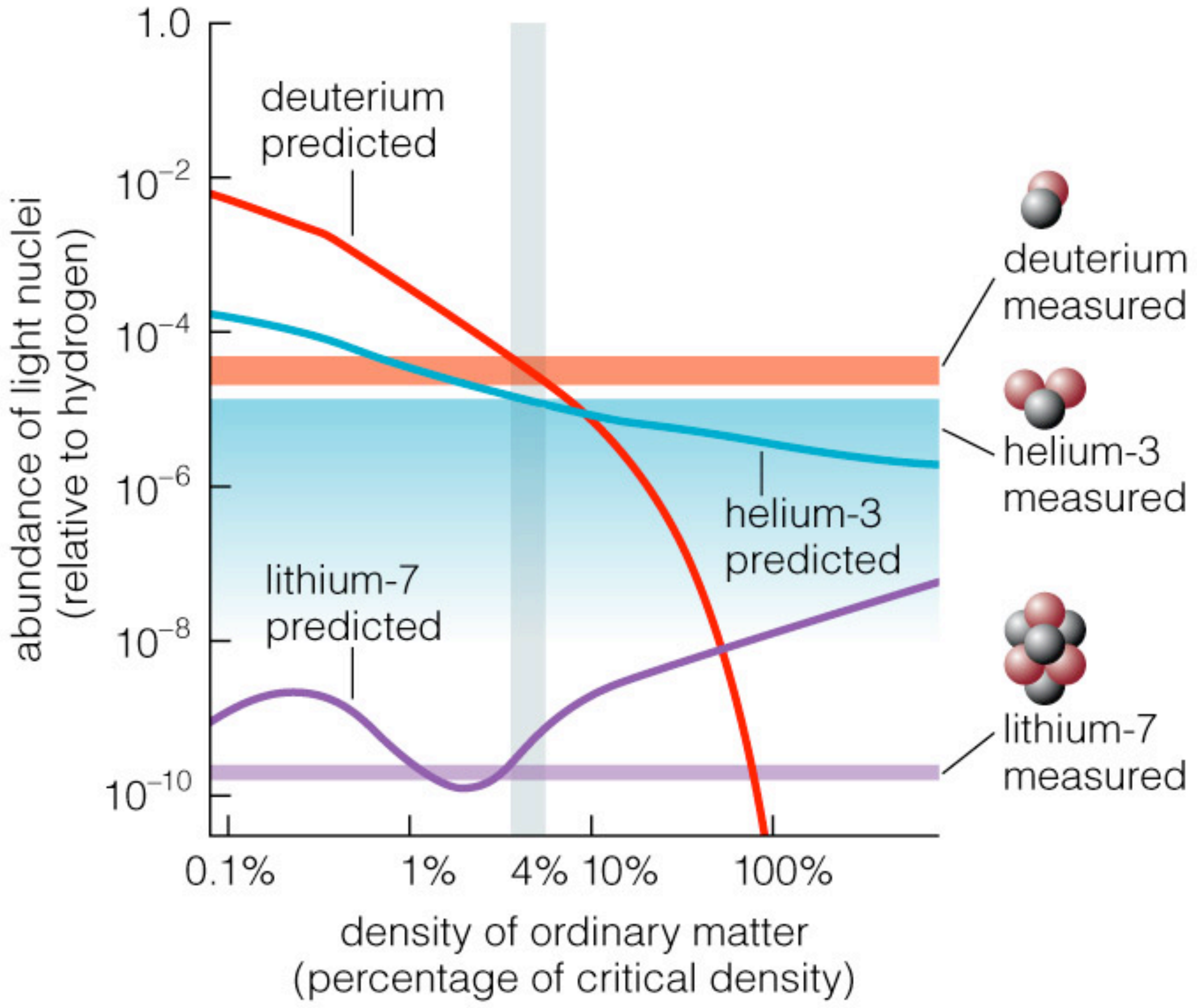


Ω_b

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 elements 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

[$\omega_b = \Omega_b h^2 = 0.019$
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

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

take error bars with a grain of salt!

The Astrophysical Journal, 376:51–69, 1991 July 20

BBN already old news in 1991

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 on 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

