Widespread star formation inside galactic outflows

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ABSTRACT

Several models have predicted that stars could form inside galactic outflows and that this would be a new major mode of galaxy evolution. Observations of galactic outflows have revealed that they host large amounts of dense and clumpy molecular gas, which provide conditions suitable for star formation. We have investigated the properties of the outflows in a large sample of galaxies by exploiting the integral field spectroscopic data of the large MaNGA-SDSS4 galaxy survey. We find that star formation occurs inside at least half of the galactic outflows in our sample. We also show that even if star formation is prominent inside many other galactic outflows, this may have not been revealed as the diagnostics are easily dominated by the presence of even faint AGN and shocks. If very massive outflows typical of distant galaxies and quasars follow the same scaling relations observed locally, then the star formation inside high-z outflows can be up to several 100 M⊙ yr⁻¹ and could contribute substantially to the early formation of the spheroidal component of galaxies. Star formation in outflows can also potentially contribute to establishing the scaling relations between black holes and their host spheroids. Moreover, supernovae exploding on large orbits can chemically enrich in-situ and heat the circumgalactic and intergalactic medium. Finally, young stars ejected on large orbits may also contribute to the reionization of the Universe.

1 INTRODUCTION

Fast outflows, extending on kiloparsec scales, are commonly found in galaxies hosting enhanced star formation (“starburst”) and in galaxies hosting accreting supermassive black holes (quasars or, more generally, Active Galactic Nuclei, AGN). Galactic outflows are often invoked as a negative feedback process in galaxies; indeed, by removing and heating gas, outflows can potentially suppress star formation in their host galaxies (e.g. Granato et al. 2004; King 2010; Fabian 2012; King & Pounds 2015). However, some models have also proposed that outflows and jets can also have a positive feedback effect; indeed, compressing gas in the interstellar and circumgalactic galactic outflows can foster the fragmentation and gravitational collapse of clouds, hence boost star formation (Rees 1989; Nayakshin & Zubovas 2012; Bieri et al. 2016; Zubovas & King 2016). However, more recently, models have proposed an even more fascinating scenario, according to which the outflowing gas should cool, fragment and, therefore, form stars inside the outflow (Ishibashi & Fabian 2012; Zubovas et al. 2013b; Silk 2013; Zubovas & King 2014; Ishibashi et al. 2013; Gaibler et al. 2012; Dugan et al. 2014; Ishibashi & Fabian 2014; Zubovas et al. 2013a; El-Badry et al. 2016; Wang & Loeb 2018; Mukherjee et al. 2018). This new star formation mode is drastically different from star formation in galactic discs and even from star formation resulting from the “standard” positive feedback scenario discussed above. Indeed, stars formed inside galactic outflows would have high velocities on nearly radial orbits. Depending on the radius and velocity at the time of formation, stars born inside outflows may escape the galaxy and/or the halo, or become gravitationally bound (Zubovas et al. 2013b). According to models this star formation mode can reach a few/several 100 M⊙ yr⁻¹ (Ishibashi & Fabian 2012; Silk 2013). The implications of this new star formation mode are potentially far reaching, ranging from the morphological/dynamical evolutionary properties of galaxies to the enrichment of the circumgalactic and intergalactic medium, as will be discussed more in detail in Sect. 4.

Observations have recently shown that fast galactic outflows contain a large amount of cold molecular gas (e.g. Feruglio et al. 2010; Sturm et al. 2011; Cione et al. 2013; García-Burillo et al. 2015; Combes et al. 2014; Sakamoto et al. 2014; Fluetsch et al. 2018, including an unusually high fraction of dense molecular gas (Aalto et al. 2012; Walter et al. 2017; Privon et al. 2017), which is also found to be highly clumpy (Pereira-Santaella et al. 2016; Finn et al. 2013; Borguet et al. 2012). These observational results provide strong support to the theoretical scenario in which star formation occur in galactic outflows, since these possess the physical conditions (cold, dense and clumpy gas) suitable for star formation.

Several clear examples of star formation triggered in shocked and compressed gas clouds have been unambiguously seen in our
Evidence for the new mode of positive feedback, i.e. star formation inside galactic outflows, has been found only recently by Maiolino et al. (2017). They analysed optical/near-IR spectroscopic data of the prominent galactic outflow previously detected in the galaxy IRAS F23128-5919 (Leslie et al. 2014; Bellocci et al. 2013; Arribas et al. 2014; Cazzoli et al. 2016; Piqueras López et al. 2016) and found that multiple optical and near-IR diagnostics of the outflowing gas are consistent with in-situ star formation, i.e. inside the outflow. However, while this has been a remarkable result, it has not been clear whether this is an isolated, rare case, or star formation is more common in galactic outflows, but it has been difficult to identify.

Indeed, outflows are often driven by AGNs, which (as we shall discuss in Sect.6) tend to dominate the diagnostics, especially in integrated or nuclear spectra, and the presence of shocks may also hinder the detection of star formation.

We have investigated the occurrence of this phenomenon in a systematic and unbiased way by exploiting the 2,800 integral field spectra of the MaNGA-SDSS4 DR2 survey. These offer high quality, spatially resolved spectra spanning a broad wavelength range, hence enabling us to probe multiple diagnostics. We identify a sub-sample of 37 galaxies which show evidence for clear outflows and which can be traced thorough all primary nebular lines required for identifying the sources of gas ionization/excitation through diagnostic diagrams. We have therefore exploited these data to map the diagnostics across each outflow, hence revealing the presence of star formation inside outflows. As we will discuss in detail, we have found that about one third of outflows are characterized by prominent star formation inside them, and about half of the outflows show evidence for at least some star formation, hence revealing that star formation is common to most galactic outflows, with major implications especially for high redshift galaxies, where outflows are much more prominent.

In this paper we assume the following cosmological parameters: \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \), \( \Omega_m = 0.7 \) and \( \Omega_{\Lambda} = 0.3 \).

2 DATA ANALYSIS

2.1 The MaNGA survey

The observations for the SDSS-IV MaNGA survey (Bundy et al. 2015; Blanton et al. 2017), are taken on the Sloan 2.5m telescope (Gunn et al. 2006), using hexagonal IFU fibre bundles, ranging from 19 to 127 fibres in size, with 17 galaxies observed simultaneously. These IFUs feed the light into the dual-channel BOSS spectrographs (Drory et al. 2015). The size of the fibre bundle is chosen to ensure coverage out to a minimum of 1.5 Re for the MaNGA primary sample, and 2.5 Re for the secondary sample. The observing strategy chosen utilises a 3-point dithering pattern, with a total exposure time per galaxy of around 3 hours, aiming to reach the MaNGA requirement of signal-to-noise of 5 per spectral pixel in the r-band continuum at a surface brightness of 23 AB arcsec\(^{-2}\). Each set of exposures is also required to provide a median seeing of 2.0 arcsec or below, providing a PSF of less than 3 arcsec in the reconstructed images (Law et al. 2015; 2016; Yan et al. 2016b).

The wavelength coverage in the MaNGA cubes ranges from 3600Å to 10300Å at \( R \sim 2000 \), providing simultaneous access to the nebular lines \([\text{OII}]3727,3730\), \( H\alpha \), \([\text{OIII}]4959,5007\), \([\text{[OII]}6300,6366, [\text{NII]}6548,6584, H\beta \) and \([\text{[SII]}6717,6731] \). These are fundamental nebular lines which can be used to investigate the excitation and physical properties of the ionized gas. In particular, the so-called “BPT” diagnostic diagrams (Baldwin et al. 1981; Kewley et al. 2006) compare the ratios of different nebular emission lines (specifically: \([\text{OIII}]5007/H\beta \) versus \([\text{NII]}6584/H\beta \) and \([\text{[SII]}6717+6731]/H\alpha \) to enable a classification in terms of sources responsible for ionizing and exciting the gas, specifically differentiating between excitation from young hot stars in star forming regions and other forms of excitation such as AGNs, evolved stellar populations and shocks.

