Radiation mechanisms of astrophysical objects: classics today

A scientific meeting in honour of 100th anniversary of V.V. Sobolev

Saint-Petersburg State University, 21-25 September, 2015

Molecular hydrogen absorption systems at high redshifts

S.A. Balashev, D.A. Varshalovich, A.V. Ivanchik, V.V. Klimenko

Ioffe Physical-Technical Institute

25 September 2015

Overview

1. Introduction

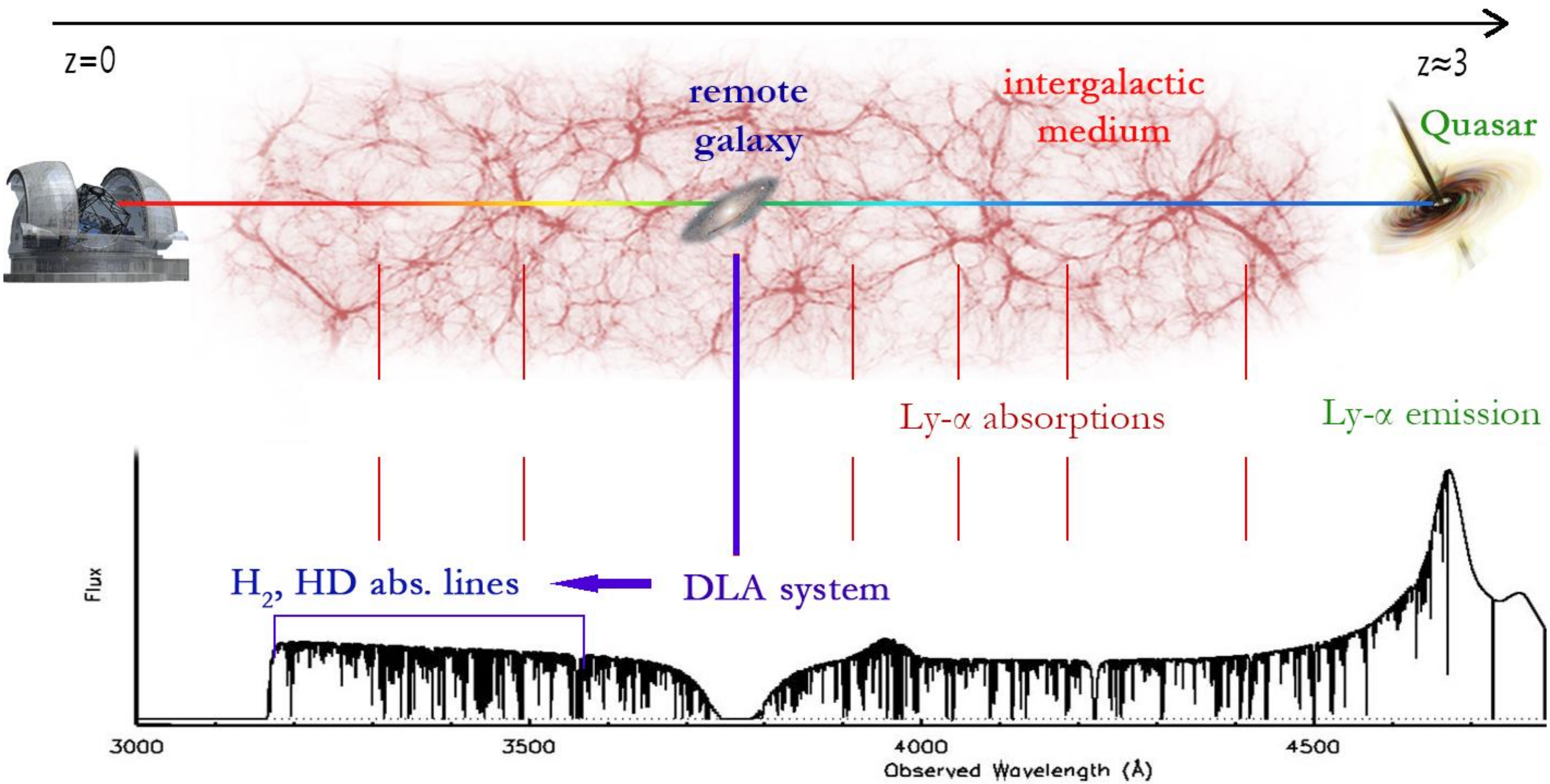
2. Physical conditions in H_2 absorption systems
   - Temperature
   - Number density
   - Metallicity
   - Associated HD. D/H ratio
   - Associated CO. T_{CMB}
   - ….

3. Search of H_2 in SDSS

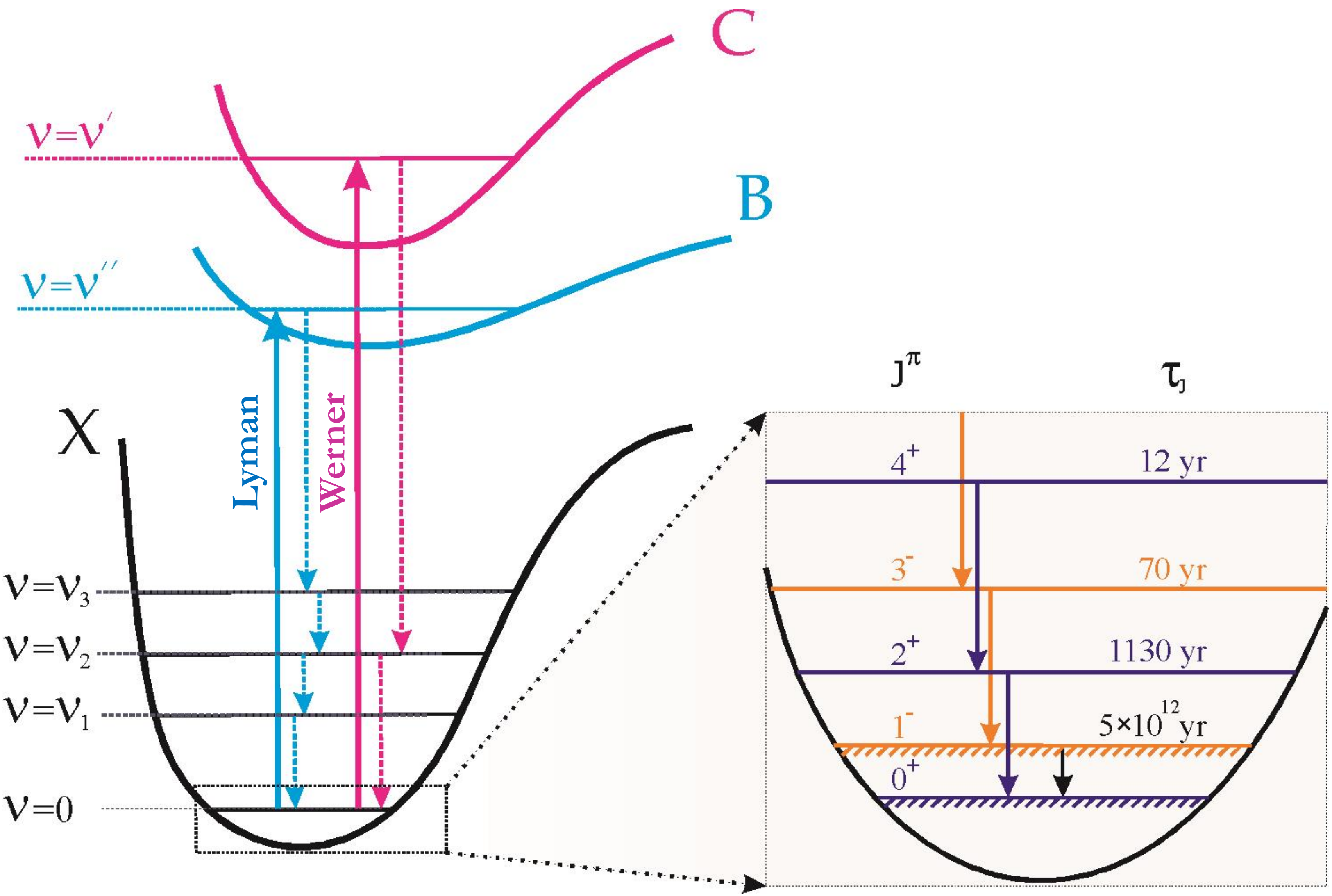
4. H_2 in J0843+0221

Introduction

Analysis of absorption systems in quasar spectra is the power tool to study the intergalactic and interstellar medium



H_2 at high redshifts. How to detect?



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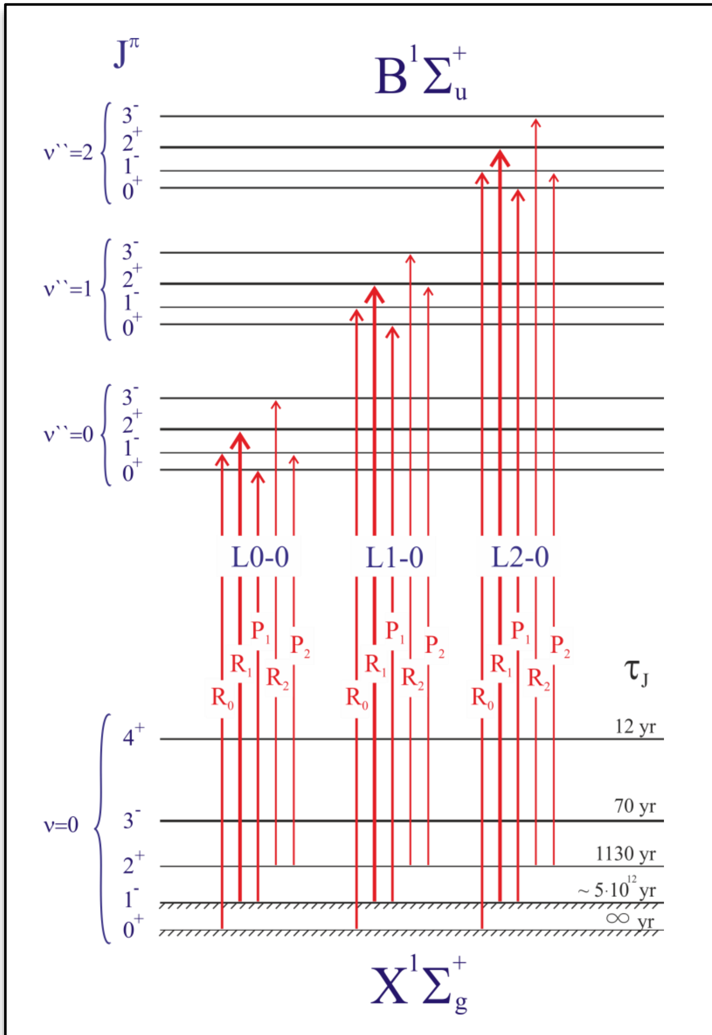
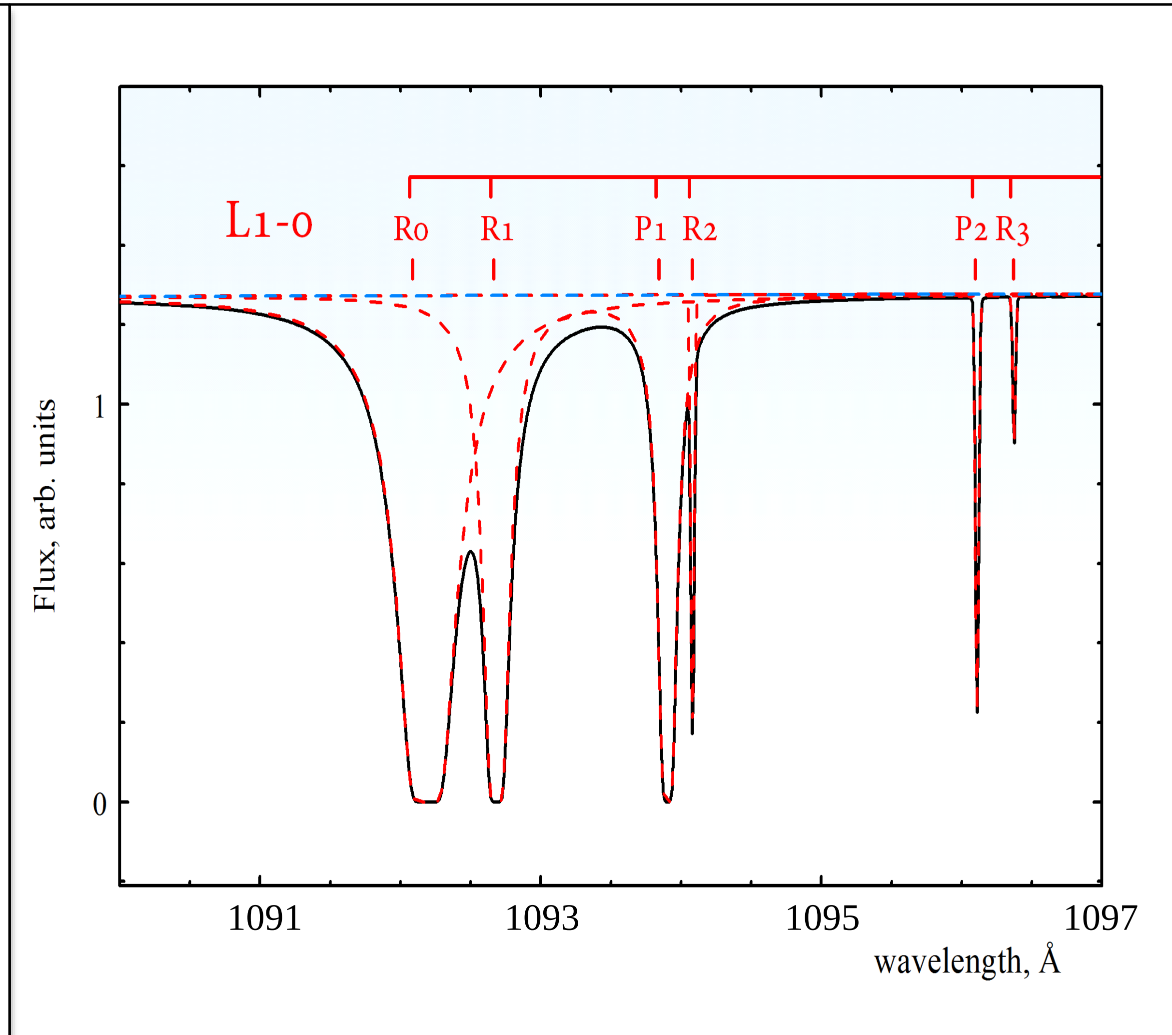




H_2 at high redshift. How to detect?

Lyman and Werner bands of H_2: **λ<1100Å** $\times(1+z)$ ⇨ Optical telescope $z > 2$

First identification of H_2 at high redshift was in 1985 (Levshakov & Varshalovich).

