Extended and broad Lyα emission around a BAL quasar at z ∼ 5

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Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT

In this work we report deep MUSE observations of a Broad Absorption Line (BAL) quasar at z ∼ 5, revealing a Lyα nebula with a maximum projected linear size of ∼ 60 kpc around the quasar (down to our 2-σ SB limit per layer of ∼ 9 × 10^{-19} erg s^{-1} cm^{-2} arcsec^{-2} for a 1 arcsec^2 aperture). After correcting for the cosmological surface brightness dimming, we find that our nebula, at z ∼ 5, has an intrinsically less extended Lyα emission than nebulae at lower redshift. However, such a discrepancy is greatly reduced when referring to comoving distances, which take into account the cosmological growth of dark matter (DM) haloes, suggesting a positive correlation between the size of Lyα nebulae and the sizes of DM haloes/structures around quasars. Differently from the typical nebulae around radio-quiet non-BAL quasars, in the inner regions (∼ 10 kpc) of the circumgalactic medium (CGM) of our source, the velocity dispersion of the Lyα emission is very high (FWHM > 1000 km s^{-1}), suggesting that in our case we may be probing outflowing material associated with the quasar.

Key words: quasars: emission lines – quasars: general – galaxies: haloes – cosmology: observations – (galaxies:) intergalactic medium

1 INTRODUCTION

The circumgalactic medium (CGM) is tightly linked to the evolutionary phases of galaxies, both by hosting the gas reservoir necessary to fuel star formation and also being subject to galactic feedback and recycling. Thus, observing the nature of the CGM and studying its interplay with the host galaxy, especially at high redshift, helps us to understand how galaxies evolve and how their evolution can influence (and be influenced by) the surrounding environment.

A common observational technique used to characterize the cold gas phase of the CGM has been the analysis of its absorption signatures along background sightlines (Hennawi et al. 2006; Prochaska & Hennawi 2009; Hennawi & Prochaska 2013; Farina et al. 2013; Bouché et al. 2013, 2016; Prochaska et al. 2017) which has provided important statistical constraints on several properties of the CGM (Adelberger et al. 2005; Steidel et al. 2010; Prochaska et al. 2013). However, this method is limited by the sparseness of bright background sources and by its one-dimensional nature, which precludes from capturing the spatial distribution of the CGM.

An alternative approach is to map the CGM through direct imaging of the Lyα line. Theoretical models suggest that three main mechanisms should be able to generate circumgalactic Lyα emission: cooling radiation of gravitationally heated gas (e.g., Haiman et al. 2000; Yang et al. 2006; Dijkstra & Loeb 2009), ultraviolet (UV) photons produced through shock mechanisms (Taniguchi & Shioya 2000; Mori et al. 2004), and recombination radiation following photoionization (often referred as fluorescence) powered by UV sources (Cantalupo et al. 2005; Geach et al. 2009; Kollmeier et al. 2010). While the fluorescent signal powered...
by the diffuse metagalactic UV background (Hogan & Weymann 1987; Binette et al. 1993; Gould & Weinberg 1996; Haardt & Madau 1996), with an expected surface brightness (SB) of $SB_{\text{LY}z} \sim 10^{-20}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$ (Cantalupo et al. 2005; Rauch et al. 2008), is still out of reach for current optical instrumentation (but see Gallego et al. 2017). Ly$\alpha$ fluorescence is predicted to be boosted up into the detectable regime in the vicinity of bright ionizing sources, as luminous quasars (Rees 1988; Haiman & Rees 2001; Alam & Miralda-Escudé 2002; Cantalupo et al. 2005). This theoretical prediction has been confirmed by a number of surveys targeting the fluorescent Ly$\alpha$ emission around luminous and radio-quiet quasars, using narrow-band (NB) filters on 8-meter class optical telescopes (e.g., Cantalupo et al. 2012, 2014; Martin et al. 2014; Arrigoni Battaia et al. 2016) and spectroscopic observations (e.g., Christensen et al. 2006; North et al. 2012; Herenz et al. 2015). However, these surveys have revealed giant Ly$\alpha$ nebulae, spanning distances from the quasar larger than 100 physical kpc (pkpc), only in less than 10% of the targets (e.g., Cantalupo et al. 2014; Hennawi et al. 2015; maximum projected linear sizes $>300$ pkpc), and emission on smaller scales ($R \lesssim 50 - 60$ pkpc) have been detected only in about 50% of the cases. This 50% detection rate is likely due to a combination of limits of the observational techniques, as for instance NB filter losses, spectroscopic slit losses, point spread function (PSF) losses and, most importantly, dilution of the signal of the Ly$\alpha$ line into the continuum flux (both background and from the host galaxy) encompassed by the width of the filter (see also Borisova et al. 2016 for a discussion).

