

Exploring the gaseous halos of $z > 3$ radio galaxies with UVES and JWST/NIRSpec

Jelena Ritter^{1,2,*}, Wuji Wang³, Dominika Wylezalek², Carlos De Breuck⁴,
Joël Vernet⁴, and Fabrizio Arrigoni Battaia¹

¹ Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Str. 1, D-85748 Garching bei München, Germany

² Astronomisches Rechen-Institut, Zentrum für Astronomie der Universität Heidelberg, Mönchhofstr. 12-14, D-69120 Heidelberg, Germany

³ IPAC, California Institute of Technology, 1200 E. California Blvd., Pasadena, CA 91125, USA

⁴ European Southern Observatory, Karl-Schwarzschild-Str. 2, D-85748 Garching bei München, Germany

Received 21 July 2025 / Accepted 5 April 2026

ABSTRACT

High-redshift radio galaxies are among the most massive galaxies in the Universe and sites of extreme active galactic nucleus feedback processes, powering energetic radio jets. They are typically embedded in giant Ly α halos that are known to extend over 100 kpc into the circumgalactic medium. We targeted the Ly α halos around four high-redshift radio galaxies in a redshift range of $3.1 < z < 4.5$ using high-resolution spectroscopy from the Ultraviolet Echelle Spectrograph (UVES) at the VLT, focusing on absorption features in the Ly α emission that trace neutral hydrogen (H I) systems. We compared the UVES data to observations obtained with the Multi Unit Spectroscopic Explorer (MUSE) of the same targets and found that the higher spectral resolution of UVES ($\Delta v \approx 12 \text{ km s}^{-1}$) allowed us to identify absorbers more completely and revealed the splitting of deep absorbers into multiple components. We identified between 6 and 14 absorbers for each target in our sample with column densities of $N_{\text{H I}} = 10^{12} - 10^{17} \text{ cm}^{-2}$. About 70% of the absorbers can be spatially resolved along the radio jet axis, showing minimal variation in column densities over extents of more than 30 kpc. Our results indicate that a fraction of the absorbers may be physically associated with the host systems. Complementary JWST/NIRSpec observations of two of the targets, 4C+03.24 and TN J0205, reveal potential outflows in the ionized interstellar medium. We discuss a kinematic link between the [O III]-emitting gas and the cool halo gas as traced by Ly α , suggesting a common outflow origin.

Key words. galaxies: active – galaxies: evolution – galaxies: halos – galaxies: high-redshift

1. Introduction

High-redshift radio galaxies (HzRGs) are massive galaxies (with stellar masses between $10^{11} M_{\odot}$ and $10^{12} M_{\odot}$; Rocca-Volmerange et al. 2004; Seymour et al. 2007), residing in overdense protocluster environments (e.g., Venemans et al. 2002; Wylezalek et al. 2013; Noirot et al. 2016, 2018). They host powerful active galactic nuclei (AGNs), which significantly affect the evolution of the host galaxy through feedback processes (Heckman & Best 2014; Harrison & Ramos Almeida 2024). HzRGs exhibit radiative mode feedback, where galactic outflows result from AGN-driven winds or radiation pressure pushing on dust and gas, and kinetic mode feedback, where collimated jets and outflows transfer energy to the surrounding medium (e.g., Fabian 2012; King & Pounds 2015; Harrison 2017; Nesvadba et al. 2017a,b). This leads to the expulsion and redistribution of gas within the host galaxy and its surrounding environment. Additionally, strong photoionization by the central AGN impacts gas cooling, which further affects the buildup of the host galaxy's stellar mass. This circumstance makes HzRGs unique and ideal targets for studying the evolution of massive galaxies and the role of AGN feedback processes.

An important characteristic of HzRGs is the giant gaseous halos in which they are embedded. They extend into the circumgalactic medium (CGM; see Tumlinson et al. 2017 for a review) of the galaxies and often reach beyond the radio

source (van Ojik et al. 1997). This extended halo structure provides a unique window into AGN-driven feedback and gas dynamics on circumgalactic scales. The gaseous halos can be observed in various emission lines, the most prominent and brightest of which is Ly α $\lambda 1216$, which can reach luminosities of $\gtrsim 10^{44} \text{ erg s}^{-1}$ (e.g., Villar-Martín et al. 2007b; Miley & De Breuck 2008; Shukla et al. 2022; Wang et al. 2023). Additionally, the halos show He II $\lambda 1640$ emission and are metal enriched, detected in C IV $\lambda 1548, 1551$, N V $\lambda 1238, 1242$ as well as in [O III] $\lambda 4959, 5007$ and [O II] $\lambda 3726, 3729$ (e.g., McCarthy 1993; De Breuck et al. 2000; Villar-Martín et al. 2007a; Humphrey et al. 2008b; Kolwa et al. 2019). In addition to atomic gas emission, molecular gas, in particular, carbon monoxide (CO), which is used as a tracer of molecular hydrogen, has been observed in HzRGs, in some cases even on halo scales (Klamer et al. 2005; Ivison et al. 2012; Emonts et al. 2014, 2015, 2016; Gullberg et al. 2016; Li et al. 2021; Falkendal et al. 2021; De Breuck et al. 2022; Emonts et al. 2023).

The Ly α nebulae of HzRGs are ubiquitously observed to show deep extended absorption features (van Ojik et al. 1997; Jarvis et al. 2003; Wilman et al. 2004; Humphrey et al. 2008a; Silva et al. 2018b; Kolwa et al. 2019; Wang et al. 2021), which were first discovered by Röttgering et al. (1995). This absorption of the Ly α emission in HzRGs has been interpreted as arising from neutral hydrogen gas (H I absorbers) in the CGM of the hosts, which surrounds the emission region. The absorbers allow us to indirectly probe the neutral gas without having to study H I

* Corresponding author: jritter@mpa-garching.mpg.de

in emission. While H I 21 cm absorption against the radio continuum is commonly used to detect neutral gas in low-redshift radio galaxies (e.g., [Morganti & Oosterloo 2018](#)), such observations are challenging at high redshift, and detections remain rare (e.g., [Röttgering et al. 1999](#); [Cody & Braun 2003](#); [Chandra et al. 2004](#); [Curran et al. 2013](#)).

The absorbers in the Ly α profiles are found to be spatially extended over almost the entire Ly α emission region, with projected spatial extents of up to 50 kpc and covering factors of approximately unity ([van Ojik et al. 1997](#); [Humphrey et al. 2008a](#); [Swinbank et al. 2015](#); [Silva et al. 2018a,b](#)). The estimated gas masses of H I can reach $\log(M_{\text{H I}}/M_{\odot}) \sim 9$ ([Silva et al. 2018a](#)).

By modeling the absorption features, we can characterize the neutral hydrogen gas in terms of column densities and kinematics. Most absorbers are found to be blueshifted with respect to the systemic redshift of the HzRGs ([van Ojik et al. 1997](#); [Jarvis et al. 2003](#); [Humphrey et al. 2008a](#)), likely indicating outflowing gas. In a few cases, redshifted absorbers have been detected, which might be a signature of infalling gas that feeds the central AGN ([Kolwa et al. 2019](#)).

A common theory to explain the nature of the absorbing gas has been developed over the years. [Binette et al. \(2000\)](#) first proposed that the absorption arises from giant expanding shells of gas, based on the blueshifted velocities, large spatial extents, and the fact that the absorbing material appears to be spatially distinct from the Ly α emission region. The expansion could be driven by energetic AGN or stellar feedback processes. The idea was further developed and confirmed using a larger sample of targets ([Jarvis et al. 2003](#); [Wilman et al. 2004](#); [Silva et al. 2018a](#); [Kolwa et al. 2019](#); [Wang et al. 2021](#)). The absorbing gas was found to extend along and perpendicular to the radio jet axis, thus providing evidence of the large-scale shell theory ([Humphrey et al. 2008a](#); [Silva et al. 2018a,b](#)). [Wilman et al. \(2004\)](#) found that the absorbers are either weak, with column densities of $N_{\text{H I}} \approx 10^{13} - 10^{15} \text{ cm}^{-2}$, or strong, with column densities $\geq 10^{18} \text{ cm}^{-2}$. Hydrodynamical simulation works suggested that strong column density absorbers might form behind the bow shock of the radio jet and be fragmented by the propagating jet ([Krause 2002, 2005](#)).

When the Ly α profiles of HzRGs are modeled, it is generally assumed that the Ly α emission region is spatially separate from the absorbers and that the Ly α photons are primarily absorbed or scattered out of our line of sight ([Binette et al. 2000](#); [Jarvis et al. 2003](#); [Wilman et al. 2004](#); [Swinbank et al. 2015](#); [Silva et al. 2018b](#); [Kolwa et al. 2019](#); [Wang et al. 2021, 2023](#)). While Ly α radiative transfer modeling is successful in reproducing some of the line shapes observed in high-redshift galaxies (e.g., [Verhamme et al. 2006](#); [Dijkstra et al. 2006](#); [Gronke et al. 2015](#); [Park et al. 2022](#)), profiles as seen in HzRGs with several absorption features and deep absorbers split into several components (e.g., [Jarvis et al. 2003](#)) are not fully accounted for by radiative transfer simulations. In studies of Ly α emission in HzRGs, it is therefore commonly assumed that absorption superimposed on the intrinsic Ly α emission, which is likely influenced by radiative transfer effects, is the primary factor shaping the profiles.

Scenarios for the evolution of the absorbing gas shells up to the present have been proposed and discussed. In a study of 18 HzRGs, [van Ojik et al. \(1997\)](#) found that smaller radio sources exhibit Ly α absorption more frequently than larger radio sources. Following these findings, [Röttgering & Pentericci \(1999\)](#) proposed an explanation based on an evolutionary scenario. While propagating through the halo, the radio jets interact

with the gas, leading to the formation of cocoons and shocks that eventually ionize the H I gas, thereby reducing the observed absorption. [Krause \(2002, 2005\)](#), [Swinbank et al. \(2015\)](#) argued that the outflowing shells might become thermally and gravitationally unstable and fragment over time.

We present the results of observations of four HzRGs in the redshift range of $3.1 < z < 4.5$. In particular, we focused on the absorption features observed in their Ly α halos. We present observations obtained with the Ultraviolet and Visual Echelle Spectrograph (UVES; [D’Odorico et al. 2000](#); [Dekker et al. 2000](#)) on the Very Large Telescope (VLT), which allowed us to analyze the absorbers at a high spectral resolution of $\Delta v \approx 12 \text{ km s}^{-1}$. In Sect. 4.1 we compare this resolution to complementary VLT Multi Unit Spectroscopic Explorer (MUSE; [Bacon et al. 2010](#)) observations of the four targets to assess how the different spectral capabilities affect the characterization of the absorbers. For two of the four targets in our sample, additional integral field unit (IFU) observations obtained with the James Webb Space Telescope (JWST)/Near Infrared Spectrograph (NIRSpec; [Jakobsen et al. 2022](#); [Gardner et al. 2023](#)) allowed us to compare the observations of the Ly α halos to the ionized phase in the interstellar medium (ISM) of the HzRGs, as traced by [O III].

The paper is structured as follows. In Sect. 2 we present the observations and data reductions. The line-fitting procedure of the UVES spectra is outlined in Sect. 3. The results are presented in Sect. 4, along with the spatially resolved fitting of the Ly α profiles and the comparison of the Ly α profiles to the NIRSpec [O III] detections. We discuss and interpret our findings in Sect. 5, and we finally summarize the results in Sect. 6. Throughout this work, we assume a flat Λ CDM cosmology with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $\Omega_m = 0.3$.

2. Observations and data reduction

2.1. UVES observations

The four HzRGs of this work’s sample were observed with the UVES instrument at the VLT under the program 108.21WL (PI: Wuji Wang) between November 2021 and March 2022. These four targets are part of a larger sample of eight HzRGs which have all been previously observed using VLT/MUSE. The selection criteria for the eight HzRGs included redshifts $z > 2.9$ to ensure the Ly α emission line falls within the MUSE spectral range, $\text{Dec} < 25^\circ$ for observability from the southern hemisphere, and the presence of known extended bright Ly α emission nebulae ($> 10''$, [Wang et al. 2023](#)). The four HzRGs we targeted were then specifically followed up with UVES observations, as they were among the sources in the eight-object sample that lacked existing high spectral resolution data. Three additional objects in the larger sample have been observed at high spectral resolution and studied in previous works ([Jarvis et al. 2003](#); [Wilman et al. 2004](#); [Kolwa et al. 2019](#)). In this paper, we focus exclusively on the newly obtained UVES data.

The UVES slit was centered on the central AGN position and oriented along the radio jet axis. The AGN coordinates and position angles of the radio jet axes are given in Table 1. In Fig. 1 we show the position and orientation of the slits on the MUSE Ly α surface brightness maps. The black contours show the extent of the radio lobes. The radio data were recorded with the Very Large Array (VLA) in the case of 4C+03.24, MRC 0316 and TN J0205 (e.g., [Carilli et al. 1997](#); [van Ojik et al. 1996](#); [Nesvadba et al. 2007](#)) and with the Multi-Element Radio Linked

Table 1. Details of the targets in the sample.

Target name	Redshift z	RA* (J2000) hh:mm:ss	Dec* (J2000) dd:mm:ss	Position angle** degree
4C+03.24	3.5657 [†]	12:45:38.37	+03:23:21.0	156
4C+04.11	4.5077 [‡]	03:11:47.97	+05:08:03.74	162
MRC 0316–257	3.1238 [‡]	03:18:12.07	–25:35:10.22	55
TN J0205+2242	3.5060 [‡]	02:05:10.69	+22:42:50.4	153

Notes. ^(*)Coordinates of the central AGN. ^(**)Radio axis position angle (from north to east) as specified for the UVES observations. ^(†)Redshift determined from the [O III] emission line (Nesvadba et al. 2017a). ^(‡)Redshift determined from the He II emission line (Kolwa et al. 2023; Wang et al. 2023 for MRC 0316).

Interferometer Network (MERLIN) in the case of 4C+04.11 (Parijskij et al. 2014).

A slit width of 1.8'' was chosen, which corresponds to a resolving power of about $\lambda/\Delta\lambda = 26\,000$ and a spectral resolution of $\Delta\lambda \approx 0.19\text{--}0.27\text{ \AA}$ over the wavelength range of the red arm or $\Delta v \approx 12\text{ km s}^{-1}$ in terms of velocity (see UVES user manual¹). The length of the slit on the sky is 12''. The CCD read-out mode for the observations is a 2×3 (spatial $\times$ spectral) binning mode. The spatial pixel scale after the binning is 0.36''. Additional binning is performed in the dispersion direction to improve the signal-to-noise ratio (S/N), resulting in pixel scales of 0.09 Å for 4C+04.11, MRC 0316 and TN J0205 and 0.14 Å for 4C+03.24.

The observations were divided into five Observation Blocks (OBs) of about 50 minutes exposure time each. For the target MRC 0316 we include an additional OB, which was observed since one of the OBs did not fulfill the seeing conditions requested in the proposal. For 4C+03.24, only 4 OBs are included, as one OB shows a much lower S/N than the other four. The final spectra thus have total exposure times on target of about 4 hours and 10 minutes for 4C+04.11 and TN J0205, 5 hours for MRC 0316 and 3 hours and 20 minutes for 4C+03.24. The exposure times, the spectral resolution around the Ly α emission region, average seeing disk diameters over all included OBs and other details of the UVES observations are summarized in Table 2. The spectra are not flux calibrated as no standard star was observed during the observing run.

2.2. UVES data reduction

We develop an optimized data reduction method for the following spectral analysis. First, cosmic rays are removed in the raw science frames of each exposure using the LACOSMIC² package (Dokkum 2001; McCully 2014) with the Laplacian S/N threshold set to a value of 3. The UVES data reduction pipeline is executed on the cleaned science frame via ESOREX (ESO Recipe Execution Tool, ESO CPL Development Team 2015), a command-line driven utility to run the pipeline recipes, with the processed calibration files provided as input and the extraction method set to 2D. The pipeline performs the bias subtraction and flat-fielding and uses order-definition frames and ThAr arc frames to locate and define the orders and perform the wavelength calibration. By setting the extraction method to 2D, the 2D long-slit spectra, containing spatial and spectral information, are extracted. To obtain the optimal signal

extraction region for the final spectra, cumulative spatial flux profiles are evaluated around the Ly α wavelength range and the signal region is chosen as the spatial region in the 2D spectra, where the cumulative flux reaches between 10% and 90% of its maximum value. The median over the sky background, corresponding to regions above and below the signal region, is subtracted from the signal region. The sky-subtracted signal region is summed to obtain the bias-subtracted, flat-fielded, wavelength-calibrated, sky-subtracted 1D spectra. Different exposures are median-combined for each target. We call the spectra extracted in the described way the UVES master spectra.

