



HAL
open science

MusE GAs FLOW and Wind (MEGAFLOW) IV: A two sightline tomography of a galactic wind

Johannes Zabl, Nicolas F. Bouché, Ilane Schroetter, Martin Wendt, Thierry Contini, Joop Schaye, Raffaella A. Marino, Sowgat Muzahid, Gabriele Pezzulli, Anne Verhamme, et al.

► **To cite this version:**

Johannes Zabl, Nicolas F. Bouché, Ilane Schroetter, Martin Wendt, Thierry Contini, et al.. MusE GAs FLOW and Wind (MEGAFLOW) IV: A two sightline tomography of a galactic wind. Monthly Notices of the Royal Astronomical Society, 2020, 492 (3), pp.4576-4588. 10.1093/mnras/stz3607 . hal-02431453

HAL Id: hal-02431453

<https://hal.science/hal-02431453v1>

Submitted on 27 May 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

MusE GAs FLOW and Wind (MEGAFLOW) IV. A two sightline tomography of a galactic wind

Johannes Zabl¹,^{*} Nicolas F. Bouché,¹ Ilane Schroetter,² Martin Wendt³,⁴ Thierry Contini,⁴ Joop Schaye⁵,⁶ Raffaella A. Marino,⁶ Sowgat Muzahid,⁵ Gabriele Pezzulli⁶,⁶ Anne Verhamme⁷ and Lutz Wisotzki⁸

¹Univ Lyon, Univ Lyon1, Ens de Lyon, CNRS, Centre de Recherche Astrophysique de Lyon UMR5574, F-69230 Saint-Genis-Laval, France

²GEPI, Observatoire de Paris, CNRS-UMR8111, PSL Research University, Univ. Paris Diderot, 5 place Jules Janssen, F-92195 Meudon, France

³Institut für Physik und Astronomie, Universität Potsdam, Karl-Liebknecht-Str. 24/25, D-14476 Golm, Germany

⁴Institut de Recherche en Astrophysique et Planétologie (IRAP), Université de Toulouse, CNRS, UPS, F-31400 Toulouse, France

⁵Leiden Observatory, Leiden University, PO Box 9513, NL-2300 RA Leiden, the Netherlands

⁶Department of Physics, ETH Zürich, Wolfgang-Pauli-Strasse 27, CH-8093 Zürich, Switzerland

⁷Observatoire de Genève, Université de Genève, 51 Ch. des Maillettes, CH-1290 Versoix, Switzerland

⁸Leibniz-Institut für Astrophysik Potsdam (AIP), An der Sternwarte 16, D-14482 Potsdam, Germany

Accepted 2019 December 19. Received 2019 December 9; in original form 2019 August 2

ABSTRACT

Galactic outflows are thought to eject baryons back out to the circumgalactic medium. Studies based on metal absorption lines (Mg II in particular) in the spectra of background quasars indicate that the gas is ejected anisotropically, with galactic winds likely leaving the host in a bi-conical flow perpendicular to the galaxy disc. In this paper, we present a detailed analysis of an outflow from a $z = 0.7$ ‘green-valley’ galaxy [$\log(M_*/M_\odot) = 9.8$; $\text{SFR} = 0.5 M_\odot \text{yr}^{-1}$] probed by two background sources from the MusE GAs FLOW and Wind (MEGAFLOW) survey. Thanks to a fortuitous configuration with a background quasar (SDSSJ1358 + 1145) and a bright background galaxy at $z = 1.4$, both at impact parameters of ≈ 15 kpc, we can – for the first time – probe *both* the receding and approaching components of a putative galactic outflow around a distant galaxy. We measure a significant velocity shift between the Mg II absorption from the two sightlines ($84 \pm 17 \text{ km s}^{-1}$), which is consistent with the expectation from our simple fiducial wind model, possibly combined with an extended disc contribution.

Key words: galaxies: evolution – galaxies: haloes – intergalactic medium – quasars: absorption lines – quasars: individual: SDSSJ1358 + 1145.

1 INTRODUCTION

Galaxies are surrounded by a complex multiphase medium, the circumgalactic medium (CGM; Tumlinson, Peebles & Werk 2017 for a recent review). Accretion from this CGM on to galaxies and winds from the galaxies into the CGM are believed to be key ingredients in regulating the evolution of galaxies.

The detailed study of absorption features detected in bright background sources is one of the main observational tools helpful in characterizing the physical properties and kinematics of the CGM gas. Among various transitions, the Mg II $\lambda\lambda 2797, 2803$ doublet is an especially useful tracer of the cool, photoionized component of the CGM ($T \approx 10^4 - 5 \text{ K}$; e.g. Bergeron & Stasińska 1986). Its strength, easy identifiability as a doublet, and convenient rest-frame wavelength have allowed the collection of large statistical samples

of Mg II absorbers (e.g. Lanzetta, Turnshek & Wolfe 1987; Steidel & Sargent 1992; Nestor, Turnshek & Rao 2005; Zhu & Ménard 2013) at redshifts $0.1 \lesssim z \lesssim 2.5$. Follow-up observations of the fields surrounding the absorbers have identified galaxies associated with the absorbers and, hence, clearly established that the Mg II absorbing gas is found in the haloes of galaxies (e.g. Bergeron 1988; Bergeron & Boissé 1991; Steidel 1995; Steidel et al. 2002; Nielsen et al. 2013a; Nielsen, Churchill & Kacprzak 2013b).

Subsequently, large observational efforts have been put into mapping the spatial distribution and kinematics of the Mg II absorbing gas w.r.t. the galaxies in whose haloes the gas resides. The major result from these studies is that the Mg II absorbing gas is not isotropically distributed around the galaxies (e.g. Bordoloi et al. 2011; Bouché et al. 2012; Kacprzak, Churchill & Nielsen 2012; Lan, Ménard & Zhu 2014; Lan & Mo 2018; Martin et al. 2019; Schroetter et al. 2019; Zabl et al. 2019). Instead, the observations support a two-component geometry: a bi-conical outflow perpendicular to the galaxy disc and an extended gas disc approximately co-planar with

* E-mail: johannes.zabl@univ-lyon1.fr

the stellar disc. This allows to split the Mg II absorber sightlines into an outflow and a disc sub-sample, which can be used to study the kinematics of the outflows (e.g. Bouché et al. 2012; Kacprzak et al. 2014; Muzahid et al. 2015; Schroetter et al. 2015, 2016, 2019; Rahmani et al. 2018b; Martin et al. 2019) and the extended gas accretion discs (e.g. Steidel et al. 2002; Chen, Kennicutt & Rauch 2005; Kacprzak et al. 2010, 2011b; Bouché et al. 2013, 2016; Ho et al. 2017; Rahmani et al. 2018a; Zabl et al. 2019; Ho & Martin 2020), respectively.

The aforementioned results have been obtained statistically by collecting single sightlines around *many galaxies*. A step forward would be to map the geometry of the CGM around *individual galaxies* directly. Such ‘tomography’ requires multiple or very extended bright background sources behind the CGM of an individual galaxy.

Taking advantage of the comparably large extent that galaxies in the local Universe span on the sky, Bowen et al. (2016) have used four different background quasars to firmly conclude for an individual galaxy that the absorbing gas is distributed in an extended gas disc. However, having multiple sufficiently bright background galaxies covering the halo of a single galaxy is rare, especially at high redshift where the virial radius corresponds to a fraction of an arcminute.

The few studies beyond the local Universe were either using quasars by chance aligned close to each other (e.g. D’Odorico et al. 1998; Crighton et al. 2010; Muzahid 2014), multiple imaged lensed-quasar pairs (e.g. Lopez et al. 1999, 2007; Rauch, Sargent & Barlow 1999; Ellison et al. 2004; Rubin et al. 2018), or extended galaxies (e.g. Péroux et al. 2018; Lopez et al. 2018, 2020). The main focus of these studies was to characterize the coherence scale of the absorbing gas.

In this paper, we present a tomographic study of the CGM around a $z = 0.70$ galaxy surrounded by two bright background sightlines that was discovered in the MusE GAs FLOW and Wind (MEGAFLOW) survey (Schroetter et al. 2016, paper I; Schroetter et al. 2019, paper III; Zabl et al. 2019, paper II). This survey consists of 79 strong MgII absorbers towards 22 quasar sightlines that have been selected to have (at least) three Mg II absorbers with rest-frame equivalent widths $EW_0^{\lambda 2796} > 0.3 \text{ \AA}$ and $0.4 < z_{\text{abs}} < 1.5$.

The paper is organized as follows. We present our observations in Section 2, the galaxies and absorption sightlines in the field in Section 3, and a model for the CGM in Section 4. We compare this CGM model to our data and discuss our results in Section 5. Finally, we present our conclusions in Section 6. Throughout, we use a 737 cosmology ($H_0 = 70 \text{ km s}^{-1}$, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$) and we state all distances as ‘proper’ (physical) distances. A Chabrier (2003) stellar initial mass function (IMF) is assumed. We refer to the [O II] $\lambda\lambda 3727, 3729$ doublet simply as [O II]. All wavelengths and redshifts are in vacuum and are corrected to a heliocentric velocity standard.

2 OBSERVATIONS

2.1 MUSE data

We observed the field around the quasar SDSSJ1358+1145 with MUSE (Multi Unit Spectroscopic Explorer; Bacon et al. 2006, 2010) for a total integration time of 3.11 h. The first four exposures ($4 \times 1500 \text{ s} = 1.67 \text{ h}$; 2016-04-09), which constitute the data used in papers II and III, were taken with the nominal wide-field mode without adaptive optics (AOs; WFM-NOAO-N), as MUSE’s AO system was not yet available at the time. After identifying the science case of this work, we realized a potential benefit from

using MUSE’s extended mode for subsequent observations of the field. Therefore, we completed the observations in extended wide-field mode, while additionally taking advantage of the available AO ($4 \times 1300 \text{ s} = 1.44 \text{ h}$; 2018-03-14; WFM-AO-E). Extended mode increases the blue wavelength coverage from 4750 \AA to 4600 \AA with the trade-off of some second-order contamination at wavelengths $\gtrsim 8000 \text{ \AA}$. The extra coverage helps to better constrain the continuum around Mg II $\lambda 2796$ at $z = 0.704$, the redshift of the foreground galaxy whose CGM we study in this work.

We reduced the data identically to paper II, except that we were using DRSv2.4 (Weilbacher et al. 2012, 2014; Weilbacher, Streicher & Palsa 2016), which allows for the reduction of the AO data. The combined AO and non-AO data have a point source Moffat full width at half-maximum (FWHM) of 0.55 arcsec at 7050 \AA . Using the depth estimator from paper II, the exposure time (3.11 h) and the seeing results in an [O II] point source detection limit of $2.7 \times 10^{-18} \text{ erg s}^{-1} \text{ cm}^{-2}$.¹

2.2 UVES data

We observed the quasar SDSSJ1358+1145 with the VLT high-resolution spectrograph UVES (Ultraviolet and Visual Echelle Spectrograph; Dekker et al. 2000) for a total integration time of 2966 s in the night of 2016-04-07. Further details about observation, reduction, and continuum normalization are given in paper II.

