Resolved galactic superwinds reconstructed around their host galaxies at z>3

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Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT
This paper presents a detailed analysis of two giant Lyman-alpha (Lyα) arcs detected near known galaxies at z = 3.038 and z = 3.754 lensed by the massive cluster MACS 1206−0847 (z = 0.44). The Lyα nebulae revealed in deep MUSE observations exhibit a double-peak profile with a dominant red peak that indicates expansion/outflowing motions. One of the arcs stretches over 1′ around the Einstein radius of the cluster, resolving the velocity field of the line-emitting gas on kpc scales around a group of three star-forming galaxies of 0.3–1.6 L* at z = 3.038. The second arc spans 15″ in size, roughly centered around a pair of low-mass Lyα emitters of ≈ 0.03 L* at z = 3.754. All three galaxies in the z = 3.038 group exhibit prominent damped Lyα absorption (DLA) and several metal absorption lines, in addition to nebular emission lines such as He II λ1640 and C III] λλ1906, 1908. Extended Lyα emission appears to emerge from star-forming regions to larger distances with suppressed surface brightness at the center of each galaxy, suggesting the presence of dusty outflowing cones of size 1–5 kpc across. Significant spatial variations in the Lyα line profile are observed which, when unaccounted for in the integrated Lyα line, leads to biased constraints for the underlying gas kinematics. The observed spatial variations are consistent with the presence of a steep negative velocity gradient in a continuous flow of high column density gas from star-forming regions into a low-density halo environment. While the observed UV nebular line ratios show no evidence of AGN activity in the galaxies, the observed Lyα signals can be explained by a combination of resonant scattering and recombination radiation due to photoionization by ionizing photons escaping from the nearby star-forming regions. These observations provide the most detailed insights yet into the kinematics of galactic superwinds associated with star-forming galaxies thought to be responsible for the chemical enrichment in the intergalactic medium.

Key words: galaxies: kinematics and dynamics – galaxies:ISM – intergalactic medium – galaxies: high-redshift – galaxies: evolution

1 INTRODUCTION
The formation and evolution of galaxies are intimately connected to the properties of the circumgalactic medium (CGM). Characterizing the interactions between galaxies and their surrounding gas, such as gas infall and outflows, is a critical step toward improving our still patchy understanding of the life cycles of baryons and galaxy evolution over cosmic time. But because of the low-density nature of the CGM, studying such tenuous gas has historically relied on absorption spectroscopy along individual QSO sightlines. Over the past few decades, absorption-line studies have yielded sensitive, mostly one-dimensional constraints on the gas density, temperature, metallicity and kinematics in the circumgalactic space (see the review by Chen 2017; Tumlinson et al. 2017; Rudie et al. 2019, and references therein). However, uncertainties remain in connecting gas to galaxies in the
absence of a spatially-resolved two-dimensional map of the gas. To access the spatial information of gas distribution in the CGM, direct detections of the tenuous gas in emission provide a promising avenue. The hydrogen Lyα line, being the strongest emission line expected of photo-ionized gas at a temperature \( T \approx 10,000 \, \text{K} \), provides a sensitive probe of the tenuous CGM (e.g., Osterbrock & Ferland 2006; Draine 2011). At \( z \approx 2 - 7 \), the Lyα line at 1215 Å is conveniently redshifted into the atmospheric transmission window and becomes accessible on the ground. In the past two decades, narrow-band imaging and deep long-slit spectroscopic observations have successfully revealed extended line-emitting gas around galaxies (e.g., Adelberger et al. 2006; Rauch et al. 2008, 2011; Steidel et al. 2011; Xue et al. 2017) and QSOs (e.g., Hennawi et al. 2009; Cantalupo et al. 2012, 2014). Those observations have shed light on several important physical processes in the CGM, such as the ubiquity of large-scale gas flows on 10–100 physical kpc (pkpc) scales at high redshifts (e.g., Rauch et al. 2016) and the possible nontrivial contribution of star-forming galaxies to reionization (e.g., Dijkstra 2014; Matthee et al. 2018).

The recent advent of high-throughput, wide-field optical integral-field spectrographs (IFSs) on large ground-based telescopes, such as the Multi Object Spectroscopic Explorer (MUSE) on the Very Large Telescopes (VLT) (Bacon et al. 2010) and the Keck Cosmic Web Imager (KCWI) on the Keck Telescopes (Morrissey et al. 2018) has brought a significant breakthrough in systematically uncovering extended Lyα emission in typical, low-mass galaxies as well as QSOs at \( z \approx 2 - 7 \) (e.g., Wisotzki et al. 2016, 2018; Borisova et al. 2016; Leclercq et al. 2017; Cai et al. 2017, 2019). These sensitive IFS observations have uncovered extended Lyα emission out to \( > 20 \) times the spatial extent of the stellar continuum, and revealed key insights into the physical nature of these extended Lyα sources. For example, significant spatial variations of Lyα line profiles are directly observed within a single line-emitting nebula (e.g., Rauch et al. 2013; Vanzella et al. 2017; Erb et al. 2018). In addition, there exists a positive correlation between the full-width-at-half-maximum (FWHM) of the Lyα line and the continuum UV brightness of the associated star-forming galaxies (e.g., Wisotzki et al. 2018; Leclercq et al. 2020), indicating an intimate connection between the origin of the Lyα photons and star-forming activities (e.g., Dijkstra & Kramer 2012; Cantalupo 2017).

Multiple processes can lead to Lyα emission in the CGM, such as fluorescence powered by ionizing photons from star-forming regions or active galactic nuclei (AGN), cooling radiation, and scattering of Lyα photons by mostly neutral hydrogen gas (e.g., Hogan & Weymann 1987; Gould & Weinberg 1996; Cantalupo et al. 2005; Kollmeier et al. 2010; Faucher-Giguère et al. 2010; Hennawi & Prochaska 2013). Disentangling different processes that contribute to the observed Lyα signal is challenging due to the resonant scattering nature of Lyα photons, especially when Lyα is the only observable line feature from the emission regions. At the same time, the detailed double-peak profiles of spectrally-resolved Lyα lines provide a sensitive probe of the underlying gas kinematics. It is expected that Lyα emission originating in infalling and outflowing medium will result in blue-enhanced and red-enhanced peak, respectively (e.g., Dijkstra 2017, and references therein). This has motivated increasingly sophisticated Monte Carlo radiative transfer models that incorporate different gas geometry and kinematics to accurately track Lyα photon scattering and infer the physical properties of the gaseous clouds (e.g., Dijkstra et al. 2006; Verhamme et al. 2006; Hansen & Oh 2006; Laursen et al. 2009; Schaerer et al. 2011; Gronke et al. 2015).

These Monte Carlo Lyα radiative transfer codes can generally reproduce the observed Lyα line width based on a combination of thermal broadening and bulk motions, but significant discrepancies are also seen between observations and model predictions (Verhamme et al. 2008; Kulka et al. 2012; Orlitová et al. 2018). Such discrepancies have both theoretical and observational implications. Theoretically, there is a lot of room for better capturing the physical processes in radiative transfer simulations, such as a realistic treatment of dust attenuation and gas clumpiness (e.g., Laursen et al. 2009; Dijkstra & Kramer 2012; Gronke et al. 2016). Observationally, as Lyα photons are scattered both in spectral and spatial dimensions, it is critical to obtain observations with not only high spectral resolution, but also high spatial resolution to provide the best constraints on the source environment.

Strong gravitational lensing provides sharpened images of the high-redshift Universe via an enhanced spatial resolution of highly magnified images of distant galaxies (e.g., Coe et al. 2013) and recently individual, luminous high redshift stars (Kelly et al. 2018). Massive galaxy and cluster lenses have revealed detailed properties of lensed background sources down to sub-kpc or even as detailed as tens of pc scales (e.g., Livermore et al. 2012; Johnson et al. 2017; Berg et al. 2018; Florian et al. 2020). Multiply-lensed QSOs and extended, lensed arcs of bright background sources have been used to spatially resolve the diffuse CGM in absorption spectroscopy (Rauch et al. 2002; Chen et al. 2014; Zahedy et al. 2016; Rubin et al. 2018; Lopez et al. 2018; Mortensen et al. 2020). Several gravitationally-lensed Lyα emitting nebulae have also been reported, in which the enhanced spatial resolution has aided to reveal the underlying physical environment of the source in greater details (Swinbank et al. 2007; Patrício et al. 2016; Caminha et al. 2017; Claeyssens et al. 2019; Erb et al. 2019).

Here we present a detailed analysis of two gravitationally-lensed Lyα emitting nebulae, System A at \( z = 3.058 \) (Figure 1) and System B at \( z = 3.754 \) (Figure 2), detected in deep MUSE observations of the field around the strong lensing cluster, MACS1206−0847 at \( z = 0.44 \) (hereafter MACS1206). Both nebulae are multiply-lensed to form giant tangential arcs in the image plane around the Einstein radius of the foreground cluster, and both exhibit a double-peaked Lyα profile. In particular, the serendipitous alignment of the nebula in System A results in an extended low surface brightness arc of \( SB_{Lyα} \approx 3 \times 10^{-18} \text{erg s}^{-1} \text{cm}^{-2} \text{arcsec}^{-2} \) and \( \approx 1' \) in length, comprising three contiguous lensed images (Caminha et al. 2017), while System B forms an arc of \( \approx 15'' \) in length with high surface brightness peaks exceeding \( SB_{Lyα} \approx 2 \times 10^{-17} \text{erg s}^{-1} \text{cm}^{-2} \text{arcsec}^{-2} \). In addition, the Lyα emitting region in System A consists of two separate nebulae, detached from a group of three continuum sources with one being an \( \approx 1.6 \, L_\odot \) galaxy and the other two being sub-\( L_\star \) galaxies. All three of these galaxies exhibit prominent interstellar absorption lines, including hydrogen damped Lyα absorption (DLA) in their spectra. One of the
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sub-$L_\star$ galaxies (A3 in Figure 1 below) is further resolved into two high-intensity peaks. In contrast, the Ly$\alpha$ nebula in System B exhibits a symmetric morphology in the source plane, centered approximately at two compact continuum sources separated by $\approx 0\farcs1$ ($\approx 0\farcs3-0\farcs5$ in the image plane), both of which are low-luminosity $\approx 0.03L_\star$ Ly$\alpha$ emitters (LAE) with a rest-frame Ly$\alpha$ equivalent width of $W$(Ly$\alpha) \approx 30\AA$

In this study, we examine the underlying gas flows by combining spatially-resolved Ly$\alpha$ emission profiles from MUSE and known star formation properties of the neighboring galaxies from available Hubble Space Telescope (HST) broadband photometry. This paper is organized as follows. First, the archival data included in our analysis are presented in Section 2, including broadband imaging data by HST and IFS data by VLT/MUSE. The lens models fine-tuned to best reproduce multiple images from Systems A and B are presented in Section 3. In Sections 4 and 5, we present detailed analysis of UV continuum galaxies and the Ly$\alpha$ line-emitting gas, respectively. We discuss our results in Section 6, and conclude in Section 7. Throughout this paper, we adopt a Hubble constant of $H_0 = 70$ km/s/Mpc, $\Omega_M = 0.3$ and $\Omega_\Lambda = 0.7$ when deriving distances, masses and luminosities. All magnitudes quoted are in the AB system.

2 OBSERVATIONAL DATA

MACS 1206 is a well studied cluster, which was first identified as a luminous X-ray source in the ROSAT All Sky Survey (Voges et al. 1999; Böhringer et al. 2001) and later confirmed to be a massive, strong-lensing cluster by the Massive Cluster Survey (Ebeling et al. 2001, 2009). It was also selected as one of the 25 clusters in the Cluster Lensing And Supernova Survey with Hubble (CLASH) program (Postman et al. 2012). Exquisite imaging and spectroscopic data of this cluster field are available in public data archives, including high-quality multi-band imaging data from the HST, follow-up galaxy spectroscopic survey data from the CLASH-VLT redshift survey (Biviano et al. 2013; Rosati et al. 2014), and wide-field IFS data obtained using VLT/MUSE (Bacon et al. 2010; Caminha et al. 2017). High-level science products are retrieved from these public data archives for our study. In this section, we provide a summary of these data products.

2.1 HST images

High spatial resolution, UV, optical and near-infrared imaging data of the field around MACS 1206 obtained using the HST were retrieved from the Mikulski Archive for Space Telescopes (MAST) archive1 (PI: M. Postman). These include images taken using the Advanced Camera for Surveys (ACS), the Wide Field Camera 3 (WFC3), and a suite of UV, optical, and near-infrared filters (see Table 2 below). Figures 1 and 2 show composite images of the central region of MACS 1206 from combining F475W (blue), F814W (green), and F160W (red) images, highlighting the lensing configurations of System A and System B, respectively. Detailed photometric properties of each system derived from these HST data are described in §4.

Given the close proximity of B1 and B2 in the source plane (see §5.1 below), it is possible that they correspond to distinct star-forming regions in the same galaxy at $z = 3.754$. However, without high-resolution infrared data, we cannot confirm the presence of a disk structure that connects these different star-forming regions. We therefore proceed with referring to B1 and B2 as individual galaxies for simplicity.

2.2 MUSE IFS Data

Wide-field IFS data of MACS 1206 were obtained using MUSE on the VLT UT4. The observations were carried out under Program ID’s 095.A-0181(A) and 097.A-0269(A) to cover an effective area of 2.63 arcmin$^2$ around the cluster in three pointings (PI: J. Richard). In the region where lensed images of Systems A and B are found, a total exposure time of $\approx 4$ hours were collected. Pipeline-processed and flux-calibrated data cubes were retrieved from the ESO Phase 3 Archive, covering a wavelength range of 4750-9300 Å with a spectral resolution of FWHM $\approx 170$ (110) km s$^{-1}$ at $\approx 5000$ (7000) Å and a pixel scale of $0\farcs2 \times 0\farcs2$. The mean point spread function (PSF) in the final combined data cube was determined using a bright star, and found to be $\approx 1\farcs1$ at 7000 Å. Astrometry of the combined MUSE data cube was re-calibrated to match the world coordinate system of available HST images. The pipeline generated combined data cube contains non-negligible sky residuals that affected the detection of faint emission features. Additional sky subtraction was therefore performed using a median sky residual spectrum generated from object-free spaxels in the data cube. Detailed spectroscopic properties of both continuum sources and Ly$\alpha$ emitting nebulae are described in §4 and §5, respectively. Finally, the wavelength array is converted to vacuum to facilitate accurate velocity calculations based on known rest-frame UV wavelengths.

3 CLUSTER LENS MODELING

To determine the intrinsic properties of both Systems A and B, it is necessary to construct a cluster lens model to correct for the gravitational lensing effect. Here we employ the software LENSTOOL (version 6.5) (Jullo et al. 2007) to construct a parametric cluster lens model of MACS 1206 by incorporating known multiply-lensed galaxies identified in the MUSE data (Camina et al. 2017) and those reported in the literature (e.g., Zitrin et al. 2012; Umetsu et al. 2012; Eichner et al. 2013). As both Systems A and B are in the core region of the cluster, we only include the strong lensing constraints and do not consider weak lensing effect in our lens modeling process. We first obtain a fiducial cluster lens model that gives a good fit to a total of 72 multiple images from 21 background sources. Those images cover a field of view (FOV) of $\approx 2\prime$ relatively evenly, providing robust constraints for the projected cluster mass distribution within this FOV. We then fine-tune the lens model by considering only multiple images of Systems A and B, optimising

1 https://archive.stsci.edu/pub/hlsp/clash/macs1206/data/hst/scale_30mas
Figure 1. Composite image of the core region of MACS 1206, produced using HST F475W (blue), F814W (green) and F160W (red) images. White contours indicate the Ly$\alpha$ emission associated with System A at a surface brightness of $SB_{Ly\alpha} = 3.7 \times 10^{-18}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$, integrated over the spectral window of 4890-4930 Å (see § 5.1 below). The surface brightness limit corresponds to a 3-$\sigma$ limiting flux over a circular aperture of 1″ in diameter, roughly the size of the PSF measured in the MUSE data. Note that a feature in our study, which is distinct from the analysis of Caminha et al. (2017), is the inclusion of Ly$\alpha$ photons emerged at the image locations of galaxies A1, A2, and A3, when constructing the pseudo narrow-band Ly$\alpha$ image. The overlap between the constant Ly$\alpha$ surface brightness contours and these galaxies after this exercise supports a continuous flow of dense gas from star-forming regions into a low-density halo environment. Yellow contours show the critical curve of the cluster lens for a source at $z = 3.038$. Left panels show zoomed-in regions around lensed images of galaxies A1, A2, and A3, along with the Ly$\alpha$ contours. Note that the galaxy A1 at $z = 3.0367$ is magnified but not multiply-lensed. Cluster member galaxy Gm1 is located close to lensed images of System A and is individually optimised in the lens modeling process as described in §3. After correcting the lensing magnification, the total Ly$\alpha$ luminosity from the nebula is $L_{Ly\alpha} = (5.2 \pm 0.1) \times 10^{42}$ erg s$^{-1}$ (see § 5.1).

