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# MusE GAs FLOW and Wind (MEGAFLOW) III: galactic wind properties using background quasars <sup>\*</sup>

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## ABSTRACT

We present results from our on-going MusE GAs FLOW and Wind (MEGAFLOW) survey, which consists of 22 quasar lines-of-sight, each observed with the integral field unit (IFU) MUSE and the UVES spectrograph at the ESO Very Large Telescopes (VLT). The goals of this survey are to study the properties of the circum-galactic medium around  $z \sim 1$  star-forming galaxies. The absorption-line selected survey consists of 79 strong Mg II absorbers (with rest-frame equivalent width (REW)  $\geq 0.3 \text{ \AA}$ ) and, currently, 86 associated galaxies within 100 projected kpc of the quasar with stellar masses ( $M_*$ ) from  $10^9$  to  $10^{11} M_\odot$ . We find that the cool halo gas traced by Mg II is not isotropically distributed around these galaxies from the strong bi-modal distribution in the azimuthal angle of the apparent location of the quasar with respect to the galaxy major-axis. This supports a scenario in which outflows are bi-conical in nature and co-exist with a coplanar gaseous structure extending at least up to 60 to 80 kpc. Assuming that absorbers near the minor axis probe outflows, the current MEGAFLOW sample allowed us to select 26 galaxy-quasar pairs suitable for studying winds. From this sample, using a simple geometrical model, we find that the outflow velocity only exceeds the escape velocity when  $M_* \lesssim 4 \times 10^9 M_\odot$ , implying the cool material is likely to fall back except in the smallest halos. Finally, we find that the mass loading factor  $\eta$ , the ratio between the ejected mass rate and the star formation rate (SFR), appears to be roughly constant with respect to the galaxy mass.

**Key words:** galaxies: evolution — galaxies: formation — galaxies: intergalactic medium — quasars: absorption lines —

## 1 INTRODUCTION

Galaxies form by the cooling and condensation of baryons at the centers of dark matter halos in an expanding universe (e.g. Rees & Ostriker 1977; White & Rees 1978). As originally described in White & Frenk (1991), in halos where the cooling time is shorter than the dynamical time, galaxies are expected to contain their fair share of baryons, namely  $f_B = 17\%$ , given by the cosmological baryon fraction  $\Omega_b/\Omega_m$ . However, galaxies contain, on average, only 10% and at most 20% of their share of baryons (e.g. Guo et al. 2010; Behroozi et al. 2013).

<sup>\*</sup> Based on observations made at the ESO telescopes at La Silla Paranal Observatory under programme IDs 094.A-0211(B), 095.A-0365(A), 096.A-0164(A), 097.A-0138(A), 099.A-0059(A), 096.A-0609(A), 097.A-0144(A), 098.A-0310(A), 293.A-5038(A).

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This low baryon fraction, often referred to as the galaxy formation ‘efficiency’ defined as  $M_*/(f_B M_h)$ , strongly depends on halo mass (e.g. Guo et al. 2010; Behroozi et al. 2013). In halos with mass below  $10^{12} M_\odot$ , the decline is directly connected to the faint-end slope of the luminosity function, and galactic (super-)winds from star-forming galaxies are thought to play a major role in causing this decline, as originally proposed by Larson (1974) who noted that the impact of supernovae (SNe) on star formation would be the highest in small halos (see also Dekel & Silk 1986). The galactic wind scenario is attractive as it is also thought to play a major role in enriching the inter-galactic medium (e.g. Aguirre et al. 2001, 2005; Madau et al. 2001; Theuns et al. 2002).

Theoretically, the successes of cosmological simulations often rely on the specifics of the feedback implementation (e.g. Schaye et al. 2010; Scannapieco et al. 2012; Vogelsberger et al. 2013; Crain et al. 2015). These implementations depend on sub-grid prescriptions, such as the wind mass loading factor  $\eta \equiv \dot{M}_{\text{out}}/\text{SFR}$  for kinetic implementation of feedback. An alternative way to implement the SN-driven outflows relies on a (stochastic) implementation of thermal feedback, where galactic winds develop without imposing any input outflow velocity or mass loading factor such as in the EAGLE simulations (e.g. Schaye et al. 2015), the FIRE simulations (Hopkins et al. 2012, 2014; Muratov et al. 2015), and the multi-phase scheme of Barai et al. (2015). For instance, Hopkins et al. (2012, 2018) predict that the loading factor is inversely proportional to the galaxy stellar mass, which is in agreement with simple momentum conservation expectations but found additional dependencies on star formation rate (SFR) surface density.

Observationally, assumed SN-driven winds are found to be ubiquitous in star-forming galaxies both at low (e.g. Heckman et al. 1990; Heckman et al. 2017; Shopbell & Bland-Hawthorn 1998; Pettini et al. 2002; Veilleux et al. 2005; Martin 2005; Sato et al. 2009; Martin & Bouché 2009; Arribas et al. 2014) and at high-redshifts (e.g. Shapley et al. 2003; Förster Schreiber et al. 2006; Weiner et al. 2009; Chen et al. 2010a; Steidel et al. 2010; Kornei et al. 2012; Martin et al. 2012; Bordoloi et al. 2014; Rubin et al. 2014; Sugahara et al. 2017; Förster Schreiber et al. 2018).

Traditionally, galactic winds are found from blue-shifted absorption lines of low-ionization ions such as Na D galaxy spectra (see reviews in Veilleux et al. 2005; Bland-Hawthorn et al. 2007a; Heckman & Thompson 2017) or other ions in the rest-frame UV spectra of galaxies (e.g. Chisholm et al. 2015; Chisholm et al. 2016b; Sugahara et al. 2017; Förster Schreiber et al. 2018). Galactic winds can also be studied using various other observational techniques using their emission (X-ray, H $\alpha$  or CO) properties (e.g. Arribas et al. 2014; Newman et al. 2012; Bolatto et al. 2013; Cicone et al. 2016, 2017; Falgarone et al. 2017), their UV fluorescent emission (e.g. Rubin et al. 2011; Martin et al. 2013; Tang et al. 2014; Zhu et al. 2015; Finley et al. 2017), or far-infrared spectra (e.g. Sturm et al. 2011; González-Alfonso et al. 2017; Spilker et al. 2018).

There are two main results from these studies. First, galactic outflows appear to be collimated (e.g. Chen et al. 2010a; Bordoloi et al. 2011, 2014; Lan et al. 2014a; Rubin et al. 2014) consistent with a bi-conical flow with a cone opening angle  $\theta_{\text{max}}^1$  that is approximately  $30^\circ$  to  $40^\circ$  from the minor axis of the host galaxy. Second, absorption lines in galaxy spectra give an accurate measurement of the outflowing gas velocity  $V_{\text{out}}$ , which is typically  $200 \text{ km s}^{-1}$  (depending on the SFR; Martin 2005), but this method has a major weakness: it gives a very poor constraint on one key property, namely the mass outflow rate, due to the unknown location of the absorbing gas, which can be located 0.1, 1 or even 10 kpc away from the host galaxy. To illustrate the degree of uncertainty in the assumptions made in the recent literature, Heckman et al. (2015); Heckman et al. (2017) assumed a wind launch radius of  $2 \times R_e$  and spherical symmetry, Chisholm et al. (2015) used a launch radius of 5 kpc, Arribas et al. (2014) assumed a wind launching radius of 0.7 kpc while Chisholm et al. (2016b,a, 2017) puts the wind material at  $< 100 \text{ pc}$  (inferred from the ionization correction).

This unknown gas location leads to large uncertainties (orders of magnitude) on the ejected mass rate  $\dot{M}_{\text{out}}$ , preventing accurate determination of the outflow rate, which increases with the square of the distance. Consequently, the loading factor  $\eta$  and its dependence on galaxy properties has not been determined unequivocally. In order to make further progress and to put strong constraints on models, we need to constrain outflow properties using objects for which the gas location can be better determined.

Background quasars naturally provide information on the location of the gas (from the impact parameter  $b$ ), and thus have the potential to lead to higher accuracy in the wind mass outflow rates and loading factors (e.g. Bouché et al. 2012; Kacprzak et al. 2014; Schroetter et al. 2015, 2016; Muzahid et al. 2015; Rahmani et al. 2018). Using this background quasar technique, the geometric uncertainty on the mass outflow rate goes from several dex to a factor of two or three.

This method suffers from the difficulty in finding large numbers of galaxy–quasar pairs, but this can be remedied with appropriate observational strategies. Over the past few years, the availability of large catalogs of the common low-ionization Mg II  $\lambda\lambda 2796, 2803$  absorption in the optical spectra of large samples of quasars from the Sloan Digital Sky Survey (Lan et al. 2014b; Zhu et al. 2015) has changed the situation.

In Schroetter et al. (2016, hereafter paper I), we presented the first results from this program, the MUSE Gas Flow and Wind (MEGAFLOW) survey, which aims to collect a statistically significant sample of approximately one hundred galaxy–quasar pairs in 22 quasar fields with multiple Mg II absorbers. In Zabl et al. (2019, hereafter paper II), we analyze

<sup>1</sup> where  $\theta_{\text{max}}$  is the half-opening angle of a bi-conical flow underling an area  $\Sigma$  of  $\pi \cdot \theta_{\text{max}}^2$ .

the sub-sample of galaxy-quasar pairs suitable for constraining the properties of accreting gas. In this paper, we present and analyze the pairs suitable to constrain outflow properties. The full MEGAFLOW survey will be presented in Bouché et al. (in prep.).

This paper is organized as follows. In section § 2, we present the MEGAFLOW observational strategy. The data acquisition is described in section § 3. Our sample selection is presented in section § 4. The analysis of our sample is presented in section § 5 while the wind modeling and results are described in section § 6. Finally, we present our conclusions in section § 7.

Throughout, we use a cosmology of 737 and the Chabrier (2003) stellar Initial Mass Function (IMF).

## 2 MEGAFLOW: SURVEY STRATEGY

Most of the work on the low-ionization, cool ( $T \sim 10^4$  K) component of the circum-galactic medium (CGM) has been focused on the Mg II  $\lambda$  2796, 2803 doublet absorption in quasar spectra (Bergeron 1988; Bergeron & Boissé 1991; Bergeron et al. 1992; Steidel et al. 1995, 1997, 2002). However, finding the galaxy counterpart for the Mg II absorption is often a complicated process. Indeed, it requires deep pre-imaging in order to identify host-galaxy candidates (and to allow the determination of the morphology/inclination) and multi-object spectroscopy, with the quasar blocking the view directly along the line-of-sight as an additional problem. Furthermore, one must also perform expensive follow-up campaigns to determine the galaxy kinematics.

Several groups have developed this imaging+multi-object spectroscopy technique using ground-based imaging (e.g. Chen & Tinker 2008; Chen et al. 2010c,b; Zhu et al. 2018; Rubin et al. 2018), but usually these lack the spatial resolution to untangle the morphological information, which is crucial to understand the absorption kinematics (e.g. Bordoloi et al. 2011; Bouché et al. 2012; Kacprzak et al. 2012). Thus, arguably the best sample of Mg II based galaxy-quasar pairs with morphological data is the MAGICAT sample (Churchill et al. 2013; Nielsen et al. 2013a,b, 2015, 2016), which consists of more than 100 foreground isolated galaxies at  $0.3 < z < 1.0$  imaged with *HST*, and with quasar impact parameters ranging from 20 to 110 kpc. However, as mentioned, the imaging+multi-object spectroscopy technique suffers from several disadvantages: (i) it requires pre-imaging and pre-identification of host-galaxy candidates based on the continuum light, thus leading to biases against emission-line galaxies; (ii) it is nearly impossible close to the line-of-sight (LOS); (iii) it is inefficient, requiring multiple campaigns, for imaging, for redshift identification, and for kinematics determination (e.g. Ho et al. 2017).

These shortcomings can be bypassed using integral field units (IFUs) data where the galaxy counterpart(s) can be readily identified at once (i.e. without pre-imaging, without knowing its location a priori). This identification can be from either emission lines or e.g. H&K and Balmer absorption lines for passive galaxies. In addition, the galaxy kinematics are part of the data, the morphological information can also be determined from 3D data (Bouché et al. 2015b; Contini et al. 2016) and the PSF can be more easily subtracted in 3D. With the VLT/MUSE instrument (Bacon et al. 2006, 2010, 2015) and its exquisite sensitivity, one can now detect galaxies further away ( $\approx 250$  kpc away at  $z = 1$ ) thanks to its field of view of  $1' \times 1'$  compared to  $8'' \times 8''$  for VLT/SINFONI. The large wavelength coverage of MUSE (4700Å to 9300Å) allows us to target quasar fields with multiple Mg II  $\lambda$  2796, 2803 absorption lines having redshifts from 0.4 to 1.5 for [O II]  $\lambda$  3727, 3729 identification. In the up-coming years, MUSE's Adaptive-Optics (AO) module will increase the quality of data, and the efficiency of such surveys.

The MEGAFLOW survey (papers I, II) aims at observing a statistical number (80+) of galaxy-quasar pairs to allow analysis of the relation between the absorption and the host galaxy properties. From the Zhu and Ménard Mg II catalog based on SDSS (Zhu & Ménard 2013), we selected quasars with multiple ( $N \geq 3$ ) Mg II  $\lambda$  2796, 2802 absorption lines with redshifts between 0.4 and 1.4 and with a Mg II  $\lambda$  2796 rest-equivalent width (REW)  $W_r^{\lambda 2796} \gtrsim 0.5 \text{Å}$ . The former criteria of having multiple absorbers in one quasar field, ensures that a large number of galaxy-quasar pairs of 80+ is reachable with 20–25 quasar fields. The latter criteria ensures that the host galaxies are within 100 kpc from the quasar LOS (at  $z \approx 1$ ), i.e. within the MUSE field-of-view, given the well known anti-correlation between the impact parameter and  $W_r^{\lambda 2796}$  (Lanzetta & Bowen 1990; Steidel 1995).

Overall, the MEGAFLOW survey is made of 22 quasar fields, with each quasar spectrum having at least 3 strong ( $W_r^{\lambda 2796} > 0.5 \text{Å}$ ) Mg II absorbers, over the redshift range between 0.4 and 1.5. Including a few serendipitous systems with  $0.3 < W_r^{\lambda 2796} < 0.5 \text{Å}$ , the survey contains a total of 79 Mg II absorbers with  $W_r^{\lambda 2796} > 0.3 \text{Å}$ .

## 3 DATA

### 3.1 MUSE Observations and data reduction

We use the MUSE observations from the MEGAFLOW survey taken from September 2014 to July 2017 during Guaranteed Time Observations (GTO) runs. The observations were optimized to cover the inner  $20''$  region uniformly by placing the quasar  $\approx 5''$  from the field center, by using small sub-pixel dithers and a rotation of  $90^\circ$  between each exposure. The individual exposure time ranges from 900 to 1500s. The resulting total exposure time per field ranges from two to four hours (See Table 1).

**Table 1.** Summary of MUSE observations

Field (1)	Program ID (2)	Exp. time (3)	Obs date (4)	Seeing (5)
SDSSJ0014m0028	095.A-0365(A), 096.A-0164(A)	6300	2015-08-24, 2015-09-11 & 10-13	0.78
SDSSJ0014p0912	094.A-0211(B)	10800	2014-10-20 10-21 10-25	0.85
SDSSJ0015m0751	096.A-0164(A), 097.A-0138(A), 099.A-0059(A)	9000	2015-10-10&11, 2016-09-01, 2017-09-22	0.80
SDSSJ0058p0111	096.A-0164(A), 097.A-0138(A)	7200	2015-11-09 2016-08-30	0.77
SDSSJ0103p1332	096.A-0164(A)	7200	2015-11-12 11-13	0.84
SDSSJ0131p1303	094.A-0211(B), 099.A-0059(A)	7200	2014-10-28 2017-09-23 09-24	0.81
SDSSJ0134p0051	096.A-0164(A), 097.A-0138(A)	7200	2015-10-15&16, 2016-09-01, 2017-09-25	0.73
SDSSJ0145p1056	096.A-0164(A), 097.A-0138(A)	6000	2015-11-13 2016-08-30	0.85
SDSSJ0800p1849	094.A-0211(B)	7200	2014-12-25	0.56
SDSSJ0838p0257	096.A-0164(A)	12000	2016-02-02 02-03	0.54
SDSSJ0937p0656	095.A-0365(A)	7200	2015-04-15 04-16 04-18	0.67
SDSSJ1039p0714	097.A-0138(A)	12000	2016-04-07 04-08 04-09	0.61
SDSSJ1107p1021	096.A-0164(A)	12000	2016-03-12	0.70
SDSSJ1107p1757	095.A-0365(A)	7200	2015-04-23 04-24	0.88
SDSSJ1236p0725	096.A-0164(A)	6000	2016-03-13	0.91
SDSSJ1314p0657	097.A-0138(A)	6000	2016-04-07 04-08	0.53
SDSSJ1352p0614	099.A-0059(A)	6000	2017-04-23 04-24	0.98
SDSSJ1358p1145	097.A-0138(A)	6000	2016-04-10	0.54
SDSSJ1425p1209	097.A-0138(A)	3600	2016-05-12	0.96
SDSSJ1509p1506	099.A-0059(A)	3000	2017-04-23	0.70
SDSSJ2137p0012 <sup>†</sup>	094.A-0211(B)	3600	2014-09-20 09-24	0.74
SDSSJ2152p0625	094.A-0211(B)	7200	2014-09-25	0.58

(1) Quasar field name; (2) Program ID; (3) Total exposure time (in seconds); (4) Observation dates of the field; (5) Seeing FWHM (in  $''$ ) from a Moffat fit of the QSO at 7000 Å; <sup>†</sup> 3 hours of this field were rejected due to bad seeing conditions ( $> 1.2''$ ).

The data are reduced as described in paper II where we used version 1.6 of the MUSE data reduction software (DRS; [Weilbacher et al. 2014, 2016](#)) pipeline. Briefly, the reduction includes an additional step on the pixtables called 'auto-calibration' described in [Bacon et al. \(2017\)](#), which removes the slight variations in the background level in each slice of each IFU caused by imperfections in the flat-fielding. After performing the self-calibration, we resampled the pixtables onto datacubes with the sky subtraction, barycentric correction turned on. Finally, we used the *Zurich Atmosphere Purge (ZAP)* software ([Soto et al. 2016a,b](#)) to remove skyline residuals from each datacube. Finally, we combined the individual cubes weighted by the inverse of the seeing full width half maximum (FWHM) when needed.

