Ioffe Institute

This work is supported by RSF 23-12-00166

ESPRESSO view on the cold and neutral gas in high-redshift galaxies

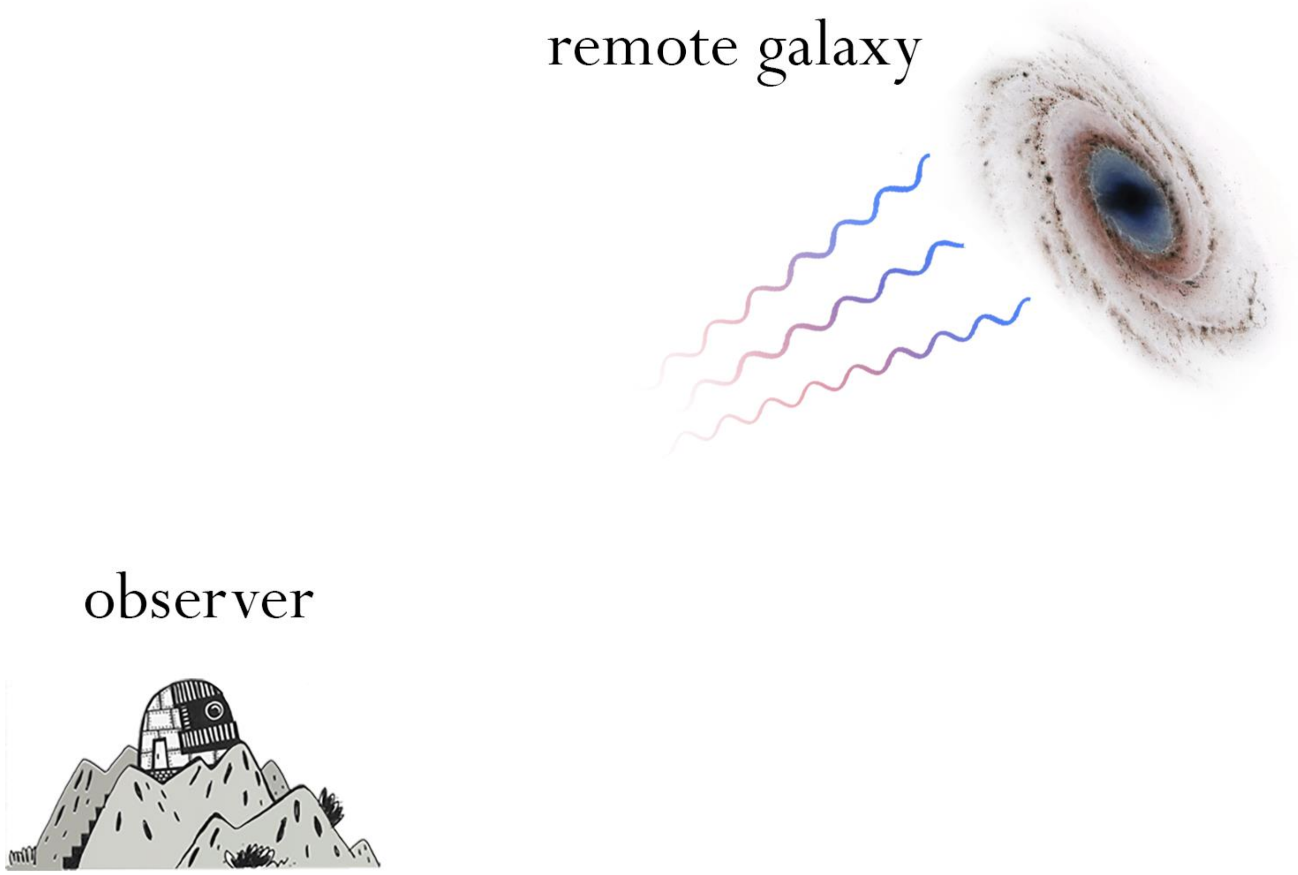
Sergei Balashev
Ioffe Institute, Saint-Petersburg

and **P. Noterdaeme**, C. Ledoux, S. Lopez, K. Telikova, C. Martins, P. Boisse, J.K. Krogager, V. Klimenko, A. Ivanchik, R. Cooke, R. Cuellar, N. Tejos, A. De Cia, J. Bergeron, G. Duchoquet, …

7 September 2023

ISM at high redshift

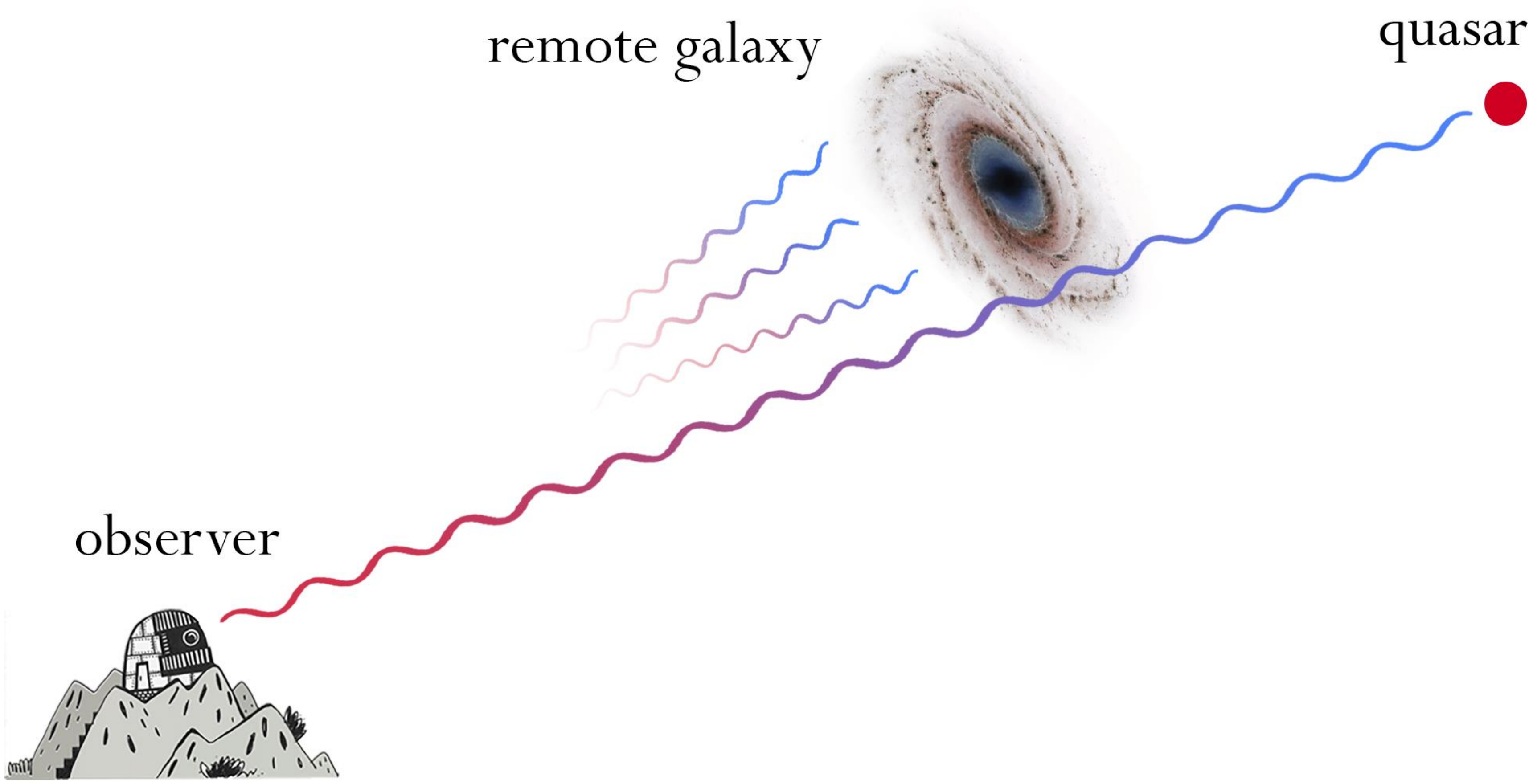
Galaxies at high redshifts are very dim



Therefore in emission we can observe only the most brightest galaxies at high redshift

