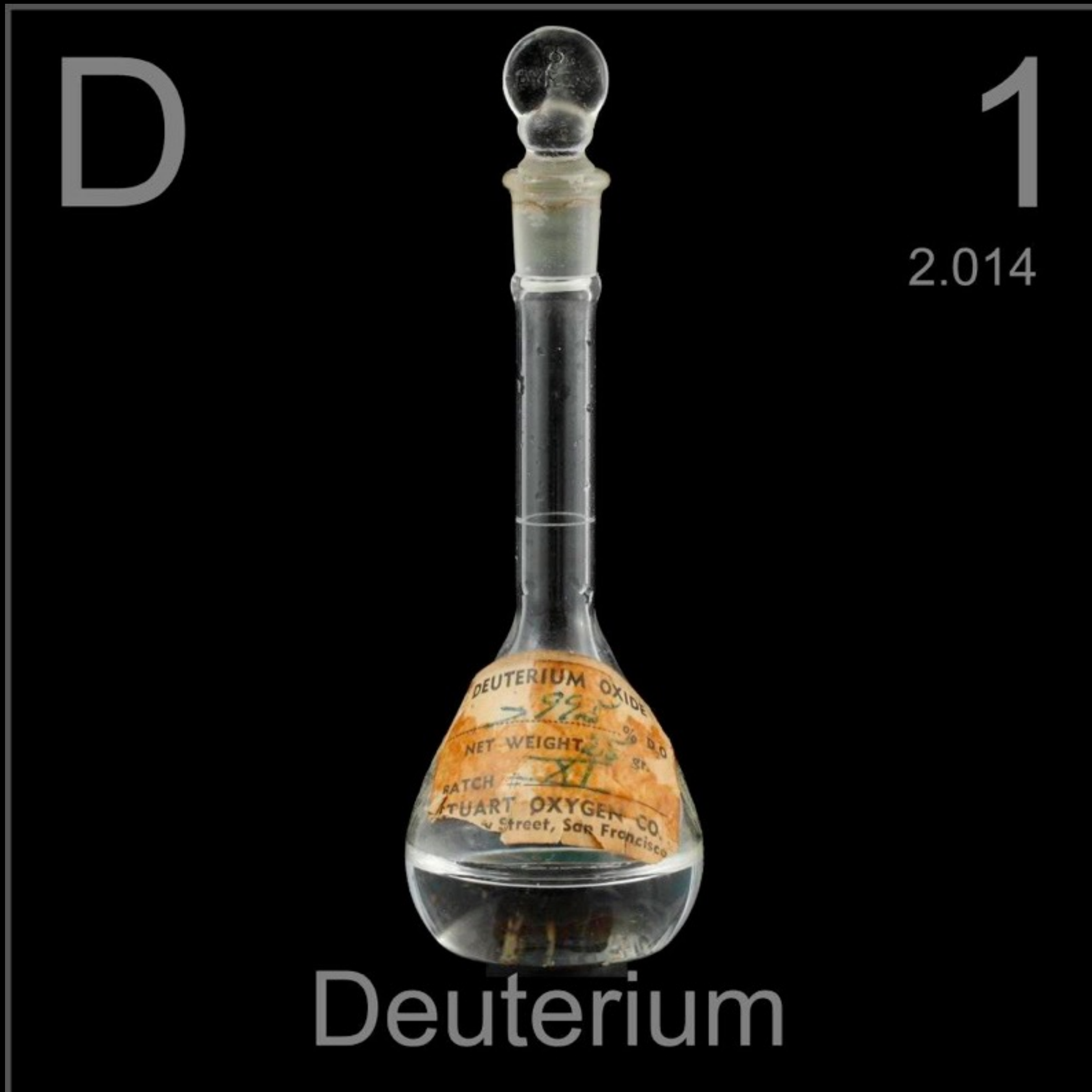
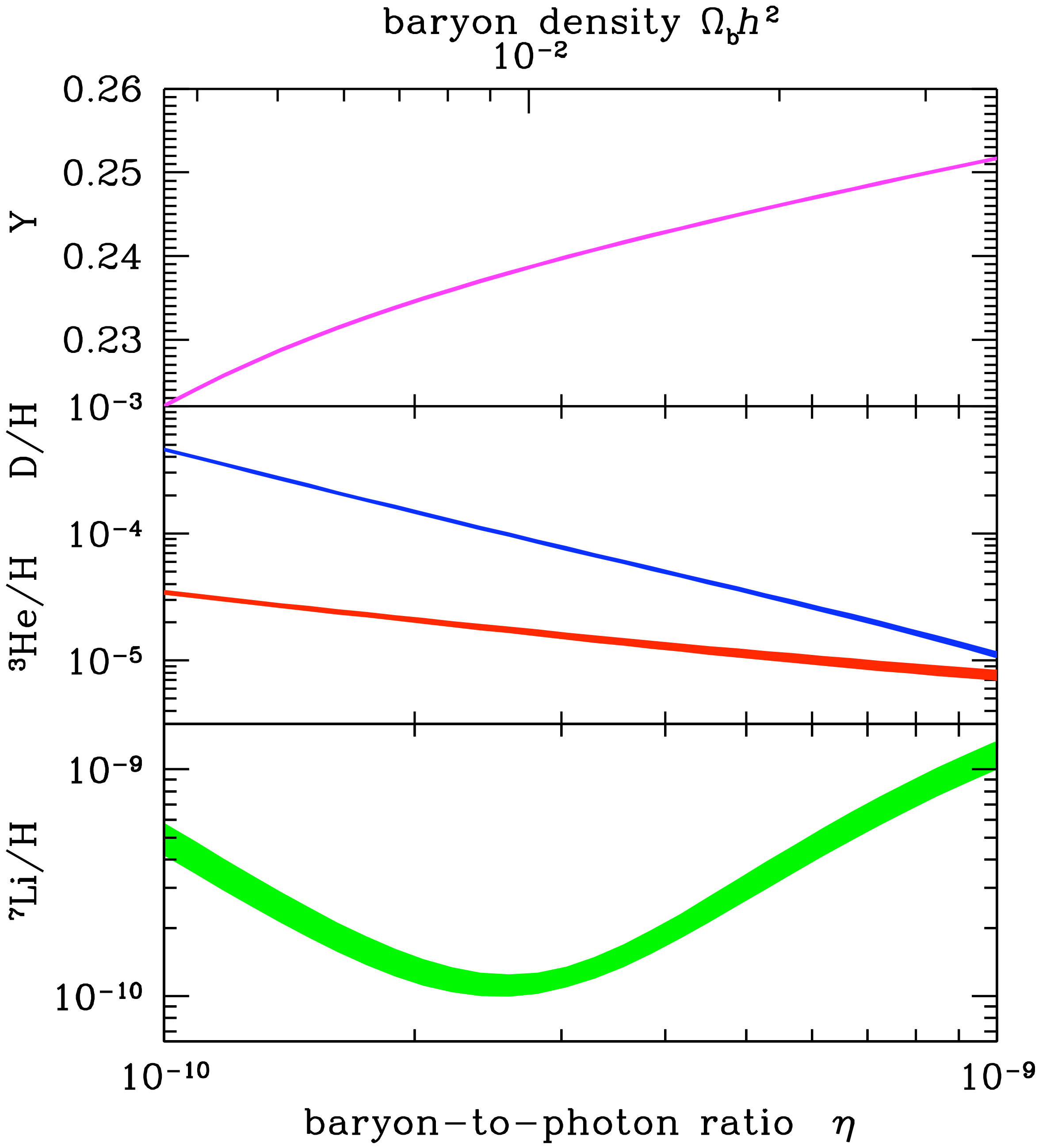
Sub-percent precision in the primordial abundance of



Max Pettini

Ryan Cooke

Deuterium is the baryometer of choice



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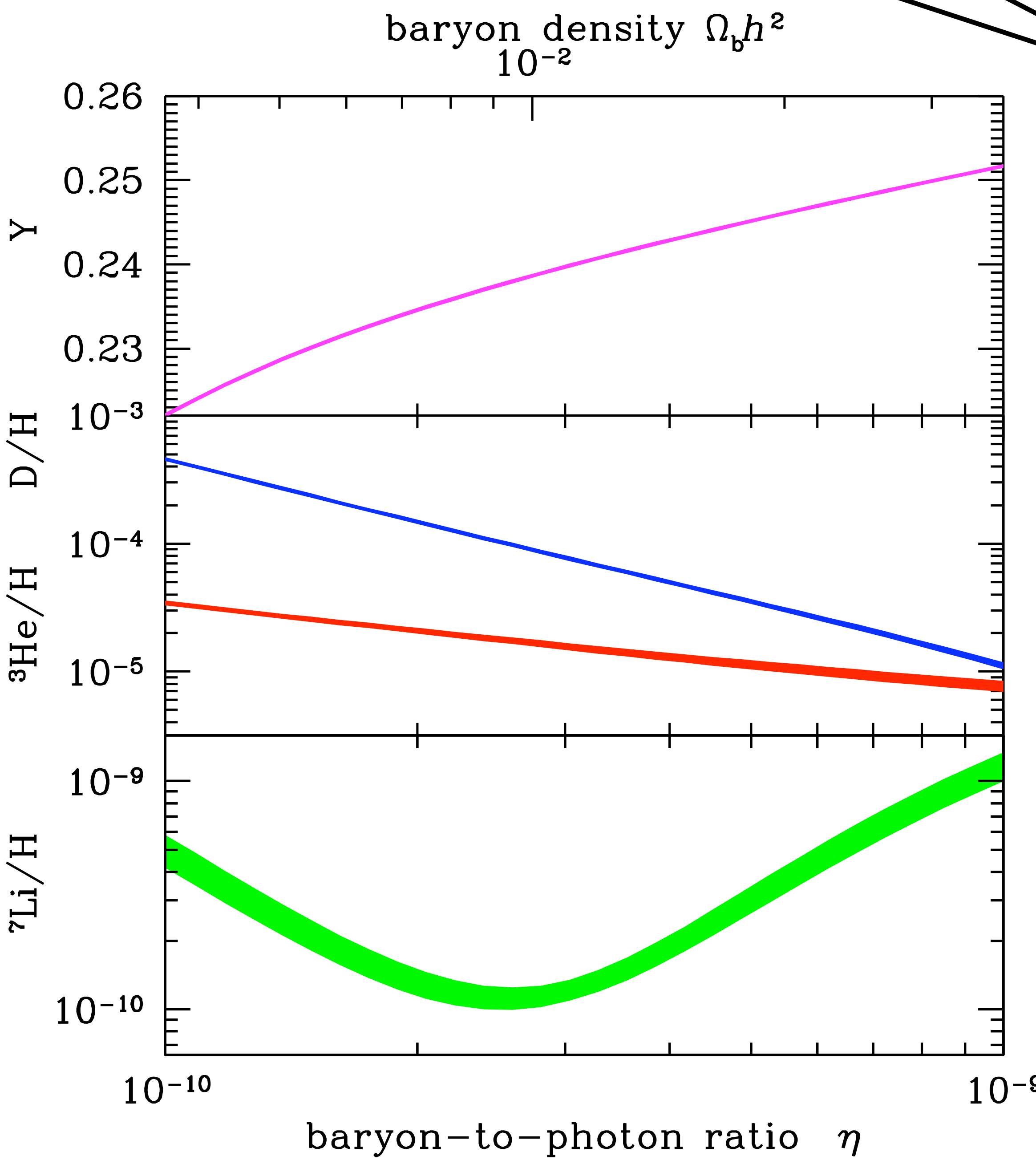

THE ASTROPHYSICAL JOURNAL, **186**:L95–L98, 1973 December 15

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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β Cen

B1 III

$V = 0.61$

$d = 120\,\mathrm{pc}$

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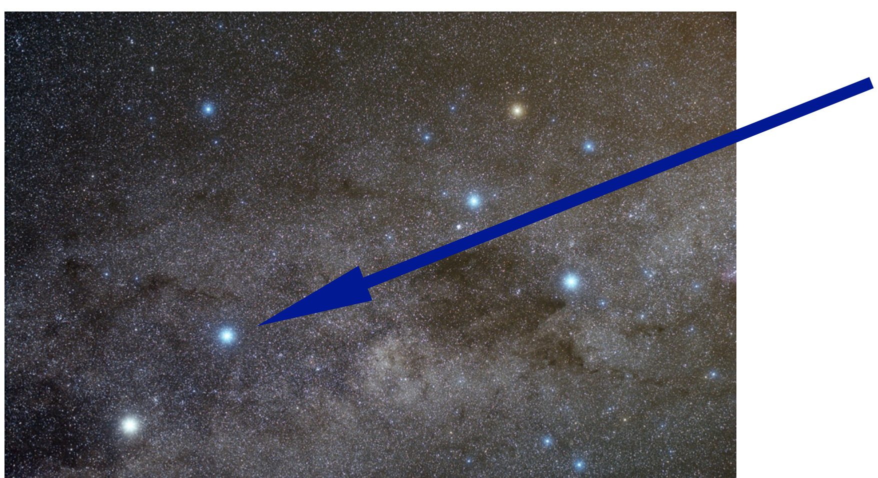


β Cen

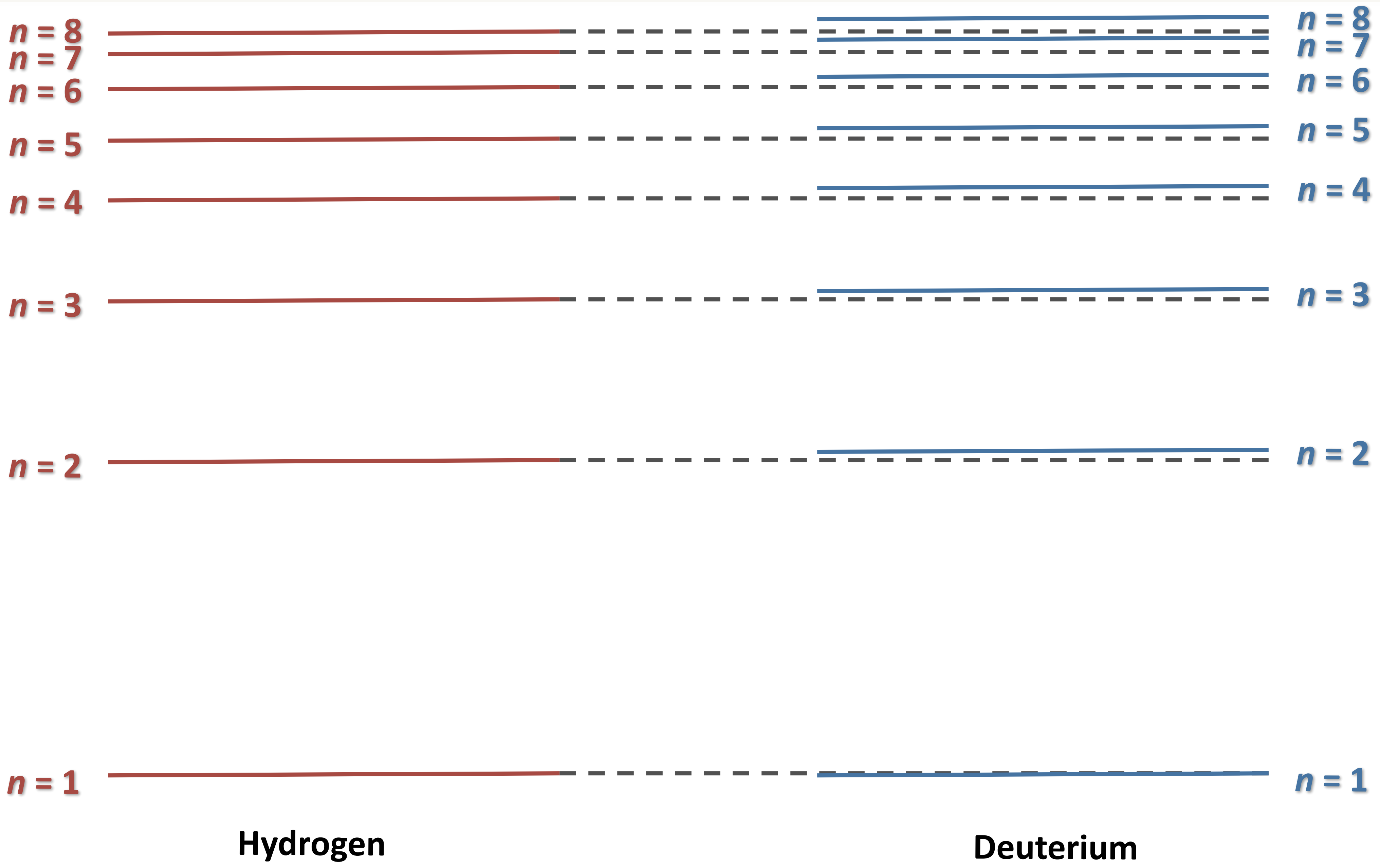
B1 III

$V = 0.61$

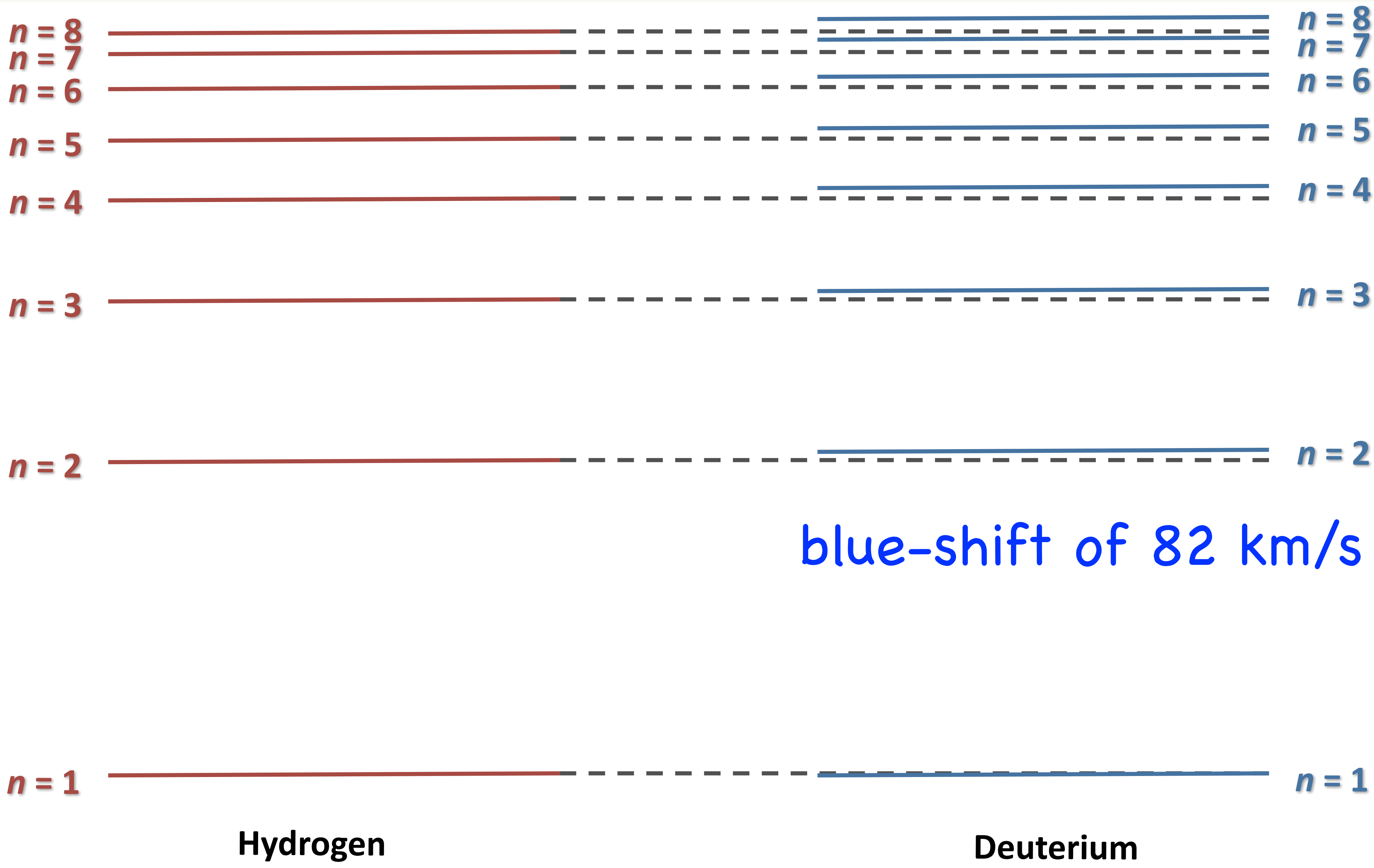
$d = 120\,\text{pc}$

$\Omega_b < 0.067$

Energy Levels



Energy Levels



Astron. & Astrophys. 50, 461 – 462 (1976)

ASTRONOMY AND ASTROPHYSICS

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.