Only recently, extraordinary advances have been made using the new Multi Unit Spectroscopic Explorer (MUSE; Bacon et al. 2010), a wide integral field spectrograph mounted on the ESO/VLT. The ability of MUSE in overcoming the technical limitations of previous observational techniques, combined with its large field of view ($1 \times 1$) have boosted the detection rate up to 100%, providing ubiquitous detections of Ly$\alpha$ nebulae with maximum projected linear sizes of $\sim 100$ pkpc around bright quasars at $3 < z < 4$ in only 1 hour observation per source (see Borisova et al. 2016 and Arrigoni-Battaia et al., in prep.).

In this study we exploit MUSE to extend the analysis of Ly$\alpha$ emission surrounding quasars towards higher redshifts and examine the nearly unexplored (within this context) class of Broad Absorption Line (BAL) quasars (another case has been recently reported by Arrigoni Battaia et al. 2018, i.e., SDSS J1020+1040 at $z = 3.167$). In particular, we report deep ($\sim 4$ h) MUSE observations of J1605-0112, a BAL quasar at $z \sim 4.92$. BALs are typically characterized by deep and blueshifted (by thousands km s$^{-1}$) broad absorption troughs associated with UV resonant lines (typically CIV and SiIV) tracing very fast outflows (e.g., Weymann et al. 1991; Maiolino et al. 2004; Dunn et al. 2010), and they are thought to mark a specific phase of galaxy evolution in which the quasar wind is particularly powerful.

We present our results in the following order. In Section 2 we describe our target, the basics steps of the data reduction processes, and the analysis performed to search for extended Ly$\alpha$ emission. In Section 3 we report the results of this work and in Section 4 a discussion of their implications. Conclusions are summarised in Section 5.

### Table 1. Summary of the properties of J1605-0112

| RA      | DEC     | Redshift | log($\lambda L_\alpha$) | BI(CIV) |
|---------|---------|----------|-------------------------|---------|
| J2000   | J2000   |          |                         |         |
| 16:05:01:2 | -01:12:20:6 | 4.92     | 46.46                   | 9300±200 |

[a] Rest-frame luminosity $\lambda L_\alpha$ at 1450 Å (Maiolino et al. 2003).
[b] Balnicity index of the CIV absorption (Maiolino et al. 2004).

#### 2 OBSERVATIONS AND DATA PROCESSING

J1605-0112, a radio-quiet quasar at $z = 4.92$, is one of the most extreme Low Ionization Lines-BAL (LoBAL) quasar in the Universe, both in terms of luminosity and in terms of depth and velocity of the absorption features (see Table 1). Indeed, the CIV $\lambda 1549$ Å absorption troughs are blueshifted by more than 30,000 km s$^{-1}$, tracing very high velocity outflowing gas, and have a balnicity index$^1$ of 9300 km s$^{-1}$ (see Maiolino et al. 2004). A full 1D spectrum obtained with MUSE and a discussion on the BAL features are reported in the Appendix A.

MUSE observations of J1605-0112 have been acquired as part of the ESO programme ID 095.A-0875 (PI: R. Maiolino) between May and August 2015 at the UT4 ESO/VLT. The collection of data was split into 5 observing blocks (OBs), each of them composed by 4 exposures of 850 s each, with the exposures rotated with respect to each other by 90 degrees. The total integration time on source was $\sim 4$ hours. Observations were carried out under good seeing conditions (FWHM $\sim 0.6$ arcsec) and airmass $< 1.5$. We achieve a SB limit of $5 \times 10^{-19}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$ ($\sigma$) for a 1 arcsec$^2$ aperture in a single wavelength layer (i.e., $1.25$ Å). The SB limit on a pseudo-NB image of 30 Å (a common size for filters used in the past NB surveys), obtained averaging 24 wavelength layers around the location of the Ly$\alpha$, is $\sim 3 \times 10^{-18}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$ ($\sigma$).

#### 2.1 Data reduction

Individual exposures have been processed with basic data reduction techniques using the standard ESO-MUSE pipeline v1.6 (Weilbacher et al. 2012, 2014). For each of them we performed bias subtraction, flat fielding, twilight and illumination correction, and wavelength calibration, using the MUSE_BIAS, MUSE_FLAT and MUSE_WAVECAL pipeline recipes. Following Borisova et al. (2016) we did not perform the sky subtraction using the pipeline receipt but we postponed this task to a later stage, as discussed below. We then registered the individual exposures using the position of point sources in the field; in this way we ensure an accurate relative position

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1 The balnicity index is similar to the Equivalent Width expressed in km s$^{-1}$, as defined in Weymann et al. (1991).

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astrometry, as shifts of a few tenths of arcsecs can occur owing to the spatial shifts introduced by the derotator wobble between exposures (Bacon et al. 2015). The next steps of the data-reduction process were performed with CubeFix and CubeSharp, custom tools for improved flat fielding correction and sky subtraction respectively, both parts of the CubExtractor software package (Cantalupo, in prep.). These tools, extensively described in Borisova et al. (2016) and Fumagalli et al. (2017), have been specifically developed to improve data quality for the detection of faint and diffuse emission in MUSE datacubes. As last step, we combined all the corrected and sky-subtracted datacubes and diffuse emission in MUSE datacubes. As last step, we developed to improve data quality for the detection of faint (2016) and Fumagalli et al. (2017), have been specifically parts of the fielding correction and sky subtraction respectively, both clip algorithm in the central 5x5 pixels region, to avoid any empirical PSF images is computed using an averaged-sigma-clip algorithm. At this point we created a white-light image (obtained by collapsing the datacube along the wavelength direction) of the combined datacube in order to identify the continuum sources. We used the positions and spectra of the detected continuum sources to perform another iteration of flat fielding correction and sky subtraction on individual exposures, before combining them again. One further iteration is enough to improve substantially the removal of self-calibration effects and data quality. The final datacube samples the instrument field of view (FOV) of 1x1 arcmin² in pixels of size 0.2 arcsec and, for each pixel, contains a spectrum covering the wavelength range 4750 − 9350Å in spectral bins of 1.25Å.