2.3. Ancillary MUSE data

The four observed high-redshift radio galaxies listed in Table 2 have previously been observed (PI: Joël Vernet and MUSE WFAO commissioning observations for 4C+03.24) and analyzed, with focus on the tomography of the Ly α emission nebulae, using the MUSE instrument at VLT (Vernet et al. 2017; Wang et al. 2021, 2023). Using an integral field spectrograph allowed us to map the CGM and the spatial extent of the gaseous Ly α emission nebulae. The observations were taken in Wide-Field-Mode (WFM) with a fov of $60 \times 60\text{ arcsec}^2$ and Adaptive Optics (AO) was only employed for 4C+03.24. 4C+04.11, MRC 0316, and TN J0205 have total exposure times of about 4.24 h and 4C+03.24 of 1.25 h. They cover an extended wavelength range of 4650–9300 Å. The spatial sampling is $0.2''\text{ pix}^{-1}$, the spectral sampling is 0.125 nm pix^{-1} and the resolving power is $\lambda/\Delta\lambda = 1750\text{--}3750$ for the covered wavelength range, corresponding to a resolution of $\Delta v \approx 171\text{--}90\text{ km s}^{-1}$ (Wang et al. 2023). The UVES spectra therefore provide a spectral resolution that is about 8 to 14 times higher compared to the spectral resolution of MUSE. The MUSE data reduction is detailed in Wang et al. (2023).

2.4. Ancillary JWST/NIRSpec data

4C+03.24 and TN J0205 have been observed using the NIRSpec IFU instrument onboard JWST as part of the JWST Cycle 1 General Observers program with proposal ID 1970 (PI: Wuji Wang). The observations zoom into the central $\sim 25 \times 25\text{ kpc}^2$ surrounding the AGNs. 4C+03.24 and TN J0205 both have total exposure times of about 4 hours. For the observations a filter/disperser combination of F170LP/G235H was chosen with a resolving power of ~ 2700 and a wavelength range of 1.66–3.17 μm (Böker et al. 2022), covering [O II] $\lambda\lambda 3726, 3729$, H β , [O III] $\lambda\lambda 4959, 5007$ and H α at the redshifts of the targets. The spectral resolution is about 110 km s^{-1} .

¹ UVES user manual, latest version: https://www.eso.org/sci/facilities/paranal/instruments/uves/doc/ESO_514367_User_Manual_117.pdf

² <https://lacosmic.readthedocs.io/en/stable/>

Table 2. Details of the UVES observations.

Target name	UT date dd/mm/yyyy	Exposure time hours	Spectral resolution* [Å]	Seeing** arcsec
4C+03.24	08/02/2022–01/03/2022	3.34	0.21	0.63 ± 0.06
4C+04.11	02/12/2021–08/12/2021	4.17	0.25	0.52 ± 0.07
MRC 0316–257	01/11/2021–30/12/2021	5.01	0.19	1.05 ± 0.24
TN J0205+2242	07/12/2021–27/12/2021	4.17	0.21	0.93 ± 0.20

Notes. (*)Spectral resolution around the observed Ly α line. (**)Seeing averaged over all included OBs, with uncertainties given by the standard error of the mean.

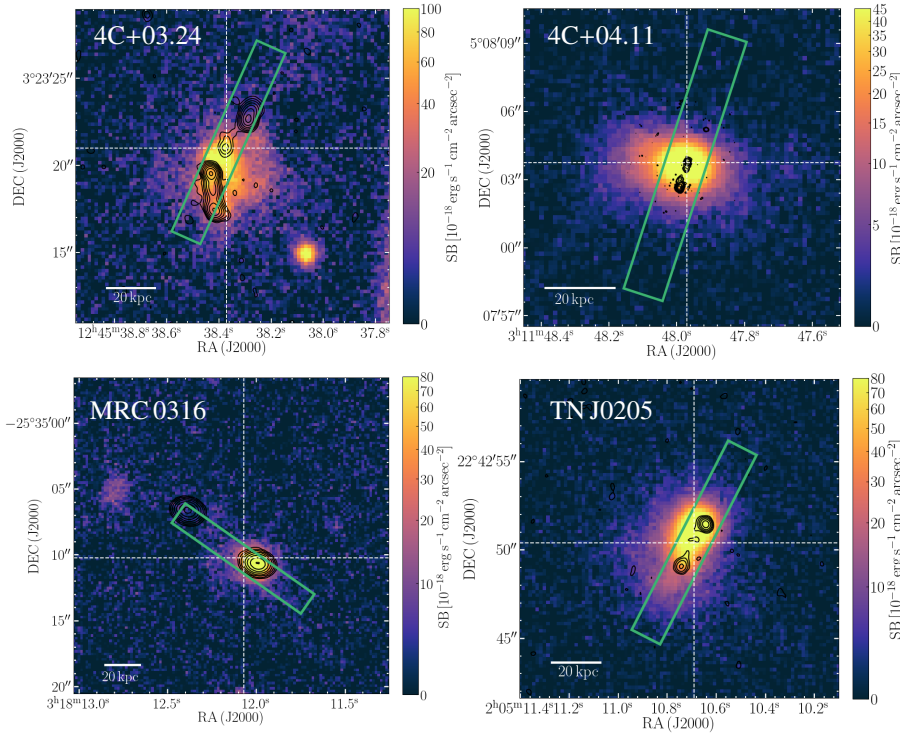


Fig. 1. MUSE surface brightness maps of the narrowband Ly α emission. The wavelength ranges in the observed frame for the narrowbands are 5550–5560 Å for 4C+03.24, 6705–6710 Å for 4C+04.11, 5018–5037 Å for MRC 0316 and 5475–5481 Å for TN J0205. The radio contours (starting at 0.2 mJy/beam and increasing by a factor of 2), showing the extent of the radio emission, are overplotted as black lines. The green rectangle shows the position of the UVES slit on the sky. The white crosshairs indicate the position of the AGN. We note that the bright emission southwest of 4C+03.24 is likely a foreground star as its continuum resembles a blackbody (Nesvadba et al. 2017a).

The data reduction performed on the JWST/NIRSpec data cubes is similar to the procedure described in Vayner et al. (2023), Wang et al. (2024, 2025). To process the data, the JWST Science Calibration pipeline³ (Bushouse et al. 2023) is used.

The first and second stage are implemented following the standard pipeline, but the *cube build* method that creates a 3D cube from the 2D spectra was applied with the *emsm* approach instead of the default *drizzle*, as using the *emsm* method reduces low-frequency ripples due to undersampling (Vayner et al. 2023; Wang et al. 2024). To combine the cubes at each dithered position, the Python package REPROJECT⁴ was implemented, following the script from Vayner et al. (2023). The pixel scale after resampling is 0.05″.

3. Line-fitting procedure

In order to characterize the absorption features in the halo emission of the four HzRGs, we implement a line-fitting procedure that has been used successfully in previous works (e.g., Jarvis et al. 2003; Swinbank et al. 2015; Silva et al. 2018b; Kolwa et al. 2019; Wang et al. 2021). We fit the Ly α pro-

files with an underlying Gaussian emission (consisting of one or two components) and superimposed Voigt profiles (e.g., Tepper-García 2006) for the absorption features. The use of a Gaussian profile for the underlying intrinsic emission is supported by previous studies (e.g., Arrigoni Battaia et al. 2019; Chang et al. 2023). The Gaussian model can be written as

$$F_{\lambda} = \frac{F}{\sigma_{\lambda} \sqrt{2\pi}} \exp \left[-\frac{1}{2} \left(\frac{\lambda - \lambda_0}{\sigma_{\lambda}} \right)^2 \right]. \quad (1)$$

Here, F_{λ} is the flux density at wavelength λ , F is the integrated flux of the emission line, σ_{λ} the line width, λ_0 is the center of the line and λ the wavelength. The absorption can be quantified in terms of the optical depth τ_{λ} as proportional to $e^{-\tau_{\lambda}}$. More specifically the Voigt-Hjerting function, also called the Voigt profile, is denoted as

$$\tau_{\lambda} = \frac{N \sqrt{\pi} e^2 f \lambda_0^2}{\Delta \lambda_D m_e c^2} H(a, x), \quad (2)$$

with the column density N of the absorbing gas, the electron charge e , the electron mass m_e , the oscillator strength f (values taken from Kramida et al. 2023) and the speed of light c . $\Delta \lambda_D$ depends on the Doppler parameter b , characterizing the width of the line, as $\Delta \lambda_D = \frac{b}{c} \lambda_0$. $H(a, x)$ is the Hjerting function, as

³ <https://github.com/spacetelescope/jwst>

⁴ <https://pypi.org/project/reproject/>

approximated in [Tepper-García \(2006\)](#) for column densities up to 10^{22} cm^{-2} with $x \equiv \frac{\lambda - \lambda_0}{\Delta \lambda_D}$ and $a \equiv \frac{\lambda_0^2 \Gamma}{4\pi c \Delta \lambda_D}$. Γ is the Lorentzian width. The Voigt profiles ($\exp(-\sum_{i=1}^n \tau_{\lambda,i})$ with n the number of absorbers) are then multiplied with the Gaussian profiles. In order to match the resolution of the UVES instrument, we convolve this with the line-spread function (LSF) of our observations using the Fast Fourier Transform (FFT) within the SCIPY library ([Virtanen et al. 2020](#)). The UVES LSF is determined to have an average Gaussian width of $\langle \sigma_\lambda \rangle \approx 0.10 \text{ Å}$ or a full width at half maximum of $\langle \text{FWHM} \rangle \approx 0.24 \text{ Å}$ from fitting a Gaussian profile to some of the strong skylines. The final fitting function is thus given by

$$F = \left(\sum_{j=1}^m F_{\lambda,j} \times \exp\left(-\sum_{i=1}^n \tau_{\lambda,i}\right) \right) \otimes \text{LSF}. \quad (3)$$

When modeling the absorbing gas, we assume that the gas clouds cover the extended emission line region and have a covering factor close to unity ($C \approx 1.0$). This assumption is supported by observations of similar absorbers with MUSE and has therefore been adopted in previous works (e.g., [Swinbank et al. 2015](#); [Kolwa et al. 2019](#); [Wang et al. 2021](#)). Moreover, the majority of absorbers in our UVES data span the full spatial extent of the Ly α emission region (see Fig. 8), and several show saturated absorption troughs that reach zero flux (e.g., absorbers 2 and 3 in MRC 0316, absorber 3 in TN J0205, and multiple systems in 4C+04.11; see Fig. 3). All of this suggests a high covering fraction of the absorbing gas.

We first employ nonlinear least-squares fitting, using the Python package LMFIT⁵ ([Newville et al. 2016](#)) and minimizing the residual. The least-squares optimization is used to determine suitable initial parameter values and to identify the preferred model complexity. The final parameter inference is obtained from Markov chain Monte Carlo (MCMC) sampling. We describe the details of the procedure in the following.

During the initial least-squares fitting, we fit the underlying Gaussian and the convolved Voigt profile simultaneously to the data, following the model derived above (see Eq. 3). We start the fitting using only one underlying Gaussian emission component and then add another component, if using two components provides better fit results according to the Bayesian Information Criterion (BIC; [Liddle 2007](#))⁶. For 4C+04.11, the blue wing of the Ly α line is heavily affected by absorbers, which makes it difficult to determine the underlying shape of the Gaussian. We therefore start by fitting a Gaussian model using only the red wing as input, following [Wang et al. \(2021\)](#). For 4C+04.11, MRC 0316, and TN J0205, we identify two Gaussian components and for 4C+03.24 one. We refer to the component closest to the systemic redshift as the systemic component and to the others as blueshifted or redshifted, depending on their velocity offset with respect to the systemic redshift. The continuum is fitted with a zero-order polynomial (the intercept) and left free to vary.

The position of the absorption troughs and the number of absorbers are identified visually. During the initial least-squares fitting, we start out with a low number of absorbers and gradually add more absorbers and narrow absorption features to the fitting. Different models with different number of absorbers are then compared using BIC to determine the preferred model complexity. The parameters of the absorbers are constrained based on

previous studies of Ly α absorption systems in HzRGs. Observations suggest that these absorbers either have lower column densities between 10^{13} cm^{-2} and 10^{15} cm^{-2} or high column densities that exceed 10^{18} cm^{-2} ([Wilman et al. 2004](#)). The column density is therefore constrained to lie between 10^{12} cm^{-2} and 10^{20} cm^{-2} following [Kolwa et al. \(2019\)](#). The lower limit on the Doppler parameter is set by the resolution of the UVES instrument as $b_{\min} \propto \sigma_\lambda = 12 \text{ km s}^{-1} / (2 \sqrt{2 \ln(2)}) \approx 5 \text{ km s}^{-1}$. The upper limit is set to $b_{\max} = 400 \text{ km s}^{-1}$ following the argument in [Kolwa et al. \(2019\)](#) that the absorbing gas is relatively quiescent compared to other regions exhibiting line widths with FWHM exceeding 1000 km s^{-1} . The redshifts of the absorbers are determined from visual inspection of the spectra and are free to vary by ± 0.001 . These limits are applied as parameter bounds in the least-squares fitting and as priors in the subsequent MCMC sampling.

Likely due to the high number of fit parameters, LMFIT did not return a covariance matrix from the least-squares fitting, and uncertainties on the fitted parameters could not be obtained this way. We therefore perform MCMC sampling to obtain parameter estimates and credible intervals using the Python package EMCEE⁷ ([Foreman-Mackey et al. 2013](#)) that implements the affine-invariant Ensemble Sampler proposed by [Goodman & Weare \(2010\)](#). For the MCMC analysis we adopt the preferred model complexity determined from the least-squares fitting and sample the full model parameter space simultaneously. The MCMC chains are initialized around the maximum-likelihood solution from the least-squares fit and explore the parameter space within the priors motivated above (see also Table A.1). The predictive models shown in the figures (e.g., Fig. 3) are derived from the MCMC posterior distributions. The shaded regions indicate the 16th–84th percentile range of the model realizations, representing the uncertainties.

4. Results

In this section, we first compare the resolution of the UVES spectra to complementary MUSE data. We then present the results of the Ly α line fitting, starting with the analysis of the UVES master spectra. We examine the spatial profiles along the radio jet axis and conclude by comparing these findings with JWST observations of 4C+03.24 and TN J0205.

4.1. Comparison with MUSE

The MUSE data of the four targets of our sample have previously been analyzed, in [Vernet et al. \(2017\)](#), [Wang et al. \(2021\)](#), [Kolwa et al. \(2023\)](#), [Wang et al. \(2023\)](#). To compare the UVES data to the MUSE data, we extract pseudo-longslit spectra from the MUSE data, simulating a slit width and length as used in the instrument setting for the UVES observations (slit width of $1.8''$ and a height of $12''$). To extract the 2-dimensional position-velocity pseudo-longslit spectra, the Python-package PVEXTRACTOR⁸ is used. The center and orientation of the slit in the extraction is chosen according to the values specified for the UVES observations as the center of the target and the position angle of the radio jet, which are listed in Table 1. For better visual comparison, the MUSE pseudo-longslit spectra are scaled to the UVES spectra by interpolating the UVES data onto the wavelength grid of the MUSE data in a region

⁵ <https://lmfit.github.io/lmfit-py/>

⁶ The results are also consistent using the Akaike information criterion ([Liddle 2007](#)).

