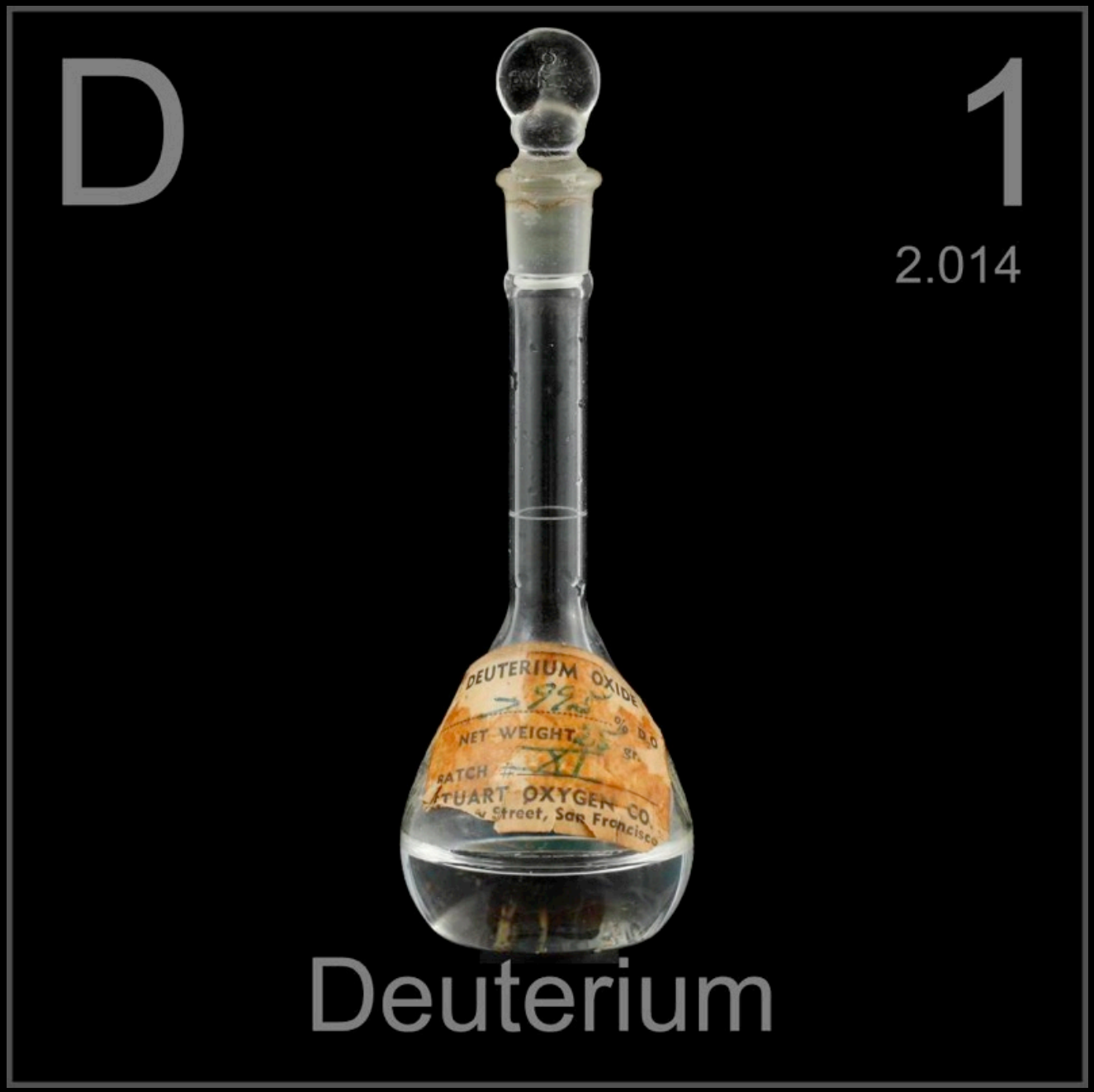
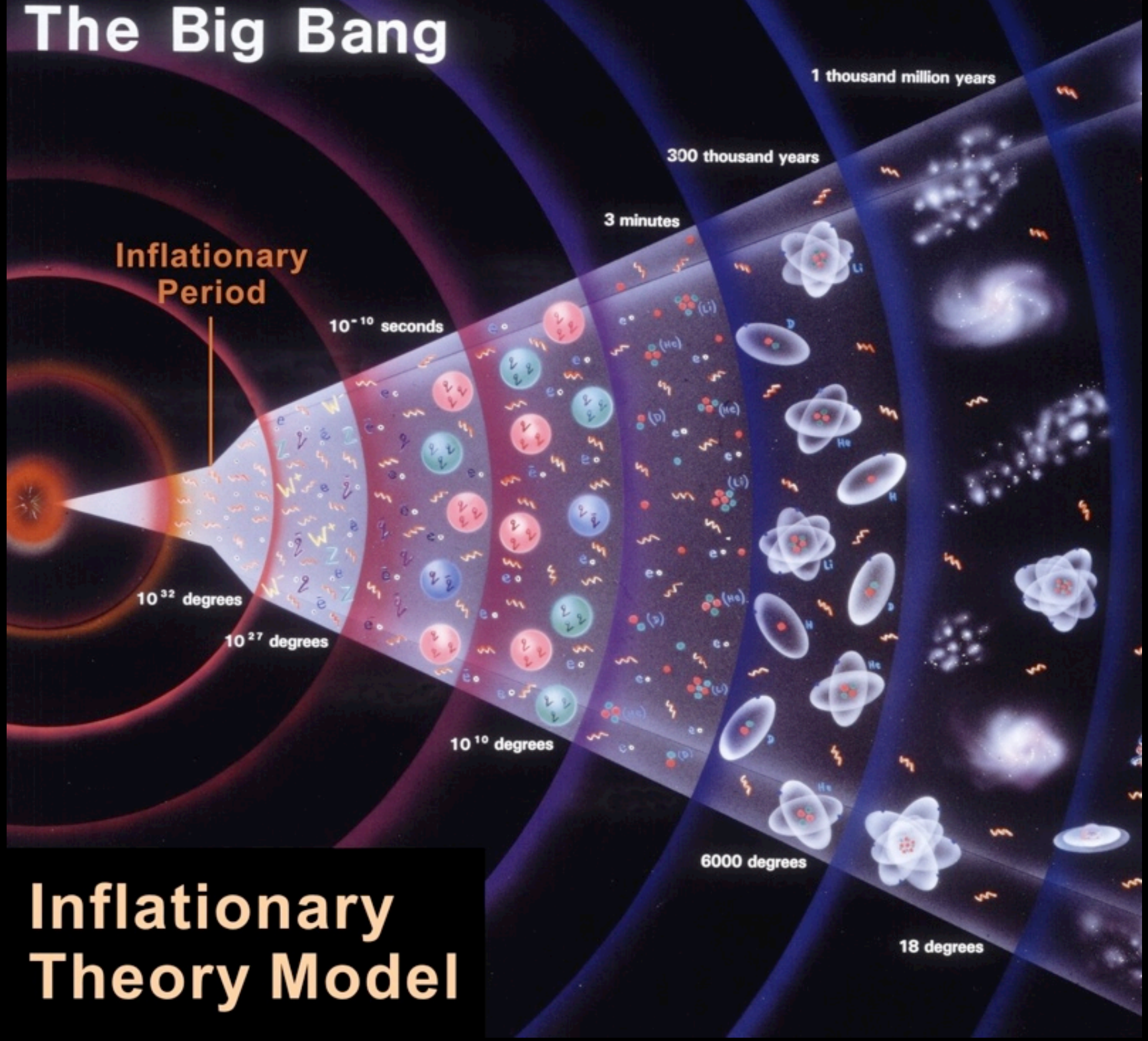
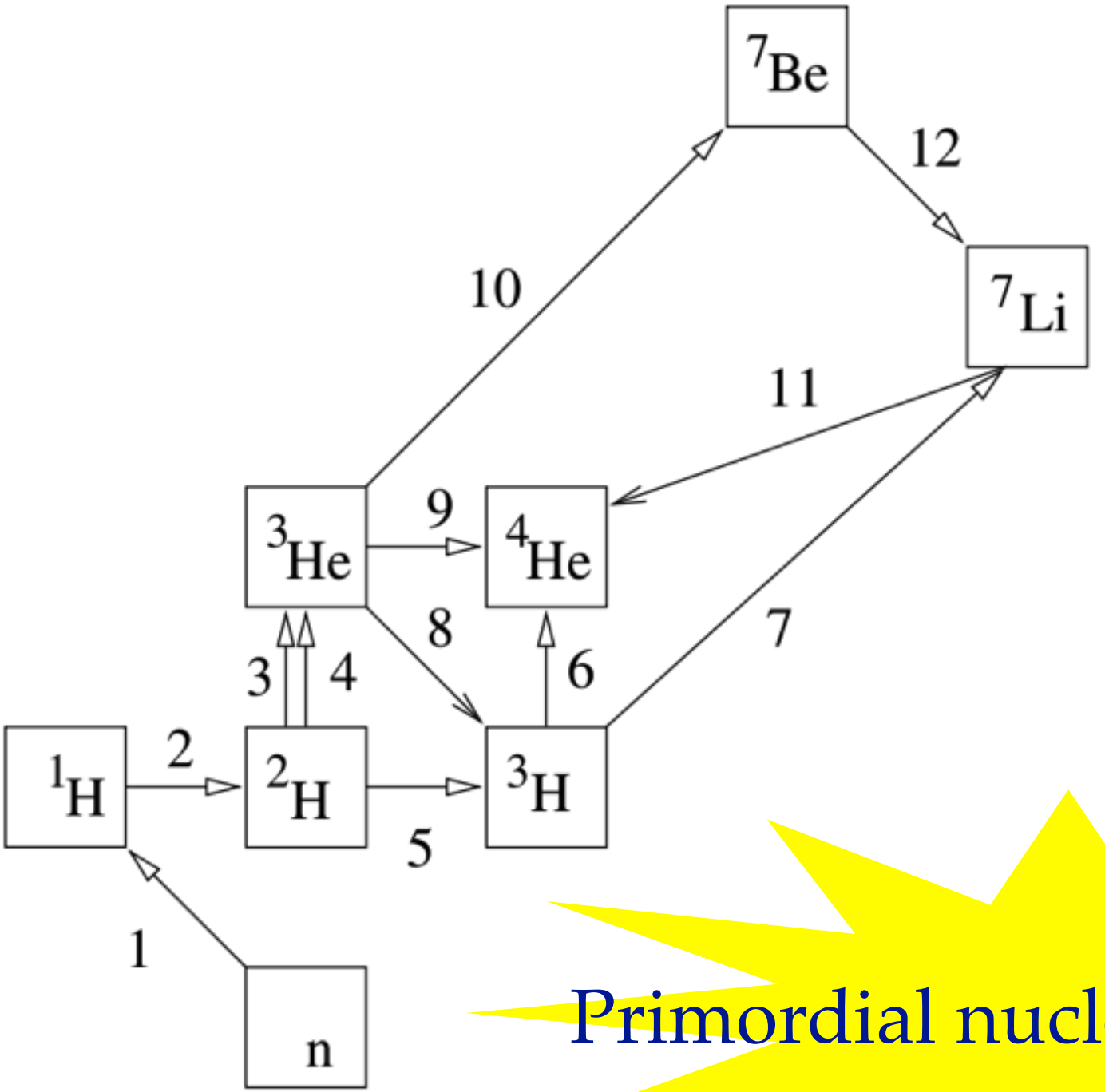
Precision measures of the primordial abundance of



Max Pettini

Cambridge Univ.


The Big Bang
1 thousand million years
300 thousand years
3 minutes
Inflationary Period
10⁻¹⁰ seconds
10³² degrees
10²⁷ degrees
10¹⁰ degrees
6000 degrees
18 degrees
Inflationary Theory Model



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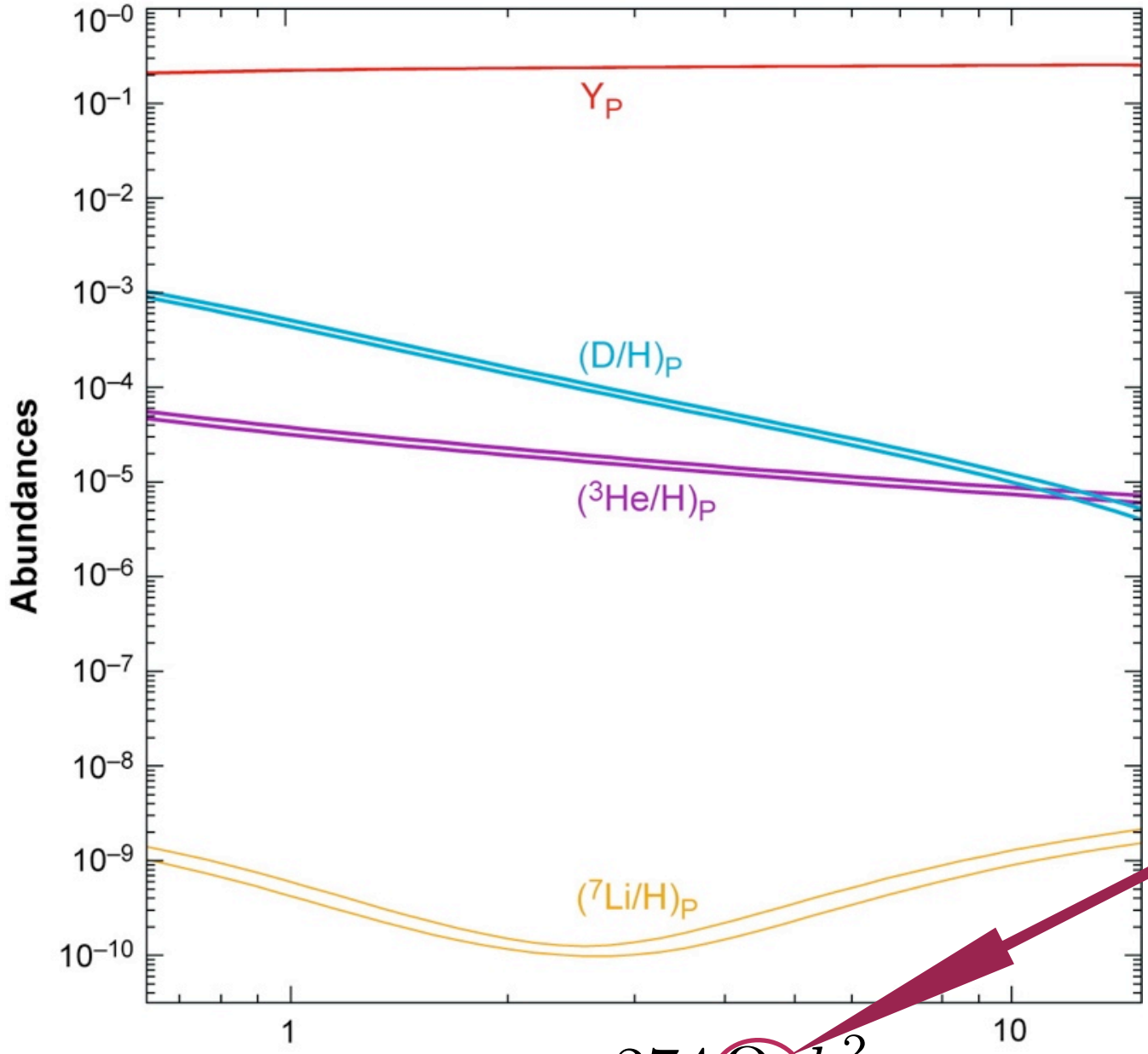
11. $^7\mathrm{Li}(p,\alpha)^4\mathrm{He}$
12. $^7\mathrm{Be}(n,p)^7\mathrm{Li}$

