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APPLICATION FOR OBSERVING TIME

110.244E

IMPORTANT NOTICE

MAUVE: Tracking the influence of the environment on the gas-star formation cycle of cluster galaxies during infall

ABSTRACT

We propose MAUVE (MUSE and ALMA Unveiling the Virgo Environment), a large MUSE program designed to shed light on the obscure evolution of the inner discs of cluster galaxies, which typically still host significant cold gas reservoirs after their first pericentre passage, and reveal how star formation ceases in these systems. We will map the full extent of the molecular gas disc (as traced by ALMA observations already at hand) of 40 late-type Virgo cluster galaxies at various infall stages using MUSE. These data will provide stellar and ionised gas kinematics and distributions, star-formation rates, and metal enrichment maps at ~100-200 pc scale, allowing us to investigate the link between cold gas and star formation when and where environmental processes are at play, and as a function of infall time. We will reconstruct detailed star-formation histories for a representative sample of cluster galaxies for the first time, assess the role and impact of outflows, and deliver a rich multi-wavelength data set with a huge legacy value for environmental studies, which no other sample currently available can provide.

SCIENTIFIC KEYWORDS

galaxies: ISM, galaxies: clusters, ISM: abundances, galaxies: star formation, galaxies: kinematics and dynamics

RUNS

Run	Period	Instrument	Tel. Setup	Constraints	Mode	Type	Propr. Time	Time Constr.	Req. Time
110.244E.001 • Run 1	110	MUSE	UT4	FLI: 40% • Turb.: 85% • pwv: 30.0mm • Sky: Clear	SM	Normal	12m	×	40h09m
110.244E.002 • Run 2	111	MUSE	UT4	FLI: 40% • Turb.: 85% • pwv: 30.0mm • Sky: Clear	SM	Normal	12m	×	43h48m
110.244E.003 • Run 3	112	MUSE	UT4	FLI: 40% • Turb.: 85% • pwv: 30.0mm • Sky: Clear	SM	Normal	12m	×	43h48m
110.244E.004 • Run 4	113	MUSE	UT4	FLI: 40% • Turb.: 85% • pwv: 30.0mm • Sky: Clear	SM	Normal	12m	×	45h01m

AWARDED AND FUTURE TIME REQUESTS

Time already awarded to this project

- none -

Future time requests to complete this project

- none -

Special Remarks

N/A

DESCRIPTION OF THE PROPOSED PROGRAMME

A- Scientific Rationale

Despite much progress in the past decades, understanding environmental effects on galaxy evolution remains challenging, even in the high-density regimes of nearby galaxy clusters [7]. The combination of large statistical studies and detailed analyses of the interstellar medium (ISM) of cluster galaxies has clarified some of the main trends, such as the outside-in removal of the cold ISM and subsequent reduction of star formation (SF) activity in satellite galaxies. However, many key questions remain unanswered – most importantly, *how and when does SF cease in these systems* [7]? As argued below, this is because we still lack a multi-wavelength sample (1) probing the multi-phase ISM and stellar populations in the inner discs of cluster galaxies at sub-kpc scales, to gain insights into the effects of environmental processes where the cold gas has not been fully stripped *and* (2) simultaneously tracing galaxies at different stages of infall (from early-infaller to post-pericentre passage). Sub-kpc resolution is critical to bridge molecular cloud scales (where scaling relations are known to break down) and global ones (where galaxy-to-galaxy variations dominate the scatter). This proposed MUSE program will deliver such a sample by mapping the full extent of the molecular hydrogen (H_2) gas disc (as traced by ALMA/VERTICO maps [5]) of 40 late-type Virgo cluster galaxies across all stages of infall.

Life in the inner regions of satellite galaxies. During their plunge into a cluster, satellite galaxies suffer environmental effects to different degrees, depending on their masses, orbits, time since first infall, etc. As galaxies approach their first pericentre passage the outer regions of their ISM (mostly atomic hydrogen, HI) are stripped first, but even in the most extreme environments satellites do not usually end up devoid of their cold gas reservoirs. Since the ISM left in the inner parts of galactic discs could potentially feed SF for billions of years, it is still unclear (a) how and when the SF in these systems will fully quench; and (b) whether the key steps of the gas-SF cycle (e.g., SF rate/efficiency, metal distribution, outflows, etc.) in the inner region are affected at all. Until recently, it was commonly assumed that the cold gas disc left after first pericentre passage is unaffected by the environment. Indeed, this is the assumption at the core of estimates of SF quenching timescales beyond the 'truncation radius' (i.e., the radius beyond which the ISM was fully stripped) [2,8]. However, it is now clear that this is an oversimplification.

