The impact of Stellar feedback from velocity-dependent ionised gas maps. – A MUSE view of Haro 11. *

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ABSTRACT

We have used the capability of the MUSE instrument to explore the impact of stellar feedback at large scales in Haro 11, a galaxy under extreme starburst condition and one of the first galaxies where Lyman continuum (LyC) has been detected. Using Hα, [OIII]λ5007 and [OI]λ6300 emission lines from deep MUSE observations, we have constructed a sequence of velocity-dependent maps of the Hα emission, the state of the ionised gas and a tracer of fast shocks. These allowed us to investigate the ionisation structure of the galaxy in 50 km s⁻¹ bins over a velocity range of -400 to 350 km s⁻¹. The ionised gas in Haro 11 is assembled by a rich arrangement of structures, such as superbubbles, filaments, arcs and galactic ionised channels, whose appearances change drastically with velocity. The central star forming knots and the star forming dusty arm are the main engines that power the strong mechanical feedback in this galaxy, although with different impact on the ionisation structure. Haro 11 appears to leak LyC radiation in many directions. We found evidence of a kpc-scale fragmented superbubble, that may have cleared galactic-scale channels in the ISM. Additionally, the southwestern hemisphere is highly ionised in all velocities, hinting at a density bound scenario. A compact kpc-scale structure of lowly ionised gas coincides with the diffuse Lyα emission and the presence of fast shocks. Finally, we find evidence that a significant fraction of the ionised gas mass may escape the gravitational potential of the galaxy.

Key words: Galaxies: starburst - galaxies: halo - galaxies: individual: Haro 11 - ISM: bubbles - ISM: jets and outflows

1 INTRODUCTION

Blue compact galaxies (BCGs) play a fundamental role in our understanding of the evolution of galaxies. They are compact, mostly metal poor galaxies, that are undergoing an extraordinary episode of star formation, characteristics that are similar to the primeval high redshift galaxies (Fanelli et al. 1988; Östlin et al. 2001; Thuan & Izotov 2005; Wu et al. 2006; Thuan 2008; Kunth & Östlin 2000).

Their current burst of star formation seems to be triggered mainly by infalling HI clouds or by gas compression in merger systems (Östlin et al. 2001). The extreme starburst condition favours the formation of massive star clusters, or even super star clusters (SSCs, Mcl > 10⁵ M☉) (Östlin et al. 2003; Adamo et al. 2011; Bik et al. 2018), each of them containing a large amount of massive stars, whose stellar feedback has strong implication in the subsequent evolution of the galaxy.

In the first ∼ 4 Myr of a star cluster evolution, OB-type stars release large amount of ionising photons to the ambient medium before they explode as supernova. This is the fraction of time in the star cluster evolution, where the ionisation and radiation feedback are at their maximum. At the same time, their stellar winds inject kinetic energy and momentum into the surrounding medium. The mechanical energy is maintained afterwards till ∼ 40 Myr by supernova

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explosions, that additionally deliver newly synthesised elements to the environment (Leitherer et al. 1999).

Stellar feedback, and especially mechanical feedback, produces shock waves that may trigger additional star formation, or suppress it by lowering the neutral gas content from the active zone of star formation (Dale et al. 2006; Hopkins et al. 2014; Krumholz et al. 2014), and thus, regulating the accelerated consumption of the cold gas. Moreover, it induces turbulence in the interstellar medium (ISM) supporting the formation of a porous medium which increases the mean free path of the ionising photons, enabling them to penetrate further into the halo (Silk 1997; Zurita et al. 2002; Bagetakos et al. 2011).

The effect of stellar feedback is not well understood in low metallicity galaxies. Numerical works show that in low mass galaxies, stellar feedback can be powerful enough to drastically modify the structure of the ISM (Ceverino & Klypin 2009; Hopkins et al. 2012; Agertz et al. 2013; Keller et al. 2015). The injected kinetic energy can develop a violent ISM, supporting the formation of large-scale bubbles, filaments, arcs, loops, rings and cavities (see Tenorio-Tagle & Bodenheimer 1988; Hunter et al. 1993; Hopkins et al. 2012). These structures are evident in several galaxies such as M82 (Lynds & Sandage 1963; Bland & Tully 1988), NGC 1705 (Meurer et al. 1992), NGC 3079 (Cecil et al. 2001) and ESO 338-IG04 (Bik et al. 2015; Bik et al. 2018). Moreover, Marlowe et al. (1995) and Martin (1998) studied the kinematics and morphology in a small sample of starburst dwarf galaxies and found in the vast majority, footprints of expanding superbubbles, traced by fragmented supershells and filaments. Hunter et al. (1993) concluded that, at least one of these structures caused by feedback, may be seen in the ISM of a large fraction of luminous low mass galaxies.

In the framework of galactic winds, these bubbles and superbubbles may drive large-scale outflows when they fragment (Chevalier & Clegg 1985; Tenorio-Tagle et al. 2006; Heckman & Thompson 2017; Fielding et al. 2018). Supernova driven galactic winds can accelerate ambient gas at velocities much greater than their escape velocities, resulting in a loss of metal enriched gas to the intergalactic medium. This process can explain the deficit of metals in dwarf galaxies (Andrews & Martini 2013; Sánchez et al. 2013). Although a large number of galaxies display fast outflows, only few galaxies develop galactic outflows with velocities greater than their escape velocities. Most of them have been inferred from absorption lines tracing the neutral and ionised gas phase (Chisholm et al. 2015; Heckman et al. 2015).

Galactic scale outflows also play a fundamental role in the escape of LyC radiation by creating galaxy-scale holes in the ISM favouring the escape of LyC photons (Fujita et al. 2003). Lyman continuum emission is hardly detected in galaxies, mainly because the neutral hydrogen column density along the line-of-sight to their production places is high enough to prevent LyC photons to escape. To date, only a small numbers of galaxies (16) have been found to leak LyC radiation (Bergvall et al. 2006; Borthakur et al. 2014; Vanzella et al. 2016; de Barros et al. 2016; Izotov et al. 2016b,a; Leitherer et al. 2016; Puchting et al. 2017; Vanzella et al. 2018; Izotov et al. 2018b,a). Although the mechanism favouring the escape of LyC radiation is still unknown, galactic holes possibly cleared by outflows may have preference from a density-bound medium, due to the relative high neutral column density measured in the ISM of those galaxies (Chisholm et al. 2015; Vanzella et al. 2018).

