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A new precise determination of the primordial abundance of deuterium: measurement in the metal-poor sub-DLA system at $z = 3.42$ towards quasar J 1332+0052

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ABSTRACT

The theory of Big Bang nucleosynthesis, coupled with an estimate of the primordial deuterium abundance $(D/H)_{\text{pr}}$, offers insights into the baryon density of the Universe. Independently, the baryon density can be constrained during a different cosmological era through the analysis of cosmic microwave background anisotropy. The comparison of these estimates serves as a rigorous test for the self-consistency of the standard cosmological model and stands as a potent tool in the quest for new physics beyond the standard model of particle physics. For a meaningful comparison, a clear understanding of the various systematic errors affecting deuterium measurements is crucial. Given the limited number of D/H measurements, each new estimate carries significant weight. This study presents the detection of D I absorption lines in a metal-poor sub-Damped Lyman- α system ($[O/H] = -1.71 \pm 0.02$, $\log N(\text{H I}) = 19.304 \pm 0.004$) at $z_{\text{abs}} = 3.42$ towards the quasar SDSS J133254.51+005250.6. Through simultaneous fitting of H I and D I Lyman-series lines, as well as low-ionization metal lines, observed at high spectral resolution and high signal-to-noise using VLT/UVES and Keck/HIRES, we derive $\log(D/\text{H I}) = -4.622 \pm 0.014$, accounting for statistical and systematic uncertainties of 0.008dex and 0.012 dex, respectively. Thanks to negligible ionization corrections and minimal deuterium astration at low metallicity, this D/H ratio provides a robust measurement of the primordial deuterium abundance, consistent and competitive with previous works. Incorporating all prior measurements, the best estimate of the primordial deuterium abundance is constrained as: $(D/H)_{\text{pr}} = (2.533 \pm 0.024) \times 10^{-5}$. This represents a 5 per cent improvement in precision over previous studies and reveals a moderate tension with the expectation from the standard model ($\approx 2.2\sigma$). This discrepancy underscores the importance of further measurements in the pursuit of new physics.

Key words: ISM: clouds – quasars: absorption lines – cosmological parameters – primordial nucleosynthesis.

1 INTRODUCTION

Primordial nucleosynthesis is one of the pillars of the Big Bang cosmology that provides the earliest robust observational constraint on the standard cosmological model. The theory of primordial nucleosynthesis predicts the values of the relative abundances of light nuclei such as H, D, ^3He , ^4He , and ^7Li . According to the standard model, these abundances depend only on the baryon-to-photon ratio, $\eta_{\text{b}} \equiv \frac{n_{\text{b}}}{n_{\gamma}}$ (where n_{b} , n_{γ} – the number densities of baryons and photons, respectively), that is linearly dependent on the baryon density, Ω_{b} . However, some of these nuclei are sensitive to effects beyond the standard model. As an example, the primordial helium abundance could provide a constraint on the effective number of neutrino species (Kurichin et al. 2021b). This draws a lot of attention to the determination of the primordial helium abundance and its estimates are steadily improving (e.g. Izotov, Thuan & Guseva 2014;

Fernández et al. 2018; Hsyu et al. 2020; Aver et al. 2021; Kurichin, Kislitsyn & Ivanchik 2021a; Valerdi, Peimbert & Peimbert 2021; Matsumoto et al. 2022). Despite growing observational constraints on helium-4, deuterium plays a key role in the modern era of precise cosmology since it has the strongest sensitivity on Ω_{b} among the other elements and its abundance can be accurately constrained using absorption-line measurements along quasar sightlines.

With the advent of high-resolution spectrographs on the largest optical telescopes, for more than two decades D/H measurements were derived from the analysis of hydrogen and deuterium absorption lines in quasar spectra (Tytler, Fan & Burles 1996; Noterdaeme et al. 2012; Cooke et al. 2014; Cooke, Pettini & Steidel 2018). The first results on D/H possessed a high dispersion, the reasons of which could be explained by systematic effects in the analysis or could have physical origins. This has motivated the search for criteria that minimize the systematics and provide the most precise D/H measurements (so called *precision sample* by Cooke et al. 2014). The main criteria are a simple velocity structure for the absorber, low deuterium astration, and depletion on the dust (Cooke, Pettini &

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Table 1. VLT/UVES observations of J 1332+0052.

UT date	Exp. time (s)	Setup ^a (nm)	Airmass	IQ ^b (arcsec)
09-04-2018	2 × 3000	437 + 760	1.27	0.83
13-04-2018	4 × 3000	437 + 760	1.12/1.16	0.55/0.6
18-05-2018	2 × 3000	390 + 564	2.02	1.24
12-06-2018	4 × 3000	390 + 564	1.23/1.44	0.98/1.05
13-06-2018	6 × 3000	437 + 760	1.19/1.36/1.70	0.78/1.08/1.22
15-06-2018	4 × 3000	437 + 760	1.11/1.14	1.09/1.17
09-07-2018	2 × 3000	390 + 564	1.70	1.23

Note.^a central wavelengths of the blue-arm (left) and red-arm (right) spectra.
^b image quality at $\lambda = 650$ nm measured by the telescope Shack-Hartmann wavefront sensor.

Steidel 2018), which are all satisfied in case of very low metallicities. Therefore, only a few D/H estimates are considered to date to provide robust results (Cooke, Pettini & Steidel 2018). Each new estimate is of utmost importance, for various combinations of parameters (e.g. metallicity, HI column density, simplicity of the velocity structure, redshift), that allow us to disentangling the influence of the aforementioned systematic effects on the measurement of D/H . Such measurements are especially important at the high-metallicity end, which can potentially increase the number of suitable targets, especially in the advent of next-generation spectrographs such as CUBES (Evans et al. 2022).

In this paper, we present the detection and analysis of D I lines in the sub-DLA system at $z_{\text{abs}} = 3.42$ towards SDSS J133254.51+005250.6. This provides a new robust determination of the D/H ratio at high redshift.

2 OBSERVATIONS AND DATA REDUCTION

2.1 VLT/UVES observations

SDSS J133254.51+005250.6 (hereafter J 1332+0052), a $z_{\text{em}} = 3.51$, $V = 18.7$ quasar (a.k.a. Q 1330+0108; Véron-Cetty & Véron 2010) was observed in service mode between 2018 April and July using the Very Large Telescope (VLT) Unit-2, Kueyen, equipped with the Ultraviolet and Visual Echelle Spectrograph (UVES; Dekker et al. 2000). Twelve exposures of 3000 s each were taken in Dichroic mode over seven different nights. This resulted in 24 individual spectra covering most of the optical range. Information about instrumental setups and observing conditions is given in Table 1. Entrance 1 arcsec-wide slits and 2×2 pixel binning were used throughout. The observations were carried out in dark time (no moon) under clear skies and excellent seeing conditions (see Table 1). For each exposure, we processed science and calibration data using the UVES pipeline v6.1 on the EsoReflex platform v2.11 (Freudling et al. 2013). Intermediate data products were inspected carefully and data-reduction parameters were optimized step by step. The nominal resolving power of the individual spectra is 50 000 in the Blue (48 800 in the Red) but can be slightly larger than that when the seeing conditions are better than 1 arcsec full width at half-maximum (FWHM). The actual resolving power of the combined spectrum used in the analysis is determined in Section 3.2. Individual exposures in each blue/red setup were co-added optimally and the overlapping regions of the resulting spectra were stitched together to create the final data product. The final UVES spectrum has a fairly high S/N ratio per pixel, peaking at ≈ 30 in the quasar continuum around the most important D I lines.

Table 2. Keck/HIRES observations of J 1332+0052.

UT date	Exp. time (s)	Wavelength range (nm)	Airmass	Decker
07-04-2006	2 × 3600	424–869	1.08/1.06	C1
12-04-2015	4 × 3600	392–686	1.06–1.20	C1
14-05-2015	3288 + 2678	424–869	1.15/1.07	C1

2.2 Keck/HIRES observations

In addition to the UVES spectra, we used archival spectra from the W.M. Keck Observatory using the High-Resolution Echelle Spectrometer (HIRES; Vogt et al. 1994). The journal of observations is given in Table 2. The nominal resolving power of the individual exposures is 47 700.

To reduce the data (eight separate exposures) and combine the extracted spectra, we used the approach described in Robert et al. (2018). To summarize it briefly, the data were reduced and the quasar spectra extracted using the MAKEE¹ package, including corrections for the blaze function using flat-field exposures and wavelength calibration from ThAr lamp exposures. The extracted spectra from all echelle orders, and all exposures, were combined into a nearly continuous 1D spectrum using the UVES_POPLER software (Murphy 2016; Murphy et al. 2018). All spectra were redispersed onto the same wavelength grid with 2.2 km s^{-1} pixels and combined using an inverse-variance-weighted mean. An initial continuum was automatically fitted to the regions redwards of the Lyman- α emission line, whilst a manually fitted polynomial was used for the bluer regions affected by the Lyman- α forest. The combined HIRES spectrum has an S/N ratio per pixel of ≈ 20 in the quasar continuum around the most important D I lines.

3 ANALYSIS

3.1 A method

To determine the properties of the sub-DLA system, we used joint multicomponent Voigt-profile fitting² of hydrogen, deuterium, and low-ionization metal absorption lines. Within this approach, each considered absorption line is described by a collection of components, that are defined by the redshift, Doppler parameter, and column density of each species. We used the same number of components for each line (except for Fe II where only the two main components are detected), with redshifts tied between lines. We also assumed that the Doppler parameters of each species within one component are tied based on the assumption of microturbulence, where the velocity distribution of each species is described by a Gaussian function with Doppler parameter

$$b_{\text{sp}} = \sqrt{b_{\text{turb}}^2 + \frac{2k_B T}{M_s}}, \quad (1)$$

where k_B is the Boltzmann constant, M_s is the atomic mass of species s , T is the kinetic temperature, and b_{turb} is the turbulent broadening parameter. Consequently, the latter two parameters were fitted independently in each velocity component.