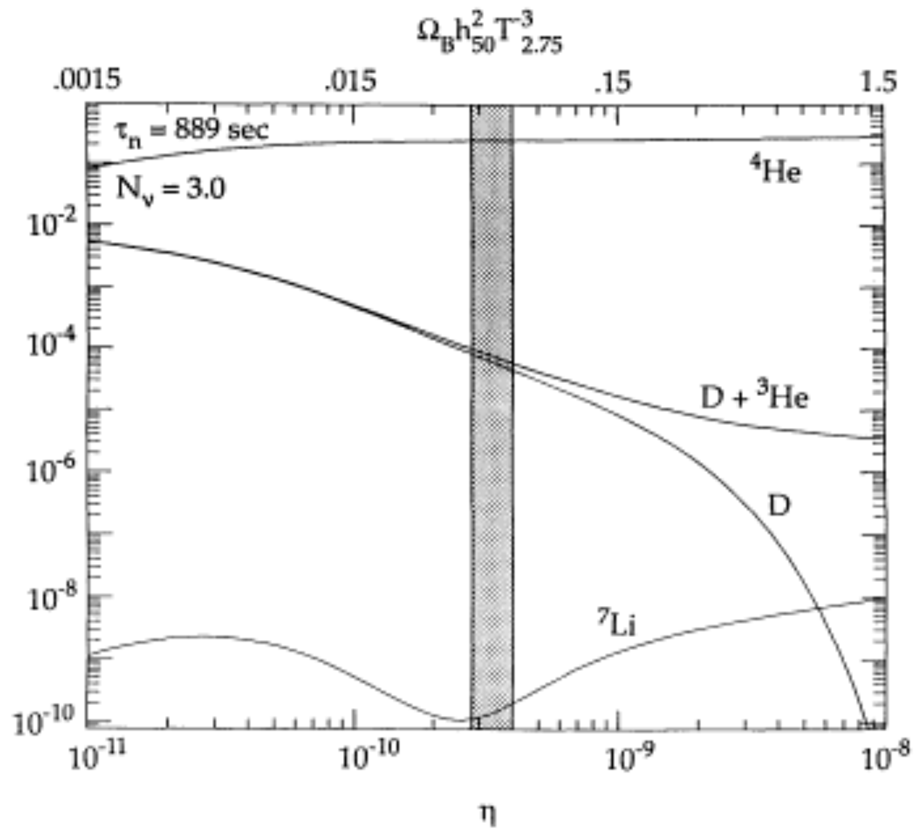


FIG. 12.—Predicted abundances (by number) of D, D + ^{3}He, and ^{7}Li, and the ^{4}He mass fraction as a function of η for $N_\nu = 3$ and $\tau_n = 889$ s for $0.1 \le \eta_{10} \le 100$. The vertical band delimits the range of η consistent with the observations.

