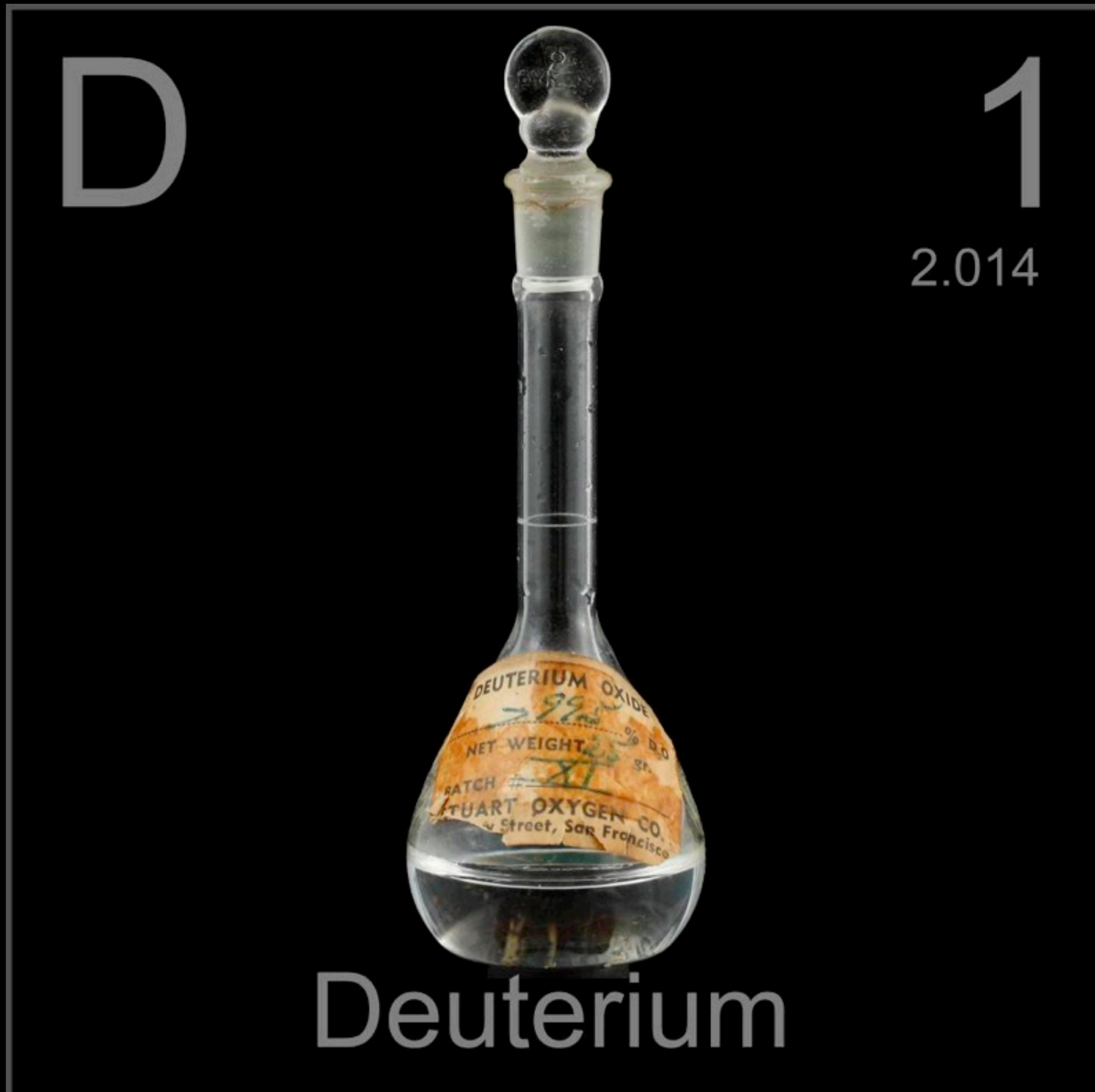
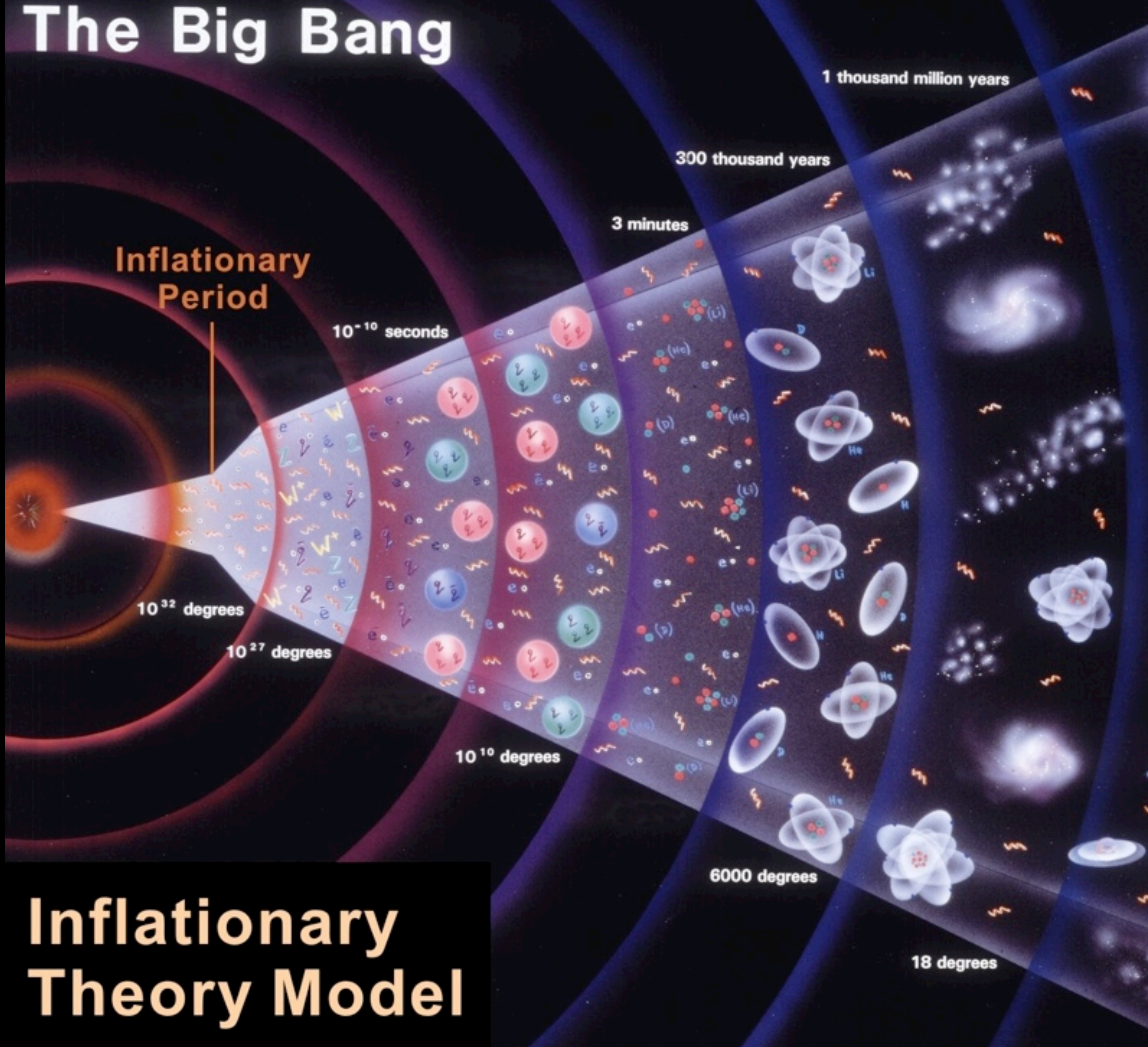
Precision measures of the primordial abundance of

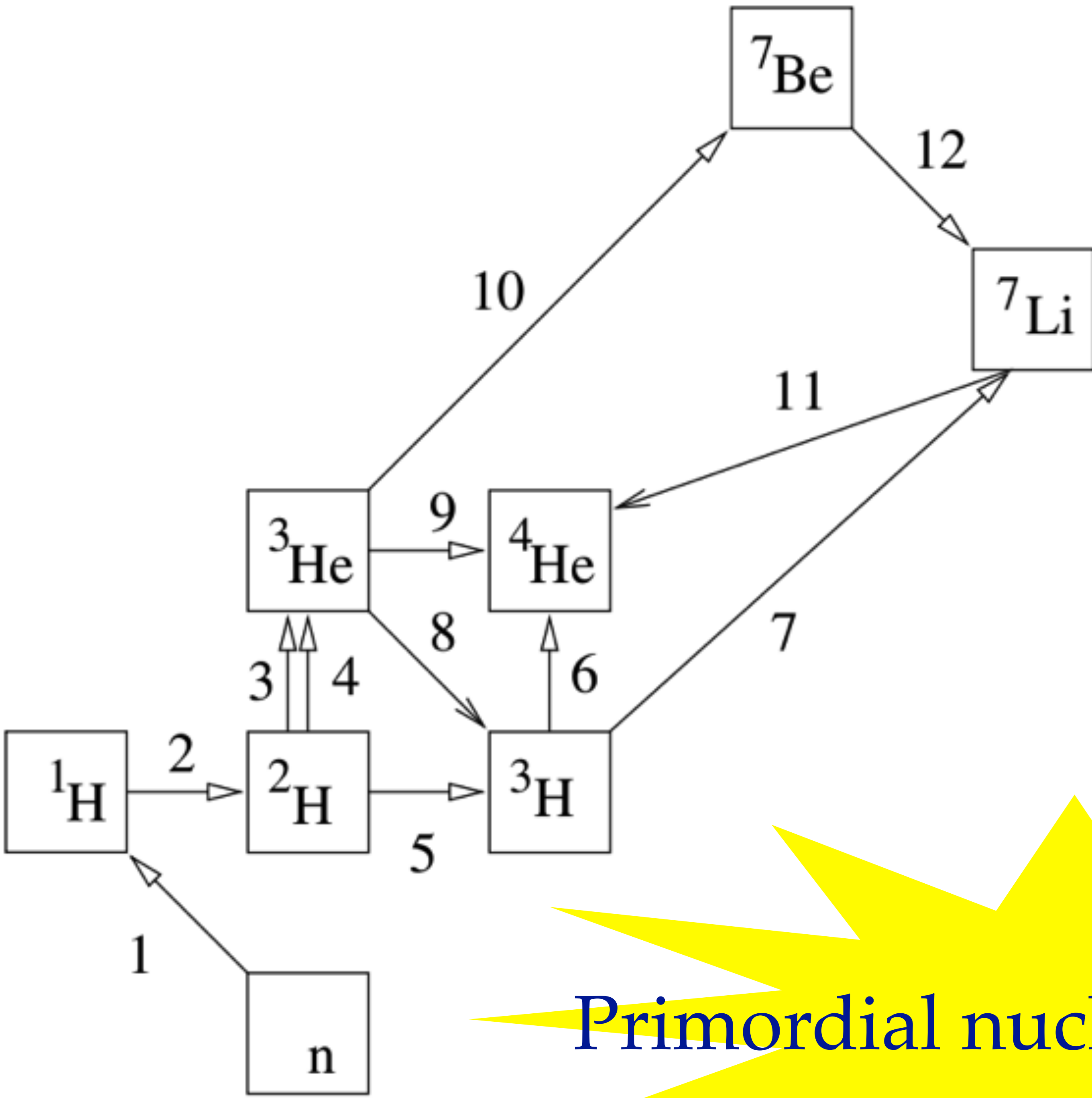


Max Pettini

Cambridge Univ.



Inflationary Theory Model



1. $p \longleftrightarrow n$
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Primordial nucleosynthesis

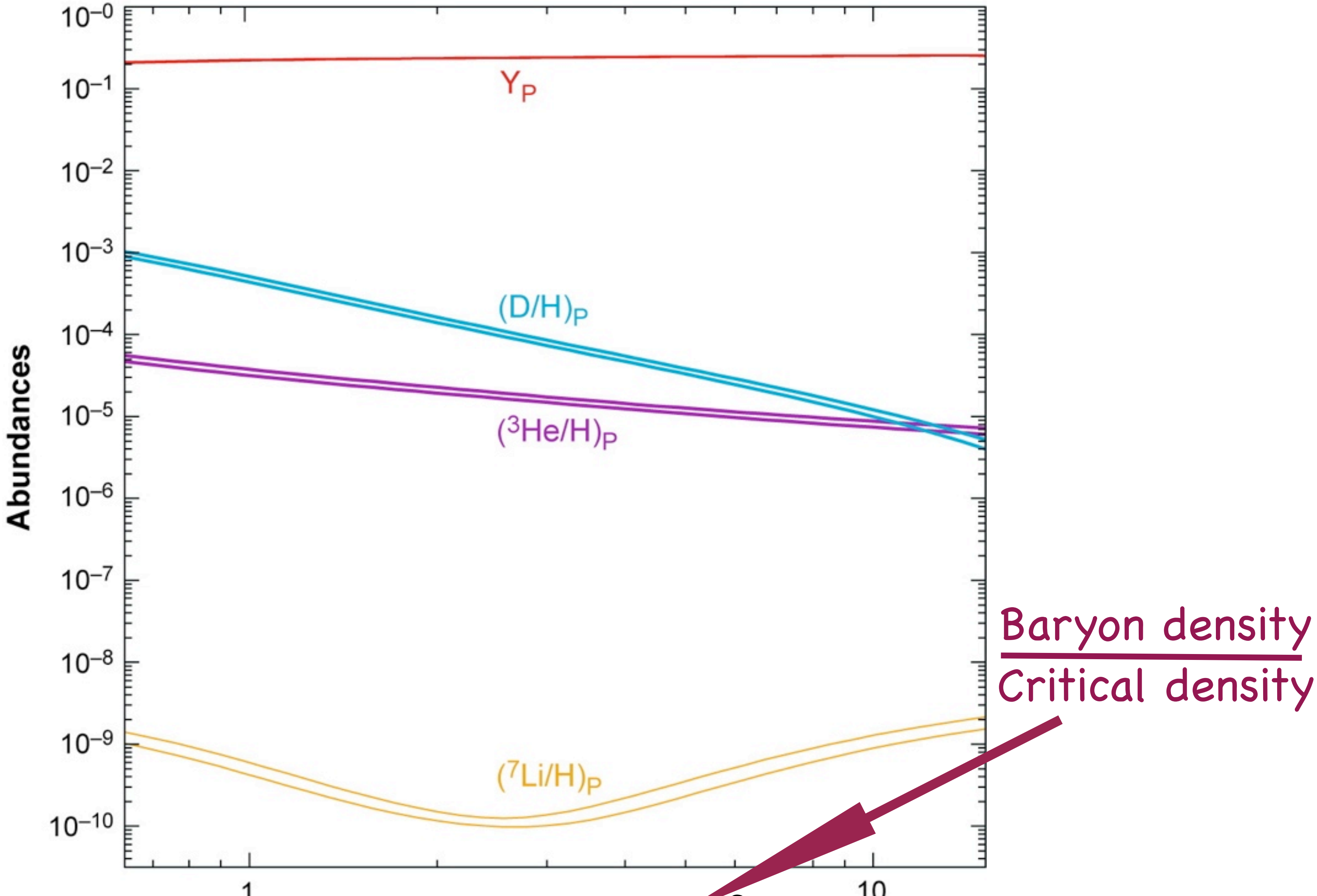
Big Bang Nucleosynthesis (BBN) Ingredients

Input parameters

- The expansion rate of the Universe
- Baryon density parameter
- Neutrino Degeneracy (i.e. lepton asymmetry)