In the Appendix B we show the whole 1x1 arcmin² field of view of the final datacube. To check the accuracy of flux calibration we compared our final product with photometric data from the Sloan Digital Sky Survey (SDSS; Eisenstein et al. 2011) without finding any flux deviation within the errors for the few sources in common.

2.2 Data Analysis

2.2.1 PSF and continuum subtraction

Revealing extended Lyα structures around a quasar requires a proper subtraction of the PSF. Generally, accurate PSF removal is a substantial issue in the case of NB imaging and long-slit spectroscopy technique (e.g., Møller et al. 2000; Møller 2000; Weidinger et al. 2005), but here we take advantage of the Integral Field Spectroscopy (IFS), which provides images of the quasar and its surroundings at different wavelengths, including spectral regions where no extended line emission is expected, thus allowing for a careful PSF modelling.

To subtract the PSF contribution we adopt a purely empirical method successfully tested in Borisova et al. (2016), using CubePSFSub, part of the CubExtractor package (Cantalupo, in prep.). The algorithm consists in producing a pseudo-NB image with a spectral width of 150 spectral pixels (∼ 187Å) for each wavelength layer. In this way we construct empirical PSF images to be rescaled and subtracted at each wavelength layer. We rescale the flux in each empirical PSF image assuming that the quasar dominates the flux within a central region of 5x5 pixels (corresponding to 1x1 arcsec²). The rescaling factor between the flux in each layer and the empirical PSF images is computed using an averaged-sigma-clip algorithm in the central 5x5 pixels region, to avoid any possible contamination by cosmic rays or other sources of noise in the individual pixels. We then cut from the rescaled empirical PSF images a central circular region with a radius of ∼ 5 times the seeing. As a last steps, we mask any pixel with negative flux from this circular cut-out region, and we subtract it from the corresponding layer in the datacube. The spectral width of ∼ 187Å is a good compromise between minimizing the PSF variations within the waveband and maximizing the signal-to-noise ratio (SNR) in the empirical PSF images. We iterate the PSF removal procedure, masking the spectral interval associated with the nebulae to avoid over-subtraction. We also remove and mask continuum sources around the quasar, to be not affected by their residuals.

We note that, by construction, our PSF subtraction has uncertainties in the 1x1 arcsec² region used for the PSF rescaling, in particular due to the poor pixel sampling in the central region, where the nuclear emission has a very steep gradient. For this reason, any data on such scales are considered not reliable in the remaining of this work. We also note that our determination of the PSF may be potentially contaminated by the emission from the host galaxy in the central region used for the PSF modelling (see e.g., Fynbo et al. 1999, 2000 and Zafar et al. 2011 for a discussion). Indeed, the continuum emission from the host galaxy may affect the rescaling factor and cause systematic effects in the PSF subtraction. However, in our case, the high luminosity of the quasar (L1450Å ∼ 3 × 10³⁶ erg s⁻¹; AB magnitude in the i-band, i-mag = 19.75 2) in comparison to the expected luminosity of its host-galaxy at z ∼ 5, motivate our assumption that the quasar dominates the flux budget within the 1x1 arcsec² used for the PSF rescaling. In addition, as discussed in the Appendix A, within the deep CIV trough, we do not see any evidence for a prominent emission from the host galaxy, further supporting that the host galaxy does not contribute significantly to the observed emission.

As shown in the next Section, our empirical PSF subtraction method produces good results, unveiling low-SB flux around the quasar on large scales. After quasar PSF subtraction has been performed, we remove any other possible continuum sources for each spaxel in the cube using a fast median-filtering approach, following Borisova et al. (2016).

2.2.2 3D detection and extraction

We use the PSF-subtracted and continuum-subtracted cube for the detection and the extraction of extended line emissions. This task has been performed using CubExtractor (Cantalupo, in prep.), a 3D automatic extraction software based on a 3D extension of the connected-labelling-component algorithm with union finding of classical binary image analysis (e.g. Shapiro & Stockman 2001). We first extracted a sub-cube (Δλ ∼ 1000 Å) from the processed datacube with wavelength range containing the expected Lyo line and, before searching for detection, we apply a spatial gaussian filtering of 0.5 arcsec (without smoothing 2 Computed from our MUSE datacube with an aperture of 3 arcsec in diameter, assuming a SDSS i-band filter. This value is not corrected for intrinsic absorption.)
in wavelength) to bring out extended but narrow features. 