The galaxy studied in this paper is Haro 11, a well known starburst luminous blue compact galaxy. Haro 11 is a Lyα emitter (Hayes et al. 2007) and one of few galaxies where Lyman continuum has been detected (Bergvall et al. 2006; Leitet et al. 2011). In contrast to most BCGs, its ionised gas mass (Östlin et al. in prep.) is larger than its neutral gas content (MacHattie et al. 2014; Pardy et al. 2016). Morphologically, it is a merger system whose appearance and kinematics resemble the Antennae galaxy (Östlin et al. 2015).

Star formation happens mostly in three knots A, B and C and a dusty arm at the centre of the galaxy (see Fig. 2) (Kunth et al. 2003). The star cluster population in Haro 11 is very young and massive. Adamo et al. (2010) identified around 200 clusters with masses ranging from $10^4$ to $10^7 M_\odot$. Most of them (90%) were formed in the current starburst that started 40 Myr ago (Adamo et al. 2010; Östlin et al. 2001). In half of them, supernova explosions may have recently started, since they were formed at the peak of the cluster formation, around 3.5 Myr ago. Thus, we are capturing Haro 11 at a time when the radiative and mechanical energy released by its massive stellar population is at its maximum. Beside the stellar components, Prestwich et al. (2015) detected hard X-ray emission in Knot B that hints at an intermediate black hole in low accretion mode.

The intense starburst condition and merger dynamics have strong impact in the kinematics of this galaxy. Several kinematic components have been reported at all wave-lengths. Grimes et al. (2007) found two main outflows at $-80$ km s$^{-1}$ (FWHM of 77 km s$^{-1}$) and $-280$ km s$^{-1}$ in the warm UV gas, that are associated with outflowing winds. Rivera-Thorsen et al. (2017) found evidence for a clumpy neutral ISM. The Lyα morphology analyzed by Hayes et al. (2007) hints to the presence of a bipolar outflow at the base of Knot C. Recently Pardy et al. (2016) found that the neutral 21 cm HI gas is moving at +56 km s$^{-1}$ (FWHM of 77 km s$^{-1}$). In the optical range, the warm ionised gas was found to have a multi-component nature by Östlin et al. (2015), with velocities ranging from -130 to 130 km s$^{-1}$. These studies give insight into the complex kinematics of this merger system.

In this paper we examine the impact of stellar feedback in Haro 11 by means of analysing the velocity resolved Hα emission, the level of ionisation in the gas and possible presence of fast of shocks. In our analysis, we use the capability of MUSE in combining the spectral and spatial high quality information at the same time, allowing us to spatially resolve the ionised gas structures in the galaxy.

This paper is organised as follow: the observations, data reduction and methods are presented in Section 2. In Section 3 we describe the most prominent structures found in the ionised gas. In section 4 we discuss the ionised gas structure and analyse the mechanism that might have facilitate the escape of LyC photons in Haro 11. Additionally, we estimate the ionised gas mass that may escape the gravitational potential in this galaxy. And last, we present a summary and conclusion in section 6.

In this paper, we use the redshift of Haro 11 of $z_{Haro11}=0.020598$ from NASA/IPAC Extragalactic Database, a Hubble constant of $H_0=73$ km s$^{-1}$ Mpc$^{-1}$ and
matter density $\Omega_0 = 0.27$) resulting in a luminosity distance of 82 Mpc.

## 2 OBSERVATIONS AND DATA REDUCTION

### 2.1 Observations

Haro 11 was observed with the Multi-Unit Spectroscopic Explorer (MUSE, Bacon et al. 2010) at the Very Large Telescope (VLT) on Paranal, Chile between December 2014 and August 2016. To cover the extended ionised halo of the galaxy, a 2x2 mosaic (see Fig. 1) centred on Haro 11 (RA=10h36m52\arcsec, DEC=-33\degree33\arcmin17\arcsec) was performed. Adjacent borders overlap by 30\arcsec. Thus, the 1.5 x 1.5 full field observed corresponds to 38.7 kpc at the redshift of Haro 11. Each pointing was observed in two observing blocks with four frames of 700s and position angles rotated by 90\degree to correct for detector systematics. The design of the mosaic resulted in a final cube with three areas of different integration time While the corners have an integration time of one hour (4x700s), the two overlapped regions have twice that integration time, 3h 6min 40s (8x700s) and the central 30\arcsec x 30\arcsec region has the longest integration time of 6h 13min 20s (16x700s).

The observations were carried out under good atmospheric conditions (photometric or clear) with seeing measurements varying between 0.6 and 0.9 arcsec. The final image quality (FWHM of a Gaussian fit) measured on the white-light image from the reconstructed cube is about 0\arcsec.8. The spectrophotometric standard star Feige 110 was observed in the same nights and is used for the spectrophotometric calibration of the data.

### 2.2 Data reduction

We apply the standard reduction procedure using the MUSE pipeline version 1.2 (Weilbacher et al. 2012) with a minor change for the sky subtraction process. To subtract the sky from each science exposure, a sky spectrum can be either provided as input file, in case sky exposures were taken, or from each science exposure, a sky spectrum can be either provided as input file, in case sky exposures were taken, or calculated from the 20% darkest pixels in the first run of the recipe. To improve the fit on the absorption features, for those pixel, having (S/N) above 20. The strongest emission lines were masked to regions where the stellar continuum has a signal-to-noise ratio smaller than 5, the best fit was subtracted from the observed spectrum. This procedure removed all the absorption line contamination leaving a emission line spectrum only.

### 2.3 Correction for stellar absorption

Galaxies with young to intermediate-age stellar populations show broad stellar absorption, that are underlying the emission lines in the Balmer series. This effect originates in the atmosphere of primarily type A stars and increases towards the higher energy levels of the Balmer series (González Delgado & Leitherer 1999; González Delgado et al. 1999).