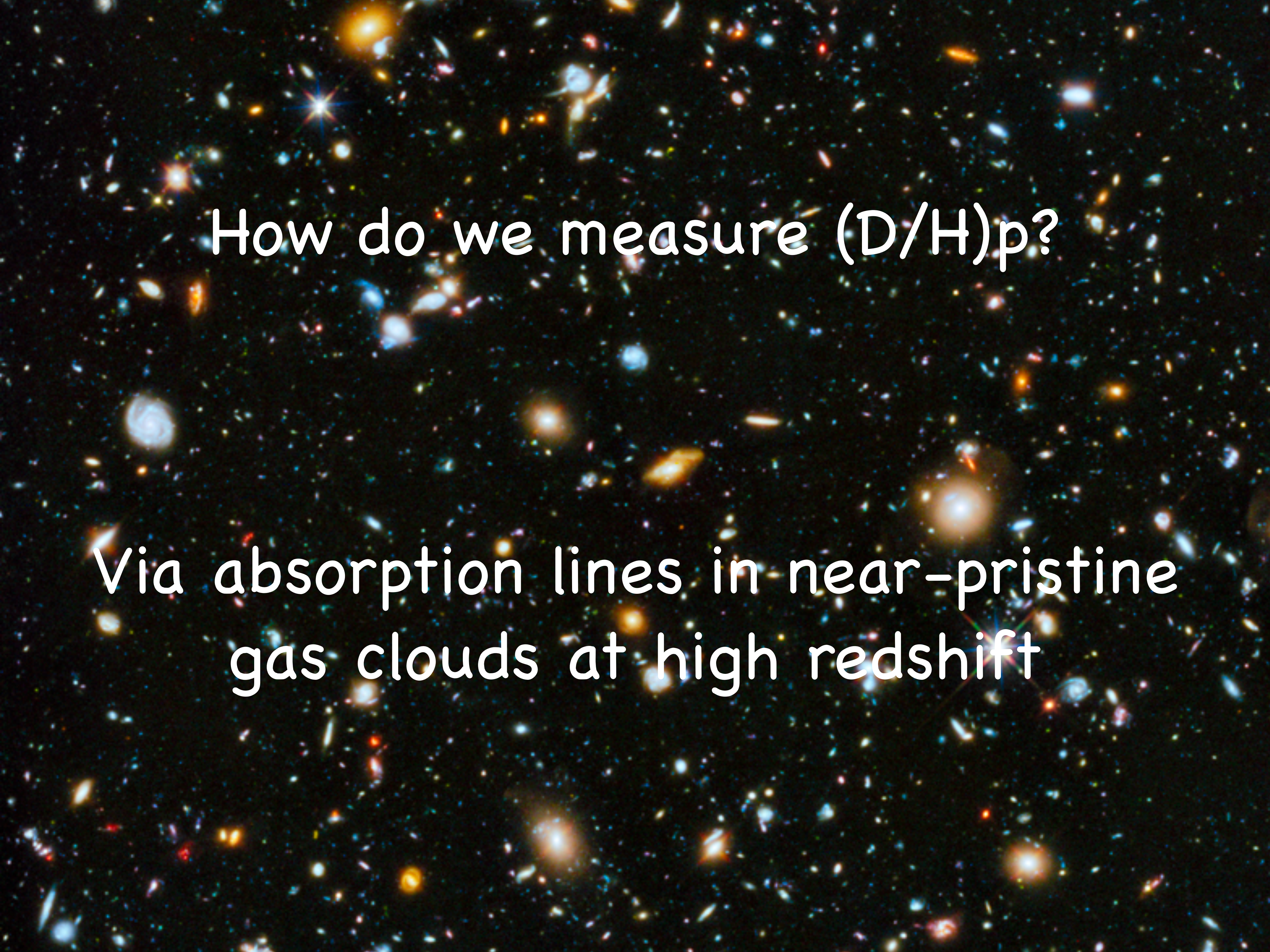
Standard Model Assumptions

- Laboratory measured reaction cross-sections
- General Relativity (i.e. the Friedmann Equations)
- 3 families of neutrinos
- No lepton Asymmetry

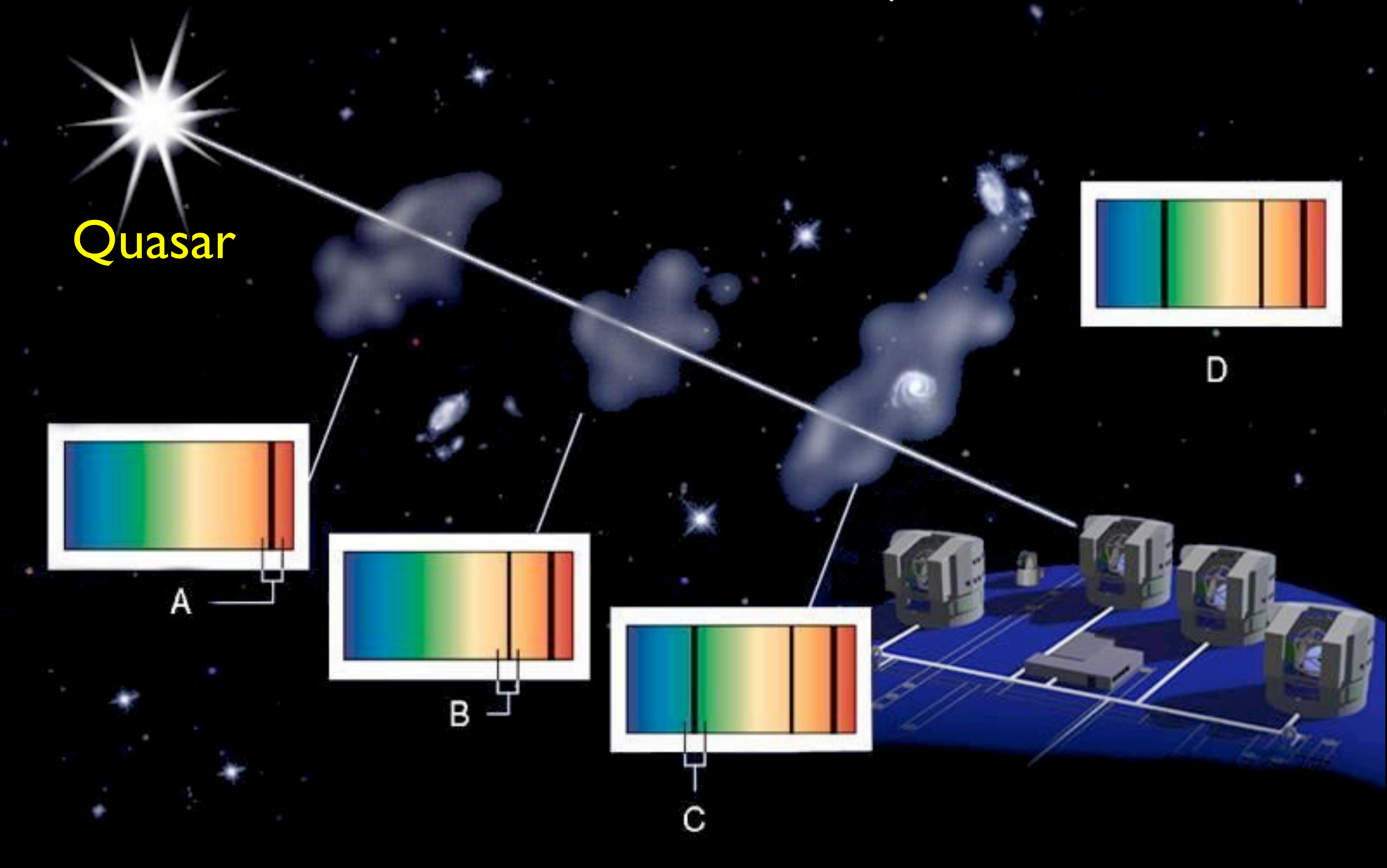


$$\eta_{10} = 274\,\Omega_b h^2$$

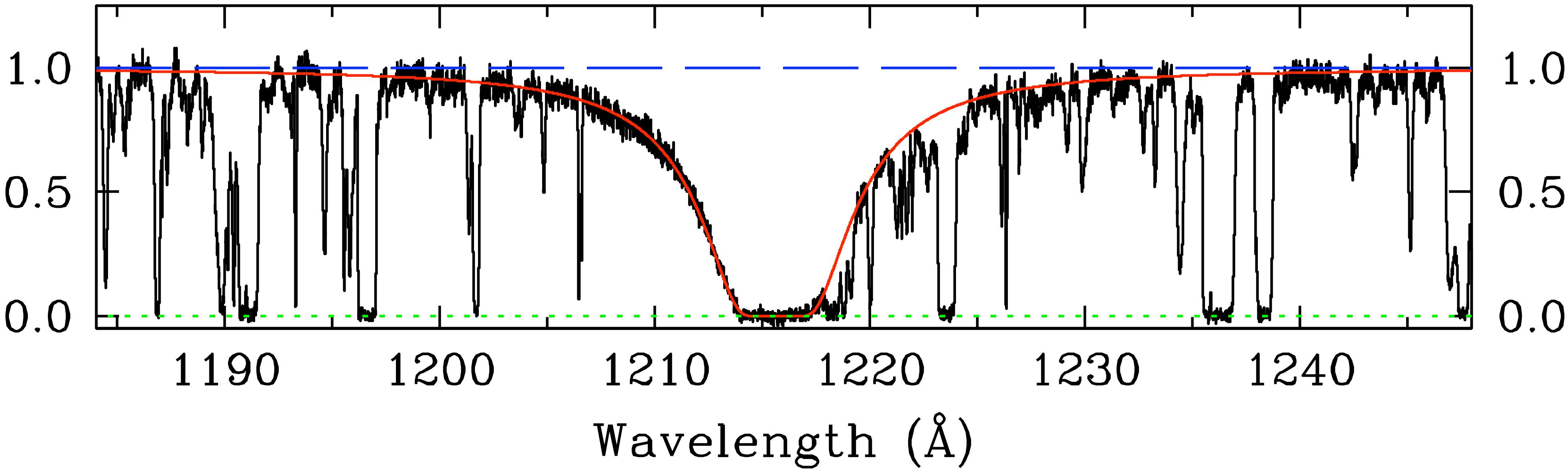
Steigman G. 2007.
Annu. Rev. Nucl. Part. Sci. 57:463–91


How do we measure (D/H)p?
Via absorption lines in near-pristine gas clouds at high redshift