2.2 Spectral fitting, identification and mapping of outflows

We have considered all IFU spectra of the 2,800 galaxies in the MaNGA DR2. We have first inspected the spectrum of the central region of the galaxy, i.e. extracted from the central 2.5” (which corresponds to the typical PSF), with the goal of identifying candidate galaxies showing indication of outflows.

The first step was to fit the stellar continuum in this central region. For this purpose, we used the full MILES empirical stellar library, consisting of 985 stellar templates. Unfortunately, this library only covers the wavelength range 3525-7500Å, hence not fully exploiting the full coverage of the MaNGA data, which extends up to 10,000Å. However, it covers the continuum beneath all nebular lines of interest, and has a spectral resolution high enough to match the MaNGA spectra. The fitting of the continuum was done by using an adapted version of the PPGF routine (Cappellari 2017).

We begin the analysis of the central spectrum by fitting the stellar continuum and kinematics, whilst also masking all nebular emission lines within ±1000 km s\(^{-1}\) from each line’s redshifted central wavelength. The continuum is fit using the PPGF routine, assuming four Lines Of Sight Velocity Distribution (LOSVD) components (v, \sigma, h3 and h4), and allowing a 6th order additive Legendre polynomial to correct the continuum shape for small residual background. The OII 5577 sky line is also masked, as although good sky subtraction has been performed on the MaNGA data, some residuals can still exist for this line.

Having fit the stellar continuum, the residual spectrum from the fit was next tested for multiple emission line components. To investigate the presence of multiple components in the emission lines we began by testing the primary nebular lines mentioned above. We first simultaneously fit all nebular lines with a single Gaussian component, imposing the same central velocity and width for all nebular lines. The intensities of the Gaussian components of the individual nebular lines were left free to vary, with the exception of...
the [NII], [OIII] and [OI] doublets, whose line ratios were tied by their Einstein coefficients.

Note that when tying the velocity dispersions, one has to take into account that the spectral resolution changes slightly across the MaNGA spectrum. However, the latter is very well characterized in each spectral region and provided together with each spectrum. Therefore, at each point we can link the intrinsic velocity dispersion/width (which is to be tied for all lines) to the observed velocity width through the relation

$$\sigma_{\text{line}} = \sqrt{\sigma_{\text{RES}}^2 + \sigma_{\text{int}}^2}$$

where $\sigma_{\text{line}}$ is the dispersion of the final Gaussian fit, $\sigma_{\text{RES}}$ is the spectral resolution at the observed wavelength of the line and $\sigma_{\text{int}}$ is the tied dispersion between all lines.

Following this, we then investigated the presence of a second, broader component of the nebular lines. Assuming the emission lines could be well modelled by Gaussian templates, we allowed up to two Gaussians to be fit to each emission line, fitting only the first two orders of the LOSVD (i.e., velocity and dispersion). In the presence of a Type-1 AGN, extremely broad Balmer lines (typically FWHM from 1,000km/s to 10,000km/s) are present. To avoid problems when classifying outflows in the BPT diagrams, the few type 1 AGNs were not included in our study.

The putative additional (broader) Gaussian component was also required to have the same velocity and width for all nebular lines, with only the intensity of the broad component of the individual nebular lines left free to vary, though with some constraints on the line doublets as discussed above. For our pipeline to accept a second component, we require a number of conditions to be met. The most basic condition is that the multiple components fit improved upon the reduced chi-squared of the single component fit by a minimum of 10%. This is always a very conservative requirement, as with so many spectral points this always translates into a statistical significance of the additional component higher than 99%. In principle, one could relax this requirement, but, in this paper, we have preferred to be conservative in the identification of the broad components. We also required that for either H$\alpha$ or [OIII]5007, a signal-to-noise ratio of 3 and Equivalent Width of 3Å must be met. In practice, for this specific paper, these requirements are overridden by the subsequent requirements of detecting also the broad component of the fainter lines required for the BPT classification.

The broad component of [OII]6300 is often very weak and often undetected. However, generally, when non-detected the upper limit on [OII]6300 is meaningful, in the sense that it locates the broad component in the HII-like (star forming) region of the [OII]-BPT diagram.

Having positively identified multiple components in a spectrum, we next performed a check to ensure the emission line masks provided in the first steps are sufficiently masking the emission lines. We define a line as being sufficiently masked if the mask covers out to $3\sigma$ from each line centre (using the updated values of line centres and widths). Insufficient masks can lead to poor recovery of the stellar kinematics. Thus, if any of the lines are broader than their initial masks, then the masks are moved and increased in size to sufficiently mask the line, and the stellar kinematics are refit as before, and emission lines tested again. This step is repeated iteratively until the reduced chi squared of the continuum fit does not improve upon the previous fit’s reduced chi squared. At this point, the stellar kinematics are assumed good, and are saved and held fixed in all future steps.

In the next stage of the fitting process, the stellar continuum is fit again, with fixed kinematics, whilst simultaneously fitting the emission lines, whose kinematics were free to vary. This method was chosen as it has been previously shown that line fluxes can be underestimated by as much as 10% when fit post continuum subtraction (Sarzi et al., 2006). With some of our lines being relatively low flux (especially for H$\beta$), we indeed found that in cases where the fit was performed post subtraction, the continuum fit itself was sometimes modified by PXF to account for template mismatch through the additive polynomials used to correct for continuum shape. In these situations, the simultaneous fitting of the continuum and the emission lines alleviated the problem.

Figure 1 shows the spectral fitting of the central region of a representative galaxy resulting from the steps described above.

For those galaxies showing evidence for an outflow in the cen-
We begin by estimating the continuum SNR of each spaxel. This was determined by taking the medians of the flux and inverse variance spectra, provided in the MaNGA cubes, within the SDSS R-band (5560 Å < λ < 6942 Å). All spaxels with SNR < 5 were removed at this point, as the spaxels were to be binned to higher signal noise, and these spaxels would lead to large bins with noisy data.

Taking the remaining spaxels, all of the spectra were first collapsed into a single integrated spectrum. This was fit using similar steps as discussed above, and the non-zero weighted templates extracted to create individual template libraries for each galaxy, typically reducing the full MILES library from 985 to 25-40 templates that best described the galaxy properties. This was done to speed up the fitting process, typically by an order of magnitude.

Next, the spaxels were Voronoi binned to increase the SNR of the continuum for the binned spectra to 25. Through the use of Monte-Carlo simulations, it was determined that a minimum SNR of 25 should be used for a sufficiently accurate recovery of the stellar kinematics (Sarzi et al. 2006). The high SNR binned spectrum is used to restrict the number of templates to be used for the stellar fitting within the bin and to provide the initial parameters for fitting the stellar kinematics and for the nebular lines. Then the latter information is used to fit each individual spaxel within the Voronoi bin, by following the same steps discussed above for the central spectrum.

Figure 2 shows the kinematics of the narrow (disc) and broad (outflow) components, along with the stellar kinematics, for the same representative galaxy analysed in Figure 1. The same figure shows the flux distribution of both the narrow and broad components of both the Hα and [OIII]5007 lines. The same flux maps have been obtained also for the other lines required for the BPT diagram.

This analysis could be performed for a total of 37 MaNGA galaxies. This does not mean that other galaxies in the MaNGA data do not show outflows, but that only for these 37 a detailed analysis of the outflow in terms of BPT diagnostics is possible.

The list of the 37 galaxies with outflows that can be characterized through the BPT diagnostics is given in Table 1 along with their stellar masses from the MPA-JHU catalogue (Brinchmann et al. 2004).

The fitting results and maps for the full set of 37 MaNGA galaxies for which this analysis has been possible can be viewed at http://www.mrao.cam.ac.uk/~rm665/mangasoutflow/.

Finally we mention that the fluxes of the nebular emission lines, both narrow and broad, were corrected for dust reddening by assuming the default (Calzetti et al. 2000) attenuation curve and using the Hα/Hβ ratio to infer reddening.

