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# Tales of Tails: Gas Stripping Phenomena in Galaxies with MUSE

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**The MUSE spectrograph is observing a sample of over 100 galaxies at $z$ = 0.04–0.07 in order to investigate how environmental effects can cause galaxies to lose their gas. These galaxies have a wide range of galaxy stellar masses and environments, from clusters and groups to isolated galaxies, and have been selected because they show unilateral debris or tails suggestive of gas stripping. MUSE's large field of view, sensitivity, and spatial and spectral resolution allow us to study the physics of the stars and ionised gas in each galaxy in great detail, including the outskirts and extraplanar tails or debris out to 50–100 kpc away from each galaxy: a distance of more than ten times the galaxy's effective radius. We present the ongoing programme, GAs Stripping Phenomena in galaxies (GASP), and report on the first set of results.**

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## Gas removal and galaxy evolution

A central question in galaxy formation and evolution is how gas flows in and out of galaxies. In the current hierarchical paradigm, the hot gas in dark matter halos cools and settles in the galactic disc, replenishing the cold gas reservoir necessary to form new stars. Any process that prevents the gas from cooling efficiently, or that removes gas from either the halo or the disc, has fundamental consequences for galaxy evolution. It is therefore of paramount importance to directly observe gas outflow and infall processes at work. Integral field spectrographs such as the Multi Unit Spectroscopic Explorer (MUSE) on the Very Large Telescope (VLT) can use both optical emission lines and light from stars to probe gas that is ionised by star formation, an active galactic nucleus (AGN), or shocks. Such observations can yield clues into stellar kinematics and star formation history.

Ram pressure stripping is believed to be an efficient mechanism to remove gas from a galaxy, affecting only the interstellar gas and not the stars. When a galaxy moves through a hot, dense intergalactic medium, the latter exerts pressure on the gas of the galaxy and can remove it from the disc and halo. The efficiency of this mechanism depends on the density of the intergalactic medium and the relative galaxy velocity. Ram pressure stripping therefore acts most strongly in galaxy clusters, but it has also been observed in galaxy groups and even pairs.

## The GASP project

GASP (GAs Stripping Phenomena in galaxies with MUSE) is an ongoing ESO Large Programme studying gas removal processes in galaxies[1]. GASP is observing 114 galaxies at $z$ = 0.04–0.07 in clusters, groups and the field, targeting 94 galaxies with optical signatures of unilateral debris or tails reminiscent of gas stripping processes, as well as a control sample of 20 disc galaxies with no morphological anomalies. The survey characteristics and strategy were presented in Poggianti et al. (2017a). The most important characteristic of the survey is its large coverage in area. At $z$ = 0.04–0.07 the MUSE field of view covers 50–80 kpc and so it is possible to study extraplanar gas and stars out to large distances from the galactic disc using only one or two MUSE pointings.

The main goal of GASP is to study gas stripping in different environmental conditions in order to understand how, why and when gas is removed. We want to investigate the fraction of galaxies, the masses of the galaxies and their host halos, as well as the orbits, velocities and halo-centric distances for which gas-only removal processes are relevant.

The link between gas and star formation is another fundamental focus of the GASP programme. Overall, the star formation activity in galaxies has strongly declined since $z$ ~ 2 owing to the combination of two effects: a large number of star-forming galaxies have evolved into passive galaxies where star formation has ceased, and the average rate of star formation has decreased in galaxies that are still producing stars. To understand the decline in star formation and the impact of gas removal processes on this galaxy quenching, it is crucial to study how gas stripping affects the stellar history in the GASP galaxies. The MUSE data reveal whether the star formation activity is globally enhanced or suppressed during the stripping, as well as how the quenching of star formation proceeds within each galaxy and over what timescales.