In Haro 11, this stellar absorption is particularly strong towards the southeast (SE) - east (E) of knot C, where the evolved progenitor is located. In the MUSE spectrum, we can see that the absorption is especially noticeable in the wings of the line. In order to have correct emission line strengths for accurate line ratios, the underlying stellar absorption affecting the Balmer lines needs to be removed.

We fitted the spectra of each pixel using the python package of the penalized pixel-fitting method (pPXF) by Cappellari (2017) with the MILES stellar spectra library (Sánchez-Blázquez et al. 2006; Vazdekis et al. 2010) in the regions where the stellar continuum has a signal-to-noise ratio (S/N) above 20. The strongest emission lines were masked to improve the fit on the absorption features. For those pixel, where the fitting resulted in a good fit ($\chi^2 < 5$), the best fit was subtracted from the observed spectrum. This procedure removed all the absorption line contamination leaving a emission line spectrum only.

### 2.4 Velocity resolved emission line maps

From the corrected data cube, we extracted the spectra of the lines $H\alpha$, $H\beta$, $[\text{OIII}]\lambda 5007$ and $[\text{OI}]\lambda 6300$ (hereafter $[\text{OIII}]$ and $[\text{OI}]$) and re-sampled them using the python package SpectRes (Carnall 2017) to 50 km s$^{-1}$ per resampled

### Table 1. Spectral and spatial resolution of the emission lines after resampling

| Emission line | $\lambda_{\text{corr}}$ | Spaxels in 50 kms$^{-1}$ | Spectral resolving power | Spatial resolution ["] |
|--------------|------------------------|--------------------------|---------------------------|--------------------------|
| $H\beta$     | 4961.4                 | 0.83                     | 3.5                       | 0.92                     |
| $[\text{OIII}]\lambda 5007$ | 5109.9                 | 0.85                     | 3.4                       | 0.92                     |
| $[\text{OI}]\lambda 6300$ | 6429.8                 | 1.07                     | 2.3                       | 0.85                     |
| $H\alpha$    | 6670.9                 | 1.12                     | 2.1                       | 0.84                     |
spaxel. The resampled spaxels have a width of 0.8 Å for Hβ and 1.1 Å for the Hα line (see Tab. 1), smaller than the original spectral sampling of MUSE (1.25 Å per spaxel). The full-width at half maximum (FWHM) of the observed line spread function (LSF) of MUSE is wavelength dependent and varies between 2.9 Å for Hβ and 2.5 Å for Hα (Bacon et al. 2017). Comparing those values to the velocity resolution of the interpolated spaxels, shows that due to the LSF of the instrument a spectrally unresolved feature will be spread out over 2 (Hα) to 4 (Hβ) velocity bins. Table 1 summarizes the values for each of the extracted emission lines. Finally, we extract line maps and their associate uncertainties from continuum-subtracted line fluxes per velocity bins for all four lines. We did not correct the line maps for extinction. The halo shows E(B-V) values between 0.02 and 0.1, indicating that there is little or no extinction. The highest E(B-V) values (between 0.1 and 0.45) were measured mostly at redshifted velocities in a small area around knot C and B and the dusty arm. We have verified that correcting our maps will not change our analysis that is dedicated in describing the dusty arm. We have verified that correcting our maps shifted velocities in a small area around knot C and B and values (between 0.1 and 0.45) were measured mostly at redshifted velocities in a small area around knot C and B and the dusty arm. We have verified that correcting our maps will not change our analysis that is dedicated in describing the dusty arm.

Since the seeing is wavelength dependent, we measure the spatial resolution of each line by performing a Gaussian fit and measuring the full width half maximum (FWHM) (see Tab. 1 col. 5) in a bright distant star in the west part of the field of view.

To unify the spatial resolution of the [OIII] and Hα for the ionisation diagnostic, we convolved the maps of the emission line with higher spatial resolution, the Hα line, with a Gaussian kernel sampled from the resolution difference of both lines. The spatial resolution of the [OIII] maps are close to the spatial resolution of the Hα maps, therefore we do not convolve the [OIII] line for the [OIII]/Hα line ratio. Finally, we created velocity sliced ionisation maps from the [OIII]/Hα line ratios and the maps tracing shocks from the [OIII]/Hα line ratios.

To keep a minimal signal to noise in the data, we masked the emission line regions in all maps, by adaptively Voronoi binning each map with a signal to noise of 4 and a maximal area of 1.68′ (Cappellari & Copin 2003; Diehl & Statler 2006). Cells with signal-to-noise ratio greater or equal are removed, leaving only the sky regions unmasked. This mask was then applied to the unbinned maps, removing the background noise and low S/N regions.

3 CONDITION OF THE IONISED GAS AT DIFFERENT VELOCITIES

Fig. 2 shows Haro 11, seen by MUSE and the Hubble Space Telescope (HST). The left image displays the integrated Hα map (Voronoi binned to a S/N ≥ 5 in Hα) from the MUSE cube. Haro 11 exhibit a huge ionised halo, that extends over 30 kpc in diameter down to a sensitivity level of 3.75 × 10⁻¹⁹ erg s⁻¹ cm⁻² arcsec⁻². In addition to the overall spherical distribution of the ionised gas, there are some faint noticeable features: for instance, the arc in the north-east and the network of filaments and clumps in the south hemisphere. Later in this section we will show that these and other features stand out clearly in the velocity resolved Hα maps.

The images in the middle and right panels in Fig. 2 were taken with the HST and show the optical continuum (red part, F763M medium filter) and the continuum subtracted Hα emission respectively. They show the arrangement of stars (central image) and warm gas (right image) in the central 5 × 5 kpc of the galaxy. The central knots A, B and C and a dusty arm (dubbed the ‘ear’ in Östlin et al. 2015) are the most active zones of star formation. The dust, which is not well traced in the images, is located mainly in the dusty arm and in dust lanes crossing knots B and C.

The contrast of the Hα map taken with the HST and constructed from MUSE data is dramatic. HST provided a high spatial resolution image that shows the central part of Haro 11 in great detail, while our MUSE image has higher sensitivity in a larger field of view.

