Gas Accretion and Giant Lyα Nebulae

Sebastiano Cantalupo

Abstract Several decades of observations and discoveries have shown that high-redshift AGN and massive galaxies are often surrounded by giant Lyα nebulae extending in some cases up to 500 kpc in size. In this chapter, I review the properties of the such nebulae discovered at $z > 2$ and their connection with gas flows in and around galaxies and their halos. In particular, I show how current observations are used to constrain the physical properties and origin of the emitting gas in terms of the Lyα photon production processes and kinematical signatures. The emerging picture from these studies suggest that recombination radiation is the most viable scenario to explain the observed Lyα luminosities and Surface Brightness for the large majority of the nebulae and imply that a significant amount of dense ($n > 1 \, \text{cm}^{-3}$), ionized and cold ($T \sim 10^4 \, \text{K}$) ”clumps” should be present within and around the halos of massive galaxies. Spectroscopic studies suggest that, among the giant Lyα nebulae, the one associated with radio-loud AGN should have kinematics dominated by strong, ionized outflows within at least the inner 30-50 kpc. Radio-quiet nebulae instead present more quiescent kinematics compatible with ”stationary” situation and, in some cases, suggestive of rotating structures. However, definitive evidences for accretion onto galaxies of the gas associated with the giant Lyα emission are not unambiguously detected yet. Deep surveys currently ongoing using other bright, non-resonant lines such as Hydrogen Hα and He II 1640 will be crucial to search for clearer signatures of cosmological gas accretion onto galaxies and AGN.

1 Introduction

This chapter reviews the properties of extended Lyα emission in the high redshift universe ($z > 2$) and their connection with gas flows in and around galaxies and
2 Observations of Giant Lyα Nebulae

2.1 Quasar Lyα Nebulae

Being the first and more luminous high-redshift object discovered above $z>2$, quasars have been obvious signposts since the mid 1980s to look for putative galactic and gaseous "companions" in Lyα emission. One of the first attempt reported in the literature is the pioneering narrow-band observation of Djorgovski et al. (1985) on the Lick Observatory 3 meter telescope centred on the radio-loud QSO PKS1614+051 at $z\sim3.2$ that resulted in the discovery of a companion Lyα emitting galaxy (a narrow-line AGN) at about 5'' from the quasar. Later observations by Hu & Cowie (1987) using the same technique on the 3.6 meter Canada France Hawaii Telescope (CFHT), showed the presence of a "bridge" of Lyα emission between the quasar and the companion galaxy. In the same year, Schneider et al. (1987) reported the discovery of "companions" Lyα emission to the triply-lensed radio-loud quasar Q2016+112.

These initial discoveries prompted an intense effort to search for Lyα emission around quasars, mostly of which radio-quiet, in subsequent years but despite the large number of quasars observed (about 50), no detectable Lyα candidates were
found (these results were mostly unpublished, see discussion in Hu et al. 1991). The situation changed in the early 1990s when observational surveys focused on the much smaller sub-sample of radio-loud quasars (Hu et al. 1991, Heckman et al. 1991) reported a detection rate of compact or extended companion Lyα emission close to 100%. In particular, Heckman et al. (1991) reported the discovery of Lyα Nebulae with sizes of about 100 kpc for 15 of the 18 radio-loud quasars observed. The contemporarily discovery of large Lyα Nebulae around non-QSO radio-sources (e.g., McCarthy et al. 1987 at $z \sim 1.8$) as I will discuss in section 2.2 suggested to these authors a possible link between the radio and the Lyα emission. At the same time, searches around radio-loud quasars were also motivated by the possibility to test the hypothesis that radio-loud quasars and radio galaxies were the same class of objects viewed along different angles with respect to the radio axis.

One of the first detection of “companion” Lyα emission to radio-quiet quasars was due to a serendipitous observation by Steidel, Sargent & Dickinson (1991) at the Palomar 5 meter telescope: originally searching for the continuum counterpart of a $z \sim 0.8$ MgII absorber in the spectrum of the radio-quiet QSO Q1548+0917, they found instead a narrow and extended Lyα emission line at the same redshift of the quasar in the spectrum of a faint continuum source $\sim 5''$ away from the QSO. Also, additional narrow-band imaging suggested the presence of extended Lyα emission around the quasar. In the following year, Bremer et al. (1992) reported the discovery of extended ($\sim 5''$) emission in long-slit spectra of two radio-quiet quasars at $z \sim 3.6$. These results showed that “companion” Lyα emission was not restricted to radio-loud quasars only.

Giant Lyα Nebulae with sizes larger than 10'' (or larger than about 100 kpc) around radio-quiet quasars remained however elusive for more than two decades after the survey of Heckman et al. (1991) around radio-loud quasars. The only exception was the serendipitous discovery of Bergeron et al. (1999) around the $z \sim 2.2$ radio-quiet quasar J2233-606 located in one of the parallel fields of the Hubble Deep Field South. The field was observed during science verification of the VLT-UT1 Test Camera using broadband filters and a narrow-band filter centred on the quasar Lyα emission. Despite some large-scale residual of the flat-fielding procedure, the narrow-band image seemed to show extended emission with a maximum projected size of about 12'' (about 100 kpc with current cosmological parameters) around the quasar.[1] On the other hand, during the same years a few individual detections of small nebulae extending up to a few arcsec around radio-quiet quasars were reported (Fried 1998; Möller et al. 2000; Bunker et al. 2003; Weidinger et al. 2004) and in some cases associated with intergalactic gas (e.g., Weidinger et al. 2004, 2005). By the beginning of the 2010a, thanks to long-slit spectroscopic surveys and small Integral-Field-Unit (IFU) observations, a common picture emerged that associated only relatively small nebulae (i.e., $< 60$-70 kpc) to about 50% of radio-quiet quasars between $2 < z < 5$ (Christensen et al. 2006; Courbin et al. 2008; North et al. 2012; Hennawi & Prochaska 2013; but see Herenz et al. 2015) However, as I discuss below, these results may have been limited by the small sizes of the IFU

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[1] A very recent and deeper observation with GMOS seems to confirm at least part of this nebula up to a size of about 70 kpc (Arrigoni-Battaia et al, in prep.).
Field-of-View (FOV) and by the use of long-slit spectroscopy that cannot capture
the full extent of asymmetric nebulae.

\subsection{Rise of the Giants}

The last few years witnessed a complete revolution in our knowledge of giant Ly$\alpha$
nebulae around radio-quiet quasars thanks to serendipitous discoveries by means
of NB imaging with custom-built filters (Cantalupo et al. 2014; Martin et al. 2014;
Hennawi et al. 2015) and dedicated surveys with VLT/MUSE (e.g., Borisova et
al. 2016). Two decades after Hu et al. (1991) and Heckman et al. (1991), a new
narrow-band campaign on quasar fields was initiated in order to search for "dark
galaxies" and fluorescently illuminated intergalactic gas following the prediction,
e.g., of Cantalupo et al. (2005). Two pilot programs using a spectroscopic "multi-
slit plus filter" technique (Cantalupo et al. 2007) and deep NB imaging ($\sim$20 hours)
on FORS/VLT using a custom-built filter for a quasar at $z \sim 2.4$ (Cantalupo et al.
2012), revealed a dozen of compact Ly$\alpha$ sources with no detectable continuum and
Equivalent Widths (EW) larger than 240$\AA$, the best candidates for "dark galaxies"
iluminated by the quasar. Circumgalactic gas was also detected in emission extend-
ing by several tens of kpc around a few bright galaxies but the quasar did not show
evidence for extended nebulae, in agreement with previous findings.