3 RESULT

3.1 Identification of background sightlines

The main galaxy at $z = 0.704$ (*main*) was discovered through association with an $EW_0^{\lambda 2796} = 2.5 \text{ \AA}$ Mg II absorber towards the quasar SDSSJ1358+1145 from MEGAFLOW at an impact parameter of $b = 2.3 \text{ arcsec}$ (16.8 kpc).

This quasar sightline is particularly interesting, as it contains two additional very strong Mg II absorbers with a rest-frame equivalent width $EW_0^{\lambda 2796} = 1.8$ and 2.6 \AA at redshifts $z_{\text{abs}} = 0.81$ and 1.42 , respectively. The galaxy counterparts of the $z_{\text{abs}} = 0.81$ and $z_{\text{abs}} = 1.42$ absorbers have been described in paper III (wind sample) and paper II (accretion sample), respectively. They are galaxies with $\log(M_*/M_\odot)$ of 9.3 and 9.9, and are at relatively small impact parameters of 1.6 and 3.6 arcsec from the quasar, as also expected from the known Mg II EW–impact parameter anticorrelation (e.g. Lanzetta & Bowen 1990; Bouché et al. 2006; Chen et al. 2010; Kacprzak et al. 2011a; Nielsen et al. 2013b). We refer to these galaxies in the following as *back2* and *back1*, respectively.

Thus, together with the quasar, the *main* ($z = 0.704$) galaxy has potentially three background sightlines (quasar, *back1*, and *back2*) that can probe the CGM kinematics. In addition to the quasar, *back1* is a useful background source, as it has a very bright UV continuum.² *back2* is not a useful background source, due to intractable contamination from the close-by quasar. The orientation of all three sightlines w.r.t. the $z = 0.704$ galaxy is shown in Fig. 1(A) and listed in Table 1. The listed errors are resulting from

¹The estimate is for $\approx 7000 \text{ \AA}$. The detection limits are higher at shorter and longer wavelengths (see e.g. Bacon et al. 2017).

²The full spectral energy distribution (SED) of the $z = 1.42$ *back1* galaxy is shown in the Supplementary Appendix of paper II. The galaxy has an $M_{2800 \text{ \AA}}$ absolute total magnitude of -20.8 , which is slightly brighter than the characteristic Schechter magnitude at its redshift (Dahlen et al. 2007).

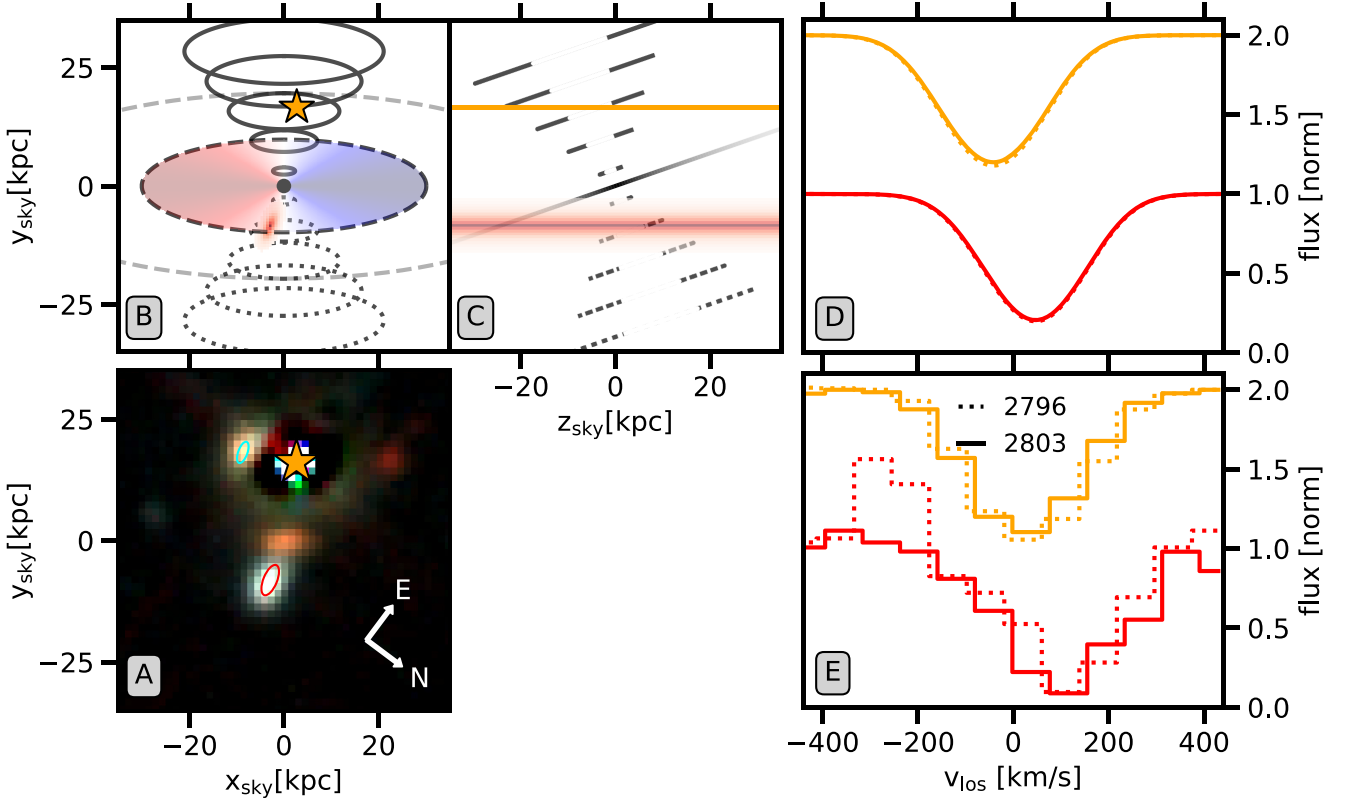


Figure 1. Comparison between data and model for the Mg II absorption seen in the MUSE spectrum for two sightlines through the CGM of the *main* galaxy. (A) 9.8 arcsec \times 9.8 arcsec field, corresponding to 70 kpc \times 70 kpc at $z = 0.70$, around the *main* foreground galaxy shown as colour image with pseudo z' , r' , V broad-band MUSE images in the red, green, and blue channels, respectively. The quasar was subtracted, but residuals are visible. The *main* foreground galaxy (centre) is surrounded by three bright background sources: the quasar towards the top (orange star), the bright galaxy towards the bottom (*back1*; red ellipse), and the second galaxy close to the quasar (*back2*; cyan ellipse). (B) View of the assumed CGM model (see Section 4) on the sky plane. The approaching outflow cone is indicated as solid concentric circles, while the receding outflow cone is indicated by dotted circles. For the extended gas disc, the rotation line-of-sight velocity field is overlaid. The orientation is identical to (A) and the positions of the quasar and *back1* are indicated by the orange dot and the red surface-brightness ellipse, respectively. (C) Geometry of the same model as in B, but here with the line-of-sight direction on the x -axis. The point-source sightline for the quasar (orange) and the extended sightline for *back1* (red) are indicated. The cone is hollow in the inner part. (D) Mg II $\lambda\lambda 2796, 2803$ line-of-sight kinematics simulated at the resolution of MUSE based on the model shown in (B) and (C) and described in Section 5.3 for the quasar (orange; offset by +1) and *back1* (red) sightlines, respectively. Both the 2796 and 2803 Å lines of the Mg II doublet are shown (dotted/solid; almost identical). The model parameters are listed as ‘disc+wind’ model in Table 4. (E) Mg II line-of-sight kinematics measured with MUSE in the background quasar (orange; offset by +1) and galaxy spectra (red), respectively. The zero-velocity corresponds to the systemic redshift of the *main* galaxy ($z = 0.70344$) as measured from the [OII] emission.

Table 1. Geometrical orientation of the system. (1) Background object ID; (2) redshift; (3) impact parameter measured from *main* $z = 0.70$ foreground galaxy (kpc at redshift of *main*); (4) azimuthal angle w.r.t. the major axis of *main* (deg); (5) magnitude in 1 arcsec diameter aperture measured in pseudo-V filter created from MUSE data.

Object	z	b	α	m_V
(1)	(2)	(3)	(4)	(5)
Quasar	1.484	16.8 ± 0.7	81 ± 8	18.5
Back1	1.417	8.8 ± 0.7	-109 ± 9	24.7
Back2	0.809	20.5 ± 0.7	115 ± 8	24.0

the uncertainties on position angle and centroid of the *main* galaxy (cf. Section 3.2 and Appendix A).

3.2 The main galaxy’s properties

The spectrum of the main $z = 0.704$ galaxy is shown in Fig. 2. The galaxy shows visibly weaker line emission than is typical

for star-forming galaxies on the star-forming ‘main sequence’ (MS) at this redshift (e.g. Speagle et al. 2014; Boogaard et al. 2018). Quantitatively, we found the galaxy to have a stellar mass of $\log(M_*/M_\odot) = 9.8^{+0.4}_{-0.0}$ and a star formation rate (SFR) of $0.5^{+0.3}_{-0.2} M_\odot \text{ yr}^{-1}$.

The corresponding specific SFR (sSFR = $0.07 \pm 0.06 \text{ Gyr}^{-1}$) is $-0.6^{+0.2}_{-0.6}$ dex (or $\approx 1.5\sigma$) below the MS prediction for $z = 0.70$ (Boogaard et al. 2018). This means our galaxy is similar to ‘green valley’ galaxies.

We determined the stellar mass and SFR as in paper II. In short, we estimated M_* from SED fitting using our custom code CONECTO (see also Zabl et al. 2016) on 13 pseudo-medium band filters created from the MUSE spectrum.³ Other values obtained from the SED fit are listed in Table 2. The (instantaneous) SFR was determined starting from the measured [OII] flux, correcting it for extinction

³Different from paper II, we assumed a delayed τ star formation history [SFH; $\text{SFR} \propto t \times \exp(-t/\tau)$], with t being the elapsed cosmic time since the galaxy started forming stars.

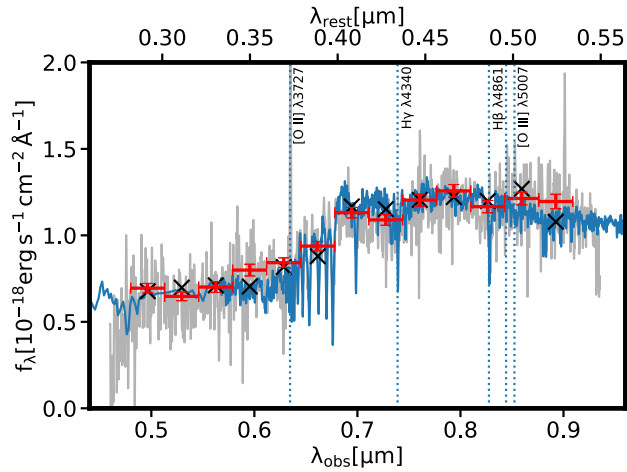


Figure 2. Best-fitting SED model (blue) for the main foreground galaxy compared to the observed spectrum (grey, smoothed with $\text{FWHM} = 8.8 \text{ \AA}$ Gaussian). The fit was done using pseudo-photometry for 13 medium-band filters created from the spectrum itself. The red errorbars indicate the filter-averaged flux densities in these filters, with the horizontal bars indicating the width of the filters. The black crosses show the flux-densities in the same filters as obtained from the best-fitting SED. While the SED fitting was done including emission lines and the shown model medium band flux-densities include this contribution, the best-fitting SED is shown without the emission to avoid visual confusion with the actual emission lines.

using the Calzetti et al. (2000) law with the strength of the extinction estimated from the $M_* - E(B - V)$ relation of Garn & Best (2010), and converted to an SFR using the Kewley, Geller & Jansen (2004) relation.