## Tales of tails

MUSE observations began in 2015 (ESO Period 96) with a sample of cluster galaxies. From these data we obtained a wide range of diagnostics including: spatially resolved morphologies and kinematics of gas and stars, gas metallicity and ionisation parameters, gas densities and masses, dust extinction, star formation densities, stellar mass densities,

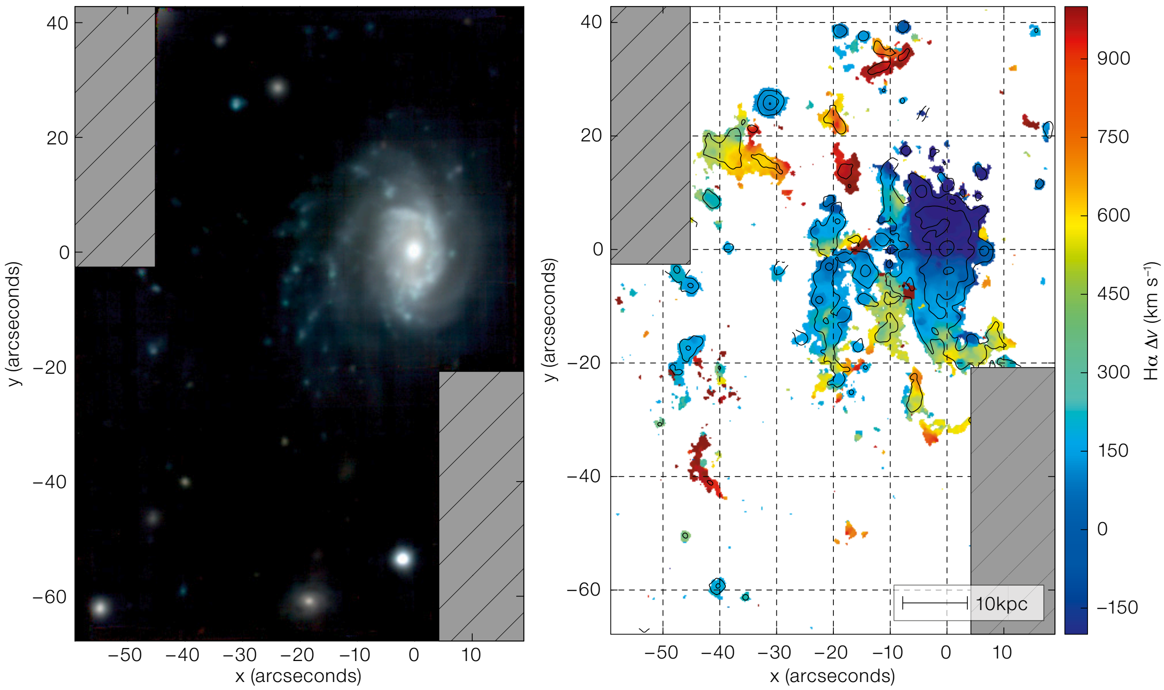



Figure 1. The GASP galaxy JO201, one of the most spectacular cases of ram pressure stripping, was studied using two MUSE pointings. It is crossing the massive cluster A85 at supersonic speed, moving towards the observer along the line of sight, and has lost 50 % of its total gas mass so far. Left: RGB (5000–6000 Å; 6000–7000 Å; 7000–8000 Å) MUSE image. Right: Hα velocity map, showing the complex velocity structure of the gas, which includes rotation in the disc, and a high velocity (> 200 km $s^{-1}$) component that corresponds to stripped gas dragging behind the galaxy (Bellhouse et al., 2017).

ionisation mechanisms, luminosity-weighted stellar ages, and star formation history. These quantities trace each galaxy's history in detail and can reveal the mechanisms that drive gas removal.

By design, the evidence for gas stripping in the GASP targets varies significantly. Some targets have long tails that are visible even in broadband optical images, while others contain only subtle indications of initial or mild stripping (see Poggianti et al., 2016 for the classification). Some of the most striking examples of ram pressure stripping in action have been presented in dedicated individual publications (Poggianti et al., 2017a; Bellhouse et al., 2017; Fritz et al., 2017; Gullieuszik et al., 2017; Moretti et al., 2017).

