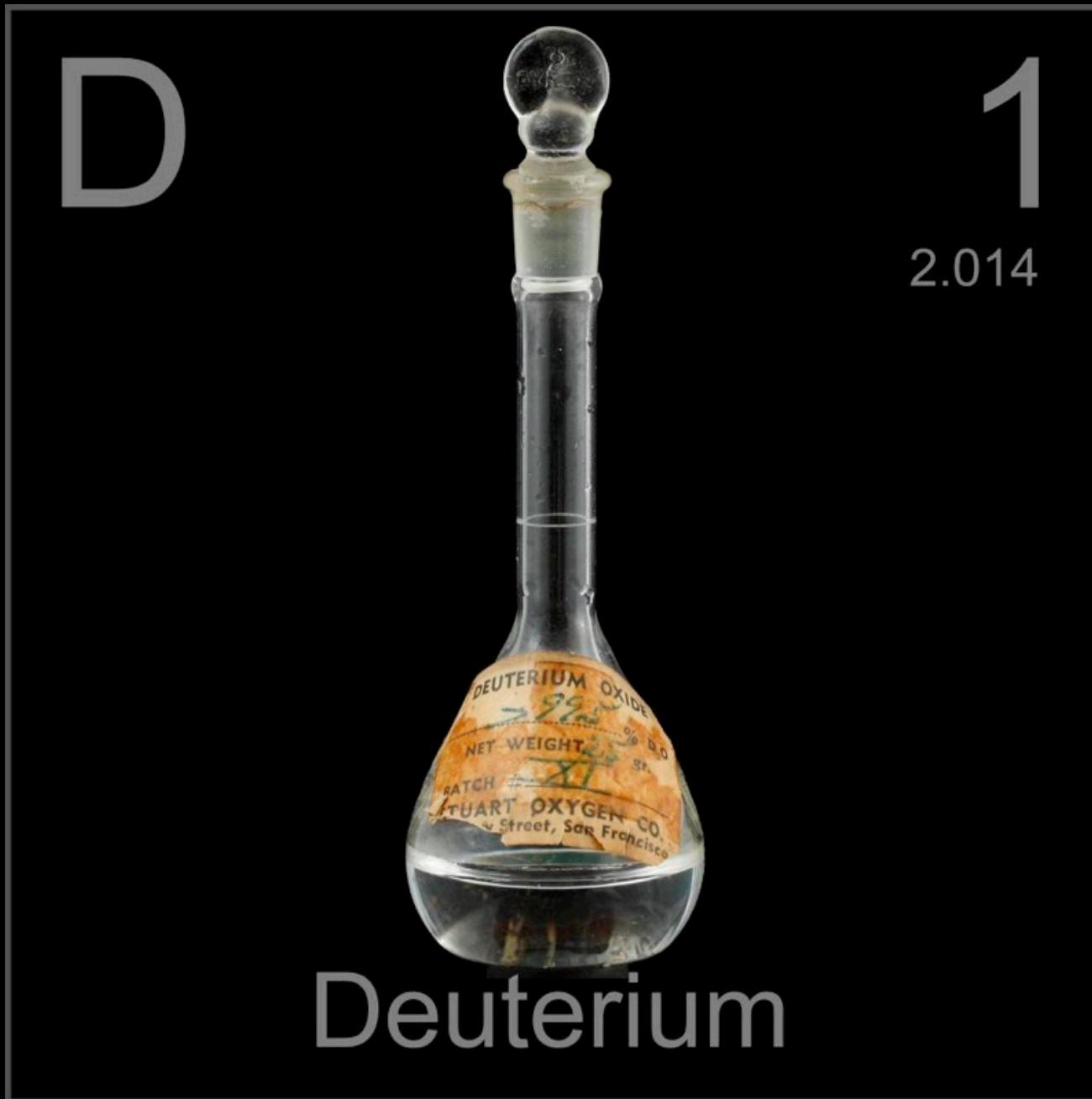
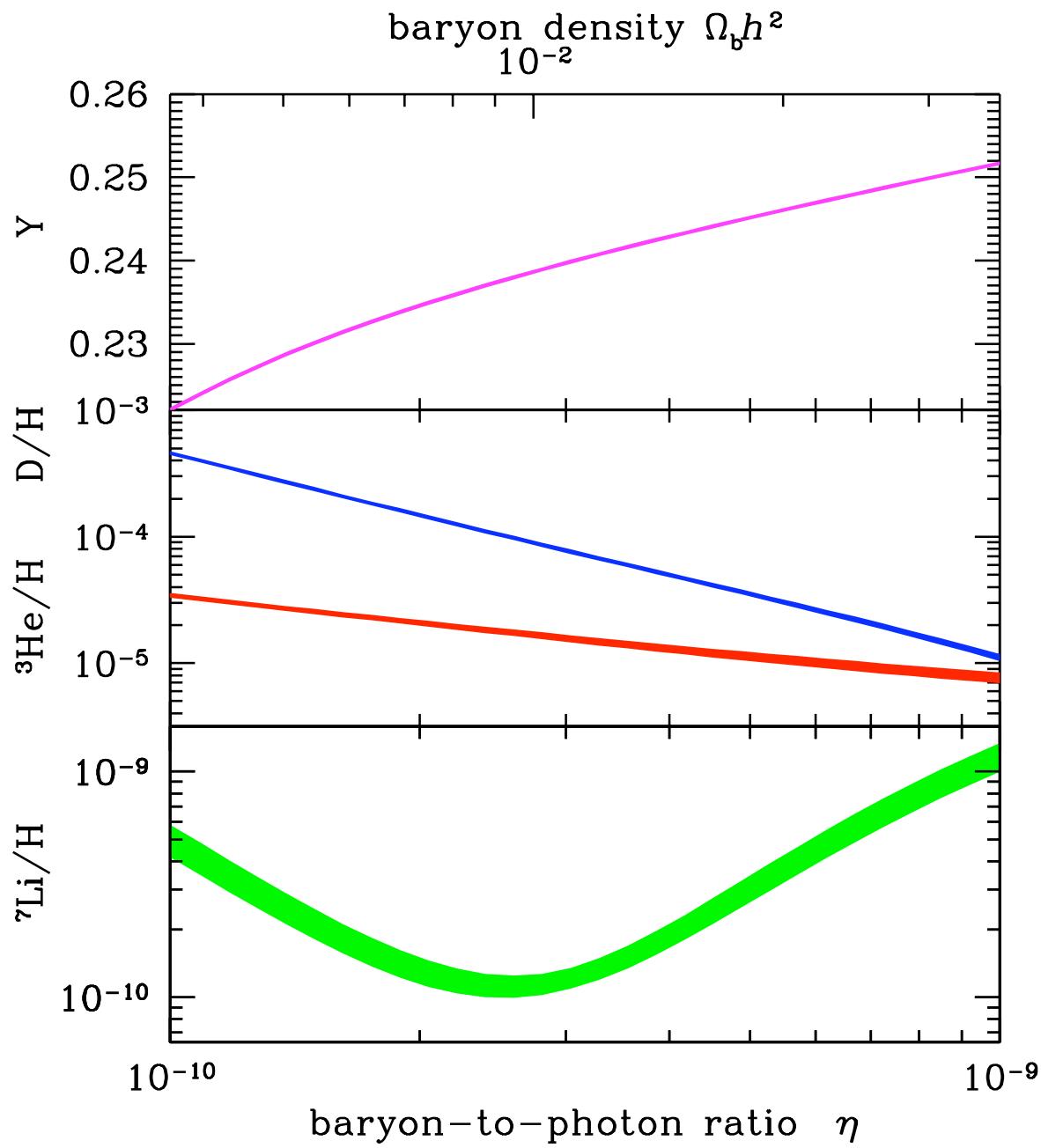


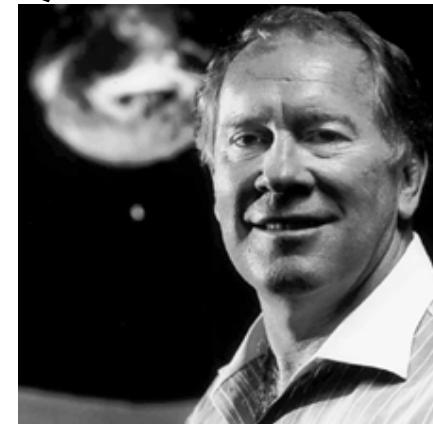
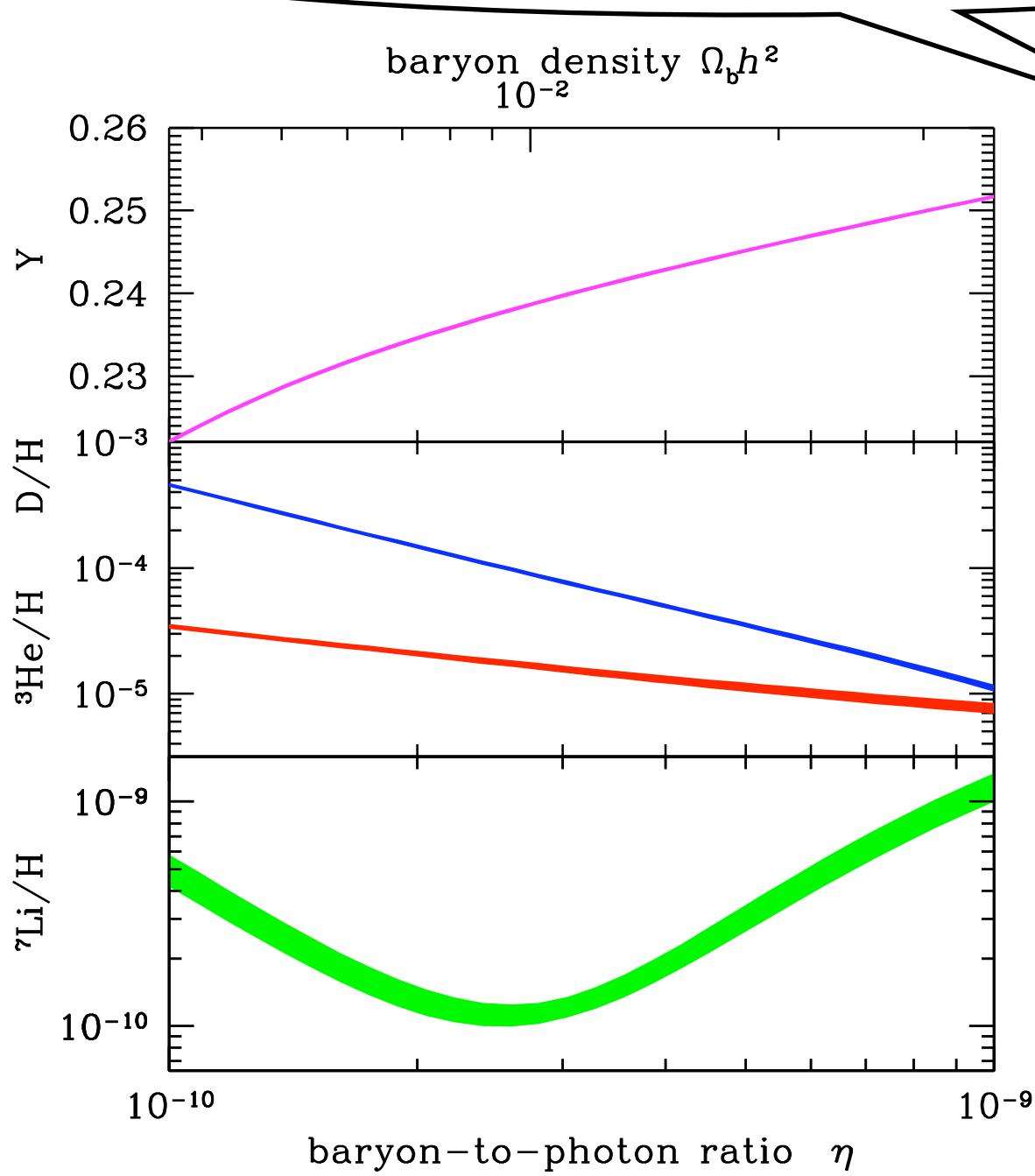
Percent precision in the primordial abundance of



Deuterium is the baryometer of choice



Deuterium is the baryometer of choice



David
Schramm



Michael
Turner

INTERSTELLAR DEUTERIUM ABUNDANCE IN THE DIRECTION OF BETA CENTAURI

JOHN B. ROGERSON, JR., AND DONALD G. YORK

Princeton University Observatory

Received 1973 September 21; revised 1973 October 18

ABSTRACT

Interstellar absorption lines due to the Lyman series transitions in hydrogen and deuterium have been observed in the spectrum of β Cen. From these, a ratio of deuterium to hydrogen, by number, of 1.4 ± 0.2 (m.e.) $\times 10^{-5}$ has been obtained. If one assumes that the present deuterium abundance is a relic of the big-bang element synthesis, a value of 1.5×10^{-31} g cm $^{-3}$ for the present density of the Universe is derived.

Subject headings: abundances — cosmology — interstellar matter — spectra, ultraviolet

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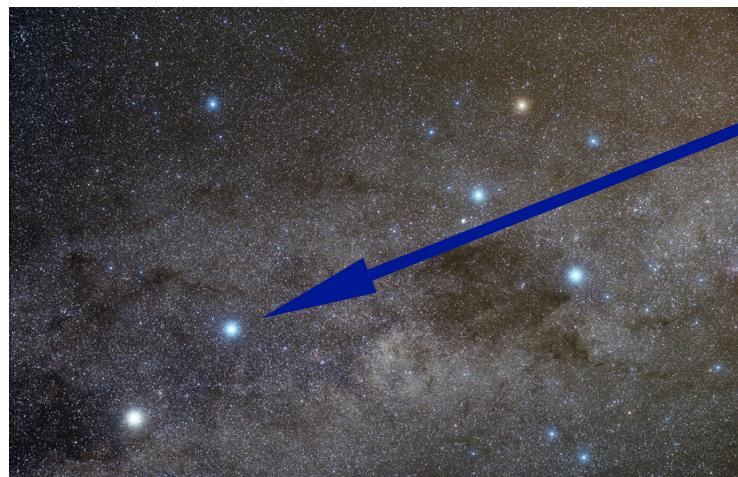
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β Cen

B1 III

$V = 0.61$

$d = 120$ pc

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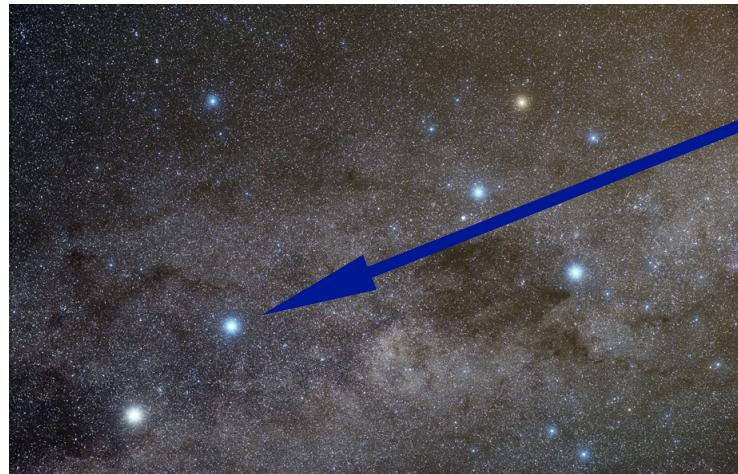
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β Cen

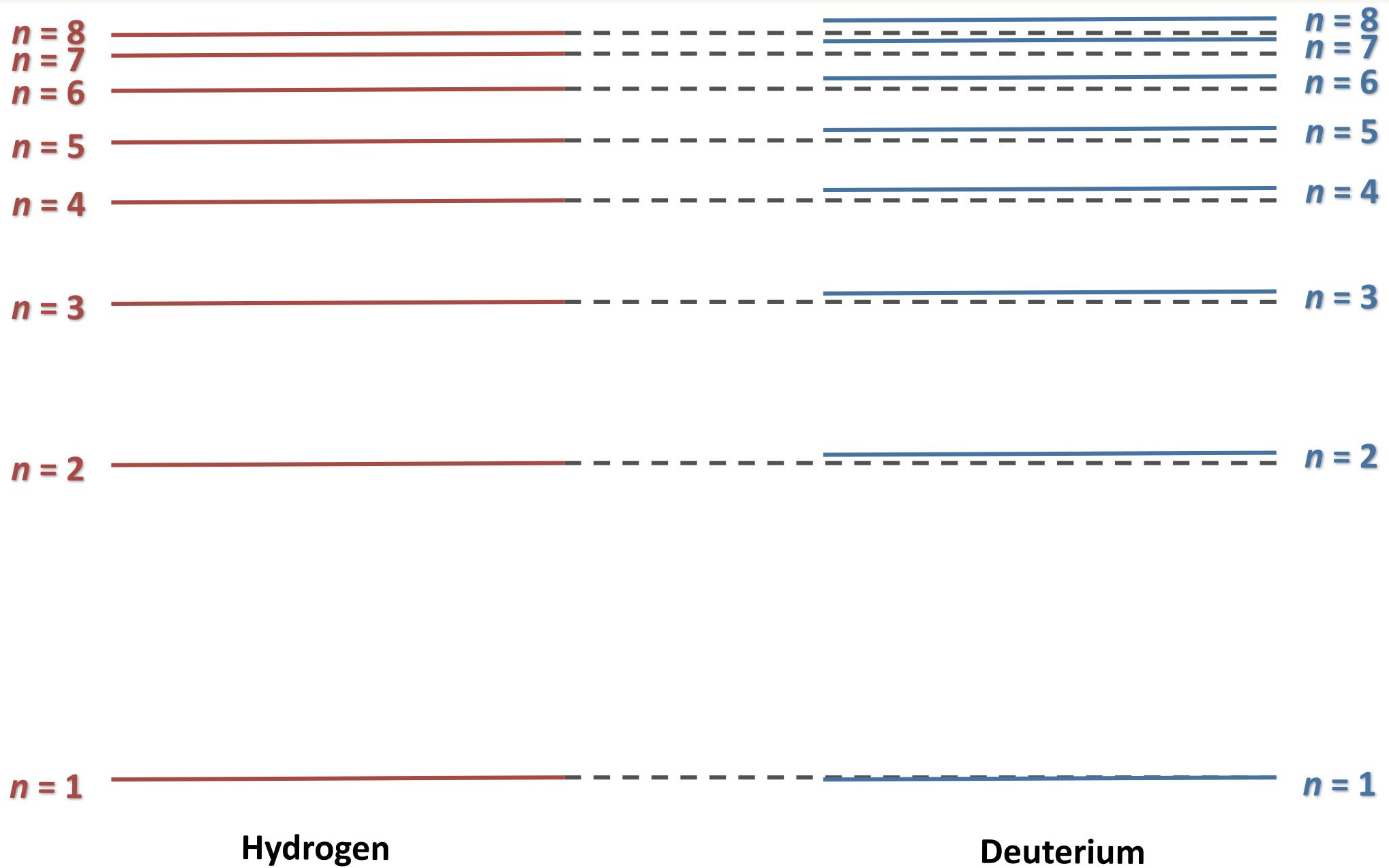
B1 III

$V = 0.61$

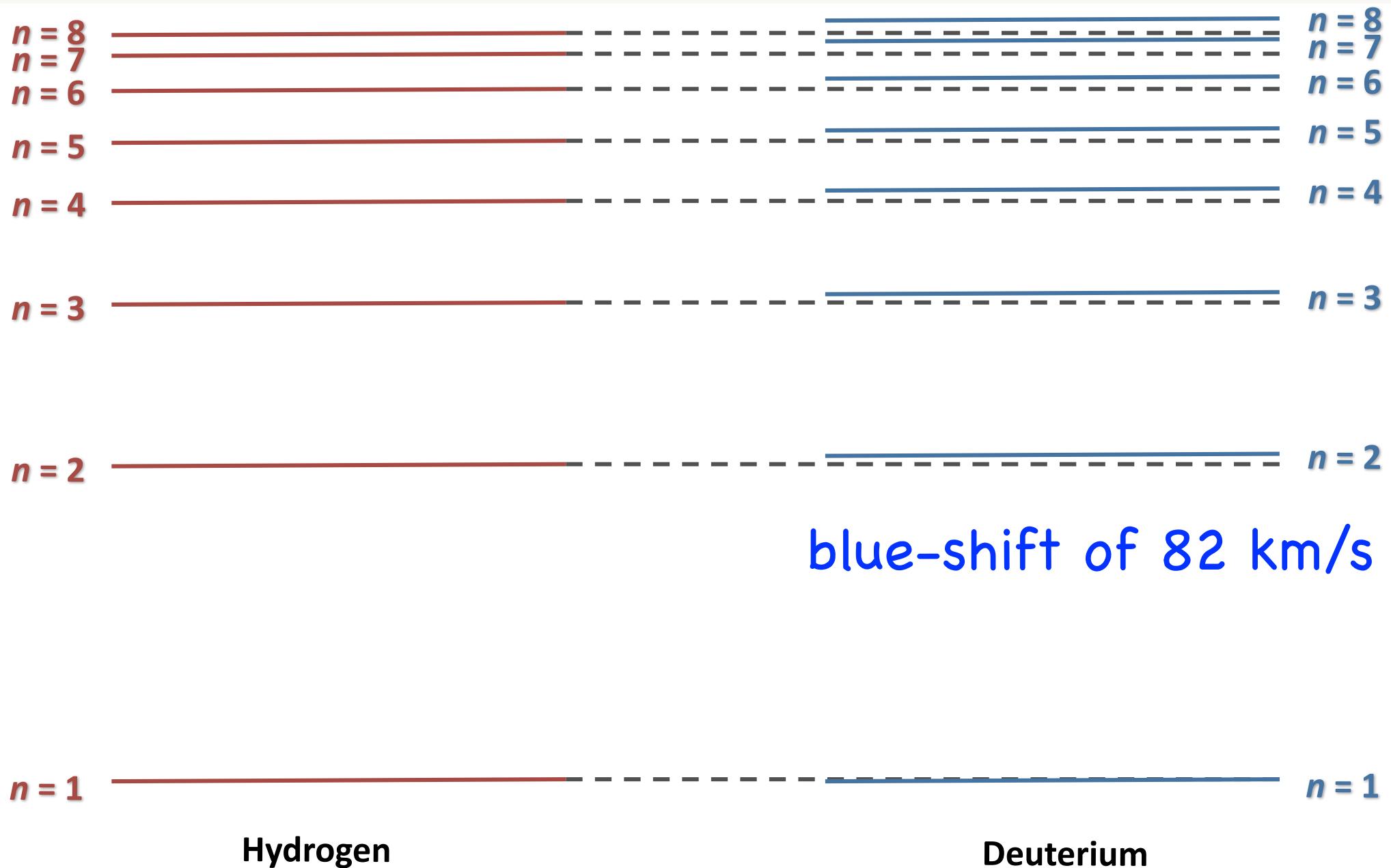
$d = 120$ pc

$$\Omega_b < 0.067$$

Energy Levels



Energy Levels



*Research Note***The Detectability of Deuterium Lyman Alpha in QSOs**

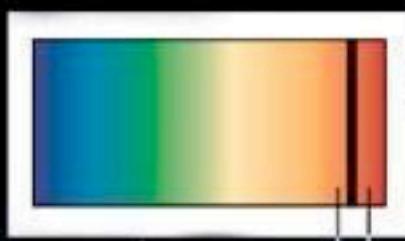
Thomas F. Adams

Department of Astronomy and Astrophysics, University of Chicago, 1100-14E. 58th Street, Chicago, Illinois 60637, USA

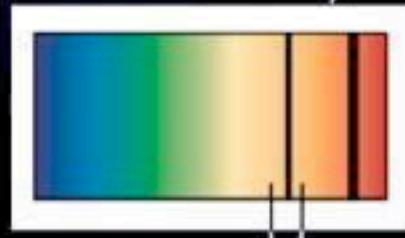
Received March 22, 1976

Summary. Blended line profiles are calculated for the deuterium and hydrogen Lyman alpha lines that might be produced by QSO absorbing clouds. It is shown that in suitable clouds the deuterium Lyman alpha line should be detectable, even if the abundance of deuterium is the same as in the interstellar medium. Observers should be alert for the deuterium Lyman alpha line since its detection would have important cosmological implications.