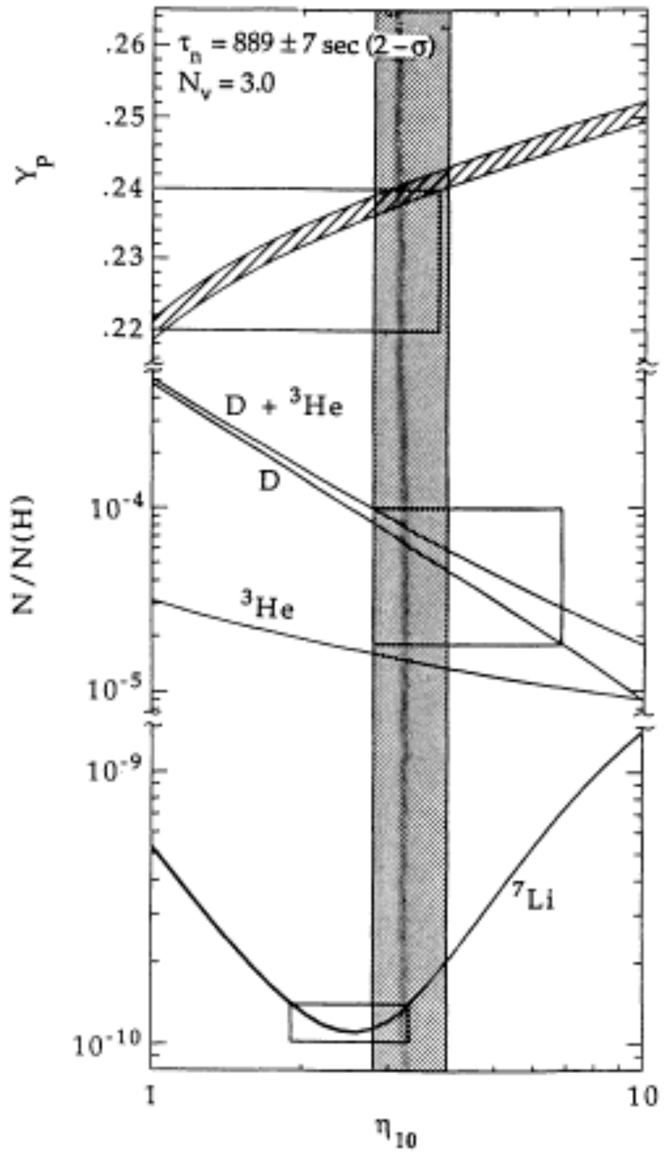


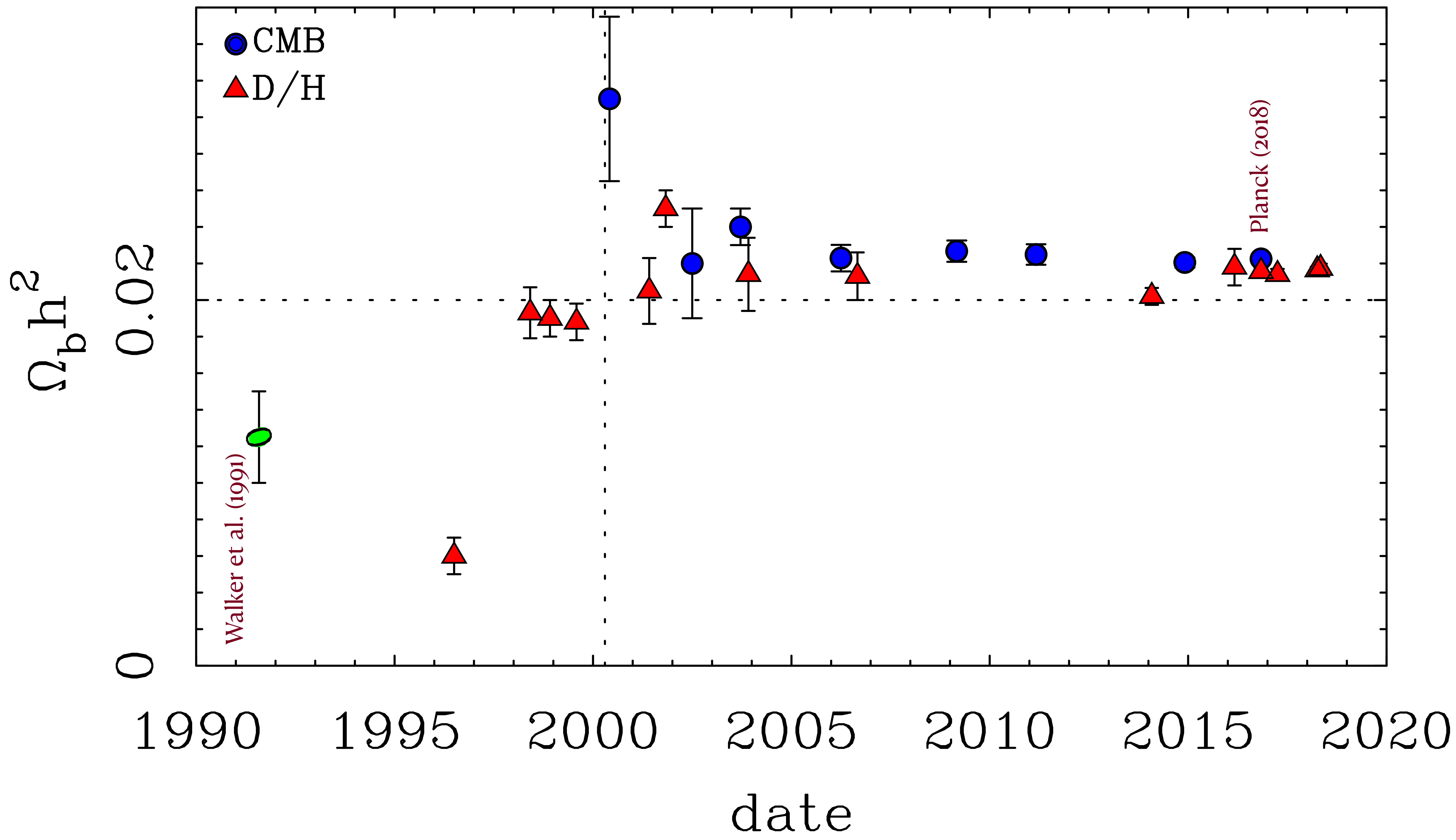
FIG. 13.—Predicted abundances (by number) of D, ^{3}He, D + ^{3}He, and ^{7}Li, and the ^{4}He mass fraction as a function of η for $N_\nu = 3$ and $882 \le \tau_n \le 896$ s. The 95% CL bounds on the abundances (see text) are shown. The vertical band delimits the range of η consistent with the observations.