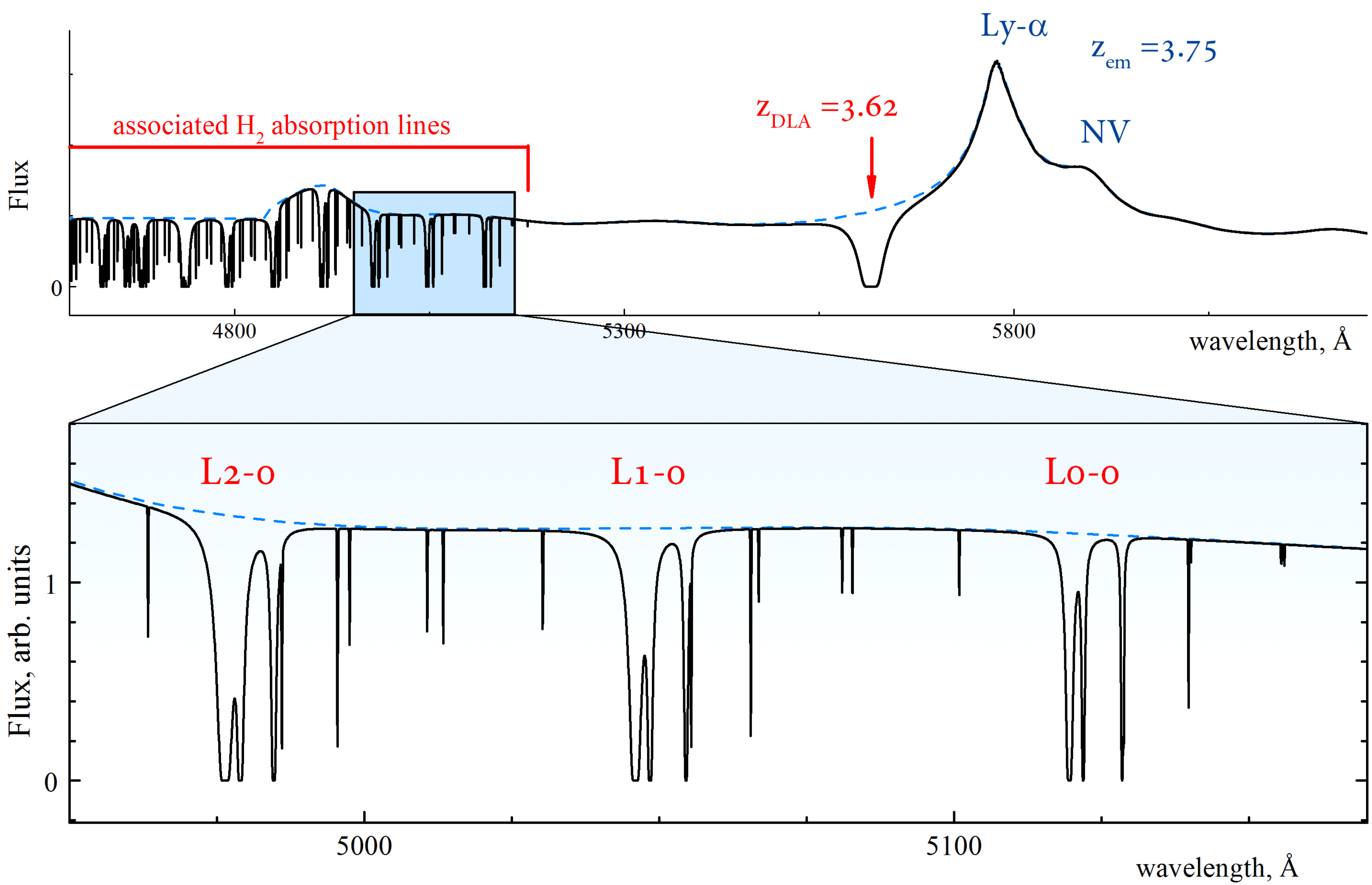
For detection and analysis of H_2 absorption system we need high S/N and resolution spectra

⇨

VLT (UVES)

KECK (HIRES)

H_2 at high redshifts. How to detect?



Simulated spectrum of H_2 absorption system at z=3.62, how it will seen in quasar spectrum

H_2 at high redshifts. Some statistics

Till now only **30** H_2 absorption systems at high z were detected.

However, in the local Universe we see H_2 very frequently:

- In **90 %** cases in Milky Way (in 65 out of 73 spectra of extragalactic source perpendicular to Galaxy plain, Wakker et al. 2006)
- In **67 %** cases in Magellanic clouds (52 % LMC and 92 % SMC, Tumlinson et al. 2002)

This is the result of three factors:

1. Quasars are **faint objects** therefore >8m telescopes are necessary to obtain high resolution spectrum

2. Only in **<10 %** of DLA systems H_2 is identified (Noterdaeme et al. 2008, Balashev et al 2014, Jorgenson et al. 2014)

3. Search of H_2 at high redshifts is the **"blind search"**

H_2 at high redshift. Physical conditions

H_2 absorption systems represent **cold (T~40-200 K)** and **dense (n~10-100 см$^{-3}$)** phase of interstellar medium

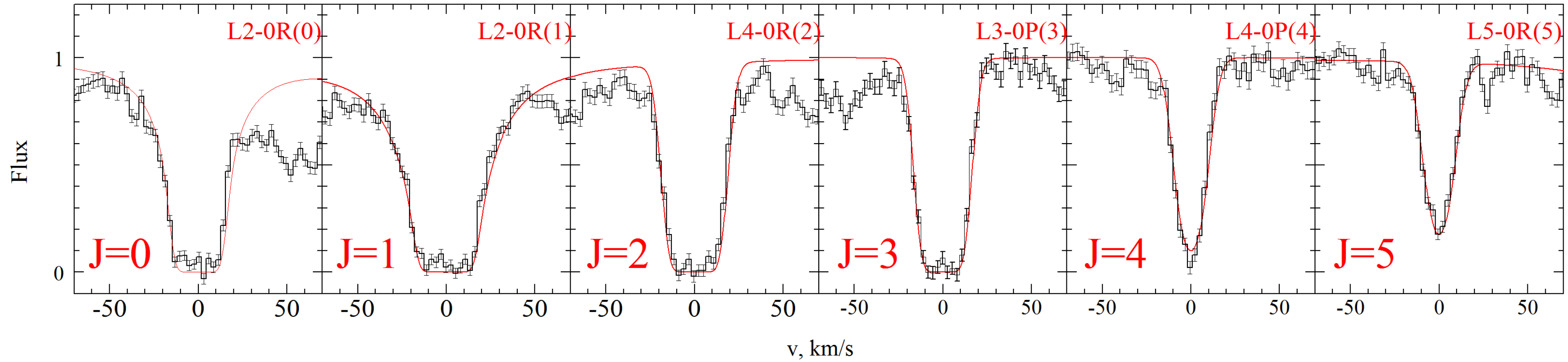
To derive physical conditions one need to study H_2 and associated species

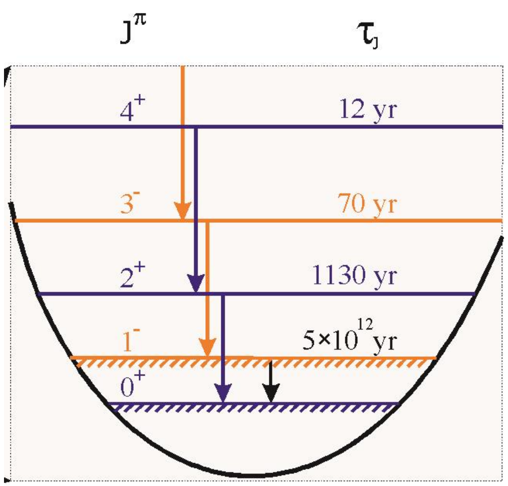
1. Population of H_2 rotational levels
2. Neutral chlorine – Cl I
3. Neutral carbon – C I
4. Dust extinction
5. HD molecules
6. CO molecules

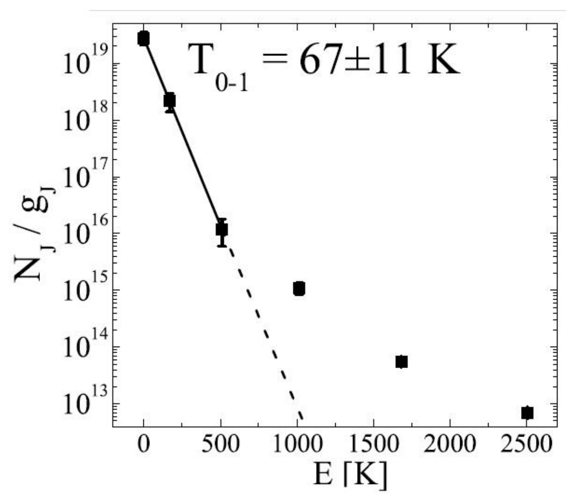
   CO are detected very rarely → H_2 absorption systems correspond to "Dark" molecular gas (i.e. gas which is not traced by CO)

H_2 rotational levels. Kinetic temperature

Relative population of lower H_2 rotational levels are used to constrain kinetic temperature





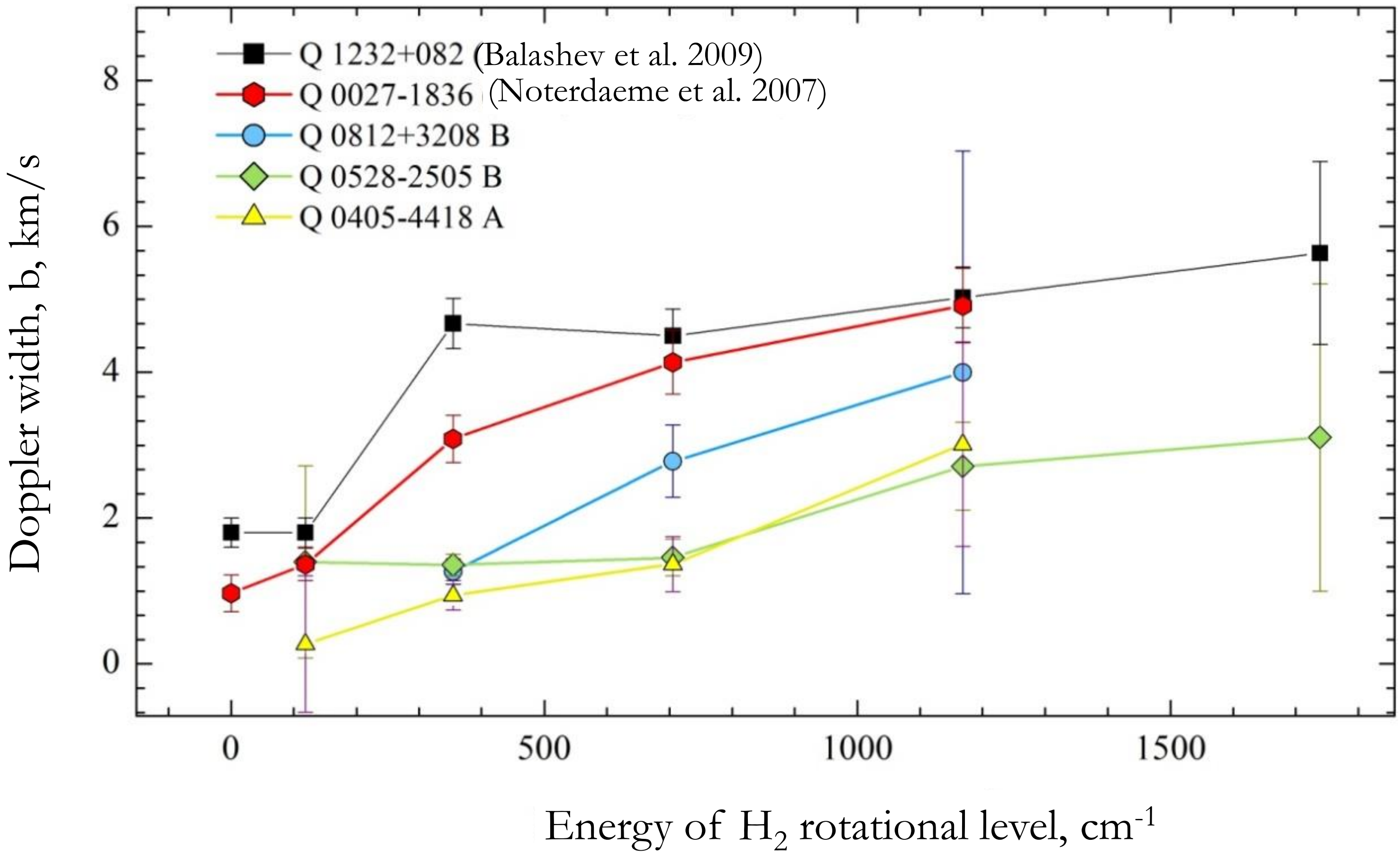


e.g. Ivanchik et al., 2010

H_2 rotational levels. Broadening effect

In some H_2 absorption systems "broadening effect" is revealed – the increase of velocity distribution width with increase of H_2 rotational level, J.

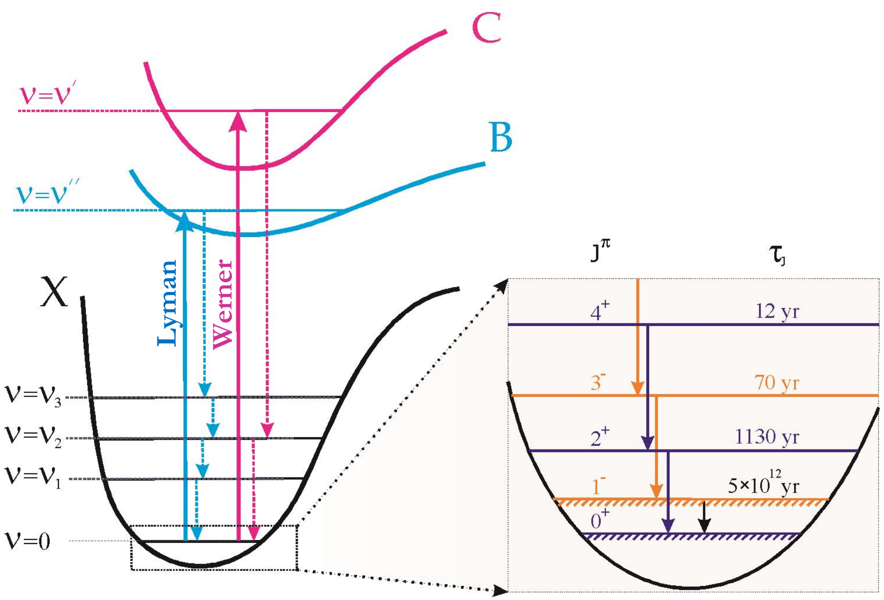
This effect was observed in H_2 abs. systems in local Universe (e.g. Lacour et al. 2005) as well as at high redshifts



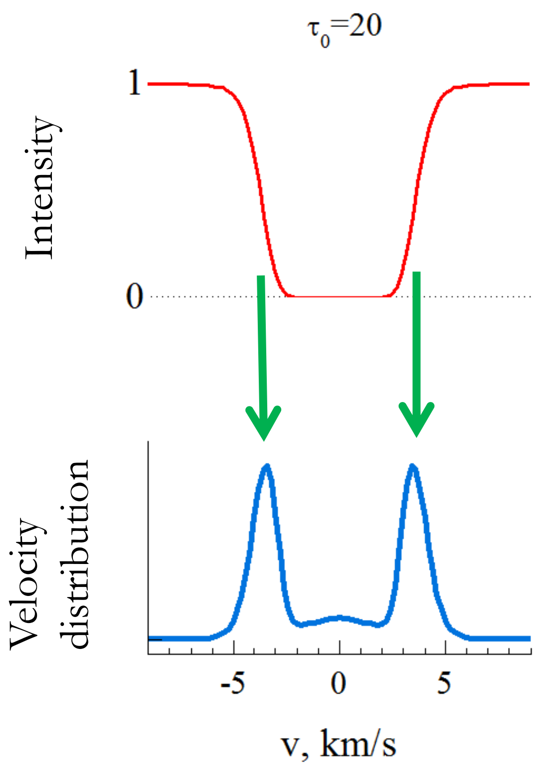
H_2 rotational levels. Broadening effect

We propose the explanation of this effect concerned with radiative transfer in H_2 lines.