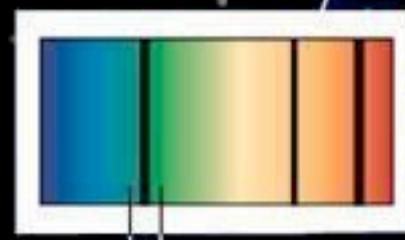
Quasar



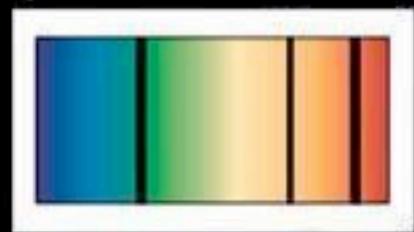
A



B



C



D

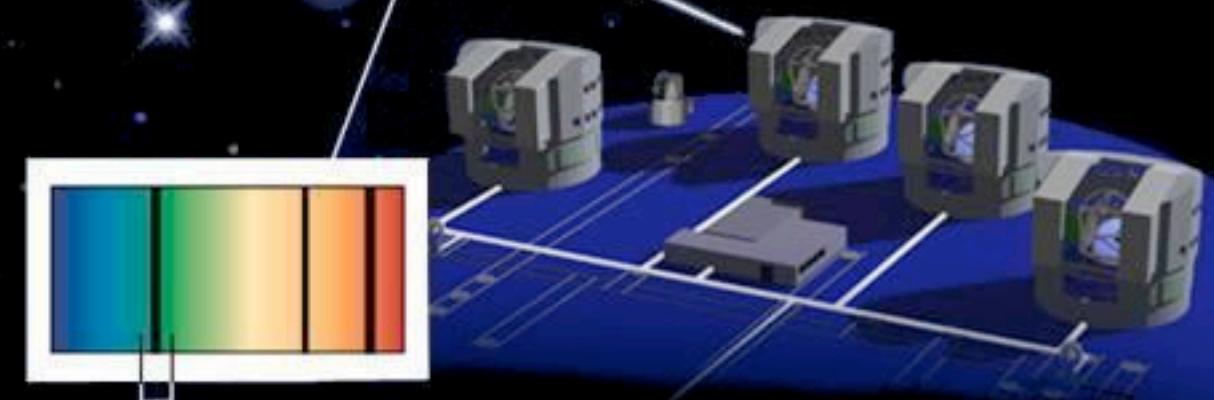


Image credit: ESO



10m Keck telescope + HIRES



10m Keck telescope + HIRES



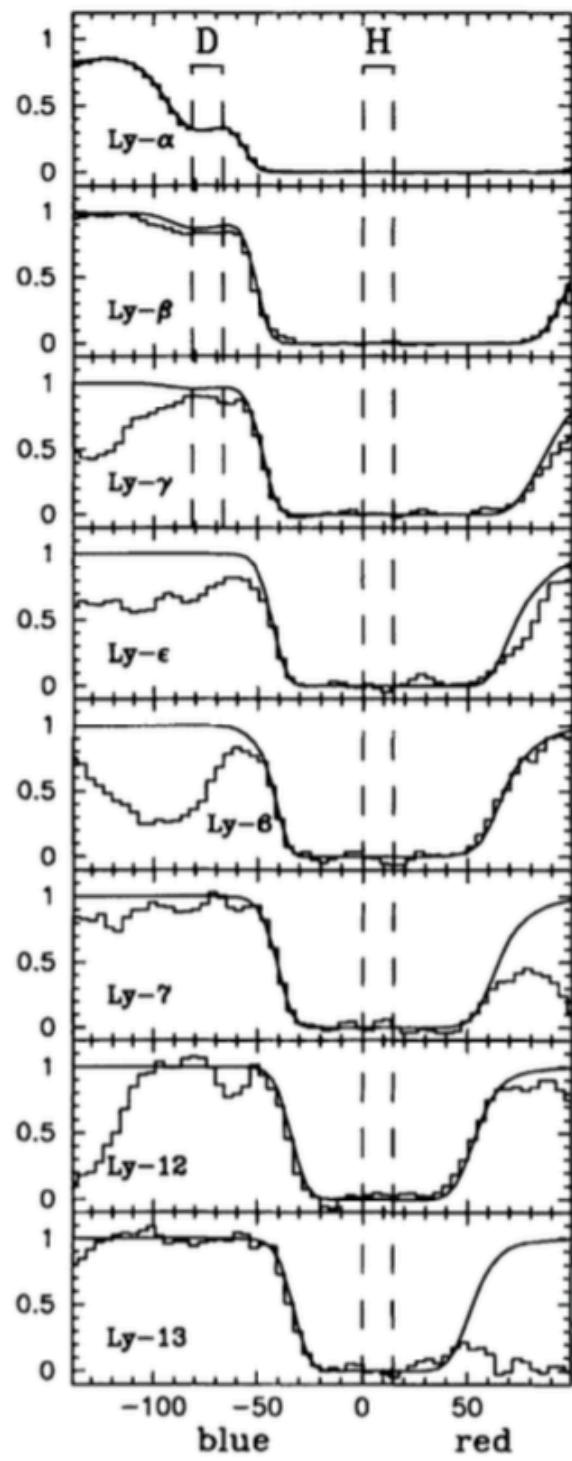
**Cosmological baryon density
derived from the deuterium
abundance at redshift $z = 3.57$**

David Tytler, Xiao-Ming Fan & Scott Burles

Department of Physics, and Center for Astrophysics and Space Sciences,
University of California, San Diego, C0111, La Jolla,
California 92093-0111, USA

NATURE · VOL 381 · 16 MAY 1996

Normalized flux



10m Keck telescope + HIRES



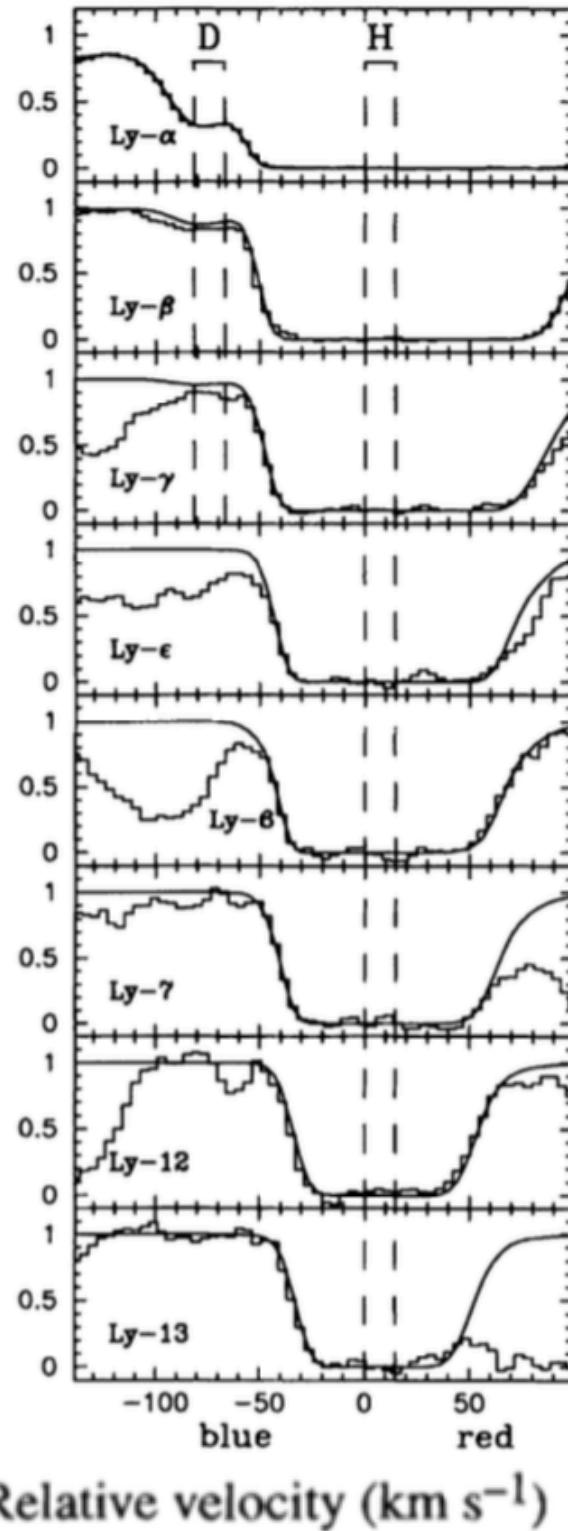
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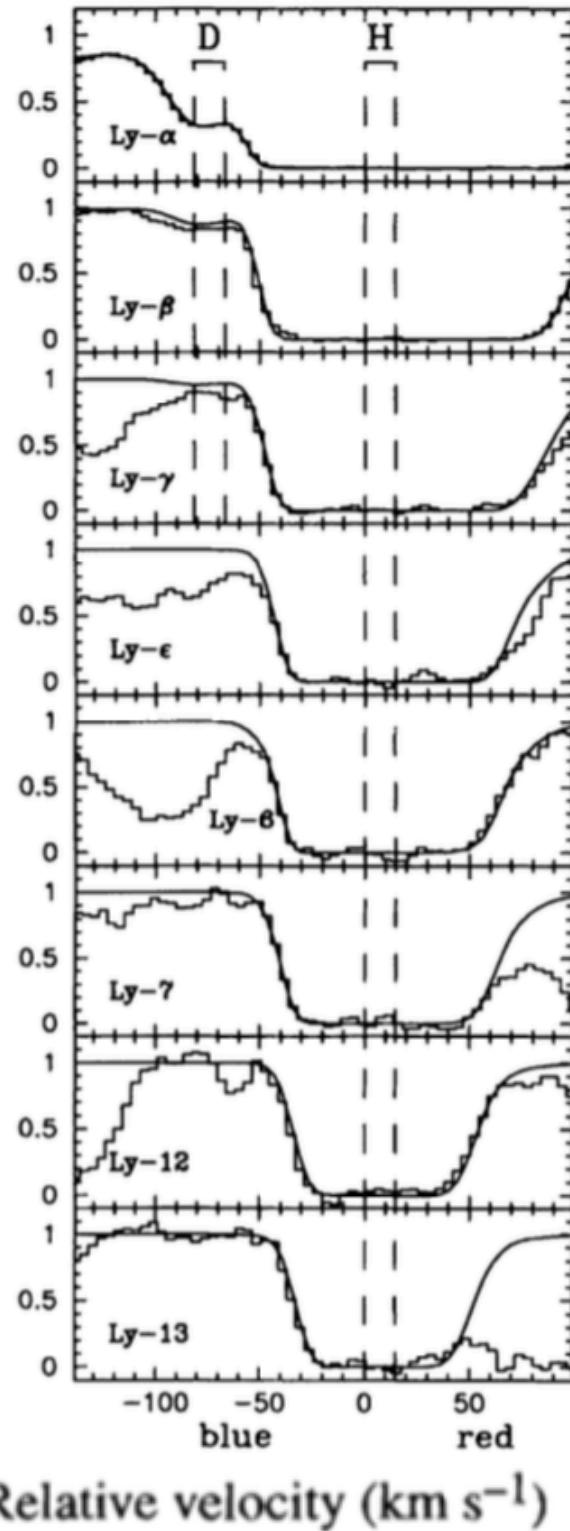
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$$10^5 \text{ D/H} = 2.3 \pm 0.6$$

Normalized flux



10m Keck telescope + HIRES



Cosmological baryon density derived from the deuterium abundance at redshift $z = 3.57$

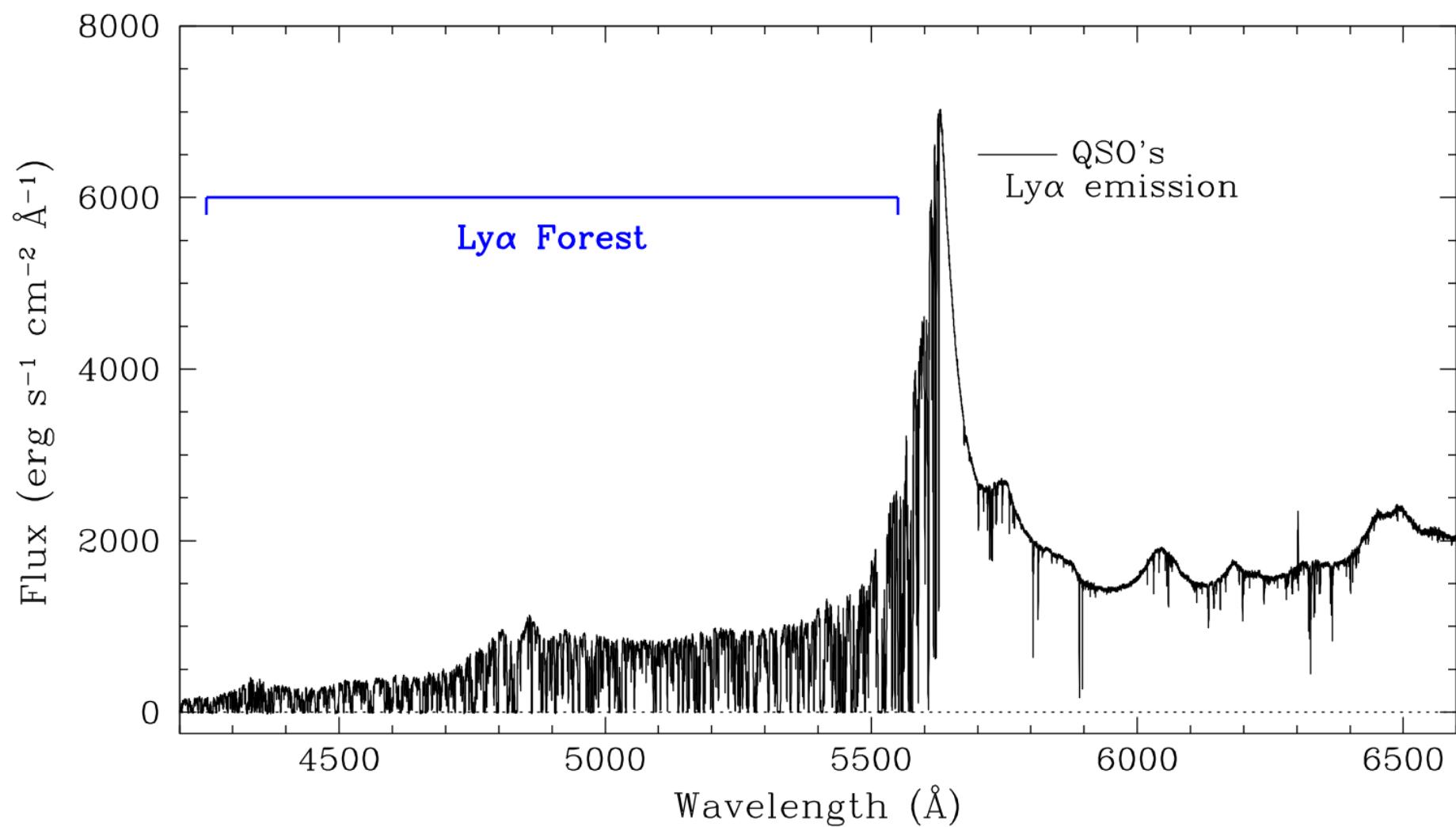
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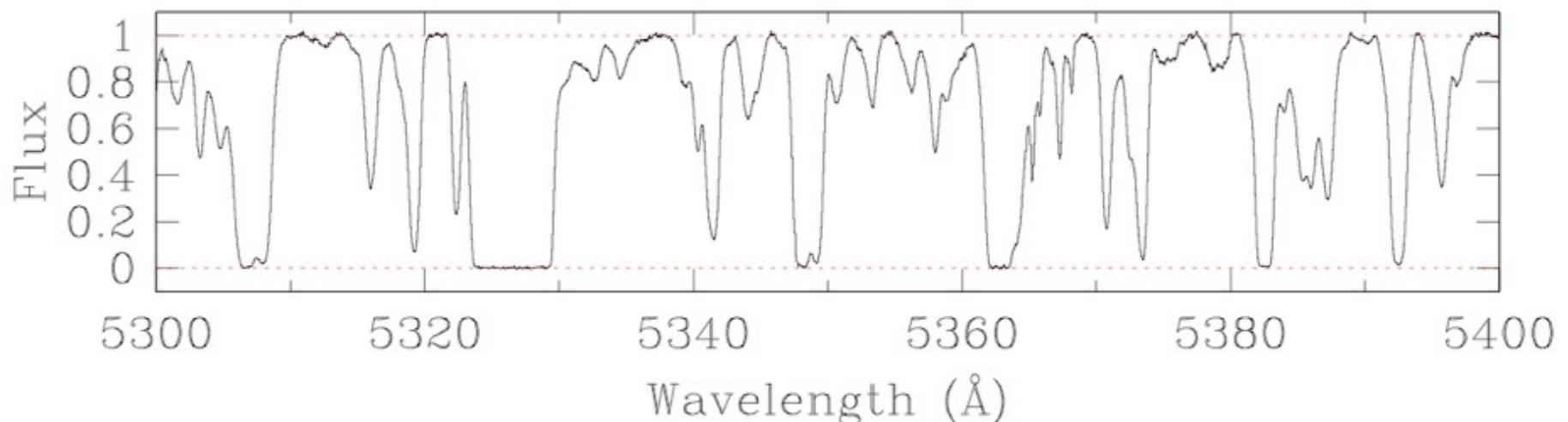
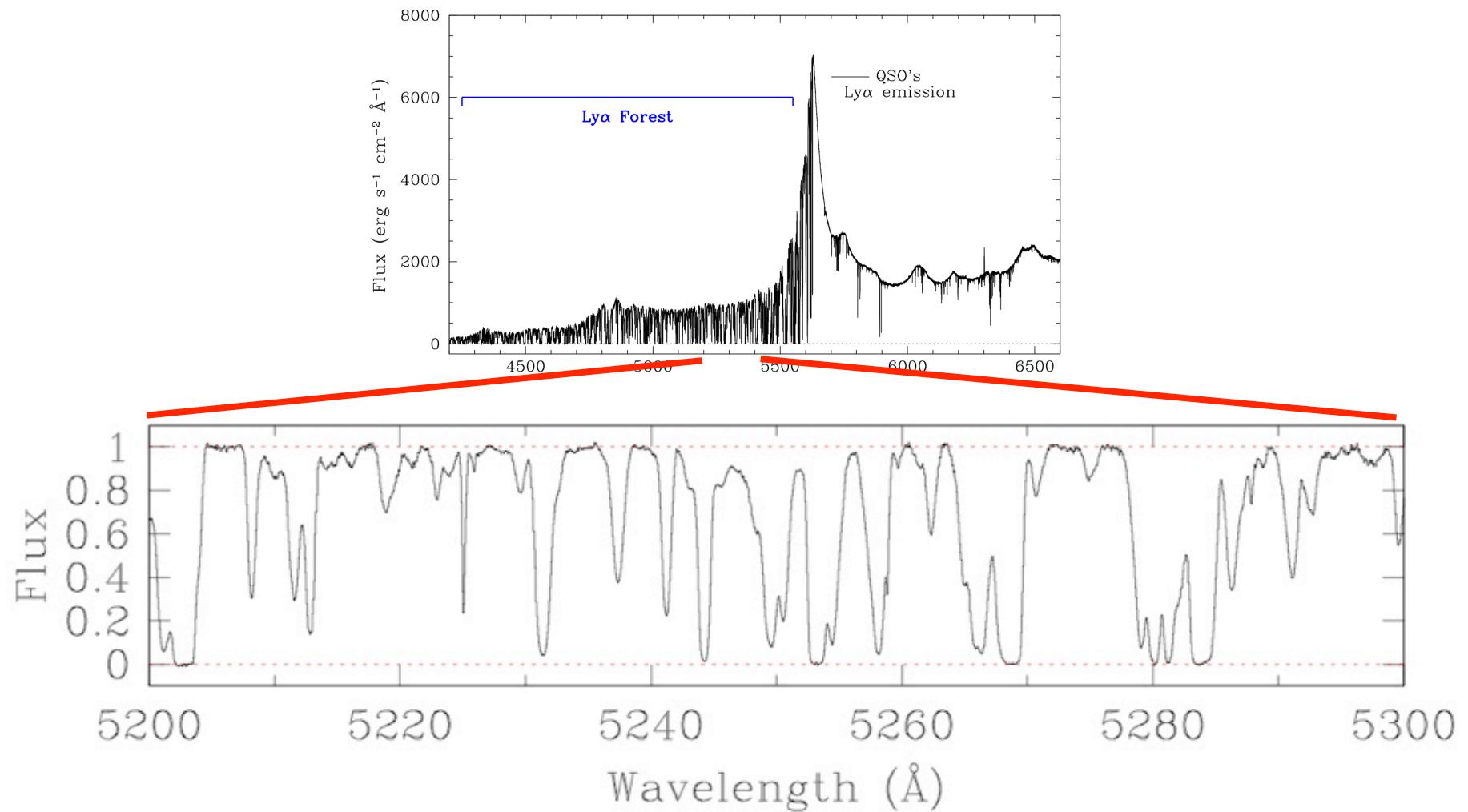
Department of Physics, and Center for Astrophysics and Space Sciences,
University of California, San Diego, C0111, La Jolla,
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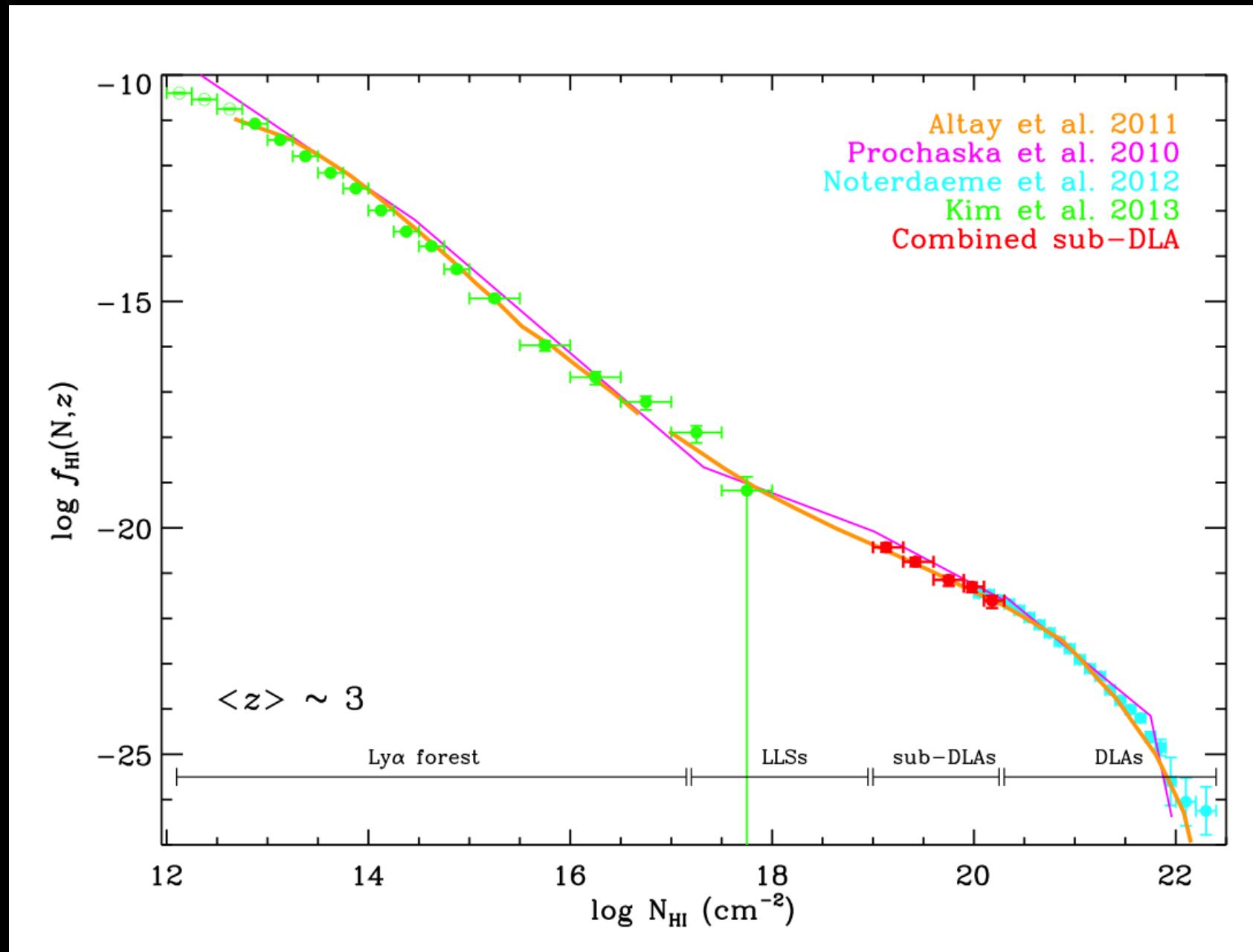
$$100\Omega_b h^2 = 2.4 \pm 0.6$$