## Common features in the GASP galaxies

The tails are much more prominent in Hα emission than in the optical and can extend out to over 100 kpc from the galactic disc (see p. 28, Figures 1 and 3). The stripped gas is ionised through stellar photoionisation due to ongoing star formation within the stripped gas. The gas tails are characterised both by regions of diffuse Hα emission and kinematically cold knots that are bright in Hα; these cold knots are identified as giant H II regions and complexes. A significant fraction of the total star formation related to each system takes place outside of the disc.

The morphology and kinematics of the gas are consistent with ram pressure stripping, and we can estimate the fraction of gas lost before the epoch of observation by considering both the extent of Hα within the disc and the increasing ram pressure as the galaxy infalls into the cluster. A comparison of gas and stellar kinematics shows that the latter is totally undisturbed, which was expected as ram pressure only affects the gas. The gas retains the velocity of the stars at the location of the disc from which it was stripped and continues to rotate coherently with the galaxy until several kiloparsecs away from the main galaxy body.

The stripping proceeds from the outside in, with the outermost regions of the disc stripped first (Figures 2 and 3). Clear post-starburst signatures are left in the regions of the disc that have recently been stripped, while strong star formation continues within the remaining gas and especially where the gas is compressed. From the MUSE data we can reconstruct the history of star formation in broad, logarithmically-spaced age bins, and observe where stars formed in each epoch at each location (Figure 3).

While it is commonly believed that ram pressure stripping is efficient only in low-mass galaxies and in the most massive clusters, we find extreme ram pressure stripping even in massive galaxies ($10^{11}$ $M_{\odot}$) and in relatively low-mass clusters (with velocity dispersions of 500–600 km $s^{-1}$). The galaxies possessing the longest tails are at their first infall into the cluster and they are located at low projected cluster-centric radii and high velocities relative to the cluster redshift: the optimal conditions for ram pressure stripping. Our results are in agreement both with the standard analytic scenario of ram pressure stripping (Gunn & Gott, 1972), and detailed hydrodynamic simulations of galaxies falling into clusters, which show long tails of stripped material with the correct conditions for star formation (Tonnesen & Bryan, 2012). These findings are consistent with a fast-acting mechanism that significantly alters the gas content of galaxies on their first passage through the dense intergalactic medium (Jaffé et al., 2017).

## Ram pressure and AGN

The mechanism responsible for the gas ionisation at any point in each galaxy can be assessed from spatially-resolved diagnostic diagrams of emission line