An object is detected if it contains a number of connected voxels (individual spatial and spectral elements in MUSE cube) above a user-defined threshold (we used a threshold of 10,000 connected voxels) above a minimum SNR of 2.5, after datacubing being smoothed. The 3D-segmentation-mask produced by CubExtractor is then used for photometry, optimally-extracted images, velocity and velocity dispersion maps.

3 RESULTS

Following the data processing steps described in Section 2 we detect a Lyα nebula, extended on circumgalactic scales around the quasar J1605-0112, at $z \sim 4.92$. The nebula has been detected with a threshold of 10,000 connected voxels, and the resulting “optimally extracted image”, obtained using the 3D-segmentation-mask produced by CubExtractor, is shown in Fig. 1. The black thick contour indicates the projection on the sky-plane of the 3D-mask, corresponding to a SB of $\sim 6 \times 10^{-15}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$.

A single spectral layer, corresponding to the central wavelength of the Lyα, has been added - by means of the union operator - to the 3D-mask for display purposes. The maximum spectral width defined in the 3D-mask corresponds to $\Delta \lambda = 38.75$ Å. The total Lyα flux, obtained integrating the 3D-mask along the wavelength and the spatial directions, is $F_{Ly\alpha} \sim 1.7 \times 10^{-16}$ erg s$^{-1}$ cm$^{-2}$, corresponding to a luminosity $L_{Ly\alpha} \sim 4.4 \times 10^{41}$ erg s$^{-1}$.

The Lyα emission projected on the sky-plane appears to extend over about 9 arcsec in RA and 8 arcsec in DEC, i.e., respectively 60 pkpc and 50 pkpc at this redshift. The position of the quasar is marked by the black dot, whose dimension indicates the region used to normalize the PSF for each layer, i.e., the spatial region where the flux is dominated by the quasar (see Paragraph 2.2.1). This image has been obtained selecting all the voxels detected by the 3D-segmentation-mask and integrating their fluxes along the wavelength direction.

Operationally speaking, this approach is equivalent to obtain various pseudo-NB images where the filter spectral size is optimized for each spaxel, to maximize the SNR of the object. However, noise estimation for an image obtained through this method is critical, as the noise associated to each spaxel depends on the number of layers that define it (i.e., the spectral size of pseudo-NB filter). This results in the optimally-extracted flux map being affected by a noise that depends on the spatial position. To address this issue, following Borisova et al. (2016), we estimated the noise and the SNR for each pixel in the map by propagating the variance and taking into account the number of layers contributing to each pixel. Using propagated variances and the integrated flux we then created the SNR contours represented by the white thin contours in Fig. 1.

In Fig. 2 we compare the Lyα profile of J1605-0112 with the Lyα profile of a region around the peak of the emission of the nebula (within an aperture of $\sim 1''$). The Lyα emitted by the nebula show a much narrower profile (FWHM $\sim 1000$ km s$^{-1}$) than the broad and complex Lyα profile coming from the BAL quasar. Given such a difference between the widths and shapes of the spectra, we are confident that the Lyα emission from the nebula emission in close proximity to the quasar cannot constitute a PSF subtraction residual.

It is worth stressing here that the “optimally extracted image” of the Lyα emission shown in Fig. 1 is different from a common standard NB image, because of the different number of spectral layers composing the pixels within the map. This type of approach, enabled by the IFU technique, allows us to reveal both kinematically narrow and broad features that would have been either lost in the noise or underestimated in a NB image with a single, fixed width. We also produced a ‘plain’ pseudo-NB image (i.e. by averaging a fixed number of spectral channels, without any tailoring) of the Lyα emission. To this aim, we average over 38.75 Å around the $\lambda_{Ly\alpha}$ (rest-frame), that is the maximum spectral width of the nebula as defined by the 3D-mask.
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Figure 2. Comparison of the Lyα line shapes between the BAL quasar J1605-0112 (blue line) and the peak of the detected Lyα nebula (green line) surrounding the quasar. The spectrum of the nebula has been extracted within a circular aperture of \( \sim 1'' \) radius centered around the peak of its emission from the PSF and continuum subtracted final datacube. Both spectra have been normalized to their maximum to facilitate the comparison. The Lyα emission of the nebula appears to be much narrower than the broad Lyα of the quasar J1605-0112, ensuring that the peak of the nebula close to the quasar position is not due to PSF residuals.

Figure 3. The circularly averaged SB profile (blue filled dots) of the Lyα nebula is shown as a function of the projected physical distance from J1605-0112. Open blue squares indicate negative values. Error bars represent 1σ errors on the mean SB level measured in a given annulus. The SB profile has been extracted using a pseudo-NB image centered at the wavelength corresponding to the Lyα of the quasar, with a fixed width of 38.75Å (see discussion in Sec. 3.1). The background flux level of the pseudo-NB image is consistent with zero. The grey shaded area is an estimate of the 2σ gaussian noise associated with the SB profiles. The pink shaded area is indicative of the 1x1 arcsec\(^2\) region used to rescale the empirical PSF models (see Sec. 2.2.1).