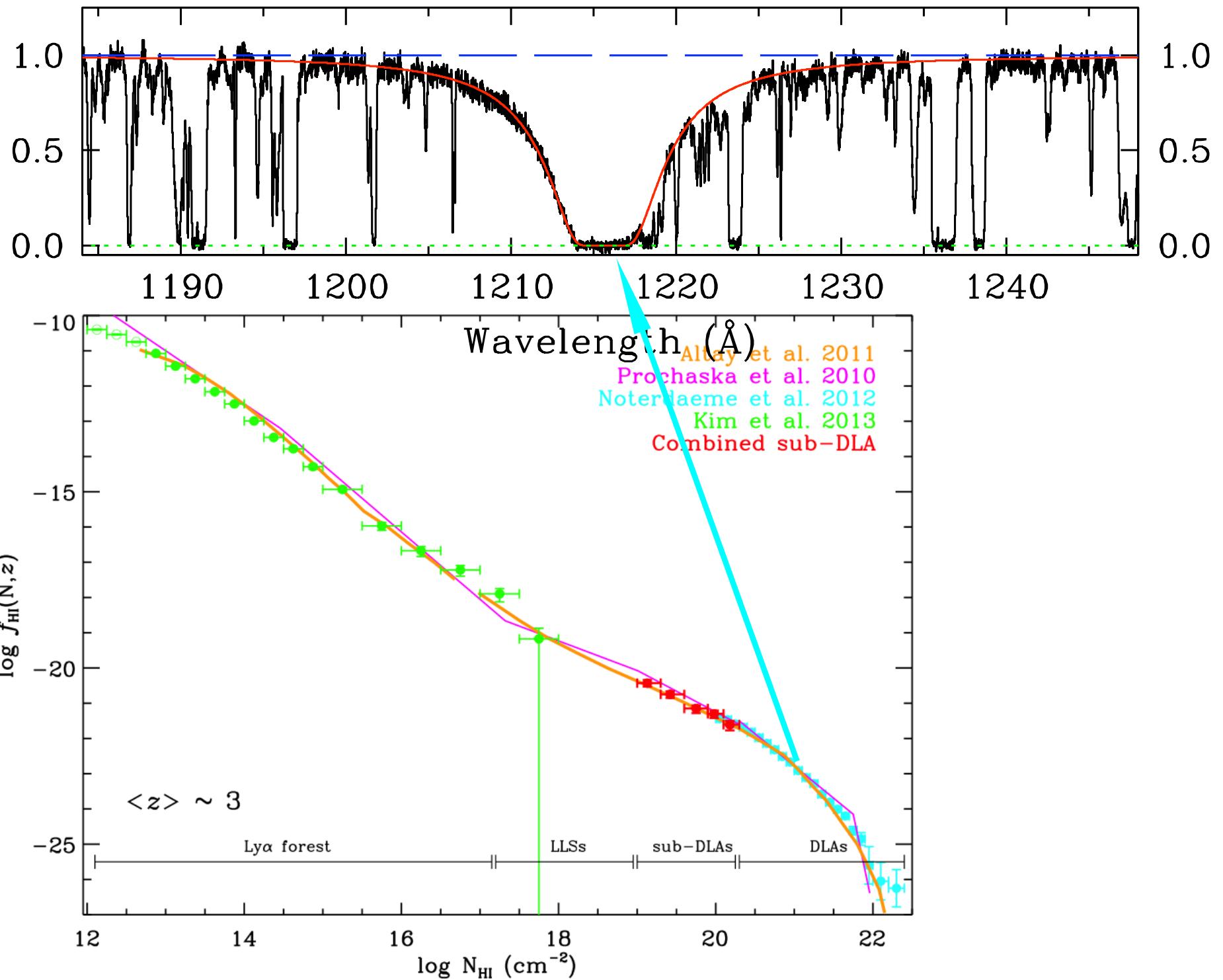
Q1422+231 $z_{\text{em}}=3.625$

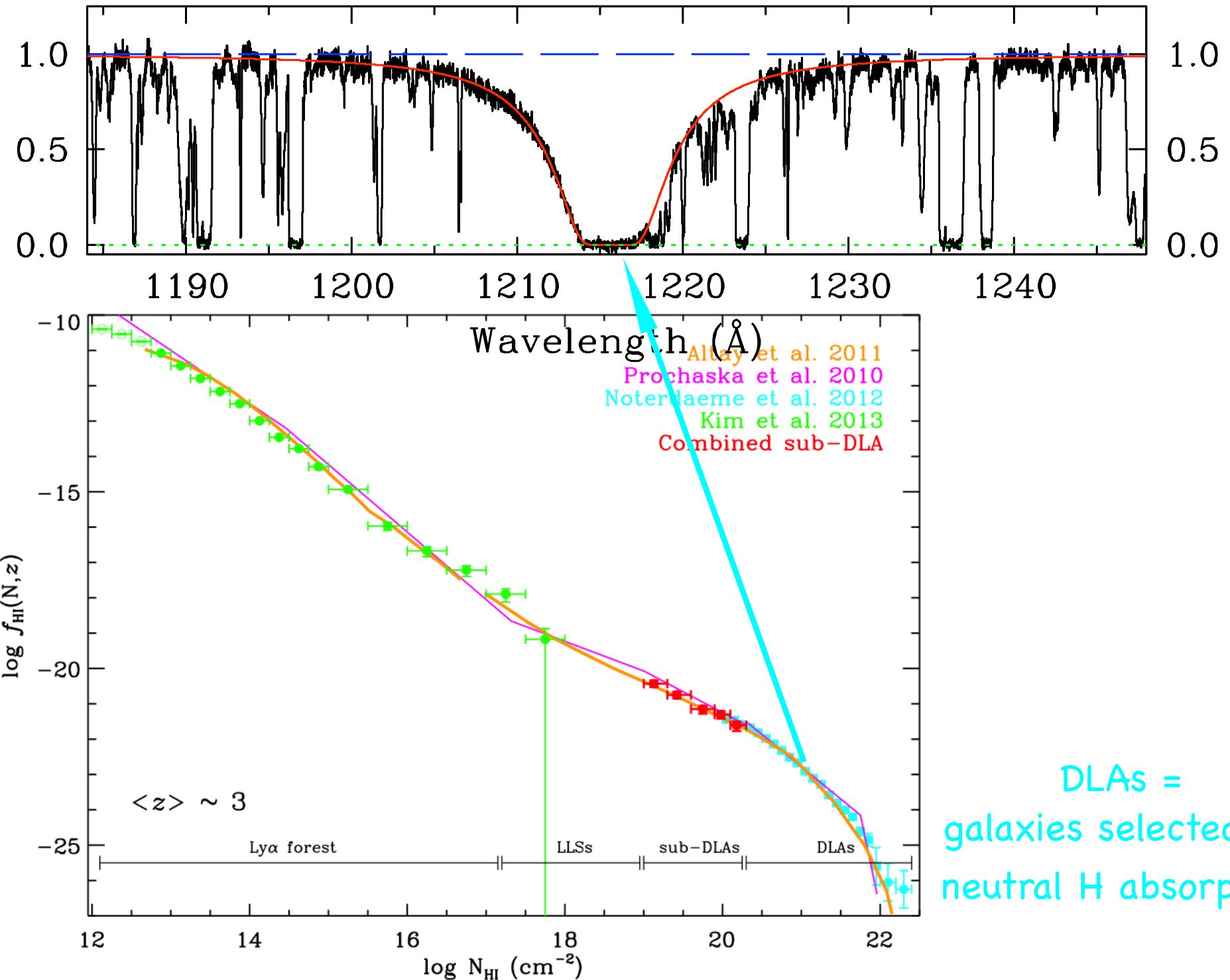


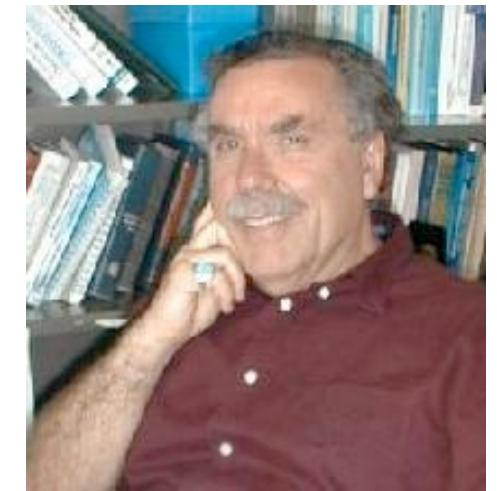
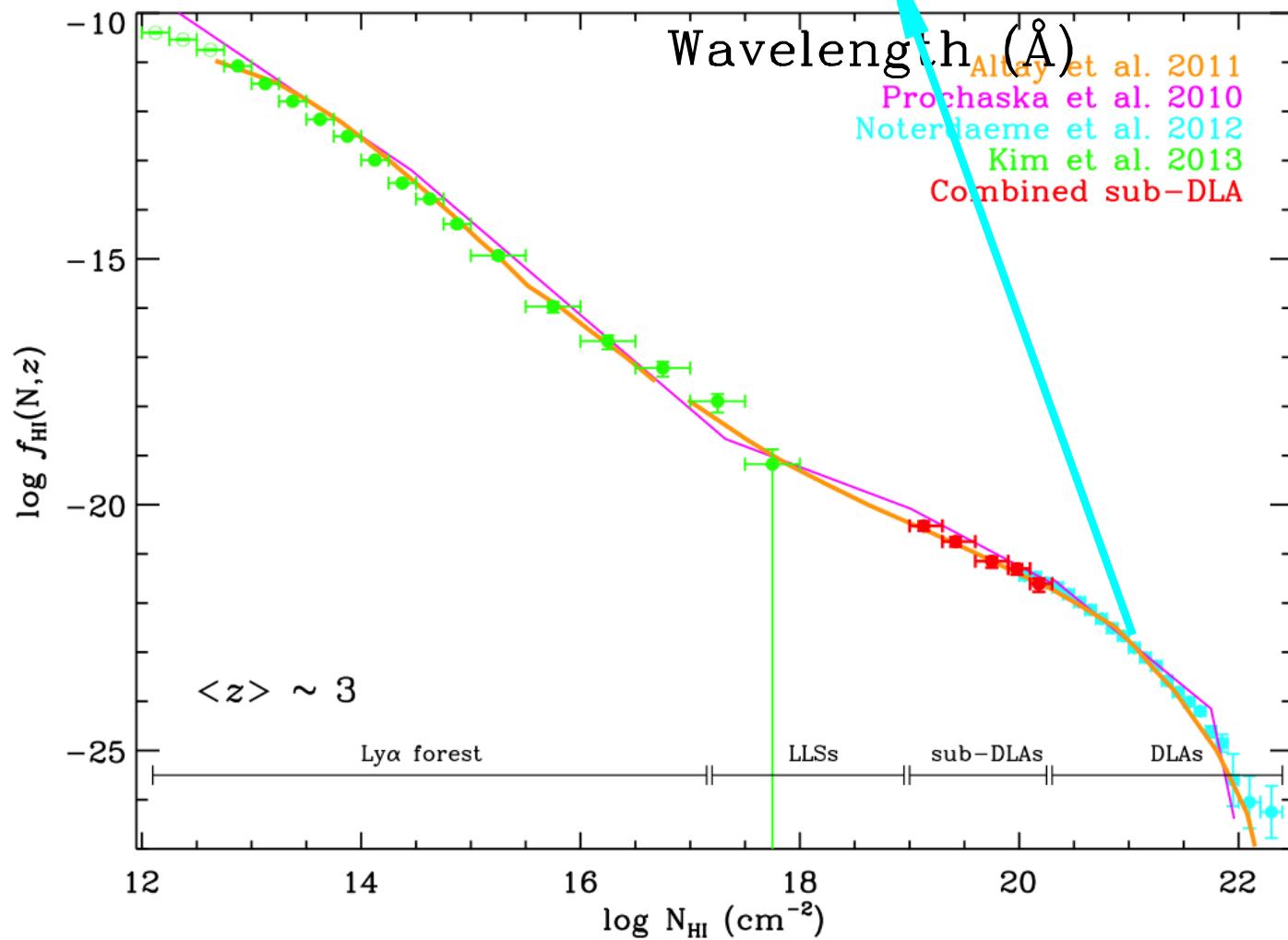
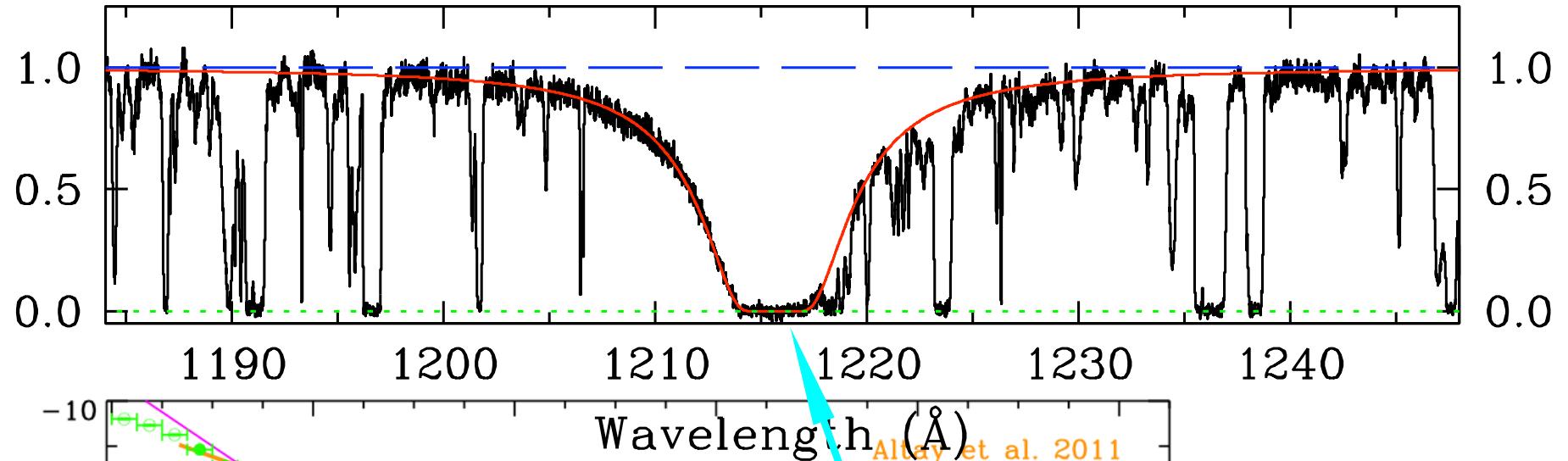


Column Density Distribution of Ly α forest lines



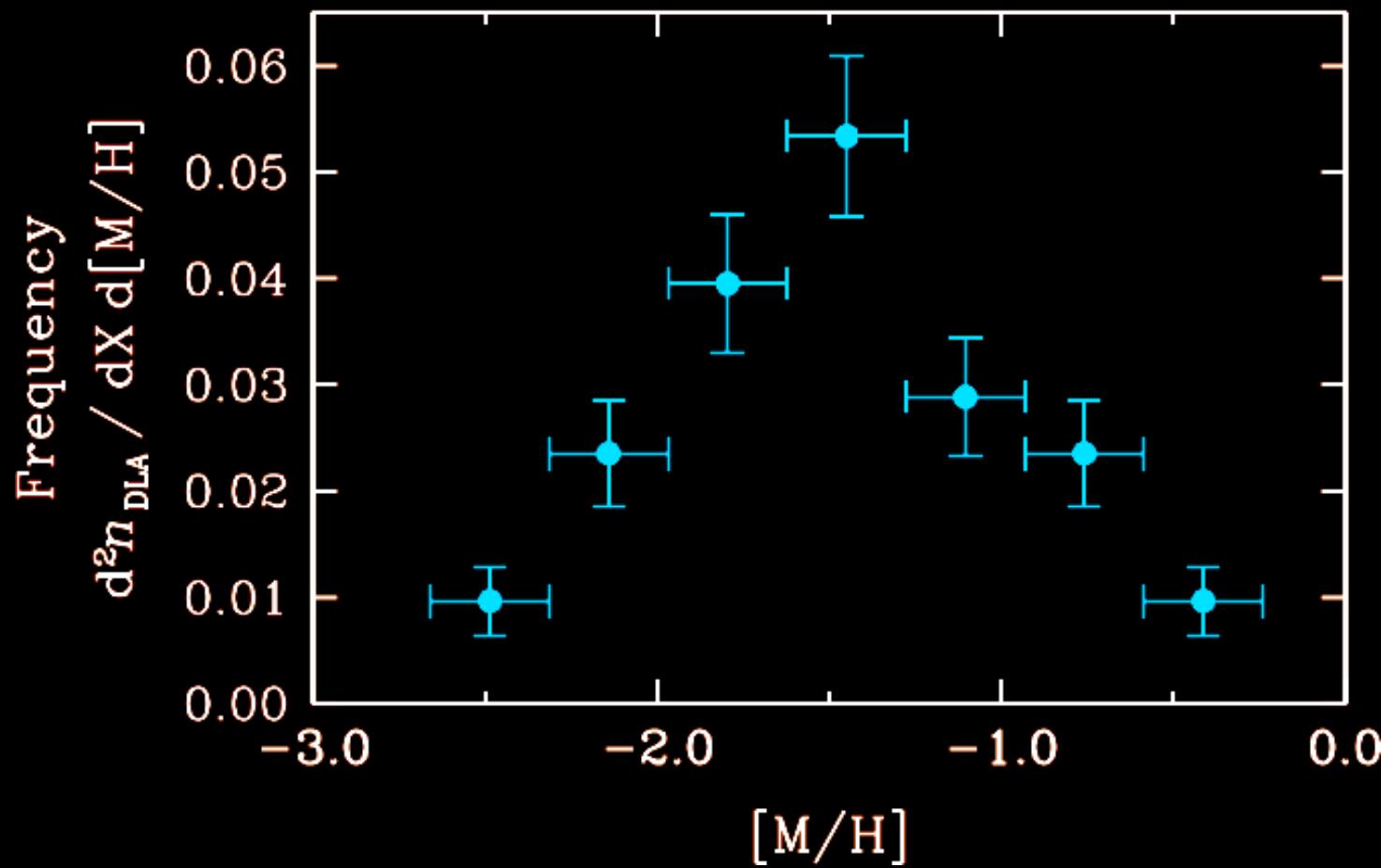






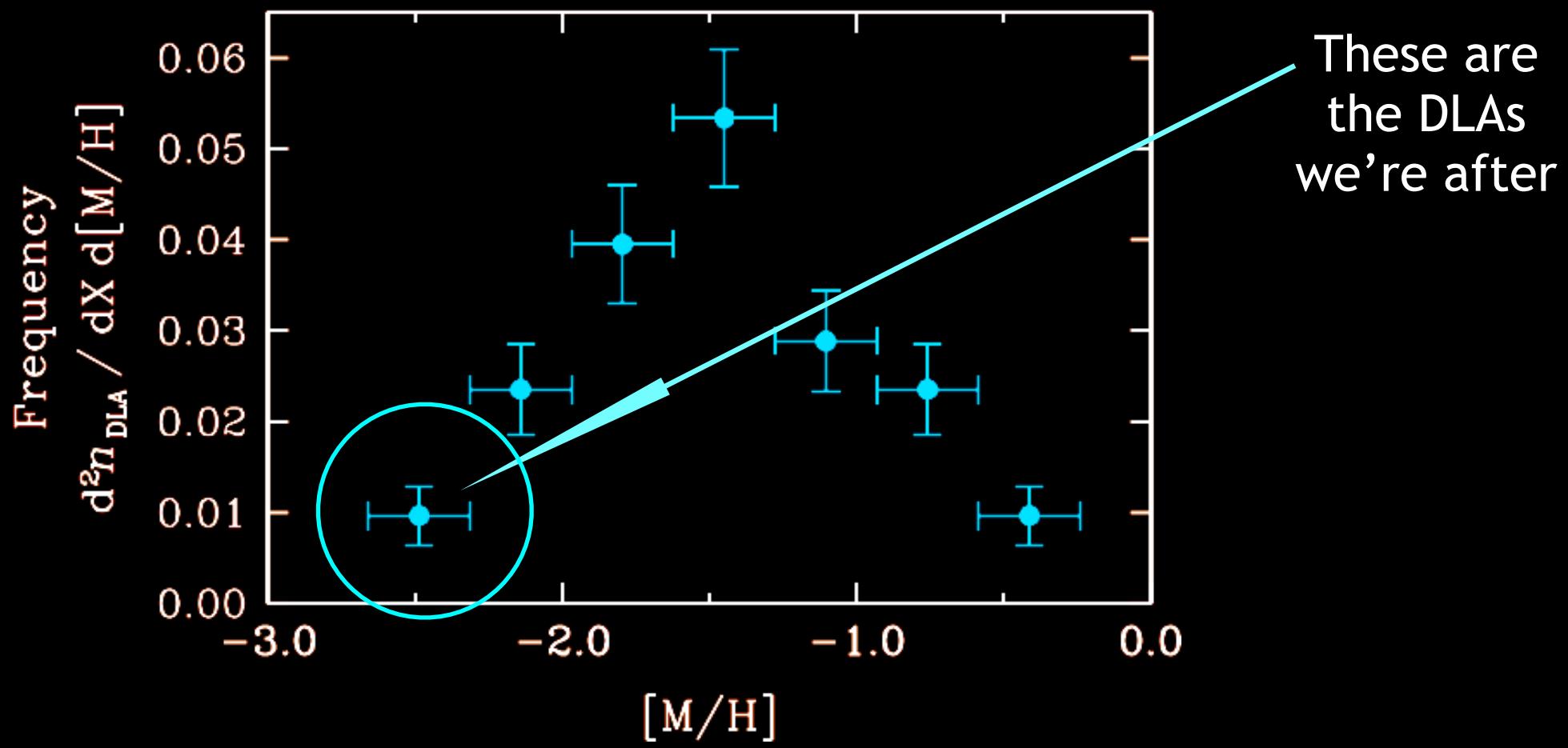
DLAs =
galaxies selected by
neutral H absorption

Metallicity Distribution



Rafelski et al. 2012

Metallicity Distribution



Rafelski et al. 2012

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

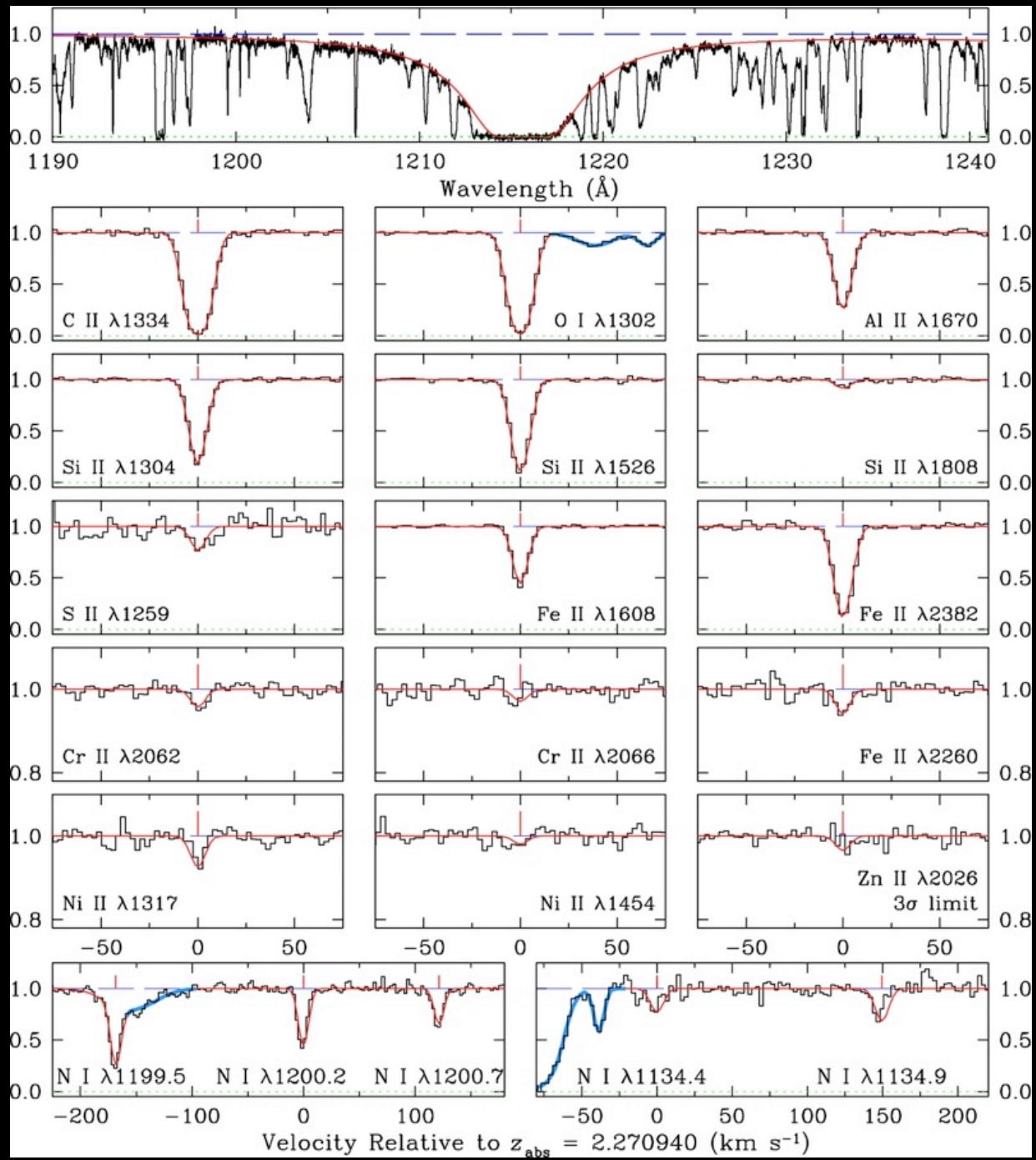
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Very Metal Poor DLAs are **the** choice astrophysical environments for measuring the primordial abundance of deuterium

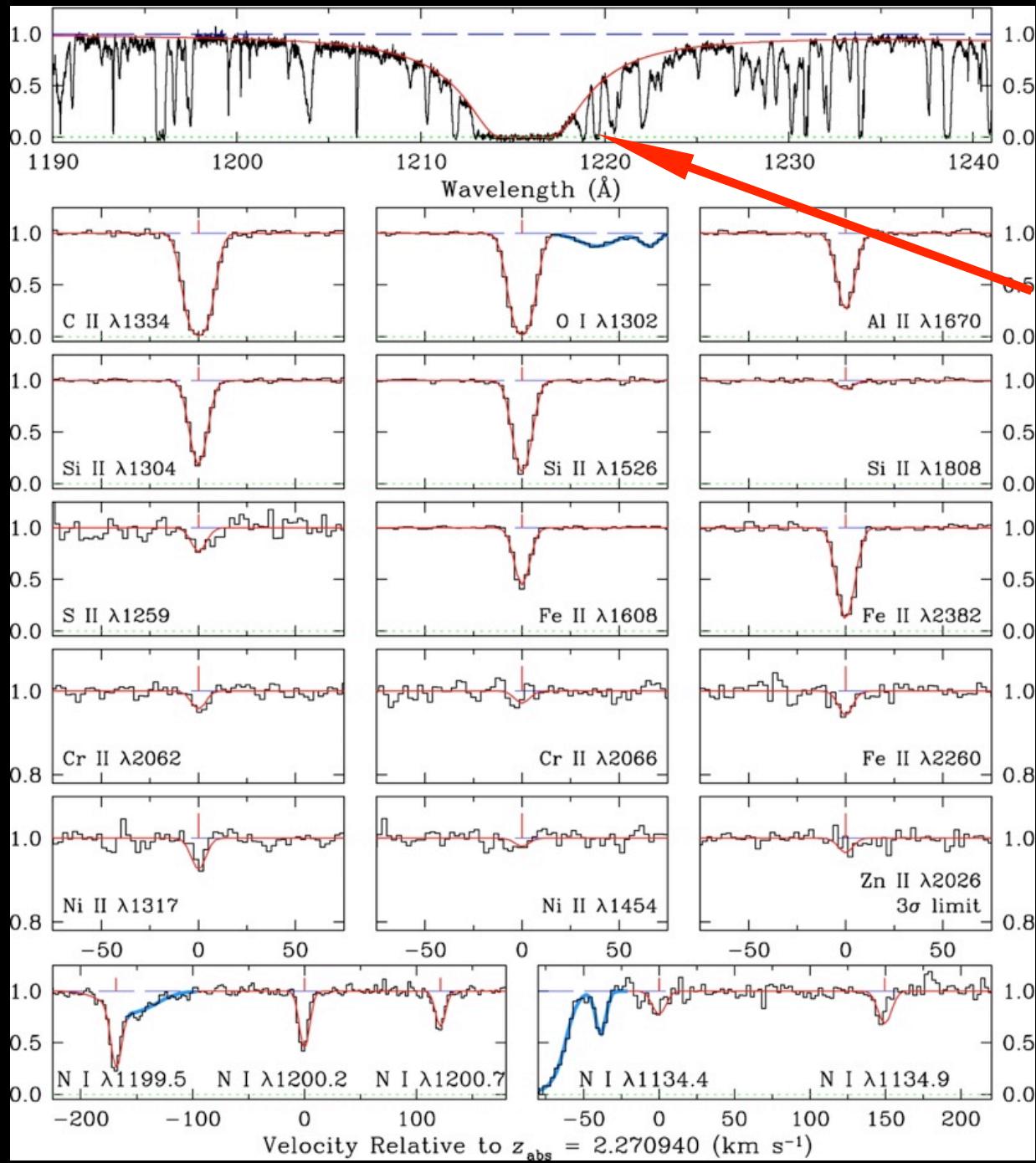
- ✓ Low metallicities imply negligible astration of D
- ✓ Narrow absorption lines make it possible to resolve the -82 km/s isotope shift between D and H