We estimated the [OII] flux from a fit to the [OII] morphokinematics using the 3D fitting tool GALPAK3D (Bouché et al. 2015). This fit provided us also with a best-fitting estimate of the kinematics (see Table 2). The steps involved in the GALPAK3D fitting were again identical to those described in paper II. However, as the [OII] flux is low for this galaxy, it was not possible to robustly measure the kinematics and morphology (inclination in particular) based on [OII] alone.⁴ Thus, we decided to constrain the inclination, i , using a continuum map in a pseudo r -band image created from the MUSE cube. We determined the galaxy morphology, including i and position angle, PA, from this continuum map using GALFIT (Peng et al. 2010). Further, we used the appropriate Moffat point spread function (PSF) for the r band as determined from the quasar. The fit was complicated by systematic residuals from the close-by quasar. Nevertheless, we could obtain a robust estimate of $i = 71 \pm 5$ deg and $PA = 37 \pm 8$ deg. Details about the fit and the method to estimate the uncertainties are given in Appendix A. Finally, we fit the [OII] kinematics with GALPAK3D using i and the PA as obtained from the continuum ($i = 71$ deg, $PA = 37$ deg).

3.3 Absorption in CGM of the main galaxy

The CGM around the $z = 0.704$ main galaxy can be probed in absorption at multiple locations using the spectra of the background quasar and the *back1* galaxy. While high spectral resolution spectroscopy is only available for the quasar, we can use the MUSE data cube to probe Mg II absorption with the same spectral resolution in both sightlines.

⁴This is the reason why the galaxy was not part of the sample in paper III.

Table 2. Physical properties of the foreground galaxy (*main*). For further details, see Section 3.2 and paper II. (1) [OII] flux obtained from GALPAK3D fit; (2) nebular extinction from $E(B - V) - M_*$ relation; (3) nebular extinction from SED fit; (4) instantaneous SFR from 1 and 2; (5) instantaneous SFR from SED fit; (6) stellar mass from SED fit; (7) rest-frame B absolute magnitude from best-fitting SED model; (8) distance from the MS (assuming MS from Boogaard et al. 2018); (9) age of galaxy from SED fit (time since onset of star formation); (10) decay time in delayed τ SFH from SED fit; (11) rotation velocity from GALPAK3D fit; (12) velocity dispersion from GALPAK3D fit; (13) virial velocity from $v_{\text{vir}} = v_{\text{max}}/(1.1 \pm 0.3)$; (14) virial radius from v_{vir} ; (15) virial mass from v_{vir} ; (16) virial mass from abundance matching (Behroozi, Conroy & Wechsler 2010); (17) escape velocities at position of quasar/*back1* sightline assuming a truncated isothermal sphere.

Row	Property	Value	Unit
(1)	$f_{[\text{OII}]}$	$(1.5 \pm 0.1) \times 10^{-17}$	$\text{erg s}^{-1} \text{cm}^{-2}$
(2)	$E(B - V) (M_*)$	$0.24_{-0.09}^{+0.12}$	mag
(3)	$E(B - V) (\text{SED})$	$0.00_{-0.00}^{+0.42}$	mag
(4)	SFR ($f_{[\text{OII}]}$)	$0.5_{-0.2}^{+0.3}$	$M_{\odot} \text{yr}^{-1}$
(5)	SFR (SED)	$0.3_{-0.0}^{+9.6}$	$M_{\odot} \text{yr}^{-1}$
(6)	M_* (SED)	$9.8_{-0.0}^{+0.4}$	$\log(M_{\odot})$
(7)	B	-19.6	mag
(8)	$\delta(MS)$	$-0.6_{-0.6}^{+0.2}$	dex
(9)	age	$9.5_{-0.3}^{+0.0}$	$\log(\text{yr})$
(10)	τ	$8.7_{-0.1}^{+0.6}$	$\log(\text{yr})$
(11)	v_{max}	118 ± 21	km s^{-1}
(12)	σ_0	38 ± 15	km s^{-1}
(13)	v_{vir}	107_{-30}^{+44}	km s^{-1}
(14)	r_{vir}	120_{-34}^{+50}	kpc
(15)	M_{vir} (from M_*)	$11.6_{-0.1}^{+0.2}$	$\log(M_{\odot})$
(16)	M_{vir} (from kin.)	$11.5_{-0.4}^{+0.5}$	$\log(M_{\odot})$
(17)	v_{esc} (quasar/ <i>back1</i>)	$261 / 287$	km s^{-1}

3.3.1 Mg II absorption at the resolution of MUSE

Mg II is the strongest among the CGM metal absorption lines covered by the MUSE data at this redshift, and hence, the most useful to probe the CGM with low signal-to-noise ratio (S/N) background galaxy sightlines. We show in Fig. 1(E) the observed $z = 0.704$ Mg II absorption for both the quasar (orange) and *back1* (red) sightlines (Mg II $\lambda 2796$ -dotted-, Mg II $\lambda 2803$ -solid-). The figure shows that Mg II absorption is not only visible in the quasar sightline ($\text{EW}_0^{\lambda 2796} = 2.7 \text{ \AA}$), as per selection, but also in the *back1* sightline ($\text{EW}_0^{\lambda 2796} = 2.0 \text{ \AA}$).

Despite the moderate spectral resolution (190 km s^{-1} at 4700 \AA), the absorption profiles encode interesting information. First, a velocity shift is clearly visible between the two sightlines. The absorption in the *back1* galaxy sightline is redshifted w.r.t. that in the quasar sightline by $84 \pm 17 \text{ km s}^{-1}$, with the absorption in the two sightlines centred at 110 ± 17 and $25.8 \pm 0.4 \text{ km s}^{-1}$, respectively. We obtained these velocity measurements by simultaneously fitting both components of the Mg II doublet with Gaussians. Secondly, we measured a $\text{EW}_0^{\lambda 2796} / \text{EW}_0^{\lambda 2803}$ ratio close to one in both sightlines. This means the Mg II absorption is strongly saturated.⁵ Thirdly, we find that the flux reaches almost zero at peak absorption. For both sightlines, this means, when accounting for the resolution of MUSE, that the Mg II absorption is spread over a large velocity range. For

⁵The $\text{EW}_0^{\lambda 2796} / \text{EW}_0^{\lambda 2803}$ ratio for optically thin absorption is 2:1.

the extended galaxy sightline (*back1*), this further means that the Mg II coverage must be complete over the extent of the aperture from which we have extracted the background spectrum. The non-circular extraction aperture, which was chosen to optimize the S/N, included 29 spatial pixels corresponding to an area of 1.2 arcsec².

3.3.2 Absorption at the resolution of UVES

In the previous section, we compared Mg II absorption along both the galaxy and the quasar sightline at the same moderate spectral resolution of MUSE. For the quasar sightline, we can use the high spectral resolution UVES spectrum (8 km s⁻¹) to study the kinematics in more detail. In Fig. 3, we show one line each for Mn II, Zn II, Fe II, Mg II, Mg I, and Na I. This is a subset of the low ionization lines covered by the UVES spectrum. In addition to the data, a multicomponent fit is shown. For this fit, the positions and total number of velocity components in the absorption system were derived from all identified species. Their wavelength positions were then fixed to avoid degeneracy with blended features. For individual elements, only a subset of components was selected and fitted with a single Gaussian each with the evolutionary algorithm described in Quast, Baade & Reimers (2005) and applied in Wendt & Molaro (2012).

As expected from the MUSE spectrum, the Mg II $\lambda 2796$ absorption covers a broad velocity range – from -130 to 205 km s⁻¹ – and is strongly saturated for most of this range. Unsaturated or weakly saturated lines, such as the Mg I $\lambda 2852$ line, are more useful to identify sub-structures. Based on these transitions, we identified three main components, which are indicated in Fig. 3 and labelled with *A* (red), *B* (magenta), and *C* (cyan). They are offset from the systemic redshift of the foreground galaxy by -49 , 10 , and 100 km s⁻¹, respectively.

From the UVES spectrum, [Zn II/Fe II] is measured for components A+B to be $\sim 1.1 \pm 0.1$,⁶ which indicates a significant amount of depletion for intervening systems (De Cia et al. 2016) of ≈ 0.3 dex (≈ 1.5 dex) for Zn (Fe), respectively. This level of depletion is also associated with more metal-rich absorption systems with [Zn/H] around 1/2 solar (De Cia et al. 2016).

4 CGM TOY MODEL

Mg II absorption around a galaxy is, in observations, pre-dominantly found either along the galaxy’s minor or major axis (e.g. Bordoloi et al. 2011; Bouché et al. 2012; Kacprzak et al. 2012; Nielsen et al. 2015; Martin et al. 2019; see also papers II and III). A natural explanation for this dichotomy is a simple model of a biconical outflow perpendicular to the galaxy disc and an extended gaseous disc aligned with the galaxy disc. This picture has gained support from both the theoretical and observational sides; that is, predictions from cosmological hydro simulations (winds: e.g. Dubois & Teyssier 2008; Shen et al. 2012, 2013; discs: e.g. Kimm et al. 2011; Pichon et al. 2011; Stewart et al. 2011, 2017; Shen et al. 2013; Danovich et al. 2015) and directly observed emission properties of local galaxies (winds: e.g. Veilleux, Cecil & Bland-Hawthorn 2005 for a review; discs: e.g. Putman et al. 2009; Wang et al. 2016; Ianjamasimanana et al. 2018).

⁶The assumed solar abundances are adopted from Jenkins (2009) (based on Lodders 2003).