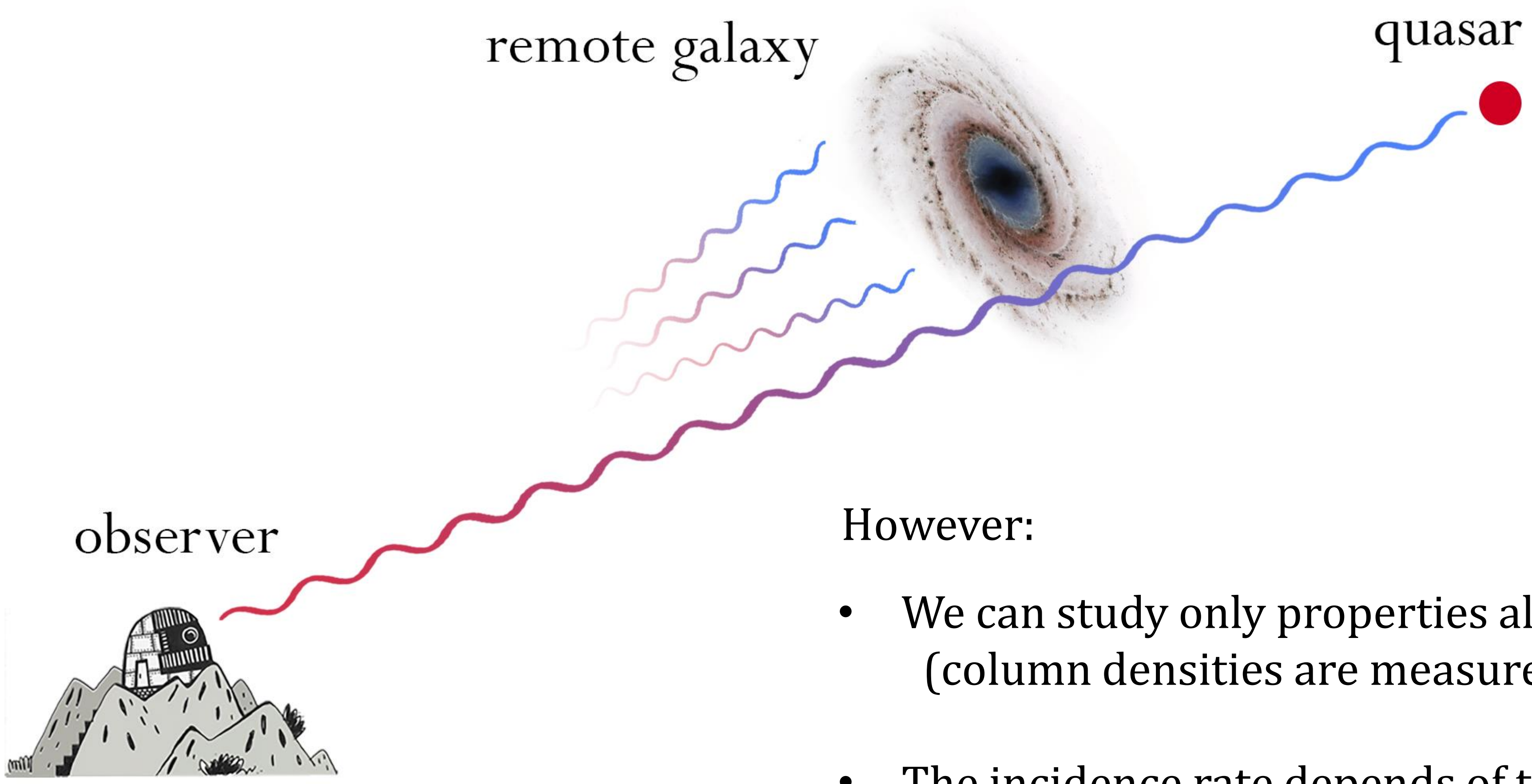
ISM at high redshift

There is no such problem for absorption line studies using background source (quasar of GRB afterglow)



ISM at high redshift

There is no such problem for absorption line studies using background source

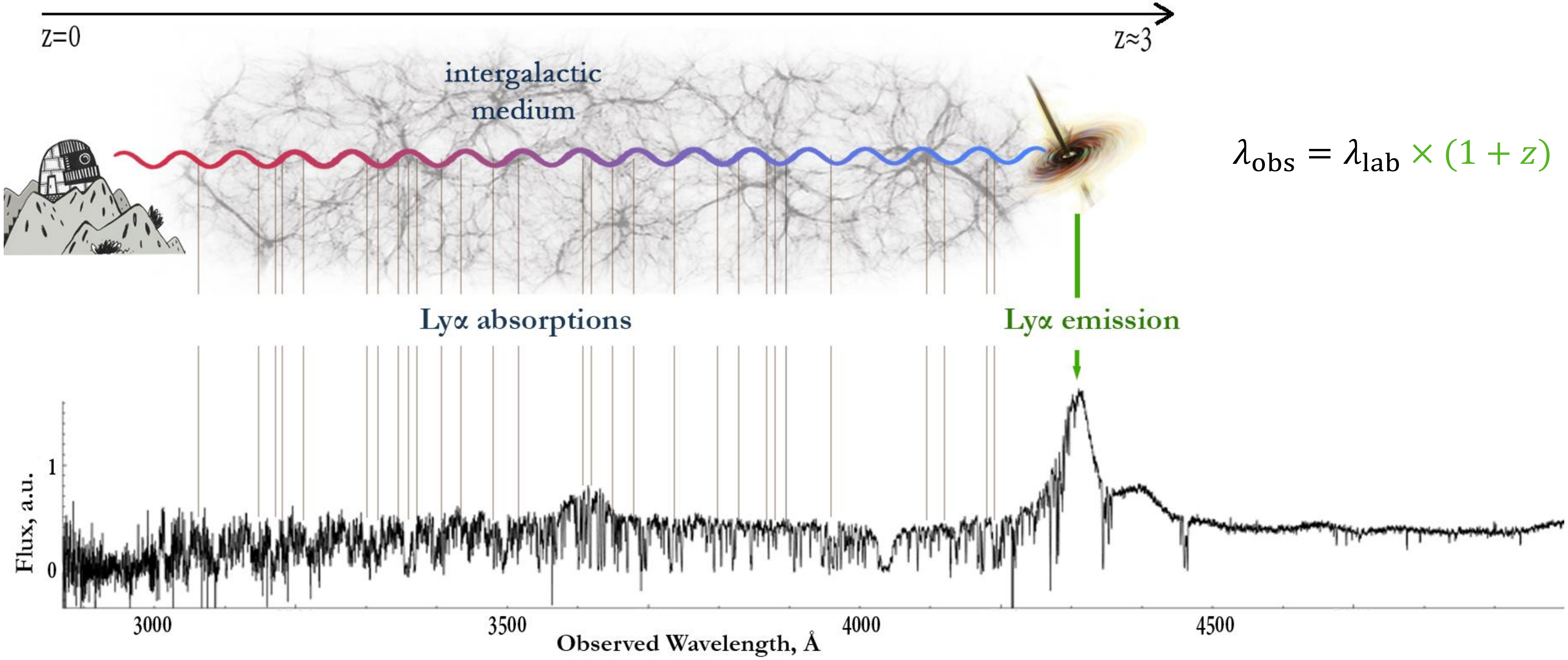


However:

- We can study only properties along the beam (column densities are measured)
- The incidence rate depends of the cross-section (that is relatively small)

