Teenage Galaxies

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The early growth stages of galaxies are still poorly understood. The aim of the MASSIV survey is to better understand the key processes that govern the evolution of galaxies at redshifts $z \sim 1$–2, a particularly turbulent period similar to the teenage years. This paper presents this ambitious survey, together with the main results obtained so far from this ESO Large Programme with SINFONI at the VLT.

The details of the evolution processes that drive galaxy assembly are still largely unconstrained. During the last decade, major spectroscopic and multi-wavelength photometric surveys explored the high-redshift Universe in depth, enabling us to follow the evolution of large numbers of galaxies over cosmological timescales. Even if these data enabled significant progress concerning the knowledge of the global properties of different galaxy populations in different environments, more detailed constraints are needed to understand the main physical processes involved in the formation and evolution of galaxies. Based on observational and/or theoretical arguments, we know that galaxy merging is at work in the growth of galaxies. Cold gas accretion along cosmic filaments has also been emphasised as an efficient process for sustaining high star formation rates and explaining the clumpy nature of high-redshift galaxy discs. However, observational signatures for cold accretion are still being debated, and we do not know yet the cosmic epoch during which either one of these two processes (mergers and cold accretion) was dominant.

Spatially-resolved observations of high-redshift galaxies have begun to give some clues that help to answer this question, as they allow us to probe both the internal properties (kinematics, distribution of metals, etc.) and close environment of distant galaxies. However, most of the previous surveys have concentrated their efforts on the $z > 2$ Universe (e.g., SINS; Förster Schreiber et al., 2009; 2011) or on lower redshifts $z < 0.8$ (IMAGES; Puech et al., 2008). Much less is known of the $z \sim 1$–2 redshift range, which corresponds to a lookback time of 8 to 10 billion years. However, we know that at the peak of cosmic star formation activity galaxies experience major transformations. Is cold gas accretion still an efficient process for assembling galaxies or are major mergers predominant, as seems to be the case at later epochs?

MASSIV (Mass Assembly Survey with SINFONI in VVDS) tackles this issue by surveying a representative sample of star-forming galaxies in the redshift range $z \sim 1$–2 (Contini et al., 2012). With the detailed information provided by SINFONI on individual galaxies, the key science goals of the MASSIV survey are to investigate: (1) the nature of the dynamical support (rotation *vs.* dispersion) of high-z galaxies; (2) the respective role of mergers (minor and/or major) and gas accretion in galaxy growth; and (3) the process of gas exchange (inflows/outflows) with the intergalactic medium through the derivation of metallicity gradients.

A representative sample of high-z galaxies

The MASSIV sample includes 84 star-forming galaxies drawn from the VIMOS VLT Deep Survey (VVDS; Le Fèvre et al., 2005) in the redshift range $0.9 < z < 2.2$. The main advantage of selecting galaxies from the VVDS is that it is a complete magnitude-selected survey avoiding the biases linked to *a priori* colour selection techniques. This unique sample of more than 4400 galaxies, with accurate and secure spectroscopic redshifts between 0.9 and 2, contains both star-forming and passive galaxies distributed over a wide range of stellar masses and star formation rates. It enabled us to easily define volume-limited subsamples of high-z galaxies for integral field spectroscopic follow-up.

Three selection criteria were applied to selected MASSIV targets inside the VVDS. First, galaxies were selected to be star-forming, in order to ensure that the brightest rest-frame optical emission lines (mainly Hα and [N II] 6584 Å, or in a few cases [O III] 5007 Å) used to probe kinematics and metallicity are observed with SINFONI in the near-infrared *J*- or *H*-bands. The selection of star-forming galaxies up to redshift $z \sim 1.5$ (75 % of MASSIV galaxies) was based on the strength and equivalent width of the [O II] 3727 Å, emission line measured on VIMOS spectra (see Figure 1). Galaxies at higher redshift (21 objects with $z > 1.5$) were selected to be star-forming on the basis of their restframe ultraviolet continuum and/or absorption lines.