3.1 Fiducial cluster lens model

Following Caminha et al. (2017), we adopt a parametric model based on a pseudo-isothermal elliptical mass distribution (PIEMD) (Kassiola & Kovner 1993) of ellipticity $\epsilon$ and include two additional isothermal halo components to represent the cluster-scale diffuse mass. This three-halo configuration is found to minimize the dispersion between predicted and observed image positions for all multiply-lensed sources (see Caminha et al. 2017, for detailed discussions). The convergence of PIEMD is given by

$$\kappa_c = \frac{\sigma_v^2}{2G \Sigma_{cr} \sqrt{R^2 + r_c^2}},$$

where $R_c$ is the distance from the center of the cluster, defined as

$$R_c^2 = \frac{x^2}{(1 + \epsilon)^2} + \frac{y^2}{(1 - \epsilon)^2},$$

$r_c$ is the core radius and $\Sigma_{cr}$ is the projected critical mass density. Given the angular diameter distances between the observer and the lens ($D_l$), the lens and the source ($D_{ls}$), and the observer and the source ($D_s$), the projected critical mass density is defined as

$$\Sigma_{cr} = \frac{c^2}{4\pi G D_s D_l D_{ls}}.$$

All six parameter of the three PIEMD halos (x, y, $r_c$, $\epsilon$, position angle, velocity dispersion $\sigma_v$) are free to vary. We also include external shear (parameterized by the intensity $\gamma_{shear}$ and position angle $\theta_{shear}$) to account for possible massive structures in regions further away from the cluster core.

In addition to the cluster-scale diffuse mass distribution, we account for local perturbations in the vicinity of individual galaxies by including 128 cluster member galaxies in the lens model. These member galaxies are selected based on
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Figure 2. Same as Figure 1, while highlighting the configuration of System B. White contours indicate the Lyα emission associated with System B at $SB_{\text{Ly} \alpha} = 2.8 \times 10^{-18}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$, integrated over the spectral window of 5766-5796 Å (see §5.1 below). The surface brightness limit corresponds to a 3-$\sigma$ limiting flux over a circular aperture of 1″ in diameter, roughly the size of the PSF measured in the MUSE data. Yellow contours show the critical curve of the cluster lens for a source at $z = 3.754$. Left panels show zoomed-in regions around the lensed images of galaxy B consisting of components B1 and B2, along with the Lyα contours. Cluster member galaxies Gm2 and Gm3 are located close to lensed images of System B and are individually optimised in the lens modeling process as described in §3. After correcting the lensing magnification, the total Lyα luminosity from the nebula is $L_{\text{Ly} \alpha} = (9.8 \pm 0.2) \times 10^{41}$ erg s$^{-1}$ (see §5.1).

their redshifts in the catalog of Molino et al. (2017), which is downloaded from the MAST archive. We first eliminate galaxies fainter than $AB = 24$ mag in the F160W band. For galaxies with spectroscopic redshifts, we select those with $0.425 < z_{\text{spec}} < 0.453$. For galaxies without $z_{\text{spec}}$, we apply the same criterion based on available photometric redshifts. A total of 128 cluster members are selected from this exercise. Note that in general, the cluster lensing potential is dominated by the large-scale diffuse mass distribution, which is primarily in the form of dark matter. Member galaxies only introduce perturbations local to the location of individual galaxies. Therefore, in cases where lensed images do not appear close to individual member galaxies ($\leq 5''$, corresponding to typical Einstein radius of individual galaxies), the variation in the selection of member galaxies does not introduce significant uncertainties to the cluster lensing potential. However, in cases where lensed images form close to individual galaxies, careful modeling of those individual galaxies is required to accurately reproduce the positions of nearby images. As our goal here is to obtain a good cluster-scale lens model instead of optimising individual galaxy mass distributions, we exclude image systems 2, 7, 13, 21, 24 and 27 in Caminha et al. (2017) (see their Fig. 1), whose multiple images fall very close to massive cluster member galaxies. This way we do not need to fine-tune every member galaxy with lensed images nearby and still maintain the accuracy of the large-scale cluster lens model.

We include cluster member galaxies as 128 dual pseudo-isothermal elliptical mass distributions (dPIE) (Elíasdóttir et al. 2007) located at their detected light centroids, with the ellipticity and position angle fixed to their observed values obtained from the Molino et al. (2017) catalog. The convergence of the dPIE profile is given by

$$\kappa_g = \frac{\sigma_{g,v}^2}{2G \Sigma_{\text{ext}}} \left( \frac{1}{R_{g,\epsilon}} - \frac{1}{\sqrt{R_{g,\epsilon}^2 + r_{g,t}^2}} \right),$$

(4)

where $r_{g,t}$ is the truncation radius. To reduce the total number of free parameters, we scale all 128 member galaxies with a constant mass-to-light ratio through

$$\sigma_{g,v} = \sigma_{g,v}^0 \left( \frac{L}{L_0} \right)^{1/4}, \quad r_{g,t} = r_{g,t}^0 \left( \frac{L}{L_0} \right)^{1/4},$$

(5)

where $L_0$ is the reference luminosity with magnitude $m_{F814W} = 19.6$. Hence there are only two free parameters for member galaxies: $\sigma_{g,v}^0$ and $r_{g,t}^0$.

\footnote{https://archive.stsci.edu/pub/hlsp/clash/macs1206/catalogs/molino/}

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3.2 Fine-tuned lens model for Systems A and B

Based on the fiducial cluster lens model described above, we now optimize the lens model for Systems A and B separately to ensure the highest accuracy in matching the observed locations of multiply-lensed images in these two systems. In the fiducial model, the respective centers of the three cluster-scale PIEMD halos are located at $\approx$ and $\approx$ between the fiducial model. We also notice that three of the cluster member galaxies (marked as Gm1, Gm2 and Gm3 in Figures 1 and 2) are located close to some images of Systems A and B. We therefore allow the velocity dispersion $\sigma_{\text{p.e.}}$ of these three cluster members to vary freely in the fine-tuned model optimization, instead of being scaled together with the rest of member galaxies. Finally, the external shear parameters are fixed to their best-fit values in the fiducial model.

Because we are particularly interested in accurately producing the lensing effect for Systems A and B, we also include constraints from the two substructures of A3 (designated A31 and A32 in Table A1), and the fainter galaxy B2 in System B, which are not used in Caminha et al. (2017). With a total of 18 multiple images of A and B as constraints (the first 18 entries in Table A1), we then run LENSTOOL again with the above set-up, and obtain a fine-tuned model. This model places significantly more weight on the local perturbers (Gm1, Gm2, and Gm3) and provides much improved root-mean-square positional offsets for the systems of interest in this study. The rms position offsets for Systems A and B are reduced to $\text{rms}_{\text{im}} = 0.1'1$ and $\text{rms}_{\text{im}} = 0.2'1$, respectively. The best-fit parameters are listed Table A3 in the Appendix. In Figures 1 and 2, we show the predicted critical curves by this fine-tuned model for sources at the redshifts of Systems A and B. Mean lensing magnification factors of multiple images of Systems A and B based on the fine-tuned lens model are presented in Table 1. Wherever required in subsequent analyses, we use this fine-tuned model to derive image position deflections and magnifications.

4 ANALYSIS: GALAXY PROPERTIES

Accurate photometric measurements of galaxies in Systems A and B are challenging due to the crowding of members of the lensing cluster and non-negligible intracluster light (e.g., Figures 1 & 2). We first measure broadband magnitudes of individual lensed images of each galaxy in different bandpasses using a combination of circular and isophotal apertures determined by SExtractor (v.2.19.5; Bertin & Arnouts 1996). These measurements (presented in the Appendix) are then corrected for lensing magnifications based on the fine-tuned lens model (see Table 1 presented in §3).

For galaxies A2 and A3 in System A, their $b$ images occur between two bright foreground galaxies, resulting in uncertain background subtraction in the photometric measurements. The de-magnified apparent magnitudes of A2 and A3 are therefore determined based on an average of images a and c. The de-magnified magnitudes of A2 and A3 in image a are $\approx 0.2$ magnitudes fainter than that in image c, suggesting that the true magnification factor for image a relative to image c is smaller than what is predicted by the lens model. In §5 below, we also show that the apparent Ly$\alpha$ surface brightness in the extended nebulae from image a is fainter than what is seen in images b and c, supporting a smaller relative magnification factor at the location of image a. Such a discrepancy in image brightnesses is commonly seen in strongly-lensed galaxies and quasars, and is often due to the limited accuracy of lens models and/or the presence of small-scale substructures in the lens (e.g. McKean et al. 2007; Hezaveh et al. 2016). The discrepancy of $\approx 0.2$ magnitudes seen here is within the typical scatter of $\geq 25\%$ between de-lensed magnitudes of multiply-lensed galaxies in cluster lenses (e.g. Lam et al. 2014; Caminha et al. 2016a). By averaging the de-lensed magnitudes between images a

| Image | $\bar{\mu}$ | Image | $\bar{\mu}$ |
|-------|-------------|-------|-------------|
| A1    | 3.8         | B1a   | 15.2        |
| A2a   | 4.3         | B1c   | 10.4        |
| A2b   | 5.4         | B1d   | 12.1        |
| A2c   | 7.5         | B1e   | 7.5         |
| A3a   | 4.5         | B2a   | 8.2         |
| A3b   | 4.4         | B2c   | 13.0        |
| A3c   | 6.2         | B2d   | 12.0        |
|       |             | B2e   | 8.4         |

Constraints of this fiducial cluster lens model are positions of 72 multiple images from 21 background sources identified by Caminha et al. (2017), excluding image systems 2, 7, 13, 21, 24 and 27 for reasons described above. The optimization is performed based on object positions in the source plane. We obtain similar best-fit parameters as Caminha et al. (2017). The root-mean-square positional offset between observed and predicted images is $(\text{rms})_{\text{im}} = 0.76''$ in the image plane, averaged over all 72 images of 21 sources. The rms position offsets for Systems A and B are found to be $(\text{rms})_{\text{im}} = 0.38''$ and $(\text{rms})_{\text{im}} = 0.73''$, respectively. In the Appendix, we list the coordinates and redshifts of all 72 images used as constraints, as well as the best-fit model parameters.
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Table 2. Summary of galaxy photometry for System A.

| redshift | $M_{1500}$ | F300W | F390W | F435W | F475W | F606W | F625W |
|----------|------------|-------|-------|-------|-------|-------|-------|
| A1       | 3.0387     | $-21.52$ | $>26.14$ | $25.85 \pm 0.08$ | $25.02 \pm 0.03$ | $24.59 \pm 0.02$ | $24.03 \pm 0.07$ | $23.90 \pm 0.01$ |
| A2       | 3.0380     | $-19.87$ | $>28.37$ | $26.97 \pm 0.12$ | $26.29 \pm 0.05$ | $26.10 \pm 0.03$ | $25.67 \pm 0.04$ | $25.43 \pm 0.02$ |
| A3       | 3.0386     | $-19.63$ | $>28.57$ | $27.53 \pm 0.12$ | $26.82 \pm 0.05$ | $26.46 \pm 0.03$ | $25.91 \pm 0.04$ | $25.76 \pm 0.02$ |

| F775W | F814W | F850LP | F105W | F110W | F125W | F140W | F160W |
|-------|-------|--------|-------|-------|-------|-------|-------|
| A1    | $23.76 \pm 0.01$ | $23.76 \pm 0.01$ | $23.73 \pm 0.02$ | $23.73 \pm 0.01$ | $23.71 \pm 0.01$ | $23.71 \pm 0.01$ | $23.52 \pm 0.01$ | $23.34 \pm 0.01$ |
| A2    | $25.37 \pm 0.02$ | $25.32 \pm 0.01$ | $25.31 \pm 0.03$ | $25.47 \pm 0.02$ | $25.50 \pm 0.01$ | $25.54 \pm 0.02$ | $25.36 \pm 0.01$ | $25.32 \pm 0.01$ |
| A3    | $25.66 \pm 0.02$ | $25.62 \pm 0.01$ | $25.61 \pm 0.03$ | $25.72 \pm 0.02$ | $25.70 \pm 0.01$ | $25.75 \pm 0.02$ | $25.51 \pm 0.01$ | $25.34 \pm 0.01$ |

Table 3. Summary of galaxy photometry for System B.

| redshift | $M_{1500}$ | F450W | F475W | F606W | F625W | F775W | F814W |
|----------|------------|-------|-------|-------|-------|-------|-------|
| B1       | 3.7540     | $-17.23$ | $>30.08$ | $29.99 \pm 0.20$ | $29.15 \pm 0.06$ | $28.94 \pm 0.08$ | $28.69 \pm 0.08$ | $28.81 \pm 0.05$ |
| B2       | 3.7540     | $-17.01$ | $>29.99$ | $>30.68^d$ | $29.59 \pm 0.11$ | $29.57 \pm 0.17$ | $29.91 \pm 0.11$ | $29.95 \pm 0.07$ |

| F850LP | F105W | F110W | F125W | F140W | F160W |
|--------|-------|-------|-------|-------|-------|
| B1     | $28.80 \pm 0.11$ | $29.29 \pm 0.09$ | $29.13 \pm 0.05$ | $29.19 \pm 0.09$ | $29.28 \pm 0.08$ | $29.22 \pm 0.08$ |
| B2     | $28.87 \pm 0.15$ | $29.15 \pm 0.10$ | $29.11 \pm 0.06$ | $29.12 \pm 0.10$ | $28.98 \pm 0.07$ | $28.83 \pm 0.07$ |

Table 4. SED fitting results, showing 16%–84% confidence interval for each parameter.

| galaxy | redshift | log($M_{\text{star}}/M_{\odot}$) | SFR (M$_{\odot}$ yr$^{-1}$) | Age (Gyr) | $\tau$ (Gyr) | $A_V$ |
|--------|----------|----------------------------------|-----------------------------|-----------|--------------|------|
| A1     | 3.0367   | [9.93, 9.98]                      | [89.84, 101.85]             | [0.11, 0.14] | [1.37, 4.35] | [0.72, 0.77] |
| A2     | 3.0380   | [8.95, 8.98]                      | [10.71, 11.45]             | [0.05, 0.06] | [1.30, 4.38] | [0.62, 0.65] |
| A3     | 3.0386   | [9.23, 9.27]                      | [13.02, 15.81]             | [0.14, 0.19] | [1.44, 4.37] | [0.64, 0.71] |
| B1     | 3.7540   | [7.59, 7.96]                      | [0.23, 0.40]               | [0.13, 0.53] | [1.26, 4.25] | [0.05, 0.25] |
| B2     | 3.7540   | [8.43, 8.72]                      | [0.50, 0.91]               | [0.43, 1.31] | [1.31, 4.35] | [0.47, 0.74] |

and c, we therefore mitigate the effect of lensing uncertainty on the magnification of these two galaxies.

Similarly, the b images of galaxies B1 and B2 are excluded due to the contamination from the nearby cluster member galaxy Gm3. In addition, image e of B1 is unusually bright compared with its counter part images a, c and d, which are between 0.8 and 1.2 magnitudes fainter than image e across different bandpasses after the lensing correction. Such an enhancement in brightness is not observed in image e of B2. This brightness anomaly of B1e can also be seen in the color image in Figure 2, and may be attributed to magnification perturbation caused by unseen substructures local to B1e (e.g. McKean et al. 2007; Hezaveh et al. 2016). Consequently, the de-magnified apparent magnitudes of B1 and B2 are determined by averaging measurements of images a, c and d. Finally, Galactic extinction corrections are calculated using the NED Galactic Extinction Calculator\(^3\) and applied to the observed magnitudes in individual bandpasses following the Schlafly & Finkbeiner (2011) extinction map.

For galaxies in System A (B), the bandpasses bluer of F390W (F475W) correspond to rest-frame wavelengths $\lambda_{\text{rest}} < 912\AA$, and no fluxes are detected above the background noise. We therefore place a 2-$\sigma$ upper limit of the observed flux in each of these bandpasses. Unfortunately, these images are not sufficiently sensitive to provide meaningful constraints for the escape fraction of ionizing photons from these galaxies. The final de-magnified apparent magnitudes of galaxies A and B in different bandpasses are presented in Tables 2 and 3, while the direct measurements of individual images are presented in Table B1 for reference.