### 2.3 Investigating the effects of beam smearing

A potential problem of the modest angular resolution of the MaNGA data is that the putative broad component in the innermost, central region may simply be an artefact of beam smearing. Many authors explore this issue by modelling the rotation curve and then simulating the effect of the beam smearing; however, such a test is dependent on the model adopted to describe the velocity field in the central region; therefore, to avoid being model-dependent we have not used this method.

Instead, we have simply compared the velocity dispersion of the broad component in the central region with the central stellar velocity dispersion, which is affected by the same beam smearing. A broadening resulting from beam smearing of the stellar velocity...
field should result in the stellar velocity dispersion being as high as the broad component of the gas. Figure 3 shows comparisons of the central velocity dispersion of both the narrow (left) and broad (right) gas components with the stellar velocity dispersion. The narrow components tend to show a similar dispersion as the stars (the solid line represents the 1:1 ratio), and in some cases a smaller dispersion, as the gaseous disk is typically dynamically cooler than the stars in the bulge. Conversely, the broad components are always found to have a dispersion much larger than the stellar component (the dashed line represents the 2:1 ratio), indicating that the broadening cannot originate from beam smearing. This further indicates that the broad component is tracing gas not in virial equilibrium with the gravitational field, which is traced by the old stellar population, hence implying that the broad component is truly tracing outflowing material. A further indication that the broad component is not resulting from effects of beam smearing is the fact that such component is not distributed along the minor axis of rotation (which instead is a typical signature of broadening by beam smearing of the rotation field) while it is well extended also fully resolved along the major axis direction. The fact that the outflow is resolved is further confirmed by the fact that the broad components have clear kinematic structures both in the velocity map and in the dispersion map.

3 FRACTION OF OUTFLOWS HOSTING STAR FORMATION

3.1 Spatially resolved BPT-diagnostics

We have explored the properties of the outflow by investigating the spatially resolved BPT diagrams of the outflow in each galaxy. We recall that these diagrams enable the classification of galactic regions in terms of gas excitation/ionization mechanisms, specifically: star formation (i.e. HII region excited by young, massive hot stars), excitation by supermassive accreting black holes (i.e. Seyfert or Quasar nuclei), and Low Ionization Nuclear Emission Line Regions (LINERs). The latter is a class of object comprising a broad range of excitation mechanisms: initially it was proposed that they are associated with excitation by weak, radiatively inefficient accreting black holes (e.g. Ho et al. 1993), however it has been realized that in most local galaxies the “LINER” emission is generally extended on kpc-scales across a large fraction of passive and green valley galaxies (hence renaming this class as “LIER”, i.e. dropping the “N” which stands for “Nuclear” in the original acronym) and correlates with the old stellar population, and this can be explained in terms of excitation by the hard radiation field produced by evolved post-AGB stars (e.g. Sarzi et al. 2010; Belfiore et al. 2016). However, in some active galaxies and outflows the LI(N)ER emission can also be associated with shocks excitation (e.g. Heckman et al. 1987; Monreal-Ibero et al. 2010). A more detailed discussion on the origin of the LI(N)ER emission goes beyond the scope of this paper.

Figure 4A shows the line of demarcation between the different excitation mechanisms identified by Kaufmann et al. (2003), Kewley et al. (2001) and Kewley et al. (2006), in the three BPT diagrams. On the [NII]-BPT diagram the Seyfert/quasars and LI(N)ER are not clearly divided and are generally classified together as “AGN”. On the same diagram Kaufmann et al. (2003) identified a demarcation curve between HII/Star-forming regions and AGNs (dashed line) empirically based on the distribution of galaxies in the SDSS survey, while Kewley et al. (2006) provided a curve (solid line) tracing the maximum line ratios associated with star forming regions according to photoionization models; galaxies/regions in the area between these two curves are often referred to as “composite” systems, in which both SF and AGN probably coexist.

We note that other diagnostic diagrams involving the equivalent width of Hα (Cid Fernandes et al. 2011) cannot be used in this case, as we cannot discriminate the continuum associated with the broad and narrow components. Therefore, in this paper we only exploit the BPT diagrams to identify the excitation mechanism in galactic regions and specifically in the outflows.

As an example of BPT diagnostics spatially resolved in outflows, Figure 4A shows the BPT classification of the broad (outflow) component of each individual spaxel of the same representative galaxy shown in representative galaxy Figure 2. Figure 4B shows how the BPT classification is distributed within the outflow

![Figure 3](image-url)
Figure 4. A: Distribution of the broad (outflow) component of the nebular lines on the BPT diagrams for the same representative galaxy of Fig.1 and Fig.2. A significant fraction of this galactic outflow is in the BPT regions typically populated by star forming regions and star forming galaxies. The magenta star shows the median location of the BPT points in the outflow. The background grey-scale contours indicate the distribution of several hundred thousand galaxies in the SDSS survey. B: Spatially resolved BPT classification of the outflowing gas, using the same colour coding as in (A). The central region of the outflow is mostly star forming, while towards the outer parts of the outflow excitation by shocks likely dominates.

Figure 5. Median BPT classification of the outflows for the galaxies in our sample. According to their median BPT classification in the [SII] and [OI] diagrams (central and right panes), about 30% of the galactic outflows in our sample are “star forming”. The same applies to the [NII] classification if one includes galaxies classified as “composite” (however, one should take into account that the [NII] classification is more ambiguous, as discussed in the text).

flow map. For this galaxy, both the [SII]-BPT and [OI]-BPT diagrams consistently indicate that the central region of the outflow is star formation-dominated, while shocks likely dominate in the outer regions of the outflow. The [NII]-BPT diagram also provides a consistent picture if one includes “composite” spaxels (green) as hosting star formation. One should also take into account that the [NII]-BPT diagram is considered as the least reliable of such diagrams because of its strong dependence on the nitrogen abundance (Masters et al. 2016) and on the ionization parameter (Strom et al. 2017a).

To have a useful quantities of comparison for the outflow in the different galaxies in our sample, we condense the information on each outflow by taking the median location on the BPT diagram of such outflow components for each galactic outflow. In the case of the galaxy shown in Figure 4A the median location in each BPT diagram is shown with a magenta star symbol. We note that
this is a considerable improvement, enabled by spatially resolved spectroscopy, relative to spatially integrated spectra, which are generally light-weighted and therefore dominated by the brightest regions (e.g. a central AGN-dominated region).

Figure 5 shows the resulting median location of the outflows on the BPT diagrams for all systems in our sample (Table 1 gives the average BPT classification for each individual object). The [SII]-BPT and [OI]-BPT diagrams indicate that in most outflows the ionized gas appears to be excited by AGN, however, about 30% of the outflows host gas whose ionization is dominated by young stars. For the [NII]-BPT a smaller fraction of outflows appears dominated by star formation excitation. However, if one also includes outflows whose [NII]-BPT classification is in the “composite” region (considered as a transition region in which star formation and AGN excitation coexist), then the fraction of outflows showing indication of star formation increases to about 30% also in the [NII]-BPT diagram. One should also take into account the concerns about the [NII]-BPT diagram discussed above.

Even for those galactic outflows whose median BPT diagnostics are associated with AGN or LIER-like ionization, there are generally still regions of the outflow that are associated with star formation. Therefore, to better quantify the occurrence of star formation in galactic outflows, we have estimated for each outflow the fraction of spaxels that can be classified as “star forming” according to each of the BPT diagnostics. Figure 6 shows the distribution of galaxies as a function of the fraction of the outflow that is classified as star forming. According to the [SII]-BPT and [OI]-BPT classifications, about half of the galactic outflows show evidence for some star formation inside the outflow (whose contribution to the overall excitation of the gas ranges from 10% to 100%). Even the [NII]-BPT diagram provides the same fraction of “star forming outflows” if one considers also outflowing regions classified as “composite” in this diagram.