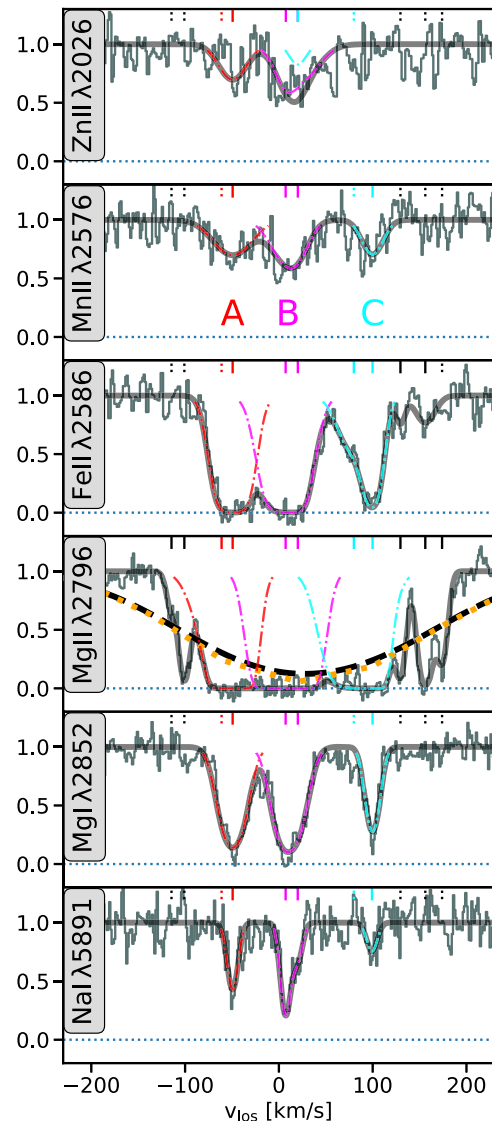


Figure 3. Absorption in the quasar sightline at the redshift of *main* measured with the high spectral resolution VLT/UVES data. Panels 1–6 from the top: The observed absorption is shown for multiple species, with a multicomponent model fit (thick grey line) overplotted over the data. The velocity components considered in the fit are indicated as little bars near the top of the panels, where a dotted bar indicates that the component was not used for the specific line. Three main kinematic components, *A*, *B*, and *C*, can be clearly identified from the unsaturated lines. The contribution of the three components, as measured from the multicomponent fit, is shown by different colours. For comparison, the panel for Mg II $\lambda 2796$ also shows the MUSE spectrum (orange dotted; identical to Fig. 1E) and the UVES spectrum artificially degraded to the resolution of MUSE (black dashed).

In the following, we investigate a toy model implementation for kinematics and morphology of a disc+outflow model to interpret the observed absorption features in both the quasar and *back1* sightlines.

4.1 Model parameters

4.1.1 Biconical outflow

For the outflow model, we assume that a galaxy launches winds from its central region into a biconical outflow with half-opening angle

Table 3. Summary of model parameters in the CGM toy model (cf. Section 4).

	Property	Description	Unit
		Sightline	
(1)	i	Inclination	deg
		Biconical outflow	
(2)	θ_{out}	Outer (half-)cone opening angle	deg
(3)	θ_{in}	Inner (half-)cone opening angle	deg
(4)	v_{out}	Outflow velocity	km s ⁻¹
(5)	σ_{gas}	Gas velocity dispersion	km s ⁻¹
(6)	ρ_1	Density at norm radius (Mg II)	cm ⁻³
		Extended gas disc	
(7)	v_{circ}	Circular velocity of gas	km s ⁻¹
(8)	v_r	Radial velocity of gas	km s ⁻¹
(9)	h_r	Exponential scale length (radial)	kpc
(10)	h_z	Exponential scale length (vertical)	kpc
(11)	σ_{gas}	Gas velocity dispersion	km s ⁻¹
(12)	ρ_0	Density at $r = 0$ and $z = 0$ (Mg II)	cm ⁻³

θ_{out} . We allow the cone to be devoid of Mg II within an inner opening angle, θ_{in} , as indicated by larger samples of wind pairs (e.g. papers I and III; Bouché et al. 2012). For the wind kinematics, we assume that the gas flows outwards radially with an outflow velocity, v_{out} , that does not change with distance from the galaxy. From mass conservation, this constant velocity necessitates a radial density $\rho(r) \propto r^{-2}$, which is normalized at 1 kpc with $\rho_1 \equiv \rho(1 \text{ kpc})$. We also account for random motions of the encountered gas with σ_{gas} . Moreover, we assume that the gas does not change its ionization state and that it is smoothly distributed. Thus, the wind parameters are θ_{out} , θ_{in} , v_{out} , ρ_1 , and σ_{gas} that are listed in Table 3.

The cone opening angle θ_{out} is ≈ 30 deg, and the inner cone is $\theta_{\text{in}} \approx 15$ deg, consistent with typical values in paper III. The outflow velocity v_{out} is assumed to be 150 km s⁻¹, corresponding to the typical v_{out} in paper III. The intrinsic dispersion σ_{gas} is chosen somewhat arbitrarily to be 10 km s⁻¹. All parameters of the fiducial model are summarized in Table 4.

4.1.2 Extended gas disc

However, as the sightlines are at relatively small impact parameters (at 8.8 kpc and 16.8 kpc), a contribution from a thick extended gas disc cannot be ruled out. We model this extended gaseous disc as an exponential profile with scale length h_r in radial direction. In the direction perpendicular to the disc (z -direction), we assume an exponential profile with scale height h_z . The gas density is normalized at the disc mid-plane in the disc centre with ρ_0 . For the disc’s kinematics, we assume that the gas is rotating parallel to the disc mid-plane with a circular velocity v_{circ} , which we assume to be identical to v_{max} from the galaxy rotation. In addition, the gas velocity vector can also have a radial infall component, v_r , which is added to the tangential component keeping v_{circ} constant.⁷ The disc parameters are v_{circ} , v_r , σ_{gas} , h_z , and ρ_0 that are summarized in Table 3.

The circular velocity v_{circ} is given by the kinematics of the host galaxy as described in Section 3.2. The stellar scale height h_z

⁷The circular and the radial moving gas are here assumed to add to a single components as in paper II, but unlike in Bouché et al. (2016), where the same gas has both a radial and infalling components.

of distant galaxies is typically 1 kpc, as suggested by studies of edge-on discs in *Hubble* deep fields (e.g. Elmegreen & Elmegreen 2006; Elmegreen et al. 2017). We assume that the extended cool gas disc probed by Mg II has similar scale height ($h_z = 1$ kpc). The gas dispersion, σ_{gas} , is assumed to be ~ 10 km s⁻¹ appropriate for the temperature of low-ionization gas (e.g. Churchill, Vogt & Charlton 2003). The density ρ_0 will be adjusted in order to match the absorption optical depth for Mg I.

4.2 Simulated absorption lines

We use our code CGMPY to calculate the Mg II absorption profile which the outflow cones and/or the extended gas disc would imprint on a background source. In short, the code calculates for each of small steps ($= 1$ pc) along the line of sight (LOS), the LOS velocity, $v_{\text{los; step}}$, and the column density, N_{step} , which can subsequently be converted to an optical depth, $\tau_{\text{step}}(v_{\text{los}})$. The full $\tau(v_{\text{los}})$ distribution for the complete sightline is then obtained by summing up the $\tau_{\text{step}}(v_{\text{los}})$ from each step and each component without the turbulent velocity dispersion σ_{gas} . We account for this random motions of the gas (σ_{gas}) by convolving the optical depth distribution with a Gaussian of the selected σ_{gas} . Finally, the absorption profile is obtained by taking $e^{-\tau(v_{\text{los}})}$ and convolving with the instrumental line spread function.

In the case of an extended sightline (such as for ‘*back1*’), the absorption from the extended object is calculated by taking the average over individual sightlines flux weighted over an elliptical aperture centred on the galaxy (for *back1* with an area of ~ 1 arcsec²).

5 DISCUSSION

Here, we describe how the toy model discussed in Section 4 performs in describing our data. However, we stress that we do not expect this simple toy model to account for all data features nor do we attempt to formally fit it to the data. Thus, if the model can, at least approximately, explain most of the absorption in *both* background sightlines, the simple toy model can be viewed as a description of the *main* galaxy’s CGM.

5.1 The fiducial (wind-only) model

We first tested the performance of a fiducial biconical outflow-only model (cf. Section 4.1.1), given that both the quasar and *back1* are positioned along the minor axis of the host galaxy, i.e. without an extended gas disc.

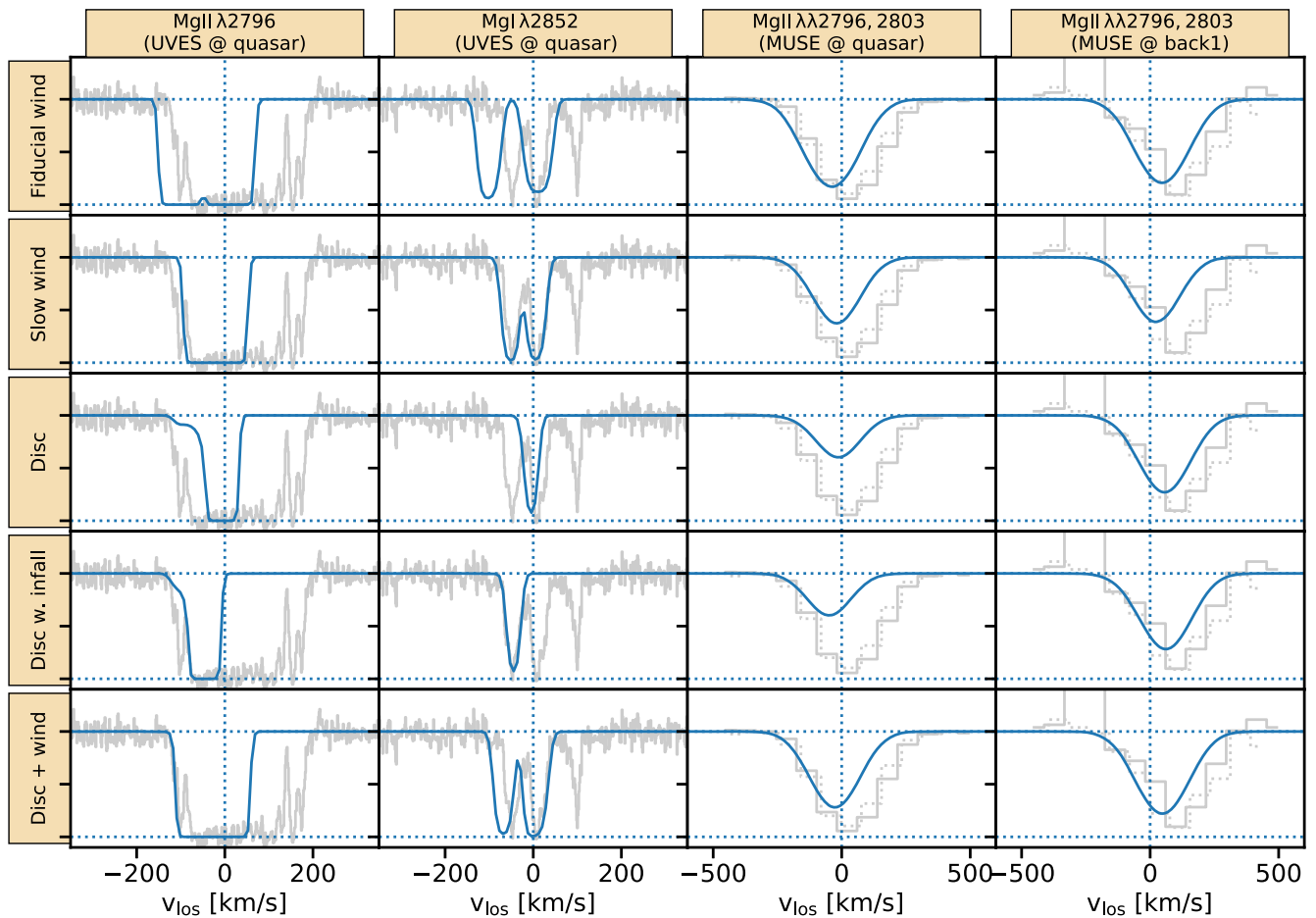
Here, the model’s orientation is set by the measurement of the galaxy’s inclination i (see Section 3.2). However, as the sign of the galaxy inclination cannot be constrained with the available data (see e.g. Ho & Martin 2020), we were left with two possible solutions. Here, we choose the sign of the inclination such that the absorbing gas in the cones is outflowing. This outflow assumption requires that redshifted absorption must originate from the far-side cone, and consequently, the *back1* galaxy sightline crosses this far-side cone. Figs 1(B) and (C) show the adopted orientation.