To characterize the intrinsic luminosities of these galax-

\(^3\) https://ned.ipac.caltech.edu/extinction_calculator
ies, we also estimate the rest-frame UV absolute magnitudes at 1500 Å, $M_{1500}$, using the observed F606W (F775W) brightness for galaxies in System A (B). At the respective redshifts of Systems A and B, these bandpasses correspond roughly to the rest-frame 1500 Å, and provide a robust estimate of the intrinsic UV luminosity. The absolute magnitudes of $A_1$, $A_2$, $A_3$, $B_1$ and $B_2$, at rest-frame 1500Å are found to be $M_{1500} = -21.52$, $-19.87$, $-19.63$, $-17.23$ and $-17.01$, corresponding to 1.61, 0.35, 0.28, 0.03, 0.03 L$_{\odot}$, respectively, for a characteristic rest-frame absolute magnitude of $M_*= -21$ (e.g., Bouwens et al. 2007; Reddy et al. 2008).

4.2 Star formation histories

The observed broadband spectral energy distributions (SEDs) of galaxies in Systems A and B based on the photometric measurements presented in Tables 3 and 3 are typical of star-forming galaxies at $z = 3-4$ (e.g., Bouwens et al. 2007). To quantify the star formation histories, we perform a stellar population synthesis analysis using Bayesian Analysis of Galaxies for Physical Inference and Parameter Estimation (BAGPIPES, Carnall et al. 2018), which employs the 2016 version of the Bruzual & Charlot (2003) stellar synthesis models. We assume an exponentially declining star formation model, $SFR(t) \propto e^{-t/\tau}$, where $\tau$ represents the e-folding time and is a free parameter, and infer the stellar mass ($M_{\text{star}}$), star formation rate (SFR), age and dust extinction ($A_V$) of the continuum sources in both systems based on the observed SEDs from F606W to F160W. Because of a strong degeneracy between stellar age, metallicity, and dust attenuation (e.g., Conroy 2013), we impose a metallicity prior based on the mass-metallicity relation for high-redshift galaxies (e.g., Ma et al. 2016) and fix the metallicity of $A_1$ to 20% of the solar value, 10% for $A_2$ and $A_3$, and 5% for $B_1$ and $B_2$.

The best-fit parameters in $M_{\text{star}}$, SFR, age, and $A_V$ and the associated 16%-84% confidence intervals are presented in Table 4. All five galaxies are best characterized by a long star formation e-folding time that exceeds $\tau = 1$ Gyr, along with a relatively young, best-fit stellar age. In particular, the best-fit stellar ages for galaxies in System A are less than 200 Myr, making the adopted exponentially declining star formation model equivalent to a constant SFR scenario. As discussed below, a constant star formation history is also consistent with the spectral features uncovered in the MUSE data. The inferred SFR for galaxies $A_1$, $A_2$, and $A_3$ range between 10 and 100 M$_{\odot}$ yr$^{-1}$ and $M_{\text{star}}$ between 10$^8$ and 10$^{10}$ M$_{\odot}$, typical of UV luminous star-forming galaxies at $z \approx 3$ (e.g., Shapley 2011). In contrast, galaxies $B_1$ and $B_2$ have significantly lower SFR and stellar mass with $M_{\text{star}} \approx 10^8$ M$_{\odot}$, more typical of Lyα emitters (LAEs) at $z \approx 3$ with a characteristic star formation time scale of $\lesssim 1$ Gyr (e.g., Feltre et al. 2020).

4.3 Spectroscopic properties

At $z = 3-4$, available MUSE data cover the rest-frame wavelength range from $\lambda_{\text{rest}} > 1200$ Å to $\lambda_{\text{rest}} < 1920$ Å, and provide additional constraints for the star-forming interstellar medium (ISM) and the stellar populations in Systems A and B. We extract individual galaxy spectra using spherical apertures centered on the location of the continuum sources, with varying sizes for different images depending on the intrinsic image size and magnification. Because galaxies $B_1$ and $B_2$ are blended in the ground-based MUSE data, we are only able to extract a single spectrum for these two galaxies. The extracted spectra (without lensing correction) are presented in Figure 3, along with the corresponding 1-$\sigma$ error spectra. For galaxies $A_1$ and $A_2$, the spectra shown are combined from images a and c, while image $b$ is excluded due to possible contamination from nearby cluster member galaxies. Similarly for $B_1$ and $B_2$, image $b$ is excluded from the combined spectrum due to possible contamination from the nearby elliptical galaxy. Note that the brightness anomaly of $B_1e$ described in §4.1 does not affect the spectral features due to the achromatic nature of lensing. Image e is therefore included in the combined spectrum.

The spectra of galaxies $A_1$, $A_2$, and $A_3$ are characterized by three distinct features: (1) a blue continuum consistent with the broadband photometry presented in Table 2; (2) strong interstellar absorption due to neutral hydrogen and heavy ions (marked in green, dotted line) that are commonly seen in $z \approx 3$ galaxies (e.g., Shapley et al. 2003; Erb et al. 2014), and (3) nebular emission lines due to He II $\lambda 1640$, O III $\lambda\lambda 1660, 1666$, and C III $\lambda\lambda 1906, 1908$, as well as excited Si II* $\lambda 1264, 1309,$ and 1530 lines. The strong DLA features observed in the spectra of galaxies $A_1$, $A_2$, and $A_3$ reveal the presence of a significant amount of neutral gas in the ISM of these galaxies. A Voigt profile analysis of the red damping wing at the systemic redshifts of these galaxies (see below) yields best-fit HI column densities of log $N$(HI)/cm$^{-2} = 20.9 \pm 0.1, 21.3 \pm 0.1, \text{ and } 21.3 \pm 0.1$ for galaxies $A_1$, $A_2$, and $A_3$, respectively, indicating a minimum surface neutral gas mass density of $\Sigma_{\text{gas}} = 8-20 M_\odot$ pc$^{-2}$. The best-fit DLA profiles are presented in the top row of Figure 4. Note that the blue-side of the observed DLA profiles are contaminated by the forest of Lyα absorption lines in the foreground and therefore excluded from the fit. In contrast, galaxies $B_1$ and $B_2$ exhibit a strong Lyα emission with no apparent DLA trough, and resolved C III* $\lambda 1906, 1908$ doublet features on top of a faint UV continuum. No strong absorption features are detected, but the spectrum does not have sufficient sensitivities for placing strong constraints. We measure a rest-frame equivalent width (EW$_{\text{rest}}$) of the Lyα emission line of galaxies $B_1$ and $B_2$ over the observed wavelength window from $\lambda_1 = 5760$ Å to $\lambda_2 = 5796$ Å, and obtain EW$_{\text{rest}}$ (Lyα) = 33.3 \pm 1.5 Å.

For all galaxies, we are able to determine an accurate systemic redshift for each of these galaxies by simultaneously fitting all available emission lines with a Gaussian function, convolved with an appropriate instrument line spread function, which shares a common velocity centroid and line width. Specifically for galaxies in System A, we adopt a single Gaussian model for He II 1640 and a double Gaussian model for all the doublets with a fixed doublet separation as expected from atomic transitions. In addition, the flux ratio of O III/\lambda 1666/O III/\lambda 1600 is fixed at 2.5 as expected from their radiative transition probabilities. For galaxies B1 and B2, we fit a double Gaussian model with a fixed doublet separation to the C III/\lambda 1906, 1908 intercombination lines. The best-fit redshifts, line widths, integrated line fluxes, and EW$_{\text{rest}}$, along with associated errors of individual galaxies
are presented in Table 5. The best-fit line profiles of the emission features are also presented in Figure 4.

4.4 Emission line diagnostics

The UV emission line properties presented in Table 5 are typical of star-forming galaxies at $z \approx 3$ (e.g., Maseda et al. 2017; Feltre et al. 2020), and reveal a turbulent and high-density nature in the ISM with a radiation field dominated by massive young stars in these galaxies. In particular, galaxy $A2$ with $M_{\text{star}} \approx 10^9 M_\odot$ is an order of magnitude less massive than typical UV bright galaxies at $z \approx 3$ (e.g., Erb et al. 2006; Kulas et al. 2012), but exhibits an emission line width that is 60% broader. The ratio between the $\text{CIII}\alpha$ intercombination lines serves as an important UV diagnostic of the electron density, $n_e$, in the ISM, although it saturates at density below $n_e \approx 10^7\text{ cm}^{-3}$ (e.g., Kewley et al. 2019). The observed $\text{[CIII]}\lambda 1906/\text{CIII}\alpha 1908$ ratios of these galaxies range from $1.2 \pm 0.2$ for $A2$ to $1.8 \pm 0.8$ for $B1$ and $B2$, constraining the ISM electron density in both Systems $A$ and $B$ to be $\leq 2 \times 10^4 \text{ cm}^{-3}$ for a gas temperature of 10,000 K (Osterbrock & Ferland 2006). The high-density limits are also comparable to what is seen in $\text{CIII}\alpha$ emitters at $z \approx 3$ (e.g., Maseda et al. 2017). In addition, the detection of $\text{He}^+\lambda 1640$ emission, along with the presence of a prominent F-Cygni profile in $\text{CIV}\lambda 1548, 1550$ with blue absorption tail extending beyond $|\Delta v| \approx 2000 \text{ km s}^{-1}$ (second and third rows in Figure 4), indicate the presence of massive young stars with $M \gtrsim 30 M_\odot$ (e.g., Leitherer et al. 1999; Pettini et al. 2000; Crowther 2007; Brinchmann et al. 2008). The presence of broad $\text{He}^+\lambda 1640$ emission line is also a sign of Wolf-Rayet stars that have a short lifetime of $\sim 5 \text{ Myr}$ (e.g., Schaerer & Vacca 1998; Crowther 2007), in agreement with the constant SFR scenario suggested by photometric SED analysis (see Table 4 and discussion in §4.2). Furthermore, there are extended blue wings in low ion absorption lines (e.g., $\text{CII} \lambda 1335$) that are particularly prominent in galaxy $A1$, suggesting the presence of strong galactic outflows.

Finally, we investigate the possibility of these galaxies hosting an active galactic nucleus (AGN) using emission line diagnostics in the UV. Specifically, Feltre et al. (2016) shows that the combination of collisionally excited nebular lines $\text{OIII}\lambda\lambda 1660, 1666, \text{CIII}\alpha\lambda 1906, 1908$ and the $\text{He}^+\lambda 1640$ recombination line can serve as a good
Figure 4. Summary of the ISM absorption and emission features of Systems A (left three columns) and B (right column). Zero velocity corresponds to the systemic redshift determined from nebular emission lines of each galaxy (see Table 5). The red curve in the H I panels shows the best-fit DLA profile with the estimated \( N(H\text{I}) \) displayed at the top of each column. At negative velocities, the DLA profiles are contaminated by the forest of Ly\( \alpha \) absorption lines in the foreground. The \( \text{C\text{IV}} \lambda\lambda 1548, 1550 \) absorption profiles are presented in the second and third rows, showing blue absorption tail extending beyond \(-2000 \text{ km s}^{-1}\). In contrast, low-ionization lines such as \( \text{C\text{II}} \lambda 1334 \) and \( \text{Si\text{II}} \lambda 1526 \) (4th and 5th rows) are narrow with a velocity centroid consistent with the emission lines to within 10 km s\(^{-1}\) and an extended blue absorption tail seen in only A1 to \( \approx -500 \text{ km s}^{-1}\). The best-fit Gaussian models of \( \text{He\text{II}} \lambda 1640 \), \( \text{O\text{III}} \lambda\lambda 1660, 1666 \) and \( \text{C\text{III}} \lambda\lambda 1906, 1908 \) emission lines are shown in red curves in bottom five rows. \( \text{He\text{II}} \lambda 1640 \) is fitted with a single Gaussian. The doublets are all fitted with a double Gaussian, and the separation between two Gaussian components are fixed by their rest-frame wavelength separation. We fix the flux ratio \( \text{O\text{III}} \lambda 1666/\text{O\text{III}} \lambda 1660 = 2.5 \). The redshift and FWHM are tied to be consistent among all lines in each galaxy, and the best-fit redshifts (shown at the top of each column) sets the zero velocity marked by the vertical dotted line. Data spectrum (continuum normalised) is shown in black, 1-\( \sigma \) error spectrum in blue and best-fit models in red. Flux and rest-frame equivalent width measured from the best-fit models for each emission line is listed in Table 5. While galaxies B1/B2 display a strong Ly\( \alpha \) and modest \( \text{C\text{III}} \lambda 1906, 1908 \) emission features, the data quality is not sufficient to place meaningful constraints on \( \text{He\text{II}} \), or \( \text{O\text{III}} \).

indicator of the ISM ionization state. We compute the expected line ratios of \( \text{O\text{III}} \lambda\lambda 1660, 1666/\text{He\text{II}} \lambda 1640 \) and \( \text{C\text{III}} \lambda 1906, 1908/\text{He\text{II}} \lambda 1640 \) under different AGN and star formation (SF) ionization radiation fields, using the CLOUDY code (version 17.01; Perland et al. 2017). For the AGN spectrum, we adopt the model continuum specified in CLOUDY with an effective temperature of \( 10^6 \text{ K} \), an X-ray to UV ratio of \( \alpha_{\text{OX}} = -1.4 \), a UV slope of \( \alpha_{\text{UV}} = -0.5 \) and an X-ray slope of \( \alpha_x = -1 \). For the SF model, we consider two stellar populations with sub-solar \( (Z = 0.001) \) and solar \( (Z = 0.02) \) metallicity, respectively. We use the FSPS code (v3.1; Conroy et al. 2009; Conroy & Gunn 2010) to generate a compos-
Table 5. Emission line fitting results, with lensing magnification corrected in all flux measurements based on mean magnification values listed in Table 1.

|       | A1 at $z = 3.0386 \pm 0.0001^{a}$ |       |       |
|-------|---------------------------------|-------|-------|
|       | FWHM$^{b}$ (km s$^{-1}$)        | Flux  | EW$_{rest}^{c}$ (Å) |
| He$\beta$ | 176 ± 20                       | 23 ± 17 | 0.09 ± 0.07 |
| O iii | ...                             | 47 ± 9    | 0.19 ± 0.04 |
| O ii | ...                             | 117 ± 23  | 0.47 ± 0.09 |
| [C iii] | 1906                             | 153 ± 28  | 0.70 ± 0.13 |
| C iii | 1908                             | 111 ± 24  | 0.51 ± 0.11 |

|       | A2 at $z = 3.0386 \pm 0.0001^{a}$ |       |       |
|-------|---------------------------------|-------|-------|
|       | FWHM$^{b}$ (km s$^{-1}$)        | Flux  | EW$_{rest}^{c}$ (Å) |
| He$\beta$ | 310 ± 22                       | 30 ± 6    | 0.47 ± 0.09 |
| O iii | ...                             | 11 ± 2    | 0.17 ± 0.03 |
| O ii | ...                             | 28 ± 5    | 0.43 ± 0.08 |
| [C iii] | 1906                             | 78 ± 9    | 1.41 ± 0.17 |
| C iii | 1908                             | 67 ± 8    | 1.21 ± 0.15 |

|       | A3 at $z = 3.0386 \pm 0.0001^{a}$ |       |       |
|-------|---------------------------------|-------|-------|
|       | FWHM$^{b}$ (km s$^{-1}$)        | Flux  | EW$_{rest}^{c}$ (Å) |
| He$\beta$ | 129 ± 9                        | 20 ± 3    | 0.61 ± 0.10 |
| O iii | ...                             | 5 ± 1    | 0.15 ± 0.03 |
| O ii | ...                             | 12 ± 3    | 0.37 ± 0.08 |
| [C iii] | 1906                             | 42 ± 5    | 1.34 ± 0.16 |
| C iii | 1908                             | 33 ± 4    | 1.07 ± 0.13 |

|       | B1/B2 at $z = 3.7540 \pm 0.0001^{a}$ |       |       |
|-------|---------------------------------|-------|-------|
|       | FWHM$^{b}$ (km s$^{-1}$)        | Flux  | EW$_{rest}^{c}$ (Å) |
| [C iii] | 1906                             | 30 ± 24  | 1.1 ± 0.3    | 4.20 ± 0.67 |
| C iii | 1908                             | 0.6 ± 0.2 | 2.25 ± 0.66 |

$^{a}$ Obtained from a simultaneous fit of the lines listed.
$^{b}$ Obtained from a simultaneous fit of the lines listed.
$^{c}$ Rest-frame equivalent width.