Stimulated by these initial results, Cantalupo et al. (2014) initiated a campaign
using Keck/LRIS and custom-built filters to search for "dark galaxies" around about
ten radio-quiet quasars at $z \sim 2$. Surprisingly, the first quasar observed at Keck/LRIS,
i.e. UM287, showed clear evidences of extended emission over scales larger than
10" after the first 20 minutes exposure was obtained. At the end of the total inte-
gration of 10 hours and detailed data reduction, a giant Ly$\alpha$ nebula extending to
about 55" ($\sim$ 460 kpc) was found around this quasar (Cantalupo et al. 2014), see
Fig. 1, and named "Slug Nebula" (given its morphology and in honor of the mascot
of the University of California, Santa Cruz). This discovery was surprising for sev-
eral reasons: i) despite its association with a radio-quiet quasar, it is at least twice
as large as any previously detected Ly$\alpha$ Nebulae including the much more common
radio-galaxy halos and Ly$\alpha$ blobs as discussed below; ii) given its size, it extend
well beyond the viral halo of the quasar into the intergalactic medium; iii) it shows a
very high Surface Brightness over very large scales that cannot be easily explained
unless a large gas clumping factor within intergalactic gas is invoked (see section
3.1). During the same night, a second quasar field was observed using a different
custom-built filter, selected among the quasar-pair sample of Hennawi & Prochaska
(2013) and showing some hints of extended emission, and another giant Ly$\alpha$ nebula
with a size of about 300 kpc was discovered (Hennawi et al. 2015). The particular-
arity of this discovery included also the presence of a physically associated quasar
quartet and a large overdensity of Ly$\alpha$ emitting galaxies (differently than the Slug
Nebula). Named "Jackpot Nebula" given the rarity of such systems, it traces likely
a very peculiar region of the Universe and possibly a proto-cluster. In the same
year of these discoveries, Martin et al. (2014) presented the detection of another gi-
ant nebula originally found around one of the six quasars observed in narrow-band imaging as a part of the Keck Baryonic Structure Survey (e.g., Trainor & Steidel 2012). Subsequent observations of other quasars as a part of the same survey and including results obtained on GMOS/Gemini (Arrigoni-Battaia et al. 2016) showed once again however that such detection of giant Lyα nebulae are apparently rare, i.e. with a frequency less than 10%.

The installation of the MUSE Integral-Field-Spectrograph on the Very Large Telescope in 2014 provided new opportunities for the detection and study of Giant Lyα nebulae around quasars thanks to its a large FOV of 1’ × 1’ (about 450 × 450 kpc²; individual spatial elements have a size of 0.2’’ × 0.2’’) and because, by design, it does not suffer from either narrow-band filter losses or spectroscopic slit losses. Also, the large number of spatial and spectral elements allows for better quasar PSF estimation and removal with respect to NB surveys. Because accurate systemic redshifts are not needed for MUSE observations (as for any other spectroscopic survey) any quasar with Lyα redshifted between the blue and red edges of the MUSE wave-
length range \((2.9 < z < 6.5)\) can be observed. In one of the first exploratory study as a part of the MUSE Guaranteed Time Observations (GTO), Borisova et al. (2016) observed with short total exposure times (1 hour) 17 of the brightest radio-quiet quasars in the Universe at \(3.1 < z < 3.7\) and complemented them with two radio-loud quasar at the same redshifts. The picture emerging from these MUSE observations is very different than that based on previous surveys, in that giant nebulae with sizes larger than 100 pkpc are found around essentially every quasar above a surface brightness level of about \(10^{-18}\) erg s\(^{-1}\) cm\(^{-2}\) arcsec\(^{-2}\). The nebulae detected with MUSE present a large range in sizes and morphologies, ranging from circular nebulae with a projected diameter of about 110 pkpc to filamentary structures with a projected linear size of 320 pkpc (see Fig.2). Despite these differences, the circularly averaged SB profiles show a strong similarity between all the giant Quasar Nebulae (including the Slug Nebula at \(z \sim 2\) once corrected for redshift-dimming) with very few exceptions, both in terms of slope and normalization, suggesting a similar origin for these systems.

This 100% detection rate of giant nebulae around radio-quiet quasars obtained with MUSE (see also, Fumagalli et al. 2016) is in stark contrast with previous results in the literature as I have reviewed in this section. While the asymmetric morphology of the MUSE nebulae may explain the discrepancy with spectroscopic surveys using a single slit position, the difference with the detection rate of NB surveys at \(z \sim 2\) cannot be completely and easily explained by observational limitations such as NB filter losses, uncertainties in quasar systemic redshifts and Quasar Point-Spread-Function (PSF) removal errors. Redshift and quasar luminosities may therefore play a role in the appearance and properties of Ly\(\alpha\) nebulae around quasars and future IFU studies extending to lower redshifts (e.g., with the Keck Cosmic Web Imager) and to lower quasar luminosities are necessary to properly address these open questions.

2.2 Radio-galaxy Ly\(\alpha\) Halos

As mentioned in the previous section, follow-up observations of radio-loud sources provided already in the second half of the 1980s the first evidences for giant Ly\(\alpha\) nebulae. In this section, I will focus on non-QSO radio sources at \(z > 1\), i.e. High-z Radio Galaxies (HzRG).

Although many different classification exists (see e.g. McCarthy 1993 and Antonucci 2012 for a review), the most obvious distinction between the QSO and non-QSO class of radio source traces its roots from the appearance of the optical morphology, i.e. from the presence of a quasi-stellar point source versus a spatially resolved galaxy. Because this distinction may be difficult to be applied at high redshift a more physical definition can be made instead from the properties of the emission-line spectra. Indeed, classical radio-galaxies have spectra with relatively narrow (FWHM < 2000 km/s) permitted lines with respect to the broader lines showed by quasars (FWHM > 5000 km/s). These are sometimes called "Narrow Line
"Optimally extracted" narrow-band images of the sample of luminous quasars at $3 < z < 4$ observed with MUSE by Borisova et al. (2016) as a part of a "snapshot" survey using short integration times, i.e. 1 hour per field (see Borisova et al. 2016 for details on the detection and extraction of these images from the datacubes). The quasars are all radio-quiet with the exception of the two fields labeled “R1” and “R2”. All nebulae are larger than 100 kpc and extending in some cases up to at least 320 kpc (e.g., the nebula number 3 or "MQN03") with various morphologies including filamentary structure. This survey showed that giant Ly$\alpha$ nebulae are ubiquitous around bright quasars, including radio-quiet ones, in contrast to previous observations at $z \sim 2$ as discussed in detail in section 2.1 (Figure reproduced with permission from Borisova et al. 2016).

Radio Galaxies” or “type 2”. Moreover, high-redshift quasars have a much brighter, "thermal" continuum than "type 2" radio-galaxies with a clear non-stellar origin.
It is important to notice however that a small fraction of "spatially resolved" radio galaxies show broad lines as well as bright thermal continuum. These are sometimes called "Broad Line Radio Galaxies". To avoid confusion, in this section and in the reminder of this chapter we will always refer to radio-galaxies as "type 2". Like their lower redshift counterparts, HzRG often show extended radio lobes that have been associated with bi-polar jets (e.g., McCarthy 1987) and show a high degree of polarization. The observation of relativistic beaming and smaller, one-sided radio-jets in radio-loud quasars have already suggested in the 1980s that radio-galaxies and radio-loud quasars may be part of the same population of AGN but seen at different orientations (e.g., Barthel 1989; see Antonucci 1993 for a review and, Antonucci 2012 for more recent discussion).