We further restricted the sample by taking into account two important observational constraints. The expected emission line to be observed with SINFONI (mainly Hα) had to fall far away from the numerous bright OH night-sky lines, restricting considerably the observable redshift domain. Moreover, 90 % of MASSIV galaxies were selected to be further observable at higher spatial resolution with the adaptive optics system of SINFONI or with future imaging/spectroscopic facilities. In these cases, a bright star close enough to the target is needed

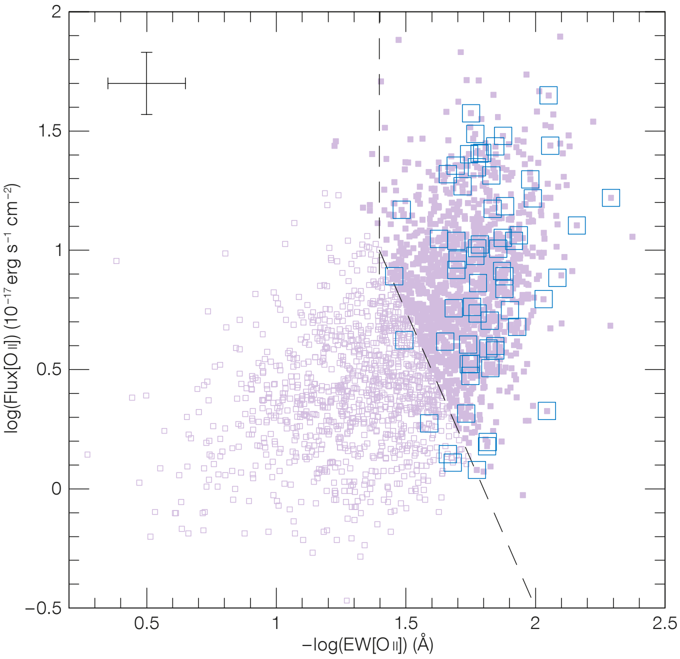

Figure 1. Selection of MASSIV star-forming galaxies in the VVDS sample (small grey symbols). The dashed line indicates the selection box based on [O II] 3727 Å, emission-line equivalent width, used as a proxy for star formation. The 63 galaxies in the redshift range z ~ 0.9–1.5 selected for SINFONI observations are indicated by large blue squares.

for the zero order tip-tilt corrections. All in all, starting from a parent sample of more than 4400 VVDS galaxies at z = 0.9–2.0, only ~ 10 % (~ 540 galaxies) satisfy the above-mentioned criteria. The 84 galaxies defining the MASSIV sample were selected randomly from these targets.

The main advantage of MASSIV, compared to other high-z integral field spectroscopic surveys, is its representativeness for galaxies with star formation rates as low as 5 $M_\odot$/yr. In contrast, surveys like SINS (e.g., Förster Schreiber et al., 2009), OSIRIS (e.g., Law et al., 2007) and LSD/AMAZE (e.g., Gnerucci et al., 2011; Mailoino et al., 2010) target galaxies selected in various, and hence heterogeneous, colour-selected samples (Lyman-break galaxies, BzK, etc.). These surveys mainly probe galaxies at a relatively higher star formation level for a given stellar mass (as shown by the comparison in Figure 2). With a selection based mainly on the [O II] 3727 Å, emission line, MASSIV is essentially a flux-limited sample which provides a fair representation of galaxies in the stellar mass regime 10^9–10^{11} $M_\odot$ down to a relatively low star formation level (Contini et al., 2012).

The integral field spectroscopic observations of the MASSIV sample were performed with SINFONI mounted at the Cassegrain focus of the Very Large Telescope (VLT) Unit Telescope 4. Most of the data (90 %) were collected in service mode during several observing periods between April 2007 and January 2011, as part of the ESO Large Programme 179-A.0823. However, 11 galaxies of the MASSIV sample (including three with duplicated observations) were observed during two pilot runs with SINFONI in September 2005 and November 2006 (performed in visitor mode).