3.2 In-situ versus external photoionization

One potential concern of our finding could be that, for those outflowing regions where the BPT diagnostics of the outflowing gas are consistent with excitation from young stars, the latter may not be located inside the outflow but in the galactic disc and the outflowing gas may simply be illuminated externally by the UV radiation coming from the disc. However, these scenarios can be distinguished by exploiting the ionization parameter, defined as ratio between ionizing photons flux ($Q_{\text{ion}}/4\pi r^2$) and gas electronic density ($n_e$), and normalized through the speed of light,

$$U = \frac{Q_{\text{ion}}}{4\pi r^2 c n_e}$$

The gas density in the outflow is similar, or even higher than in the disc, as inferred from the [SII] doublet (Gallagher et al. in prep.). Therefore, in the scenario of external photoionization one would expect that the ionizing flux should be much lower than in the case of in-situ photoionization, therefore resulting into an ionization parameter orders of magnitude lower than observed in standard star forming regions.

The ionization parameter can be traced through the [OIII] $\lambda 5007$/[OII] $\lambda 3727$ line ratio (Díaz et al. 2000). This ratio has however also a secondary dependence on the gas metallicity. The latter can however be monitored through the $R_{23}$ parameter defined as the ratio ([$\text{OIII}]_{5007,5010} + [\text{OII}]_{3727})/H\beta$, which is primarily sensitive to the oxygen abundance, and with a secondary dependence on the ionization parameter. Therefore, diagrams with both these quantities are used to help disentangling these properties (e.g. Nagao et al. 2006).

Figure 7 shows the [OIII] $\lambda 5007$/[OII] $\lambda 3727$ ratio as a function of the $R_{23}$ parameter. The right-hand axis translates the [OIII] $\lambda 5007$/[OII] $\lambda 3727$ ratio into $U$ following the relation provided by Díaz et al. (2000). The shaded contours indicate the distribution of star forming galaxies from the SDSS survey (68%, 95% and 99.7% of the population), illustrating the well-known correlation between $U$ and metallicity (e.g. Nagao et al. 2006). Blue symbols indicate the median values observed in the galactic outflows of our sample that are dominated by star formation, according to the [SII]-BPT diagnostic diagram, as in Figure 5 Figure 7 shows that the ionization parameter of the gas in the star forming outflows, as inferred from the [OIII] $\lambda 5007$/[OII] $\lambda 3727$ line ratio, is undistinguishable from that of normal star forming regions/galaxies and, if
Figure 7. Ionization parameter (right hand Y axis) as traced by the [OIII]/[OII] ratio (left hand Y axis) as a function of the $R_{23}$ parameter, which is primarily sensitive to the gas metallicity. Blue symbols indicate the median values observed in those galactic outflows dominated by star formation, according to the [SII]-BPT diagnostic diagram, as in Figure 5. The shaded contours indicate the distribution of star forming galaxies from the SDSS survey (68%, 95% and 99.7% of the population). Star forming outflows (blue symbols) have similar ionization parameter as normal star forming regions, and possibly even slightly higher.

Figure 8. Star formation rate inside the outflow as a function of total star formation rate in the disc of the host galaxy.

Figure 9. Star formation rate inside the outflow as a function of the star formation rate in the same central projected area in which the outflow is detected.

4 STAR FORMATION RATE INSIDE OUTFLOWS

4.1 Contribution to the total star formation

For those outflows showing evidence for star formation, we can estimate the star formation rate by using the broad component of H$\alpha$ as a tracer of star formation (Kennicutt & Evans 2012). The star formation rates inferred in these local outflows are of the order of 0.1–1 $M_\odot$ yr$^{-1}$ (Table 2). In Figure 8 we compare the star formation rate inside the outflow with the total star formation rate of the galaxy, as inferred by the total H$\alpha$ emission, integrated across the entire galaxy. Star formation in the outflow contributes “only” between 5% and 30% to the total star formation rate of these local galaxies (with one extreme case dominating the total SFR).

However, in the central few kpc the star formation inside the outflow can dominate the local star formation formation rate. This is illustrated in Figure 9 where the star formation rate inside the outflow is compared with the star formation rate in the same (central) projected region in which the outflow is detected.

These star formation rates are certainly modest and may be regarded as currently not very relevant for galaxy evolution. However, one should also take into account that these are relatively mild outflows, while star formation may be much more prominent inside the massive outflows driven by massive star forming galaxies at high redshifts or powerful distant quasars. To investigate this possibility in the following we explore the scaling relation between star formation inside the outflow and mass outflow rate.
4.2 Ionized outflow rate

Unfortunately we only have information on the ionized component of the outflowing gas, therefore we can only obtain information on the ionized gas outflow rate. The ionized phase generally accounts for a small fraction of the total gas content in outflows (Carniani et al. 2015; Fiore et al. 2017; Fluetsch et al. 2018), however it can be used as a proxy of the global outflow rate.

We have adopted a method similar to the one described by Carniani et al. (2015) and Cicone et al. (2015). More specifically, for each point where we detect an outflow component we estimate the contribution to the outflow rate as the mass of ionized gas at that point divided by the dynamical time from the centre:

\[
M_{\text{out-fl}} = \frac{M_{\text{out-fl} \cdot \text{ion}}}{\tau_{\text{dyn}}} = \frac{M_{\text{out-fl} \cdot \text{ion}} v_{\text{outfl}}}{R_{\text{outfl}}}
\]

where \(v_{\text{out}}\) is the outflow velocity at that location, which we define as \(|v| + \text{FWHM/2}\) of the broad component, \(R_{\text{out}}\) is the distance of the specific location to the galaxy centre (within the central PSF region this is taken as the size of the PSF, which actually gives a lower limit to the contribution to the outflow rate in this region) and \(M_{\text{out-fl} \cdot \text{ion}}\), is the mass of ionized gas at that location (spaxel). Projection effects, resulting from the direction of the outflowing gas relative to the line of sight, affect both the observed velocity and the observed radius. However, it can be easily shown (Cicone et al. 2015) that the correction factor, averaged over the entire galaxy solid angle, is one; therefore, statistically, projection effects do not plague results, although they certainly introduce scatter. Assuming \(T_e \sim 10^4\) K, the mass of ionized gas in the outflow at that location is given by the luminosity of the \([\text{OIII}]5007\) emission at the same location through the following relation:

\[
M_{\text{out-fl} \cdot \text{ion}[\text{OIII}]} = 2 \times 10^5 M_\odot \left( \frac{L_{\text{[OIII]}}}{10^4 \text{ erg s}^{-1}} \right) \left( \frac{n_e}{200 \text{ cm}^{-3}} \right)^{-1}
\]

where \([\text{O/H}]\) is the oxygen abundance relative to solar and \(n_e\) is the electron density in the outflow, which we have assumed to be 200 cm\(^{-3}\), which is intermediate between the results obtained by Perna et al. (2017) (for AGN-driven outflows) and the result obtained by Genzel et al. (2014) (for outflow in massive star forming galaxies). In a future work (Gallagher et al., in prep.) we will refine the outflow rates by taking the gas density inferred directly from the sulphur doublet at each location of each outflow.

Alternatively, the mass of the ionized outflow can be inferred from the broad component of \(H\alpha\) from the following equation:

\[
M_{\text{out-fl} \cdot \text{ion}[H\alpha]} = 1.5 \times 10^5 M_\odot \left( \frac{L_{H\alpha}}{10^4 \text{ erg s}^{-1}} \right) \left( \frac{n_e}{200 \text{ cm}^{-3}} \right)^{-1}
\]

As already pointed out by Carniani et al. (2015), if assuming solar metallicity, the outflow mass inferred from \([\text{OIII}]\) broad component gives an outflow rate which is about a factor of \(~3 - 5\) lower than inferred from \(H\alpha\) or \(H\beta\). This is either because the gas metallicity may be lower than solar or, more likely, because \([\text{OIII}]\) does not account for the contribution from lower ionization stages of oxygen.

In either cases, the total outflow rate was then obtained by summing the individual contributions to the outflow rate of all individual spaxels.