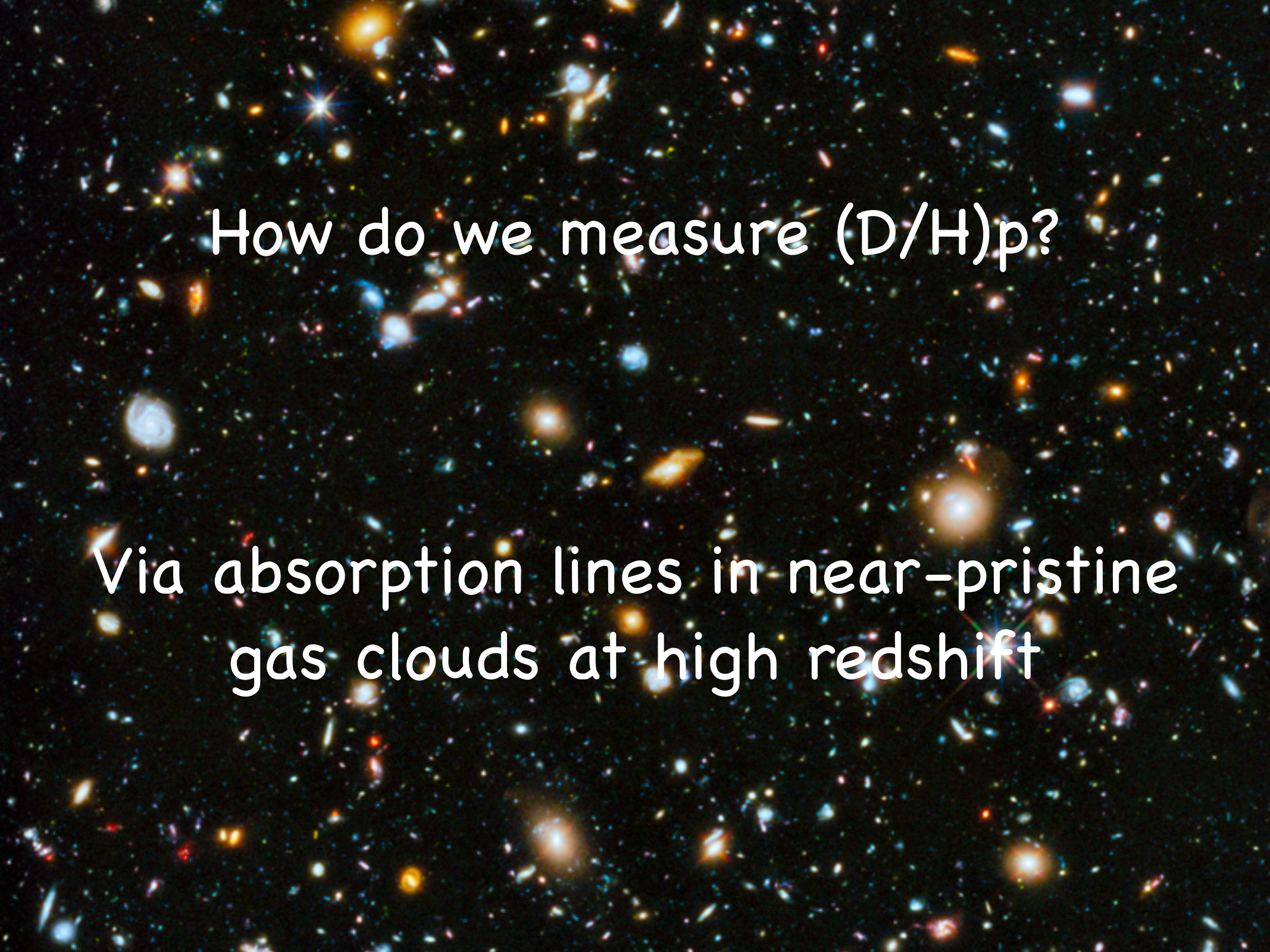
Primordial nucleosynthesis



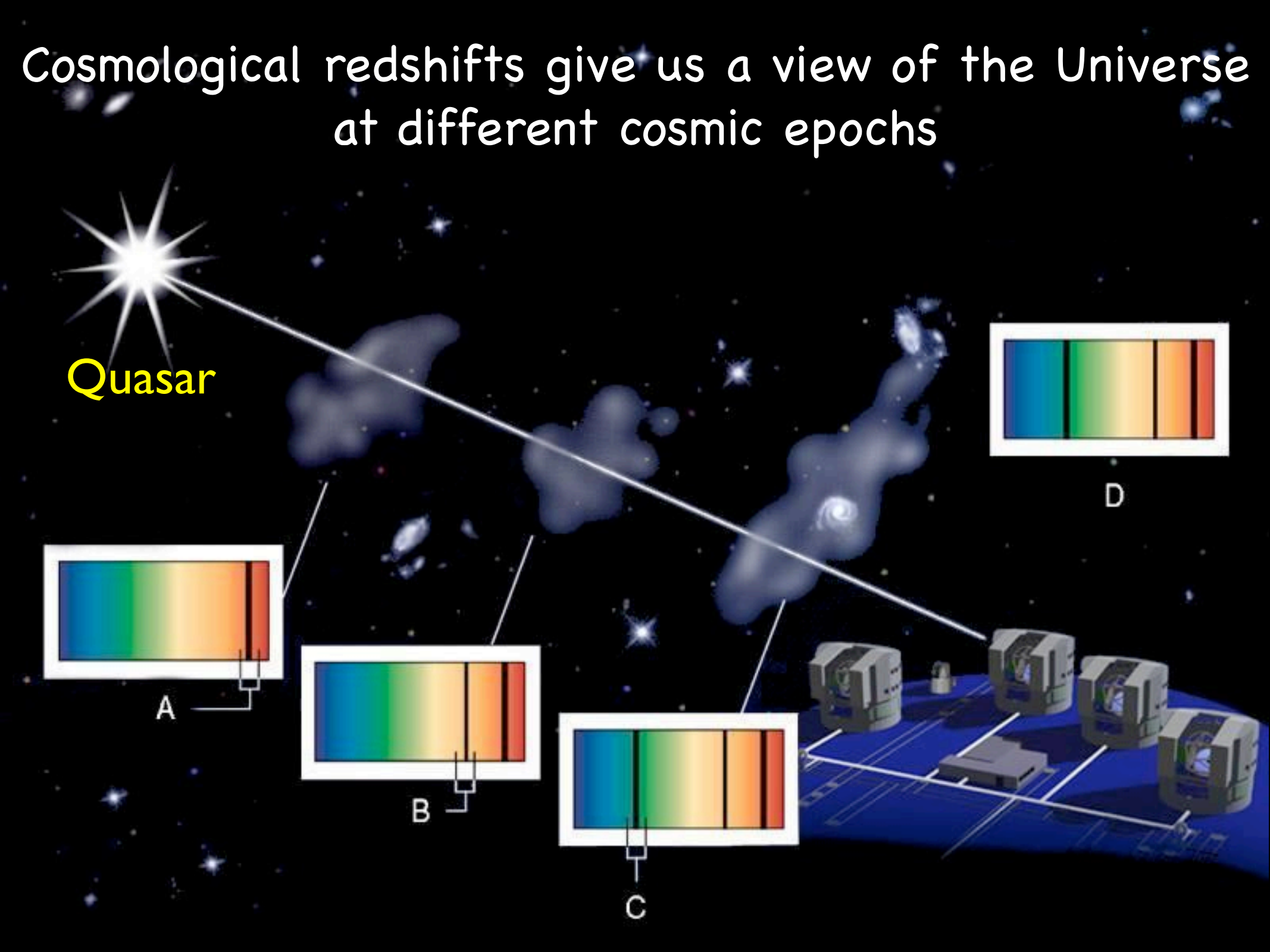
Baryon density / Critical density

$$\eta_{10} = 274\,\Omega_{\rm b} h^2$$

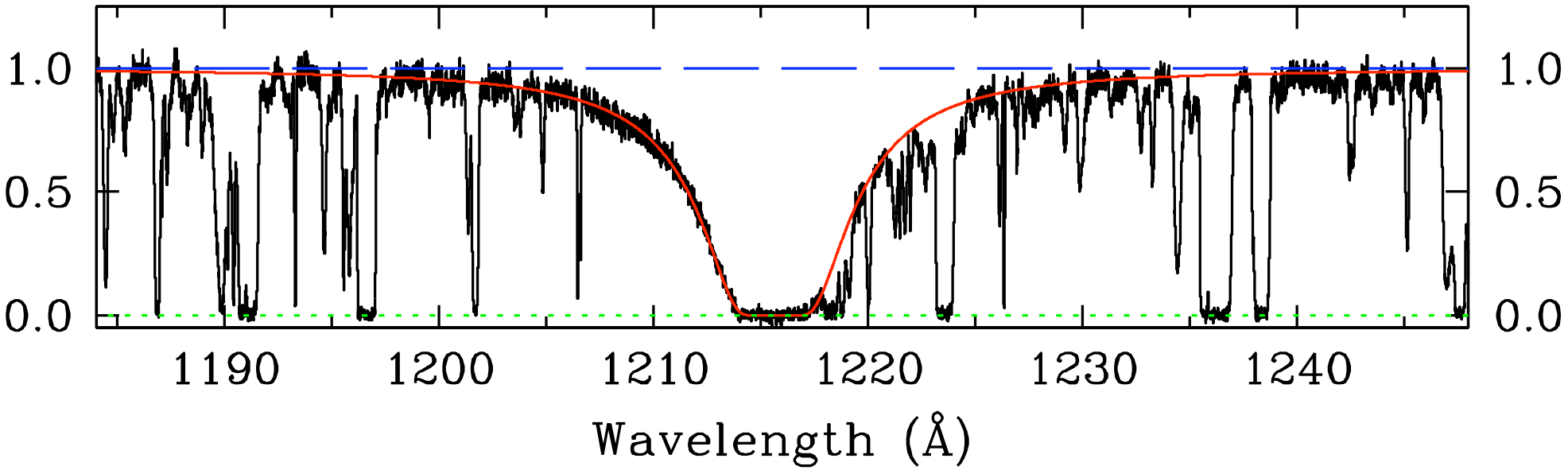
Steigman G. 2007.
Annu. Rev. Nucl. Part. Sci. 57:463–91


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

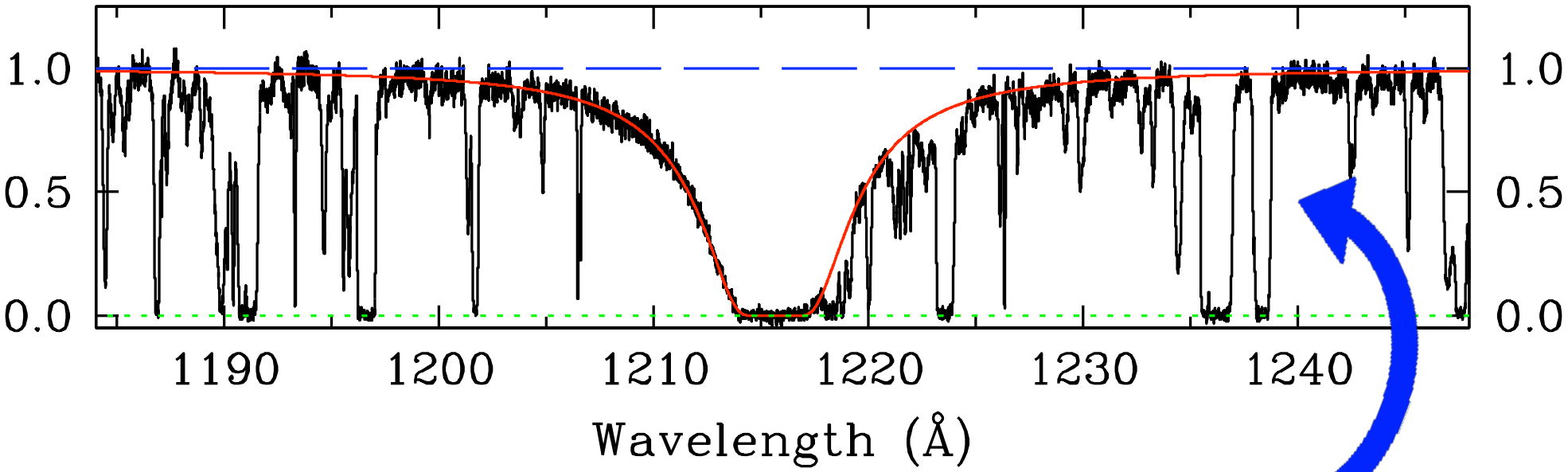


A sample portion of a quasar absorption spectrum

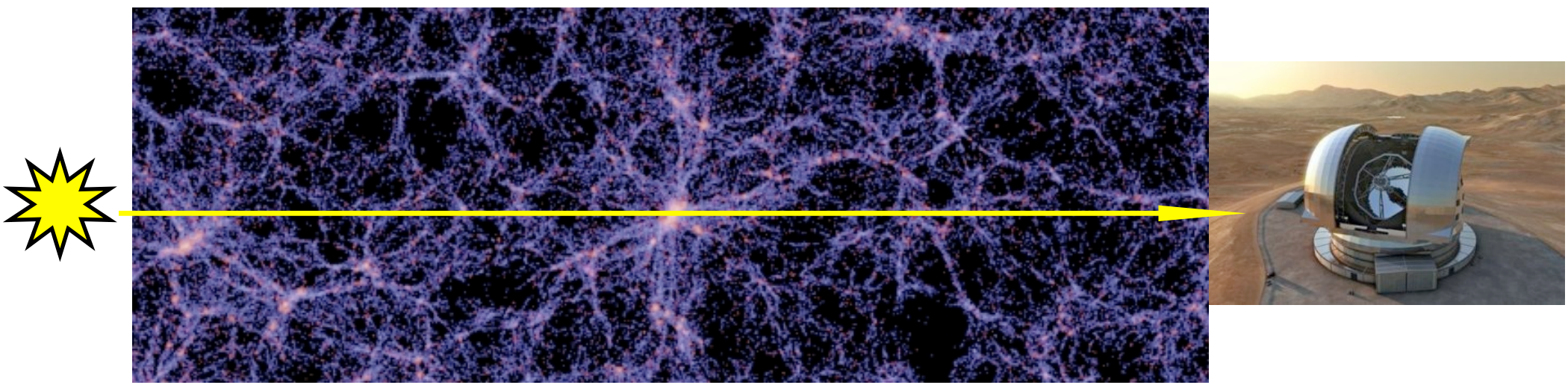


10m Keck telescope + HIRES

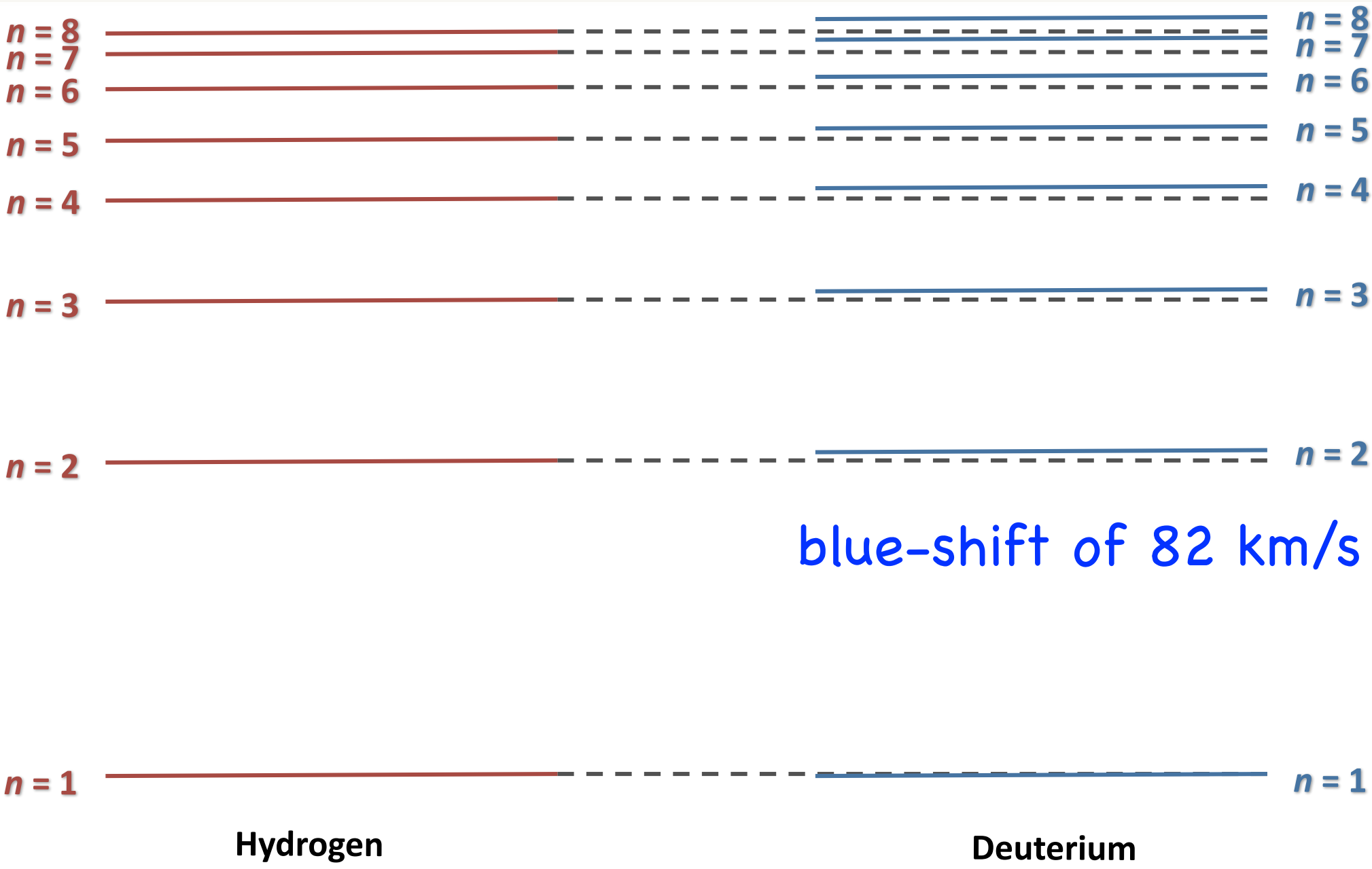
A sample portion of a quasar absorption spectrum