Quasars: spectroscopy

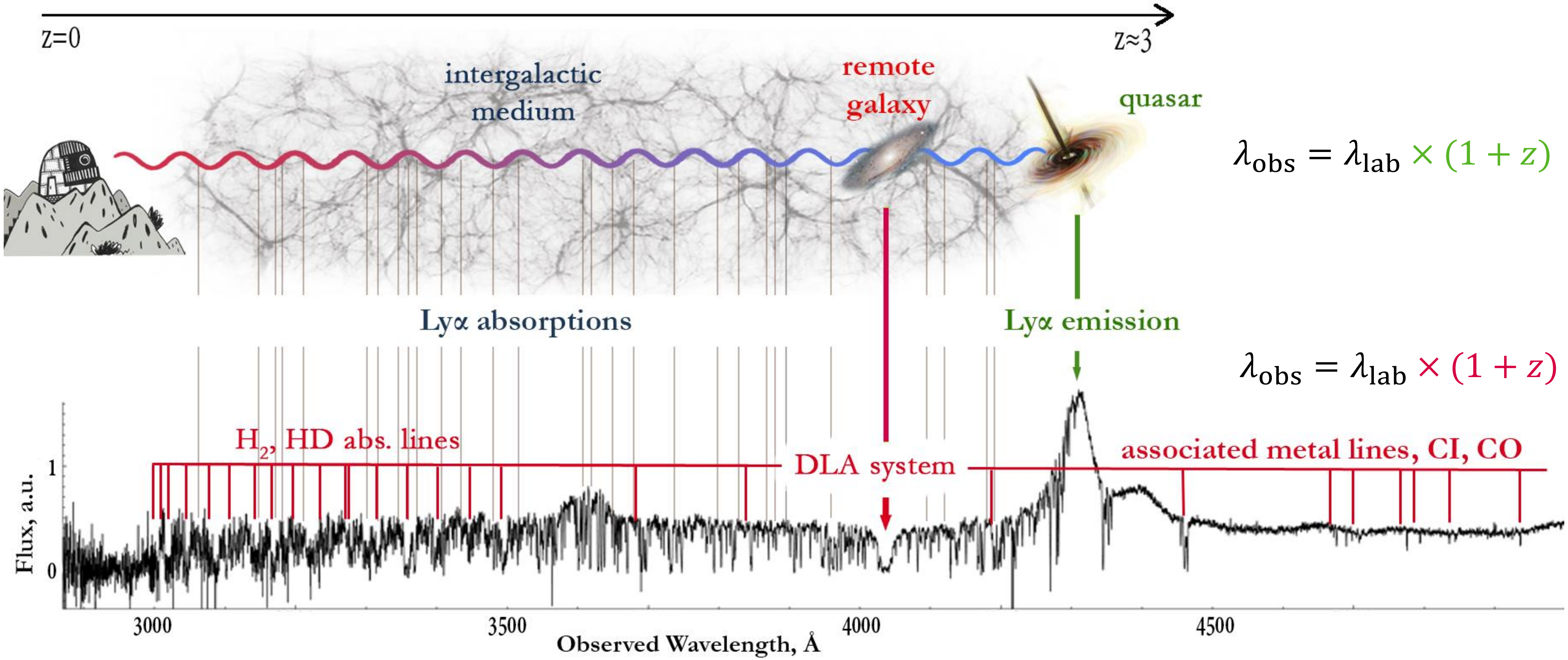
Studies of absorption lines in quasar spectra provide an unique information about the cosmological parameters and intergalactic, circumgalactic and interstellar medium of high redshift galaxies.



$$\lambda_{\text{obs}} = \lambda_{\text{lab}} \times (1 + z)$$

Quasars: spectroscopy

Studies of absorption lines in quasar spectra provide an unique information about the cosmological parameters and intergalactic, circumgalactic and interstellar medium of high redshift galaxies.



$$\lambda_{obs} = \lambda_{lab} \times (1 + z)$$

$$\lambda_{obs} = \lambda_{lab} \times (1 + z)$$

Cold phase of the neutral ISM

Due to the thermal balance, the neutral ISM segregates into two distinct stable phases:

1. **Warm** neutral (WNM)

$$\begin{cases} T_{\rm kin} \approx 8000~{\rm K} \\ n \lesssim 10~{\rm cm}^{-3} \\ \boldsymbol{b_{\rm th} \sim {\rm few} \times {\rm km/s}} \end{cases}$$

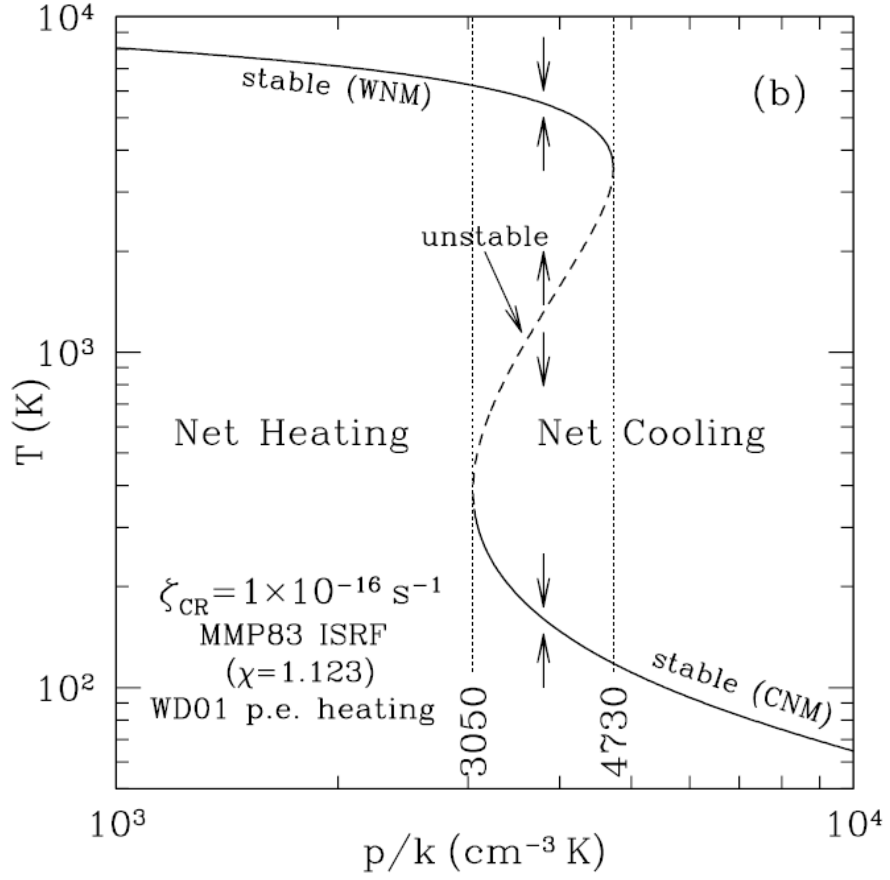
2. **Cold** neutral (CNM)

$$\begin{cases} T_{\rm kin} \approx 100~{\rm K} \\ n \gtrsim 10~{\rm cm}^{-3} \\ \boldsymbol{b_{\rm th} \lesssim {\rm km/s}} \end{cases}$$

Phases can be in equilibrium at some range of the thermal pressure:

$$P \sim 3000 - 5000~{\rm K~cm}^{-3} \qquad \text{(depends on the physical conditions, metallicity, UV, ...)}$$

Draine 2011



Cold phase of the neutral ISM

Due to the thermal balance, the neutral ISM segregates into two distinct stable phases:

1. **Warm** neutral (WNM)

$$\begin{cases} T_{\text{kin}} \approx 8000\ \text{K} \\ n \lesssim 10\ \text{cm}^{-3} \\ \boldsymbol{b}_{\textbf{th}} \sim \textbf{few} \times \textbf{km/s} \end{cases}$$

2. **Cold** neutral (CNM)

$$\begin{cases} T_{\text{kin}} \approx 100\ \text{K} \\ n \gtrsim 10\ \text{cm}^{-3} \\ \boldsymbol{b}_{\textbf{th}} \lesssim \textbf{km/s} \end{cases}$$

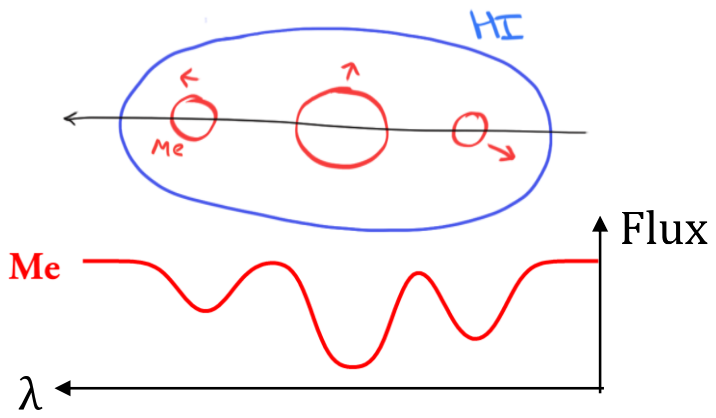
But there is also non-thermal motions:

1. turbulent (peculiar) broadening.