J1111+1332



Cooke+ 2015

J1111+1332

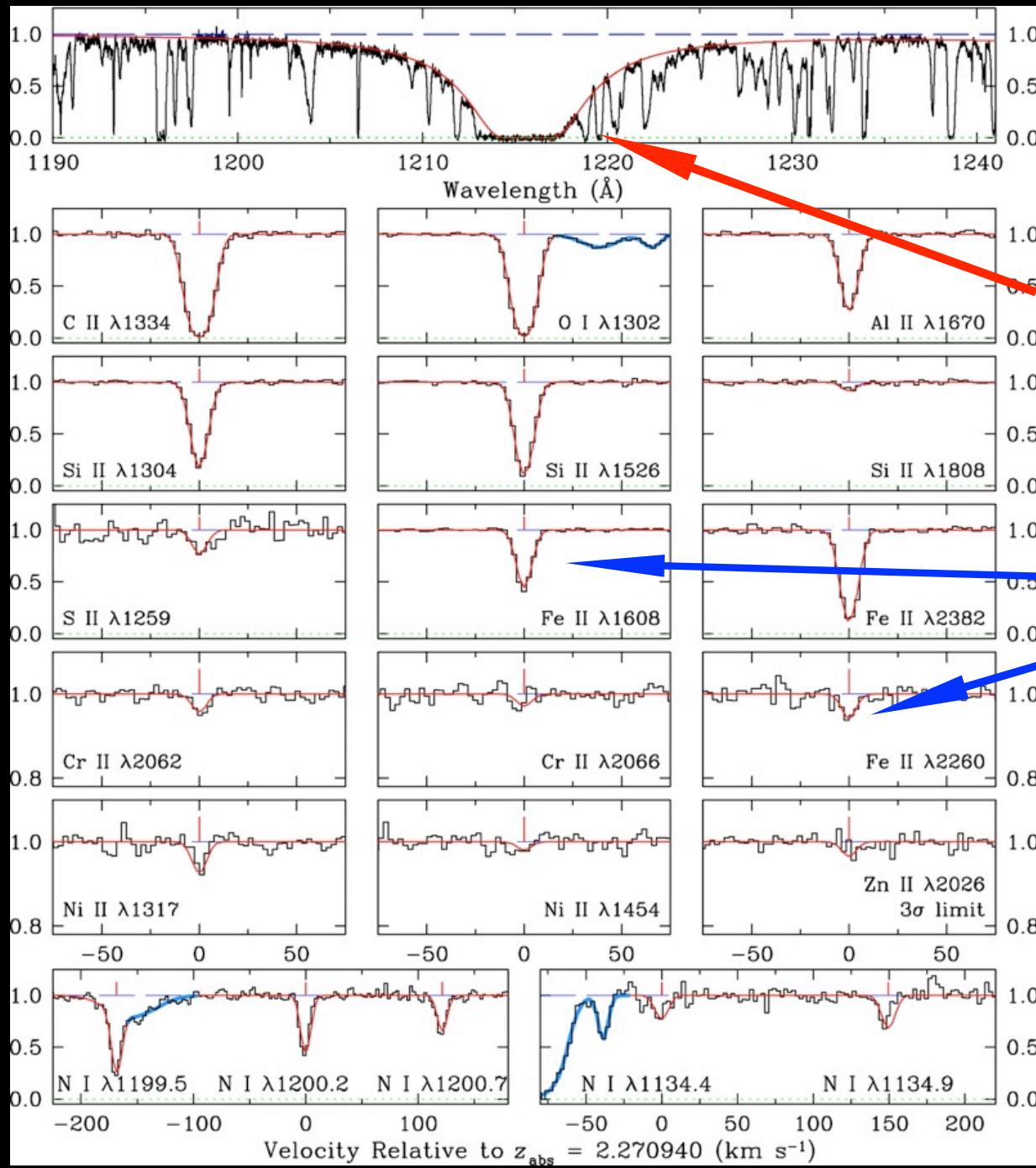


DLA at $z = 2.270940$

$$N(\text{H I}) = 2.5 \times 10^{20} \text{ cm}^{-2}$$

Cooke+ 2015

J1111+1332

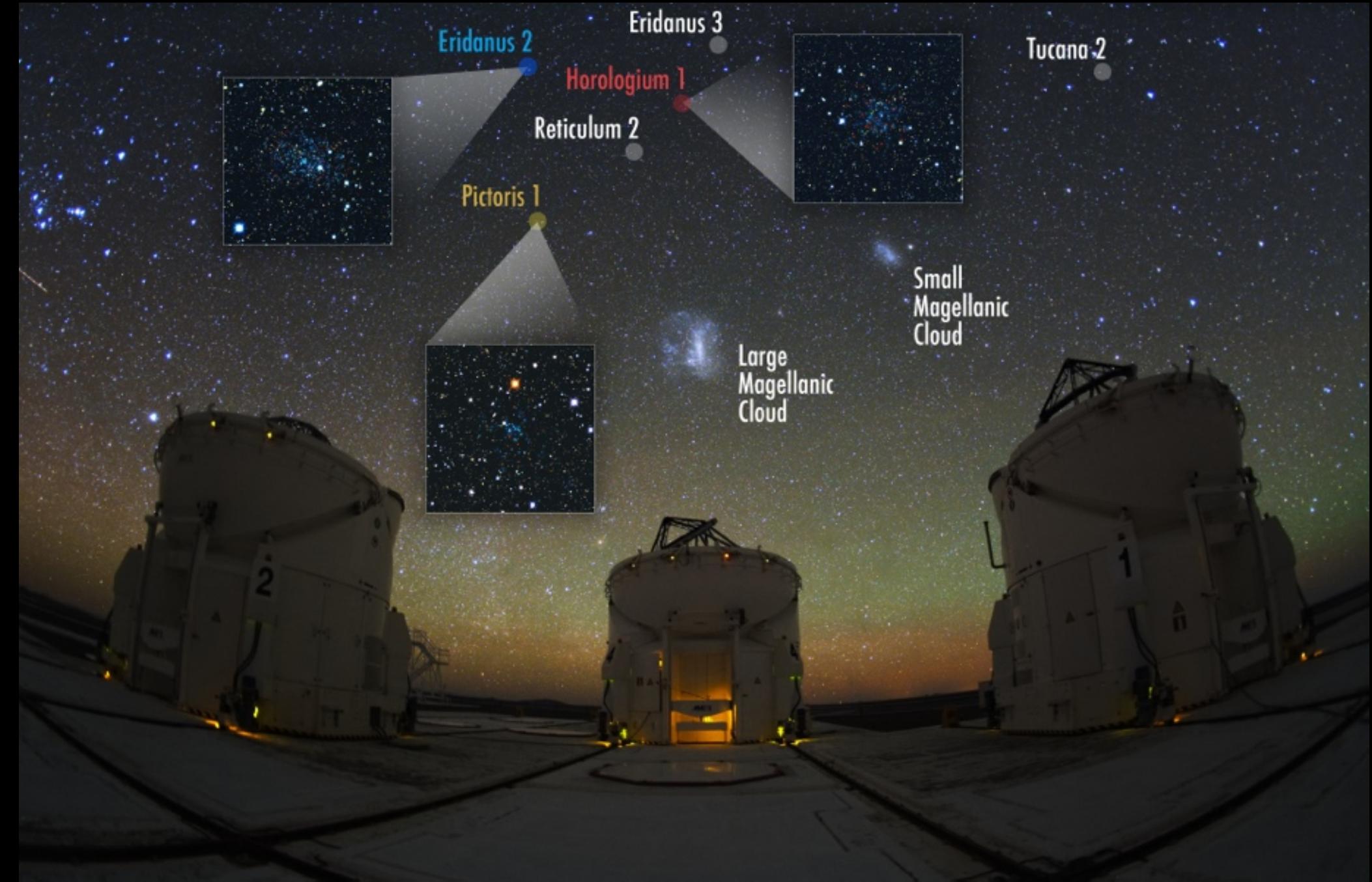


DLA at $z = 2.270940$

$$N(\text{H I}) = 2.5 \times 10^{20} \text{ cm}^{-2}$$

$\text{Fe/H} = 1/200$ solar

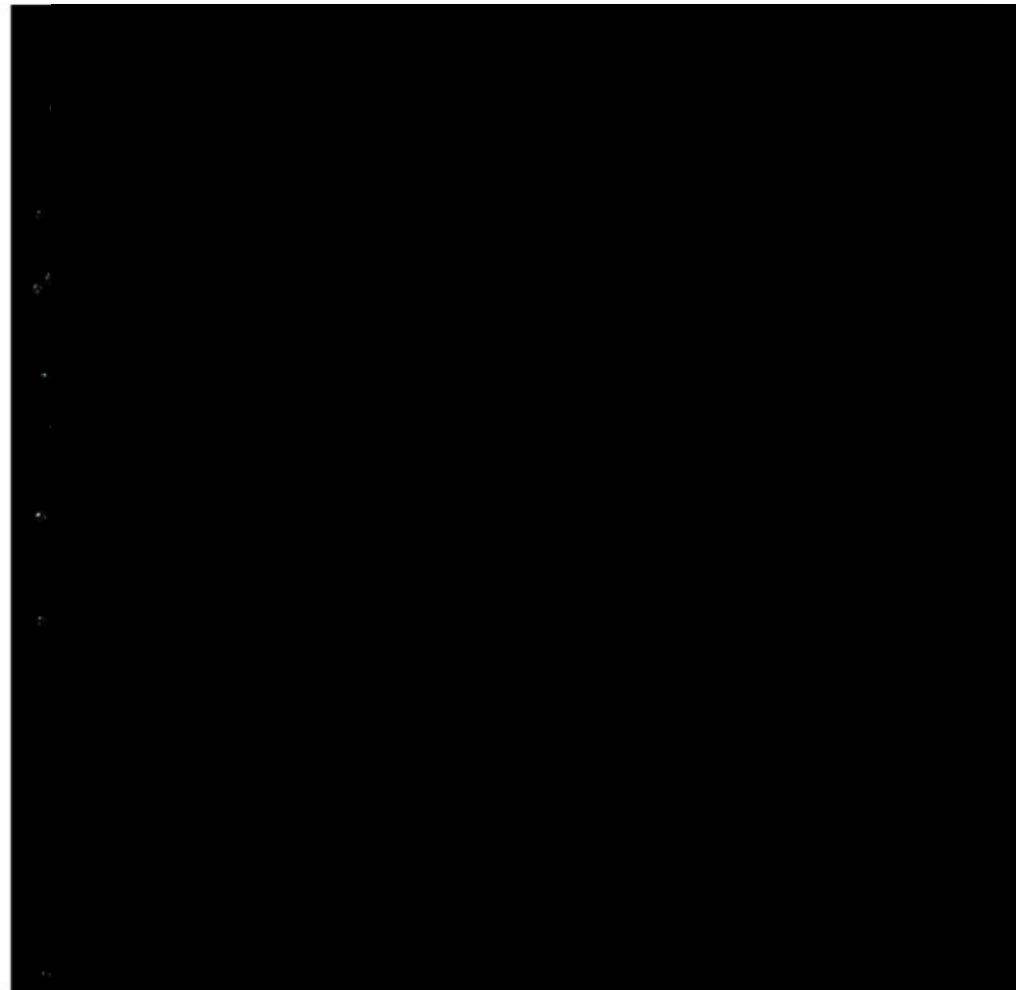
Cooke+ 2015



Dark Energy Survey



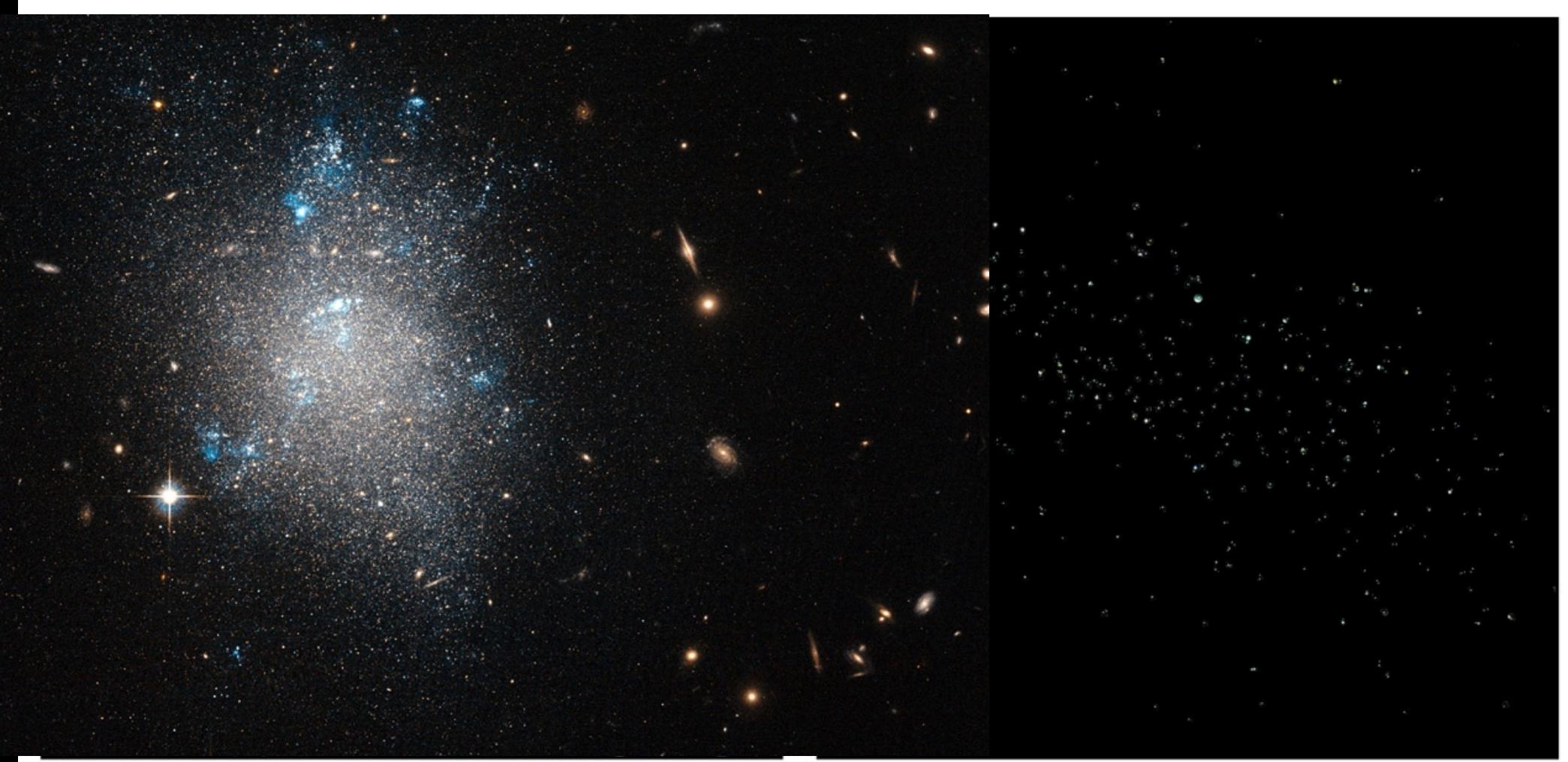
Reticulum 2



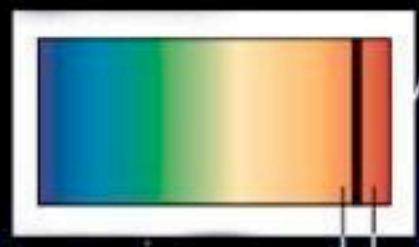
Reticulum 2



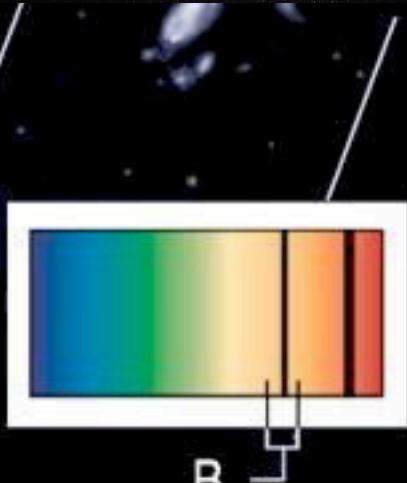
Reticulum 2



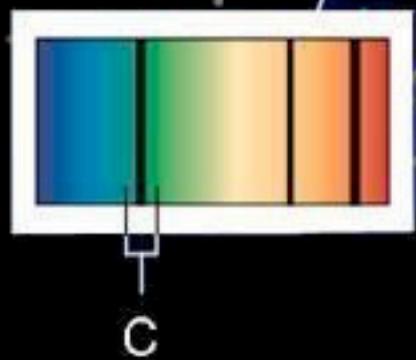
Quasar



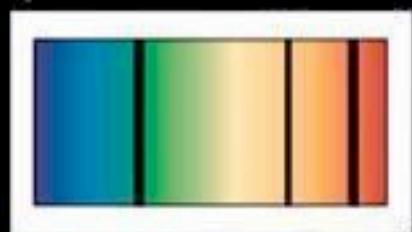
A



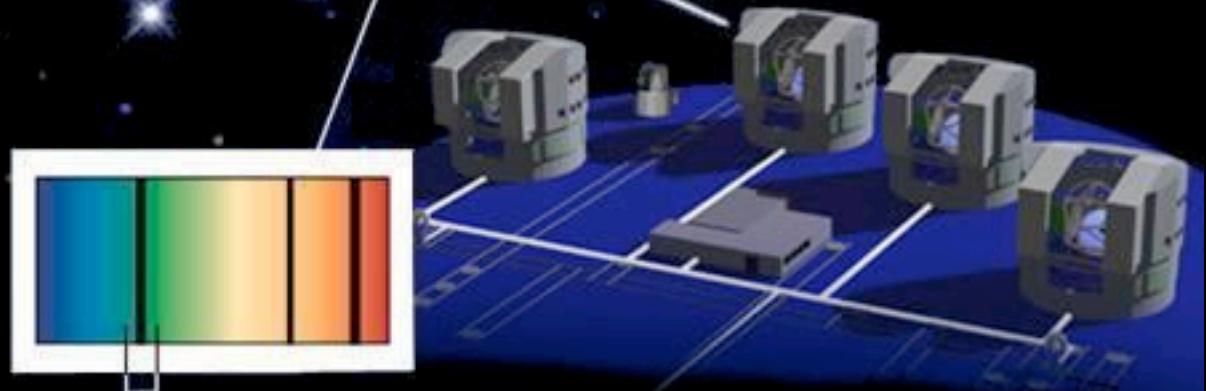
B



C



D



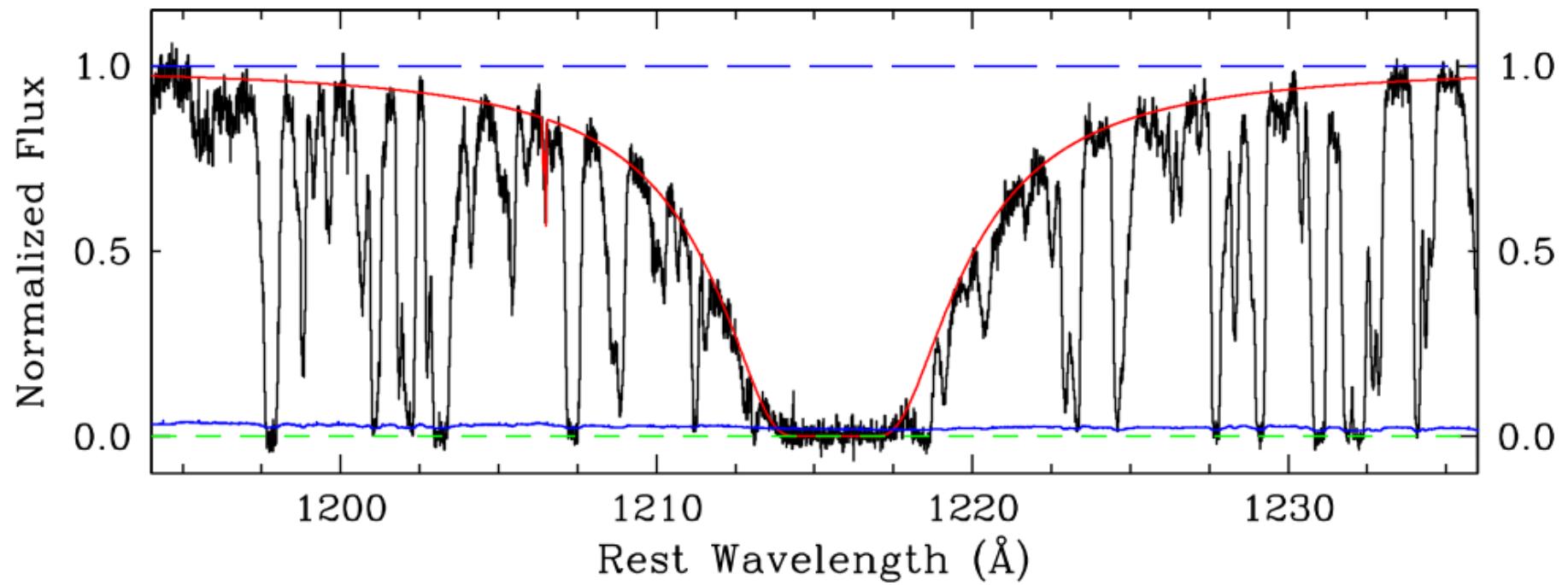
E

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

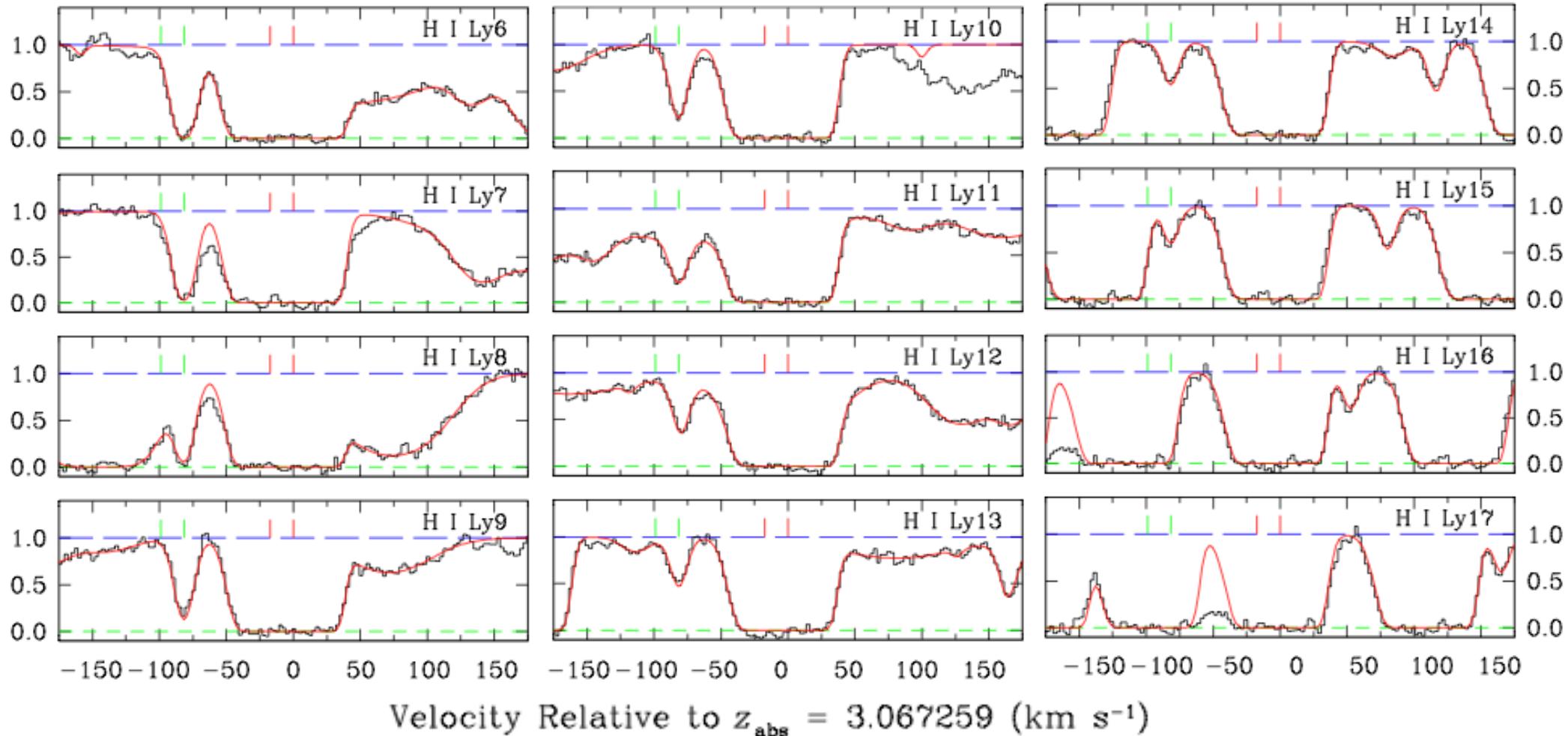
J1358+6522, $z = 3.0673$, Fe/H = 1/750 solar

$$N(\text{HI}) = 3.1 \times 10^{20} \text{ cm}^{-2}$$



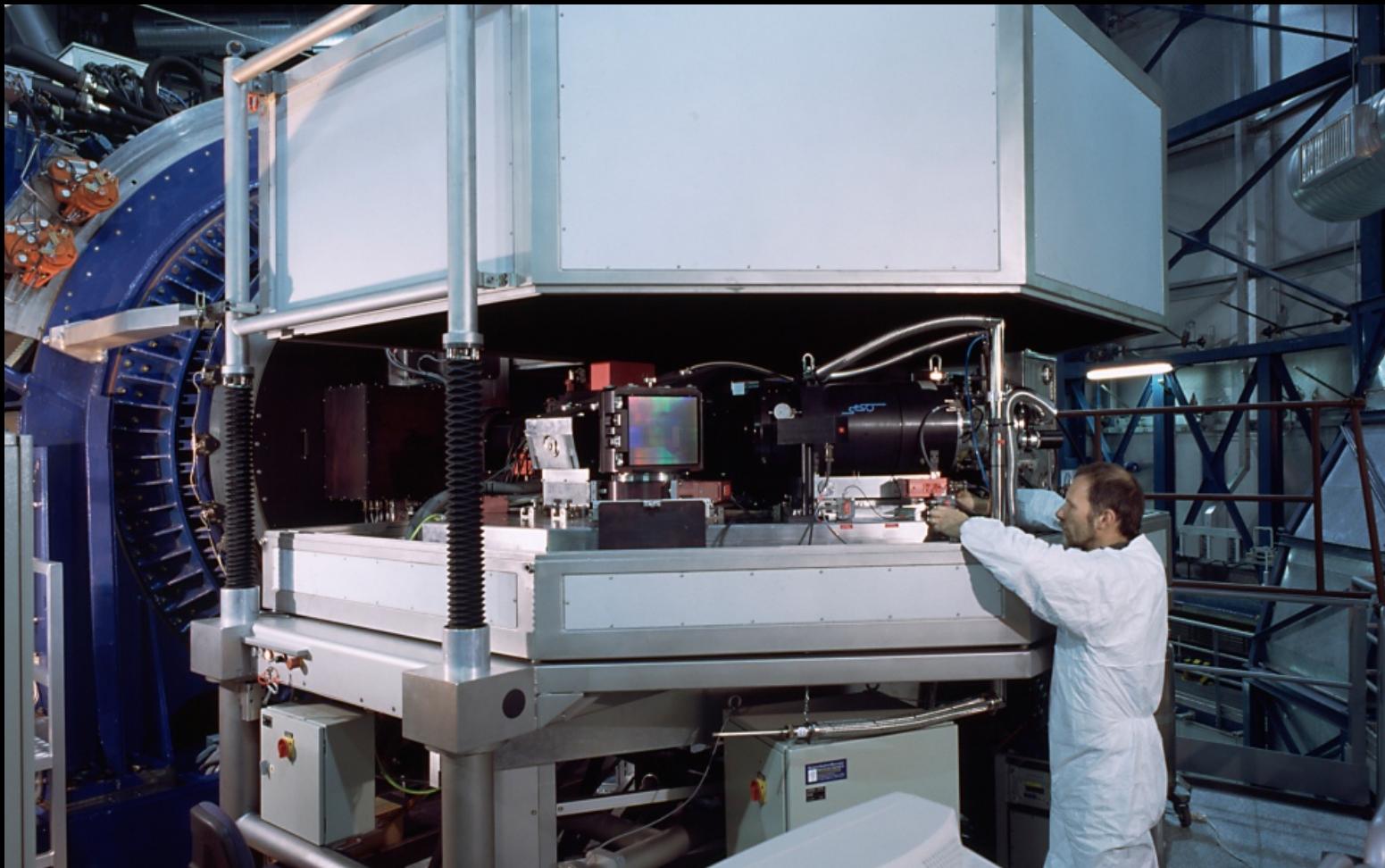
Cooke+ 2014

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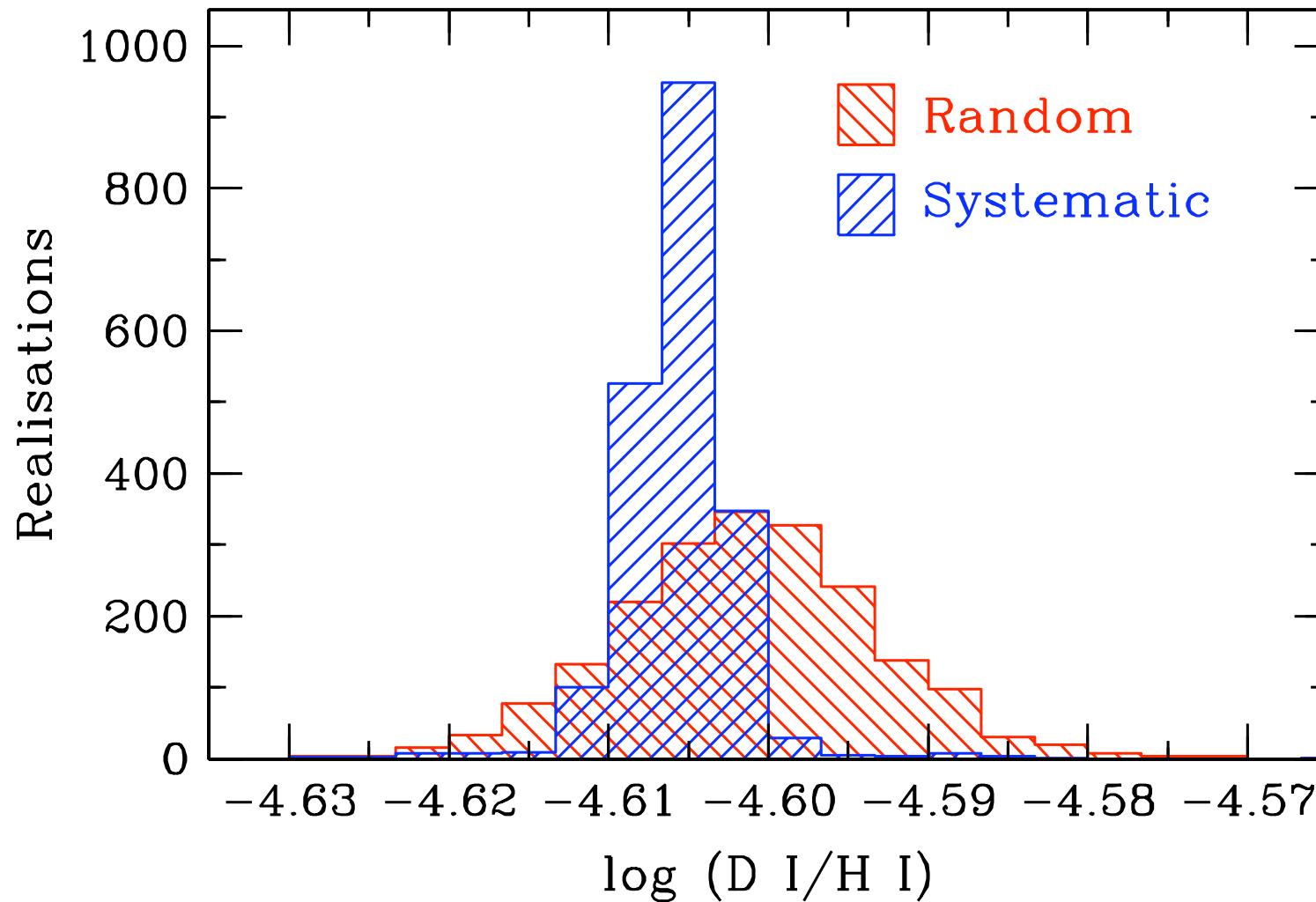