Since $N_\nu \ge 3$ (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

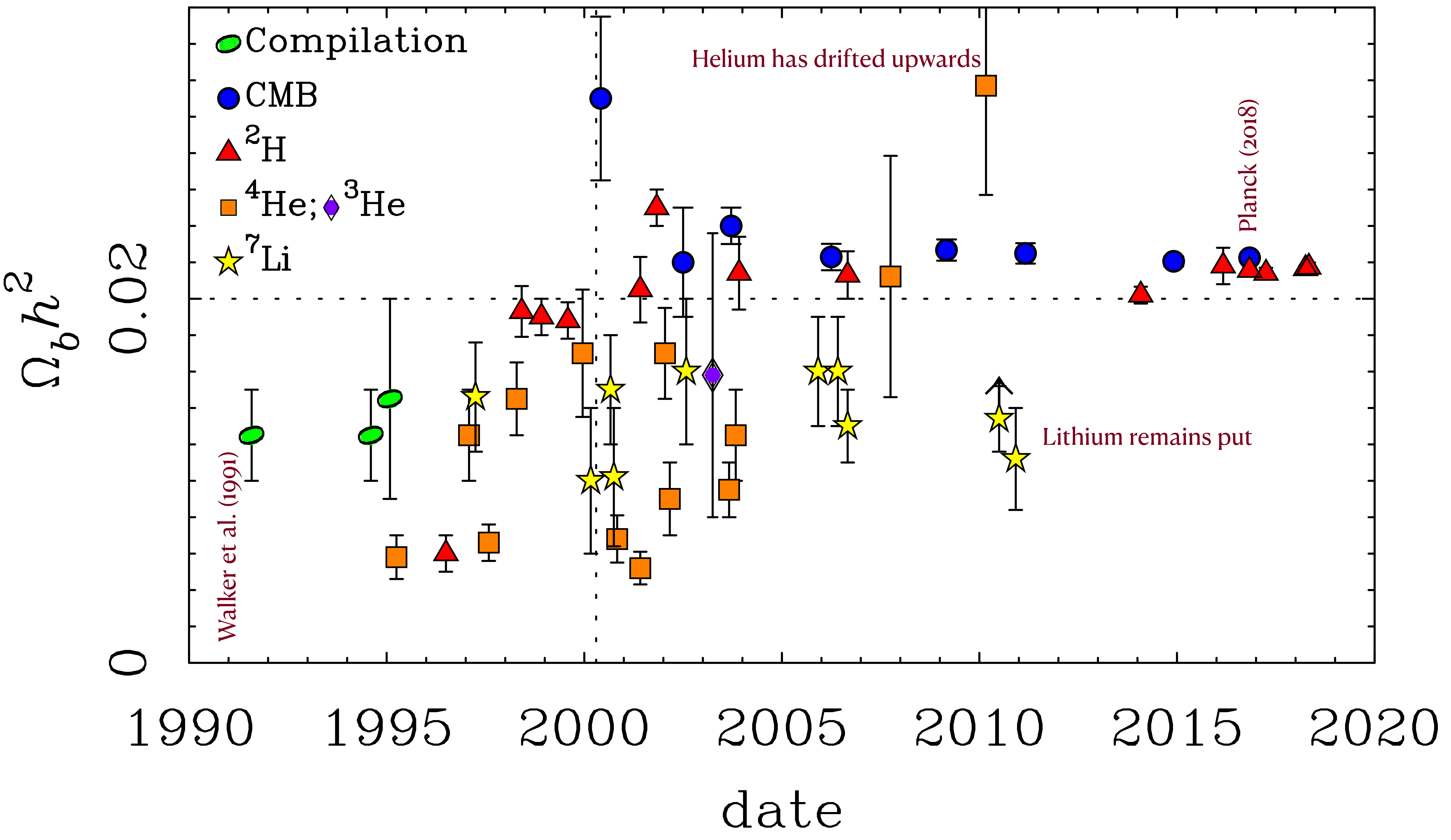
$$Y_p \ge 0.227 + 0.010 \ln \eta_{10} , \qquad (30)$$

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

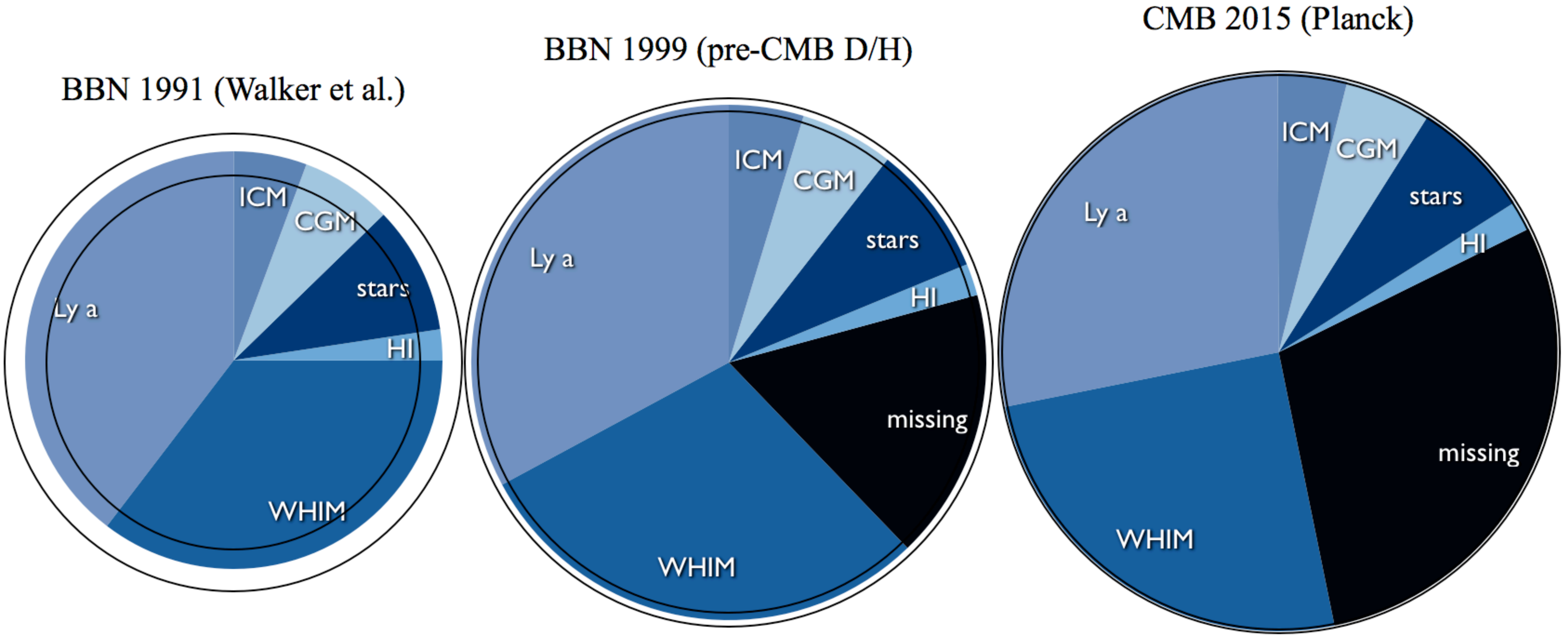
where T is in kelvins. Comparing the baryon mass density