⁷ <https://emcee.readthedocs.io/en/stable/>

⁸ <https://pvextractor.readthedocs.io/en/latest/api.html#module-pvextractor>

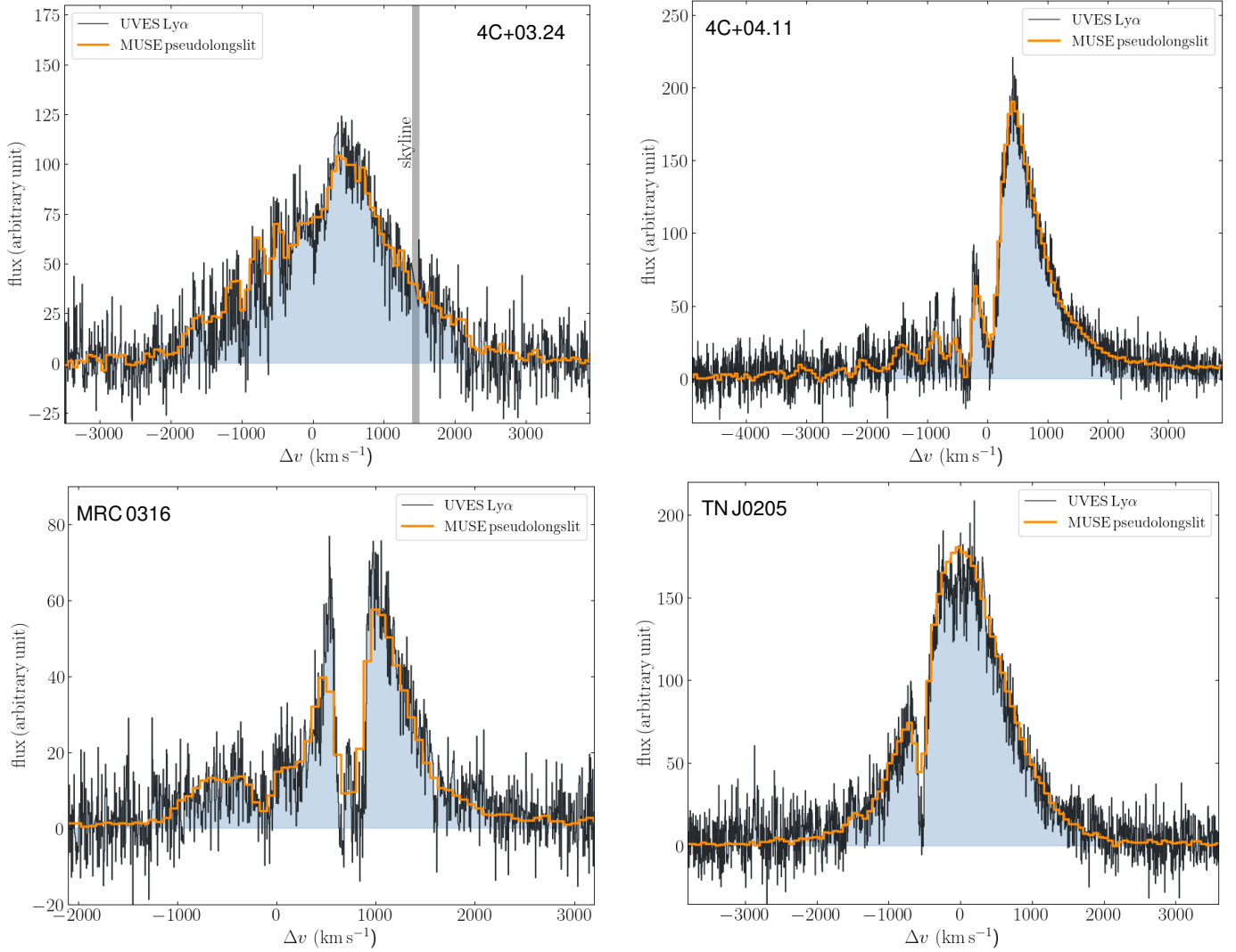


Fig. 2. UVES spectra of the four targets around the Ly α emission with the MUSE pseudo-longslit spectra overplotted in orange. The gray shaded area in the spectrum of 4C+03.24 marks the position of the strong sky line around 5577 Å.

alongside the main Ly α peak and calculating a scaling factor accordingly. The MUSE pseudo-longslit spectra and UVES spectra are overplotted in Fig. 2. UVES allows us to observe much narrower absorption features, which get broadened due to the moderate resolution in the case of the MUSE instrument. For MRC 0316, the deep absorber observed with MUSE at around 800 km s^{-1} splits into two separate, almost fully saturated absorbers when observed with UVES. A similar result was previously found in Jarvis et al. (2003) for MRC 0200+015, where a $N_{\text{HI}} \sim 10^{19} \text{ cm}^{-2}$ absorber (observed with the ESO Multi Mode Instrument (EMMI): van Ojik et al. 1997) split into two $N_{\text{HI}} \sim 10^{14} \text{ cm}^{-2}$ absorbers when observed with UVES. Some narrow absorbers, e.g., the very narrow feature on the red wing of the Ly α emission line of MRC 0316 at around 1600 km s^{-1} could not be identified using the MUSE observations. Additionally, for some of the deep features, visible in the spectra (e.g., the feature at around 0 km s^{-1} for 4C+04.11) for which previously only one absorber was identified (compare Wang et al. 2021), BIC and AIC now favor additional absorbers. For TN J0205, the dips observed on the emission line in the UVES spectra, but not in the MUSE data, are likely due to differences in observational setup and flux scaling.

4.2. Line-fitting results

We identify 6 absorbers for 4C+03.24, MRC 0316 and TN J0205. 4C+04.11 shows absorption features out to large velocity shifts from the Ly α line center and we identify altogether 14 absorbers for this target. The fitted spectra can be seen in Fig. 3. The posterior parameter estimates for the Gaussian emission components and Voigt absorbers are listed in Tables 3, 4, 5, and 6.

The line centers for the underlying Gaussian emission of 4C+04.11 and TN J0205 are found to be close to the systemic velocity shift of the host galaxy, determined from the He II emission line at the position of the central AGN. This is to be expected if the Ly α emission gas is located in the potential well of the radio galaxy. For 4C+03.24 and MRC 0316, the Ly α line is however redshifted, by about 300 km s^{-1} for 4C+03.24 and about 580 and 710 km s^{-1} for the two velocity components of MRC 0316. Such velocity offsets between Ly α emission and the systemic redshift are commonly observed and can arise from radiative transfer effects and bulk gas motions, in addition to uncertainties in the systemic redshift estimate. For 4C+03.24, He II emission could not be identified and the systemic redshift is therefore based on the [O III] emission from Nesvadba et al.

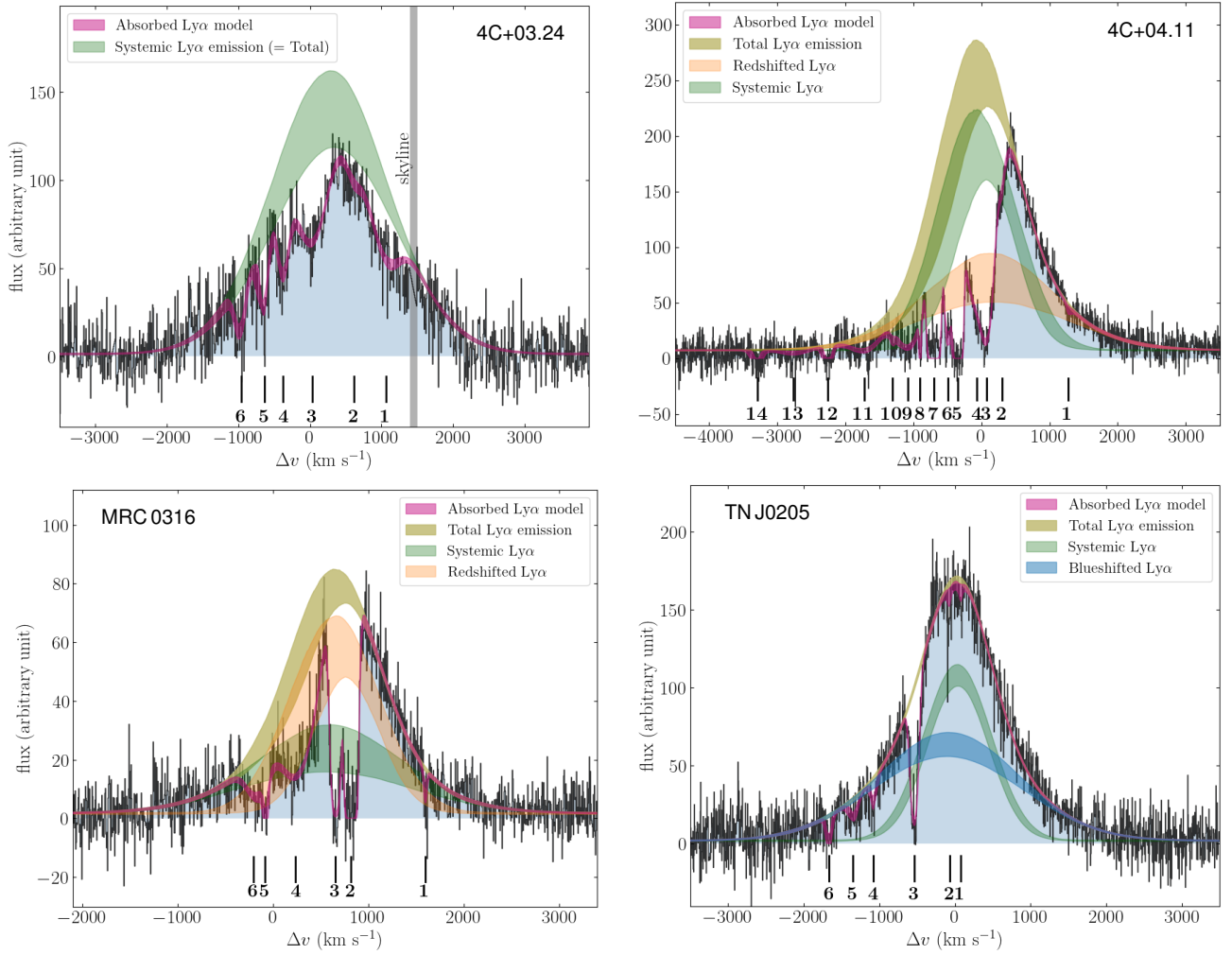


Fig. 3. UVES Ly α master spectra of the four targets. The shaded regions indicate the posterior predictive 68% credible intervals of the Ly α model and its Gaussian emission components. The colors correspond to the full absorbed model (magenta), intrinsic Gaussian emission (olive), systemic component (green), blueshifted component (blue), and redshifted component (orange). The systemic component is the one closest to the 0 km s $^{-1}$ as determined from the systemic redshift of the target. The position of the absorbers are marked with black vertical lines. The gray shaded area in the spectrum of 4C+03.24 marks the position of the strong Ly α emission around 5577 Å, which was interpolated for the fitting.

(2017a), which also agrees with the [O III] redshift at the host galaxy position in our NIRSpect data.

We find that most of the absorbers are blueshifted with respect to the systemic redshift of the HzRG and the Ly α line center, which is in agreement with previous studies of HzRGs (e.g., Jarvis et al. 2003; Humphrey et al. 2008a; Kolwa et al. 2019). This suggests that the absorbing gas is outflowing relative to the Ly α emission line region. For MRC 0316 and 4C+04.11, we identify absorbers (absorbers 1 for both targets) that are clearly redshifted with respect to the Ly α line center and the systemic redshift of the AGN ($\Delta v_{\text{sys}} \sim 1600$ km s $^{-1}$ and $\Delta v_{\text{sys}} \sim 1270$ km s $^{-1}$ respectively). These two absorbers are found to be very narrow with low column densities $\log(N_{\text{H I}}/\text{cm}^{-2})$ of approximately 13.4 and 12.9 and could potentially trace inflowing gas. However, we cannot exclude the possibility that they are intervening metal absorbers at unrelated redshifts. This will be further discussed in Sect. 5.1.

For our sample of four HzRGs, about 90% of the absorbers are optically thin with column densities of $N_{\text{H I}} = 10^{12} - 10^{15}$ cm $^{-2}$. Only overall four absorbers have column densities 10^{15} cm $^{-2} < N_{\text{H I}} < 10^{17}$ cm $^{-2}$ and we do not find any high column densities $> 10^{17}$ cm $^{-2}$. About 60% of the identified

absorbers have Doppler parameters $b < 80$ km s $^{-1}$. The high spectral resolution of UVES allowed us to detect these narrow absorbers more accurately compared to instruments with lower spectral resolution, such as MUSE.

There is a known degeneracy between column density and Doppler parameter, such that different combinations of these two parameters may lead to similar Voigt profiles, as discussed previously in Silva et al. (2018b). Inspection of the MCMC corner plots (Figs. A.1, A.3, and A.4) shows that several parameters are only weakly constrained and exhibit extended posterior tails and degeneracies. This behavior is expected given the large number of free parameters in the multicomponent fits, the limited S/N in the data, and the intrinsic degeneracy between column density and Doppler parameter. In particular, we note that parameters associated with absorbers in the outer wings of the Ly α line are not as well constrained due to the decreased S/N in these regions.

We further note that some of the broad Ly α absorption features may in fact represent blends of multiple narrower components that cannot be fully resolved at the given spectral resolution. This effect is expected to become more pronounced toward higher redshift, where the number density of intergalactic

Table 3. Median posterior parameter estimates with 68% credible intervals (16th–84th percentiles) from the MCMC sampling of the Ly α emission and the Voigt absorption model of 4C+03.24.

Emission fitting results				
Line	Line center (rest) λ_0 [Å]	Line center (obs.) λ [Å]	Line flux F [arb. unit]	Line width FWHM [km s ⁻¹]
Ly α	1215.67	5555.98 ^{+0.78} _{-0.63}	5174 ⁺⁷⁴² ₋₅₁₂	1973 ⁺⁷⁷ ₋₈₄
Absorption fitting results				
Absorber	Absorber redshift z	Column density $\log(N_{\text{HI}}/\text{cm}^{-2})$	Doppler parameter b [km s ⁻¹]	
1	3.5819 ^{+0.0004} _{-0.0004}	14.22 ^{+0.11} _{-0.11}	249 ⁺³¹ ₋₂₆	
2	3.5751 ^{+0.0003} _{-0.0003}	13.72 ^{+0.42} _{-0.50}	191 ⁺⁸⁹ ₋₇₂	
3	3.5660 ^{+0.0002} _{-0.0002}	14.40 ^{+0.16} _{-0.17}	280 ⁺⁵² ₋₄₅	
4	3.5599 ^{+0.0002} _{-0.0002}	13.94 ^{+0.11} _{-0.11}	101 ⁺¹⁹ ₋₁₅	
5	3.5556 ^{+0.0003} _{-0.0002}	14.03 ^{+0.18} _{-0.11}	87 ⁺³⁸ ₋₃₆	
6	3.5507 ^{+0.0002} _{-0.0002}	14.15 ^{+0.14} _{-0.17}	90 ⁺¹⁶ ₋₂₃	

Table 4. Median posterior parameter estimates with 68% credible intervals (16th–84th percentiles) from the MCMC sampling of the Ly α emission and the Voigt absorption model of 4C+04.11.

Emission fitting results				
Line	Line center (rest) λ_0 [Å]	Line center (obs.) λ [Å]	Line flux F [arb. unit]	Line width FWHM [km s ⁻¹]
Ly α	1215.67	6695.78 ^{+2.09} _{-2.25}	5130 ⁺¹⁴⁶⁰ ₋₁₁₈₀	1179 ⁺¹⁵⁰ ₋₁₄₂
Ly α (r.)	1215.67	6699.17 ^{+1.27} _{-2.03}	3471 ⁺⁹⁰³ ₋₇₆₄	2343 ⁺³³⁴ ₋₂₃₆
Absorption fitting results				
Absorber	Absorber redshift z	Column density $\log(N_{\text{HI}}/\text{cm}^{-2})$	Doppler parameter b [km s ⁻¹]	
1	4.5313 ^{+0.0005} _{-0.0006}	12.88 ^{+0.44} _{-0.55}	63 ⁺¹⁰⁸ ₋₄₄	
2	4.5132 ^{+0.0003} _{-0.0004}	12.89 ^{+0.42} _{-0.53}	53 ⁺⁴⁵ ₋₂₈	
3	4.5090 ^{+0.0002} _{-0.0002}	14.25 ^{+0.16} _{-0.12}	93 ⁺²¹ ₋₁₇	
4	4.5068 ^{+0.0003} _{-0.0007}	14.76 ^{+0.07} _{-0.11}	254 ⁺²⁶ ₋₂₆	
5	4.5013 ^{+0.0002} _{-0.0001}	15.47 ^{+0.36} _{-0.39}	44 ⁺⁹ ₋₆	
6	4.4988 ^{+0.0004} _{-0.0002}	14.34 ^{+0.17} _{-0.15}	73 ⁺³⁴ ₋₂₄	
7	4.4949 ^{+0.0001} _{-0.0001}	15.58 ^{+0.30} _{-0.47}	57 ⁺¹⁴ ₋₅	
8	4.4911 ^{+0.0001} _{-0.0001}	14.05 ^{+1.08} _{-0.39}	14 ⁺¹¹ ₋₆	
9	4.4880 ^{+0.0004} _{-0.0004}	14.66 ^{+0.16} _{-0.17}	206 ⁺⁵² ₋₅₄	
10	4.4837 ^{+0.0005} _{-0.0005}	13.32 ^{+0.62} _{-0.84}	37 ⁺¹²⁴ ₋₂₇	
11	4.4761 ^{+0.0006} _{-0.0006}	14.48 ^{+0.16} _{-0.20}	222 ⁺⁶⁵ ₋₄₃	
12	4.4662 ^{+0.0003} _{-0.0004}	15.07 ^{+0.62} _{-0.56}	47 ⁺²³ ₋₁₄	
13	4.4570 ^{+0.0007} _{-0.0007}	14.31 ^{+0.25} _{-0.47}	248 ⁺⁸⁸ ₋₆₀	
14	4.4471 ^{+0.0005} _{-0.0005}	16.81 ^{+1.47} _{-1.89}	32 ⁺²⁸ ₋₂₀	

Notes. Ly α is the systemic emission component (the one closest to 0 km s⁻¹), and Ly α (r.) is the emission component redshifted with respect to the systemic component.

absorbers increases. The inferred Doppler parameters should therefore be interpreted with caution.

4.3. Spatially resolved Ly α fitting

The UVES data are long-slit spectra obtained using a slit-length on the sky of 12''. The final 2D UVES spectra span a spatial

extent of approximately 10.9'' with a spatial pixel scale of about 0.36'' due to i.a. projection effects or rebinning of the spectra during the data reduction. By extracting 1-dimensional spectra from different regions along the length of the slit, we can analyze the spatial distribution of the Ly α emission and the absorption features. To this end, the 2D spectra of the different OBs obtained during the data reduction are median combined to obtain one

Table 5. Median posterior parameter estimates with 68% credible intervals (16th–84th percentiles) from the MCMC sampling of the Ly α emission and the Voigt absorption model of MRC 0316.