   In microturbulent assumption ($b_{\text{turb}} \lesssim \text{several} \times \text{km/s}$) the total broadening of the lines:

$$b = \sqrt{b_{\text{th}}^2 + b_{\text{turb}}^2}$$

2. Several velocity components along the line of sight:



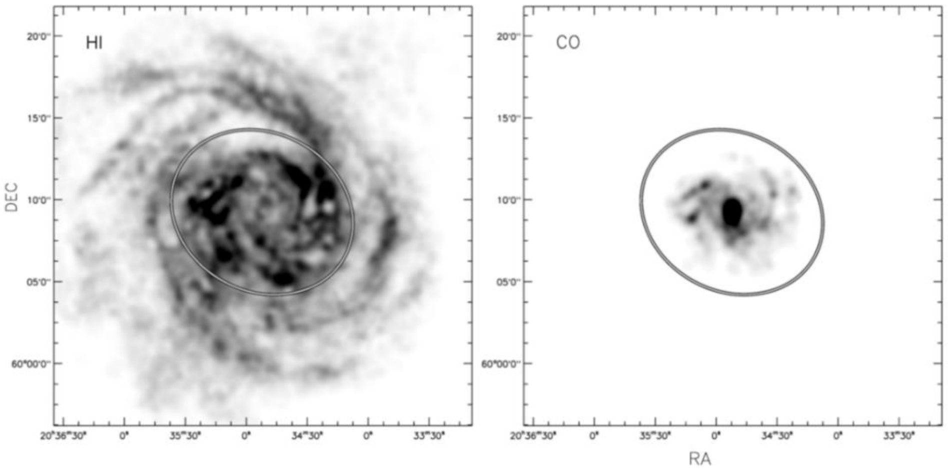
Quasars: the cold neutral medium

The cold phase of the ISM is probe by:

RARE, <5%

1. Low ionization metals: C I, Cl I, Si I, Fe I, Mg I
2. Molecules: H_2, HD, CO
3. Indirectly by dust (and 2175A)

Explained by the difference in the cross–section of cold and warm phase:

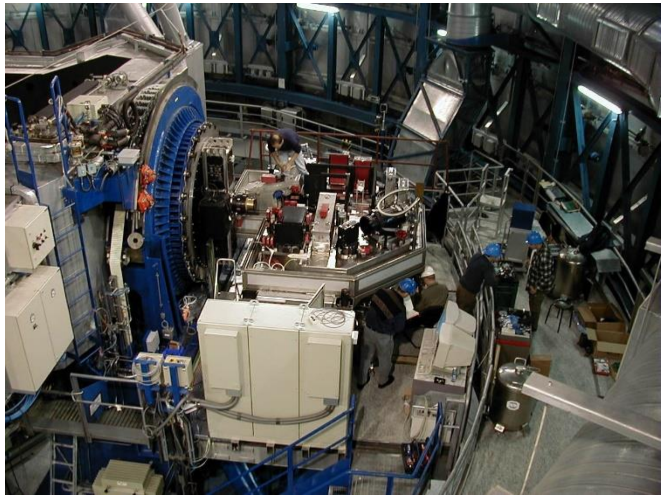


NGC 6946

UVES

Most of the information of the cold ISM in absorption at high z was collected by UVES (and HIRES):

UVES



$R \approx 50000$

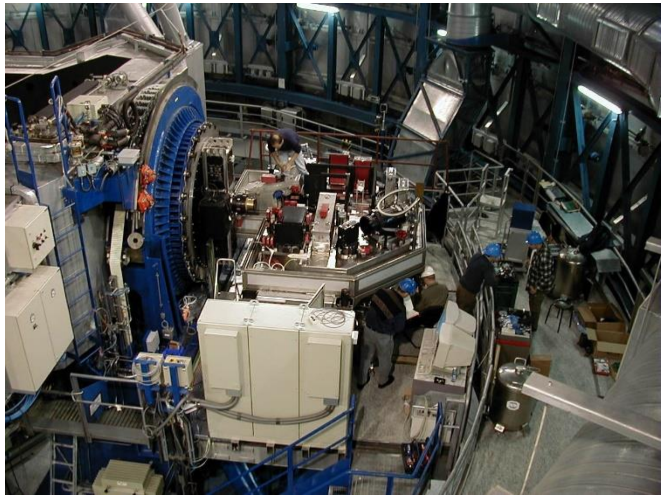
$\mathrm{FWHM} \sim 6\ \mathrm{km/s}$

(in case of joint fit of several transition one can go **below this limit**, but the velocity structure should be confidently resolved)

UVES and ESPRESSO

Most of the information of the cold ISM in absorption at high z was collected by UVES (and HIRES):

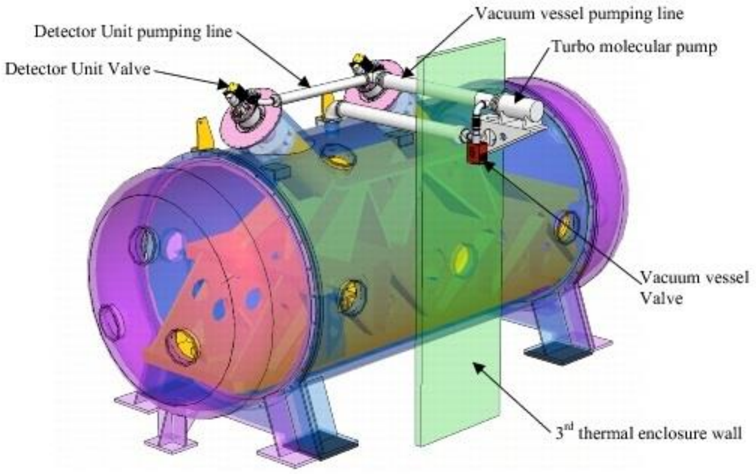
UVES



$R \approx 50000$

$\mathrm{FWHM} \sim 6\ \mathrm{km/s}$

ESPRESSO



$R \approx 140000$

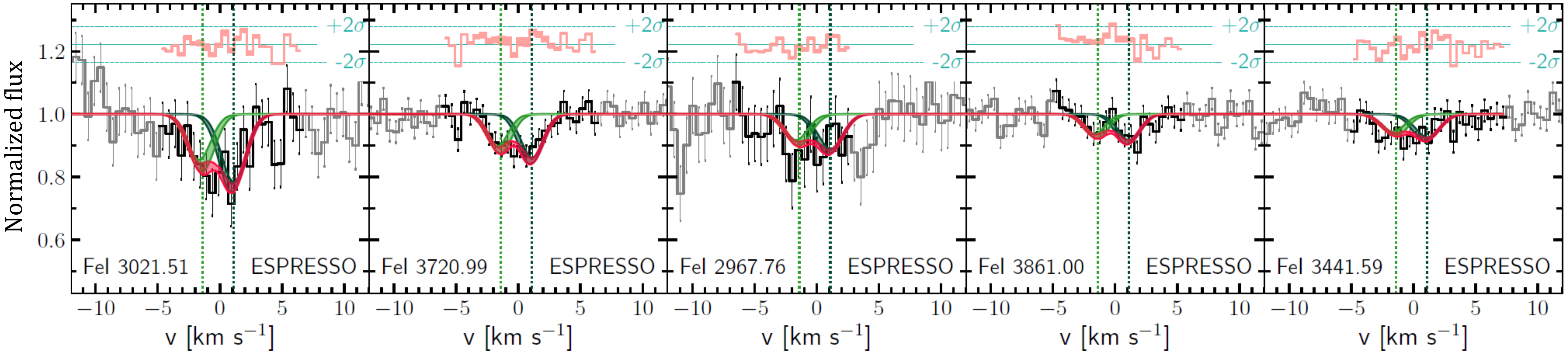
$\mathrm{FWHM} \sim 2\ \mathrm{km/s}$

(in case of joint fit of several transition one can go below this limit, but the **velocity structure** should be confidently **resolved**)

(i) Resolving the velocity structure

The comparison of the ESPRESSO and UVES spectra allows to resolve a velocity structure in **FeI z=0.45** absorber towards HE 0001-2340

Noterdaeme,SB+2021

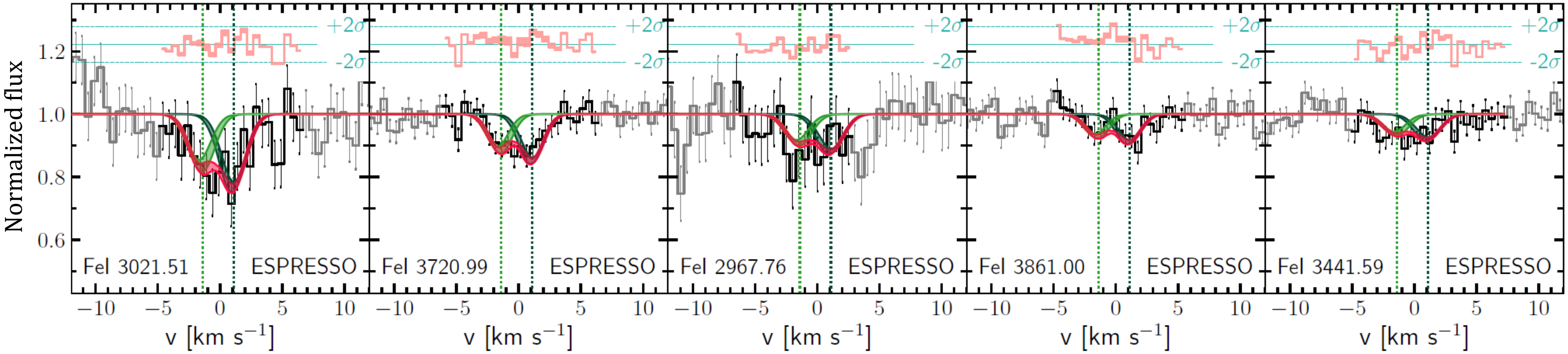


Fit to FeI absorption system at z=0.45 towards HE0001-2340 using **ESPRESSO spectrum**