Cosmological redshifts give us a view of the Universe at different cosmic epochs

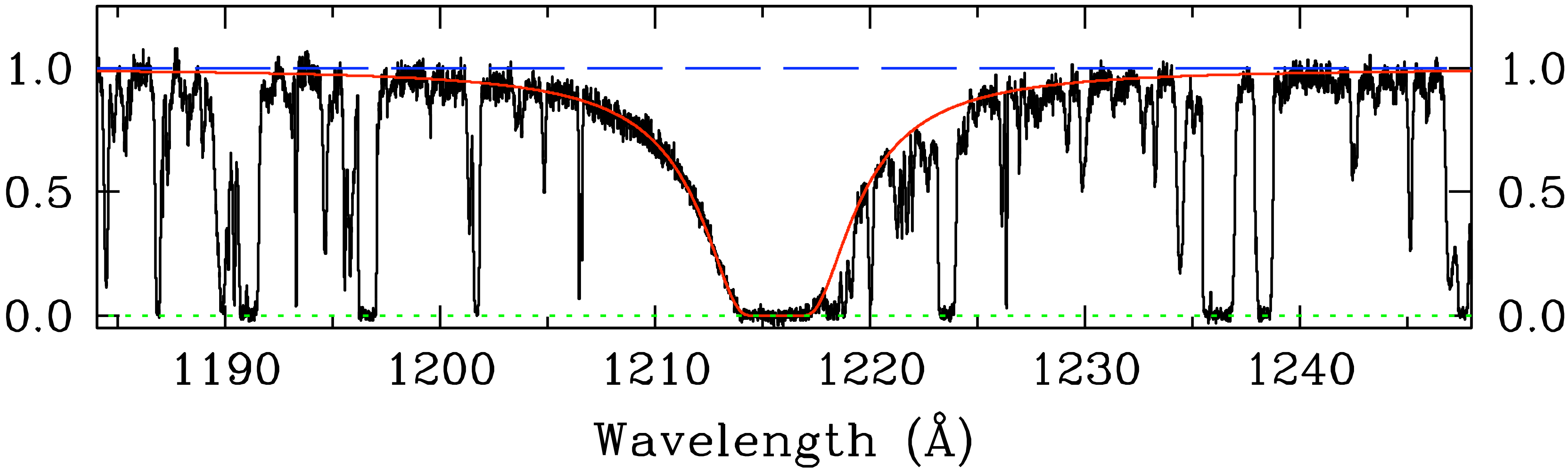


A sample portion of a quasar absorption spectrum



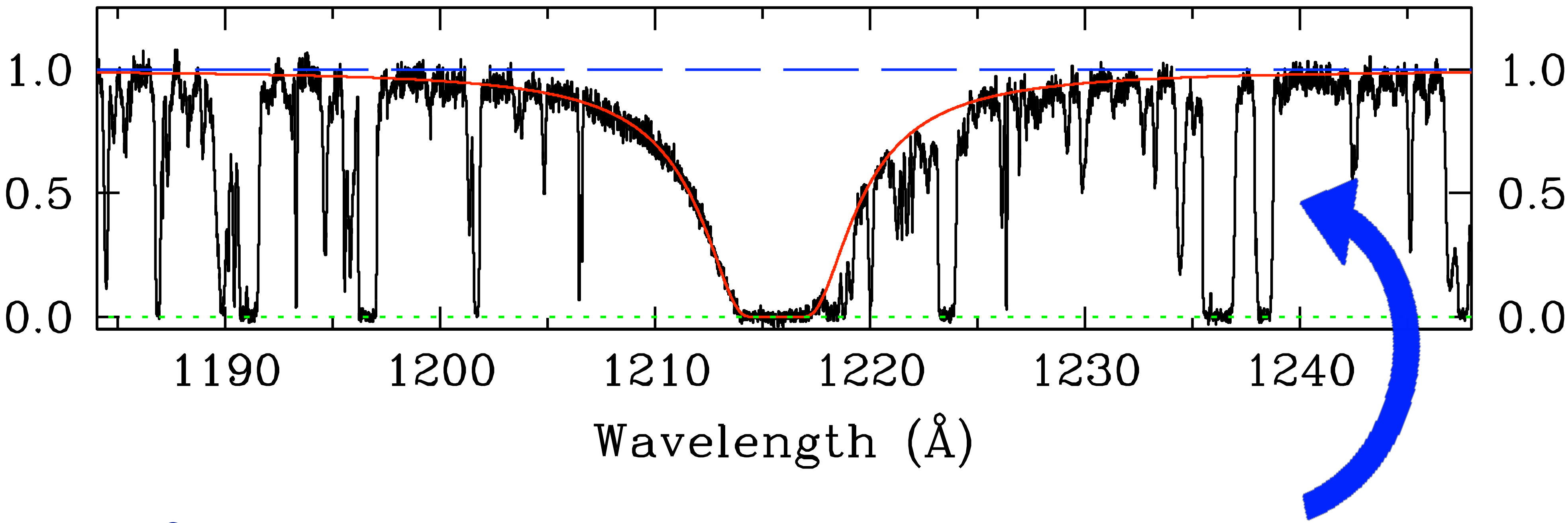
10m Keck telescope + HIRES

A sample portion of a quasar absorption spectrum

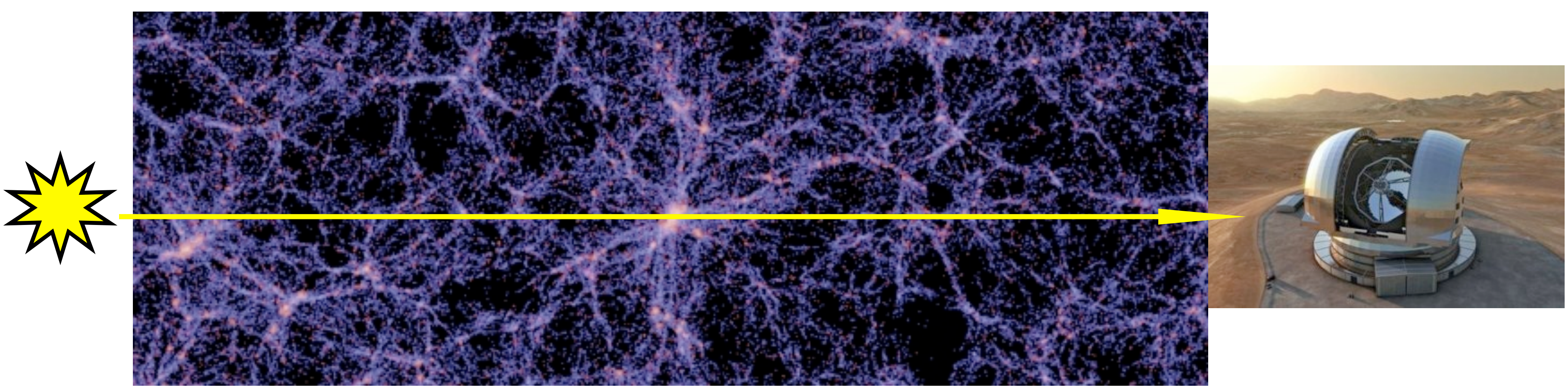


showing HI Lyman alpha (1215.67 A) absorption lines

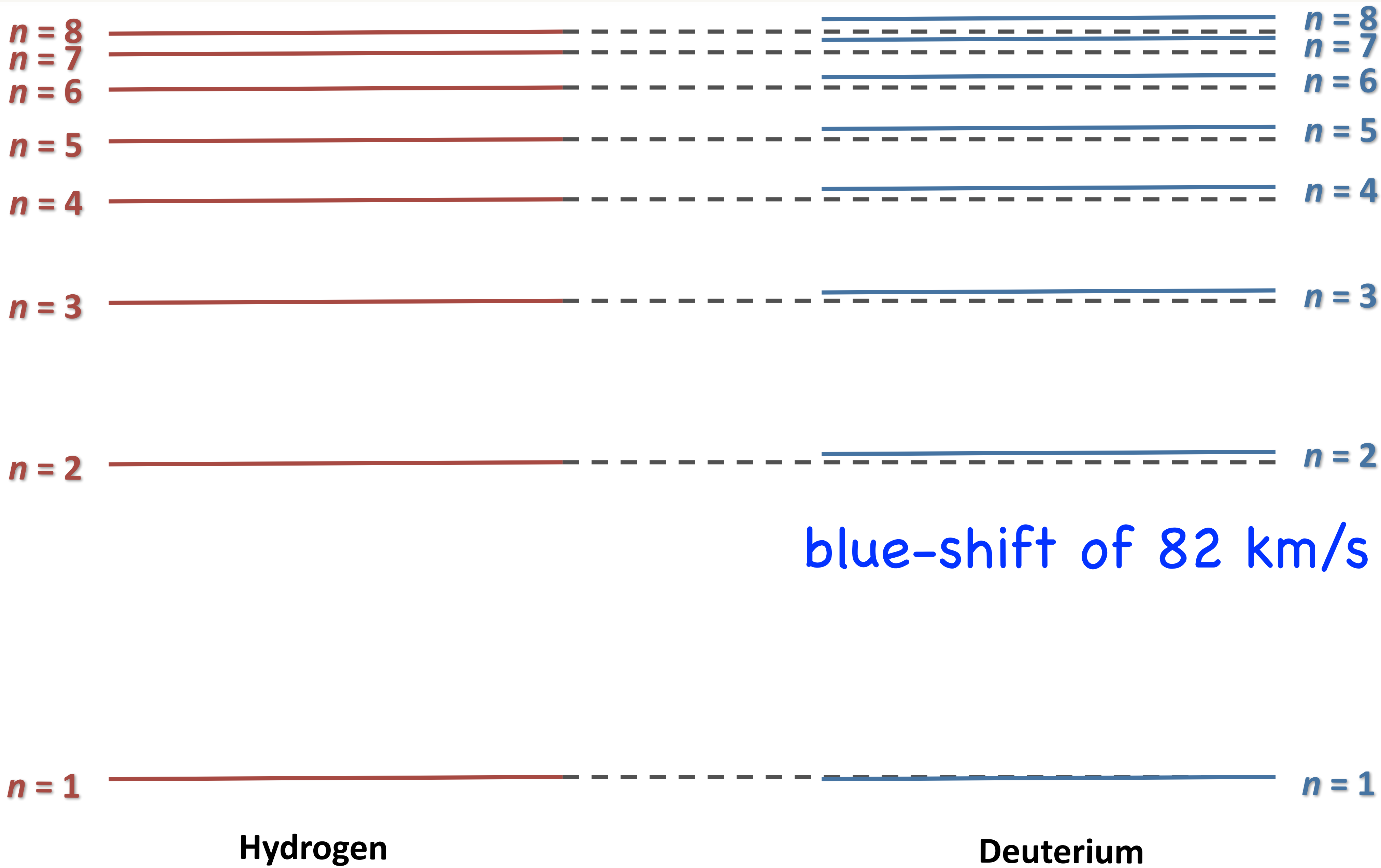
A sample portion of a quasar absorption spectrum



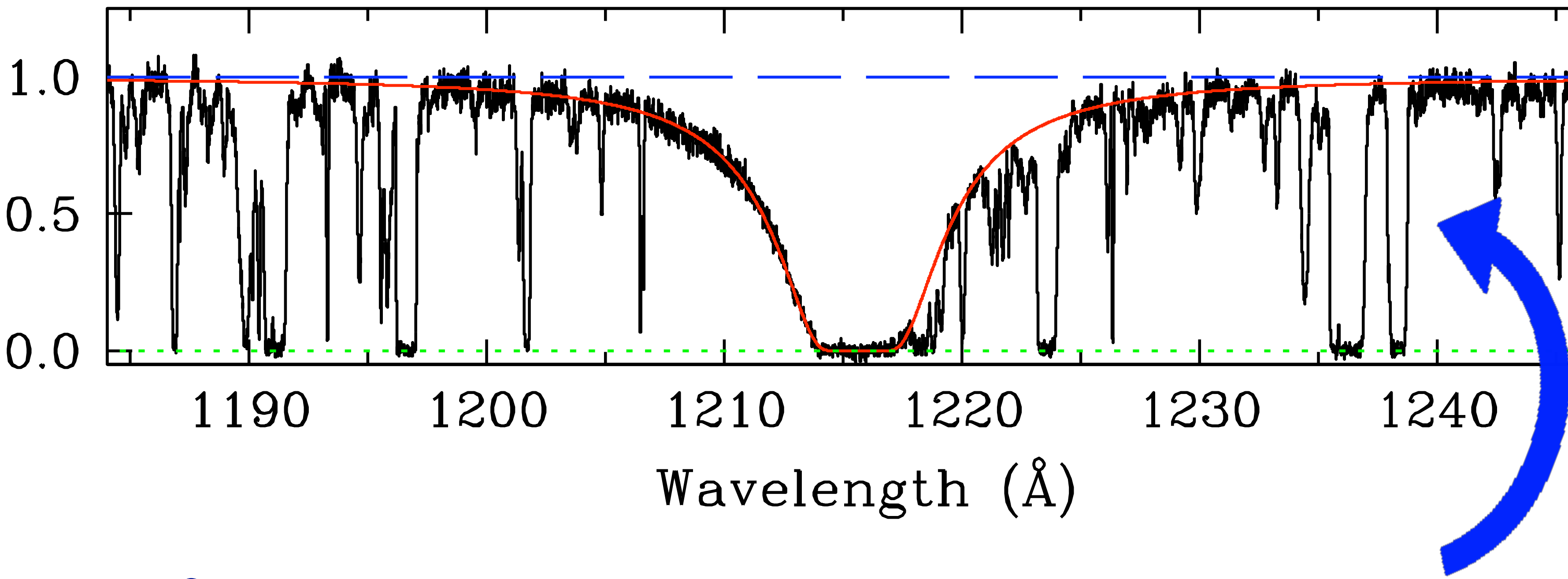
Lya forest: low-density, ionised, intergalactic gas



Energy Levels



A sample portion of a quasar absorption spectrum



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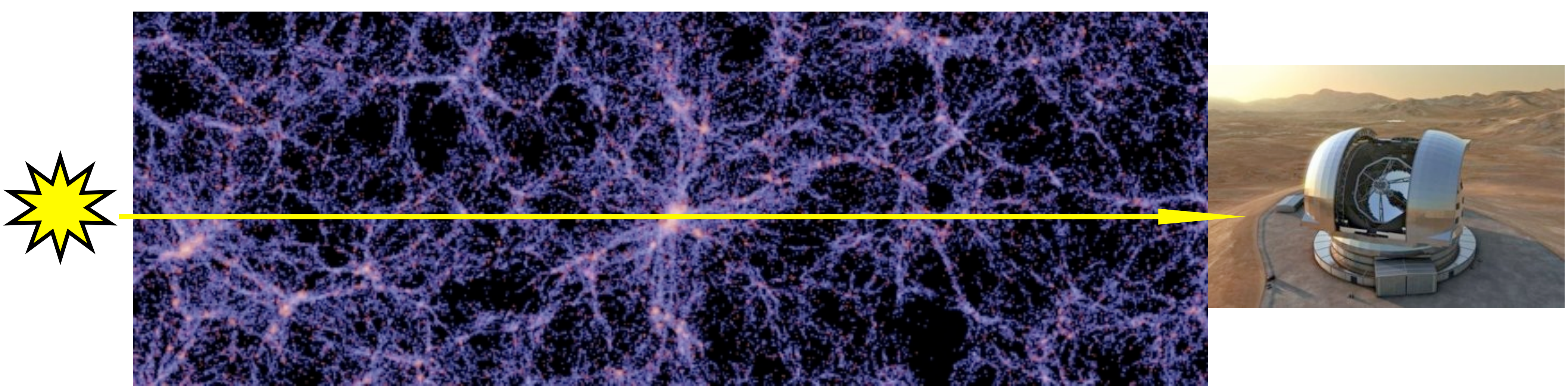
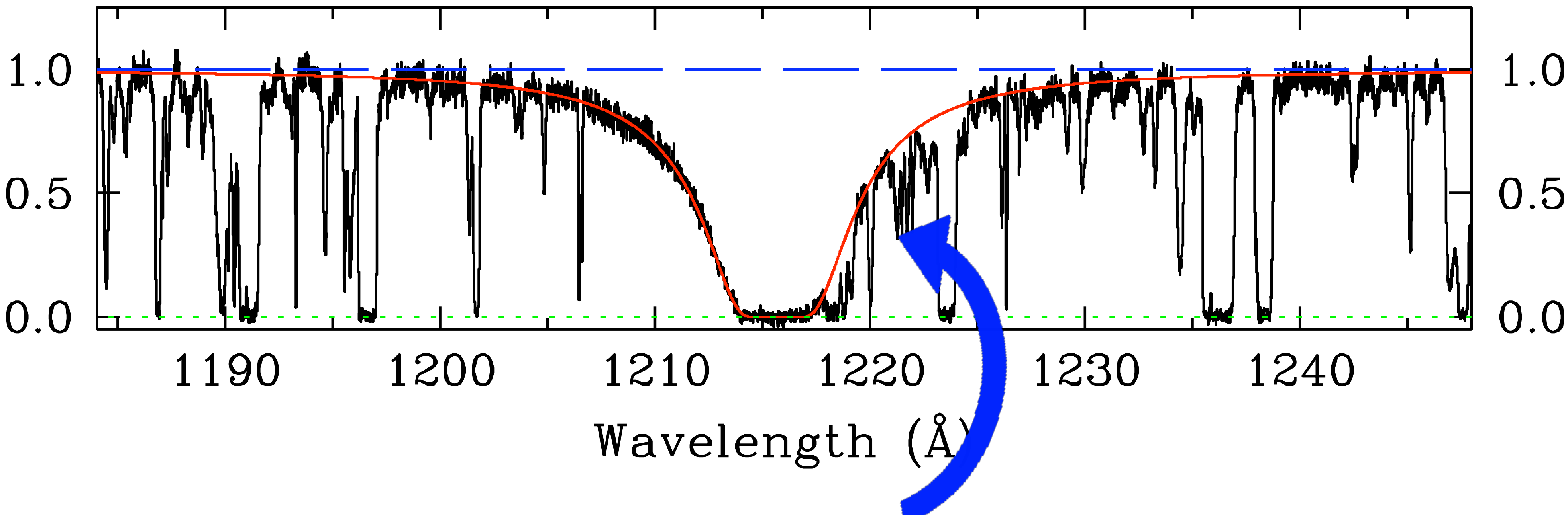
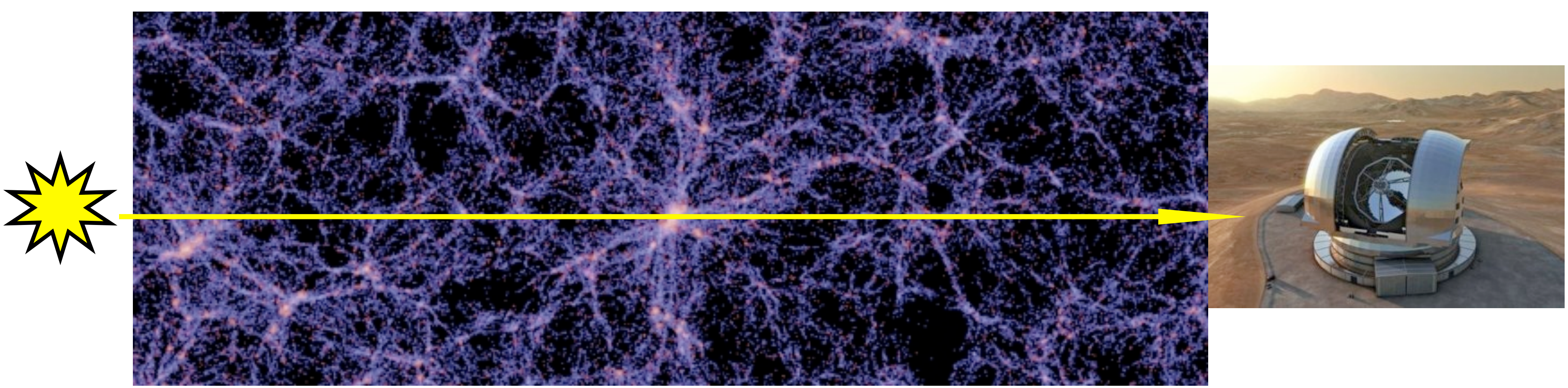