To map the Hα, [N II] 6584 Å, and [S II] 6717, 6731 Å, emission lines, or [O III] 5007 Å, and Hβ for four galaxies of the MASSIV sample, we used the J or H gratings, depending on the redshift of the sources. The vast majority of the observations (74 galaxies) were carried out in seeing-limited mode with the largest pixel scale of 0.125 arcseconds/pixel, giving a field of view (FoV) of 8 by 8 arcseconds. However, we were able to observe 11 galaxies at higher spatial resolution with adaptive optics. For seven of these, we selected the intermediate 0.05 arcsecond/pixel scale with FoV of 3.2 by 3.2 arcseconds to take full advantage of the gain in angular resolution provided by the adaptive optics. For the four other targets, we used the larger pixel scale as a trade-off between enhanced angular resolution and sensitivity (see Contini et al. [2012] for a detailed discussion). The observing conditions were generally good, with clear-to-photometric sky transparency and typical seeing of 0.5–0.8 arcseconds at near-infrared wavelengths. The total on-source integration times ranged on average from 80 to 120 minutes.

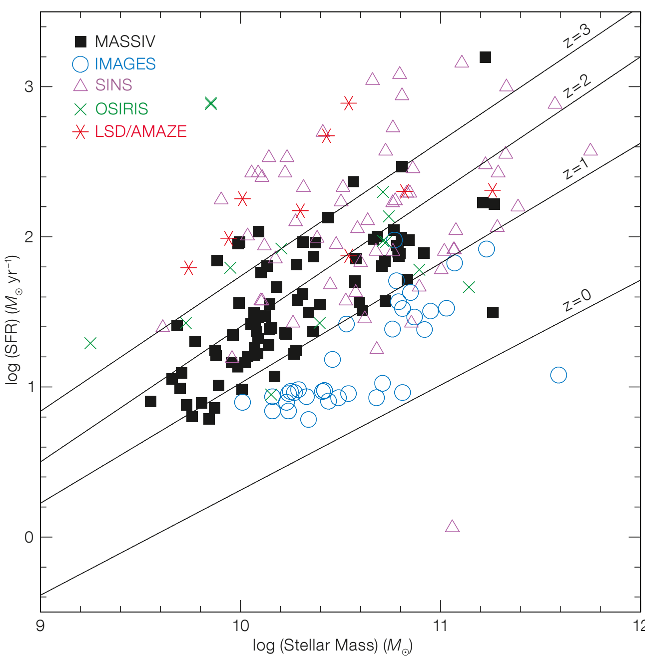

Figure 2. Relation between star formation rate and stellar mass for high-z galaxies is shown. The MASSIV sample (black filled squares) is compared with other major integral field spectroscopic surveys of distant galaxies: IMAGES (z ~ 0.4–0.75, blue circles), SINS (z ~ 1.4–2.6, magenta triangles), OSIRIS (z ~ 1.5–3.3, green crosses), and LSD/AMAZE (z ~ 2.6–3.8, red asterisks). The black lines represent the empirical relations between star formation rate and stellar mass for different redshifts between z = 0 and z = 3 (Bouché et al., 2010).

The first results of the MASSIV survey, recently published in Epinat et al. (2012), Queyrel et al. (2012), and Vergani et al. (2012), are based on the first epoch sample. It contains 49 galaxies in the redshift range $0.9 < z < 1.6$ that were observed before January 2010. The fully calibrated datacubes and derived properties of this sample are already publicly available through the MASSIV database[1].

Mergers and discs at $z \sim 1.2$

The ionised gas kinematics of MASSIV galaxies was studied through the brightest emission line available in the SINFONI spectra: mainly Hα, or [O III] 5007 Å in a few cases. Among the various dynamical states of galaxies, the easiest to probe is the rotating disc. We have thus tested for the presence of a rotating disc in each MASSIV galaxy and then recovered the fundamental dynamical parameters within this hypothesis (Epinat et al., 2012). However, some parameters, such as the rotation velocity, are difficult to constrain from the kinematic modelling alone. In order to reduce the number of free parameters, we first estimated the centre and the inclination of the galaxies from their morphology as measured on the Canada France Hawaii Telescope (CFHT) Legacy Survey *I*-band images, making the assumption that the stars and the ionised gas follow a common distribution.