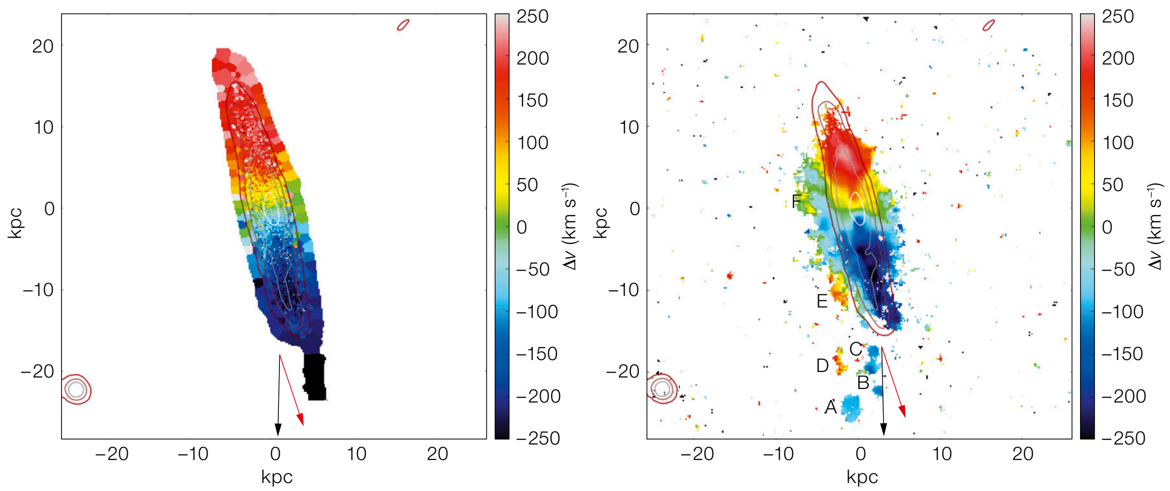



Figure 2. The GASP sample comprises a number of galaxies with truncated Hα discs. The gas stripping proceeds from the outside in, and the gas has already been removed from the outer disc regions in these objects. JO36 is an example of this (Fritz et al., 2017) and its stellar velocity map (left) is more extended than the map of the Hα-emitting gas (right). JO36 experienced a burst of star formation between 20 and 500 Myr ago in the outer regions of the disc, which are now devoid of gas and passively evolving. The inner disc is still gas-rich and forming stars, and X-ray data indicate the presence of a deeply obscured AGN that is hidden at optical wavelengths.

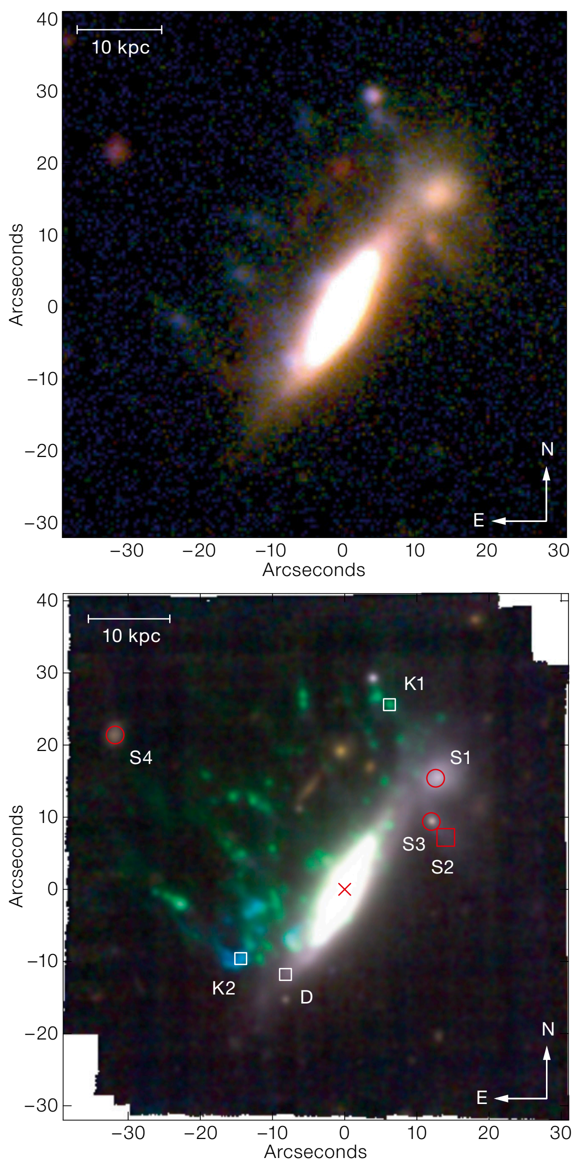
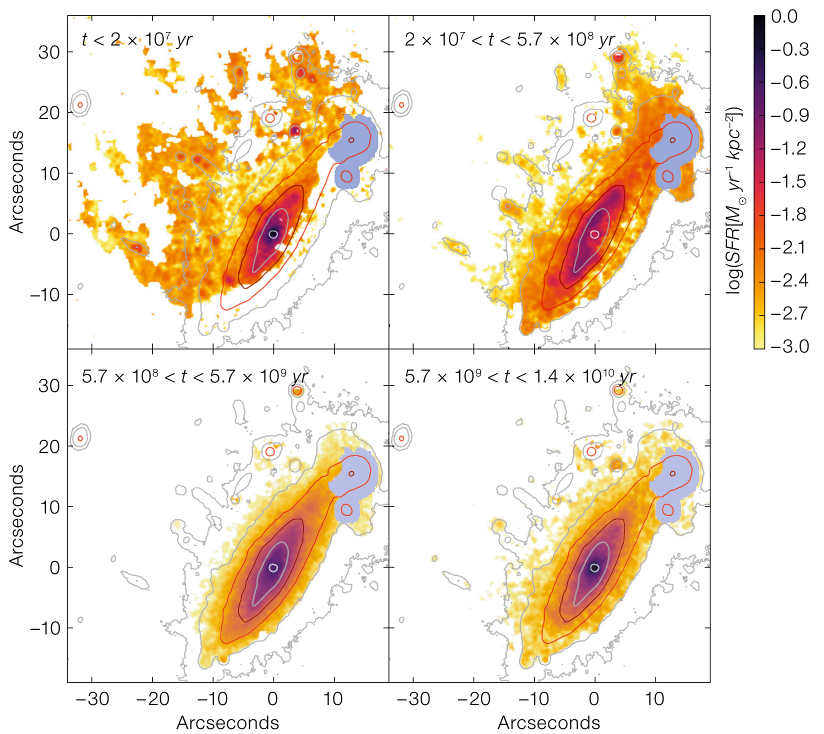