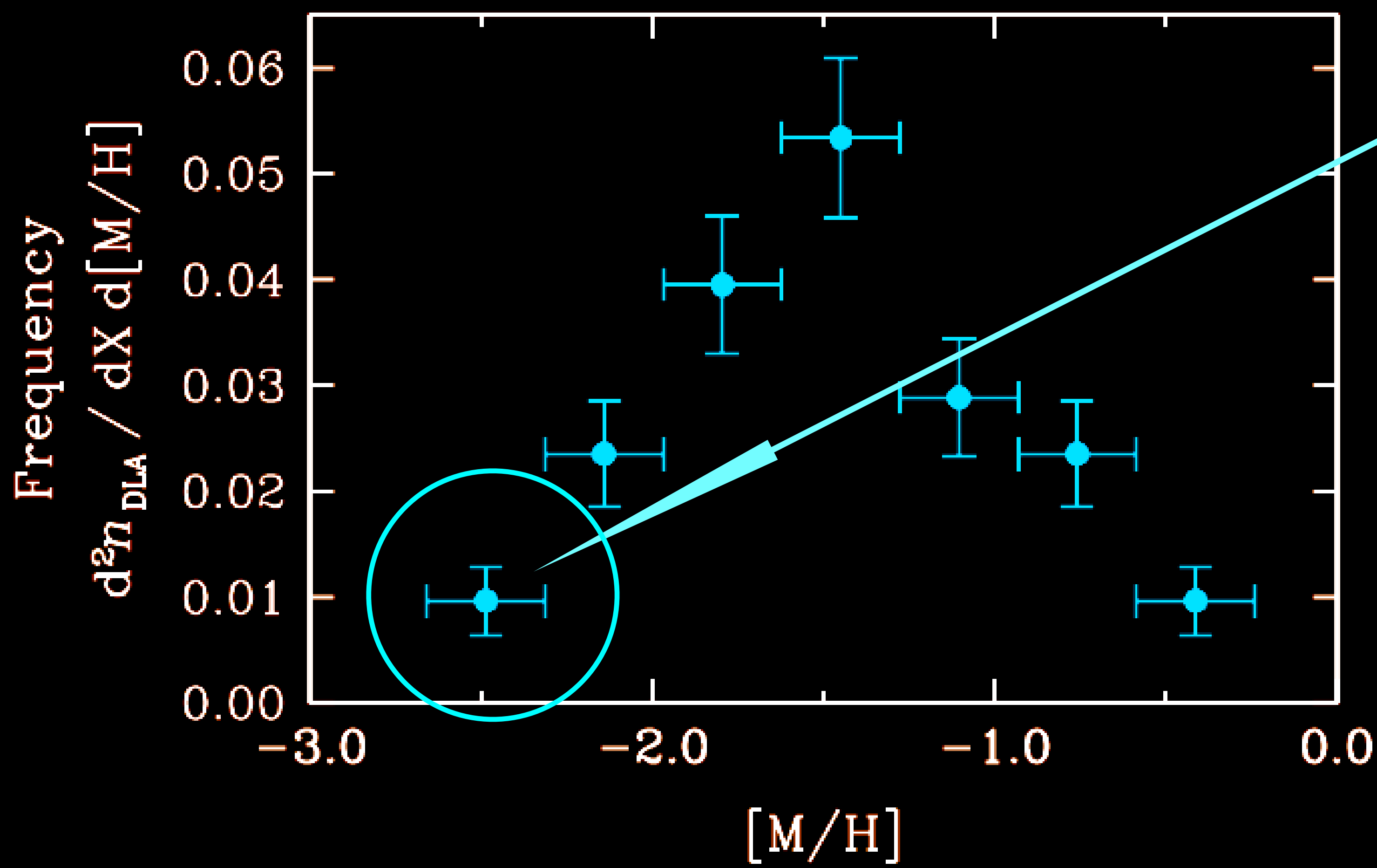
A sample portion of a quasar absorption spectrum



Damped Lyα: high-density, neutral, galactic(?) gas



Metallicity Distribution

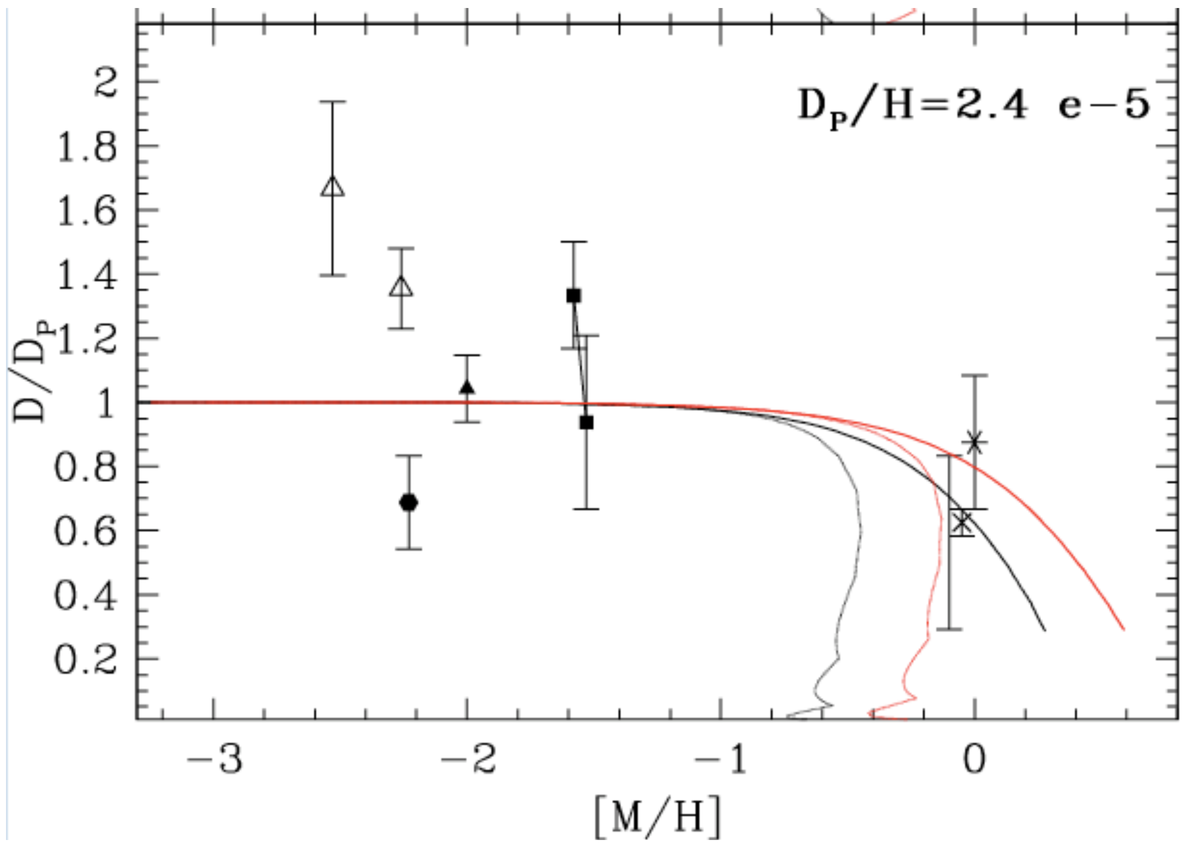


These are the DLAs we're after

Rafelski et al. 2012

Very Metal Poor DLAs are **the** choice astrophysical environments for measuring the primordial abundance of deuterium

✓ Low metallicities imply negligible astration of D



Prantzos & Ishimaru 2001

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- ✓ Low metallicities imply negligible astration of D
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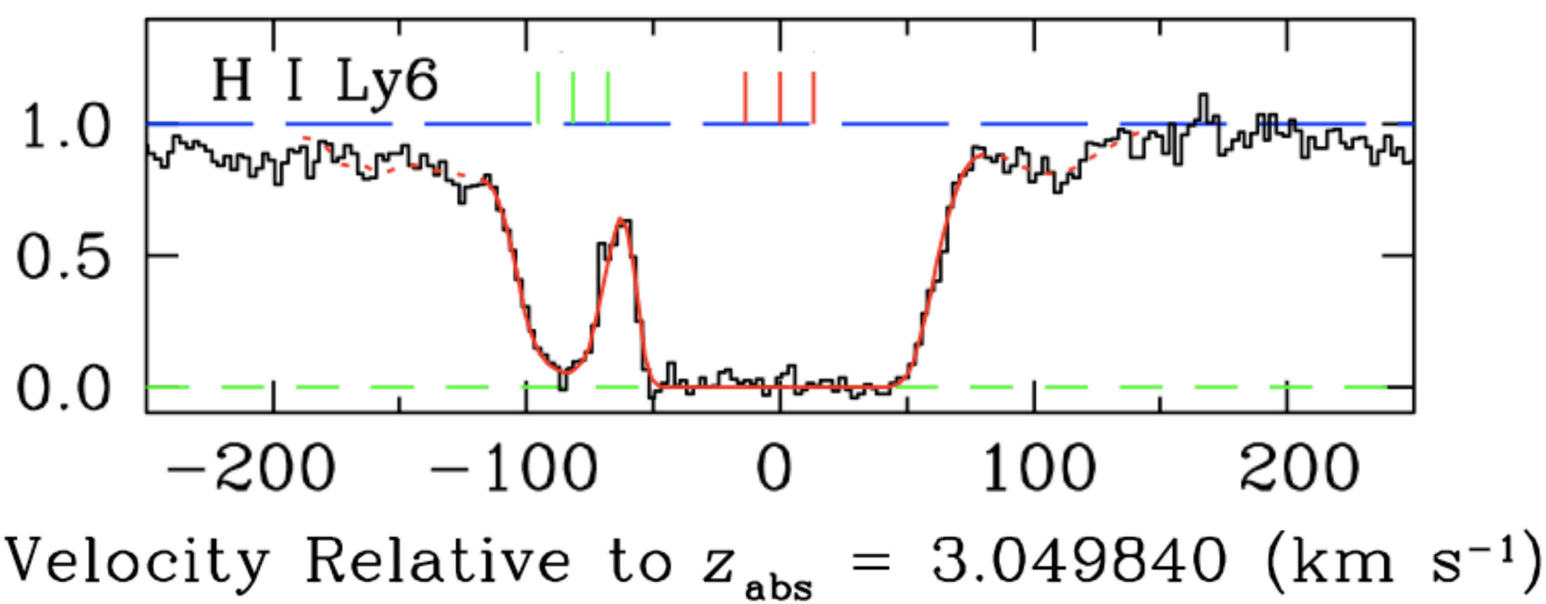
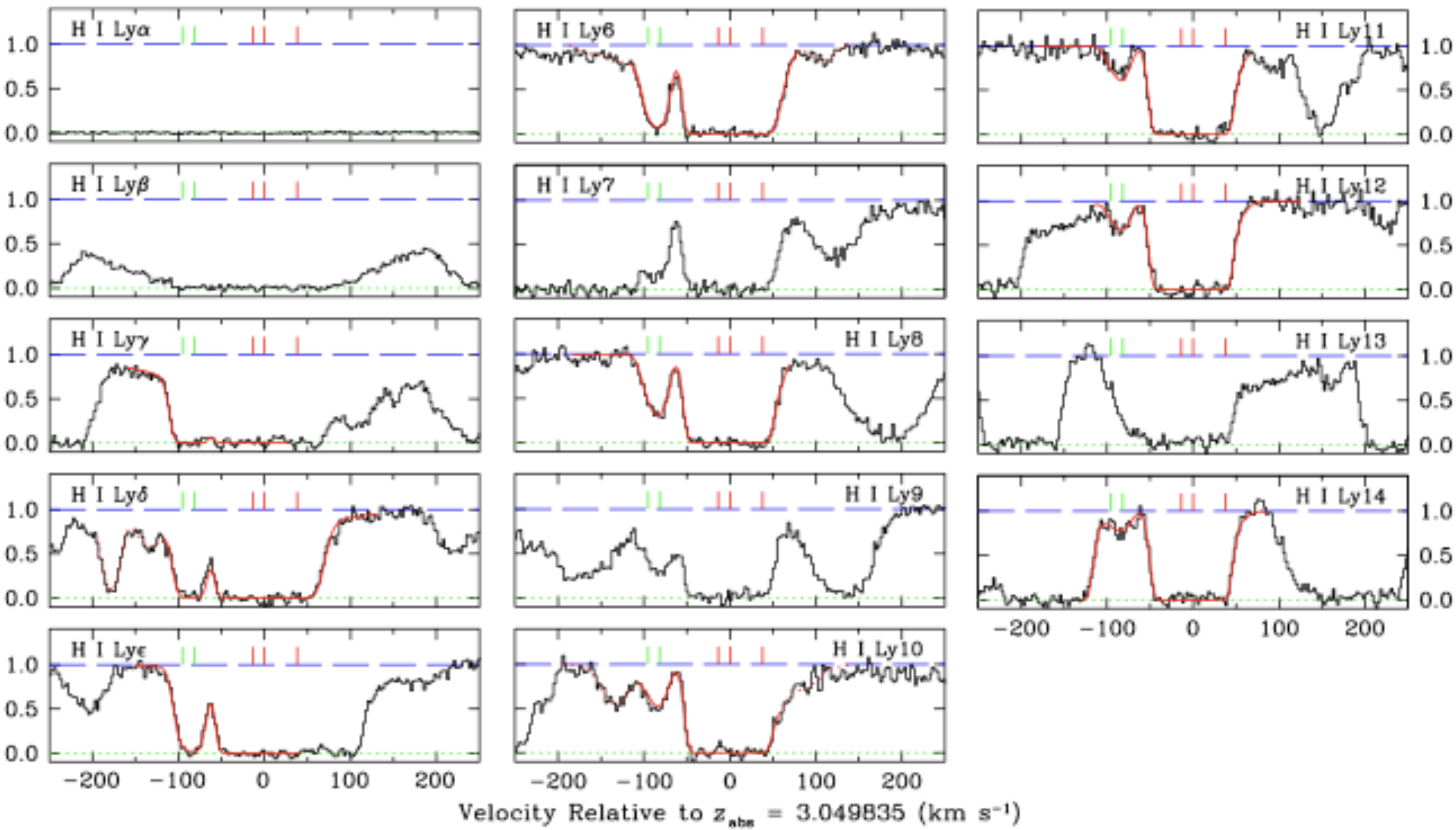


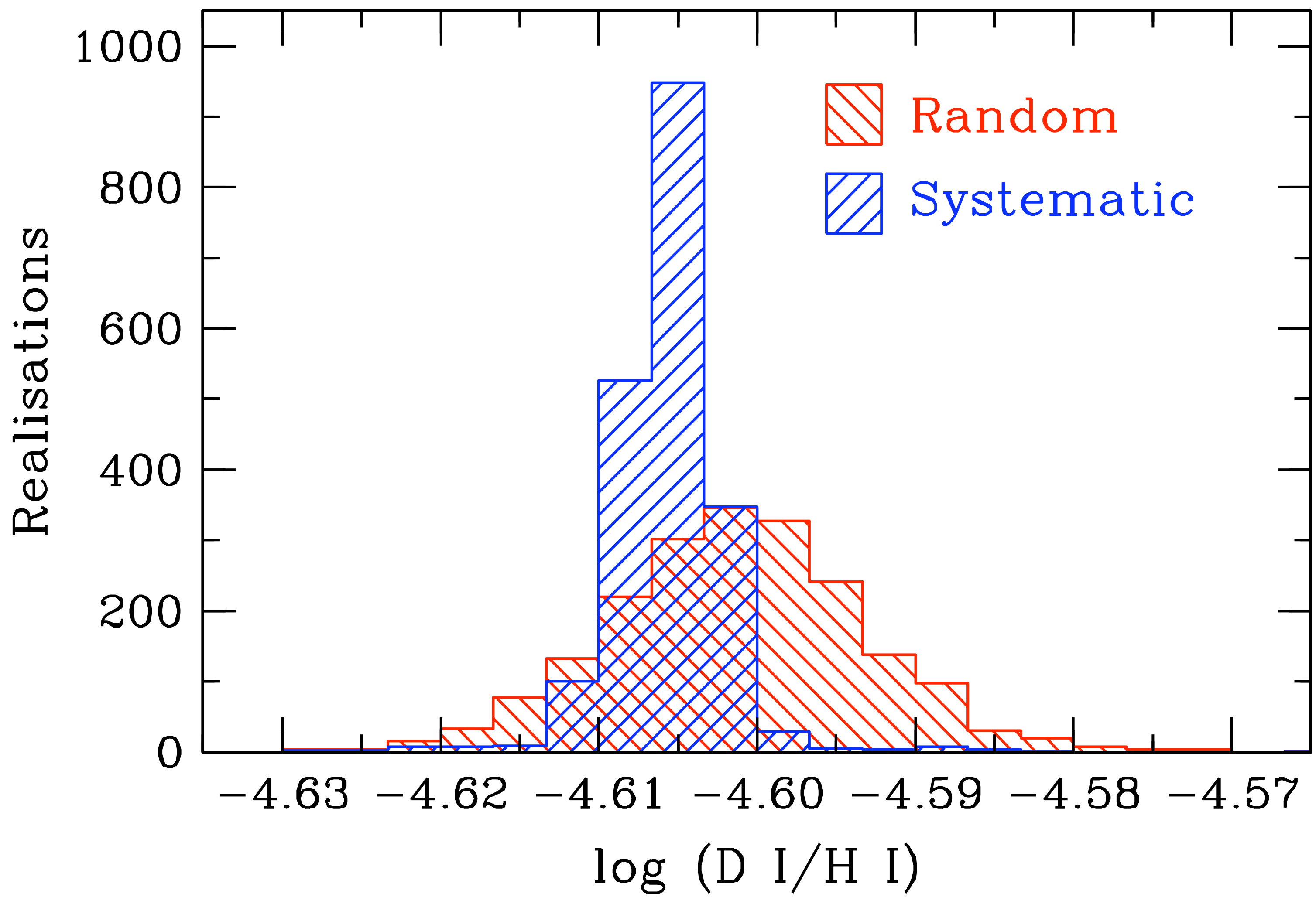
Very Metal Poor DLAs are **the** choice astrophysical environments for measuring the primordial abundance of deuterium