The observed broadband photometric and spectroscopic properties of galaxies in System A indicate that these galaxies are typical of UV continuum selected star-forming galaxies at $z \approx 3$ with an ISM radiation field dominated by massive young stars, while galaxies in System B display properties that resemble low-mass LAEs in the early epoch. The large amount of ISM gas revealed in the spectra of galaxies A1, A2, and A3, coupled with a wide-spread Ly$\alpha$ nebula revealed in the MUSE data shows that this is a particularly gas-rich system. Here we present an analysis of the morphologies and line profiles of the extended Ly$\alpha$ nebulae in these two systems.

5.1 Pseudo narrow-band Ly$\alpha$ image and source plane reconstruction

To characterize the extended Ly$\alpha$ nebulae in both systems, we first form a pseudo narrow-band Ly$\alpha$ image for each system. We first note that all three galaxies in System A exhibit asymmetric Ly$\alpha$ emission feature within the DLA trough, with an enhanced red peak at $\Delta v \approx +500$ km s$^{-1}$ (e.g., top row of Figure 4) from the respective systemic redshifts. The observed asymmetric profile of these emerged Ly$\alpha$ photons is similar to what is seen in the extended nebulae in MUSE data (e.g. Caminha et al. 2017) and is characteristic of large-scale outflows that have been commonly identified in high-redshift galaxies (e.g. Franz et al. 1997; Frye & Broadhurst 1998; Pettini et al. 2000; Frye et al. 2002). An origin of the emerged Ly$\alpha$ photons in outflows is qualitatively consistent with the presence of massive young stars inferred from the UV spectral properties of the galaxies described in §4.4 (see also Pettini et al. 2000, for an example), but whether these photons originate in the star-forming ISM of the galaxies or in the extended nebulae that are blended with the galaxy image by projection remains uncertain. Therefore, we construct two versions of the pseudo narrow-band Ly$\alpha$ image for System A: one without including the emerged Ly$\alpha$ photons in the DLA trough of the continuum sources, and a second one which incorporates both the Ly$\alpha$ photons in the DLA.
troughs and those in the extended nebulae. As discussed below and shown in Figures 6 and 7, this exercise enables a clearer understanding of the differences in the observed surface brightness profiles between multiple images, as well as establishing a direct connection between the galaxies and the line-emitting gas at large distances.

To construct a pseudo narrow-band Lyα image for System A without including the Lyα photons from the DLA troughs, we perform a local continuum subtraction per spaxel within the Lyα line. We determine a wavelength-dependent continuum level based on a linear interpolation of the continuum fluxes observed on the blue and red sides of the Lyα line. Specifically, we determine a medium flux over a spectral window of 4830-4863 Å on the blue side and a medium flux over 4961-4994 Å on the red side. At z ≈ 3.04, these correspond roughly to [−5000, −3000] and [+3000, +5000] km/s from the Lyα centroid (see Figure 10 below). The interpolated value is then subtracted from the observed flux at each spaxel. A pseudo narrow-band image of the Lyα emission is then created by integrating the flux of each spaxel over the wavelength range from 4890 Å to 4930 Å, where Lyα flux is detected at a high level of significance (see Figure 10 below). A smoothed pseudo narrow-band Lyα image, using a Gaussian kernel of FWHM = 1″, is presented in Column (1) of Figure 6, which shows two nebulae separated roughly by ≈ 2″ in the image plane and bracketing galaxies A1, A2, and A3 from the north and south. Furthermore, at the locations of galaxy continuum, there is a net absorption in this pseudo narrow-band image due to the presence of DLAs.

Next, we construct a pseudo narrow-band image that includes the emerged Lyα photons in the DLA troughs. This is accomplished by first identifying the spaxels within the continuum emitting regions of galaxies A1, A2, and A3 as defined by SExtractor (see §4.1). We then adopt the best-fit DLA model profile for each galaxy presented in Figure 4, and multiply the model by the best-fit continuum obtained using a low-order polynomial fit to line-free regions in the integrated continuum spectrum presented in Figure 3. Next, the combined DLA-continuum model spectrum is scaled to match the continuum level of the spectrum in each spaxel and subtracted from the data. The amplitude of the continuum model for each spaxel is determined using the spectrum in the wavelength window from 5430 Å to 5560 Å, corresponding to rest-frame wavelengths from 1345 Å to 1375 Å, where no narrow-line features are present. The resulting difference data cube is combined with the previous continuum-subtracted data cube in the extended nebula region. A pseudo narrow-band image is then created by integrating over the wavelength range from 4890 Å to 4930 Å. Similarly, we smooth the image using a Gaussian kernel of FWHM = 1″, and present the smoothed pseudo narrow-band image in Column (2) of Figure 6.

In both versions of the pseudo narrow-band image presented in Columns (1) and (2) of Figure 6, the white contours mark a constant Lyα surface brightness of 3.7 × 10^{-18} erg s^{-1} cm^{-2} arcsec^{-2}, which is detected at the 3-σ level of significance. A strong variation in Lyα surface brightness is clearly seen across both the northern and southern nebulae, suggesting large spatial fluctuations in the underlying gas properties. While there exists a clear gap between the northern and southern nebulae, after including the Lyα signal inside the DLA troughs, the Lyα emission extends continuously into the star-forming regions in the galaxies. Furthermore, the surface brightness of the southern nebula in the vicinity of the galaxy continuum in images b and c is relatively more enhanced than that in image a after incorporating the Lyα signal in the DLA troughs (also see Figures 7 and 9 below). Specifically, in Column (2) of Figure 6, the Lyα surface brightness in image a in the vicinity of galaxies A2 and A3 is fainter by ≈ 25% compared with images b and c. The reduced Lyα surface brightness in images a suggests that the magnification factor of image a relative to images b and c is smaller than what is predicted by the lens model. Such a difference in surface brightness of lensed Lyα nebulae is also seen in Caminha et al. (2016b), and is consistent with the discrepancy in de-lensed continuum brightnesses of A2 and A3, for which image a is fainter by ≈ 0.2 magnitude (see discussion in §4.1).

In Column (3) of Figure 6, Lyα surface brightness contours showing 3.7 × 10^{-18} erg s^{-1} cm^{-2} arcsec^{-2} and 7.3 × 10^{-18} erg s^{-1} cm^{-2} arcsec^{-2} (i.e., 3-σ and 6-σ determined from the pseudo narrow-band image shown in Column 2) are overlaid on top of the HST composite image from Figure 1. Note that image b is north-south flipped from images a and c in this lensing configuration. As a guide, we include the magnification map in Column (4) of Figure 6 (negative magnification factors indicate flipped parity of the image), overlaid with the same Lyα contours.

Through the deflection field calculated using the fine-tuned lens model (see §3.2), we de-lens both the pseudo narrow-band image and the HST images back to the source plane. The de-lensed pseudo narrow-band image smoothed with a Gaussian kernel of FWHM = 0.5″ in the source plane is presented in Columns (1) and (2) of Figure 7 for before and after including Lyα emission in the DLA troughs, respectively. The reconstructed source-plane images clearly show that most of the northern nebula is merely singly-lensed like galaxy A1, while the southern nebula stretches across the lensing field with rapidly changing magnification factors. Image a, covering the full extent of the nebula in the source plane, constrains the projected size of the Lyα nebulae to approximately 30 pkpc from north to south. The de-lensed HST broadband images, as shown in Columns (3), are in excellent agreement among three multiple images, consistent with the low image position dispersion of rms_{im} = 0′′.1 predicted by the fine-tuned lens model (see §3). The de-lensed pseudo narrow-band images show the same surface brightness discrepancy between multiple images as seen in the image plane (see Figure 6), where the surface brightness near the galaxy continuum regions is fainter in image a as discussed above. The white and red contours in Figure 7 correspond to surface brightnesses of 3.7 × 10^{-18} erg s^{-1} cm^{-2} arcsec^{-2} and 7.3 × 10^{-18} erg s^{-1} cm^{-2} arcsec^{-2}, same as the contours shown in Figure 6.

When computing the total Lyα flux in the nebulae, we consider image a for the northern nebula to avoid the confusion of partially lensed multiple images, and average images a and c for the southern nebula. Due to the contamination from a nearby galaxy at the east side of the southern nebula in image b, we leave out image b in the average. In contrast with the continuum sources, the Lyα nebulae span a much larger area in the image plane, within which the
Page dimensions: 595.3x841.9

Figure 6. Summary of the lensing configuration of the observed Lyα arc in System A. Column (1): pseudo narrow-band images without the emerged Lyα flux within the DLA troughs at the locations of galaxy continuum. The images have been smoothed using a Gaussian kernel of FWHM$\text{smooth} = 1''$. The contour marks constant surface brightness of $3.7 \times 10^{-18} \text{erg s}^{-1} \text{cm}^{-2} \text{arcsec}^{-2}$, which is detected at the 3-σ level of significance in the smoothed image. Star symbols mark the positions of the associated star-forming galaxies identified in HST images. Column (2): same as Column (1) but includes Lyα flux from the DLA troughs at the locations of galaxy continuum (see text). Column (3): contours of multiply-lensed Lyα nebulae determined from Column (2) overlaid on individual galaxy images in the HST data to illustrate the relative alignment between star-forming regions and the line-emitting gas (see also Figure 1). Lyα surface brightness contours of $3.7 \times 10^{-18} \text{erg s}^{-1} \text{cm}^{-2} \text{arcsec}^{-2}$ and $7.5 \times 10^{-18} \text{erg s}^{-1} \text{cm}^{-2} \text{arcsec}^{-2}$ are shown in white and red, respectively, and the yellow contours mark the critical curves of the cluster lens for sources at $z = 3.038$. Column (4): the magnification map overlaid with the same Lyα contours to illustrate the spatial variation of lensing magnification across the nebulae. Negative magnification factors indicate flipped parity of the image.

The magnification factor can vary significantly (see Column(4) of Figure 6). Therefore, instead of using a mean magnification factor, we correct the lensing magnification for each spaxel within the extended nebulae before summing over all spaxels within the 3-σ contour for these images. We then integrate the flux over the wavelength range of 4890–4930 Å (the same wavelength window for constructing the narrow-band image described above). The total de-lensed Lyα flux of the southern nebula obtained from image a is ≈5% (25%) lower than that from image c before (after) including the Lyα flux from the DLA troughs. This difference of Lyα flux between images a and c is in agreement with what is observed in the Lyα surface brightness and de-lensed magnitudes of galaxies A2 and A3 (see §4), suggesting again that the magnification factor near the continuum regions in image a is smaller than what is predicted by the lens model.

After excluding the Lyα flux from within the DLA troughs and correcting the lensing magnification, we obtain a total flux of $f_{\text{Lyα}}(\text{A}_{\text{north}}) = (2.0 \pm 0.1) \times 10^{-17} \text{erg s}^{-1} \text{cm}^{-2}$ for the northern nebula, and $f_{\text{Lyα}}(\text{A}_{\text{south}}) = (2.9 \pm 0.1) \times 10^{-17} \text{erg s}^{-1} \text{cm}^{-2}$ for the southern nebula. Including the Lyα flux from the DLA troughs, the total flux is increased to $f_{\text{Lyα}}^\text{tot}(\text{A}_{\text{north}}) = (2.7 \pm 0.1) \times 10^{-17} \text{erg s}^{-1} \text{cm}^{-2}$ for the northern nebula, and $f_{\text{Lyα}}^\text{tot}(\text{A}_{\text{south}}) = (3.8 \pm 0.1) \times 10^{-17} \text{erg s}^{-1} \text{cm}^{-2}$ for the southern nebula. The Lyα signal inside the DLA troughs therefore accounts for ≈25% of the total Lyα emission from both the northern and southern nebulae. At $z \approx 3.038$, these flux measurements (including the Lyα flux in the DLA troughs) correspond to a Lyα luminosity of $L_{\text{Lyα}}(\text{A}_{\text{north}}) = (2.15 \pm 0.07) \times 10^{42} \text{erg s}^{-1}$ for the northern nebula, and $L_{\text{Lyα}}(\text{A}_{\text{south}}) = (3.03 \pm 0.08) \times 10^{42} \text{erg s}^{-1}$ for the southern nebula. Combining both northern and southern nebulae together leads to a total Lyα luminosity of $L_{\text{Lyα}}(A) = (5.2 \pm 0.1) \times 10^{42} \text{erg s}^{-1}$.

For System B, no apparent DLA or strong ISM absorption features are detected in the MUSE spectra of the star-forming regions, but the low $S/N$ as a result of a faint continuum makes gas column density estimates highly uncertain. The apparent discontinuity in the continuum blue-ward and redward of the Lyα emission line is consistent with the expectation from the Lyα forest in the intergalactic medium at $z \approx 3.75$ (e.g. Becker et al. 2007). To con-
Figure 7. Column (1): de-lensed narrow-band image without Lyα flux from the DLA troughs at the locations of galaxy continuum. The images are smoothed using a Gaussian kernel of FWHM = 0.5″ in the source plane. The contour marks constant surface brightness of 3.7 × 10⁻¹⁸ erg s⁻¹ cm⁻² arcsec⁻², corresponding to the 3-σ level of significance detected in the image plane, same as contours shown in Column (1) of Figure 6. Star symbols mark the de-lensed positions of the associated star-forming galaxies identified in HST images. Column (2): same as Column (1) but includes Lyα flux from the DLA troughs at the locations of galaxy continuum. Column (3): de-lensed Lyα contours overlaid on de-lensed HST data, with the yellow contours showing the caustics in the source plane. The blue dashed circles in Column (2) mark the apertures for the template spectrum extraction, which we use for the shell model analysis (see §5.3). The cyan dashed arrows show the directions along which we extract the one-dimensional surface brightness profile (see Figure 9 below).

Figure 8. Same as contours shown in Column (1) of Figure 6. The first aperture (distance of zero) is 3 pkpc from the center of the de-lensed Lyα surface brightness contours, as the lensed Lyα emission morphology, roughly centered near the UV continuum sources. Using image e, we estimate the projected size of the Lyα emitting nebula to be approximately 10 pkpc in diameter. A small spatial offset, ≈ 0′.1, is seen between UV continuum sources and the peak of Lyα emission, corresponding to ≈ 0.7 pkpc at z = 3.754. It is commonly observed among LAEs that the Lyα emission signals can have an offset from the UV continuum, with a median 1D projected offset of ≈ 0.6 pkpc in previous slit spectroscopic data (e.g., Hoag et al. 2019; Ribeiro et al. 2020; Lemaux et al. 2020). Larger offsets have also been found in narrow-band imaging data (e.g., Shibuya et al. 2014). However, we note that the continuum fluxes of galaxies B1 and B2 are much fainter than the LAEs considered in those studies.

We use image e, the most complete image among all five multiple images of System B, to compute the total flux of the Lyα emission. Despite of the flux anomaly observed in image e of galaxy B1 as discussed in §4.1, the effect is likely localised (since image e of B2 does not show the same brightness enhancement) and therefore will not significantly bias the total Lyα flux from the extended nebula. After correcting the lensing magnification for each spaxel, we obtain a total flux of $f_{\text{Ly}\alpha}(B) = (7.4 \pm 0.2) \times 10^{-18}$ erg s⁻¹ cm⁻², integrated across the wavelength range of 5766-5796 Å (the same wavelength window for constructing the narrow-band image described above) and summed over all spaxels within the 3-σ contour in image e. At z = 3.754, the observed Lyα flux translates to a total luminosity of $L_{\text{Ly}\alpha}(B) = (9.8 \pm 0.2) \times 10^{41}$ erg s⁻¹.