For our ‘fiducial’ outflow model, we assume a value for θ_{out} (35 deg), which is at the higher end of typical values found in paper III. We made this choice, to ensure very high coverage over the extended *back1* galaxy sightline in the model, as required by the observed absorption strength (see Section 3.3.1).

In Fig. 4 (row 1 – ‘Fiducial wind’), we overlay the resulting absorption profiles over the UVES and MUSE data for the ‘quasar’

Table 4. The choice for each of the parameters in Table 3 as used for the five models described in Section 5 and shown in Fig. 4.

Model	i (1)	θ_{out} (2)	θ_{in} (3)	v_{out} (4)	σ_{gas} (5)	ρ_1 (6)	v_{circ} (7)	v_r (8)	h_r (9)	h_z (10)	σ_{gas} (11)	ρ_0 (12)
Fiducial wind	71	35	15	150	10	8×10^{-5}	–	–	–	–	–	–
Slow wind	71	35	15	75	10	8×10^{-5}	–	–	–	–	–	–
Disc	71	–	–	–	–	–	118	–	5	1	10	3×10^{-3}
Disc w. infall	71	–	–	–	–	–	118	–40	5	1	10	3×10^{-3}
Disc + wind	71	35	15	100	10	8×10^{-5}	118	–	5	1	10	3×10^{-3}

**Figure 4.** Comparison between data and various models. Each row shows a different model, as listed in Table 4. In each panel, the light grey curve is the observed absorption, while the blue line shows the modelled absorption. The first two columns show Mg II $\lambda 2796$ (column 1) and Mg I $\lambda 2852$ (Column 2) in the quasar sightline at the resolution of UVES. The third and fourth columns show Mg II $\lambda 2796, 2803$ for the quasar sightline (column 3) and the *back1* galaxy sightline (column 4) at the resolution of MUSE. Here, the solid line is Mg II $\lambda 2796$ (data and model) and the dotted line is Mg II $\lambda 2803$ (data).

(Columns 1, 2, and 3) and ‘*back1*’ (Column 4) sightlines. Column 1 (2) shows the model for the quasar sightlines for Mg II (Mg I), respectively, where we scaled the Mg I density by 1/600 compared to Mg II according to Lan & Fukugita (2017). Comparing our UVES data to the model for the quasar sightlines shown in Columns 1 and 2, we find that the absorption is made of two separate components that arise from the assumption of an empty inner cone. These two components might correspond to components A and B in the observed spectrum (see Section 3.3.2). Comparing our MUSE data and the fiducial wind model (Columns 3 and 4), we find that the model and data match qualitatively for the blue- (red-)shifted absorptions in the quasar (galaxy) sightlines absorption shown in

Column 3 (4), respectively. However, there are some discrepancies between the model and the data.

The main discrepancy is that the wind model cannot explain the redshifted third component C. Another discrepancy is that, for the quasar absorption, the model predicts a blue-shift (-75 km s^{-1}), whereas the observed absorption is close to systemic at $\approx +25 \text{ km s}^{-1}$.

A model with lower outflow velocity ($v_{\text{out}} \approx 75 \text{ km s}^{-1}$) would better match to components A and B in the Mg I absorption (Fig. 4; row 2 – ‘Slow wind’). However, it underpredicts the redshift compared to the Mg II data in the *back1* galaxy sightline. Note that this potential velocity difference between the two sightlines could

indicate deceleration of the gas with distance from the galaxy, as the quasar sightline is probing gas at a larger impact parameter than the *back1* sightline does (16.8 kpc versus 8.8 kpc). Strong, non-gravitational, deceleration in an outflow could be due to drag forces (in observations e.g. Martini et al. 2018; in simulations e.g. Oppenheimer et al. 2010). However, this interpretation would require the strong assumption that the two opposite cones have the same velocity profile.

5.2 Disc model

Given the limitations of the fiducial wind only-model, and the relatively small impact parameters, we discuss the extended gaseous disc model presented in Section 4.1.2. Indeed, the two minor-axis sightlines cross the disc mid-plane at galactocentric radii of 26 kpc ($0.21 r_{\text{vir}}$) and 51 kpc ($0.42 r_{\text{vir}}$), within the extent of co-rotating gas discs from paper II and Ho et al. (2017). Before discussing a potential combination of wind and disc model, we test whether a simple thick disc model similar to Steidel et al. (2002), Kacprzak et al. (2010), Ho et al. (2017) can potentially explain all absorption on its own.

In Fig. 4 (row 3 – ‘Disc’), we overlay the resulting absorption profiles over the MUSE and UVES data as before. Comparing the UVES data to our model shows that a thick disc model can only explain component B in the Mg I spectrum.⁸ As for the wind model, the thick disc model cannot explain the redshifted third component C. However, component A in the UVES spectrum could be accounted for with an extension of this disc model with a radial inflow component (shown in row 4 of Fig. 4 – ‘Disc + infall’). The observed velocity of -49 km s^{-1} would require a radial velocity component of $v_r \approx -40 \text{ km s}^{-1} = -0.4 v_{\text{vir}}$.⁹ Such a radial inflow velocity is feasible, based on results from simulations (e.g. Rosdahl & Blaizot 2012; van de Voort & Schaye 2012; Goerdt & Ceverino 2015; Ho, Martin & Turner 2019) and observational studies targeting the major axis sightlines (e.g. Bouché et al. 2013, 2016; Rahmani et al. 2018a; paper II).

5.3 Combined disc and wind

The observed absorption might be a combination of absorption from both a disc and an outflow component. As discussed in Section 5.1, the outflow component alone, a faster wind (150 km s^{-1}) matches better the observed absorption in the *back1* sightline, while a slower wind (75 km s^{-1}) matches better the absorption in the quasar sightline. For the following, we assume a wind speed of 100 km s^{-1} as a compromise to match approximately both sightlines with a single wind speed. Fig. 4 (row 5 – ‘Disc + wind’) shows the resulting absorption profile when combining the disc and the wind toy model (the same model is also shown in Fig. 1D). While imperfect, the toy model is qualitatively in agreement with the observed spectra, apart from component C. Component C might be an unrelated component, similar to the high-velocity clouds (HVC) seen around the Milky Way (e.g. Wakker & van Woerden 1997 for a review). In summary, a plausible interpretation of the observed

kinematics in the two sightlines is absorption in a bi-conical outflow with a potential disc contribution.

5.4 Feasibility of the outflow

As discussed in Section 3.2, the SFR of the *main* galaxy is low compared to star-forming galaxies with similar mass at similar redshift. This raises the question whether the energy and the momentum that are required to explain the wind are at all feasible. To answer this question, we estimated the mass outflow rate, \dot{M}_{out} , the energy-outflow rate, \dot{E}_{out} , and the momentum outflow rate, \dot{p}_{out} . These estimates can subsequently be compared to the estimated SFR and the corresponding energy and momentum deposition rates from supernovae (SNe).

We estimated \dot{M}_{out} for the biconical outflow of cool gas using equation 5 from paper III. As inputs to the equation we assumed $\theta_{\text{out}} = 35 \text{ deg}$, $\theta_{\text{in}} = 15 \text{ deg}$, $b = 15 \text{ kpc}$, $v_{\text{out}} = 100 \text{ km s}^{-1}$, $\log(N_{\text{HI}}/\text{cm}^{-2}) = 20.0$. Here, we estimated the HI column density using the $\text{EW}_0^{\lambda 2796}$ -HI relation from Ménard & Chelouche (2009) and Lan & Fukugita (2017), which has an uncertainty of around 0.3 dex. Using these values in the equations, we obtain $\dot{M}_{\text{out}} = 2.0 M_{\odot} \text{ yr}^{-1}$. This corresponds with the assumed $v_{\text{out}} = 100 \text{ km s}^{-1}$ to $\dot{E}_{\text{out}} = 6.0 \times 10^{39} \text{ erg s}^{-1}$ and $\dot{p}_{\text{out}} = 1.3 \times 10^{33} \text{ g cm s}^{-1}$.

A comparison of \dot{M}_{out} to the estimated SFR allows us to infer the mass-loading ($\eta = \dot{M}_{\text{out}}/\text{SFR}$), which characterizes the efficiency of a star formation powered wind to remove gas from the galaxy. Assuming that the wind was powered by the current SFR of $0.5 M_{\odot} \text{ yr}^{-1}$, we infer $\eta \approx 4$. This value can be compared to measurements of η both from individual estimates (quasar sightlines e.g. paper III, Bouché et al. 2012; Schroetter et al. 2015; down the barrel: e.g. Weiner et al. 2009; Martin et al. 2012; Rubin et al. 2014; Sugahara et al. 2017), indirect observational evidence (e.g. Zahid et al. 2014; Mitra, Davé & Finlator 2015), or simulations (e.g. Hopkins, Quataert & Murray 2012; Muratov et al. 2015). For the mass and redshift of our main galaxy, the values in these studies typically range from $\eta \approx 1$ –10 (see also discussion in paper III). Hence, we conclude that the η corresponding to our preferred model seems feasible.

A direct comparison of the measured \dot{E}_{out} and \dot{p}_{out} to the momentum and energy injected by SNe leads to a similar conclusion. Per $1 M_{\odot} \text{ yr}^{-1}$ of star formation SNe deposit mechanical energy and momentum with rates of approximately $1.6 \times 3 \times 10^{41} \text{ erg s}^{-1}$ (from Chisholm et al. 2017 based on Leitherer et al. 1999) and $1.6 \times 2 \times 10^{33} \text{ g cm s}^{-1}$ (Murray, Quataert & Thompson 2005).¹⁰ This means that our measured values correspond to energy and momentum loading of 3 per cent and 80 per cent, respectively. These values are comparable to those found by Chisholm et al. (2017) for a sample of local star-forming galaxies when considering the relevant mass range.¹¹

Finally, we note that the actual loading factors could be smaller. The SFR might have been higher at the time when the wind was launched. It would have taken the wind $\approx 200 \text{ Myr}$ ($\approx 100 \text{ Myr}$) to travel to the quasar (*back1*) sightline, assuming $v_{\text{out}} = 100 \text{ km s}^{-1}$. With the limited available data we cannot rule out that there was a significant burst of star formation about 200–300 Myr ago, as motivated by tests with non-parametric SFHs with PPF (Cappellari & Emsellem 2004; Cappellari 2017).