- ✓ Low metallicities imply negligible astration of D
- ✓ Narrow absorption lines make it possible to resolve the -82 km/s isotope shift between D and H
- ✓ High H I column densities give detectable D I lines in many transitions of the Lyman series

J1419+0829, z= 3.050, Fe/H = 1/200 solar

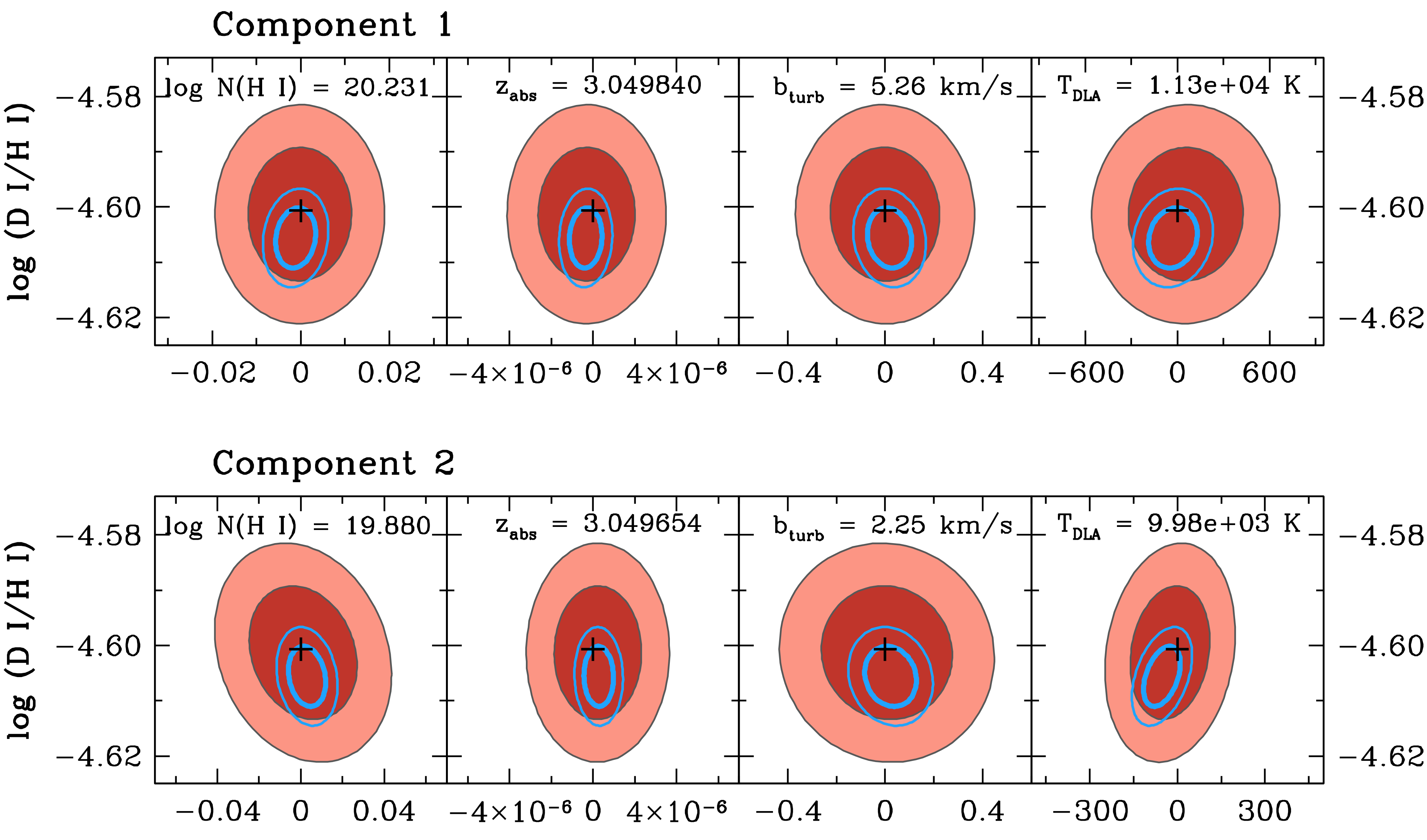


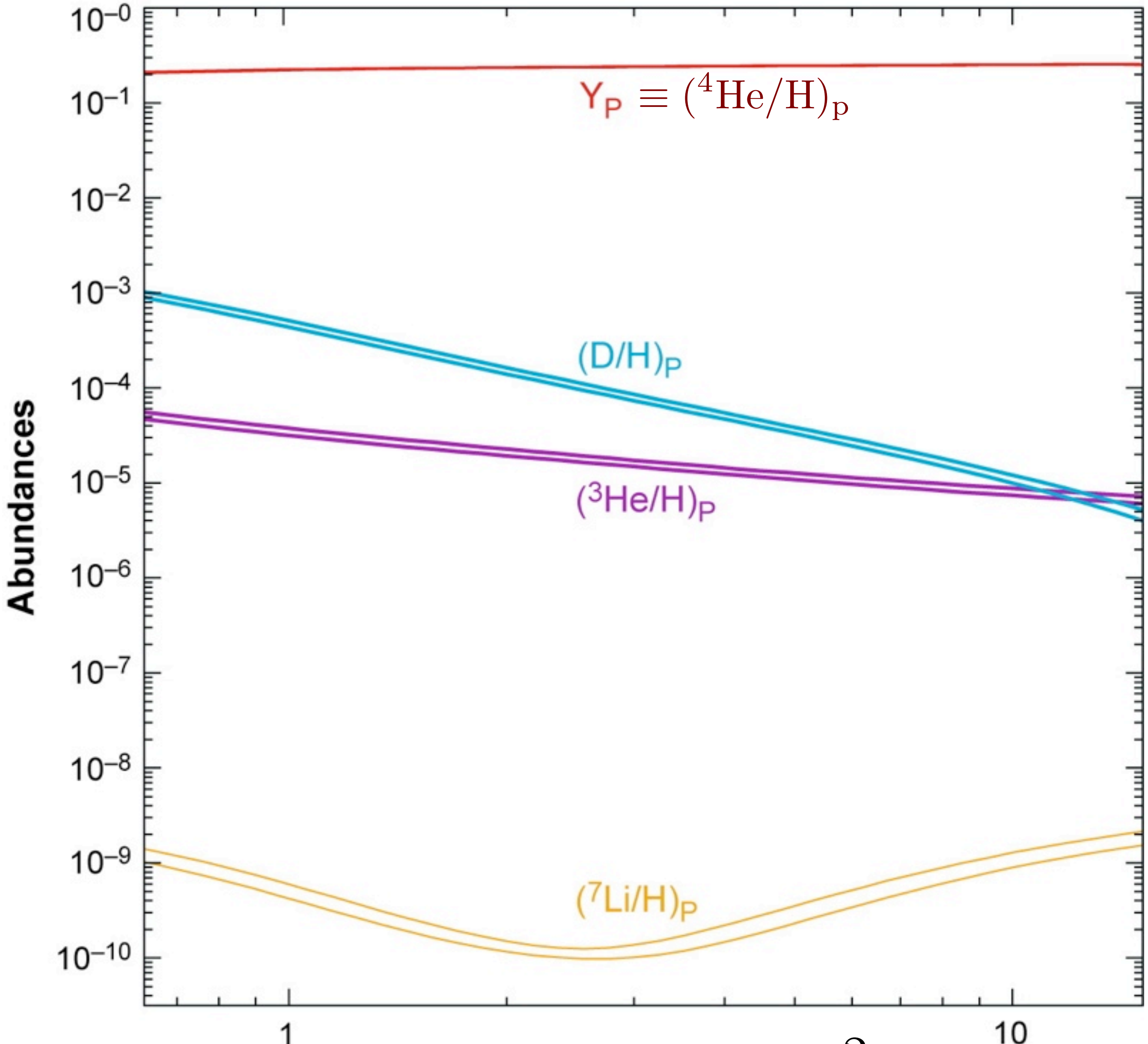
Spectral analysis tailored specifically to the determination of D/H and its error



Pettini & Cooke 2012

Spectral analysis tailored specifically to the determination of D/H and its error



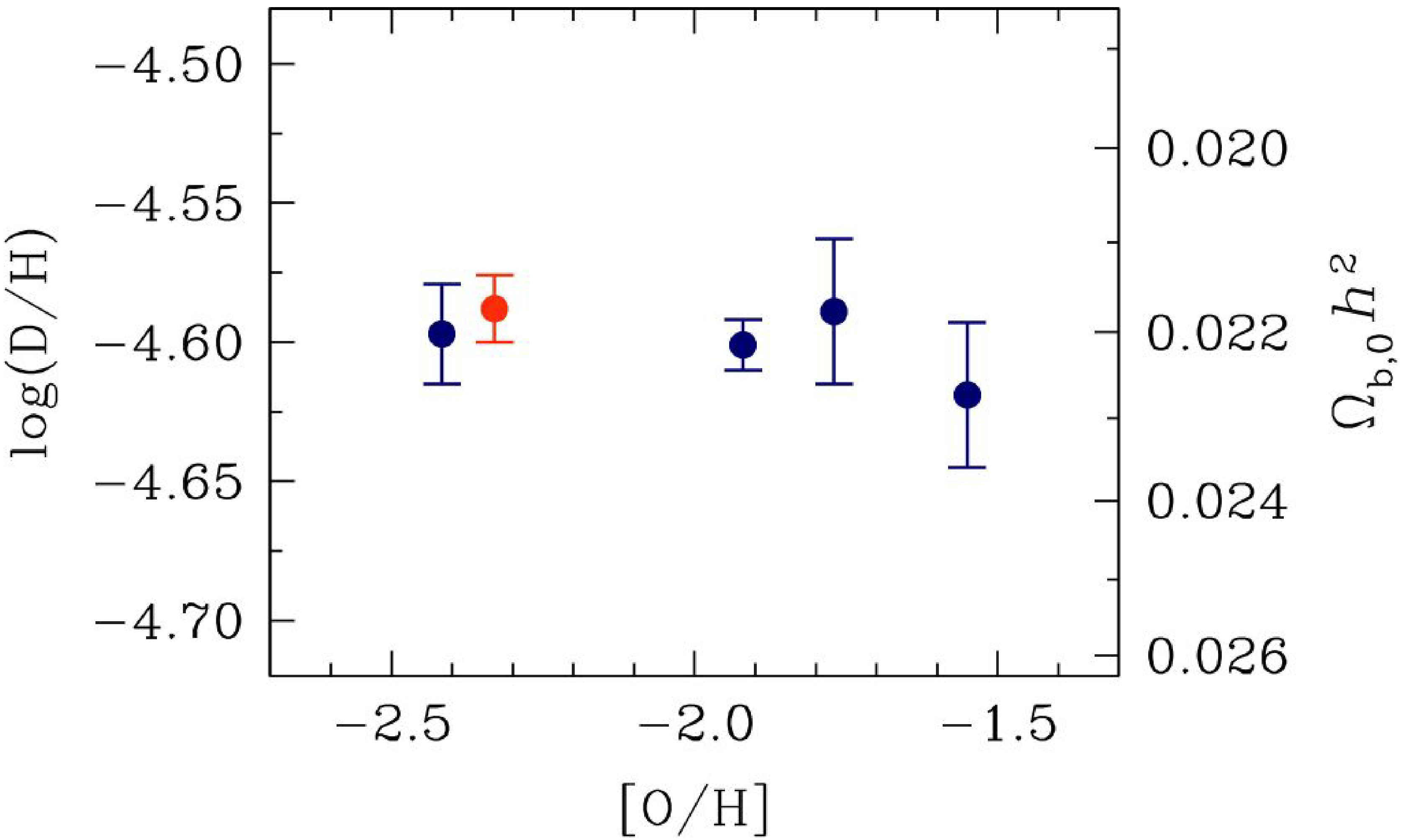


$$\eta_{10} = 274\,\Omega_b h^2$$

$$(D/H)_p = 2.55 \times 10^{-5} (6/\eta_{10})^{1.6}$$

Precision Measures of (D/H) [Cooke et al. 2014]