To investigate the structure of the ionised gas in details, we further use ionisation maps and a tracer of fast shocks. Ionisation maps are constructed from nebular emission line ratios of two ions with different ionisation potential. They trace the level of ionisation in a nebula and the strength of the UV radiation field. We use the ratio of the two most intense optical emission lines, [OIII]/Hα, as they trace the halo to the furthest. Since the ionisation potential of hydrogen is significantly lower (13.6 eV) than that of the double ionised oxygen (35 eV), a rise in the [OIII]/Hα ratio implies therefore, a rise in the number of energetic photons capable of double ionise oxygen.

The forbidden [OII]λ6300 line is widely used to trace the radiation of the ISM heated by shocks. Neutral oxygen atoms are found in a neutral and weakly ionised gas. Thermal electrons of low energy (∼1.9 eV) are able to excite these atoms through collisions and produce the observed [OII]λ6300 line. Shocks can increase the thermal energy of the free electrons in proportion to the shock velocity, and thus enhancing the number of collisional excitations by a single electron. Consequently, higher [OII]λ6300/Hα ratios are expected to arise in the ISM where intermediate to strong shocks are present (Veilleux & Osterbrock 1987).

Fig 3 presents the velocity sliced ionised gas structures in Haro 11. The columns from left to right show: the ionised gas architecture (traced by Hα emission), the degree of ionisation of the ISM ([OIII]/Hα) and the regions where intermediate to fast shocks are present ([OII]λ6300/Hα). The I-band continuum emission from the MUSE data is over-plotted in contours. These are shown to provide a spatial reference in the maps. Each gas diagnostic is extracted in velocity bins of 50 km s⁻¹ (rows in fig. 3) starting from -400 to 350 km s⁻¹. These velocities correspond to the limits of the Hα wings uncontaminated by the broad [NII] lines. Since the [OIII]/λ5007 is uncontaminated by strong lines, we extract additional maps of this line to velocities up to 1000 km s⁻¹. These are referred in the discussion section.

Below we describe each of the diagnostics from high blueshifted velocities (−400 km s⁻¹) towards high redshifted velocities (350 km s⁻¹) in further detail. The number of features is too large for each one to be individually described, but we list some of the most prominent and give a general description of the structure seen at different velocities. A summary of the features seen in the Hα and ionisation maps are listed in Table 2.
3.1 Velocity sliced Hα maps

The Hα emission shows plenty of structures, many of which only become visible when we slice the galaxy in velocity space. The most prominent features by their Hα intensity are the three starburst knots: A, B and C. They are visible in all velocity bins, but each with their own characteristics. Knot C can be seen as a compact source with a broad velocity width. Knot B is a complex structure whose morphology changes with velocity, while knot A becomes more prominent at positive velocities.

From -400 to -50 km s$^{-1}$, an arc develops in the northeast (NE) at a radius of $r\sim3.3$ kpc and is best visible at -300 km s$^{-1}$ where it subtends an angle of 180 degrees. This arc is also visible in the HST Hα map seen in the third panel of the Fig. 2.

In the same velocity range, a group of winding filaments develop somewhat radially in the south-southwest (S-SW) at $r>3$kpc and bend slightly towards the east (E) and west (W) in a symmetrical fashion. At redshifted velocities, the filamentary structure is not clearly disentangled from new (oncoming) structures. These filaments extend to the edges of the observed emission and cover the entire S-SW halo, while the northern halo is nearly free of structures and its intensity drops considerably with radius, rapidly becoming diffuse and faint.

From -400 to -250 km s$^{-1}$, two compact clumps become visible in the halo and may be locally ionised by their young stellar components. We detected these sources in the blue (HST filter F336W) and weakly in the red continuum (HST filter F763M).

At velocities from -100 to 100 km s$^{-1}$, but best visible at 50 km s$^{-1}$, three tidal tails (two displaying an arc-shape) develop at the east, northeast and east part of the galaxy respectively. From 50 to 250 km s$^{-1}$ a structure that seems to belong to the tidal tail 2 or the tidal tail 3 becomes pronounced. It whirls from the SE to the S of the galaxy. Within this structure, from 50 to 150 km s$^{-1}$ a bright and compact clump becomes visible.

At 0 and 50 km s$^{-1}$ three faint clumps appear at the farthest side of the tidal tail 3 at distances $>15$ kpc. The closest one is weakly traced in the [OIII]λ5007 line, while the remaining two are not observed. These clumps might be locally ionised by their stellar components or in case of the furthermore, they could be ionised by photons originated from the central clusters of the galaxy. At high redshifted velocities ($v\geq200$ km s$^{-1}$) a blob develops in the NE.

3.2 Velocity sliced ionisation maps

The halo is highly ionised over all velocities, although the areas with the highest level of ionisation change with velocity. In the inner part ($r<10$ kpc) of the galaxy, there is plenty of kpc-scale lowly ionised structures that contrast over the bright highly ionised halo. Some features resemble the structures seen in the Hα maps, while new ones arises.

From -350 to 100 km s$^{-1}$ the southwestern hemisphere is highly ionised and is particularly enhanced at -250 km s$^{-1}$ in two highly ionised channels, reaching [OIII]/Hα ratios up to 10. In the Hα maps, this part of the halo is entirely populated by the filamentary structure. Moreover, the areas between the filaments are in general more enhanced and suggest areas of low density gas.

At $v=-300$ km s$^{-1}$, a system of circumferentially oriented lowly ionised arcs define what seems to be a slightly fragmented shell of $\sim1.7$ kpc of radius that is centred on the massive star forming knot C. Its interior is highly ionised, suggestive of a low density hot gas. When comparing the position of the lowly ionised arcs with the arc seen in the Hα map, the latest seems to be located slightly more outside. At $v>300$ km s$^{-1}$ part of this lowly ionised arc system reappears and it probably show the same structure in its farthest side. We note also a narrow lowly ionised pillar crossing knot C, that could trace outflows of neutral and low-ionised gas.

From -250 to -150 km s$^{-1}$, two narrow and slightly bent highly ionised channels stand out over a lowly ionised structure (see also Fig. 4 b). These channels seems to be tracing the footpath of outflows which are carrying the hot high ionised gas from the knot C superbubble cavity to the halo.