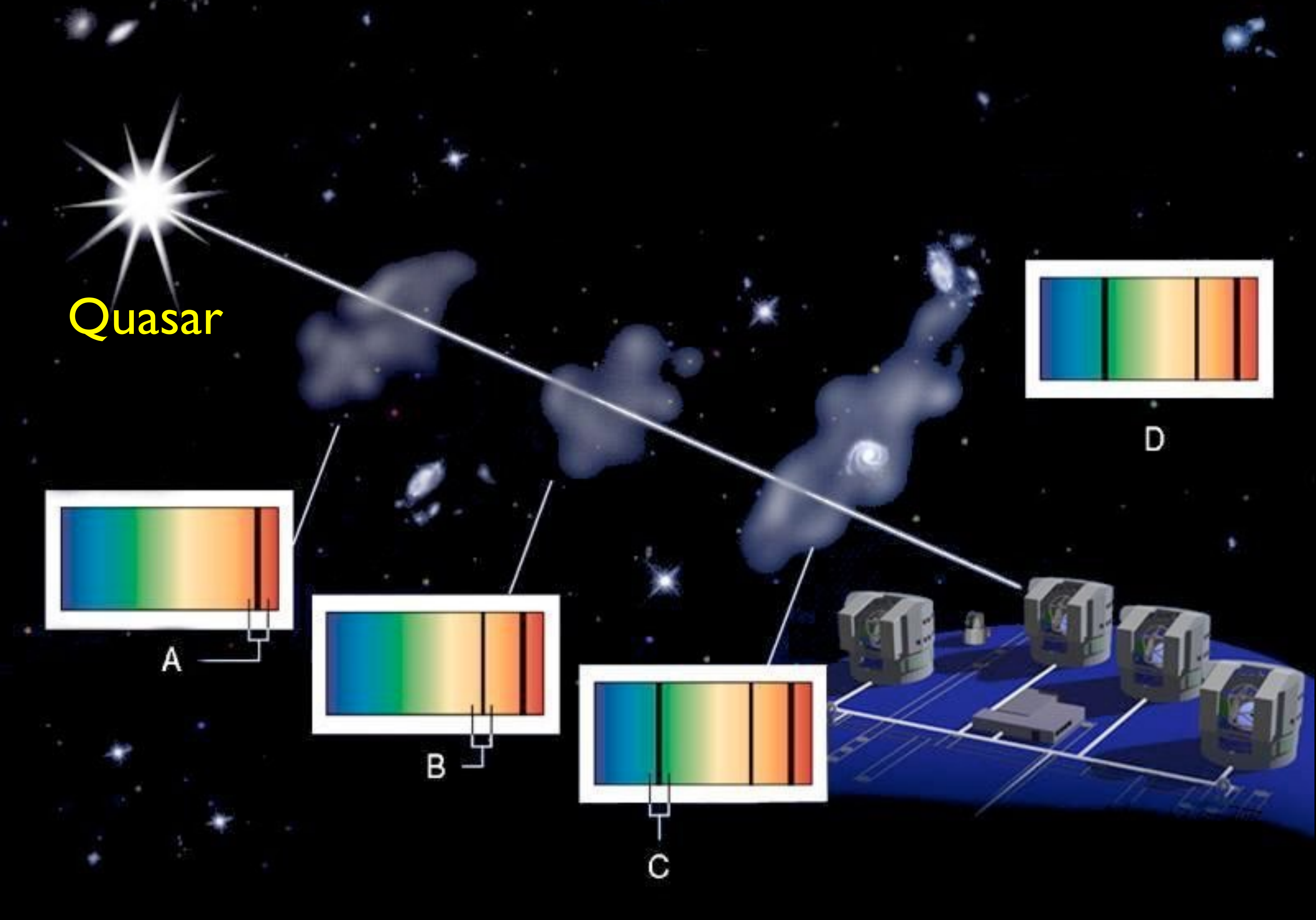


Image credit: ESO

10m Keck telescope + HIRES

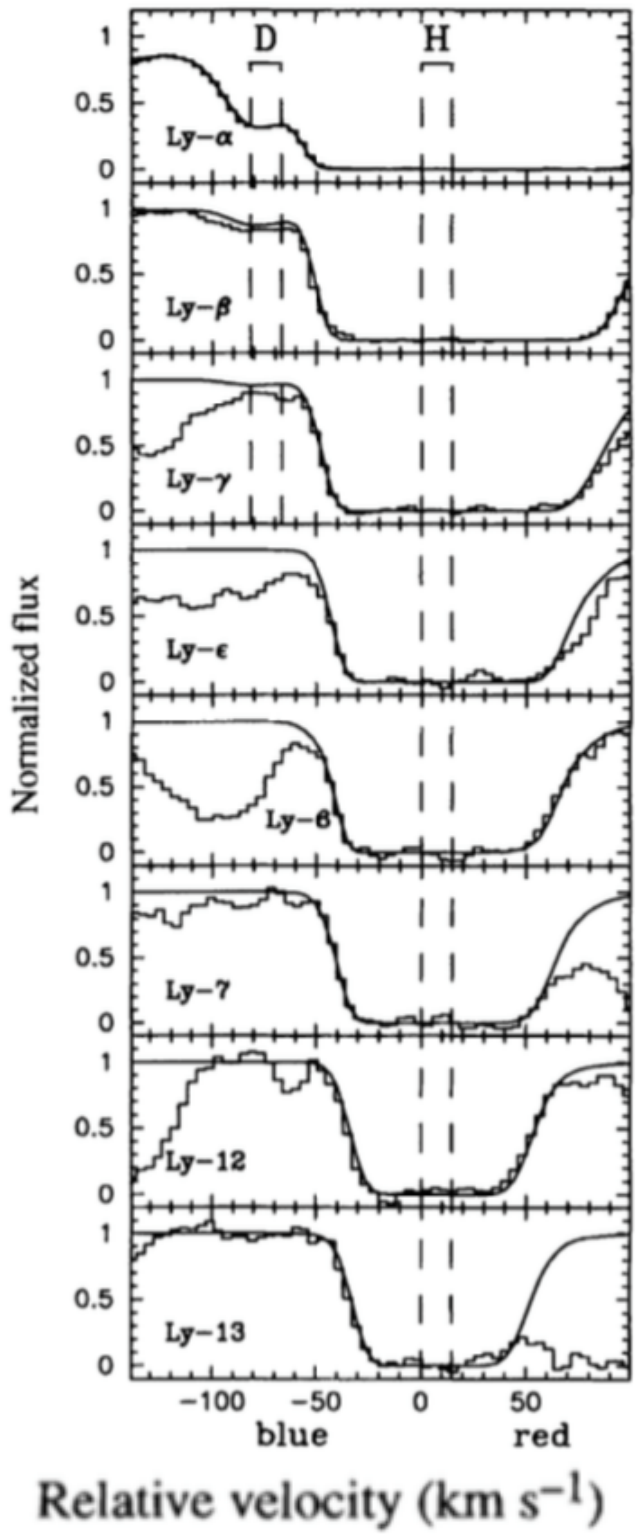
10m Keck telescope + HIRES

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



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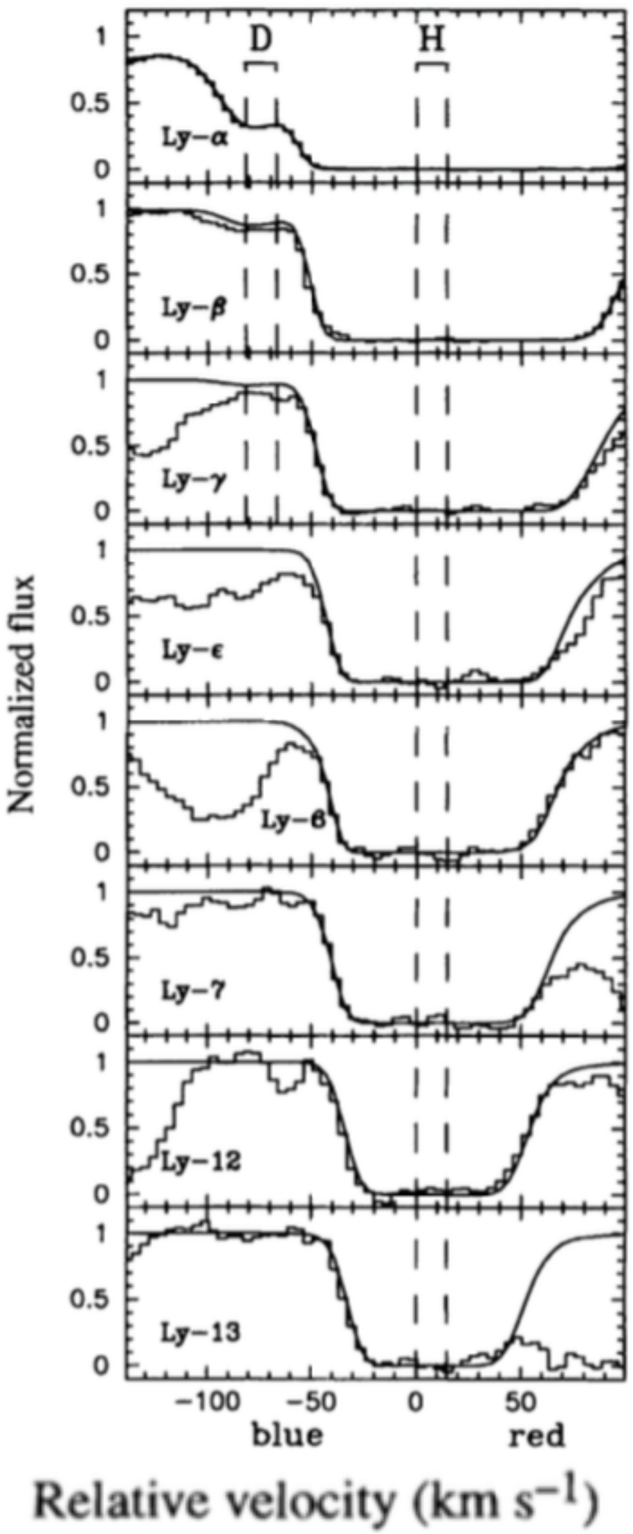

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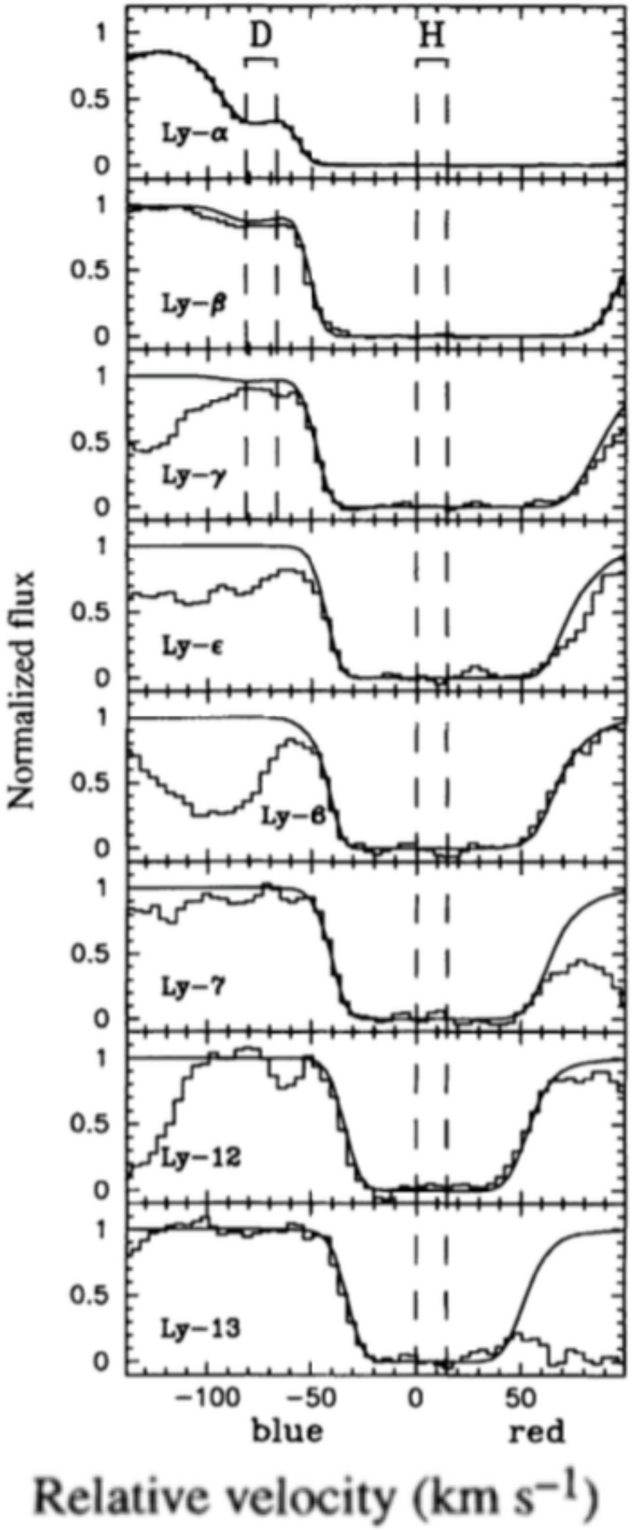
$$10^5 \ \mathrm{D/H} = 2.3 \pm 0.6$$