### 3.2 UVES Observations and data reduction

Because we are interested in constraining the kinematics of gas surrounding star-forming galaxies, we need quasar spectra with a resolution better than MUSE (which has  $R \sim 2000$  or 150 km/s) in a wavelength range not covered by MUSE (4700-5000Å). We choose high-resolution spectroscopy of the quasars with the VLT/UVES instrument.

The 22 quasar fields were observed with the high-resolution spectrograph UVES ([Dekker et al. 2000](#)) between 2014 and 2016 (Table 2). The settings used in our observation were chosen in order to cover the Mg II  $\lambda\lambda 2796, 2803$  absorption lines and other elements like Mg I  $\lambda 2852$ , Fe II  $\lambda 2586$  when possible. The details of the observational campaigns are presented in Table 2. A slit width of 1.2 arcsec and a CCD readout with 2x2 binning were used for all the observations, resulting in a spectral resolving power  $R \approx 38000$  dispersed on pixels of  $\approx 1.3$  km s<sup>-1</sup>. The Common Pipeline Language (CPL version 6.3) of the UVES pipeline was used to bias correct and flat field the exposures and then to extract the wavelength and flux calibrated spectra. After the standard reduction, the custom software UVES Popler ([Murphy 2016](#), version 0.66) was used to combine the extracted echelle orders into single 1D spectra. The continuum was fitted with low-order polynomial functions.



**Table 2.** Summary of UVES observations

Field (1)	Program ID (2)	Exp. time (3)	Obs date (4)	Setting (5)	seeing (6)
SDSSJ0014m0028	096.A-0609(A)	9015	2015-10-04	DIC1 390+564	0.81
SDSSJ0014p0912	096.A-0609(A), 098.A-0310(A)	7493	2015-11-10, 2016-10-29	DIC1 390+564; DIC2 437+760	0.66
SDSSJ0015m0751	098.A-0310(A)	12020	2016-10-30 12-28 12-29	DIC1 390+564	0.69
SDSSJ0058p0111	098.A-0310(A)	2966	2016-12-30 12-31	DIC1 390+564; DIC2 437+760	0.52
SDSSJ0103p1332	098.A-0310(A)	9015	2016-10-29 10-30 11-02	DIC1 390+564	0.60
SDSSJ0131p1303	096.A-0609(A)	6010	2015-10-15	DIC1 390+580	1.03
SDSSJ0134p0051	098.A-0310(A)	7193	2016-10-30 12-04	DIC1 390+580; DIC2 437+760	0.57
SDSSJ0145p1056	096.A-0609(A), 097.A-0144(A), 098.A-0310(A)	12020	2015-11-12, 2016-09-04, 2016-10-29	DIC1 390+564	0.63
SDSSJ0800p1849	096.A-0609(A)	6010	2015-12-11	RED 520	0.90
SDSSJ0838p0257	096.A-0609(A), 098.A-0310(A)	2966	2015-11-21, 2016-12-23	DIC1 390+564; RED 600	0.76
SDSSJ0937p0656	096.A-0609(A)	9015	2015-12-21 2016-01-12 03-08	DIC1 390+564	0.74
SDSSJ1039p0714	097.A-0144(A)	9015	2016-04-04	DIC1 346+580	0.76
SDSSJ1107p1021	096.A-0609(A)	6010	2016-02-10 03-08	DIC1 390+580	1.02
SDSSJ1107p1757	096.A-0609(A)	9015	2016-01-12 03-07 03-08	DIC2 437+760	0.99
SDSSJ1236p0725	096.A-0609(A), 097.A-0144(A)	7493	2016-03-07, 2016-04-07	DIC2 437+760; RED 600	0.61
SDSSJ1314p0657	097.A-0144(A)	1483	2016-04-07	DIC1 390+564	0.46
SDSSJ1352p0614	097.A-0144(A)	1483	2016-05-31 06-01	DIC2 437+760	0.70
SDSSJ1358p1145	097.A-0144(A)	2966	2016-04-07	DIC1 390+564; DIC2 346+860	0.51
SDSSJ1425p1209	097.A-0144(A)	2966	2016-04-07 06-01	DIC1 390+564; RED 520	0.56
SDSSJ1509p1506	097.A-0144(A)	6010	2016-04-04 04-07	RED 600	0.57
SDSSJ2137p0012	293.A-5038(A)	4487	2014-10-19	DIC1 390+564	0.99
SDSSJ2152p0625	293.A-5038(A)	9015	2014-10-21 10-24 11-18	DIC1 390+580	1.21

(1) Quasar field name; (2) Program ID; (3) Total exposure time (in seconds); (4) Observation dates of the quasar; (5) Instrument setting; (6) average seeing FWHM (")

## 4 SAMPLE SELECTION

### 4.1 Galaxy detection

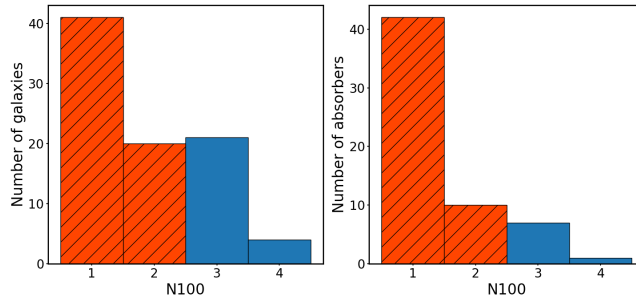
In each of the 22 quasar fields, we search for galaxies (emitters and/or passive) responsible for the Mg II absorption lines. In order to find the potential host galaxy/ies, we run our detection algorithm as described in paper II. Briefly, the algorithm is designed to detect galaxies using both emission lines and absorption lines using pseudo narrow-band (NB) images made of, depending on the redshift, [O II], H $\beta$ , Ca H&K, and/or O III $\lambda$ 5007 over a velocity range of 400 km s<sup>-1</sup>. The NB images were created for each absorber, at three different velocity offsets from the absorber redshifts. Finally, galaxy candidates are detected on these pseudo NB images using the source detection algorithm *SExtractor* (Bertin & Arnouts 1996). We optimized *SExtractor* in order to detect low signal-to-noise ratio (SNR) objects and ensure completeness, leading to a significant fraction of false positives, which had to be removed manually.

Using the wavelength dependent per-pixel noise, we derive a typical 5 $\sigma$  detection limit of  $\approx 4 \times 10^{-18} \times (\text{FWHM}_{\text{Moffat}}/0''.6) \times (\text{T}_{\text{exp}}/6\text{ks})^{-0.5} \text{ erg s}^{-1} \text{ cm}^{-2}$  (see paper II) centered at 7000 Å. This corresponds to an un-obscured SFR limit of 0.07M $_{\odot} \text{ yr}^{-1}$  using [O II] emission line.

#### 4.1.1 Redshifts

For all the detected galaxies, we determined their redshifts using three methods. For all three methods we use the MUSE data. The first method consists in manually deriving the redshift of each galaxy using the [O II] emission line position. The central position of the line is given by a Gaussian fit. A pseudo long slit is also used on each galaxy (along the apparent PA of the galaxy) to obtain a 2D spectrum which provides an additional redshift measurement. In the second method, we use a line fitting code which fits the [O II] doublet automatically using a double Gaussian. Using the output of a 3D fitting tool called GalPaK<sup>3D</sup> (Bouché et al. 2015a) is the third method we employ to derive galaxy redshifts. Some details on GalPaK<sup>3D</sup> are given below.

Each of those methods gives us with a redshift for each galaxy. Those redshifts are consistent with each other and differ by only a few km s<sup>-1</sup>. We choose to use redshifts derived by the line fitting method as the standard deviation of the redshift differences (between manual and automatical fits) is lower (15 km s<sup>-1</sup>) than the one using GalPaK<sup>3D</sup> (26 km s<sup>-1</sup>). Thus, throughout this paper we use the systemic redshifts derived by the line fitting method (i.e. method 2).



**Figure 1.** Histogram of N100, the number of galaxies at the redshift of an absorber separated by less than 100 kpc, for the 86 galaxy-quasar pairs (left) and the 59 absorbers (right). Out of the 86 pairs (59 absorbers), 61 (51) have  $N100 \leq 2$  (hashed), respectively

## 4.2 Absorber-galaxy pairs: Parent sample

From our 22 quasar fields, we have found 165 galaxies around 79 absorbers with  $W_r^{\lambda 2796} \geq 0.3 \text{ \AA}$ . Those detected galaxies lie at impact parameters from 0 to 350 kpc from the QSO LOS. Among these 165 galaxies, 86 have an impact parameter smaller than 100 kpc out of 59 Mg II absorbers.

In order to avoid groups of galaxies, we restricted the sample to absorbers with at most two ( $\leq 2$ ) galaxies within 100 transverse kpc from the QSO LOS. Among these 86 galaxies, there are 61 galaxies with  $N100 \leq 2$ , where N100 is the number of galaxies within 100 kpc. These 61 galaxies correspond to 51 Mg II absorbers. The N100 distribution is presented in Figure 1 where the 61 pairs are represented by hashed regions (on left panel for galaxies and on right panel for absorbers). 41 of the 61 galaxies are “isolated” (i.e. with  $N100=1$ ). For those galaxies we also search for secondary neighbors at  $b > 100$  kpc and a separation lower than 50 kpc. We only found two cases of two independent primary galaxies with a secondary companion within approximately 40 kpc. Those two primary galaxies are not matching our selection criteria described later in the text (i.e. inclination and azimuthal angle).

## 4.3 Absorber-galaxy pairs: Morphology selection

From this parent sample of 61 pairs, we wish to select those for which the location of the line of sight to the quasar is favorable for intercepting outflows, assuming that outflows are oriented along the galaxy’s minor axis (as in Bouché et al. 2012; Schroetter et al. 2015, 2016). To do so, we select galaxy-quasar pairs where the apparent quasar location is within  $\approx 30^\circ$  of the galaxy’s minor-axis. Defining  $\alpha$  as the azimuthal angle between the galaxy’s major axis and the apparent quasar location, we divide the pairs into two classes: “wind-pair” and “inflow-pair” for pairs with  $55^\circ \leq \alpha \leq 90^\circ$  and  $0^\circ \leq \alpha \leq 40^\circ$  respectively.

For each of the 61 galaxies, the orientation is derived using the 3D fitting tool called GalPaK<sup>3D</sup> from Bouché et al. (2015a). This algorithm uses a parametric disk model with 10 free parameters (such as total line flux, half-light radius, inclination, maximum rotation velocity, velocity dispersion and position angle [PA] of the major-axis) and an MCMC algorithm in order to efficiently probe the parameter space. The algorithm also uses a 3-dimensional kernel to account for the instrument PSF and line spread function (LSF). GalPaK<sup>3D</sup> thus returns the “intrinsic” galaxy properties.

Extensive tests presented in Bouché et al. (2015a) show that the algorithm requires data with a  $\text{SNR}_{\text{max}} > 3$  in the brightest pixel. However, for SNRs approaching this limit and for compact galaxies, degeneracies can appear, such as between the turn-over radius<sup>2</sup> and  $V_{\text{max}}$ .

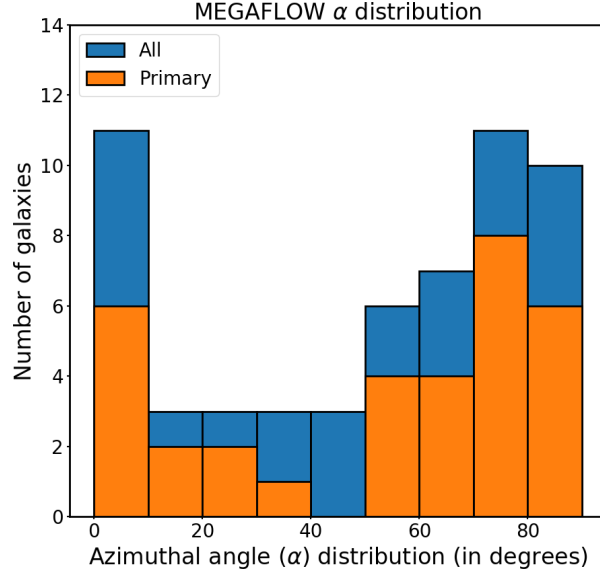
For each of the 61 galaxies, we checked manually the morpho-kinematical results as well as the GalPaK<sup>3D</sup> MCMC chains. We then flagged the results according to the following scheme:

- 0: when neither  $V_{\text{max}}$  nor the morphological parameters (PA, inclination) are constrained. This usually occurs for galaxies with a very low SNR, e.g. with flux lower than  $1.5 \times 10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2}$ .
- 1: when at least one morphological parameter (at least PA) is constrained.
- 3: when some of the kinematic parameters are either not well constrained or degenerate with other (e.g.  $V_{\text{max}}$ -inclination,  $V_{\text{max}}$ -turn-over radius).
- 5: when all of the morphological and kinematic parameters are constrained.

Given our  $\alpha$  cut, we select galaxies which have a reliable PA, i.e. with a flag  $\geq 1$ . From the 61 galaxies, this criterion brings our sample to 57 galaxies.

Figure 2 shows the distribution of azimuthal angle for the current MEGAFLOW sample. In this Figure, we also show

<sup>2</sup> which is defined by an arctan function for the rotation curve of the galaxy.



**Figure 2.** Azimuthal angle distribution of 57 selected galaxies (PA and inclination selected) from the MEGAFLOW survey in blue. In orange are the "primary" galaxies (see text). We note the bimodal distribution of the whole survey.

the subsample of galaxies that are the closest to the QSO LOS as well as being the brightest in [O II] flux/luminosity (defined as 'primary', see Paper II for more details). This azimuthal distribution of the primary galaxies (in orange) shows a clear bimodal behavior, confirming previous results (e.g. Bordoloi et al. 2011; Bouché et al. 2012; Kacprzak et al. 2012). This bimodal distribution means that the cool gas traced by Mg II is either along the galaxy minor axis or aligned with the disk and can be interpreted as the simultaneous signature of bi-conical outflows along the minor axis and an extended/infalling gaseous disk along the major-axis.

In this paper, we focus on outflowing gas around galaxies, and thus, we restrict ourselves to pairs whose azimuthal angle  $\alpha$  is larger than  $55^\circ$  (according to the bimodality of  $\alpha$  distribution), bringing our wind subsample to 31 wind pairs from the 57 galaxy-quasar pairs.

In addition, we impose a minimum [O II] flux of  $1.5 \times 10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2}$ , leaving 30 galaxies meeting this criterion. Finally, we set a minimum inclination of  $35^\circ$  in order to avoid face-on galaxies with inevitably large errors on the galaxy PA (and thus large errors on  $\alpha$ ), bringing our final subsample to 28 wind pairs.

Out of this subsample, we found two possible major mergers<sup>3</sup> and chose to not include them in the analysis. Thus, our wind sub-sample is made of 26 pairs. Out of those 26 pairs, 21 are "isolated" ( $N_{100} = 1$  and no other galaxy detected within 50 kpc transverse distance and within the searched velocity window from those galaxies).

#### 4.4 Final subsample selection summary

To summarize, from the 79 strong Mg II absorbers in our 22 fields, we identified one or more galaxies for 59 (75%). A total of 165 galaxies were detected, among which 86 galaxies are found within 100 kpc of the QSO LOS.

Out of these 86 galaxies within 100 kpc to the QSO LOS, we selected those with

- at most one companion, i.e.  $N_{100} \leq 2$ <sup>4</sup>: 61;
- with a well constrained PA (i.e. a flag  $\geq 1$ ): 57;
- that are suitable for studying winds, i.e. with an azimuthal angle  $\alpha \geq 55^\circ$ : 31;
- that have a [O II] flux greater than  $1.5 \times 10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2}$ : 30;
- have an inclination  $i \geq 35^\circ$ : 28;
- not be a major merger: 26.

In order to uniquely identify our galaxies, we adopt a specific nomenclature convention for them, like J0103p1332-1048-1-136 in Table 3 for instance. The first part of a galaxy name corresponds to the quasar field in which it belongs (J0103p1332 for 01:03:32.37 +13:32:36.05). Then the next numbers correspond to the absorber redshift (1048 for  $z = 1.048$ ), the impact

<sup>3</sup> Including the galaxy corresponding to J213748+0012G2 in Schroetter et al. (2016).

<sup>4</sup> we also searched for other companions further away from those galaxies and found none within 50 kpc.