Excited levels of H_2 ($J \geq 2$) are populated by radiative pumping in lines of Lyman and Werner band

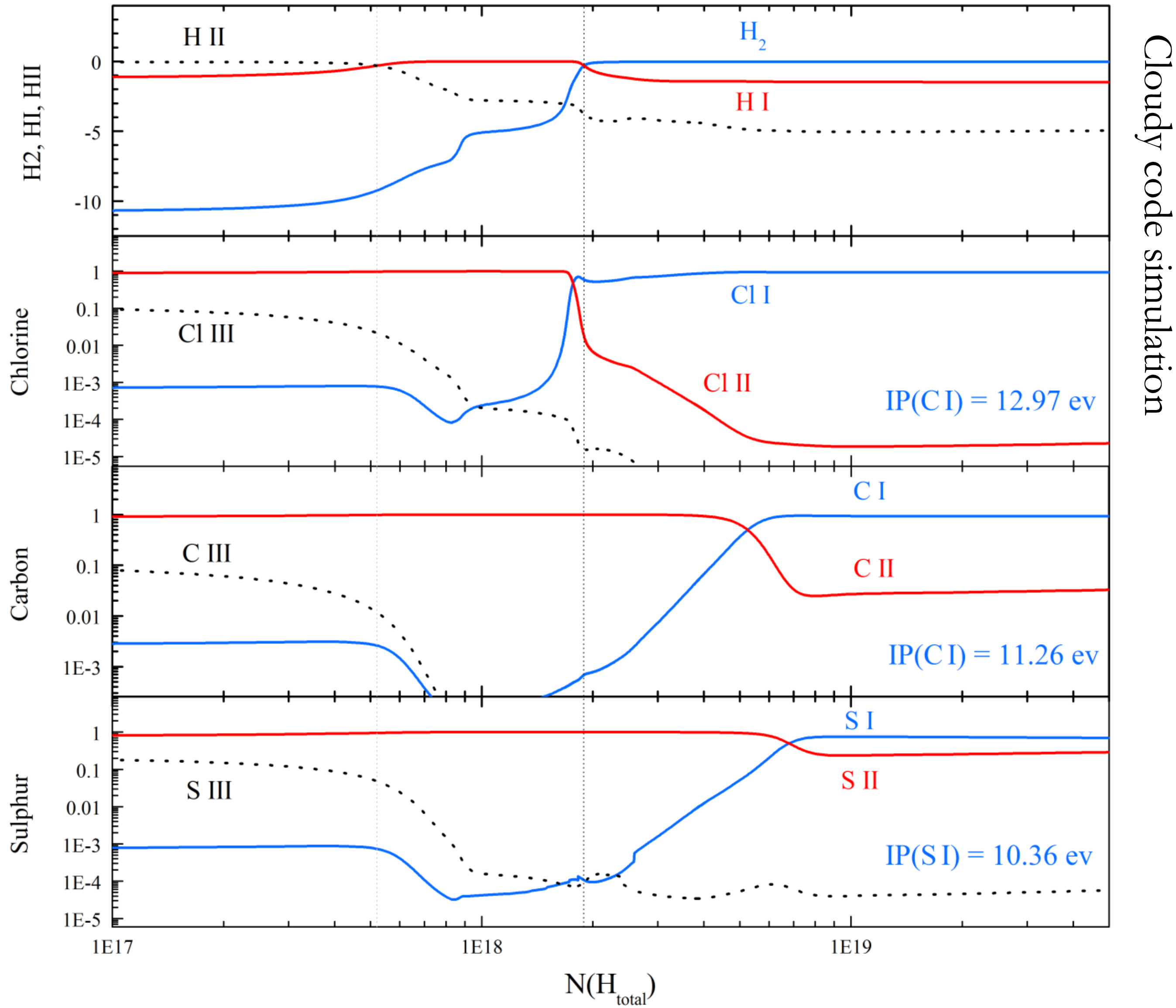


see Balashev et al., 2009



When lines in which radiative pumping occurs becomes **saturated**, there is **no photons in the center of line**, therefore only molecules at the wings of velocity distribution will be excited.

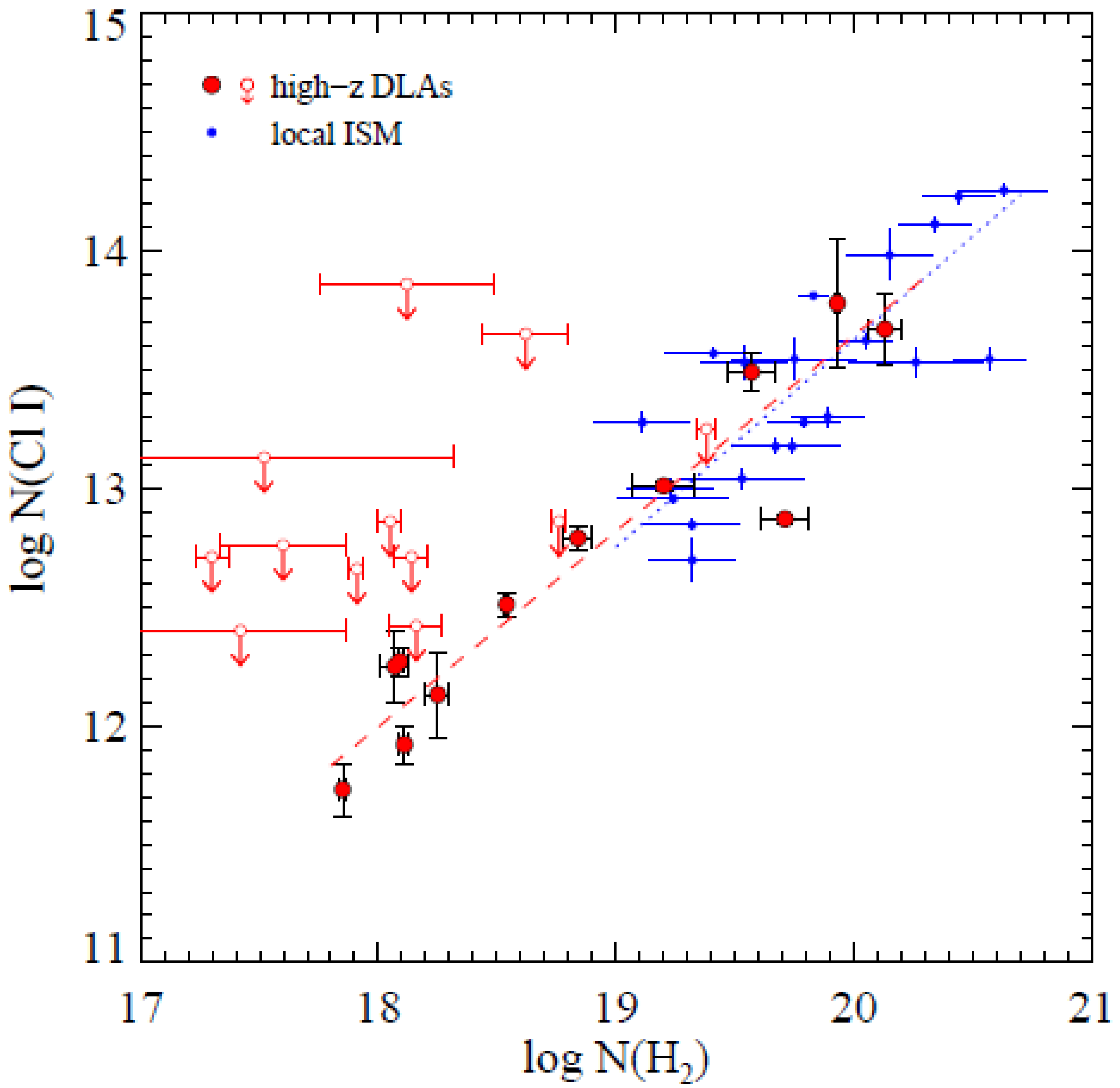
Associated neutral chlorine



See Jura 1974, and Neufeld & Wolfire, 2009

Associated neutral chlorine

Balashev et al. 2015



Associated neutral chlorine

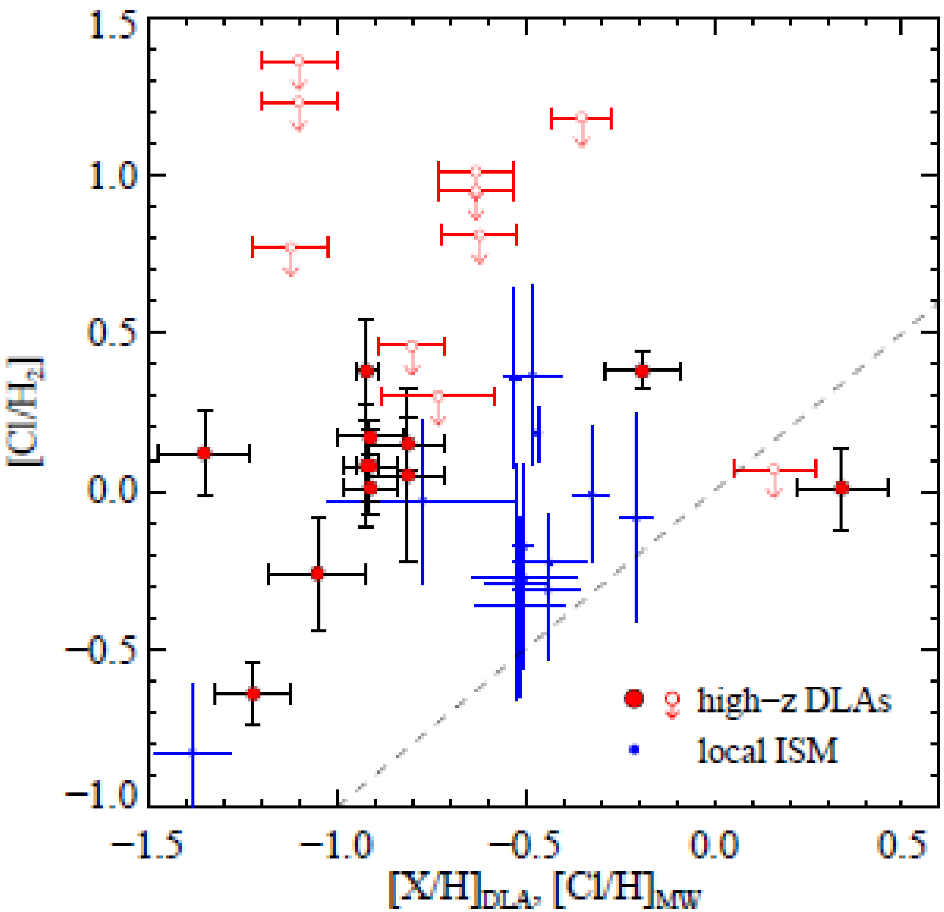
$$\left[\frac{\mathrm{Cl}}{\mathrm{H}}\right] = \left[\frac{\mathrm{Cl\,I}}{\mathrm{H_2}}\right] + \log f,$$

where f is molecular fraction

In assumption

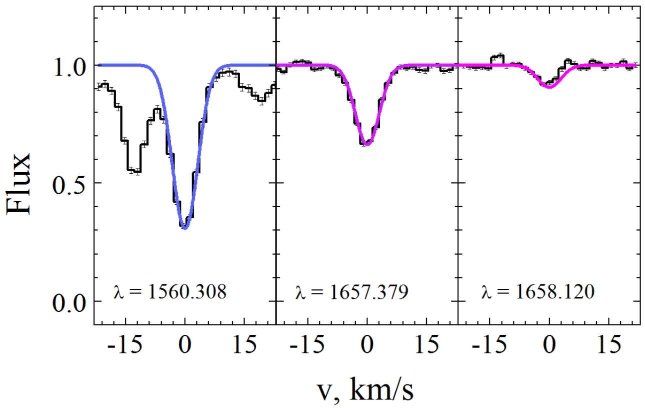
$$\log f = 0 \quad (f = 1)$$

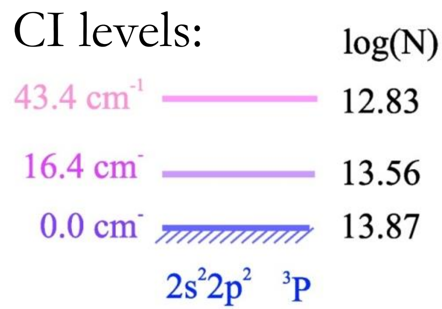
$$\left[\frac{\mathrm{Cl}}{\mathrm{H}}\right] = \left[\frac{\mathrm{Cl\,I}}{\mathrm{H_2}}\right],$$



Associated neutral carbon. Number density

1. **Relative population of C I fine structure levels:**



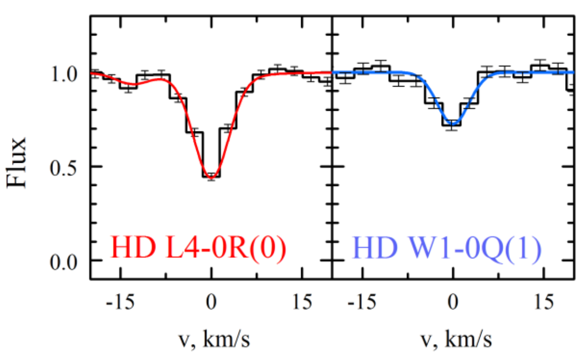


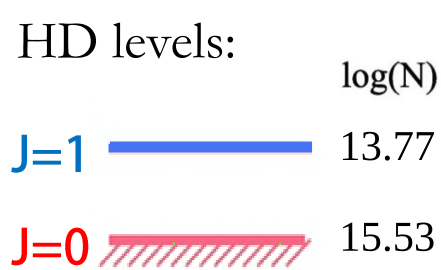
$$n = 105^{+24}_{-27}\ \mathrm{cm}^{-3}$$

(Balashev et al. 2011)

(See also Noterdaeme et al. 2007, Jorgenson et al. 2010)

2. **Relative population of HD rotational levels:**





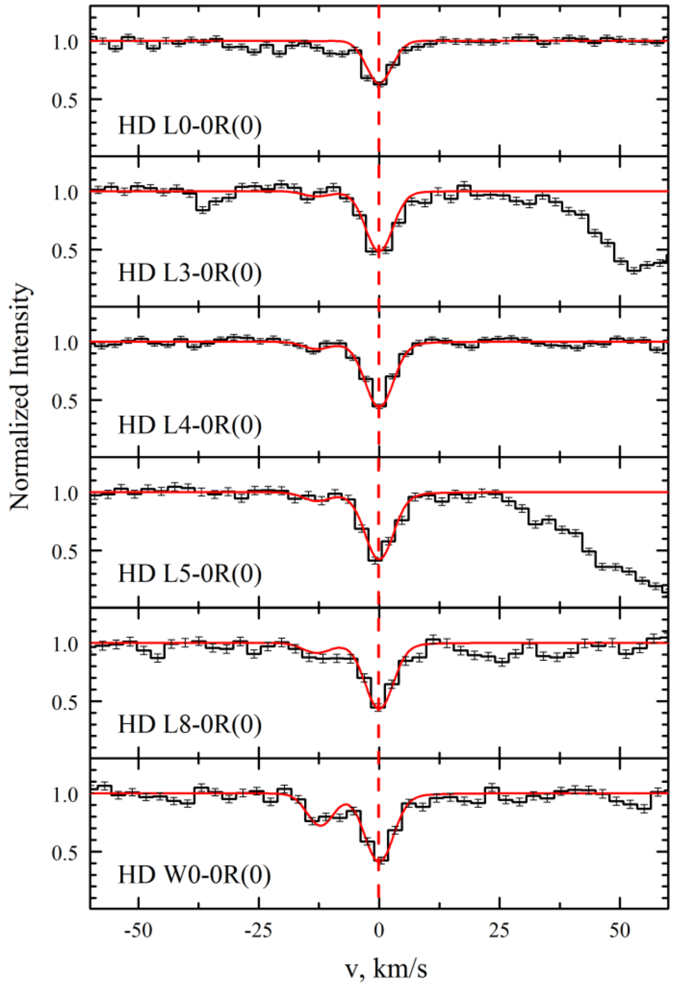
$$n = 54^{+36}_{-24}\ \mathrm{cm}^{-3}$$

(See Balashev et al. 2010)