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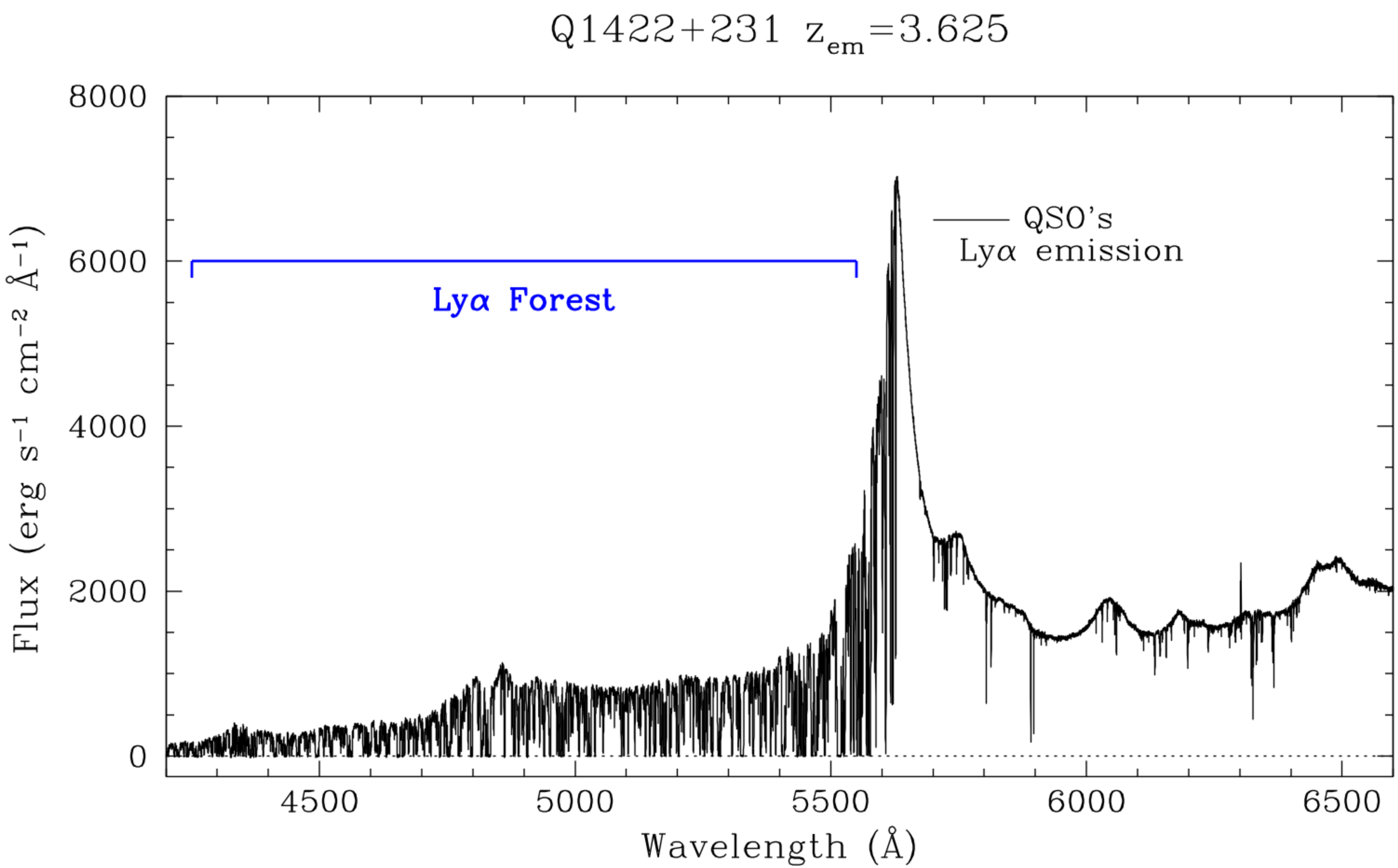
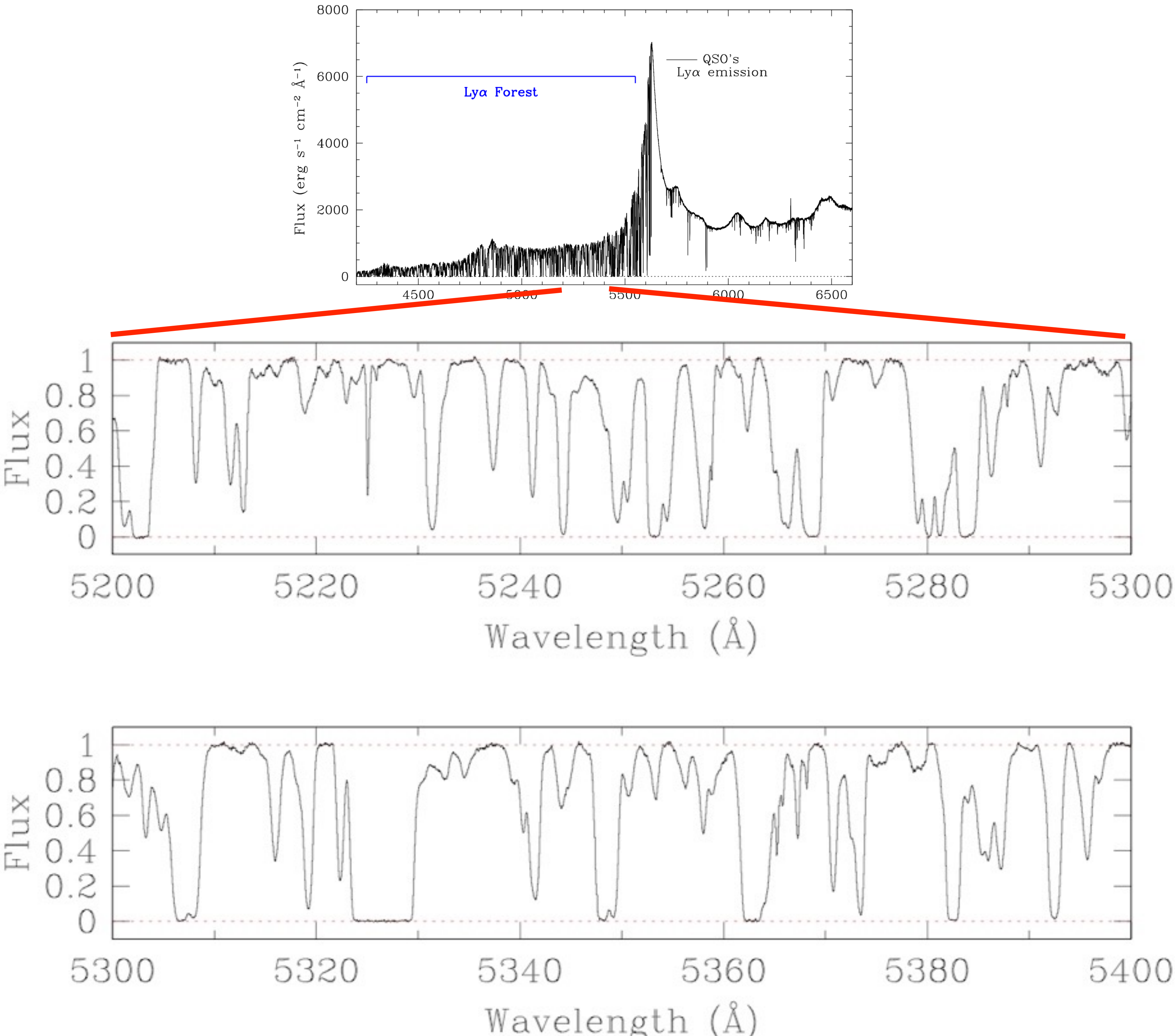
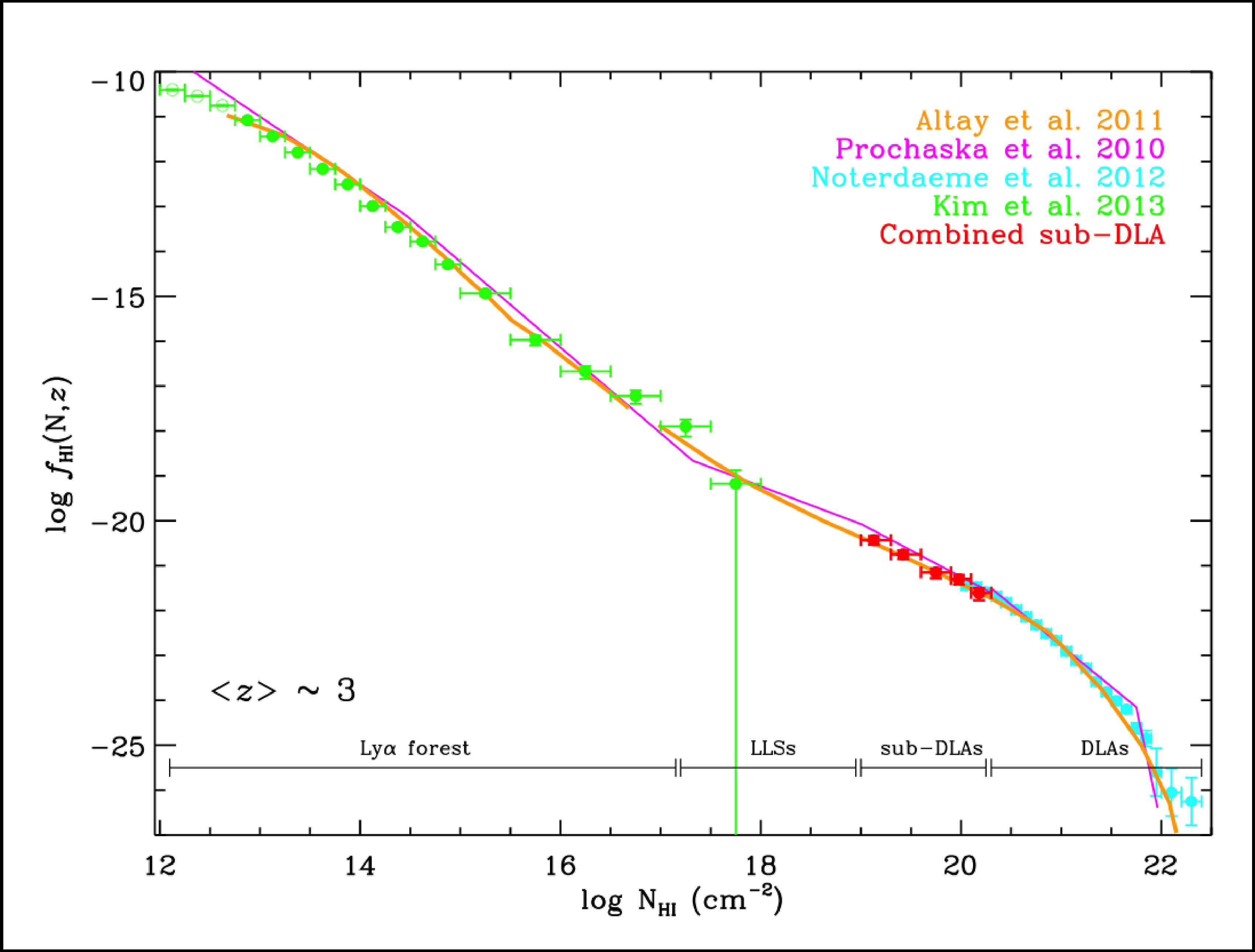
$$100\Omega_{\rm b}h^2 = 2.4 \pm 0.6$$


Q1422+231 z_em=3.625
8000
6000
4000
2000
0
Flux (erg s⁻¹ cm⁻² Å⁻¹)
Lyα Forest
QSO's
Lyα emission
4500
5000
5500
6000
6500
Wavelength (Å)

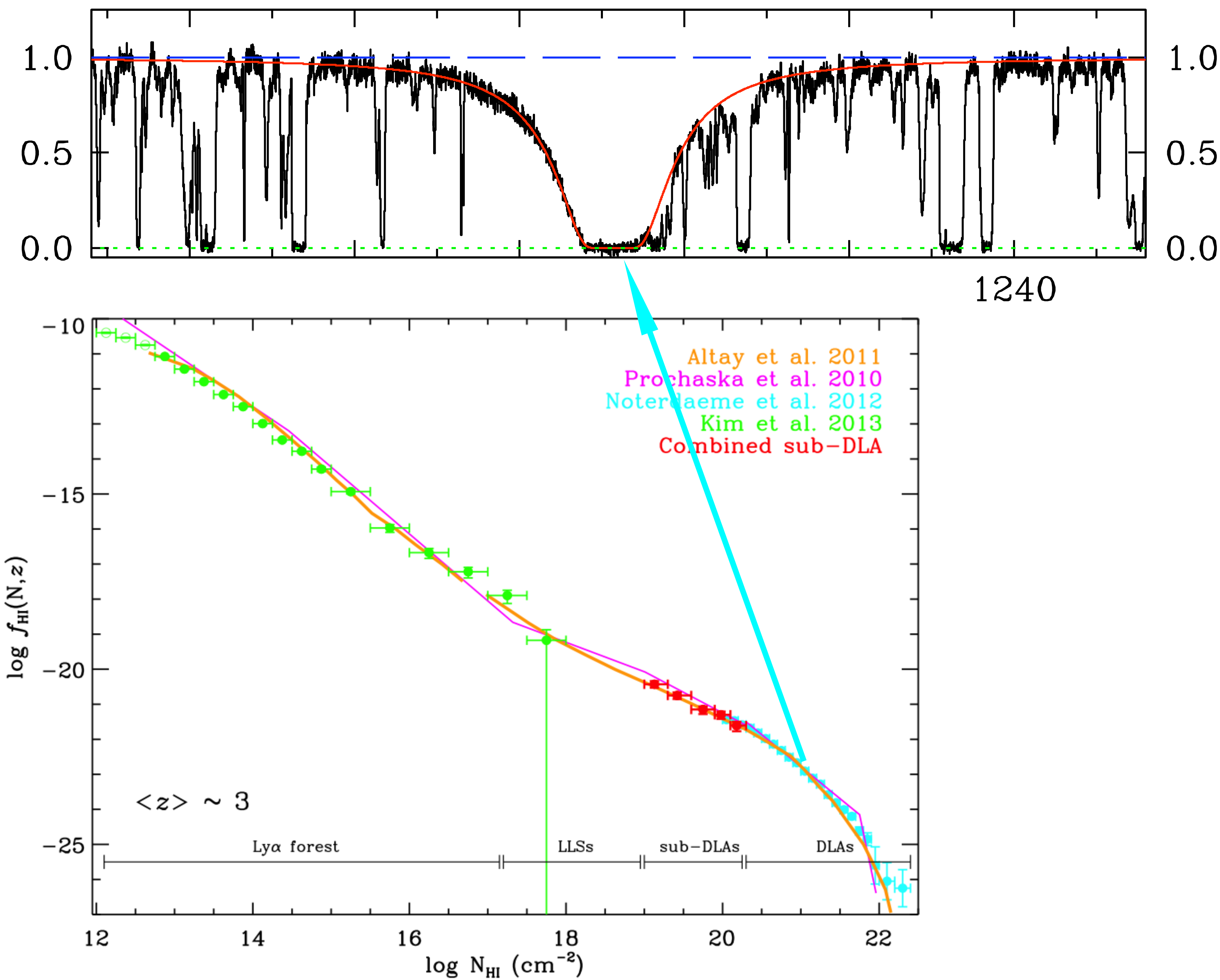


Lyα Forest
QSO's
Lyα emission
Flux (erg s⁻¹ cm⁻² Å⁻¹)
8000
6000
4000
2000
0
4500
5000
5500
6000
6500
Flux
1
0.8
0.6
0.4
0.2
0
5200
5220
5240
5260
5280
5300
Wavelength (Å)
Flux
1
0.8
0.6
0.4
0.2
0
5300
5320
5340
5360
5380
5400
Wavelength (Å)

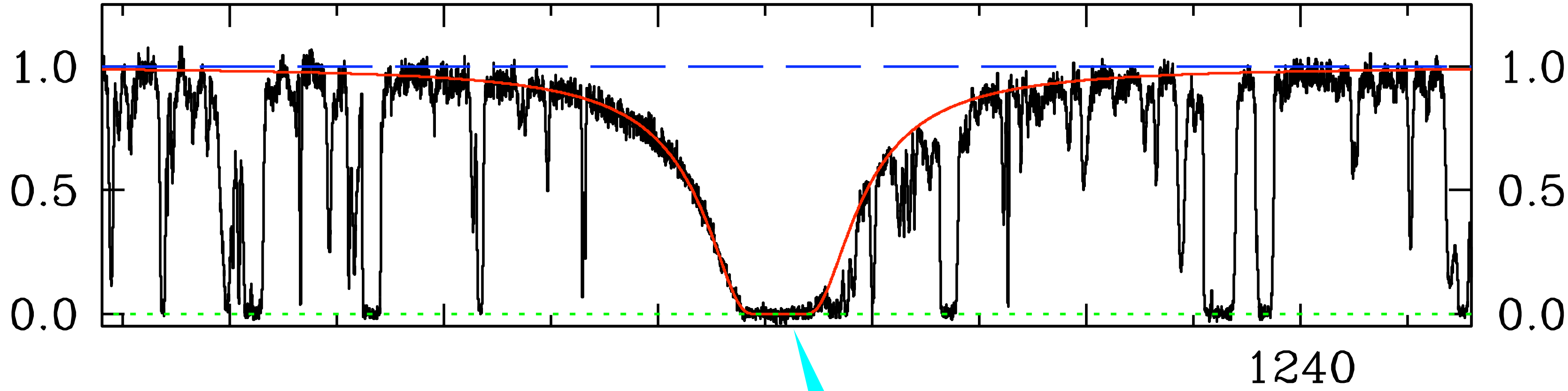
Column Density Distribution of Lya forest lines



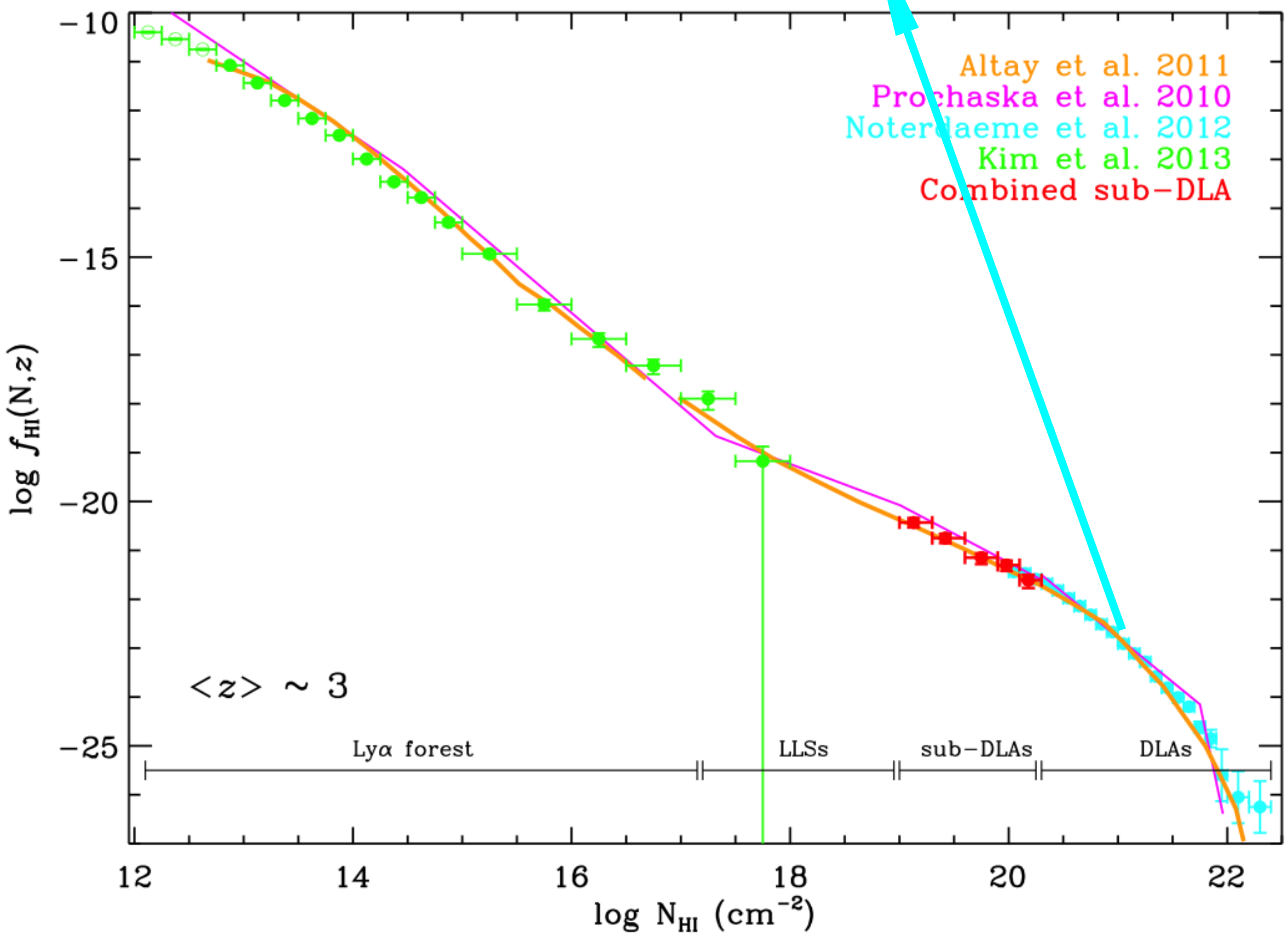
Zafar+ 2013



1.0
0.5
0.0
1.0
0.5
0.0
1240
Altay et al. 2011
Prochaska et al. 2010
Noterdaeme et al. 2012
Kim et al. 2013
Combined sub−DLA
<z> ~ 3
Lyα forest
LLSs
sub−DLAs
DLAs
log $f_{HI}(N,z)$
log N_{HI} (cm^{-2})
−10
−15
−20
−25
12
14
16
18
20
22