**Table 3.** MEGAFLOW final wind pairs subsample

#	Galaxy name	redshift	$b$	incl	$V_{\max}$	$\sigma$	$r_{1/2}$	$\alpha$	Flux[O II]	flag	N100	comment
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
1	J0014m0028-0834-1-159	0.8340	9.7	86±3	8±5	40±3	3.0±0.1	89±0	0.31±0.01	5	1	
2	J0014m0028-1052-6-268	1.0536	52.4	65±5	44±15	77±4	3.5±0.2	80±3	0.35±0.01	5	1	
3	J0015m0751-0500-4-35	0.5073	24.1	87±2	262±11	35±4	6.6±0.2	71±1	0.72±0.01	5	1	H&K
4	J0015m0751-0731-5-3	0.7305	35.5	66±2	266±13	33±6	8.4±0.3	71±1	0.33±0.01	3	1	H&K
5	J0015m0751-0810-3-357	0.8160	20.7	38±3	284±26	45±7	2.4±0.2	73±4	0.35±0.01	3	1	H&K
6	J0103p1332-1048-1-136	1.0483	9.1	76±9	45±41	87±13	1.9±0.4	89±9	0.33±0.01	3	1	
7	J0131p1303-1010-3-45	1.0103	26.4	62±2	108±4	33±2	3.2±0.1	71±1	1.24±0.01	5	1	
8	J0131p1303-1104-9-351	1.1049	75.5	83±3	94±8	66±4	3.9±0.1	61±1	0.86±0.01	5	2	
9	J0145p1056-0770-1-93	0.7699	12.9	87±2	103±15	21±10	1.9±0.5	89±5	0.16±0.01	3	1	
10	J0800p1849-0843-3-254	0.8429	20.9	70±1	138±4	15±5	7.0±0.2	79±1	0.64±0.01	3	1	
11	J0800p1849-0993-9-282	0.9936	78.0	71±1	79±2	46±1	8.3±0.1	65±1	1.48±0.02	5	1	
12	J0937p0656-0702-10-197	0.7019	69.0	50±1	136±5	39±2	3.0±0.1	58±1	1.14±0.01	5	2	2nd; 13
13	J0937p0656-0702-6-209	0.7020	38.7	55±1	215±11	51±2	4.3±0.1	87±1	1.81±0.01	3	2	H&K; 2nd; 12
14	J0937p0656-0933-5-6	0.9337	41.4	77±1	107±7	44±2	4.6±0.1	75±1	0.91±0.01	5	1	
15	J1039p0714-0819-3-124	0.8192	24.5	73±1	243±6	30±5	6.7±0.2	63±1	0.23±0.01	5	1	H&K
16	J1039p0714-0949-9-344	0.9492	72.2	61±2	129±10	50±6	1.5±0.1	68±3	0.34±0.01	3	2	2nd; in paper II
17	J1039p0714-1359-1-123	1.3589	8.6	70±1	34±12	46±2	6.1±0.2	80±1	0.37±0.01	3	1	
18	J1107p1021-1015-10-272	1.0150	80.9	54±3	373±18	10±9	7.2±0.4	75±3	0.26±0.01	5	1	H&K
19	J1107p1757-1063-3-140	1.0637	22.1	77±7	75±14	45±6	2.2±0.3	78±7	0.39±0.01	5	1	
20	J1107p1757-1163-6-166	1.1618	44.4	57±5	113±13	44±4	4.5±0.3	88±4	0.78±0.03	5	2	2nd; low $i$ , accr
21	J1236p0725-0639-10-256	0.6382	66.9	68±1	230±10	24±6	6.7±0.2	70±1	0.85±0.01	5	2	H&K, 2nd closer
22	J1352p0614-0604-2-260	0.6039	14.0	80±7	35±11	24±8	3.8±0.5	79±1	0.29±0.02	5	1	
23	J1358p1145-0809-2-202	0.8093	12.7	65±2	61±5	47±2	2.5±0.1	80±2	0.55±0.01	5	1	
24	J1425p1209-0597-1-87	0.5968	9.6	54±1	56±3	6±4	0.9±0.1	64±2	1.09±0.02	5	1	compact
25	J1425p1209-0865-8-353	0.8657	60.8	43±2	101±5	18±2	3.4±0.1	59±2	1.02±0.01	5	1	
26	J2152p0625-1319-4-187	1.3181	32.5	71±6	82±16	37±6	4.3±0.4	88±4	0.19±0.01	3	1	has companion

(1) Galaxy number; (2) Extended name; (3) Redshift; (4) Impact parameter  $b$  (kpc) (with typical errors of  $\approx 0.2$  kpc); (5) inclination (degrees); (6) Maximum rotational velocity  $V_{\max}$  ( $\text{km s}^{-1}$ ); (7) Dispersion velocity  $\sigma$  ( $\text{km s}^{-1}$ ); (8) Half-light radius (kpc); (9) Azimuthal angle  $\alpha$  (degrees); (10) [O II] flux ( $\times 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2}$ ); (11) GalPaK<sup>3D</sup> flag; (12) N100, the number of galaxies for one absorber within 100 kpc; (13) Comments if needed.  
*Note.* Errors are  $1\sigma$ .

parameter (in arcseconds,  $1''$  for this pair) and finally the angle where the galaxy is located with respect to the QSO LOS (defined like the PA of a galaxy,  $136^\circ$ ).

## 5 RESULTS

### 5.1 Radial dependence: How far do winds propagate?

For the 26 wind-pairs in our sample, we investigate the radial dependence of  $W_r^{\lambda 2796}$  as a function of impact parameter  $b$ . Figure 3 shows the Mg II REW<sup>5</sup> as a function  $b$  for each of the 26 galaxies. The blue squares are the MEGAFLOW wind-pairs whereas orange circles are from the SINFONI-based SIMPLE sample (Bouché et al. 2007; Schroetter et al. 2015). Hexagons correspond to the MEGAFLOW pairs for which N100=2. Dark stars and cyan crosses are wind-pairs from Bordoloi et al. (2011)<sup>6</sup> and Kacprzak et al. (2011) respectively. We choose not to include the fit from MAGIICAT (Nielsen et al. 2013b) since we are only showing the wind-selected galaxies and they do not make such selection. The dashed line shows the relation  $W_r^{\lambda 2796} \propto b^{-1}$  expected for a bi-conical geometry and mass conservation from Bouché et al. (2012). It is evident from this figure that an anti-correlation between  $W_r^{\lambda 2796}$  and  $b$  appears to be consistent with the  $b^{-1}$  expectation. In other words, it seems that galactic outflows (as traced by strong Mg II absorbers) are able to travel at least 80-100 kpc away from their host galaxy. In section § 6.3, we will address the question whether the clouds escape the potential well of the host.

### 5.2 Galaxy properties

#### 5.2.1 Stellar Mass

Our sample of galaxy-absorber pairs is Mg II absorption selected sample. We therefore investigate whether the host galaxies are normal star-forming galaxies, i.e. whether they lie on the SFR– $M_*$  main sequence (MS). Any deviations from the MS could shed light on the connection between outflow properties and star-formation activity.

We first estimate the galaxy stellar masses from the tight correlation between stellar mass and the dynamical estimator  $S_{0.5} = \sqrt{0.5 \times V_{\max}^2 + \sigma^2}$  (e.g. Weiner et al. 2006; Kassin et al. 2007; Price et al. 2016; Straatman et al. 2017; Alcorn et al. 2018; Aquino-Ortiz et al. 2018), which combines the galaxy dispersion velocity,  $\sigma^7$ , and its rotational velocity  $V_{\max}$ . Then, we use the following relation from Alcorn et al. (2018):

$$\log(S_{0.5}) = A \log(M_*/M_\odot - 10) + B \quad (1)$$

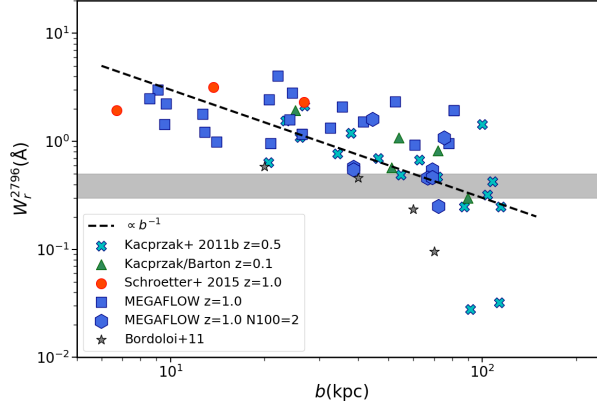
where the slope  $A = 0.34$  and the zero-point  $B = 2.05$ , appropriate for a Chabrier (2003) IMF.

For self-consistency, we checked that this relation (obtained from 2D spectra) agrees when the kinematics are determined with IFU 3D data, such as in our case using the kinematic 3D data-set obtained with MUSE at  $\approx 30$ hr depth. There are

<sup>5</sup> Mg II REW are from SDSS catalog and also derived from our UVES data for cross checking.

<sup>6</sup> as in their paper, due to low spectral resolution, they only have EWs for both Mg II components, we divided their values by a factor 2 in this Figure.

<sup>7</sup> Derived by GalPaK<sup>3D</sup>



**Figure 3.** Mg II ( $\lambda 2796$ ) rest equivalent width as a function of impact parameter  $b$  for galaxy-quasar pairs classified as wind-pairs. The REWs were measured from the UVES spectra. The gray area represents the REW selection criterion (see text). The thick black dashed line represents the expected  $W_r^{\lambda 2796} \propto b^{-1}$ . The blue square and hexagon below the threshold appears because we plot the UVES derived REWs whereas the survey threshold was for the SDSS spectra. The blue hexagons are the cases with 2 galaxies detected within 100 kpc from the QSO LOS.

two such data sets. The first one is from ? who presented the kinematic analysis of the Hubble-Deep-Field-South (HDFS Bacon et al. 2015), extending the Tully-Fisher (TF) relation to the low mass regime,  $M_{\star} = 10^8$ - $10^9 M_{\odot}$  for  $\approx 30$  galaxies. The second data set consists of  $\approx 300$  galaxies from Contini et al. (in prep.), who used the  $3' \times 3'$  MUSE mosaic of the Hubble-Ultra-Deep-Field (HUDF Bacon et al. 2017). The  $S05$ - $M_{\star}$  relation of Eq. 1 is found to be consistent with the MUSE results of Contini et al. (in prep.).

### 5.2.2 Star Formation Rate (SFR)

To estimate SFRs from [O II] fluxes, we proceed as in Paper II, namely, we use the  $M_{\star} - E(B - V)$  relation obtained by Garn & Best (2010) due to the lack of multiple lines and direct constraints on the amount of extinction,  $E(B - V)$ . The Garn & Best (2010) relation corrected from a Kroupa (2001) to a Chabrier (2003) IMF is:

$$E(B - V) = (0.93 + 0.77X + 0.11X^2 - 0.09X^3)/k_{H\alpha} \quad (2)$$

where  $X = \log(M_{\star}/M_{\odot}) - 10$  and  $k_{H\alpha} = 3.326$  for the Calzetti et al. (2000) extinction law. Errors on  $E(B - V)$  are calculated from the 0.3 mag scatter of this relation combined with the 0.15 dex error from the  $M_{\star}$  estimation.

We correct the observed [O II] luminosities  $L_o$  with these extinctions using a Calzetti et al. (2000) extinction curve. From these intrinsic luminosities  $L_i$ , we estimate the SFRs using the Kewley et al. (2004) calibration

$$SFR([\text{O II}]) = 4.1 \times 10^{-42} (L_i[\text{O II}] \text{ erg s}^{-1}) M_{\odot} \text{ yr}^{-1} \quad (3)$$

adjusted from a Salpeter (1955) to a Chabrier (2003) IMF.

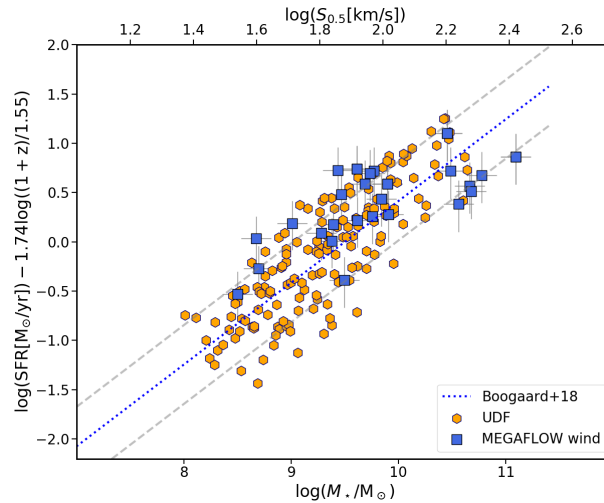
## 5.3 Main-Sequence

Having estimated stellar masses and star-formation rates, we can place our galaxies on the SFR- $M_{\star}$  diagram. Figure 4 shows the SFR- $M_{\star}$  diagram for the HUDF (orange hexagons) and the MEGAFLOW (blue squares) wind subsample. In this Figure, the SFRs and stellar masses were derived using the method described before and the MS is presented at a common redshift ( $z = 0.55$ ) using the redshift evolution from Boogaard et al. (2018). The MS relation obtained from the HUDF using different  $M_{\star}$  and SFR derivations is shown by the blue dashed line (Boogaard et al. 2018).

Figure 4 shows that the wind subsample from the MEGAFLOW survey tends to follow the galaxy MS. However, the data suggest that below  $\log(M_{\star}/M_{\odot}) \approx 10$ , our wind galaxies could be slightly above the galaxy MS, while galaxies above this mass tend to be preferentially below the MS, suggesting that these are in the process of quenching their SF. See Rhodin et al. (2018) for a similar result for HI-selected hosts.

## 6 WIND MODELING

Having measured the morpho-kinematic properties of our galaxies, we focus on deriving outflow properties. For the 26 wind-pairs, we attempt to constrain the wind kinematics using the same method as used in Bouché et al. (2012); Schroetter et al. (2015, 2016).



**Figure 4.** Star formation rate as a function of galaxy stellar mass (bottom x-axis) and dynamical estimator  $\log(S_{0.5})$  (top x-axis). The blue squares represent the MEGAFLOW wind subsample, while the orange points represent the MUSE-HUDF data from Contini et al. (in prep.). The data are corrected to redshift  $z = 0.55$  using the Boogaard et al. (2018) redshift evolution of the MS. The blue dashed line represents the Boogaard et al. (2018) fit to the MS and the grey dashed lines the 0.4 dex intrinsic scatter of this relation.

### 6.1 Classic wind model

We use a bi-conical wind model filled with randomly distributed particles<sup>8</sup>. We assume mass conservation throughout the outflowing cone (thus, density evolves like  $1/r^2$ ,  $r$  being the distance to the galaxy center). The clouds are also assumed to be accelerated with respect to their terminal velocity  $V_{\text{out}}$  in a few kpc ( $< 10$  kpc), i.e. the wind speed is assumed to be constant in the observed impact parameter (range from 10 to 100 kpc).

The particle observed velocities are then projected onto the quasar LOS at the impact parameter. This projection gives an optical depth  $\tau_\nu$  which we turn into a simulated absorption profile (flux  $\propto \exp(-\tau_\nu)$ ).

The geometrical configuration, namely the wind direction, is determined from the galaxy’s orientation (inclination and PA), assuming a wind flowing radially from the host galaxy. The wind model thus has two free parameters: the wind speed  $V_{\text{out}}$  and the cone opening angle  $\theta_{\text{max}}$ . They can both be adjusted to match the absorption profile seen in the data<sup>9</sup>.

In order to facilitate comparison with the data, we add Poisson noise (corresponding to instrumental noise) to the simulated absorption profile. We thus derive an outflow velocity as well as a cone opening angle for each individual wind-pair. This is achieved by visually matching<sup>10</sup> the absorption profile edges, shape and asymmetry.

### 6.2 Empty inner cone

While we use a filled cone by default, in some cases, the data require us to use a hollow (within  $\theta_{\text{in}}$ ) cone. This hollow inner cone produces a gap in absorption velocities in our simulated profiles. These gaps in absorption velocities can occur in the data when  $\alpha$  is close to  $90^\circ$ , i.e. when the quasar LOS intercepts the middle of the outflowing cone. This is the case for the galaxy-quasar pairs #1, 7, 9, 17, 19, 20, 22, 24 and 26. 9 out of 26 galaxies with  $\alpha \geq 65^\circ$  require a hollow inner cone.

As mentioned in Paper I, this empty inner cone could be the signature of a highly ionized gas component filling the inner cone. Thus, the low-ionized gas which we are tracing is entrained along the outskirts of the outflowing cone, in a manner similar to Fox et al. (2015) for the MilkyWay as well as observations from Veilleux & Rupke (2002); Veilleux et al. (2003) and Bland-Hawthorn et al. (2007b).

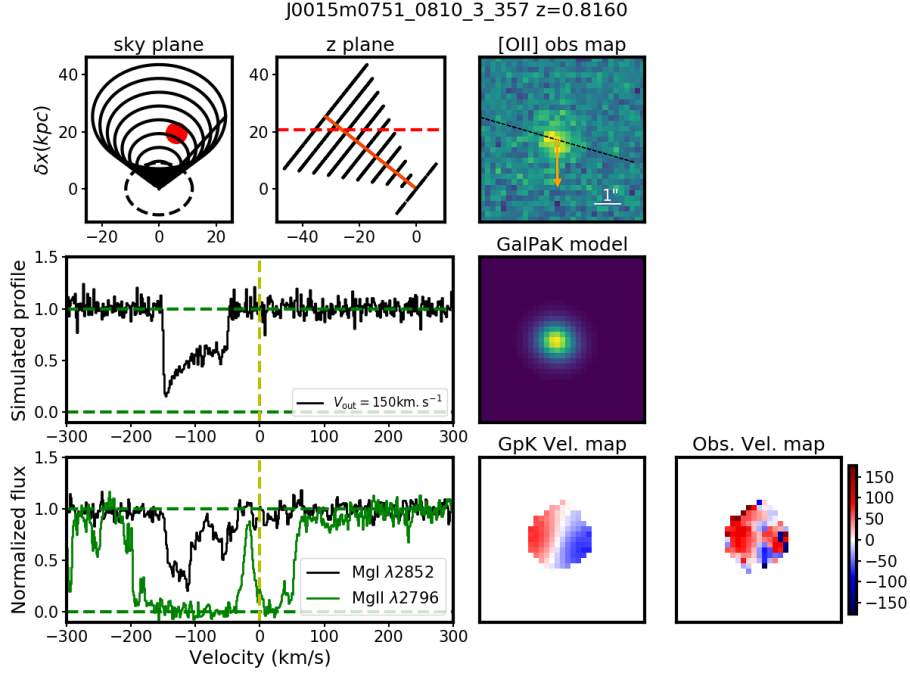
For four wind-pairs (#7, 12, 13 and 18), the Mg II absorption seen in the UVES quasar spectrum is too complex to determine which component is actually the signature of outflows. Therefore, we create a wind model for each component when possible. The results of these models are listed in Table 4.

Figure 5 shows the best-fit wind model for the galaxy J0015m0751-0810-3-357 (#5). The top two left panels represent the geometrical configuration of the system. The top left panel represents the sky view of this galaxy-quasar pair. The QSO

<sup>8</sup> These particles represent cold gas clouds being pushed away by the hot medium or radiation pressure.

<sup>9</sup> We also model a disk contribution for each wind model, as in Schroetter et al. (2015); Zabl et al. (2019) but found the disk contribution too low due to the large galactic-radius resulting from the high-inclinations of our galaxies.

<sup>10</sup> The EW, taking into account the depth of the profile, cannot be estimated as the normalization of the particles in  $\tau$  in our model is arbitrary.