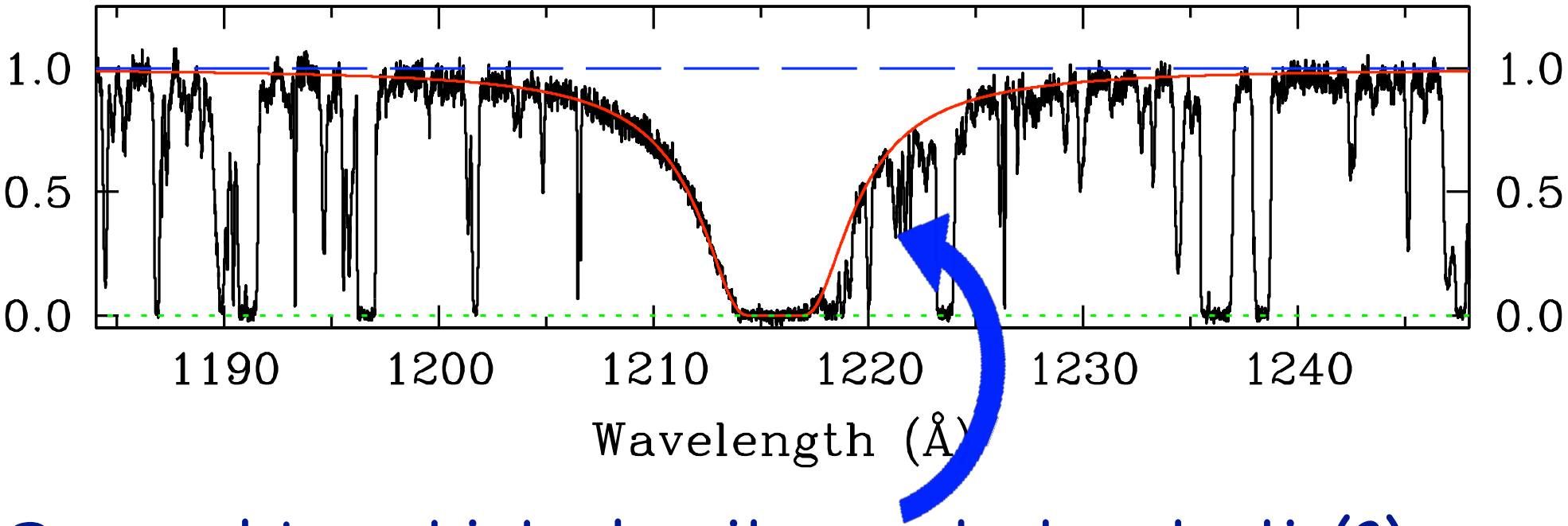
Lya forest: low-density, ionised, intergalactic gas



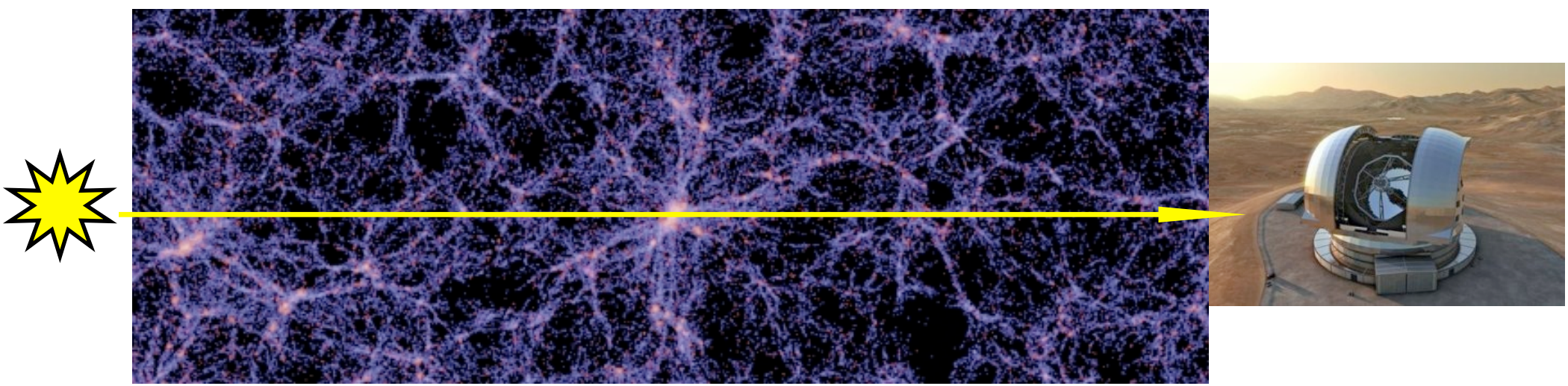
Energy Levels

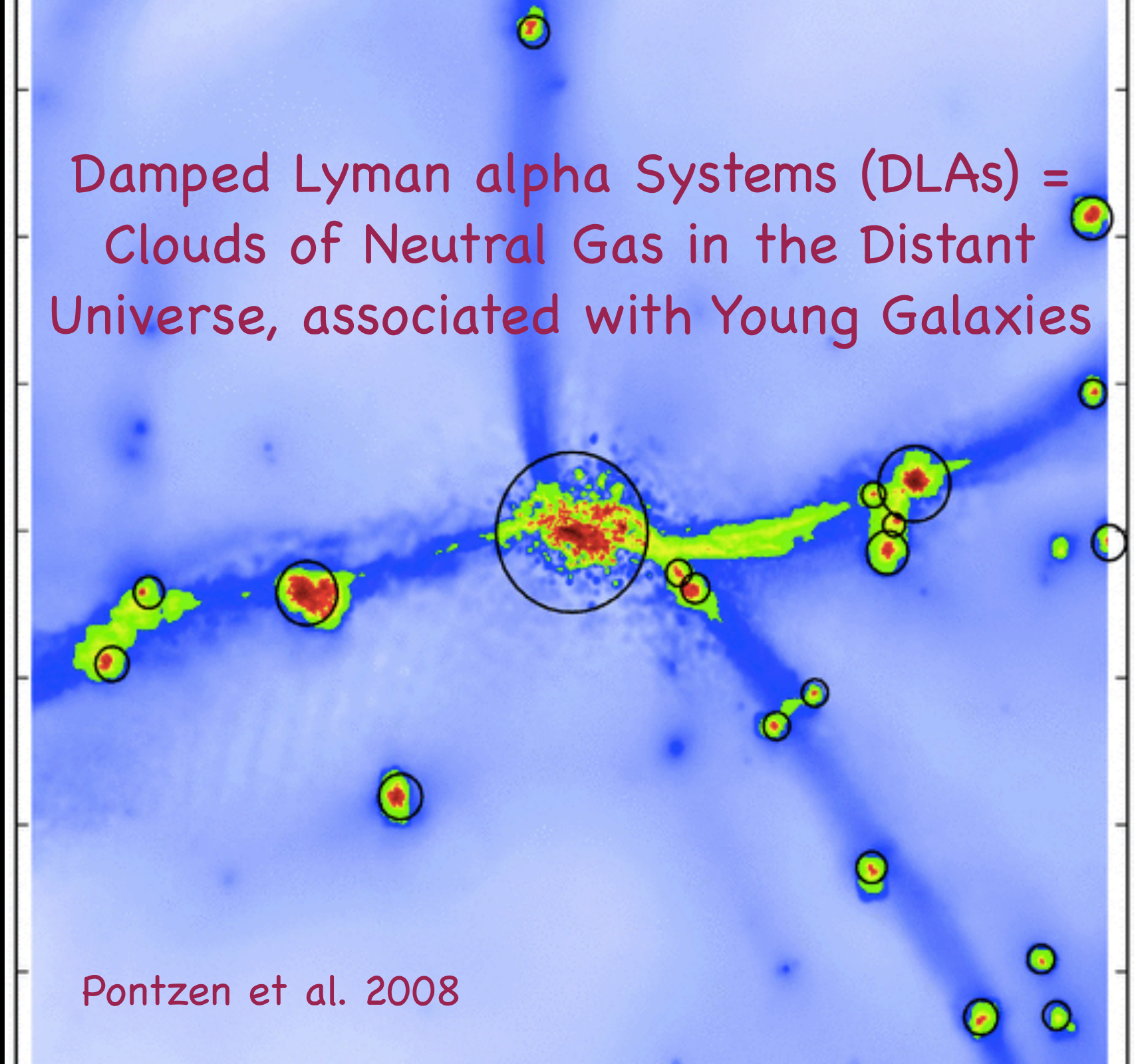


A sample portion of a quasar absorption spectrum

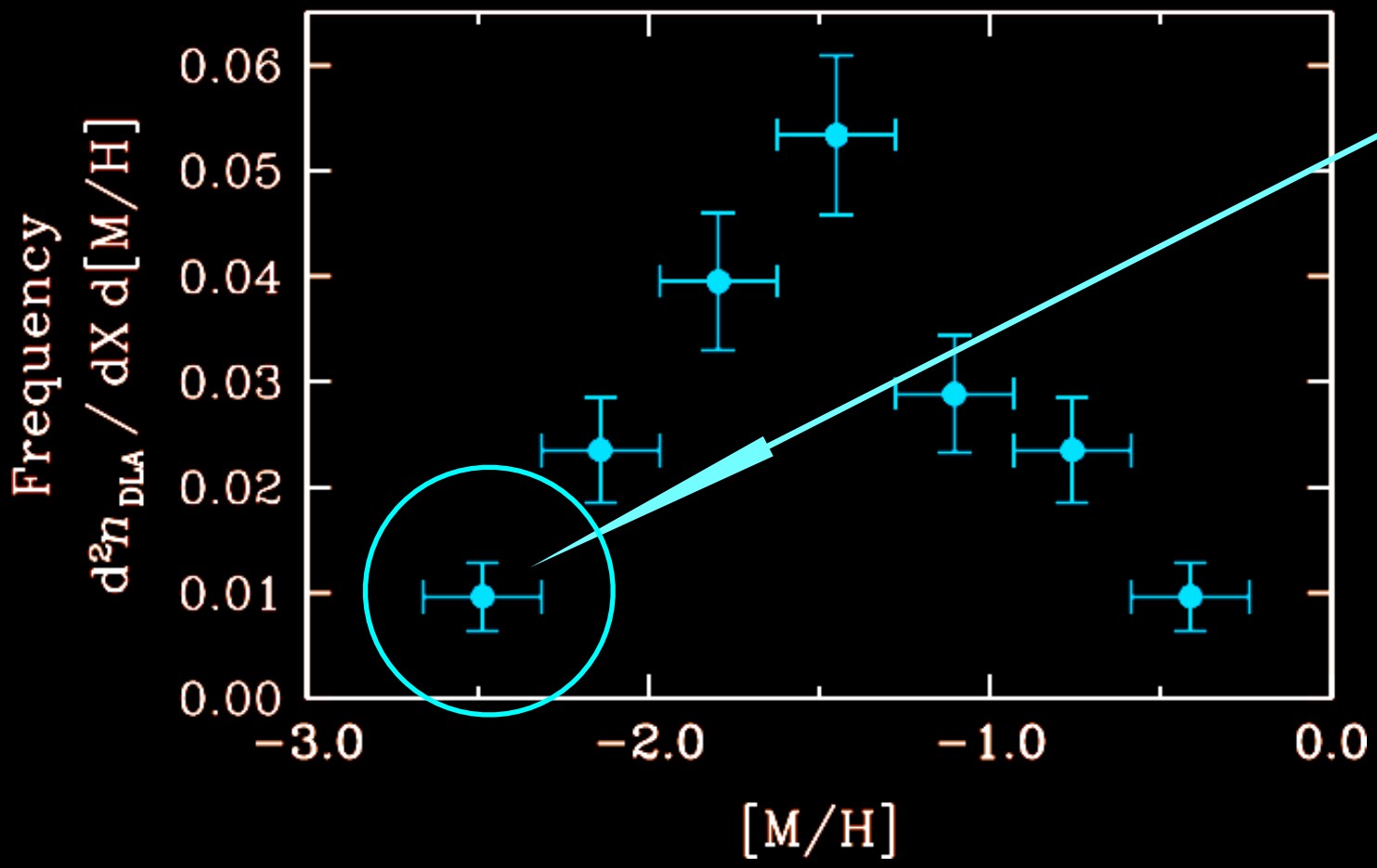


Damped Lyα: high-density, neutral, galactic(?) gas



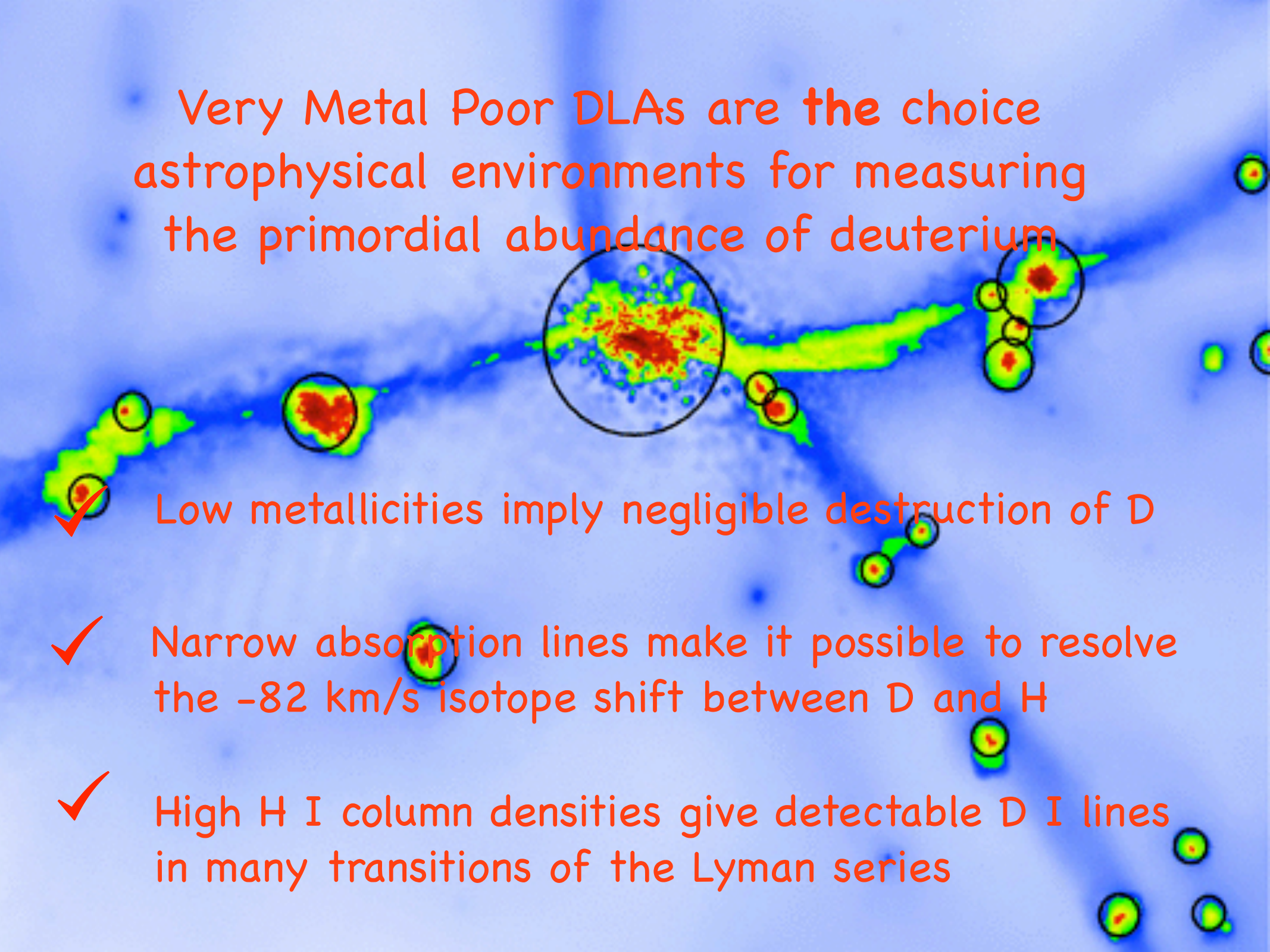

Damped Lyman alpha Systems (DLAs) =
Clouds of Neutral Gas in the Distant
Universe, associated with Young Galaxies
Pontzen et al. 2008