1.0
0.5
0.0
1240



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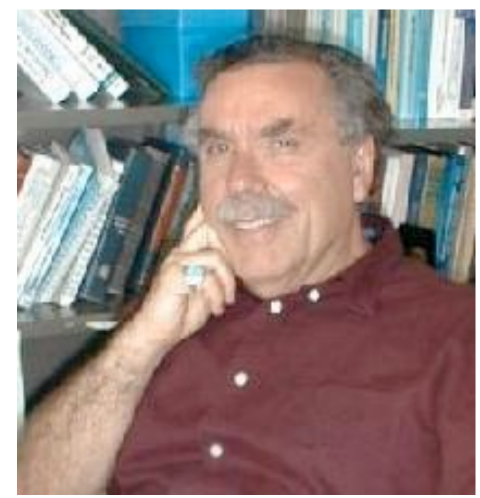
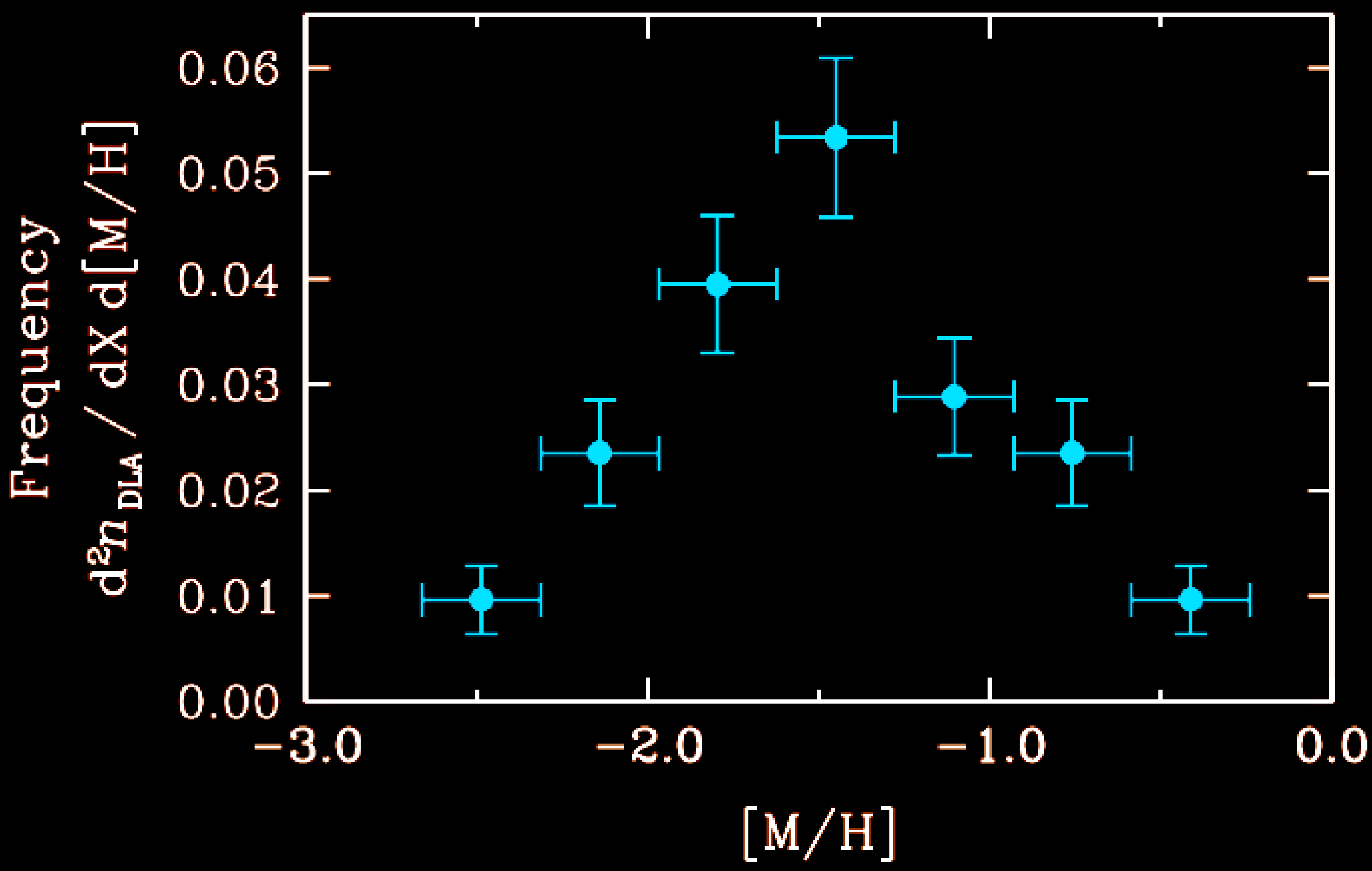
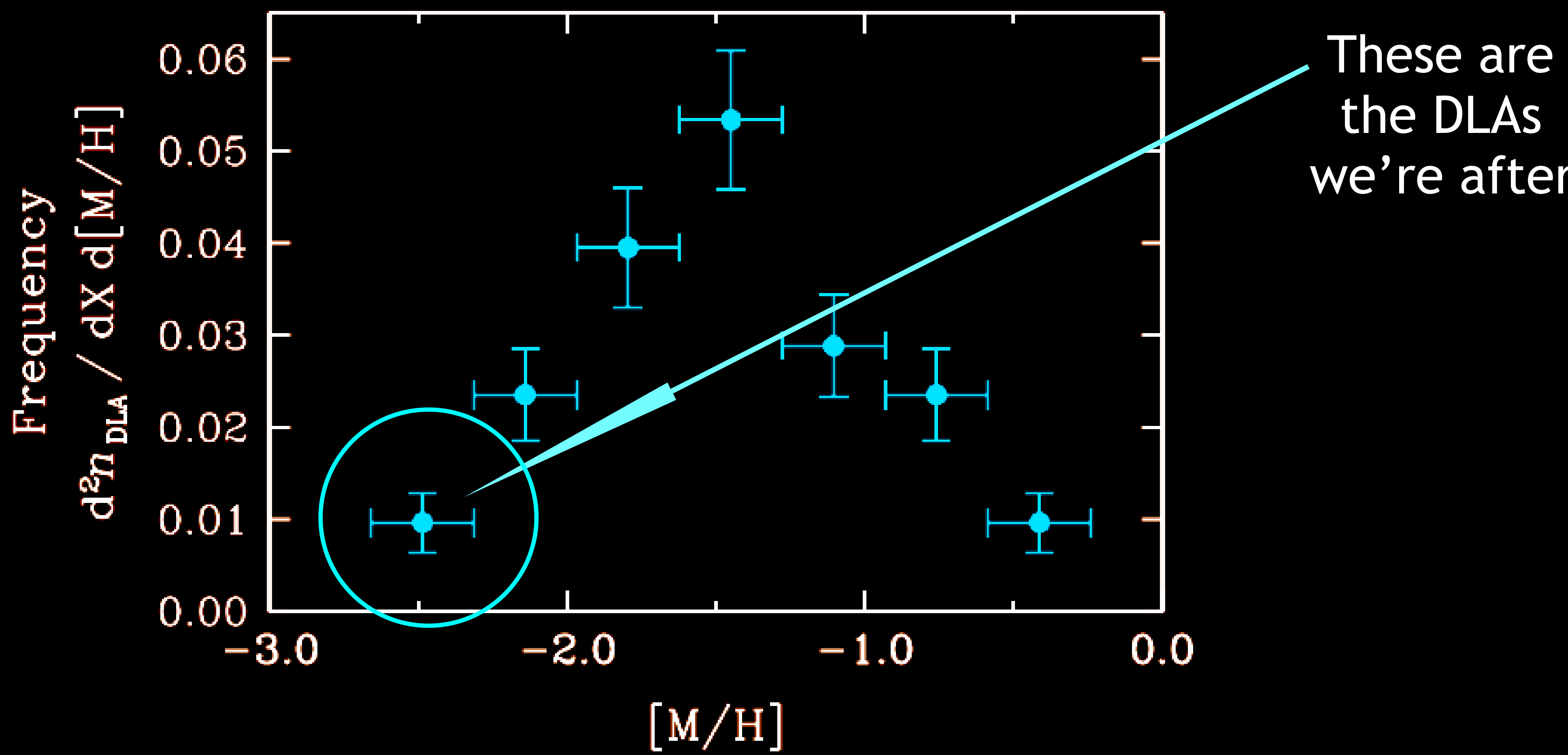


Metallicity Distribution



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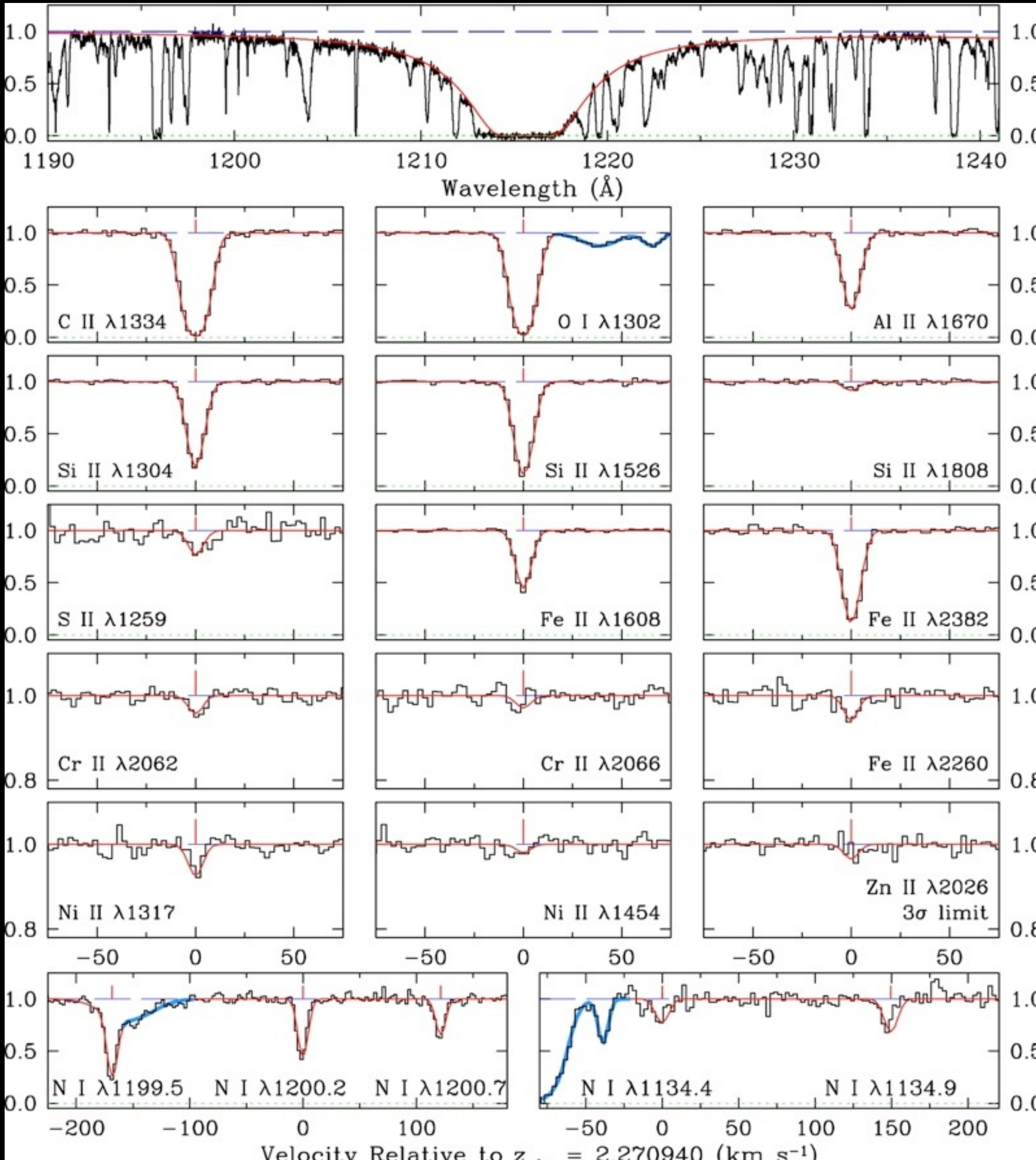
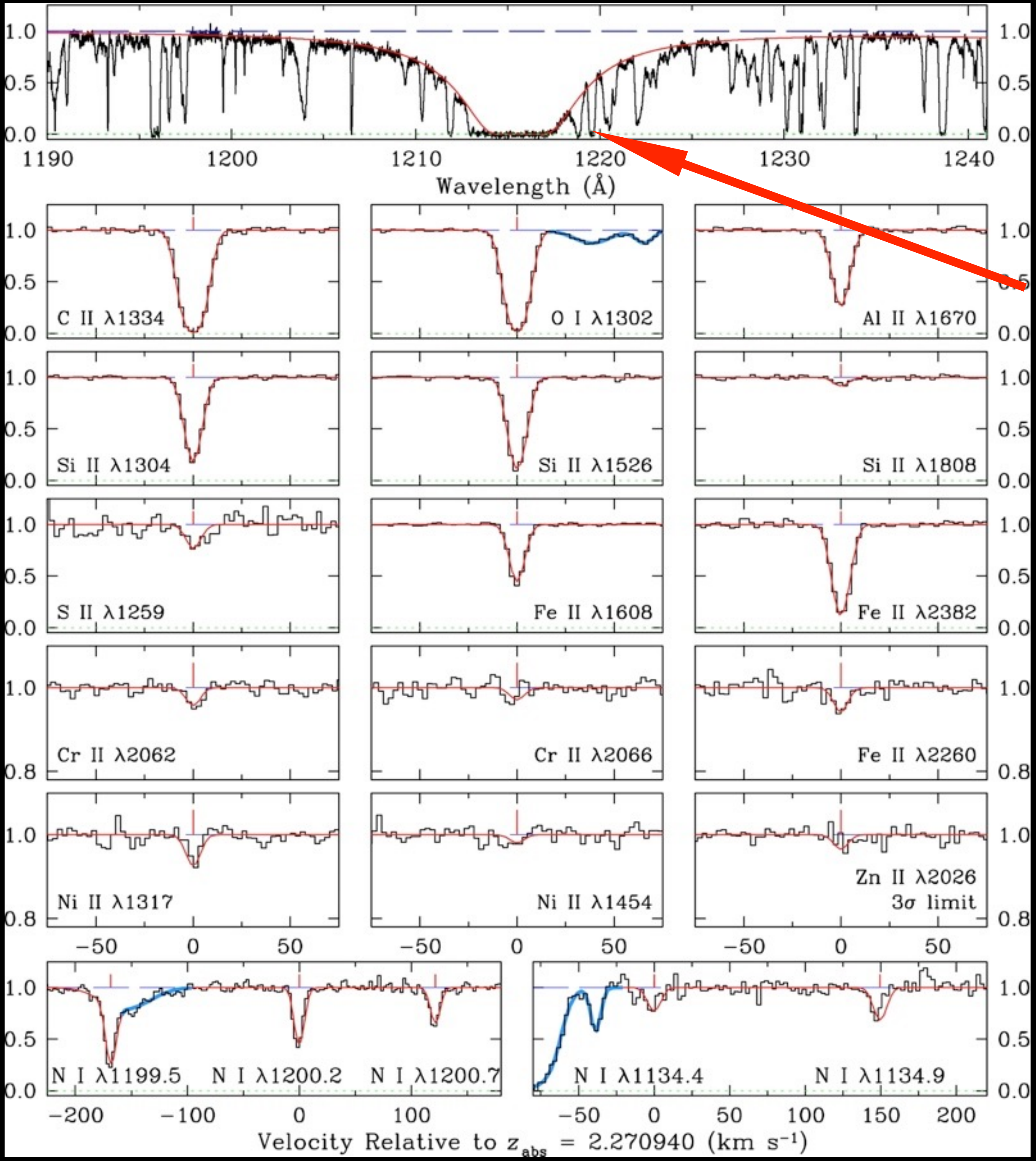
- ✓ Low metallicities imply negligible astration of D
- ✓ Narrow absorption lines make it possible to resolve the −82 km/s isotope shift between D and H