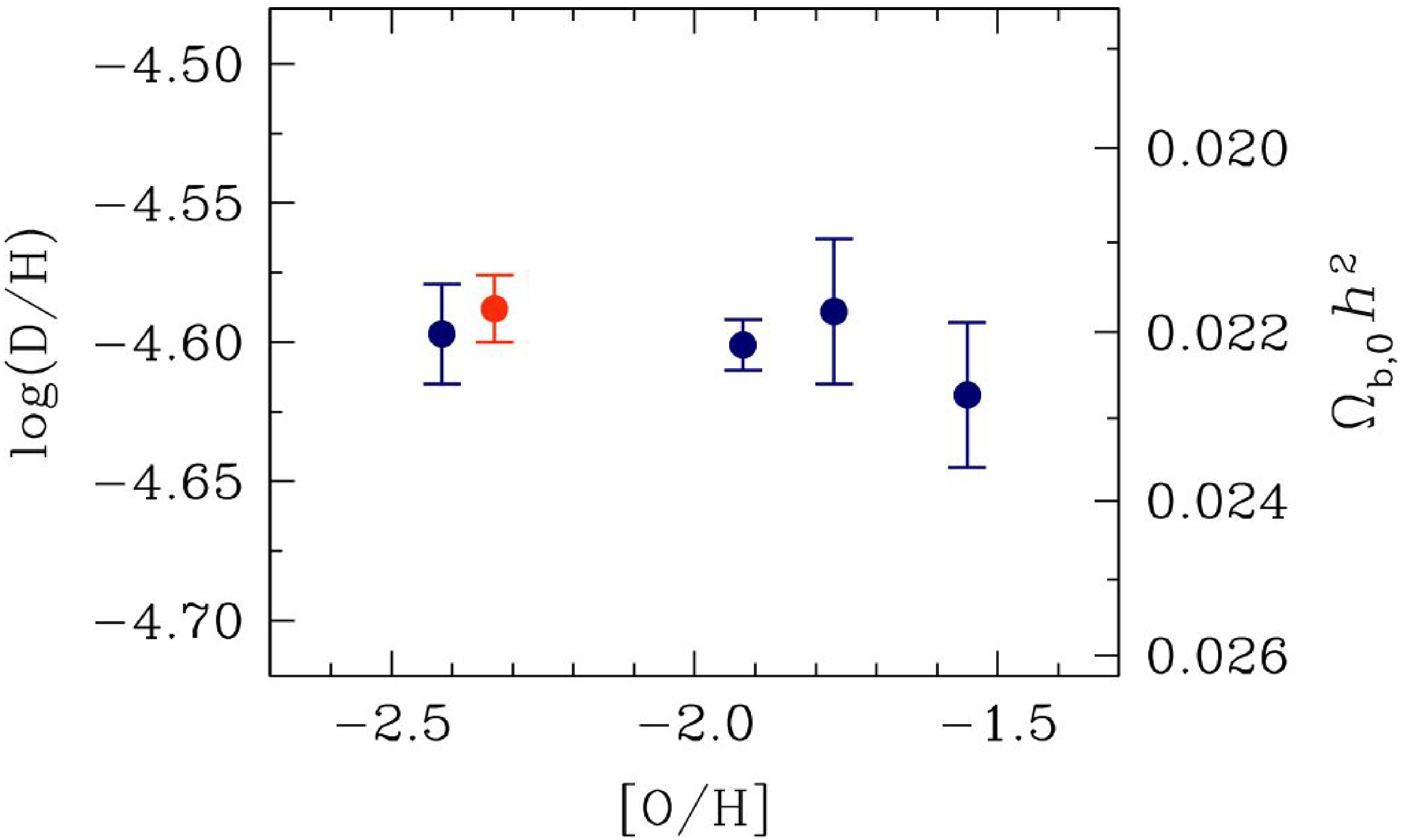
$$(\mathrm{D/H})_{\mathrm{DLA}} = (2.53 \pm 0.04) \times 10^{-5}$$

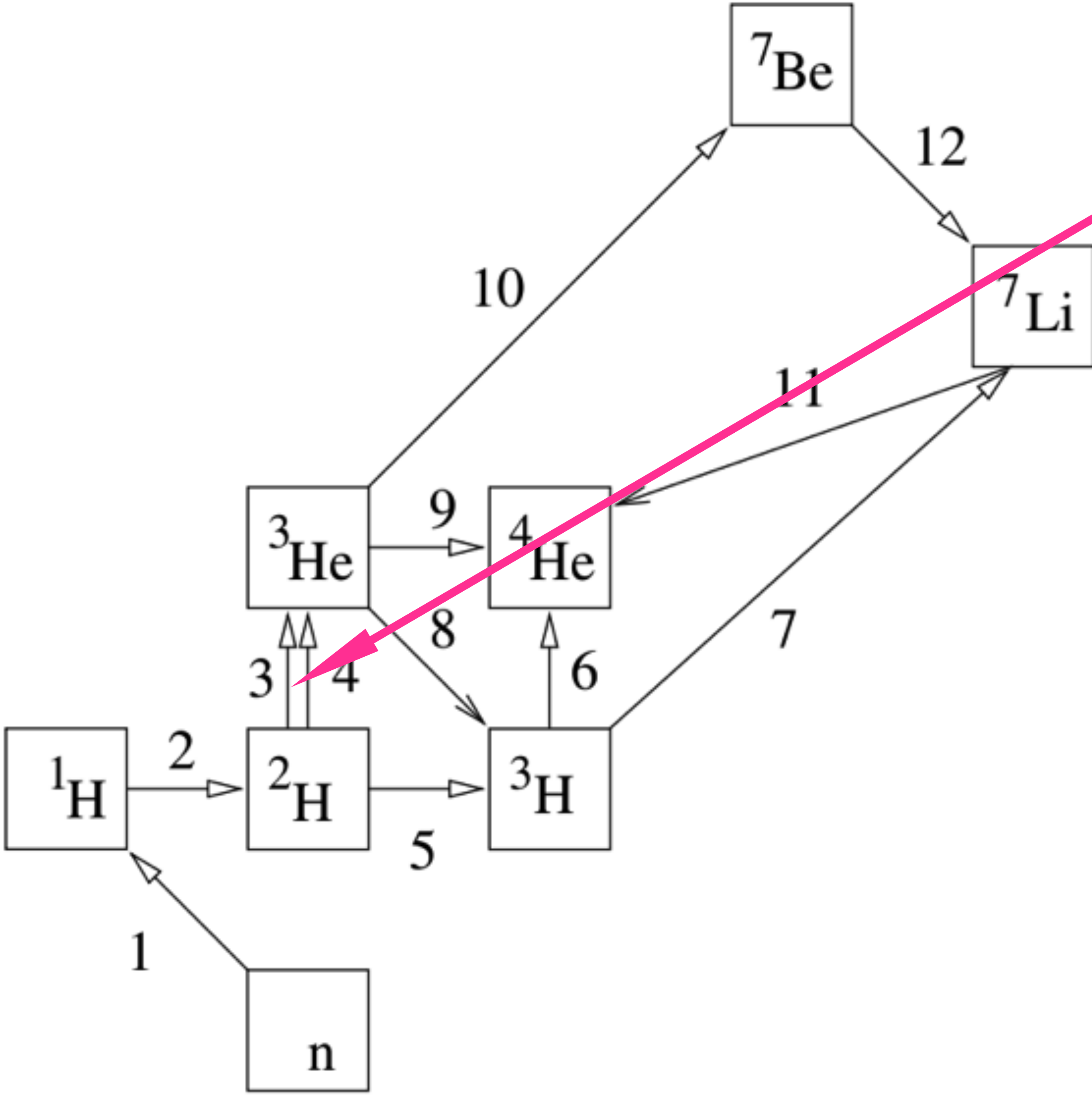


Precision Measures of (D/H) [Cooke et al. 2014]

$$100\,\Omega_{\rm b} h^2 = 2.202 \pm 0.045$$

(Random + Systematic Error)





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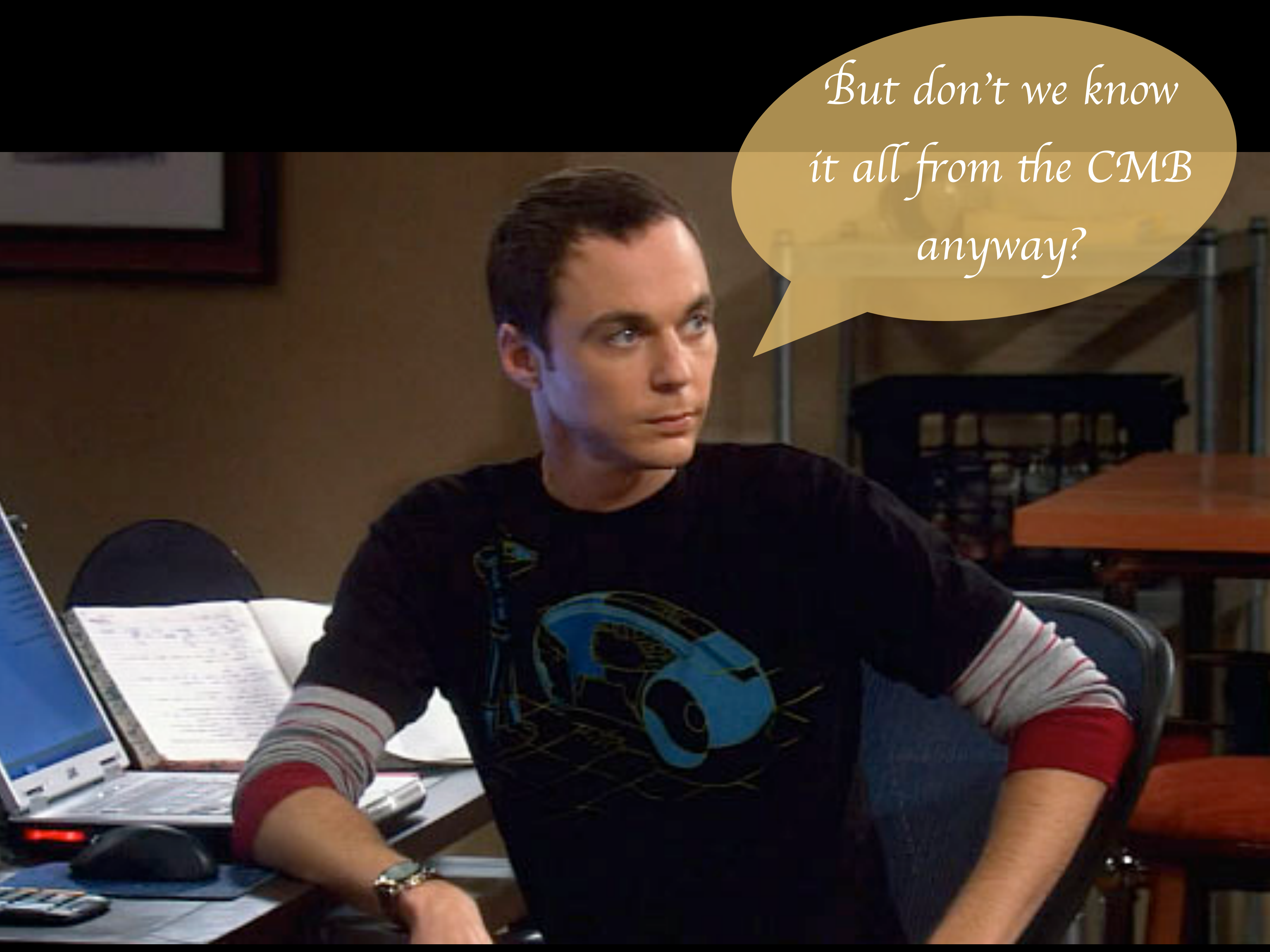
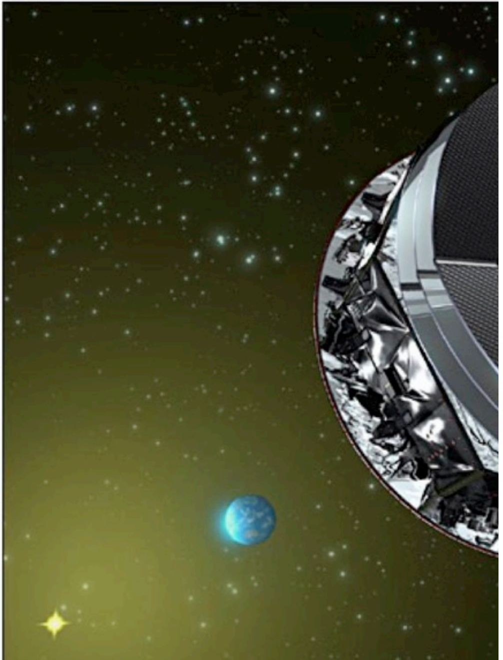
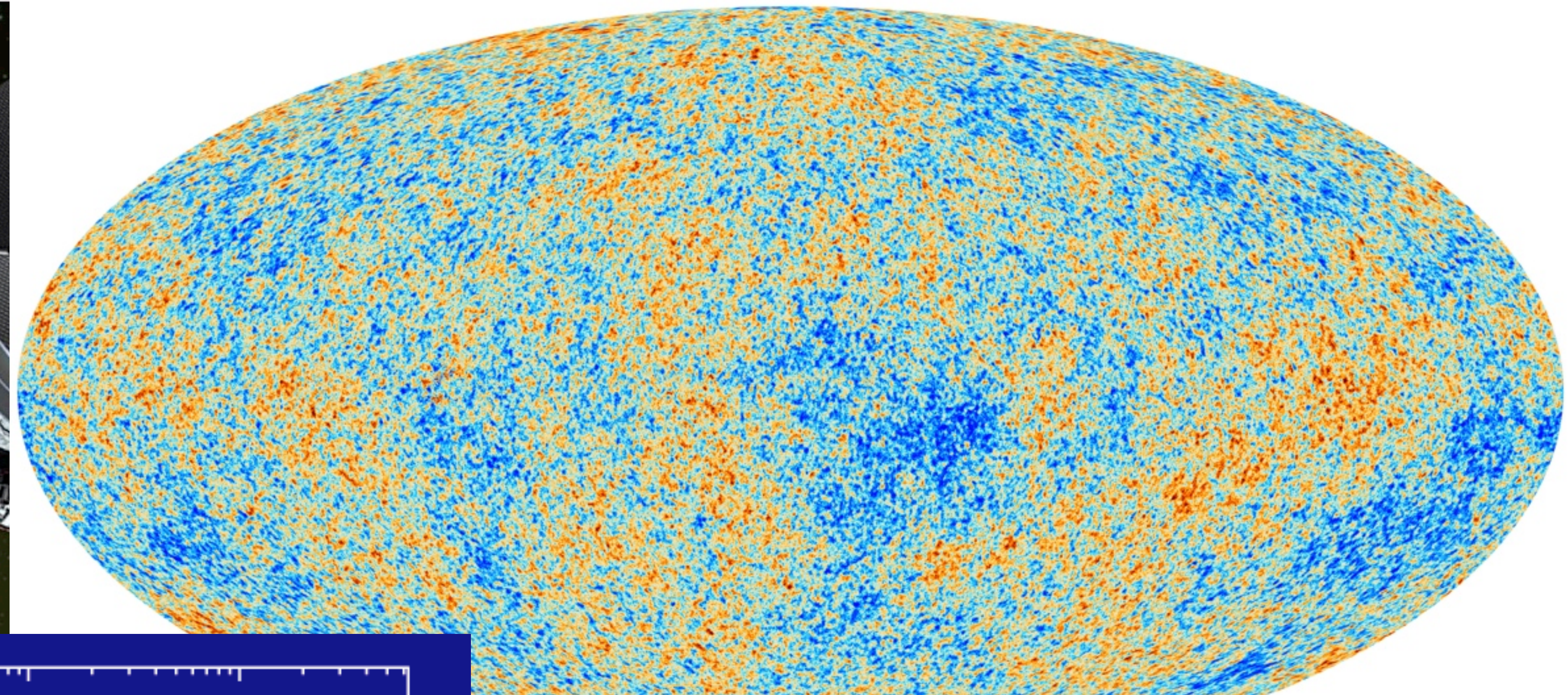
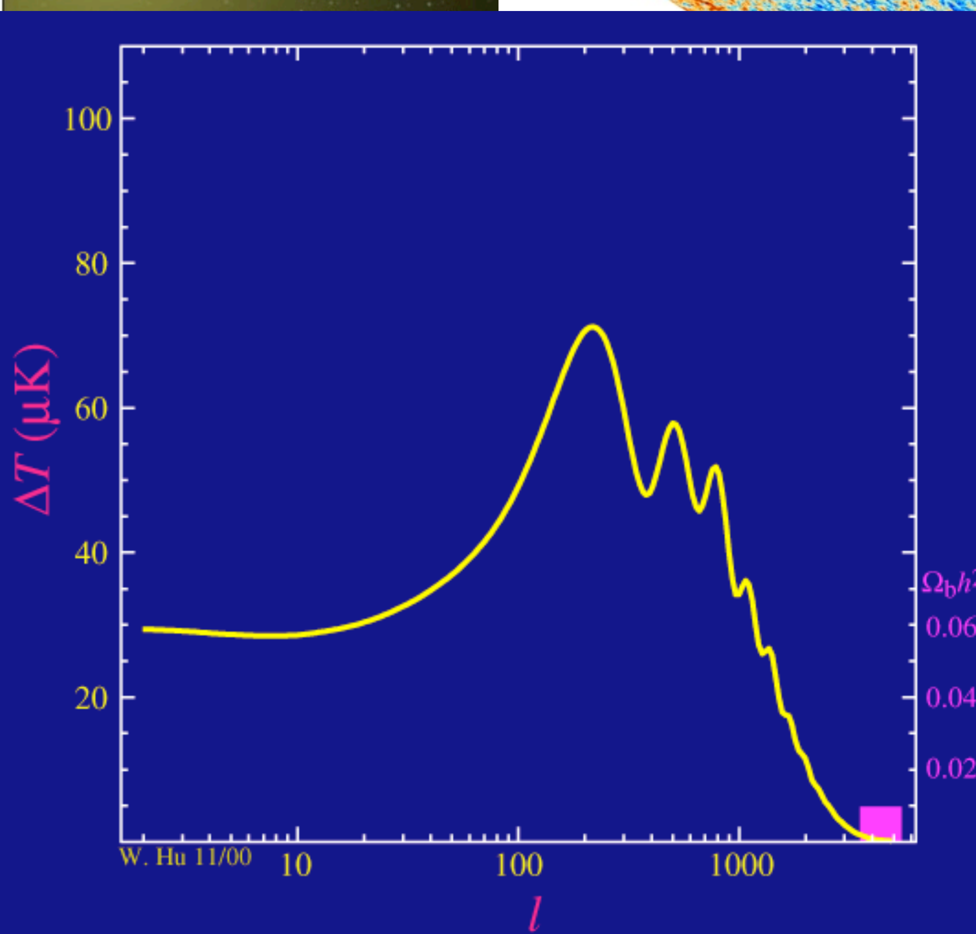
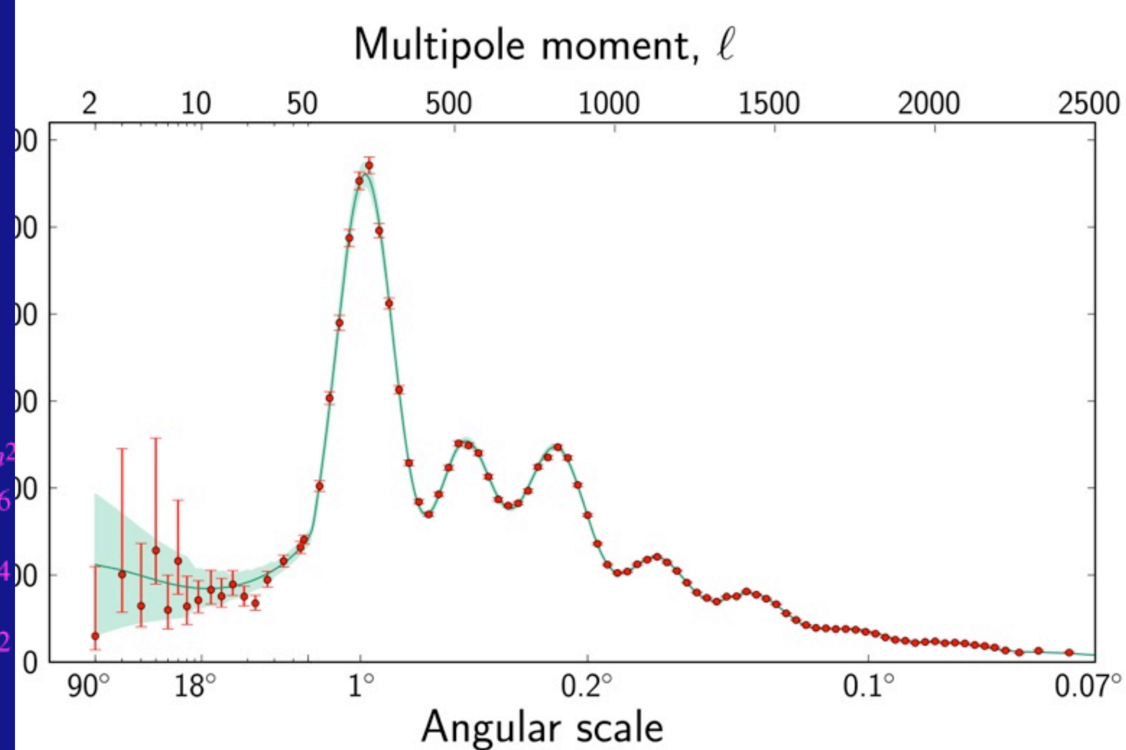
Nollett & Burles 2000