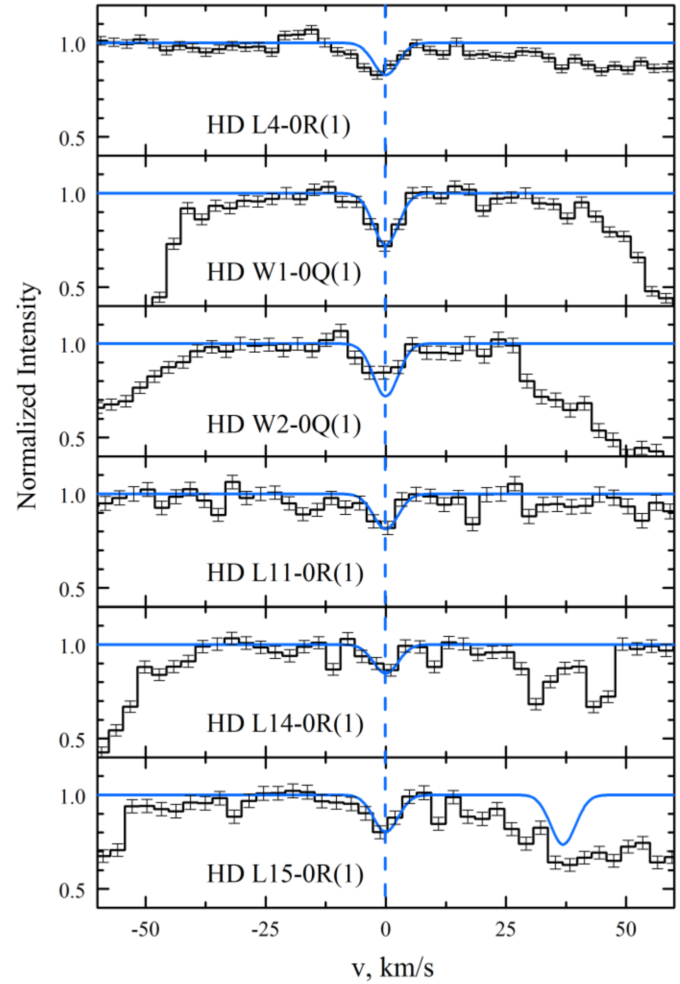
Associated HD molecules

There are 8 detection of HD molecules associated with H_2

example: Q0812+3208 (z_{abs}=2.6265) Balashev et al. 2010, Tumlinson et al. 2010



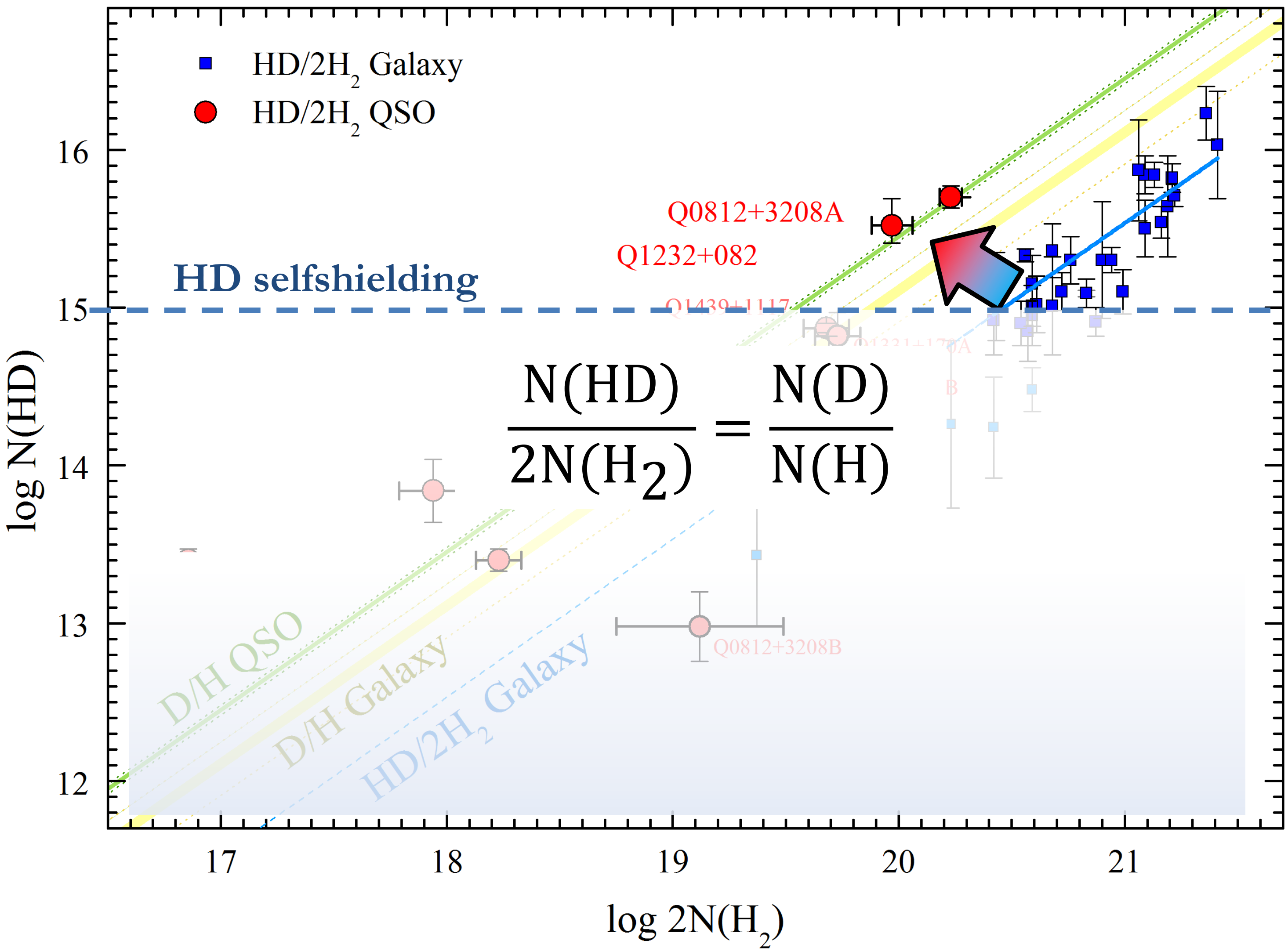
HD J=0



HD J=1

Associated HD molecules

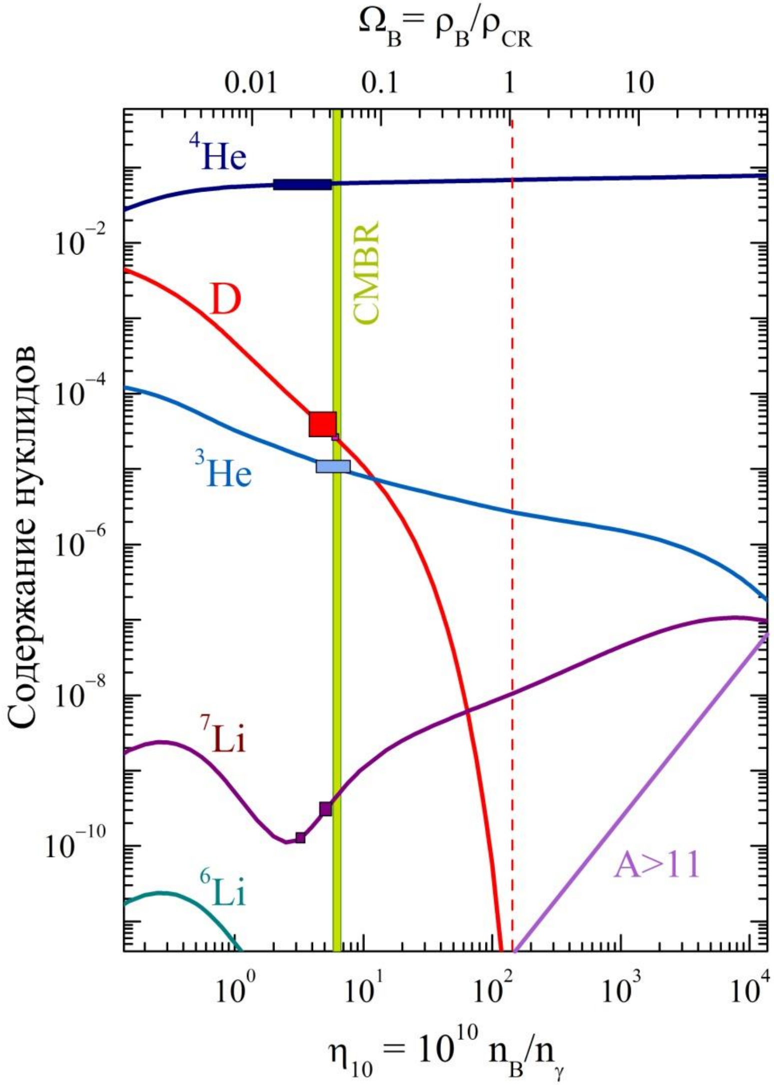
There is systematic difference between HD/H_2 absorption systems in our Galaxy and at the high redshifts.

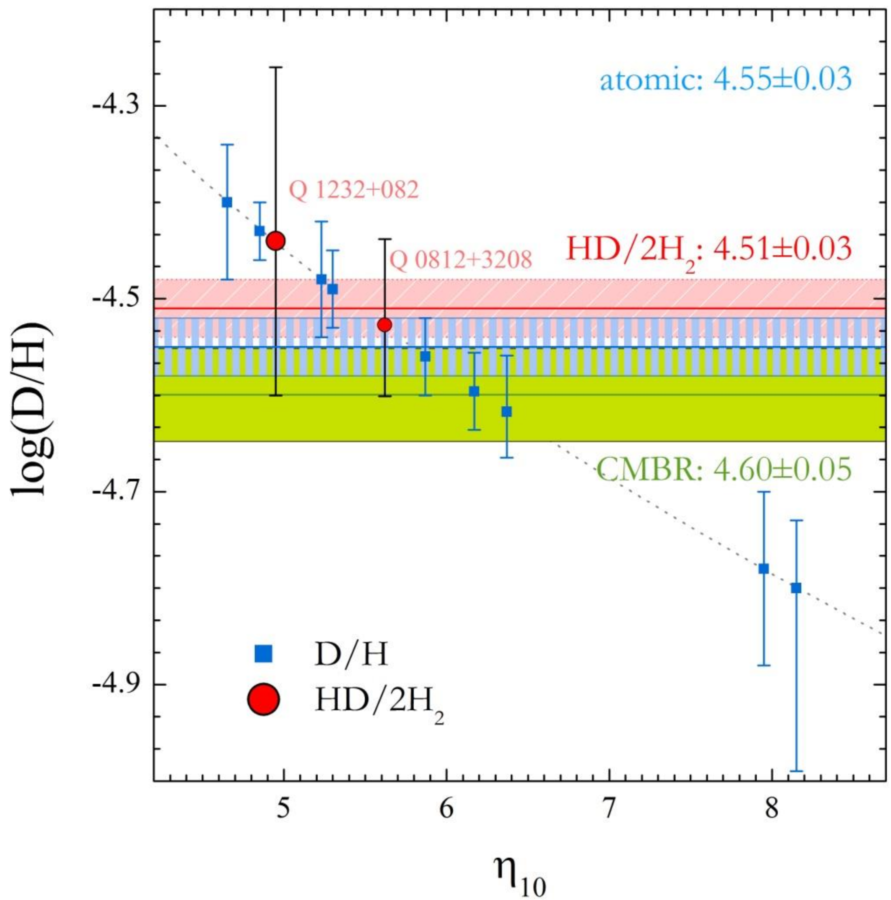


$$\frac{N(HD)}{2N(H_2)} = \frac{N(D)}{N(H)}$$

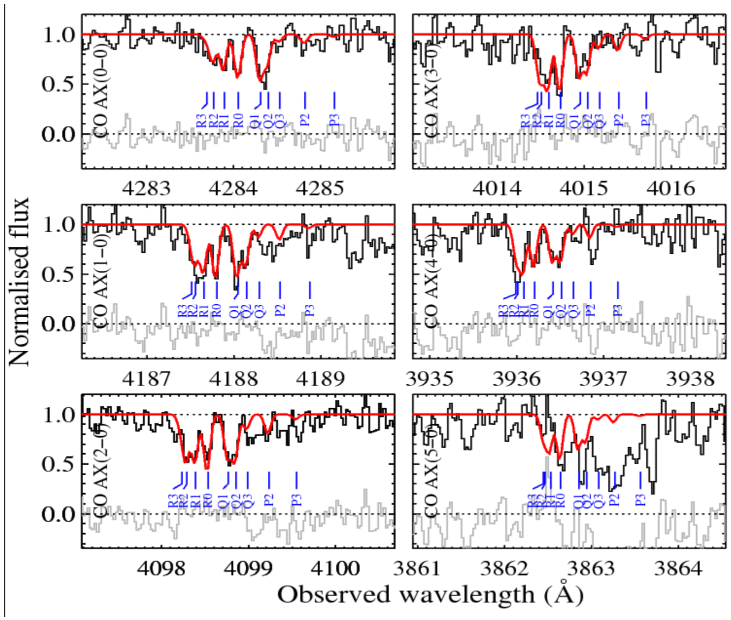
Associated HD molecules

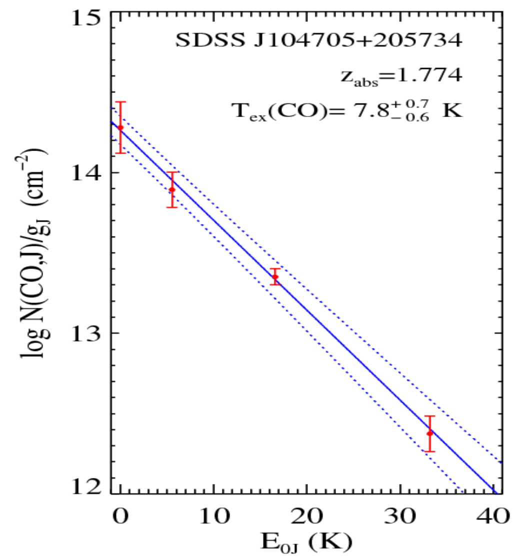
In case of selfshielding of HD and H_2 molecules D/H isotopic ratio can be estimated and therefore Ω_b can be derived using some additional assumptions (Ivanchik et al. 2010, Balashev et al. 2010)

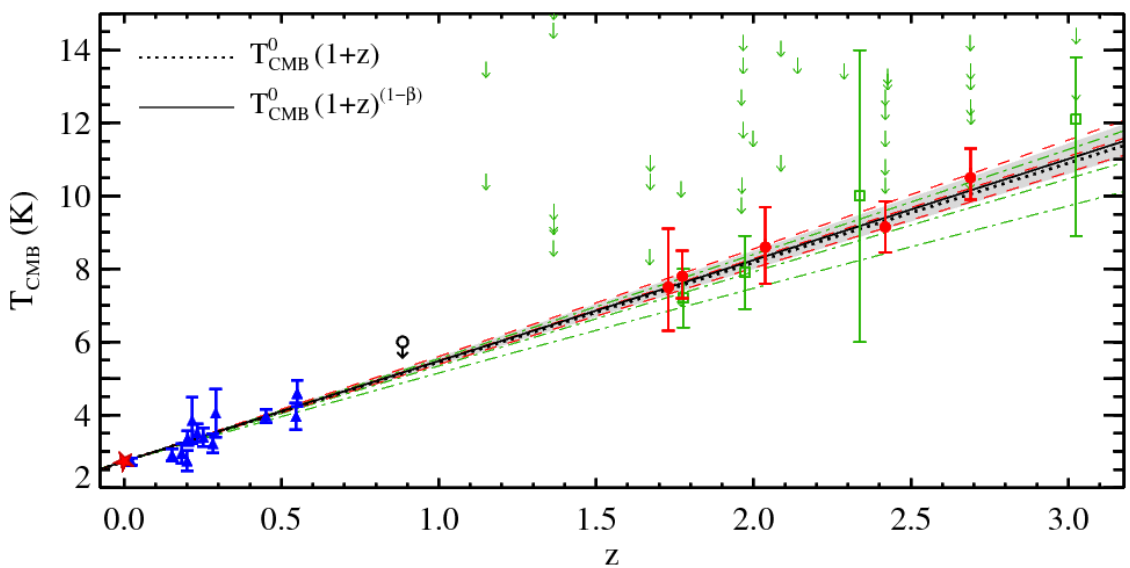




Associated CO. CMB Temperature







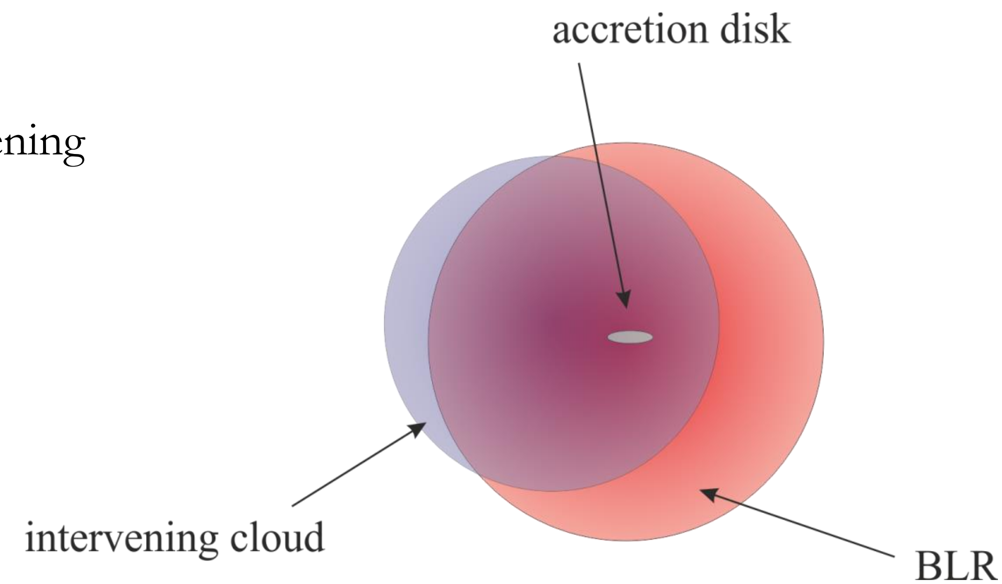
$$
\begin{cases} T_{\mathrm{CMB}} \sim (1+z)^{1-\beta} \\ \beta = -0.012 \pm 0.029 \end{cases}
$$