J1111+1332



Cooke+ 2015

J1111+1332

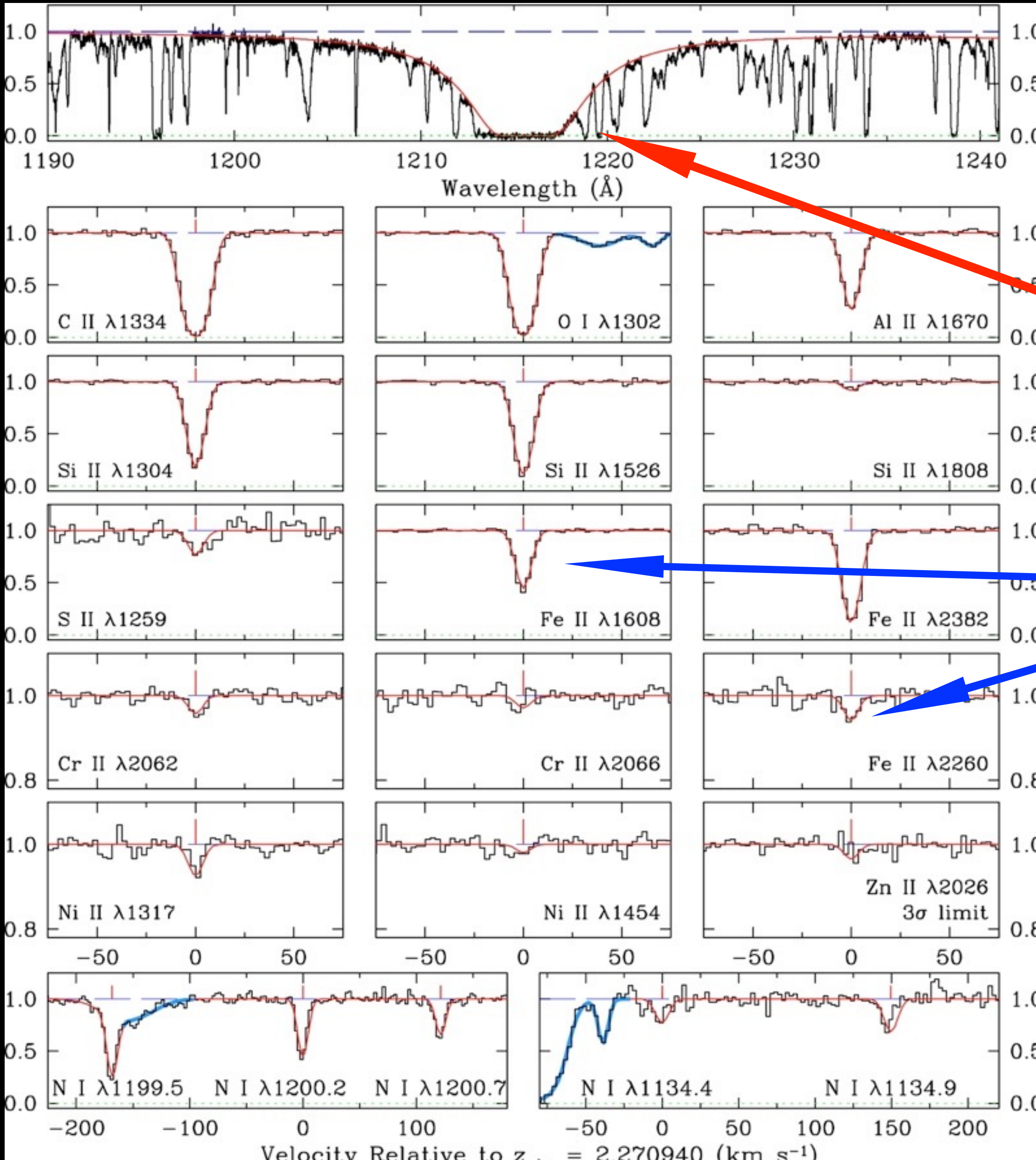


DLA at z = 2.270940

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

Cooke+ 2015

J1111+1332



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Fe/H = 1/200 solar

Cooke+ 2015

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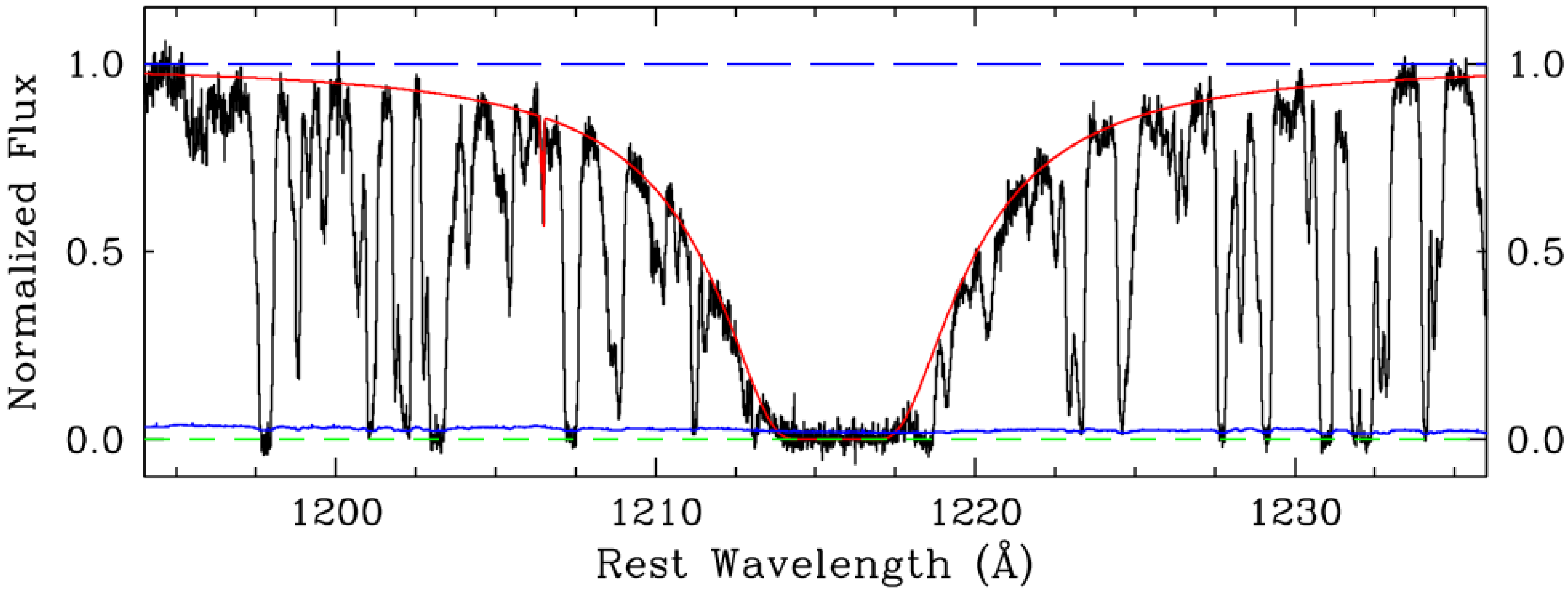
- ✓ Low metallicities imply negligible astration of D
- ✓ Narrow absorption lines make it possible to resolve the −82 km/s isotope shift between D and H
- ✓ High H I column densities give detectable D I lines in **many** transitions of the Lyman series

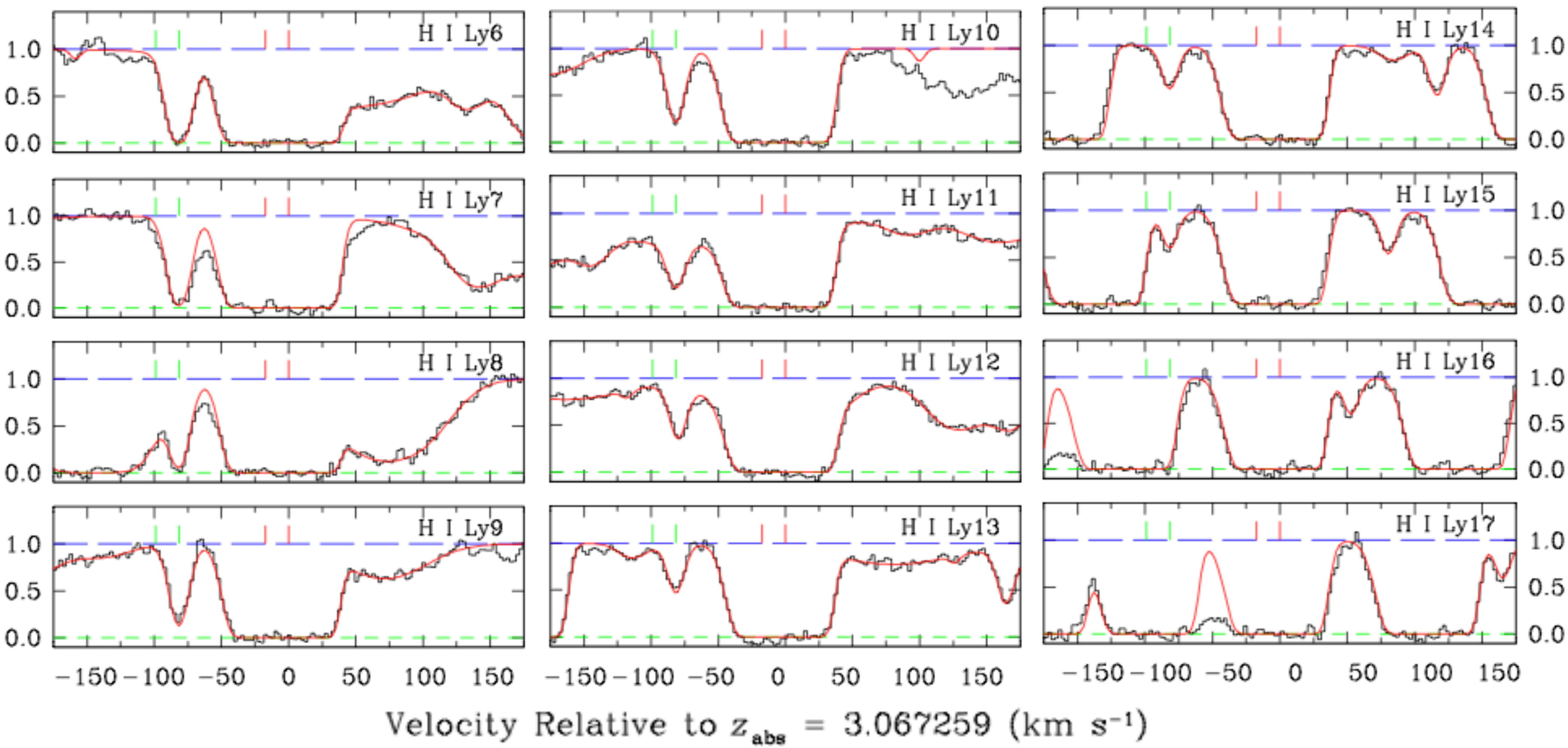
J1358+6522, z= 3.0673, Fe/H = 1/750 solar