**Figure 5.** Simulated profile and quasar spectrum associated with the J0015m0751-0810-3-357 (#5) galaxy. The first top-left two panels represent the geometrical configuration of the galaxy-quasar system with the quasar line of sight in red (dot for sky plane representation in the top left panel and dashed horizontal line for the z plane), the outflowing cone as black circles and the host galaxy in a dashed black circle. The middle left panel shows the best fit simulated wind profile corresponding to the observed Mg I absorption profile (centered at  $z = 0.8160$ ) from UVES shown in the bottom left panel (the green Mg II absorption profile is present to show that this line is saturated). This outflow has  $V_{\text{out}} = 150 \pm 10 \text{ km s}^{-1}$  and opening angle  $\theta_{\text{max}} = 35 \pm 2^\circ$ . The top right panel shows the observed [O II] flux map of the galaxy from the MUSE cube including a representation of the galaxy PA (black dashed line) as well as an orange arrow showing the direction to the associated quasar. The middle right panel shows the GalPaK<sup>3D</sup> model (convolved with the PSF), the panel below shows the model velocity map of the galaxy obtained with GalPaK<sup>3D</sup> (convolved with the PSF), and the bottom right panel shows the observed velocity map obtained with *CAMEL*.

LOS is represented by the red dot and the galaxy by the dashed black circle. The outflowing cone is represented by the black circles. The middle top panel of shows a side view of the same system. The quasar LOS is the horizontal dashed red line (the observer being to the left), the galaxy is represented by the dashed inclined black line at the bottom and the outflowing cone by the increasing black lines.

The right column of Figure 5 shows, from top to bottom, the MUSE host galaxy [O II] map, the GalPaK<sup>3D</sup> model and the model velocity map. On the top right observed flux map we represent the galaxy PA by the dashed black line and the direction of the quasar with the orange arrow.

The last two panels of this Figure show the simulated profile of our wind model (middle left) and the UVES Mg I absorption lines (bottom left). On both panels the galaxy systemic redshift is represented by the vertical yellow dashed line. With an outflow velocity  $V_{\text{out}} = 150 \text{ km s}^{-1}$  and a cone opening angle of  $35^\circ$ , we reproduced the width and asymmetry of the observed Mg I absorption.

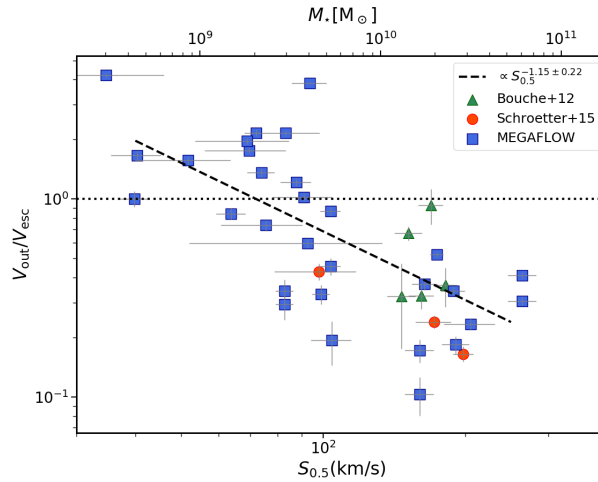
Outflow velocities and cone opening angles fit with our model are listed for each wind-pair in Table 4. Representations of each model are shown in the Appendix.

### 6.3 Does the wind material escape?

Here, we will address the question of whether outflows can escape the gravitational potential well of their host galaxy. To estimate the escape velocity of our galaxies, we use the relation for an isothermal sphere given by equation 4 from Veilleux et al. (2005):

$$V_{\text{esc}} = V_{\text{vir}} \times \sqrt{2 \left[ 1 + \ln \left( \frac{R_{\text{vir}}}{r} \right) \right]} \quad (4)$$

where  $V_{\text{vir}}$  is the virial velocity of the galaxy,  $r$  is taken to be the impact parameter  $b$  and  $R_{\text{vir}}$  its virial radius. The virial radius is defined approximately as  $R_{\text{vir}} \approx V_{\text{vir}}/10H(z)$  where  $H(z)$  is the Hubble constant at redshift  $z$ . For our galaxies, we



**Figure 6.** Ratio of best-fit outflow and escape velocity,  $V_{\text{out}}/V_{\text{esc}}$ , as a function of dynamical mass indicator  $S_{0.5}$  (bottom x-axis) and  $M_*$  (top x-axis). Green triangles are from Bouché et al. (2012), red circles are from Schroetter et al. (2015). The blue squares correspond to the MEGAFLOW wind subsample. The horizontal line corresponds to  $V_{\text{out}} = V_{\text{esc}}$ . The dashed black line corresponds to a fit with coefficients shown in the legend.

choose to use  $1.2 \times S_{0.5}$  as a proxy for  $V_{\text{vir}}$ . Indeed, several groups have shown that  $V_{\text{vir}}$  is  $V_{\text{max}}/1.1\text{--}1.3$  (Dutton et al. 2010; Cattaneo et al. 2014), which is a factor similar to  $(1.2 \times \sqrt{0.5})^{-1}$  in S05.

Figure 6 presents the ratio between the outflow velocity and the escape velocity ( $V_{\text{out}}/V_{\text{esc}}$ ) as a function of  $S_{0.5}$  (and the galaxy stellar mass along top x-axis).

Figure 6 also shows results from other studies using the background quasar technique. In particular, green triangles for Bouché et al. (2012) (a combination of LRIS and SDSS data) and red circles for Schroetter et al. (2015) (SIMPLE, a combination of SINFONI and UVES) are shown. The blue squares are the MEGAFLOW wind sub-sample. We can see that for galaxies with stellar masses lower than  $\approx 4 \times 10^9 M_{\odot}$ , for most of the cases,  $V_{\text{out}}/V_{\text{esc}} > 1$ . Those outflows can thus escape the gravitational potential well of their host galaxies.

The ability of the cool wind material (traced by Mg II) to escape the galaxy appears to be limited to low-mass galaxies, with  $M_* \lesssim 4 \times 10^9 M_{\odot}$ . For galaxies above this mass, outflows are likely to fall back onto their host and thus fuel future star formation, which is consistent with theoretical expectations (e.g. Oppenheimer & Davé 2008; Oppenheimer et al. 2010; Torrey et al. 2017; Anglés-Alcázar et al. 2017).

#### 6.4 The mass outflows rate

For a mass conserving flow, the mass outflow rate  $\dot{M}_{\text{out}}$  is  $\rho(R) R^2 V_{\text{out}} \Omega$ , i.e. it depends critically on four factors, the outflow speed  $V_{\text{out}}$ , the gas mean localization  $R$ , the column density  $N = \rho R$  and the wind solid angle  $\Omega$ . For a down-the-barrel observations of such a wind, the mass outflow rate reduces to  $\propto N_{\text{H}} R_0 V_{\text{out}} \Omega$  (Heckman et al. 2000; Martin 2005; Martin et al. 2012) where  $R_0$  the launch radius. For transverse sight-lines,  $\dot{M}_{\text{out}}$  is proportional to  $\propto N_{\text{H}} b V_{\text{out}} \theta$  where  $b$  is the impact parameter and  $\theta$  the wind opening angle, as derived in Bouché et al. (2012). This can be understood using the following two observations: (i)  $\dot{M}_{\text{out}}$  is  $\propto \rho(b) b^2 V_{\text{out}} \theta^2$  from mass conservation and (ii) the gas column density  $N$  depends linearly on the opening angle  $N \propto \rho(b) b \theta$  for a transverse sight-line.

Hence, for a potentially hollow bi-conical flow, the mass outflow rate is (as in Bouché et al. 2012; Schroetter et al. 2015, and paper I) :

$$\frac{\dot{M}_{\text{out}}}{M_{\odot} \text{ yr}^{-1}} \approx \frac{\mu}{1.5} \cdot \frac{N_{\text{H}}(b)}{10^{19} \text{ cm}^{-2}} \cdot \frac{b}{25 \text{ kpc}} \cdot \frac{V_{\text{out}}}{200 \text{ km s}^{-1}} \cdot \frac{\theta_{\text{max}} - \theta_{\text{in}}}{30^{\circ}}, \quad (5)$$

where  $\mu$  is the mean mass per hydrogen particle,  $b$  the impact parameter,  $\theta_{\text{max}}$  the cone opening angle<sup>11</sup>,  $\theta_{\text{in}}$  the opening angle of the inner empty cone,  $V_{\text{out}}$  the outflow velocity and  $N_{\text{H}}(b)$  the hydrogen column density at the  $b$  distance. The numerical factor here includes a factor of  $2 \times$  to sum the mass flux for both cones.

The parameters  $V_{\text{out}}$ ,  $b$  and the cone opening angle can be constrained from our data. To estimate the last parameter  $N_{\text{H}}(b)$ , we use the empirical relation (Eq. 6) from Ménard & Chelouche (2009), re-derived by Lan & Fukugita (2017), between

<sup>11</sup>  $\theta_{\text{max}}$  ( $\theta_{\text{in}}$ ) is defined from the central axis, and the cone subtends an area  $\Sigma$  of  $\pi \cdot \theta_{\text{max}}^2$ .



**Table 4.** Results on outflow properties for MEGAFLOW galaxies.

# (1)	Galaxy (2)	$z_{\text{gal}}$ (3)	$b$ (4)	$\log(N_{\text{H}}(b))$ (5)	$V_{\text{out}}$ (6)	$\theta_{\text{max}}$ (7)	$\theta_{\text{in}}$ (8)	$\log(M_{\star})$ (9)	SFR (10)	$\dot{M}_{\text{out}}$ (11)	$V_{\text{out}}/V_{\text{esc}}$ (12)	$\eta$ (13)
1	J0014m0028-0834-1-159	0.8340	9.7	$20.0^{+0.2}_{-0.2}$	180.0	28	2	8.7	$0.7^{+0.5}_{-0.3}$	$3.3^{+0.3}_{-2.1}$	2.07	4.6
2	J0014m0028-1052-6-268	1.0536	52.4	$20.2^{+0.2}_{-0.2}$	360.0	15	0	9.6	$2.7^{+2.0}_{-1.3}$	$28.1^{+5.0}_{-18.0}$	2.77	10.6
3	J0015m0751-0500-4-35	0.5073	24.1	$19.6^{+0.2}_{-0.2}$	200.0	30	0	10.7	$3.5^{+2.6}_{-1.7}$	$4.2^{+0.5}_{-2.2}$	0.42	1.4
4	J0015m0751-0731-5-3	0.7305	35.5	$20.0^{+0.2}_{-0.2}$	100.0 <sup>†</sup>	25	0	10.7	$3.9^{+2.9}_{-1.9}$	$5.3^{+1.9}_{-3.1}$	0.23	1.4
5	J0015m0751-0810-3-357	0.8160	20.7	$20.1^{+0.2}_{-0.2}$	150.0	35	0	10.8	$6.2^{+4.6}_{-3.0}$	$9.2^{+1.9}_{-5.2}$	0.29	1.4
6	J0103p1332-1048-1-136	1.0483	9.1	$20.4^{+0.3}_{-0.3}$	170.0	30	0	9.8	$2.9^{+2.1}_{-1.4}$	$6.9^{+1.1}_{-4.6}$	0.74	2.0
7	J0131p1303-1010-3-45	1.0103	26.4	$19.6^{+0.2}_{-0.2}$	70.0 <sup>†</sup>	40	18	9.6	$8.6^{+6.3}_{-4.1}$	$1.2^{+0.1}_{-0.7}$	0.43	0.1
					60.0 <sup>†</sup>	40	0			$1.9^{+0.2}_{-1.1}$	0.37	0.1
8	J0131p1303-1104-9-351	1.1049	75.5	$19.6^{+0.2}_{-0.2}$	650.0	30	0	9.8	$8.9^{+6.6}_{-4.3}$	$41.4^{+9.5}_{-20.4}$	5.05	4.6
9	J0145p1056-0770-1-93	0.7699	12.9	$19.6^{+0.2}_{-0.2}$	160.0	30	10	9.5	$0.5^{+0.4}_{-0.2}$	$1.0^{+0.1}_{-0.6}$	0.91	2.0
10	J0800p1849-0843-3-254	0.8429	20.9	$19.4^{+0.2}_{-0.2}$	90.0	30	0	9.8	$3.7^{+2.7}_{-1.8}$	$1.0^{+0.1}_{-0.6}$	0.41	0.8
11	J0800p1849-0993-9-282	0.9936	78.0	$19.5^{+0.2}_{-0.2}$	250.0	25	0	9.4	$8.3^{+5.9}_{-3.9}$	$10.1^{+1.7}_{-5.2}$	2.90	1.4
12	J0937p0656-0702-10-197	0.7019	69.0	$19.0^{+0.1}_{-0.1}$	100.0 <sup>†</sup>	30	0	9.9	$4.6^{+3.4}_{-2.2}$	$1.2^{+0.1}_{-0.6}$	0.58	0.8
					190.0 <sup>†</sup>	25	0			$1.5^{+0.1}_{-0.7}$	1.11	0.8
13	J0937p0656-0702-6-209	0.7020	38.7	$19.0^{+0.1}_{-0.1}$	45.0 <sup>†</sup>	30	0	10.5	$14.9^{+11.0}_{-7.1}$	$0.3^{+0.1}_{-0.2}$	0.13	0.0
					75.0 <sup>†</sup>	30	0			$0.5^{+0.2}_{-0.3}$	0.21	0.0
14	J0937p0656-0933-5-6	0.9337	41.4	$19.8^{+0.2}_{-0.2}$	240.0	20	0	9.7	$5.7^{+4.2}_{-2.7}$	$6.7^{+1.0}_{-3.9}$	1.21	1.4
15	J1039p0714-0819-3-124	0.8192	24.5	$20.2^{+0.2}_{-0.2}$	270.0	30	0	10.6	$3.2^{+2.4}_{-1.5}$	$21.2^{+5.0}_{-12.1}$	0.65	6.8
16	J1039p0714-0949-9-344	0.9492	72.2	$18.5^{+0.1}_{-0.1}$	40.0 <sup>†</sup>	35	0	9.9	$2.8^{+2.1}_{-1.4}$	$0.2^{+0.1}_{-0.1}$	0.25	0.1
17	J1039p0714-1359-1-123	1.3589	8.6	$20.3^{+0.3}_{-0.3}$	220.0	27	12	9.0	$3.2^{+2.2}_{-1.5}$	$4.0^{+1.2}_{-3.0}$	1.94	1.4
18	J1107p1021-1015-10-272	1.0150	80.9	$20.0^{+0.2}_{-0.2}$	270.0 <sup>†</sup>	20	0	11.1	$11.5^{+8.5}_{-5.4}$	$30.1^{+6.3}_{-17.5}$	0.52	2.4
					200.0 <sup>†</sup>	25	0			$27.9^{+6.4}_{-15.6}$	0.38	2.4
19	J1107p1757-1063-3-140	1.0637	22.1	$20.6^{+0.3}_{-0.3}$	300.0	30	20	9.4	$2.5^{+1.8}_{-1.2}$	$16.7^{+15.0}_{-12.8}$	2.21	6.8
20	J1107p1757-1163-6-166	1.1618	44.4	$19.9^{+0.2}_{-0.2}$	200.0	20	5	9.7	$8.8^{+6.5}_{-4.2}$	$7.6^{+1.0}_{-4.9}$	1.30	0.8
21	J1236p0725-0639-10-256	0.6382	66.9	$18.8^{+0.1}_{-0.1}$	150.0 <sup>†</sup>	25	0	10.5	$5.8^{+4.3}_{-2.8}$	$1.0^{+0.1}_{-0.5}$	0.47	0.0
22	J1352p0614-0604-2-260	0.6039	14.0	$19.3^{+0.2}_{-0.2}$	360.0	30	15	8.5	$0.3^{+0.2}_{-0.1}$	$1.1^{+0.1}_{-0.7}$	4.21	3.4
23	J1358p1145-0809-2-202	0.8093	12.7	$19.9^{+0.2}_{-0.2}$	150.0	45	0	9.3	$1.6^{+1.1}_{-0.8}$	$4.2^{+0.6}_{-2.4}$	1.05	2.4
24	J1425p1209-0597-1-87	0.5968	9.6	$19.6^{+0.2}_{-0.2}$	110.0	45	21	8.7	$1.1^{+0.8}_{-0.5}$	$0.7^{+0.1}_{-0.4}$	1.25	0.1
25	J1425p1209-0865-8-353	0.8657	60.8	$19.4^{+0.2}_{-0.2}$	190.0	35	0	9.5	$4.2^{+3.0}_{-2.0}$	$7.0^{+1.2}_{-3.3}$	1.76	1.4
26	J2152p0625-1319-4-187	1.3181	32.5	$19.9^{+0.2}_{-0.2}$	285.0	12	3	9.4	$2.1^{+1.5}_{-1.0}$	$4.0^{+0.1}_{-3.0}$	2.50	1.4

(1) Galaxy number; (2) Galaxy name; (3) Galaxy redshift; (4) Impact parameter (kpc); (5) Gas column density at the impact parameter ( $\text{cm}^{-2}$ ); (6) Wind velocity ( $\text{km s}^{-1}$ ); (7) Cone opening angle (degrees) (8) Inner empty cone opening angle (degrees) (9) Galaxy stellar mass  $\log(M_{\odot})$ , errors are 0.14 dex (10) Star Formation Rate ( $M_{\odot} \text{ yr}^{-1}$ ) from [O II] (see text); (11) Ejected mass rate ( $M_{\odot} \text{ yr}^{-1}$ ); (12) Ejection velocity divided by escape velocity; (13) Mass loading factor: ejected mass rate divided by star formation rate; †: cases of less convincing wind model (see text)

the neutral gas column density and  $W_r^{\lambda 2796}$  :

$$N_{\text{HI}}(\text{cm}^{-2}) = A \left( \frac{W_r^{\lambda 2796}}{1 \text{ \AA}} \right)^{\alpha} (1+z)^{\beta}. \quad (6)$$

Where  $A = 10^{18.96 \pm 0.10}$ ,  $\alpha = 1.69 \pm 0.13$  and  $\beta = 1.88 \pm 0.29$ .