Metallicity Distribution

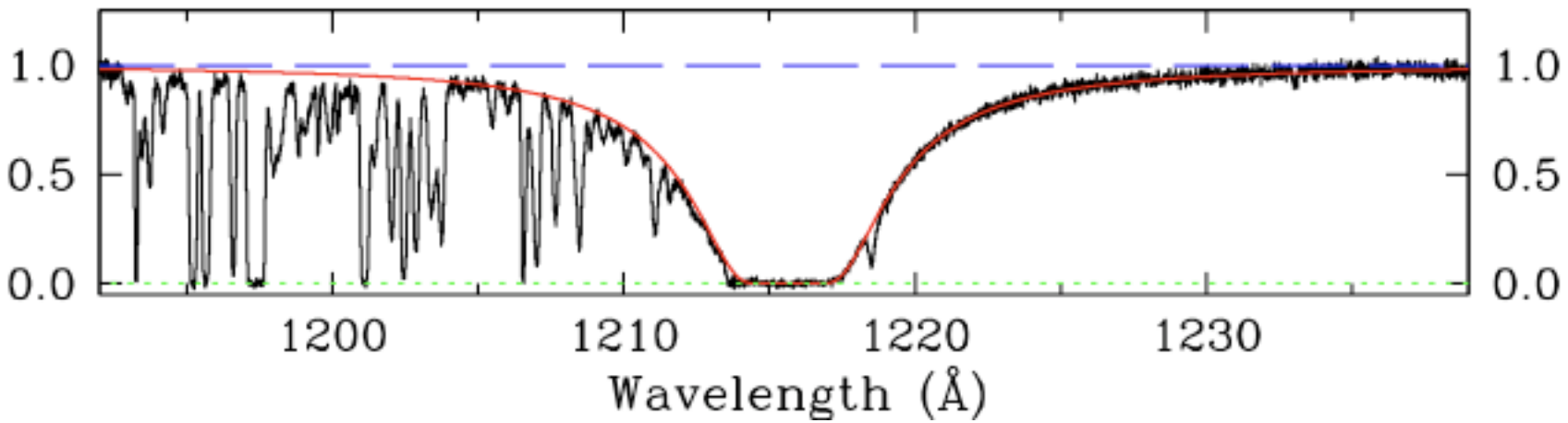


These are the DLAs we're after

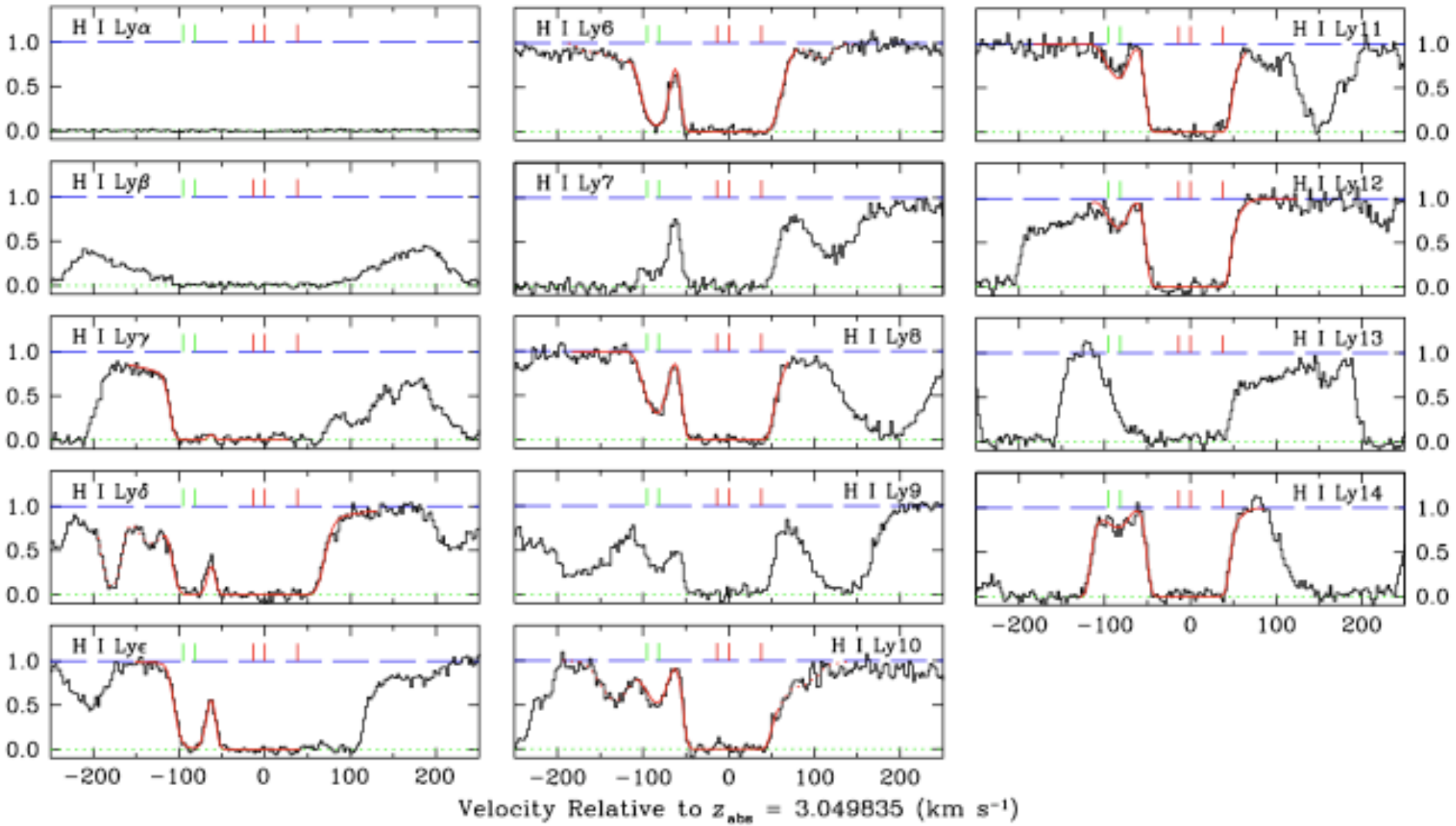
Rafelski et al. 2012


Very Metal Poor DLAs are **the** choice astrophysical environments for measuring the primordial abundance of deuterium
✓ Low metallicities imply negligible destruction 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

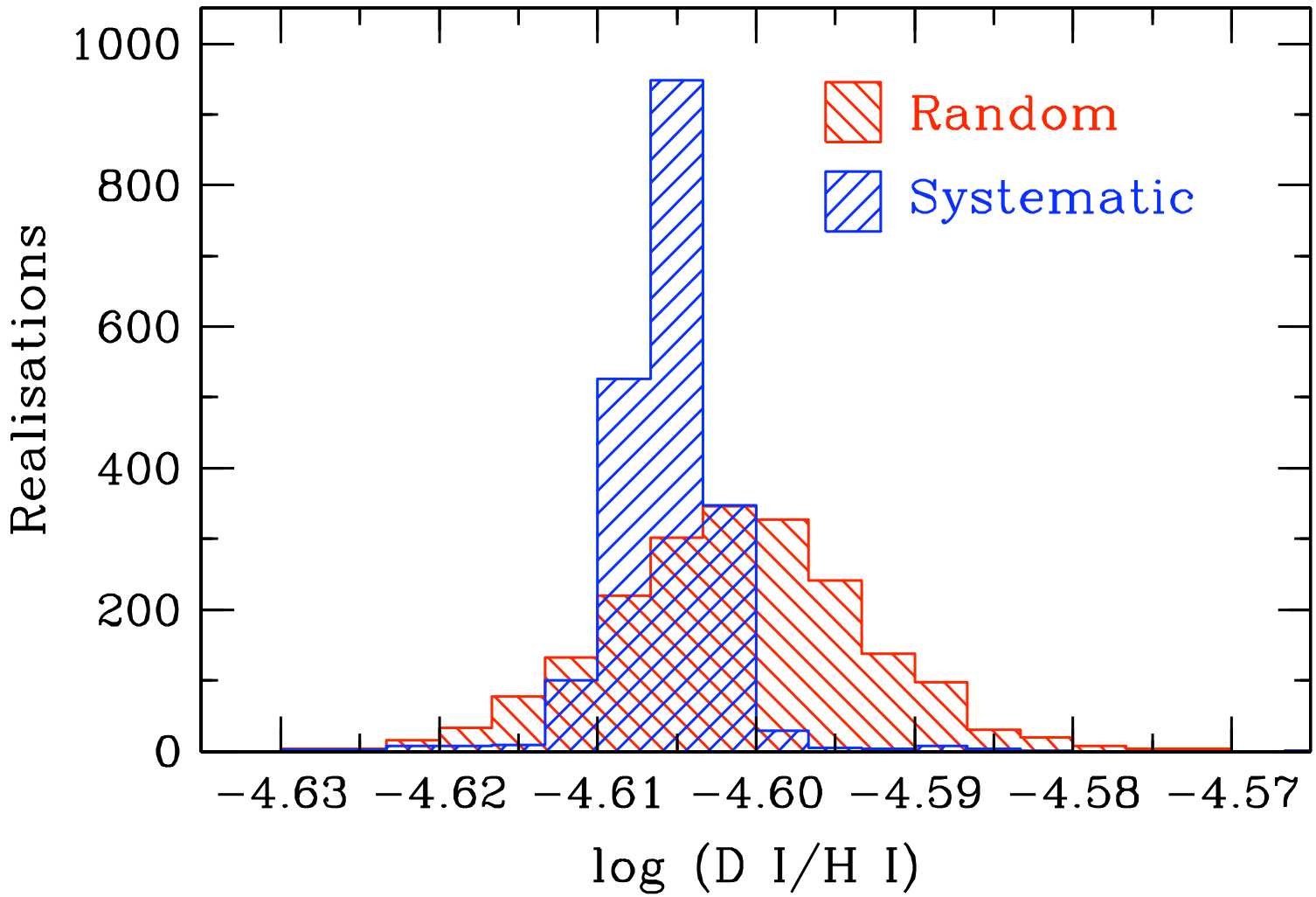
J1419+0829, z= 3.050, Fe/H = 1/200 solar



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

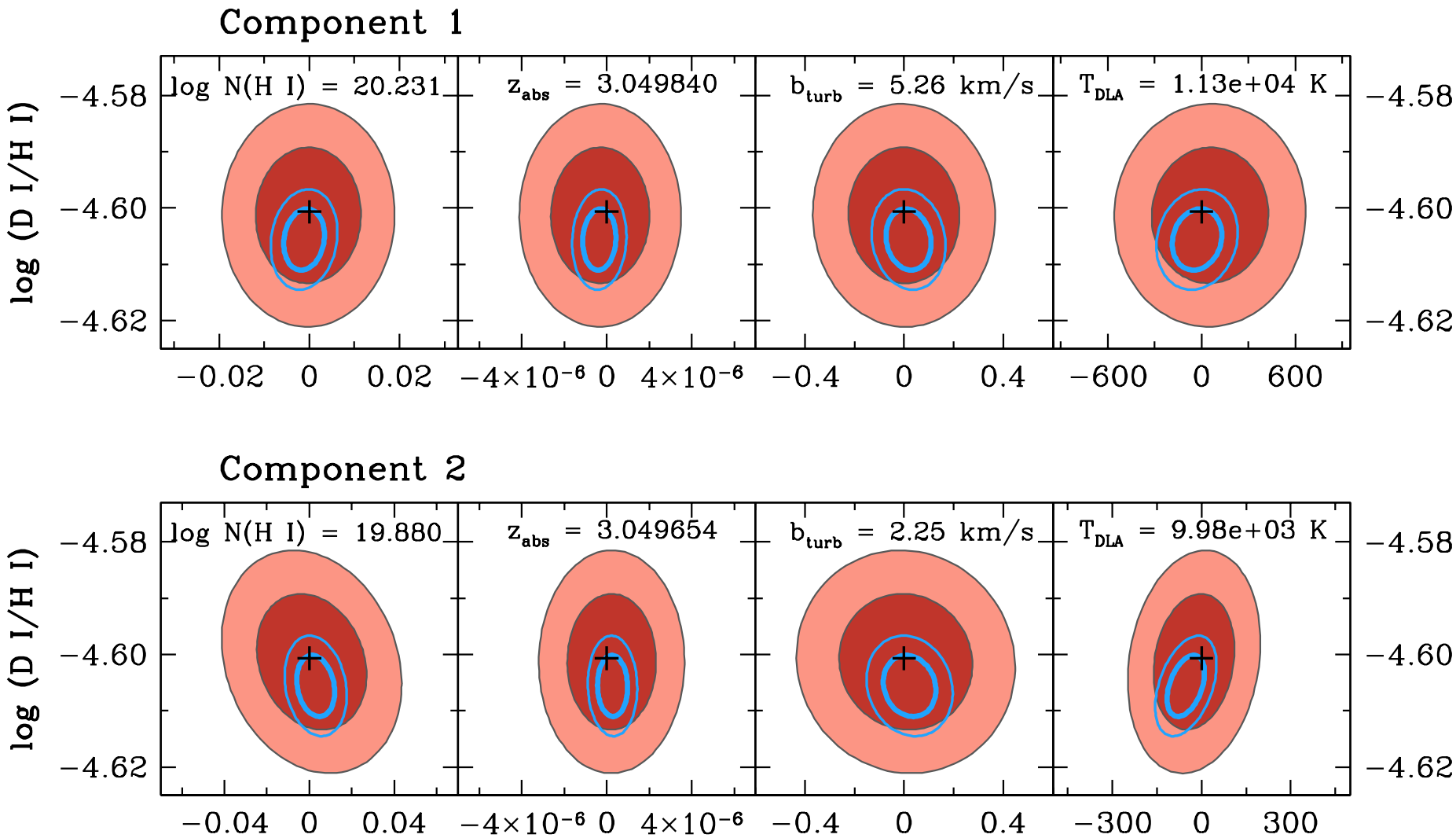


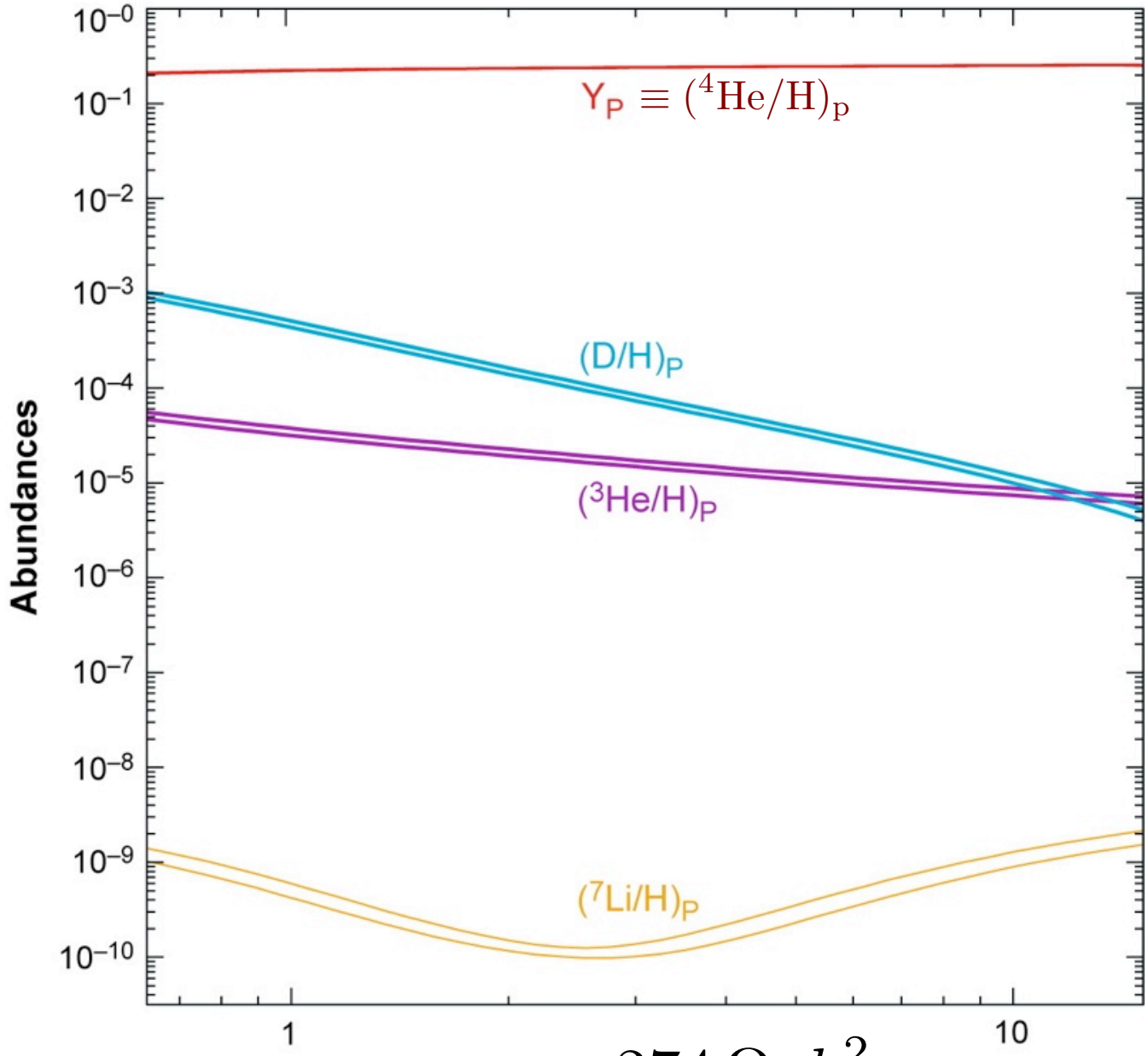
Spectral analysis tailored specifically to the determination of D/H and its error