$$N(\mathrm{H\,I}) = 3.1 \times 10^{20}\,\mathrm{cm}^{-2}$$



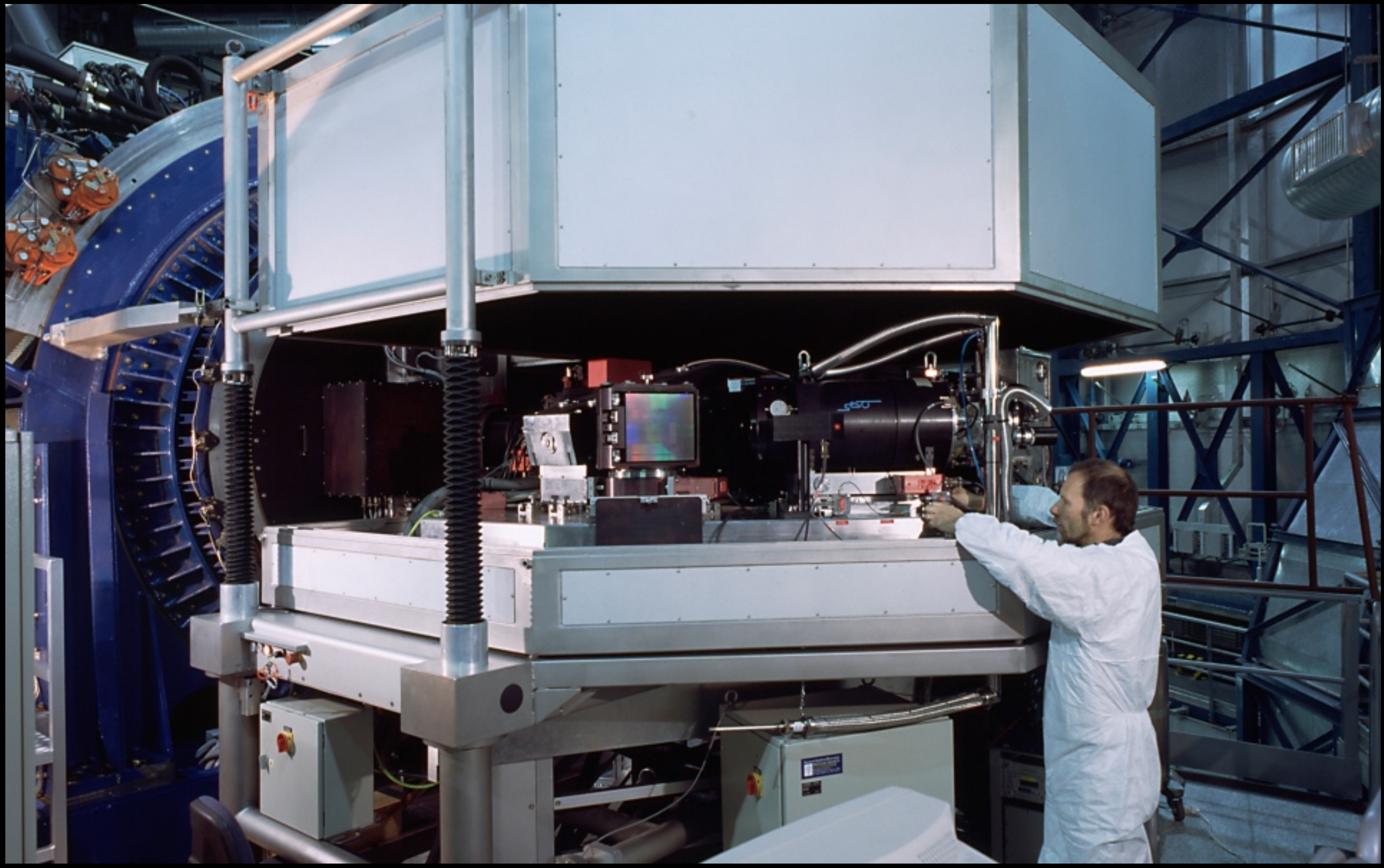
Cooke+ 2014

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

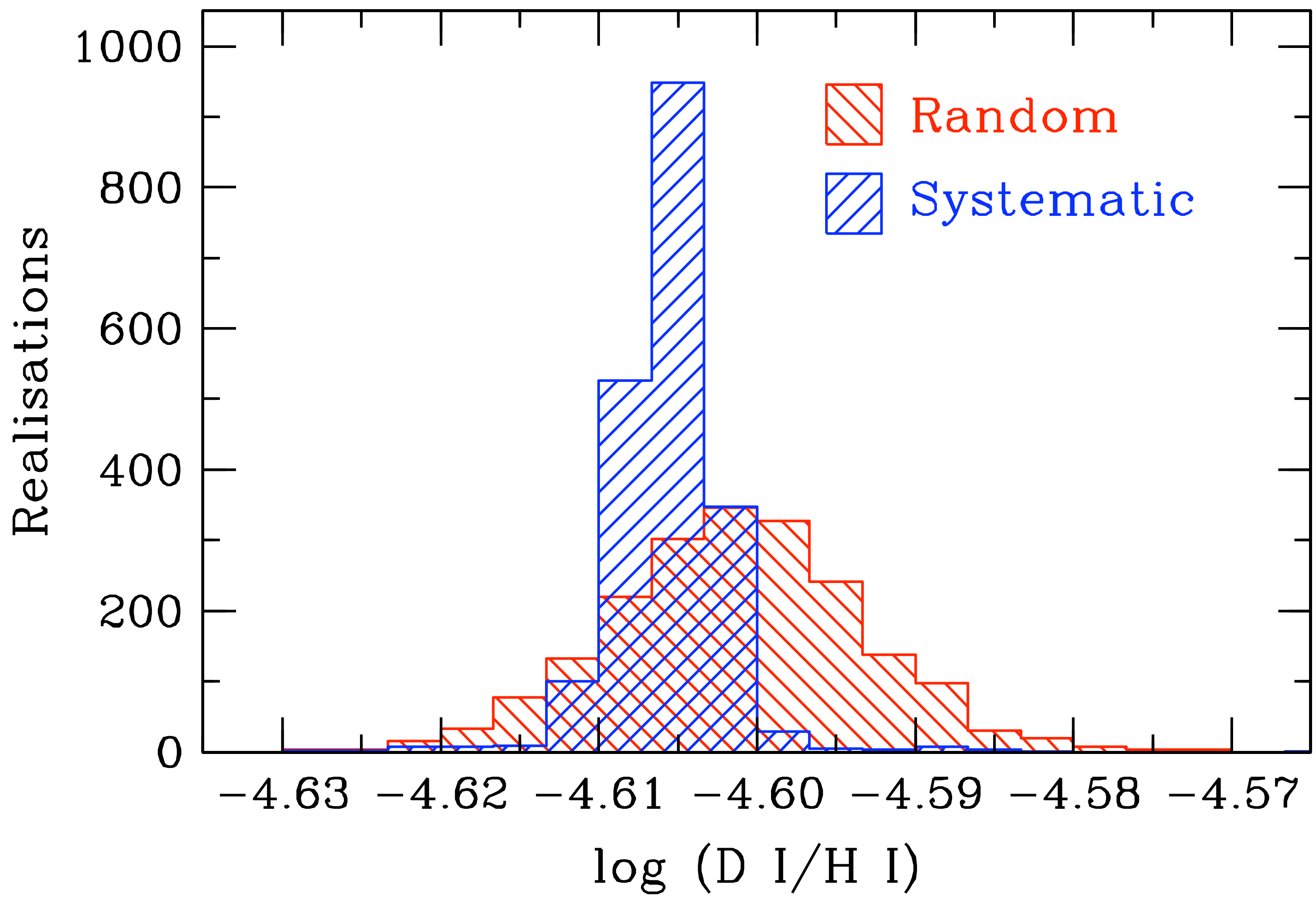


Cooke+ 2014

30,000 s
integration
with UVES
on VLT-2



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



Pettini & Cooke 2012

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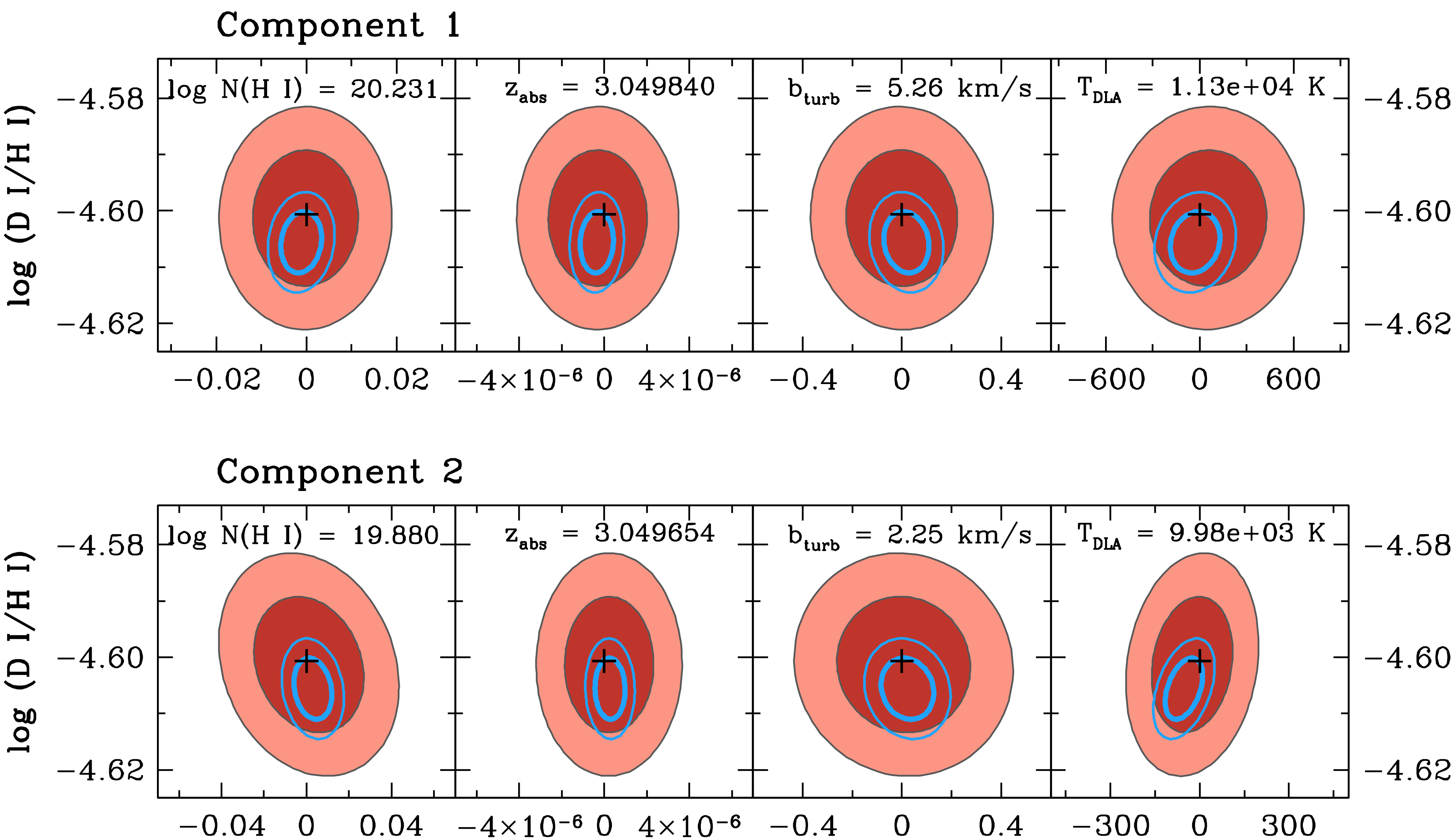
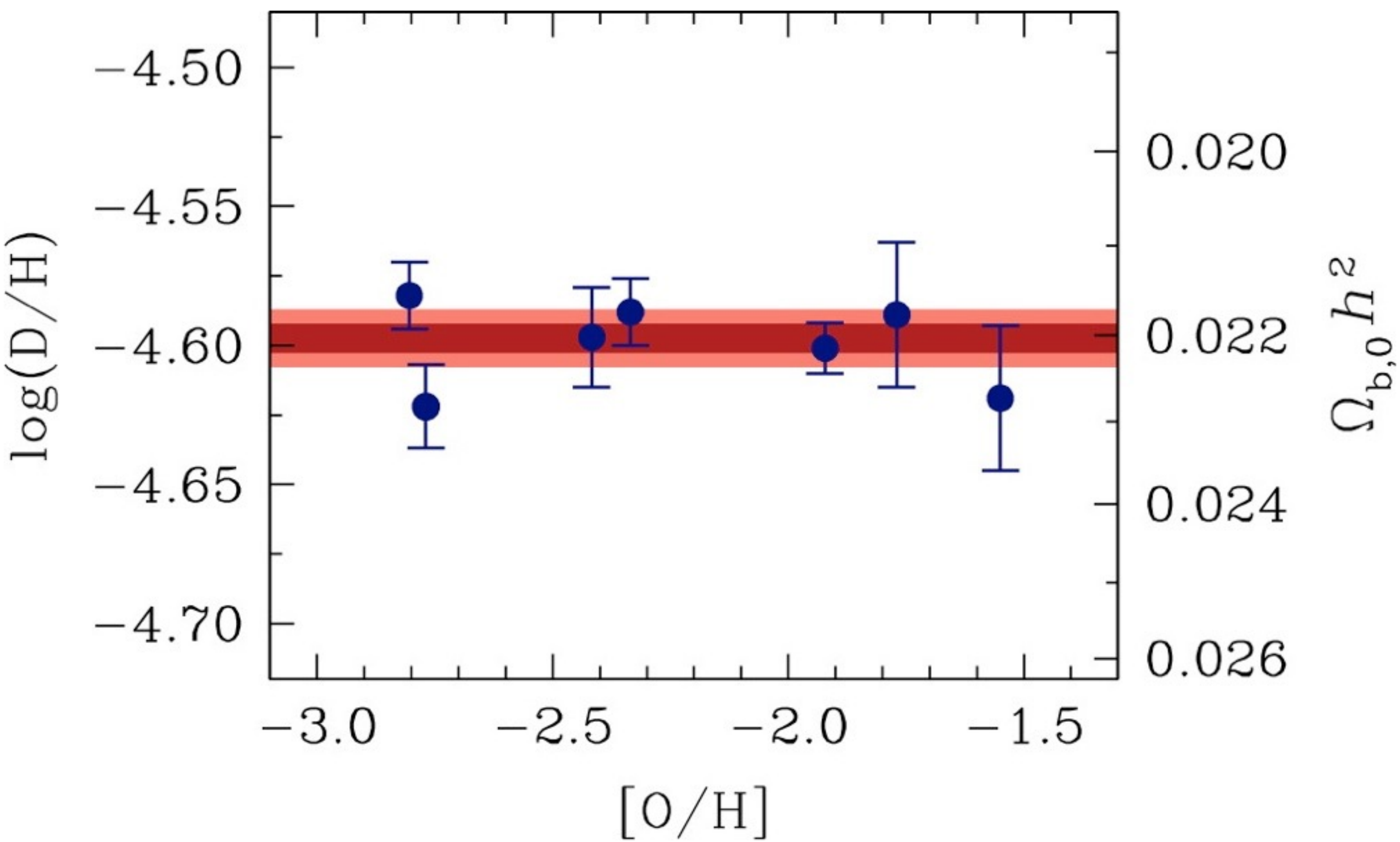
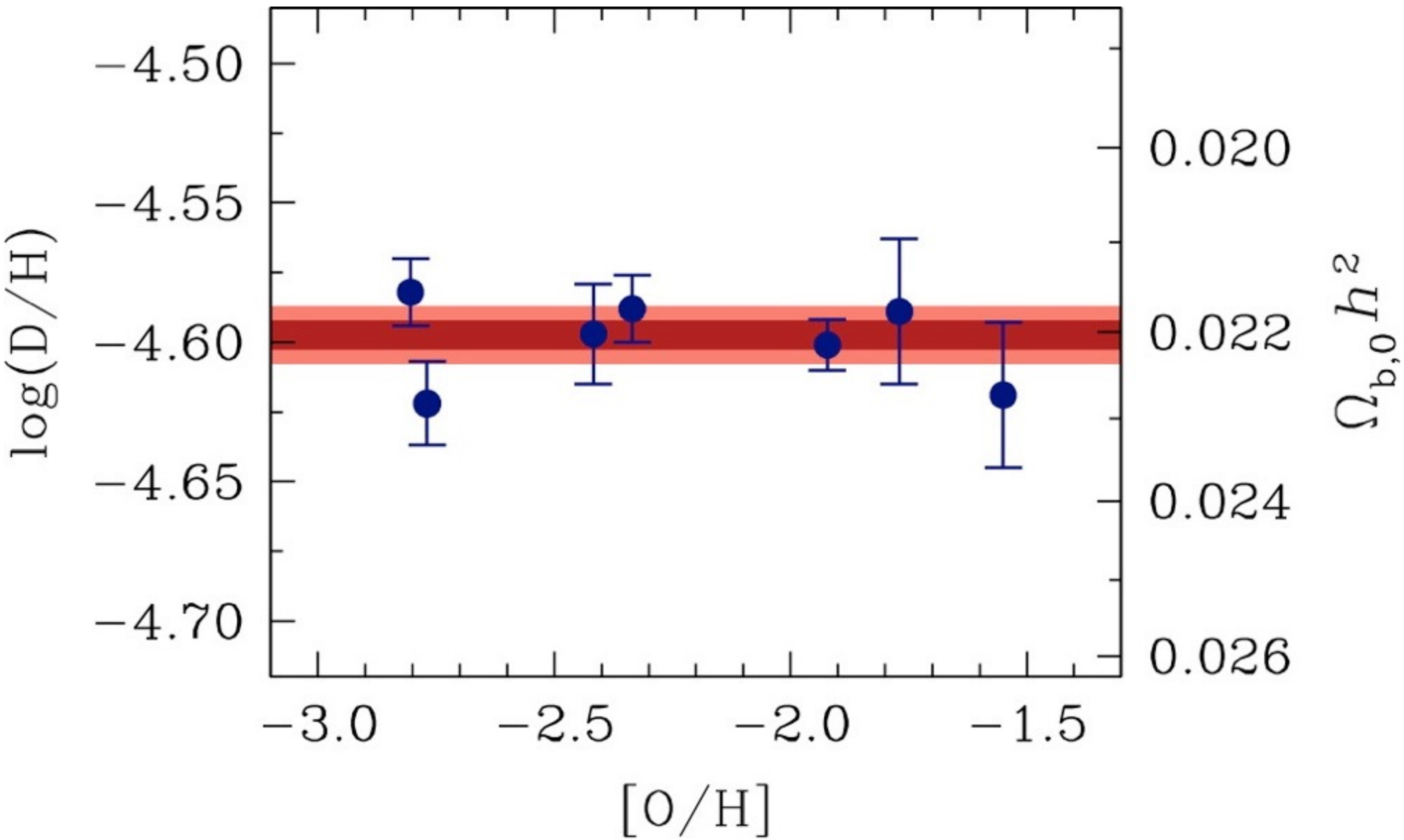


Percent Measure of (D/H) [Cooke et al. 2018]



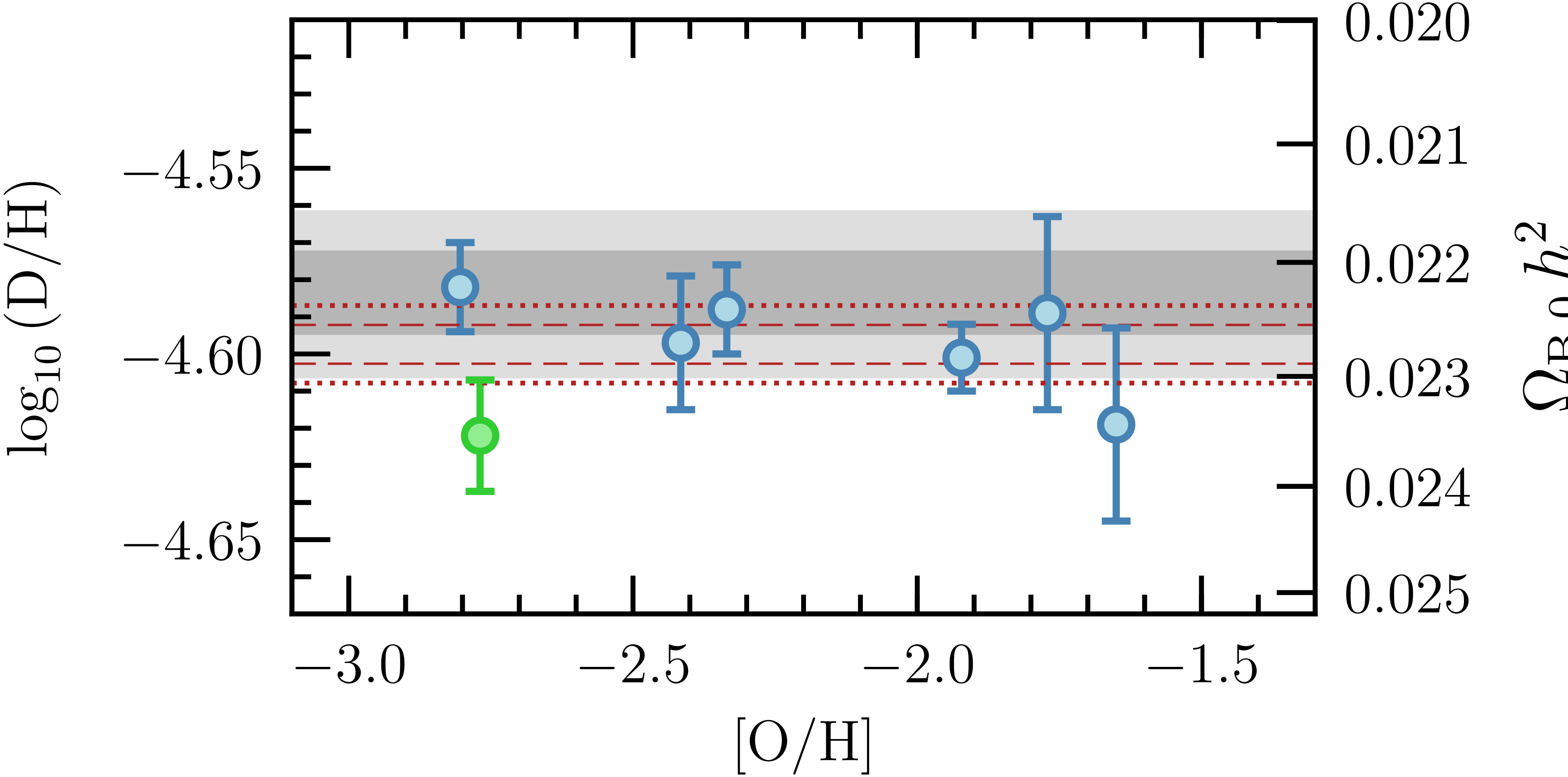
Percent Measure of (D/H) [Cooke et al. 2018]

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



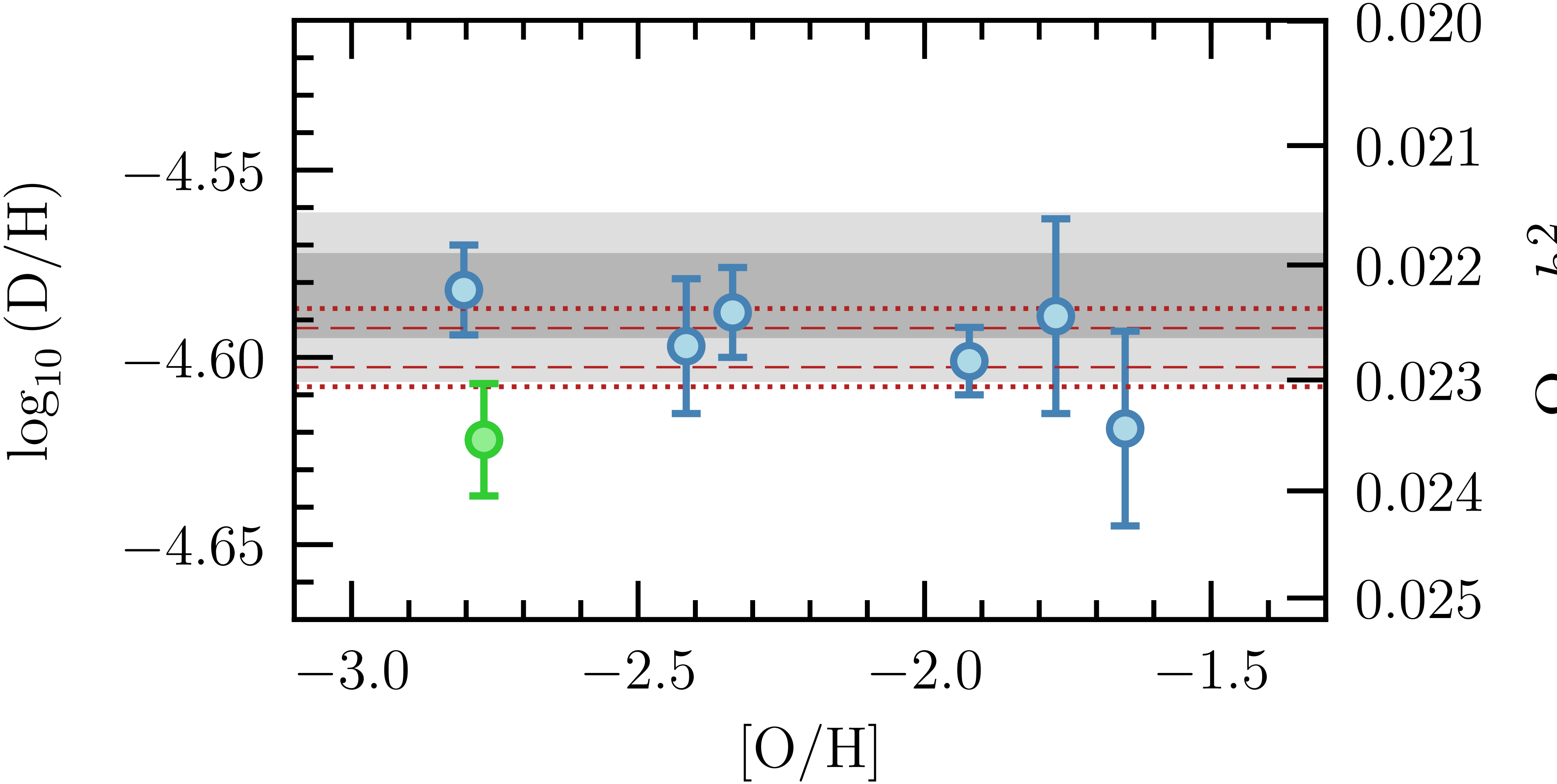
$$100\Omega_{\rm b}h^2({\rm BBN}) = 2.235 \pm 0.016 \pm 0.033$$