(i) Resolving the velocity structure

The comparison of the ESPRESSO and UVES spectra allows to resolve a velocity structure in **FeI z=0.45** absorber towards HE 0001-2340

Noterdaeme,SB+2021



Fit to FeI absorption system at z=0.45 towards HE0001-2340 using **ESPRESSO spectrum**

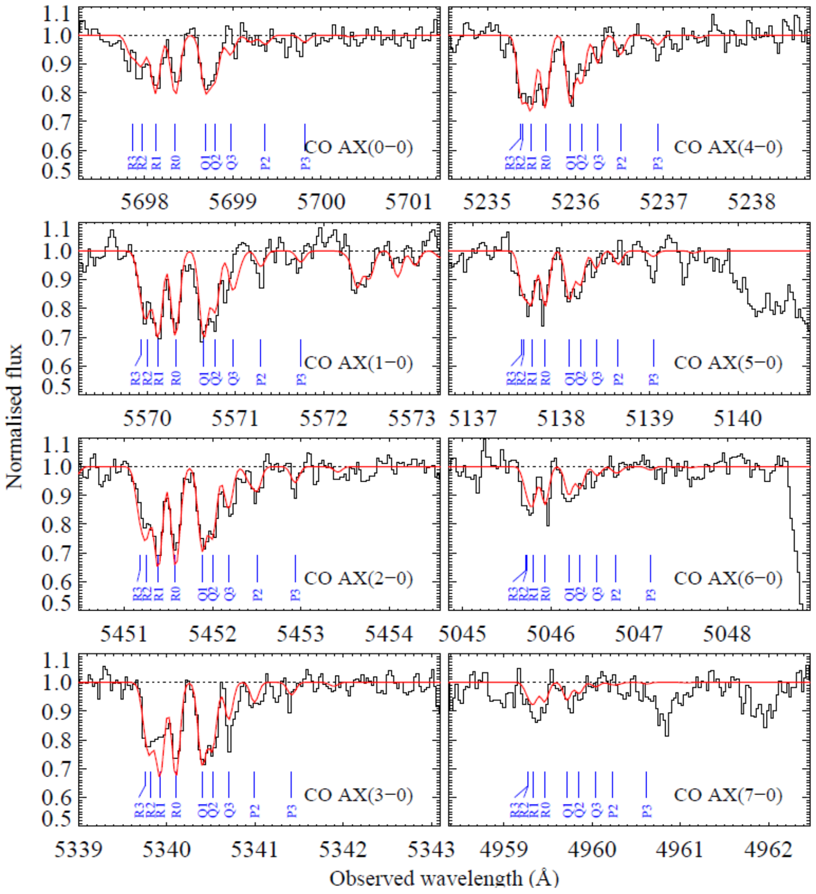
Each system indicates a very small Doppler parameters:

Species (X)	z	b ($\mathrm{km\,s^{-1}}$)	$\log N(\mathrm{X})$	C_f [(a)]
Fe I	$0.4520546(^{+5}_{-4})$	$0.22^{+0.05}_{-0.03}$	$11.94^{+0.03}_{-0.06}$	$0.45^{+0.06}_{-0.05}$
Fe I	$0.4520668(^{+6}_{-5})$	$0.39^{+0.06}_{-0.04}$	$12.02^{+0.03}_{-0.04}$	

⟹ Corresponding to temperatures $T_{\mathrm{kin}} \lesssim 200$ K and low turbulent broadening

(ii) Resolving CO lines

In a very small fraction of DLAs **CO absorption lines** can be detected:

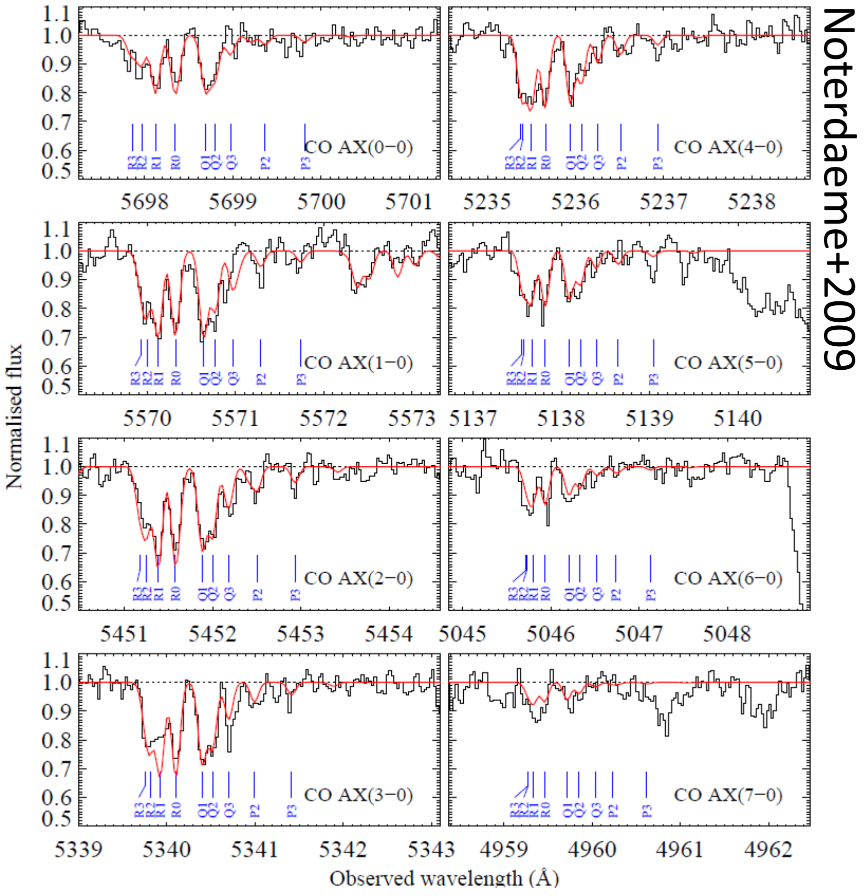


Noterdaeme+2009

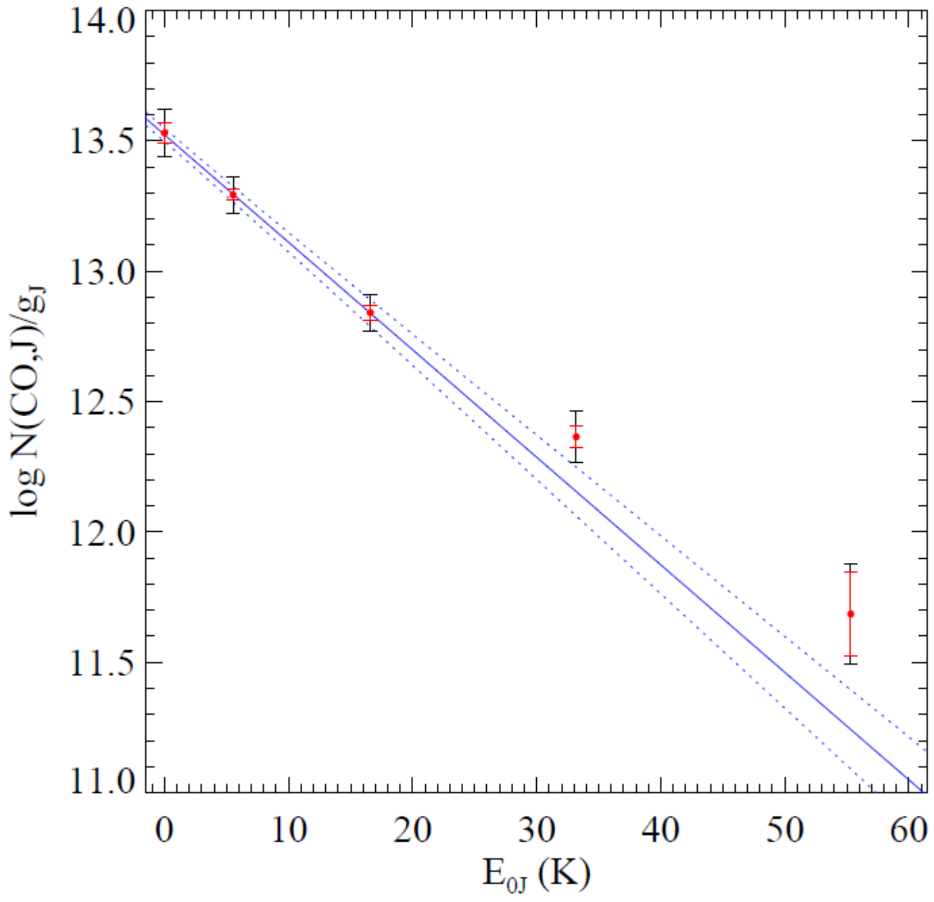
The UVES spectrum of CO at z=2.47 towards J1237+0647