Cooke+ 2014

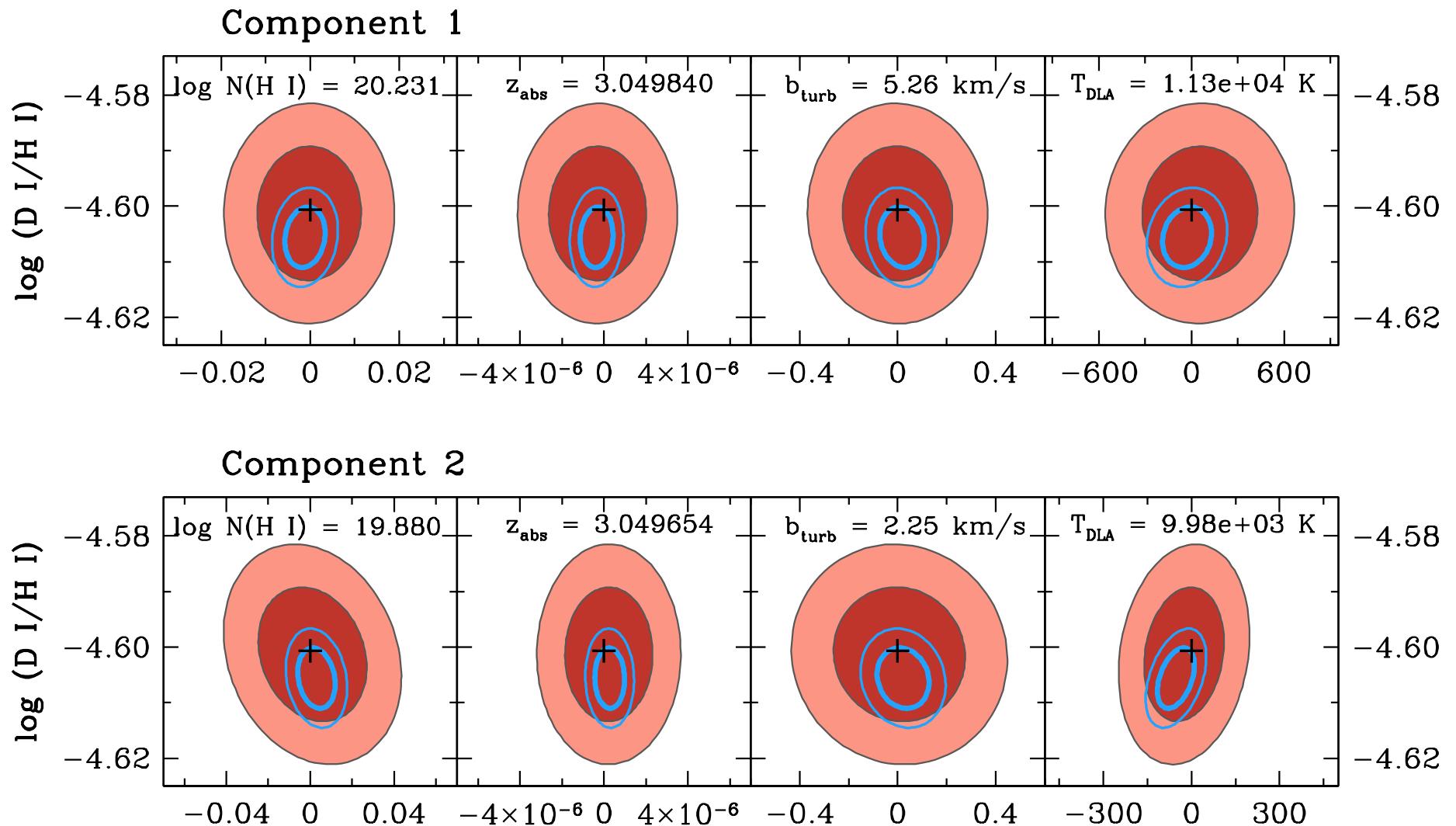
30,000 s
integration
with UVES
on VLT-2



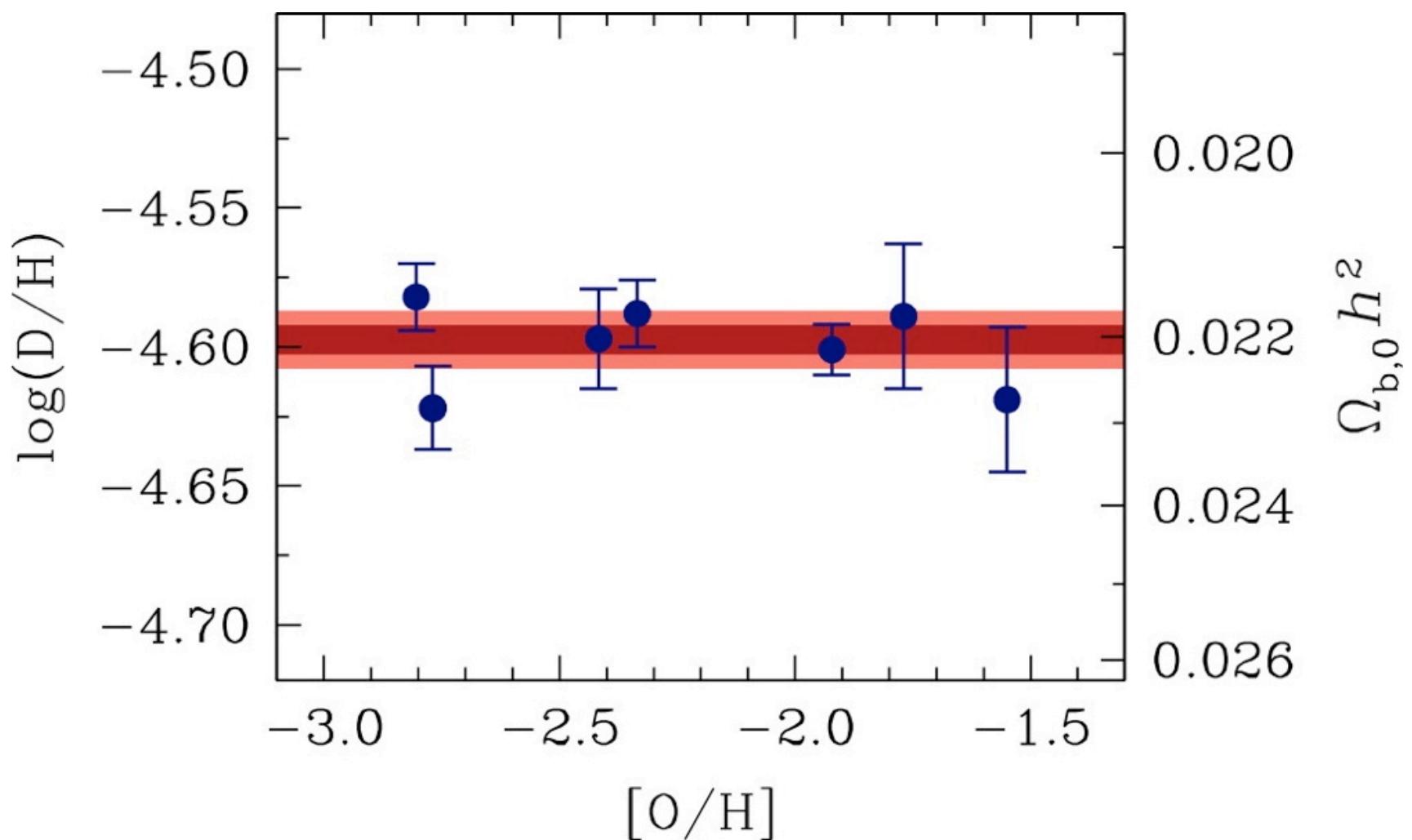
Spectral analysis tailored specifically to the determination of D/H and its error



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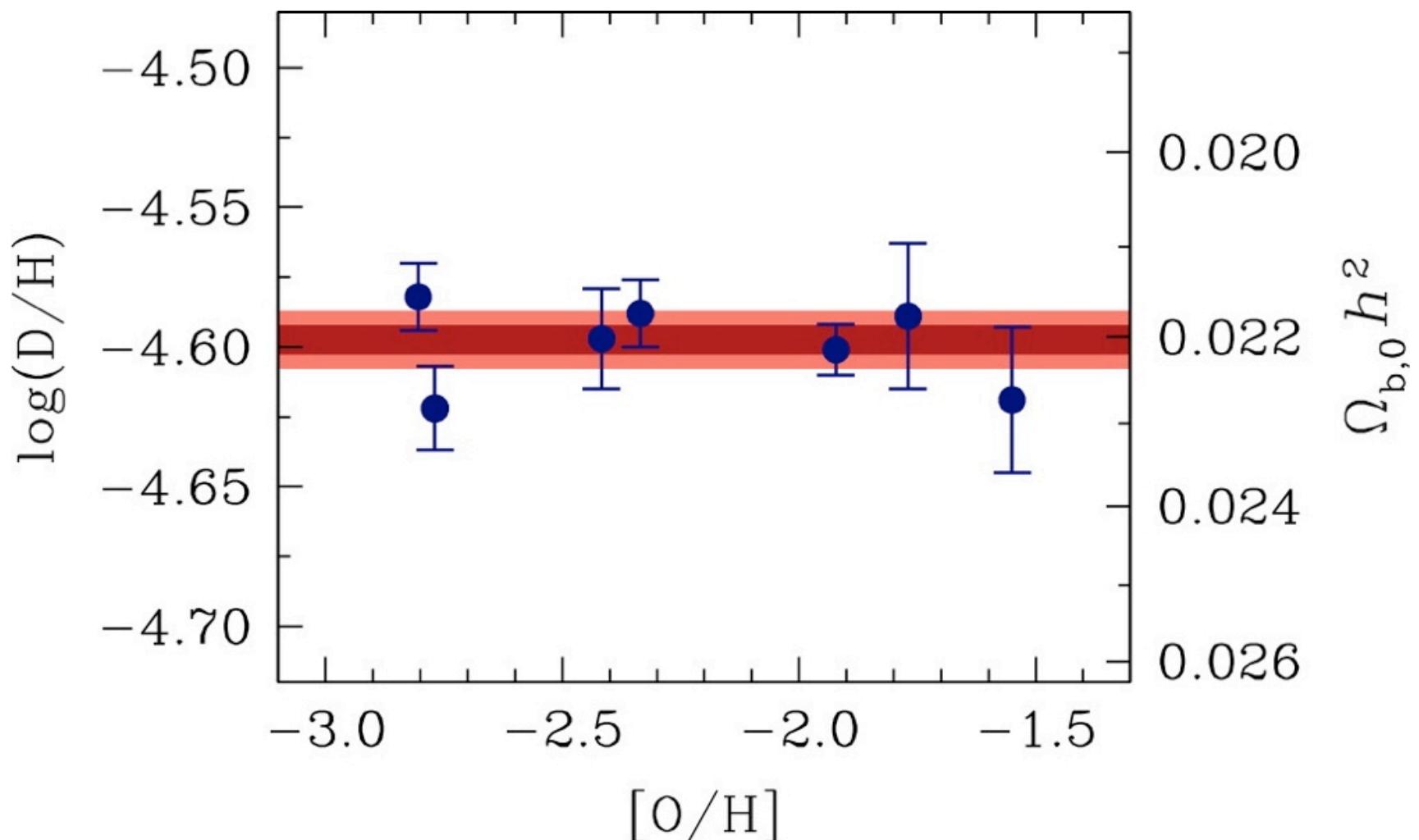


Percent Measure of (D/H) [Cooke et al. 2018]



Percent Measure of (D/H) [Cooke et al. 2018]

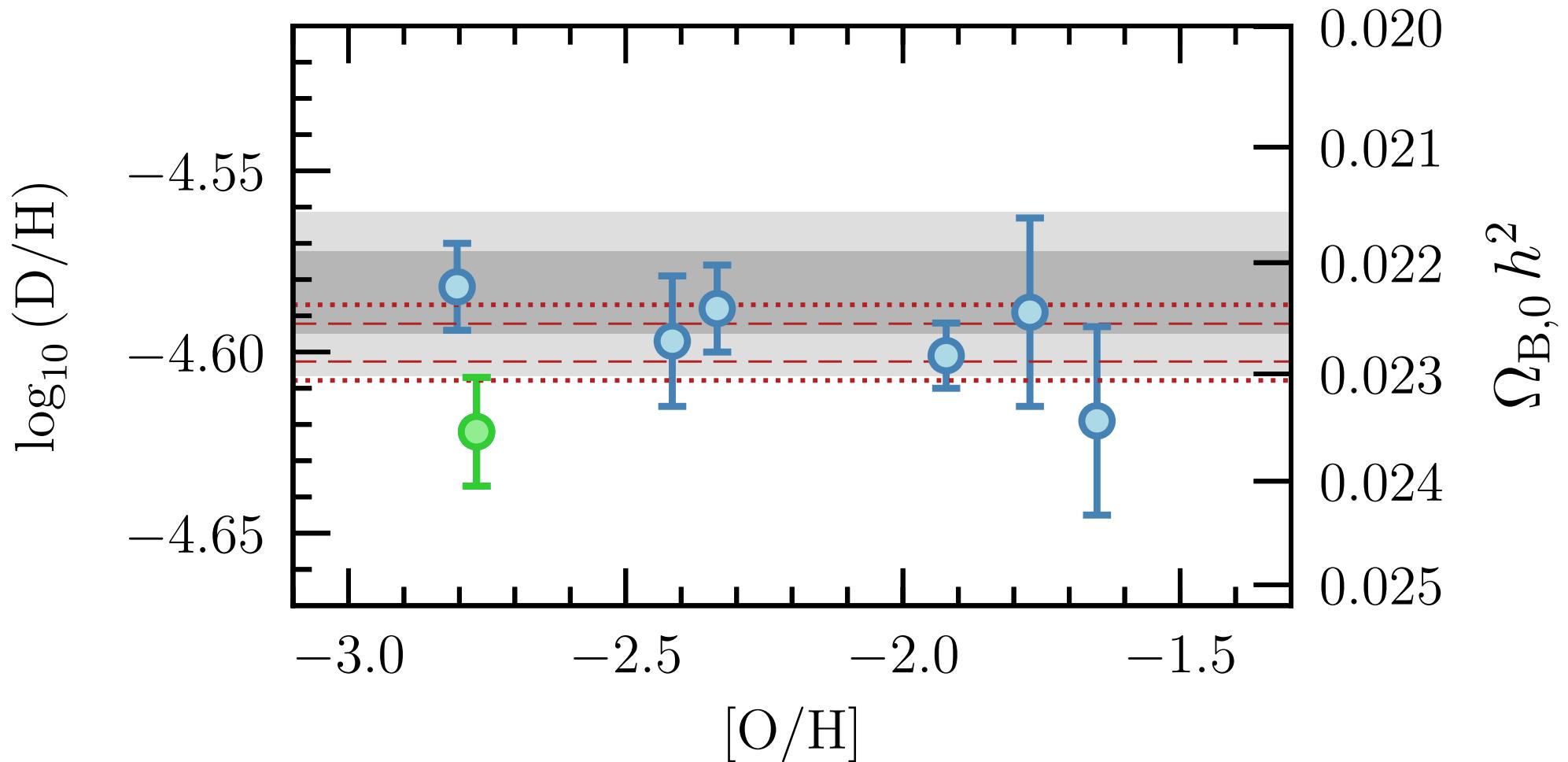
$$10^5 \text{ D/H} = 2.527 \pm 0.030$$





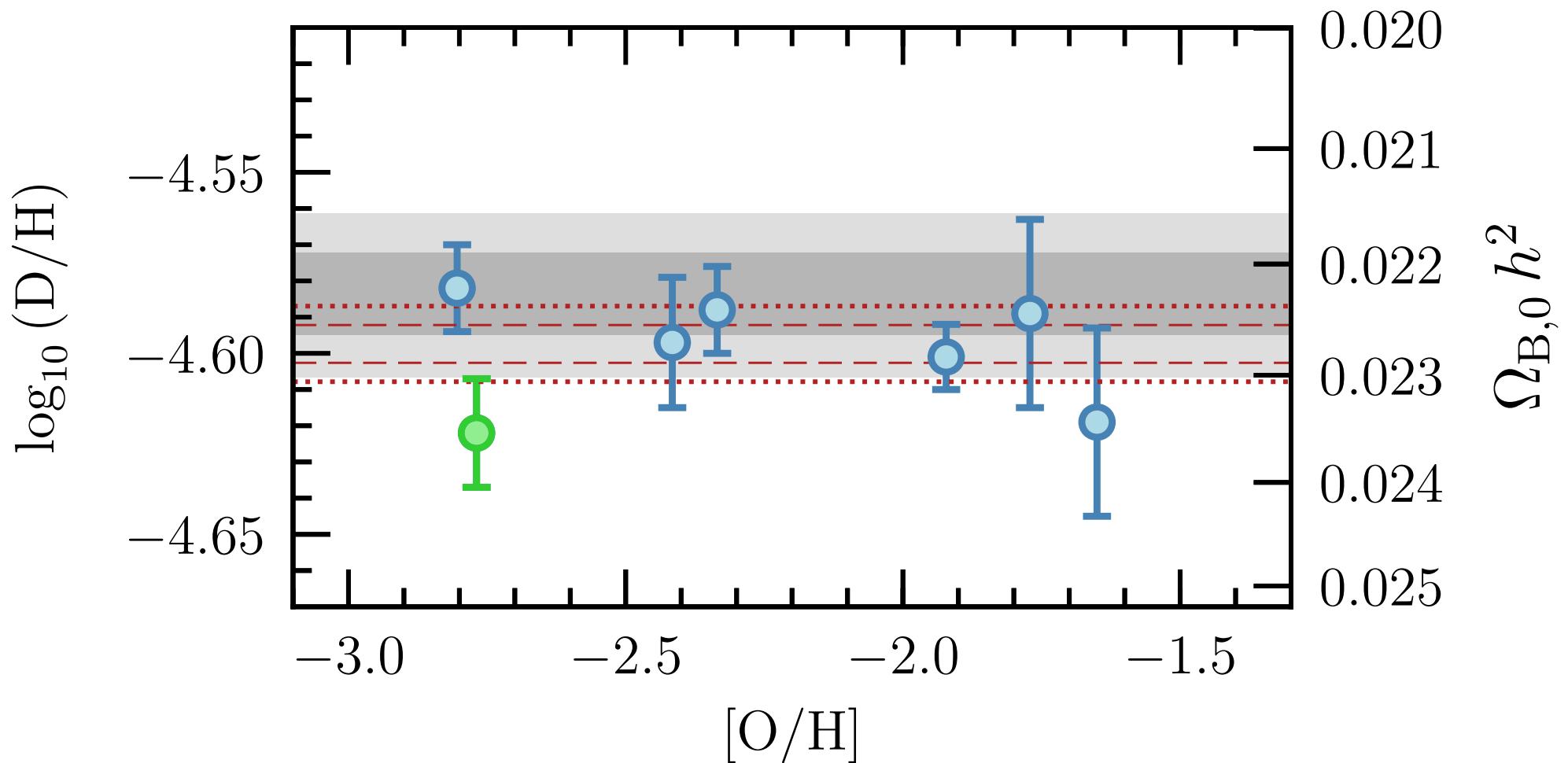
$$100\Omega_b h^2(\text{BBN}) = 2.235 \pm 0.016 \pm 0.033$$