Cooke+ 2018



$$100\Omega_{\rm b}h^2({\rm CMB}) = 2.226 \pm 0.023$$

Planck Coll. 2015



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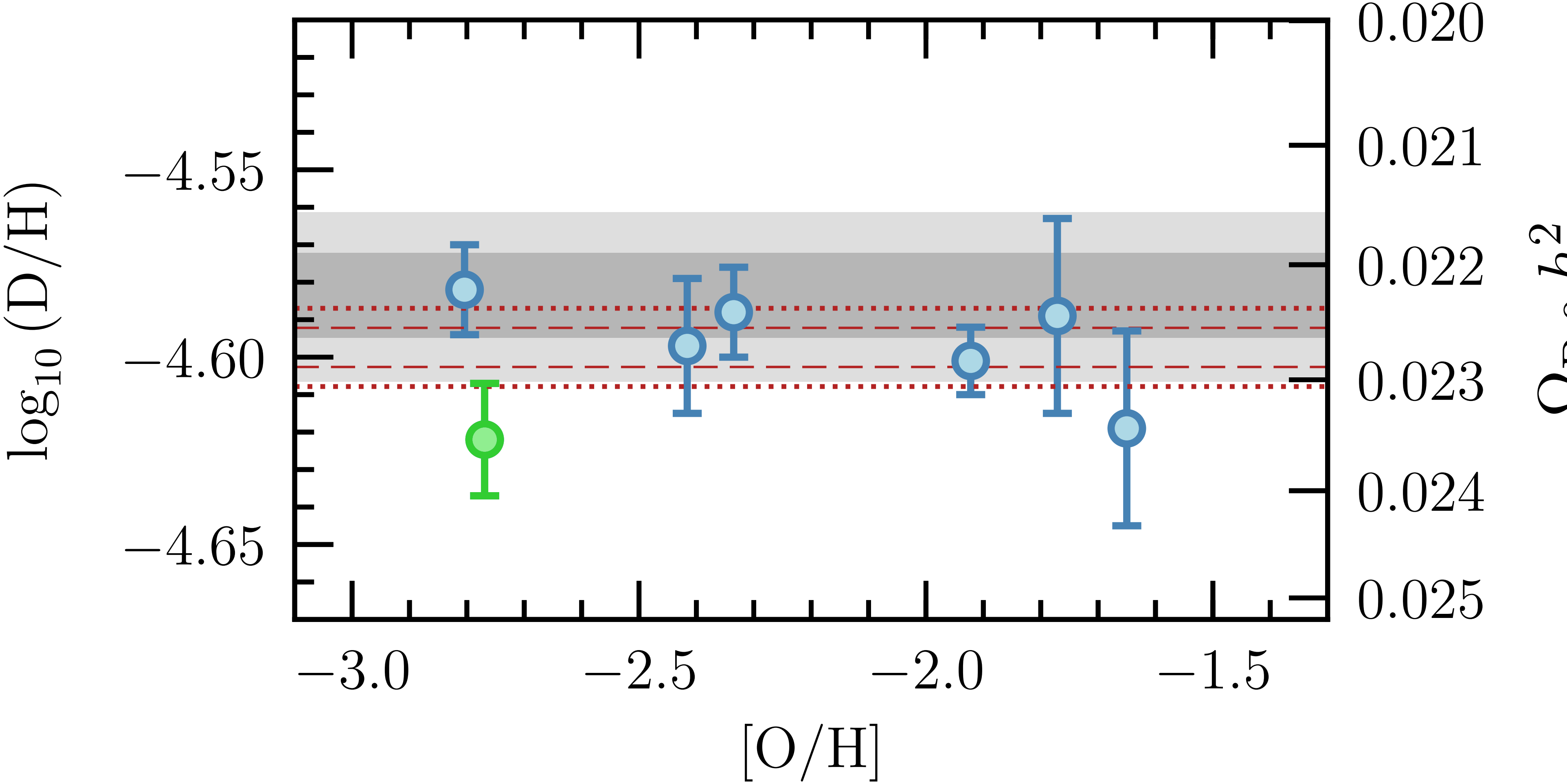
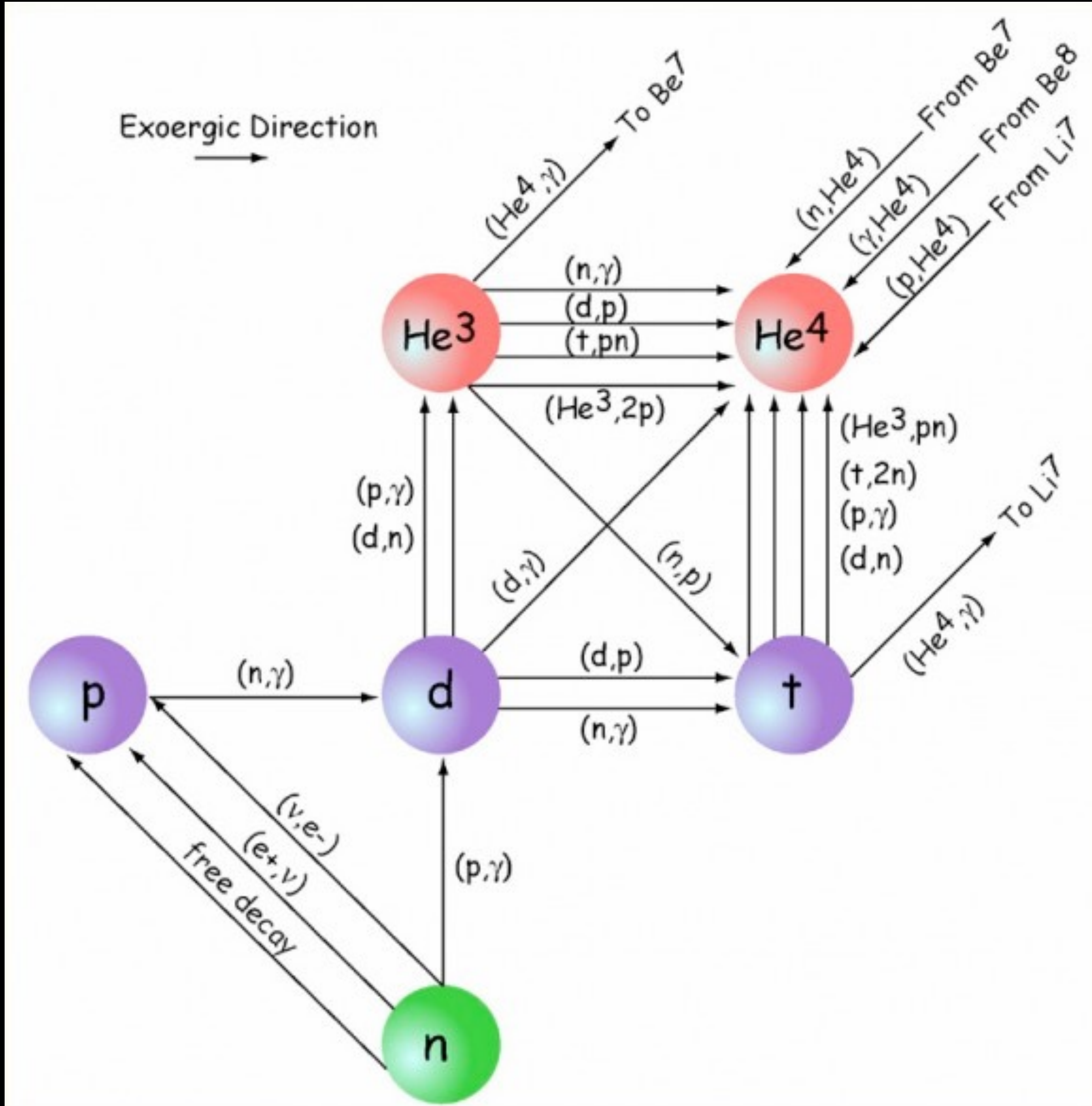
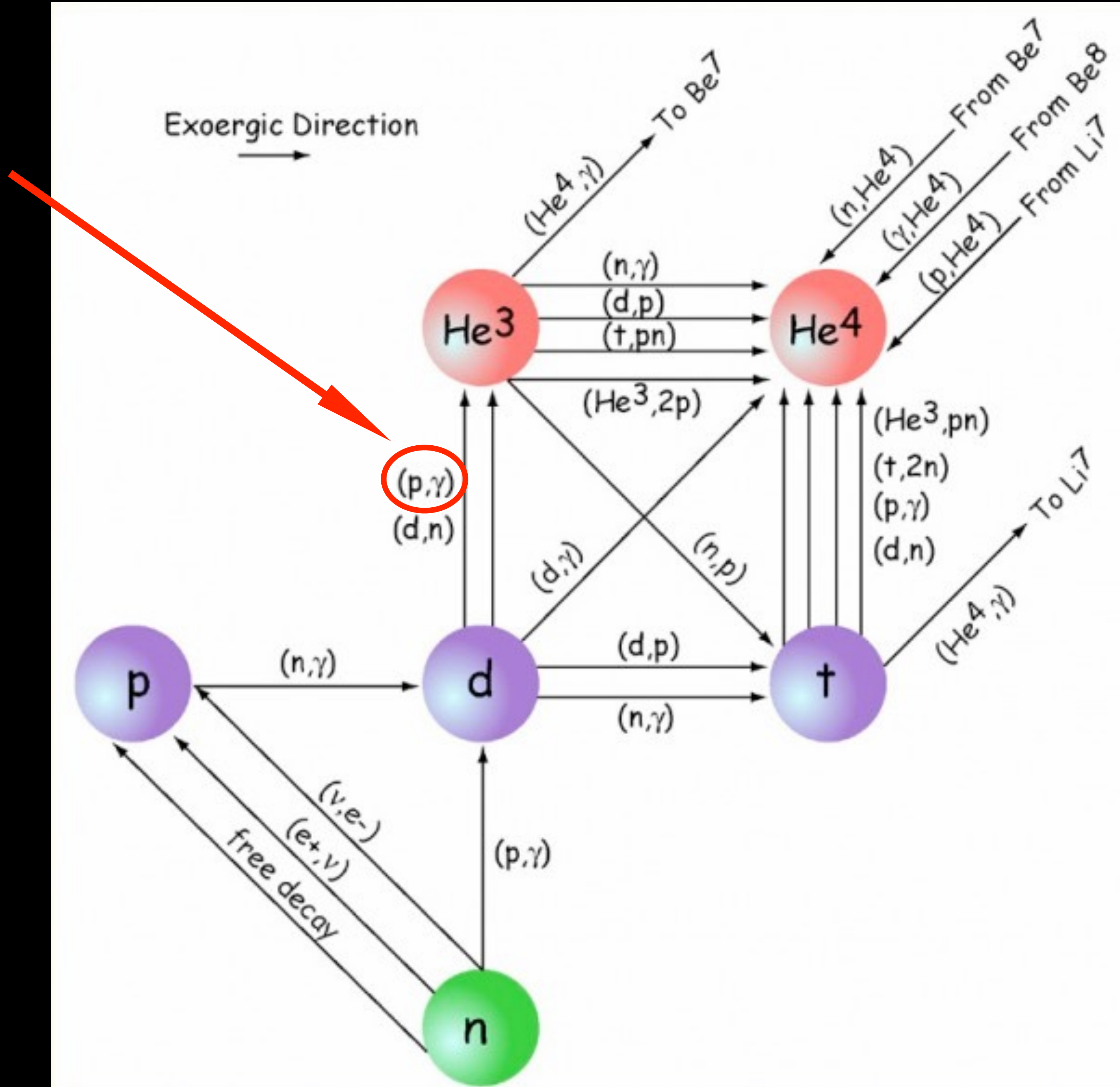
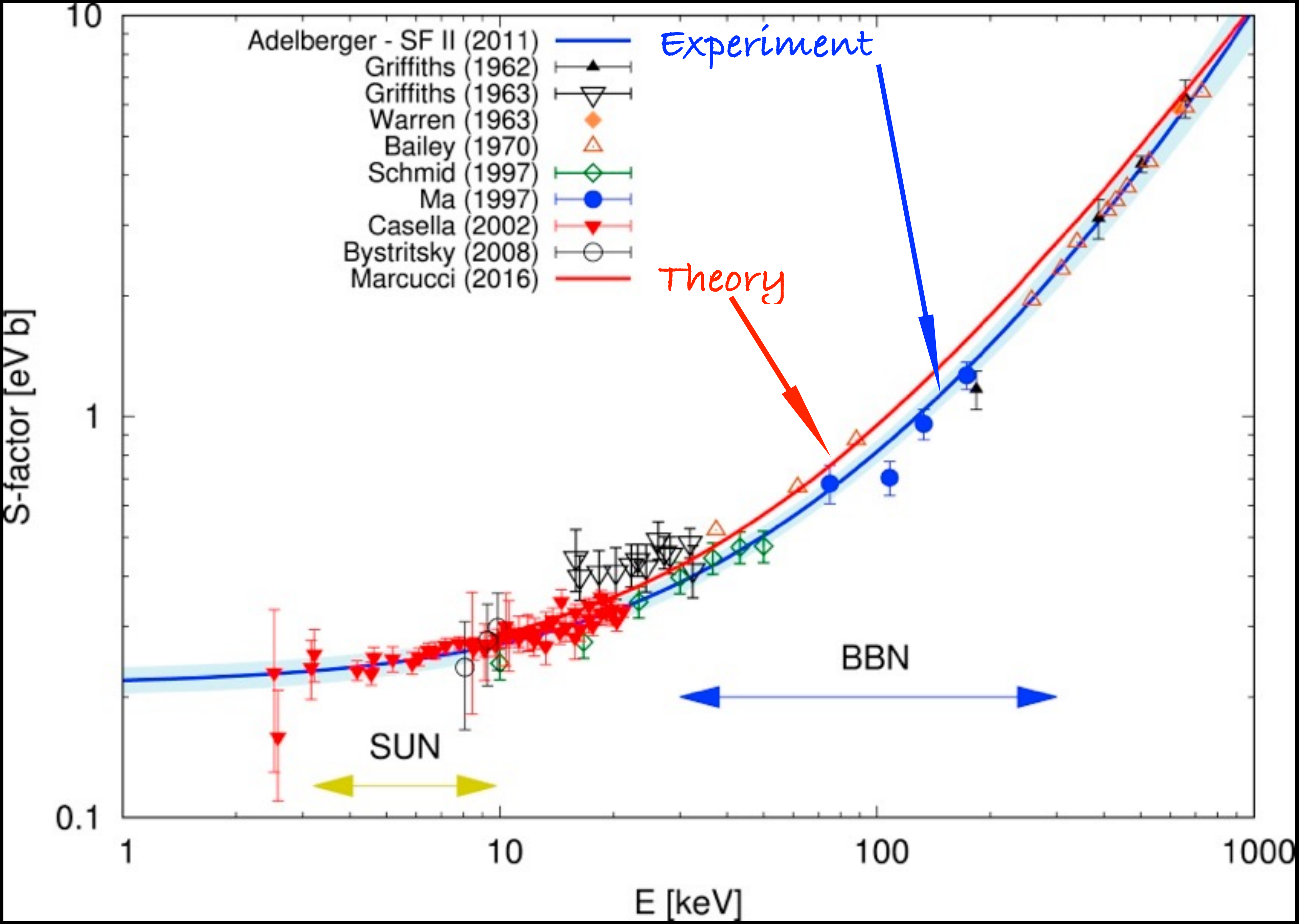




Exoergic Direction
To Be7
From Be7
From Be8
From Li7
(He4,γ)
(n,He4)
(γ,He4)
(p,He4)
He3
He4
(n,γ)
(d,p)
(t,pn)
(He3,2p)
(He3,pn)
(t,2n)
(p,γ)
(d,n)
To Li7
(p,γ)
(d,n)
(d,γ)
(n,p)
(He4,γ)
p
d
t
(n,γ)
(d,p)
(n,γ)
(ν,e-)
(e+,ν)
free decay
(p,γ)
n



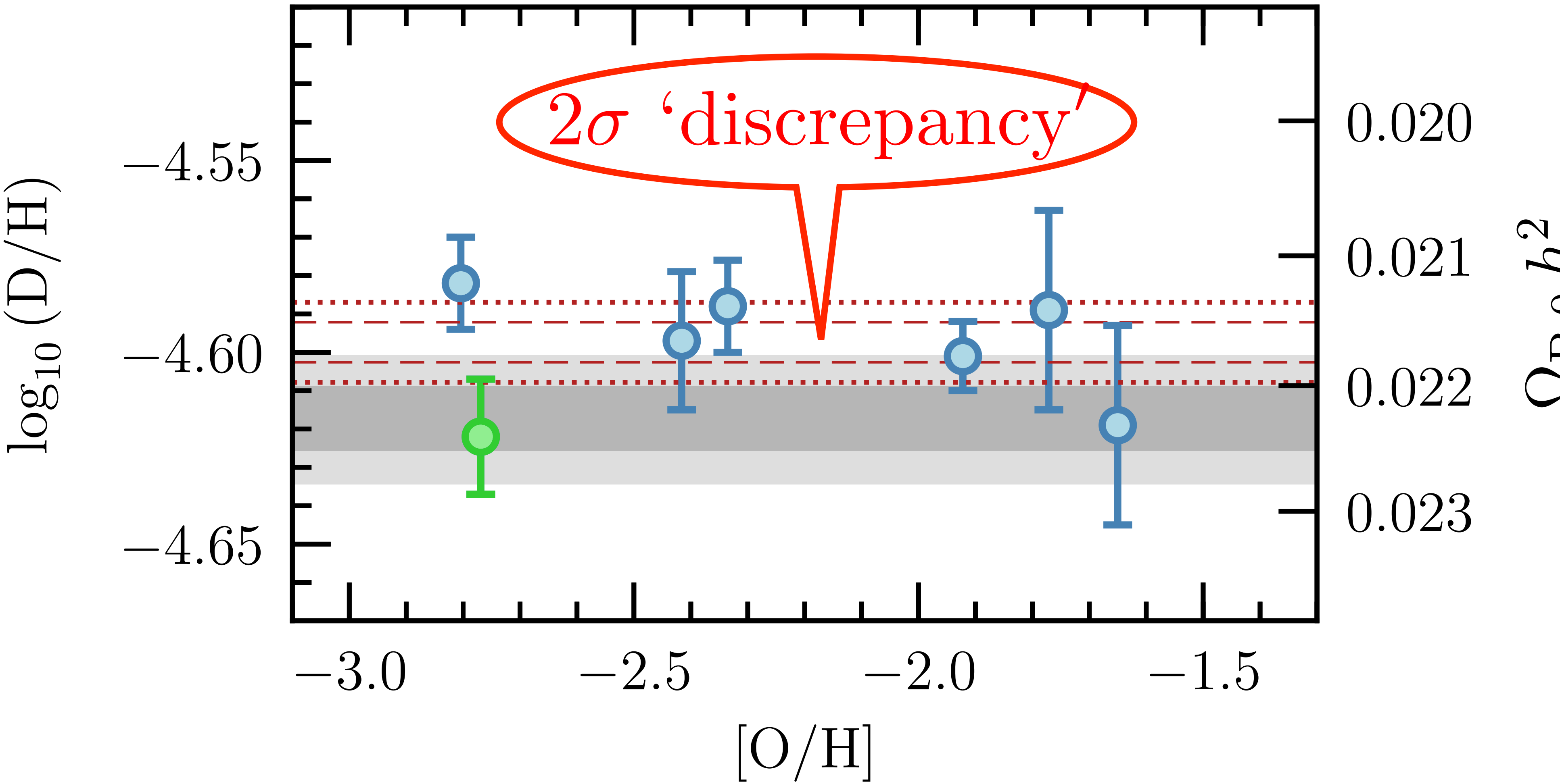
Exoergic Direction
He3
He4
p
d
t
n
(He4,γ)
To Be7
(n,He4)
From Be7
(γ,He4)
From Be8
(p,He4)
From Li7
(n,γ)
(d,p)
(t,pn)
(He3,2p)
(He3,pn)
(t,2n)
(p,γ)
(d,n)
(p,γ)
(d,n)
(d,γ)
(n,p)
(He4,γ)
To Li7
(n,γ)
(d,p)
(n,γ)
(ν,e-)
(e+,ν)
free decay
(p,γ)



Broggini+ 2018

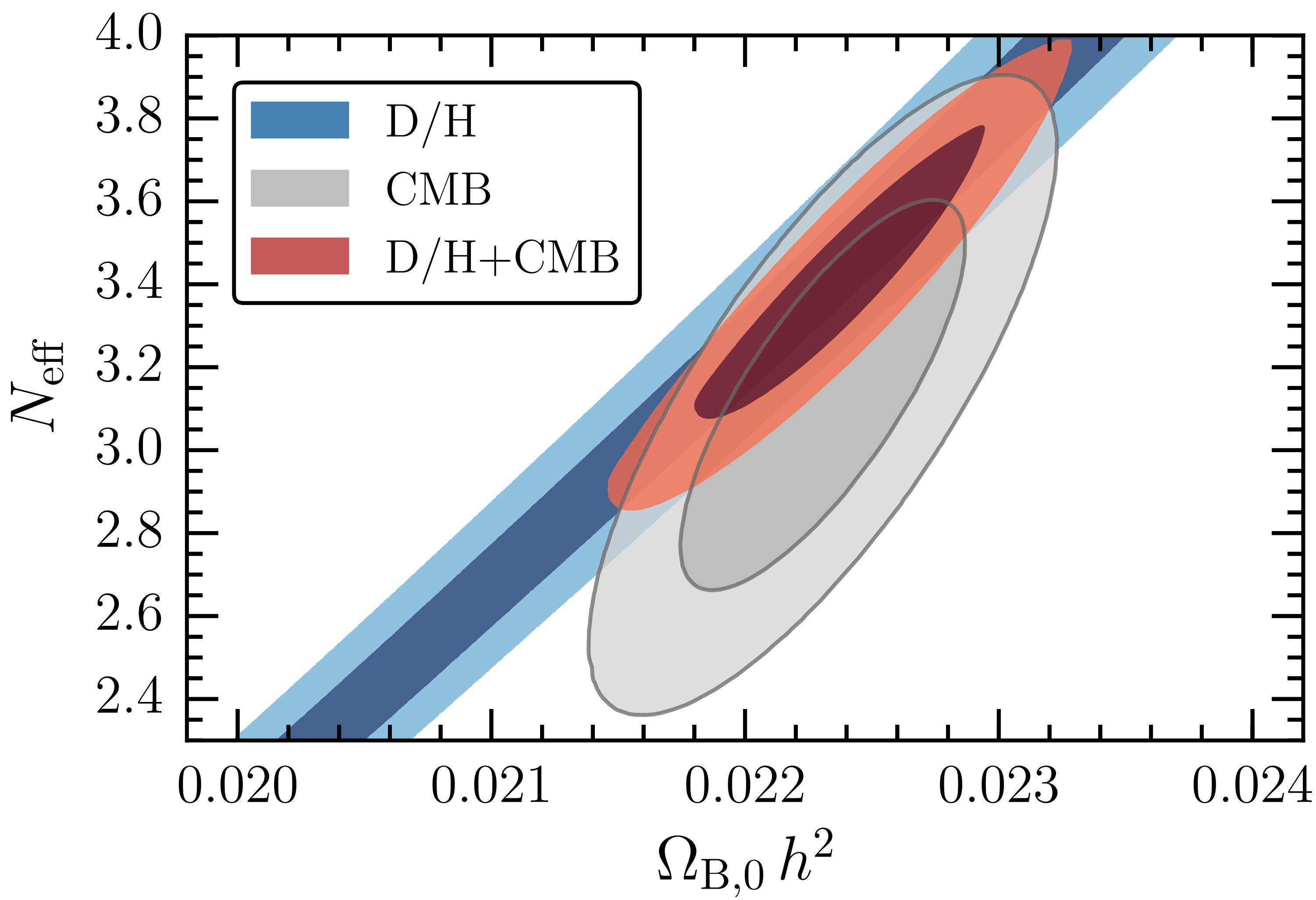
$$100\Omega_{\rm b}h^2({\rm BBN}) = 2.166 \pm 0.015 \pm 0.011$$

Cooke+ 2018



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

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



Cooke+ 2018

Looking to the future…

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

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✓ Three more metal-poor DLAs in the bag, bringing the total sample of high precision measures to 10 by the end of 2018.