For both systems, we also extract the de-lensed one-dimensional Lyα surface brightness profile in the source plane starting from the galaxy continuum regions to the edge of each nebula (near the 3-σ surface brightness contours), as shown in Figure 9. We extract the surface brightness profiles along directions guided by the velocity gradient within the nebulae (cyan dashed arrows in Figures 7 and 8; see also §5.3 below). As the velocity gradient suggests bipolar gas flows in both systems, we therefore use a series of 2° × 0′6 (1″ × 0′.15) pseudo slits for System A (System B), instead of circular annuli. The position angle of the pseudo slit is 25° north through east for System A and 60° north through west for System B. The first aperture (distance of zero) is centered on the de-lensed locations of galaxy A1 (A2 and A3) for the northern (southern) nebula in System A, and the distance of the subsequent apertures are measured from these corresponding continuum regions. For System B, the distance is measured from the location of B1, where we put the first aperture. We show the surface brightness profiles

Figure 9. The cyan dashed arrows show the directions along which we extract the one-dimensional surface brightness profile (see Figure 8 below).
Figure 8. Summary of the lensing configuration of the observed Lyα arc in System B. Column (1): pseudo narrow-band image of the Lyα emission, smoothed with a Gaussian kernel of FWHM_{smooth} = 1″. The contour marks constant surface brightness of 2.8 \times 10^{-18}\text{erg s}^{-1}\text{cm}^{-2}\text{arcsec}^{-2}, which is detected at the 3-σ level of significance. Star symbols mark the positions of the associated star-forming galaxies identified in HST images, and the yellow contours show the critical curve for a source at z_{sys} = 3.754. Column (2): contours of multiply-lensed Lyα nebulae overlaid on individual galaxy images in the HST data. Lyα surface brightness contours of 2.8 \times 10^{-18}\text{erg s}^{-1}\text{cm}^{-2}\text{arcsec}^{-2} and 7.5 \times 10^{-18}\text{erg s}^{-1}\text{cm}^{-2}\text{arcsec}^{-2} are shown in white and red, respectively. Column (3): the magnification map overlaid with the same Lyα contours to illustrate the spatial variation of lensing magnification across the nebulae. Column (4): de-lensed narrow-band image, smoothed with a Gaussian kernel of FWHM_{smooth} = 0.5″ in the source plane. White contours mark constant surface brightness of 2.8 \times 10^{-18}\text{erg s}^{-1}\text{cm}^{-2}\text{arcsec}^{-2}, corresponding to the 3-σ level of significance detected in the image plane, same as contours shown in Column(1). Column (5): de-lensed Lyα contours overlaid on de-lensed HST data, with the yellow contours showing the caustics in the source plane. White and red contours mark the 3- and 8-σ Lyα surface brightness, same as the contours in Column(2). The cyan dashed arrow shows the direction along which we extract the one-dimensional surface brightness profile (see Figure 9 below). Compared with System A, the lensing configuration of System B is much more complicated, with images a-d being partial images with different levels of completeness. Image e is the only complete image of Lyα emission above 3-σ limiting surface brightness.

for System A both before and after including the Lyα flux inside the DLA troughs from star forming regions (see Figure 4).

As discussed above, Lyα surface brightness from the southern nebula agrees well across all three multiple images before including Lyα flux from DLA troughs, while image a becomes dimmer than images b and c after including the Lyα flux from the DLA troughs, suggesting a relatively smaller magnification factor in image a than what is predicted by the lens model at the locations of A2a and A3a. Figure 9 shows that both Systems A and B exhibit a general decline in Lyα surface brightness with increasing projected distance. Applying a simple exponential profile to characterize the observed surface brightness, SB(Lyα) \propto \exp(-D/D_s), we
find a best-fit scale radius of $D_s \approx 18$ pkpc for System A and $D_s \approx 1.5$ kpc for System B (see Figure 9), corresponding to a half-light radius of $r_e \approx 30$ and 2.5 pkpc for Systems A and B, respectively. These are consistent with the typical size found for Lyman break galaxies (e.g. Steidel et al. 2011) and LAEs (e.g. Wisotzki et al. 2016; Leclercq et al. 2017).

At the same time, we also see a suppressed Lyα surface brightness at the locations of the galaxies. The suppression resembles what is seen in the “net absorption” sub-sample of stacked Lyα surface brightness profiles of Steidel et al. (2011). We propose that the suppression may be attributed to attenuation by dusty outflows, which is supported by the observed high neutral gas column density and blueshifted low-ionization ISM absorption line in System A. Under this dust attenuation scenario, the radial extent of the observed dip in the center of the Lyα surface brightness profile is then a direct measure of the projected radius of the dusty outflow cones, which in the present cases amounts to $\lesssim 5$ pkpc for System A and $\lesssim 1$ pkpc for System B. Alternatively, the suppression may be attributed to a reduced $N$(HI) as a result of galactic scale outflows or galaxy interactions (e.g., Johnson et al. 2014).

5.2 Spatial variation of line profiles

In addition to the surface brightness variation in the narrow-band images, the Lyα nebulae in both systems exhibit a double-peak profile with a significantly enhanced red peak that indicates expansion/outflowing motions. In the top-left panel of Figure 10, we present stacked Lyα spectra from the northern and southern nebulae in System A. The spectra are extracted separately from within the $3$-$\sigma$ contours in Column (2) of Figure 6. In the top-right panel of Figure 10, we present stacked Lyα spectra for System B, extracted from within the low-surface brightness (between $3$-$\sigma$ and $8$-$\sigma$ contours) and high-surface brightness (within the $8$-$\sigma$ contours) regions shown in Figure 8. An overall shift in wavelength, both in the peak locations and the location of the valley of the Lyα line, is clearly seen between the northern and southern nebulae in System A, with the northern nebula being blue-shifted by $\approx 200$ km s$^{-1}$ relative to the southern one, suggesting a large velocity gradient across the line-emitting region. At the same time, no significant differences are seen between low- and high-surface brightness regions in System B.

To investigate in detail the velocity offset and possible spatial fluctuations in the Lyα profiles across both nebulae, we need to employ smaller apertures for extracting Lyα spectra. Specifically, we consider two competing factors when determining the extraction apertures: (1) the $S/N$ necessary to obtain significant signal in both the blue and red peaks and (2) possible spatial smearing of the extracted Lyα profile over a large aperture that may lead to erroneous characteristics of the Lyα profile. Because of the low surface brightness nature across all regions in System A, the Lyα line per spaxel does not have sufficiently high signals. We therefore experiment with extracting Lyα spectra from a range of aperture sizes to identify an appropriate aperture size for achieving a sufficiently high $S/N$ while limiting the smearing effect from combining different regions. We obtain the optimal extraction aperture from a localized, small area with a radius of $0.5$ centered near the highest surface brightness peak in the reconstructed source-plane narrow-band image (blue dashed circles in Column (2) of Figure 7). We then identify the spaxels located within this area in the image plane in all three multiple images $a$, $b$, and $c$, and construct a template spectrum for System A by coadding the spectra for all identified spaxels, which contains the information of gas properties in the brightest region of the

![Figure 9](image-url) De-lensed Lyα surface brightness profile, extracted along the directions indicated in Figures 7 and 8. For System A, we present the surface brightness profile both before and after including the Lyα flux from the DLA troughs at the locations of galaxy continuum. Distance is measured from the location of A1 (A2 and A3) for the northern (southern) nebula. For System B, zero distance corresponds to the location of B1. Note that we use rectangle apertures to extract the surface brightness profile as guided by the velocity gradient within the nebulae, instead of circular annuli (see text). In both systems, there is a decrease in surface brightness at small distances. The suppression may be attributed to either attenuation by the observed high neutral gas column density and possibly high dust content in System A or by a reduced total gas column as a result of galactic scale outflows in System B.
nebula. The template spectrum is displayed in the bottom-left panel of Figure 10. Although the S/N of the template spectrum is lower than what is seen in the large-area stacks (upper-left panel of Figure 10), the signal is strong enough to demonstrate the significant difference between the Lyα profiles extracted from small and large areas. Specifically, the template spectrum has a narrower width than the large-area stacks from both the northern and southern nebulae. In addition, the template spectrum exhibit a flux level that is consistent with zero at the bottom of the valley between the red and blue peaks. The observed zero flux in the valley is consistently seen across the nebulae in all spectra extracted from small apertures, and differs from the distinctly non-zero flux observed in the stacked spectra over the larger nebulae (see also Figure 3 of Caminha et al. 2017). Such difference can be naturally explained by the presence of a large velocity gradient in the nebulae that results in smearing of the combined Lyα profile. But because a non-zero flux in the valley of a double-peak Lyα profile would lead to very different parameters constraints for the expanding shell model (e.g. Dijkstra et al. 2006; Verhamme et al. 2006; Hansen & Oh 2006; Laursen et al. 2009; Schaerer et al. 2011; Gronke et al. 2015, also see below), the ability to spatially resolve the velocity field is necessary for obtaining accurate constraints for the underlying gas properties. In our study, we leverage lensing magnifications to resolve spatial variations on scales as small as \( \approx 2 \) pkpc along both nebulae (Systems A and B) in ground-based, seeing-limited data, though we caution that variations on smaller scales may still be present in these clouds (e.g. Cantalupo et al. 2019).

For System B, because the nebula is significantly brighter than what is seen in System A and the distinction in the observed Lyα profile is subtle between different locations, we construct a template spectrum using only the brightest pixels in images c, d and e to better constrain possible velocity gradient and spatial variation over a small area. The template spectrum for System B is displayed in the bottom-right panel of Figure 10, and does not show significant differences from the stacked spectra from larger areas (upper-right panel of Figure 10).

5.3 Physical properties of Lyα nebulae under an expanding shell model

We utilize the spatially and spectrally resolved Lyα profiles from MUSE observations and a Lyα Monte Carlo radiative transfer code \( \text{tlac} \) (Gronke & Dijkstra 2014; Gronke et al. 2015) to determine the physical properties of the line-emitting gas. We adopt an expanding shell model that has successfully explained many observed Lyα spectra across a wide range of redshifts based on a finite set of parameters, including the neutral hydrogen column density, \( N(\text{H}1) \), the
future. For each model, we compute a likelihood function of dust in our models and it will be explored separately in the ratio increases with $\alpha$ compared to observations. Given the uncertainty of the frequency bins to generate each model profile. Each model to explore the allowed parameter space, we construct a model grid data (e.g. Kulas et al. 2012; Orlitová et al. 2018).

Known cases where the model failed to provide a good fit to frequencies between different parameters, the peak separation increases primarily with $N(\text{H})$, and the red-to-blue peak ratio increases with $v_{\text{exp}}$, while $T_{\text{eff}}$ and $\sigma_i$ set the overall line width (see also Gronke et al. 2015, for a more detailed discussion on the effect of these parameters). In most cases this simple shell model provides a crude estimate of the underlying kinematic properties of the gas, but there are also known cases where the model failed to provide a good fit to data (e.g. Kulas et al. 2012; Orlitová et al. 2018).

For our analysis, we assume a homogeneous medium of constant gas density and compare the observed Ly$\alpha$ profiles with predictions over a grid of model parameters. To fully explore the allowed parameter space, we construct a model grid that covers log $N(\text{H})$/cm$^{-2}$ from 15.1 to 21.1, $v_{\text{exp}}$ from 10 to 400 km s$^{-1}$, $\sigma_i$ from 25 to 700 km s$^{-1}$, log $T_{\text{eff}}$/K from 3.0 to 6.0, and $\Delta v$ from 100 to 550 km s$^{-1}$. The velocity offset, $\Delta v$, is calculated with respect to the systemic redshift $z_{\text{sys}}$ listed in Table 6. We use 10,000 photons and 100 frequency bins to generate each model profile. Each model profile is also convolved with MUSE line spread function before compared to observations. Given the uncertainty of the dust attenuation effect on Ly$\alpha$ photons, we do not include dust in our models and it will be explored separately in the future. For each model, we compute a likelihood function $\mathcal{L}$ defined as

$$\mathcal{L}(N_{\text{HI}}, v_{\text{exp}}, \sigma_i, T_{\text{eff}}, \Delta v) = \prod_j \exp \left\{ \frac{[D(\lambda_j) - M(\lambda_j, N_{\text{HI}}, v_{\text{exp}}, \sigma_i, T_{\text{eff}}, \Delta v)]^2}{2S^2(\lambda_j)} \right\},$$

(6)

where $D(\lambda_j)$ and $M(\lambda_j)$ are the observed and model spectra, respectively, and $S(\lambda_j)$ is the corresponding error spectrum. The likelihood function is computed over the wavelength range of 4890–4930 Å ($5766$–$5796$ Å) for System A (System B), and can be translated to $\chi^2$ following $\chi^2 = -2\ln \mathcal{L}$. We then construct a marginalised likelihood function for each parameter by integrating $\mathcal{L}$ over all other parameters, and find the 95% confidence interval centered around the best-fit value. Note that since we do not explicitly include turbulent broadening in the models here, the temperature inferred from the model represents an effective temperature that includes non-thermal motion. For reference, for an intrinsic gas temperature of $T = 10^4$ K, an inferred effective temperature of $T_{\text{eff}} = 10^4$ (10$^5$) K implies an underlying bulk flow of $\sigma_{\text{bulk}} \approx 30$ (90) km s$^{-1}$.

To illustrate the impact of velocity smearing on the Ly$\alpha$ profile analysis, we first consider stacked spectra obtained over a large area along with the best-fit model profiles (top panels of Figure 10). The best-fit parameters and the associated 95% confidence intervals are presented in Table 6. The large $\chi^2$ values in Table 6 show that an expanding shell model fails to provide a good fit for the high S/N stacked Ly$\alpha$ spectra for both systems. A close examination of the profiles in the top panels of Figure 10 shows that the best-fit models with an uncharacteristically large intrinsic line width of $\sigma_i \approx 500$–650 km s$^{-1}$ provide a poor fit to the blue peak of the northern and southern nebulae in System A. The best-fit $\sigma_i$ is substantially broader than either what is seen in the ISM (see Table 5) or what is expected for the velocity dispersion in halos of a comparable mass scale for the host galaxies (e.g. $M_{\text{halo}} < 10^{12} M_{\odot}$; Traxor & Steidel 2012). For System B, while the small $\chi^2$ for the stacked spectrum from low-surface brightness regions suggests a good fit to the data, the model remains poorly constrained with large associated uncertainties due to the low S/N of the data. At the same time, the best-fit shell model produces a relatively poor fit to the blue peak of high S/N, high-surface-brightness regions, leading to a large $\chi^2$. To improve the precision and accuracy of the model constraints, we perform the profile analysis for the template spectra extracted from localized, small apertures presented in the bottom panels of Figure 10. In addition, we adopt the observed nebular line width from the ISM (see Table 5) as a prior for modelling the Ly$\alpha$ profiles. This is justified by the understanding that these Ly$\alpha$ photons likely originate in the star-forming regions of the associated galaxies (see §6 below). Specifically, we set $\sigma_i = 125$ km s$^{-1}$ for System A based on the observed FWHM of $\approx 310$ km s$^{-1}$ in

Table 6. Summary of the best-fit parameters (95% confidence interval) for characterizing the observed Ly$\alpha$ profile under an expanding shell model.

| System | $z_{\text{sys}}$ | $v_{\text{exp}}$ | $\sigma_i$ | $T_{\text{eff}}$ | $\Delta v$ | $\chi^2$ |
|--------|----------------|----------------|-----------|----------------|----------|--------|
| North  | 3.0367         | 19.3$^{+0.2}_{-0.3}$ | 300$^{+40}_{-30}$ | 637$^{+28}_{-51}$ | 4.2$^{+0.6}_{-1.2}$ | 253$^{+60}_{-37}$ | 6.6 |
| South  | 18.9$^{+0.2}_{-0.1}$ | 255$^{+6}_{-4}$ | 500$^{+49}_{-7}$ | 4.2$^{+0.1}_{-0.5}$ | 394$^{+7}_{-44}$ | 10.6 |
| Template | 20.3$^{+0.1}_{-0.2}$ | 110$^{+11}_{-22}$ | 125 | 5.3$^{+0.2}_{-0.2}$ | 200$^{+44}_{-30}$ | 2.3 |
| System B, $z_{\text{sys}} = 3.7540$ | | | | | | |
| 3$\sigma$ – $8\sigma$ | 16.2$^{+3.4}_{-0.7}$ | 271$^{+63}_{-174}$ | 154$^{+218}_{-57}$ | 5.7$^{+0.2}_{-2.4}$ | 57$^{+57}_{-138}$ | 0.9 |
| 8$\sigma$ | 19.3$^{+0.2}_{-0.2}$ | 134$^{+10}_{-15}$ | 343$^{+20}_{-22}$ | 5.2$^{+0.2}_{-0.2}$ | $-63^{+19}_{-7}$ | 5.3 |
| Template spectrum | 19.7$^{+0.1}_{-0.2}$ | 114$^{+16}_{-21}$ | 13 | 5.2$^{+0.1}_{-0.2}$ | $-82^{+25}_{-19}$ | 1.3 |

* Values without errors indicate a prior specified by the ISM nebular lines (see Table 5).

* Relative velocity with respect to $z_{\text{sys}}$.  