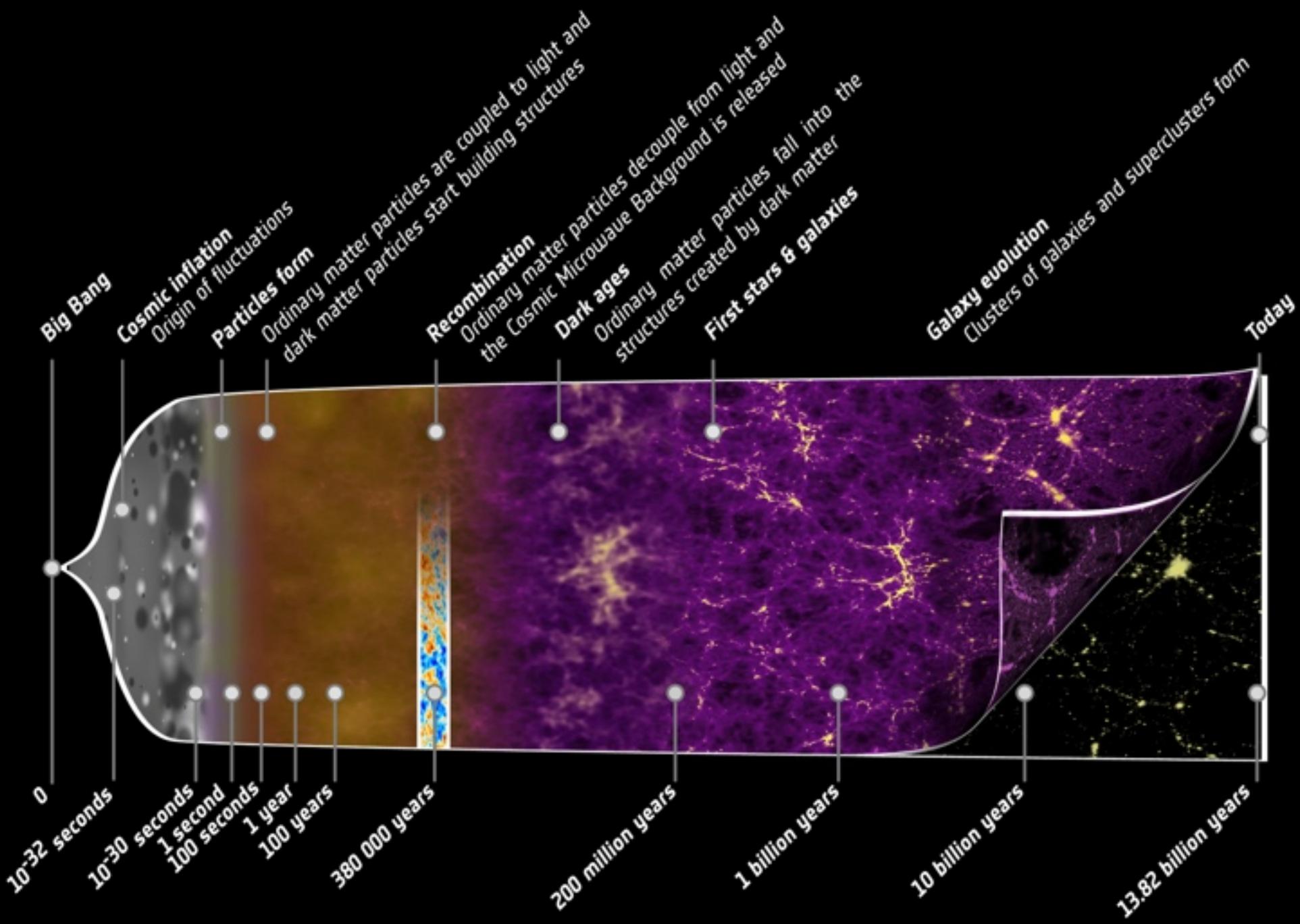
Cooke+ 2018



$$100\Omega_b h^2(\text{CMB}) = 2.226 \pm 0.023$$

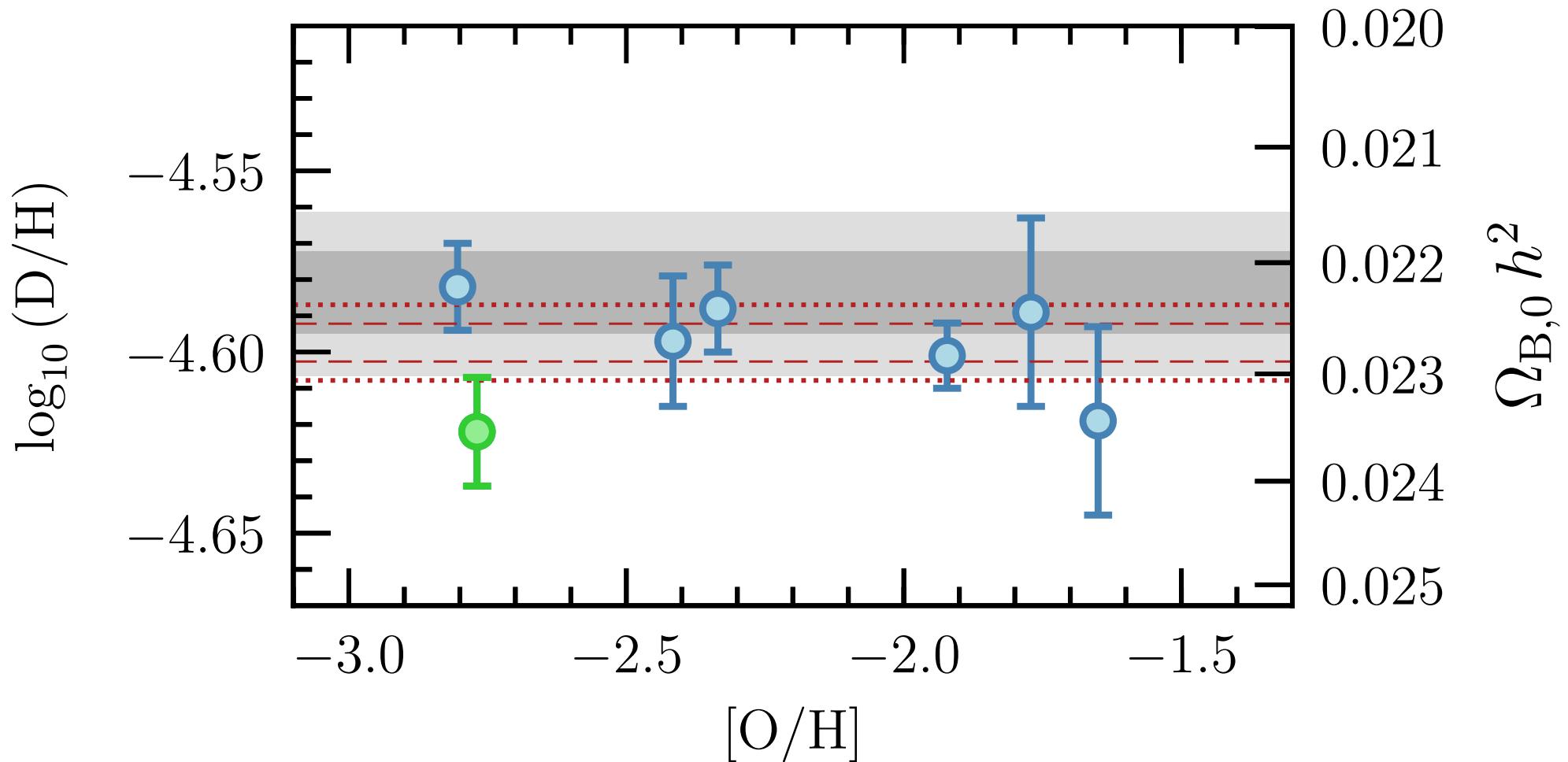
Planck Coll. 2015

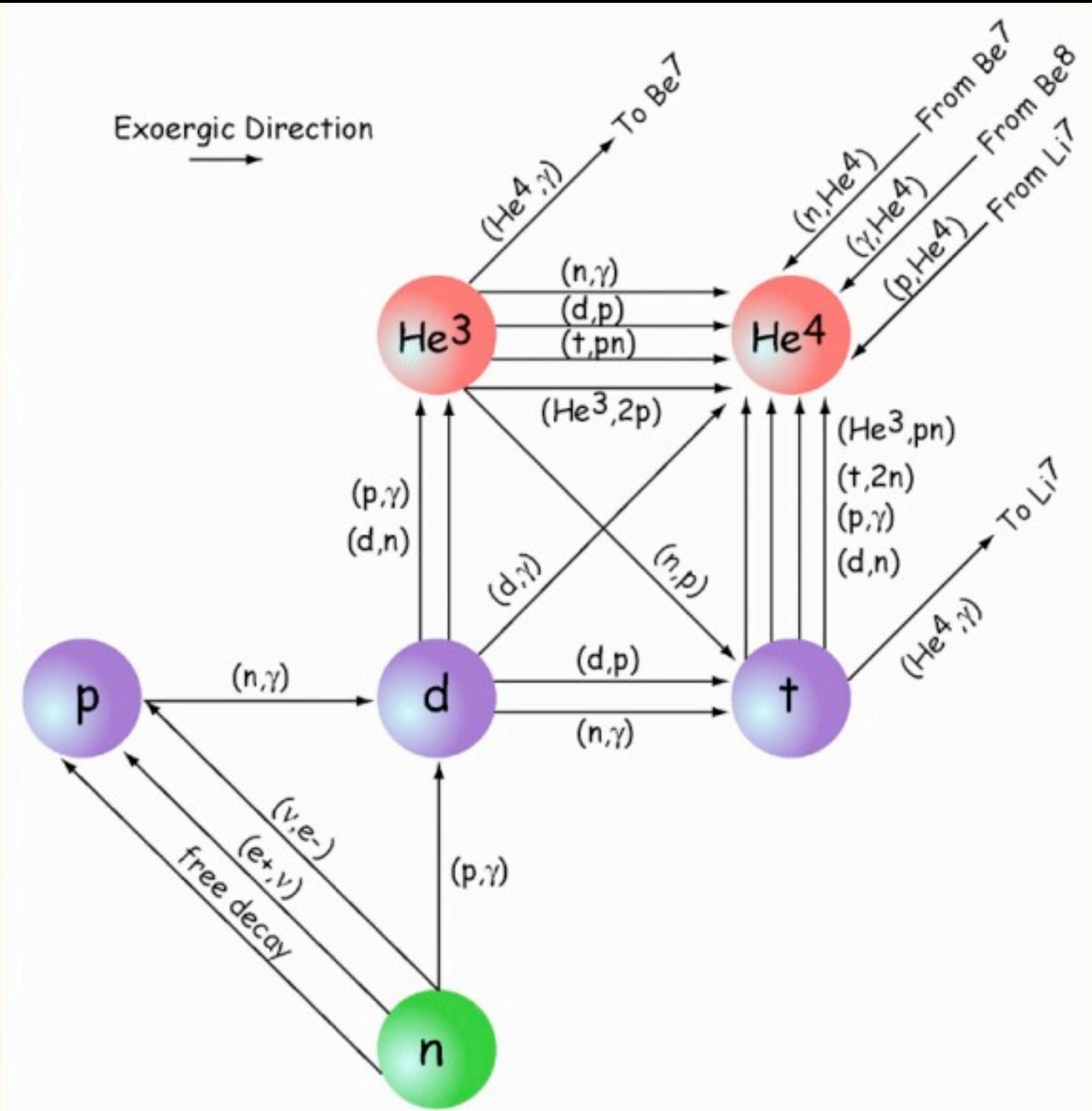


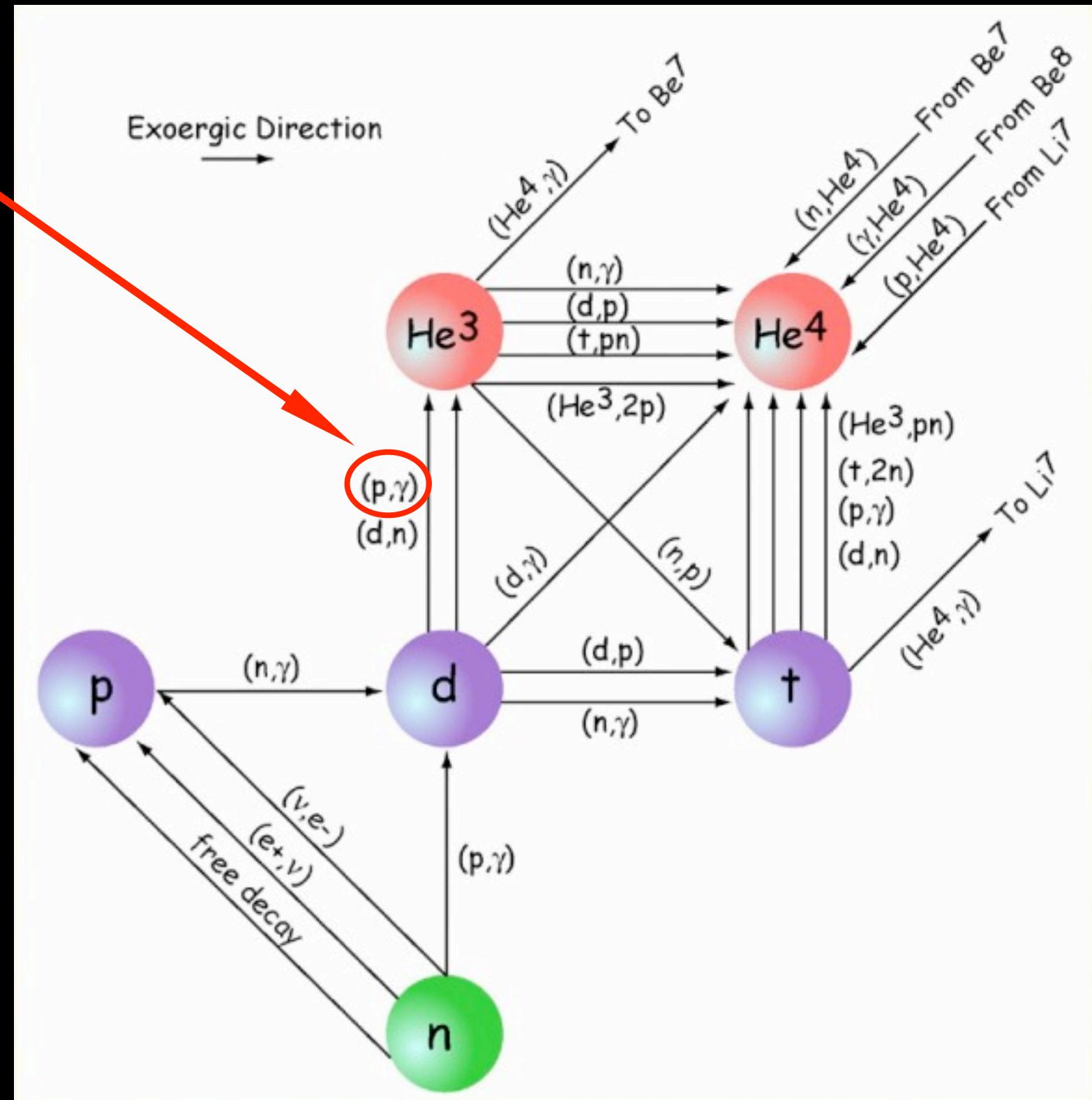


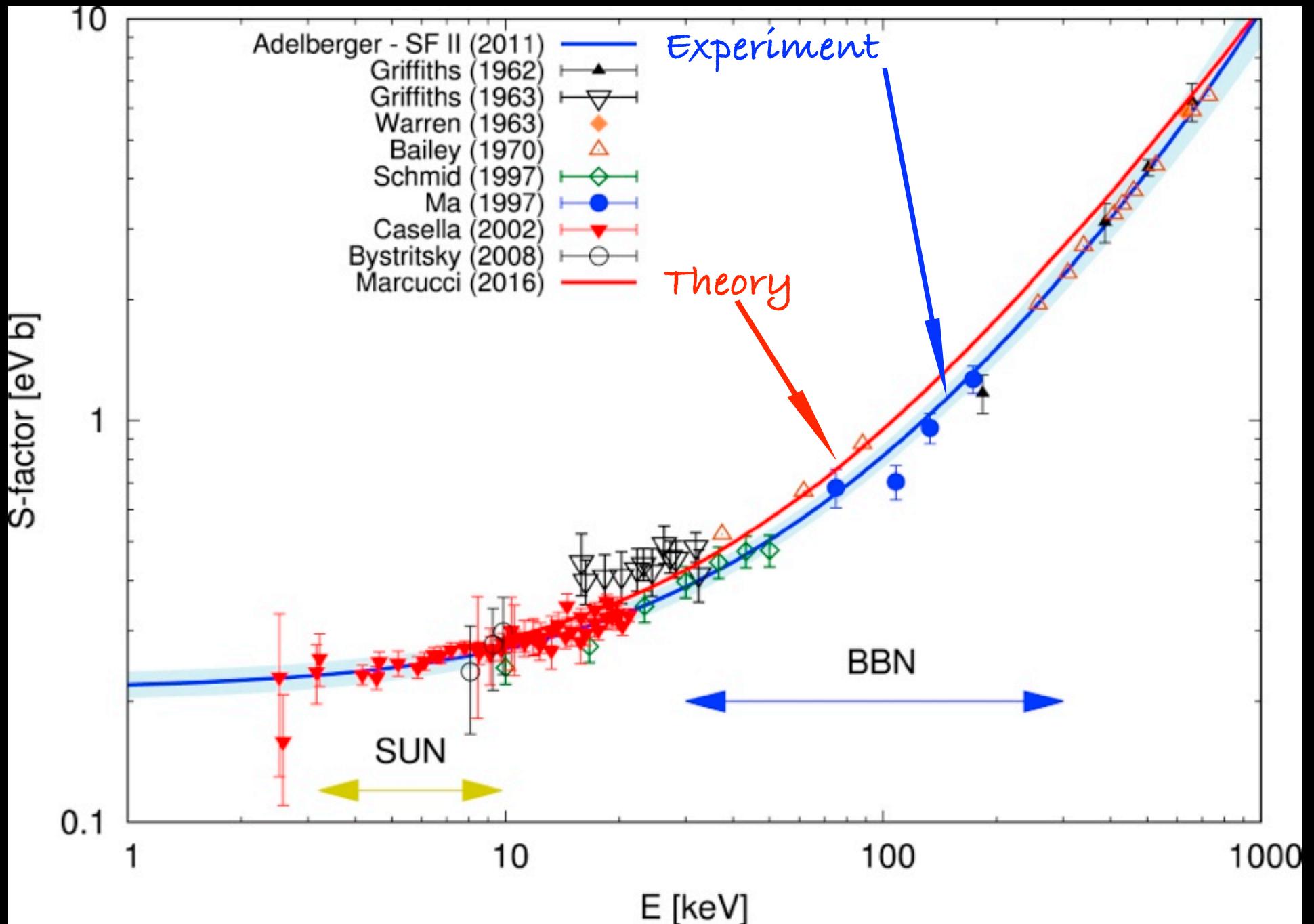
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Cooke+ 2018



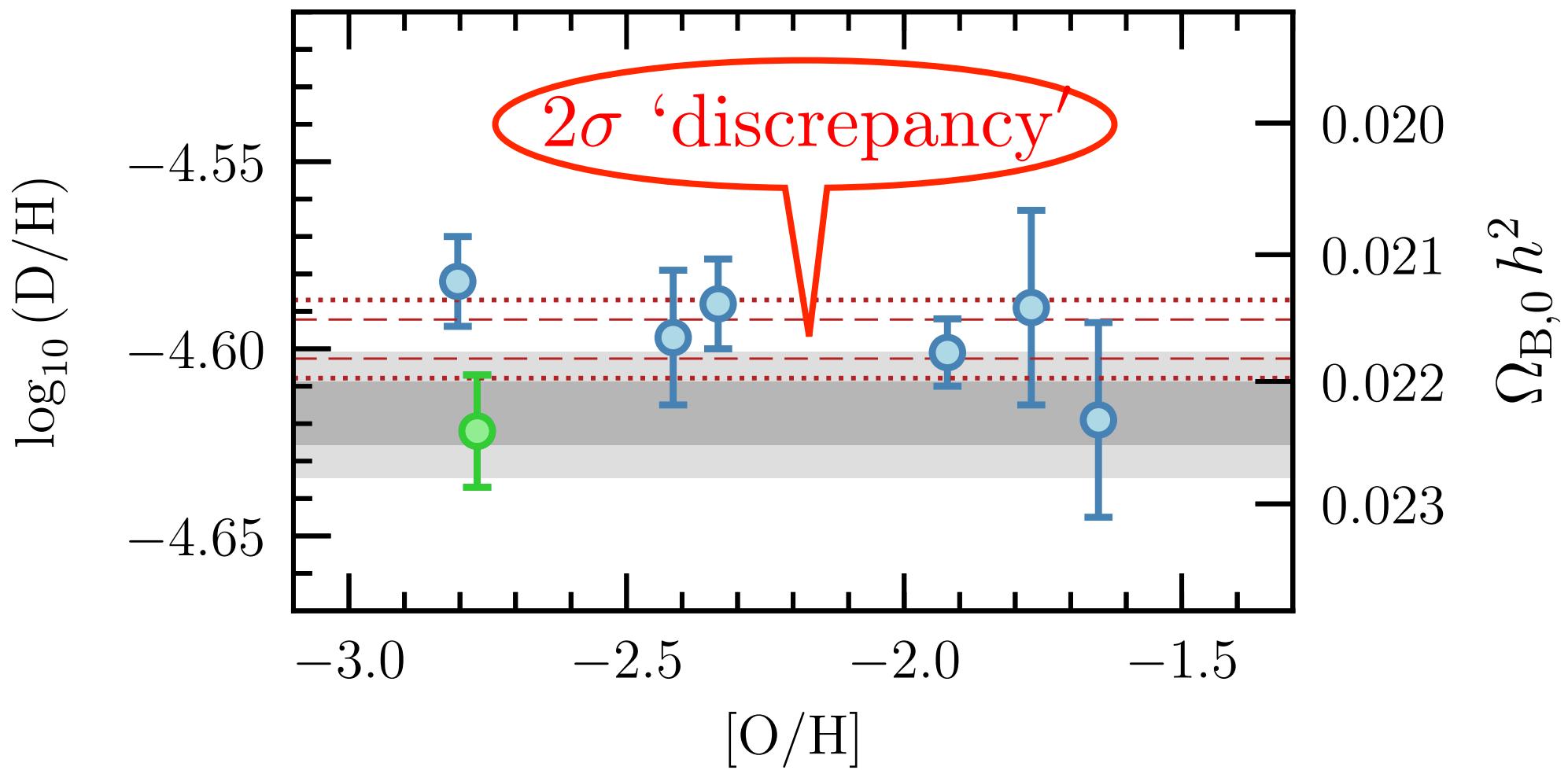






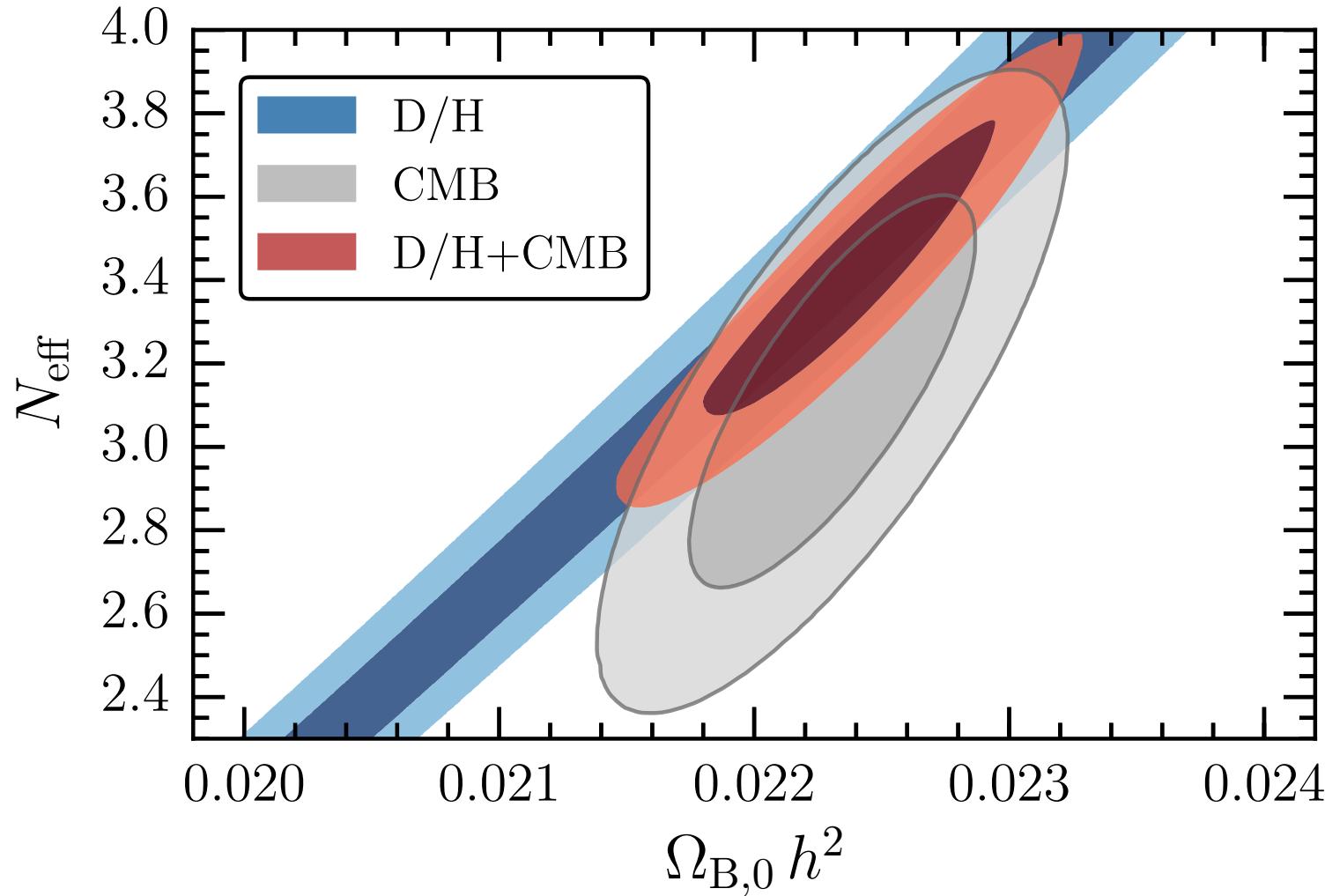
$$100\Omega_b h^2(\text{BBN}) = 2.166 \pm 0.015 \pm 0.011$$

Cooke+ 2018



Joint D/H and CMB Constraints on ‘dark radiation’

$$N_{\text{eff}} = 3.41 \pm 0.45$$



Cooke+ 2018

Looking to the future...



Good prospects for further improvements in
the near/medium term future

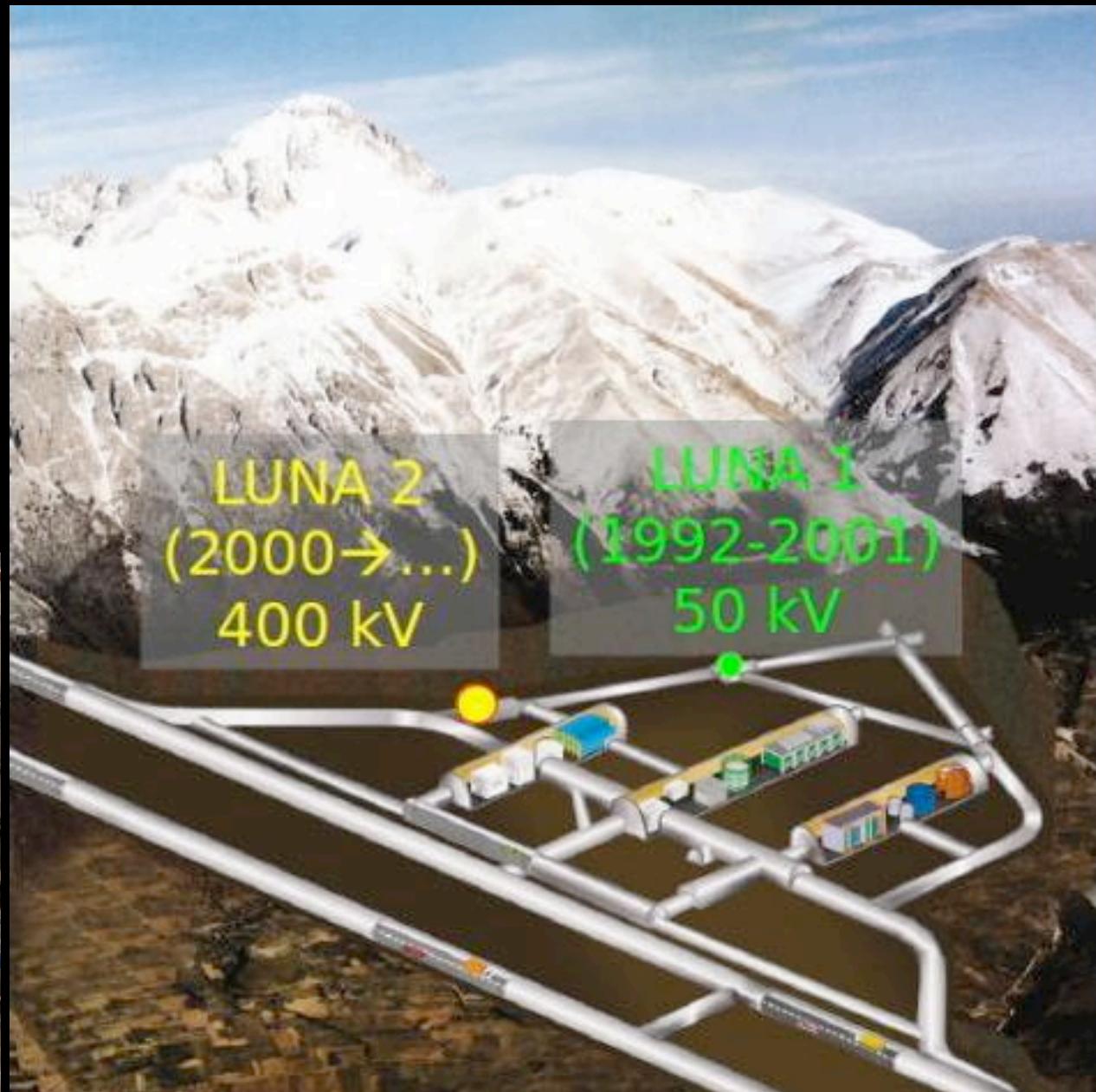
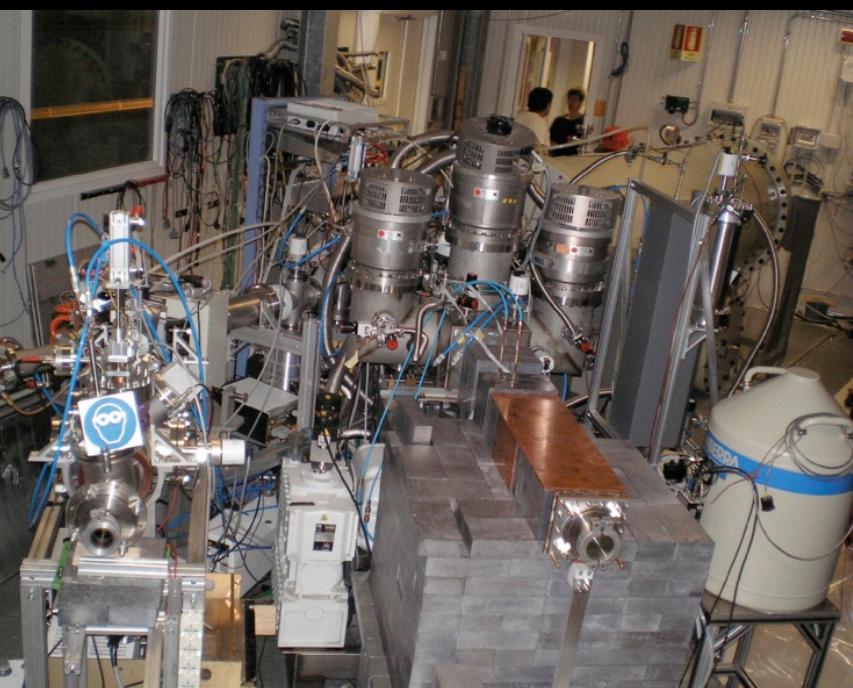
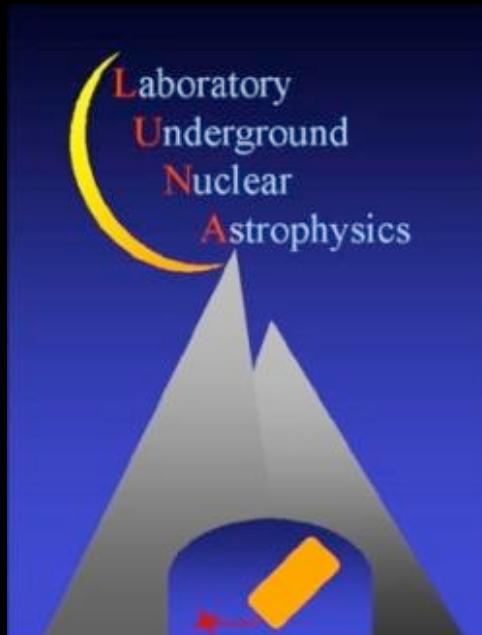
Good prospects for further improvements in the near/medium term future

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- ✓ Modern laboratory measurement of the cross-section for ${}^2\text{H} + \text{p} \rightarrow {}^3\text{He} + \gamma$ by the end of 2018.

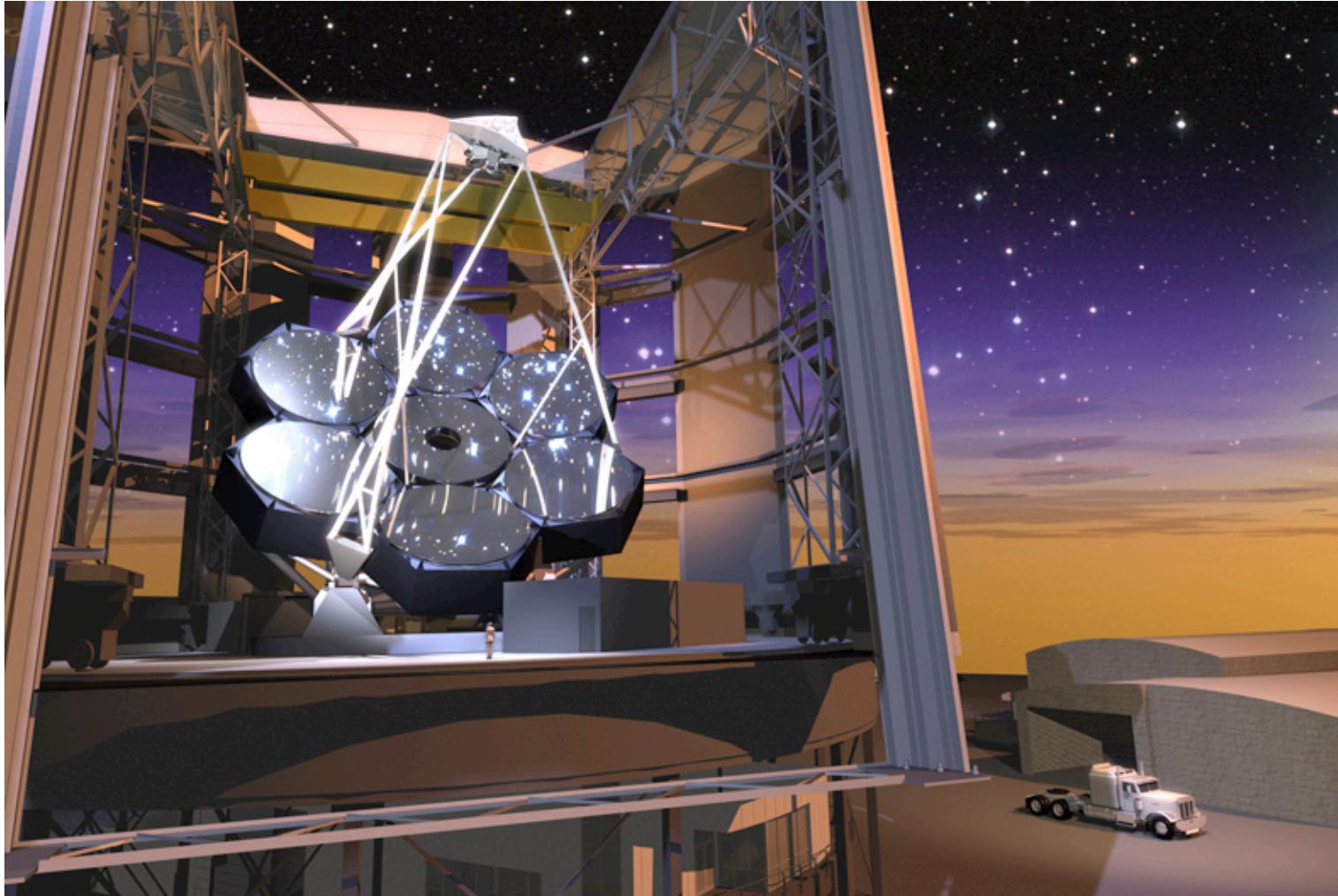
The LUNA Accelerator at Gran Sasso



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- ✓ 30m telescopes in mid-2020s

Good prospects for further improvements in
the near/medium term future



30m telescopes in mid-2020s

Summary



With modern astronomical instrumentation, we can now verify experimentally the framework of Big-Bang nucleosynthesis which has its origin in ideas first put forward in the 1950s