SF activity in the inner disc. The last few years have seen mounting observational evidence that environment affects the cold gas of galaxies even within their truncation radius. In particular, resolved studies of the ISM of cluster galaxies are providing evidence for systematic variations of both HI and H_2 surface densities within the truncation radius of satellites compared to isolated systems (at fixed stellar surface density $\Sigma_\star$), as shown in Fig. 1. The causes for these changes are still debated and might include: (a) stripping carving its way into the inner parts of the disc and removing both phases of the ISM, reducing SF [1]; (b) lack of HI inhibiting the formation of H_2 and SF [10]; (c) a more efficient HI-to-H_2 conversion and an enhancement of SF [13], and (d) variations in the efficiency with which H_2 is converted into stars [14]. As it can be seen, some of the proposed scenarios contradict one another, highlighting how current datasets (providing either global information or coarse spatial resolution) are not able to discriminate between them.

To progress, we need to link the cold ISM to the SF and stellar properties at a spatial and temporal scale where the environment is acting on the galaxy, and as a function of infall time. This task requires, in addition to sub-kpc scale H_2 observations of a representative sample of cluster galaxies at different infall stages, detailed information across the entire ISM disc on: (a) a current SF rate (SFR) indicator, sensitive to short-scale variations ($\sim$10 Myr) such as $\mathrm{H}\alpha$; (b) accurate dust corrections; (c) means to separate $\mathrm{H}\alpha$ emission caused by SF from shock-heated gas; (d) longer-term (0.1 to a few Gyr) SF history (SFH) indicators to connect the current SFR to the past activity. Clearly, while narrow-band surveys like VESTIGE [3] provide us with exquisite $H\alpha + [NII]$ maps, they do not meet all these requirements (i.e., b to d) and thus are no substitute for optical integral field spectroscopy (IFS).

Metal enrichment of the ISM. Hints that environment might affect the inner regions of cluster satellites also emerge from studies of the oxygen abundance of their ISM. Evidence for an increased global oxygen abundance in satellite galaxies dates back to the mid 1990s [21], and used to be attributed to the stripping of metal-poor gas from the outer parts of the disc. However, recent observational and theoretical works prompted several other scenarios, such as stopping the infall of pristine gas from the halo onto the galaxy, preventing radial flows of low-metallicity gas through the disc, reducing outflows of metal-enriched gas out of the disc (e.g. due to the external pressure of the intracluster medium), or accretion of preferentially metal-enriched gas [11,15,16]. Admittedly, these remain mostly speculations as current data sets have limited constraining power. For instance, identifying and characterising gas flows within the disc, extra-planar motions and regions where gas stripping is still at play requires the ability to resolve the metal content of the ISM at the scale of giant HII regions ($\sim$100-200 pc), something never achieved so far for representative samples of cluster galaxies. At the same time, establishing whether differences in gas-phase oxygen abundances are due to environmental effects or variations in the recent SFH (and thus metal enrichment) of galaxies requires that we compare stellar- and gas-phase metallicities [9] at the same spatial scales.

The last stages of quenching. How is the cold gas left in the inner discs consumed after first pericentre passage? To what extent do environmental and internal processes help stopping SF? Outflows due to SF or active galactic nuclei (AGN) have been observed in individual galaxies [3,17] and might be the culprit, but do they provide a common path to quenching for all satellites? Crucially, in addition to small number statistics, we have not been able to identify the outflows kinematically, and characterise their properties and effect on the gas-SF cycle. Moreover, environmental effects do not stop after the first pericentre passage. As hydro-dynamical stripping mechanisms become less efficient after that point, longer time-scale processes such as gravitational interactions become more important and might inhibit SF. For instance, the increase of thickness of the inner disc shown by numerical simulations [22] could stabilise the gas disc against SF (due to increased velocity dispersion), or redistribute the gas in the disc making it easier to strip. It is clear that a detailed reconstruction of the kinematic state of gas and stars and of the incidence and strengths of outflows for galaxies at different stages of infall is needed to address this.