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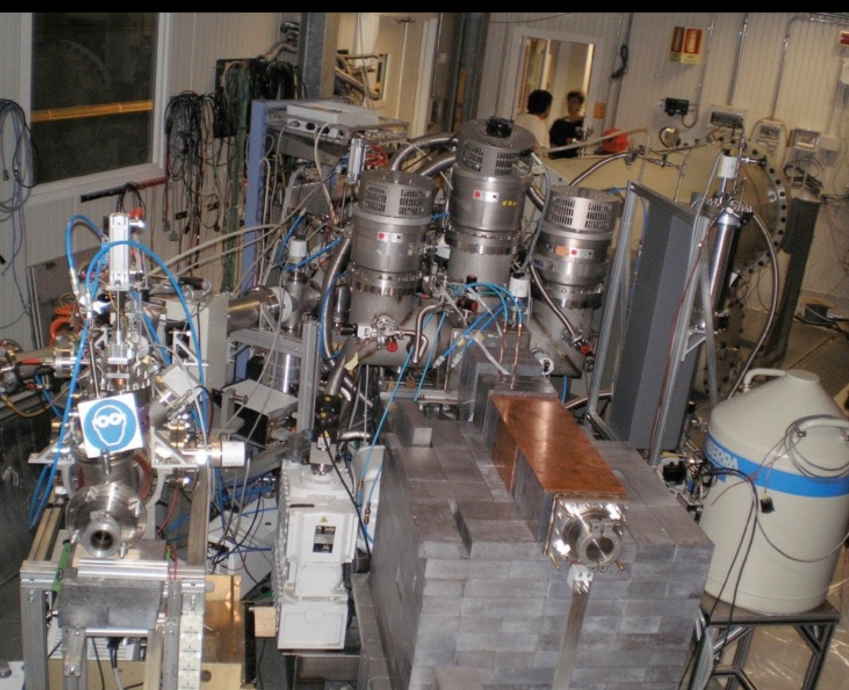
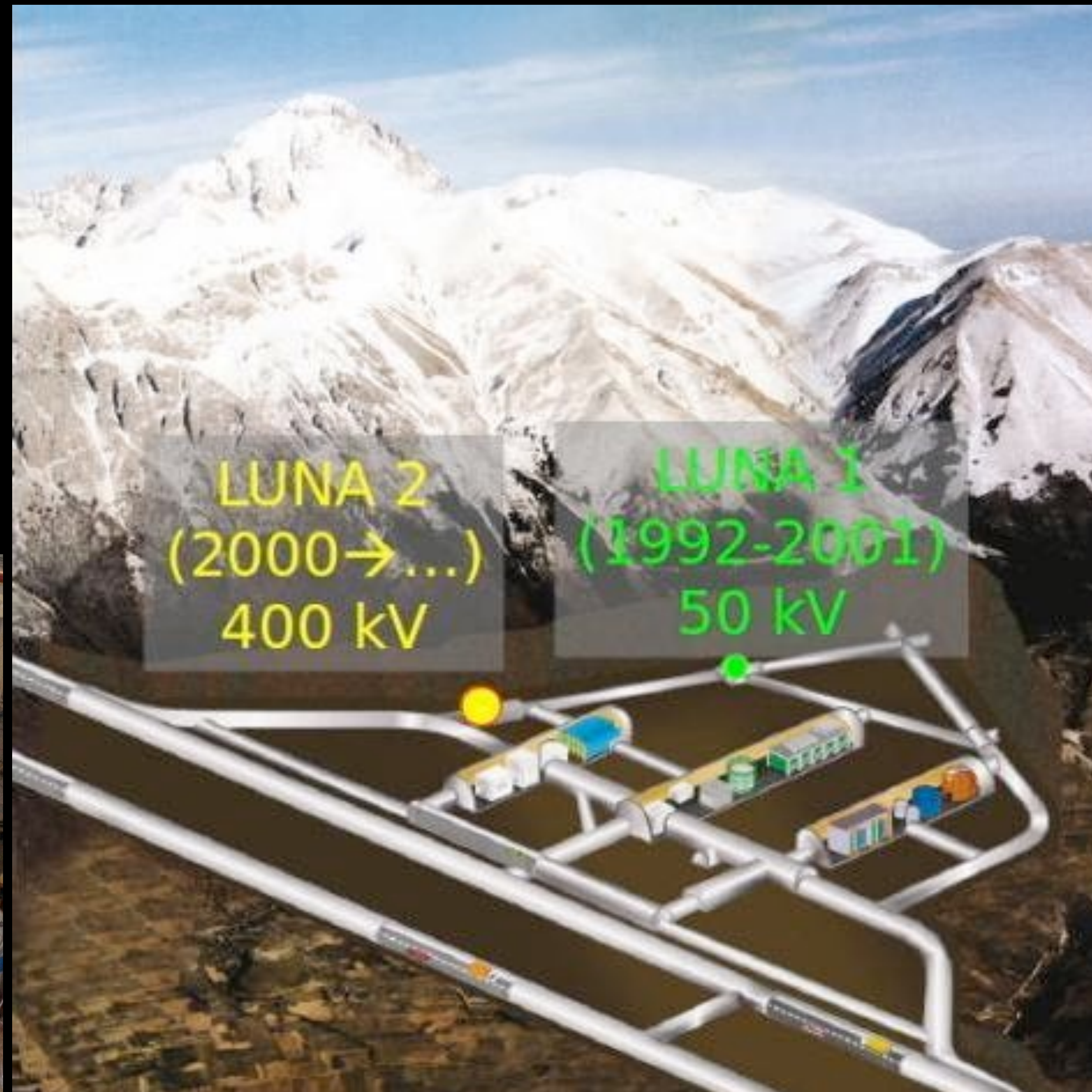
- ✓ Modern laboratory measurement of the cross-section for $^2\mathrm{H} + \mathrm{p} \rightarrow {}^3\mathrm{He} + \gamma$ by the end of 2018.

The LUNA Accelerator at Gran Sasso

Laboratory
Underground
Nuclear
Astrophysics

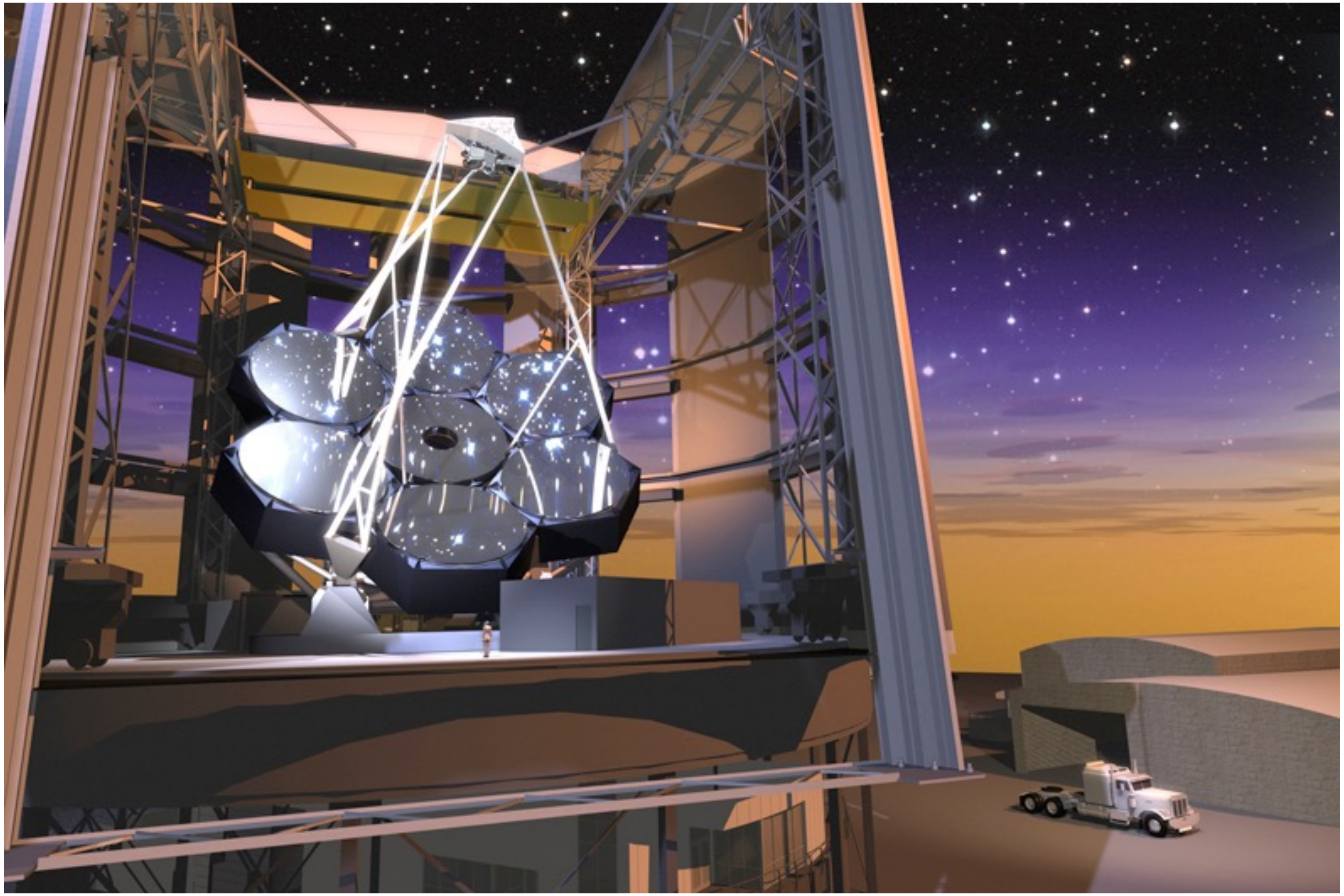




Good prospects for further improvements in the near/medium term future

- ✓ Three more metal-poor DLAs in the bag, bringing the total sample of high precision measures to 10 by the end of 2018.
- ✓ Modern laboratory measurement of the cross-section for $^{2}\mathrm{H} + \mathrm{p} \rightarrow {}^{3}\mathrm{He} + \gamma$ by the end of 2018.
- ✓ 30m telescopes in mid-2020s

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



✓ 30m telescopes in mid-2020s

Summary

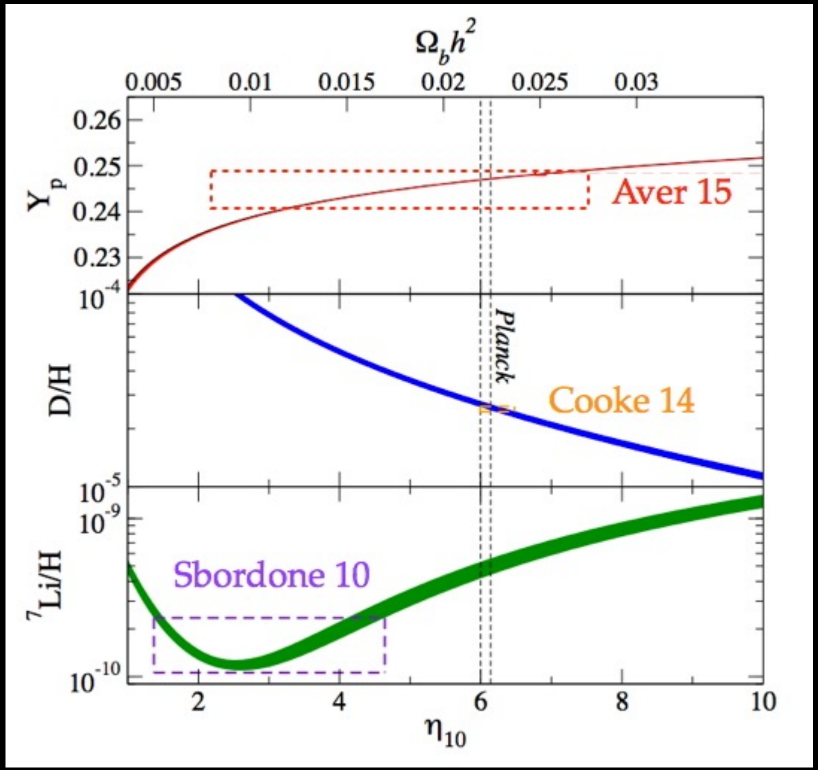
With modern astronomical instrumentation, we can now verify experimentally the framework of Big-Bang nucleosynthesis which has its origin in ideas first put forward in the 1950s

Herman Gamow Alpher

Hayashi

BBN

CMB



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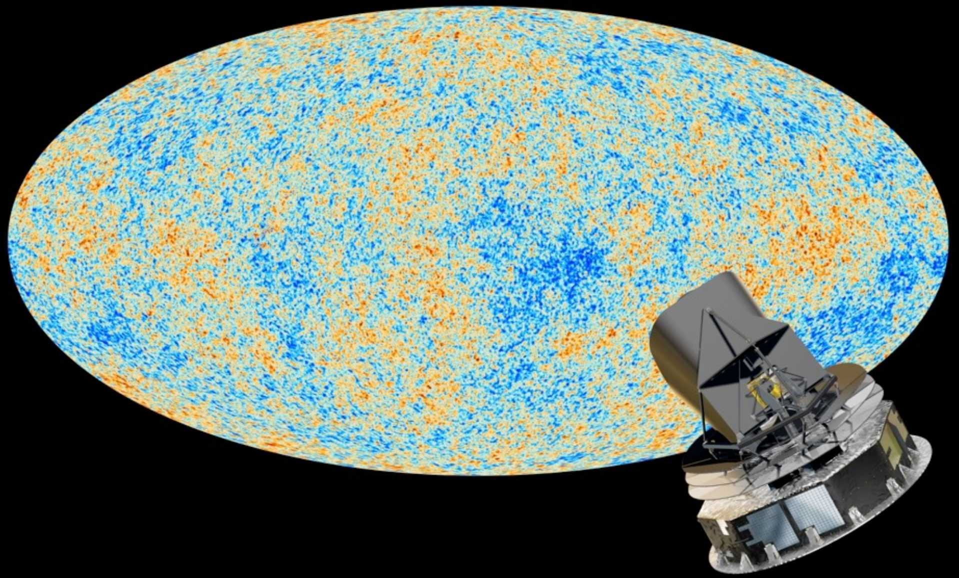
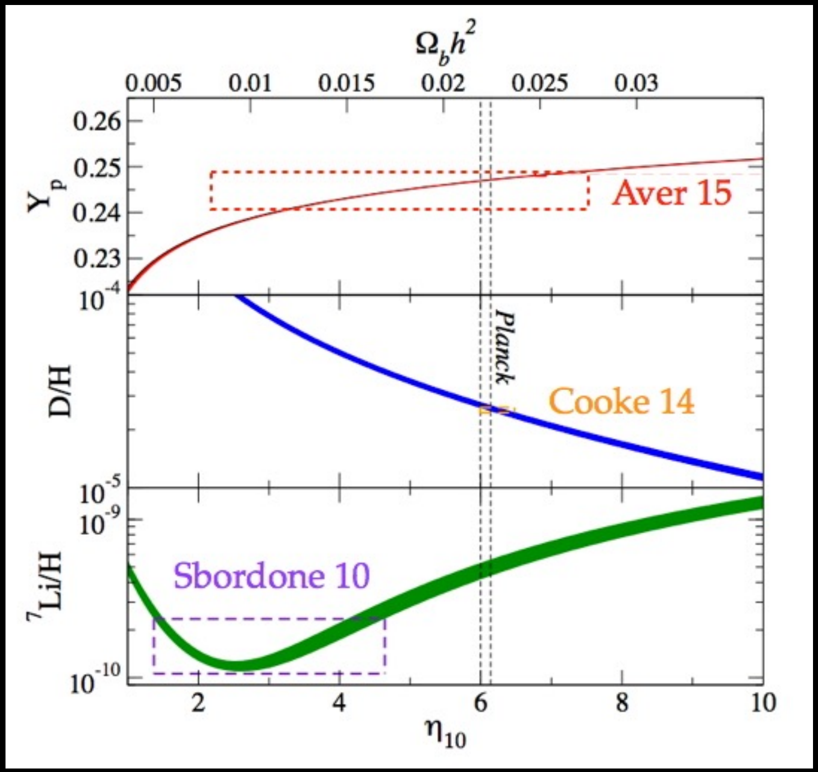


= New Physics?

BBN

CMB



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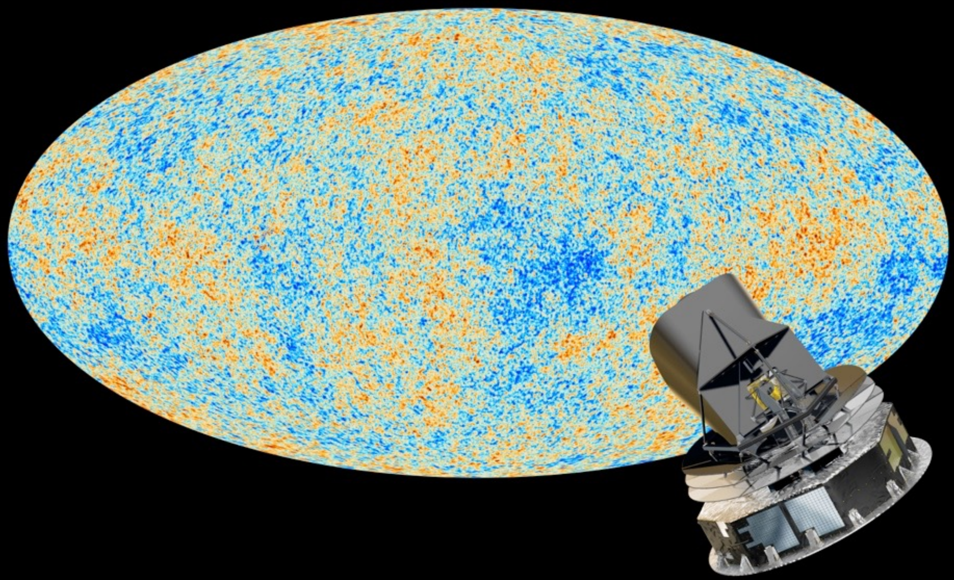

= New Physics? Not yet...