But don't we know it all from the CMB anyway?



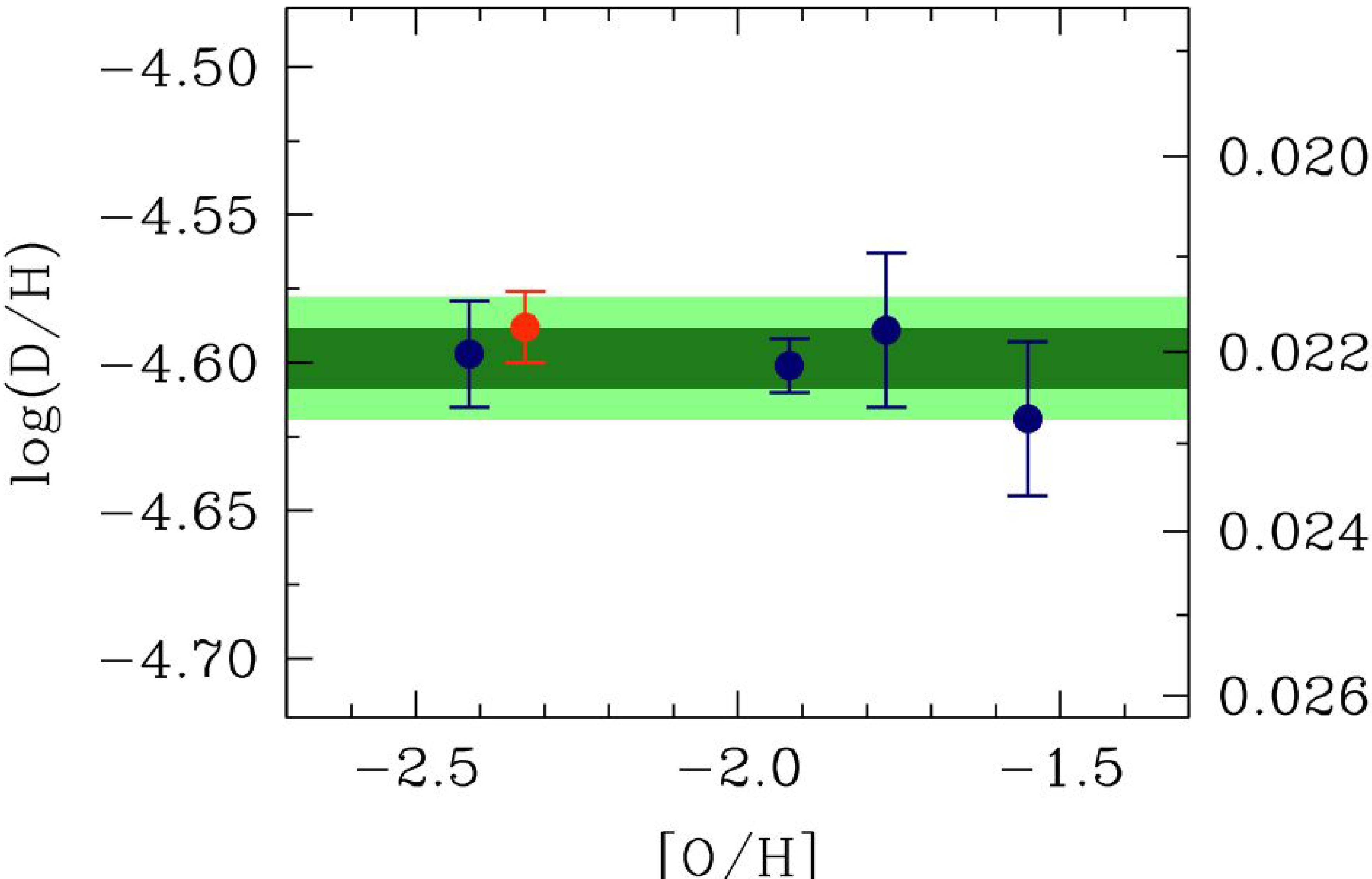



100
80
60
40
20
ΔT (μK)
Ωbh2
0.06
0.04
0.02
W. Hu 11/00
10
100
1000
l


Multipole moment, ℓ
2
10
50
500
1000
1500
2000
2500
0
90°
18°
1°
0.2°
0.1°
0.07°
Angular scale

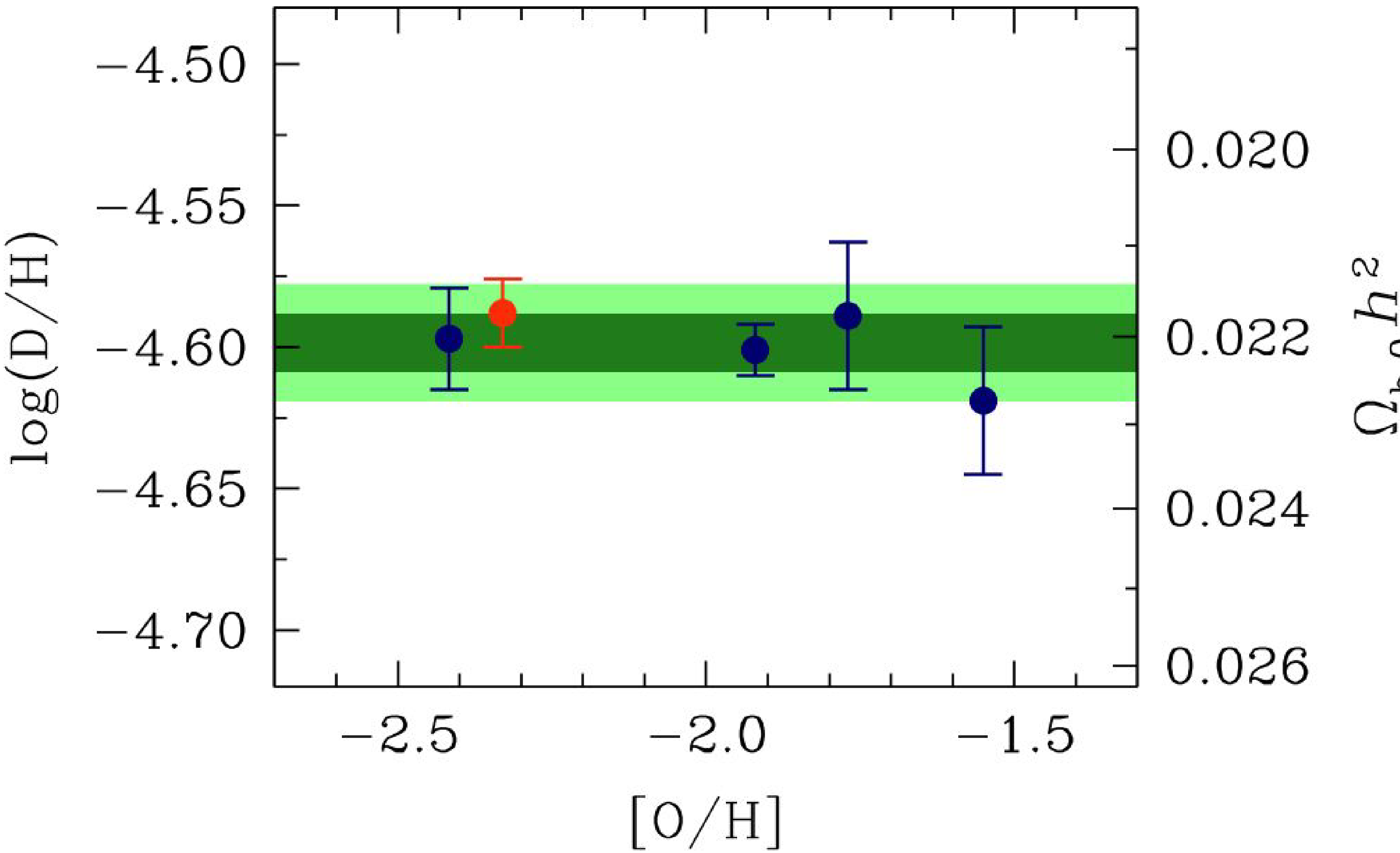
$$100\,\Omega_b h^2(\mathrm{CMB}) = 2.205 \pm 0.028$$

Planck XVI 2013



$$100\,\Omega_b h^2(\mathrm{BBN}) = 2.202 \pm 0.045$$

(Random + Systematic Error)



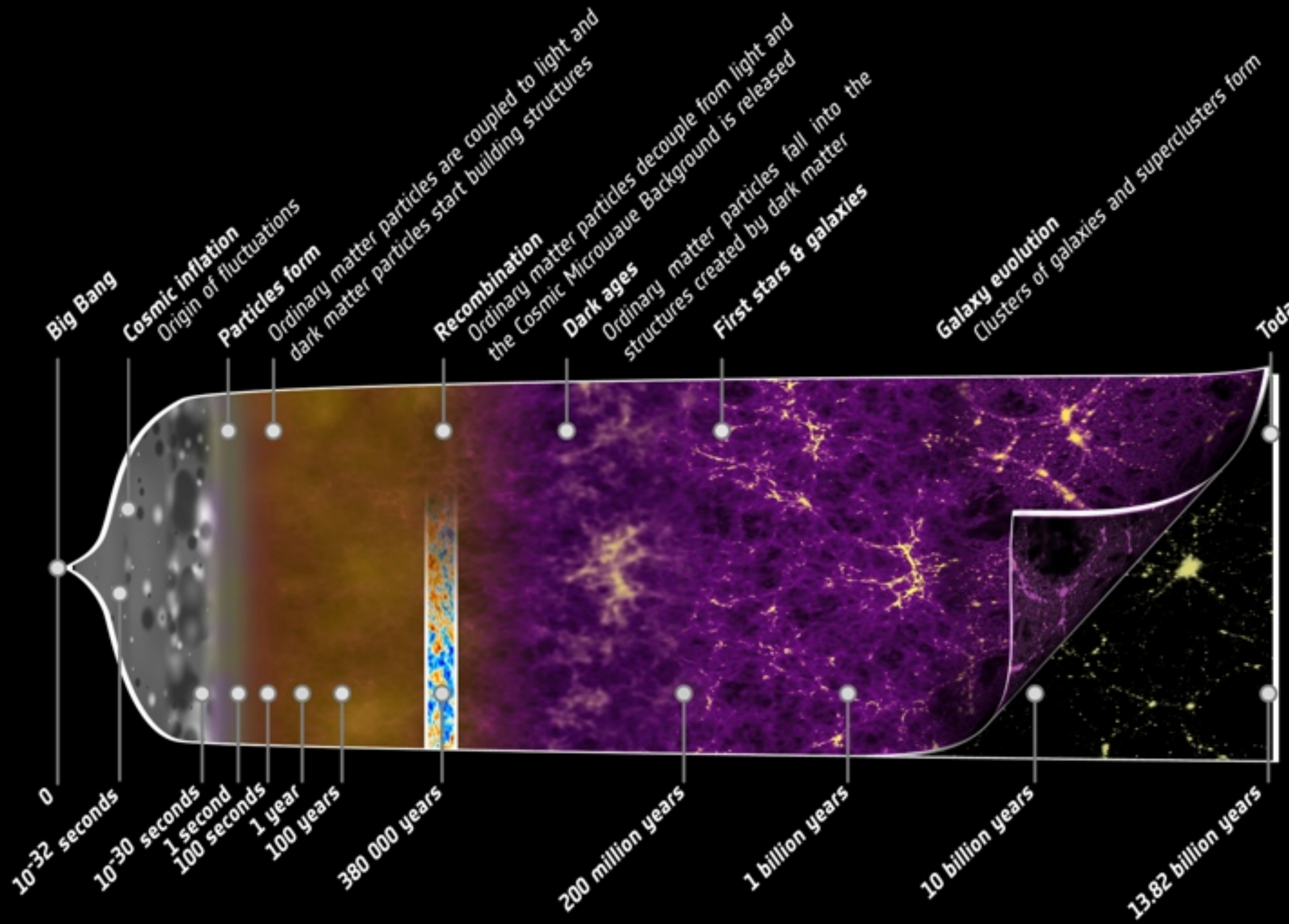


Image credit: ESA

BBN and CMB measurements have now reached a level of accuracy sufficient to start testing for departures from the `standard model'.