3.1 Surface brightness profile

We computed the circularly averaged SB profile of the Lyα nebula surrounding J1605-0112, at \( z = 4.92 \), by using the pseudo-NB image of Lyα, extracted as discussed above. The resulting profile, as a function of projected physical distance from the quasar, is presented in Fig. 3a (blue dots), where the expected 2-σ gaussian SB limit for each aperture is also shown (grey shaded area). To avoid the cosmological SB dimming effect and facilitate comparisons with similar objects at different redshifts, we computed the circularly averaged SB profile in units of SB\(\times(1+z)^4\), i.e., cosmologically invariant brightnesses. The resulting profile is shown in Fig. 4a, where the redshift of the quasar, \( z = 4.92 \), has been used as scaling value. Along with our results we also show the averaged profiles of two samples of quasars at redshift \( z \sim 3 - 4 \) (the mean redshift is \( z \sim 3.2 \) in both samples) by Borisova et al. (2016) and Arrigoni-Battaia et al. (in preparation) (violet and red solid lines respectively). Also these profiles are reported in cosmologically invariant SB units, using the mean redshift of the samples as scaling value.

Both Fig. 3 and Fig. 4a show that the circularly averaged SB radial profile of the nebula surrounding J1605-0112 extends up to \( \sim 30 \) pkpc from the quasar; the mean flux measured in annuli at larger radii is consistent with the noise (2-σ) limit. However, Fig. 4a shows that at distances consistent with the maximum extension of the radial profile of our nebula (\( \sim 30 \) pkpc), the sensitivity provided by our deep MUSE observations would be enough to detect with high SNR (\( \geq 5 \)) any more extended emission, such as that expected by the averaged radial profiles of similar quasars at lower redshift.

This suggests that the Lyα nebula detected in the surrounding of J1605-0112, at \( z \sim 5 \) is intrinsically smaller than typical Lyα nebulae observed with MUSE around luminous quasars at lower redshifts, \( z \sim 3 - 4 \). We stress that such size discrepancy is intrinsic and not an artefact of the cosmological SB dimming; indeed the radial profiles have been expressed in invariant units, rescaling the quantities with redshift as discussed above.

In Fig. 4b we report the same SB radial profiles of Fig. 4a, but in this case we show them as a function of the projected comoving distance from the quasar. Using comoving distances, instead of physical, we can account for the cosmological growth of DM haloes, whose virial radii, for a fixed halo mass, scale as \( \propto (1+z)^{-1} \) (Barkana & Loeb 2001). Fig. 4b shows that the intrinsic size discrepancy between our nebula at \( z \sim 5 \) and typical nebulae at \( z \sim 3 - 4 \) is greatly reduced, or even disappears, when referring to comoving distances from the quasar. This suggests that our nebula...
Figure 4. a) The radial profile shown in Fig. 3 here is expressed in units of $SB \times (1+z)^4$ to avoid the cosmological SB dimming effect. Redshift-corrected averaged profiles of two samples of quasars observed with MUSE at mean redshift $\sim 3.2$ (Borisova et al. 2016; Arrigoni-Battaia et al., in prep.) are also shown for comparison. With a maximum linear projected size of $\sim 30$ pkpc from the quasar, our nebula appears to be intrinsically smaller than typical nebulae observed around similar quasars at lower redshift. b) The same radial profile is shown as a function of the projected comoving distance from the quasar, to take into account the cosmological growth of dark matter haloes. In this case, the intrinsic size discrepancy revealed in Fig. 4a. is reduced (see Sec. 3.1 and Sec. 4 for an interpretation of such findings).

Figure 5. a) Velocity map traced by the Ly$\alpha$ emission around J1605-0112. The black circle indicates the position of the quasar. The velocity map does not show any clear evidence of rotation nor other coherent kinematic patterns, in line with similar recent MUSE observations at lower redshift (e.g., Borisova et al. 2016). However we note that, due to its res-
onant nature, Lyα is usually not a good tracer of kinematics as any coherence on 10 pkpc scales may be disrupted by radiative transfer effects (Cantalupo et al. 2005). In Fig. 5b we present the map of the second moment of the Lyα flux distribution, i.e., the velocity dispersion (for consistency with previous works in the literature we show the Gaussian-equivalent FWHM derived by multiplying the second moment by 2.35). The Lyα velocity dispersion map shows a particularly high broadening of the line (FWHM > 1000 km s$^{-1}$), especially in the inner regions of the CGM, at ~10 pkpc from the quasar. Such a high velocity dispersions are in contrast with previous MUSE observations by Borisova et al. (2016), which found narrower nebulae with FWHM ~ 500-700 km s$^{-1}$ surrounding 16 (out of 17) radio-quiet quasars, and are more similar to what found in nebulae around radio-loud systems (Borisova et al. 2016). Two notable exceptions are the nebula #6, surrounding J0124+0044 at z ~ 3.8 (Borisova et al. 2016), and the Enormous Lyman-Alpha Nebula (ELAN) surrounding J1020+1040 at z = 3.164 (Arrigoni Battaia et al. 2018), both showing a broad Lyα emission (FWHM ~ 1000 km s$^{-1}$) on similar scales (~ 10 kpc from the quasar) as for our nebula.