CMB
D/H
Planck (2018)
Walker et al. (1991)
$\Omega_b h^2$
0.02
0
1990
1995
2000
2005
2010
2015
2020
date



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
0.02
1990
1995
2000
2005
2010
2015
2020
date

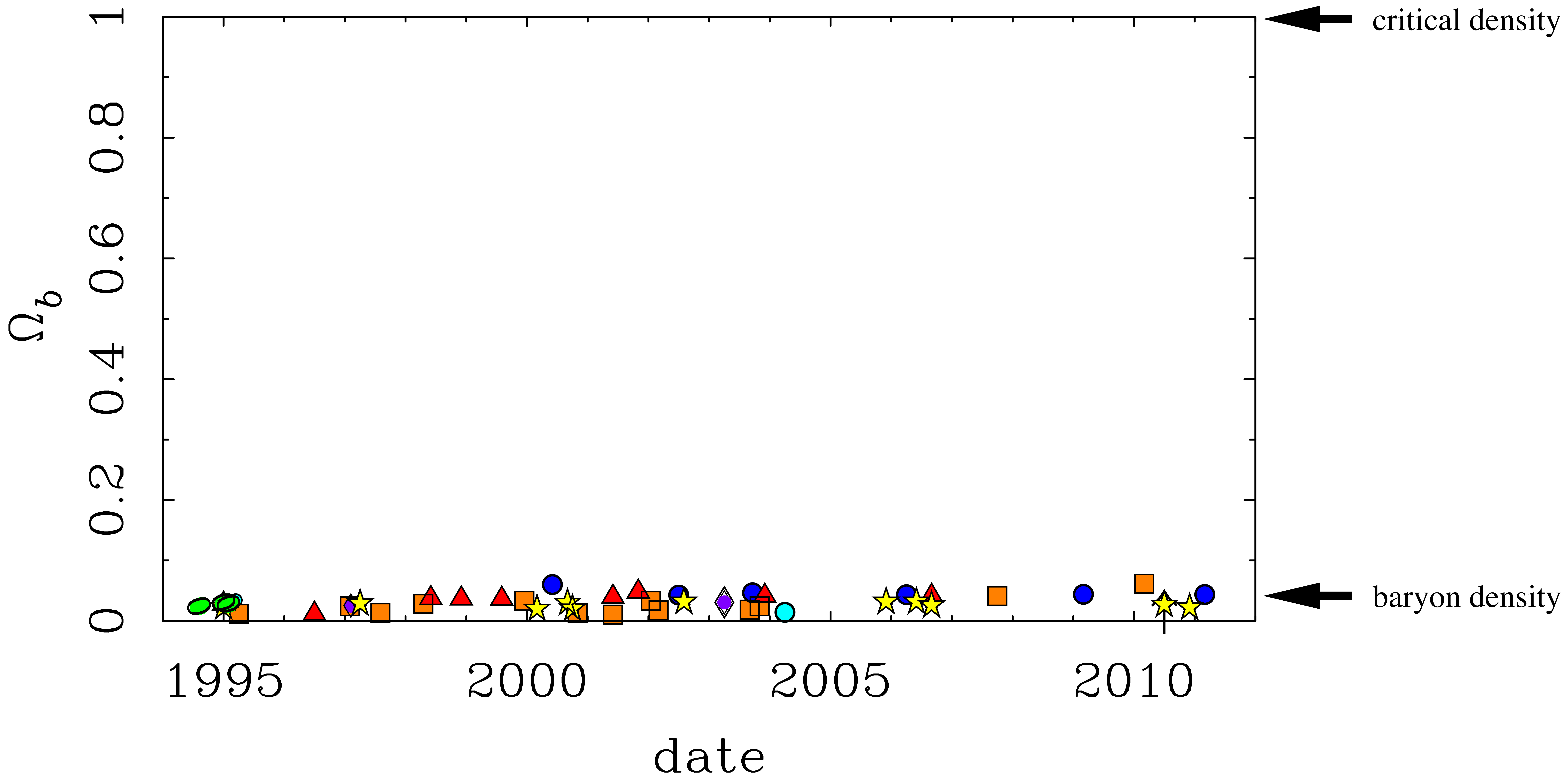


$\Omega_b h^2 = 0.0125 \pm 0.0025$

$\Omega_b h^2 = 0.019 \pm 0.001$

$\Omega_b h^2 = 0.02230 \pm 0.00023$

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



Despite tensions between independent measurements of different isotopes, the baryon density is much less than critical.