(ii) Resolving CO lines

These lines allows to measure the population of CO rotational levels



⇒



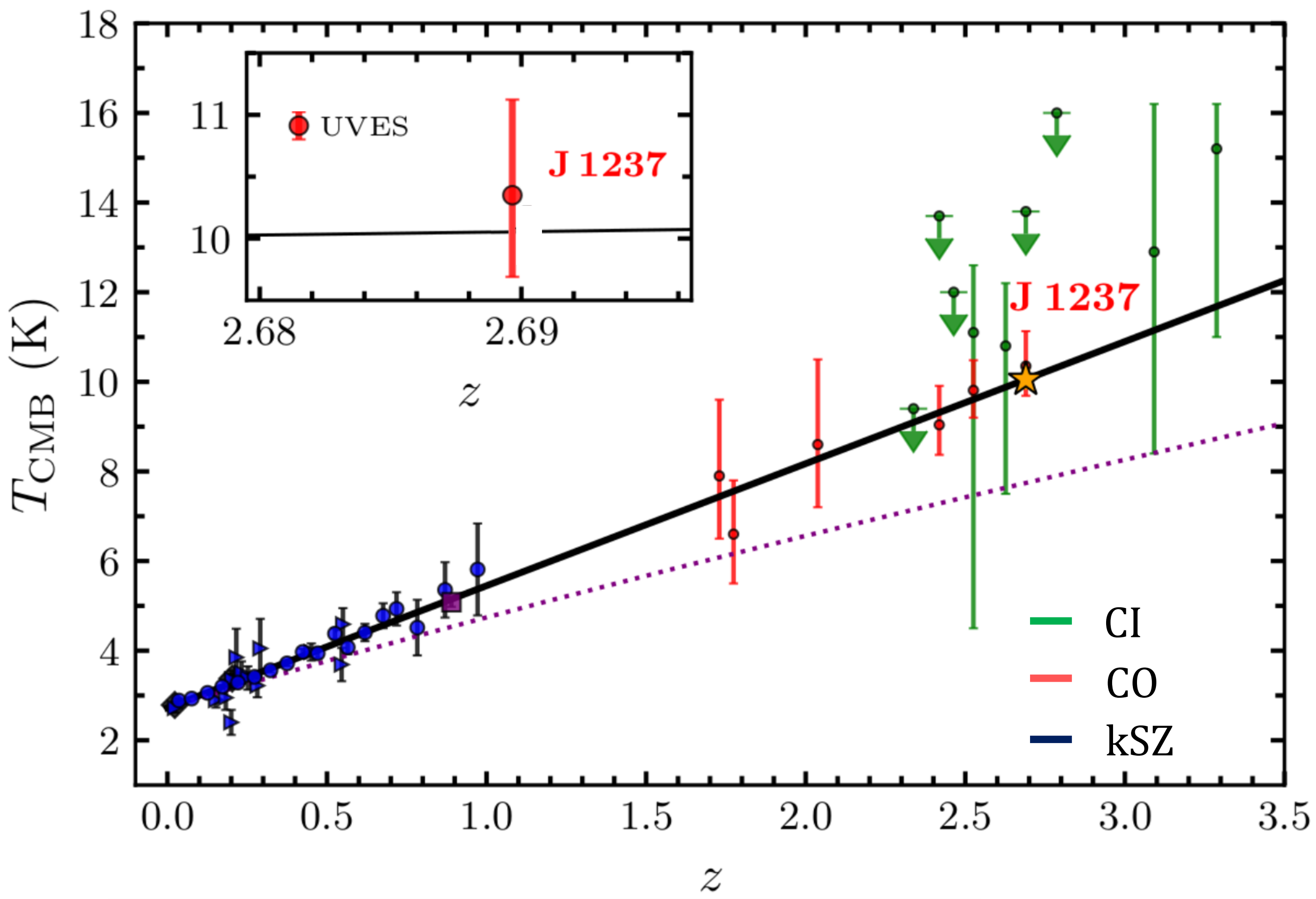
The UVES spectrum of CO at z=2.47 towards J1237+0647

Excitation diagram of CO rotational levels

(ii) Resolving CO lines

... and to constrain the temperature of CMB at high redshifts:

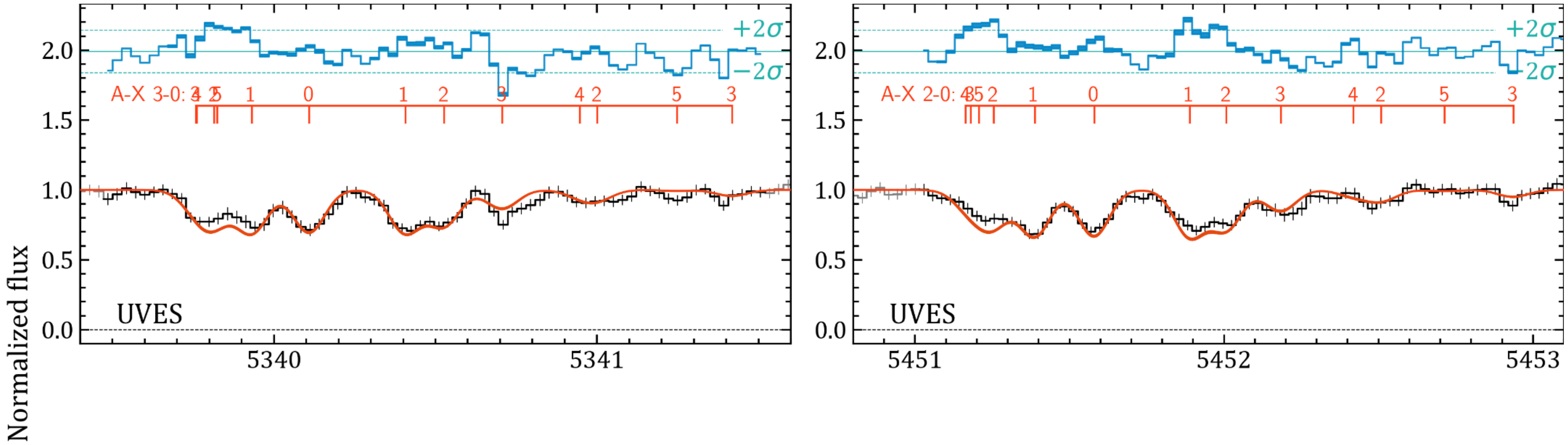
⇒



Constraint on the CMB Temperature over the redshifts

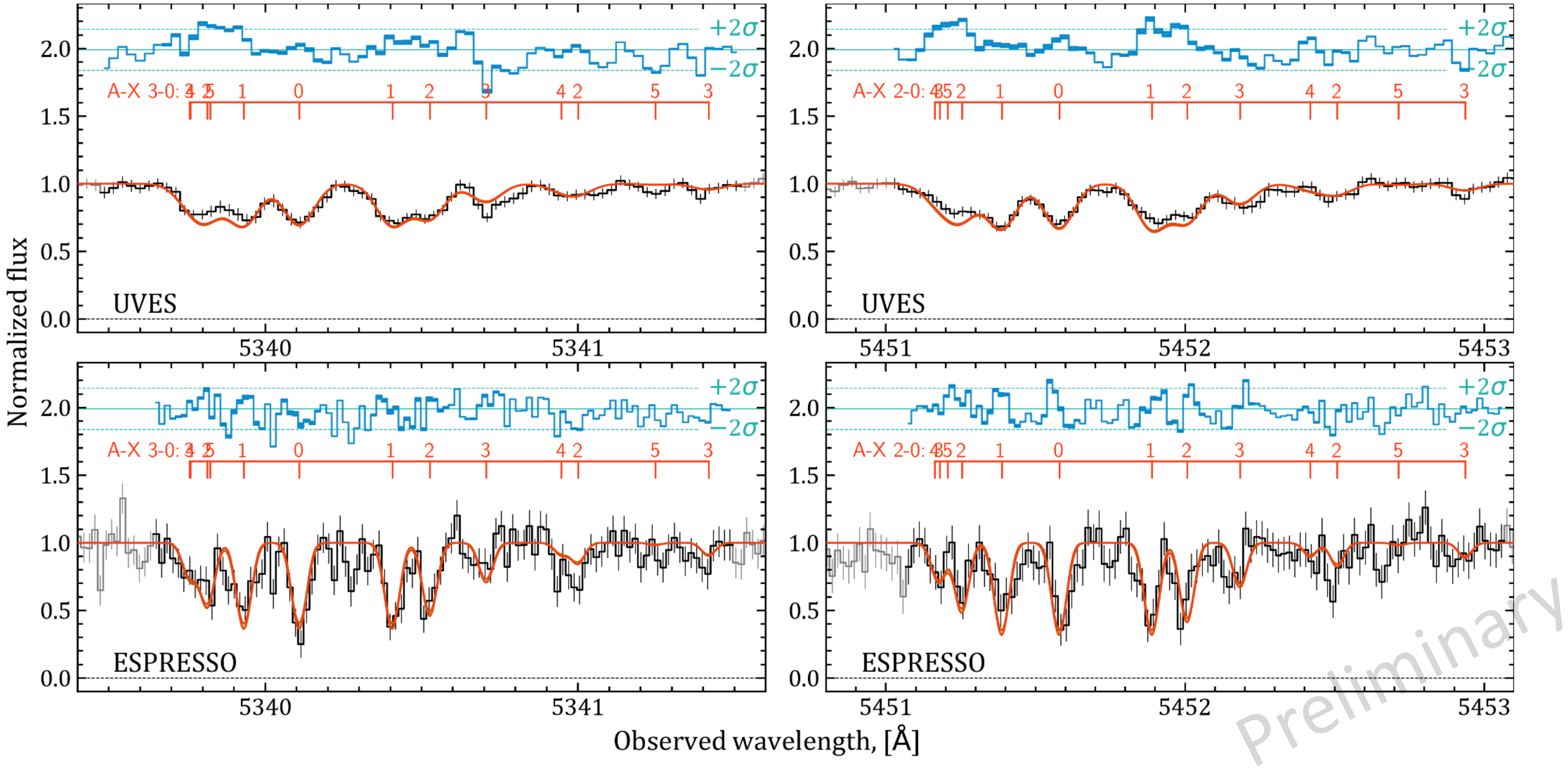
(ii) Resolving CO lines

CO absorption lines are not well resolve in UVES spectrum:



(ii) Resolving CO lines

The ESPRESSO allows to resolve **CO absorption lines** along bands of electronic transitions:

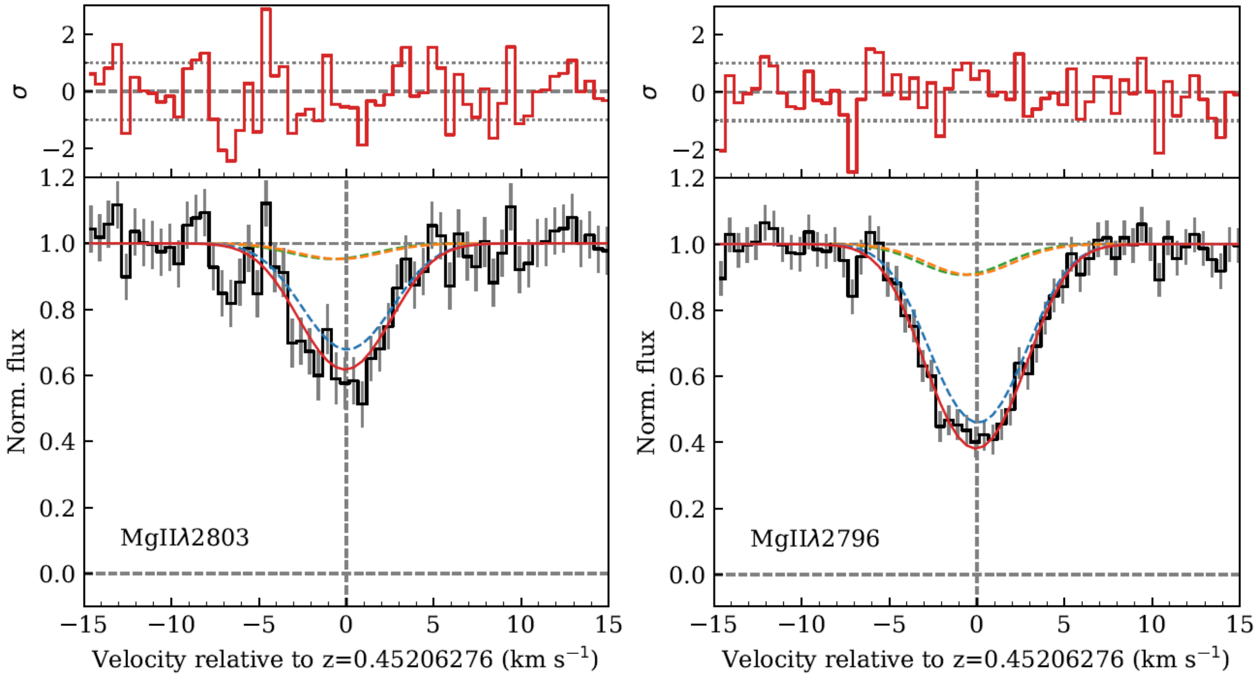


The comparison between UVES and ESPRESSO (30 % of the data) spectrum of CO at z=2.47 towards J1237+0647

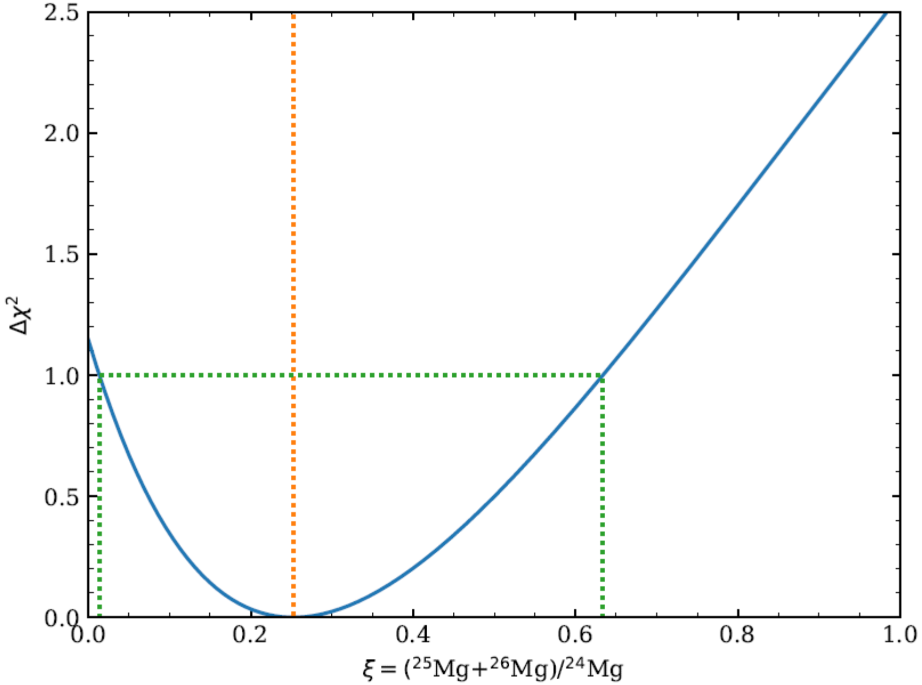
(iii) Isotopic ratio: MgII

The ESPRESSO allows to confidently constrain **MgII isotopic ratio** at z=0.45 towards HE 0001-2340