Using this information, 46 MASSIV galaxies have been classified into four broad classes (see Figure 3), based on their kinematics (rotating discs or not) and close environment (isolated galaxies *vs.* interacting/merging systems).

The fraction of interacting/merging systems in the MASSIV sample is at least ~ 30 % (Epinat et al., 2012). At first glance, this fraction looks comparable to that found at $z \sim 2$ in the SINS sample. However, SINS mergers are identified mainly using kinemetry, a technique based on the degree of perturbation observed in the velocity fields, whereas the identification of interacting systems in MASSIV is based essentially on the detection of several star-forming components inside ongoing mergers or of companions around the main galaxy. The proportion of mergers in MASSIV is thus a lower limit, as it could well be that a significant number of apparently isolated non-rotating

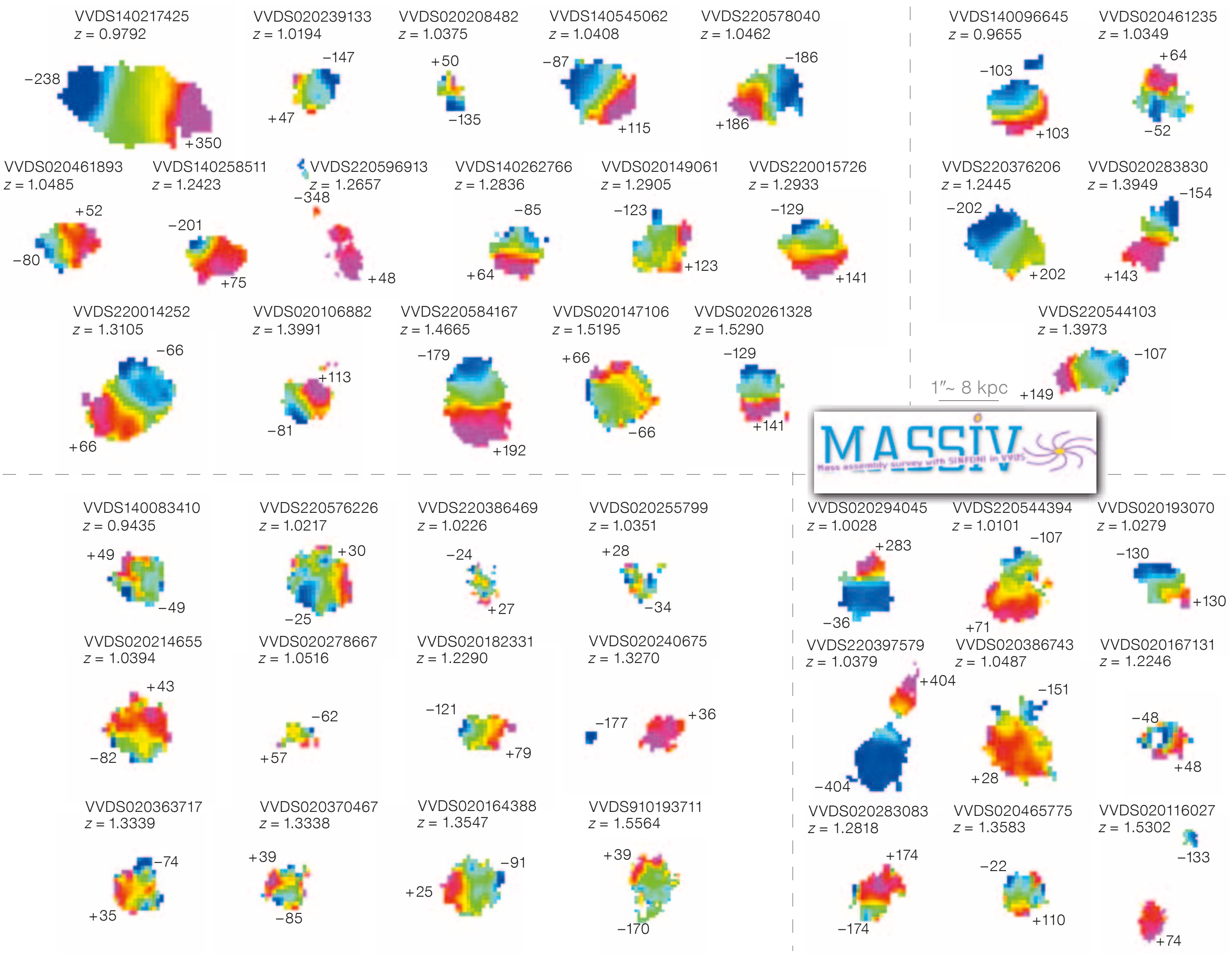

Figure 3. Velocity fields for 42 star-forming galaxies at $z \sim 0.9$–1.6 observed with SINFONI as part of the MASSIV survey. Blue to red colours correspond to regions of the galaxies that are approaching