Figure 3. JO204 is seen almost edge-on while falling into a cluster approximately along the plane of the sky. Left: RGB and [O III], Hα and continuum images of J0204. The RGB (*uBV*) image in the top left shows faint traces of tails to the left of the disc, while in the bottom left panel a composite [O III] 5007 Å (blue), Hα (green) and 7100–7200 Å continuum (red) image displays the striking tails of ionised gas (Gullieuszik et al., 2017). Below: This set of four figures shows the star formation rate in four age bins at each spatial location. Star formation was confined to the stellar disc until less than 600 Myr ago (two bottom panels), then the first extraplanar stars were formed in the stripped gas between 20 and 600 Myr ago while new stars were also forming everywhere in the disc (top right). At the time of the observations, ongoing star formation (< 20 Myr) is taking place throughout the tails and in the central part of the disc (top left).



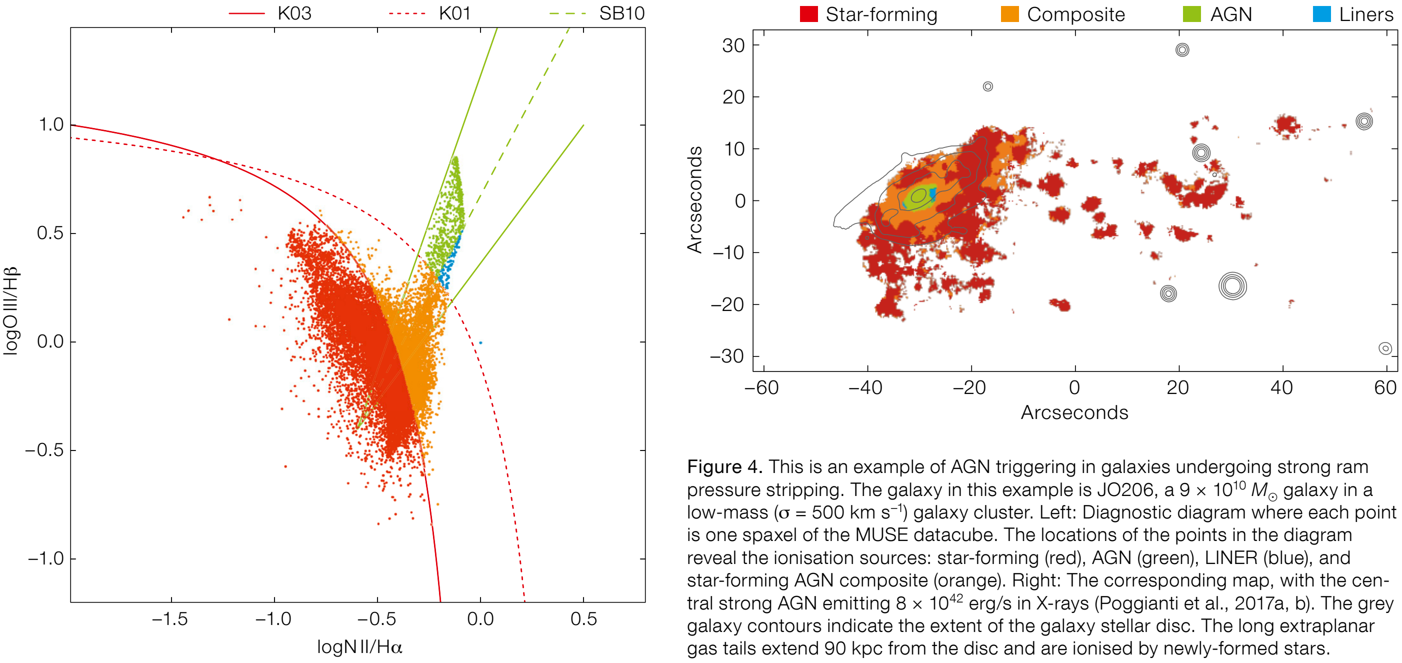



Figure 4. This is an example of AGN triggering in galaxies undergoing strong ram pressure stripping. The galaxy in this example is JO206, a 9 × $10^{10}$ $M_{\odot}$ galaxy in a low-mass (σ = 500 km $s^{-1}$) galaxy cluster. Left: Diagnostic diagram where each point is one spaxel of the MUSE datacube. The locations of the points in the diagram reveal the ionisation sources: star-forming (red), AGN (green), LINER (blue), and star-forming AGN composite (orange). Right: The corresponding map, with the central strong AGN emitting 8 × $10^{42}$ erg/s in X-rays (Poggianti et al., 2017a, b). The grey galaxy contours indicate the extent of the galaxy stellar disc. The long extraplanar gas tails extend 90 kpc from the disc and are ionised by newly-formed stars.

ratios as measured from MUSE spectra (Figure 4). As GASP data began to pour in, one of the first unexpected results was the high incidence of AGN in the galaxies undergoing the strongest stripping: six out of seven galaxies with the most spectacular tails host a central AGN. Five of these display typical Seyfert 2 emission line ratios and one is a low-ionisation nuclear emission-line region (LINER) powered by a low-luminosity AGN, which was confirmed by data from the Chandra X-ray Observatory. Although the sample is still too small to draw definitive statistical conclusions, this fraction is surprisingly high compared to the low occurrence of AGN activity among emission line galaxies in clusters (3 %) and the general field (8 %) at similar redshifts.

This "AGN excess" may result from ram pressure causing gas to flow towards the galaxy centre, or from an enhancement in the stripping strength due to energy injection from the AGN, or both. The proximity of the sample galaxies to the cluster core and their high relative speeds strongly support the hypothesis that ram pressure triggers AGN activity and not *vice versa*. How this occurs is still unknown, as simulations of ram pressure in the presence of an AGN do not yet exist. However, hydrodynamic simulations have shown that when gas in a galaxy disc interacts with a non-rotating intracluster medium, it loses angular momen-