### 3.3 CIV/Lyα line ratio

After hydrogen Lyα line, CIV $\lambda 1549$ Å and HeII $\lambda 1640$ Å are the brightest UV lines found within quasar-powered nebulae, and their line ratios have been often used to constrain the ionisation parameter, gas density and metallicity, providing information on the origin and physical properties of the emitting gas (see Nagao et al. 2006; Arrigoni Battaia et al. 2015b,a; Prescott et al. 2015, and references therein). For instance, giant Lyα nebulae around high-z radio galaxies typically show high CIV/Lyα and HeII/Lyα (ratios $> 0.1$; see Villar-Martín et al. 2007), which are currently explained by high metallicity gas whose emission is driven by ionization and jet-ambient interaction. We searched only for possibly extended CIV within our MUSE datacube. We note that, at $z = 4.92$, the MUSE wavelength coverage does not enable us to study the HeII emission line. In order to search for spatially extended CIV emission we used the Lyα-defined 3D-mask produced by CubExtractor. Following the analysis of Borisova et al. (2016) we scanned spectral layers around the location of CIV, by shifting the mask along the wavelength direction of the PSF and continuum subtracted datacube. Using the same 3D-mask defined for the Lyα avoids any aperture effects in the line ratios. As the Lyα is expected to be intrinsically brighter and more extended than CIV, this approach gives us very conservative limits in case of non-detection. Considering the possibility of radiative transfer-induced velocity shift between the Lyα line emission and the CIV we have scanned spectral layers within a window of 3000 km s$^{-1}$ on both side of the expected CIV line. We then compute the total flux of the voxels associated with the 3D-mask at each spectral location.

With this approach we do not detect any CIV extended emission around J1605-0112, within a 1σ limit of SBC$_{3UV}$ (1σ) ~ 4.5 $\times$ 10$^{-18}$ erg s$^{-1}$ cm$^{-2}$. This yields a 2σ upper limit on the CIV/Lyα ratio of ~0.06, consistently with what found in the majority of radio-quiet quasars at lower redshifts (e.g., Borisova et al. 2016). In the Appendix D, we show a 30A-width NB image of the CIV, clearly showing that the CIV emission is undetected.

### 4 DISCUSSION

#### 4.1 The nebula small size relative to lower redshift nebulae observed with MUSE

With a maximum projected linear size of ~60 physical kpc (pkpc), the Lyα nebula around J1605-0112, at $z \sim 5$, appears to be smaller than typical nebulae ubiquitously detected with MUSE around quasars at lower redshifts ($z \sim 3-4$), extended on linear sizes larger than 100 pkpc, up to ~300 pkpc (see Borisova et al. 2016).

As discussed in Sec. 3.1, we verified that such a size discrepancy is not a trivial effect of the surface brightness (SB) cosmological dimming. Fig. 4a shows that, after correcting for the cosmological dimming effect (i.e., by expressing SB in units of SB$(1+z)^{-3}$), our ~5h on-source MUSE integration provides a sensitivity level such that we should detect with high SNR ($\gtrsim 5$) any typical emission at physical distances $\gtrsim 30$ pkpc from the quasar, which would be expected by the averaged radial profiles of similar nebulae at lower redshift. In the following we provide two different scenarios whose combination is most likely the correct way to interpret such a physical size discrepancy.

Cosmological theories of structure formation and, more in general the ΛCDM paradigm, predict that dark matter (DM) haloes collapsing at redshift $z$ have a (physical) virial radius $r_{vir} \propto M^{1/3}(1+z)^{-1}$ (e.g., Barkana & Loeb 2001). Thus, DM haloes at higher redshifts, if they remain in the same mass range, are smaller than DM haloes at lower redshifts. In Fig. 4b we showed the same SB dimming-corrected radial profiles shown in Fig. 4a, but as a function of projected comoving distance from the quasars. Expressing distances in comoving units, defined as $d_{com} = d_{phys} \times (1 + z)$, compensates the redshift evolution of virial radii accounting for the cosmological growth of DM haloes across the cosmic time. Fig. 4b shows that, when referring to comoving distances, the intrinsic size discrepancy between our nebula at $z \sim 5$ and typical nebulae at $z \sim 3-4$ is greatly reduced. This suggests that our nebula appears to be less extended because quasar hosting DM haloes at high redshift are smaller than haloes at lower redshifts, assumed that they are hosted on average by haloes with comparable masses in the redshift range 3-5.