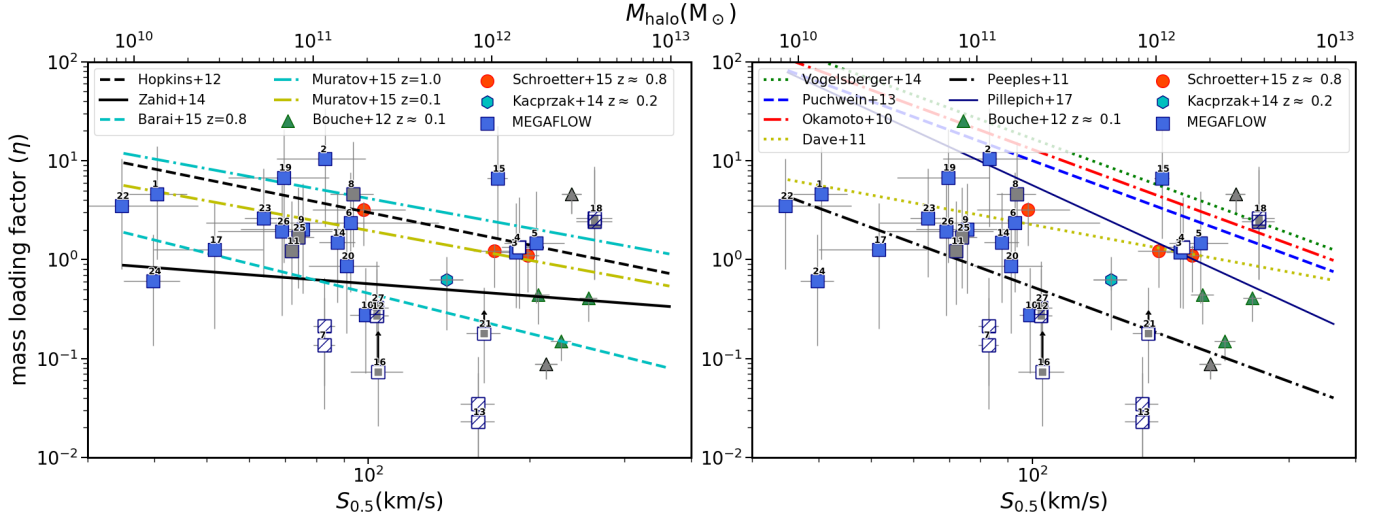
If a region has an HI column density above  $\log(N_{\text{HI}}/\text{cm}^{-2}) \approx 19.5$ , the ionized gas contribution is negligible. Thus, one can use the correlation between Mg II equivalent width and  $N_{\text{HI}}$  as a proxy for the hydrogen gas column density (also argued by Jenkins 2009). Typical errors on our  $\log(N_{\text{HI}})$  estimates are 0.2-0.3 dex (at  $1\sigma$ ). Those errors, together with errors on the other parameters ( $V_{\text{out}}$ ,  $\theta_{\text{max}}$  and  $b$ ), allow us to get estimates of mass outflow rates within a factor 2 or 3. The mass outflow rates are listed in Table 4.

## 6.5 Mass loading factors

Figure 7 shows the loading factor (defined as  $\dot{M}_{\text{out}}/\text{SFR}$ ) as a function of galaxy halo mass (derived from  $V_{\text{max}}$  and redshift 0.8 from Mo & White (2002) relation). The blue squares represent the MEGAFLOW results, and the gray symbols represent the galaxy-quasar pairs where the quasar is located at an impact parameters  $b$  larger than 60 kpc<sup>12</sup>. The mass loading factors were all derived taking into account the empty inner cone (when needed). For the 4 cases (IDs 7, 12, 13 and 18) with multiple wind model possibilities, the squares are hatched.

In addition, we show in white squares the cases for which wind models are found less convincing at reproducing the

<sup>12</sup> the  $b > 60$  kpc is an arbitrary value, see the discussion on this criterion in Paper I and later in this §.



**Figure 7.** Comparison of mass loading factors (left: measured, right: injected) by theoretical/empirical models (curves) with values derived from background quasar observations (data points) as a function of the maximum rotational velocity. MEGAFLOW results are represented by blue squares. The dashed squares correspond to the 4 cases with multiple possible wind models. The orange circles show the results for galaxies at  $z \approx 0.8$  from [Schroetter et al. \(2015\)](#). The light blue hexagon shows the mass loading factor for a  $z \approx 0.2$  galaxy ([Kacprzak et al. 2014](#)). The green triangles show the results for  $z \approx 0.2$  galaxies from [Bouché et al. \(2012\)](#). The gray triangles and squares show the galaxies with quasars located at  $b > 60\text{kpc}$  where the mass loading factor is less reliable due to the large travel time needed for the outflow to cross the quasar LOS (several 100 Myr) compared to the short time scale of the derived SFRs ( $\sim 10\text{Myr}$ ). The white squares represent the cases where the agreement between the wind model and the UVES data is poor and lower limits indicate systems where ionization correction might be significant. The upper halo mass axis is scaled by  $V_{\text{max}}$  at redshift 0.8 from [Mo & White \(2002\)](#).

absorption. Those cases are the following numbers: #4, 7, 12, 13, 16, 18 and #21. The main reasons we classify those cases into less convincing are:

- #4 has another absorption component at  $\approx 200 \text{ km s}^{-1}$  which cannot be reproduced by our wind model.
- #7 has two different blended absorptions centered around the systemic redshift. It is thus difficult to determine where one absorption begins and the other ends.
- #12 and #13 are two different galaxies for the same absorption system. We either fit the two absorption components closer to the systemic redshift or the two others. However, we cannot reproduce the three components simultaneously.
- #16 has two absorption components. We choose to fit the closest from the systemic redshift as this galaxy is the second detected in Paper II for this system. This galaxy could also contribute to the absorption at  $\approx -150 \text{ km s}^{-1}$  which is identified as an accretion component in Paper II.
- #18 also has two absorption components, one blue-shifted and one redshifted with respect to the galaxy systemic redshift. Even if both wind models for this system are similar in outflow velocities ( $270 \text{ km s}^{-1}$  and  $200 \text{ km s}^{-1}$  for the black and red models respectively), we consider this case as complex and therefore less convincing.
- #21 has a complex absorption system. Giving the geometrical configuration of the system, our wind model can reproduce the closest component to the systemic redshift. We assumed this component to be the signature of the outflowing gas but the other components at  $\approx 150 - 200 \text{ km s}^{-1}$  could also be a part of it.

Errors on mass loading factors are described in details in [Schroetter et al. \(2015\)](#) and Paper I. As a short summary, for the derived parameters (i.e.  $V_{\text{out}}$  and  $\theta_{\text{max}}$ ), we assume a Gaussian error distribution and the errors are given by the range of values given by the data. Errors on  $V_{\text{out}}$  are  $10 \text{ km s}^{-1}$ , which correspond to a step of this parameter while eye-fitting the data. Those errors are over-estimated since  $V_{\text{out}} + 10 \text{ km s}^{-1}$  and  $V_{\text{out}} - 10 \text{ km s}^{-1}$  give simulated absorption profiles which does not fit the data at all. The same is used for the cone opening angle  $\theta_{\text{max}}$ . The most important source of errors is given by the SFR and the hydrogen column density estimations.

Compared to the plot from Paper I, we separated simulation results in two panels. On left panel, we show loading factors in which simulations measure them. On right panel, we show the injected loading factors (and thus not measured).

From the two panels on this figure, we can see that the measured loading factors (curves in left panel) tend to be in agreement with the data points whereas injected loading factors on right panel appears to over-estimate them (apart from [Davé et al. \(2011\)](#) and [Peebles & Shankar \(2011\)](#)). Overall, theoretical and empirical wind models are in agreement with

the observational constraints but it seems that simulations in which they measure loading factors are a better estimation to compare with observations.

As already discussed in Paper I, there is a timescale problem concerning the mass loading factor. Indeed, the SFR measured from [O II] emission lines has a typical timescale of  $\sim 10$  Myr whereas the mass outflow rate  $\dot{M}_{\text{out}}$  has a typical timescale of hundreds of Myr (assuming  $b > 20$  kpc and  $V_{\text{out}} \approx 200 \text{ km s}^{-1}$ ). Therefore, both numerator and denominator of  $\eta$  are, in most cases, on a different timescale. This leads to the conclusion that the mass loading factor may not be physically meaningful, if the SFR changes on short time scales.

In addition,  $\eta$  comparison with simulations may not be the best solution as we do not have the radius dependency for them. However, since we can only compare with what has been done so far, we can claim that, even regarding those differences, the mass loading factor does not seem to evolve strongly with the host galaxy mass. If we do not take into account the white squares, our results are less scattered and press on the previous statement. Systems with low REW or  $\log N_{\text{HI}}$  lower than  $\approx 19.0$  might suffer from an unknown ionization correction, and thus their outflow rate should be treated as lower limits.

## 7 SUMMARY AND CONCLUSIONS

Using our MEGAFLOW survey (Schroetter et al. 2016; Zabl et al. 2019, Bouché et al. (in prep.)) which aims to observe galaxies responsible for  $\sim 80$  strong Mg II absorbers ( $W_r^{\lambda 2796} > 0.3 \text{ \AA}$ ) seen in quasar spectra at  $0.4 < z < 1.5$  with MUSE and UVES, we investigated the distribution of the gas surrounding those galaxies. Without any pre-selection on their geometrical configuration, we clearly see a bi-modal distribution of this low-ionized gas (see Figure 2). This distribution of azimuthal angles suggests a bi-conical outflow geometry and a co-planar extended gas disk. This in turn supports our geometrical assumption for such phenomena.

We then selected 26 galaxy-quasar pairs suitable for wind study (i.e.  $\alpha \geq 55^\circ$ ). Outflowing gas properties for 26 of the host galaxies were constrained. Those properties were the outflow velocity  $V_{\text{out}}$ , the mass outflow rate  $\dot{M}_{\text{out}}$  and the mass loading factor  $\eta$  (as shown in Figure 7 and Table 4).

A summary of our results is as follows:

- Without morphology or geometry pre-selection (only absorption-selection), we find a bimodal distribution of azimuthal angles (Figure 2). This suggests that the geometry of the gas surrounding galaxies is outflow dominated with a cone along the galaxy minor axis and accretion dominated coplanar to the disk, within 100 kpc.
- Mass loading factors tend to be  $\eta \sim 1$ , which means that the mass outflow rate is of the same order of magnitude as the galaxy SFR.
- The cool gas traced with the low-ionization element Mg II is likely to fall back onto the galaxy for galaxies with stellar mass larger than  $4 \times 10^9 M_\odot$  (Figure 6).

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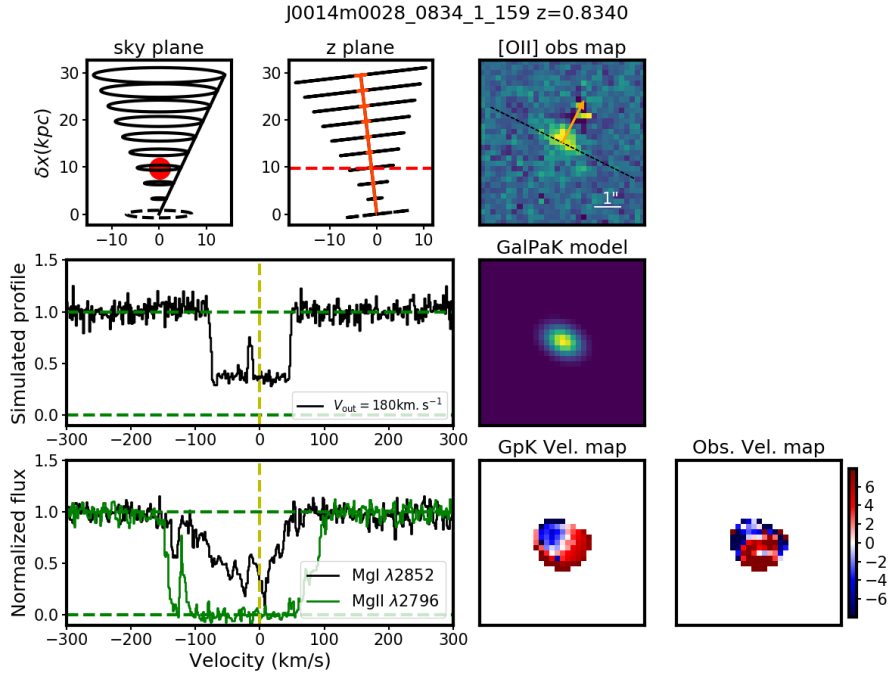
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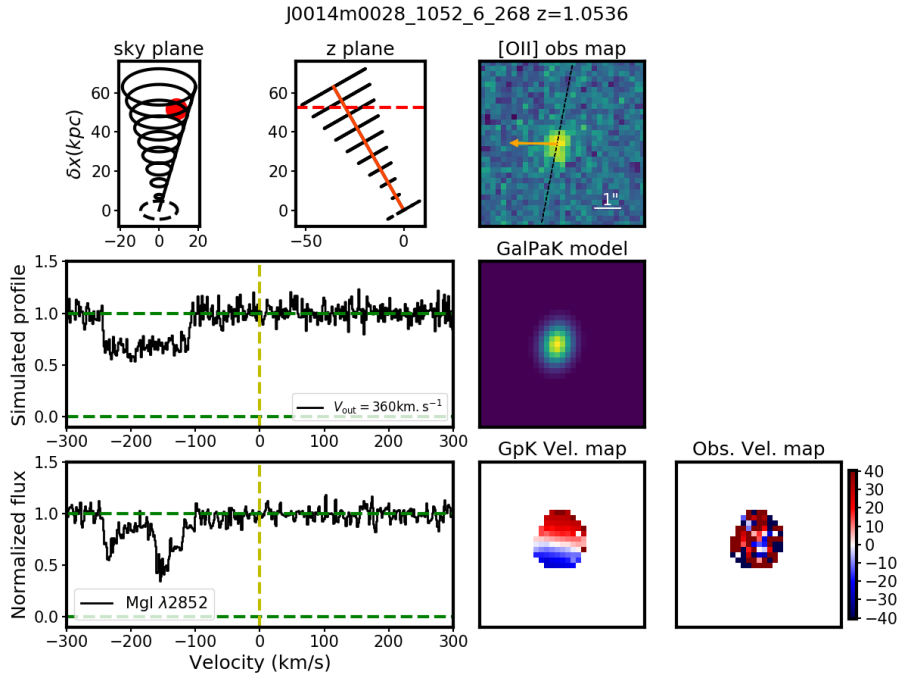
## 8 APPENDIX

Here we present the wind models for each wind subsample galaxy-quasar pairs.

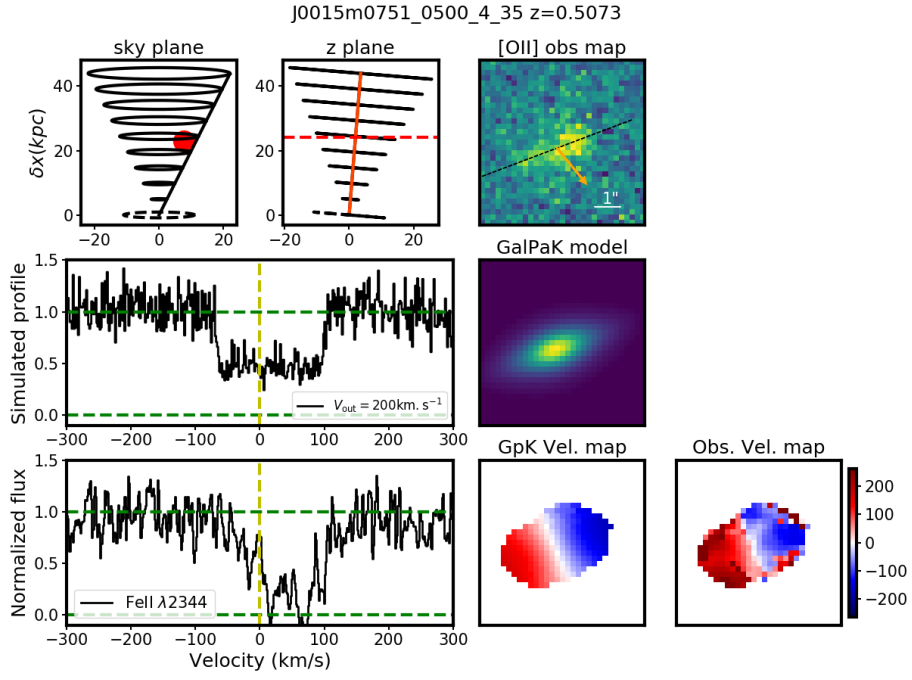




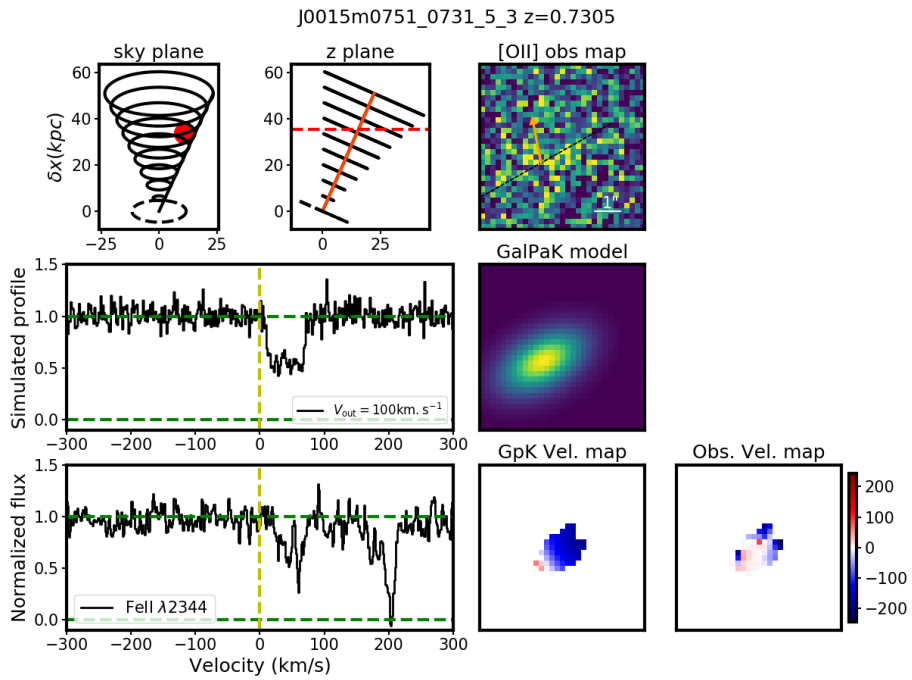
**Figure A.1.** Same as Figure 5 but for the galaxy #1 at redshift  $z = 0.8340$ . This outflow has a  $V_{\text{out}}$  of  $180 \pm 10 \text{ km s}^{-1}$ , an opening angle  $\theta_{\text{max}}$  of  $28 \pm 2^\circ$  and an inner empty cone  $\theta_{\text{in}}$  of  $2^\circ$ .