Narrow-band imaging and spectroscopy of HzRGs, soon after their discovery in the 1980s and until very recently, has produced a large literature of detections and studies of large Lyα nebulae, similarly to radio-loud quasars. The first observations by McCarthy et al. (1987) of the radio-galaxy 3C 326.1 at $z \sim 1.8$ at the Lick Observatory revealed Lyα emission surrounding the radio lobes and extending by about 70 kpc (with current cosmological parameters). Few years later, McCarthy et al. (1990) reported the discovery of the first giant Lyα nebula extending over 120 kpc around the $z \sim 1.8$ radio galaxy 3C 294. This nebula is highly elongated and well aligned with the inner radio source axis. Extended C IV and He II emission was also detected. One of the first detection of extended Lyα emission around a radio-galaxy above redshift of three was reported by Eales et al. (1993) studying the $z = 3.22$ radio galaxy 6C 1232+39, a system with a "classical" double radio structure oriented along the same direction of the Lyα emission but showing some differences in the morphology and symmetry of the optical emission with respect to the radio.

Larger sample of HzRG observations were started to be obtained in the 1990s as a part of several campaigns that resulted in the discovery of several tens of HzRG at $z > 2$ (e.g., Röttgering et al. 1994). The most notably discoveries included a giant Lyα halo extending over 140 kpc around a HzRG at $z \sim 3.6$ (van Ojik et al. 1995) showing a complex kinematical structure spatially correlated with the radio jet: large velocity widths (FWHM $\sim 15000$ km/s) in proximity of the radio jets and a aligned, low SB component with narrow velocities (FWHM $\sim 250$ km/s) extending 40 kpc beyond both sides of the radio source. I will discuss and compare in detail in section the kinematical properties of radio-loud and radio-quiet nebulae, including this system.

Subsequent observational campaigns found almost ubiquitous detection of extended Lyα emission around HzRG extending in several cases above 100 kpc in size (e.g., Pentericci et al. 1997, Kurk et al. 2000, Reuland et al. 2003, Villar-Martin et al. 2003, Venemans et al. 2007, Villar-Martin et al. 2007, Humphrey et al. 2008, Sanchez & Humphrey 2009, Roche et al. 2014) and showing a wealth of morphological structures, including filaments, clumpy regions and cone-shaped structures. The common features of all these detections include: i) apparent alignment between Lyα emission and the radio jet axis (e.g. Villar-Martin et al. 2007), ii) broad kinematics (with some exceptions at the far edge of the nebulae), iii) associated extended C IV and He II emission, iv) invariable association with large overdensity as traced
by companion Lyα galaxies (e.g., Venemans et al. 2007) or multi-wavelength observations from X-ray to the infrared (Pentericci et al. 1997). In terms of luminosities and surface brightness the HzRG halos show similar values with respect to radio-loud and radio-quiet quasar nebulae, while UV line ratios and kinematics seems to be quite distinct form the radio-quiet quasar Nebulae (see e.g., Borisova et al. 2016) as I will discuss in section 4.

### 2.3 Lyα blobs

The historically-distinct category of giant Lyα Nebulae called "Lyα blobs" made their appearance with the deep narrow-band observations of Steidel et al. (2000) of a region containing a high overdensity of galaxies both in projected and velocity space in the so called "Small Selected Area 22h" (SSA22) field (Lilly et al. 1991; Steidel et al. 1998). While searching for candidates Lyα emitting galaxies in this field at $z=3.09$, Steidel et al. (2000) found to their surprise "two very luminous, very extended regions of line emission which we descriptively call "blobs"". Extending by about 15 to 17 arcsec (115 to 132 kpc with current cosmology), they were among the largest Lyα Nebulae found at that epoch, with similar extent and luminosities to radio-loud quasar and radio-galaxy Nebulae. However, these "blobs" were apparently lacking any associated, bright continuum or radio source and therefore considered as a possibly different category of objects. In particular, Steidel et al. (2000) considered the possibility of a "cooling flow" origin for the emission, by analogy with Hα emission from observed cooling-flow clusters or photo-ionization by heavily obscured, highly star forming galaxies. However, no firm conclusion was possible with the available data for that time. The "mysterious" nature of these Lyα blobs attracted the attention of several theoretical and numerical studies, right after their discoveries until very recently, that tried to explain the peculiarity of these systems with a variety of physical explanations that did not require a bright photo-ionizing source such as an AGN. These models ranged from galactic superwinds (including e.g., Taniguchi & Shioya 2000) to cooling radiation from the so called "cold-mode accretion" (including, e.g. Haiman et al. 2001; Fardal et al. 2001; Dijkstra & Loeb 2009) as I discuss more in detail in section 4.

From an observational and historical point of view, a Lyα "blob" (LAB) could then be defined as an extended Lyα emission over scales significantly larger than a single galaxy that does not seem to contain an AGN (at the time of their discovery). Extended Lyα nebulae around galaxies that did not contain optically bright or radio-loud AGN in overdense fields were already known before the observations of Steidel et al. (2000), e.g. Francis et al. (1996) and later re-observations published in Francis et al. (2001), and Keel et al. (1999), although in most cases hints of obscured AGN were present in these studies. Steidel "blobs" however were the first one in this category to exceed the "giant Lyα Nebula" size of 100 kpc. Later Subaru observations of the same SSA22 field made by Matsuda et al. (2004) exploring a much larger area than the original survey by Steidel et al. (2000) found several extended Lyα...
nebulae around galaxies, i.e. 33 nebulae with area exceeding 15 arcsec$^2$ in addition to the Steidel "blobs" (also called LAB1 and LAB2). However, none of those new detections were close to LAB1 and LAB2 in terms of overall sizes. For instance, the largest new detection by Matsuda et al. (2004) had an area that was only half the one of LAB2 and a maximum projected size of about 75 kpc. Nevertheless, this overdense field showed clearly an excess of extended sources with respect to "blank" observation suggesting a possible relation between galaxy (or AGN) overdensities and extended Ly$\alpha$ emission. Similarly, deep narrow band imaging obtained by Palunas et al. (2004) of the overdense field at $z \sim 2.38$ found by Francis et al. (2001), revealed a large Ly$\alpha$ blob with sizes compatible with Steidel’s LAB1 and several smaller nebulae around galaxies.

LAB1 was the first LAB to be studied in detail in multi wavelength observations and revealed the presence of a strong submillimeter source with a bolometric luminosity in excess of $10^{13} L_\odot$ (e.g., Chapman et al. 2001, Geach et al. 2005) but no evidence from deep Chandra X-ray observations of a clear X-ray counterpart (Chapman et al. 2004). However, these limits did not exclude the possibility of a luminous AGN but heavily obscured along our line of sight. LAB2 instead showed, in addition to a (fainter) submillimeter source (Chapman et al. 2001), clear evidences for hard X-ray emission (e.g., Basu-Zych & Scharf 2004) and therefore for the presence of a partially unobscured AGN. This link between LABs and luminous star forming galaxies stimulated new observational campaigns to detect LABs by searching, e.g. around luminous infrared sources. During one of such campaigns, Dey et al. (2005) discovered a 160 kpc Ly$\alpha$ emitting nebula around a luminous mid-infrared source first detected with the Spitzer Space Telescope. This nebula shared many similarities with the previously detected LAB1 and LAB2. Although X-ray information was not available at that time, the presence of narrow and centrally concentrated C IV and He II emission within the Nebula suggested again an association with a Type-2 AGN. Differently from radio-galaxy halos, this nebula showed however relatively narrow Ly$\alpha$ emission in velocity space and possibly a ordered velocity shear. As we will discuss in section 4, this is compatible with other nebulae associated with radio-quiet AGN.