This proposal. Quantifying the impact of the cluster environment on the gas-SF cycle of galaxies demands to simultaneously tracing multiple properties (namely H_2 content, current SFR, SFH, gas ionisation state, gas and stellar kinematics) at sub-kpc scale across the entire H_2 disc for a statistical sample of galaxies at different infall stages – i.e., early infallers, near pericentre and after first pericentre. The requirements of different infall stages and spatial resolution are driven by the need to simultaneously (a) reconstruct an infall time sequence of the effects of the cluster environment; and (b) 'resolve' local variations in stellar/ISM properties over the shortest timescales ($\sim$10 Myr) in which environment is expected to act on. Given Virgo's proximity (17 Mpc distance), a spatial resolution of <200 pc can be reached even in not ideal seeing conditions (i.e., $\sim$1.3 arcsec). Moreover, Virgo is the best studied galaxy cluster, providing an unparalled suite of state-of-the-art multi-wavelength data to be combined with these MUSE observations.

To reach these goals we designed MAUVE (**M**USE and **A**LMA **U**nveiling the **V**irgo **E**nvironment), a MUSE proposal targeting a representative sample of late-type (Sa to Sd) Virgo galaxies at different stages of environmental perturbation. Our targets are extracted from the ALMA/VERTICO survey [5] that, together with VLA/VIVA data [6], provides an unprecedented view of the H_2 and HI properties of galaxies in the cluster environment. We restrict our sample to galaxies with stellar mass $M_* > 10^{9.3}$ $M_\odot$, with H_2 left in their discs, and for which it has been possible to determine the infall stage via accurate orbital reconstruction and analysis of their gas disc morphologies [23,26] (N=40 galaxies). This sample allows us to probe the full environmental time sequence (which also nicely corresponds to different stages in HI gas stripping, as shown in Fig. 3), from first infallers where only the outer disc is affected (N=10), to galaxies close to pericentre (N=13), to those that have already passed first pericentre passage (N=17). MUSE archival data are already available for 3 of these galaxies, thus this proposal is focused on the remaining 37, for which we plan to cover the entire extent of the H_2 disc (see Fig. 5; on average $\sim$4 MUSE pointings per target). We further motivate our selection and strategy below.

MAUVE vs other MUSE cluster programs. Current/past MUSE programs targeting nearby cluster galaxies (GASP and FORNAX 3D) cannot address our goals (see Fig. 2). GASP [18] focuses on galaxies above the locus of the star-forming main sequence and in the early stages of infall [24] and lacks sub-kpc H_2 observations for a statistically significant sample of galaxies (very challenging to obtain at distances of $\sim$170-300 Mpc, i.e., 10-20 times more distant than Virgo, see Fig. 2). Orbital reconstructions for GASP galaxies are also significantly more uncertain than for Virgo. FORNAX 3D [20] targets galaxies at similar distances as Virgo, but includes mostly early-type systems (whereas to follow various stages of infall it is paramount to focus on late-type discs), with only a handful of late-type galaxies in the stellar mass range of interest with ALMA data [27], most of which are very gas poor (see Fig. 2). Fornax also probes lower halo masses than Virgo, lacks a reconstruction of the infalling histories at the same level of detail as done for Virgo, and lags behind in terms of multi-wavelength coverage.

Why map the entire disc? In most instances, MUSE mapping of nearby galaxies has focused on only one side of their discs [20], as undisturbed systems should be, to first order, symmetric. This is certainly not the case for environmental effects, which can be very localised (e.g., compression, stripping, outflows, radial motions) and for which it is impossible to predict which side of the disc will be affected the most.

Sample size. To maximise its scientific impact, MAUVE focuses on an optimised sub-sample of ALMA/VERTICO galaxies (40 vs. 51), covering the key stellar mass range and stages of infall. While a large number of early-infallers is not required, the increasing diversity of physical processes potentially at play as time spent within the cluster increases demands larger statistics for pre-pericentre and post-pericentre galaxies. A major reduction (>20%) in sample size would make MAUVE no longer representative of the entire Virgo infall sequence (Fig. 3).

B- Immediate Objective

We propose MAUVE, a large MUSE program designed to characterise environmental effects on the stellar and ISM components of cluster galaxies by mapping their entire H_2 discs (where the gas has not been fully stripped). The primary aim is to answer the following four key questions, for which the combination of gas emission line and stellar continuum diagnostics is critical.