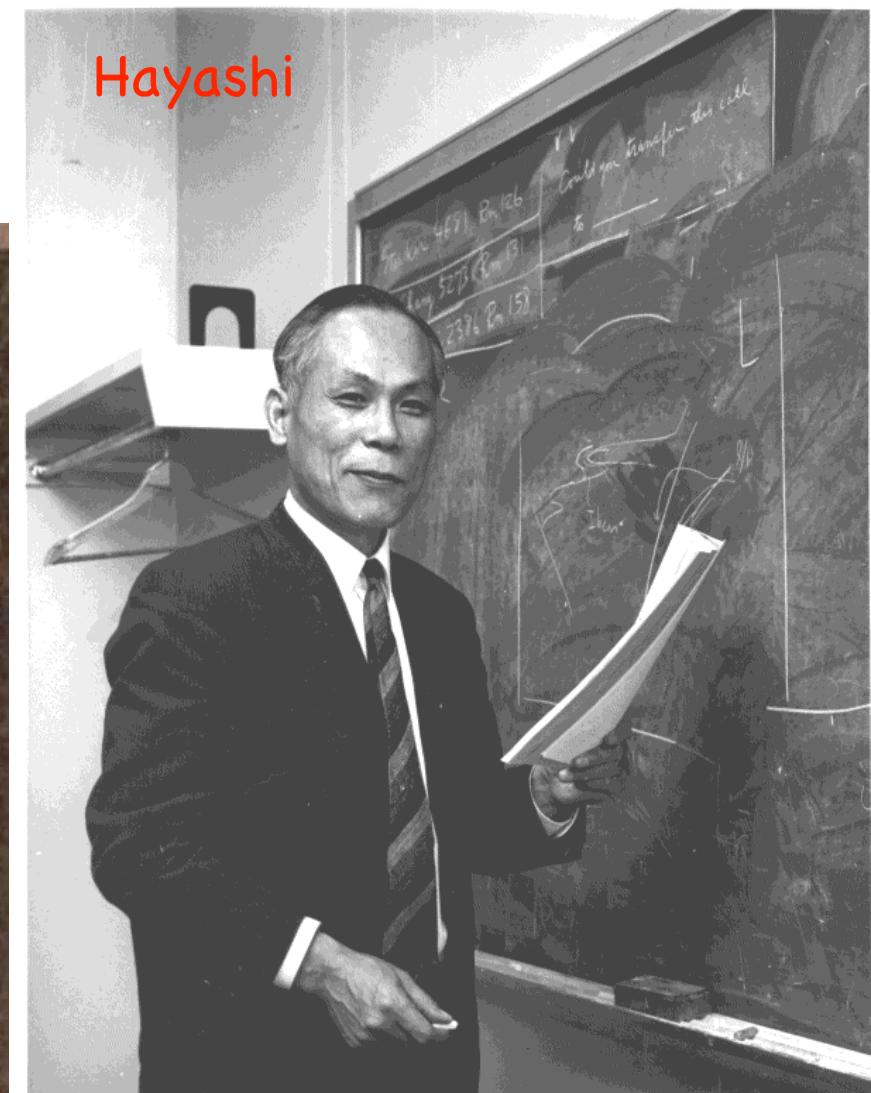
Herman



Gamow

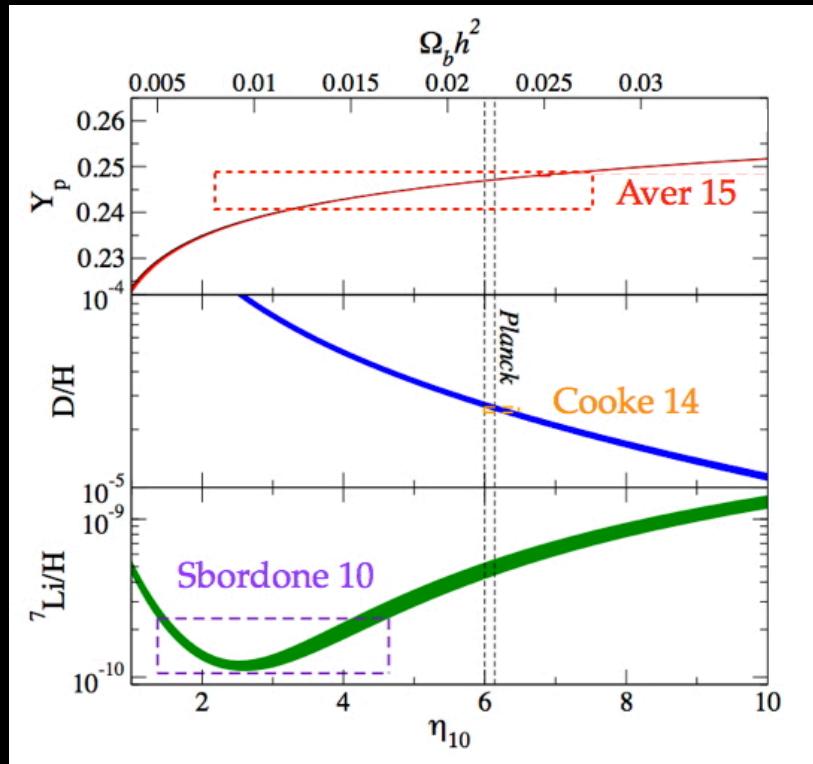
Alpher

Hayashi

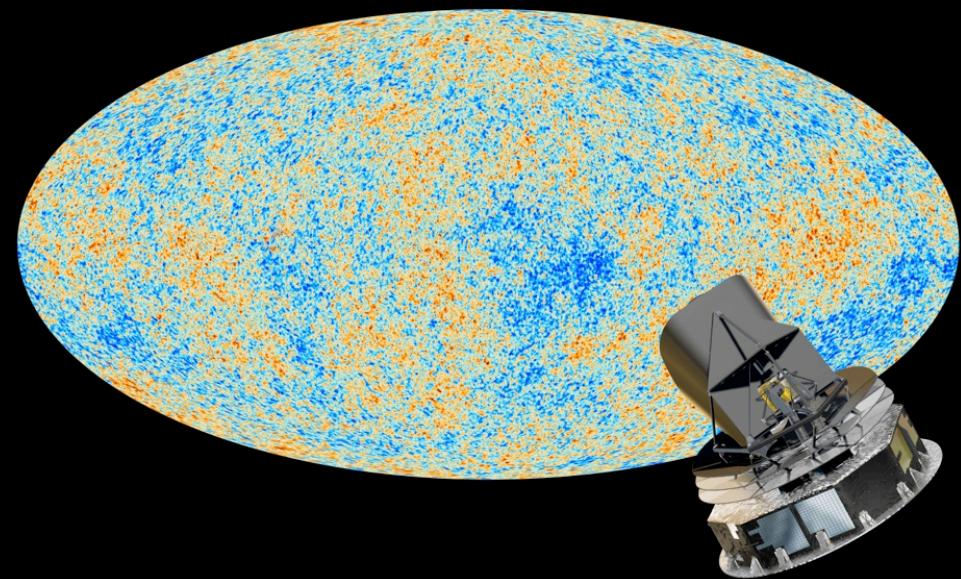


BBN

CMB



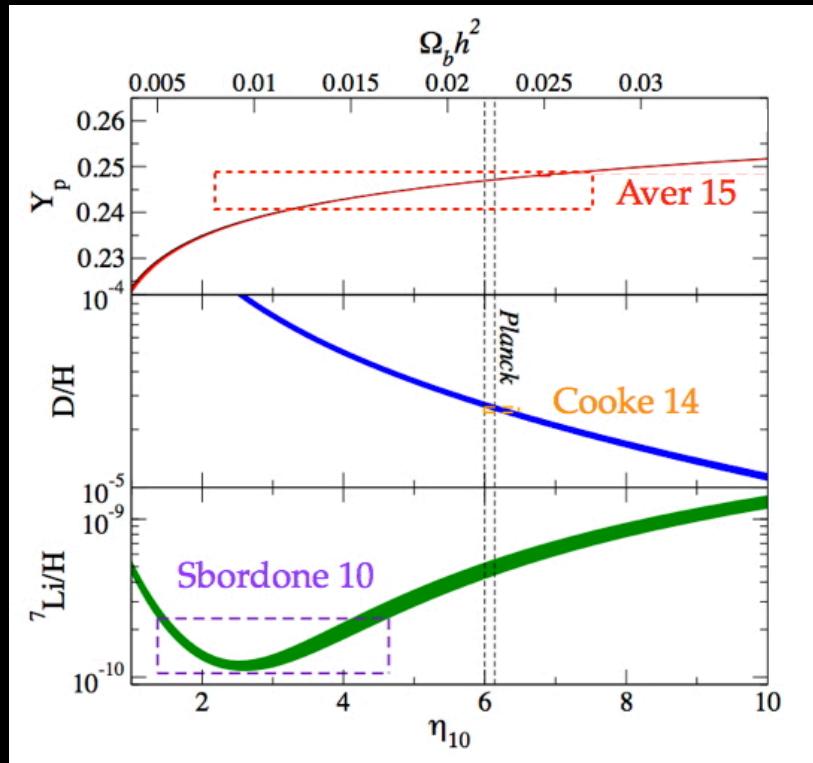
+



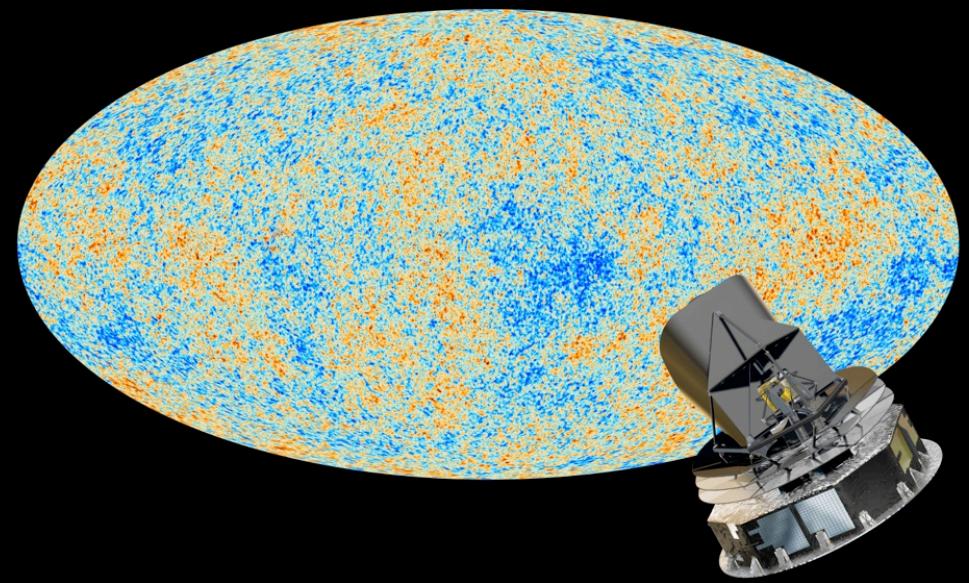
= New Physics?

BBN

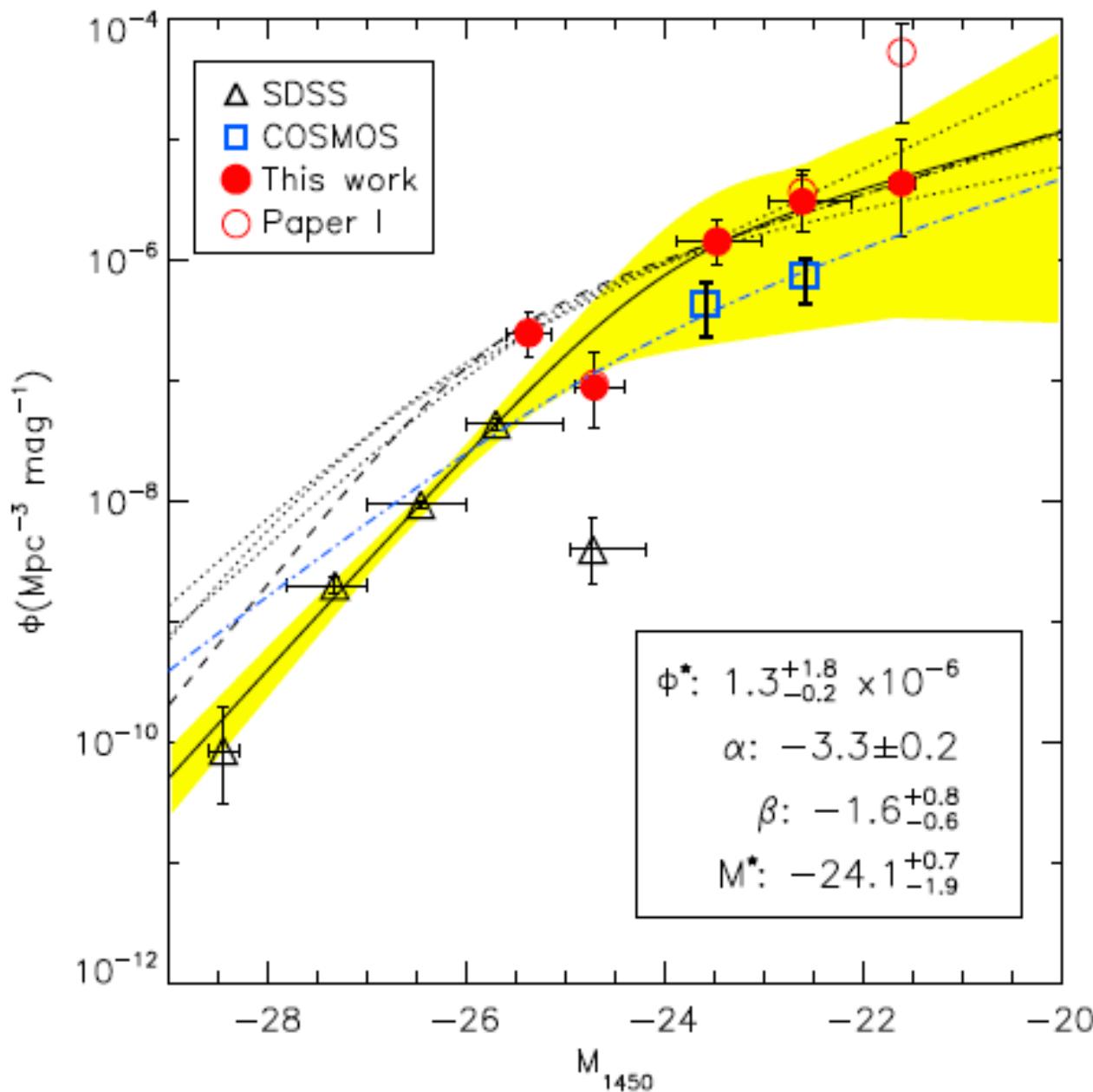
CMB



+

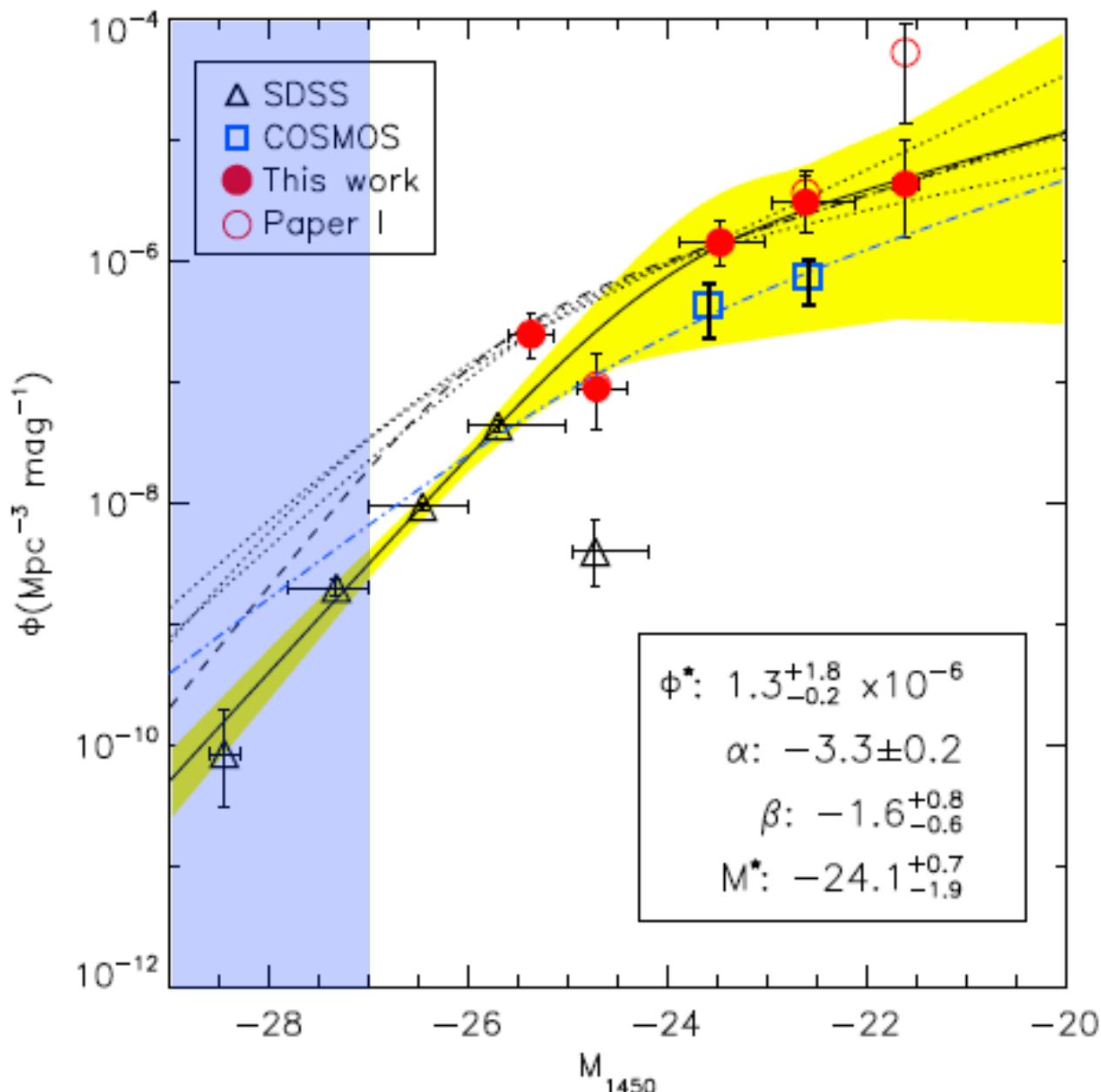


= New Physics? Not yet...

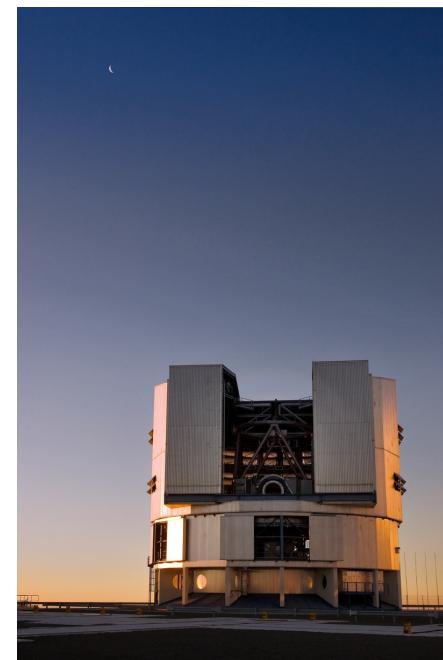


QSO Luminosity Function

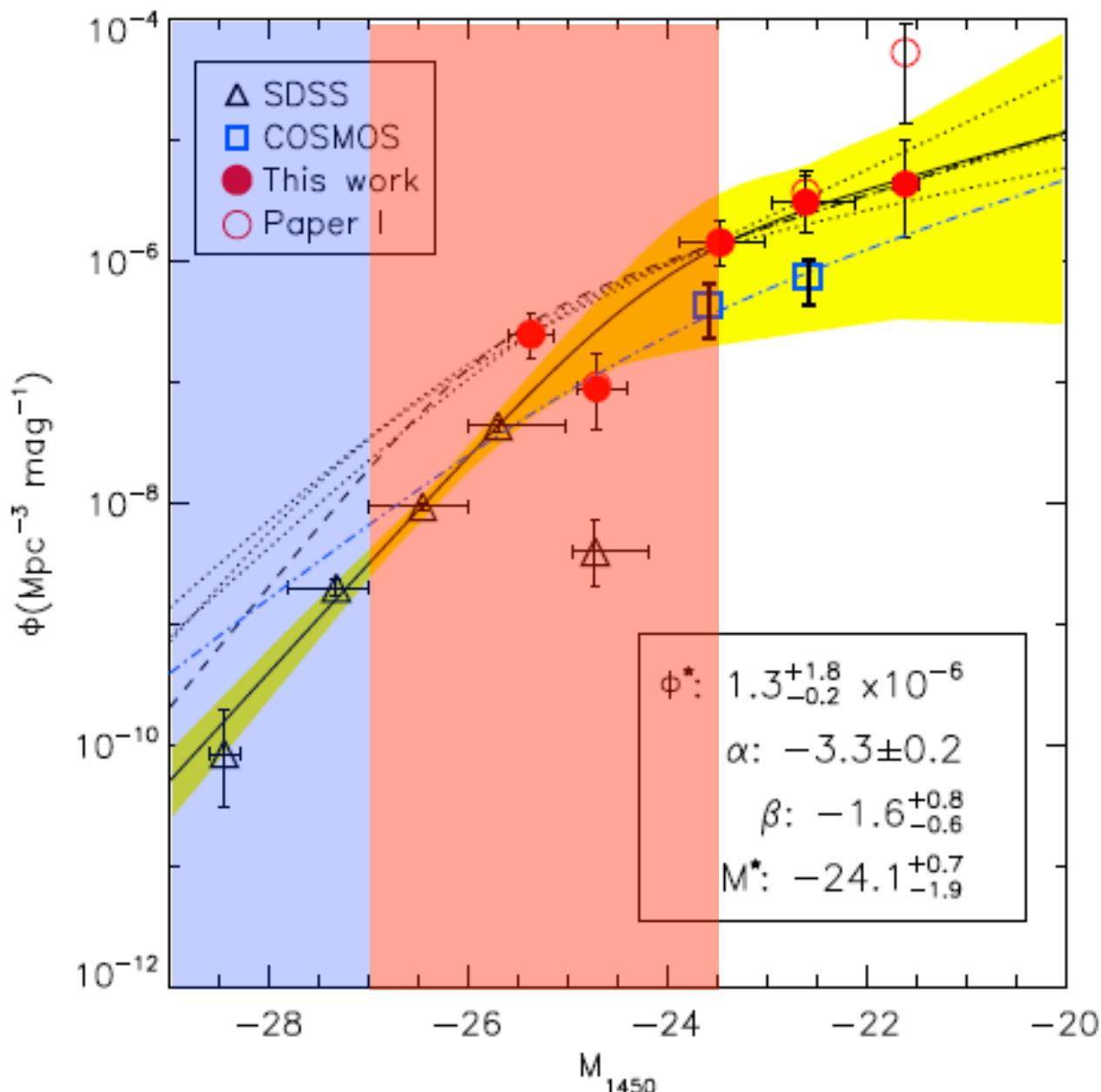
Glikman et al. 2011



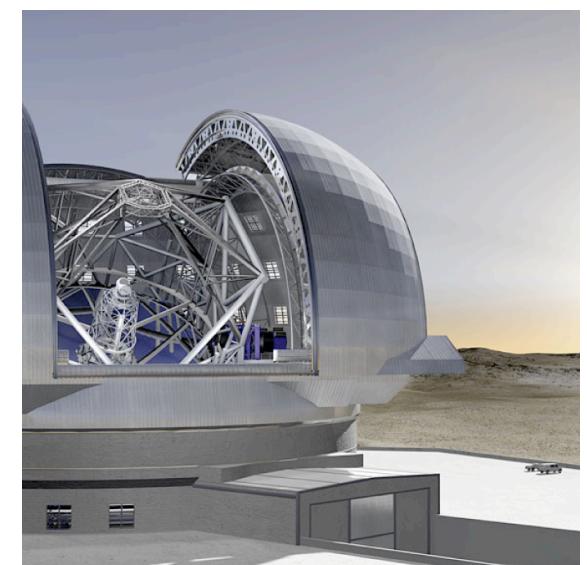
QSO Luminosity Function



Glikman et al. 2011

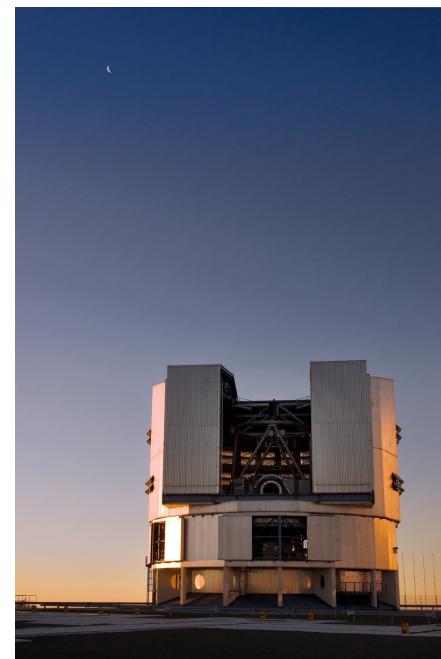
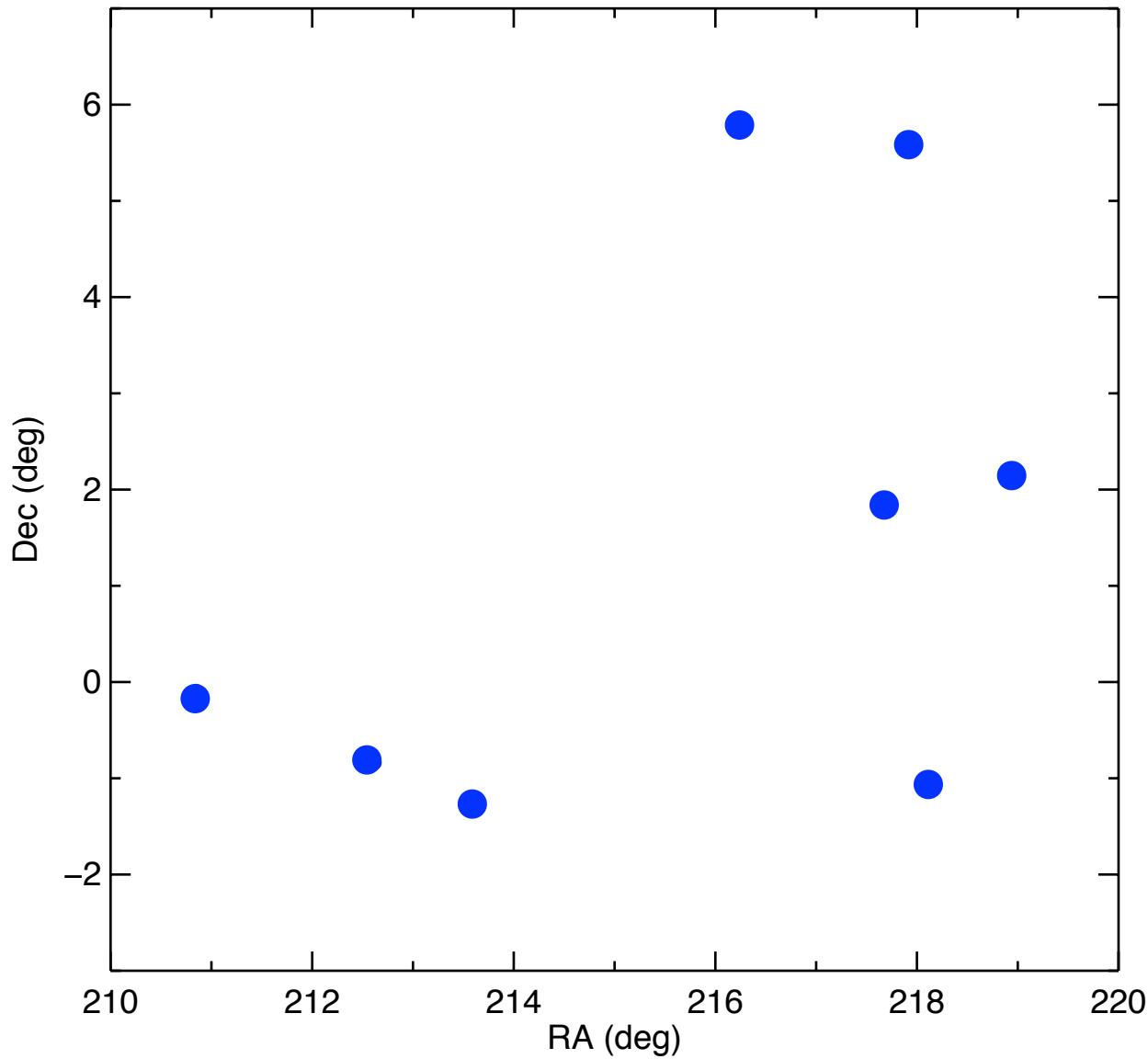