¹⁰Factor of 1.6 is to convert from the Salpeter (1955) to the Chabrier (2003) IMF.

¹¹We have only included the cool phase of the outflow, so the total loading factors could be higher.

⁸We note that a very thin disc would have a narrower profile, hence a lower equivalent width, and also a lower velocity shift than a thick disc. This is, because a sightline crossing a thick disc encounters different velocities at different heights above the disc, up to $\sin(i)v_{\text{circ}}$ (e.g. Steidel et al. 2002).

⁹ $v_r \approx -40 \text{ km s}^{-1}$ is enough to match the observed blueshift of component A, because the model has also a contribution from the rotational component (v_{circ}).

6 CONCLUSIONS

It is now statistically well established that there is a dichotomy in the spatial distribution of the cool CGM gas probed through Mg II absorption, where the two components have been identified as arising in an extended gas disc and a biconical outflow. In this paper, we present a rare chance alignment of a quasar and a UV-bright background galaxy at relatively small impact parameters (16.8 and 8.8 kpc) from a $z = 0.7$ foreground galaxy. As the two sightlines are close to the foreground galaxy's projected minor axis, but on opposite sides of the major axis, the configuration is ideal to test the biconical outflow component. Through studying the observed absorption both in MUSE and UVES data from the MEGAFLOW survey, and comparison to modelled absorption, we reached the following conclusions:

- (i) Both sightlines show very strong Mg II absorption ($EW_0^{\lambda 2796} > 2.0 \text{ \AA}$).
- (ii) We find a significant velocity shift of $84 \pm 17 \text{ km s}^{-1}$ between the two sightlines.
- (iii) The observed velocity shift is in broad agreement with a biconical outflow toy model with a moderate outflow velocity of $\approx 100 \text{ km s}^{-1}$, possibly combined with a disc model.
- (iv) The foreground galaxy has a relatively low sSFR ($0.07 \pm 0.06 \text{ Gyr}^{-1}$), which puts the galaxy 0.6 dex below the MS at $z = 0.7$. However, the mass loading (η) required to explain the modelled outflow is not unrealistic high ($\eta \approx 4$). Moreover, the sSFR may have been higher when the wind was launched, $\sim 10^8 \text{ yr}$ before.

This study presented a ‘tomographic’ study (i.e. with multi-sightline) of the CGM around an individual galaxy in the distant Universe ($z \approx 0.7$), and hence goes beyond the statistical inference from single sightline samples. While we find the data to be in broad agreement with our fiducial CGM model, we cannot rule out alternative explanations. A comparison of the CGM model to larger samples of rare multisightline cases, including cases with even more sightlines as e.g. provided by background groups or gravitationally lensed arcs (e.g. Lopez et al. 2018, 2020), will be an important test for our assumed geometry. Additionally, it will be necessary to test the geometry against observations of the CGM in emission (e.g. Finley et al. 2017; Rupke et al. 2019).

ACKNOWLEDGEMENTS

This paper is dedicated to the memory of our wonderful friend and colleague, Hayley Finley.

We thank the anonymous referee for a constructive report, which helped to improve the quality of this manuscript. This study is based on observations collected at the European Southern Observatory under ESO programmes 097.A-0138(A), 097.A-0144(A), 0100.A-0089(A). This work has been carried out thanks to the support of the ANR FOGHAR (ANR-13-BS05-0010), the ANR 3DGasFlows (ANR-17-CE31-0017), the OCEVU Labex (ANR-11-LABX-0060), and the A*MIDEX project (ANR-11-IDEX-0001-02) funded by the ‘Investissements d’avenir’ French government programme.

This work made use of the following open source software: GALPAK3D (Bouché et al. 2015), ZAP (Soto et al. 2016), MPDAF (Piqueras et al. 2019), MATPLOTLIB (Hunter 2007), NUMPY (van der Walt, Colbert & Varoquaux 2011; Oliphant 2007), ASTROPY (Astropy Collaboration et al. 2013).

REFERENCES

- Astropy Collaboration et al., 2013, *A&A*, 558, A33
 Bacon R. et al., 2006, *Messenger*, 124, 5
 Bacon R. et al., 2010, *Proc. SPIE*, 7735, 773508
 Bacon R. et al., 2017, *A&A*, 608, A1
 Behroozi P. S., Conroy C., Wechsler R. H., 2010, *ApJ*, 717, 379
 Bergeron J., 1988, in Audouze J., Pelletan M.-C., Szalay S., eds, *IAU Symp.* 130: Large Scale Structures of the Universe. Kluwer, Dordrecht, p. 343
 Bergeron J., Boissé P., 1991, *A&A*, 243, 344
 Bergeron J., Stasińska G., 1986, *A&A*, 169, 1
 Boogaard L. A. et al., 2018, *A&A*, 619, A27
 Bordoloi R. et al., 2011, *ApJ*, 743, 10
 Bouché N. et al., 2016, *ApJ*, 820, 121
 Bouché N., Murphy M. T., Péroux C., Csabai I., Wild V., 2006, *MNRAS*, 371, 495
 Bouché N., Hohensee W., Vargas R., Kacprzak G. G., Martin C. L., Cooke J., Churchill C. W., 2012, *MNRAS*, 426, 801
 Bouché N., Murphy M. T., Kacprzak G. G., Péroux C., Contini T., Martin C. L., Dessauges-Zavadsky M., 2013, *Science*, 341, 50
 Bouché N., Carfantan H., Schroetter I., Michel-Dansac L., Contini T., 2015, *AJ*, 150, 92
 Bowen D. V., Chelouche D., Jenkins E. B., Tripp T. M., Pettini M., York D. G., Frye B. L., 2016, *ApJ*, 826, 50
 Calzetti D., Armus L., Bohlin R. C., Kinney A. L., Koornneef J., Storchi-Bergmann T., 2000, *ApJ*, 533, 682
 Cappellari M., 2017, *MNRAS*, 466, 798
 Cappellari M., Emsellem E., 2004, *PASP*, 116, 138
 Chabrier G., 2003, *PASP*, 115, 763
 Chen H.-W., Kennicutt R. C., Jr., Rauch M., 2005, *ApJ*, 620, 703
 Chen H.-W., Helsby J. E., Gauthier J.-R., Shectman S. A., Thompson I. B., Tinker J. L., 2010, *ApJ*, 714, 1521
 Chisholm J., Tremonti C. A., Leitherer C., Chen Y., 2017, *MNRAS*, 469, 4831
 Churchill C. W., Vogt S. S., Charlton J. C., 2003, *AJ*, 125, 98
 Crighton N. H. M., Morris S. L., Bechtold J., Crain R. A., Jannuzi B. T., Shone A., Theuns T., 2010, *MNRAS*, 402, 1273
 D’Odorico V., Cristiani S., D’Odorico S., Fontana A., Giallongo E., Shaver P., 1998, *A&A*, 339, 678
 Dahlen T., Mobasher B., Dickinson M., Ferguson H. C., Giavalisco M., Kretchmer C., Ravindranath S., 2007, *ApJ*, 654, 172
 Danovich M., Dekel A., Hahn O., Ceverino D., Primack J., 2015, *MNRAS*, 449, 2087
 De Cia A., Ledoux C., Mattsson L., Petitjean P., Srianand R., Gavignaud I., Jenkins E. B., 2016, *A&A*, 596, A97
 Dekker H., D’Odorico S., Kaufer A., Delabre B., Kotzłowski H., 2000, in Iye M., Moorwood A. F., eds, *Proc. SPIE Conf. Ser. Vol. 4008, Optical and IR Telescope Instrumentation and Detectors*. SPIE, Bellingham, p. 534
 Dubois Y., Teyssier R., 2008, *A&A*, 477, 79
 Ellison S. L., Ibata R., Pettini M., Lewis G. F., Aracil B., Petitjean P., Srianand R., 2004, *A&A*, 414, 79
 Elmegreen B. G., Elmegreen D. M., 2006, *ApJ*, 650, 644
 Elmegreen B. G., Elmegreen D. M., Tompkins B., Jenks L. G., 2017, *ApJ*, 847, 14
 Finley H. et al., 2017, *A&A*, 605, A118
 Garn T., Best P. N., 2010, *MNRAS*, 409, 421
 Goerd T., Ceverino D., 2015, *MNRAS*, 450, 3359
 Hopkins P. F., Quataert E., Murray N., 2012, *MNRAS*, 421, 3522
 Ho S. H., Martin C. L., 2020, *ApJ*, 888, 14
 Ho S. H., Martin C. L., Kacprzak G. G., Churchill C. W., 2017, *ApJ*, 835, 267
 Ho S. H., Martin C. L., Turner M. L., 2019, *ApJ*, 875, 54
 Hunter J. D., 2007, *Comput. Sci. Eng.*, 9, 90
 Ianjamasimanana R., Walter F., de Blok W. J. G., Heald G. H., Brinks E., 2018, *AJ*, 155, 233
 Jenkins E. B., 2009, *ApJ*, 700, 1299
 Kacprzak G. G. et al., 2014, *ApJ*, 792, L12