Where, how and for how long does SF proceed in the inner gas disc of cluster galaxies? We will measure emission line ratios to correct and trace the effect of dust, establish where SF is still active, whether its efficiency was hampered or boosted, and where the gas is ionised by other processes (e.g., shock-heated). We note that current datasets based on the combination of ultraviolet and infrared tracers are not only sensitive to longer time-scales ($\sim$100 Myr, hence less suited than Hα for tracing fast processes such as stripping), but also limited in resolution and prone to contamination by old stellar populations or other physical processes. Previous work has shown that gas at the edges of the truncation radius is shock-heated [4]. Since we detect H_2 in these regions, we expect that SF efficiency - or gas depletion time - is affected (as hinted by integrated studies, see Fig. 2), and the proposed MUSE observations will allow us to quantify this at a scale of 700 pc set by the ALMA/VERTICO data (i.e., well within the requirements of this proposal), and reveal its causes. We will also obtain, for the first time, a time sequence of how the cold gas-SF cycle is affected during the various infall stages.

While Hα traces SFR in the last 10 Myr, stellar continuum provides critical information on the recent past of galaxies, specifically their last few Gyr. We will use spectral fitting to reconstruct the recent SFH of cluster satellites (see Fig. 3). We will build and improve upon the approach of [8] that, surprisingly after $\sim$15 years, remains the best study of resolved stellar populations in infalling cluster galaxies. One of the most exciting aspects of our approach is that, by combining emission and absorption-based techniques for galaxies at different infall stages, we will be able to look for evidence of a coherent time sequence of environmental effects on the SFH of satellites at scales of 500 pc or less. For example, if pre-pericentre galaxies show consistent signs of major localised bursts of SFR via Hα emission, we should see the same feature encoded in the stellar populations of galaxies that have already gone through their first pericentre passage. We will thus construct the largest collection ever of spatially-resolved SFHs for cluster galaxies and connect our different classes through a time sequence of environmental effects.

How is the metal content of the ISM affected by the environment? We will map the metal enrichment of cluster galaxies with unprecedented detail and move beyond traditional, azimuthally-averaged metallicity gradients. We will look for $\sim$100-200 pc scale variations of gas-phase metallicity *across the disc*, which is critical to establish the causes for the increased oxygen abundance observed in cluster galaxies – i.e., stripping of metal-poor gas, or an increase in the amount of metals stored by the ISM (due to either less efficient outflows or accretion of metal-rich gas). For example, the ability to identify regions where stripping has been efficient (thanks to our H I and H_2 maps) would allow us to test the stripping hypothesis. At the same time, the comparison between gas-phase and stellar metallicities, Z_{gas} and $Z_\star$, will determine whether their ratio is consistent with the recent observed SFH. A local enhancement of $Z_{gas}/Z_\star$ ratio would signal the impact of the environment on the metal cycle within the disc, allowing us to reconstruct a time evolution for the variations of Z_{gas} during infall. This analysis will be combined with a search for outflows and signs of metal redistribution due to environmental effects, as discussed below.

Do outflows contribute to shutting off SF in the inner disc? We will quantify the incidence of SF- and AGN-driven outflows in our sample by mapping the entire gas discs. We will identify their ionised component and compare their properties (e.g., velocity, gas density and geometry) to estimate their effect on the metal and gas content, as well as SFR of galaxies at different stages of infall. It will also be possible to study the interaction between the outflowing gas and the cluster medium. Intriguingly, two galaxies in our sample with MUSE data already available show evidence for massive ionised gas outflows playing a role in their recent evolution ([4], see also Fig. 4, private communication). But it remains unclear how common these systems are and, if they are not isolated cases, at which stage of the infall outflows start developing. At the same time, these observations will show whether stripping simultaneously enhances AGN activity [17].

Does environment affect the kinematic structure of the inner disc? MAUVE will provide the strongest constraints on the effect of environment on the stellar structure of galaxies during their first orbit through the cluster. While stellar kinematics (velocity, velocity dispersion and higher-order moment maps) will be key to identify variations in stellar orbits, high spatial resolution kinematics of the ionised gas will be critical to localise regions where environmental effects are stronger, and catch them at their inception. Notably, it would take at least one or two orbital times before such effects would be visible on the kpc or global scales traced by IFS surveys such as SAMI/MaNGA. As such, we are in a unique position to unveil whether gas stripping can (alone) transform a disc into an S0 galaxy by both quenching SF and dynamically heating the disc.