Giant LABs with sizes above 100 kpc are mainly discovered by targeting known overdense regions or bright infrared and submillimeter galaxies. Blank-field surveys using narrow-band imaging confirmed that giant LABs were indeed extremely rare (e.g. Saito et al. 2006, Yang et al. 2009), i.e. presenting a comoving number density less than $10^{-6}$ Mpc$^{-3}$ (e.g., Yang et al. 2009). Broadband surveys plus spectroscopic follow-ups were slightly more successfully, detecting one LAB with a size of about 100 kpc and three smaller nebulae in a volume of about $10^8$ Mpc$^3$ (Prescott, Dey & Jannuzi 2013). It is instructive to compare these numbers with the comoving number densities at $2 < z < 3$ of bright X-ray selected AGN, i.e. $n_X \sim 10^{-6}$ Mpc$^{-3}$ for $L_X > 10^{44.5}$ erg s$^{-1}$ (Ueda et al. 2003), optically-bright quasars at $z \sim 3$, i.e. $n_{QSO} \sim 10^{-7}$ Mpc$^{-3}$ for $M_i(z = 2) < -26.7$ (Shen et al. 2007), and HzRG, i.e. $4 \times 10^{-8}$ Mpc$^{-3}$ for $L_{2\,\nu_{21\,cm}} > 10^{33}$ erg s$^{-1}$ Hz$^{-1}$ sr$^{-1}$ (see Venemans et al. 2007).

Detection of smaller nebulae with sizes up to 40-70 kpc are less rare in blind narrow-band surveys and about ten of such discoveries were reported in the past,
including Nilsson et al. (2006), Yang et al. (2009), Smith et al. (2009), and Prescott et al. (2009). Deeper and larger narrow-band observations around the SSA22 fields and including some blank fields over a total volume of about $10^6$ Mpc$^3$ as a part of the "Subaru Ly$\alpha$ blob survey" resulted in the discovery of about seven new giant LAB with sizes around 100 kpc (Matsuda et al. 2006). An estimation of the number densities of these systems in this survey however, could be affected by the presence of the very overdense region in SSA22. In almost all cases, evidences for associated submillimeter or AGN sources were found at the time of the discovery or with subsequent multi-wavelength observations (e.g., Geach et al. 2009, Overzier et al. 2013, Hine et al. 2016; see also Scarlata et al. 2009 and Ao et al. 2015).

Despite the different techniques and volume probed, clustering analysis suggests that the sizes of detected LABs could be positively correlated with the environment overdensity, although the statistic is small (e.g., Yang et al. 2009, Matsuda et al. 2006). The very recent detection reported by Cai et al. (2016) of a LAB with a projected size of about $\sim$440 kpc at the center of one of the largest overdensity known at $z \sim 2.3$ seem to provide additional support for this suggestion. However, also in this case, there are evidences for at least one associated AGN (see also Valentino et al. 2016 for another example).

As I have review in this section, several decades of observations and discoveries have produced a large literature of extended and giant Ly$\alpha$ nebulae that have been classified in various ways and with different nomenclatures depending on the technique and target of the original surveys, i.e. quasars, radio-galaxies, overdense regions or "apparently blank" fields. Their comparable volume densities and the almost invariable association with AGN or massively star forming galaxies seem to suggest however that most of these distinction may be artificial. There are however some indication that the kinematical properties and line ratios (e.g., considering He II, C IV and Ly$\alpha$) are distinct among radio-quiet and radio-loud nebulae, as well as for some LAB, as I will discuss in section 4.

3 Origin of the emission

In this section, I will review the three physical processes that are able to produce extended and bright Ly$\alpha$ emission: i) recombination radiation following hydrogen photoionization (by a quasar or star forming galaxy), ii) "continuum-pumping" or Ly$\alpha$ scattering of the photons produced in the quasar broad-line-region or within the Interstellar Medium (ISM) of a star forming galaxy, and iii) Ly$\alpha$ collisional excitation and recombination radiation following collisional ionization (so called Ly$\alpha$ cooling radiation). All these mechanisms require the presence of "cool" gas (i.e., with temperatures well below $10^3$ K). In addition, recombination radiation and "continuum-pumping" also require that the gas is "illuminated" by the quasar or by some other bright source of UV photons. In this case, the resulting Ly$\alpha$ emis-
sion is sometimes called "fluorescent" in the literature (e.g., Cantalupo et al. 2005, Kollmeier et al. 2010, Cantalupo et al. 2012, 2014; Borisova et al 2016).

### 3.1 Recombination radiation

In this case, Ly$\alpha$ photons are produced in a (photo-)ionized medium as a consequence of radiative recombination cascades and the Ly$\alpha$ emissivity will be simply proportional to the hydrogen recombination rate times the ionized hydrogen density squared. Because the hydrogen recombination rate has a relatively mild dependence from temperature, i.e. about linear (e.g., Osterbrock 1989) around $10^4$ K, this is the easiest case to model. The actual number of Ly$\alpha$ photons produced by each recombination event (and therefore by each ionizing photon, in photoionization equilibrium) will depend on the details of the recombination cascades that populate the 2P$_2$ state that will decay to the 1S$_2$ producing a Ly$\alpha$ photon. A good approximation, even in the low-density Intergalactic Medium, is to assume that every Lyman-line photon from $n > 2$ levels is converted into lower series photons plus either Ly$\alpha$ or two-photon continuum (Case B approximation, Baker & Menzel 1938). In this case, the fraction of Ly$\alpha$ photons for each recombination event ranges between 0.68 and 0.61 for $10^3 < (T/K) < 10^4$ (Cantalupo et al. 2008) showing again only a mild dependence on temperature. For reference, in the opposite case (Case A) when all Lyman-series photons leave the cloud, the fraction of Ly$\alpha$ photons for each recombination will be reduced by about a half. Combining these information with the Case B hydrogen recombination coefficient, one can obtain the effective Ly$\alpha$ recombination coefficient $\alpha_{\text{Ly}\alpha}^{\text{eff}}$ for Case B, that can be approximated with the expression (Cantalupo et al. 2008):

$$\alpha_{\text{Ly}\alpha}^{\text{eff}} \sim 2 \times 10^{-13} T_4^{-1.26} \text{cm}^3 \text{s}^{-1},$$  \hspace{1cm} (1)

where, $T_4 = 10^4 K$, for $10^3 < (T/K) < 10^4$. For a fully ionized cloud of hydrogen and helium, the Ly$\alpha$ integrated volume emissivity is therefore:

$$4\pi j_{\text{Ly}\alpha} \sim 3.7 \times 10^{-24} n^2 T_4^{-1.26} \text{erg s}^{-1} \text{cm}^{-3},$$  \hspace{1cm} (2)

where $n$ is the gas density in units of atoms per cm$^{-3}$. For a uniform gas slab with depth $L$ in units of kpc at redshift $z$, the observed surface brightness - equivalent to the surface brightness ignoring radiative transfer effects - will be given therefore by:

$$SB_{\text{Ly}\alpha} \sim 8 \times 10^{-17} n^2 T_4^{-1.26} L \cdot [(1+z)/4]^{-4} \text{erg s}^{-1} \text{cm}^{-2} \text{arcsec}^{-2}. $$  \hspace{1cm} (3)

The observed values of the SB of giant Ly$\alpha$ nebulae range from a few times $10^{-18}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$ in the external parts (at distances of 50-100 kpc from the central sources or the central peak of the Ly$\alpha$ emission) to $10^{-16}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$ in the central regions. From this simple calculation, it is easy to understand
that the observed SB would inevitably require large gas densities \((n > 0.1)\) in order to be explained by pure recombination emission. These high density estimates were obtained and claimed since the discoveries of the first nebulae around radio-loud quasars and galaxies (e.g. Heckman et al. 1991).