Emission fitting results				
Line	Line center (rest) λ_0 [Å]	Line center (obs.) λ [Å]	Line flux F [arb. unit]	Line width FWHM [km s ⁻¹]
Ly α	1215.67	5022.87 ^{+0.61} _{-0.91}	761 ⁺¹⁸⁸ ₋₂₁₅	1942 ⁺³¹⁶ ₋₂₀₄
Ly α (r.)	1215.67	5025.12 ^{+1.19} _{-1.23}	915 ⁺³⁶⁷ ₋₂₂₇	930 ⁺¹⁴⁹ ₋₁₁₀
Absorption fitting results				
Absorber	Absorber redshift z	Column density $\log(N_{\text{HI}}/\text{cm}^{-2})$	Doppler parameter b [km s ⁻¹]	
1	3.1458 ^{+0.0001} _{-0.0001}	13.37 ^{+0.18} _{-0.25}	22 ⁺¹¹ ₋₅	
2	3.1350 ^{+0.00004} _{-0.00004}	15.02 ^{+0.34} _{-0.19}	50 ⁺⁷ ₋₇	
3	3.1328 ^{+0.0001} _{-0.0001}	14.45 ^{+0.06} _{-0.05}	51 ⁺⁵ ₋₄	
4	3.1272 ^{+0.0002} _{-0.0002}	14.57 ^{+0.09} _{-0.13}	223 ⁺²⁵ ₋₂₆	
5	3.1227 ^{+0.0001} _{-0.0001}	14.29 ^{+1.04} _{-0.41}	22 ⁺¹⁵ ₋₁₀	
6	3.1215 ^{+0.0003} _{-0.0003}	14.29 ^{+0.13} _{-0.16}	135 ⁺³² ₋₂₈	

Notes. Ly α is the systemic emission component (the one closest to 0 km s⁻¹), and Ly α (r.) is the emission component redshifted with respect to the systemic component.

Table 6. Median posterior parameter estimates with 68% credible intervals (16th–84th percentiles) from the MCMC sampling of the Ly α emission and the Voigt absorption model of TN J0205.

Emission fitting results				
Line	Line center (rest) λ_0 [Å]	Line center (obs.) λ [Å]	Line flux F [arb. unit]	Line width FWHM [km s ⁻¹]
Ly α	1215.67	5478.48 ^{+0.19} _{-0.19}	2082 ⁺²⁵⁷ ₋₂₄₅	1006 ⁺⁵⁴ ₋₅₆
Ly α (bl.)	1215.67	5476.15 ^{+0.44} _{-0.50}	2716 ⁺²³⁴ ₋₂₄₃	2260 ⁺¹²⁸ ₋₁₀₉
Absorption fitting results				
Absorber	Absorber redshift z	Column density $\log(N_{\text{HI}}/\text{cm}^{-2})$	Doppler parameter b [km s ⁻¹]	
1	3.5071 ^{+0.0004} _{-0.0005}	12.44 ^{+0.30} _{-0.29}	55 ⁺¹³² ₋₃₀	
2	3.5049 ^{+0.0005} _{-0.0004}	12.56 ^{+0.30} _{-0.34}	66 ⁺⁷⁶ ₋₃₈	
3	3.49792 ^{+0.00004} _{-0.00004}	14.19 ^{+0.03} _{-0.03}	60 ⁺⁴ ₋₄	
4	3.4898 ^{+0.0002} _{-0.0002}	13.50 ^{+0.14} _{-0.18}	53 ⁺¹⁹ ₋₂₃	
5	3.4858 ^{+0.0003} _{-0.0003}	13.72 ^{+0.13} _{-0.18}	75 ⁺²¹ ₋₂₁	
6	3.4809 ^{+0.0002} _{-0.0002}	14.14 ^{+0.91} _{-0.26}	40 ⁺²⁰ ₋₁₉	

Notes. Ly α is the systemic emission component (the one closest to 0 km s⁻¹), and Ly α (bl.) is the emission component blueshifted with respect to the systemic component.

combined 2D spectrum for each target. We extract 1D spectra from different spatial regions with similar S/N along the slit in the 2D spectra following the procedure described in Sect. 2.2.

As the UVES slit was centered on the position of the AGN and oriented along the radio jet axis, we extract spatial regions approximately corresponding to the regions where the radio jet is either predominantly receding from us or approaching us. The jet kinematics are determined from the [O III] velocity shifts of SINFONI observations for 4C+03.24, MRC 0316 and TN J0205 (Nesvadba et al. 2007, 2008, 2017a). For 4C+04.11 the jet kinematics was determined in Parijskij et al. (2014) by using high-resolution radio polarization measurements. For 4C+03.24,

TN J0205 and MRC 0316, we extract spectra from three regions in the 2D long-slit spectra. One region where the jet is predominantly approaching, one region close to the central AGN position where the jet is predominantly receding and one region further away from the AGN where the jet is receding. As 4C+04.11 shows a more compact Ly α emission region, spectra from two regions are extracted, where the jet is predominantly approaching and receding. The flux of the spatial spectra is normalized to the spatial extent along the slit that they cover. We fit the spatial spectra of 4C+04.11, MRC 0316 and TN J0205 with two Gaussian components, consistent with the modeling of the master spectra, while we adopt a single Gaussian component for 4C+03.24.

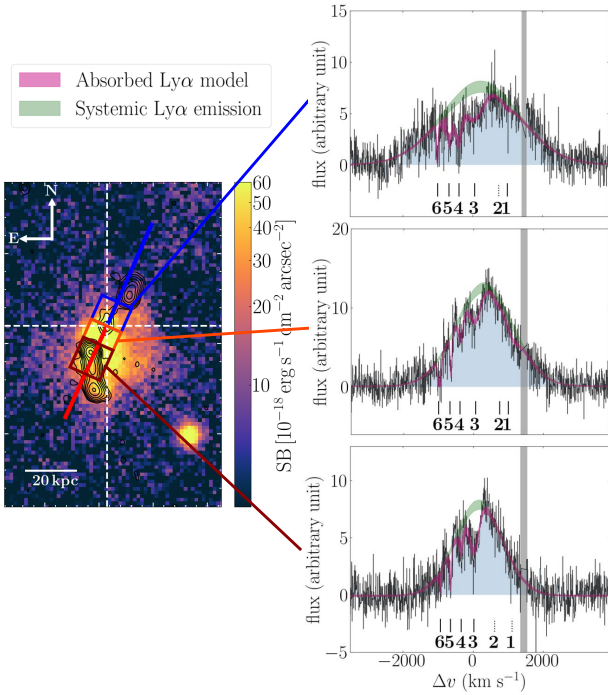


Fig. 4. Spatially resolved analysis of the UVES spectra of 4C+03.24. Left: MUSE surface brightness map of the Ly α emission showing the receding and approaching radio jet side with red and blue lines. The dark red, orange and blue squares approximately correspond to the three regions on the sky from which the UVES spectra are extracted. The white crosshairs indicate the position of the AGN. Right: UVES spectra extracted from the three regions with the magenta shaded region indicating the 68% credible interval of the posterior model. The absorbers not identified in the respective spectrum are marked with dotted black lines. We call the region (and the corresponding UVES spectra) marked in blue the approaching, the one marked in orange the central receding, and the one marked in dark red the outer receding part. The regions cover a spatial extent along the radio jet of about 10.6 kpc, 7.9 kpc, and 13.2 kpc, respectively.

We first perform a least-squares fit, using the best-fit parameters of the master spectra as initial values. If some of the absorbers identified in the master spectra cannot be identified in the spatially resolved spectra, we set their column density to zero in the fitting. MCMC sampling is then applied, initialized around the least-squares solution and adopting priors similar to before. The absorbers appear to show similar velocity shifts across the extent of the Ly α emission region, suggesting that they do not exhibit strong velocity gradients.

The approaching jet and receding jet sides and the spectra with the model results are shown in Figs. 4, 5, 6, and 7. 66% (21 out of 32) of the absorbers identified in our UVES master spectra are clearly detected over the entire extent of the spatial regions from which the spectra are extracted. Figure 8 shows a comparison between the column densities in the receding and approaching jet side. In an analysis of the MUSE data for the target 4C+04.11, Wang et al. (2021) identified a column density gradient from the southwest to the northeast region in a direction perpendicular to the radio jet axis with an increase of about 1 dex over the range of 24 kpc for one of the absorbers, as well as a small gradient along the jet axis. In our analysis, this absorber corresponds to absorber 3, for which we identify a similar gradient along the jet axis, as $\log(N/\text{cm}^{-2})$ increases towards the receding jet side by about 0.7 dex. We can therefore tentatively confirm the column density gradient. Under the assumption of the expanding shell scenario this gradient could be explained by

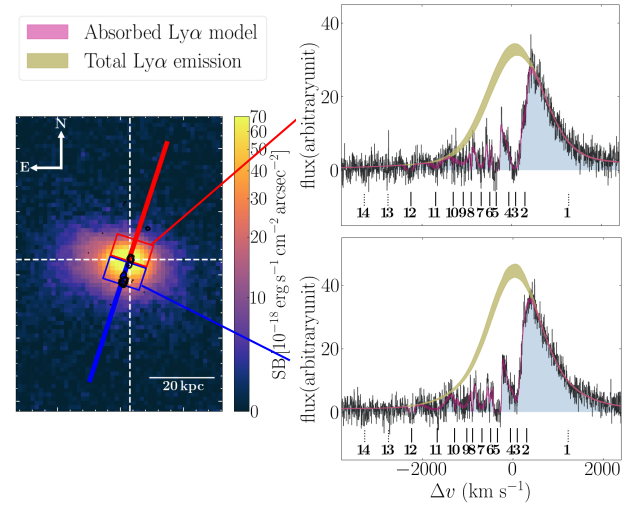


Fig. 5. Similar to Fig. 4, but for 4C+04.11. We only distinguish two regions for this target, namely the approaching and receding jet side. The two regions cover a spatial extent along the radio jet of about 7.2 kpc.

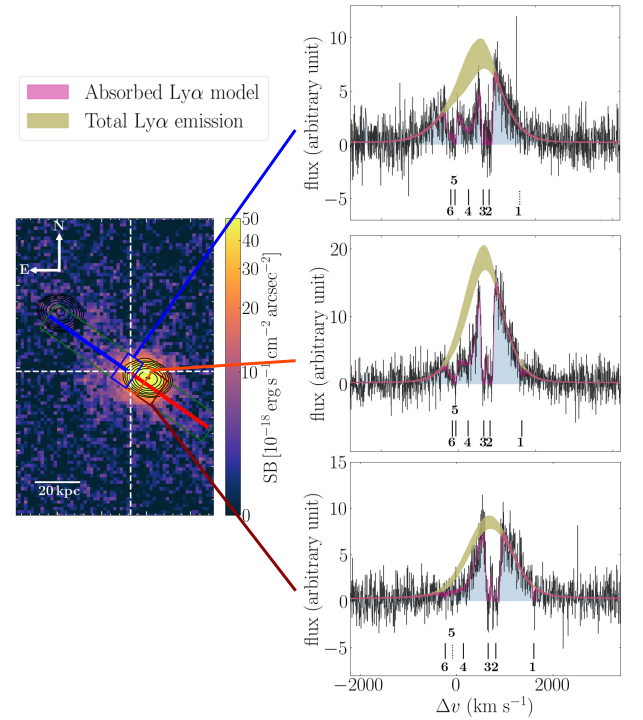


Fig. 6. Similar to Fig. 4, but for MRC 0316. The regions cover a spatial extent along the radio jet of about 8.3 kpc, 5.5 kpc, and 8.3 kpc, respectively.

the geometry of the gas shell as well as possible jet-gas interactions (see Wang et al. 2021). Our analysis of the other absorbers and targets suggests that this is not a general trend in HzRGs. Most absorbers exhibit little variation in column densities across the Ly α emission region. We also do not see any trend in column densities towards the receding or approaching jet sides.

4.4. Comparison with [O III] emission

The JWST/NIRSpec observations zoom into the central $\sim 25 \times 25$ kpc² of the HzRGs 4C+03.24 and TN J0205 and thus allow us to map the interstellar gas close to the central AGN with $\lesssim 1$ kpc

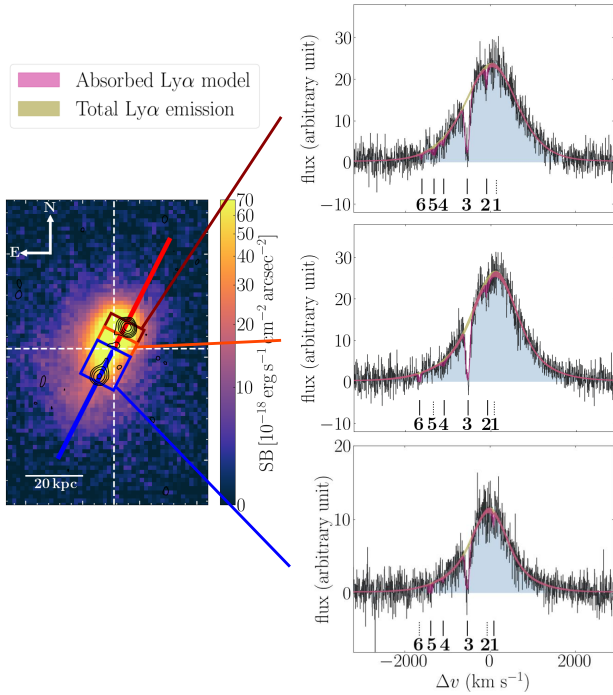


Fig. 7. Similar to Fig. 4, but for TN J0205. The regions cover a spatial extent along the radio jet of about 5.3 kpc, 5.3 kpc, and 13.3 kpc, respectively.

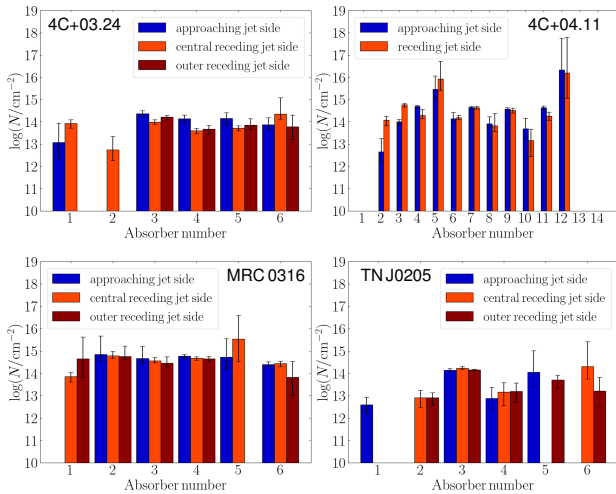


Fig. 8. Histogram of the logarithmic column density plotted against the absorber number for the different spatial spectra. The colored bars show the median posterior values of $\log(N_{\text{HI}}/\text{cm}^{-2})$ for each absorber, while the error bars indicate the 16th–84th percentile uncertainties derived from the MCMC sampling. For 4C+03.24, MRC 0316 and TN J0205, we call the different spatial regions the outer receding jet side, the central receding jet side and the approaching jet side (see also Figs. 4, 6, and 7). For 4C+04.11, we analyze two spatial regions, namely the approaching and the receding jet side (see Fig. 5).

resolution. The NIRSpect data cover several important emission lines, in particular [O II] $\lambda\lambda 3726, 3729$, H β , [O III] $\lambda\lambda 4959, 5007$ or H α . Hereafter, the forbidden singly and doubly ionized oxygen lines will be referred to as [O II] and [O III]. As [O III] has the highest S/N in comparison and as it is often used in studies of AGN narrow-line regions (e.g., Harrison et al. 2014; Wylezalek et al. 2017), we use this doublet line as indicator of the ionized gas morphology. For both of the targets, [O III] shows a very complicated

morphology and velocity structure. Multiple narrowband images of the [O III] $\lambda 5007$ emission, corresponding to different velocity ranges relative to the systemic, can be found in Figs. B.1 and B.2.

We examine the [O III] emission of the two targets in our sample to compare the morphology and kinematics of the ionized gas with those of the Ly α emission and absorption systems. As JWST is calibrated using vacuum wavelengths and UVES using air wavelengths, we convert the JWST data into air wavelengths for better comparison, following Wang et al. (2021), using the equation from Morton (2000)⁹. To account for the differences in spatial resolution between UVES and NIRSpect, we convolve the NIRSpect datacubes to match the seeing-limited resolution of UVES. For comparison, we then extract rectangular apertures from the convolved NIRSpect datacubes, which are chosen to match the regions on the sky corresponding to several 1D UVES spectra extracted along the slit. The UVES spectra are extracted following the same procedure as described in Sect. 2.2.

The UVES and NIRSpect spectra extracted for this comparison and the Ly α and [O III] surface brightness maps showing the corresponding regions on the sky are presented in Figs. 9 and 10. The [O III] emission lines are fitted with least-squares fitting with up to three Gaussian components and the continuum with a zero-order polynomial. For the UVES spectra we perform MCMC sampling to explore the posterior distribution. The components closest to 0 km s⁻¹, calculated from the systemic He II or [O III] redshifts, are called the systemic component and the other components are called blueshifted and redshifted.

When comparing the intrinsic Ly α emission with the [O III] emission, it is apparent that Ly α shows less spectral variation along the jet axis compared to [O III], where many different narrow, broad, blueshifted, and redshifted components appear in different spatial regions, which are indicative of outflows and inflows. The Ly α emission, on the other hand, is more uniform and homogeneous over the extent of the radio galaxy. While the NIRSpect data have higher spatial resolution than seeing-limited UVES observations, the main reason for the observed discrepancy can likely be attributed to the different physical nature of the lines. Ly α is optically thick and resonant, leading to diffusion of photons and smoother observed structures (e.g., Osterbrock & Ferland 2006), whereas [O III] traces lower surface brightness clumps.