**Figure 10.** Star formation rate inside the outflow as a function of ionized gas mass outflow rate inferred from the \(H\alpha\). Blue symbols are star forming outflows in local MaNGA galaxies studied in this paper. The red symbol indicates the star forming outflow previously detected in IRAS F23128-5919 (Maiolino et al. 2017). The dashed line shows the fit to the MaNGA outflows presented in this paper (blue points). The solid line is the linear fit including IRAS F23128-5919 (Eq. 1). The blue shaded regions indicate the ionized outflow rate inferred for high-z massive galaxies and quasars. The orange shaded regions indicates the star formation rate inside these distant galactic outflows if they follow the same correlation observed locally.

4.3 Scaling relations and implications for high redshift galaxies

We have explored the connection between outflow rate and star formation in the outflow.

We have initially focused the outflow rate inferred from the \(H\alpha\) broad component, because less subject to ionization and metallicity corrections. For those galaxies whose outflow is dominated by star formation in terms of BPT diagnostics, Figure 10 shows the star formation rate inside the outflow as a function of the ionized outflow rate estimated from the broad component of \(H\alpha\). Blue symbols are star forming outflows discovered in this paper, while the red symbol is the star formation previously discovered inside the outflow of the galaxy IRAS F23128-5919 (Maiolino et al. 2017). The data reveal a clear correlation between the two quantities. The dashed line shows the fit to the MaNGA outflows presented in this paper, whose extrapolation is nicely consistent with the star formation observed in the outflow of IRAS F23128-5919. Including the latter galaxy in the fit results into the solid line, which is only slightly different from the fit to the MaNGA galaxies only, and it has the form:

\[
\log (\text{SFR}_{\text{outfl}}) = 1.21 \log (M_{\text{out-fl} \cdot \text{ion}[H\alpha]}) + 0.13
\]

We recall again that generally the ionized outflow rate is a small fraction of the total outflow rate (especially relative to the molecular phase). The blue shaded regions indicate the ionized
outflow rate inferred for high-z massive galaxies and quasars, as inferred from Hα or Hβ data (Carniani et al. 2015; Genzel et al. 2014; Fiore et al. 2017). The orange shaded regions indicates the star formation rate inside these distant galactic outflows if they follow the same correlation observed locally, implying star formation rate inside these distant galactic outflows if they follow the same correlation observed locally, implying star formation rate inside these distant galactic outflows if they follow the same correlation observed locally, implying star formation rate inside these distant galactic outflows if they follow the same correlation observed locally, implying star formation rate inside these distant galactic outflows if they follow the same correlation observed locally, implying star formation rate inside these distant galactic outflows if they follow the same correlation observed locally, implying star formation rate inside these distant galactic outflows if they follow the same correlation observed locally, implying star formation rate inside these distant galactic outflows if they follow the same correlation observed locally, implying star formation rate inside these distant galactic outflows if they follow the same correlation observed locally, implying star formation rate inside these distant galactic outflows if they follow the same correlation observed locally. The solid line shows the linear fit including both the MaNGA galaxies and the outflow in IRAS F23128-5919, which is given by the following equation

$$\log (SFR_{\text{out}}) = 0.94 \log (M_{\text{out}}/\text{OIII}) + 1.2$$

5 DISTRIBUTION OF GALAXIES WITH OUTFLOWS ON THE SFR-M∗ DIAGRAM

The distribution of galaxies on the SFR-M∗ diagram is often used to identify their properties. Most star forming galaxies are distributed along the so-called “Main Sequence”, a tight relation in which the SFR is nearly proportional to the stellar mass (Kennicutt & Peng 2015). This is thought to represent the sequence along which galaxies form stars through secular, smooth evolution. Passive galaxies have SFRs well below the “Main Sequence”, while galaxies distributed between the Main Sequence and the Passive population (in the region that is often referred to as “green valley”) are believed to be in the process of being quenched or being “rejuvenated”. The distribution of the 2,800 MaNGA galaxies (our parent sample) on the SFR-M∗ diagram is shown with grey contours in Figure 12. The Main Sequence in this sample is less populated than in other samples (such as, for instance, SDSS-DR8) primarily as a consequence of the MaNGA selection criterion of having a flat distribution in stellar mass. The MaNGA galaxies with outflows investigated in this paper, i.e. those for which the outflow can be studied in terms of BPT diagram, are shown with symbols, which are color-coded according to the [SII]-BPT classification of the gas in the outflow as in Figure 5. Most of the galaxies with outflow are distributed around the massive end of the Main Sequence. Outflows hosting star formation (blue symbols) are along the Main Sequence or slightly above it. There are some outflows among passive and green-valley galaxies, but only with AGN and LIER-like excitation. The lack of outflows in low mass galaxies may primarily result from selection effects, as these tend to be fainter and are likely characterized by milder outflows (either SF-driven or AGN-driven), below our detection threshold. A more detailed analysis of the statistical properties of outflows will be discussed in another paper. However, the finding that outflows hosting star formation are
Figure 12. Star formation rate versus stellar mass diagram. The background contour plot shows the distribution of all 2,800 galaxies in the MaNGA sample. The symbols show the distribution of galaxies with outflows presented in this study, i.e. those for which the outflows can be analysed in the BPT diagram. The BPT classification of the outflow is the same as in the [SII]-BPT diagram of Fig.5. Most outflows, especially those hosting star formation inside the outflow, are located around the massive end of the Main Sequence, or slightly above it.

located primarily on, or slightly above, the massive end of the main sequence supports the scenario in which this star formation mode may contribute to the population of stars in the bulge; although the overall contribution to the bulge population at this late epoch is minor, the contribution of this mechanism to the evolution of the bulge may have been significant at high-z, in the early phase of galaxy formation. This result is in line with the recent finding that galaxies above the Main Sequence have bluer bulges, which may still be in the process of forming a fraction of their stars (Morselli et al. 2017). This finding also suggest that star formation inside outflows may be similar to star formation in starburst systems, i.e. more efficient than star formation in galactic discs. Ongoing ALMA observations aimed at probing the molecular gas content in star forming galactic outflows will enable us to test this scenario.

We finally mention that, both morphologically and kinematically, nearly all galaxies showing star formation inside outflows appear to be isolated systems, typically regular galaxy disc. Only two of these galaxies are interacting systems, which are marked with an asterix in Table 1.

6 WHY HAS STAR FORMATION IN OUTFLOWS BEEN ELUSIVE?

If star formation in outflows is as common as inferred in Sec. 4 and can reach star formation rates as high as inferred in Sec. 4.3 in high-z galaxies, why has this phenomenon remained elusive so far?

One of the primary reasons is that different excitation mechanisms do not have the same weight in affecting the location of galaxies or galactic regions on the BPT diagrams. In particular, in this section we show that even if prominent star formation is taking place inside the outflow, the presence of an even weak AGN photoionizing the gas within the outflow generally dominates these diagnostic diagrams, even in the scenarios with the most conservative assumptions, implying that the fraction of star forming outflows inferred in section 4 is actually a lower limit.

To show this, we make two simplifying assumptions: firstly, we assume that the BH accretion and star formation in the spheroidal component of the galaxy evolve along the local $M_{\text{BH}} - M_{\text{spheroid}}$ relation; secondly, we take the most extreme (and most conservative) case possible, wherein we assume that all stars in the spheroid form through star formation within the outflow.