Are these densities compatible with our picture of cold gas within massive halos? It is instructive to rewrite the previous expression rewriting the density \(n\) in terms of the baryonic overdensity with respect to the canonical value of 200 for collapsed objects \((\delta_{200})\). Making use of the definition of clumping factor, i.e. \(C_L = \langle n^2 \rangle_L / \langle n \rangle_L^2\) where the average is made over a cylinder with depth \(L\) and projected area of 1 arcsec\(^2\) on the sky, we obtain:

\[
SB_{Ly\alpha}^m \sim 5 \times 10^{-20} C_L < \delta_{200} >^2_{L_{100}} L_{100} T^{-1.26}_4 \cdot [(1 + z)/4]^2 \text{ erg s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2},
\]

where \(L_{100} = L/100\) kpc. In this formula, no assumptions have been made about the density distribution and density inhomogeneities are encoded in the clumping factor term \(C_L\). Assuming that 100 kpc is the typical projected length of the cold gas distribution in the halo, it is then straightforward to see that, even if all the halo gas is in the form of a fully ionized and uniform medium at \(T = 10^4\) K, the predicted SB will be smaller than the observed values by several orders of magnitude. In this case, the observed SB constrains the clumping factor on scales corresponding to 1 arcsec\(^2\) on the sky plane, i.e. on a square with side of about 7 kpc at \(z \sim 3\) and on 100 kpc along the line of sight to be at least \(C_L \sim 20 - 2000\). This simple estimates is confirmed by detailed radiative transfer and cosmological simulations, e.g. Cantalupo et al. (2014). For a series of small clouds with uniform density in a empty medium, the clumping factor is equal to the inverse of the volume filling factor \(f_v\), and therefore the implied values of \(f_v\) are smaller than \(10^{-3}\) and likely much lower (i.e., \(10^{-4} \sim 10^{-5}\)), considering that, if a hot medium is present as it should be in these massive halos, most of the mass and density will be in the hot component rather than the cold one used for the estimate above. These small filling factors would imply again that the individual densities of the clouds should be higher than \(n > 0.1\) and likely closer to \(n \sim 1 - 10\) cm\(^{-3}\) considering the presence of a hot medium.

A similar analysis can be made considering the total Ly\(\alpha\) luminosity, see e.g. the classical approach used by McCarthy et al. (1990). In this case, integrating the Ly\(\alpha\) emissivity given above one would simply obtain:

\[
L_{Ly\alpha} \sim 3.7 \times 10^{-24} n^2 T_4^{-1.26} f_v V \text{ erg s}^{-1},
\]

where \(V\) is the total volume in cm\(^3\), or more conveniently expressed in terms of the halo virial masses:

\[
L_{Ly\alpha} \sim 2.6 \times 10^{47} n^2 T_4^{-1.26} f_v M_{12} \cdot [(1 + z)/4]^{-3} \text{ erg s}^{-1},
\]

where \(M_{12}\) is the virial mass in units of \(10^{12}\) \(M_\odot\). In this case, the value of \(f_v\) in the literature is typically fixed to the one derived from extended line emission in local AGN (\(10^{-6}\) to \(10^{-4}\), e.g. Heckman et al. 1989). McCarthy et al. (1990) adopted \(f_v\)
to $10^{-5}$ "as a guess", as reported in their paper, and this value was then adopted later in the literature as a sort of "standard" value. As discussed above, our SB consideration lead to similar values. Once $f_c$ is fixed, the individual densities of the clouds are therefore constrained to be of the order of 1-100 cm$^3$ given the Lyα luminosities obtained by the various studies in the literature ($10^{43} < L_{Ly\alpha}/(\text{erg s}^{-1}) < 10^{45}$) and assuming that the nebulae are associated with massive halos ($1 < M_{12} < 10$). Interestingly enough, similar densities are required in the pure recombination case to explain the reported limits on He II emission compared to Lyα for some cases, e.g. for the Slug Nebula (Arrigoni-Battaia et al. 2015) and for the MUSE radio-quiet quasar nebulae (Borisova et al. 2016).

The analysis above shows that recombination radiation is a viable scenario to explain the observed Lyα luminosities and SB if the nebulae are composed by dense ($n > 1$ cm$^{-3}$), highly ionized and cold ($T \sim 10^4$) clumps with volume filling factors smaller than $10^{-3}$ or, analogously, if the gas clumping factor is larger than about a thousand on projected scales with size of about 5-8 kpc. Assuming that such a population of clouds - not resolved by current cosmological simulation - do exists within massive halos, we should examine if they can be indeed ionized by the observed sources within or around the Lyα Nebulae. The required ionizing luminosities $Q_{ion}$ are simply derived using photoionization equilibrium and considering that about 68% of recombinations produce Lyα photons (Case B) at $T \sim 10^4$ as discussed above:

$$Q_{ion} \sim f_c^{-1} L_{Ly\alpha} \times 10^{11} \text{photons s}^{-1}, \quad (7)$$

where $f_c$ is the covering factor of the gas as seen by the ionizing source. Assuming $f_c \sim 1$ this would imply that the required ionization luminosities to explain the Lyα emission of the giant Lyα nebulae ($10^{43} < L_{Ly\alpha}/(\text{erg s}^{-1}) < 10^{45}$) are in the range $10^{54} - 10^{56}$ s$^{-1}$. These ionization luminosity could be explained easily by AGN, even with modest luminosities, or by starbursts with star formation rates of at least a few hundred to few thousand solar masses per year (depending on the ionizing photon escape fraction from the galaxy ISM and on the stellar Initial Mass Function, e.g. Leitherer et al. 1999). As a reference, the quasar associated with the Slug Nebula, the largest and more luminous Lyα nebula discovered to date (Cantalupo et al. 2014) has an expected $Q_{ion} \sim 10^{57.5}$ photons s$^{-1}$ using the measured rest-frame UV luminosity and assuming a standard for this type of quasars (e.g., Lusso et al. 2015). Given the ubiquity of AGN and massively star forming galaxies (traced, e.g. in submm) within or around giant Lyα nebulae, there are therefore enough ionizing photons for the recombination scenario. In section 4 I will review the possible origin of the illuminated gas in terms of kinematical signatures of inflows or outflows.

### 3.2 Continuum pumping (scattering)

Due to the resonant nature of the Lyα emission, the detected photons from extended nebulae may also "originate" from the ISM of embedded galaxies or from
the broad line region of the associated AGN, rather than being produced “in situ” by recombination processes. A “scattering” scenario for some nebulae and in particular for LABs have been proposed in the past as a possible origin of the level of polarization detected in some sources, e.g. in SSA22-LAB1 by Hayes et al. (2011) and Beck et al. (2016), and in a radio-galaxy nebula by Humphrey et al. (2013). In other cases, radio-quiet nebulae imaged in polarization failed to show any detectable level of polarization, e.g. Prescott et al. (2011). Theoretical prediction for the level of polarization produced by scattering by a central source have been presented, e.g. by Dijkstra & Loeb (2008) using idealized geometries and velocity fields and extended recently to radiative hydrodynamics simulations by Trebitsch et al. (2016). These models suggest that scattering from a central source is able to produce a larger and steeper polarization profile with respect to scattering by photons produced by “in situ” processes, such as collisional excitation. Comparison with the data cannot clearly exclude one of these two scenarios but current data, at least for SSA22-LAB1, seems more compatible with a ”in situ” Ly$\alpha$ photon production rather than scattering from a ”central” source.