To make the column-density determinations trustworthy, we carefully inspected each portion of the spectra to which the fitting procedure was applied. We simultaneously fitted any unrelated

¹See <http://www.astro.caltech.edu/~tb/makee>.

²We used the python package SPECTRO (<https://github.com/balashv/spectro>).

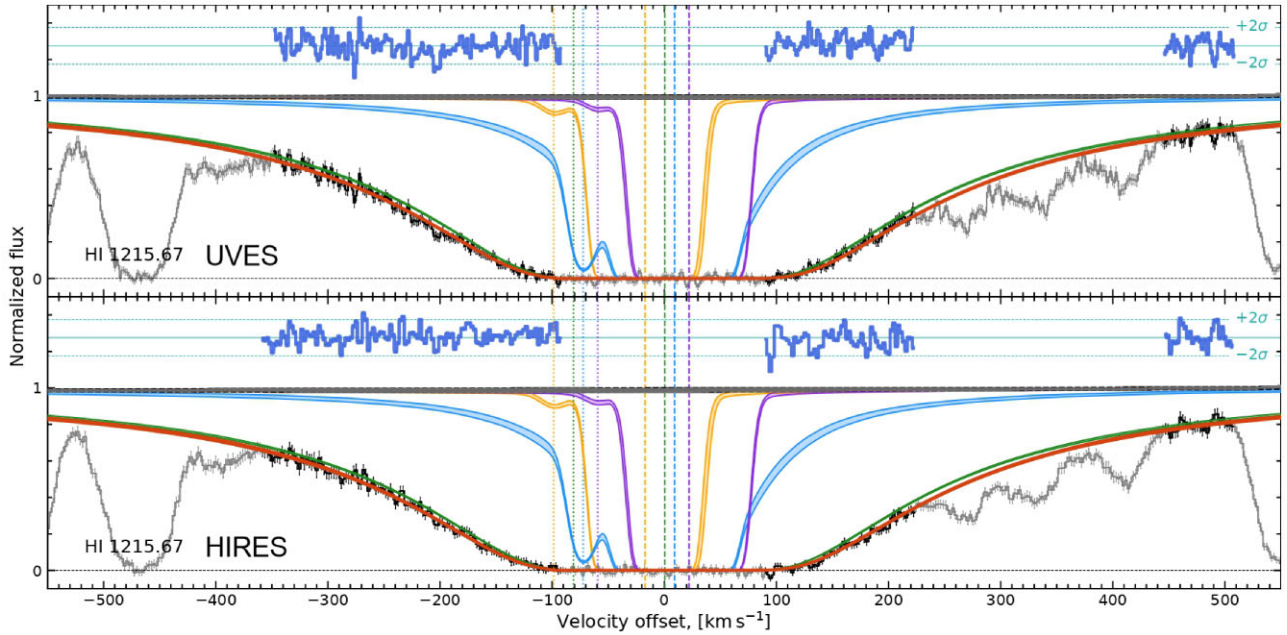


Figure 1. Fit to the H I Ly- α line at $z_{\text{abs}} = 3.42$ towards J 1332+0052. The black error bars show the pixels of the observed spectra used in the fit. Other pixels are displayed in grey. The total model profile is shown by red lines, while the other coloured lines indicate the contribution of individual components. The filled regions between lines correspond to 0.68 credible intervals drawn from the posterior parameter distribution estimated during MCMC fitting. Fit residuals are displayed above the profiles.

absorption which might have an impact on the fit. We also paid special attention to including all available D I and H I lines to avoid unconscious bias leading to include/exclude lines which may seem to be more/less suitable.

For the metal lines and Lyman-series lines, we first reconstructed a local continuum by spline interpolation from regions without evident absorption. While for the metal lines, outside Ly α forest, we found that continuum can be well constrained, for some of Ly-series lines it is not the case, and assumed continuum may impact on the derived H I and D I column densities (see e.g. Balashev et al. 2016). Therefore we fitted the continuum for several selected Lyman-series lines simultaneously with line profiles to exclude a bias related to a manual continuum placement. To do this we used Chebyshev polynomials of the order of five, three, and one in the regions near Ly α , Ly β , other Lyman-series lines, respectively. In addition, we fitted the effective resolutions of the final UVES and HIRES spectra as independent parameters.

We constrained the probability density distribution of the fit parameters within the Bayesian framework, using the Monte Carlo Markov Chain technique with Affine invariant sampler (Goodman & Weare 2010). We assumed flat priors on b_{turb} , T_{kin} , z , $\log N$, the continuum Chebyshev coefficients, C_i , and resolutions of the spectra R_{UVES} , R_{HIRES} , with enough width to guarantee independence of the posteriors on it. We also assumed a same D/H value for all components, i.e. we used a single parameter for the whole subDLA. To report the resulting fit parameters and their uncertainties, we used the maximum posterior probability estimates and highest posterior density 68.3 per cent credible intervals, respectively.

3.2 Fit description and results

We used a four-component model to fit H I, D I, and low-ionization metal lines. While the absorption profile is dominated by two main components, with a velocity separation smaller than 10 km s^{-1} , we added two weak components within a $\approx 40 \text{ km s}^{-1}$ span, barely

seen in the strong C II 1334 and Si II 1260 transition lines. The line profiles of H I Ly α , low-ionization metal species, and the higher order Lyman series of H I and D I are presented in Figs 1, 2, 3, 4, and 5. The values of the fitting parameters are given in Table 3. In the figures, we demonstrate the portions of UVES and HIRES spectra near the sub-DLA absorption system with the best-fitting model and the confidence intervals for all components inside the sub-DLA system. The first thing that could catch the eye is a high signal-to-noise ratio which we consider the main source of the small statistical error of our D/H determination. Another point is that despite individual components having noticeable uncertainties shown by the width of colourful lines, the total fit shown in red is very well constrained. To make the analysis more robust we examined the residuals of the fit which we also show in these figures. In general, the residuals comfortably lie in the range inside 2σ with rare outliers in good agreement with the statistical predictions. There are, however, some regions where one could see a quite significant structure and this is also discussed in Section 3.3. We also note that the estimated resolving powers of UVES and HIRES spectra are $R_{\text{UVES}} = 50800 \pm 1400$, $R_{\text{HIRES}} = 49200 \pm 1500$. These values are in excellent agreement with the nominal values for these spectrographs, and the posterior distribution function indicates no correlation between the D/H value and resolution.

The total H I column density is $\log N = 19.304 \pm 0.004$, indicating that this system belongs to the class of sub-DLAs, where one may expect substantial ionization corrections. However, thanks to almost the same ionization potentials of hydrogen and deuterium these ionization corrections are not suitable for the problem of the D/H determination. It has been also shown that the D/H ionization correction is typically an order of magnitude smaller than current uncertainties of D/H determinations even for sub-DLA systems (Cooke & Pettini 2015).

Since oxygen has an ionization potential close to the ionization potential of hydrogen too, our constraint on the O I column density could be used to derive the metallicity of the system: $[\text{O}/\text{H}] =$

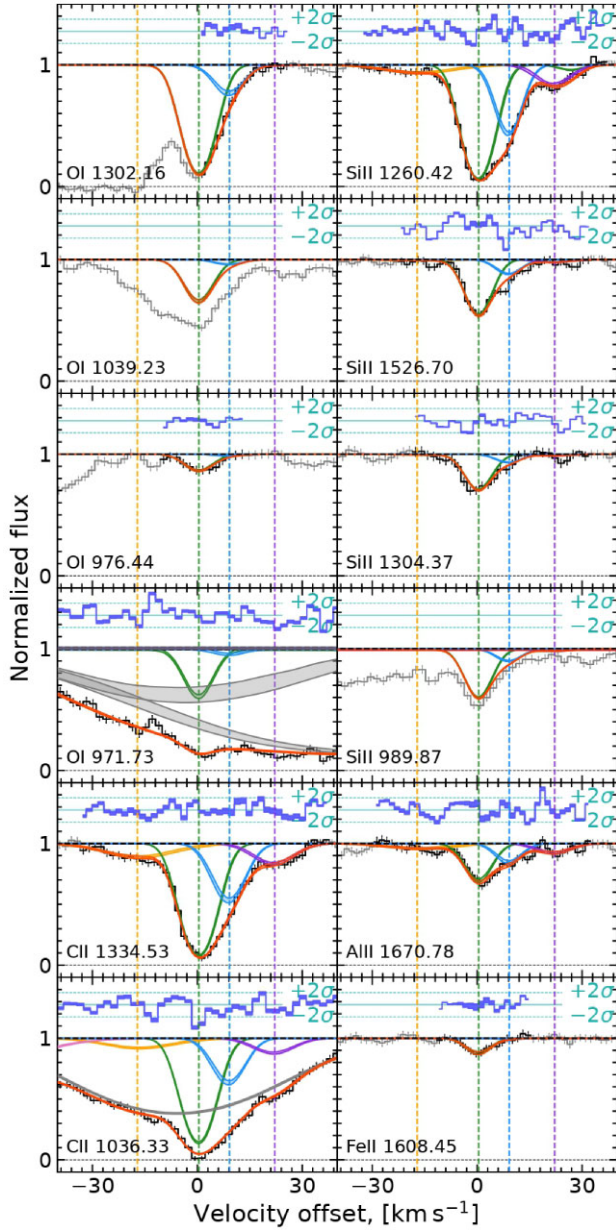


Figure 2. Fits to the metal absorption lines at $z = 3.42$ towards J 1332+0052 in the UVES spectrum. The graphical conventions of Fig. 1 are used. Transition lines are labelled in each panel.