5. Discussion

In this section, we discuss the possible origins of the absorption troughs identified in the Ly α spectra of HzRGs and compare them to observations of other quasar types. We then examine a possible connection to the ionized ISM traced by [O III] and discuss simulations of Ly α radiative transfer.

5.1. Origin of the absorbers

The Ly α emission and absorption probe the gas exclusively along our line of sight. A key question is therefore whether the absorbers are physically associated with the HzRG systems or instead trace large-scale intergalactic structures, such as the Ly α forest (e.g., Rauch 1998).

The spatial fitting along the length of the slit shows that many absorbers (about 66%), especially the deep and broad ones (with typical column densities in our case of $\geq 10^{14} \text{ cm}^{-2}$) are detectable over large projected spatial extents along the jet, of about 30 kpc for 4C+03.24, 14 kpc for 4C+04.11, 22 kpc for MRC 0316 and 23 kpc for TN J0205 (Fig. 8). Over these spatial extents, the absorbers exhibit remarkably coherent column densities (see Fig. 8), indicating that the absorbing gas is dis-

⁹ $\lambda_{\text{air}} = \lambda_{\text{vac}}/n$, with $n = 1 + 8.34254 \cdot 10^{-5} + 2.406147 \cdot 10^{-2}/(130 - s^2) + 1.5998 \cdot 10^{-4}/(38.9 - s^2)$, $s = 10^4/\lambda_{\text{vac}}$ with λ_{vac} in Å.

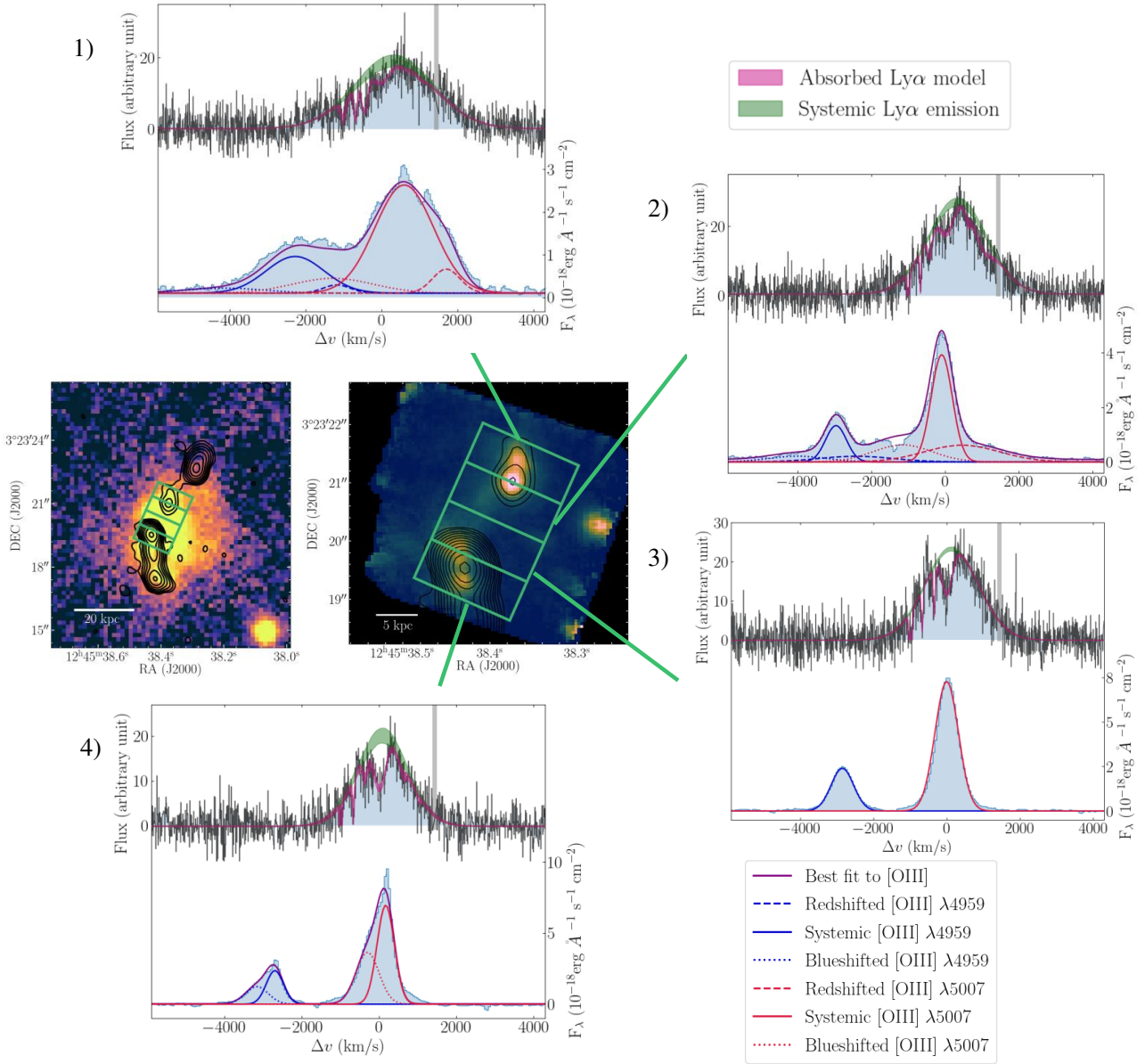


Fig. 9. Comparison between the UVES Ly α emission profiles and the JWST/NIRSpec [OIII] emission profiles of 4C+03.24. The radio contours (black) indicate the positions of the radio jets and the central AGN. The different spatial regions from which we extract the spectra are shown with green rectangles on the MUSE Ly α (left) and NIRSpec [OIII] (right) surface brightness maps. We number the regions and the corresponding spectral panels from 1 to 4, as shown in the plot. In each panel, the UVES Ly α spectrum is shown at the top and the NIRSpec [OIII] spectrum at the bottom.

tributed over large, contiguous structures. The absorbers cover almost the entire Ly α emission region and are found to be predominantly blueshifted with respect to the center of the Ly α emission. If we assume that the velocity offsets between the absorbers and the systemic redshift of the host galaxies trace physical separations along the line of sight, we infer comoving transverse distances of approximately 4–24 cMpc for the majority of absorbers. For comparison, we estimate virial radii for the HzRGs of between ~ 450 and 640 ckpc using the relation from Dekel et al. (2013)¹⁰, assuming a conservative stellar mass to halo mass ratio of 0.02 (Behroozi et al. 2013) and adopting the stellar masses from De Breuck et al. (2010) and Wang et al. (2021).

Interpreted purely as cosmological distances, the absorbers would therefore lie far beyond the virial radii of the host halos

and would not be physically associated with the HzRGs, placing the systems in the intergalactic medium (IGM). Our inferred column densities and Doppler parameters are consistent with typical values measured for Ly α forest absorbers (e.g., Hu et al. 1995; Kim et al. 2002, 2013). Moreover, studies of closely separated quasar sightlines at redshifts $z \lesssim 3$ have shown that intergalactic hydrogen absorbers can exhibit transverse coherence over tens to hundreds of kiloparsecs (Bechtold et al. 1994; Dinshaw et al. 1997; Rorai et al. 2017). The extended absorbers observed in our data could thus trace comparable large-scale intergalactic structures. In particular, our highest-redshift target 4C+04.11 (at $z \sim 4.5$) exhibits the largest number of absorption features. This is in line with the known increase in the abundance of low column density HI absorbers ($\sim 10^{14} - 10^{15} \text{ cm}^{-2}$) toward higher redshift, driven by the rising neutral fraction of the IGM (e.g., Kim et al. 2002, 2013, 2021; Rahmati et al. 2013). Thus, a

¹⁰ $R_{\text{vir}} \approx 100 \text{ kpc} (M_{\text{vir}}/10^{12} M_{\odot})^{1/3} \left(\frac{1+z}{3}\right)^{-1}$.

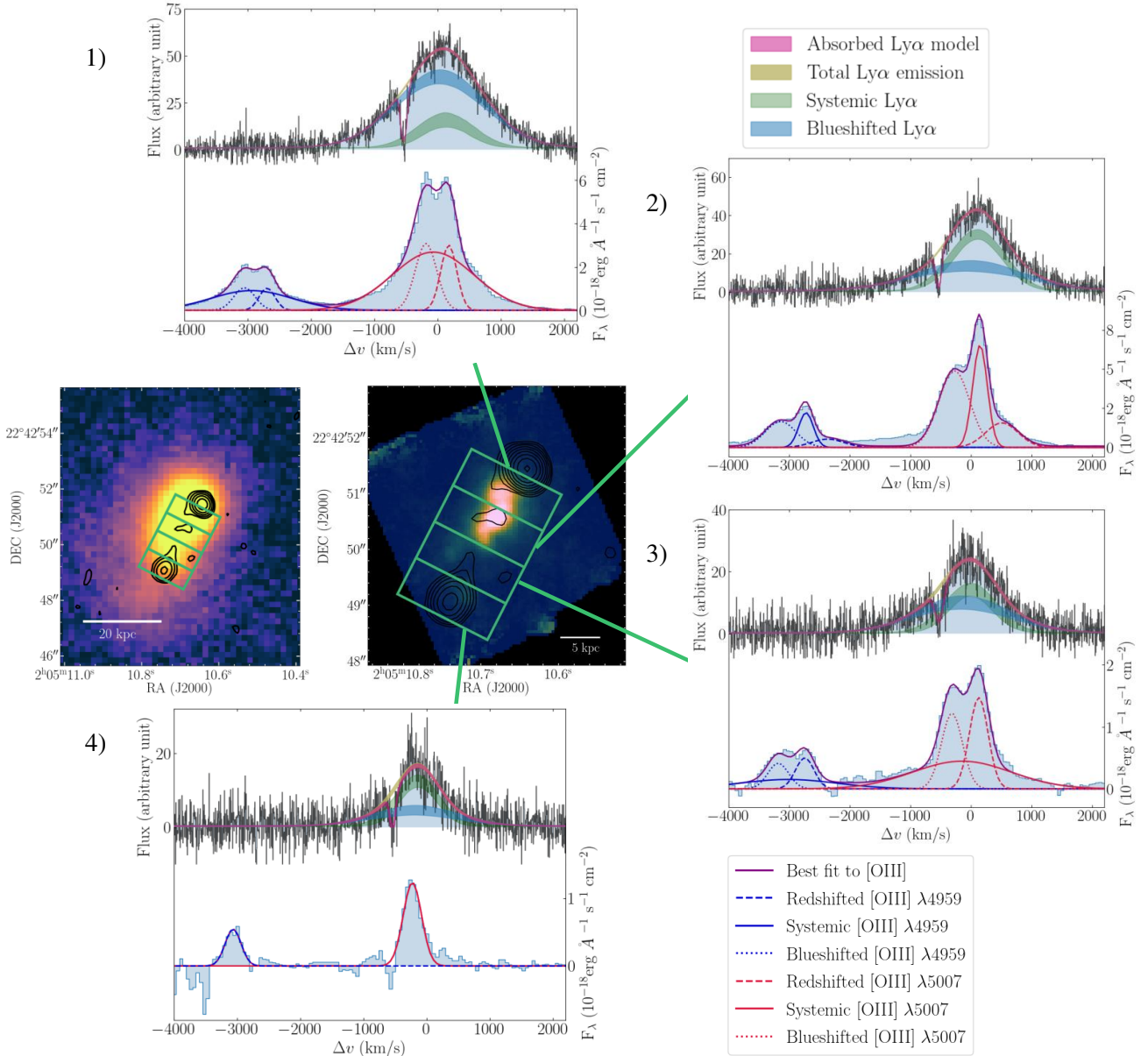


Fig. 10. Comparison between the UVES Ly α emission profiles and the JWST/NIRSpec IFU [O III] emission profiles of TN J0205. The radio contours (black) indicate the positions of the radio jets and the central AGN. The different spatial regions from which we extract the spectra are shown with green rectangles on the MUSE Ly α (left) and NIRSpec [O III] (right) surface brightness maps. We number the regions and the corresponding spectral panels from 1 to 4, as shown in the plot. In each panel, the UVES Ly α spectrum is shown at the top and the NIRSpec [O III] spectrum at the bottom.

substantial contribution from Ly α forest absorption is expected for this system.

Alternatively, if the observed velocity offsets of the absorbers relative to the systemic redshift are interpreted as reflecting line-of-sight gas motions rather than cosmological separations, this would indicate that the neutral clouds are outflowing structures in the CGM of the HzRGs. This interpretation has been proposed and studied in previous works. Binette et al. (2000) first interpreted the Ly α absorbers in HzRGs as expanding shells of neutral hydrogen intersecting the emission-line region, motivated by their blueshifted velocities, large spatial scales, and metallicity. Subsequent studies have shown that such extended hydrogen absorbers are a common feature of Ly α halos surrounding HzRGs, further developing and supporting this scenario (e.g., Wilman et al. 2004; Swinbank et al. 2015; Silva et al. 2018b; Kolwa et al. 2019; Wang et al. 2021). We note here that

we do not expect to observe any of the outflowing or inflowing gas behind the AGN and the bright Ly α emission nebulae due to attenuation effects. The kinematics and column densities of most absorbers in our sample remain remarkably consistent over large spatial extents. A similar behavior is for example seen in the Makani galaxy, where the large-scale outflow shows coherent kinematics over tens of kiloparsecs (Rupke et al. 2019, 2023). Coherent, shell-like outflows driven by AGN feedback are also predicted in hydrodynamical simulations (e.g., Krause 2002; Nelson et al. 2019; Ehlert et al. 2021; Ayromlou et al. 2024).

Previous studies of absorption in the Ly α emission of HzRGs have identified kinematic links between the absorbing gas and the radio jets. Using MUSE, Wang et al. (2021) found that one absorber in 4C+04.11 – also included in our UVES sample (absorber 3 in our analysis) – exhibits a velocity pattern aligned with the jet axis, consistent with jet–gas interactions. Similarly,

Swinbank et al. (2015) reported spatial variations in the velocity structure of the absorption that follow that of the underlying Ly α emission, while the column densities remain largely uniform.

In addition to these kinematic signatures, several works have revealed that extended absorbers associated with HzRGs show significant metal enrichment (same absorbers identified in C IV, S II, and N V; e.g., Kolwa et al. 2019; Wang et al. 2021), implying chemical abundances well above those expected for pristine or weakly enriched intergalactic gas. Such metallicity levels point to an origin within the host galaxy, with the enriched material subsequently transported to large radii. We stress here that the HzRG 4C+04.11, which shows metal-enriched absorption (for absorber 3 in our UVES analysis) as reported by Wang et al. (2021), is also included in our sample of UVES observations. These results demonstrate that absorbers with properties comparable to those in our sample can be directly influenced by the host galaxy, reinforcing the possibility that some of the systems we observe are likewise associated with the HzRGs.

Furthermore, cosmological hydrodynamical simulations suggest that the environments of massive halos at these epochs contain significant excess H I absorption relative to the ambient IGM (Meiksin et al. 2015, 2017; Conaboy et al. 2025). This excess arises from a combination of dense gas that can be ejected in the form of feedback-driven shells and large-scale filaments feeding the halo, which is also supported by observations (Prochaska et al. 2013; Matthee et al. 2024).

We note that several weaker and narrower absorbers, particularly those with column densities $<10^{14} \text{ cm}^{-2}$, are not detected across the full spatial extent of the Ly α nebulae. This can be explained by a combination of lower Ly α surface brightness and reduced S/N in the spatially resolved spectra, which limits our ability to detect small or narrow features in particular in the outer wings of the Ly α emission line. Alternatively, their limited spatial coverage may indicate that these systems are intrinsically not spatially extended or represent fragments of larger shell-like structures associated with the host system.

In summary, several lines of evidence indicate that at least some of the hydrogen absorbers in our sample could be associated with the HzRGs themselves, tracing outflowing shells of gas. At the same time, we cannot exclude that some absorbers arise in the intergalactic medium at Mpc-scale distances from the host galaxies, particularly for the lower-density absorbers with large velocity offsets with respect to the Ly α emission. Deep, high-resolution spectroscopic observations of associated metal lines will be crucial for distinguishing between these scenarios.

5.2. Comparison to other quasar studies

In addition to HzRGs (which are effectively obscured type-2 quasars), quasars at high redshift ubiquitously show extended Ly α emission halos that have been studied extensively in the past using IFU observations. Some examples are the Ly α nebulae around type-I quasars at redshifts $z \sim 3$ (e.g., Borisova et al. 2016; Arrigoni Battaia et al. 2019) or around ultra-luminous type-1 quasars at redshifts $z \sim 2$ (Cai et al. 2019), as well as around quasars at $z \sim 6$ (Farina et al. 2019). Ly α nebulae around quasars typically exhibit fewer and less prominent absorption features compared to HzRGs, and their spectra can generally be reasonably fitted with a Gaussian profile without the need to introduce absorption features (e.g., Arrigoni Battaia et al. 2018; Vayner et al. 2023). This difference can be naturally explained by the strong, unobscured ionizing continuum in type-I quasars, which creates large proximity zones (that can extend over thousands of km s^{-1} , corresponding to distances of several physical Mpc; e.g., Satyavolu et al. 2023). These ionized regions suppress the amount of neutral gas capable of producing absorption lines

and therefore prevent the appearance of strong absorption close to the Ly α peak. In contrast, HzRGs lack observable quasar proximity zones, because their ionizing radiation is blocked along the line of sight by obscuring material. As a result, neutral gas, potentially from Ly α forest absorption systems in the IGM, can persist close to the systemic redshift.