In case a significant fraction of Ly$\alpha$ photons detected in the extended nebulae are produced by scattering from the ”central” source, then all the estimates of masses and densities based on the assumption of pure recombination emission discussed above should be revised. The ”scattering” contribution will be of course related to the density of neutral hydrogen atoms ($n_{H_0}$) rather than the ionized density squared as in the recombination case. The Ly$\alpha$ optical depth at line center is given by:

$$\tau_0 \sim 3.3 \times 10^{-14}T_4^{-1/2}N(HI),$$

where $N(HI)$ is the neutral hydrogen column density in units of cm$^{-2}$. As an example, using the estimated hydrogen ionization rates of the Slug Nebula quasar (UM287), i.e. $\Gamma \sim 7.7 \times 10^{-9}$ at distances of 100 kpc, we can derive $N(HI)$ in the simple case of uniform small clouds with individual densities of $n$ and filling factor $f_v$ exposed to ionizing radiation as discussed in the previous section. In photoionization equilibrium, the averaged neutral fraction of hydrogen along a path of length $L$ from the quasar will be given by:

$$<x^{eq}>_L = L^{-1} \int_0^L x^{eq}dL' \sim L^{-1} \int_0^L n\alpha(T)\Gamma^{-1}dL' \sim 10^{-9}L^2n,$$

where the last term is valid at $T \sim 10^4$K, $\alpha(T)$ is the hydrogen recombination coefficient ($\sim 3 \times 10^{-13}$ at $T_4 \sim 1$), $L$ is the length in units of kpc. Because the $N(HI)$ column density up to a length $L$ is given in this case by $N(HI,L) = <x^{eq}>_L \cdot n \cdot f_v \cdot L$, then the Ly$\alpha$ optical depth at line center is simply:

$$\tau_0 \sim 10^{-6}(L/1\text{kpc})^3(n/1\text{cm}^{-2})^2(f_v/10^{-5}).$$

Assuming that most of the scatterings are produced at line center, then a continuum photon produced by the AGN is only scattered into Ly$\alpha$ at distances larger than 100 kpc from the source, even for large clump densities. These distances are
only reduced by about a factor of two for sources that are ten times fainter than UM287. Because most of the emission is concentrated in the inner parts, scattering contribution in the case the gas is illuminated by the ionizing radiation of a source should be therefore negligible and recombination radiation should be the dominant mechanism.

The only case in which scattering may be the dominant production mechanism of the large Ly$\alpha$ emission of the giant nebulae is when the central source is not highly ionizing the gas but still producing copious amounts of Ly$\alpha$ and continuum photons slightly blueward of Ly$\alpha$. In this case, studied numerically by, e.g. Cantalupo et al. (2014), the gas will be mostly neutral and the optical depths will become very large. The scattering will be extremely efficient and the main problem with this scenario would be to transport out to hundred kpc scales, as observed for the Ly$\alpha$ Nebula, the photons that are resonantly trapped in the inner regions. During scattering, the Ly$\alpha$ photons will perform a random walk both in space and in frequency. Unless the parameters are fine tuned, most of the scatterings in space will be very close to each other and the photons will escape, with a single fly-out, only when scattered in the wings of the line spectral distribution. In order to transport out these photons to another scattering location and increase the size of the Nebula, the column densities need to be large enough to produce scattering in the wings of the line, i.e. $N(\text{HI}) > 10^{21}\text{cm}^{-2}$, resulting in much larger column densities and masses of neutral gas with respect to what observed in absorption around quasars (e.g. Prochaska et al. 2013; see also Cantalupo et al. 2014 for discussion). Although scattering and a mostly "neutral" scenario for the gas seems less plausible than recombination emission to explain the origin of giant Ly$\alpha$ nebulae, observations of non-resonant lines such He II 1640 and hydrogen H$\alpha$ from giant Ly$\alpha$ Nebulae may be used in the next future to better constrain the scattering contribution to the emission.

### 3.3 Collisional Excitation (cooling)

When both neutral hydrogen and free electrons are present and the electron temperature is around a few times $10^4\text{K}$, the collisional excitation rate of Ly$\alpha$ ($q_{\text{Ly}\alpha}$) may be several orders of magnitude larger than the Ly$\alpha$ effective recombination rate (see, e.g. Cantalupo et al. 2008) and therefore produce in principle very strong Ly$\alpha$ emission from lower density gas. Differently than the recombination case, however, the collisional excitation rates are a very strong function of temperature, with an exponential decline for temperatures lower than a few times $10^4\text{K}$ dropping strongly below the recombination rate just below $T \sim 10^3\text{K}$. On the other hand, when the electron temperature approaches $10^5\text{K}$ collisional ionization dominates over collisional excitations. As a result, collisional excitation is a very efficient process to produce Ly$\alpha$ photons in a partially ionized medium only for electron temperatures around $2\sim 5 \times 10^4\text{K}$. In absence of photoionization and heating sources, e.g. in collisional ionization equilibrium, radiative losses (cooling) due to collisional excited Ly$\alpha$ would quickly reduce the electron temperature effectively suppressing further
Ly$\alpha$ emission. A source of heating is therefore required in order to balance the Ly$\alpha$ cooling effects. On the other hand, if heating brings electron temperatures close to $10^5$K, Ly$\alpha$ collisional excitation would be suppressed again, therefore the heating source should be fine tuned in order to produce a stable supply of Ly$\alpha$ emission with collisional excitation.

Since the discovery of the Steidel’s LABs in SSA22, a numerous series of theoretical and numerical papers have addressed the possibility that these nebulae - apparently lacking a source of ionization - could be powered instead by Ly$\alpha$ cooling (including, e.g., Haiman et al 2001, Fardal et al. 2001, Furlanetto et al. 2005, Dijkstra & Loeb 2009, Goerdt et al. 2010, Faucher-Giguere et al. 2010, Rosdahl & Blaizot 2012). The suggested source of heat in all these studies is given by the conversion of the gravitational potential energy due to cosmological accretion of gas into massive dark matter halos. Alternative sources of energy such as galactic superwinds have been also proposed by Taniguchi & Shioya (2000) with a similar energy budget with respect to the gravitational accretion case but also sharing the same limitations as discussed below.

A simple estimate of the energy associated with cosmological gas accretion for a Navarro-Frenk-White profile with concentration parameter $c = 5$ gives (Faucher-Giguere et al. 2010):

$$<\dot{E}_{\text{grav}} > \sim 3.8 \times 10^{43} M_{12}^{1.8} [(1+z)/4]^{3.5} \text{erg s}^{-1}.$$  \hspace{1cm} (11)

For Ly$\alpha$ nebulae associated with very massive halos with $M \sim 10^{13} M_\odot$, this order of magnitude estimate for the potential energy is interestingly close to the observed Ly$\alpha$ emission. In our standard picture for the formation of these massive halos, we think however that a significant fraction of this potential energy should result in the formation of a hot gaseous halo with temperatures of the order of $T \sim 10^7$K as a result of the virial shocks. At these temperatures, the gas would more slowly lose energy by other radiation channels rather than Ly$\alpha$, e.g., free-free continuum radiation in the Extreme UV and X-ray, and, once the temperature decreases, further energy may be radiated away via line emission from He II or from heavier elements, if present. Analytical and numerical models in the past ten years have nonetheless suggested that some fraction of the densest accreting material could not form a stable shock and therefore could cool and produce Ly$\alpha$ (e.g. Dekel & Birnboim 2006). Cooling Ly$\alpha$ emission models have therefore introduced an efficiency factor that takes into account how much of the potential energy is dissipated by this cold gas phase and required that this efficiency factor is at least few tens of percent in order to obtain enough Ly$\alpha$ photons. Unfortunately, it is very difficult to predict the value of this efficiency factor as it would depend on the details of accretion and cosmological structure formation and on a very accurate estimate of the ionization and temperature state of the gas. Depending on these details, many questions remain open about how and where within the halo the potential energy (or the energy produced by galactic superwinds) could be dissipate in form of Ly$\alpha$.