Pettini & Cooke 2012

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





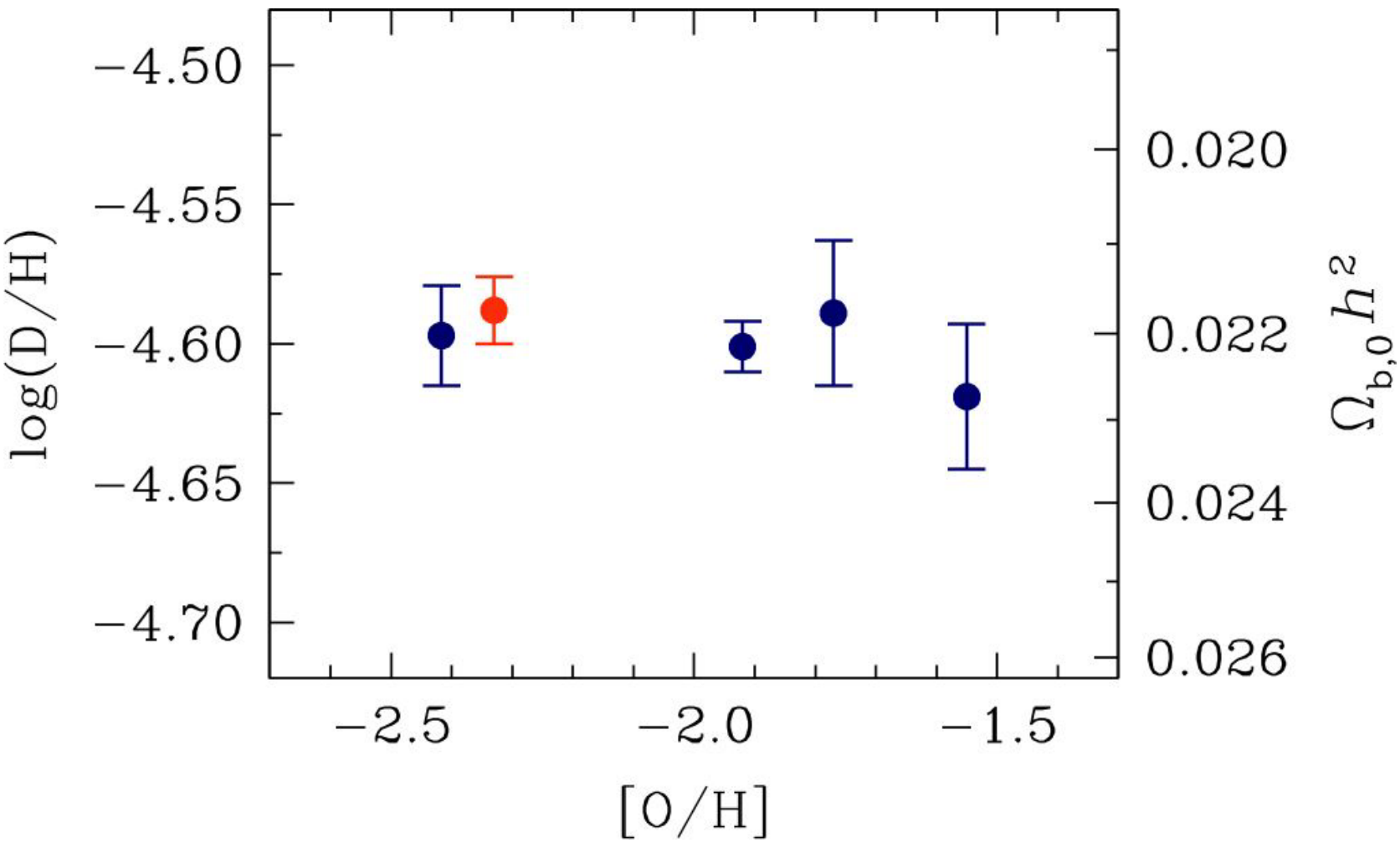
$$\eta_{10} = 274\,\Omega_\mathrm{b} h^2$$

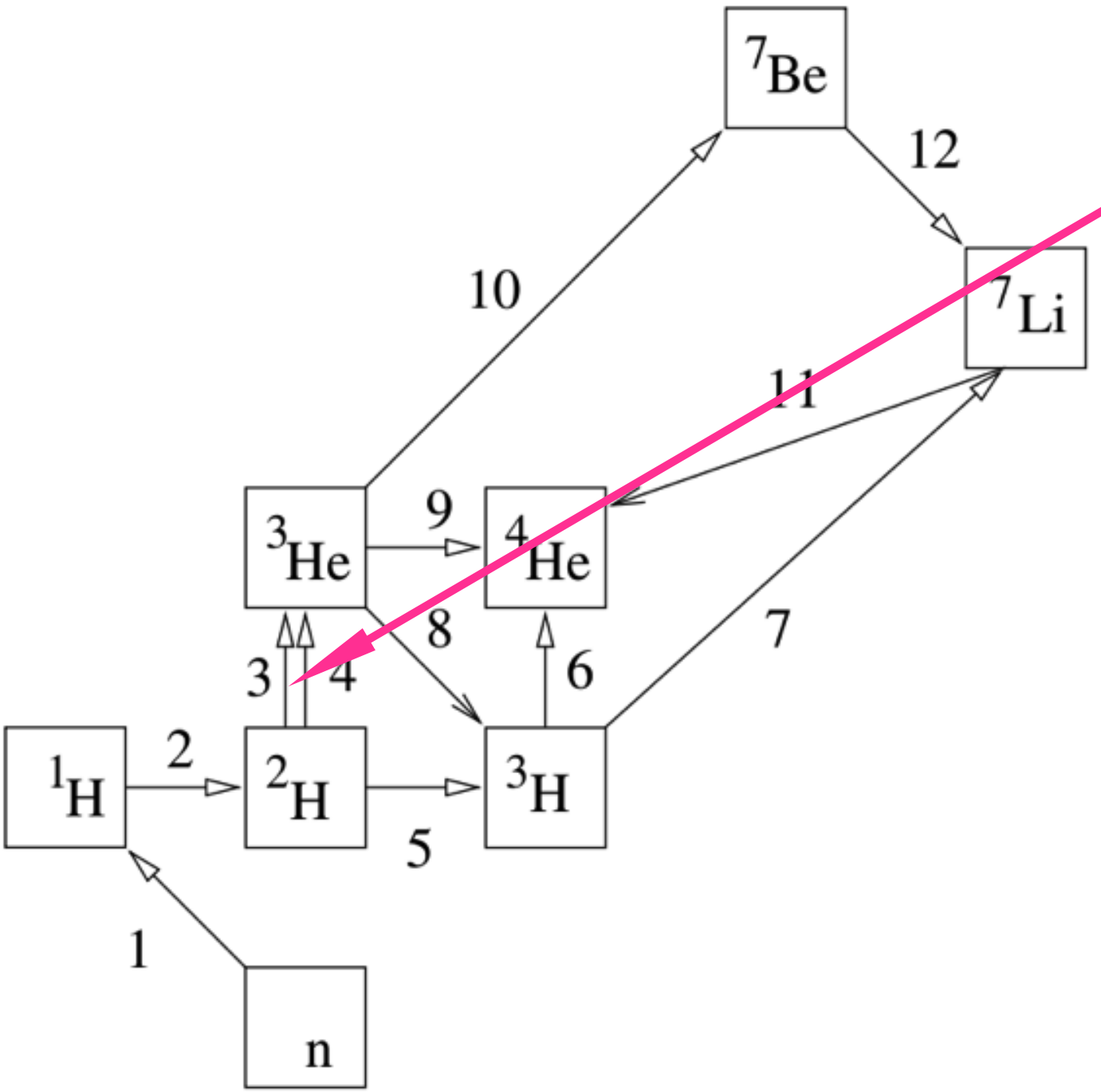
$$(\mathrm{D/H})_\mathrm{p} = 2.55 \times 10^{-5} (6/\eta_{10})^{1.6}$$

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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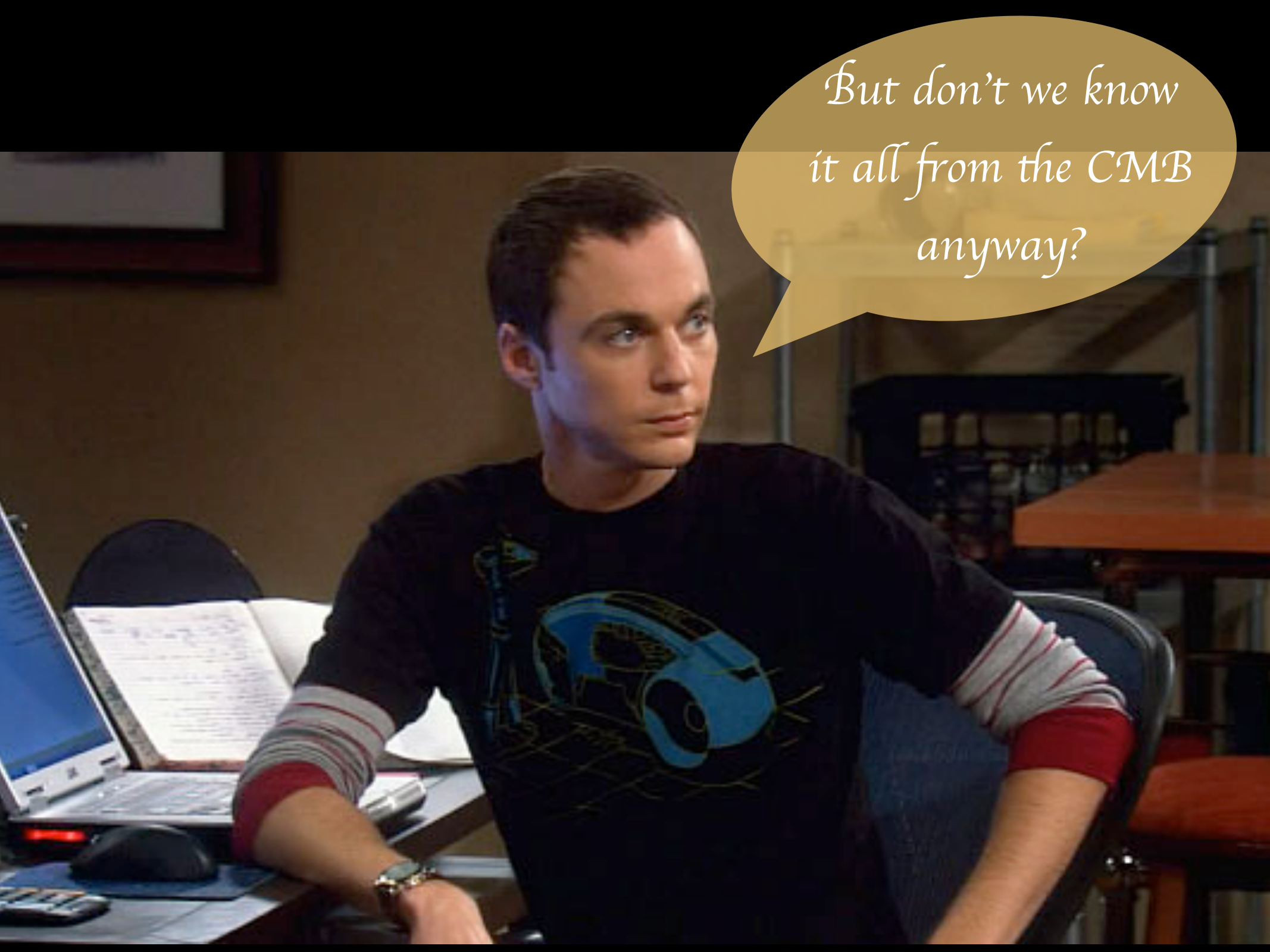
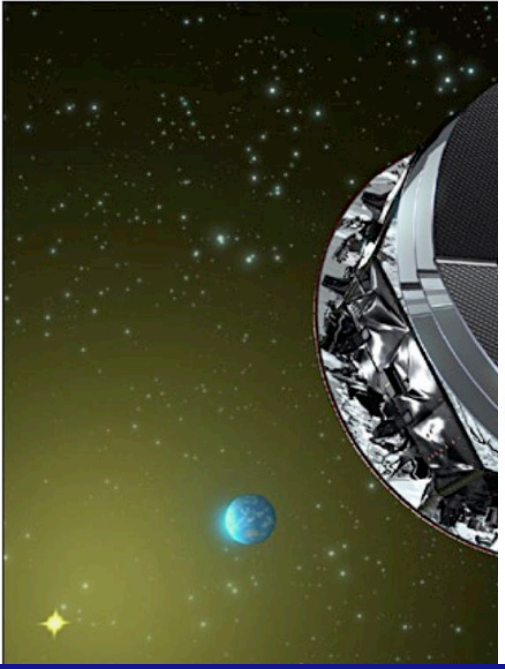
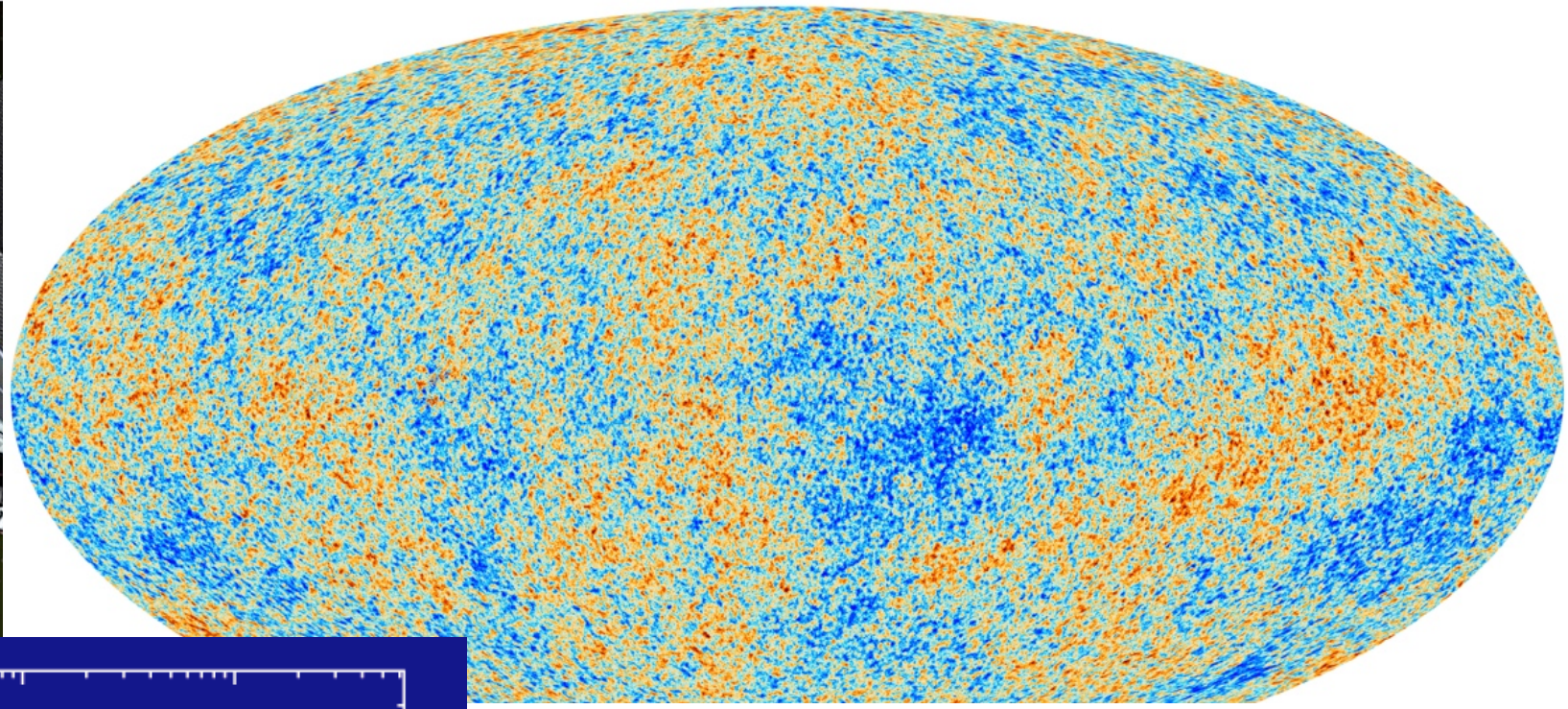
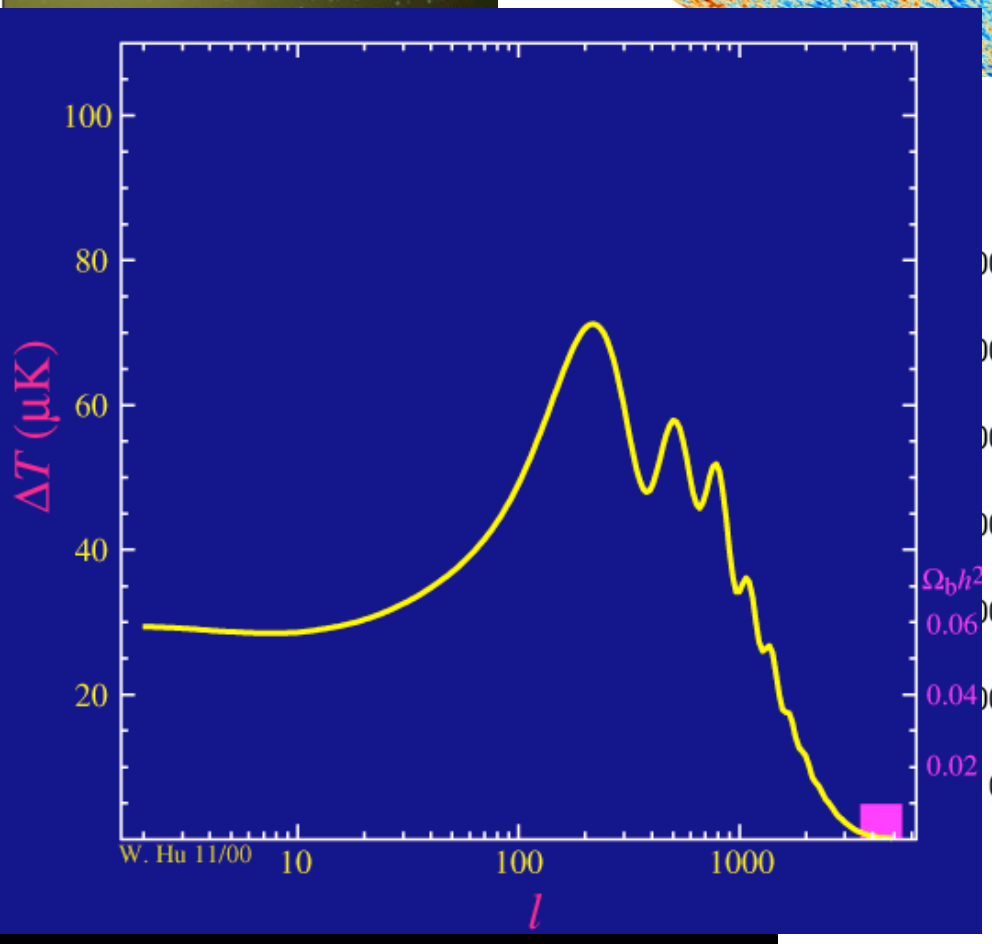
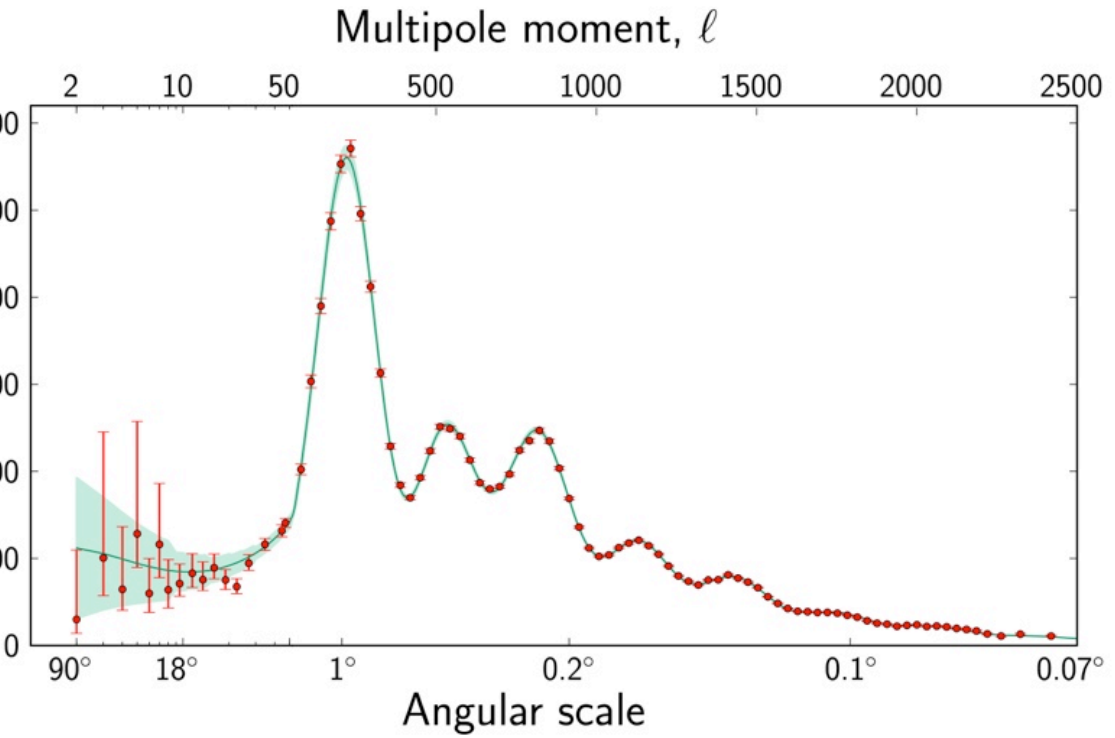
Nollett & Burles 2000