In addition to the proximity zone effects, HzRGs and the considered type-I quasars also differ in their typical Mpc-scale environments and feedback regimes. HzRGs are known to occupy overdense, gas-rich protocluster environments (e.g., Wylezalek et al. 2013; Noirot et al. 2018) and shocks driven by their powerful radio jets as well as strong AGN winds are expected to produce large-scale outflowing gas shells (e.g., Nesvadba et al. 2008; Wagner et al. 2012; Mukherjee et al. 2018; Meenakshi et al. 2022; Heckman & Best 2023; Roy et al. 2025). The type-I quasars discussed above are predominantly radio-quiet objects and comparable jet-driven shells are not expected to be prevalent in these systems. If some of the absorbers seen in the Ly α profiles of HzRGs are associated with jet-driven gas structures, their lower incidence toward radio-quiet quasars may also reflect differences in the dominant feedback mode (e.g., Wang et al. 2023). It could therefore be of interest to systematically target the Ly α emission of radio-loud quasars at high spectral resolution in future studies.

5.3. Connection between Ly α emission and ionized gas as revealed by JWST

The complicated velocity structure of the [O III] emission, with narrow, broad, blueshifted, and redshifted components (see Figs. B.1 and B.2), provide evidence of AGN-driven outflows and potentially inflows in the central region. Wang et al. (2024) analyzed the NIRSpec IFU data of the ionized ISM of another HzRG in the JWST program (PI: Wuji Wang) and found evidence of a radiatively driven outflow that is only weakly coupled to the quasar. The jet may therefore dominate the outflow (Nesvadba et al. 2017a).

For both 4C+03.24 and TN J0205, there is a spatial correlation between the broadening of [O III] and Ly α , with broader [O III] emission appearing in regions with broad Ly α . This suggests a shared underlying kinematic structure between [O III] and Ly α , potentially driven by outflows or turbulent gas motions. In the case of Ly α , however, additional line broadening arises due to resonant scattering, as photons in the line wings can escape more easily than those near the line center (Dijkstra 2014).

There is known jet-gas interaction south of the AGN of 4C+03.24, which can be seen from the bent structure of the radio jet contours (Fig. 1) and which has also been discussed in van Ojik et al. (1996). Wang et al. (2025) discovered several companions surrounding 4C+03.24 and TN J0205 in the NIRSpec observations of [O III] and ALMA (Atacama Large Millimeter/Submillimeter Array; Wootten & Thompson 2009) observations of [C II]. 4C+03.24 in particular shows [C II] companions, tracing cold gas systems, as well as optical continuum emission tracing the stellar component, to the south of the AGN, which might have been stripped during previous merger activity. The merger could have triggered the radio jet and its debris, the dense gas systems in the south, may have consequently deflected the jet, which would explain the bent radio structure (Wang et al. 2025).

Since the absorbers seen in the Ly α emission could potentially correspond to outflowing shells of gas that were ejected from the host galaxy at earlier times, they might be connected to outflows detected in the ISM. A comparison between the velocity shifts of the H I absorbers and the velocity shifts of the [O III] emission components does not show a clear correlation. The lack of correlation in velocity shifts suggests that the gas may

not be kinematically linked. Furthermore, the significant spatial variation in the [O III] emission contrasts with the consistent identification of H I absorbers across the entire spatial extent of the UVES spectra. This difference can be attributed to the fact that the H I absorbers and the [O III] emission trace distinct gas phases, which are subject to different physical conditions and kinematic behaviors.

When comparing the morphologies of Ly α observed with VLT/MUSE and [O III], we find that the Ly α emission is more extended and exhibits a rounder distribution, while [O III] is confined to more compact, localized regions (see also Peng et al. 2025). This likely reflects distinct physical processes, with Ly α emission shaped by resonant scattering and diffusion over large scales, while [O III] emission traces more localized ionization mechanisms (see also Sect. 4.4).

5.4. Absorption fitting and Ly α radiative transfer

We note here that our modeling of the Ly α profiles is based on the assumption that the Ly α photons are mostly absorbed or scattered out of our line of sight in gas shells that are not co-spatial with the emission line region (as also done in past works; see, e.g., Binette et al. 2000; Jarvis et al. 2003; Wilman et al. 2004; Swinbank et al. 2015; Silva et al. 2018b; Kolwa et al. 2019; Wang et al. 2021). As Ly α is a resonant line, the Ly α photons will scatter many times within the ISM and CGM of the galaxies before reaching the observer. This means that in principle, scattered photons also contribute to the emergent line profiles, and a full radiative transfer treatment is needed to properly predict the line shapes. Pioneering works by Verhamme et al. (2006) and Dijkstra et al. (2006) and other works following them (e.g., Gronke et al. 2015; Gronke & Dijkstra 2016; Park et al. 2022) revealed that Monte Carlo radiative Ly α transfer modeling of outflowing or infalling gas shells can produce asymmetric double-peaked line profiles that agree with observations at high redshifts. 3D radiative transfer simulations additionally allow to account for the spatial variations in Ly α (Seon & Kim 2020; Chang et al. 2023).

However, the very complicated line profiles and deep absorption troughs split into multiple components that we observe in our sample of HzRGs cannot be reproduced by current radiative transfer simulations. Our approach of fitting Voigt absorption troughs superimposed on a Gaussian emission profile (that might be shaped by radiative transfer effects) is therefore assumed to provide a sufficiently accurate representation of the observed line shapes for the purposes of our analysis. Nevertheless, incorporating radiative transfer effects into future studies of HzRG Ly α halos or comparisons with radiative transfer simulations could provide valuable insights into the nature of the line-emitting gas.

6. Conclusions

We investigated the neutral hydrogen gas detected in absorption against the Ly α nebulae of four high-redshift radio galaxies ($z \approx 3.1\text{--}4.5$). We complemented our UVES absorption results with comparisons to MUSE and JWST/NIRSpec observations. The main conclusions are summarized below.

1. We detected between 6 and 14 absorbers in the spectra of the four high-redshift radio galaxies in our sample. We found low column densities between $N_{\text{H I}} = 10^{12}\text{--}10^{17} \text{ cm}^{-2}$ and a wide range of Doppler parameters between ~ 14 and 300 km s^{-1} .
2. Most of the absorbers (about 66%) are visible over large spatial extents (up to 30 kpc along the radio jets), but vary little in column density overall. Taken together, our results indicate that a fraction of the absorbing gas is likely physically associated with the host halos. However, absorption from the IGM might contaminate our sample of absorbers.
3. Comparison between the UVES spectra and pseudo-longslit spectra extracted from MUSE data showed that a high spectral resolution is required for a complete identification of absorption features in the halos of HzRGs. For MRC 0316, the deep absorber observed with MUSE is split into multiple components when observed at higher spectral resolution using UVES. The UVES data thus allowed us to constrain the kinematics and morphology of the absorbing gas better.
4. The JWST/NIRSpec data of two of the four HzRGs in our sample revealed complicated morphologies and kinematics of the ionized interstellar gas traced by [O III] within about 20 kpc surrounding the AGN. We found no clear evidence of a relation between outflows in the ISM and the absorbers seen in the Ly α profiles. However, the kinematics of the [O III] and Ly α emission indicate a possible connection between the ionized and cool gas phases.

HzRGs are strong cosmological probes and present ideal targets for studying the evolution of massive galaxies and the role of AGN feedback. The analysis of Ly α absorption features provides valuable insights into the distribution of neutral hydrogen gas in the environments of these systems. Various datasets, including MUSE, UVES, JWST, and ALMA, were acquired for our sample of high-redshift radio galaxies. Future work will focus on integrating these datasets to study the CGM in multiple phases and explore the connections between different gas tracers. This will ultimately contribute to our understanding of the (re)distribution of gas in massive galaxies.

Data availability

The JWST data used in this work are publicly available from the Mikulski Archive for Space Telescopes (MAST) under programme JWST-GO-01970 and can be accessed via <https://dx.doi.org/10.17909/ataa-hn19>. The corner plots associated with the MCMC analysis are additionally made available as supplementary online material on Zenodo at <https://doi.org/10.5281/zenodo.19737893>.

Acknowledgements. We thank the anonymous referee for valuable comments, that helped improve this manuscript. J.R. thanks Seok-Jun Chang and Aniket Bhagwat for useful discussions. This work is based [in part] on observations made with the NASA/ESA/CSA *James Webb* Space Telescope. The data were obtained from the Mikulski Archive for Space Telescopes at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-03127 for JWST. W.W. acknowledges the grant support through JWST programs. Support for programs JWST-GO-03045 and JWST-GO-03950 was provided by NASA through a grant from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-03127. This work uses a number of open source software other than the aforementioned ones such as Jupyter notebook (Kluyver et al. 2016); matplotlib (Hunter 2007); SciPy (Virtanen et al. 2020); NumPy (Harris et al. 2020); Astropy (Price-Whelan et al. 2018).

References

- Arrigoni Battaia, F., Prochaska, J. X., Hennawi, J. F., et al. 2018, *MNRAS*, **473**, 3907
- Arrigoni Battaia, F., Hennawi, J. F., Prochaska, J. X., et al. 2019, *MNRAS*, **482**, 3162
- Ayromlou, M., Nelson, D., Pillepich, A., et al. 2024, *A&A*, **690**, A20
- Bacon, R., Accardo, M., Adjali, L., et al. 2010, *SPIE Conf. Ser.*, **7735**, 773508
- Bechtold, J., Crotts, A. P. S., Duncan, R. C., & Fang, Y. 1994, *ApJ*, **437**, L83
- Behroozi, P. S., Wechsler, R. H., & Conroy, C. 2013, *ApJ*, **770**, 57
- Binette, L., Kurk, J. D., Villar-Martín, M., & Röttgering, H. J. A. 2000, *A&A*, **356**, 23
- Böker, T., Arribas, S., Lützgendorf, N., et al. 2022, *A&A*, **661**, A82
- Borisova, E., Cantalupo, S., Lilly, S. J., et al. 2016, *ApJ*, **831**, 39