The answers to the four questions described above will provide much needed constraints to state-of-the-art simulations, which still struggle at reproducing the detailed effect of environment on the ISM (see [7] for a review). Particularly exciting is the prospect to constrain: (a) feedback effects; (b) the incidence of localised environmentally-triggered burst of SF and (c) changes in stellar kinematics. This will be achieved by taking advantage of both cosmological hydro-dynamical simulations (e.g., IllustrisTNG, COLIBRE) and idealised (but higher resolution) runs focused on tracing specific environmental effects [25].

Lastly, MAUVE will be the largest sample of cluster galaxies with MUSE data at sub-kpc resolution and will have a huge legacy value. MAUVE will enable a number of other projects, such as: a quantification of the effect of stripping on the diffuse ionised component of discs; detailed reconstructions of stellar orbits using Schwarzschild modelling; and the highest resolution study of the effect of stripping on stellar and gas dust attenuation.

Figures

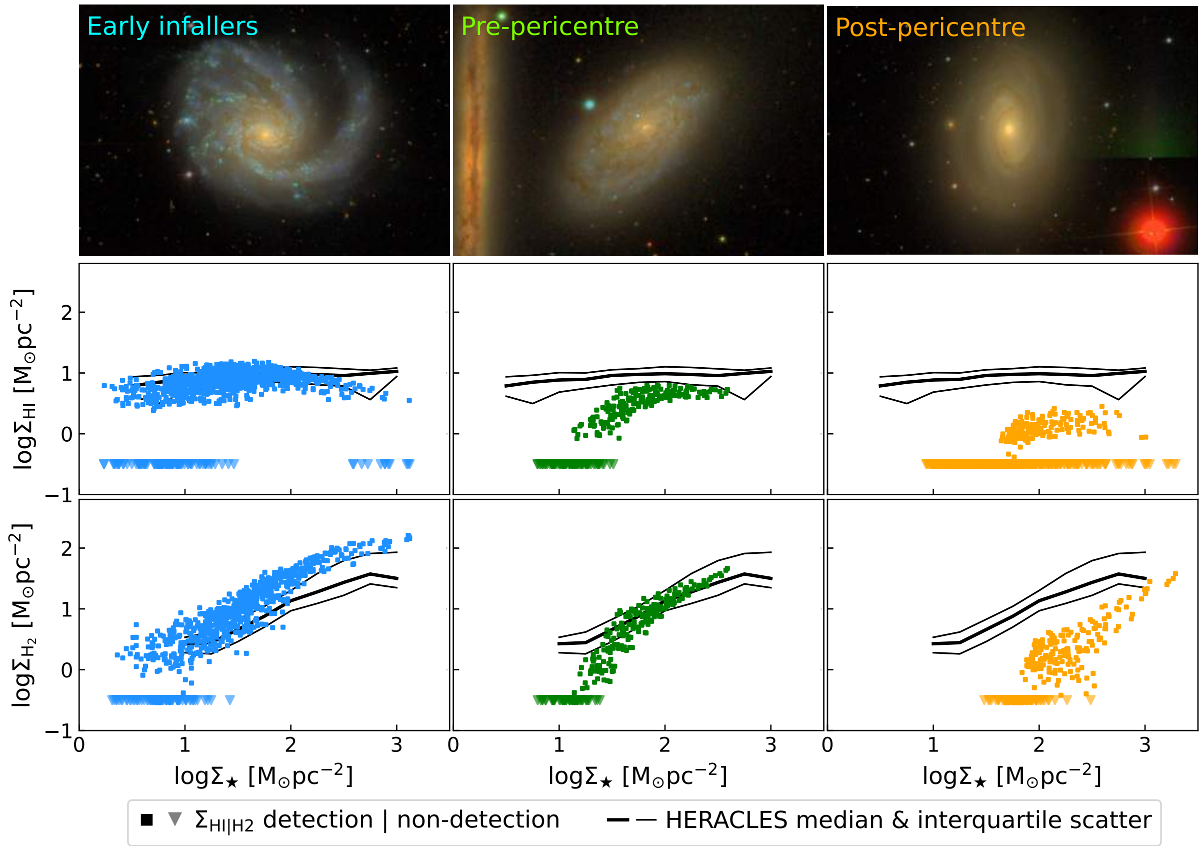

Figure 1 -The effect of the cluster environment on the inner disc. Stellar mass surface density (Σ_*) vs. HI (middle row) and H_2 (bottom) surface densities for 3 Virgo galaxies (part of MAUVE) at different stages of infall, as noted on the SDSS images (top). Symbols are defined below the figure; individual points are spaxels at ~650 pc spatial scale, and black lines show median trends for isolated star-forming galaxies from HERACLES [12], matched by mass and inclination. These high-quality ISM data demonstrate that departures of gas surface density from the control sample at fixed Σ_* are present well within the highest Σ_* regions where the gas has not been stripped.

