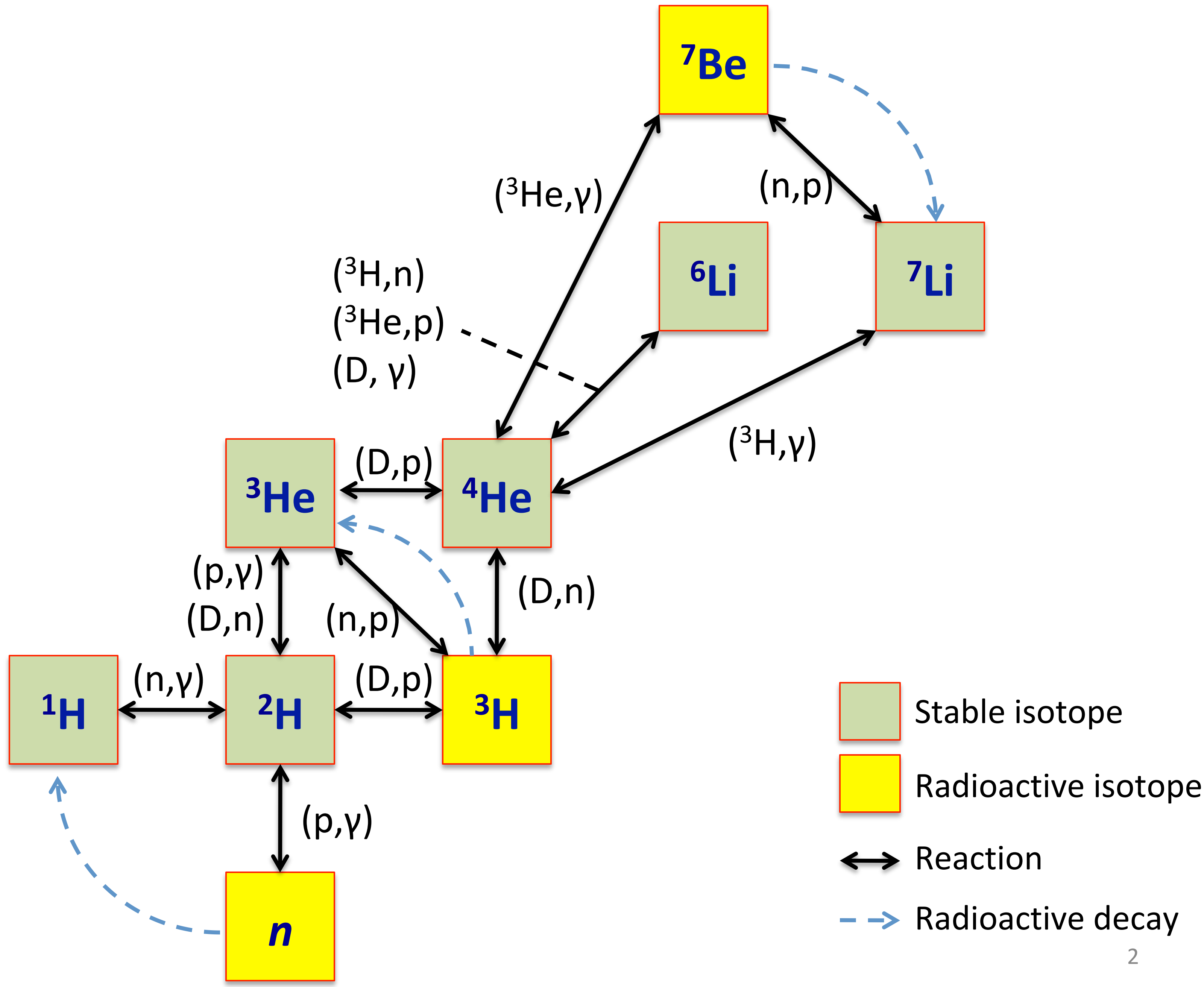
Big Bang Nucleosynthesis

[Supplement to Lecture VII]