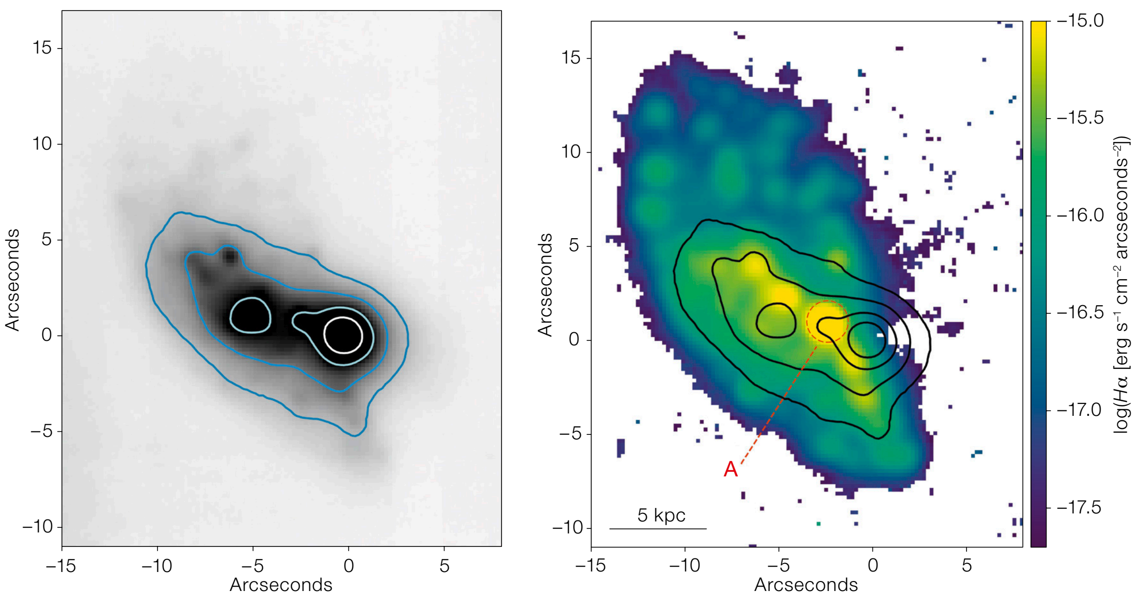



Figure 5. P96949 is the only merger found in the GASP sample so far. A late-type galaxy is merging with an early-type galaxy of similar mass (~ $10^{10}$ $M_{\odot}$), inducing high levels of star formation activity and the formation of a tidal dwarf galaxy in the compression zone between the two galactic nuclei. In the MUSE white-light image (left), the two galaxy centres are visible as the two peaks in the stellar light contours. The Hα intensity map (right) shows the regions of enhanced star formation. The forming dwarf galaxy is enclosed by the red dotted circle (Vulcani et al., 2017b).

tum and can therefore spiral into the galaxy's central region. Oblique shocks in a flared galaxy disc might also play a role.

These results put forward ram pressure as a possible, albeit as yet unknown, mechanism for feeding the central supermassive black hole of an AGN with gas (Poggianti et al., 2017b; ESO Release eso1725[2]). A complete census of AGN activity among galaxies in different stages of gas stripping, from initial stripping to peak and post stripping, must await the completion of the survey.

## Ongoing work, data release and prospects

At the time of writing, three quarters of the GASP data have been taken. The first ESO GASP data release was published on 26 October 2017 and is accessible from the ESO archive[3]. As observations approach completion, we will finish the statistical analysis of the GASP sample and begin to address more general questions including:

- What is the amount of stars contributed by the stripping to the intracluster light and what are their metallicities?
- What is the amount and metallicity of the stripped gas?
- What are the characteristics of the star formation activity happening outside galaxy discs?
- What are the common features in gas stripping phenomena, when do the long tails form and how long do they last?
- And finally, how many galaxies undergo gas stripping depending on environment, and by what mechanism?

While observations of our group and field sample are still ongoing, our preliminary analysis shows that various phenomena can give rise to optical morphologies resembling gas stripping. Among the galaxies analysed so far there are good candidates of stripping in groups, low-mass clusters and even filaments (Vulcani et al., in preparation). There is also an interesting case of likely gas accretion — instead of removal — onto an isolated galaxy (Vulcani et al., 2017a), and the only case so far of a merger in GASP (Vulcani et al., 2017b, Figure 5).

Multi-wavelength follow-up studies of GASP include: the Atacama Pathfinder EXperiment, APEX CO(2-1) observations (completed, Moretti et al., in preparation); Atacama Large Millimeter/submillimeter Array (ALMA) CO(2-1) and CO(1-0) observations, approved for ALMA Cycle 5; JVLA C-array H I imaging (completed); and ongoing far-ultraviolet and near-ultraviolet imaging using the Ultraviolet Imaging Telescope (UVIT) on Astrosat (George et al., in preparation). The combination of MUSE and ancillary data will provide a panoramic view of the stellar content and the ionised, neutral and molecular gas.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## Links

1 The GASP website: http://web.oapd.inaf.it/gasp/index.html
2 ESO Press Release: https://www.eso.org/public/news/eso1725/
3 GASP's first data release: http://www.eso.org/sci/publications/announcements/sciann17080.html

ESO/GASP collaboration

MUSE observations of the galaxy JO206 from the GASP programme. Red shows the glow from ionised hydrogen and white shows where most of the stars are located.