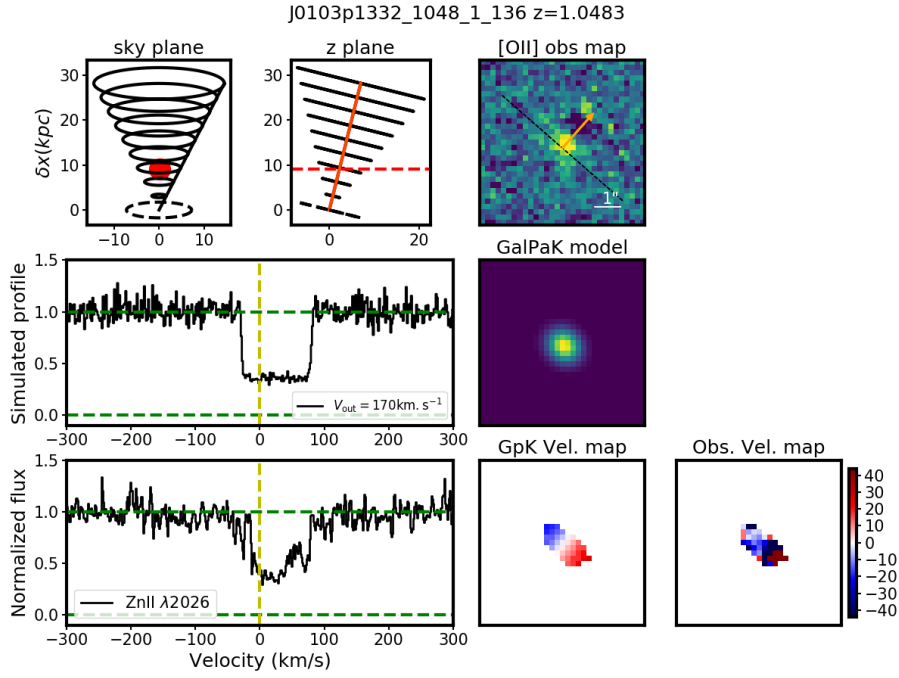
**Figure A.2.** Same as Figure 5 but for the galaxy #2 at redshift  $z = 1.0536$ . This outflow has a  $V_{\text{out}}$  of  $360 \pm 10 \text{ km s}^{-1}$  and an opening angle  $\theta_{\text{max}}$  of  $15 \pm 2^\circ$ .



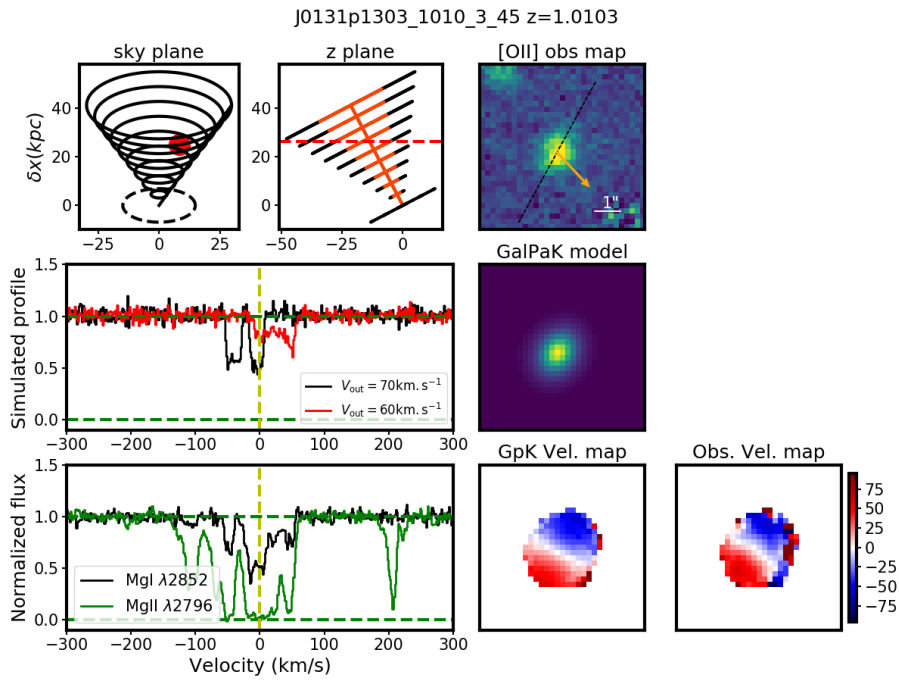
**Figure A.3.** Same as Figure 5 but for the galaxy #3 at redshift  $z = 0.5073$ . This outflow has a  $V_{\text{out}}$  of  $200 \pm 10 \text{ km s}^{-1}$  and an opening angle  $\theta_{\text{max}}$  of  $30 \pm 2^\circ$ .



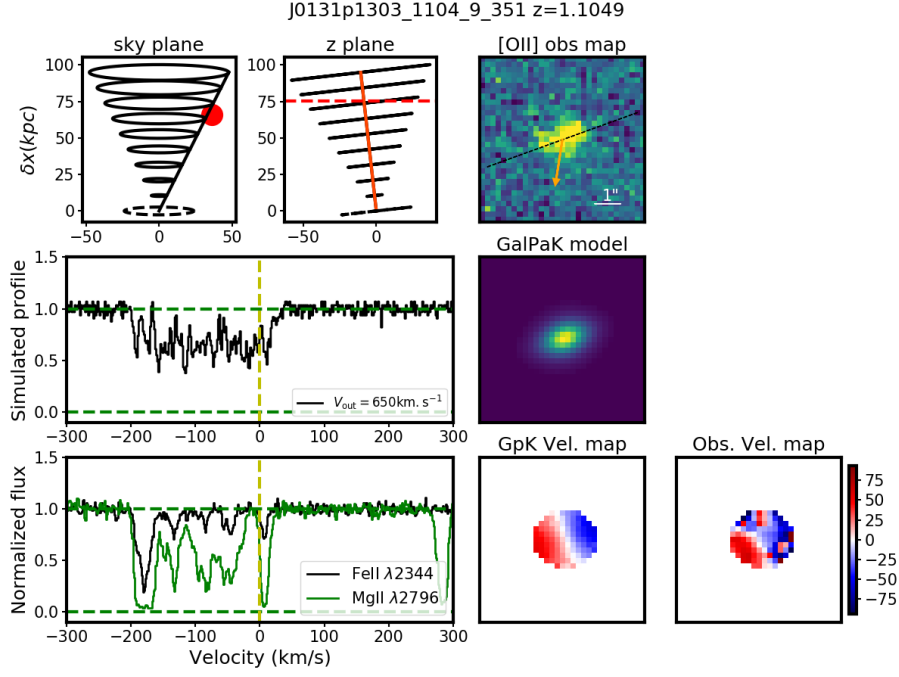
**Figure A.4.** Same as Figure 5 but for the galaxy #4 at redshift  $z = 0.7305$ . This outflow has a  $V_{\text{out}}$  of  $100 \pm 10 \text{ km s}^{-1}$  and an opening angle  $\theta_{\text{max}}$  of  $25 \pm 2^\circ$ .



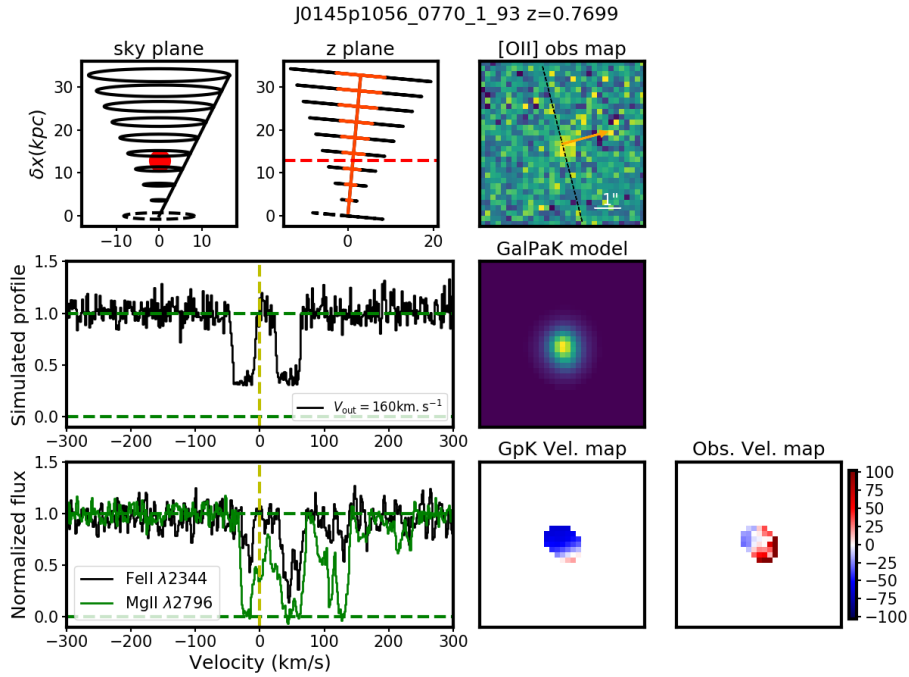
**Figure A.5.** Same as Figure 5 but for the galaxy #6 at redshift  $z = 1.0483$ . This outflow has a  $V_{\text{out}}$  of  $170 \pm 10 \text{ km s}^{-1}$  and an opening angle  $\theta_{\text{max}}$  of  $30 \pm 2^\circ$ .



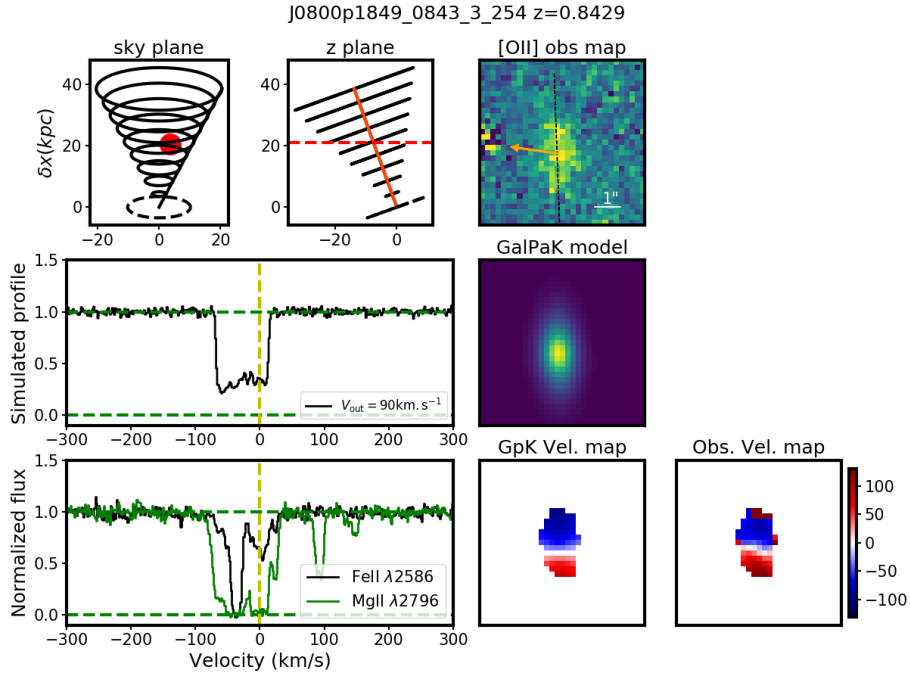
**Figure A.6.** Same as Figure 5 but for the galaxy #7 at redshift  $z = 1.0103$ . This is one of the "multiple model" outflows cases. The black (red) outflow has a  $V_{\text{out}}$  of  $70 \pm 10$  ( $60 \pm 10$ )  $\text{km s}^{-1}$ , an opening angle  $\theta_{\text{max}}$  of  $40 \pm 2^\circ$  (same) and an empty inner cone  $\theta_{\text{in}}$  of  $18^\circ$  ( $0^\circ$ ).



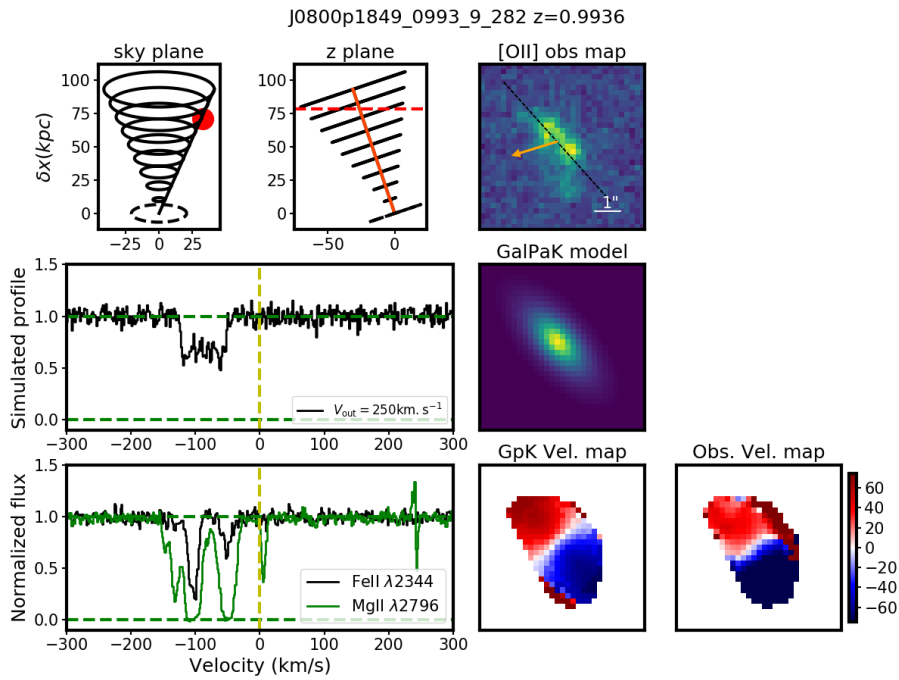
**Figure A.7.** Same as Figure 5 but for the galaxy #8 at redshift  $z = 1.1049$ . This outflow has a  $V_{\text{out}}$  of  $650 \pm 10 \text{ km s}^{-1}$  and an opening angle  $\theta_{\text{max}}$  of  $30 \pm 2^\circ$ . We note here that to reproduce the data, only a fraction of the outflow cone is crossed by the QSO LOS, therefore a very high  $V_{\text{out}}$  is needed.



**Figure A.8.** Same as Figure 5 but for the galaxy #9 at redshift  $z = 0.7699$ . This outflow has a  $V_{\text{out}}$  of  $160 \pm 10 \text{ km s}^{-1}$ , an opening angle  $\theta_{\text{max}}$  of  $15 \pm 2^\circ$  and an empty inner cone  $\theta_{\text{in}}$  of  $10^\circ$ . The component at  $\sim 120 \text{ km s}^{-1}$  could not be reproduced given the geometry of the system.

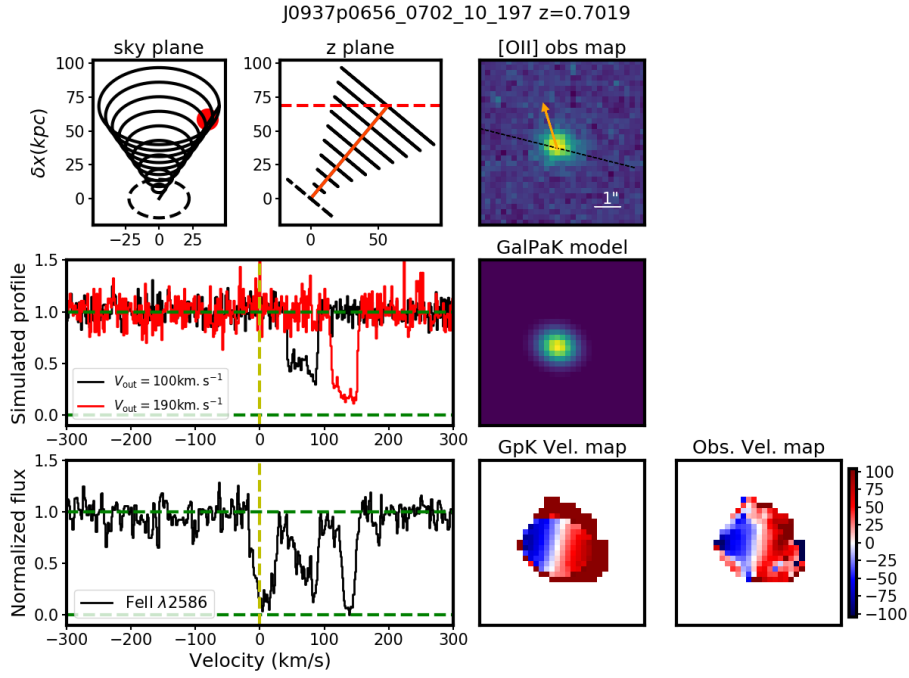


**Figure A.9.** Same as Figure 5 but for the galaxy #10 at redshift  $z = 0.8429$ . This outflow has a  $V_{\text{out}}$  of  $90 \pm 10 \text{ km s}^{-1}$  and an opening angle  $\theta_{\text{max}}$  of  $30 \pm 2^\circ$ .