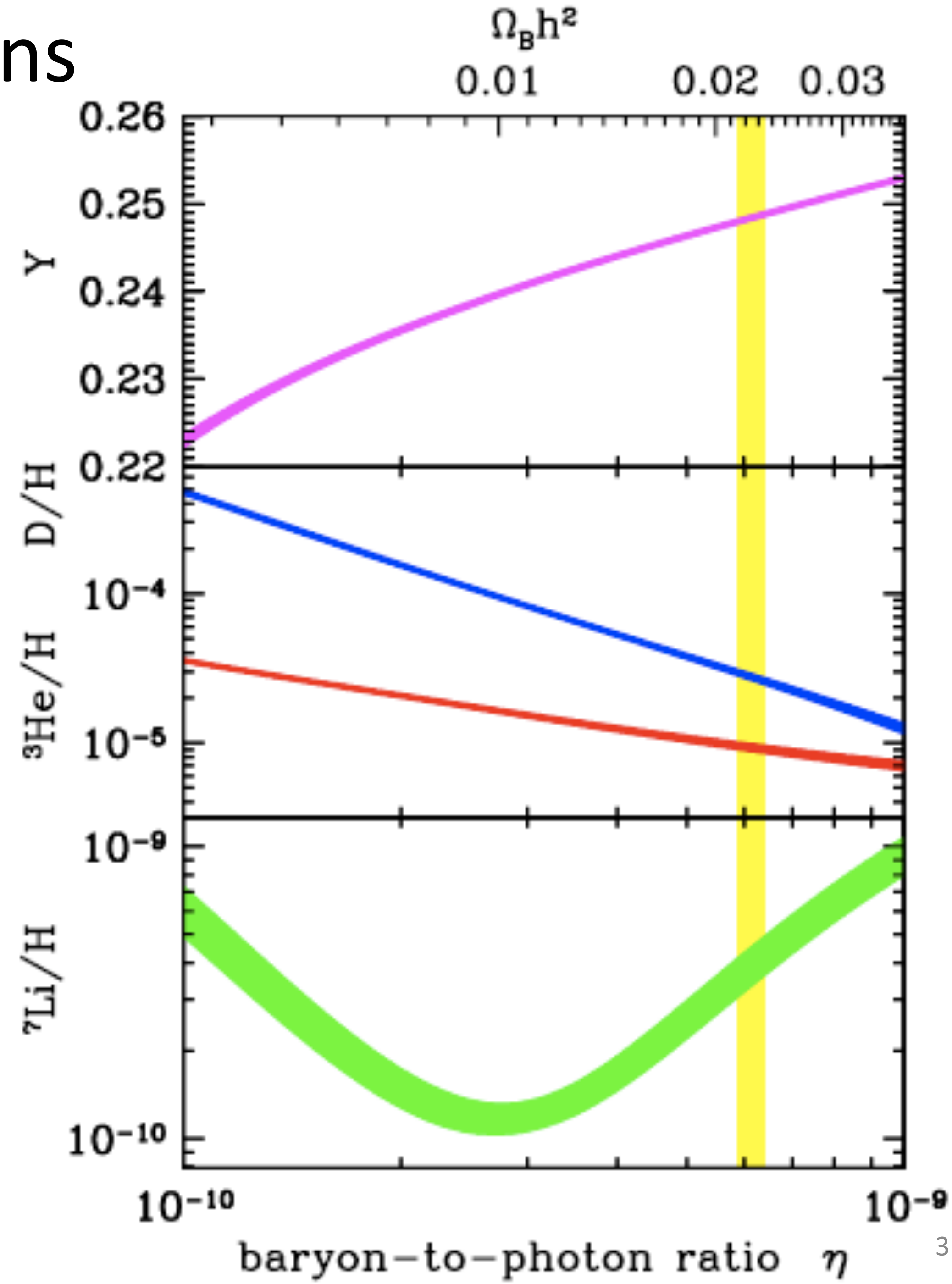
7Be
(3He,γ)
(n,p)
6Li
7Li
(3H,n)
(3He,p)
(D, γ)
(3H,γ)
3He
(D,p)
4He
(p,γ)
(D,n)
(n,p)
(D,n)
1H
(n,γ)
2H
(D,p)
3H
(p,γ)
n
Stable isotope
Radioactive isotope
Reaction
Radioactive decay