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



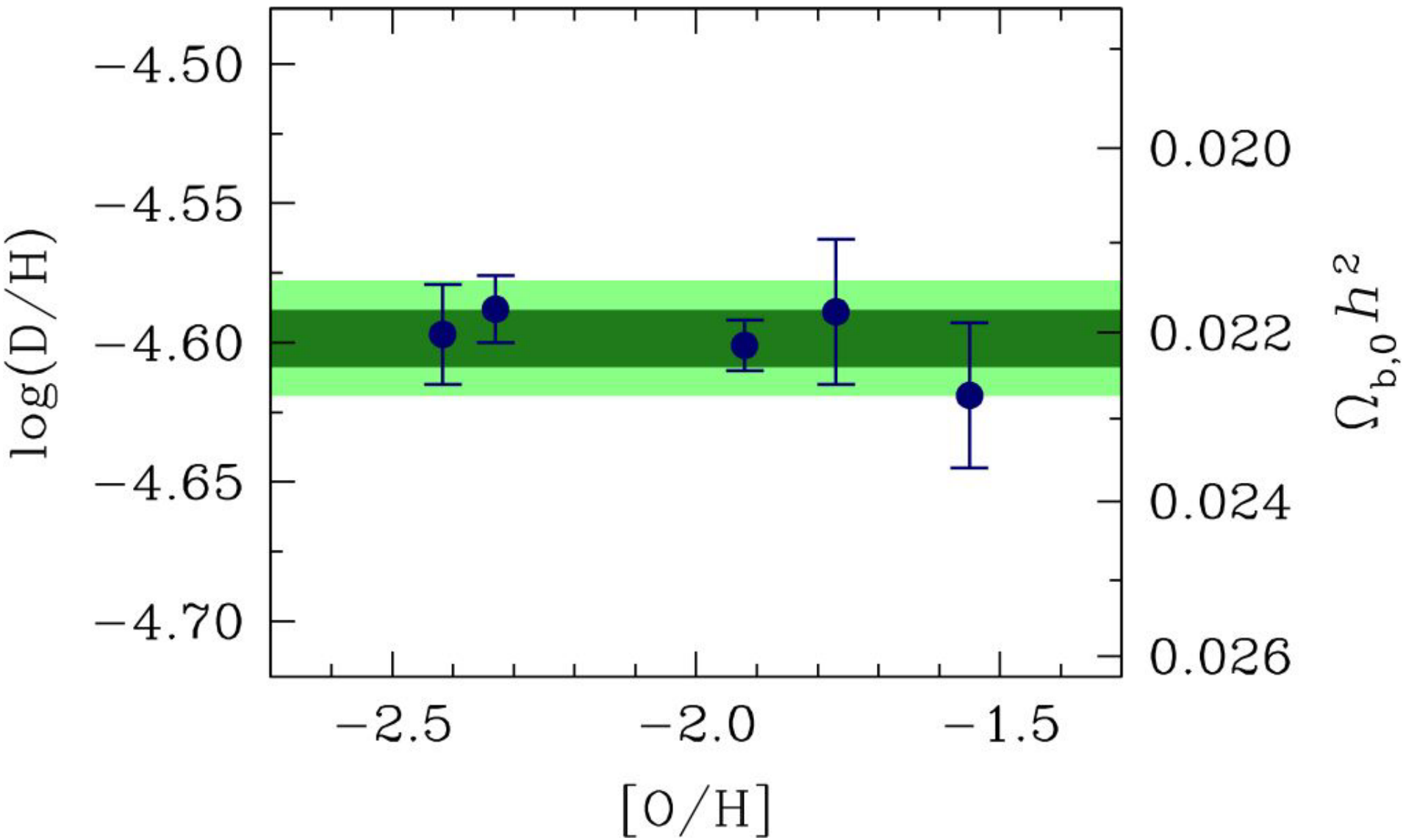



100
80
60
40
20
ΔT (μK)
$\Omega_b h^2$
0.06
0.04
0.02
W. Hu 11/00
10
100
1000
l


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

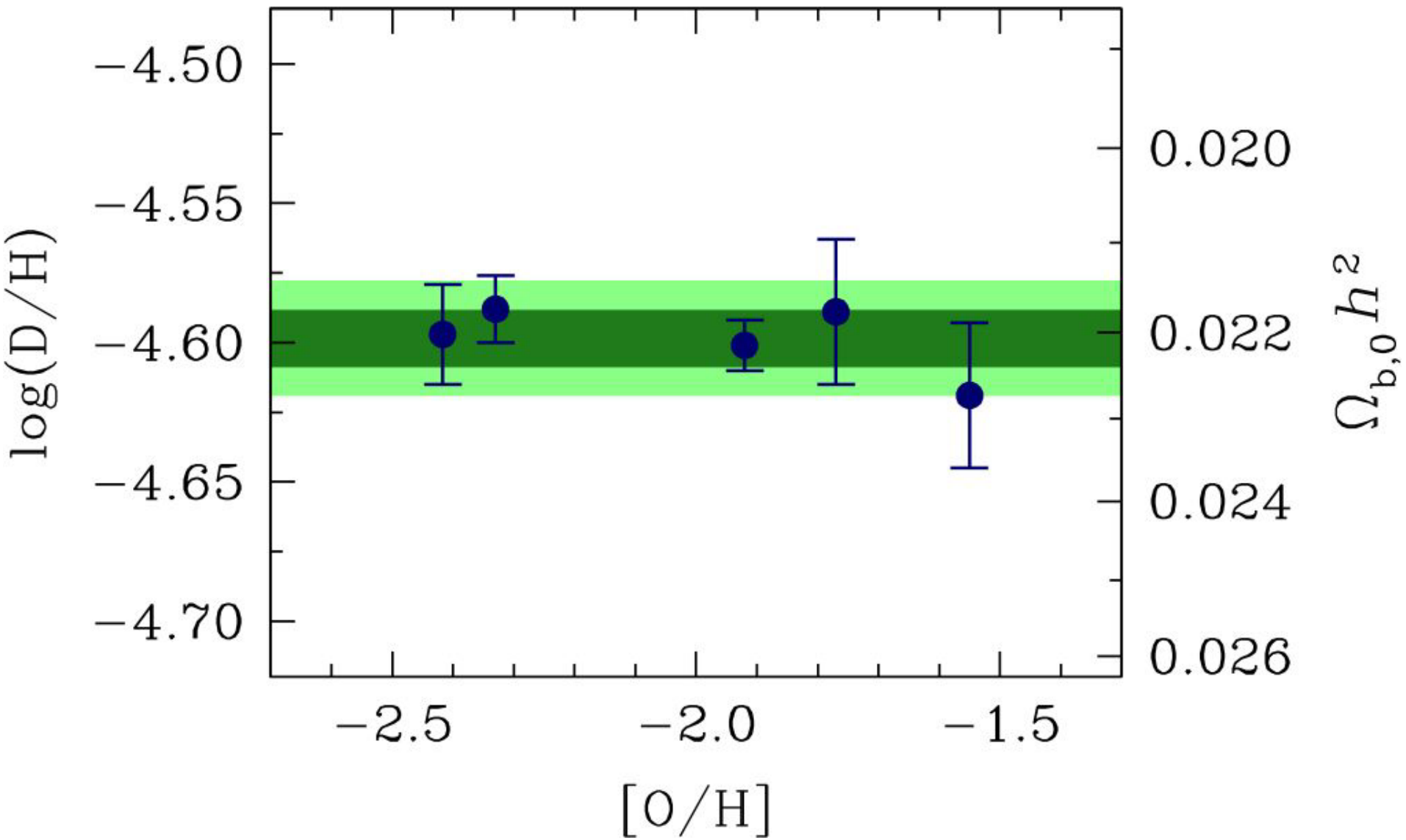
$$100\,\Omega_{\rm b}h^2({\rm CMB}) = 2.205 \pm 0.028$$

Planck XVI 2013



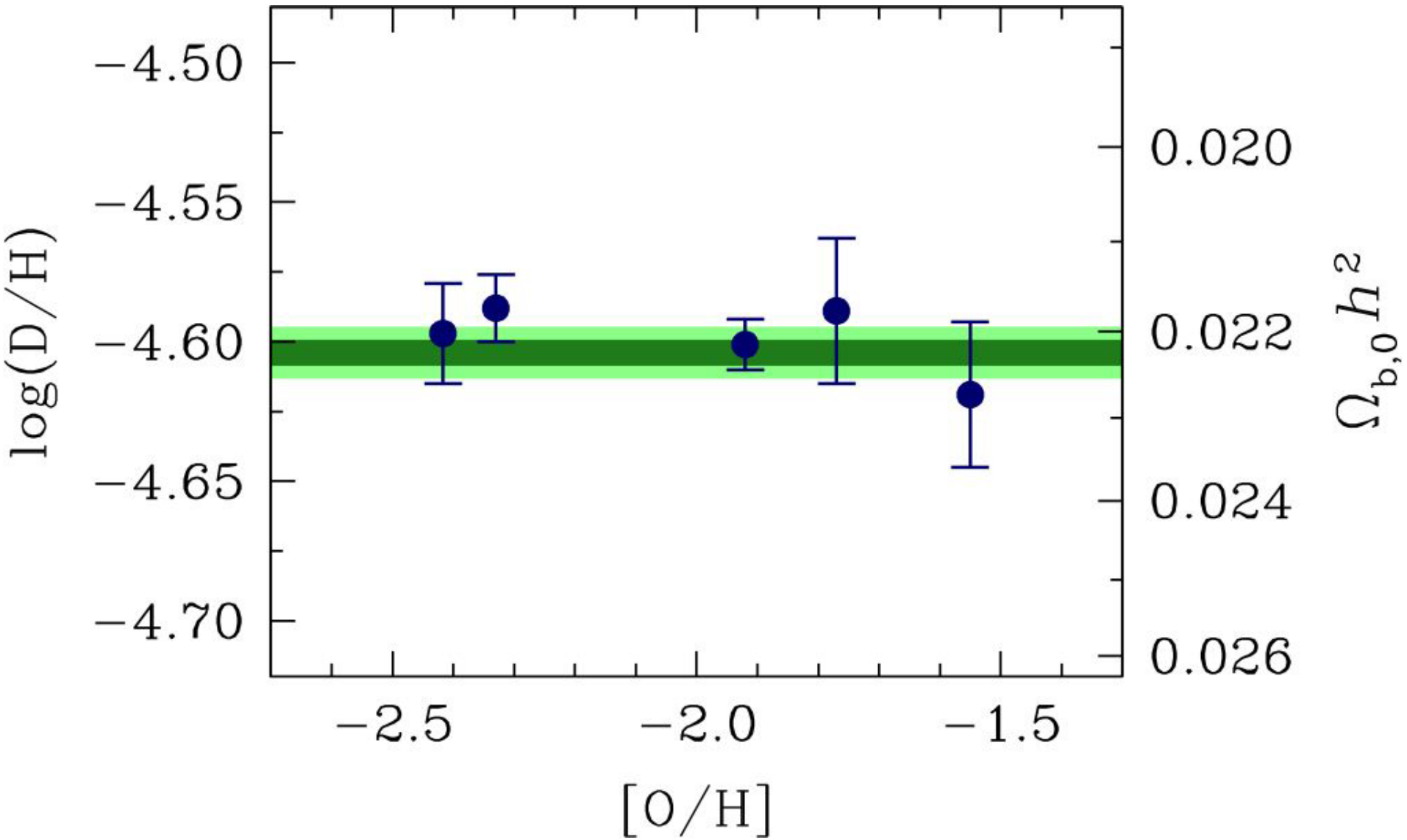
$$100\,\Omega_{\rm b}h^2({\rm BBN}) = 2.202 \pm 0.045$$