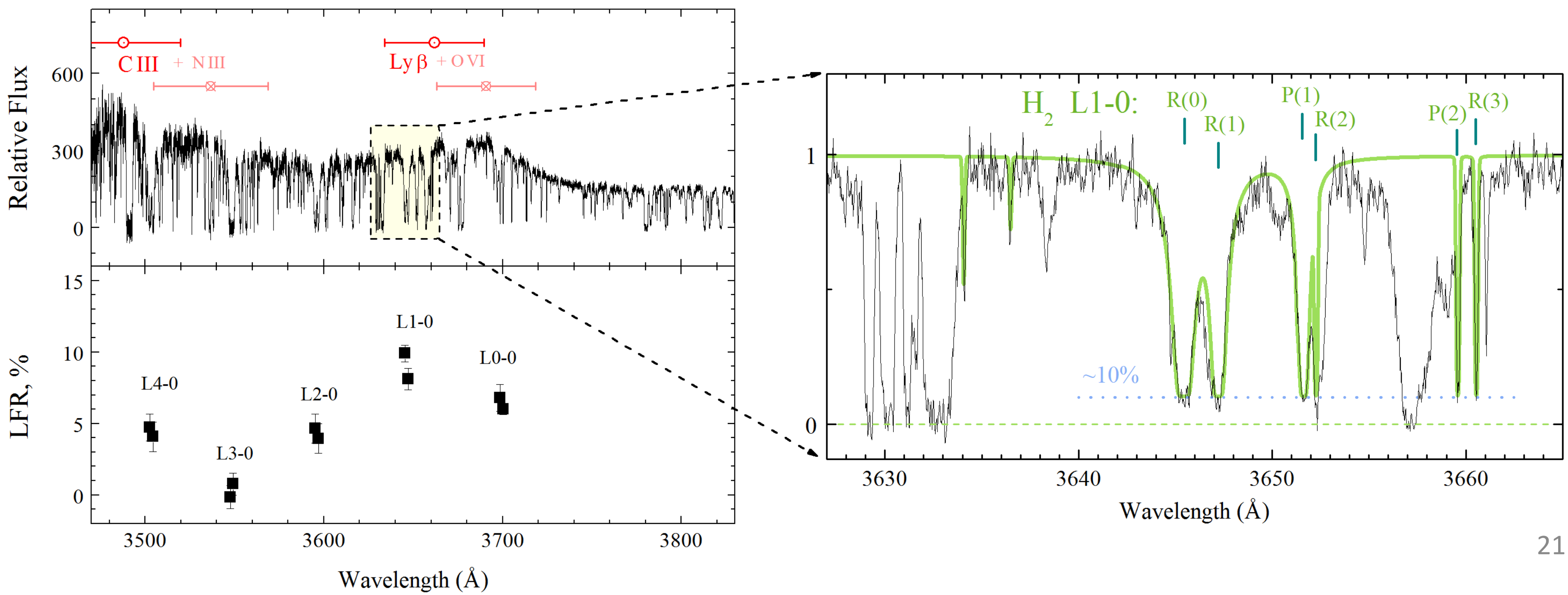
(Noterdaeme et al. 2011)

Partial coverage of the BLR. QSO 1232+082

We have found partial coverage of the Q1232+082 (z_{abs}=2.57) BLR by an intervening H_2 absorption system (z_{abs}=2.3377) (Balashev et al. 2011)

QSO is not a point source compared to compact H_2 absorption system!

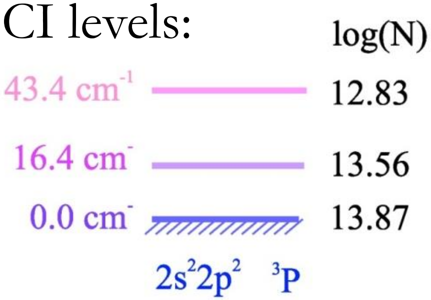




Size of the BLR of Q1232+082

1. **The size of the absorption cloud:**

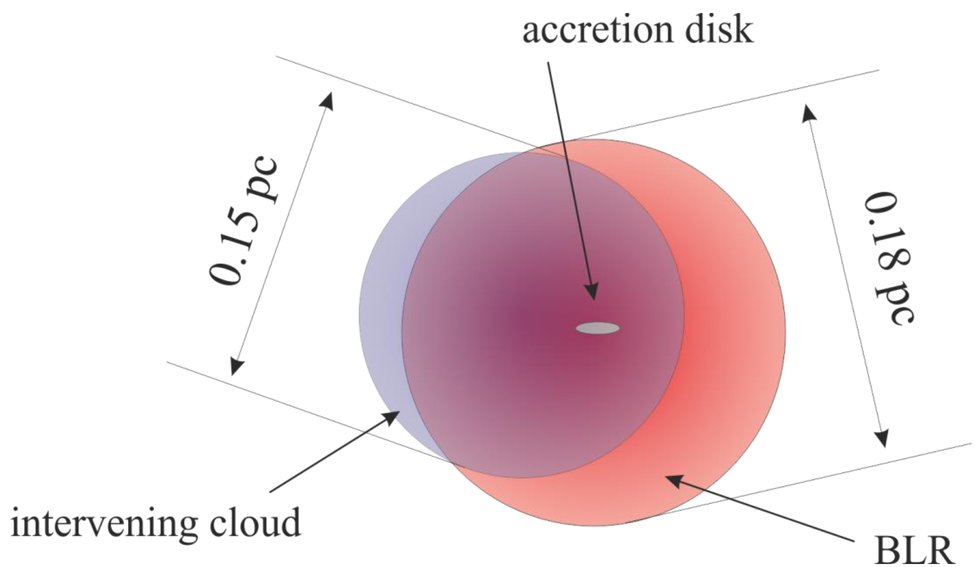
CI levels:



$\Rightarrow$ $n = 105^{+24}_{-27}\ \mathrm{cm}^{-3}$ $\Rightarrow$ $R_{abs} = 0.15^{+0.05}_{-0.05}\ \mathrm{pc}$

2. **The covering factor:**

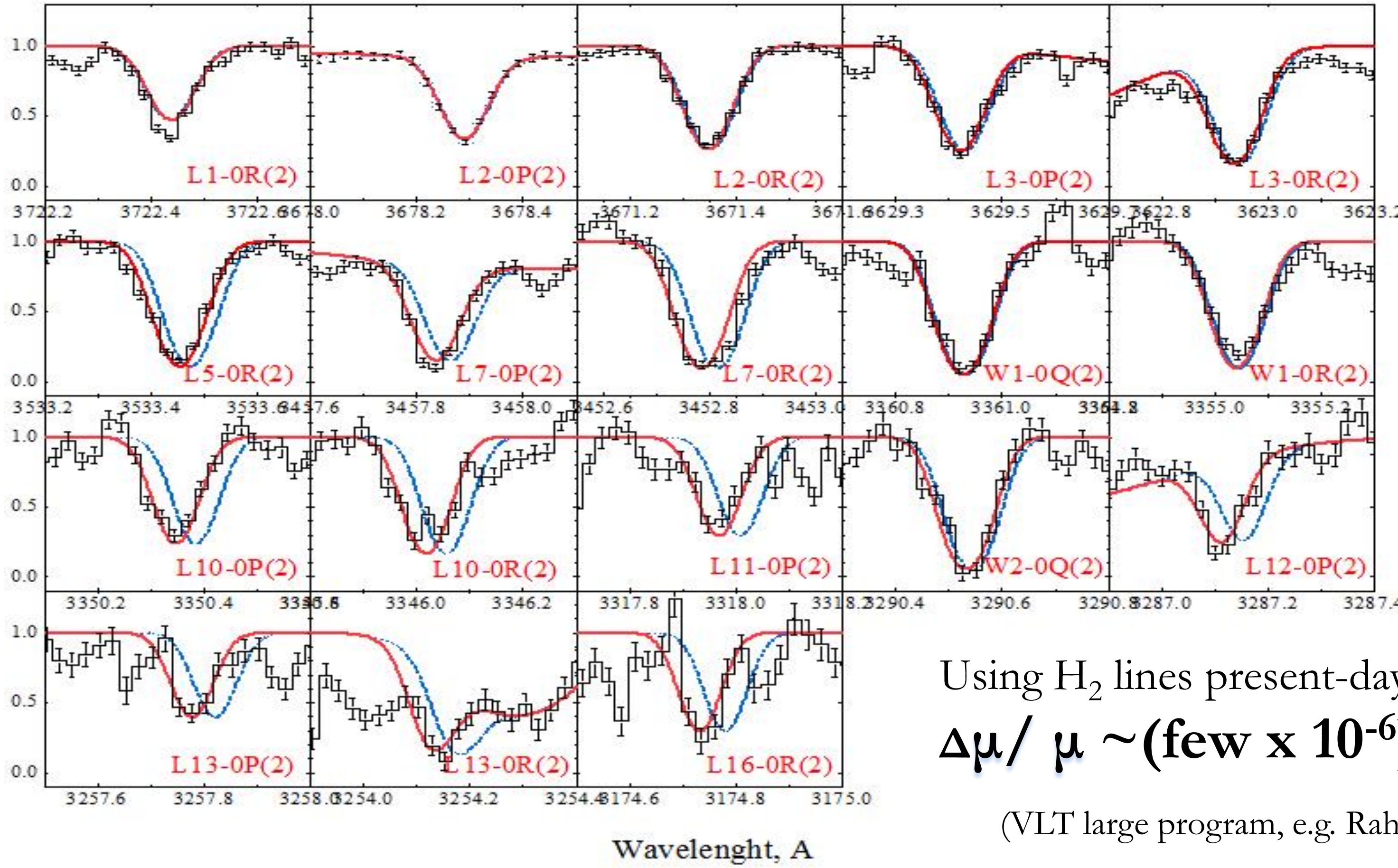
$$f_{CIV} = 0.48^{+0.07}_{-0.12}$$



It allow us to measure the size of BLR $\Rightarrow$ $R_{BLR} = 0.18^{+0.08}_{-0.12}\ \mathrm{pc}$

There is another example of partial coverage of H_2 clouds (see Klimenko et al. 2015)

Limits on the variation of $\mu = m_p/m_e$



Using H_2 lines present-day limit is

$\Delta\mu/\ \mu$ ~(few x 10^{-6})

(VLT large program, e.g. Rahmani et al. 2013)

There are two obstacles:

1. Limits are restricted by the systematical errors of telescopes. Wait for the next generation of stable echelle spectrographs mounted on the large telescopes.
2. There are more sensitive species to do this, like CH_4 (talk of S.A. Levshakov, or Bagdoniate et al. 2013).

Sloan Digital Sky Survey

SDSS is the largest spectroscopic survey.

The latest release – Data Release 12 (DR12) contains

~ 300,000 quasars

$z_{em} > 2.0$

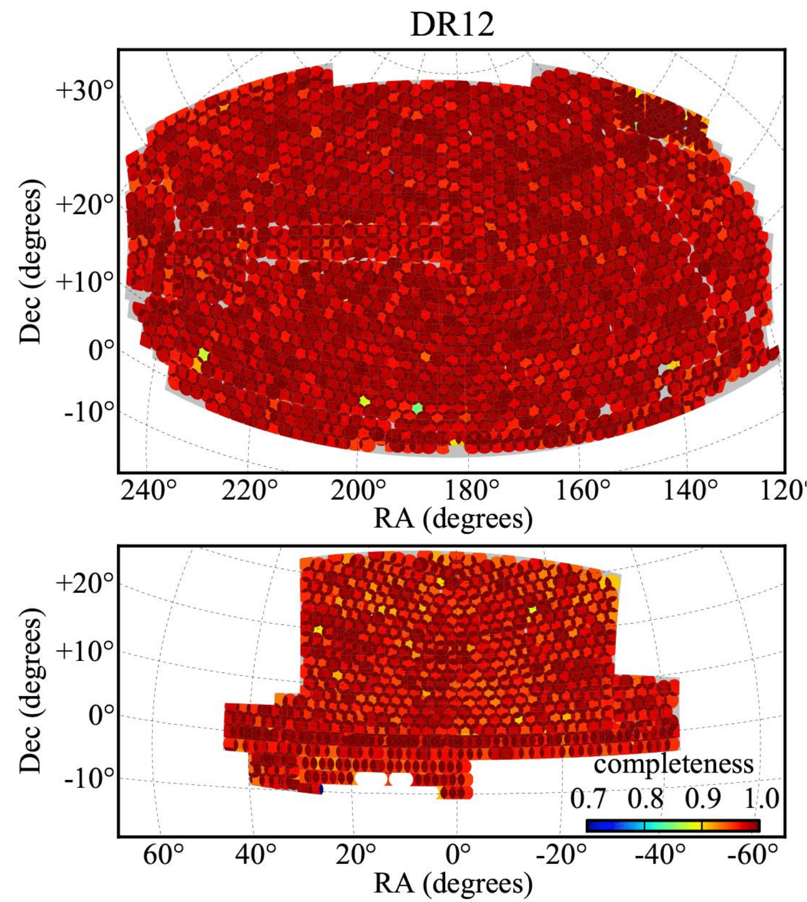
~200,000

(Noterdaeme et al. 2009 + 2012
+ priv. comm.)

~34,000 DLA identified

× 0.10 - probability to detect H_2
in DLA

~ 3400 H_2 absorption systems are expected?