- Kacprzak G. G., Churchill C. W., Ceverino D., Steidel C. C., Klypin A., Murphy M. T., 2010, *ApJ*, 711, 533
- Kacprzak G. G., Churchill C. W., Evans J. L., Murphy M. T., Steidel C. C., 2011a, *MNRAS*, 416, 3118
- Kacprzak G. G., Churchill C. W., Barton E. J., Cooke J., 2011b, *ApJ*, 733, 105
- Kacprzak G. G., Churchill C. W., Nielsen N. M., 2012, *ApJ*, 760, L7
- Kewley L. J., Geller M. J., Jansen R. A., 2004, *AJ*, 127, 2002
- Kimm T., Devriendt J., Slyz A., Pichon C., Kassin S. A., Dubois Y., 2011, preprint (arXiv:1106.0538)
- Lan T.-W., Fukugita M., 2017, *ApJ*, 850, 156
- Lan T.-W., Mo H., 2018, *ApJ*, 866, 36
- Lan T.-W., Ménard B., Zhu G., 2014, *ApJ*, 795, 31
- Lanzetta K. M., Bowen D., 1990, *ApJ*, 357, 321
- Lanzetta K. M., Turnshek D. A., Wolfe A. M., 1987, *ApJ*, 322, 739
- Leitherer C. et al., 1999, *ApJS*, 123, 3
- Lodders K., 2003, *ApJ*, 591, 1220
- Lopez S. et al., 2018, *Nature*, 554, 493
- Lopez S. et al., 2020, *MNRAS*, 491, 4442
- Lopez S., Reimers D., Rauch M., Sargent W. L. W., Smette A., 1999, *ApJ*, 513, 598
- Lopez S., Ellison S., D’Oroico S., Kim T. S., 2007, *A&A*, 469, 61
- Martini P., Leroy A. K., Mangum J. G., Bolatto A., Keating K. M., Sandstrom K., Walter F., 2018, *ApJ*, 856, 61
- Martin C. L., Shapley A. E., Coil A. L., Kornei K. A., Bundy K., Weiner B. J., Noeske K. G., Schiminovich D., 2012, *ApJ*, 760, 127
- Martin C. L., Ho S. H., Kacprzak G. G., Churchill C. W., 2019, *ApJ*, 878, 84
- Ménard B., Chelouche D., 2009, *MNRAS*, 393, 808
- Mitra S., Davé R., Finlator K., 2015, *MNRAS*, 452, 1184
- Muratov A. L., Kereš D., Faucher-Giguère C.-A., Hopkins P. F., Quataert E., Murray N., 2015, *MNRAS*, 454, 2691
- Murray N., Quataert E., Thompson T. A., 2005, *ApJ*, 618, 569
- Muzahid S., 2014, *ApJ*, 784, 5
- Muzahid S., Kacprzak G. G., Churchill C. W., Charlton J. C., Nielsen N. M., Mathes N. L., Trujillo-Gomez S., 2015, *ApJ*, 811, 132
- Nestor D. B., Turnshek D. A., Rao S. M., 2005, *ApJ*, 628, 637
- Nielsen N. M., Churchill C. W., Kacprzak G. G., Murphy M. T., 2013a, *ApJ*, 776, 114
- Nielsen N. M., Churchill C. W., Kacprzak G. G., 2013b, *ApJ*, 776, 115
- Nielsen N. M., Churchill C. W., Kacprzak G. G., Murphy M. T., Evans J. L., 2015, *ApJ*, 812, 83
- Oliphant T. E., 2007, *Comput. Sci. Eng.*, 9, 10
- Oppenheimer B. D., Davé R., Kereš D., Fardal M., Katz N., Kollmeier J. A., Weinberg D. H., 2010, *MNRAS*, 406, 2325
- Peng C. Y., Ho L. C., Impey C. D., Rix H.-W., 2010, *AJ*, 139, 2097
- Péroux C., Rahmani H., Arrigoni Battaia F., Augustin R., 2018, *MNRAS*, 479, L50
- Pichon C., Pogosyan D., Kimm T., Slyz A., Devriendt J., Dubois Y., 2011, *MNRAS*, 418, 2493
- Piqueras L., Conseil S., Shepherd M., Bacon R., Leclercq F., Richard J., 2019, in Molinaro M., Shorridge K., Pasian F., eds, ASP Conf. Ser. Vol. 521, Astronomical Data Analysis Software and Systems XXVI. Astron. Soc. Pac., San Francisco, p. 545
- Putman M. E. et al., 2009, *ApJ*, 703, 1486
- Quast R., Baade R., Reimers D., 2005, *A&A*, 431, 1167
- Rahmani H. et al., 2018a, *MNRAS*, 474, 254
- Rahmani H. et al., 2018b, *MNRAS*, 480, 5046
- Rauch M., Sargent W. L. W., Barlow T. A., 1999, *ApJ*, 515, 500
- Rosdahl J., Blaizot J., 2012, *MNRAS*, 423, 344
- Rubin K. H. R. et al., 2018, *ApJ*, 859, 146
- Rubin K. H. R., Prochaska J. X., Koo D. C., Phillips A. C., Martin C. L., Winstrom L. O., 2014, *ApJ*, 794, 156
- Rupke D. S. N. et al., 2019, *Nature*, 574, 643
- Salpeter E. E., 1955, *ApJ*, 121, 161
- Schroetter I. et al., 2016, *ApJ*, 833, 39 (paper I)
- Schroetter I. et al., 2019, *MNRAS*, 490, 4368 (paper III)
- Schroetter I., Bouché N., Péroux C., Murphy M. T., Contini T., Finley H., 2015, *ApJ*, 804, 83
- Shen S., Madau P., Aguirre A., Guedes J., Mayer L., Wadsley J., 2012, *ApJ*, 760, 50
- Shen S., Madau P., Guedes J., Mayer L., Prochaska J. X., Wadsley J., 2013, *ApJ*, 765, 89
- Soto K. T., Lilly S. J., Bacon R., Richard J., Conseil S., 2016, Astrophysics Source Code Library, record ascl:1602.003)
- Speagle J. S., Steinhardt C. L., Capak P. L., Silverman J. D., 2014, *ApJS*, 214, 15
- Steidel C. C., 1995, in Meylan G., ed., QSO Absorption Lines. ESO Astrophysics Symposia. Springer-Verlag, Berlin, p. 139
- Steidel C. C., Sargent W. L. W., 1992, *ApJS*, 80, 1
- Steidel C. C., Kollmeier J. A., Shapley A. E., Churchill C. W., Dickinson M., Pettini M., 2002, *ApJ*, 570, 526
- Stewart K. R. et al., 2017, *ApJ*, 843, 47
- Stewart K. R., Kaufmann T., Bullock J. S., Barton E. J., Maller A. H., Diemand J., Wadsley J., 2011, *ApJ*, 738, 39
- Sugahara Y., Ouchi M., Lin L., Martin C. L., Ono Y., Harikane Y., Shibuya T., Yan R., 2017, *ApJ*, 850, 51
- Tumlinson J., Peebles M. S., Werk J. K., 2017, *ARA&A*, 55, 389
- van de Voort F., Schaye J., 2012, *MNRAS*, 423, 2991
- van der Walt S., Colbert S. C., Varoquaux G., 2011, *Comput. Sci. Eng.*, 13, 22
- Veilleux S., Cecil G., Bland-Hawthorn J., 2005, *ARA&A*, 43, 769
- Wakker B. P., van Woerden H., 1997, *ARA&A*, 35, 217
- Wang J., Koribalski B. S., Serra P., van der Hulst T., Roychowdhury S., Kamphuis P., Chengalur J. N., 2016, *MNRAS*, 460, 2143
- Weilbacher P. M., Streicher O., Urrutia T., Jarno A., Pécontal-Rousset A., Bacon R., Böhm P., 2012, *Proc. SPIE*, 8451, 84510B
- Weilbacher P. M., Streicher O., Urrutia T., Pécontal-Rousset A., Jarno A., Bacon R., 2014, in Manset N., Forshay P., eds, ASP Conf. Ser. Vol. 485, Astronomical Data Analysis Software and Systems XXIII. Astron. Soc. Pac., San Francisco, p. 451
- Weilbacher P. M., Streicher O., Palsa R., 2016, Astrophysics Source Code Library, record ascl:1610.004
- Weiner B. J. et al., 2009, *ApJ*, 692, 187
- Wendt M., Molaro P., 2012, *A&A*, 541, A69
- Zabl J. et al., 2019, *MNRAS*, 485, 1961 (paper II)
- Zabl J., Freudling W., Möller P., Milvang-Jensen B., Nilsson K. K., Fynbo J. P. U., Le Fèvre O., Tasca L. A. M., 2016, *A&A*, 590, A66
- Zahid H. J., Torrey P., Vogelsberger M., Hernquist L., Kewley L., Davé R., 2014, *Ap&SS*, 349, 873
- Zhu G., Ménard B., 2013, *ApJ*, 770, 130

APPENDIX A: UNCERTAINTY ON INCLINATION AND POSITION ANGLE

In our analysis, we tied the orientation of our toy model (Section 4) to the orientation of the *main* foreground galaxy. Therefore, a robust measurement of position angle (PA) and inclination (i) is important. As discussed in Section 3.2, the measurement of the galaxy’s morphology is somewhat complicated by residuals from the PSF subtraction. The residuals made a formal assessment of the uncertainties based on the χ^2 doubtful. Therefore, we preferred to rely on a visual assessment of the uncertainties. For this purpose, we created GALFIT models deviating from the best-fitting model either in PA or inclination. Fig. A1 shows models and residuals all for the best-fitting model, the $PA_{\text{best}} - 15$ deg, $PA_{\text{best}} + 15$ deg, $i_{\text{best}} - 10$ deg, $i_{\text{best}} + 10$ deg. Except for the modified PA or i , we used in each case identical morphological parameters to those in the best-fitting model. The only free fit parameter in each of the alternative models was the total flux. Both for $PA \pm 15$ deg and $i \pm 10$ deg, the residuals are much stronger than for the best-fitting model and the models seems essentially inconsistent with the data. Therefore, it seems plausible to define these PA and incl. differences

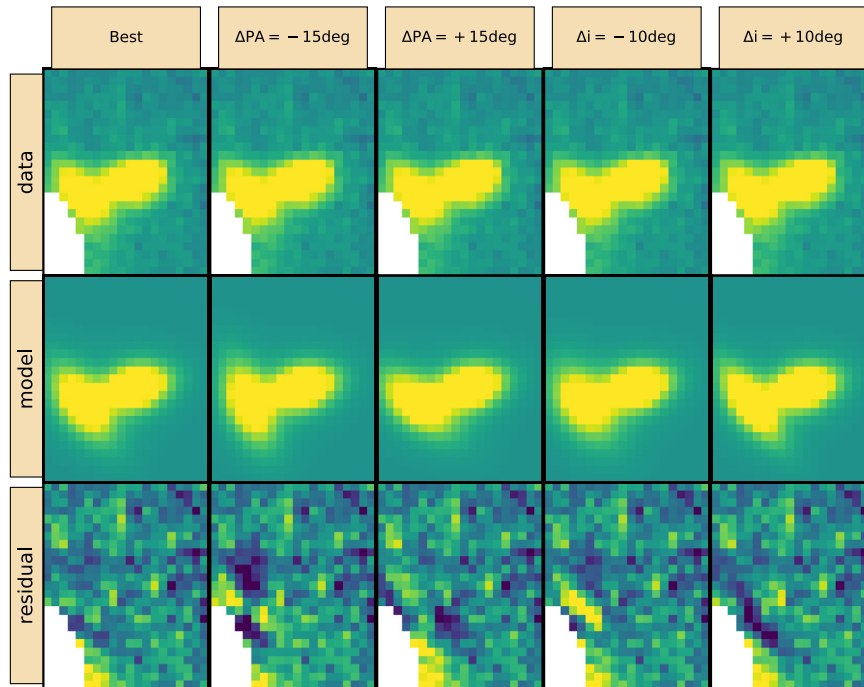


Figure A1. Data, GALFIT model, and residuals (data-model) are shown for each of five models in the top, centre, and bottom row, respectively. The data, which are identical in each of the four columns, are a pseudo broad-band r image created from the MUSE cube. The *main* foreground galaxy is to the left and the *back1* background galaxy is to the right (north is to the top, east to the left; different orientation from Fig. 1). The white region to the lower left masks residuals from the quasar subtraction. Left column: Best-fitting GALFIT model, where both *main* and *back1* were fit simultaneously. The *main* galaxy has best-fitting $PA_{\text{best}} = 37$ deg and $i_{\text{best}} = 71$ deg, assuming a $n = 1$ Sérsic profile. Centre left column: This column and the other three columns show the best-fitting model with either the PA or i of the *main* galaxy adjusted. Here, $PA = PA_{\text{best}} - 15$ deg; centre column: $PA = PA_{\text{best}} + 15$ deg; centre right column: $i = i_{\text{best}} - 10$ deg; right column: $i = i_{\text{best}} + 10$ deg.

as 2σ uncertainties. In summary, we conclude therefore that the 1σ uncertainties for PA and i are 8 and 5 deg, respectively.