QSO Luminosity Function



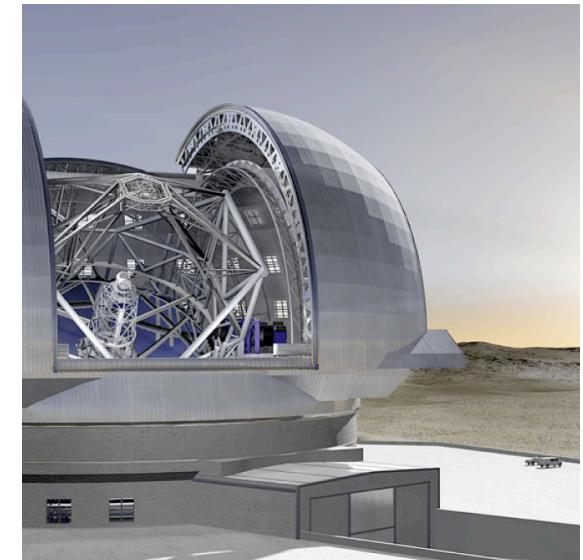
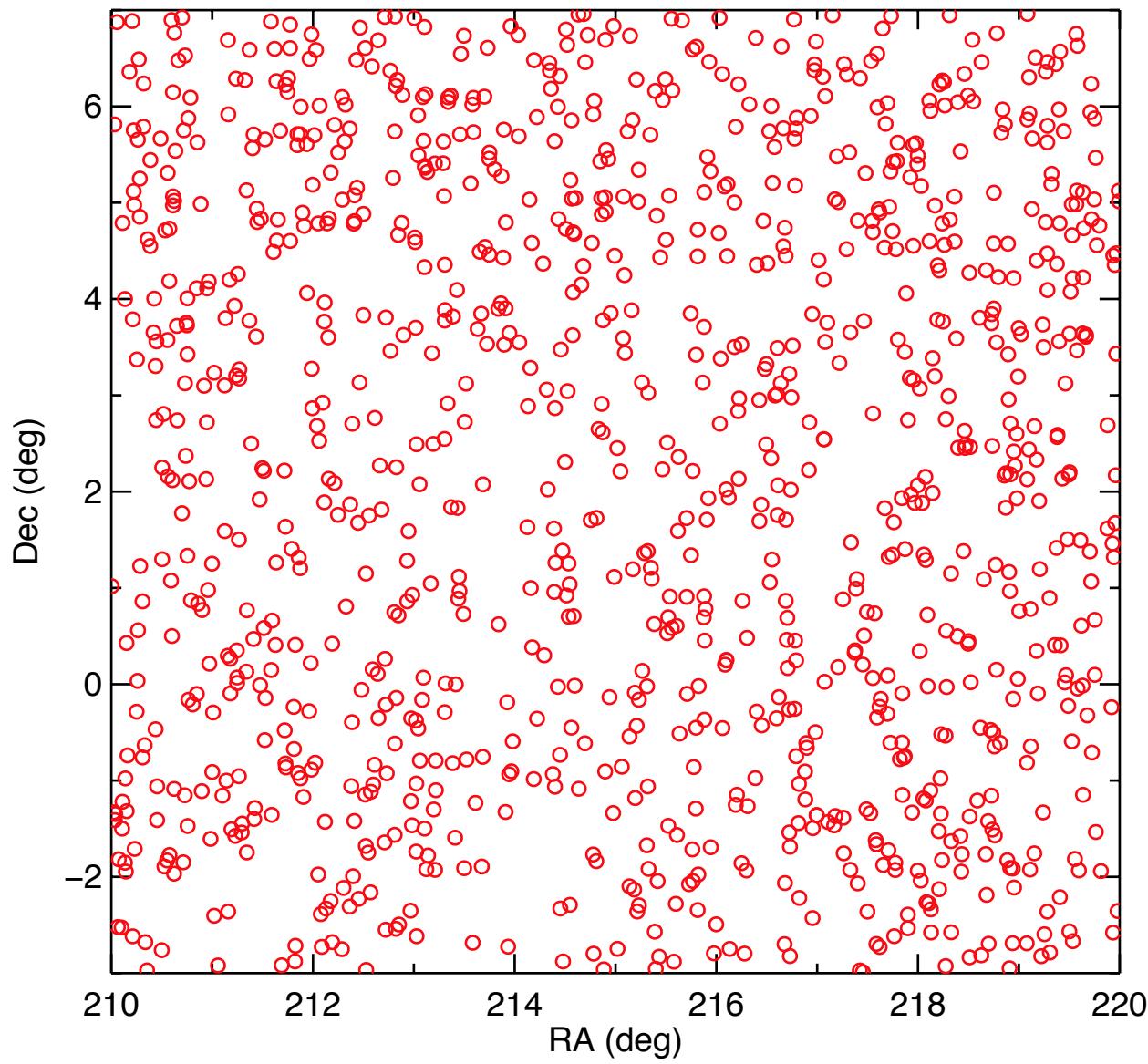
Glikman et al. 2011

8 SDSS QSOs with $z \geq 2, r \leq 18$



(courtesy of G. Becker)

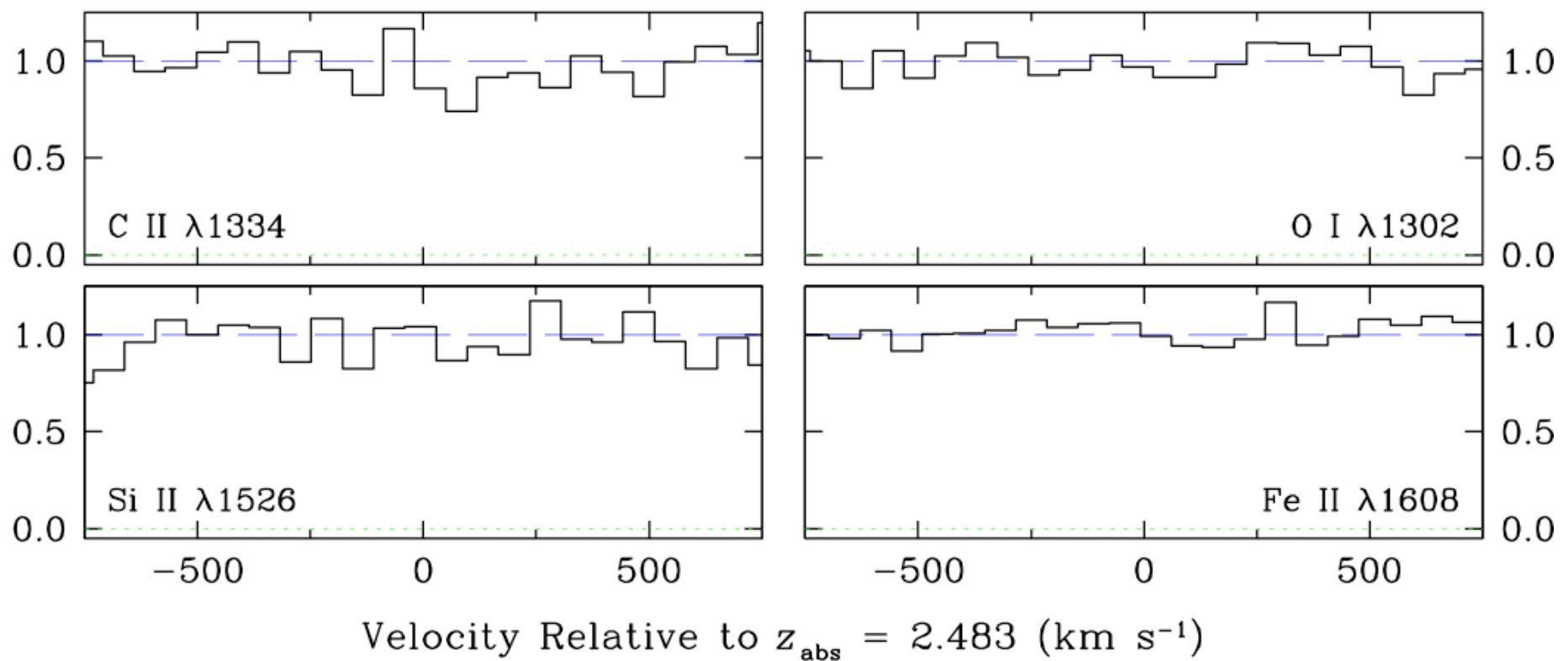
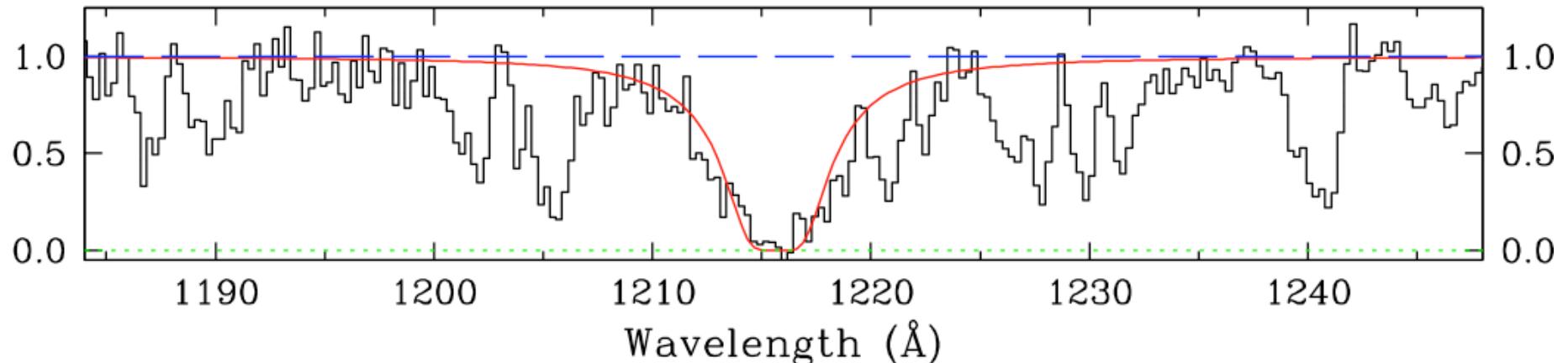
~ 1000 SDSS QSOs with $z \geq 2, r \leq 21$



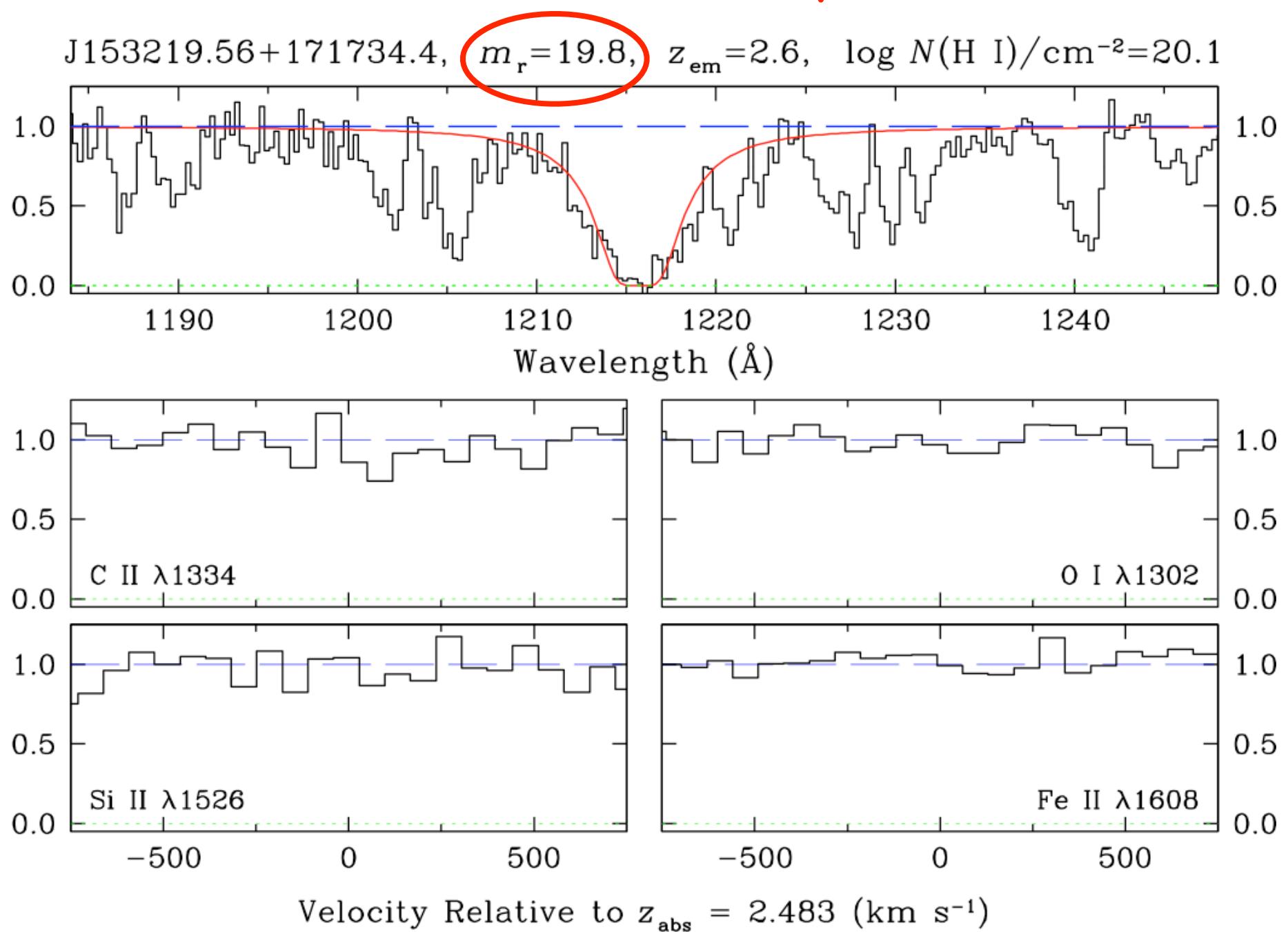
(courtesy of G. Becker)

Here's an example:

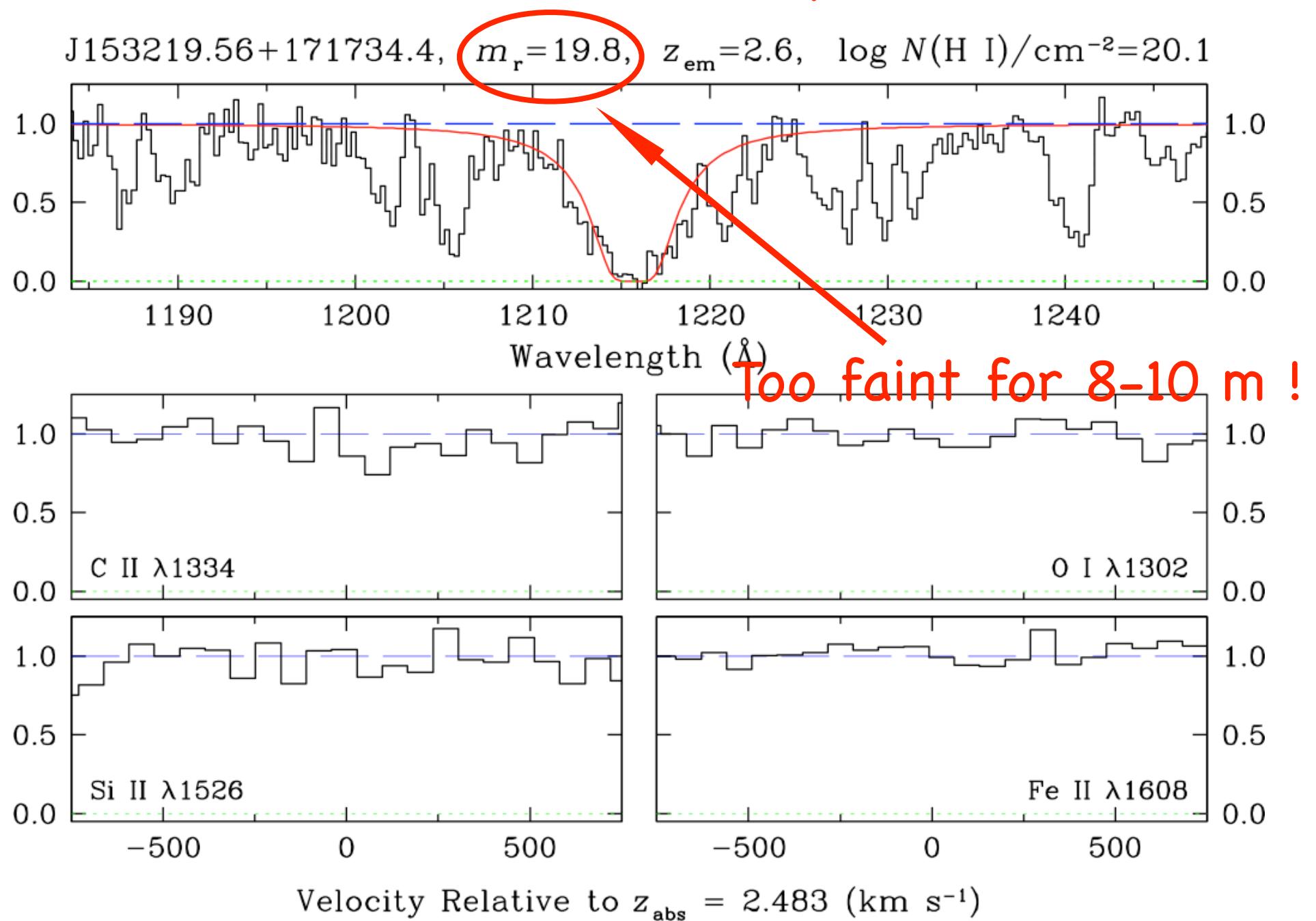
J153219.56+171734.4, $m_r=19.8$, $z_{\text{em}}=2.6$, $\log N(\text{H I})/\text{cm}^{-2}=20.1$



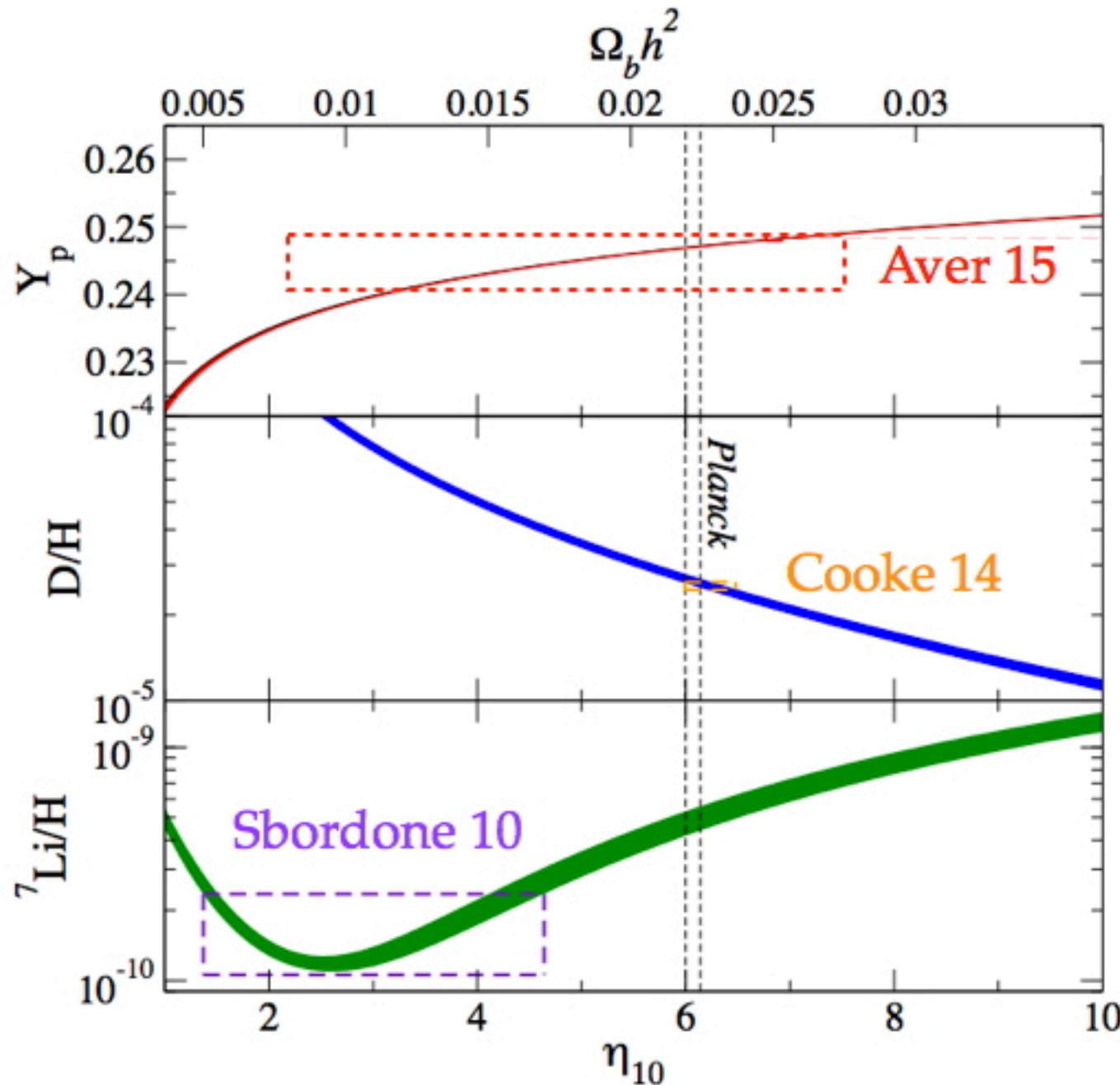
Here's an example:



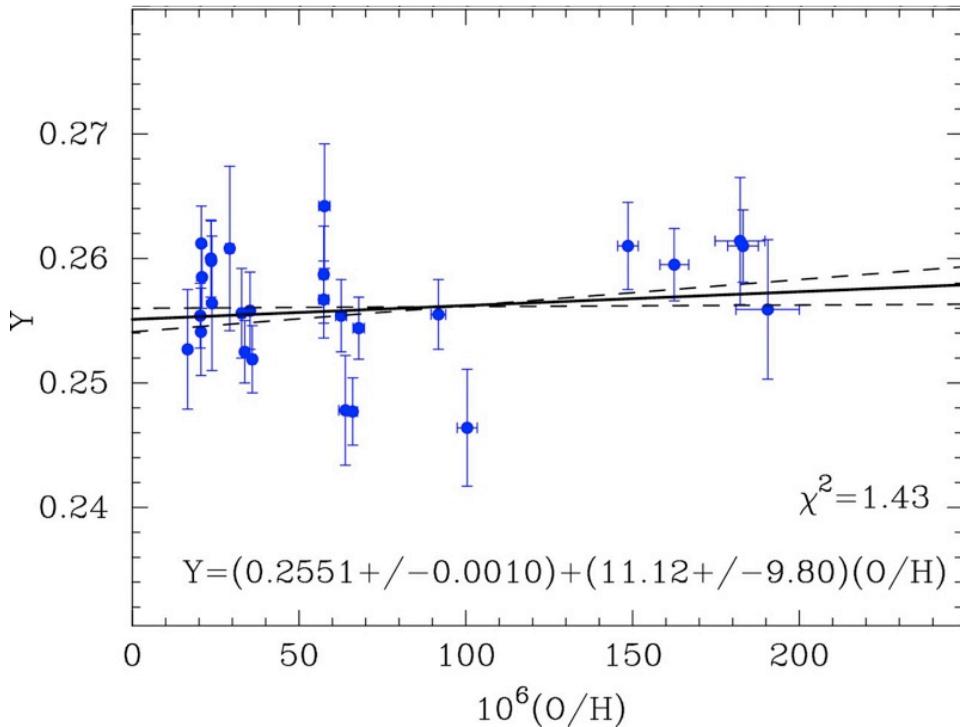
Here's an example:



BBN theory confronts observations



The primordial ${}^4\text{He}$ abundance



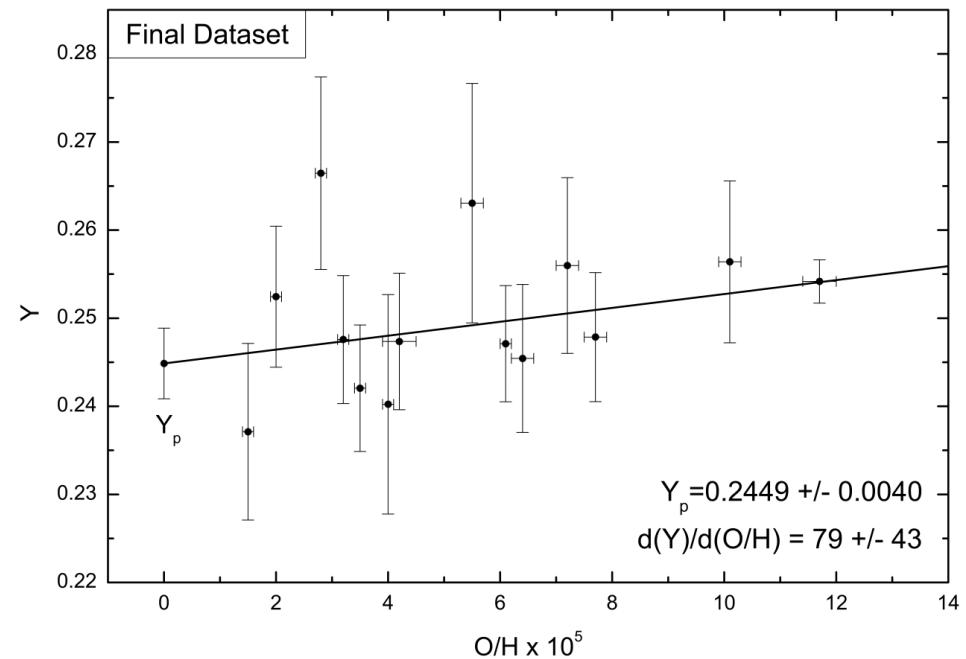
Izotov et al. (2014), MNRAS, 445, 778

$$Y_{\text{P}} = 0.2551 \pm 0.0022$$

Peimbert et al. (2016), RMxAA, 52, 419

$$Y_{\text{P}} = 0.2446 \pm 0.0029$$

Standard model prediction: $Y_{\text{P}} = 0.24709 \pm 0.00017$



Aver et al. (2015), JCAP, 07, 011

$$Y_{\text{P}} = 0.2449 \pm 0.0040$$

$$Y_{\text{P}} = 0.2515 \pm 0.0017$$

Standard Model values

$$100 \Omega_{B,0} h^2(\text{CMB}) = 2.226 \pm 0.023$$

PRIMAT

$$\begin{aligned} Y_P &= 0.24709 \pm 0.00017 \\ (\text{D}/\text{H})_P &= (2.459 \pm 0.036) \times 10^{-5} \\ (^3\text{He}/\text{H})_P &= (1.074 \pm 0.026) \times 10^{-5} \\ (^7\text{Li}/\text{H})_P &= (5.624 \pm 0.245) \times 10^{-10} \end{aligned}$$

Pitrou et al. (2018), arXiv:1801.08023

Kawano (Wagoner)

$$\begin{aligned} Y_P &= 0.2471 \pm 0.0005 \\ (\text{D}/\text{H})_P &= (2.414 \pm 0.047) \times 10^{-5} \\ (^3\text{He}/\text{H})_P &= (1.110 \pm 0.022) \times 10^{-5} \\ (^7\text{Li}/\text{H})_P &= (5.566 \pm 0.269) \times 10^{-10} \end{aligned}$$

Cooke et al. (2017), ApJ, 830, 148
Lopez & Turner (1999), PRD, 59, 103502

Kawano (Wagoner)

$$\begin{aligned} Y_P &= 0.2480 \\ (\text{D}/\text{H})_P &= 2.365 \times 10^{-5} \\ (^3\text{He}/\text{H})_P &= 1.088 \times 10^{-5} \\ (^7\text{Li}/\text{H})_P &= 5.042 \times 10^{-10} \end{aligned}$$

Grohs et al. (2016), PRD, 93, 083522

PArthENoPE

$$\begin{aligned} (\text{D}/\text{H})_P &= 2.478 \times 10^{-5} \\ (^3\text{He}/\text{H})_P &= 1.086 \times 10^{-5} \\ (^7\text{Li}/\text{H})_P &= 4.927 \times 10^{-10} \end{aligned}$$

Consiglio et al. (2018), arXiv:1712.04378