DR12 BOSS coverage

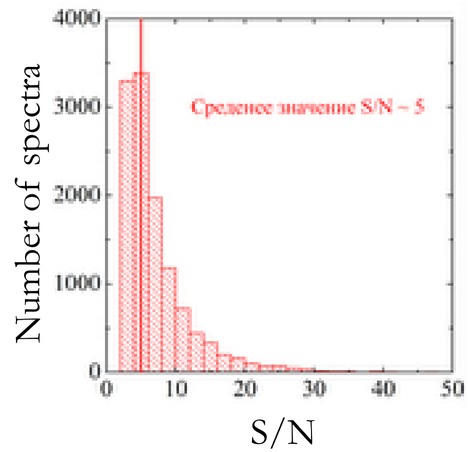
Sloan Digital Sky Survey

There are three main obstacles for detection of H_2 absorption system in SDSS

1. Ly-α forest

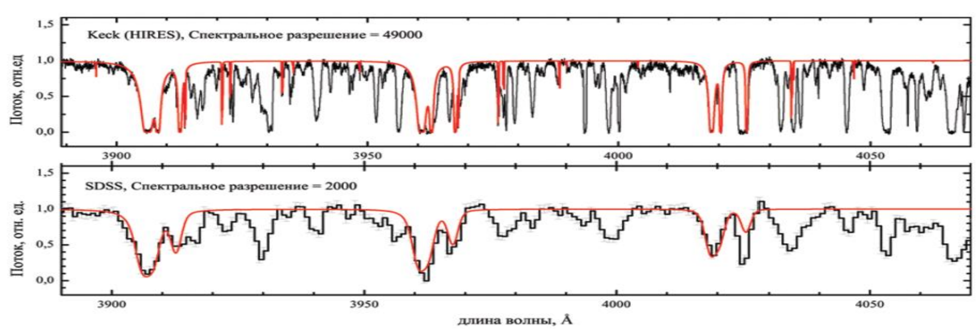
Average S/N ~ 5

2. Low Signal to Noise (S/N)

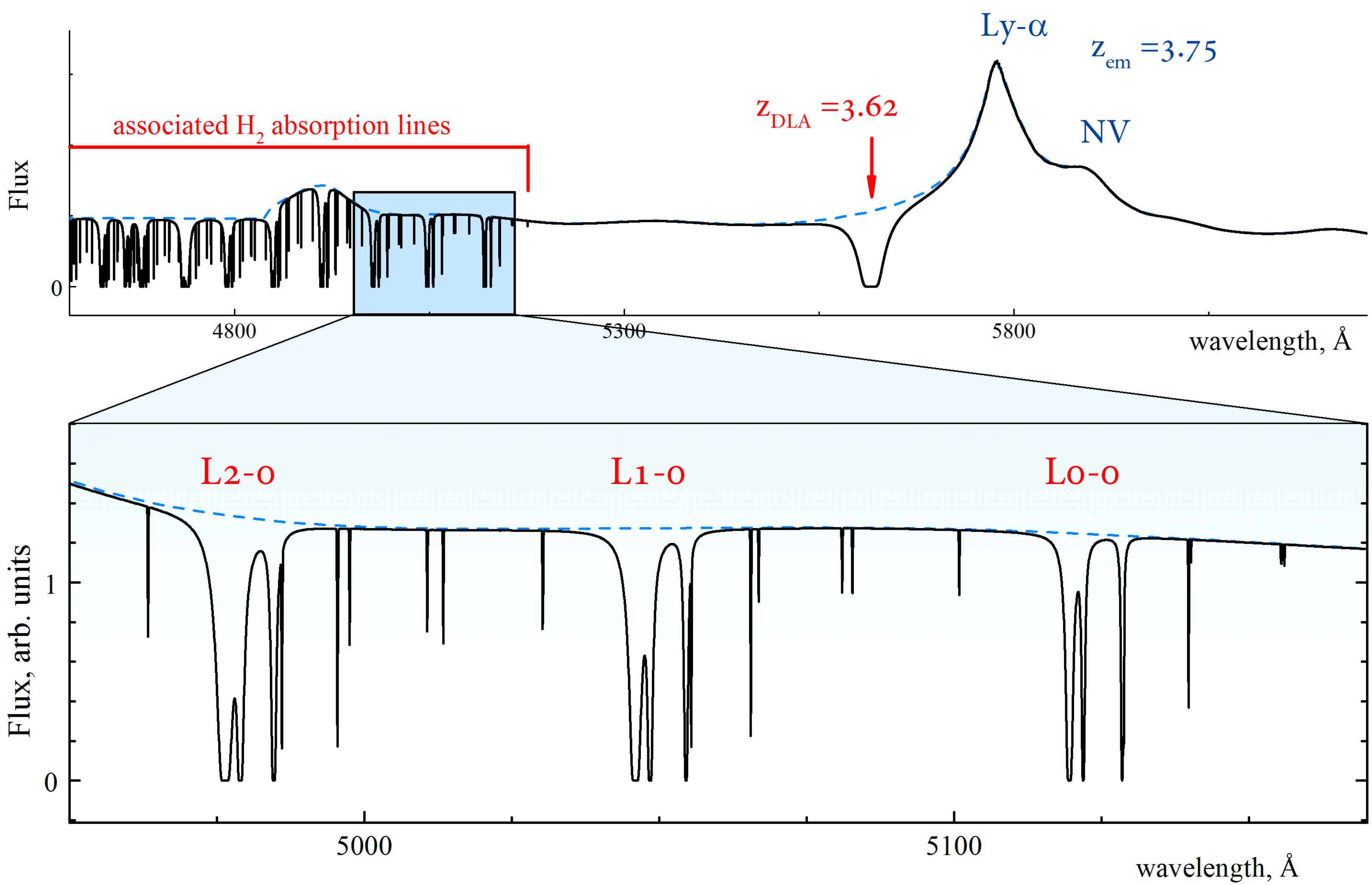


3. Spectral resolution of SDSS

R~2000

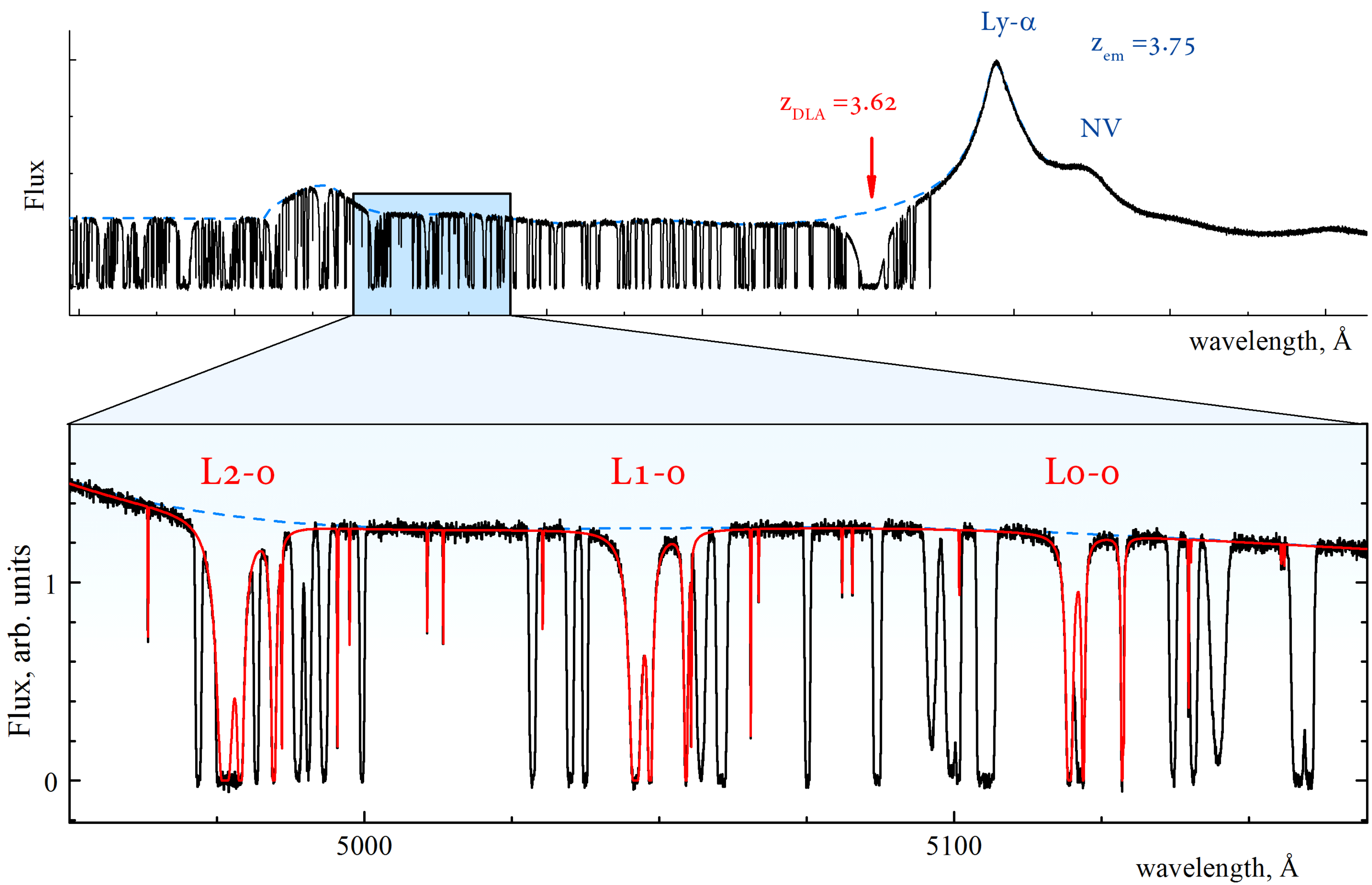


Sloan Digital Sky Survey



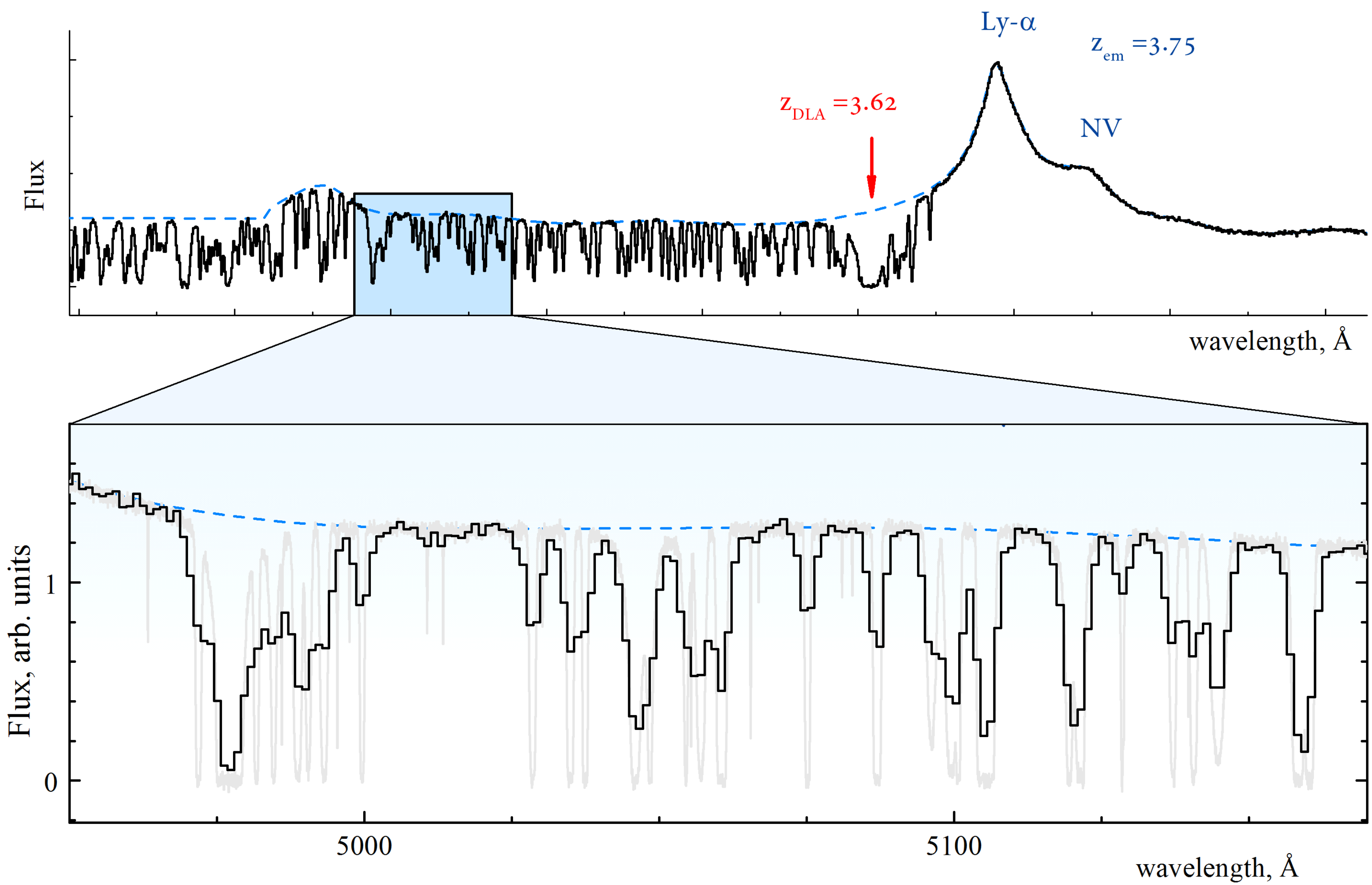
Simulated quasar spectrum with H_2 absorption system at z=3.62

Sloan Digital Sky Survey



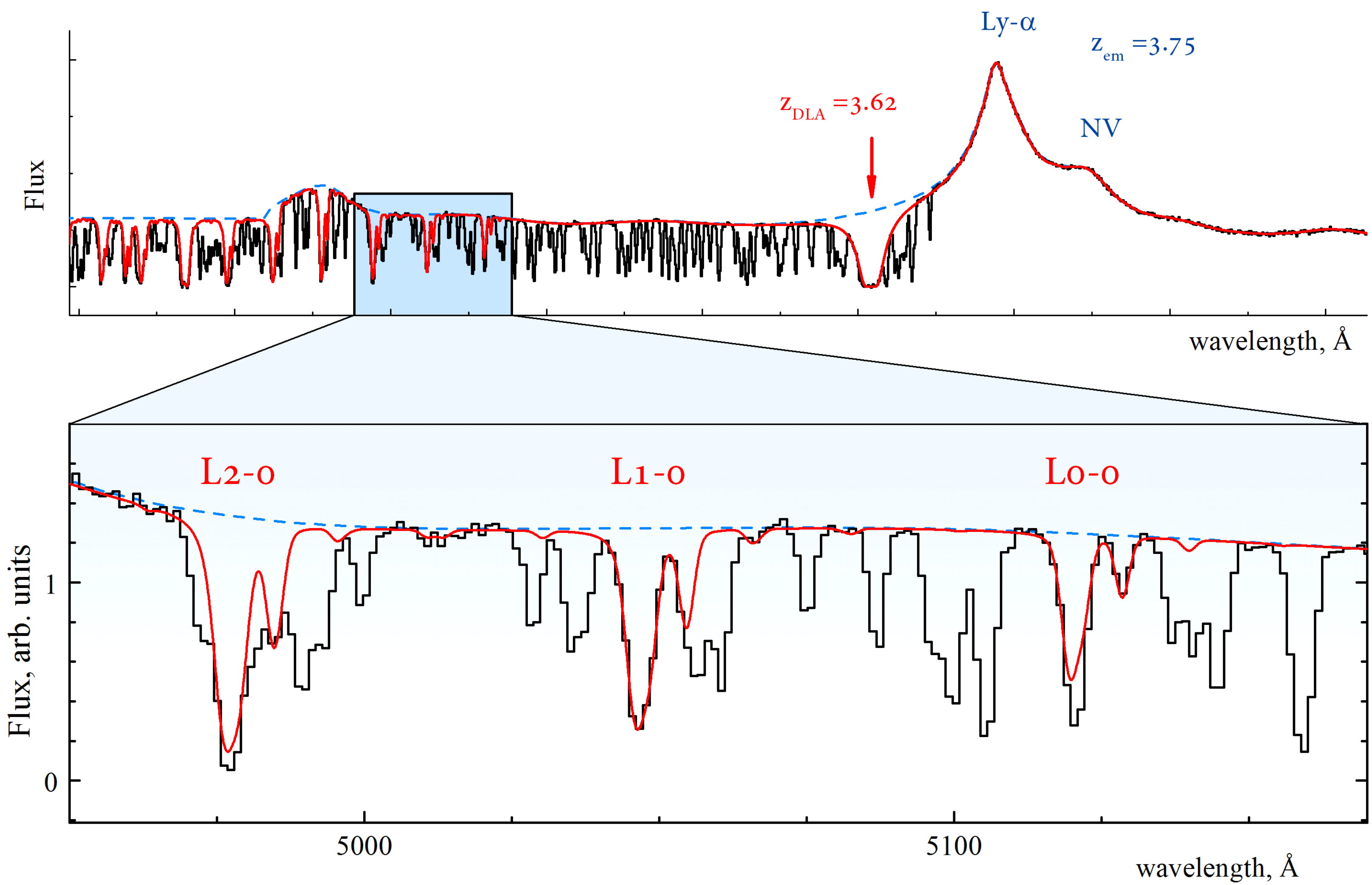
High resolution spectrum → VLT, KECK → Identification and analysis