-1.71 ± 0.02 . Other metal column densities, such as C II, Si II, Al II, and Fe II have values which are consistent with the oxygen metallicity with small depletion factors (dust content), which is expected at low metallicities.

From the simultaneous fit of the UVES and HIRES spectra, we find $\log(N(D\text{I})/N(\text{H}\text{I})) = -4.623 \pm 0.008$. The quoted error is the formal statistical uncertainty from the Bayesian analysis.

3.3 Systematic uncertainty

The results derived in the previous section only reported a statistical uncertainty since they were obtained using the specific model assumptions described in Section 3.1. To understand the impact of the chosen model assumptions and estimate systematic uncertainties, we subsequently changed each model assumption and performed

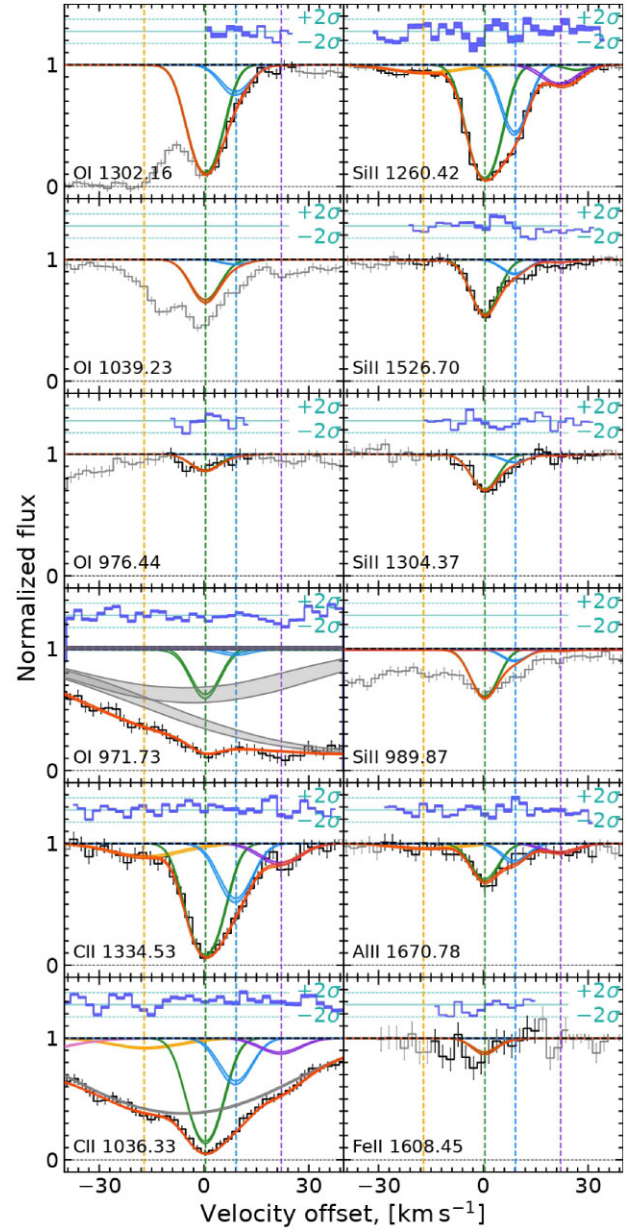


Figure 3. Fits to the metal absorption lines at $z = 3.42$ towards J 1332+0052 in the HIRES spectrum. The graphical conventions of Fig. 1 are used. Transition lines are labelled in each panel.

independent fits. The results are summarized in Fig. 6 where we plot the D/H ratios derived through each modification and compare them with our base model.

Using blue symbols in Fig. 6, we show models where we excluded a region near each H I line. These determinations are quite consistent and only the model without a region near H 1973 Å line is a little bit outstanding. Using olive symbols in Fig. 6, we present the model, where we changed the assumption on the metallicity through the components of the sub-DLA system. We used different elements as a metallicity tracer, as well as fitted the spectrum with a model without this assumption, and we found no significant changes in the D/H ratio in comparison with the base model. By purple colour in Fig. 6, we plot the models where we used only a wing of H I Ly α line. These models indicate typical systematic uncertainty concerned with the measurement of $N(\text{H}\text{I})$.

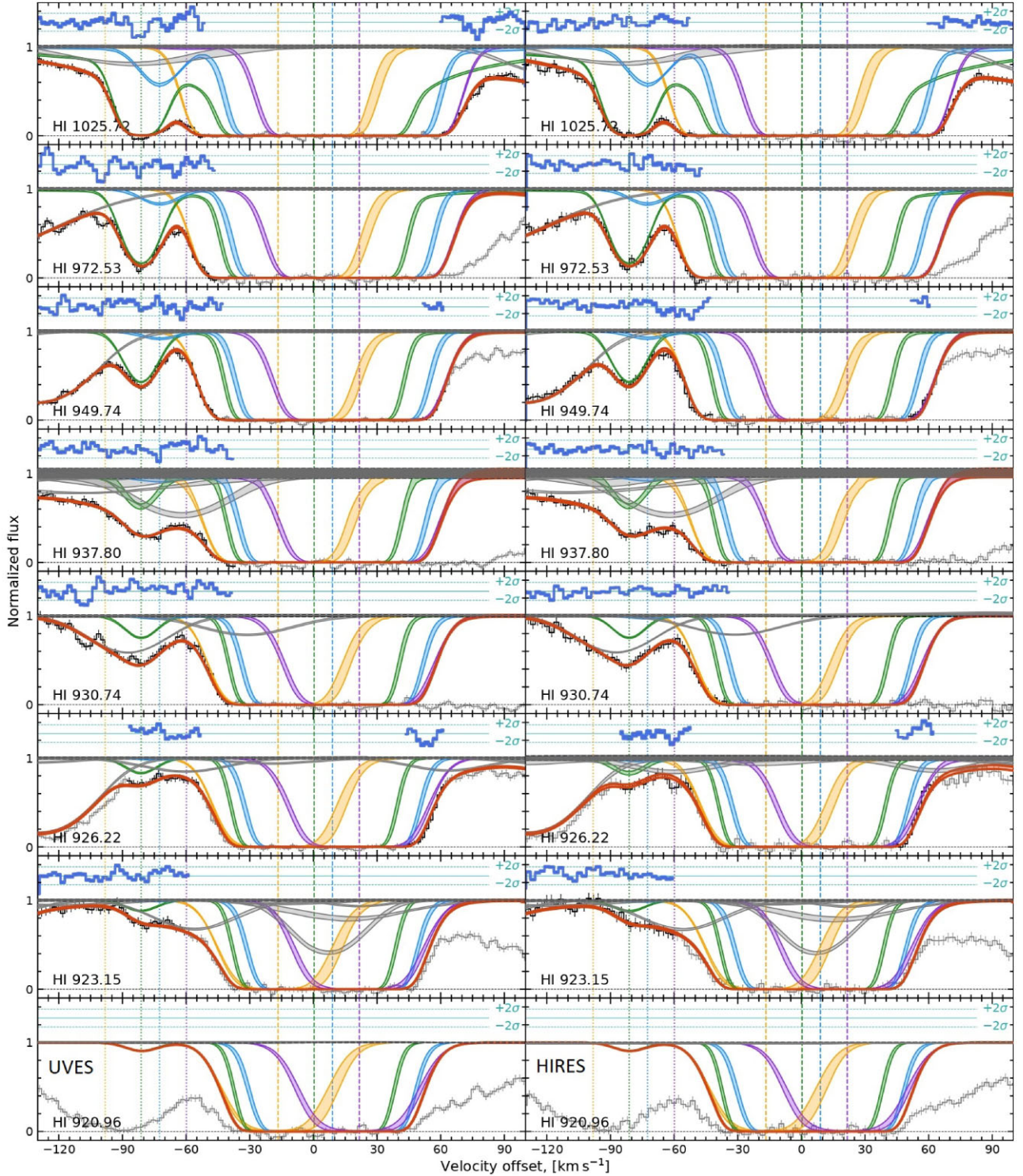


Figure 4. Fits to the H I and D I Lyman-series lines at $z_{\text{abs}} = 3.42$ towards J 1332+0052. The left panels show the UVES spectrum while the right panels show the HIRES spectrum. The graphical elements are the same as in Fig. 1. Transition lines are labelled in each panel.

We also fitted VLT/UVES and Keck/HIRES spectra independently and the results are shown in Fig. 6 by orange error bars. Posterior distributions of the main parameters are presented in Fig. 7. These $N(\text{D I})/N(\text{H I})$ determinations differs by $\approx 1.7\sigma$, which is quite unexpected. As could be seen in Fig. 7, determinations of the total $\log N(\text{H I})$ and $[\text{O}/\text{H}]$ (as well as other nuisance parameters not shown

in the figure) are more consistent between two fits, so the main source of the discrepancy is likely the difference in $\log N(\text{D I})$.

We additionally test how the order of the polynomial used for continuum fitting influences the estimated $\log N(\text{H I})$. To do this, we fit only the region near Ly α with different polynomial order for the continuum and only a single component for the Ly α absorption

Table 3. Overall fit results for the absorption-line system at $z = 3.4210863(15)$ towards J 1332+0052. These results correspond to the base model (see Section 3.1). We used values from Asplund et al. (2009) for solar abundances: $12 + \log(C/H) = 8.43$, $12 + \log(Si/H) = 7.51$, $12 + \log(Al/H) = 6.45$, $12 + \log(Fe/H) = 7.50$, $12 + \log(O/H) = 8.69$.