BBN Yield Predictions

Cyburt, Fields & Olive 2003
Phys Lett B 567,227

^{4}He fraction by mass

Abundance relative to H by number

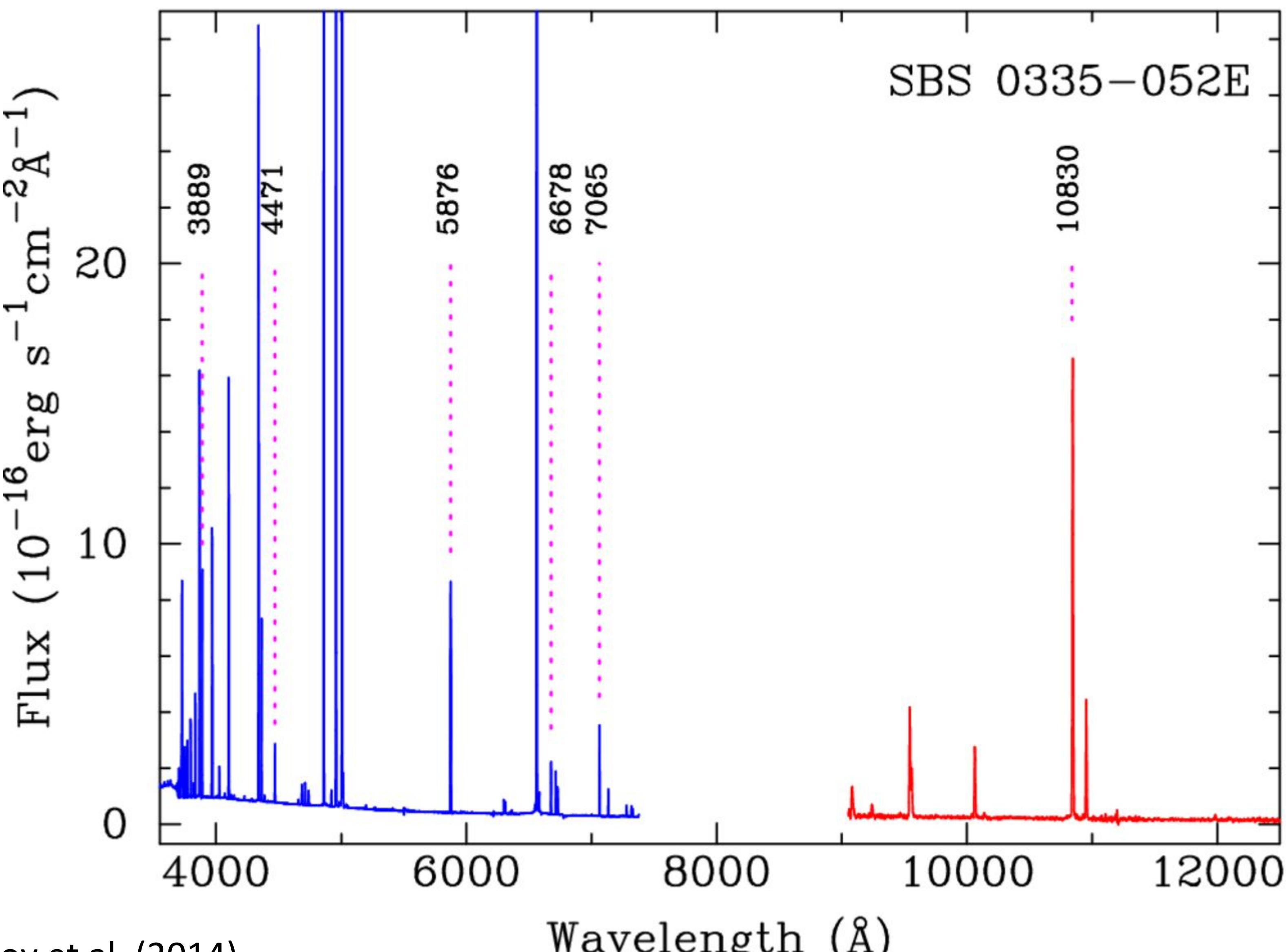


^4He

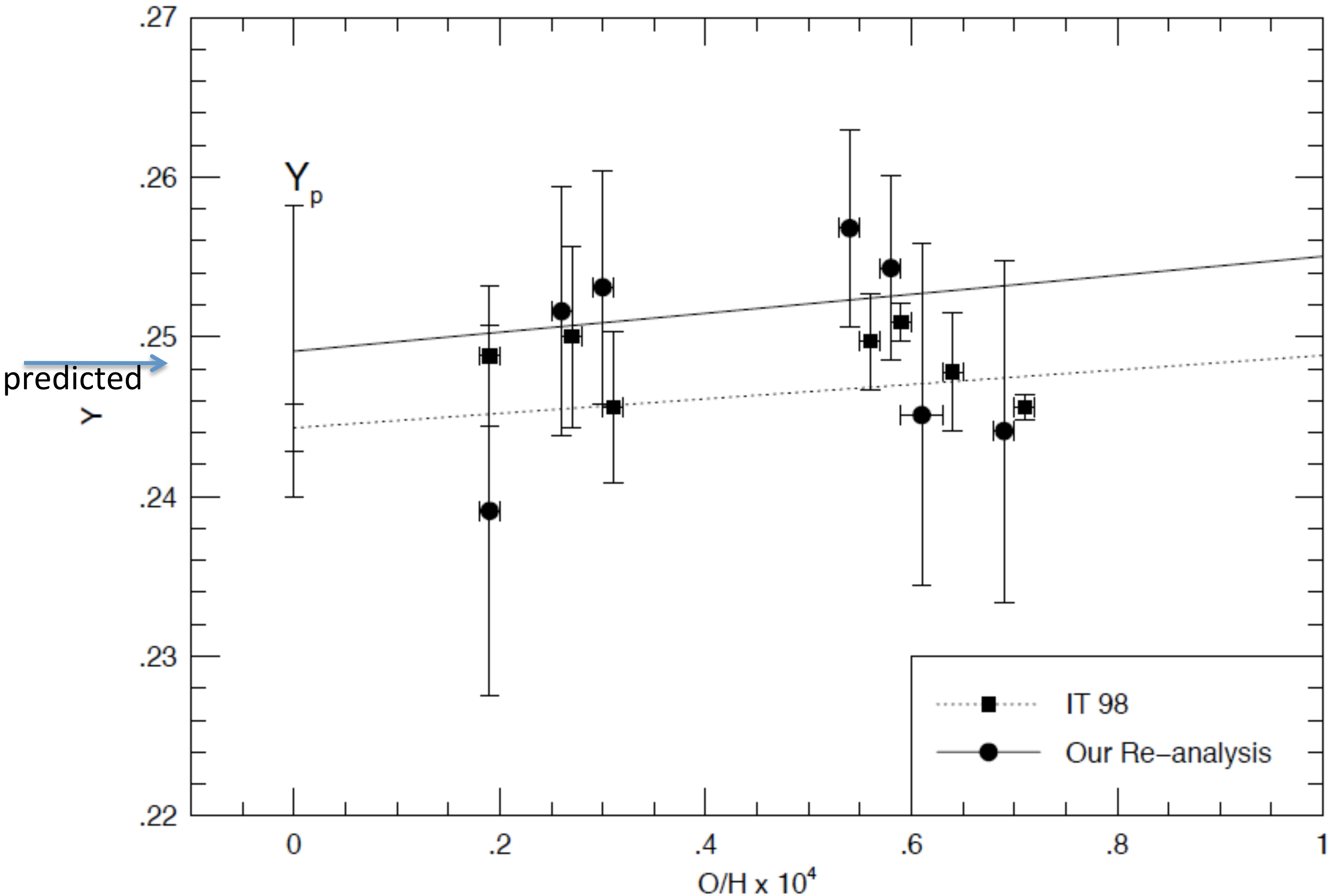
- Prediction: Y = 0.2482±0.0003±0.0006
- Usually estimate He abundance from H II region spectra (H I and He I recombination lines).
  - Determine temperature (self-consistent or using [O III]).
  - Model collisional excitation, fluorescence.
  - Optical depth effects. He I 2^3S_1 is metastable.
  - Model reddening.
  - Model stellar He I absorption.
  - Ionization correction factors (H II and He I can coexist).
  - Extrapolate to zero metallicity to get primordial value.
- Major recent development is NIR spectroscopy to get 1.08 µm line as a density diagnostic.