Such a result would suggest a physical correlation between the size of Lyα nebulae and the sizes of DM haloes/structures around quasars. This conjecture is supported by the qualitative analysis of other observations of Lyα nebulae in an even wider redshift range. In Fig. 6 we report the sizes (maximum linear projected sizes) of a compilation of Lyα nebulae (including non-

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3 We updated the collection reported in the PhD thesis of Arrigoni-Battaia (Table 1.2; https://www.imprs-hd.mpg.de/49473/thesis_Arrigoni.pdf). The updated list includes data from: Heckman et al. (1991a,b); Bremer et al. (1992); Roettgering et al. (1997); van Ojik et al. (1996); Lehner & Becker (1998);
Other quasars (see Maiolino et al. 2004). In particular J1605-0112 requires a reddening $E_{B-V} = 0.03$ of SMC extinction curve in order to match the observed near-IR continuum slope (Reichard et al. 2003; Maiolino et al. 2004). This high reddening is often related to a high column density of dust in the circumnuclear medium around the Active Galactic Nucleus (AGN), able to efficiently absorb the AGN-powered UV photons, able to suppress the escape fraction of the ionizing radiation necessary to induce fluorescence in the neutral circumgalactic gas.

4.2 The origin of the high Lyα broadening
Although Lyα, due to its resonant nature, is not generally considered a good tracer of kinematics, the analysis of circumgalactic gas kinematics of the nebula surrounding J1605-0112, reported in Sec. 3.2, shows peculiar results. In particular the velocity dispersion map reported in Fig. 5b (where the gaussian-equivalent FWHM of the line is shown at each spatial location) shows a particularly high broadening of the line (FWHM $> 1000$ km s$^{-1}$), especially in the inner regions of the CGM, at $\sim 10$ kpc from the quasar, in agreement with the scales in Arrigoni Battaia et al. (2018). Such a high value of FWHM exceeds by a factor of $\sim 2$ the typical FWHM observed in other works. For instance Borisova et al. (2016) reported observations of narrower nebulae, e.g., with FWHM $\sim 500$-700 km s$^{-1}$, surrounding almost all the radio-quiet quasars in their sample (with the notable exception of the nebula #6, surrounding J0124+0044 at $z \sim 3.8$, showing a radial profile and a kinematics that looks similar to our nebula).

A possible interpretation of such high broadening of the Lyα line emission in the inner region of our nebula may be ascribed to the BAL nature of the quasar J1605-0112 (Maiolino et al. 2004). Indeed, the outflow inferred from the BAL features, may not be restricted to the circumnuclear region, but extend to large scales. For instance, based on a detailed spectral analysis of a few BAL quasars, Borguet et al. (2012) infer that in some cases the outflowing gas traced by the absorption troughs is distributed on scales of 10-30 kpc, hence revising the standard scenario in which BALs are only considered a good tracer of kinematics, the analysis of circumgalactic gas kinematics, the outflowing gas traced by the absorption troughs is distributed on scales of 10-30 kpc, hence revising the standard scenario in which BALs are only considered a good tracer of kinematics, the analysis of circumgalactic gas kinematics of the nebula surrounding J1605-0112, reported in Sec. 3.2, shows peculiar results. In particular the velocity dispersion map reported in Fig. 5b (where the gaussian-equivalent FWHM of the line is shown at each spatial location) shows a particularly high broadening of the line (FWHM $> 1000$ km s$^{-1}$), especially in the inner regions of the CGM, at $\sim 10$ kpc from the quasar, in agreement with the scales in Arrigoni Battaia et al. (2018). Such a high value of FWHM exceeds by a factor of $\sim 2$ the typical FWHM observed in other works. For instance Borisova et al. (2016) reported observations of narrower nebulae, e.g., with FWHM $\sim 500$-700 km s$^{-1}$, surrounding almost all the radio-quiet quasars in their sample (with the notable exception of the nebula #6, surrounding J0124+0044 at $z \sim 3.8$, showing a radial profile and a kinematics that looks similar to our nebula).

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Ly$\alpha$ emission projected on the sky-plane appears to extend over $\sim 8-9$ arcsec, i.e., $50-60$ kpc at $z = 4.92$ (Fig. 1);

(ii) after correcting for the cosmological surface brightness (SB) dimming, we compared the circularly averaged SB radial profile of our nebula with the averaged radial profiles of other nebulae at lower redshift, observed with MUSE. The profile of our Ly$\alpha$ nebula, at $z \sim 5$, shows a steeper slope than typical nebulae at lower redshifts and indicate a less extended gas distribution (Fig. 4a). It is important to note, however, that single nebulae at lower redshift show a large variability, also in terms of radial profiles;

(iii) the effect described in (ii) is greatly reduced when referring to comoving distances (Fig. 4b), which take into account the cosmological growth of dark matter (DM) haloes (whose virial radius is expected to evolve proportionally to $1/(1 + z)$). This suggests that the discrepancy between the Ly$\alpha$ extensions may be ascribed to the smaller size of DM haloes with comparable mass at higher $z$, implying an interesting empirical relation between the size of Ly$\alpha$ nebulae and sizes of DM haloes around quasars. This conjecture is supported by a qualitative analysis of other observations of Ly$\alpha$ nebula in a larger redshift range (see Fig. 6);

(iv) while the velocity map does not show any clear pattern (Fig. 5a; in line with similar observations at lower redshift), the velocity dispersion map shows a particularly high broadening of the line (FWHM $>1000$ km s$^{-1}$) in the inner regions of the nebula (Fig. 5b).