Sloan Digital Sky Survey



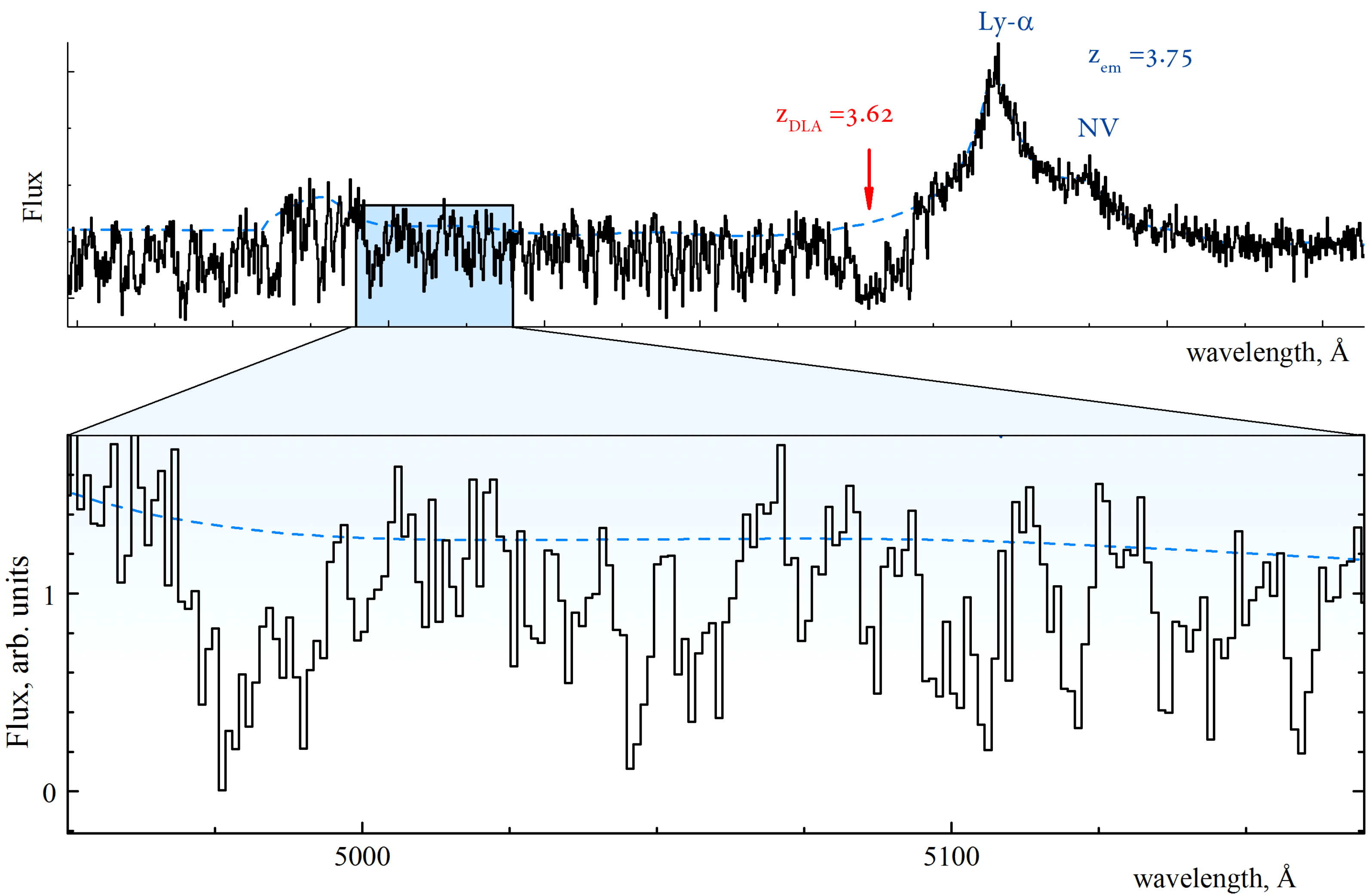
Spectrum with resolution R ≈ 2000 (SDSS)

Sloan Digital Sky Survey



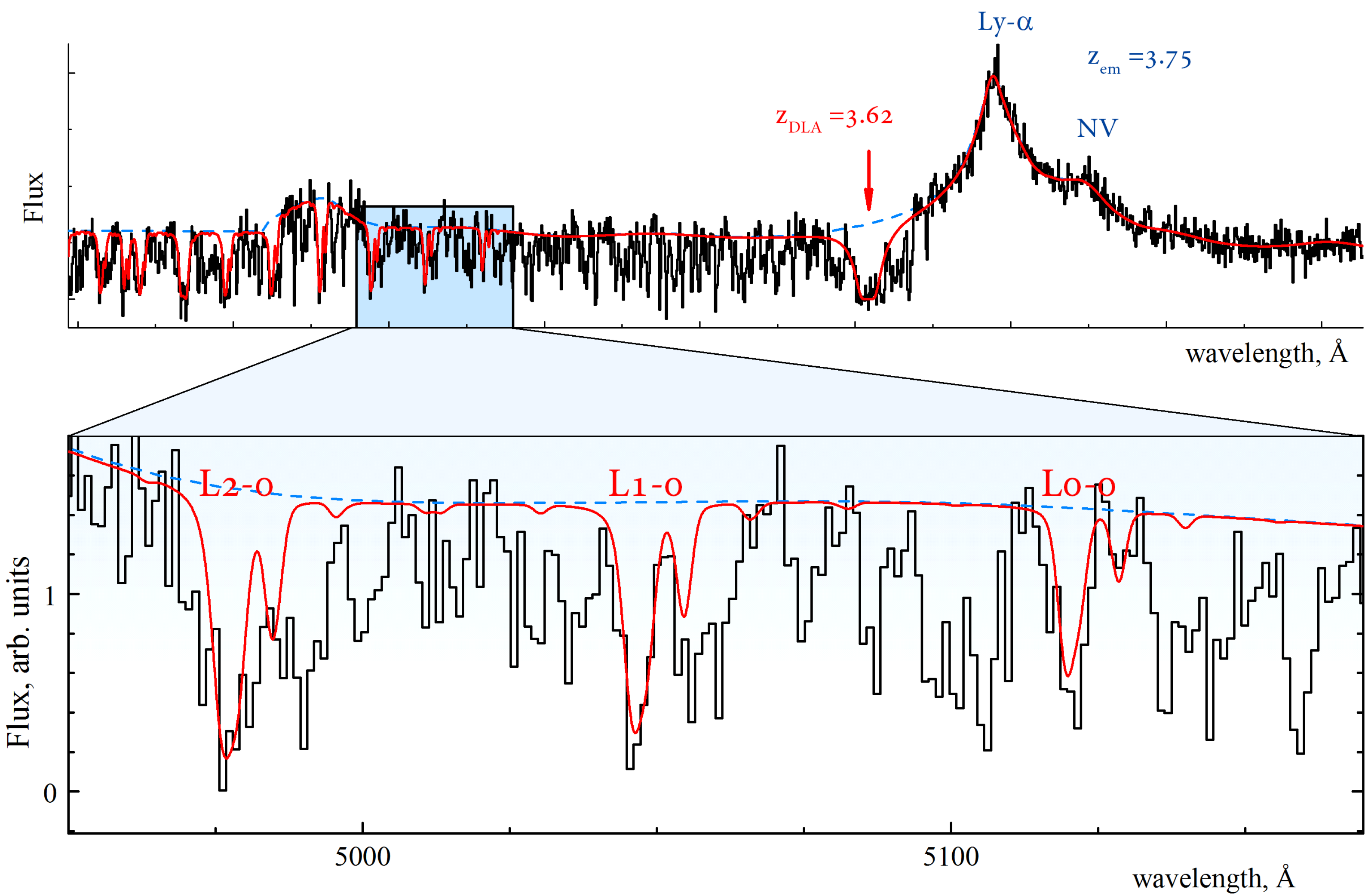
Spectrum with resolution R ≈ 2000 (SDSS)

Sloan Digital Sky Survey



Spectrum with resolution R ≈ 2000 и S/N ≈ 5 (SDSS) → Is identification possible?

Sloan Digital Sky Survey

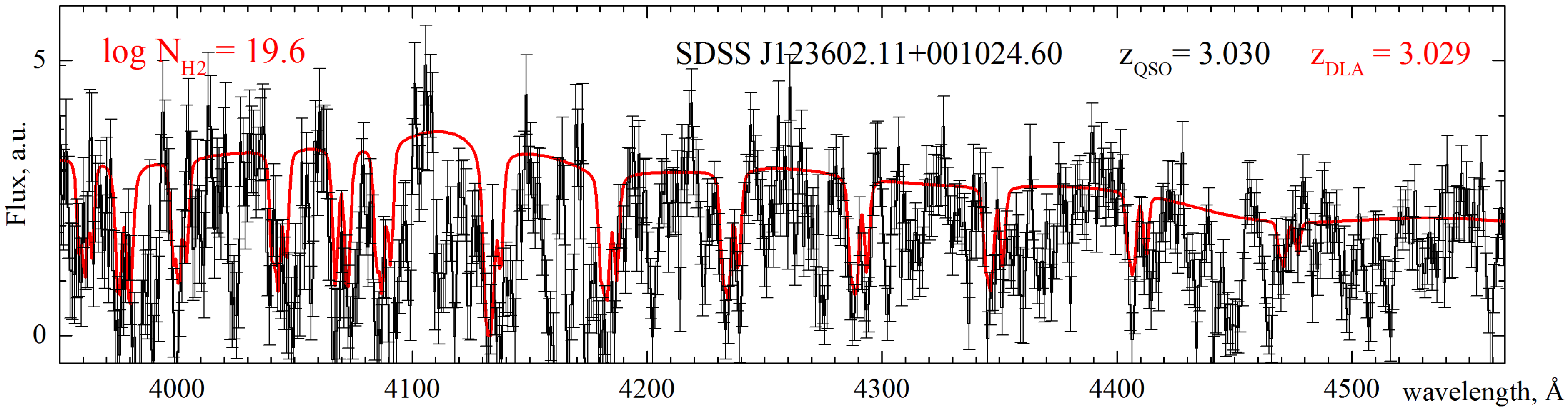


Spectrum with resolution R ≈ 2000 и S/N ≈ 5 (SDSS) → **Identification is possible!**

H_2 in SDSS. Follow up of H_2 candidates

Using automatic technique (see Balashev et al. 2014) we found about **75 (from DR12)** confident candidates.

We have started to follow up these candidates.



Using observations with Xshooter/VLT during P94 we confirm **7 out of 7** H_2 candidates.

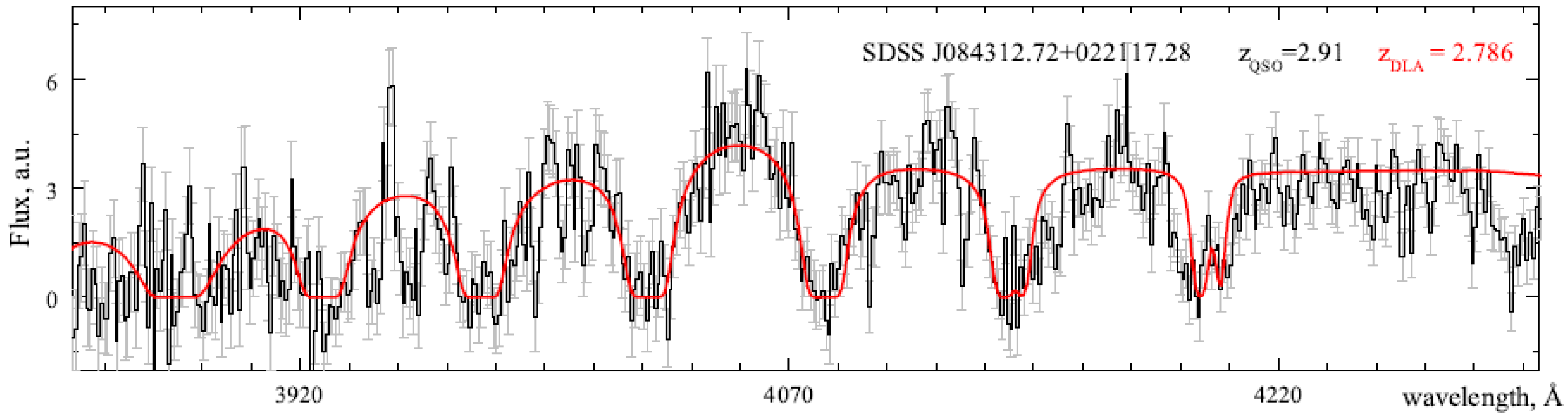
SDSS can be **very efficiently** used to detect H_2 absorption systems for the follow up studies,

i.e. we propose replacement of very inefficient blind search of H_2 that was previously used.

H_2 in J0843+0221

One of the H_2 candidate in SDSS was

Balashev et al. 2014



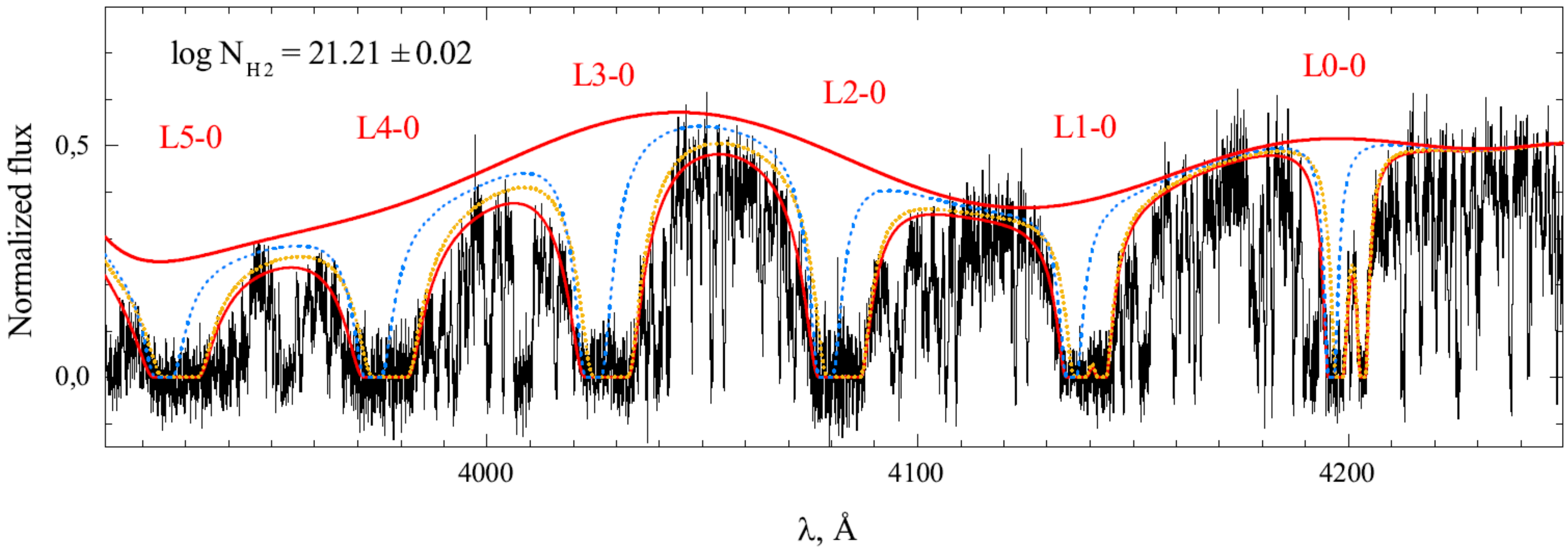
We follow up **J0843+0221** using **UVES/VLT**. Observation were done in 92 period (autumn 2013 – spring 2014) **092.A.0345** (PI: **D.A. Varshalovich**)

No.	Date	Starting time, UT	Setting	Exposure, sec	Seeing	Airmass
1	01.07.2014†	07:19:05	437+760	4800	1.00→0.78	1.162→1.377
2	01.28.2014	03:06:44	437+760	4800	0.83→1.10	1.265→1.131
3	24.02.2014	01:07:58	390+564	4800	0.97→0.92	1.306→1.141
4	26.02.2014	01:34:21	437+760	4800	0.81→1.00	1.211→1.122
5	26.02.2014	02:58:31	437+760	4800	0.98→1.24	1.121→1.188
6	27.02.2014	01:32:14	390+564	4800	0.99→0.96	1.207→1.122
7	27.02.2014	02:55:32	390+564	4800	0.94→0.74	1.121→1.190
8	27.02.2014	04:16:46	390+564	4800	0.69→0.75	1.192→1.466
9	02.03.2014	01:02:50	437+760	4800	0.69→0.84	1.249→1.127
total				43200		