Back to expansion dynamics

Friedmann equation can be written

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\left(\rho_m + \frac{\varepsilon_r}{c^2}\right) - \frac{kc^2}{(aR_0)^2} + \frac{c^2}{3}\Lambda$$

$$H \equiv \frac{\dot{a}}{a}$$

where

split density into mass and radiation

$$\Omega_m = \frac{8\pi G}{3H^2}\rho$$

mass density; radiation density

$$\Omega_r = \frac{8\pi G}{3H^2}\frac{\varepsilon_r}{c^2} = \frac{8\pi G}{3H^2}\frac{\alpha T_r^4}{c^2}$$

$$\Omega_k = -\frac{kc^2}{(aR_0H)^2}$$

curvature and cosmological constant terms as before

$$\Omega_\Lambda = \frac{c^2\Lambda}{3H^2}$$

Can play this trick with any substance you want to make up. E.g., we can distinguish between baryons and dark matter, both of which contribute to Ω_m here because they share the same equation of state (w=0). Different equations of state lead to different redshift dependences.

the sum of density parameters must be unity: $\Omega_m + \Omega_r + \Omega_k + \Omega_\Lambda = 1$

Expansion dynamics

Friedmann equation can be written

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\left(\rho_m + \frac{\varepsilon_r}{c^2}\right) - \frac{kc^2}{(aR_0)^2} + \frac{c^2}{3}\Lambda$$

$$H \equiv \frac{\dot{a}}{a}$$

where

split density into mass and radiation

$$\Omega_m = \frac{8\pi G}{3H^2}\rho$$

mass density; radiation density

$$\Omega_r = \frac{8\pi G}{3H^2}\frac{\varepsilon_r}{c^2} = \frac{8\pi G}{3H^2}\frac{\alpha T_r^4}{c^2}$$

Want to make this distinction because mass evolves as $(1+z)^3$ and radiation as $(1+z)^4$.

Now the Friedmann equation becomes

$$\left(\frac{H}{H_0}\right)^2 = \frac{\Omega_m}{a^3} + \frac{\Omega_r}{a^4} + \frac{\Omega_k}{a^2} + \Omega_\Lambda$$

$$\frac{1}{a} = 1 + z$$

Expansion dynamics

Using $$\frac{1}{a} = 1 + z$$ $$H \equiv \frac{\dot{a}}{a}$$

Friedmann equation can be written

$$\left(\frac{H}{H_0}\right)^2 = \Omega_m(1+z)^3 + \Omega_r(1+z)^4 + \Omega_k(1+z)^2 + \Omega_\Lambda$$

Where these are the Ω_0 at the current time, but I've left off the 0 because there are enough subscripts already.

Peebles's book calls this $E^2(z)$ as this expansion term appears in many contexts.

In general, this must be solved numerically - see the cosmology calculators linked from the course web page.
Sometimes it is possible to obtain an analytic solution if one term or another can be ignored.
E.g., the universe is either matter or radiation dominated except very near the epoch of equality, so one term or the other can usually be neglected. If there is no cosmological constant, the curvature can be replaced by $\Omega_k = 1 - \Omega_m$; similarly for the Lambda term if the geometry is flat.