From -200 to 200 km s$^{-1}$, the lowly ionised gas is mainly condensed in a kpc-scale compact structure that turn with velocities from the SE to the N and end at $v>200$ km s$^{-1}$ in the blob identified in the Hα maps. From 100 to 200 km s$^{-1}$ the filamentary structure at positive velocities. The most prominent features by their Hα intensity are the three starburst knots: A, B and C. They are visible in all velocity bins, but each with their own characteristics. Knot C can be seen as a compact source with a broad velocity width. Knot B is a complex structure whose morphology changes with velocity, while knot A becomes more prominent at positive velocities.

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From -200 to 200 km s$^{-1}$, the lowly ionised gas is mainly condensed in a kpc-scale compact structure that turn with velocities from the SE to the N and end at $v>200$ km s$^{-1}$ in the blob identified in the Hα maps. From 100 to 200 km s$^{-1}$
s\(^{-1}\), but best visible in Fig. 4 a, this lowly ionised structure becomes multi-structured. Its morphology resembles somehow a fishing hook, although this effect could be caused by projection effect of lowly ionised gas clouds along the line of sight.

From -100 to 100 km s\(^{-1}\), three highly ionised channels become visible towards the N, W and the S of the halo. In Fig. 4 a, the northern channel can be traced to the place where it originates, at the basis of knot B. The western and southern channels however might be created by photons produced in knot A and B. Additionally, there are few smaller highly ionised channels (see Fig. 4 a) at the top of the lowly ionised structure that seems to be created by photons leaking from knot C.

From -50 to 50 km s\(^{-1}\) at central velocities, the level of ionisation decrease in the halo and the lowly ionised structure predominates. In this velocity range, the most prominent filaments become lowly ionised, most likely due to an increase in their gas density, rising their neutral and lowly ionised gas content.

From 100 to 350 km s\(^{-1}\), the western hemisphere is highly ionised and especially enhanced at 250 km s\(^{-1}\) towards the SW, where one of the highly ionised channel elongates.

### 3.3 Fast shocks

The [OI]\(\lambda 6300\) faint line traces only the high signal to noise areas, therefore the detected regions are basically reduced to the central part of the galaxy. The third column of Fig. 3 shows the [OI]\(\lambda 6300/\text{H}\alpha\) line ratio maps for the different velocity bins. The value of these ratios varies between \(\sim 0.01\) and 0.3. In our maps, we show in yellow the areas with ratios [OI]\(\lambda 6300/\text{H}\alpha\) \(\geq 0.1\) (or \(\log([\text{OI}]\lambda 6300/\text{H}\alpha) \geq -1.0\)). Comparing the location of these areas to the [OIII]\(\lambda 5007/\text{H}\alpha\) maps, shows that these high [OI]\(\lambda 6300/\text{H}\alpha\) areas have [OIII]\(\lambda 5007/\text{H}\alpha\) values between 0.7 and 1.5 or their equivalent \(\log([\text{OIII}]\lambda 5007/\text{H}\beta)\) between 0.3 and 0.6 assuming case B recombination, with \(\text{H}\alpha/\text{H}\beta = 2.86\) (Veilleux & Osterbrock 1987). The combination of these line ratios can not be reproduced by photoionisation models of HH regions with typical ionisation parameters \((\log(U) \sim 3.5\) and \(-2\)) and the SMC-like metallicity of Haro 11 (Kewley et al. 2001). They are located above the HH-star forming area and within the LINERs-shocked gas area in the [OI]-BPT diagram (Veilleux & Osterbrock 1987; Kewley et al. 2001).

This combination of line ratios, however, can be explained by fast radiative shock models. Allen et al. (2008) showed that the value of these line ratios strongly depends on the metal abundance and magnetic parameter of the interstellar medium. In the shock + precursor models, both line ratios increases, although in a different manner, with increasing shock velocity. By comparing the observed values of the high [OI]\(\lambda 6300/\text{H}\alpha\) (yellow) areas to the shock + precursor models of Allen et al. (2008) with the Haro 11 metal abundance, we find that this would correspond to shocks with velocities from 200 to 600 km s\(^{-1}\).

We also note that the high [OI]\(\lambda 6300/\text{H}\alpha\) areas are consistently associated with areas of low [OIII]\(\lambda 5007/\text{H}\alpha\) ratios (blue-green areas in the [OI]\(\lambda 6300/\text{H}\alpha\) maps, i.e. at 150 km s\(^{-1}\)). This would suggest a relatively low ionisation radiation compared to the surrounding gas with much higher [OIII]\(\lambda 5007/\text{H}\alpha\) ratio.

Due to the fact that neutral oxygen is found in the neutral to lowly ionised gas, the shocks hinted here likely arise from this gas. In the highly ionised gas, we would need a different line diagnostic to trace shocks as the oxygen atoms would all be ionised (the ionisation potential of neutral oxygen is almost identical to that of hydrogen). We will present an extended analysis of shocks, inclusive a more precise pre-
Figure 3. Velocity sliced Hα maps (left) of Haro 11. The overlaid contours show the MUSE I-Band stellar continuum in blue. The isophotal level of the faintest contours is $7.5 \times 10^{-19} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2} \text{ Å}^{-1}$. The middle column shows the [OIII]/Hα ratio tracing the ionisation of the gas, while the right column shows [OI]/Hα highlighting the shocked gas. The colorbar of the maps in each emission line diagnostic is fixed to the same scale and limit parameters. For the Hα maps, the lower surface brightness limit of $2.5 \times 10^{-19} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2}$ at 50 km s$^{-1}$. For the [OIII]/Hα and [OI]/Hα maps, the limits range from 0 to 3 and to 0.1 respectively. The maps in the velocity range from -100 to 100 km s$^{-1}$ are displayed in the full field of view. The yellow boxes in the Hα maps show the zoom in region displayed on the the maps at higher blue- and redshift velocities. The clumps 50 km s$^{-1}$ were plot A small area covering the clumps in the 50 km s$^{-1}$ Hα map is shown with an intensity one hundred times higher to highlight the presence of these clumps.
Figure 3. Ibidem. Gas diagnostics maps for velocities from -200 to -50 km s$^{-1}$.
Figure 3. Ibidem. Gas diagnostics maps for velocities from 0 to 150 km s$^{-1}$.
Figure 3. Ibidem. Gas diagnostics maps for velocities from 200 to 350 km s$^{-1}$. 
Figure 4. Three ionisation maps at velocities of 100, -200 and -50 km s\(^{-1}\) with higher contrast in the colour map (scale range from 0.3 to 2.5) highlighting the features of feedback origin. The left (a) and top right (b) panels show highly ionised channels with sizes ranging from 1 to 10 kpc. The narrow highly ionised channels of (b) are most likely created by outflowing hot gas from knot C, while the large conical channels of (a) seems to be created by huge amount of ionising photons released by the central knots. Moreover, panel (a) shows the lowly ionised structure with a hook-like shape in this velocity bin. The bottom right panel (c) shows circumferentially oriented arcs, resembling an expanding shell.