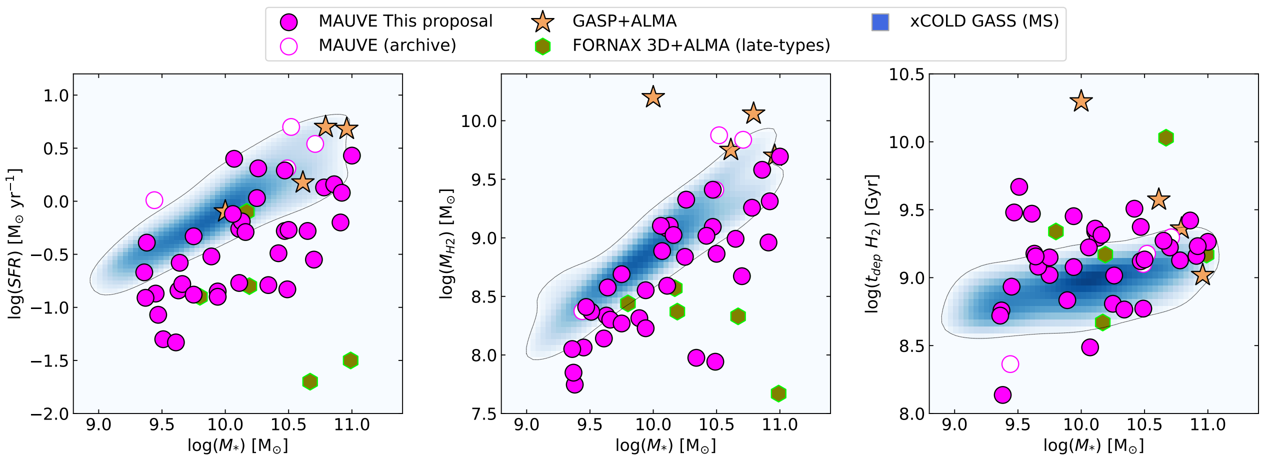

Figure 2 -MAUVE vs. other MUSE cluster samples. Stellar mass vs. SFR (left), H_2 mass (centre) and depletion time ($\mathrm{M_{H2}/SFR}$, right) for MAUVE galaxies (circles), compared to GASP galaxies (stars, [13]) and FORNAX 3D late-types (hexagons, [27]) with ALMA data. For reference, the SF main sequence from xCOLD GASS [19] is shown as a shaded blue region. MAUVE will significantly improve upon what is currently available in the MUSE and ALMA archives and explain the causes for the large spread of depletion times compared to local central galaxies (here represented by xCOLD GASS).