In addition to the uncertainty in PA and i , there is also a small uncertainty on the centroid. We estimated this uncertainty through comparison between the continuum centroid obtained from this GALFIT fit and the [O II] centroid obtained from the GALPAK3D fit. We find a deviation of 0.16 arcsec between the two centroids. Therefore, we can assume as 1σ uncertainty 0.1 arcsec both in right ascension and declination.

APPENDIX B: IMPACT OF UNCERTAINTIES ON INCLINATION AND POSITION ANGLE ON MODELS

In this section, we assess the impact of the uncertainties for i and PA on the simulated absorption in our toy models.

In Fig. B1, we show the ‘Slow wind’ model (see Table 4) with either i or PA changed compared to the fiducial values (row 1). Rows 2 and 3 show the result for changing the i by ± 5 deg (i.e. 66 deg and 76 deg), while keeping the fiducial value for the PA. Rows 4 and 5 show the impact of varying the PA of *main* by ± 10 deg. Assuming $\Delta PA \pm 10$ deg means that the azimuthal angle α is changed by ∓ 10 deg both for the quasar and the *back1* sightline (equally) compared to the values stated in Table 1. All other parameters are kept identical to those listed for the ‘Slow wind’ model in Table 4 and shown in the first row of Fig. B1.

In general, the differences between the absorption profiles for these variants appear small. The strongest visible impact is for $\Delta PA = +10$ deg (corresponding to $\alpha = 71$ deg for quasar and $\alpha = -119$ deg for *back1*). In this case, the Mg I absorption profile is not double-peaked and the Mg II absorption in the *back1* sightline is visibly weaker than in the fiducial model. The double peak is absent, because the distance from the minor axis is larger than in the fiducial case and, consequently, the quasar sightline does not cross the hollow part of the cone. The weaker Mg II absorption for *back1* is also a consequence of a larger distance from the minor axis. At $\alpha = -119$ deg part of the extended *back1* galaxy sightline is no longer covered by the cone at all, which reduces the effective $EW_0^{\lambda 2796}$.

In Fig. B2, we test the impact of the same i and PA variations, but now for the ‘Disc’ model (see Table 4). Here, the differences in absorption strength appear stronger than in the wind case. This is especially the case for changes in i . Here, the strength varies – especially for the Mg I absorption in the quasar sightline – as the sightline crosses the disc mid-plane at larger galactocentric radii, the larger the i is. We note, though, that most of the changes could be compensated for by merely choosing a disc with higher density. For the variations with PA, the centroid of the absorption shifts, but only slightly.

In summary, we can conclude that the uncertainties on i and PA/ α , as estimated in Appendix A, only subtly change our simulated profiles. Therefore, we can decide that our conclusions in Section 5 are not impacted by these uncertainties.

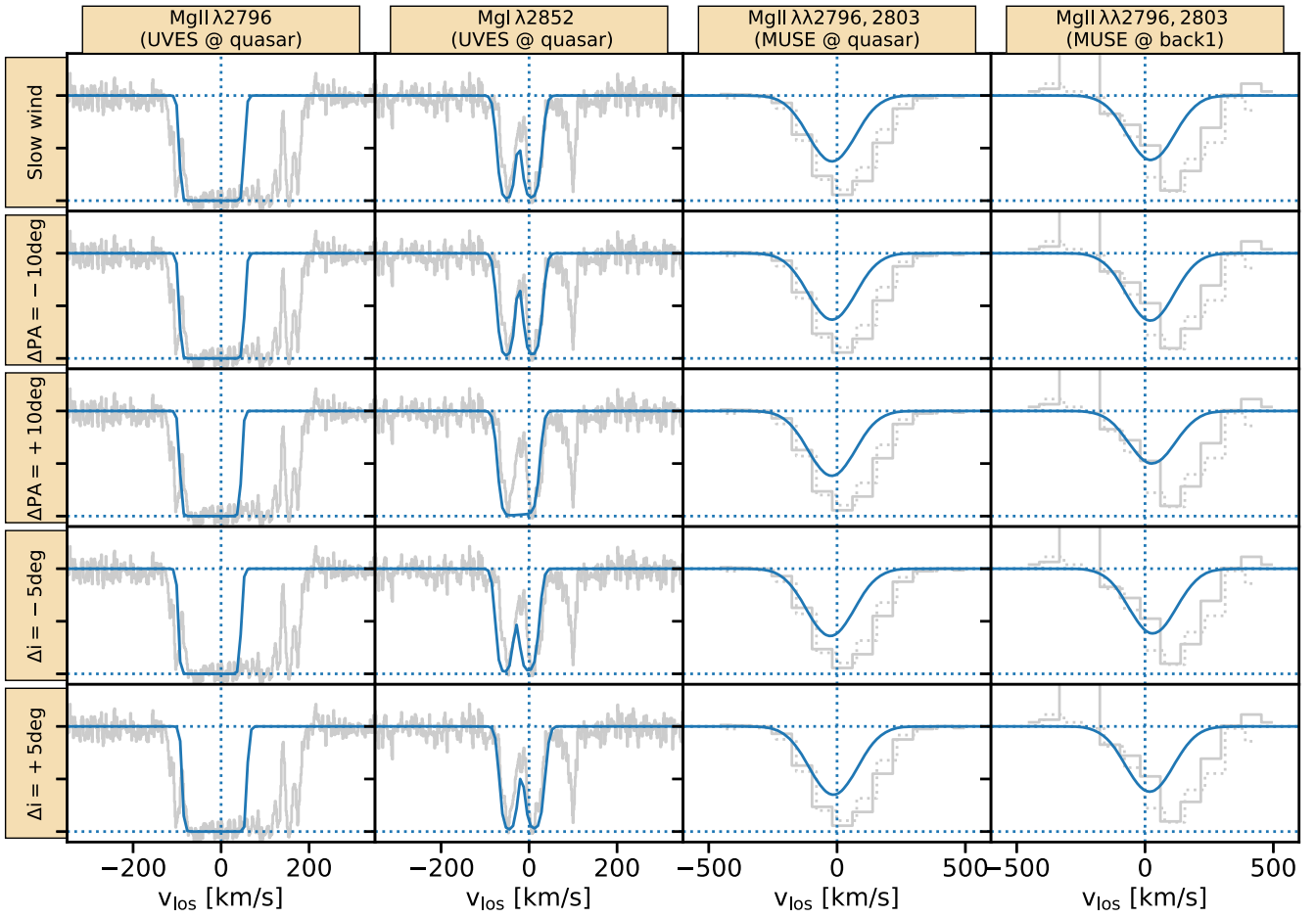


Figure B1. Comparison between modelled and observed absorption for the ‘Slow wind’ model, assuming different inclinations and position angles. The first row is identical to row 2 in Fig. 4, where the best-fitting i and PA were assumed. Details about the content displayed in the four columns are given in the caption of Fig. 4. The subsequent rows (2–5) show the same model, but with i or PA changed by the values stated in the row labels. For further details, see Appendix B.

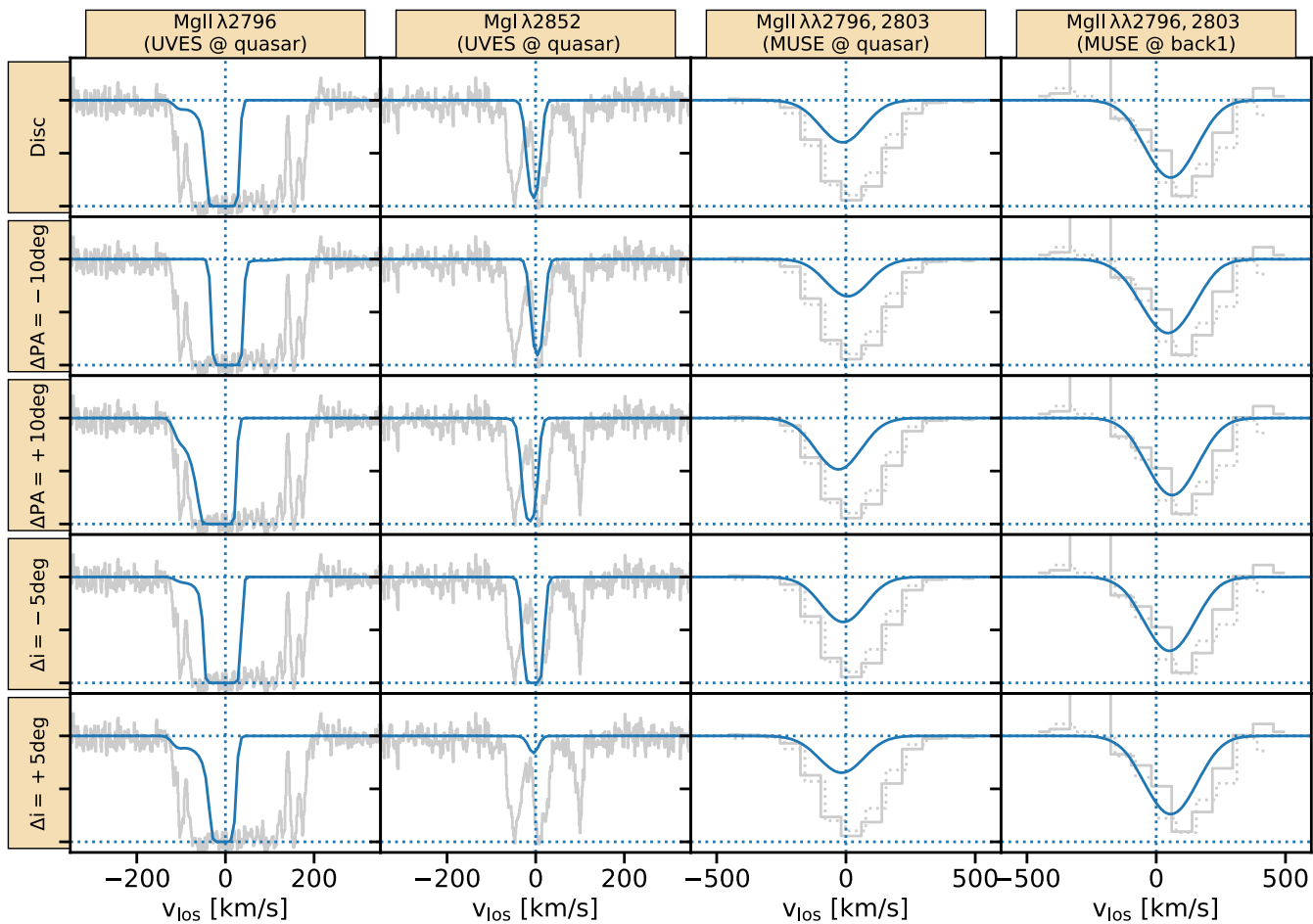


Figure B2. As Fig. B1, but here for the ‘Disc’ model (cf. row 3 in Fig. 4). For further details, see Appendix B.

This paper has been typeset from a $\text{\TeX}/\text{\LaTeX}$ file prepared by the author.