(Random + Systematic Error)



$$100\,\Omega_{\rm b}h^2({\rm CMB}) = 2.224 \pm 0.015$$

Planck 2015



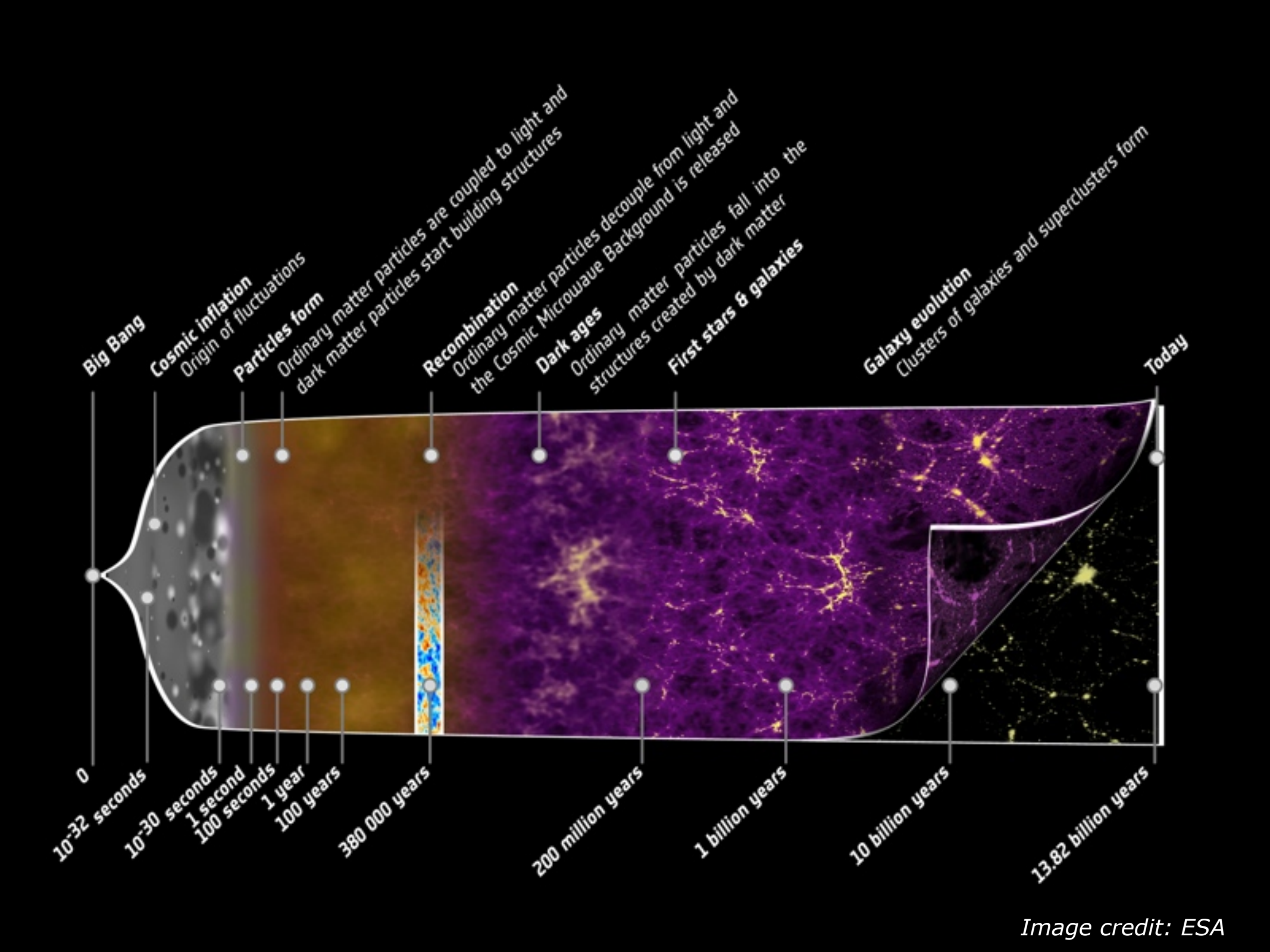


Image credit: ESA

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

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

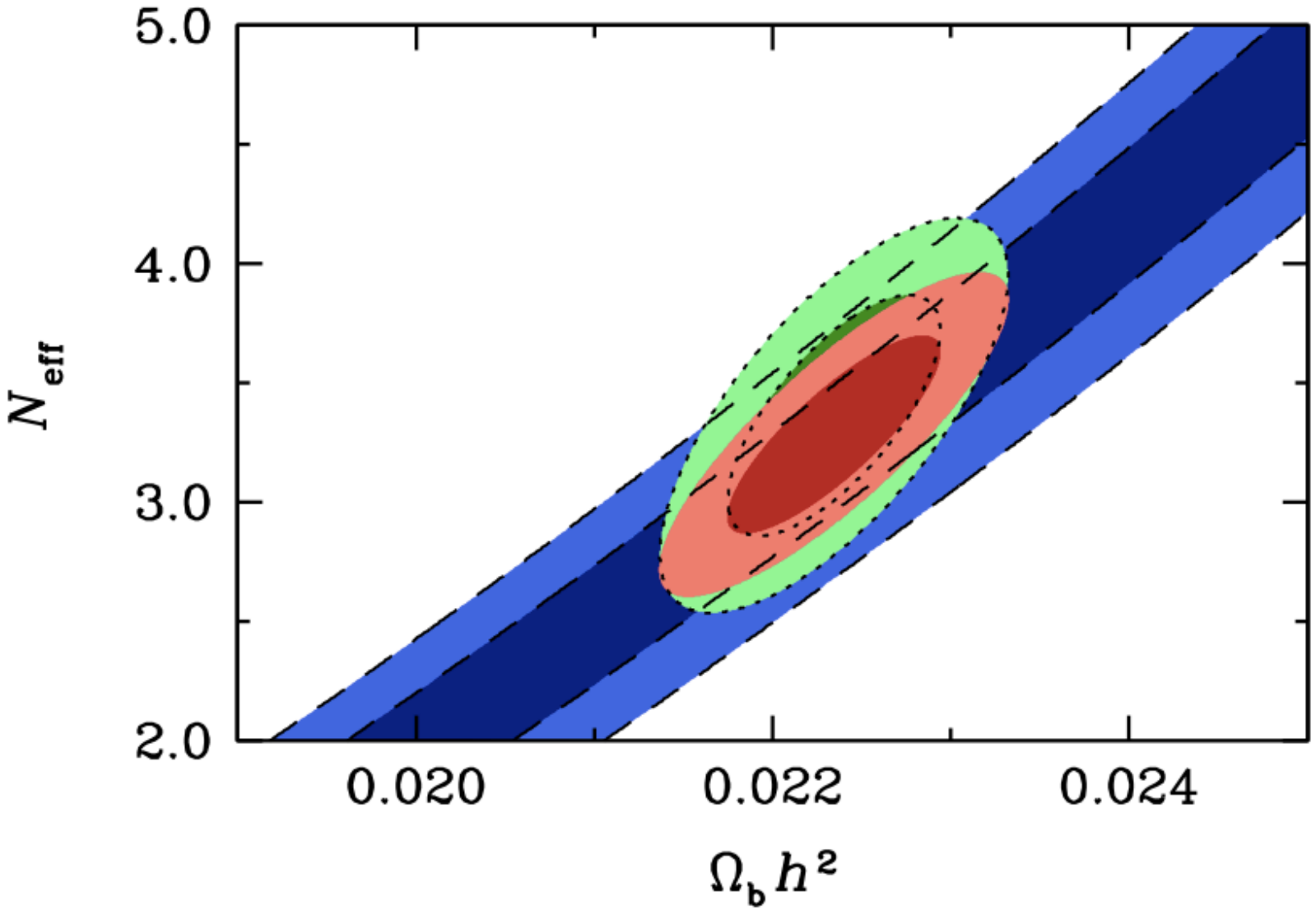
$\mathcal{N}_{\rm eff} = 3.046$ in standard BBN

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'

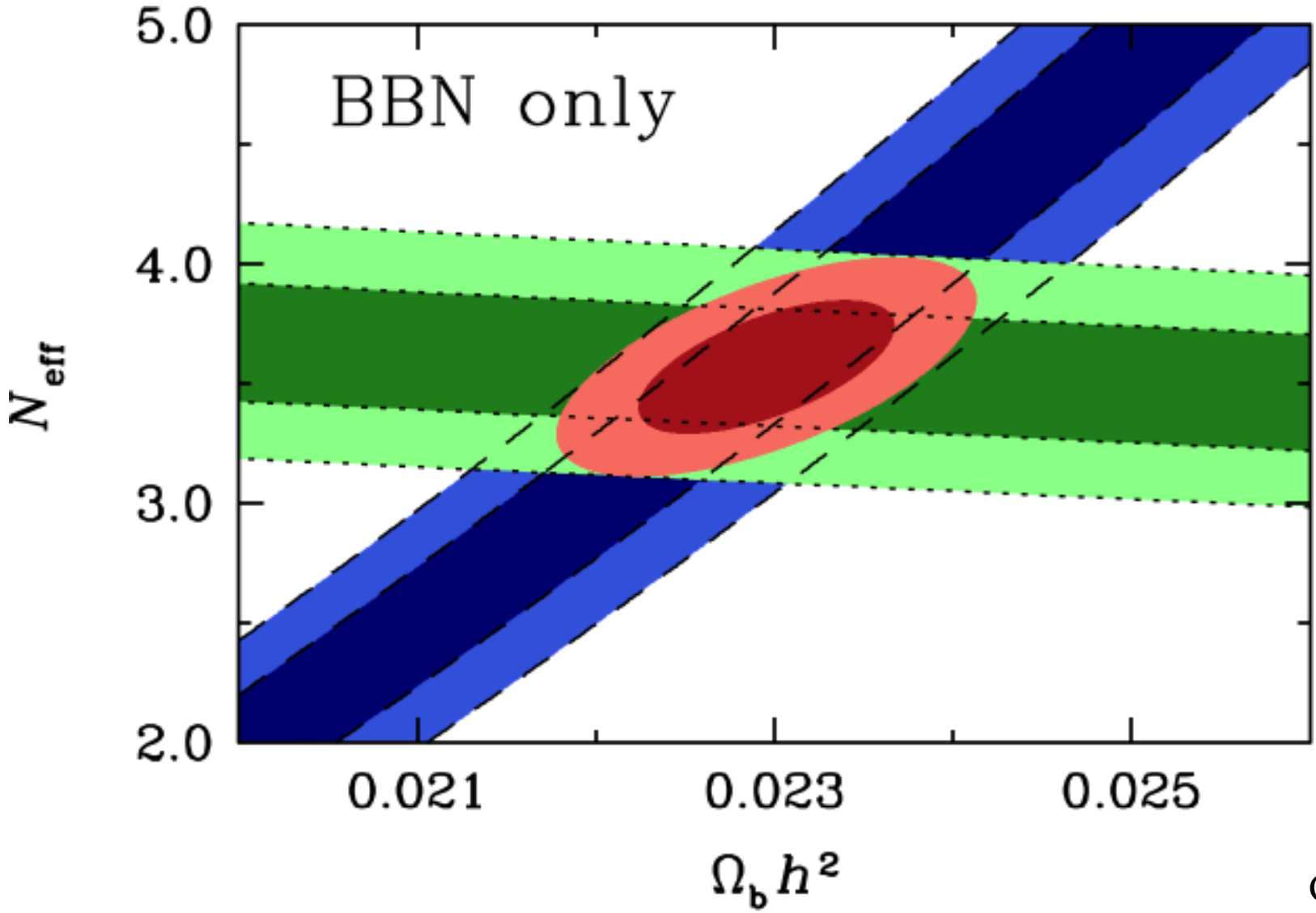
$$N_{\rm eff} = 3.28 \pm 0.28$$



Cooke et al. 2014

BBN Constraints on `dark radiation'

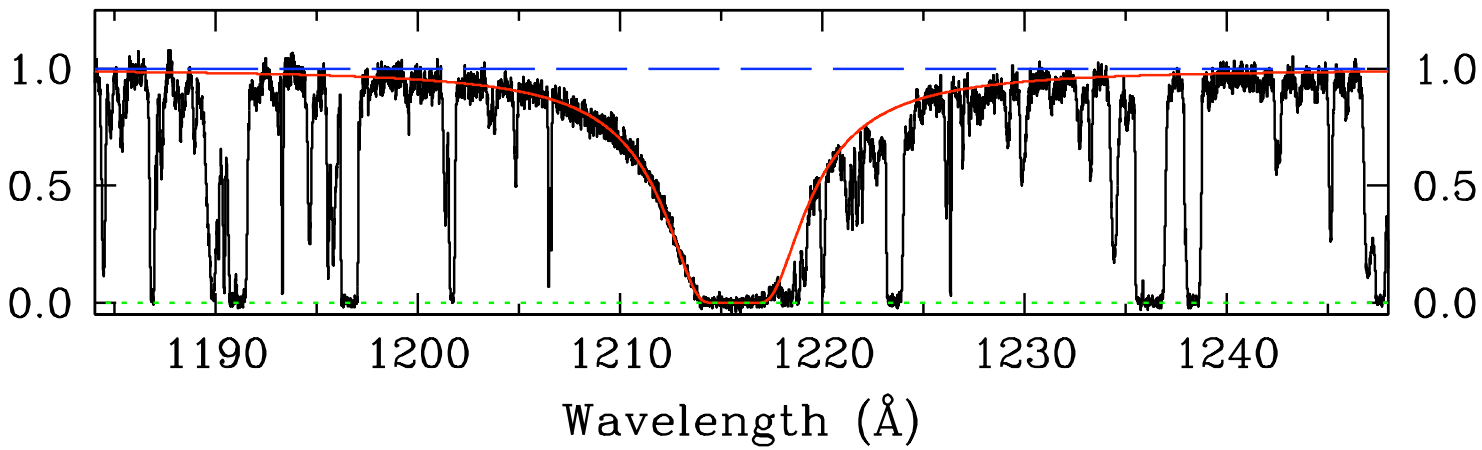
$$N_{\rm eff} = 3.50 \pm 0.20$$



Cooke et al. 2014

Summary

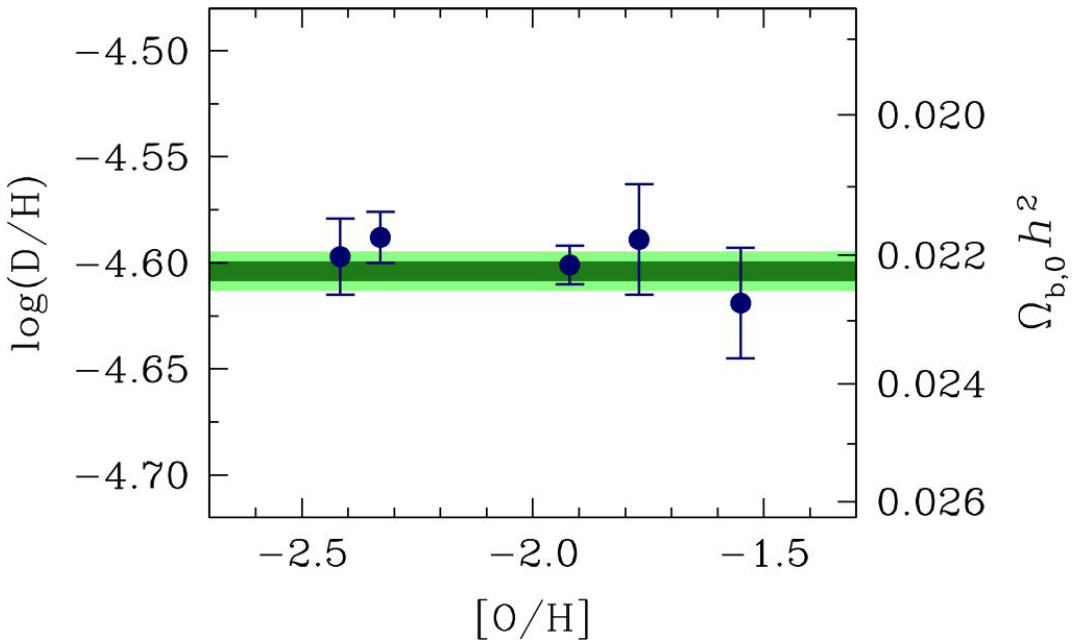
There exists a population of neutral gas clouds which at redshifts z = 2 - 4 had undergone minimal enrichment by stellar nucleosynthesis.



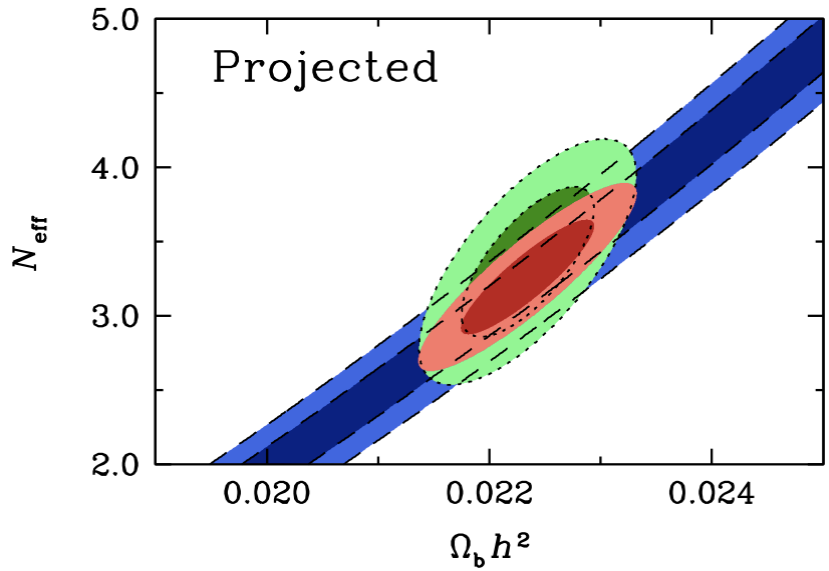
Chemical studies of these `Extremely Metal-Poor Damped Lyman Alpha Systems' complement very effectively analogous measures in old stars of the Milky Way and nearby galaxies.