This implies that

$$M_{\text{BH}} \approx \frac{5 \times 10^{-3}}{\text{SFR}_{\text{spheroid}}}$$

(Kormendy & Ho 2013). Assuming a radiative efficiency of 0.1 for black hole accretion, the relationship between Hz emission (in the NLR) and X-ray luminosity for type 2 AGNs given in Ueda et al. (2015), and the X-ray to bolometric AGN luminosity correction given in Marconi et al. (2004) (here we take the bolometric correction appropriate for the typical AGN luminosity considered by Ueda et al. 2015) implying $L_{\text{bol}}/L_{\text{X}(2-10keV)} = 20$, we get

$$L_{\text{H\alpha}}/(\text{AGN}) = \frac{2 \times 10^{42}}{M_{\text{BH}} [\text{M}_\odot / \text{yr}]}$$

By also using the relation between $L(H\alpha)$ and SFR given in Kennicutt & Evans (2012), in combination with Eqs. (3) and (4) we obtain

$$L_{\text{H\alpha}}/(\text{AGN}) = \frac{5}{L_{\text{H\alpha}}(\text{SFR})}$$

and, of course, the same relation applies to H$\beta$. Moreover, for most local star forming galaxies typically $L_{\text{HII}}/(\text{SFR}) < L_{\text{H\alpha}}/(\text{SFR})$, whilst for AGNs $L_{\text{HII}}/(\text{AGN}) \approx 10 L_{\text{H\alpha}}/(\text{AGN})$; as a consequence, together with Eq. (5) this implies that the BPT diagnostics will be totally skewed towards the AGN region on their Y-axis. Similarly, given that [NII], [SII] and [OII] are all more luminous in AGNs than in SF galaxies, together with Eq. (5), this implies that the BPT diagnostics will be all skewed towards the AGN region also on the X-axis. Therefore, even in the most conservative scenario assumed above, in which the formation of the spheroidal component of the galaxy results entirely from star formation in the outflow, implying prominent star formation in the outflow, such star formation may go entirely undetected in the BPT diagrams as the excitation diagnostics are totally dominated by AGN excitation.

This issue has been clearly directly demonstrated in detailed spatially resolved cases in which star forming clumps have remained elusive because diagnostics have been dominated by the photoionization of an even weak AGN (Santoro et al. 2016).

One consideration that complicates things further is the presence of shocks. In these cases, the detection of SF is even more difficult as they are expected to move the diagnostics towards the LIER regions on the diagrams.

Summarizing, the lack of star formation-like BPT diagnostics in outflows does not necessarily exclude the presence of star formation inside the outflow, as such outflows may still host prominent star formation but may struggle to be detected as other sources of excitation may be dominating the diagnostics. Star formation inside outflows becomes easier to detect when the AGN has faded away, and when shocks are weak.

The implications in the context of this paper is that the fraction
of outflows with star formation may be higher than what estimated in Sect. [3].

In integrated, spatially unresolved (or poorly resolved) spectra the light-weighting further enhance the bright, central AGN-dominated emission (especially in the case of powerful quasars) relative to weaker star forming regions. This issue is obviously more problematic at high redshift. However, despite these difficulties, current data already show some indications of star formation in high redshift outflows. Genzel et al. (2014) could investigate the diagnostic diagram in the outflow of five galaxies and two of them have diagnostic ratios consistent with star formation inside the outflow.

The finding that at high redshift star forming regions tend to shift towards the AGN locus on the BPT diagrams (e.g. Strom et al. 2017b) is a further complication which may have led the classification of some outflows as AGN-dominated, while actually being powered by star formation inside the outflow.

Another problem is that often only the [NII]-BPT diagram is used to classify outflows. As discussed in Strom et al. (2017a) and Masters et al. (2016) the [NII]-BPT is much more subject to changes in the ionization parameters and nitrogen abundance relative to the other two BPT diagrams. In Sect. [5] we have seen that star forming outflows are clear identified in the [SII]- and [OII]-BPT diagrams, while in the [NII]-BPT diagram they are located primarily in the “composite” region. Therefore, studies based only on the [NII]-BPT diagnostics may have mis-identified the excitation of galactic outflows. For instance, Leung et al. (2017) classify the outflows of 13 AGNs at z ∼ 2 only based on the [NII]-BPT diagram; about half of these outflows are located in the “composite” region of the [NII]-BPT diagram, hence these outflows could be hosting star formation, similarly to the outflows investigated in this paper.

Another problem is that in many spectroscopic surveys outflows are searched through blue wings of the [OIII]5007 line. Because of the dominance of this line in AGN-driven outflows, as discussed above, many of these surveys have certainly biased their search toward outflows whose diagnostics are AGN-dominated.

We finally conclude this section mentioning that in local galaxies outflows are being studied in greater detail thanks to improved, high sensitivity and wider area integral field spectrometers (e.g. MUSE at the VLT) and evidence for star formation is being found in additional individual outflows studied in detail (Venturi et al., in prep.; Fluetsh et al., in prep., Maiolino et al. 2017).

7 IMPLICATIONS FOR GALAXY EVOLUTION

Stars formed in galactic outflows have completely different dynamical properties relative to the stars forming in galactic discs. Indeed, as soon as stars form in the outflow they only respond to gravity, hence moving ballistically. If the velocity at the time of formation inside the outflow exceeds the escape velocity then the newly formed stars will leave the galaxy and disperse in the intergalactic medium (IGM). If the velocity is lower than the escape velocity then the newly formed stars will be bound; they will be rapidly decelerated and will start oscillating around the galactic center. The latter is also one of the reasons why it is difficult to identify the young stars formed in the outflows, since as soon as they form they decouple from the outflow and their velocity is quickly reduced (within a few Myr, Maiolino et al. 2017) becoming kinematically difficult to distinguish from the stars in the disc.

In the case of the stars formed in the outflows that are gravitationally bound, their resulting orbits may predominantly be radial. However, as shown in Maiolino et al. (2017) for the specific case of IRAS F23128-5919, the gravitational interaction with the galactic disc, or any other non-spherically symmetric potential (stellar bar, flyby galaxies) will introduce a tangential component to the stellar velocities, hence randomizing their orbits. Moreover if the expelled gas was initially in rotation around the galactic center, then the resulting stars formed in the outflow star can also preserve some minor rotation component.

What is the primary fate of stars formed in the outflow has still to be investigated properly in a statistical way. Models expect both scenarios, i.e. escaping and gravitationally bound, depending on the nature and properties of the outflow (Zubovas et al. 2013b). In the case of the star forming outflow in IRAS F23128-5919, which has been studied in great detail, Maiolino et al. (2017) has shown that most of the stars born in the outflow are gravitationally bound. A detailed study of both the MaNGA galaxies shown here (as well as those for which a BPT analysis has not been possible) is postponed to a later paper, however a rough analysis of the kinematics and of the galaxy dynamics suggest a broad range of possibilities, from stars on close, gravitationally bound orbits to stars escaping the galaxy potential.

In either case, the fact that star formation in outflows has been found by us to be so common implies that this newly discovered phenomenon may have major implications for galaxy evolution and even result into a paradigm change in some specific areas. In the following we discuss some of the potential implications of star formation in outflows for galaxy evolution and to explain some of the galactic properties.

7.1 Formation of the spheroidal component of galaxies

If stars formed in outflows are gravitationally bound, then they can contribute significantly to the formation and evolution of the spheroidal component of galaxies, i.e. bulge, halo, and even contribute to the formation of elliptical galaxies. Indeed, Silk (2013) have proposed that such positive feedback mechanism may explain some of the extreme star forming galaxies at high redshift, which are thought to be progenitors of local ellipticals. Shibashit et al. (2013) have even suggested that star formation in AGN-driven outflows can contribute to the observed size evolution of elliptical galaxies across the cosmic epochs. Wang & Loeb (2018) have also suggested that the double-shells often observed in elliptical galaxies, typically ascribed to merging events, can actually be the result of star formation in outflows.

The integrated spectra of local elliptical galaxies does not seem to show evidence a large fraction of stars on radial orbits (Cappellari et al. 2007). However, the study of Cappellari et al. (2007) of 24 local elliptical galaxies result into a radial anisotropy parameter βr > 0 (i.e. preference for radial orbits) in ~ 2/3 of their sample. The kinematics of individual stars would be needed to properly assess the fraction of the radial orbits. Anyhow, as discussed above, even for stars formed in outflows various effects contribute to introduce significant tangential components to the stellar orbits.