Comp.	#1	#2	#3	#4	$\log N_{tot}$	$[X/H]_{total}$
Δv , km s ⁻¹	$-17.4^{+1.1}_{-0.8}$	0	$8.7^{+0.2}_{-0.2}$	$21.3^{+0.4}_{-0.4}$	–	–
b_{turb} , km s ⁻¹	$11.7^{+1.9}_{-1.2}$	$2.8^{+0.1}_{-0.1}$	$1.0^{+0.5}_{-0.5}$	$4.2^{+0.8}_{-1.1}$	–	–
T , K	12600^{+1900}_{-2300}	10100^{+200}_{-200}	15100^{+900}_{-700}	22200^{+1200}_{-900}	–	–
$\log N(C\ II)$	$12.83^{+0.05}_{-0.04}$	$13.86^{+0.02}_{-0.02}$	$13.18^{+0.03}_{-0.03}$	$12.75^{+0.04}_{-0.03}$	$14.003^{+0.01}_{-0.011}$	$-1.728^{+0.01}_{-0.013}$
$\log N(Si\ II)$	$11.59^{+0.06}_{-0.05}$	$13.05^{+0.01}_{-0.01}$	$12.33^{+0.03}_{-0.03}$	$11.74^{+0.03}_{-0.03}$	$13.157^{+0.009}_{-0.008}$	$-1.656^{+0.009}_{-0.01}$
$\log N(Al\ II)$	$11.1^{+0.09}_{-0.11}$	$11.66^{+0.03}_{-0.02}$	$11.29^{+0.04}_{-0.05}$	$11.06^{+0.08}_{-0.08}$	$11.949^{+0.017}_{-0.017}$	$-1.806^{+0.019}_{-0.016}$
$\log N(Fe\ II)$		$12.65^{+0.05}_{-0.04}$	$10.65^{+0.5}_{-0.59}$		$12.664^{+0.044}_{-0.047}$	$-2.140^{+0.043}_{-0.048}$
$\log N(O\ I)$	$11.77^{+0.49}_{-0.57}$	$14.25^{+0.02}_{-0.02}$	$13.2^{+0.05}_{-0.06}$	$12.13^{+0.13}_{-0.14}$	$14.29^{+0.02}_{-0.02}$	$-1.705^{+0.021}_{-0.022}$
$\log N(H\ I)$	$16.68^{+0.06}_{-0.05}$	$19.25^{+0.01}_{-0.01}$	$18.39^{+0.05}_{-0.09}$	$16.8^{+0.09}_{-0.07}$	$19.304^{+0.004}_{-0.004}$	–
$\log(N(D\ I)/N(H\ I))$	$-4.623^{+0.008}_{-0.008}$	–	–	–	–	–
$[O/H]_{individual}$	$-1.61^{+0.49}_{-0.58}$	$-1.69^{+0.03}_{-0.03}$	$-1.86^{+0.06}_{-0.07}$	$-1.39^{+0.16}_{-0.15}$	–	–

feature. The results are presented in Fig. 8. Orders of 3 and 4 are too low to fit the spectrum in the region while the higher orders fit the data quite well and do not show a significant scatter in the estimated $\log N(H\ I)$. Therefore, we choose five as a compromise between the unacceptably simple model and the overfitting.

We then combined all posterior distribution functions (estimated by MCMC chains) of D/H ratios for these models into one and defined the uncertainty of the $N(D\ I)/N(H\ I)$ determination of 0.014 dex directly from the final posterior distribution (see Fig. 6). It consists of both statistical and systematic uncertainty.

Another potential source of systematic uncertainty is the fact that there are some regions in the UVES spectrum where noise does not seem to be Gaussian. One could recognize additional absorption features in such a portion of the spectrum like near the $D\ I\ \lambda 973$ line. For all these cases, comparison with the same regions in the HIRES spectrum mainly shows that there is no demonstration of any additional absorption in the HIRES spectrum and thus we suppose that such a noise is an artefact of the procedure of the UVES spectrum reduction and hence we did not fit all these tiny features as real absorption systems. However, given a noticeable deviation of the D/H value obtained with the model where we exclude $D\ I\ 973\ \text{\AA}$ line, from the majority of other models (see Fig. 6), we also fitted all $D\ I$ lines but $973\ \text{\AA}$ for UVES and HIRES spectra independently to test how fluctuations near $H\ I\ 973\ \text{\AA}$ line in the UVES spectrum may affect to the estimated $D\ I/H\ I$ value. Using both spectra we estimated $\log(D\ I/H\ I) = -4.647 \pm 0.012$, while for UVES and HIRES spectra only we got $\log(D\ I/H\ I) = -4.647 \pm 0.017$ and $\log(D\ I/H\ I) = -4.665 \pm 0.022$, respectively. It allows us to suppose that the fluctuations near $H\ I\ 973\ \text{\AA}$ line is not related to the relatively low $D\ I/H\ I$ value for fit without $D\ I\ 973\ \text{\AA}$, since the $D\ I/H\ I$ value from the fit of the HIRES spectrum alone is even lower than from the fit of the UVES one.

As a concluding remark on Fig. 6, we would like to highlight two key points. First, all the presented D/H values are demonstrated as alternatives to the base model, and we maintain neutrality among these alternatives; there is no preference for any specific option. Upon analysing the results in the figure, it becomes apparent that a majority of the D/H values tend towards the ‘UVES’ value or suggest that the $D\ I\ 973\ \text{\AA}$ line plays a decisive role, contributing to a higher D/H value. It is crucial to note that, in all cases except ‘UVES’ and ‘HIRES’, we fitted *both* spectra. Our base model involves fitting *all* $D\ I$ lines in *both* spectra, without favouring any particular metal

element and considering *both* wings of the $H\ I\ Ly\ \alpha$ line. Secondly, any further analysis is against the ‘blind’ methodology, as explained in Section 4.2. There is no evident reason to favour one spectrum over another, deem one $D\ I$ line superior to others, or assert the superiority of a specific wing of the $H\ I\ Ly\ \alpha$ line. Therefore, we amalgamate all the results to present the final posterior distribution of the D/H value and its associated error.

We also checked another fit model where an additional $H\ I$ component was added with the velocity offset of $-81.5\ \text{km s}^{-1}$ relative to the major component so $H\ I$ lines of this additional component were overlapped with $D\ I$ lines. Obtained result is $N(D\ i)/N(H\ i) = -4.685 \pm 0.014$ (only statistical uncertainty). In principle, there is always such opportunity for any considered D/H measurement, therefore, while we did not include this uncertainty in our final results, we need to bear in mind that the result may be biased. Thus the value of $\Delta = -0.06\text{dex}$ could be perceived as a bias that might take place in the case of $D\ I$ lines that are blended with an unmodelled $H\ I$ component.

Lastly, we discussed the uncertainty, related to the profiles of interloping absorption systems, which may partially blend the total fit near sub-DLA $D\ I$ lines. In Appendix A, we show a set of figures which represent the fit to spectral regions around $D\ I$ lines in the UVES spectrum. In each figure, we present all the lines for each additional $H\ I$ component that are available for fitting and were used during the fit. Looking at, e.g. Figs A4 and A7, one can notice that all features near the $D\ I\ \lambda 931$ line are well constrained by clear absorption by other lines of those absorption systems. The same is relevant for the $D\ I\ \lambda 950$ line. With such a reliable constraint on the blending absorption features, we suppose that there is only a little bias of the usage of the partially blended $D\ I$ lines, as we did in this work.

4 DISCUSSION

The system presented here allowed us to robustly determine the D/H ratio thanks to clear damping wings in $Ly\ \alpha$, especially in the regions where the flux immediately recovers from zero (DLA core), which is necessary to accurately constrain the total $H\ I$ column density in gas-rich (sub-DLA and DLA) systems. Several $D\ I$ lines are also detected, providing strong constraints on the $D\ I$ column density. Finally, this particular sub-DLA system exhibits a quite simple velocity structure. With such a precise measurement, one can discuss the possible