and receding relative to their systemic velocity. All galaxies are shown on the same angular scale indicated by the horizontal bar (1 arcsecond ~ 8 kiloparsecs at $z \sim 1$–2). Galaxies are classified into four broad classes based on their kinematics (top: rotating discs, bottom: non-rotating objects) and close environment (left: isolated galaxies, right: interacting/merging systems), demarcated by dashed lines.

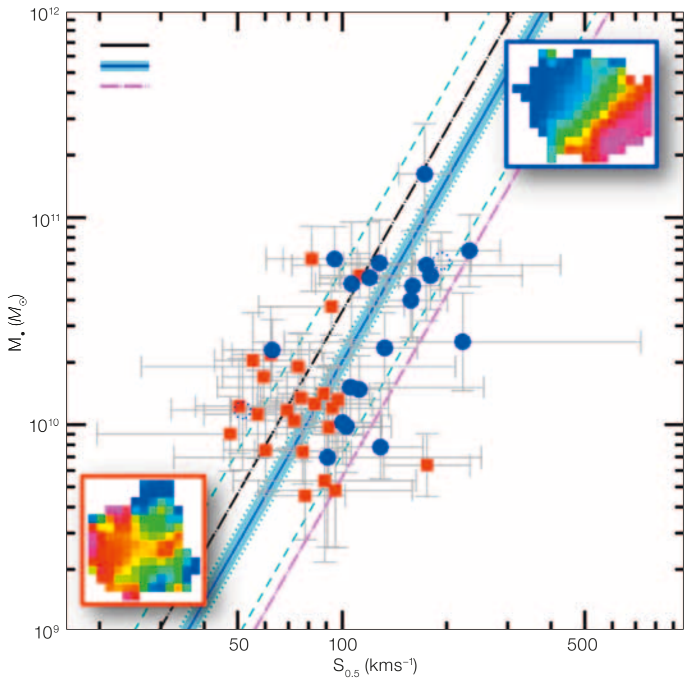

Figure 4. Relation between stellar mass and velocity (rotation + dispersion) of MASSIV galaxies. Blue points indicate rotating discs whereas red squares are for non-rotating galaxies. Examples of SINFONI velocity fields for these two kinematic classes are shown in insets. The relation obtained with MASSIV at $z \sim 1.2$ (highlighted blue line) is compared with those derived at $z \sim 1$ (black line; Kassin et al., 2007) and $z \sim 3$ (magenta line; Gnerucci et al., 2011).

galaxies are in fact ongoing mergers or merger remnants. A dedicated analysis of the merger rate from the observed pairs at $z \sim 1$–2 is underway and makes use of the entire MASSIV sample (López-Sanjuan et al., in prep).