For galactic bulges and galactic halos, for which the phenomenon discussed in this paper is likely more important, a similar analysis on the distribution of radial and tangential orbits has not yet been performed to our knowledge. It is however interesting to note that recent studies of the stellar velocity distribution in the 5 kpc around the Sun, based on Gaia data, have revealed a significant population of stars with highly radial galactocentric or-
Widespread star formation inside galactic outflows

7.2 BH-galaxy correlations

Clearly stars formed in AGN-driven outflows can potentially directly produce the $M_{\text{BH}} - M_{\text{spheroid}}$ relation. In particular, given the correlation between outflow rate and AGN luminosity (i.e., BH accretion rate), obtained by various observational works (Fiore et al. 2017; Fließ et al. 2018), and the correlation between outflow rate and star formation in the outflow found in Sect. 4.3 (Figs. 10-11), it is clear that the combination of the two can result into a correlation between black hole mass and stars formed in the outflows.

Quantifying the expected relation is yet not simple, as different authors have found different scaling relations between ionized outflows and AGN luminosity (Fiore et al. 2017; Fließ et al. 2018). However, if we consider the compilation by Fiore et al. (2017) (where the correlation between ionized outflow rate and AGN luminosity is slightly superlinear), and assume an AGN radiative efficiency of 0.1, then the relation between AGN luminosity and ionized outflow rate translates into

$$\log \left( \frac{M_{\text{outf-ion}}}{M_{\odot}} \right) = 0.85 + 1.29 \log \left( \frac{M_{\text{BH}}}{M_{\odot}} \right)$$

where both the ionized outflow rate and black hole accretion rate are in units of $M_{\odot}$ yr$^{-1}$, and where we have corrected the outflow rates estimated by Fiore et al. (2017) (specifically by a factor of three) to account for the different assumptions to derive the outflow rate in our work. Combining Eq[6] with the relation between ionized outflow rate and star formation in the outflow, i.e. Eq[3] gives

$$\text{SFR}_{\text{outf-ion}} = 15 \left( \frac{M_{\text{BH}}}{M_{\odot}} \right)^{1.56}$$

were $\text{SFR}_{\text{outf-ion}}$ is the star formation rate inside the outflow, again in units of $M_{\odot}$ yr$^{-1}$. The relation is superlinear. At low/intermediate accretion rates ($M_{\text{BH}} < 5 M_{\odot}$ yr$^{-1}$) the relation gives a SFR/$M_{\text{BH}}$ ratio lower than the observed local bulge-to-black hole mass ratio, i.e. $M_{\text{bulge}}/M_{\text{BH}} \sim 200$ (Kormendy & Ho 2013), while at high accretion rates ($M_{\text{BH}} > 5 M_{\odot}$ yr$^{-1}$) the implied SFR/$M_{\text{BH}}$ ratio is higher than the local bulge-to-black hole mass ratio. This behaviour in different regimes can potentially explain the very low $M_{\text{star}}/M_{\text{BH}} \sim 30$ observed at high redshift (e.g. Wang et al. 2013; Decarli et al. 2018), which can be reached through the first (low accretion rate) regime, in which the black hole forms faster than the stellar population (relative to the local relation), while later (in the high accretion rate regime) the implied higher star formation in the outflow can enable the galaxy to build up quickly enough stellar mass to reach the local relation.

Of course, due to the relations being non linear and the correlations not yet well established, more work is needed to properly assess exactly whether the BH-galaxy correlations and their evolution can be fully explained through star formation in outflows or not.

It is finally interesting to note that Fiore et al. (2017) and Bischetti et al. (2018) have identified a very steep relationship between outflow velocity and AGN luminosity. More specifically, the outflow velocity (combining molecular and ionized outflows) scales with AGN luminosity, i.e., black hole accretion rate, as

$$L_{\text{AGN}} \propto v_{\text{out}}^{4.6}$$

The slope of this correlation is comparable to the slope of the correlation between black hole mass and stellar velocity dispersion:

$$M_{\text{BH}} \propto \sigma^5.5$$

(e.g., Shankar et al. 2016). Therefore, if during the active outflow phases black holes are accreting close to the Eddington limit (hence $L_{\text{AGN}} \propto M_{\text{BH}}$), as expected by many outflow models (King & Pounds 2015), and stars form inside such AGN-driven outflows, then the stellar velocity dispersion of the resulting spheroidal stellar component would have a velocity dispersion consistent with that of the $M_{\text{BH}} - \sigma$ relation.

7.3 Extragalactic supernovae, CGM/IGM in-situ enrichment and halo heating

The population of stars formed in galactic outflows can result in supernovae exploding on large orbits, outside the galaxy. As discussed in the previous sections most of the stars formed in the outflow are rapidly decelerated (within a few Myr) and will quickly fall back onto the galaxy, hence a significant fraction of the associated supernovae explode close to the galaxy. However, a fraction of stars in the outflow may have larger orbits or even escape the galaxy, as expected in models (Zubovas et al. 2013b) and as observed (Maiolino et al. 2017). The resulting supernovae should appear as supernovae exploding outside galaxies.

Search for supernovae tend to be biased toward supernovae exploding inside galaxies, as monitoring and followup is typically focussed on galaxies. However, hostless or intergalactic SNe have been observed in clusters (Gal-Yam et al. 2003; Graham et al. 2015; Gupta et al. 2016).

It should be reminded that locally star formation in outflows is a relatively mild phenomenon, hence supernovae outside galaxies are not expected to be very common. However, at high-z, where this phenomenon is expected to be much more prominent, supernovae exploding in the Circum-Galactic Medium (CGM) or even in the Inter-Galactic Medium (IGM) should have been much more common. Such extragalactic SNe would have directly enriched, in situ, the CGM and IGM, relaxing the need of metals to be expelled from galaxies through winds.

An additional implication is that SNe in the halo would be expanding in a very low density environment, hence releasing most of the energy to the halo (in contrast to galactic SNe, which explode in dense environments hence losing most of their energy through radiative losses, Walch & Naab 2015). As a consequence, SNe outside the galaxy can be very effective in heating the halo, hence suppressing the accretion of cold gas onto the galaxy, resulting in a delayed (“preventive”) feedback, which may result in quenching star formation as a consequence of starvation. Therefore, while galactic outflows have a positive initial effect, resulting in new stars born in the outflow, eventually they may actually have a net negative feedback effect on the entire galaxy through halo heating and galaxy starvation.

7.4 Reionization of the Universe

As discussed above, as soon as stars form in the outflow they only respond to gravity, hence they quickly decouple from the outflow-
ing clouds (which are instead also subject to radiation pressure, ram pressure and other fluidodynamic effects). As a consequence, the massive young, hot stars formed in the outflow will have very high escape fraction of ionizing photons. Therefore, if this phenomenon is taking place in the early Universe, star formation in outflows can greatly contribute to the reionization of the Universe. Indeed, one of the main problems of current theories is that the ionizing photons escape fraction typically observed in galaxies is very low (less than 5%-10%), making it difficult for models to account for the reionization of the Universe. The large escape fraction expected for stars formed in outflows may help to tackle this long standing issue.

8 CONCLUSIONS

Several authors have proposed that massive galactic outflows may form stars inside them, with potentially far reaching implications as star formed inside outflows would have completely different kinematic properties than those formed in galactic discs. The detection of large amounts of molecular gas, dense and clumpy, in galactic outflows does indeed support the scenario that galactic outflows should form stars. However, direct evidence of star formation inside galactic outflows was so far found only in a single galaxy, leaving unclear whether this is a rare phenomenon or common to galactic outflows.

In order to address this issue, we have analysed integral field spectroscopic data of 2,800 local galaxies in the MaNGA DR2. Through a detailed spectral analysis we have identified a sample of 37 galaxies that show clear evidence for outflows and whose excitation mechanism can be investigated through the detection of multiple nebular lines, which can be used to trace the excitation of outflowing gas through the BPT diagnostic diagrams.

We have obtained the following results:

- About 30% of the outflows have BPT diagnostic diagrams consistent with being star forming, i.e. the nebular lines in the outflow are primarily excited by the UV radiation of young hot stars. Moreover, we find that half of the outflows show at least some fraction of them (>10%) being excited by star formation. These results highlight that star formation is common in a large fraction of galactic outflows.