4 DISCUSSION
In this section we discuss the ionised gas assembly of Haro 11 and its connection with the LyC escape. Furthermore, we examine the connection seen between the lowly ionised gas and the diffuse Ly\(\alpha\) emission in the galaxy.

4.1 Ionised gas structures and their origin
Haro 11 shows complex kinematics of the ionised gas in a broad velocity range. Mechanical feedback appears to be the main driver of the internal kinematics at all velocities, as it has built and accelerate most of the structures seen in our diagnostic maps. The dynamics of the merger however, is traced only in a narrow velocity width at central and redshifted velocities, as evidenced by the tidal tails in the outermost part of the halo.

Fig. 5 shows a sketch of the main ionised gas components that might be found in the centre of Haro 11, as interpreted from our maps. The central star forming knots A, B and C and in less proportion the dusty arm are the main sources that produce the strong stellar feedback in the galaxy. They appear to be surrounded by a superbubble (~3.3 kpc) that is open in the south, where the roughly radial oriented kpc-scale filaments develop. Knot C seems to be surrounded by a thick fragmented supershell (~1.7 kpc) of lowly ionised gas. Additionally, but not seen in Fig. 5, there seems to be a compact kpc-scale structure of lowly ionised gas that extend from the E to the N of knot C. The halo, which might start from the edges of the outer main supershell as inferred from the weak H\(\alpha\) emission, is populated by a filamentary structure towards the S and three tidal tails towards the E, NE and N.

Besides, Haro 11 has a large number of secondary structures, such as small-scale filaments and clumps, that we do not refer here to keep the simplicity in our analysis. We note however that identifying well defined structures in our rich data becomes very hard, hence the features seen in our maps are subject to interpretation. The majority of these structures are clearly observed in the H\(\alpha\) maps and/or ionisation maps, while other less prominent structures are additionally supported by features that hint to their existence. In the following subsections we describe these structures in more detail.

4.1.1 Evidence of kpc-scale superbubbles
We find evidence of two kpc-scale superbubbles. The main superbubble (r~3.3 kpc) is surrounding the star forming...
knots. Principal evidences of its existence come from the bright Hα arc (NE) seen mainly at blueshifted velocities, that partially covers a dark cavity, while the halo towards the N is free of structures (at blueshifted velocities) and its Hα intensity decreases strongly with radius. Further evidence comes from the group of filaments that develop roughly in radial direction towards the S. These features are clearly seen at blueshifted velocities and might describe the morphology of the superbubble sketched in Fig. 5.

At redshifted velocities, the main supershell might have small openings in the north as hinted by the relatively smaller filaments that emanate. However, the filaments that predominate towards the S, appear to belong to the tidal smaller filaments that emanate. However, the filaments that comes from the group of filaments that develop roughly in radial direction towards the S. These features are clearly seen at blueshifted velocities and might describe the morphology of the superbubble sketched in Fig. 5.

The main superbubble might be collectively inflated by SNe from all star clusters located in the centre, mainly within the three central knots. Because a large number of star clusters might be involved, the time between SN events might be short. Kim et al. (2017) showed that for higher SN rate, the energy injected in the ambient medium develops a hot superbubble that rapidly propagates into the ISM. In these superbubbles, a significant fraction of the total injected energy, remains in the bubble while a smaller fraction is radiated away. Thus, this superbubble might have expanded rapidly and at some point, due to Rayleigh-Taylor instabilities, the shell might have fragmented, resulting in the hot material blowout of the bubble. It is not clear which mechanism has favoured the breakout of the bubble in the S. The group of filaments towards the S suggest, that the shell has fragmented in several places at the same time, creating several openings where the interior hot gas has vented. Fielding et al. (2018) has demonstrated that a clustering of SNe develops superwinds, powerful enough to escape the galaxy. These galactic winds are able to eject a considerable fraction of gas to the IGM. The authors also showed, that the dense ISM clumps struck by the winds are immediately ripped forming a filamentary structure while some fraction might entrain in the wind. The same process might have formed the filamentary complex in the S of Haro 11, where part of the shell might be dragged by the superwinds. In the simulations presented in Fielding et al. (2018), the superbubble breaks before the last SN in the clusters has exploded. Thus, the energy released by post-breakout SNe will easily escape the galaxy though the channels cleared by the superwinds.

Typical velocities of galactic winds range from the escape velocity of the galaxy to thousand of km s$^{-1}$ (Heckman et al. 2015). Assuming that the escape velocity of Haro 11 is about 400 km s$^{-1}$ (derived in a subsequent subsection), the time needed to develop the filaments of $\sim$10 kpc seen in the S, range from 10 to 25 Myr, for galactic winds with velocities between 1000 and 400 km s$^{-1}$. This might be the time range when the superbubble has fragmented. Typical time for superbubble breakout range from few Myr to about 10 Myr (Hopkins et al. 2012; Kim et al. 2017). Thus, the main superbubble might have started to develop between 15 and 35 Myr ago by the current starburst population. Because the cluster formation rate steeply decreases with look-back time in Haro 11, and the number of SNe to develop such superbubble might be very high, it is likely that the main superbubble started to develop about 15 Myrs ago.