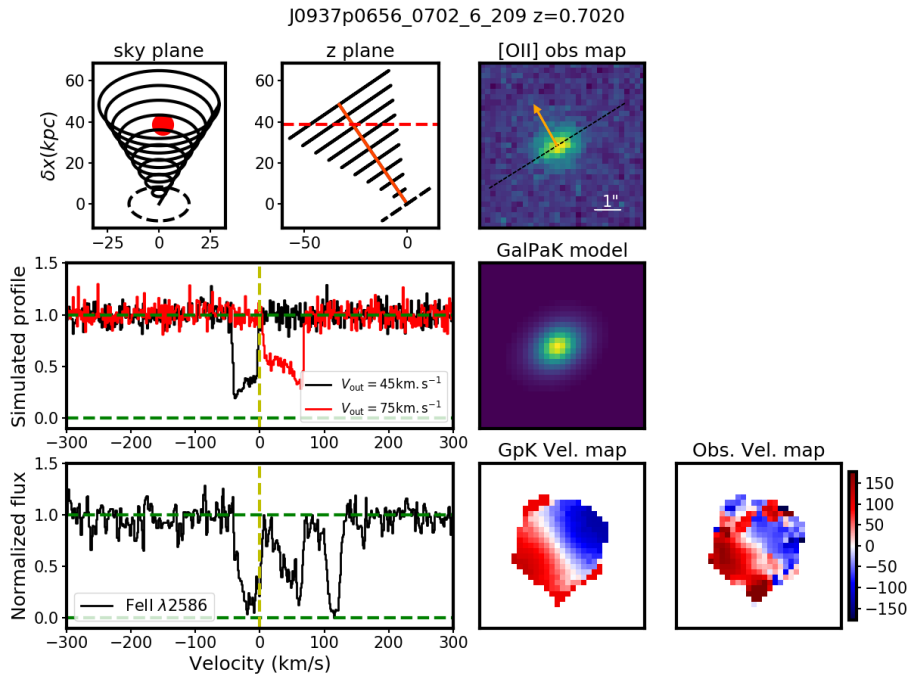


**Figure A.10.** Same as Figure 5 but for the galaxy #11 at redshift  $z = 0.9936$ . This outflow has a  $V_{\text{out}}$  of  $250 \pm 10 \text{ km s}^{-1}$  and an opening angle  $\theta_{\text{max}}$  of  $25 \pm 2^\circ$ .

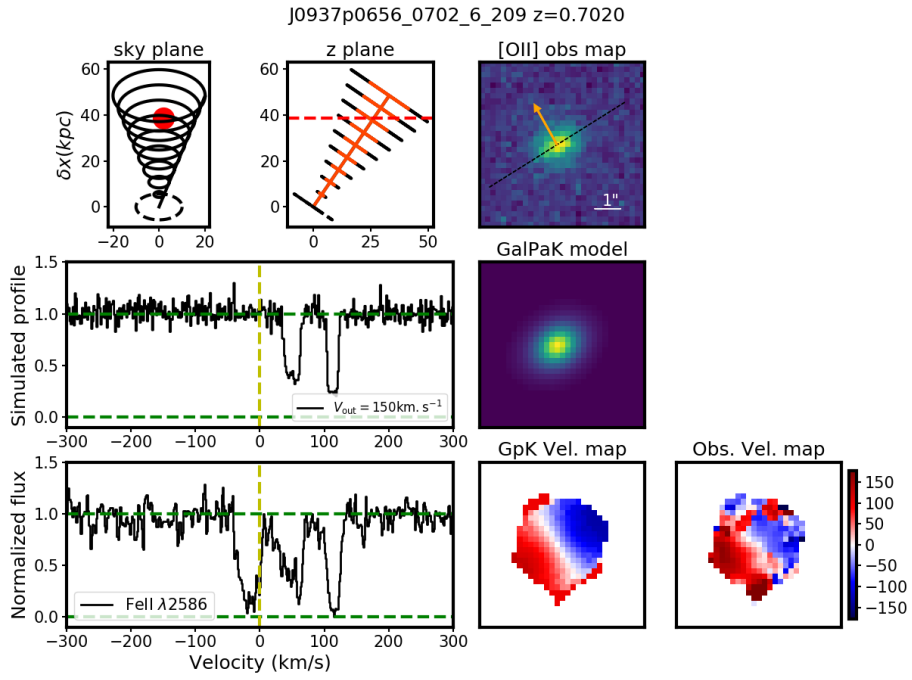




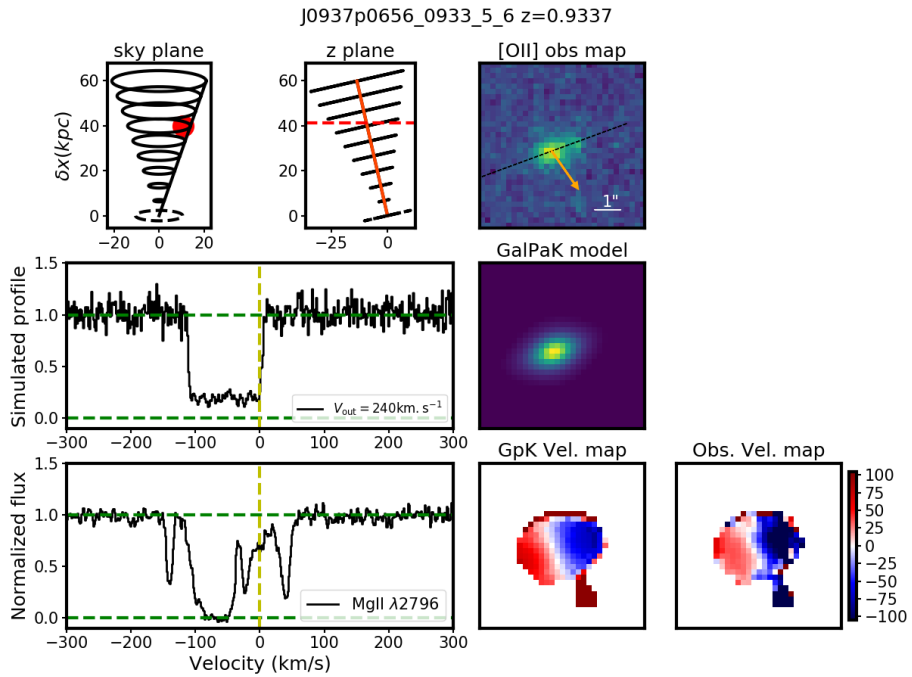
**Figure A.11.** Same as Figure 5 but for the galaxy #12 at redshift  $z = 0.7019$ . This is one of the "multiple model" outflows cases. The black (red) outflow has a  $V_{\text{out}}$  of  $100 \pm 10$  ( $190 \pm 10$ )  $\text{km s}^{-1}$  and an opening angle  $\theta_{\text{max}}$  of  $30 \pm 2^\circ$  ( $25^\circ$ ).



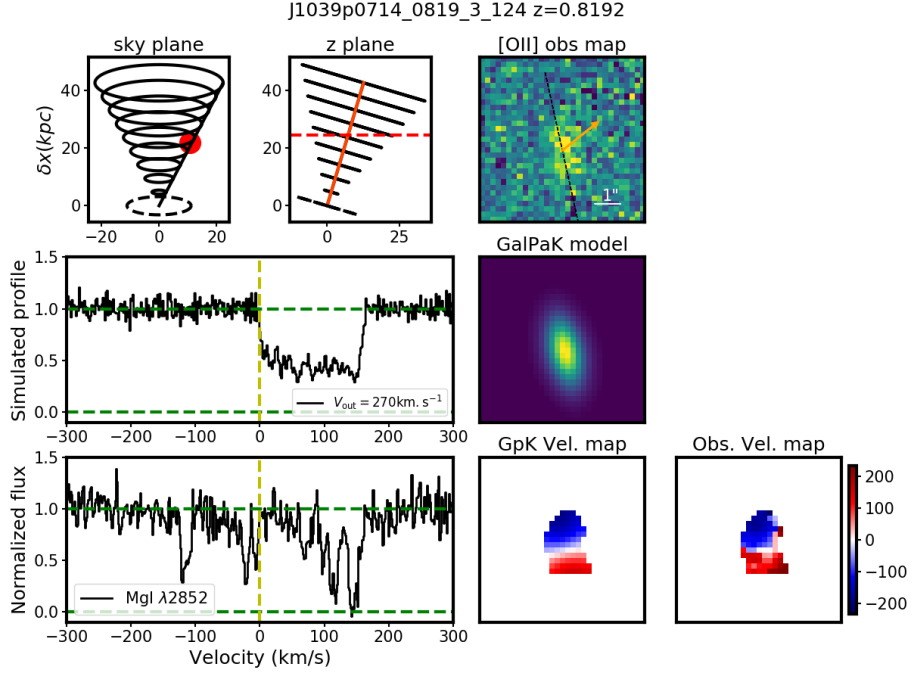
**Figure A.12.** Same as Figure 5 but for the galaxy #13 at redshift  $z = 0.7020$ . This is one of the "multiple model" outflows cases. The black (red) outflow has a  $V_{\text{out}}$  of  $45 \pm 10$  ( $75 \pm 10$ )  $\text{km s}^{-1}$  and an opening angle  $\theta_{\text{max}}$  of  $30 \pm 2^\circ$  (same).



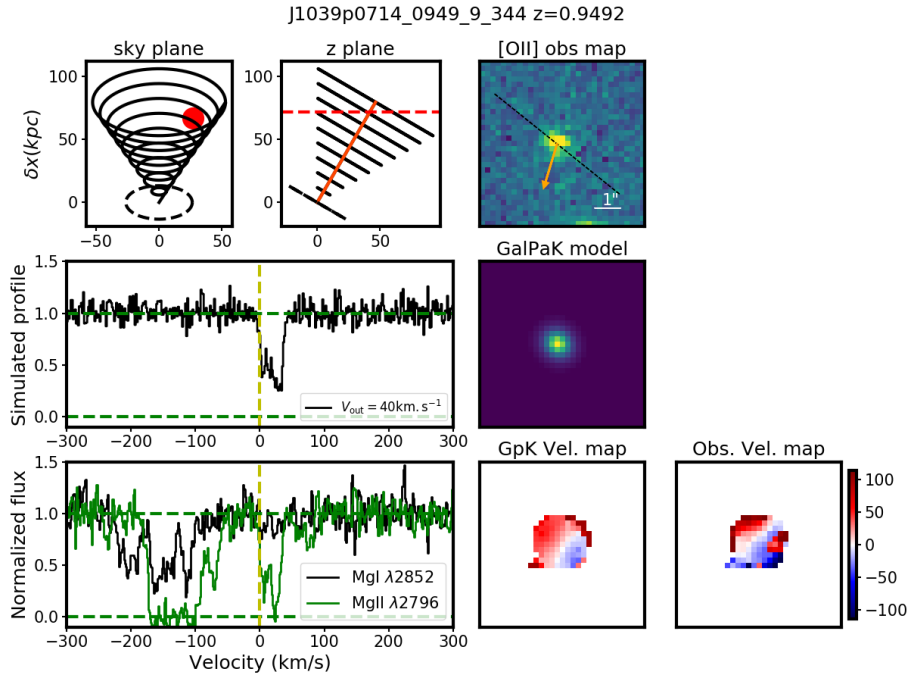
**Figure A.13.** Same as Figure 5 but for the galaxy #13 at redshift  $z = 0.7020$ . This is one other alternative wind model for this galaxy. The black (red) outflow has a  $V_{\text{out}}$  of  $150 \pm 10 \text{ km s}^{-1}$  an opening angle  $\theta_{\text{max}}$  of  $30 \pm 2^\circ$  and an empty inner cone  $\theta_{\text{in}}$  of  $10^\circ$ .



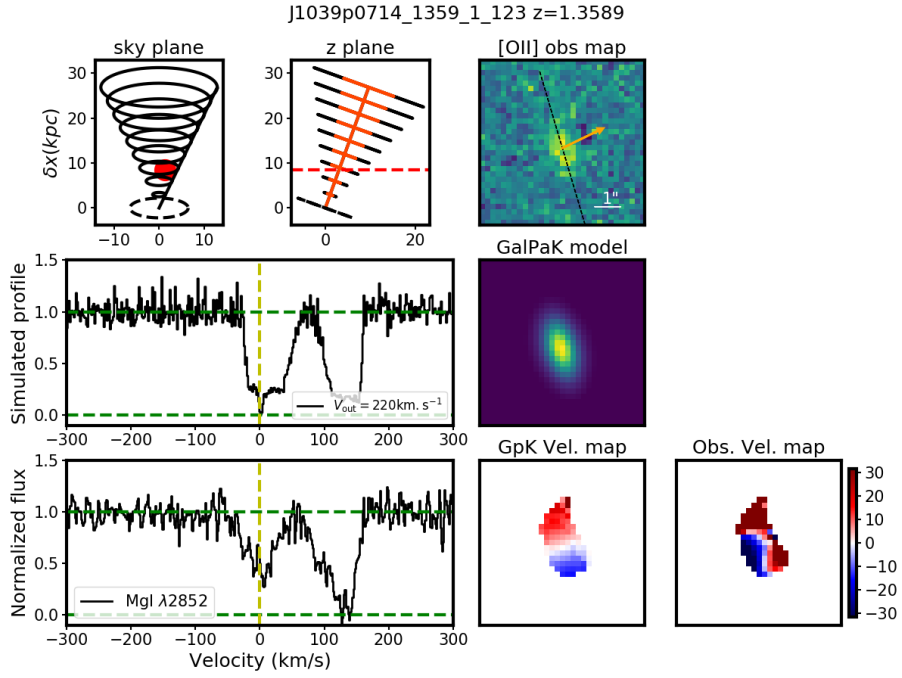
**Figure A.14.** Same as Figure 5 but for the galaxy #14 at redshift  $z = 0.9337$ . This outflow has a  $V_{\text{out}}$  of  $240 \pm 10 \text{ km s}^{-1}$  and an opening angle  $\theta_{\text{max}}$  of  $20 \pm 2^\circ$



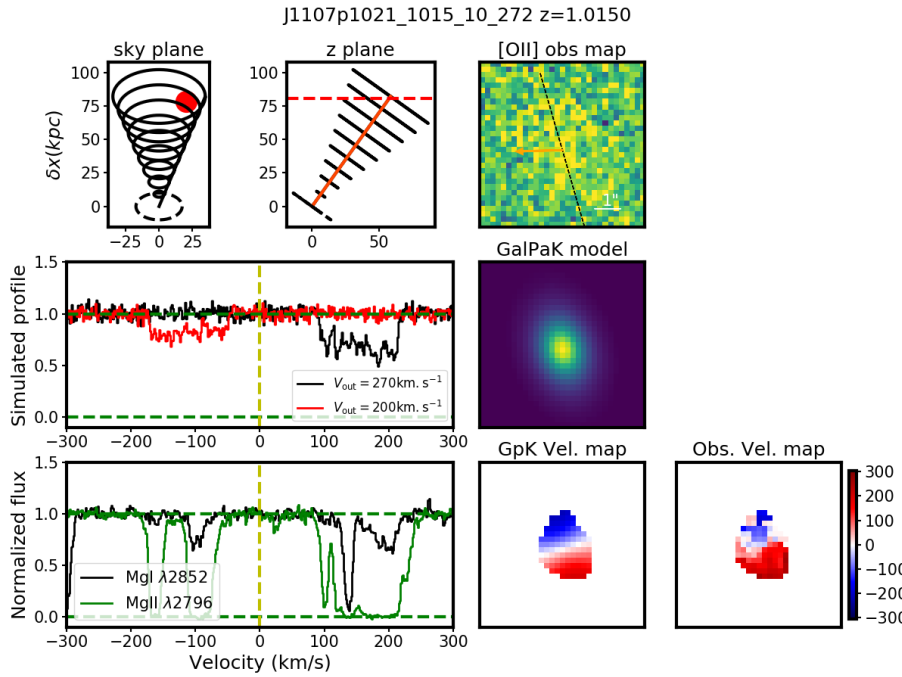
**Figure A.15.** Same as Figure 5 but for the galaxy #15 at redshift  $z = 0.8192$ . This outflow has a  $V_{\text{out}}$  of  $270 \pm 10 \text{ km s}^{-1}$  and an opening angle  $\theta_{\text{max}}$  of  $30 \pm 2^\circ$ .



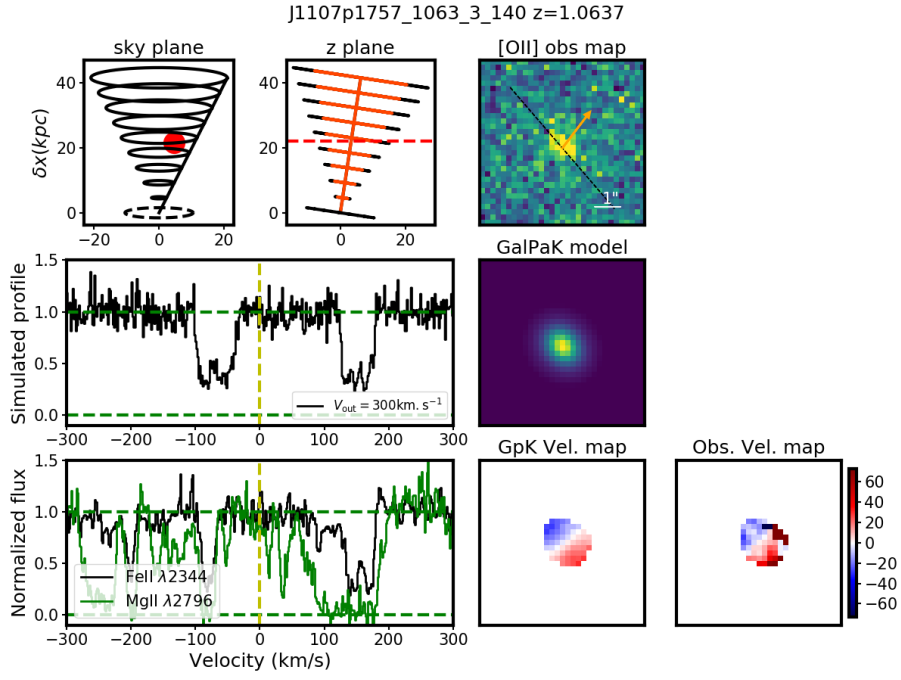
**Figure A.16.** Same as Figure 5 but for the galaxy #16 at redshift  $z = 0.9492$ . This outflow has a  $V_{\text{out}}$  of  $40 \pm 10 \text{ km s}^{-1}$  and an opening angle  $\theta_{\text{max}}$  of  $35 \pm 2^\circ$ . This galaxy is believed to produced the absorption the closest to the systemic redshift as the other absorption appears to come from a closer galaxy described in Paper II.