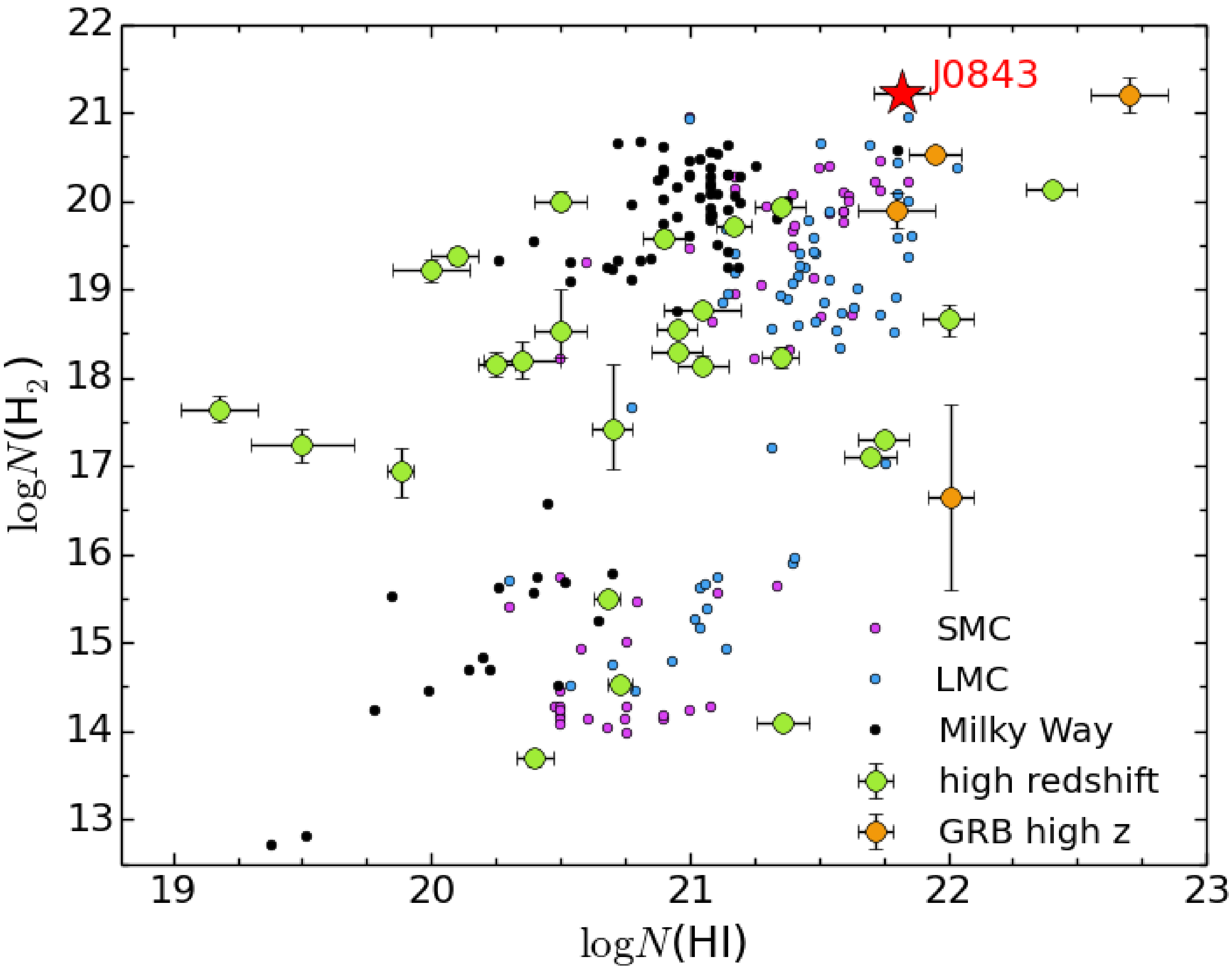
H_2 in J0843+0221

Using high resolution spectrum we confirm very high H_2 column density in this system

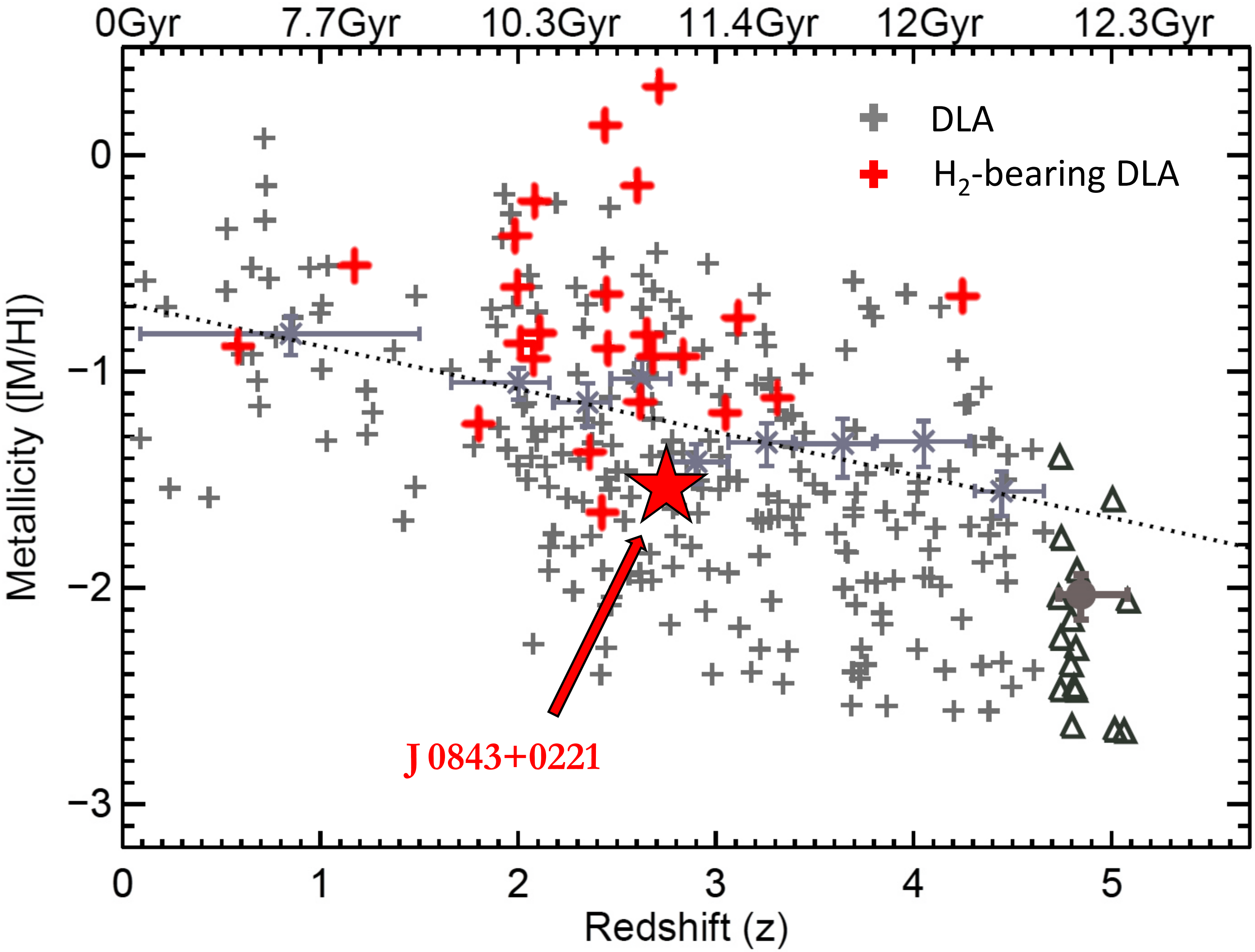
$$\log \mathrm{N}(\mathrm{H_2}) = 21.21^{+0.02}_{-0.02}$$



H_2 in J0843+0221. H_2 vs HI



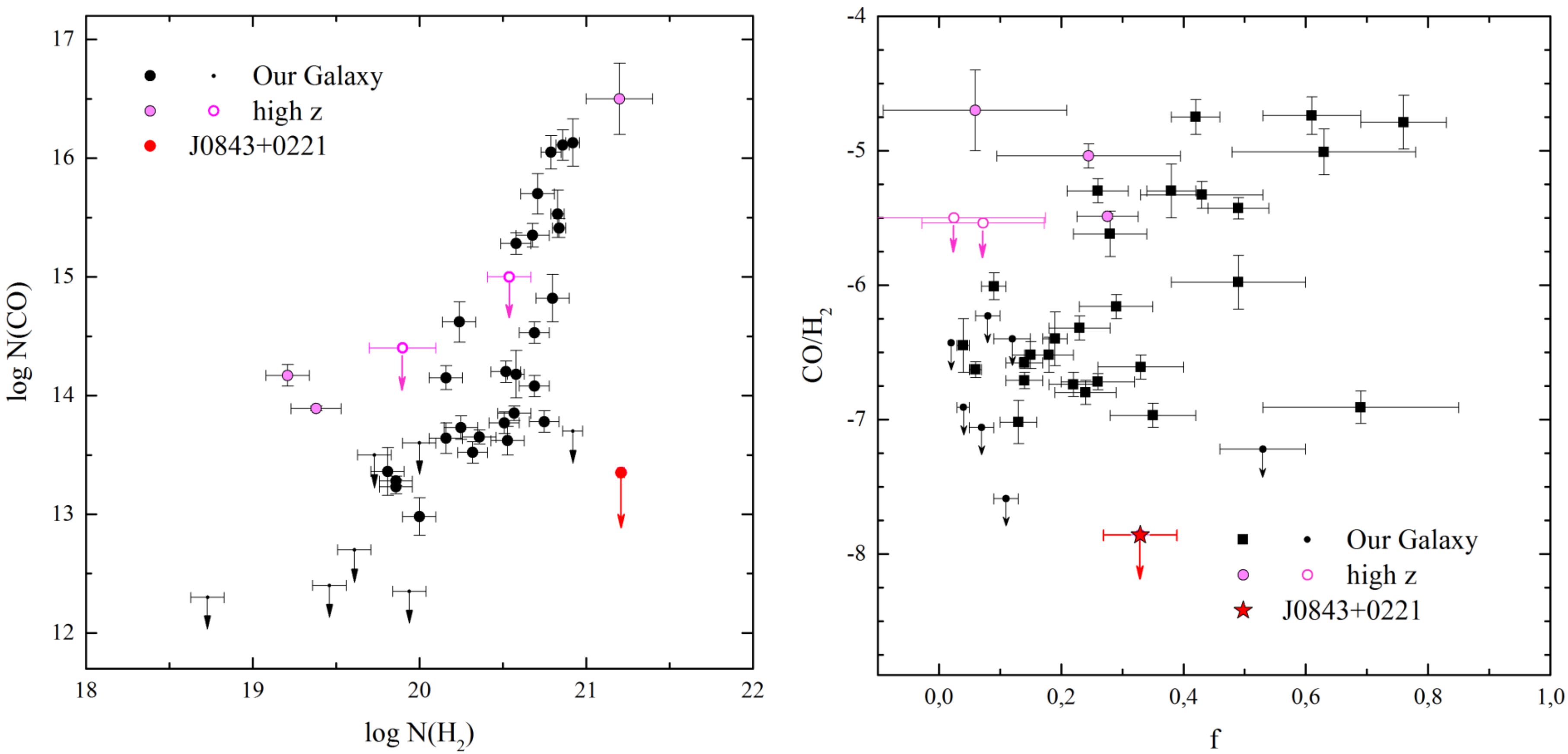
H_2 in J0843+0221. Metallicity



(DLAs data from Rafelsky et al. 2013)

H_2 in J0843+0221. CO/H_2

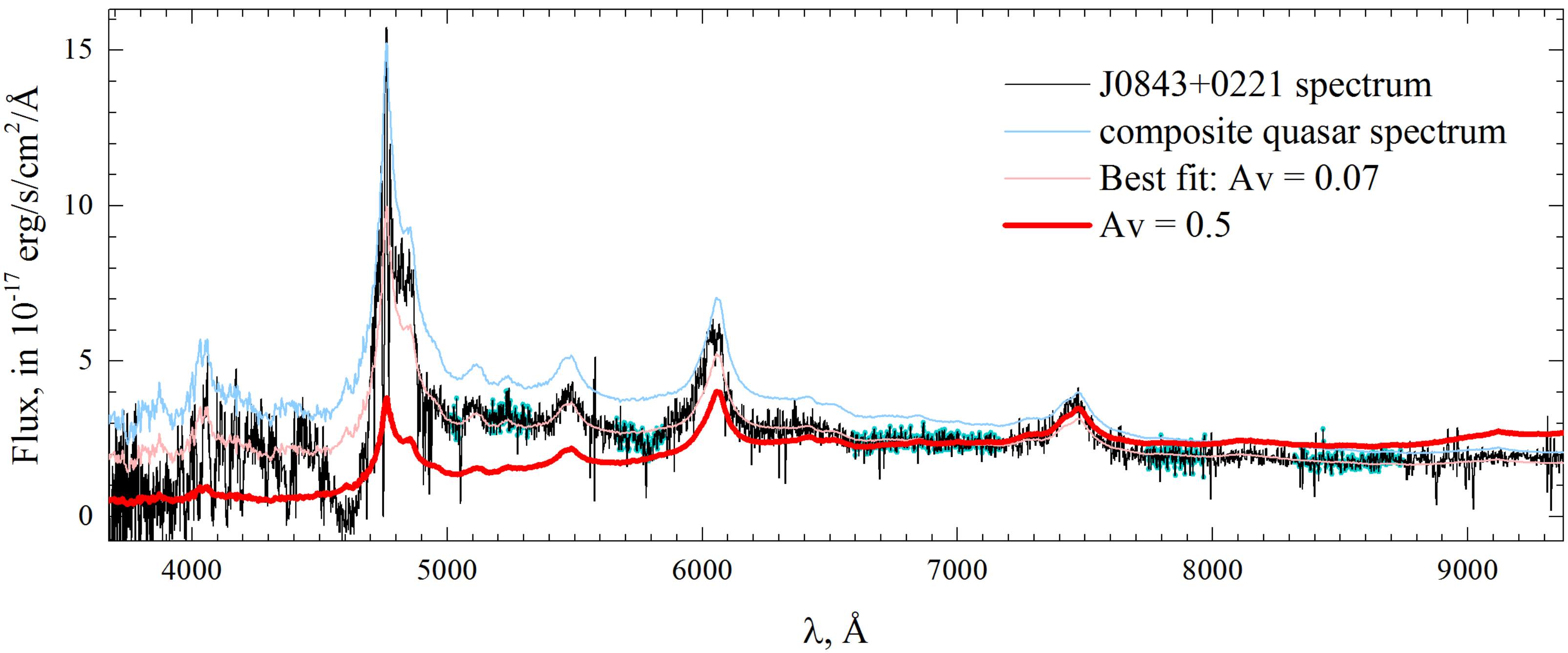
In spite of high H_2 column density we did not detect CO lines. $N_{\rm CO} < 10^{13.4}$ cm^{-2}



H_2 absorption system in J0843+0221 corresponds to “dark” molecular gas.

H_2 in J0843+0221. Dust extinction

We constrain the extinction A_V associated with H_2 absorption system using SDSS spectrum.



$$\boxed{A_V = 0.09 \pm 0.10(\mathrm{syst.})}$$

If one will use well known relation in our Galaxy:

$$\frac{N(\mathrm{H})}{A_V} = 1.8 \times 10^{21}\,\mathrm{cm}^{-2}\mathrm{mag}^{-1} \quad \Rightarrow \quad \underline{A_V^{exp} \approx 5} \quad (N(\mathrm{H}) = 10^{22}\mathrm{cm}^{-2})$$

H_2 in J0843+0221. Open question

Large amount of H_2 but Low dust content

$\log N(H_2) = 21.21^{+0.02}_{-0.02}$

$[Zn/H] = -1.46^{+0.14}_{-0.15}$

$\log N(CO) < 13.4 \Rightarrow CO/H_2 \lesssim 10^{-8}$

$A_v = 0.09 \pm 0.10$

In cold neutral medium H_2 forms only on dust

The rate of H_2 formation on dust is very low

$$t_{\rm form} = \frac{1}{n R_{\rm form} D} = \frac{3 \times 10^{10}\,{\rm yr}}{n,\ {\rm cm}^{-3}}$$

How to create such large amount of H_2 without dust?

Summary

1. H_2 absorption systems identified in quasar spectra provide an opportunity to study in details cold phase of the interstellar at the high redshift.

2. The analysis of H_2 absorption system allow us to investigate several cosmological tasks.

3. SDSS can be used for the identification of H_2 absorption system candidates.

4. Follow up of one of H_2 candidate from SDSS reveal unique high H_2 column density absorption system with very low dust extinction.