Spectrum Of Extragalctic H II Region Showing Helium Lines

[LBT (optical) + VLT (NIR)]



Izotov et al. (2014)



$0.232 < Y_p < 0.258$

Olive & Skillman 2004 ApJ 617,29

He Abundances

✔*

Measured from H II Regions

0.2551 ± 0.0022	Izotov et al. (2014)
0.2449 ± 0.0040	Aver et al. (2015)
0.2446 ± 0.0029	Peimbert et al. (2016)

Measured from recombination (CMB anisotropies)

0.241 ± 0.025	Planck 2018 VI
0.246 ± 0.035	Planck 2018 VI (allowing N_ν free)

Theory

0.2470 ± 0.0002	(with Planck $\Omega_b h^2$)

* Determinations are only marginally consistent with each other.

Examples of Deuterium Measurements

Location	D/H (ppm)	Method
Earth	150	
Venus	16000±2000	Mass spec. Donahue et al 1982
Mars	900±400	IR lines (HDO/H_2O) Owen et al 1988
Jupiter	22—50 50±20	IR lines (CH_3D/CH_4) Kunde et al 1982 Mass spec. Niemann et al 1996
Saturn	4—29	IR lines (CH_3D/CH_4) Courtin et al 1984
Local ISM	~ 7 – 20	Absorption lines in stellar spectra. Depends on line of sight; see tabulation by Linsky et al 2006
Lyman-α absorbers	25.3±0.4	H vs D Lyman absorption lines in QSO spectra, Cooke et al. 2014

Warnings on D/H

- Not all D/H is the primordial value, or even that at the formation of the solar system.
- Problems:
  - Astration: burning of D to ^{3}He etc. in stars.
  - Chemical fractionation: At low temperatures D binds more tightly to molecules than H due to vibrational zero point energy.

$$XH^{+} + D \rightarrow XD^{+} + H$$

  - Fractionation due to depth of planetary gravity well. (This is why Jupiter was once used for BBN D/H.)