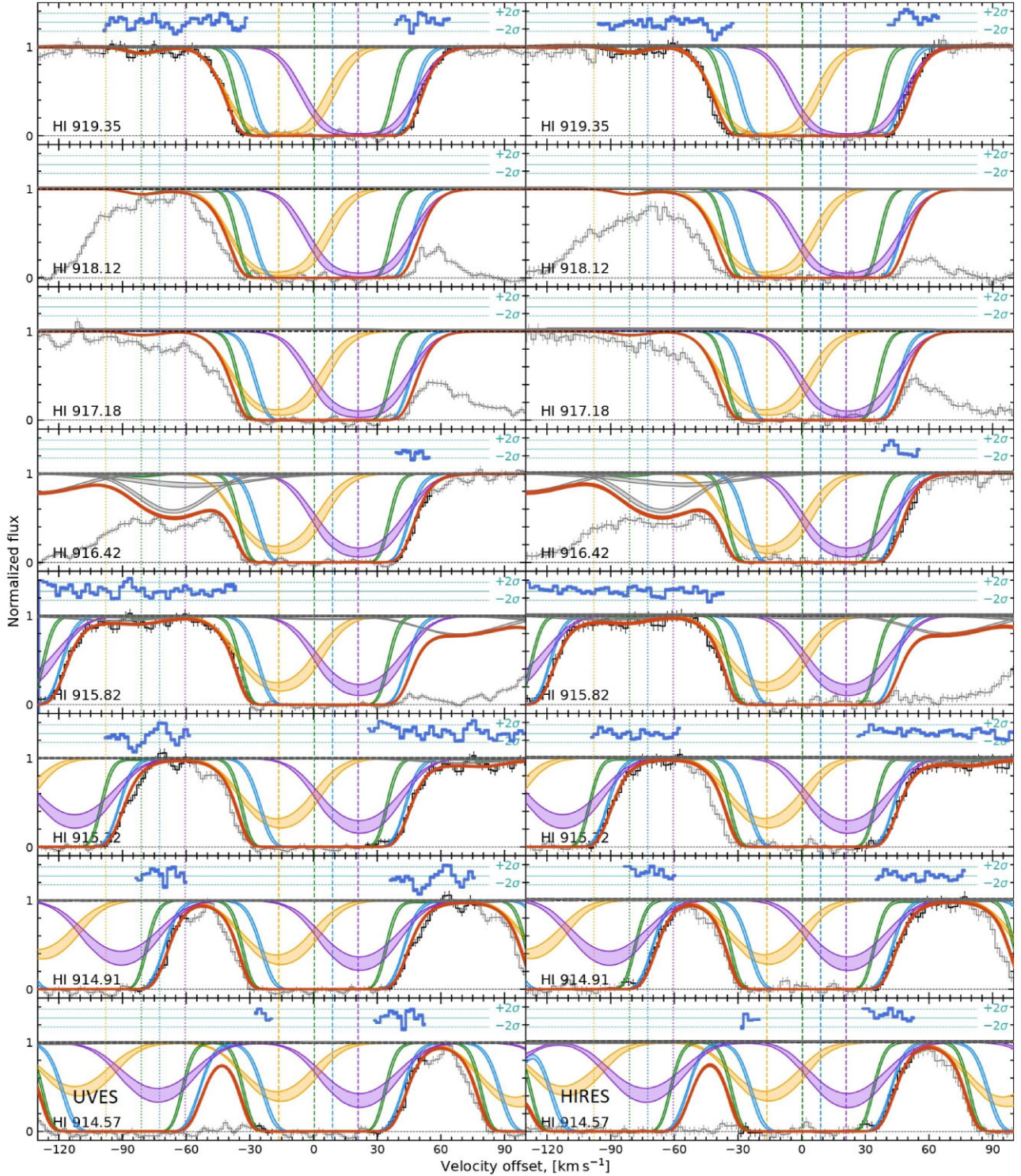


Figure 5. Fits to the H I and D I Lyman-series lines at $z_{\text{abs}} = 3.42$ towards J 1332+0052 (continuation of Fig. 4).

astration of deuterium, which is easily destroyed in stars. Chemical evolution models predict little deviation of D/H from the primordial abundance in predominantly unprocessed gas, i.e. at low metallicity (e.g. Dvorkin et al. 2016). Weinberg (2017) predicted an astration smaller than 2 percent at $[O/H] \approx -1.0$ while similar results were presented by van de Voort et al. (2018). The latter authors found a mean deviation of D/H from the primordial value in simulations

that is smaller than 2 percent up to $[O/H] \approx -0.6$. The system studied here offers a new opportunity to observationally test this at a slightly higher metallicity ($[O/H] \approx -1.7$) than previously possible, confirming the lack of detectable dependence of D/H on metallicity, as also noticed by Cooke et al. (2016). In short, we showed that astration remains negligible compared to measurement uncertainties for metallicities of up to at least $[O/H] \approx -1.7$. Naturally, larger

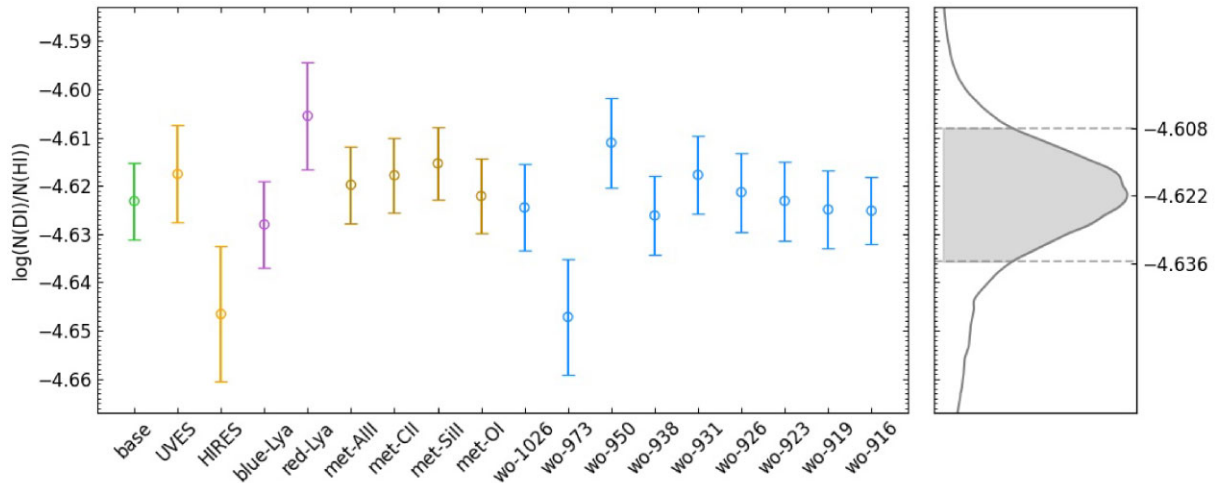


Figure 6. D/H I estimates using different model assumptions or spectra (left panel) and joint estimate (right panel). Different keywords along the x-axis denote a modification of the base model (labelled as ‘base’ and described in Section 3.2) as follows: ‘UVES’ and ‘HIRES’: only UVES or HIRES is fitted; ‘blue-Ly α ’ and ‘red-Ly α ’: only the bluer or the redder wing of the H I Ly α line is fitted; ‘met-AllI’, ‘met-CII’, ‘met-SiII’ and ‘met-OI’: $N(H I)$ is tied to either $N(Al II)$, $N(C II)$, $N(Si II)$, or $N(O I)$ along the components; ‘wo- λ ’: the region near the D I ‘ λ ’ (in \AA) line is excluded from the fit.

statistics are needed to observe tiny deviations from the primordial abundance at the level predicted by the models.

Another point worth mentioning is that this new D/H measurement was performed in a sub-DLA system with outstanding properties compared to previously studied systems. Indeed, this sub-DLA has the highest redshift amongst systems in the *precision sample*, has the lowest H I column density, and has one of the highest metallicities. These peculiarities make this measurement rather unique and relax the conditions allowing for a robust D/H determination. This is especially important in view of the next generation of ground-based telescopes (e.g. ELT, TMT, and GMT) which will be able to observe fainter targets (see also the appendix in Cooke et al. 2016).

One may also be interested in how metallicity varies from one component to another in the sub-DLA system since it can be used to explore variations in metallicity and study the dust content (see e.g. Ramburuth-Hurt et al. 2023). In the last row of the Table 3 we show the [O/H] for individual components derived using the base model. Oxygen is the best-suited element for metallicity determination, since its ionization potential is very close to the hydrogen one (and so the ionization correction is negligible) and there are several strong transitions with appropriate wavelengths. [O/H] determinations for individual components differ from the overall oxygen metallicity by no more than 0.3 dex. This is slightly smaller than the metallicity variations proposed by De Cia et al. (2021) and is consistent with other estimates of the metallicity variations (Esteban et al. 2022).

4.1 Cosmological implementation

The main advantage of the D/H measurements is their direct connection to the primordial deuterium abundance which can be used to infer the cosmological baryon density. Using all available D/H determinations from the literature, which are summarized in Table 4, one can derive the average value (weighted mean):

$$(D/H)_{\text{all}} = (2.533 \pm 0.024) \times 10^{-5}. \quad (2)$$

This is our conservative estimate in the sense that it incorporates all previous determinations. We also show the comparison of the new D/H measurement with the previous ones in Fig. 9. In this figure, we show D/H versus [O/H] for all known determinations and we used blue colour for measurements which meet the selection

criteria proposed by Cooke et al. (2014), red colour for our new determination, and grey colour for all other determinations. The new measurement is consistent with other precision measurements and has a similar uncertainty. Fig. 9 also shows that there is no obvious correlation between metallicity and D/H ratio.

Up to now, there is no robust verification that the spread of the D/H determinations is not physical. However, more high-quality observations can clarify estimates as shown by Cooke et al. (2014). Moreover, these authors offered a set of criteria to select the most suitable cases for D/H determinations where some systematic effects are negligible. Based on the nine systems which agree with these criteria (see Table 4), one can obtain a weighted mean of presumably best-suited measurements:

$$(D/H)_{\text{ps}} = (2.501 \pm 0.028) \times 10^{-5}. \quad (3)$$

Even if measurements that meet the selection criteria of the *precision sample* are presumed to be the most suitable for D/H determination, we suggest that it is important to use all available data and measurements made by different researchers, and using different techniques, until this presumption is demonstrated conclusively.

Both values [equations (2) and (3)] are in moderate tension ($\approx 2.2\sigma$, $\approx 1.4\sigma$ respectively) with the theoretically predicted value of the primordial deuterium abundance computed using the PRIMAT code and based on the cosmological parameters derived from CMB + BAO (Planck Collaboration VII 2020) presented by Pitrou et al. (2021):

$$(D/H)_{\text{th}} = (2.439 \pm 0.037) \times 10^{-5} \quad (4)$$

assuming $\tau_n = 879, 4(6)s$ and $100h^2\Omega_b = 2.242(\pm 0.014)$. An important and significant achievement in the $D(p, \gamma)^3\text{He}$ rate determination was reached in the last years by the Laboratory for Underground Nuclear Astrophysics (LUNA) staff (Mossa et al. 2020). This reaction was the main source of uncertainty in predicting the theoretical primordial D/H ratio. Pitrou et al. (2021) used the new rate of this reaction for the computations and the new rate enhanced the tension.