Main Results: Deuterium

- Concordance between values of $\Omega_{\rm b}h^2$ from CMB and D/H in metal-poor DLAs.



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



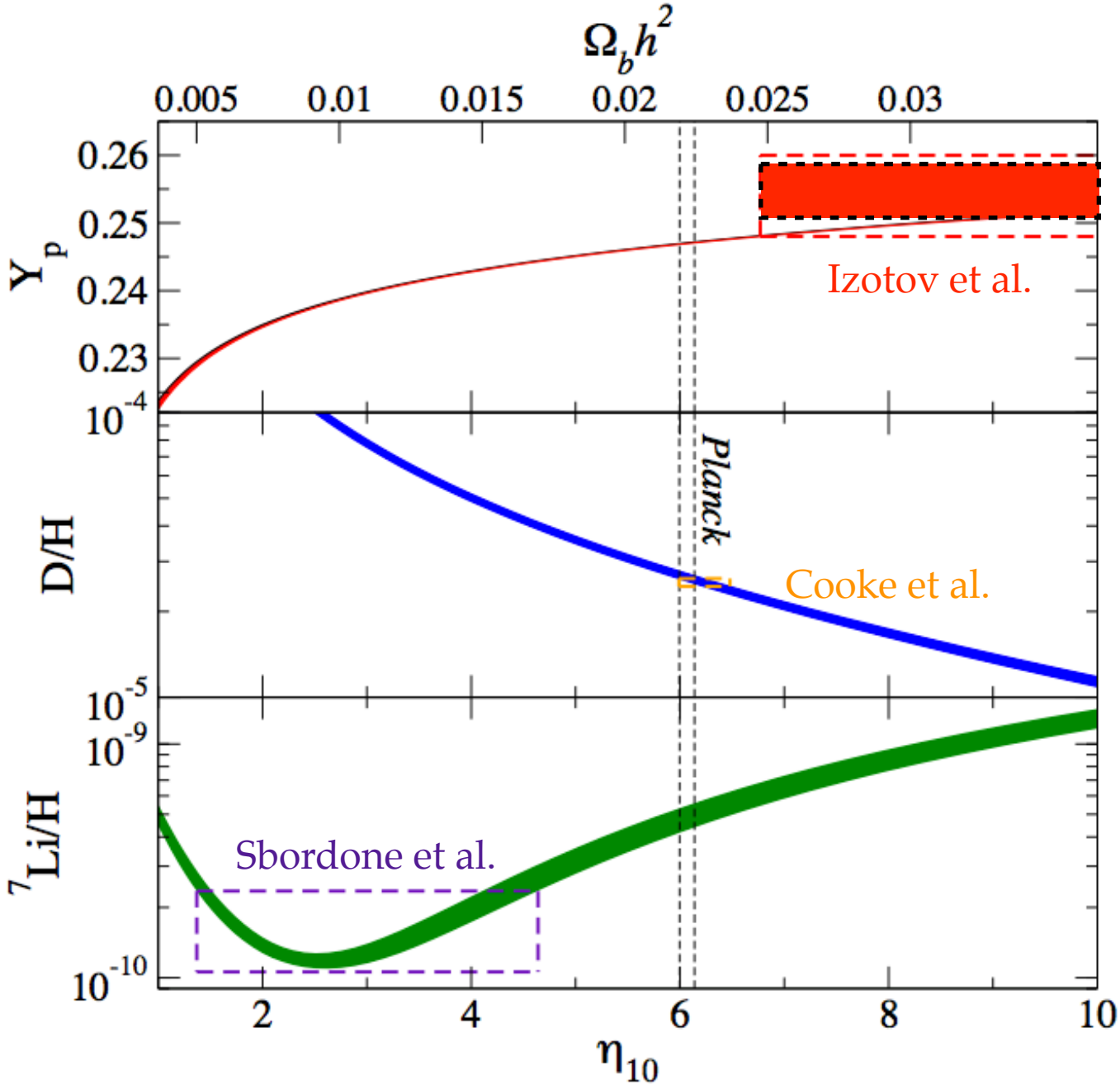
With Thanks to:

Ryan Cooke (UCSC)


The End


Epilogue…

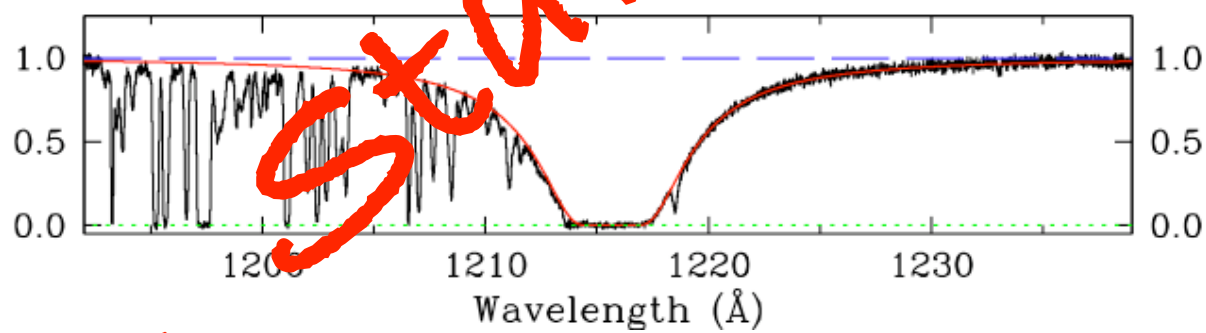
BBN theory confronts observations 2014



Oldest stars

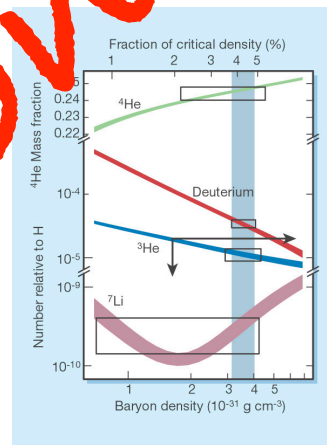
Metal-poor DLAs

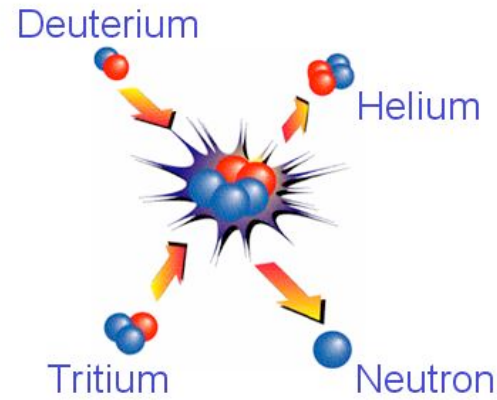
Starved

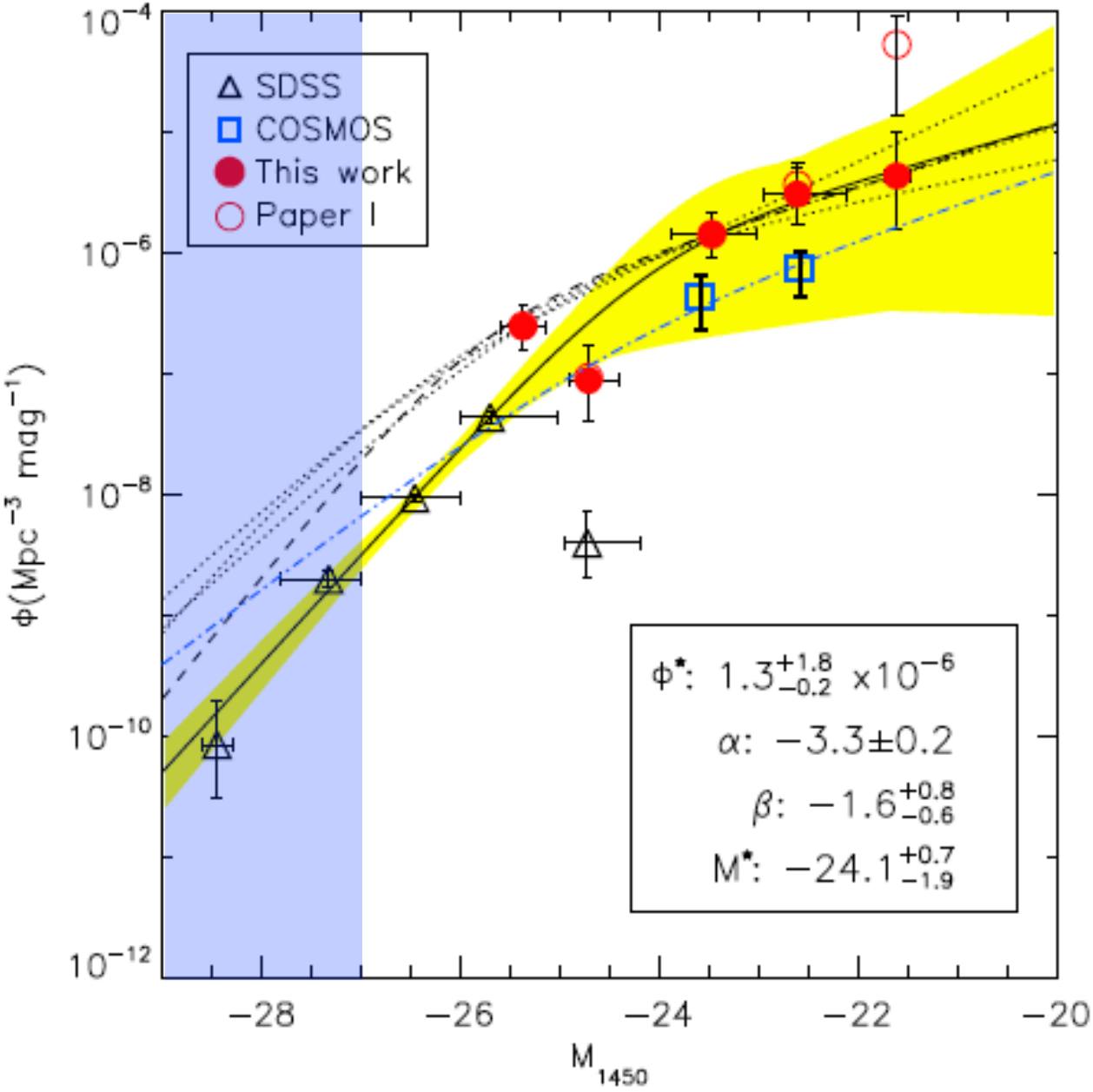


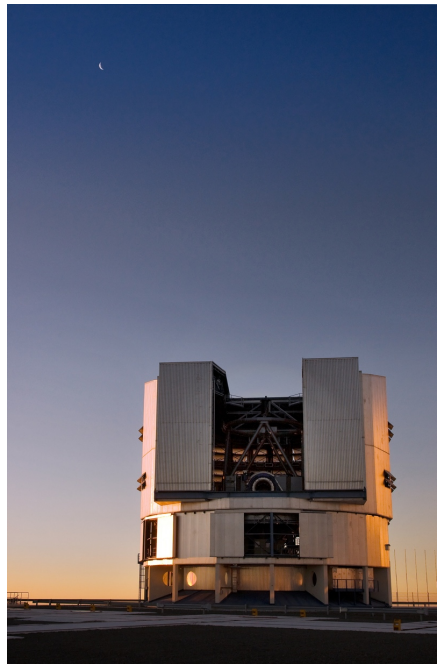
Light Elements

Photon



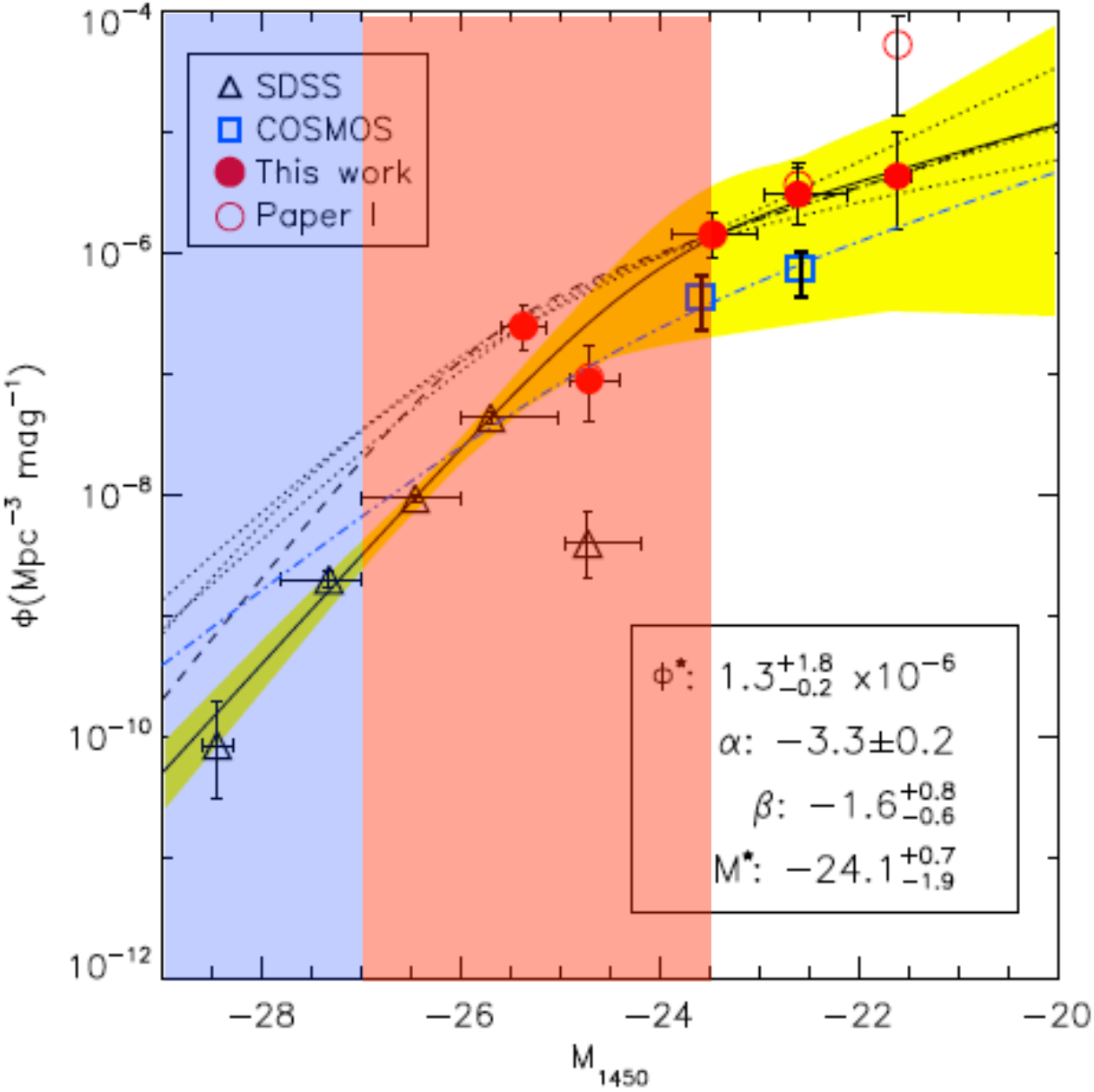


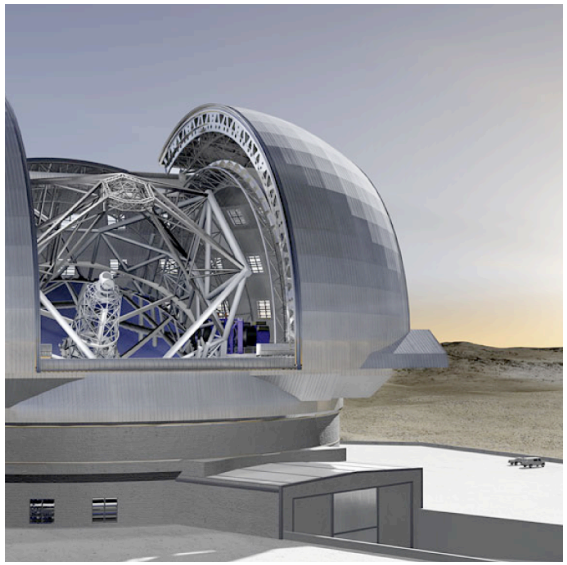




QSO Luminosity Function

Glikman et al. 2011





QSO Luminosity Function

Glikman et al. 2011

The Future