Solutions from Felten & Isaacman (1986) Reviews of Modern Physics, **58**, 689

No cosmological constant

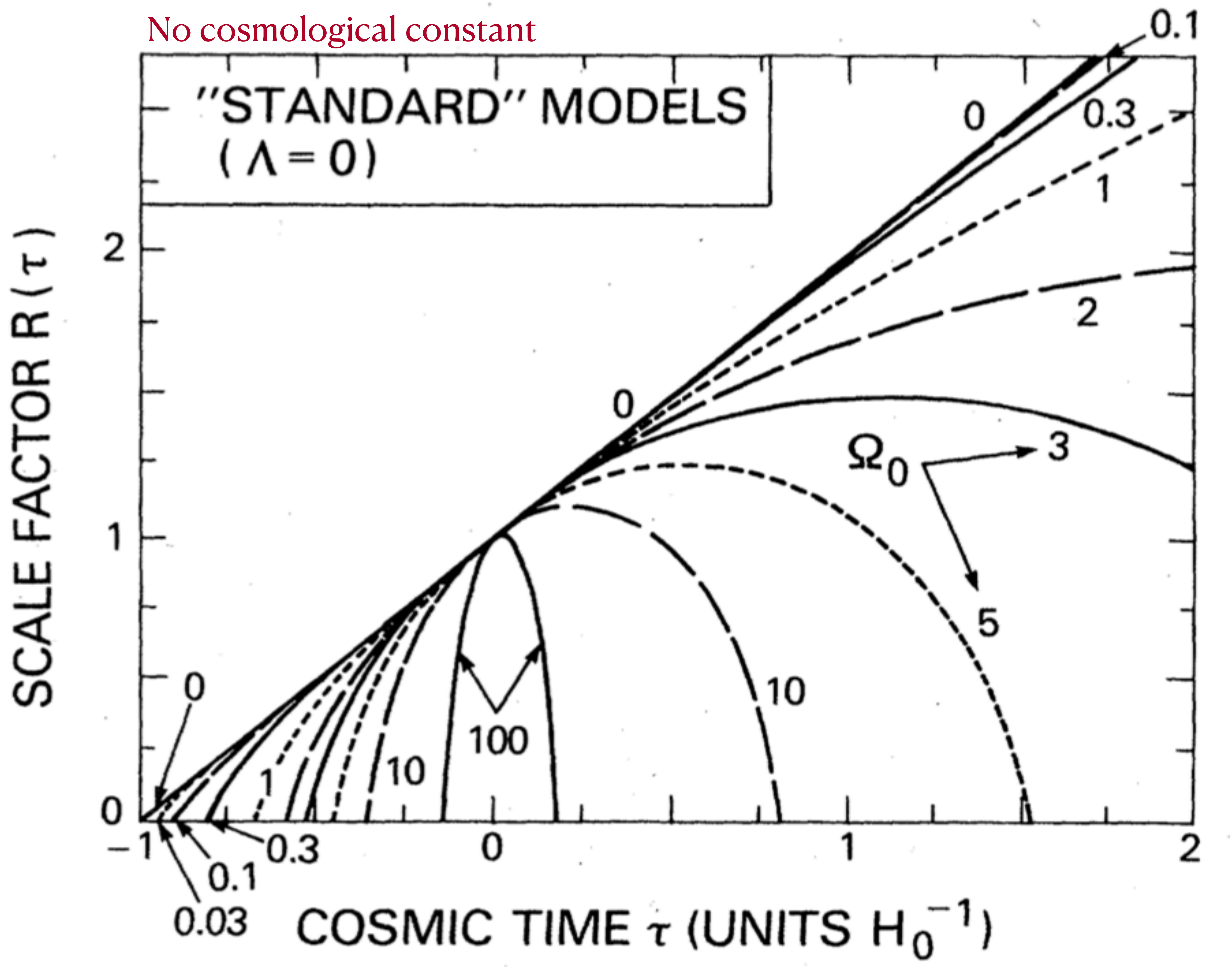


FIG. 3. "Standard" Friedmann models. The family of scale factors $R(\tau)$ for the "standard models" ($\Lambda=0$). The free parameter, shown on the curves, is Ω_0. As shown by the τ intercepts, all models have ages ≤ 1 ($\leq H_0^{-1}$ yr).

Flat geometry

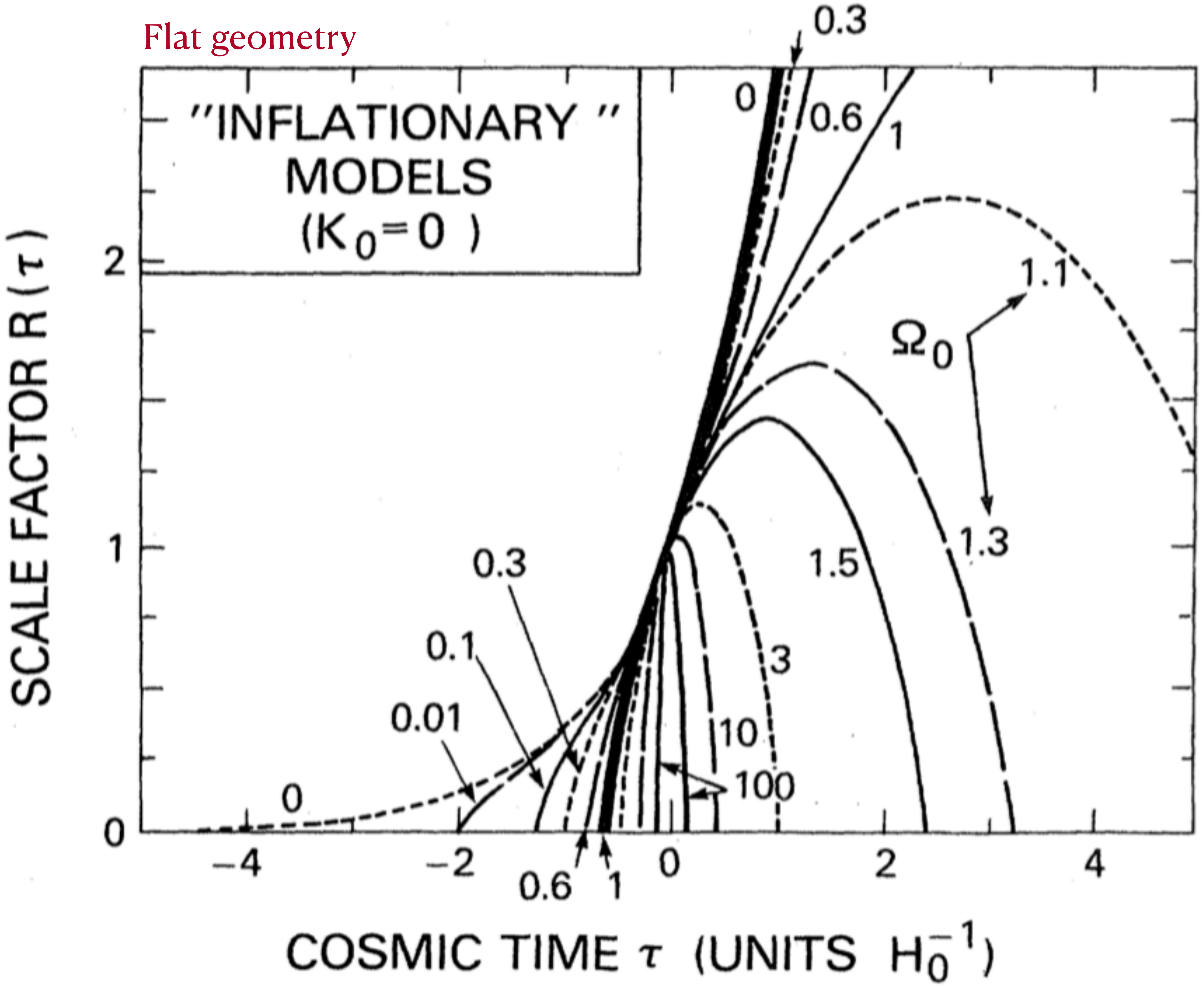


FIG. 2. "Inflationary" Friedmann models. The family of scale factors $R(\tau)$ for models satisfying the "inflationary constraint" (three-space curvature $K_0=0$). The free parameter, shown on the curves, is Ω_0. The cosmological constant Λ is determined from Ω_0 by Eq. (14).