We suggest that (iii) and (iv) findings may be favoured by the BAL nature of the observed quasar. Indeed BAL quasars are characterized by redder continua with respect to non-BALs (e.g., Reichard et al. 2003; Maiolino et al. 2004) and this is often associated with high dust column densities in the circumnuclear regions around the AGN. Such a large dust content may efficiently absorb the UV photons emitted by the AGN and suppress the escape fraction of the ionizing radiation responsible for producing the Ly$\alpha$ fluorescence in the CGM, thus reducing the detectable size of Ly$\alpha$ nebulae. Moreover, BALs have been observed to experience powerful outflows and in particular LoBALs (as J1605-0112) show extremely deep troughs of low-ionization lines (e.g., Maiolino et al. 2004), indicative of very large columns of outflowing gas. This is consistent with BALs tracing a phase of quasar feedback particularly effective in ejecting gas (e.g., Dunn et al. 2010). In this light, the broad Ly$\alpha$ emission observed in the inner region (on $\sim 10$ kpc scales) around our BAL quasar may trace both highly turbulent circumgalactic gas as well as outflowing material escaped from the galaxy.

ACKNOWLEDGEMENTS

The authors would like to thank the anonymous referee for the useful comments. M. Ginolfi thanks F. G. Saturni for helpful discussions. The research leading to these results has received funding from the European Research Council (ERC) under the European Union’s Seventh Framework Programme (FP/2007-2013) / ERC Grant Agreement n. 306476. R. Maiolino acknowledges support from the ERC Advanced Grant 695671 ‘QUENCH’. R. Maiolino and S. Carniani acknowledge support from the Science and Technology Facilities Council (STFC). S. Cantalupo gratefully acknowledges support from Swiss National Science Foundation grant PP00P2_163824. The work is based on observations collected at the European Organisation for Astronomical Research in the Southern Hemisphere under ESO programme 095.B-0875(A). This research made use of ASTROPY, a community-developed core PYTHON package for Astronomy (Astropy Collaboration et al. 2013).

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APPENDIX A: MUSE SPECTRUM OF J1605-0112 AND ITS BAL FEATURES

In Fig. A1 we show the 1D spectrum of the BAL quasar J1605-0112, at \( z = 4.92 \). The spectrum has been extracted in a 1.5 arcsec radius circular aperture, containing most of the flux, consistently with SDSS. As visible from the spectrum, the deepest trough of the CIV, at \( \lambda_{obs} \sim 9070 \ \AA \), absorbs almost completely the light emitted by the quasar. In particular, using the spectral information of our MUSE observations, after computing a linear fit of the continuum emission in the wavelength range of the deep CIV trough, we estimate that the absorption leaves a residual flux which is only about 3% of the continuum emission at those wavelengths. Such a residual light in the deepest absorption trough is consistent with a BAL covering fraction of the order of unity (e.g., Elvis 2000). It is unlikely that such 3% residual emission is associated with the host galaxy as the radial profile is consistent with what observed in the quasar continuum outside the trough. Applying the same analysis to the other troughs of CIV, SiV, and NV, we found less extreme residual fluxes, ranging from 20% to 60%. A more detailed analysis of the emission in the BAL troughs is beyond the scope of this paper and we leave it for future works.

APPENDIX B: WHITE-LIGHT IMAGE

In Fig. B1 we show the whole 1x1 arcmin² field of view of the final datacube as a “white-light” image, obtained by collapsing the datacube along the wavelength direction.

APPENDIX C: PSEUDO-NB IMAGE OF THE LYα EMISSION

In Fig. C1 we show a pseudo-NB image of the Lyα emission, obtained by averaging 38.75 \( \AA \) (i.e., the maximum spectral width of the nebula as defined by the 3D-mask) around the rest-frame wavelength of Lyα (see Table 2).
Extended and broad Lyα emission at $z \sim 5$

Figure A1. One-dimensional spectrum of J1605-0112 obtained with MUSE. The spectrum has been extracted in a 1.5 arcsec radius circular aperture, containing most of the flux. The red lines indicate the location of UV emission lines, e.g., Lyα, NV, SiV, CIV.

Figure B1. White-light image of the whole 1x1 arcmin$^2$ FOV of the final datacube. The red circle indicates the position of the quasar.

Figure C1. Pseudo-NB image of the Lyα emission around J1605-0112, centered at the wavelength corresponding to the Lyα of the quasar, with a width coincident with the maximum spectral width of the nebula as defined by the 3D-mask, i.e., 38.75Å. To facilitate the comparison, the data are shown on the same scale of Fig. 1.

Figure D1. NB image of the CIV emission around J1605-0112, obtained by averaging 30Å around the CIV central wavelength (rest-frame 9170Å). The CIV emission is clearly undetected.

APPENDIX D: NON-DETECTION OF CIV EMISSION

In Fig. D1 we show a pseudo-NB image of the CIV emission, obtained by averaging 30Å around the CIV central wavelength (rest-frame 9170Å). It is evident that the CIV emission is undetected.

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