In particular, test for the possible existence of `dark radiation', i.e. any hidden radiation decoupled from photons.

If dark matter, why not `dark radiation'?

Departures from the standard model are often parameterised by the effective number of neutrino species.

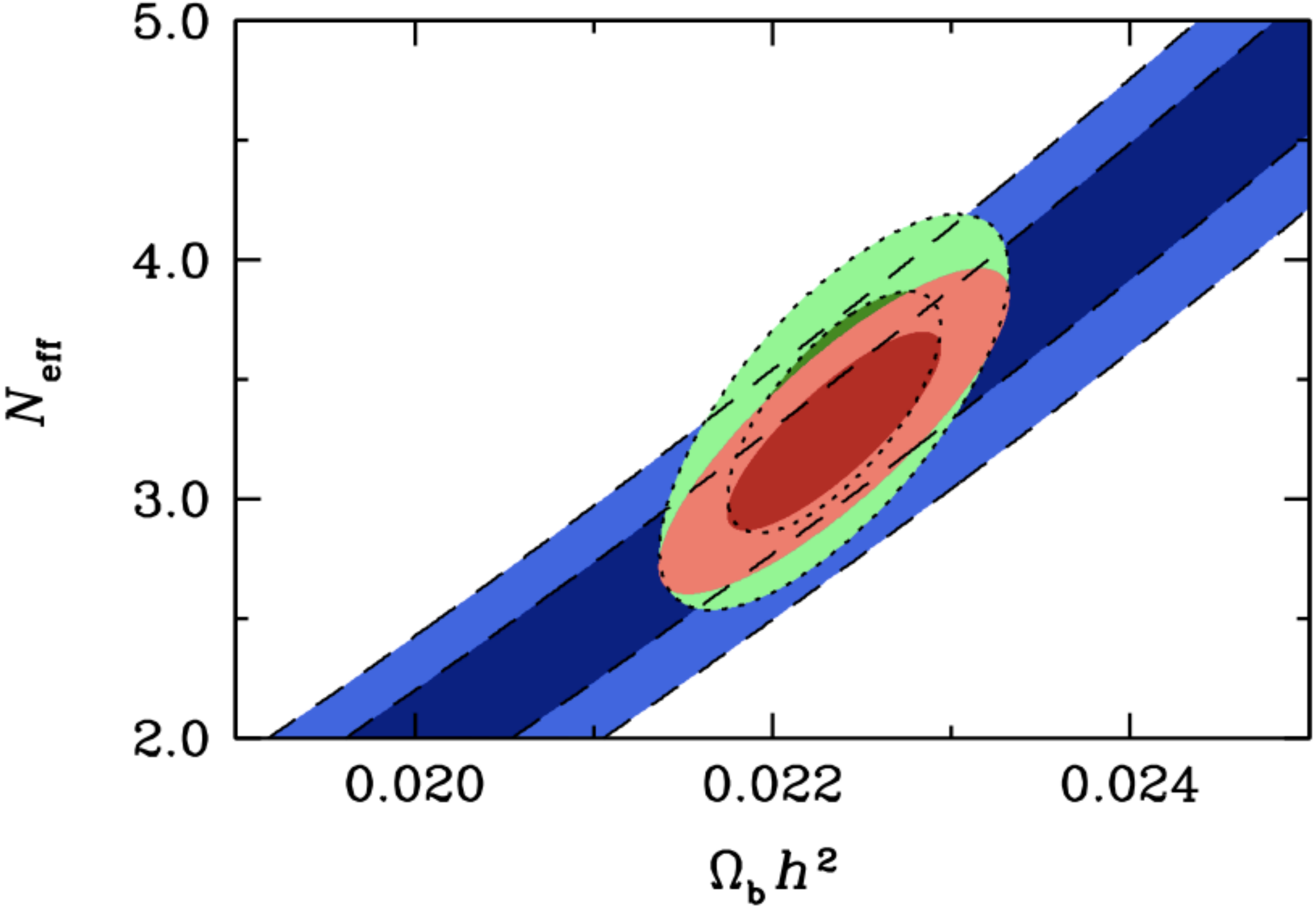
$\mathcal{N}_{\rm eff} = 3.046$ in standard BBN

The expansion rate factor S is altered by the presence of additional radiation components:

$$S = \left(1 + \frac{7\Delta\mathcal{N}_{\rm eff}}{43}\right)^{1/2}$$

Joint D/H and CMB Constraints on `dark radiation'

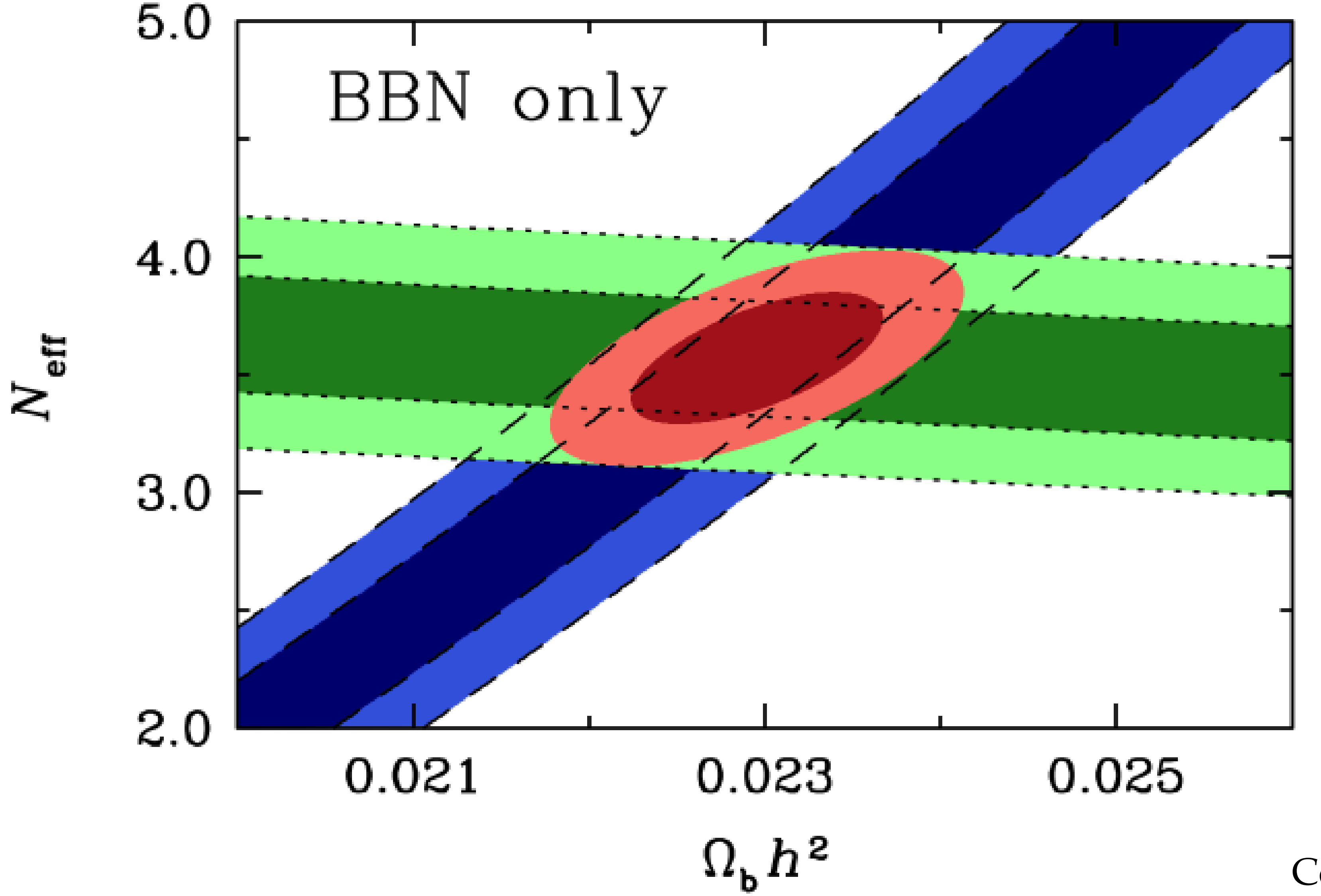
$$N_{\text{eff}} = 3.28 \pm 0.28$$



Cooke et al. 2014

BBN Constraints on `dark radiation'

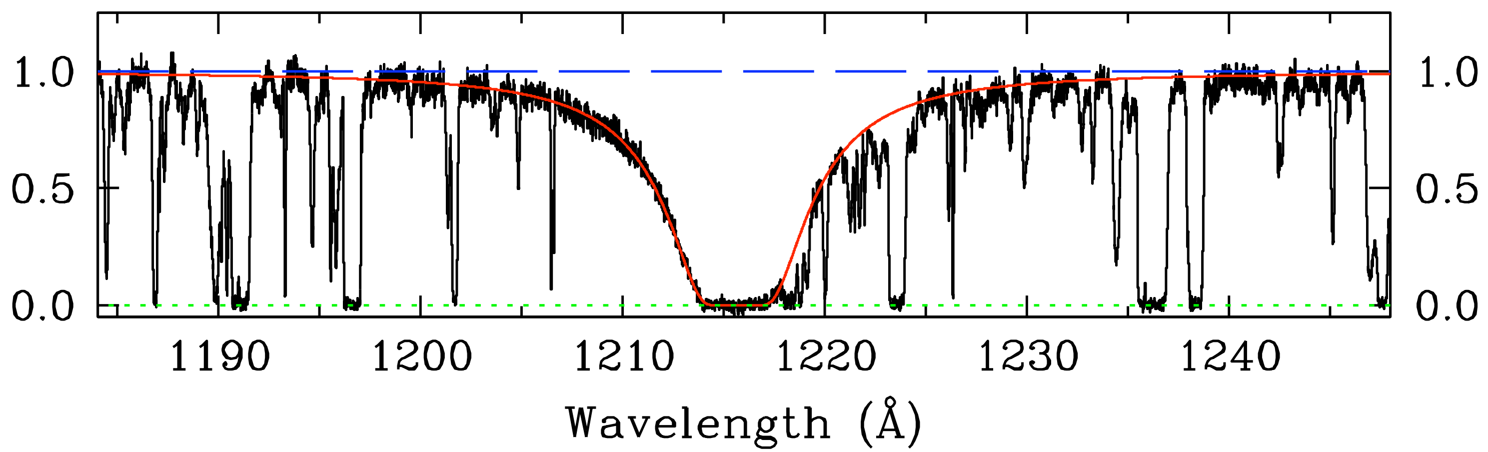
$$N_{\rm eff} = 3.50 \pm 0.20$$



Cooke et al. 2014

Summary

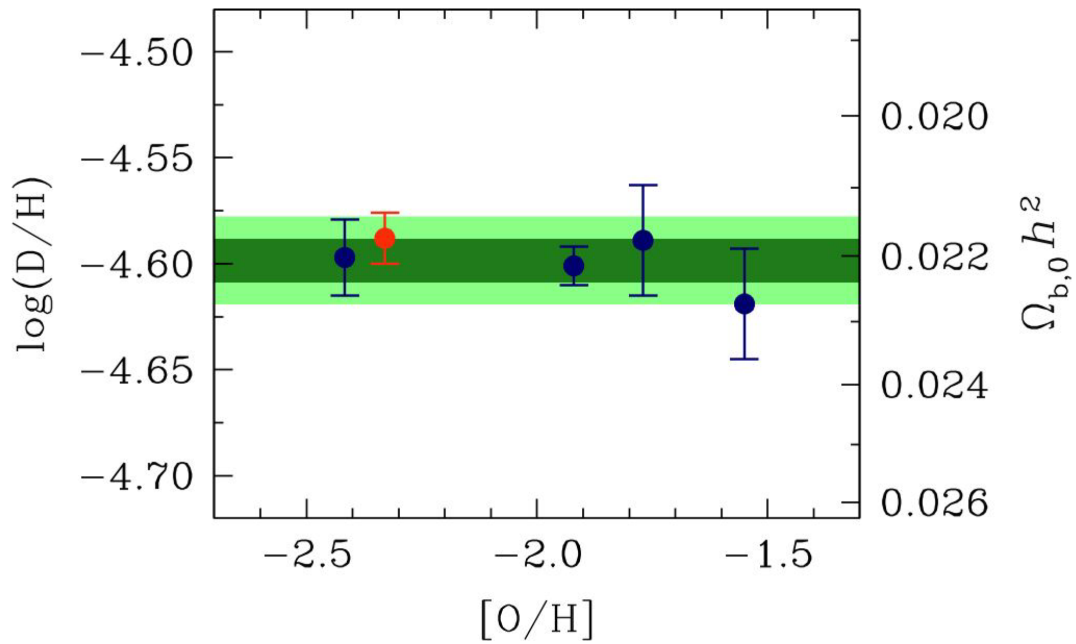
- There exists a population of neutral gas clouds which at redshifts z = 2 - 4 had undergone minimal enrichment by stellar nucleosynthesis.



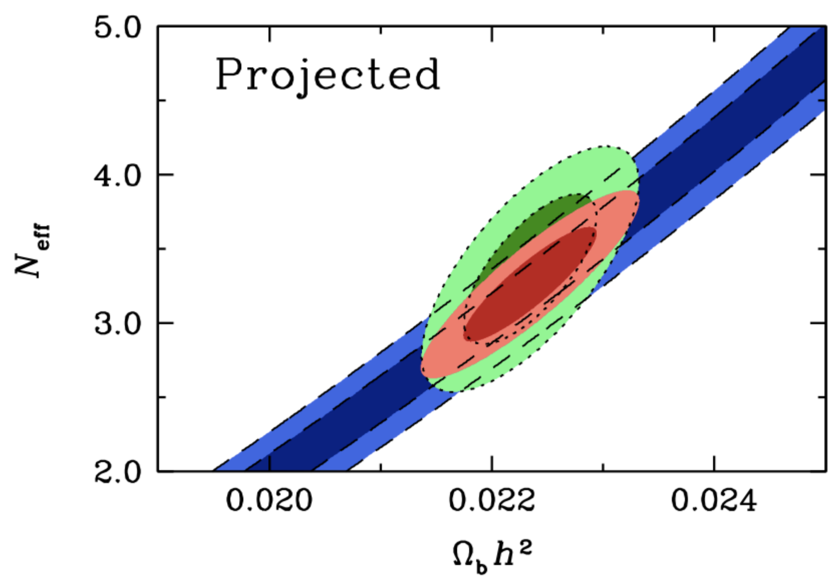
- Chemical studies of these `Extremely Metal-Poor Damped Lyman Alpha Systems' complement very effectively analogous measures in old stars of the Milky Way and nearby galaxies.

Main Results: Deuterium

- Concordance between values of $\Omega_b h^2$ from CMB and D/H in metal-poor DLAs.



- In future, offers the means to test for non-standard physics, e.g. axions.



With Thanks to:

Ryan Cooke (UCSC)

The End