This growing discrepancy which was also mentioned by Cooke, Pettini & Steidel (2018) and Pitrou et al. (2021) could be a manifestation of new physics beyond the standard cosmological model.

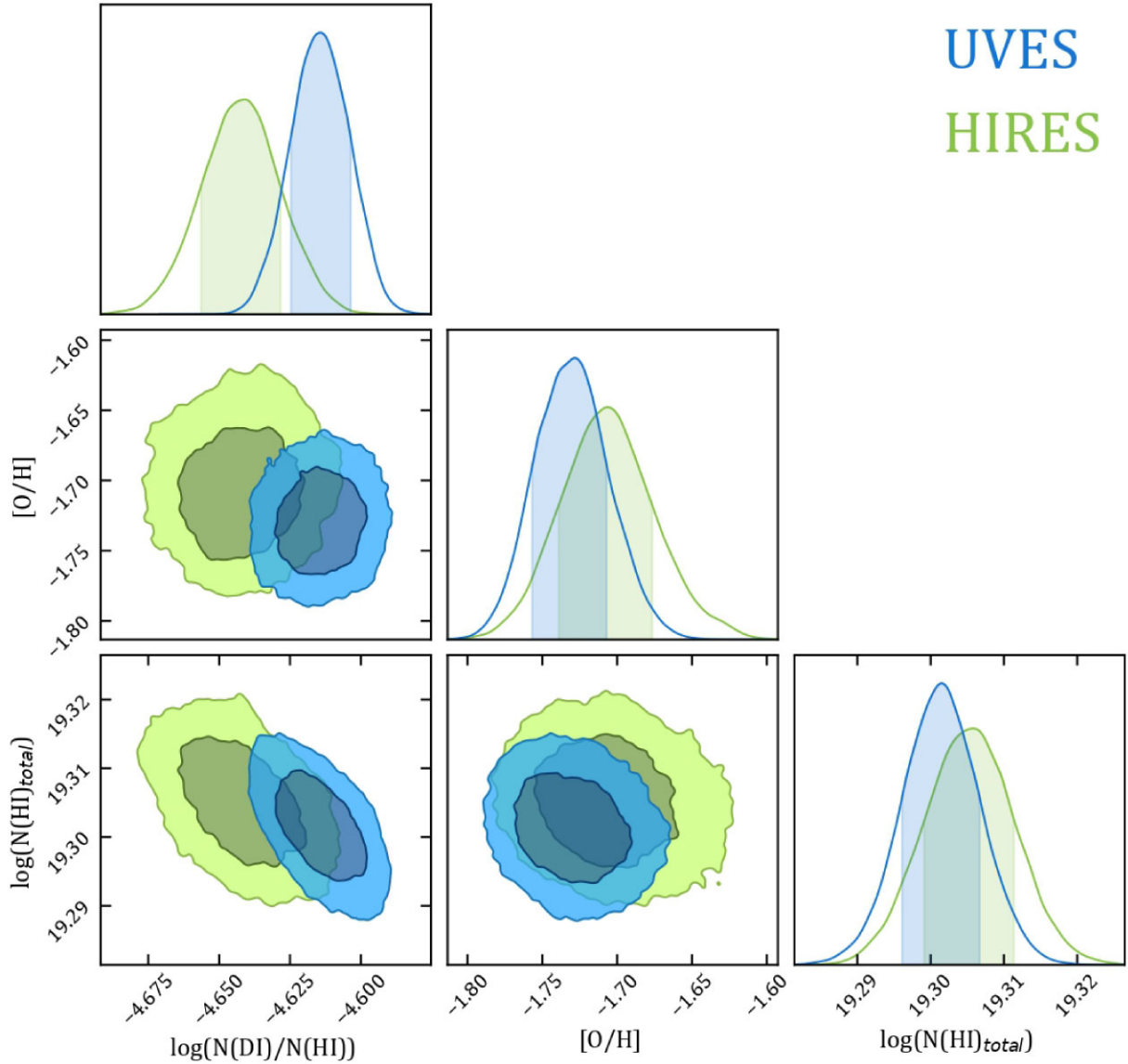


Figure 7. Corner plots showing the posterior distributions of the main parameters in the fitting chains applied to the UVES and HIRES spectra.

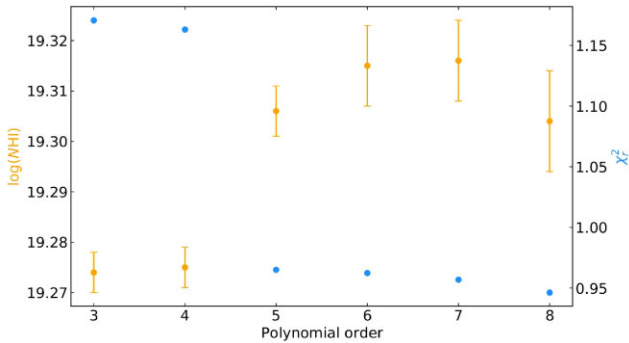


Figure 8. Dependence of the total measured $\log N(\text{HI})$ on the order of the polynomial used for continuum fitting. The error bars show the estimated $\log N(\text{HI})$ using a one-component model for $\text{Ly}\alpha$ absorption (left ordinate axis). The dots show the reduced χ^2 of the fits (right ordinate axis).

4.2 Avoiding confirmation bias

Given the number of previous works on the primordial D/H ratio measurements as well as BBN + CMB value, one could expect that a new determination should be consistent with others. This could in principle influence the decisions made through the analysis of new D/H systems.

First of all, it is worth reminding that D/H measurements are only a few so any new measurement is extremely valuable. The detection of a clear H I $\text{Ly}\alpha$ line and several optically thin D I lines lead us to make the analysis to the end, regardless of the obtained D/H value.

While not performing a complete blind analysis (as done by Cooke et al. 2014), where the value of D/H is kept unknown until all decisions about the modelling are accepted based on the visual matching of the data by the fit and χ^2 values, we did not favour any D/H value during the fitting process. In fact, Fig. 6 presents only a small scatter in the D/H determinations between our different models. Any prior based on values by, e.g. Cooke, Pettini & Steidel (2018) could be anywhere within a ~ 0.1 dex range around $\log(\text{D}/\text{H}) = -4.61$, and all our models are comfortably within this range. We

Table 4. Current sample of D/H determinations. In the last column we show either a measurement meets or not the selection criteria of the *precision sample* proposed by Cooke et al. (2014).

QSO	[O/H]	log (D/H)	Reference	Meet the selection criteria?
HS 0105+1619	-1.771 ± 0.021	-4.589 ± 0.026	Cooke et al. (2014)	✓
Q0913+072	-2.416 ± 0.011	-4.597 ± 0.018	Cooke et al. (2014)	✓
SDSS J1358+6522	-2.335 ± 0.022	-4.588 ± 0.012	Cooke et al. (2014)	✓
SDSS J1419+0829	-1.922 ± 0.010	-4.601 ± 0.009	Cooke et al. (2014)	✓
SDSS J1558-0031	-1.650 ± 0.040	-4.619 ± 0.026	Cooke et al. (2014)	✓
Q1243+307	-2.769 ± 0.028	-4.622 ± 0.015	Cooke, Pettini & Steidel (2018)	✓
SDSS J1358+0349	-2.804 ± 0.015	-4.582 ± 0.012	Cooke et al. (2016)	✓
J1444+2919	-2.042 ± 0.005	-4.706 ± 0.067	Balashev et al. (2016)	✓
CTQ 247	-1.990 ± 0.100	-4.560 ± 0.100	Noterdaeme et al. (2012)	×
PKS 1937-1009 (1)	-1.870 ± 0.200	-4.610 ± 0.050	Riemer-Sørensen et al. (2015)	×
J1337+3152	-2.640 ± 0.170	-4.930 ± 0.150	Srianand et al. (2010)	×
J1134+5742	< -1.9	-4.690 ± 0.130	Fumagalli, O’Meara & Prochaska (2011)	×
Q2206-199	-2.070 ± 0.050^a	-4.786 ± 0.100	Pettini & Bowen (2001)	×
Q0347-3819	-0.820 ± 0.060	-4.426 ± 0.028	Levshakov et al. (2002)	×
PKS 1937-1009 (2)	-2.250 ± 0.250	-4.581 ± 0.008	Riemer-Sørensen et al. (2017)	×
Q1009+2956	-2.500 ± 0.200	-4.606 ± 0.066	Zavarygin et al. (2018)	×
J1332+0052	-1.725 ± 0.019	-4.622 ± 0.014	this paper	✓

Note.^a presented in Pettini et al. (2008)

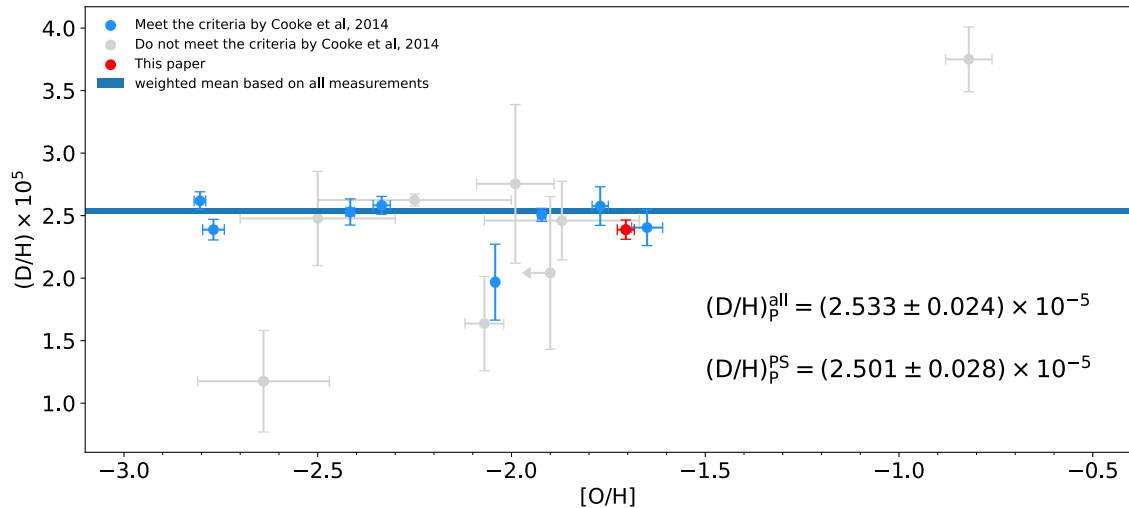


Figure 9. Current D/H measurements. The systems matching the criteria defined by Cooke et al. (2014) are shown in blue while other determinations are displayed in grey. Our new measurement is shown in red. The weighted mean D/H value based on all measurements is represented by the horizontal line. The weighted mean values based on either all measurements or only the systems matching the above criteria (systems in the *precision sample*) are displayed at the bottom right.

would have no reason to subconsciously prefer some value within that range. In other words, a confirmation bias would rather take place for a choice between, e.g. a value of -4.6 and -4.4 , i.e. with a deviation much more substantial than observed here. The best way to avoid subjectivity remains to perform a D/H determination in each system where it is possible to do and confront analysis obtained by different groups and methods.