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**References**

Verhamme et al. 2006; Yang et al. 2017; Gronke et al. 2017.
strong degeneracy between different model parameters with modest $S/N$ data, we continue the analysis with a focus on constraining the velocity field, $\Delta v$, across the Ly$\alpha$ nebulae. This is achieved by cross-correlating the best-fit shell model for the template Ly$\alpha$ spectra in both systems to measure velocity offsets at different locations. To optimize the cross-correlation analysis, we spatially smooth the data cube with a Gaussian filter of FHWM$_{\text{smooth}} = 1''$ before extracting individual spectra. The resulting velocity maps are presented in Figure 11 for System A and Figure 12 for System B. We also present de-lensed velocity maps of both nebulae in the source plane. We have also experimented with constraining the velocity gradient by fitting an asymmetric Gaussian function (e.g., see Eq.1 of Leclercq et al. 2020) to the red peak of the Ly$\alpha$ profile from every spaxel within the 3-$\sigma$ contour in both systems, and we obtain a similar velocity gradient as shown in Figures 11 and 12. Our method utilising the best-fit model of the template spectra allows us to directly connect the velocity offset in the nebulae with the associated star-forming regions.

Our analysis of System A has uncovered a highly organized velocity field across the Ly$\alpha$ emitting nebulae, with increasing velocity offset from $\Delta v \approx 0$ km s$^{-1}$ at $\approx 11$ pkpc south of galaxies A2 and A3 to $\Delta v \approx +250$ km s$^{-1}$ at the location of galaxy A1 to $\Delta v \approx -150$ km s$^{-1}$ at $\approx 13$ pkpc northwest of A1. The observed steep velocity gradient, $|\Delta v/\Delta r_1| \approx 22 - 27$ km s$^{-1}$ pkpc$^{-1}$, together with a large best-fit $N$(HI) and an enhanced red peak in the Ly$\alpha$ profile across the nebula supports a scenario in which high column density gas is driven outward from the galaxies to beyond 10 pkpc in projected distance into the low-density surroundings. Due to a lack of AGN activities (see §4.4), the outflows are likely driven by star formation in these young galaxies.

It is interesting that there exists an apparent gap in Ly$\alpha$ signal between the northern and southern nebulae. One possible explanation for this gap is a reduced $N$(HI) as a result of galaxy interactions. A lack of strong Ly$\alpha$ absorber has been seen at projected distances of $<20$ pkpc from an in-

Figure 11. Column (1): velocity map of multiple images a, b and c in System A, derived from cross-correlating the best-fit shell model for the template spectrum (bottom-left panel of Figure 10) and spectra extracted from spaxels within the 3-$\sigma$ contours. Zero velocity corresponds to $z_{\text{sys}} = 3.0367$, which is the systemic redshift of A1 derived from ISM nebular emission lines. Column (2): de-lensed velocity map of individual images in the source plane. Star symbols mark the positions of the associated star-forming galaxies identified in HST images (see Figures 6 and 7).

Figure 12. Left: velocity map of image e in System B, derived from cross-correlating the best-fit shell model for the template spectrum (bottom-right panel of Figure 10) and spectra extracted from spaxels within the 3-$\sigma$ contour. Zero velocity corresponds to $z_{\text{sys}} = 3.7540$, which is the systemic redshift of B1/B2 derived from ISM nebular emission lines Right: de-lensed velocity map of image e in the source plane. Star symbols mark the position of B1/B2 determined from HST images (see Figure 8).
tering galaxy pair at low redshift with an upper limit of \( \log N(\text{HI})/\text{cm}^{-2} \lesssim 13.7 \) (e.g. Johnson et al. 2014). In the optically thin regime, we estimate a 2-\( \sigma \) upper limit of \( \log N(\text{H}i)/\text{cm}^{-2} < 16.4 \) at \( \approx 5 \) pkpc based on the observed 2-\( \sigma \) upper limit in Lya surface brightness and an assumption of 100\% escape fraction of ionizing photons from the galaxies. While at this limit, the gas would still be optically thick to Lya photons, we cannot rule out the possibility of a significantly lower \( N(\text{HI}) \). Other plausible explanations for the gap also include a lack of illumination from young stars due to anisotropic leakage of Lya and ionizing photons, and attenuation of Lya signal due to highly neutral, dusty gas in-between these galaxies (also see discussion in §6 below).

In contrast, System B exhibits distinct properties from System A. The Lya nebula appears to be distributed symmetrically around galaxies A1 and B2 with the peak intensity located close to star forming regions. The inferred line-of-sight velocity offset of \( \approx -100 \) km s\(^{-1}\) near the location of the galaxies, coupled with the observed Lya profile, again supports an outflow scenario from the galaxies. The observed velocity gradient of \( |\Delta v/\Delta r| \approx 20 \) km s\(^{-1}\) kpc\(^{-1}\) toward the outer edge of the nebula may be explained by a line-of-sight projection effect.

### 6 Discussion

We have shown that by accounting for spatial variations in the observed Lya line profiles, we are able to determine the velocity field and constrain gas flows across the nebulae. Given the proximity of the line-emitting gas to star-forming regions and the relative velocity offset between gas and galaxies, we argue that the gas is being driven out of the star-forming regions at a modest speed. Specifically, the Lya nebula of System B exhibits a relatively symmetrical morphology with the peak of the Lya emission located close to the star-forming regions. This configuration is typical of low-mass LAEs at high redshifts (e.g. Wisotzki et al. 2016; Leclercq et al. 2017), and suggests that gas flows outward from the star-forming regions into the low-density halo environment. In System A, however, the Lya nebulae are clearly offset to one side of the galaxies with the highest surface brightness regions bordering the continuum-emitting regions (see Figures 6 and 7). While the star-forming regions contribute significantly to the extended Lya emission, the connection between the star-forming regions and the large-scale outflows remains uncertain.

We consider two plausible scenarios for the origin of the outflows. First, the northern nebula originates in gas flowing out of A1, while the southern nebula originates in gas flowing out of galaxies A2 and A3. This is plausible if all three galaxies are capable of driving galactic scale super winds. Applying the conversion factor of Madau & Dickinson (2014), we estimate an unobscured SFR of \( \approx 22, 5 \) and \( 4 M_\odot\text{yr}^{-1} \) for galaxies A1, A2, and A3, respectively, based on the observed rest-frame UV absolute magnitudes \( M_{1500} \) presented in Table 2. In the presence of dust, this observed \( M_{1500} \) and inferred SFR are likely lower limits to the intrinsic values. In addition, we estimate a total projected area based on the continuum regions determined by SExtractor (see §4.1) and apply lensing magnification corrections based on the fine-tuned lens model (see §3). We find the intrinsic projected area of A1, A2, and A3 to be \( \approx 50, 11 \) and \( 11 \) pkpc\(^2\), respectively. For galaxies A2 and A3, these are based on an average over all three images, a, b, and c after lensing magnification corrections. Combining the estimated unobscured SFR and projected area leads to an estimate of SFR per unit area of \( \gtrsim 0.4 M_\odot\text{yr}^{-1} \) pkpc\(^{-2}\) in these individual galaxies. This exceeds the empirical threshold seen in driving galactic scale super winds in local starburst galaxies (e.g. Heckman et al. 2015).

Alternatively, galaxy A1 may be the single dominant source driving the outflows seen in both the northern and southern nebulae. Apart from being the most massive galaxy with the highest SFR in the group, A1 also shows more extended blue wings in the low-ionization ISM absorption lines (see Figure 4), suggesting the presence of galactic outflows that are more prominent than what is seen from the same line features in galaxies A2 and A3. In this scenario where galaxy A1 is the origin of the outflows on both sides, the gap in Lya emission between the northern and southern nebulae is likely due to dusty outflow materials from galaxy A1 that cover the gap area along the line-of-sight.

A remaining question of the observed line-emitting nebulae is the origin of Lya photons. As described earlier, multiple mechanisms can lead to Lya emission in diffuse gas, including cooling radiation, fluorescence powered by ionizing photons from either star-forming regions or AGN, and resonant scattering by neutral hydrogen gas (e.g., Hogan & Weymann 1987; Gould & Weinberg 1996; Cantalupo et al. 2005; Kollmeier et al. 2010; Faucher-Giguère et al. 2010; Hennawi & Prochaska 2013). Disentangling between different mechanisms that are responsible for the observed Lya signals is challenging, especially when the Lya line is the only observable feature in the nebulae.

For the two systems in our study, however, the observed spectral properties of the Lya line enable us to rule out cooling radiation and photo-ionization due to the cosmic UV background radiation as a dominant mechanism for powering the observed emission. Specifically, radiatively cooled gas is expected to condense and sink through the hot ambient medium, resulting in infall, and the majority of the photons will travel through the infalling clouds before escaping the medium (e.g., Faucher-Giguère et al. 2010). The expectation of an enhanced blue-peak from infalling gas in inconsistent with the observations. In addition, the expected Lya fluorescence signal from cosmic UV background alone is low with surface brightness of \( \lesssim 10^{-19} \) erg s\(^{-1}\) cm\(^{-2}\) arcsec\(^{-2}\) (e.g., Kollmeier et al. 2010).

We therefore proceed with considerations of the two remaining scenarios: (1) Lya photons arising as a result of fluorescence powered by ionizing photons from star-forming regions and (2) Lya photons produced in the galaxies and resonantly scattered by neutral hydrogen in the nebulae. The first scenario requires a non-zero escape fraction of ionizing photons from the galaxies, while the second scenario corresponds to the shell model analysis described in §5.3. Here we also discuss the implications of these scenarios.

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6.1 Lyα emission from recombination radiation and implications for the escape fraction of ionizing radiation from star-forming galaxies

We first consider the possibility that the observed Lyα signals are powered by in situ star formation directly underneath the nebulae. Available deep HST F606W image places strong constraints on the rest-frame UV continuum flux at the location of the nebulae. Using the integrated Lyα luminosity of $L_{\text{Ly}\alpha} = (2.15 \pm 0.07) \times 10^{42} \text{erg s}^{-1}$ ([3.49±0.08]×10$^{42}$ erg s$^{-1}$) for the northern (southern) nebula of System A, we infer an SFR of $\approx 1.1 (2.3) M_\odot \text{yr}^{-1}$ based on a conversion factor of Lyα/Hα = 8.7 (Hayes 2015, and references therein) and the Ho-SFR relation of Kennicutt & Evans (2012). From the inferred SFR, we derive the expected apparent magnitude in the F606W bandpass (corresponding to 1500 Å in the rest frame at $z \approx 3$) of $AB(F606W) \approx 27.3 (26.5)$ using the FUV flux-SFR relation of Madau & Dickinson (2014) for the underlying star-forming regions in the northern (southern) nebula. The inferred F606W magnitude is roughly more than two magnitudes brighter than the 2-σ detection limit in the F606W bandpass ($AB(F606W) \approx 29$ within an aperture of 0.5′ in diameter), but no flux is detected at the location of the nebulae away from the galaxies. We therefore rule out the possibility that the Lyα signals are predominantly powered by in situ star formation.

For photo-ionization by the nearby galaxies, the observed Lyα intensity is connected to the incident ionizing radiation field and the discussion often involves considerations of two different regimes, optically thin versus optically thick gas. For the purpose of our study, both Systems A and B consistently require a large $N$(H$\text{I}$), exceeding $\log N$(H$\text{I}$)/cm$^{-2} \approx 19$ (Table 6), for explaining the observed Lyα profile. We therefore consider only optically-thick regime in the subsequent discussion.

In optically-thick regime, ionization occurs in the surface of a cloud illuminated by the ionizing source and roughly 66% of all ionizing photons are converted into Lyα photons through recombination cascades in the surface layer (i.e., $\eta = 0.66$) (Osterbrock & Ferland 2006). The surface brightness of Lyα emission is connected to ionizing photon flux according to

$$S_{B\text{Ly}\alpha} = f_f f_{\text{esc}} \frac{\eta \mu h \eta_{\text{Ly}\alpha} \Phi}{(1+z)^4 \pi}$$

$$= 3.2 \times 10^{-18} f_f f_{\text{esc}} \left( \frac{1+z}{4.0} \right)^4 \left( \frac{D}{10 \text{ pkpc}} \right)^{-2} \left( \frac{\Phi_0}{10^7 \text{ s}^{-1} \text{ cm}^{-2}} \right)^{-2} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2}$$ (7)

where $f_f$ is the geometric correction coefficient to account for partial illumination of the nebula and redistribution of Lyα photons, $f_{\text{esc}}$ is the fraction of ionizing photons that escape the galaxies, $D$ is the distance of the cloud from the ionizing source, and $\Phi_0$ is the ionizing photon flux at a distance of 1 kpc from the source. In principle, comparing the observed Lyα surface brightness with the expected ionizing radiation field from the SED analysis of the galaxies constrains $f_f$ and $f_{\text{esc}}$ based on Eq. 7. In practice, uncertainties in the inferred galaxy spectra are large. Therefore, it is not trivial to obtain accurate constraints for $f_f$ and $f_{\text{esc}}$.

For System A, we estimate the total ionizing photon fluxes from A1, A2 and A3 using the best-fit Bagpipes model spectra and find respectively $\Phi_0 \approx 3.4 \times 10^6, 8.1 \times 10^6, 5.1 \times 10^6 \text{ s}^{-1} \text{ cm}^{-2}$ at $D = 10 \text{ pkpc}$. Assuming $f_f = 0.5$ from numerical simulations (e.g., Cantalupo et al. 2005; Kollmeier et al. 2010) and $f_{\text{esc}} < 10\%$ as a fiducial upper limit for ionizing photon escape fraction (e.g. Chen et al. 2007; Vanzella et al. 2010; Grazian et al. 2017), the observed peak Lyα surface brightness of $7.3 \times 10^{-18} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2}$ (the 6-σ contour in Figure 7) implies a distance limit of $D < 8.5 \text{ pkpc}$ from A1 and $D < 3.3 \text{ pkpc}$ from A3. Adopting the low-intensity contour of $3.7 \times 10^{-18} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2}$ would increase the distance limit by 40% to $D < 12 \text{ pkpc}$ from A1 and $D < 4.6 \text{ pkpc}$ from A3. The observed extent of Lyα emission of $\gtrsim 10 \text{ pkpc}$ (see Figure 7) therefore requires A1 to be the dominant source of ionizing photons with an escape fraction $\lesssim 10\%$. While current observations suggest that the escape fraction of ionizing photons from massive ($>L_\ast$) galaxies at $z \approx 3$ is much smaller than 10% (e.g. Grazian et al. 2017), an escape fraction of $\sim 10\%$ towards the direction of the Lyα nebulae is possible due to anisotropic escape of ionizing photons in an inhomogeneous, clumpy medium. Furthermore, with possible contribution from resonant scattering of Lyα photons produced in the star-forming regions (see §6.2 below), the required $f_{\text{esc}}$ of ionizing photons could be lower.

We repeat the same exercise for System B. Due to the smaller physical scale of System B, we estimate the ionizing photon flux at a distance of $D = 1 \text{ pkpc}$. Using the best-fit Bagpipes model spectra, we obtain the total ionizing photon flux from B1 and B2 combined to be $\Phi \approx 1.4 \times 10^6 \text{ s}^{-1} \text{ cm}^{-2}$ at 1 pkpc. The observed surface brightness of $7.5 \times 10^{-18} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2}$ (the 8-σ contour in Figure 8) leads to $(f_f f_{\text{esc}}) \approx 33\%$, or $f_{\text{esc}} = 66\%$ assuming $f_f = 0.5$. At the limit of $f_{\text{esc}} < 1$, we infer the distance limit of $D < 1.2 \text{ pkpc}$ for the high-intensity contours. With the low-intensity surface brightness of $2.8 \times 10^{-18} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2}$ (the 3-σ contour in Figure 8), the inferred distance limit is increased to $D < 2 \text{ pkpc}$. Because the observed Lyα emission extends to $\gtrsim 4 \text{ pkpc}$ in the source plane (see Figure 8), we conclude that recombination radiation from photo-ionized gas alone cannot explain all of the observed Lyα photons away from the galaxies in System B.

6.2 Lyα emission from scattering and implications for dust attenuation

Given the star-forming nature of the galaxies in both Systems A and B, we now consider the scenario in which the Lyα photons are produced in the star-forming ISM of the galaxies and resonantly scattered through the spatially extended nebulae. Using the estimated SFR in the 16%-84% confidence interval for galaxies A1, A2 and A3 (see Table 4), we infer a total intrinsic Lyα luminosity of $L_{\text{Ly}\alpha}^\ast/(10^{44} \text{ erg s}^{-1}) = 1.46–1.65, 0.17–0.19, \text{ and } 0.21–0.26$ for galaxies A1, A2, and A3, respectively, using the conversion factor of Lyα/Hα = 8.7 (Hayes 2015, and references therein) and the Ho-SFR relation of Kennicutt & Evans (2012). For System B, the same exercise leads to an intrinsic Lyα luminosity of $L_{\text{Ly}\alpha}^\ast = (1.2–2.1) \times 10^{42} \text{ erg s}^{-1}$ for galaxies B1 and B2 combined.