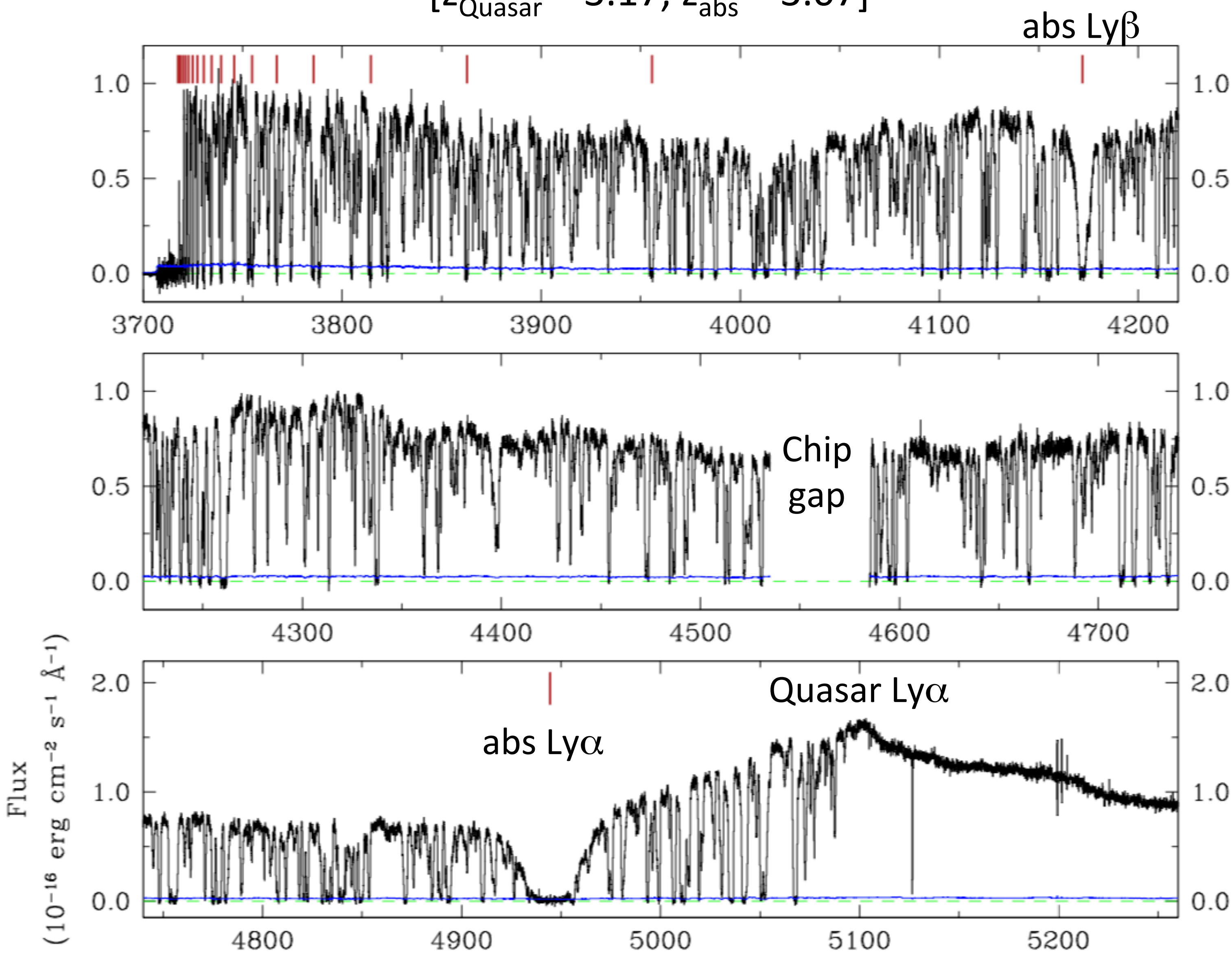
Intergalactic D/H

✔

- Probably most reliable method is low-metallicity quasar absorption line systems.
  - Little processing by stars
  - Less opportunity to hide deuterium in molecules or dust grains
- Reduced mass of e^-D^+ is greater than e^-p^+ by 1 part in 3600, rescaling all hydrogenic energy levels. Equivalent to velocity shift of c/3600 = 80 km/s.
- Absorber value 25.3±0.4 ppm agrees with predicted 25.8±0.4 ppm.