This superbubble might have had similar physical properties as the superbubble that has developed the bipolar outflow in M82. Both structures seems to have collectively been inflated by SNe of many massive star clusters within their starburst region. In both galaxies, the superbubble breakout might have developed galactic winds with velocities larger than the escape velocity. Additionally, M82 and Haro 11 might have similar escape velocities (Strickland & Stevens 2000). Thus, the different fate of the superbubble in M82 is exclusively due to the morphological structure of the galaxy. Superbubbles that develop in disk galaxies rapidly reach a scale height perpendicular to the disk, in both side of the minor axis. The strong density gradient causes a fast acceleration of the bubble and its subsequent quick fragmentation, whose interior hot gas is able to open a wide outflow such as the outflow seen in M82 (Strickland & Heckman 2009; Fielding et al. 2018). In case of Haro 11, the radial density might be somewhat homogeneous. After breakout, the hot gas has then vented from several small openings.

The smaller superbubble centred at Knot C appears to be driven by SNe originated exclusively in this knot. It is covered by a thick shell and filled by highly ionised gas. The shell is already fragmented, and is leaking the hot interior
The merger-driven structures and the lowly ionised gas structure tracing the Lyα emission

The largest structures assembling the ionised gas of Haro 11 are three tidal tails that are probably lying in a plane perpendicular to the line-of-sight, as hinted by their low velocity dispersions. Along these structures, gas is condensing in clumps. Three small faint clumps are visible a in the farthest part of the largest tidal tail. An additional closer bright clump is detected in the stellar continuum in our MUSE data, suggesting that some star cluster are forming in the halo.

A huge lowly ionised gas structure is also seen in our maps, that turn from E to N from -250 to 200 km s\(^{-1}\). This region overlap well with the diffuse Lyα emission (see Fig. 6) from Hayes et al. (2007). This emission originates from resonance scattering of Lyα photons with neutral hydrogen atoms and might suggest that the lowly ionised gas structure is tracing the structure where the neutral HI gas is concentrated. Pardy et al. (2016) found that the neutral gas peak at 50 km s\(^{-1}\) and extend in a narrow velocity range at central velocities, although they were unable to map the HI gas distribution in the galaxy. Shocks with velocities ranging from 200 to 600 km s\(^{-1}\) are traced in the same area and could have enhanced somehow the diffuse Lyα emission here.

Interestingly, we do not see Lyα emission in the highly ionised area. This suggest that the highly ionised areas might have hydrogen column densities high enough to absorb the Lyα radiation, even in the galactic holes transparent to LyC photons, that could exist in this region.

The highly ionised gas and the escape routes of Lyman Continuum radiation

The ionisation structure of Haro 11 shows a fully ionised halo, but is especially enhanced towards the S and W at blue- and redshifted velocities. Copious amounts of ionising photons produced mainly in central actively star forming zone seems to travel further out, ionising the halo.

Knot B appears to be the most powerful source of ionising photons, as it has develop a galactic-scale highly ionised channel towards the N (see Fig. 4, a) and two towards the W and S conjointly with knot A and the dusty arm. However, it is not clear whether the large amount of ionising photons needed to develop these channels are produced solely by the young stellar population of knot B, or there is a contribution of a black hole in low accretion mode as suggested by Prestwich et al. (2015). Moreover, we have measured extreme [OIII]λ5007/Hα values (≥5) in two broad channels at velocities between -300 and -250 km s\(^{-1}\). Such high ratios can not be explained by ionisation models of typical HII regions, but only by a hard-UV ionisation field typical of Seyfert II galaxies (Kewley et al. 2001). There could be several explanation for it: we might see through channels of low density gas that has been highly ionised by a combination of photo-ionisation from the young massive stars in the central knots and X-ray shocked gas streaming out from the bubble into the ionization channels. An alternative scenario implies that this gas is photo-ionised by the AGN in low accretion mode. This scenario is less probable, because the contribution of the AGN extreme UV radiation strongly depend on the projected distance to the centre, with the highest ionisation values at the centre and decreasing smoothly with radius (Davies et al. 2014; D’Agostino et al. 2019). In Haro 11 however, these highly ionised regions are located between 3.8 and 6 kpc towards the south of knot B. Moreover, we do not see very high [OIII]λ5007/Hα values in the knots at these velocities.

Haro 11 is the first local of a handful of galaxies where LyC has directly been measured (Bergvall et al. 2006). LyC leakers need to have a highly ionised medium with low column density of neutral gas, at least along the line-of-sight to the production places for LyC photons to escape.

From the observed starburst driven LyC leakers, several mechanism have been proposed to favour the escape of LyC radiation, for instance a porous interstellar medium (Puschign et al. 2017), the presence of galactic holes
(Chisholm et al. 2015) and a density bounded interstellar medium with optically thin gas (Vanzella et al. 2018). But up to date, it has been impossible to spatially resolve the origin place of this radiation mainly because of resolution limitation of the UV-detector instrument. Moreover, the mechanisms favouring the escape of LyC radiation in these galaxies have not been studied in detail, as most of them are compact and not well resolved with the current instruments.

In Haro 11, Hayes et al. (2007) and Rivera-Thorsen et al. (2017) suggested LyC to be leaking from knot C, since it hosts several young clusters and is in general highly ionised although at large velocities the ionisation level decreases. In our analysis we found strong evidence of candidate, since it hosts several young clusters and is in general highly ionised although at large velocities the ionisation level decreases. In our analysis we found strong evidence of a fragmented superbubble that might have originated powerful galactic winds which in turn may have created galactic holes where LyC photons can escape.

Nevertheless, the density bound scenario might also be an important mechanism in Haro 11. This scenario supports the escape of LyC photons in the greatest ionised zones in the halo, towards the S and W, but particularly at an important mechanism in Haro 11. This scenario supports level decreases. In our analysis we found strong evidence of a fragmented superbubble that might have originated powerful galactic winds which in turn may have created galactic holes where LyC photons can escape.

The circular velocity ($v_{circ}$) can be approximated using the virial theorem: $v_{circ} = \sqrt{G \frac{M_{tot}}{r_{max}}}$.

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4.3 Can the gas escape the galaxy?

Fig. 7 shows [OIII]λ5007 emission maps in 50 km s$^{-1}$ bins at velocities $v = -750$, 850 and 1000 km s$^{-1}$. At higher blueshifted velocities, the [OIII] line is contaminated by a faint emission line (FeIII λ4986). The white line in each map shows the size of the outflowing gas, that is used to derive the escape velocities. These are: 1.6 kpc at $v = -750$ km s$^{-1}$, 1.46 kpc at $v = 850$ km s$^{-1}$ and 1.0 kpc at $v = 1000$ km s$^{-1}$.