- Bushouse, H., Eisenhamer, J., Dencheva, N., et al. 2023, <https://doi.org/10.5281/zenodo.10022973>
- Cai, Z., Cantalupo, S., Prochaska, J. X., et al. 2019, *ApJS*, **245**, 23
- Carilli, C. L., Röttgering, H. J. A., van Ojik, R., Miley, G. K., & van Breugel, W. J. M. 1997, *ApJS*, **109**, 1
- Chandra, P., Swarup, G., Kulkarni, V. K., & Kantharia, N. G. 2004, *JApA*, **25**, 57
- Chang, S.-J., Yang, Y., Seon, K.-I., Zabludoff, A., & Lee, H.-W. 2023, *ApJ*, **945**, 100
- Cody, A. M., & Braun, R. 2003, *A&A*, **400**, 871
- Conaboy, L., Bolton, J. S., Keating, L. C., et al. 2025, *MNRAS*, **539**, 2790
- Curran, S. J., Whiting, M. T., Sadler, E. M., & Bignell, C. 2013, *MNRAS*, **428**, 2053
- De Breuck, C., Röttgering, H., Miley, G., van Breugel, W., & Best, P. 2000, *A&A*, **362**, 519
- De Breuck, C., Seymour, N., Stern, D., et al. 2010, *ApJ*, **725**, 36
- De Breuck, C., Lundgren, A., Emonts, B., et al. 2022, *A&A*, **658**, L2
- Dekel, A., Zolotov, A., Tweed, D., et al. 2013, *MNRAS*, **435**, 999
- Dekker, H., D'Odorico, S., Kaufer, A., Delabre, B., & Kotzłowski, H. 2000, *SPIE Conf. Ser.*, **4008**, 534
- Dijkstra, M. 2014, *PASA*, **31**, e040
- Dijkstra, M., Haiman, Z., & Spaans, M. 2006, *ApJ*, **649**, 14
- Dinshaw, M., Weymann, R. J., Impey, C. D., et al. 1997, *ApJ*, **491**, 45
- D'Odorico, S., Cristiani, S., Dekker, H., et al. 2000, *SPIE Conf. Ser.*, **4005**, 121
- Dokkum, P. 2001, *PASP*, **113**, 1420
- Ehlert, K., Weinberger, R., Pfrommer, C., & Springel, V. 2021, *MNRAS*, **503**, 1327
- Emonts, B. H. C., Norris, R. P., Feain, I., et al. 2014, *MNRAS*, **438**, 2898
- Emonts, B. H. C., Mao, M. Y., Stroe, A., et al. 2015, *MNRAS*, **451**, 1025
- Emonts, B. H. C., Lehnert, M. D., Villar-Martín, M., et al. 2016, *Science*, **354**, 1128
- Emonts, B. H. C., Lehnert, M. D., Lebowitz, S., et al. 2023, *ApJ*, **952**, 148
- ESO CPL Development Team 2015, Astrophysics Source Code Library [record ascl:1504.003]
- Fabian, A. C. 2012, *ARA&A*, **50**, 455
- Falkendal, T., Lehnert, M. D., Vernet, J., De Breuck, C., & Wang, W. 2021, *A&A*, **645**, A120
- Farina, E. P., Arrigoni-Battaia, F., Costa, T., et al. 2019, *ApJ*, **887**, 196
- Foreman-Mackey, D., Hogg, D. W., Lang, D., & Goodman, J. 2013, *PASP*, **125**, 306
- Gardner, J. P., Mather, J. C., Abbott, R., et al. 2023, *PASP*, **135**, 068001
- Goodman, J., & Weare, J. 2010, *Commun. Appl. Math. Comput. Sci.*, **5**, 65
- Gronke, M., & Dijkstra, M. 2016, *ApJ*, **826**, 14
- Gronke, M., Bull, P., & Dijkstra, M. 2015, *ApJ*, **812**, 123
- Gullberg, B., De Breuck, C., Lehnert, M. D., et al. 2016, *A&A*, **586**, A124
- Harris, C. R., Millman, K. J., van der Walt, S. J., et al. 2020, *Nature*, **585**, 357
- Harrison, C. M. 2017, *Nat. Astron.*, **1**, 0165
- Harrison, C. M., & Ramos Almeida, C. 2024, *Galaxies*, **12**, 17
- Harrison, C. M., Alexander, D. M., Mullaney, J. R., & Swinbank, A. M. 2014, *MNRAS*, **441**, 3306
- Heckman, T. M., & Best, P. N. 2014, *ARA&A*, **52**, 589
- Heckman, T. M., & Best, P. N. 2023, *Galaxies*, **11**, 21
- Hu, E. M., Kim, T.-S., Cowie, L. L., Songaila, A., & Rauch, M. 1995, *AJ*, **110**, 1526
- Humphrey, A., Villar-Martín, M., Sánchez, S. F., et al. 2008a, *MNRAS*, **390**, 1505
- Humphrey, A., Villar-Martín, M., Vernet, J., et al. 2008b, *MNRAS*, **383**, 11
- Hunter, J. D. 2007, *Comput. Sci. Eng.*, **9**, 90
- Iverson, R. J., Smail, I., Amblard, A., et al. 2012, *MNRAS*, **425**, 1320
- Jakobsen, P., Ferruit, P., Alves de Oliveira, C., et al. 2022, *A&A*, **661**, A80
- Jarvis, M. J., Wilman, R. J., Röttgering, H. J. A., & Binette, L. 2003, *MNRAS*, **338**, 263
- Kim, T. S., Carswell, R. F., Cristiani, S., D'Odorico, S., & Giallongo, E. 2002, *MNRAS*, **335**, 555
- Kim, T.-S., Partl, A. M., Carswell, R. F., & Müller, V. 2013, *A&A*, **552**, A77
- Kim, T.-S., Wakker, B. P., Nasir, F., et al. 2021, *MNRAS*, **501**, 5811
- King, A., & Pounds, K. 2015, *ARA&A*, **53**, 115
- Klamer, I. J., Ekers, R. D., Sadler, E. M., et al. 2005, *ApJ*, **621**, L1
- Kluyver, T., Ragan-Kelley, B., Pérez, F., et al. 2016, *IOS Press*, **87**
- Kolwa, S., Vernet, J., De Breuck, C., et al. 2019, *A&A*, **625**, A102
- Kolwa, S., De Breuck, C., Vernet, J., et al. 2023, *MNRAS*, **525**, 5831
- Kramida, A., Ralchenko, Y., Reader, J., & NIST ASD Team 2023, *NIST Atomic Spectra Database (version 5.11)*, Online, available: <https://physics.nist.gov/asd>, National Institute of Standards and Technology, Gaithersburg, MD
- Krause, M. 2002, *A&A*, **386**, L1
- Krause, M. 2005, *A&A*, **436**, 845
- Li, J., Emonts, B. H. C., Cai, Z., et al. 2021, *ApJ*, **922**, L29
- Liddle, A. R. 2007, *MNRAS*, **377**, L74
- Matthee, J., Golling, C., Mackenzie, R., et al. 2024, *MNRAS*, **529**, 2794
- McCarthy, P. J. 1993, *ARA&A*, **31**, 639
- McCully, C. 2014, *PASP*
- Meenakshi, M., Mukherjee, D., Wagner, A. Y., et al. 2022, *MNRAS*, **516**, 766
- Meiksin, A., Bolton, J. S., & Tittley, E. R. 2015, *MNRAS*, **453**, 899
- Meiksin, A., Bolton, J. S., & Puchwein, E. 2017, *MNRAS*, **468**, 1893
- Miley, G., & De Breuck, C. 2008, *A&ARv*, **15**, 67
- Morganti, R., & Oosterloo, T. 2018, *A&ARv*, **26**, 4
- Morton, D. C. 2000, *ApJS*, **130**, 403
- Mukherjee, D., Bicknell, G. V., Wagner, A. Y., Sutherland, R. S., & Silk, J. 2018, *MNRAS*, **479**, 5544
- Nelson, D., Pillepich, A., Springel, V., et al. 2019, *MNRAS*, **490**, 3234
- Nesvadba, N. P. H., Lehnert, M. D., De Breuck, C., Gilbert, A., & van Breugel, W. 2007, *A&A*, **475**, 145
- Nesvadba, N. P. H., Lehnert, M. D., De Breuck, C., Gilbert, A. M., & van Breugel, W. 2008, *A&A*, **491**, 407
- Nesvadba, N. P. H., De Breuck, C., Lehnert, M. D., Best, P. N., & Collet, C. 2017a, *A&A*, **599**, A123
- Nesvadba, N. P. H., Drouart, G., De Breuck, C., et al. 2017b, *A&A*, **600**, A121
- Newville, M., Nelson, A., Ingargiola, A., et al. 2016, <https://doi.org/10.5281/zenodo.58759>
- Noiro, G., Vernet, J., De Breuck, C., et al. 2016, *ApJ*, **830**, 90
- Noiro, G., Stern, D., Mei, S., et al. 2018, *ApJ*, **859**, 38
- Osterbrock, D. E., & Ferland, G. J. 2006, *Astrophysics of Gaseous Nebulae and Active Galactic Nuclei* (Sausalito: University Science Books)
- Parijskij, Y. N., Thomasson, P., Kopylov, A. I., et al. 2014, *MNRAS*, **439**, 2314
- Park, H., Kim, H. J., Ahn, K., et al. 2022, *ApJ*, **931**, 126
- Peng, B., Arrigoni Battaia, F., Vishwas, A., et al. 2025, *A&A*, **694**, L1
- Price-Whelan, A. M., Sipőcz, B., Günther, H., et al. 2018, *AJ*, **156**, 123
- Prochaska, J. X., Hennawi, J. F., Lee, K.-G., et al. 2013, *ApJ*, **776**, 136
- Rahmati, A., Pawlik, A. H., Raičević, M., & Schaye, J. 2013, *MNRAS*, **430**, 2427
- Rauch, M. 1998, *ARA&A*, **36**, 267
- Rocca-Volmerange, B., Le Borgne, D., De Breuck, C., Fioc, M., & Moy, E. 2004, *A&A*, **415**, 931
- Rorai, A., Hennawi, J. F., Oñorbe, J., et al. 2017, *Science*, **356**, 418
- Röttgering, H., & Pentericci, L. 1999, in *The Most Distant Radio Galaxies*, eds. H. J. A. Röttgering, P. N. Best, & M. D. Lehnert, 85
- Röttgering, H. J. A., Hunstead, R. W., Miley, G. K., van Ojik, R., & Wieringa, M. H. 1995, *MNRAS*, **277**, 389
- Röttgering, H., de Bruyn, G., & Pentericci, L. 1999, in *The Most Distant Radio Galaxies*, eds. H. J. A. Röttgering, P. N. Best, & M. D. Lehnert, 113
- Roy, N., Heckman, T., & Henry, A. 2025, ArXiv e-prints [arXiv:2508.06707]
- Rupke, D. S. N., Coil, A., Geach, J. E., et al. 2019, *Nature*, **574**, 643
- Rupke, D. S. N., Coil, A. L., Perrotta, S., et al. 2023, *ApJ*, **947**, 33
- Satyavolu, S., Eilers, A.-C., Kulkarni, G., et al. 2023, *MNRAS*, **522**, 4918
- Seon, K.-I., & Kim, C.-G. 2020, *ApJS*, **250**, 9
- Seymour, N., Stern, D., & De Breuck, C. 2007, *ASP Conf. Ser.*, **380**, 393
- Shukla, G., Srikanth, R., Gupta, N., et al. 2022, *MNRAS*, **510**, 786
- Silva, M., Humphrey, A., Lagos, P., et al. 2018a, *MNRAS*, **481**, 1401
- Silva, M., Humphrey, A., Lagos, P., et al. 2018b, *MNRAS*, **474**, 3649
- Swinbank, A. M., Vernet, J. D. R., Smail, I., et al. 2015, *MNRAS*, **449**, 1298
- Tepper-García, T. 2006, *MNRAS*, **369**, 2025
- Tumlinson, J., Peebles, M. S., & Werk, J. K. 2017, *ARA&A*, **55**, 389
- van Ojik, R., Roettgering, H. J. A., Carilli, C. L., et al. 1996, *A&A*, **313**, 25
- van Ojik, R., Roettgering, H. J. A., Miley, G. K., & Hunstead, R. W. 1997, *A&A*, **317**, 358
- Vayner, A., Zakamska, N. L., Ishikawa, Y., et al. 2023, *ApJ*, **955**, 92
- Venemans, B. P., Kurk, J. D., Miley, G. K., et al. 2002, *ApJ*, **569**, L11
- Verhamme, A., Schaerer, D., & Maselli, A. 2006, *A&A*, **460**, 397
- Vernet, J., Lehnert, M. D., De Breuck, C., et al. 2017, *A&A*, **602**, L6
- Villar-Martín, M., Humphrey, A., De Breuck, C., et al. 2007a, *MNRAS*, **375**, 1299
- Villar-Martín, M., Sánchez, S. F., Humphrey, A., et al. 2007b, *MNRAS*, **378**, 416
- Virtanen, P., Gommers, R., Oliphant, T. E., et al. 2020, *Nat. Meth.*, **17**, 261
- Wagner, A. Y., Bicknell, G. V., & Umemura, M. 2012, *ApJ*, **757**, 136
- Wang, W., Wylezalek, D., De Breuck, C., et al. 2021, *A&A*, **654**, A88
- Wang, W., Wylezalek, D., Vernet, J., et al. 2023, *A&A*, **680**, A70
- Wang, W., Wylezalek, D., De Breuck, C., et al. 2024, *A&A*, **683**, A169
- Wang, W., De Breuck, C., Wylezalek, D., et al. 2025, *A&A*, **696**, A88
- Wilman, R. J., Jarvis, M. J., Röttgering, H. J. A., & Binette, L. 2004, *MNRAS*, **351**, 1109
- Wooten, A., & Thompson, A. R. 2009, *IEEE Proc.*, **97**, 1463
- Wylezalek, D., De Breuck, C., Vernet, J., et al. 2013, *Tracing Cosmic Evolution with Clusters of Galaxies*, 87
- Wylezalek, D., Schnorr Müller, A., Zakamska, N. L., et al. 2017, *MNRAS*, **467**, 2612

Appendix A: Additional material of the MCMC sampling

In this appendix we present auxiliary material related to the MCMC sampling used to estimate the statistical uncertainties on the fitted Ly α line parameters from the UVES master spectra. In table A.1, the priors for the MCMC sampling of the UVES master spectra are listed. Figures A.1, A.2, A.3, and A.4 show the corner plots obtained from the MCMC sampling. These plots are additionally made available as supplementary online material on Zenodo. The corner plots display the probability distribution of parameters and their pairwise correlations. The off-diagonal subplots are contour plots of parameter pairs, indicating their joint distributions. Degeneracies between fitted parameters can appear as elongated or curved shapes in the off-diagonal subplots, typically oriented diagonally. We evaluate here the correlations between the Voigt parameters, namely the H I absorber redshifts z_i , logarithmic column densities N_i and Doppler parameters b_i (in km s⁻¹). As we identify 14 absorbers for 4C+04.11, we only show the corner plots for the column density and Doppler parameter. The majority of parameters seem well constrained, but several are only weakly constrained and show extended posterior tails. This behavior is likely due to a combination of the noisy data, the large number of free parameters and intrinsic degeneracies in the model. In particular, the degeneracy between column density N and Doppler parameter b implies that combinations of small N and large b can produce Voigt profiles similar to those obtained with large N and small b . This is an issue that has been already identified by Silva et al. (2018b) in the fitting of the Ly α profile of the HzRG MRC 0943–242.

Table A.1. Fitting constraints for the MCMC sampling of the UVES master spectra.

Fitting parameter	lower boundary	upper boundary
Gaussian parameters		
Line center, λ_c [Å]	$\lambda_{c,i} - 10$	$\lambda_{c,i} + 10$
Line flux, F	-	-
Line width, σ	0.001	60
Intercept	-2	10
Voigt parameters		
Column density, $\log(N_{\text{H}}/\text{cm}^{-2})$	12	20
Doppler parameter, b [km s ⁻¹]	5	400
Redshift, z	$z_i - 0.001$	$z_i + 0.001$

Notes. $\lambda_{c,i}$ and z_i are the initial-guess values for the emission-line center and absorber redshifts, respectively. For multicomponent Gaussian fits, we impose an ordering constraint on the line centers. For 4C+04.11, the two Gaussian line centers are constrained to lie within ± 3 Å of the wavelength obtained from a preliminary least-squares fit of the red wing of the emission line, as the blue wing is heavily affected by absorption.

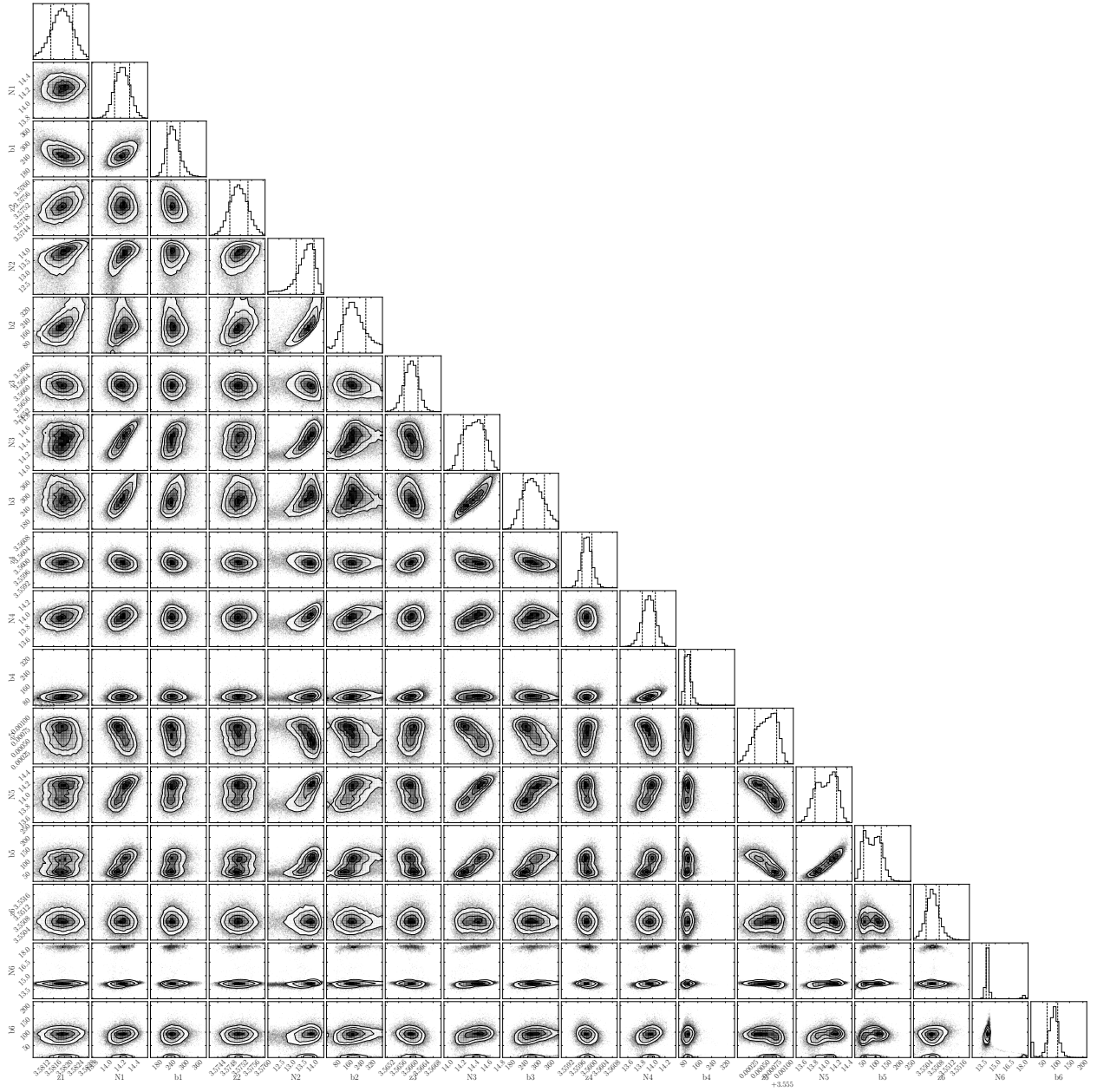


Fig. A.1. Corner plot derived from MCMC sampling of Ly α of 4C+03.24. The HI absorber redshifts z_i , logarithmic column densities N_i and Doppler parameters b_i (in km s $^{-1}$) are shown. The black dotted lines in the histograms indicate the uncertainty ranges, namely the 16th and 84th percentiles. The mean acceptance fraction of the sampling is 0.301.

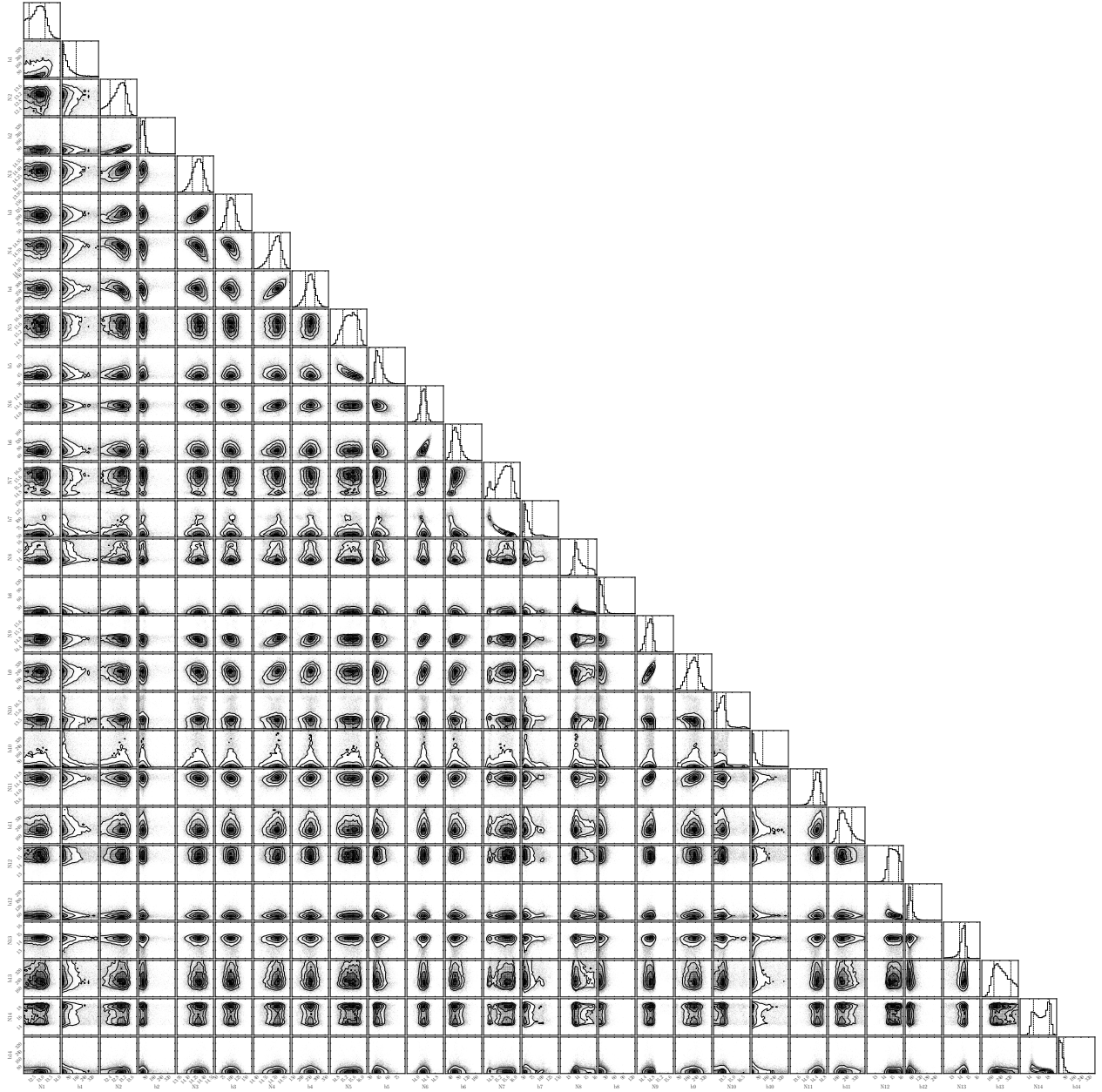


Fig. A.2. Corner plot derived from MCMC sampling of Ly α of 4C+04.11. We only show the HI logarithmic column densities N_i and Doppler parameters b_i (in km s^{-1}) because of the large number of absorbers identified for this target. The black dotted lines in the histograms indicate the uncertainty ranges, namely the 16th and 84th percentiles. The blue lines mark the median, i.e., the reported fit values. The mean acceptance fraction of the sampling is 0.140.