The majority of the models discussed so far ignore however that sources of ionization do exist within all nebulae observed to date. In most cases, as I have re-
viewed in section 2, these sources are AGN or massively star forming galaxies. The estimated ionization rates show that there are enough ionizing photons to power the nebulae and therefore it seems current clearer that a pure Ly\(\alpha\) cooling origin of the nebulae is not necessarily required by the majority of the observations. This may be confirmed by duty cycle arguments and comparing the number densities of quasars, radio-galaxies and overdense regions where LABs are found as discussed in previous section (see also Borisova et al. 2016 and Overzier et al 2013 for further discussion). Questions however remain about the possible contribution of collisional Ly\(\alpha\) emission to recombination radiation as this would have important consequences on the estimates of densities and masses of the nebulae. Addressing these questions would likely require a new generation of theoretical and numerical models able to resolve the physics and the small scales associated with dense regions within massive halos and, at the same time, the interplay between the gas and the local radiation sources (e.g., in terms of photoionization, photo-heating and feedback).

4 Origin of the emitting gas, kinematics and gas flows

In the previous sections, we have seen that extended Ly\(\alpha\) emission is a common phenomenon around bright high redshift quasars (with possible differences below \(z \sim 3\) for radio-quiet systems), radio-galaxies and in overdense regions of the Universe. The ubiquity of AGN and massively star forming galaxies associated with these nebulae and simple analytical considerations discussed in section 3 suggest that most of the emission may be due to recombination radiation from dense and cold clouds within the nebulae. Because the emission is sensitive to gas density squared, the emitting gas could be a small fraction of the total gas in and around the massive halos associated with these systems, both in terms of volume and mass. In this section, we will look at the kinematical signatures derived from Ly\(\alpha\) spectra of these sources in order to address the questions about the possible origin and fate of this cold gas component.

The proposed origins for the emitting gas and its relation to gas flows in the literature include: i) cosmological accretion from the IGM, ii) outflowing material from galaxy and AGN feedback, iii) in-situ formation from hot gas condensation. The suggested options about the fate of the gas include: i) accretion or “recycling” into galaxies (inflow) or into gaseous disks (rotation), ii) expulsion from the galaxy halos towards the IGM, iii) disruption and thermalization into the hot halo gas. Each of these hypothesis could potentially leave an imprint into the observed gas kinematics in terms of Ly\(\alpha\) spectral profile shapes, velocity shears and velocity dispersion. However, it is important to stress that Ly\(\alpha\) line is a resonant line and therefore any spectral information may also reflect complex radiative transfer effects rather than kinematics, especially if the gas is not highly ionized as it may be the case for a Ly\(\alpha\) cooling origin of the emission.

The first spectroscopic measurements on giant Ly\(\alpha\) nebulae were obtained on radio-galaxies and radio-loud quasar nebulae by McCarthy et al. (1987), McCarthy
et al. (1990), Heckman et al. (1991b), McCarthy et al. (1996). The properties of these systems from a kinematical point of view appeared remarkably similar: the Full Width Half Maximum (FWHM) of the Ly$\alpha$ emission presented large values typically around 1000-1500 km s$^{-1}$ for all radio-loud nebulae. No hints of velocity shear in excess of 500 km s$^{-1}$ were found, although radio-galaxy nebulae seemed to show a more complex kinematical structure. Given the alignment effect between the radio-jets and Ly$\alpha$ emission discussed in section 2.2, these large FWHM were interpreted preferentially as being associated with powerful outflows from these AGN as a result of the jet-gas interaction (e.g., van Ojik et al. 1997, Humphrey et al. 2006). However, it was early recognized that such large velocity widths could have been also caused by gravitational motion in very massive halos (e.g., Heckman et al. 1991b). More recent spectroscopic observations of radio-loud systems confirmed these large FWHM (e.g., Villar-Martin et al. 2003, Humphrey et al. 2006, Villar-Martin et al. 2007, Roche et al. 2014) but found that some radio-galaxies show, in addition, extended and lower-SB halos that appear more kinematically quiet, e.g. with FWHM~500 km s$^{-1}$. Moreover, some of these extended "quiescent" regions show indication for velocity shifts of few hundred km s$^{-1}$ that in some cases have been interpreted as a possible sign of rotating disks (e.g., Villar-Martin et al. 2007) or cosmological gas infall (e.g., Humphrey et al. 2007). These models are based on the correlation seen in several radio-galaxy nebulae i.e. that the more redshifted side of the nebula is the brighter in both Ly$\alpha$ and radio flux, and on the interpretation that this side of the radio-lobes and associated nebula is closer to the observer. This is based on the fact that the radio jet directed towards the observer will be Doppler-boosted and on the assumption that the Ly$\alpha$ emitting gas closer to the observer will be less "absorbed", i.e. scattered to a larger projected area, by neutral gas in the halo. The relative redshift of this near-side relative to the observer would then imply that the emitting nebula has a significant component of infall towards the galaxy.

Kinematical signatures in radio-galaxy and radio-loud quasars are however difficult to interpret because of the complex interaction between the possibly accreting gas and the massive energy input of the radio jet. The analysis of extended, rest-frame optical emission lines from several HzRG, e.g. Nesvadba et al. (2006), suggests indeed that kinematics in the brightest parts of the radio-loud nebulae should be dominated by powerful outflows. These observations, together with the measured line ratios using, He II, C IV, O III and S II with respect to H$\alpha$, H$\beta$ and Ly$\alpha$, all suggest that this outflowing material is metal rich (solar or super-solar), dusty ($A(\text{H}\beta) \sim 1-4$ mag) and very dense ($n_e \sim 500$ cm$^{-3}$) (see e.g., Villar-Martin et al. 2003, Nesvabda et al. 2008).

Long-slit and integral field spectroscopy of radio-quiet nebulae show instead that the large majority of these systems have much smaller FWHM, i.e. FWHM~300–500 km s$^{-1}$ than radio-loud systems (e.g., Weidinger et al. 2005, Christensen et al. 2006, Arrigoni-Battaia et al. 2015, Borisova et al. 2016), unless they are associated with very overdense environment like in the case of SSA22-LAB1 and SSA22-LAB2 (e.g., Matsuda et al. 2006) or in the case of the "Jackpot" Nebula (Hennawi et al. 2015). These smaller velocity widths are indicative of better environments where signs of infall or rotation could be studied more in detail without the need
to disentangle them from the broad component associated with the radio-jets and powerful outflows.

In particular, some radio-quiet giant Lyα Nebulae, such as the Slug Nebula (Cantalupo et al. 2014) are extended by several hundred of kpc and therefore the kinematics in their external parts are less likely to be "contaminated" by AGN outflows, if present. Long-slit spectroscopy (Arrigoni-Battaia et al. 2015) and integral field observations (Martin et al. 2015) have revealed relatively narrow Lyα emission (FWHM < 350 km s\(^{-1}\)) at distances larger than 100 kpc from the quasar and apparent velocity shears of about 800 km s\(^{-1}\) that seem coherent over the brightest part of the Nebula (i.e., over 200 kpc in projected length). These velocity shears have been interpreted as evidence for rotation and would imply therefore that a massive, gaseous disk-like structure with size of about 150 kpc could be present in the brightest part of the Nebula (Martin et al. 2015) while the more tenuous, extended part have been interpreted as signatures of gas infall from the Intergalactic Medium. In particular, the velocity profile seems consistent with the rotation curve of a disk within a NFW profile of a massive halo but only if the "center" of the disk-like structure is located 25" away from the main quasar, in a region of low SB. Considering only the high SB regions, the spectra could be also interpreted however as arising from projection effects of two different structures located at about 500-800 km s\(^{-1}\) in velocity space away from each other. The presence of a relatively bright continuum source in the "redshifted" part of the velocity profile could support this interpretation. Ongoing observations of other emission lines such as He II, C IV (e.g., with MUSE) and Hα (e.g., with Keck/MOSFIRE) will help disentangling these two possibilities.