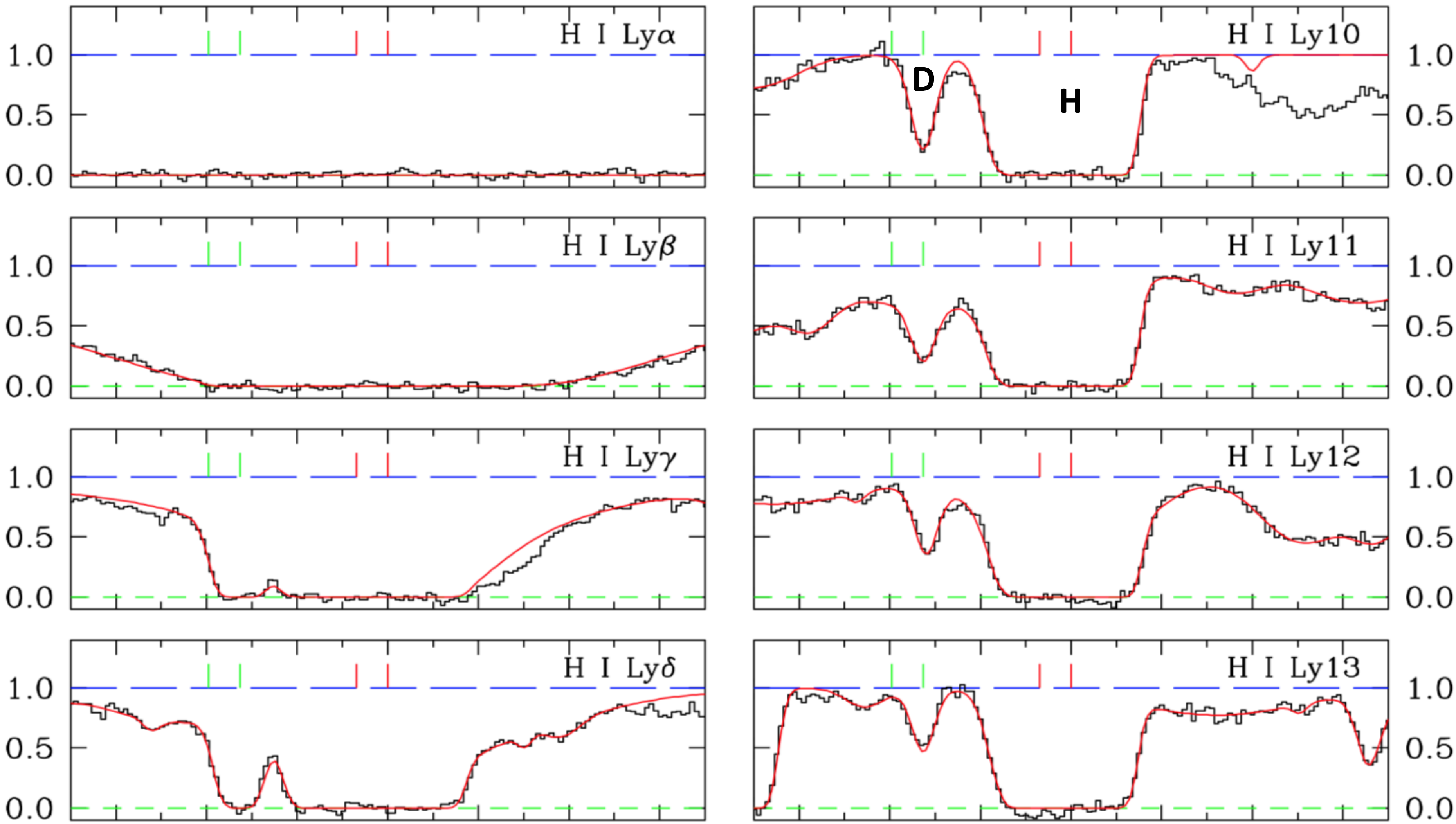
Spectrum of SDSS J1358+6522

$[z_{Quasar} = 3.17,\ z_{abs} = 3.07]$



Cooke et al. (2014)

H vs. D Lines in the absorber



Cooke et al. (2014)