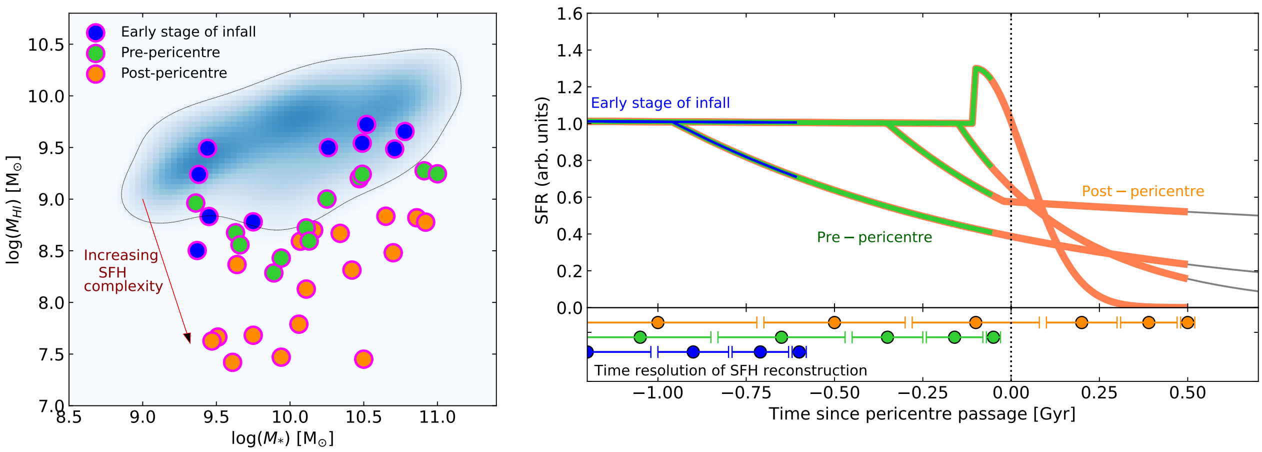

Figure 3 -Tracing the entire infall sequence. *Left:* M_* vs. HI mass relation for MAUVE galaxies color-coded by stage of infall: early-infallers (blue), $\lesssim$500 Myr before first pericentre (green) and after pericentre (orange). The blue shaded region shows local star-forming galaxies from xCOLD GASS. *Right:* Cartoon showcasing the variety of SFHs as a function of infall stage (top), and the expected time resolution of SFH reconstruction per spaxel from the combination of Hα emission and spectral continuum fitting (bottom). The longer a galaxy has spent in Virgo, the less HI it has, and the more diverse its SFH can be (hence justifying the increase in sample size when moving from early infallers to pre-pericentre to post-pericentre galaxies). MAUVE will connect different stages of quenching and deliver the largest library of spatially-resolved, sub-kpc scale SFHs ever assembled for cluster galaxies.

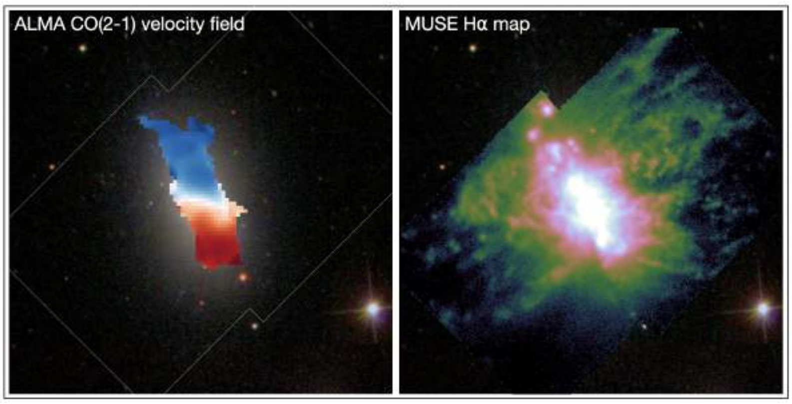

Figure 4 - Discovering outflows with MUSE. ALMA observations of a MAUVE galaxy (NGC4383, left) show a regular, rotating gas disc. MUSE data from a pilot program led to the discovery of a massive gas outflow (right), demonstrating that MAUVE/MUSE is essential to obtain a complete picture of the gas-SF cycle in cluster galaxies.

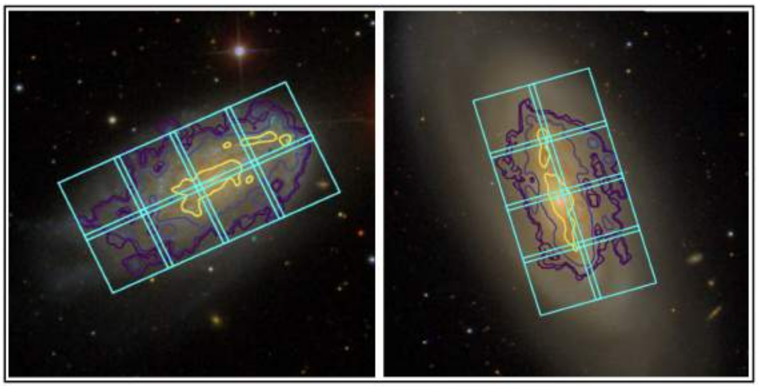

Figure 5 -MAUVE observing strategy. MUSE pointings for two of the largest MAUVE galaxies are shown as blue boxes, overlaid on SDSS optical images. Contours indicate the extent of the H_2 emission as traced by ALMA/VERTICO data. As environmental signatures are local, MAUVE needs map the full CO disc.

References

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