Other spectroscopic observations of radio-quiet nebulae (e.g., Martin et al. 2014, Prescott et al. 2015) have found signatures of coherent velocity fields over scales of several tens of kpc that have been interpreted as evidence of infall (e.g., Martin et al. 2014) or large scale rotation in a disk (Prescott et al. 2015). In particular, the observations of Prescott et al. (2015) of coherent velocity shears of about ∼500 km s\(^{-1}\) in both Lyα and in non-resonant lines such as He II within the central 50 kpc of a 80 kpc-sized Lyα nebula at z ∼ 1.67 provide evidences that the extended gas in this system is produced in situ by recombination radiation and settled in a rotating disk that is at least partially stable against collapse. In a larger spectroscopic study of eight small radio-quiet nebulae at z ∼ 2.3 including rest-frame optical emission lines (mostly OIII and Hα), Yang et al. (2014) found instead no significant evidences for bulk motions such as inflow, rotation or outflows and suggested that the gas should be "stationary" or slowly outflowing at speed less than 250 km s\(^{-1}\) with respect to the central galaxies in these systems.

The MUSE observations of about 17 bright radio-quiet quasars and 2 radio-loud quasars at 3 < z < 4 presented by Borisova et al. (2016) provided the first large statistical sample of giant (> 100 kpc) Lyα nebulae with full kinematical information from integral field spectroscopy over their full detectable extent. Figures 3 and 4 show, respectively, the maps of the first and second moment of the flux distribution, i.e. the flux-weighted velocity centroid shift and the dispersion relative to the peak of the integrated Lyα emission for each of the MUSE Quasar Nebulae (MQN) (figures taken from Borisova et al. 2016). While some systems, e.g.,
Fig. 3 "Velocity maps" of the MUSE Quasar Nebulae presented in Fig. 2 obtained from the first moment of the flux distribution (see Borisova et al. 2016 for details). This is the largest sample to date of kinematical maps of giant Ly\(\alpha\) nebulae obtained with integral-field-spectroscopy. As discussed in section [4] while some systems (e.g. MQN15) show possible evidences of rotation in a disk-like structure the majority of the nebulae do not show clear evidences of rotation or other ordered kinematic patterns. Several nebulae show instead coherent kinematical structures over scales as large as 100 kpc (e.g. MQN01 and MQN03). (Figure reproduced with permission from Borisova et al. 2016).
Fig. 4 “Velocity dispersion maps” of the MUSE Quasar Nebulae presented in Fig. 2 obtained from the second moment of the flux distribution and expressed in terms of Gaussian-equivalent FWHM (see Borisova et al. 2016 for details). This figure shows that the large majority of radio-quiet nebulae are narrower in Ly$\alpha$ emission (FWHM $\sim 500$ km s$^{-1}$) than radio-loud systems, i.e. MQN-R1 and MQN-R2 (FWHM $> 1000$ km s$^{-1}$), in agreement with the overall kinematical results discussed in section 4 (Figure reproduced with permission from Borisova et al. 2016).
MQN15, show possible evidences of rotation in a disk-like structure with a velocity shear of about 800 km s$^{-1}$, the majority of the MQN do not show clear evidences of rotation or other ordered kinematic patterns. Several MQN, especially the largest ones, show instead coherent kinematical structures over scales as large as 100 kpc, e.g. MQN01 and MQN03. The velocity dispersions, expressed in terms of Gaussian-equivalent FWHM, clearly shows the main difference between radio-quiet and radio-loud systems: the large majority of radio-quiet nebulae are narrower in Ly$\alpha$ emission (FWHM $\sim$ 500 km s$^{-1}$) than radio-loud systems (FWHM $>$ 1000 km s$^{-1}$) in agreement with previous results discussed in this section. The only exception is MQN06 but this nebula is peculiar and more similar to radio-loud nebulae in terms of all the properties studied in Borisova et al. (2016), including the SB profiles and higher He II/Ly$\alpha$ and C IV/Ly$\alpha$ ratios with respect to the non detection for radio-quiet systems.

The emerging picture from these observations seems to suggest therefore that kinematics in radio-loud nebulae may be dominated by ionized outflows of relatively cold and metal-enriched material within at least the inner 30-50 kpc from the AGN, while, on average, the ionized and clumpy gas in radio-quiet nebulae may be in a more "stationary" situation and in some cases settled in a possibly rotating structure. Clear evidences from Ly$\alpha$ emission for gas accretion into galaxies from these cold gas reservoirs are not currently detected, either because “washed-out” by Ly$\alpha$ radiative transfer effects or because their magnitude and projection effects could make them to small to be detected with current facilities. Future deep surveys using other bright, non-resonant lines such as hydrogen H$\alpha$ or He II 1640 would be extremely helpful to search for small velocity shears and therefore for signature of cosmological gas accretion onto galaxies and AGN.

5 Summary

Several decades of observations and discoveries have produced an extensive literature of large and giant Ly$\alpha$ nebulae. Depending on the technique and original target of the observation, i.e. quasars, radio-galaxies, overdense regions or "blank" fields, they have been classified in various ways and with different nomenclatures. For historical and practical reasons, I have divided them in quasar Ly$\alpha$ nebulae, radio-galaxy halos and Ly$\alpha$ Blobs (LAB) but, as discussed in section 2, their comparable volume densities, luminosities and their almost invariable association with AGN or massively star forming galaxies suggest however that these nebulae could be just apparently different manifestations of the same phenomenon.

Among the three processes associated with the production of Ly$\alpha$ photons (recombination radiation, "scattering" and collisional excitation; see section 3), recombination radiation currently appears as the most viable scenario to explain the observed Ly$\alpha$ luminosities and Surface Brightness for the large majority of the nebulae. If contribution from scattering and Ly$\alpha$ collisional excitation is negligible, this would imply that the emitting gas should be in the form of dense ($n > 1$ cm$^{-3}$),
highly ionized and cold ($T \sim 10^4$) structures ("clumps") with volume filling factors smaller than $10^{-3}$ or, analogously, with clumping factors larger than about a thousand on projected scales with size of about 5-8 kpc. The apparent ubiquity of giant Ly$\alpha$ nebulae around bright AGN, at least at $3 < z < 4$, and in overdense environment suggests that this cold gas should be a common occurrence within and around the halos of massive galaxies. Deep observations of non-resonant lines such He II 1640 and hydrogen H$\alpha$ from giant Ly$\alpha$ nebulae can better constrain the scattering and collisional contribution to the emission but their are currently lacking for the majority of the nebulae. Ongoing surveys (e.g., with MUSE, MOSFIRE, KMOS and JWST in the future) will soon provide these data and therefore potentially help in refining our understanding of the physical properties of this cold gas.

Ly$\alpha$ integral-field and long-list spectroscopy shows that radio-loud nebulae (i.e. associated with radio-galaxies and radio-loud quasars) are almost invariably associated with larger velocity widths with respect to the majority of radio-quiet systems (see section [F]). Together with the analysis of the He II/Ly$\alpha$ and C IV/Ly$\alpha$ ratios, these observations seem to suggest that kinematics in radio-loud nebulae may be dominated by ionized outflows of relatively cold and metal-enriched material within at least the inner 30-50 kpc from the AGN. On the other hand, these observations suggest that ionized and clumpy gas in radio-quiet nebulae should be in a more "stationary" situation and in only in some cases there are possible evidences that this gas is settled in rotating structures. Definitive evidences for the accretion of this cold gas into galaxies from Ly$\alpha$ emission are not clearly detected in the current data. However, it is important to notice that accretion signatures could be "washed-out" by Ly$\alpha$ radiative transfer effects or too small to be detected with current facilities because of their magnitude and possible projection effects. Again, future deep surveys using other bright, non-resonant lines such as hydrogen H$\alpha$ or He II 1640 would be extremely helpful to search for small velocity shears and therefore for clearer signature of cosmological gas accretion onto galaxies and AGN.

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