^{3}He

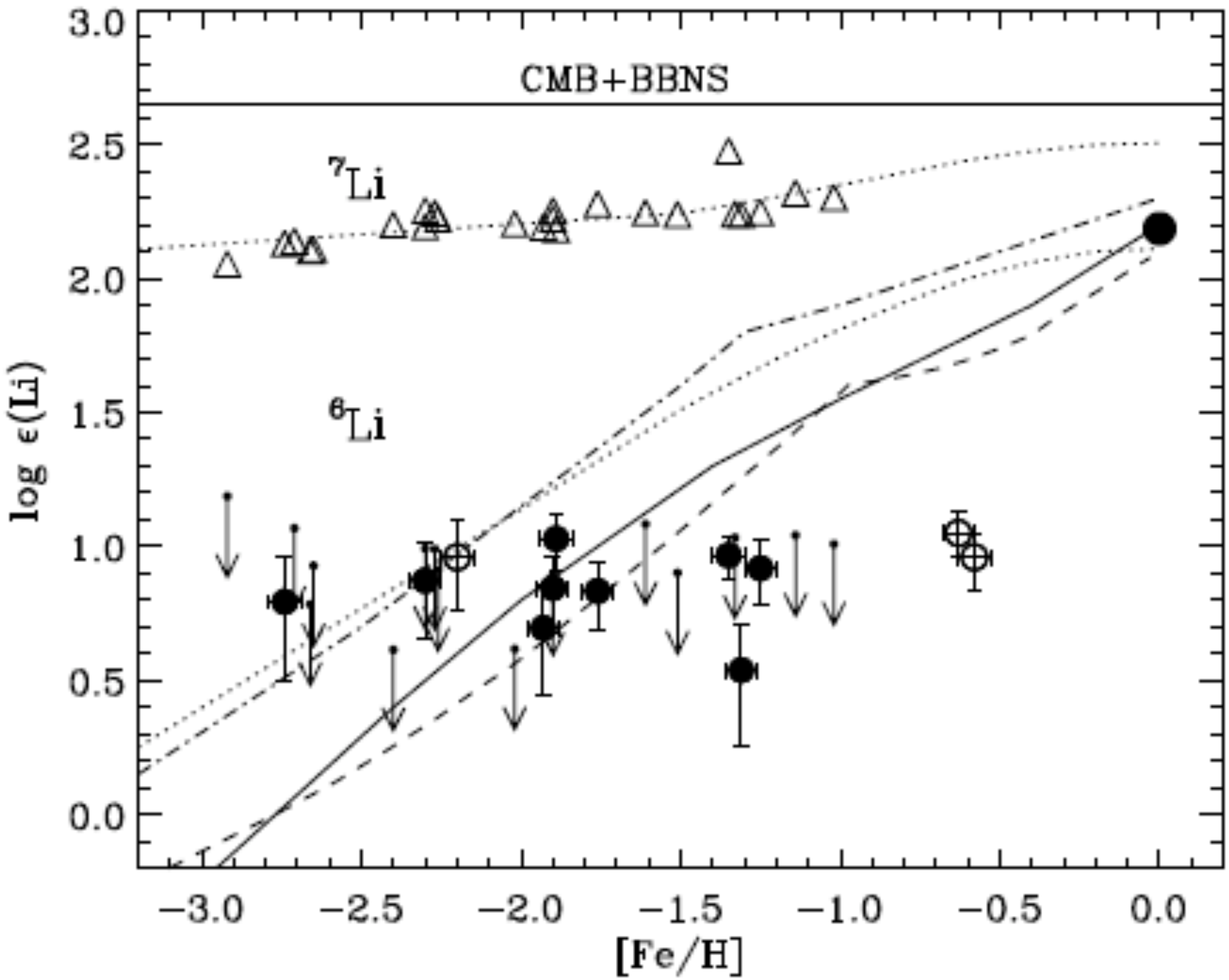
- Difficulties:
  - Can be both produced and destroyed in stars.
  - No IGM measurement.
- Most(?) accepted measurement is $^{3}He^{+}$ hyperfine line (λ=3.46cm) low-metallicity H II regions. Bania et al (2002) find $^{3}He/H < 15$ ppm.
  - Directly observed 11±2 ppm, argue that stars would lead to net increase in ^{3}He.
- Predicted from WMAP baryon abundance: $^{3}He/H = 10.5 \pm 0.3 \pm 0.3$ ppm. ✔?
  - Aside: Jupiter atmosphere ratio $^{3}He{:}^{4}He = (1.1 \pm 0.2) \times 10^{-4}$ [Niemann et al 1996].

Lithium

- Can be measured in low-metallicity stars.
  - Two multiplets available for Li I: 6708Å (2s—2p) and 6104Å (2p—3d).
  - ^{7}Li destroyed at high T, ^{7}Li + p → 2^{4}He. Avoid low-mass stars due to deep convective zone.
  - Slight isotope shift of ^{6}Li vs. ^{7}Li.
- Li can also be produced via cosmic rays:
  - Spallation of CNO elements (also gives Be, B)
  - ^{4}He + ^{4}He collisions at low energies.

Li abundance evolution

12 + $\log_{10} X_{Li}$



Asplund et al (2006) ApJ 644, 229

The Lithium Problem(s)

- ^{7}Li: Predicted $(4.7\pm0.7)\times10^{-10}$.
  - See update from Cyburt et al. 2016.
- Observations give lower values ✗
  - e.g. $(1.1—1.5)\times10^{-10}$ from Asplund et al. 2006.
  - Other determinations are typically $\sim(1—2)\times10^{-10}$.
- ^{6}Li: there have been reports of a plateau at $\sim6\times10^{-12}$, although now mostly interpreted as due to line asymmetry from convection. ?

- Unclear whether ^{7}Li problem indicates new physics, versus our understanding of stellar evolution.