While these star-forming galaxies may be intrinsically luminous in Lyα, we expect that a large fraction of these Lyα photons are unable to escape the ISM due to a substantial
amount of dust attenuation. We obtain an empirical estimate of the attenuation factor $k_{\text{dust}} = 1 - L_{\text{dust}}^\text{int}/L_{\text{Ly} \alpha}^\text{int}$, based on the observed Ly$\alpha$ luminosity of $2.15 \times 10^{42}$ erg s$^{-1}$ for the northern nebula and $3.43 \times 10^{42}$ erg s$^{-1}$ for the southern nebula, and the intrinsic Ly$\alpha$ luminosity from star-forming regions described above. Attributing the Ly$\alpha$ emission of the northern (southern) nebula to the scattering of Ly$\alpha$ photons from galaxy A1 (galaxies A2 and A3), we estimate $k_{\text{dust}}$ to be $\approx 98\%$ and $\approx 92\%$ for the northern and southern nebula, respectively.

Following the optically-thick prescription from Equation 7 and replacing ionizing photon flux with Ly$\alpha$ photon flux $\Phi_{\text{Ly} \alpha}$, we can now connect the Ly$\alpha$ scattering surface brightness to $L_{\text{Ly} \alpha}^\text{int}$, following

$$\text{SB}_{\text{Ly} \alpha} = \frac{h \nu_{\text{Ly} \alpha} \Phi_{\text{Ly} \alpha}}{(1+z)^4 \pi} = \frac{h \nu_{\text{Ly} \alpha}}{(1+z)^4 \pi} \left(1 - k_{\text{dust}}\right) \frac{L_{\text{Ly} \alpha}^\text{int}}{4\pi D^2 h \nu_{\text{Ly} \alpha}} = 2.4 \times 10^{-18} \frac{1+z}{4.0} \left(\frac{D}{10 \text{pkpc}}\right)^{-2} \left(1 - k_{\text{dust}}\right) \frac{L_{\text{Ly} \alpha}^\text{int}}{10^{42} \text{erg s}^{-1} \text{cm}^{-2} \text{arcsec}^{-2}}.$$

Eq. 8 leads to a distance estimate of $D_{\text{north}} \approx 14$ pkpc between the northern nebula and galaxy A1 for an observed Ly$\alpha$ surface brightness of $3.7 \times 10^{-18}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$ (the 3-$\sigma$ contour in Figure 7), an intrinsic Ly$\alpha$ luminosity of $L_{\text{Ly} \alpha}^\text{int} = (1.46-1.65) \times 10^{44}$ erg s$^{-1}$ for A1, and an attenuation factor of 98%. At higher intensity of $7.3 \times 10^{-18}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$ (the 6-$\sigma$ contour in Figure 7), the distance is reduced to $\approx 10$ pkpc. The inferred distance range is fully consistent with the extent of the northern nebula relative to A1. In addition, the estimated amount of dust attenuation agrees with $A_V \approx 0.7$ mag inferred from the SED analysis presented in §4.2 (see also Table 4). Based on the Calzetti et al. (2000) extinction law for starburst galaxies, the estimated stellar extinction of $A_V \approx 0.7$ mag corresponds to an extinction magnitude of $A_{1215} \approx 5.2$ mag for the Ly$\alpha$ emission line, or $k_{\text{dust}} \approx 99\%$ for the Ly$\alpha$ photons. It suggests that resonant scattering alone can fully account for the observed Ly$\alpha$ brightness in the northern nebula.

For the southern nebula, galaxies A2 and A3 together contribute to a total intrinsic Ly$\alpha$ luminosity of $L_{\text{Ly} \alpha}^\text{int} = 3.8-4.5 \times 10^{43}$ erg s$^{-1}$. Adopting $k_{\text{dust}} = 92\%$ leads to a distance estimate of $D_{\text{south}} \approx 10$ pkpc for the high-intensity region and $D_{\text{south}} \approx 15$ pkpc for the low-intensity region between galaxies A2/A3 and the southern nebula. Similarly, the estimated size is consistent with the observed extent of the southern nebula (see §5.1). Although the dust attenuation of 92% is in tension with the estimated $k_{\text{dust}} \approx 99\%$ based on the SED analysis, we argue that a possible contribution of Ly$\alpha$ photons from galaxy A1, together with uncertainties in $f_{\text{esc}}$ (see §6.1) and $k_{\text{dust}}$ in an inhomogeneous, clumpy medium could account for the observed extent of Ly$\alpha$ signals in the southern nebula (e.g., Neufeld 1991; Hansen & Oh 2006).

For galaxies B1 and B2, the uncertainty in $k_{\text{dust}} = 1 - L_{\text{dust}}^\text{int}/L_{\text{Ly} \alpha}^\text{int}$ is larger, ranging between $\approx 20-50\%$. Meanwhile, uncertainties in $A_V$ are also larger, ranging between $A_V \approx 0.05-0.25$ for B1 and $A_V \approx 0.5-0.7$ for B2 (see Table 4), corresponding to a wide range of dust attenuation of $\approx 30-99\%$ for Ly$\alpha$ photons, in agreement with the empirical $k_{\text{dust}}$ of $\approx 20-50\%$. Adopting $k_{\text{dust}} = 50\%$, Eq. 8 leads to a distance estimate of $D \approx 3$ pkpc between galaxies B1/B2 and the observed Ly$\alpha$ intensity peak of $7.5 \times 10^{-18}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$ (the 8-$\sigma$ contour in Figure 8). At $SB_{\text{Ly} \alpha} = 2.8 \times 10^{-18}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$ (the 3-$\sigma$ contour in Figure 8), we estimate a distance of $\approx 5$ pkpc, which agrees well with the observed extent of the nebula. While resonant scattering alone can also account for the observed Ly$\alpha$ brightness in System B in the presence of a modest dust attenuation, the uncertainty on $k_{\text{dust}}$ is large. A lower $k_{\text{dust}}$ would require additional dust attenuation within the nebula itself, while a higher attenuation factor of $k_{\text{dust}}$ (up to 90%) would require additional source to account for the observed Ly$\alpha$ signals.

The above exercises suggest that the observed Ly$\alpha$ emission in both systems arises from a combination of recombination radiation from photoionized gas and resonant scattering of Ly$\alpha$ photons produced in nearby star-forming regions. The relative contribution from resonant scattering is likely more significant with the assumption of a low $f_{\text{esc}}$ of UV continuum photons from galaxies. However, with the current data, it is challenging to precisely determine the contribution from these two mechanisms given the uncertainties in $f_{\text{esc}}$, $k_{\text{dust}}$, the inferred galaxy UV spectra from the SED analysis, as well as the possibility of anisotropic escape of Ly$\alpha$ and UV continuum photons.

6.3 Systematics in interpreting the spatial and spectral profiles of the nebulae

Due to the clumpy nature of line-emitting gas, the surface brightness profile of extended nebulae is subject to the spatial variation of lensing magnification and its associated uncertainties in the image plane. In principle, gravitational lensing conserves surface brightness of a light-emitting source. However, the conservation of surface brightness does not apply when the lensed image of the source is not resolved in the data. In our study, the spatial resolution is limited by the size of the seeing disk in ground-based observations. We see that the source-plane image reconstructed from less magnified regions appear to be fainter (e.g., image a of System A) than those reconstructed from more highly magnified images (e.g., images b and c of System A). This surface brightness discrepancy suggests that the individual clumps, even after being magnified by the cluster lens, are still not resolved by the data. Apart from the decrease of surface brightness in image a of System A as discussed in §5.1, we also see discrepancy of Ly$\alpha$ surface brightness near critical curves where the magnification factor is much larger (e.g., in System B, the Ly$\alpha$ emitting region that straddles the critical curve between images a and b shows the highest apparent surface brightness across the whole lensed arc). Adopting $\mu \approx 20$ as the fiducial magnification factor near the critical curves, we estimate that the clump size should be $\lessapprox 1.5$ kpc in order for the gas clumps to remain unresolved in lensed images recorded under 1" seeing. This upper limit is in agreement with clump sizes of cold gas in the CGM constrained in absorption studies (e.g. Zahedy et al. 2019). Furthermore, small-scale substructures in the lens can also introduce additional perturbations to the lensing effect across an extended source (e.g., the unusually large mag-
nification at the location of image B1e, see §4.1. In order to accurately quantify the intrinsic surface brightness distribution of extended and clumpy sources in strong lensing fields, a better understanding of the systematic uncertainties of lensing magnification as a function of image position is necessary.

Systematic uncertainties also remain in the shell model analysis on the Lyα line profiles and the interpretation of the velocity gradient derived from spatially-varying Lyα lines in both Systems A and B. For example, our shell model does not include radiative transfer effects inside the galaxies, which would re-shape the input Lyα line from a single Gaussian into a double-peak profile. This provides a likely explanation for the large redshift observed at the location of the continuum regions in System A (see Figure 11). However, a clumpy ISM may also be transparent to Lyα photons, resulting in a wider Gaussian linewidth instead. In addition, because the signal strength is dominated by the much stronger red peak in the Lyα line (see Figure 10), the inferred velocity offset could simply represent a shift in the location of the red peak. The observed blueshifted velocity with increasing projected distance in System A (see Figure 11) may also be explained in part due to line-of-sight projection of a uniformly expanding sphere. While a complete 3D radiative transfer model to consider different possible cloud geometry is beyond the scope of this paper, an initial exercise that explores different cloud geometry and velocity fields shows that the emergent spectrum will be increasingly blueshifted (redshifted) from the center to the edge of the cloud with decelerating (accelerating) gas expansions. We argue that System A is likely decelerating while System B is accelerating as the gas move outward from the star-forming regions.

In summary, the observed Lyα emission morphology in System A clearly indicates a more complicated gas geometry than what is assumed in current radiative transfer simulations. In addition, significant uncertainties remain in terms of the origin and the spatial distribution of Lyα emission sources, the effect of local ISM on the Lyα spectra emergent from the the star-forming regions prior to the scattering of large-scale gas in the CGM, as well as the effect of dust and gas clumpiness. All of these factors can alter the shape of the emerging line profile, the surface brightness profile, and the velocity gradient of Lyα emission in an extended gas cloud. A more sophisticated radiative transfer model is needed to fully explore the parameter space.

7 SUMMARY AND CONCLUSIONS

Combining the strong cluster lensing power with deep wide-field integral field spectroscopic data, we have carried out a detailed analysis of two giant Lyα arcs to spatially and spectrally resolve gas flows around two active star-forming regions at $z > 3$. Both Lyα nebulae are found to be spatially offset from the associated star-forming region and both exhibit a double-peak profile with a significantly enhanced red peak that indicates expansion/outflowing motions. One of the arcs with Lyα surface brightness of $3.7 \times 10^{-18}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$, detected at the 3-$\sigma$ level of significance, stretches over 1$'$ around the Einstein radius of the cluster, resolving the velocity field of the line-emitting gas on sub-kpc scales around a group of three star-forming galaxies of $0.3-1.6\,L_\odot$ at $z = 3.038$. Based on a lens model constructed from deep HST images, the de-magnified source-plane Lyα image exhibits a symmetric double-lobe structure of $\approx 30$ pkpc across, encompassing the galaxy group. The total integrated Lyα flux across the nebula is $(6.5 \pm 0.1) \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$ after correcting lensing magnifications, corresponding to a total Lyα luminosity of $L_{\text{Ly}\alpha} = (5.2 \pm 0.1) \times 10^{42}$ erg s$^{-1}$ at $z \approx 3.038$. The second arc with Lyα surface brightness of $2.8 \times 10^{-18}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$ (3-$\sigma$) spans 15$''$ in size, roughly centered around a pair of low-mass dwarf Lyα emitters of $\approx 0.03\,L_\odot$ at $z \approx 3.754$. The total integrated Lyα flux is $(7.4 \pm 0.2) \times 10^{-18}$ erg s$^{-1}$ cm$^{-2}$, corresponding to a total luminosity of $L_{\text{Ly}\alpha} = (9.8 \pm 0.2) \times 10^{41}$ erg s$^{-1}$ at $z \approx 3.754$.

Here we summarize the main findings of our study:

1) A strong variation in the observed Lyα surface brightness is seen across both nebulae, suggesting large spatial fluctuations in the underlying gas properties. While the nebulae at $z = 3.038$ is split into northern and southern lobes bracketing the group of luminous star-forming galaxies, the one at $z = 3.754$ appears to be more symmetrically distributed around the associated low-mass galaxies.

2) Spatial variations in the kinematics profile of the Lyα emission line are also detected in both nebulae, revealing highly organized velocity fields across the nebulae. We show that such spatial variations, if unaccounted for in integrated Lyα profiles, may lead to biased results in constraining the underlying gas kinematics. By applying a simple expanding shell model to the spatially-varying Lyα line, we infer a large velocity gradient of $|\Delta v/\Delta r_\perp| \approx 22 - 27$ km s$^{-1}$ pkpc$^{-1}$ and high neutral hydrogen column density of $N(\text{H}I)/\text{cm}^{-2} \gtrsim 19.5$ for both nebulae. The result supports a scenario in which high column density gas is driven outward from the galaxies to beyond 10 pkpc in projected distance into the low-density surroundings.

3) Combining known star formation properties of the galaxies and the observed extent and surface brightness of the Lyα signals, we show that the observed Lyα photons likely originate from a combination of resonant scattering of Lyα photons from the nearby star-forming regions and recombination radiation due to escaping ionizing photons, although the relative contribution of these two mechanisms cannot be accurately determined with the current data.

Both nebulae provide clear-cut examples of gas outflows that are thought to be widespread at high redshift and may be responsible for metal enrichment of the Lyα forest in general. While the hydrogen Lyα line, being the strongest emission line in diffuse, photo-ionized gas, enables sensitive studies of spatially extended outflows beyond active star-forming regions, large uncertainties remain due to the resonant nature of this transition. Future observations targeting non-resonant transitions, such as [O II]λ3727, 3730, Hβλ4863, O III]λ5008, and Hαλ6565, within the line-emitting nebulae will provide the necessary discriminating power to resolve the degeneracy between different physical parameters. Based on the observed Lyα surface brightness in Systems A and B and under the assumption that the Lyα emission arises from recombination radiation of photo-ionized gas, we estimate the expected Hα and Hβ surface brightness to be approximately 3 and $1 \times 10^{-19}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$, respectively.
The $[\text{O}III]\lambda5008$ line is expected to be between 3 and 10 times brighter than $H\beta$ in photo-ionized, low-metallicity gas (e.g. Kewley et al. 2019). While the $H\alpha$ line is redshifted out of the detection window with existing near-infrared spectrographs on the ground, it is possible to detect $H\beta$ of the current observing facilities. We therefore argue that follow-up near-infrared integral field observations, targeting rest-frame optical, non-resonant lines in known Ly$\alpha$ nebulae, will greatly improve the physical constraints of gas flows around distant star-forming galaxies.

ACKNOWLEDGEMENTS

We thank Erin Boettcher, Fakhri Zahedy, Claude-André Faucher-Giguère and Irina Zhuravleva for helpful discussions. HWC and MCC acknowledge partial support from Faucher-Giguère and Irina Zhuravleva for helpful discussions. HWC and MCC acknowledge partial support from NASA through the NASA Hubble Fellowship grant HST-HF2-51409. This research has made use of the services of the ESO Science Archive Facility and the Astrophysics Data Service (ADS)\footnote{https://ui.adsabs.harvard.edu/classic-form}. The analysis in this work was greatly facilitated by the following python packages: 

- Rumpy (Olliphant 2015), 
- Scipy (Virtanen et al. 2020), 
- Astropy (Astropy Collaboration et al. 2013; Price-Whelan et al. 2018), 
- Matplotlib (Hunter 2007), and 
- MPDAF (Bacon et al. 2016).

DATA AVAILABILITY

The data used in this article are available for download through the Mikulski Archive for Space Telescopes (MAST) and the ESO Science Archive Facility.

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APPENDIX A: LENS CONSTRAINTS AND PARAMETERS

In Table A1, we list the coordinates of all multiple images used as constraints in our lens modeling process, while the best-fit parameters for the fiducial and fine-tuned model are listed in Tables A2 and A3, respectively.