- The analysis of the ionization parameter in the outflows, which is undistinguishable from (or even higher than) normal star forming regions, confirms that the outflowing gas is not photoionized by the UV radiation coming from the underlying galactic discs, but must be photoionized by in-situ (i.e. within the outflow) star formation.

- In these local galaxies the star formation inside the outflow generally accounts only for about 5%-30% of the total star formation in the galaxy. However, star formation inside the outflow can contribute significantly, or even dominate star formation in the central few kpc.

- We find that, for those galaxies whose outflow is dominated by star formation, the star formation rate inside the outflows correlates with the ionized outflow rate. If extrapolated to the outflow rates observed in distant massive galaxies and quasars, then the implied star formation rate inside those outflows can be up to several 100 M⊙ yr⁻¹, hence potentially contributing significantly to the evolution of galaxies. We suggest that evidence for star formation in the outflows of distant galaxies may already be present.

- We show that galaxies with star formation inside the outflow are primarily distributed along the “Main Sequence” (or, in some cases, slightly above it) and are typically isolated, regular disc galaxies.

- We discuss the possible reasons why star formation may have remained elusive until recently. We show that even if prominent star formation in the outflow, the presence of an even faint AGN generally dominates the diagnostics. This may have precluded the detection of star formation in many outflows, especially in integrated spectra or with poor spatial resolution. We also point out that outflows identified through the [OIII]5007 line may have biased the samples against those dominated by star formation. Moreover, the use of the [NII]-BPT diagnostic diagram may also have resulted in improperly classifying the nature of some outflows.

- As soon as stars form inside galactic outflows they react only to gravity, they decouple from the gaseous outflow and move ballistically. Stars formed in galactic outflows may be either escape the galaxy, or remain gravitationally bound. As our study has revealed that star formation inside galactic outflows is a relatively common phenomenon, we have discussed the implications of such widespread production of stars with kinematic properties completely different from those formed in galactic discs. Specifically:

  - Star formation inside outflows can potentially contribute significantly to the formation of the spheroidal component of galaxies (bulge, halo, and possibly also part of elliptical galaxies). Within this context stars formed inside galactic outflows can explain the population of stars on radial orbits recently discovered in our Galaxy, as well as the population of hyper-velocity stars. The same phenomenon can explain the double-shells observed in elliptical galaxies.

  - This phenomenon can contribute to establish the correlations between black holes and their host galaxies, and in particular the M_{BH} – σ and the M_{BH} – M_{spheroid} relations.

  - Stars formed in galactic outflows and escaping the galaxy would produce SNe exploding outside galaxies, hence accounting for the population of hostless SNe observed in galaxy cluster. SNe exploding on large orbits, or outside galaxies, can contribute to the in-situ enrichment of the Circum-Galactic Medium and of the Inter-Galactic Medium. Such SNe can also result in a very effective heating of the galactic halo, hence preventing cold gas accretion onto the galaxy and therefore contributing to the delayed quenching of star formation in the galaxy as a consequence of starvation.

  - Young stars formed in the outflow quickly decouple from their molecular cloud and therefore are expected to have large escape fraction of ionizing photons. As a consequence, if star formation in outflows is common to primeval galaxies, this phenomenon can contribute significantly to the reionization of the Universe.

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## Table 1.

| PID   | IFU   | RA [deg] | DEC [deg] | z   | log (M_{star}/M_{⊙}) |
|-------|-------|----------|-----------|-----|-----------------------|
| 8588  | 6101  | 248.45675| 39.26320  | 0.03176 | 10.74 |
| 7443  | 12703 | 229.52558| 42.74584  | 0.04027 | 10.82 |
| 8241  | 6102  | 126.05963| 17.33195  | 0.03725 | 10.45 |
| 8244  | 3702  | 131.81500| 51.24580  | 0.02754 | 10.01 |
| 8250  | 12704 | 138.98137| 44.33276  | 0.03978 | 10.95 |
| 8252  | 1902  | 146.09183| 47.45985  | 0.02589 | 9.35  |
| 8256  | 12704 | 166.12940| 42.62455  | 0.12610 | 11.16 |
| 8257  | 12701 | 165.49581| 45.22802  | 0.01999 | 10.38 |
| 8263  | 3701  | 184.76431| 46.10679  | 0.03856 | 10.09 |
| 8318  | 6102  | 197.23931| 45.90544  | 0.12907 | 11.34 |
| 8329  | 3701  | 213.43219| 43.66248  | 0.08934 | - |
| 8341  | 12704 | 189.21325| 45.65117  | 0.03034 | 10.62 |
| 8439  | 6102  | 142.77816| 49.07974  | 0.03393 | 10.72 |
| 8482  | 12704 | 243.58182| 50.46561  | 0.06025 | 11.39 |
| 8550  | 3704  | 248.42638| 39.18511  | 0.02984 | 10.44 |
| 8550  | 9102  | 247.20905| 39.83508  | 0.03585 | 10.67 |
| 8612  | 12704 | 254.56457| 39.39146  | 0.03431 | 10.76 |
| 8715  | 3702  | 119.92067| 50.83397  | 0.05436 | 10.33 |
| 8931  | 9101  | 193.07383| 27.08555  | 0.02098 | 10.25 |
| 8946  | 3701  | 168.95772| 46.31956  | 0.05328 | 10.67 |
| 8948  | 12704 | 167.30601| 49.51943  | 0.07242 | 11.02 |
| 8952  | 3703  | 205.44092| 27.10634  | 0.02878 | 10.33 |
| 8979  | 6102  | 241.82338| 41.40360  | 0.03463 | 10.76 |
| 9026  | 9101  | 249.31841| 44.41822  | 0.03141 | 10.82 |
| 9049  | 1901  | 247.56097| 26.20647  | 0.13145 | 11.38 |
| 10001 | 6102  | 132.65399| 57.35966  | 0.02610 | 10.67 |
| 7992  | 6104  | 255.27948| 64.67687  | 0.02713 | 10.21 |
| 8078  | 6104  | 42.739429| 0.369408  | 0.04421 | 10.05 |
| 8082  | 12701 | 48.896456| -1.01628  | 0.02680 | 10.44 |
| 8249  | 3703  | 139.72046| 45.72778  | 0.02643 | 9.79  |
| 8250  | 3703  | 139.73996| 43.50057  | 0.04005 | 9.62  |
| 8262  | 1902  | 184.55356| 44.17324  | 0.02452 | 10.29 |
| 8315  | 12705 | 235.92048| 39.54035  | 0.06347 | 10.60 |
| 8464  | 3702  | 187.0635 | 44.45313  | 0.02289 | - |
| 8550  | 12703 | 247.67443| 40.52938  | 0.02981 | 10.55 |
| 8726  | 12701 | 115.71703| 22.11273  | 0.02864 | 10.72 |
| 8931  | 12702 | 192.76494| 27.36996  | 0.02772 | 10.07 |

**Widespread star formation inside galactic outflows**

List of MaNGA galaxies whose outflow can be characterized through the BPT diagrams. The columns provide the following information: 1) Plate ID; 2) IFU ID; 3) Right Ascension; 4) Declination; 5) Stellar Mass taken from the MPA-JHU catalog (Brinchmann et al. 2004) (lack of entry means that the stellar mass is not available in the MPA-JHU catalogue). *Interacting systems.
Table 2. Properties of the star formation rates, outflow rate and BPT classification of the discs and of the outflows. The columns provide the following information: 1) Plate ID; 2) IFU ID; 3) Star Formation Rate in the disc; 4) Star Formation Rate in the outflow (only for those galaxies that are dominated by star formation in the outflow according to the [SII]-BPT diagram); 5) Ionized outflow rate determined through the broad Hα emission; 6) Ionized outflow rate determined through the broad [OIII] emission; 7–9) BPT classification of the nebular emission of the galaxy disc; 10–12) BPT classification of the nebular emission of the outflow.