Noterdaeme,SB+2021



Noterdaeme,SB+2021

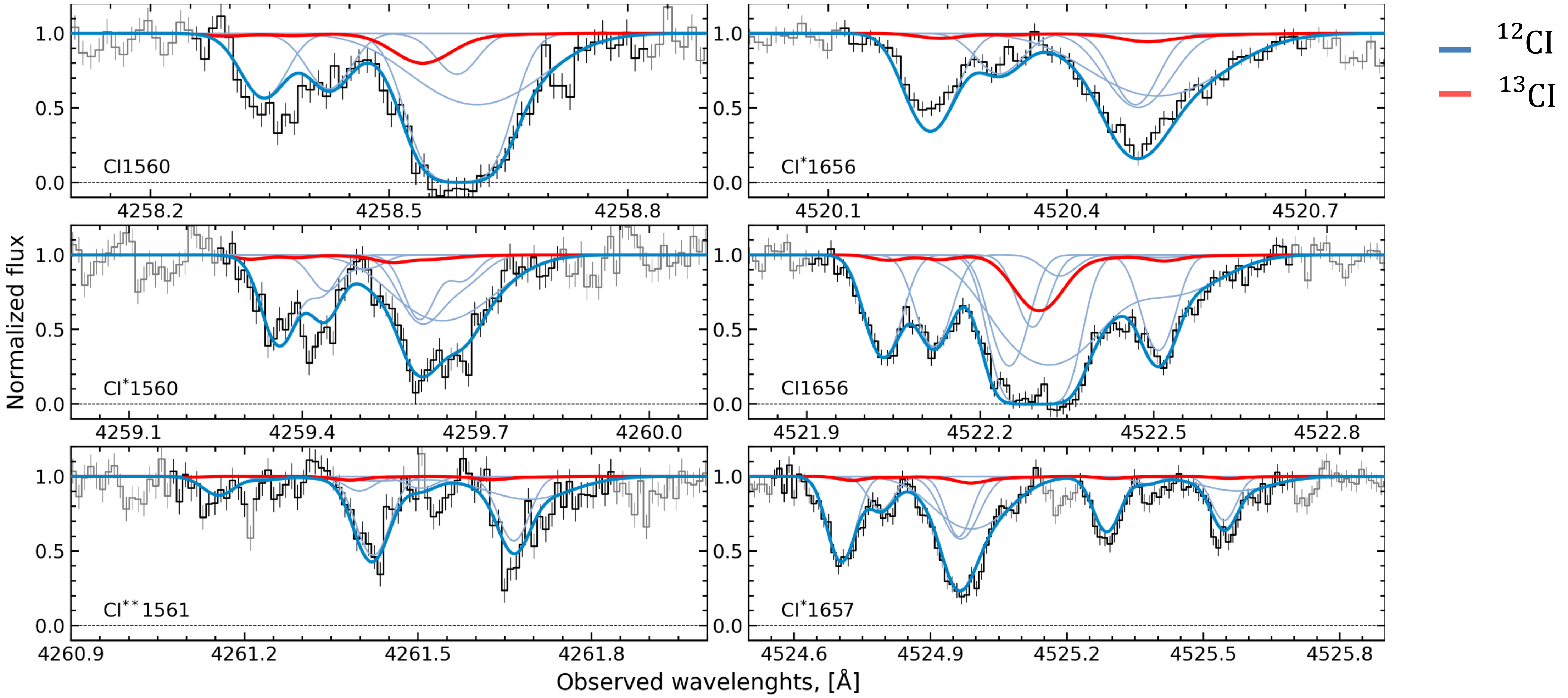


MgII isotopic ratios **consistent with solar**, i.e. w/o hints of heavy enrichment, which was previously reported based on UVES data (Agafonova+2007).

The same problem is for CII (see ESPRESSO results from Welsh+2020)

(iii) Isotopic ratio: CI

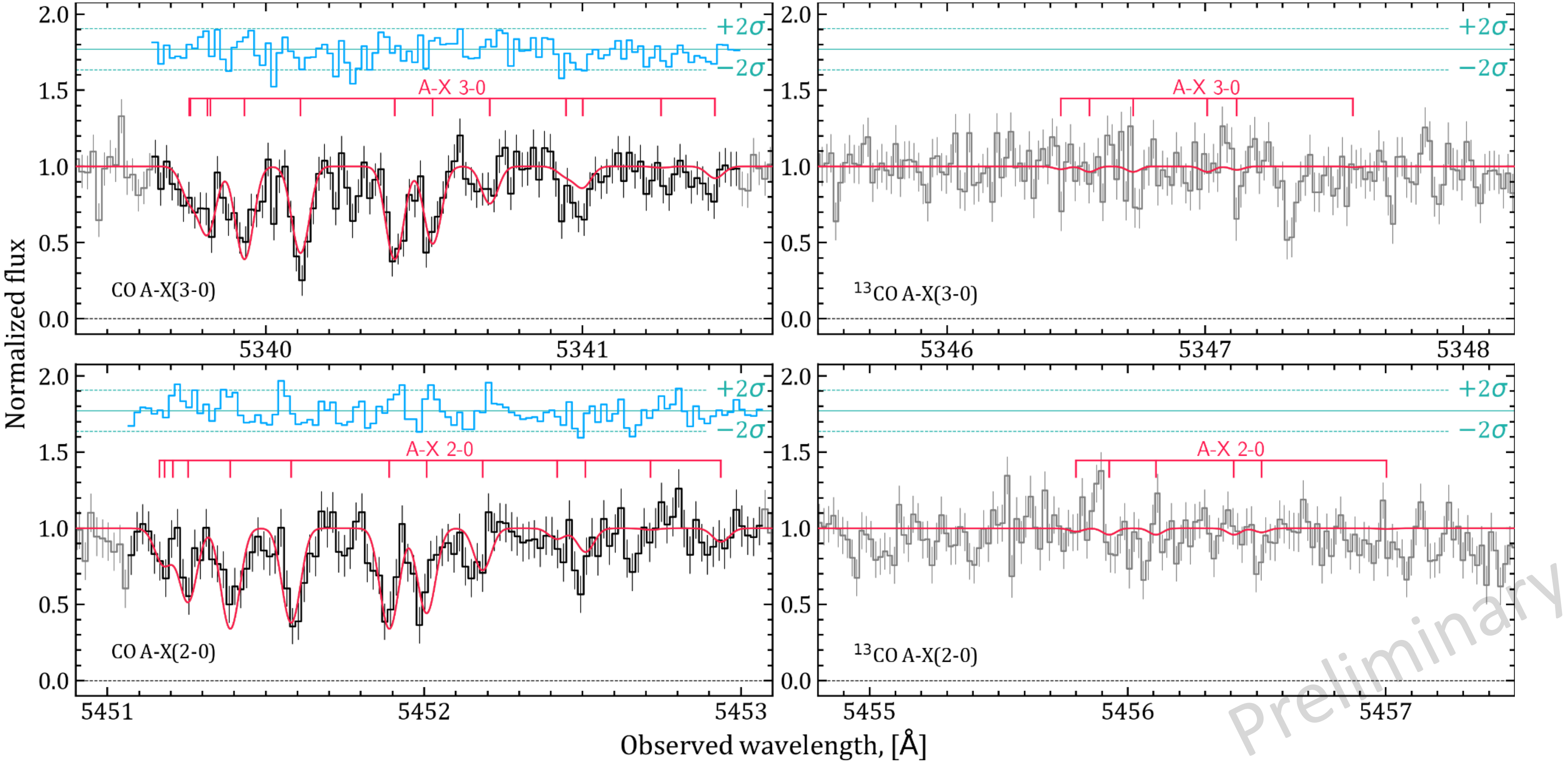
In principle, the ESPRESSO spectrum allows to constrain **C isotopic ratio:**



The ESPRESSO spectrum towards J0857+1855. Fit to CI absorption lines $z \approx 1.8$ including ^{13}CI

(iii) Isotopic ratio: CO

The ESPRESSO will possibly allow constrain ^{13}**CO/**^{12}**CO ratio** using absorption lines:



The ESPRESSO (30 % of the data) spectrum of CO at z=2.47 towards J1237+0647

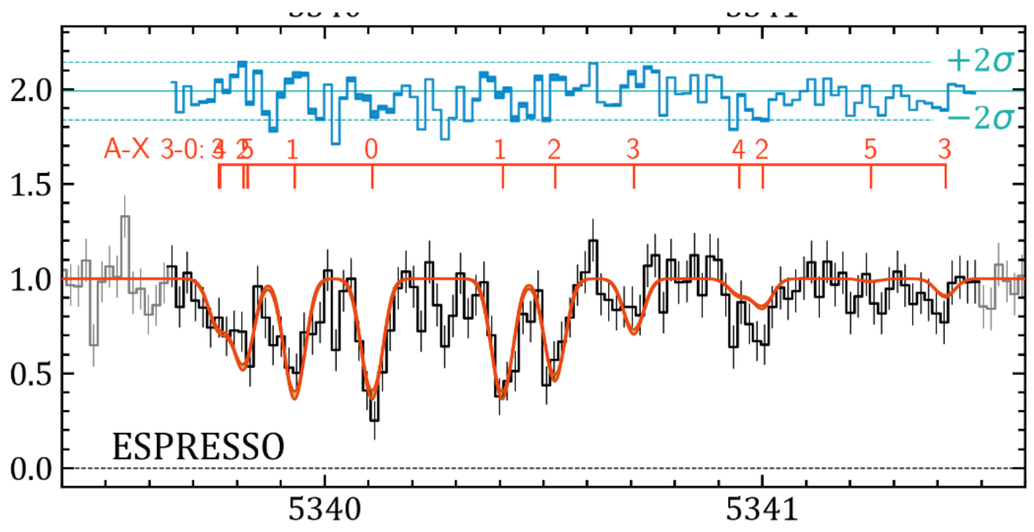
Conclusions

Due to unprecedent spectral resolution ESPRESSO provides an unique insight on the cold gas at high redshift galaxies:

1. To resolve velocity structure of the absorber

2. To resolve CO absorption band and improve the accuracy of the CMB temperature measurements

3. To constrain the isotopic ratios of metals (e.g. Mg, C)



This work is supported by RSF 23-12-00166