5 CONCLUSIONS

To date, there are only 17 determinations of the D/H ratio in metal-poor absorption systems at high redshift. Nine of them agree with the criteria defined by Cooke et al. (2014) to qualify as robust measurements. In this way, each new determination is crucial, as well as any re-analysis of known systems based on new high-quality data.

Our main conclusions are:

- (i) Based on high-quality spectra we obtained a new measurement of the deuterium abundance in the metal-poor sub-DLA system at $z = 3.42$ towards quasar J 1332+0052: $D/H = (2.388 \pm 0.078) \times 10^{-5}$.
- (ii) This new measurement is consistent with previous determinations of the same precision level and meets the selection criteria proposed by Cooke et al. (2014).
- (iii) Based on all available D/H measurements we estimated a new primordial deuterium abundance $D/H_{pr} = (2.533 \pm 0.024) \times 10^{-5}$. Based on nine measurements which meet the criteria of a precise one we find $D/H_{pr} = (2.501 \pm 0.028) \times 10^{-5}$.
- (iv) We used a new method for accounting the systematic effects based on multiple times fitting, when we do an independent fitting

for each model we consider it appropriate for describing the data. The main advantage of this method is that we do not choose which model is better or worse which might be subconsciously biased by our human nature and combine all the results from any possible model instead. Despite it being very time-consuming, it is possibly the single ability to realize how different aspects could affect the results of the analysis.

(v) A new determination of the D/H_{pr} based on all measurements is still marginally inconsistent ($\approx 2.2\sigma$) with the theoretical value predicted by Pitrou et al. (2021) based on the cosmological parameters derived from CMB + BAO (Planck Collaboration VII 2020). The reasons for this remain unsettled and could potentially be an indication of new physics.

(vi) There is still no obvious correlation between D/H and $[O/H]$ or $N(H\text{I})$.

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This work is based on archival data collected at the European Southern Observatory under programme 0101.A-0061(A) and W.M. Keck Observatory under programmes U152Hr, U088Hb, and U088Hr.

DATA AVAILABILITY

The pipeline-reduced spectra underlying this article are readily available from the ESO science portal (<http://archive.eso.org/scienceportal/home>) and partially from the Keck observatory archive (<https://koa.ipac.caltech.edu>). Re-reduced spectra can be shared upon request to the corresponding author.

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APPENDIX A: INTERLOPING SYSTEMS

In this section, we present the modelling of unrelated absorption-line systems. In Fig. A1 we present strongest DI absorption lines of the sub-DLA system and interloping absorption features near them in the UVES spectrum. Each following figure shows a portion of the UVES spectrum with the fit in more details as summarised in Table A1. In particular, these figures show additional absorption lines which

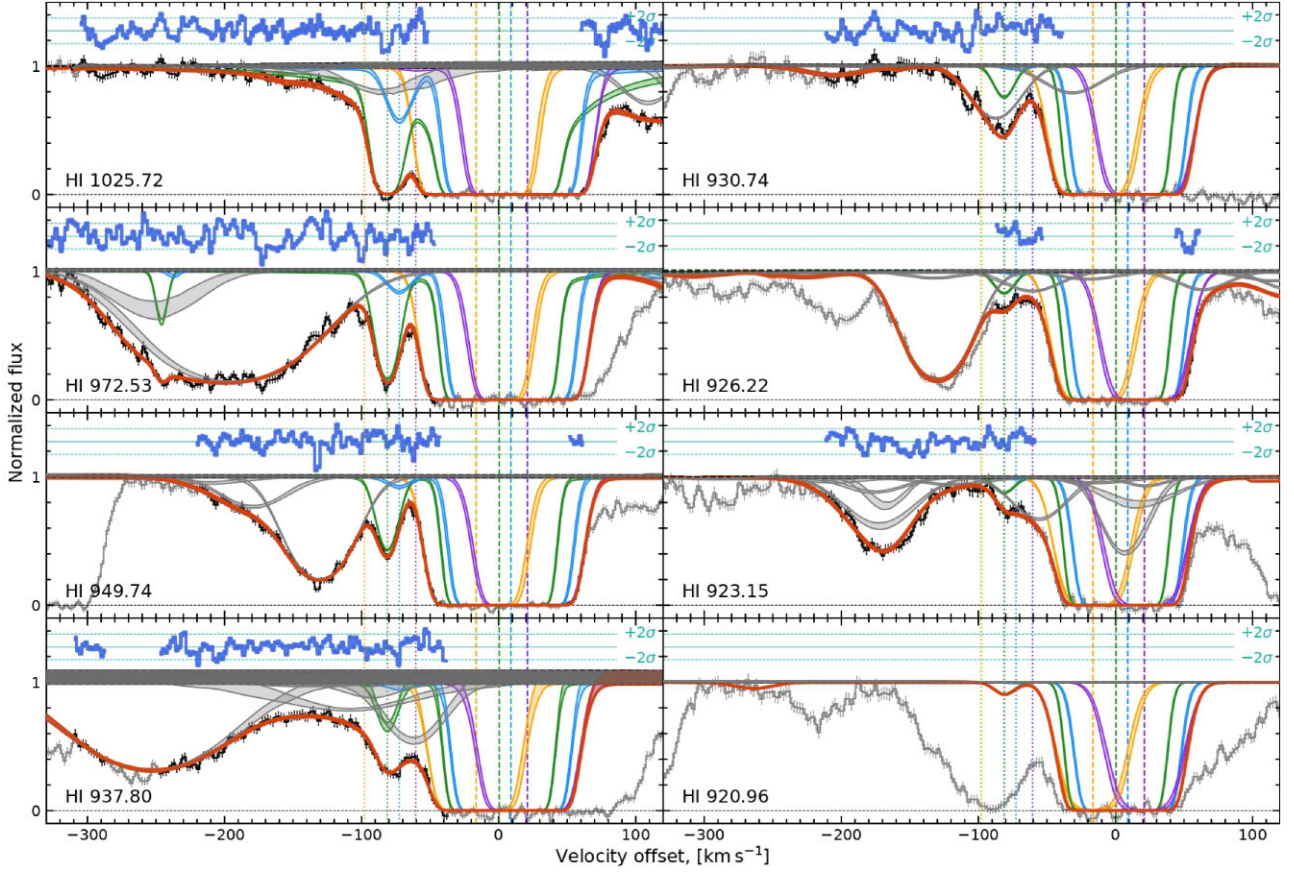


Figure A1. Portion of UVES spectrum with a focus on unrelated absorption features.

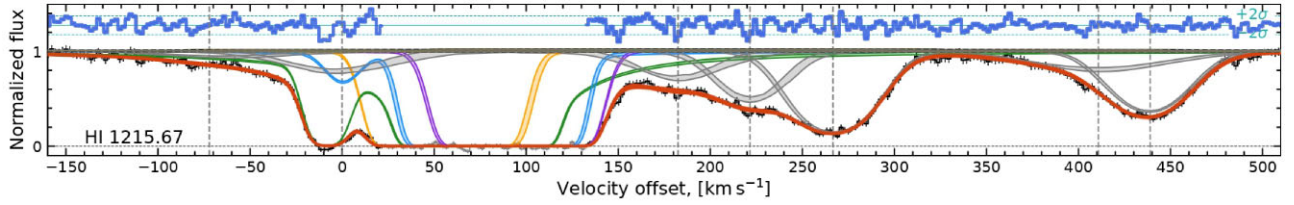


Figure A2. Absorption system interloping with D I λ 1026. The system is located at redshift $z = 2.729383$. Other systems which affect total fit near the H I line are also shown.

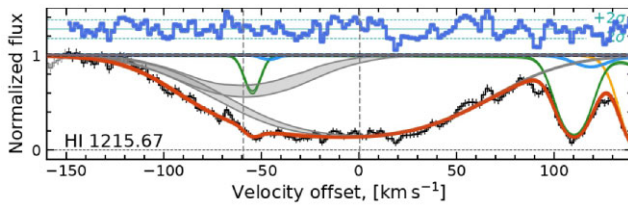


Figure A3. Absorption system interloping with D I λ 973. The system is located at redshift $z = 2.534616$. Another system nearby is also shown.

allow one to better constrain parameters of a system. The interloping systems are shown in grey. The other colours are those used in the main figures to either depict the total model profile (red) or individual sub-DLA components (i.e. orange, green, blue, and violet for components #1, #2, #3, and #4, respectively). D I lines usually appear in green.