APPENDIX B: PHOTOMETRY FOR INDIVIDUAL IMAGES OF SYSTEMS A AND B

In §4.1, we presented the photometric magnitudes of galaxies in Systems A and B after correcting the lensing magnification and averaging among multiple images. Here in Table B1, we list the direct measurements from the data for each individual images without correcting for lensing effect. Note that the Galactic extinction is corrected for each bandpass.

APPENDIX C: FITTING A SHELL MODEL TO STACKED SPECTRA OBTAINED OVER A LARGE AREA WITH FIXED INTRINSIC Lyα LINE WIDTH \( \sigma_f \)

In §5.3, we have shown that the best-fit shell models for stacked spectra extracted from a large area in both Systems
Table A1 – continued

| Image ID | RA    | DEC   | Redshift |
|----------|-------|-------|----------|
| 15a      | 181.55562 | −8.794635 | 3.7611   |
| 15b      | 181.55760 | −8.803056 | 3.7611   |
| 15c      | 181.55174 | −8.810964 | 3.7611   |
| 16a      | 181.55458 | −8.791202 | 3.7617   |
| 16b      | 181.54645 | −8.799871 | 3.7617   |
| 16c      | 181.55650 | −8.802471 | 3.7617   |
| 17a      | 181.55613 | −8.795620 | 3.8224   |
| 17b      | 181.55698 | −8.799422 | 3.8224   |
| 18a      | 181.55537 | −8.796714 | 3.9400   |
| 18b      | 181.55597 | −8.798595 | 4.0400   |
| 19a      | 181.56208 | −8.794875 | 4.0520   |
| 19b      | 181.56187 | −8.805239 | 4.0520   |
| 19c      | 181.55978 | −8.809463 | 4.0520   |
| 20a      | 181.54742 | −8.800476 | 4.0553   |
| 20b      | 181.55683 | −8.803813 | 4.0553   |
| 22a      | 181.54432 | −8.791418 | 4.2913   |
| 22b      | 181.54028 | −8.796562 | 4.2913   |
| 22c      | 181.54088 | −8.806094 | 4.2913   |
| 23a      | 181.56325 | −8.796893 | 4.7293   |
| 23b      | 181.56353 | −8.808670 | 4.7293   |
| 23c      | 181.55983 | −8.811526 | 4.7293   |
| 25a      | 181.55971 | −8.796562 | 5.7927   |
| 25b      | 181.56010 | −8.800177 | 5.7927   |
| 26a      | 181.55071 | −8.803112 | 6.0106   |
| 26b      | 181.55121 | −8.803668 | 6.0106   |

A and B require the intrinsic Lyα line width $\sigma_i$ to be much larger than the observed ISM emission line width. We argue that the large $\sigma_i$ is caused by the smearing effect due to the velocity gradient in the nebulae. Here in Figure C1, we show the best-fit models for the same spectra shown in the top row of Figure 10 in the main text, and demonstrate that by fixing $\sigma_i$ to the observed values from galaxy spectra, the best-fit models provide a worse fit to the data.

We adopt the multiple image identifications from Caminha et al. (2017), while excluding image systems 2, 7, 13, 21, 24 and 27 (see §3 for detailed discussions). We rename their image system 11 to be A2, and add A31 and A32 (the north and south substructures of A3). Similarly, we rename image system 14 to be B1, and add B2 (the fainter structure near B1 at the same redshift). We also update redshifts for A2, A3, B1 and B2 to be their best-fit values from fitting the observed emission lines (see §4). For the fiducial model, we use all images listed except for A31, A32 and B2. For the fine-tuned model, we only use systems A2, A31, A32, B1 and B2, excluding all other lensed systems, in order to optimise the model specifically for A and B.
### Table A2. Best-fit `LENSTOOL` parameters of the fiducial lens model.

| First cluster-scale PIEMD halo |  |  |
|-------------------------------|--|--|
| $x$ ("') | $-1.420^{+0.314}_{-0.157}$  |
| $y$ ("') | $1.047^{+0.149}_{-0.109}$  |
| $\epsilon$ | $0.598^{+0.038}_{-0.005}$  |
| $\theta$ (deg) | $19.790^{+1.265}_{-0.268}$  |
| $r_c$ (kpc) | $35.941^{+0.814}_{-1.984}$  |
| $\sigma_v$ (km/s) | $986.284^{+4.338}_{-8.487}$  |

| Second cluster-scale PIEMD halo |  |  |
|-------------------------------|--|--|
| $x$ ("') | $-11.566^{+0.034}_{-0.014}$  |
| $y$ ("') | $5.729^{+0.001}_{-2.367}$  |
| $\epsilon$ | $0.429^{+0.067}_{-0.00}$  |
| $\theta$ (deg) | $100.856^{+3.853}_{-1.232}$  |
| $r_c$ (kpc) | $212.843^{+9.732}_{-28.724}$  |
| $\sigma_v$ (km/s) | $1078.762^{+5.161}_{-63.885}$  |

| Third cluster-scale PIEMD halo |  |  |
|-------------------------------|--|--|
| $x$ ("') | $29.401^{+0.629}_{-0.437}$  |
| $y$ ("') | $-8.171^{+0.719}_{-0.239}$  |
| $\epsilon$ | $0.453^{+0.009}_{-0.074}$  |
| $\theta$ (deg) | $8.895^{+3.891}_{-2.328}$  |
| $r_c$ (kpc) | $88.386^{+5.336}_{-6.954}$  |
| $\sigma_v$ (km/s) | $746.233^{+11.612}_{-18.050}$  |

| External Shear |  |  |
|----------------|---|---|
| $\gamma_{\text{shear}}$ | $0.334^{+0.031}_{-0.022}$  |
| $\theta_{\text{shear}}$ (deg) | $92.177^{+1.939}_{-1.357}$  |

| Galaxy members |  |  |
|----------------|---|---|
| $r^0_{g,t}$ (kpc) | $22.940^{+2.600}_{-2.848}$  |
| $\sigma^0_{g,v}$ (km/s) | $197.907^{+11.636}_{-11.880}$  |

### Table A3. Best-fit `LENSTOOL` parameters of the fine-tuned lens model.

| Third cluster-scale PIEMD halo |  |  |
|-------------------------------|--|--|
| $x$ ("') | $13.847^{+0.497}_{-9.301}$  |
| $y$ ("') | $-5.008^{+1.849}_{-1.849}$  |
| $\epsilon$ | $0.573^{+0.102}_{-0.099}$  |
| $\theta$ (deg) | $9.269^{+1.418}_{-1.431}$  |
| $r_c$ (kpc) | $97.114^{+3.834}_{-11.217}$  |
| $\sigma_v$ (km/s) | $799.654^{+4.018}_{-43.115}$  |

| Gm1 PIEMD halo |  |  |
|----------------|---|---|
| $r_{g,t}$ (kpc) | $28.104^{+22.0}_{-20.0}$  |
| $\sigma_{g,v}$ (km/s) | $203.412^{+68.590}_{-63.967}$  |

| Gm2 PIEMD halo |  |  |
|----------------|---|---|
| $r_{g,t}$ (kpc) | $24.369^{+26.0}_{-20.0}$  |
| $\sigma_{g,v}$ (km/s) | $210.705^{+61.428}_{-52.603}$  |

| Gm3 PIEMD halo |  |  |
|----------------|---|---|
| $r_{g,t}$ (kpc) | $7.272^{+12.8}_{-6.6}$  |
| $\sigma_{g,v}$ (km/s) | $83.873^{+28.112}_{-23.457}$  |

Positions $x$ and $y$ are relative to the position of the BCG at RA = 181.550648$^\circ$ and DEC = $-8.800952^\circ$, with positive offsets point to west and north. The first and second cluster-scale PIEMD halos, external shear, and galaxy members are fixed to their best-fit values from the fiducial model, as listed in Table A2.

Positions x and y are relative to the position of the BCG at RA = 181.550648$^\circ$ and DEC = $-8.800952^\circ$, with positive offsets point to west and north.
Table B1. Photometry from HST data, directly measured for each individual image without correcting for lensing magnification. The foreground Galactic extinction is corrected (see §4.1 for details).

|        | F330W<sup>a</sup> | F390W | F435W | F475W | F606W | F625W | F775W | F814W |
|--------|------------------|-------|-------|-------|-------|-------|-------|-------|
| A1     | 23.40 ± 0.08     | 23.35 ± 0.03 | 22.94 ± 0.02 | 22.42 ± 0.07 | 22.31 ± 0.01 | 22.21 ± 0.01 | 22.22 ± 0.01 |
| A2a    | 26.07 ± 0.13     | 25.47 ± 0.05 | 24.33 ± 0.03 | 24.05 ± 0.03 | 23.77 ± 0.02 | 23.72 ± 0.02 | 23.70 ± 0.01 |
| A2b    | 26.80 ± 0.09     | 24.22 ± 0.05 | 24.07 ± 0.03 | 23.53 ± 0.02 | 23.31 ± 0.02 | 23.19 ± 0.02 | 23.17 ± 0.01 |
| A2c    | 27.26 ± 0.32     | 23.78 ± 0.04 | 23.69 ± 0.03 | 23.22 ± 0.02 | 23.04 ± 0.02 | 22.98 ± 0.01 |               |
| A3a    | 26.59 ± 0.21     | 25.04 ± 0.07 | 24.67 ± 0.05 | 24.24 ± 0.08 | 24.09 ± 0.03 | 24.08 ± 0.03 | 24.05 ± 0.02 |
| A3b    | 27.85 ± 0.15     | 25.03 ± 0.10 | 24.52 ± 0.05 | 23.83 ± 0.02 | 23.70 ± 0.03 | 23.51 ± 0.03 | 23.43 ± 0.01 |
| A3c    | 26.49 ± 0.11     | 24.55 ± 0.08 | 24.23 ± 0.04 | 23.67 ± 0.02 | 23.54 ± 0.03 | 23.43 ± 0.03 | 23.39 ± 0.02 |

|        | F850LP | F105W | F110W | F125W | F140W | F160W |
|--------|--------|-------|-------|-------|-------|-------|
| A1     | 22.20 ± 0.02 | 22.22 ± 0.01 | 22.20 ± 0.01 | 22.21 ± 0.01 | 22.03 ± 0.01 | 21.86 ± 0.01 |
| A2a    | 23.67 ± 0.03 | 23.82 ± 0.02 | 23.86 ± 0.02 | 23.90 ± 0.02 | 23.73 ± 0.02 | 23.68 ± 0.02 |
| A2b    | 23.21 ± 0.03 | 23.20 ± 0.01 | 23.18 ± 0.01 | 23.21 ± 0.01 | 23.04 ± 0.01 | 22.92 ± 0.01 |
| A2c    | 23.01 ± 0.03 | 23.24 ± 0.02 | 23.26 ± 0.01 | 23.31 ± 0.02 | 23.14 ± 0.01 | 23.12 ± 0.01 |
| A3a    | 24.08 ± 0.05 | 24.16 ± 0.03 | 24.14 ± 0.02 | 24.22 ± 0.03 | 23.96 ± 0.02 | 23.86 ± 0.02 |
| A3b    | 23.29 ± 0.03 | 23.33 ± 0.01 | 23.30 ± 0.01 | 23.26 ± 0.01 | 23.10 ± 0.01 | 22.95 ± 0.01 |
| A3c    | 23.38 ± 0.03 | 23.54 ± 0.02 | 23.54 ± 0.01 | 23.59 ± 0.02 | 23.38 ± 0.02 | 23.15 ± 0.01 |

|        | F450W<sup>b</sup> | F475W | F606W | F625W | F775W | F814W | F850LP | F105W |
|--------|-------------------|-------|-------|-------|-------|-------|--------|-------|
| B1a    | 27.42 ± 0.32     | 26.48 ± 0.11 | 26.38 ± 0.16 | 26.95 ± 0.13 | 25.98 ± 0.09 | 25.82 ± 0.15 | 26.36 ± 0.13 |
| B1c    | 27.39 ± 0.27     | 26.34 ± 0.09 | 26.07 ± 0.11 | 25.78 ± 0.11 | 26.00 ± 0.08 | 26.23 ± 0.21 | 26.48 ± 0.14 |
| B1d    | 27.25 ± 0.41     | 26.41 ± 0.10 | 26.17 ± 0.13 | 26.14 ± 0.15 | 26.26 ± 0.11 | 26.15 ± 0.21 | 26.82 ± 0.19 |
| B1e    | 27.41 ± 0.25     | 26.17 ± 0.24 | 25.73 ± 0.09 | 25.62 ± 0.09 | 25.77 ± 0.07 | 25.63 ± 0.13 | 25.81 ± 0.09 |
| B2a    | 27.39 ± 0.27     | 27.04 ± 0.19 | 26.67 ± 0.21 | 26.40 ± 0.20 | 26.23 ± 0.10 | 26.78 ± 0.37 | 26.45 ± 0.14 |
| B2c    | 27.37 ± 0.27     | 26.74 ± 0.13 | 26.85 ± 0.24 | 26.37 ± 0.18 | 26.36 ± 0.12 | 25.97 ± 0.17 | 26.25 ± 0.12 |
| B2d    | 27.43 ± 0.27     | 26.69 ± 0.49 | 27.24 ± 0.22 | 27.41 ± 0.41 | 26.18 ± 0.17 | 26.48 ± 0.13 | 26.08 ± 0.20 | 26.97 ± 0.22 |
| B2e    | 27.24 ± 0.49     | 27.62 ± 0.29 | 27.22 ± 0.20 | 26.51 ± 0.19 | 26.93 ± 0.34 | 26.80 ± 0.18 | 26.56 ± 0.30 | 26.74 ± 0.20 |

|        | F110W | F125W | F140W | F160W |
|--------|-------|-------|-------|-------|
| B1a    | 26.41 ± 0.12 | 26.24 ± 0.13 | 26.41 ± 0.13 | 26.69 ± 0.17 |
| B1c    | 26.39 ± 0.09 | 26.44 ± 0.15 | 26.44 ± 0.13 | 26.30 ± 0.12 |
| B1d    | 26.39 ± 0.09 | 26.67 ± 0.19 | 26.77 ± 0.17 | 26.47 ± 0.14 |
| B1e    | 25.74 ± 0.10 | 25.97 ± 0.10 | 26.02 ± 0.11 | 26.26 ± 0.15 |
| B2a    | 26.39 ± 0.10 | 26.49 ± 0.16 | 26.29 ± 0.11 | 26.09 ± 0.10 |
| B2c    | 26.33 ± 0.09 | 26.22 ± 0.13 | 26.19 ± 0.10 | 26.00 ± 0.09 |
| B2d    | 26.84 ± 0.14 | 26.88 ± 0.23 | 26.68 ± 0.16 | 26.66 ± 0.16 |
| B2e    | 27.09 ± 0.10 | 26.36 ± 0.14 | 26.44 ± 0.15 | 26.45 ± 0.15 |

<sup>a</sup> 2σ UV flux upper limit, averaged among the F225W, F275W and F336W bandpasses.
<sup>b</sup> 2σ UV flux upper limit, averaged among the F225W, F275W, F336W, F390W and F435W bandpasses.
<sup>c</sup> 2σ flux upper limit.
Resolved galactic superwinds at $z > 3$

Figure C1. **Left:** Stacked spectra from all spaxels within the $3\sigma$ contour in System A, divided into northern and southern nebulae (see Figures 1 and 6). The best-fit models are shown in dash-dotted and dotted curves for the northern and southern nebula, respectively. To obtain the best-fit models, we fix the intrinsic Ly$\alpha$ line width $\sigma_i$ to be 125 km/s, corresponding to the observed ISM line width measured from the nebular emission lines (see §4.3 and Table 5). Compared with the best-fit models shown in Figure 10 in the main text where $\sigma_i$ is a free parameter, the models shown here with a fixed $\sigma_i$ provide a worse fit to the data (particularly on the blue peak), which is also reflected with the increased $\chi^2_\nu$. **Right:** Stacked spectral from low- and high-surface brightness regions in System B, extracted from within and outside of the $8\sigma$ contours. The best-fit models are shown in dash-dotted and dotted curves for low- and high-surface brightness spectra, respectively. Similar to the models for System A, we fix $\sigma_i$ to be 13 km/s as measured from the galaxy spectrum. Although these models with fixed $\sigma_i$ also provide a worse fit to the data compared with the models presented in Figure 10 where $\sigma_i$ is a free parameter, the difference in $\chi^2_\nu$ is not as significant as the difference seen in System A. This is consistent with System A having a steeper velocity gradient across the nebulae, leading to a more significant smearing effect in the stacked spectra from a large area.