Solutions from Felten & Isaacman (1986) Reviews of Modern Physics, **58**, 689

Can in principle have solutions in which there was no Big Bang in the past, depending on the value of Lambda.

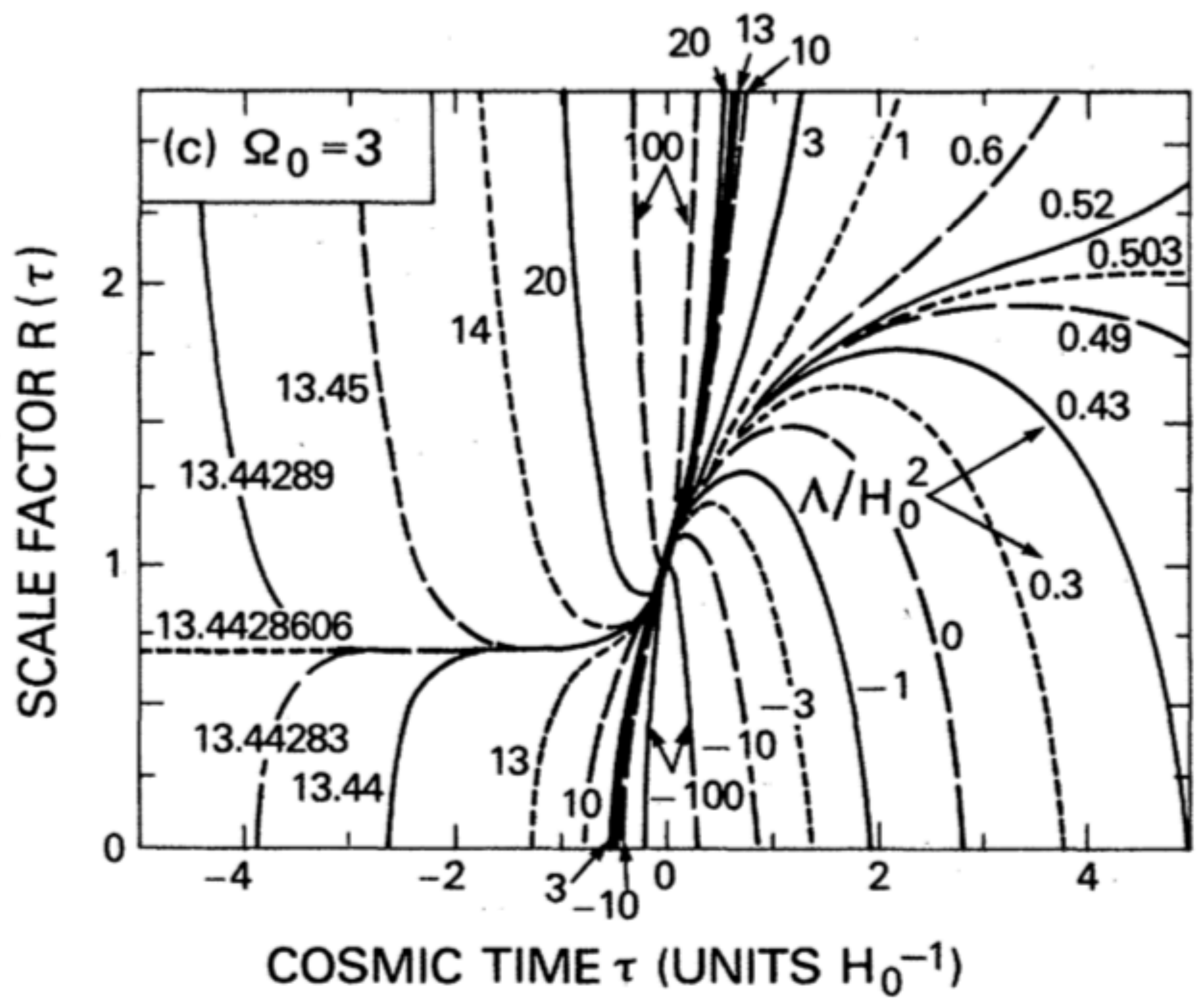


FIG. 1. Solutions of the Friedmann equation. Three families of scale factors $R(\tau)$ for Friedmann (zero-pressure) universes, with three fixed values of the present density parameter Ω_0: (a) $\Omega_0 = 0.1$; (b) $\Omega_0 = 1$; (c) $\Omega_0 = 3$. The free parameter, shown on the curves, is the cosmological constant Λ in units of H_0^2, where H_0 is the present Hubble parameter. The time τ is measured in units of the Hubble time H_0^{-1} and is taken $=0$ at present. The scale factor $R(\tau)$ is normalized to unity at present: $R_0 = 1$. For further discussion see the text.