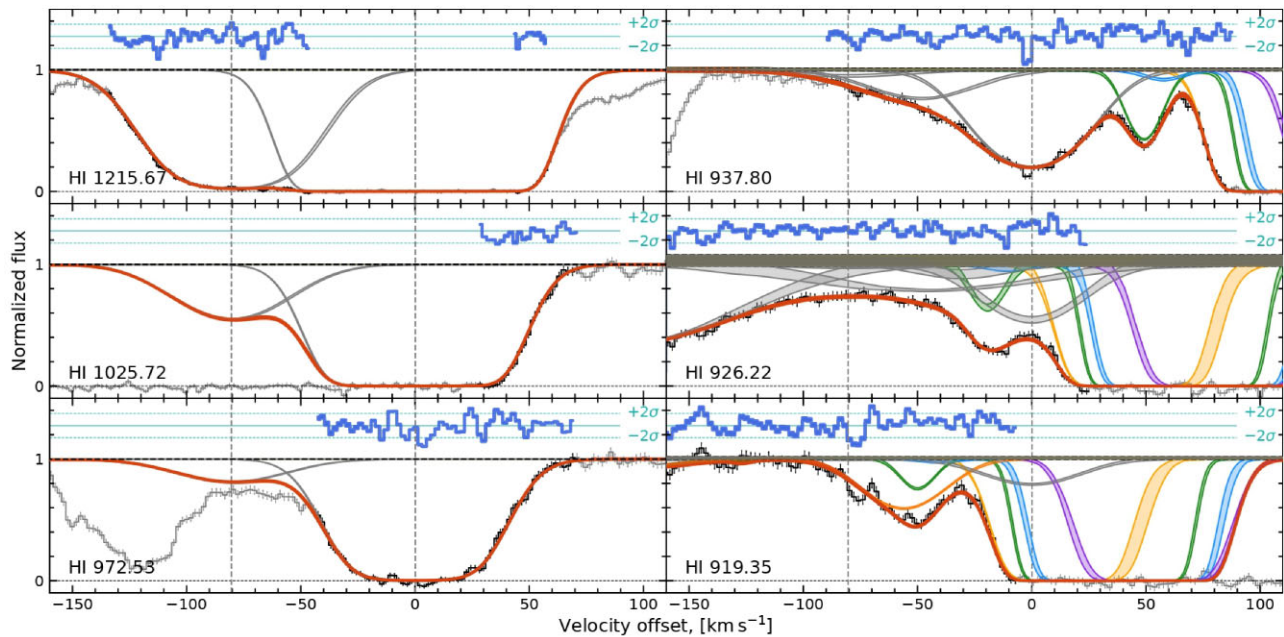


Figure A4. Absorption systems interloping with D1 λ 950. The velocity offset is counted relative to the system located at redshift $z = 3.475422$.

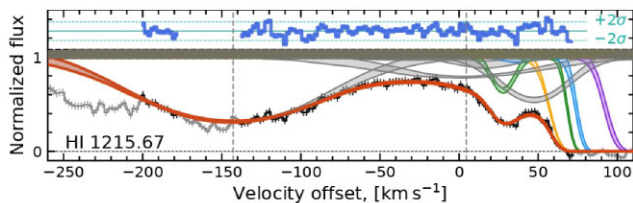


Figure A5. The first absorption system interloping with D1 λ 938. The velocity offset is counted relative to the system located at redshift $z = 2.409310$.

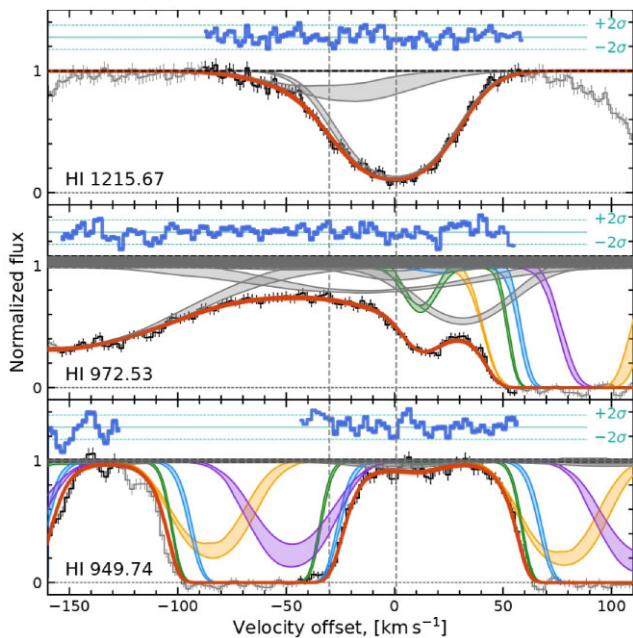


Figure A6. The second absorption system interloping with D1 λ 938. The velocity offset is counted relative to the system located at redshift $z = 3.261862$.

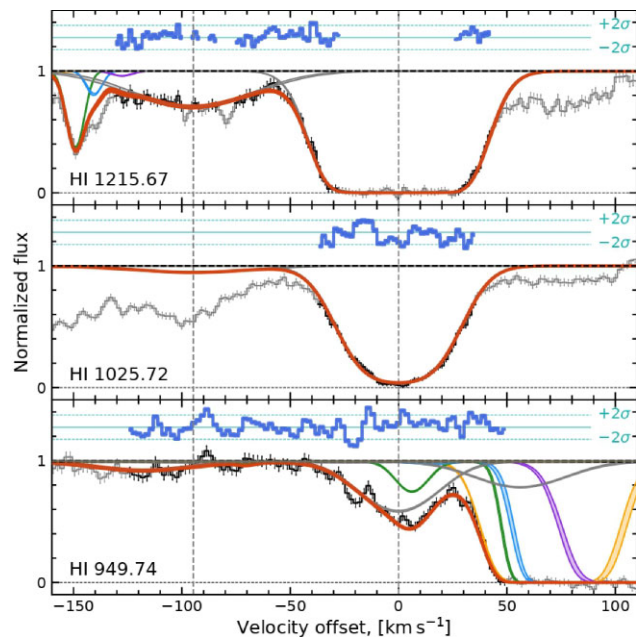


Figure A7. Absorption system interloping with D1 λ 931. The velocity offset is counted relative to the system located at redshift $z = 3.331398$.

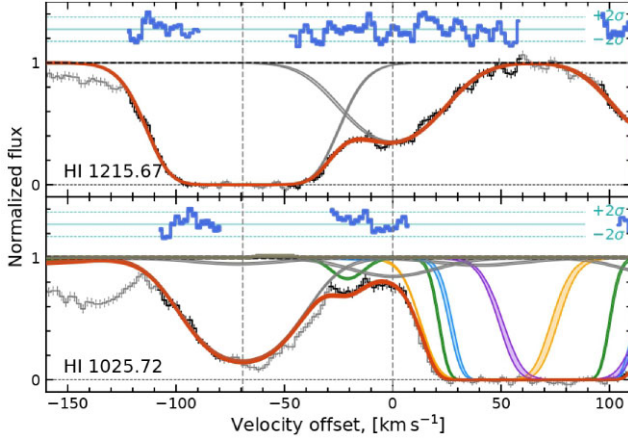


Figure A8. Absorption system interloping with D I $\lambda 926$. The velocity offset is counted relative to the system located at redshift $z = 2.991426$.

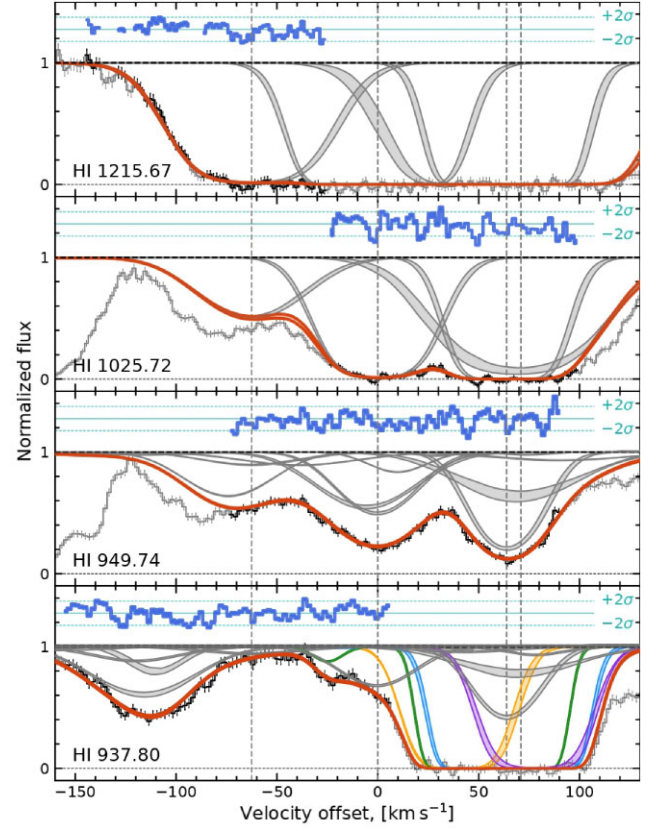


Figure A9. Absorption system interloping with D I $\lambda 923$. The velocity offset is counted relative to the system located at redshift $z = 3.351185$.

Table A1. Unrelated absorption systems.

Line in sub-DLA system	Blending system
$\lambda 1026$	Fig. A2
$\lambda 973$	Fig. A3
$\lambda 950$	Fig. A4
$\lambda 938$	Figs A5, A6
$\lambda 931$	Fig. A7
$\lambda 926$	Fig. A8
$\lambda 923$	Fig. A9

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