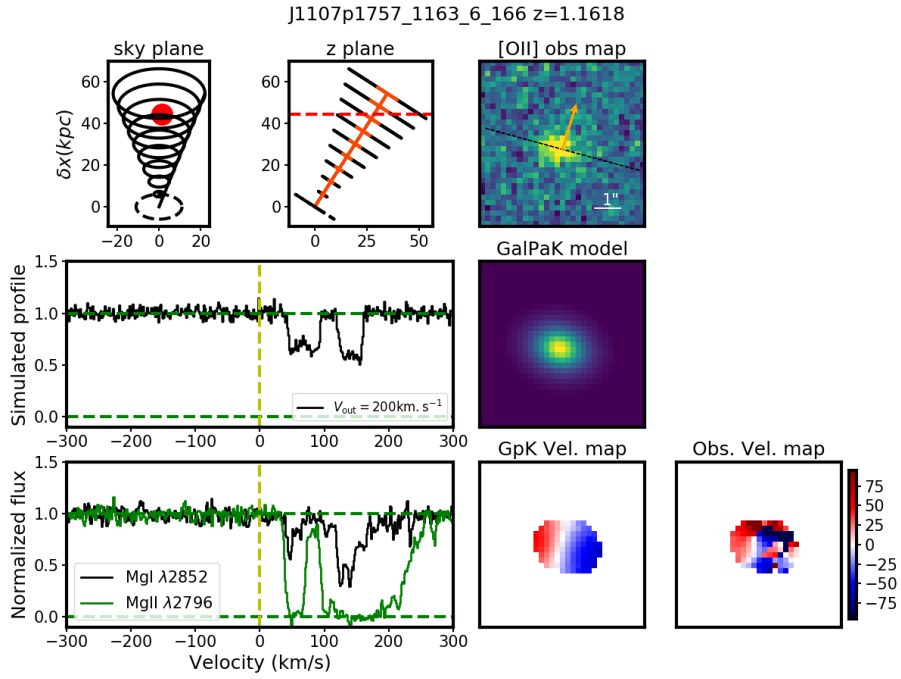
**Figure A.17.** Same as Figure 5 but for the galaxy #17 at redshift  $z = 1.3589$ . This outflow has a  $V_{\text{out}}$  of  $220 \pm 10 \text{ km s}^{-1}$ , an opening angle  $\theta_{\text{max}}$  of  $27 \pm 2^\circ$  and an empty inner cone  $\theta_{\text{in}}$  of  $12^\circ$ . The observed velocity map appears slightly different due to the quasar subtraction of the subcube.



**Figure A.18.** Same as Figure 5 but for the galaxy #18 at redshift  $z = 1.0150$ . This is one of the "multiple model" outflows cases. The black (red) outflow has a  $V_{\text{out}}$  of  $270 \pm 10$  ( $200 \pm 10$ )  $\text{km s}^{-1}$  and an opening angle  $\theta_{\text{max}}$  of  $20 \pm 2^\circ$  ( $25^\circ$ ).

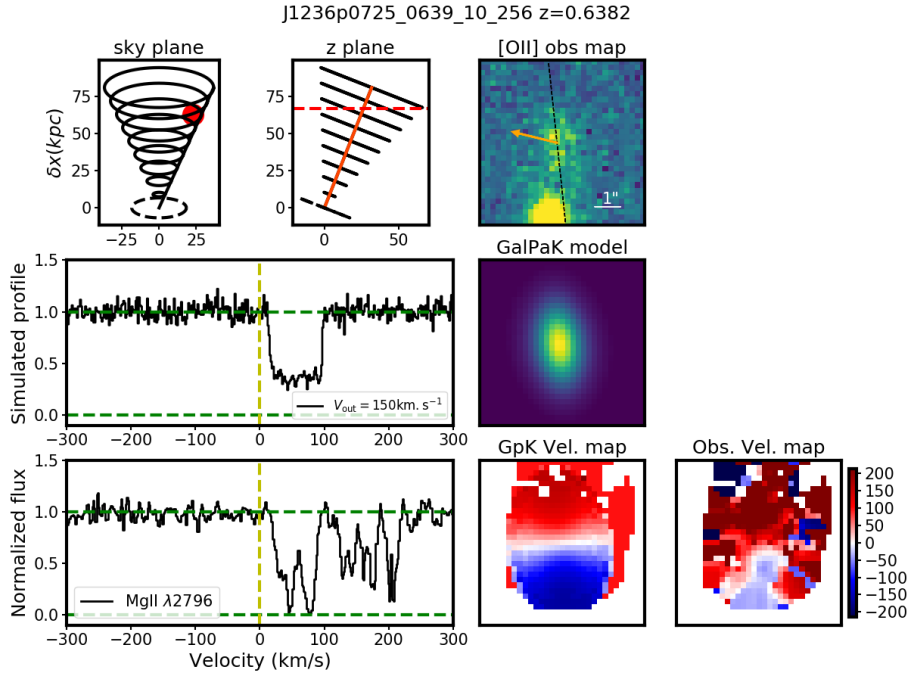


**Figure A.19.** Same as Figure 5 but for the galaxy #19 at redshift  $z = 1.0637$ . This outflow has a  $V_{\text{out}}$  of  $300 \pm 10 \text{ km s}^{-1}$ , an opening angle  $\theta_{\text{max}}$  of  $30 \pm 2^\circ$  and an empty inner cone  $\theta_{\text{in}}$  of  $20^\circ$ .

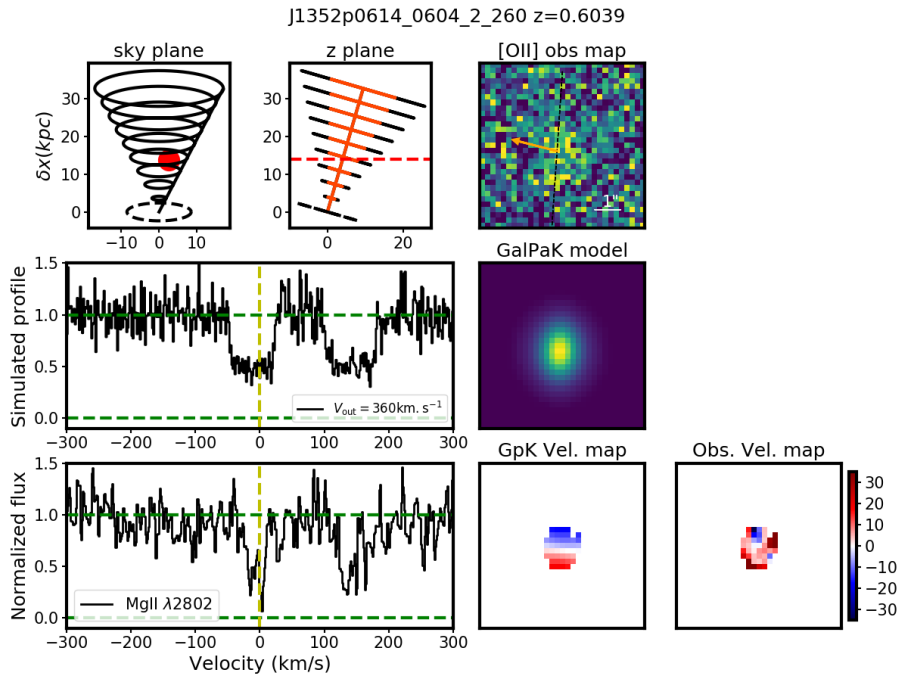


**Figure A.20.** Same as Figure 5 but for the galaxy #20 at redshift  $z = 1.1618$ . This outflow has a  $V_{\text{out}}$  of  $200 \pm 10 \text{ km s}^{-1}$ , an opening angle  $\theta_{\text{max}}$  of  $20 \pm 2^\circ$  and an empty inner cone  $\theta_{\text{in}}$  of  $5^\circ$ .

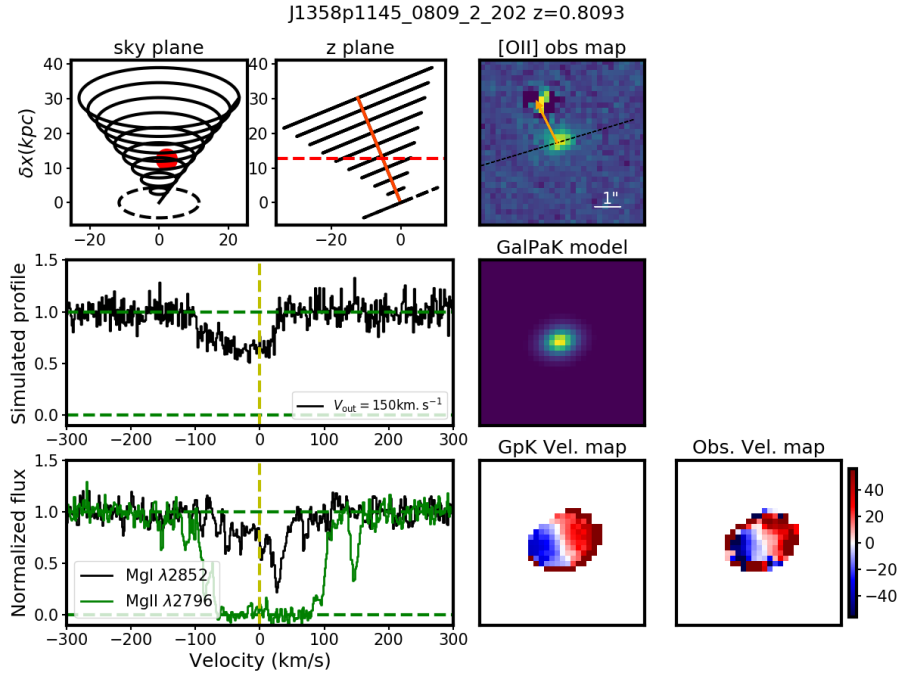




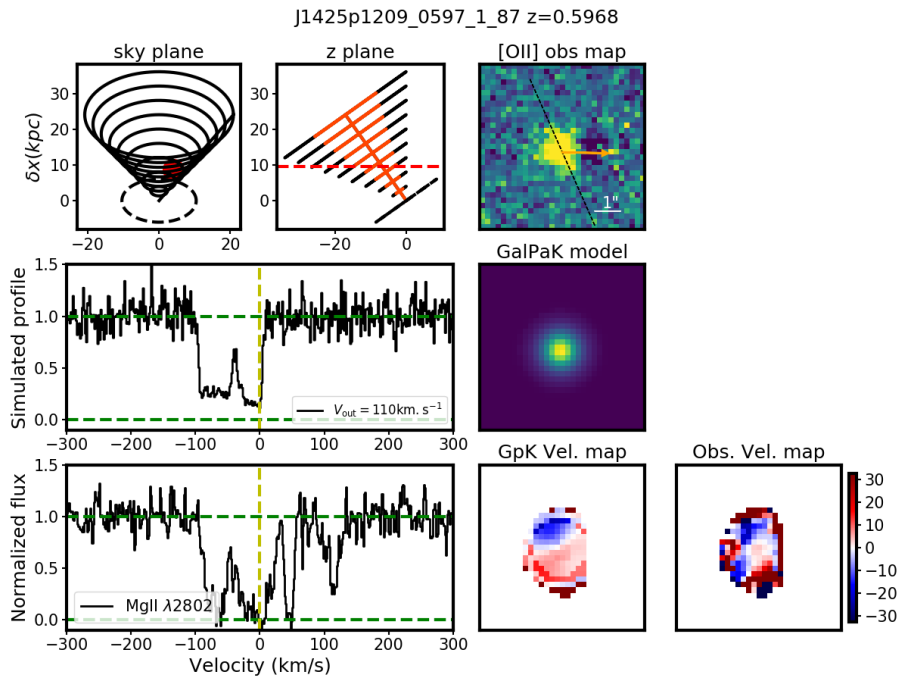
**Figure A.21.** Same as Figure 5 but for the galaxy #21 at redshift  $z = 0.6382$ . This outflow has a  $V_{\text{out}}$  of  $150 \pm 10 \text{ km s}^{-1}$  and an opening angle  $\theta_{\text{max}}$  of  $25 \pm 2^\circ$ . The measured velocity map appears to be different at the lower left part since there is a very close galaxy at the same redshift (which we can see on the observed [O II] map). However, the galaxy PA and rotational velocity are in good agreement.



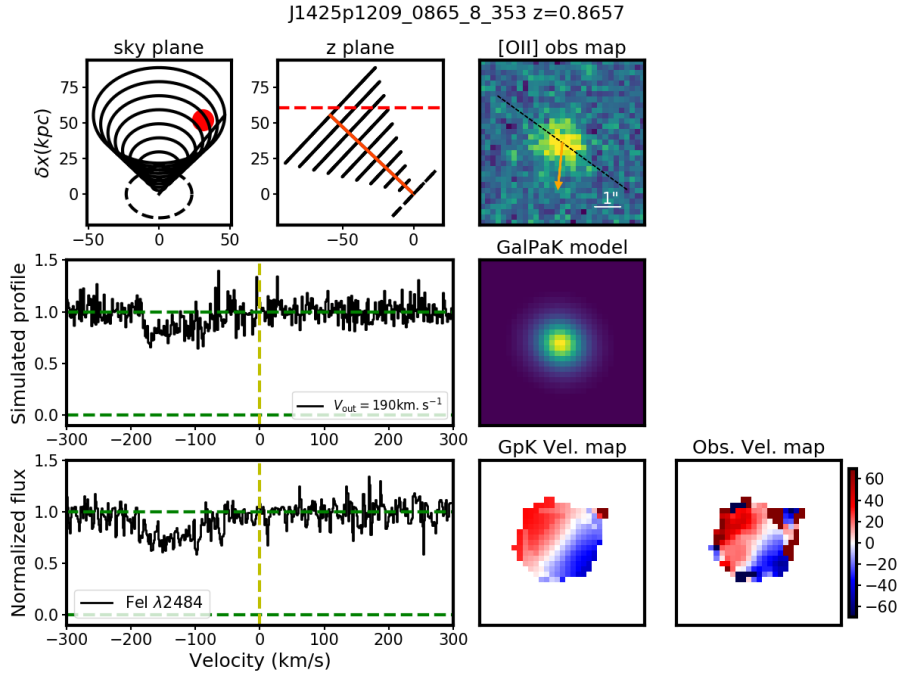
**Figure A.22.** Same as Figure 5 but for the galaxy #22 at redshift  $z = 0.6039$ . This outflow has a  $V_{\text{out}}$  of  $80 \pm 10 \text{ km s}^{-1}$  and an opening angle  $\theta_{\text{max}}$  of  $30 \pm 2^\circ$ .



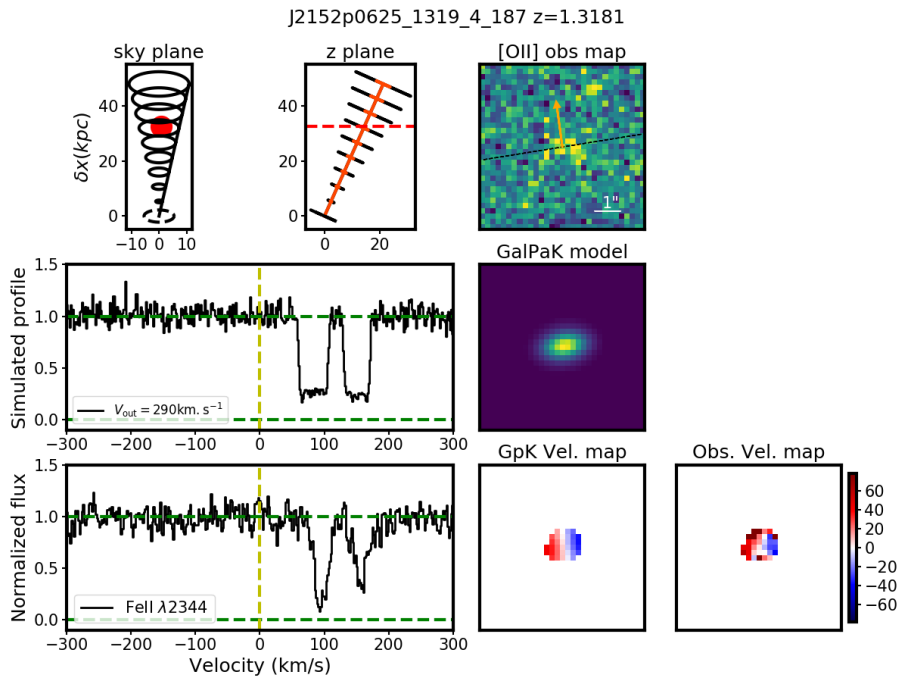
**Figure A.23.** Same as Figure 5 but for the galaxy #23 at redshift  $z = 0.8093$ . This outflow has a  $V_{\text{out}}$  of  $150 \pm 10 \text{ km s}^{-1}$  and an opening angle  $\theta_{\text{max}}$  of  $45 \pm 2^\circ$ .



**Figure A.24.** Same as Figure 5 but for the galaxy #24 at redshift  $z = 0.5968$ . This outflow has a  $V_{\text{out}}$  of  $110 \pm 10 \text{ km s}^{-1}$ , an opening angle  $\theta_{\text{max}}$  of  $45 \pm 2^\circ$  and an empty inner cone  $\theta_{\text{in}}$  of  $21^\circ$ .



**Figure A.25.** Same as Figure 5 but for the galaxy #25 at redshift  $z = 0.8657$ . This outflow has a  $V_{\text{out}}$  of  $190 \pm 10 \text{ km s}^{-1}$  and an opening angle  $\theta_{\text{max}}$  of  $35 \pm 2^\circ$ .



**Figure A.26.** Same as Figure 5 but for the galaxy #26 at redshift  $z = 1.3181$ . This outflow has a  $V_{\text{out}}$  of  $290 \pm 10 \text{ km s}^{-1}$ , an opening angle  $\theta_{\text{max}}$  of  $12 \pm 2^\circ$  and an empty inner cone  $\theta_{\text{in}}$  of  $3^\circ$ .