To examine if this gas will escape the galaxy, we estimate the escape velocity in Haro 11, following the recipe described in Marlowe et al. (1995). They use a simple approximation of a spherical symmetric isothermal potential and a halo cutoff at $r_{max}$. The escape velocity at a radius $r$ is then:

$$v_{esc} = \sqrt{\frac{2}{\gamma} \cdot v_{circ} \sqrt{1 + \ln (r_{max}/r)}}$$

where $\gamma$ is the Planck's constant, $c$ is the speed of light, and $a_{eff}$ is the Hz recombination coefficient for case B. Then, we have derived the total ionised gas mass assuming that 25% of total gas mass is in form of helium. Haro 11 has an hydrogen ionised gas mass ($M_{HII}$) of $9.2 \times 10^8$ M$_\odot$ and a total ionised gas mass ($M_{HII}$) of $1.2 \times 10^9$ M$_\odot$. These properties are shown in Table 4. Lastly, we have consider the ionised gas mass at velocities $v \geq v_{esc}$ ($L_{Halpha,v_{esc}}$) for the gas that will escape the galaxy.

We consider only the gas that is flowing out at inclinations $< 45$. For velocities $v \leq -450$ and $v \geq 450$ km s$^{-1}$, the Hz luminosity was inferred from the [OIII]λ5007 surface brightness using a conversion factor chosen as the median

$$M_{HII,v_{esc}} = \frac{\mu m_{H} \lambda_{Halpha} L_{Halpha,v_{esc}}}{hcG a_{eff} n_{e}}$$

where $\mu$ is the atomic weight and is chosen to be 1, $\lambda_{Halpha}$ is the wavelength of Hz line, $M_{HII}$ is the hydrogen mass, $h$ is the Planck's constant, $c$ is the speed of light, and $a_{eff}$ is the Hz recombination coefficient for case B. Then, we have derived the total ionised gas mass assuming that 25% of total gas mass is in form of helium. Haro 11 has an hydrogen ionised gas mass ($M_{HII}$) of $9.2 \times 10^8$ M$_\odot$ and a total ionised gas mass ($M_{HII}$) of $1.2 \times 10^9$ M$_\odot$. These properties are shown in Table 4. Lastly, we have consider the ionised gas mass at velocities $v \geq v_{esc}$ ($L_{Halpha,v_{esc}}$) for the gas that will escape the galaxy.

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Figure 7. [OIII]λ5007 emission gas seen at velocities -750, 850 and 100 km s\(^{-1}\) respectively. The white lines mark the size in kpc of the emitting regions. These are used to calculate the escape velocity of the outflowing gas. Knot B appears to be the main driver of fast outflows.

Table 3. Row 1) Average escape velocities (v\(_{\text{esc}}\)) calculated for different inclination angles and dark matter content for the three outflows seen in Fig 7. Row 2) Projected escape velocities of these outflows, after correcting them by the inclination effects in the velocity.

Table 4. Ionised gas properties of Haro 11. Additionally we show the the ionised gas mass for the gas observed at velocities larger than 100, 200, 300 and 400 km s\(^{-1}\).

5 CONCLUSIONS

Thanks to the unprecedented capability of the MUSE instrument in combining the spectral and spatial information at the same time, we were able to study the ionisation structure of Haro 11 in maps of 50 km s\(^{-1}\) bins, in a velocity range of -400 to 350 km s\(^{-1}\). Here we analyse the impact of stellar feedback by means of the H\(\alpha\) radiation, the state of the ionised gas and the presence of fast shocks in the lowly ionised gas. In summary:

- The ionised gas of Haro 11 is rich in structures that appears to be exclusively shaped by effect of its intense stellar feedback. This includes arcs, bubbles, filaments and galactic ionised channels whose configuration in the ionised gas structure changes with velocity.

- Perhaps the most striking structure uncovered in our maps is the presence of a superbubble (r ~ 3.3 kpc), that is already fragmented in the south originating the complex filamentary structure seen at blueshifted velocities. The interior hot gas might have powered superwinds clearing galactic channels where LyC photons can escape. Given that Haro 11 is a LyC leaker, it is very likely that one of these channels is along the line of sight connecting us directly to the LyC source.

- The southwestern hemisphere shows the highest ionisation values along the velocity range and has been found to be density bound (Östlin in prep.) favouring the escape of
LyC radiation. Therefore, this mechanism might also allow the escape of LyC photons in Haro 11.

- Knot B appears to be a powerful source of ionising radiation as in its bases arises galactic highly ionised channels. However it is not clear whether the black hole in low accretion mode suggested by Prestwich et al. (2015) might have contribute to create this structure.

- The stellar feedback of knot C has created a local kpc-scale superbubble ($r \sim 1.7$ kpc) visible at $-300$ km s$^{-1}$. This bubble appears to be already fragmented and its interior hot gas seems to escape the halo through narrow highly ionised channels.

- The ionisation maps reveal a huge locally ionised gas structure that rotates counterclockwise with velocities. This structure overlaps with the diffuse Lyα emission found by Hayes et al. (2007) which is originated by Lyα photons scattering in the neutral HI gas. Therefore, this structure might trace the location of the neutral gas mixed perhaps with the locally ionised metal gas. This structure has most likely been shaped by the merger dynamics, compressing the cold neutral and locally ionised gas in a compact structure of several kpc.

- Fast shocks (200 – 500 km s$^{-1}$) are present in a low to intermediate ionisation zones, almost exclusively within the low ionisation structure. These shocks contribute to collisionally excited metal atoms, while ionising photons might be responsible for the ionisation structure.

- Haro 11 shows gas emission at very high velocities. Assuming various dark matter fractions and outflows inclinations, we have derived escape velocities that range from 240 to 600 km s$^{-1}$, increasing with dark matter content and outflows inclination.

- We calculate that the fraction of ionised gas mass that will escape the galaxy, is about 31, 23 and 9% for dark matter fractions of 70, 80 and 90%.

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