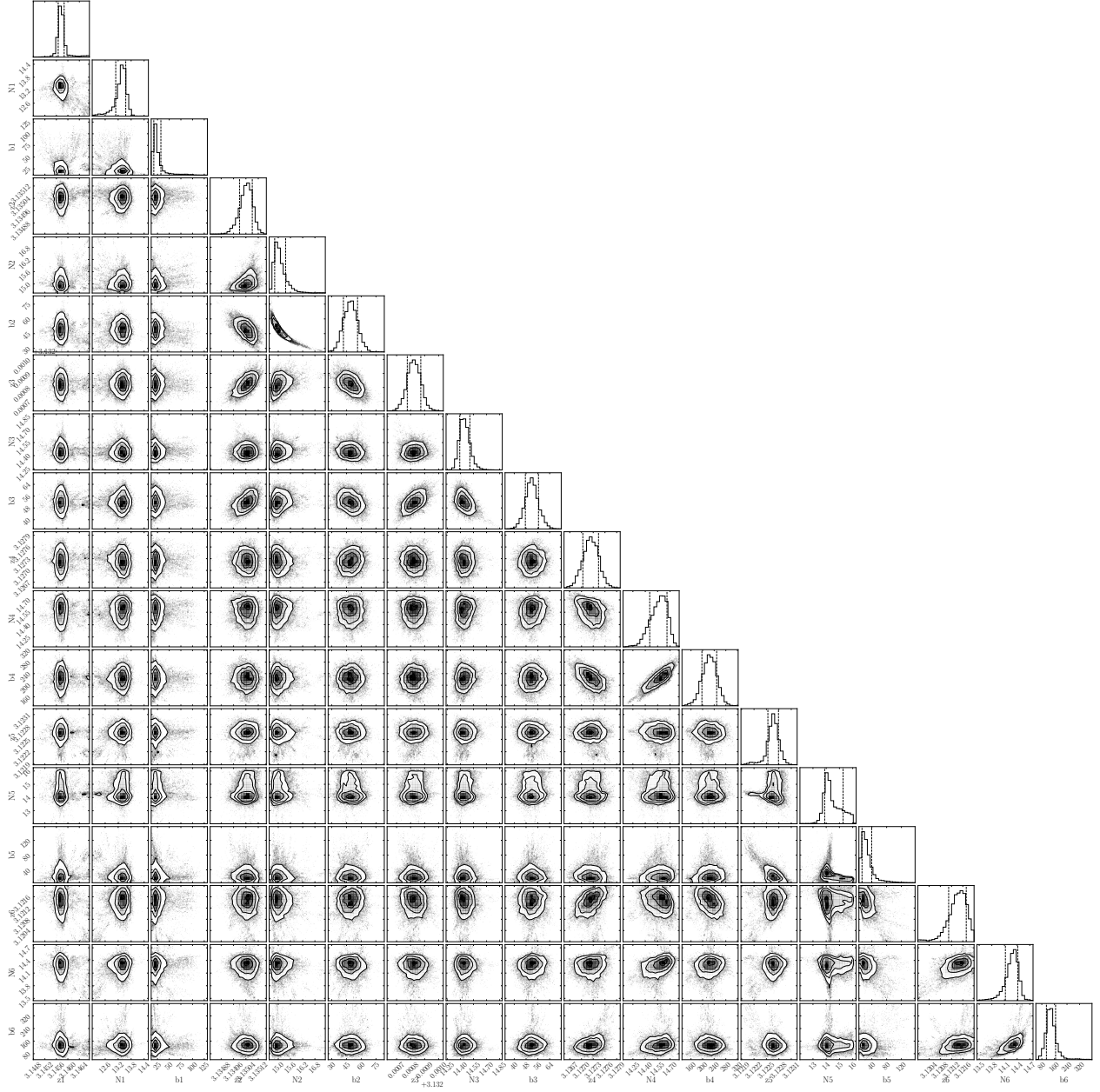


Fig. A.3. Corner plot derived from MCMC sampling of Ly α of MRC 0316. The H I absorber redshifts z_i , logarithmic column densities N_i and Doppler parameters b_i (in km s $^{-1}$) are shown. The black dotted lines in the histograms indicate the uncertainty ranges, namely the 16th and 84th percentiles. The blue lines mark the median, i.e., the reported fit values. The mean acceptance fraction of the sampling is 0.270.

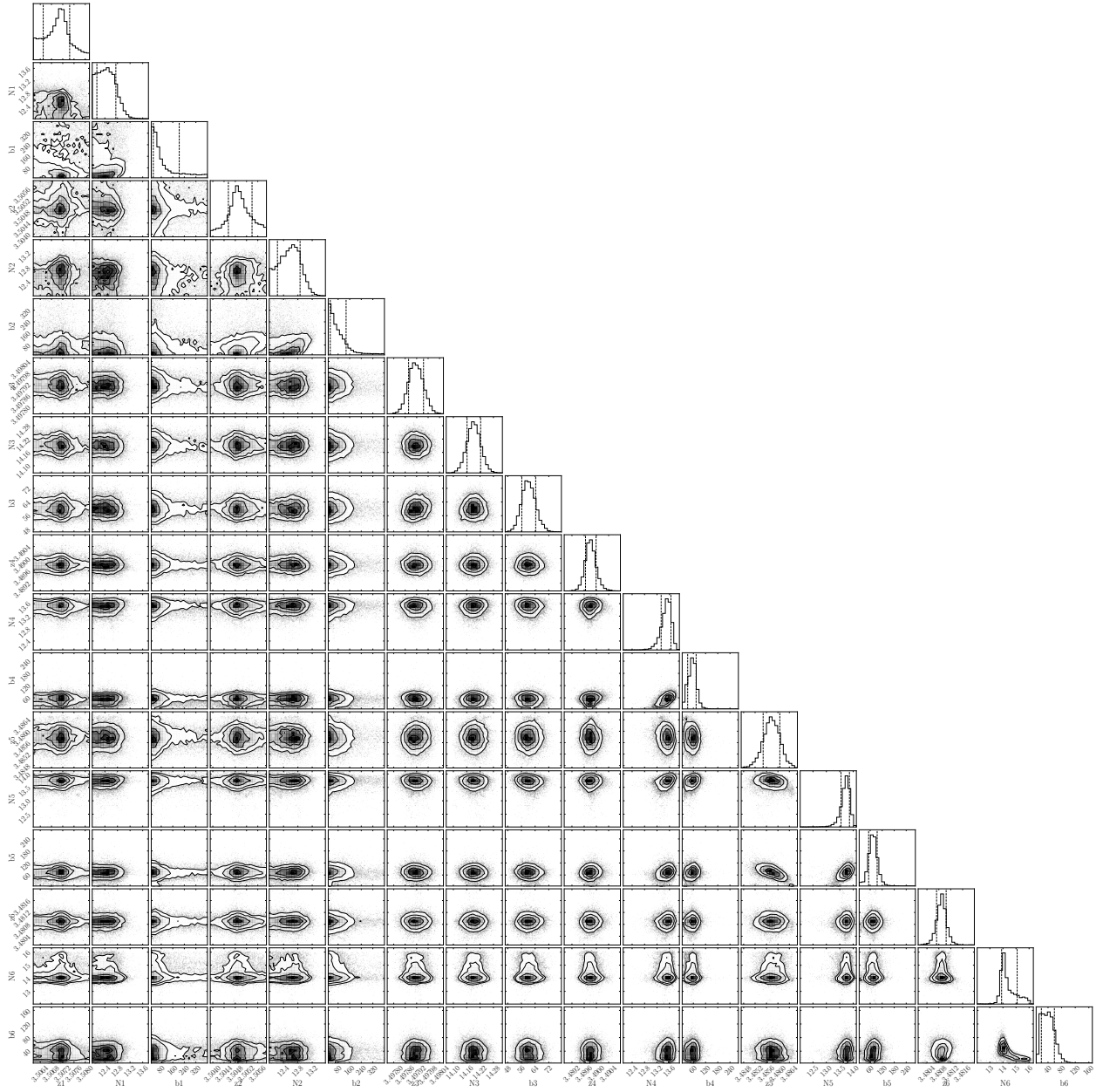


Fig. A.4. Corner plot derived from MCMC sampling of Ly α of TNJ0205. The HI absorber redshifts z_i , logarithmic column densities N_i and Doppler parameters b_i (in km s^{-1}) are shown. The black dotted lines in the histograms indicate the uncertainty ranges, namely the 16th and 84th percentiles. The blue lines mark the median, i.e., the reported fit values. The mean acceptance fraction of the sampling is 0.305.

Appendix B: JWST NIRSpec narrowband images for 4C+03.24 and TN J0205

In this appendix we show the NIRSpec narrowband images of the [O III] λ 5007 emission for 4C+03.24 (Fig. B.1) and TN J0205 (Fig. B.2). They reveal complex kinematics of the ionized interstellar gas. In particular, 4C+03.24 shows blueshifted emission extended towards the south, where jet-gas interactions are taking place (e.g., van Ojik et al. 1996).

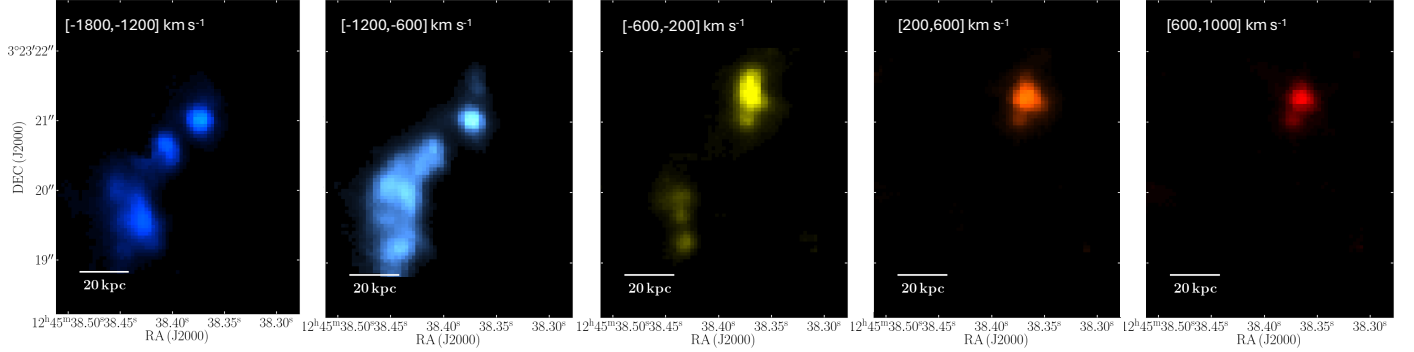


Fig. B.1. Narrowband images of the [O III] λ 5007 emission of 4C+03.24, collapsed at different velocity ranges.

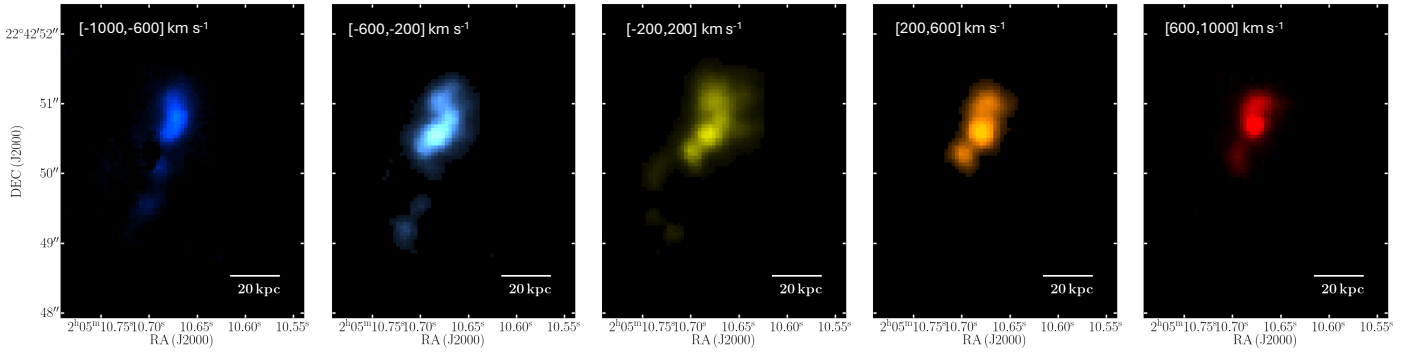


Fig. B.2. Narrowband images of the [O III] λ 5007 emission of TN J0205, collapsed at different velocity ranges.

We also list the fit results of the comparison between the UVES Ly α profiles and the JWST [O III] profiles, as shown in Figs. 9 and 10 in the following. We model the [O III] emission lines using up to three Gaussian components and fit the continuum with a zero-order polynomial. The UVES spectra are fitted with the same procedure as used for the UVES master spectra, using MCMC sampling. The velocity shifts Δv and the FWHM of the [O III] λ 5007 and Ly α emission components in the different spatial regions are shown in Tables B.1 and B.2.

Table B.1. Gaussian fit results for 4C+03.24 in the different regions shown in Fig. 9.

		JWST [O III] λ 5007 emission			UVES Ly α emission
		Systemic	Blueshifted	Redshifted	Systemic
Region 1:	Δv [km s $^{-1}$]	579 ± 13	-1389 ± 129	1692 ± 33	236^{+75}_{-44}
	FWHM [km s $^{-1}$]	1820 ± 27	2526 ± 107	853 ± 33	2351^{+116}_{-107}
Region 2:	Δv [km s $^{-1}$]	-99 ± 5	-1155 ± 93	105 ± 82	317^{+23}_{-23}
	FWHM [km s $^{-1}$]	674 ± 12	2073 ± 75	2034 ± 98	1890^{+45}_{-48}
Region 3:	Δv [km s $^{-1}$]	96 ± 2			132^{+14}_{-17}
	FWHM [km s $^{-1}$]	727 ± 5			1758^{+39}_{-39}
Region 4:	Δv [km s $^{-1}$]	184 ± 5	-286 ± 13		67^{+31}_{-31}
	FWHM [km s $^{-1}$]	470 ± 12	653 ± 22		1537^{+70}_{-75}

Notes. The velocity shifts and FWHM of the Gaussian components for the JWST [O III] λ 5007 emission are shown on the left and for the UVES Ly α emission on the right. The Ly α parameters and uncertainties are derived from the posterior distributions of the MCMC sampling. The velocity shifts are calculated with respect to the systemic redshift of the target as determined from the [O III] line (Nesvadba et al. 2017a).

Table B.2. Gaussian fit results for TN J0205 in the different regions shown in Fig. 10.

		JWST [O III] λ 5007 emission			UVES Ly α emission	
		Systemic	Blueshifted	Redshifted	Systemic	Blueshifted
Region 1:	Δv [km s $^{-1}$]	-53 ± 9	-186 ± 5	169 ± 4	117^{+23}_{-21}	33^{+14}_{-19}
	FWHM [km s $^{-1}$]	1448 ± 25	364 ± 13	275 ± 8	1007^{+99}_{-105}	1773^{+85}_{-68}
Region 2:	Δv [km s $^{-1}$]	151 ± 4	-263 ± 9	538 ± 23	108^{+12}_{-12}	-28^{+35}_{-44}
	FWHM [km s $^{-1}$]	301 ± 7	645 ± 16	498 ± 19	1014^{+57}_{-59}	2173^{+196}_{-159}
Region 3:	Δv [km s $^{-1}$]	-201 ± 44	-313 ± 8	128 ± 6	-11^{+27}_{-27}	-155^{+53}_{-88}
	FWHM [km s $^{-1}$]	1944 ± 69	410 ± 13	369 ± 11	963^{+123}_{-125}	1885^{+239}_{-171}
Region 4:	Δv [km s $^{-1}$]	-235 ± 5			-144^{+19}_{-19}	-183^{+26}_{-35}
	FWHM [km s $^{-1}$]	340 ± 13			755^{+68}_{-66}	1591^{+122}_{-121}

Notes. The velocity shifts and FWHM of the Gaussian components for the JWST [O III] λ 5007 emission are shown on the left and for the UVES Ly α emission on the right. The Ly α parameters and uncertainties are derived from the posterior distributions of the MCMC sampling. The velocity shifts are calculated with respect to the systemic redshift of the target as determined from the He II line (Kolwa et al. 2023). We note that the naming conventions for the systemic and blueshifted components of the Ly α emission are based on comparison with the UVES master spectra.