Rotating discs represent ~ 50 % of the MASSIV first epoch sample (Epinat et al., 2012). These galaxies are on average more massive, more star-forming and larger than non-rotating ones (Vergani et al., 2012), but with similar velocity dispersion (~ 60 km/s). An evolution in the fraction of rotating discs is clearly seen over the last 10 Gyr of the Universe. The fraction of rotating systems indeed increases continuously from $z \sim 3$ (~ 35 %, Gnerucci et al., 2011) to $z \sim 0.6$ (~ 65 %; Puech et al., 2008), supporting the scenario in which gas in star-forming systems is stabilising into discs as the Universe evolves.

It appears clearly that the non-rotating systems (~ 30 % of the MASSIV sample; Epinat et al., 2012) are galaxies with a low observed velocity shear (< 50 km/s) or galaxies for which the kinematics indicate some ongoing interactions. Such a population of galaxies has already been observed at higher redshift both in the SINS and LSD/AMAZE samples. These objects are smaller on average than rotators and are often associated with interacting systems. However, the exact nature of these non-rotating objects (spheroids, face-on discs, or merger remnants) is still unclear. Higher spatial resolution imaging and integral field spectroscopy is clearly needed to solve this issue.

The evolution with cosmic time of fundamental scaling relations, connecting for example mass and dynamics of galaxies (the well-known Tully–Fisher relation), is still a matter of debate and controversy. The discordant results obtained so far might be due to differences in sample selection and/or observing limitations, but there is another quantity which could play a significant role: the gas turbulence.

Indeed, the median value of velocity dispersion measured in MASSIV galaxies (~ 60 km/s) marks a transition between turbulent discs (~ 80–100 km/s) seen at higher redshift ($z \sim 2$–3) and more "stable" discs (~ 20–40 km/s) observed in the nearby Universe. This transition of the gaseous velocity dispersion is partly responsible for the increase of the rotational support when galaxies evolve. Taking into account the ordered (rotation) and chaotic (dispersion) motions, there is a clear relation between stellar mass and dynamics of MASSIV galaxies (see Figure 4), a relation which evolved significantly between $z \sim 3$ and $z \sim 1$ (Vergani et al., 2012). At high redshift, we think that mass assembly driven by cold flows is responsible for the high level of turbulence in the gaseous discs. In this framework, results from the MASSIV survey suggest that at $z \sim 1.2$ cold gas accretion is less efficient than at higher redshift.

A surprising distribution of metals

Unveiling the chemical enrichment of galaxies at various epochs is a key issue to constrain their star formation history and their interplay with the surrounding intergalactic medium. In particular, the way metals are distributed inside galaxies gives valuable information about the gas exchange processes (accretion and ejection) between galaxies and their close environment. Until recently, only global measurements of galaxy metallicity were available in the high-z Universe. The high sensitivity of SINFONI enabled resolved metallicity distributions in high-z galaxies to be achieved and was one of the major objectives of our survey.

This goal has been achieved so far for 26 MASSIV galaxies, where we have measured the flux ratio between [N II] 6584 Å, and Hα emission lines (used as a proxy for metallicity) in concentric regions (Queyrel et al., 2012). These regions are centred on the Hα peak emission in each galaxy, which most often corresponds to the kinematical centre of the galaxy. The sizes of the annular regions were adjusted so as to have enough signal for a reliable measurement of the faint [N II] 6584 Å line. This allowed us to quantify the radial profile of the [N II]/Hα line ratio and hence to derive the metallicity from the inner to the outer parts of each galaxy. The metallicity gradients of the 26 MASSIV galaxies are shown in Figure 5.

The most surprising result is the discovery of seven galaxies with a positive metallicity gradient (Queyrel et al., 2012), where the metal content increases from the centre to the outer parts of the galaxy. This result is surprising because this behaviour is rarely observed in nearby galaxies. A close inspection of these galaxies reveals that the majority of them (5/7) are interacting or merging systems. This indicates that interactions might be

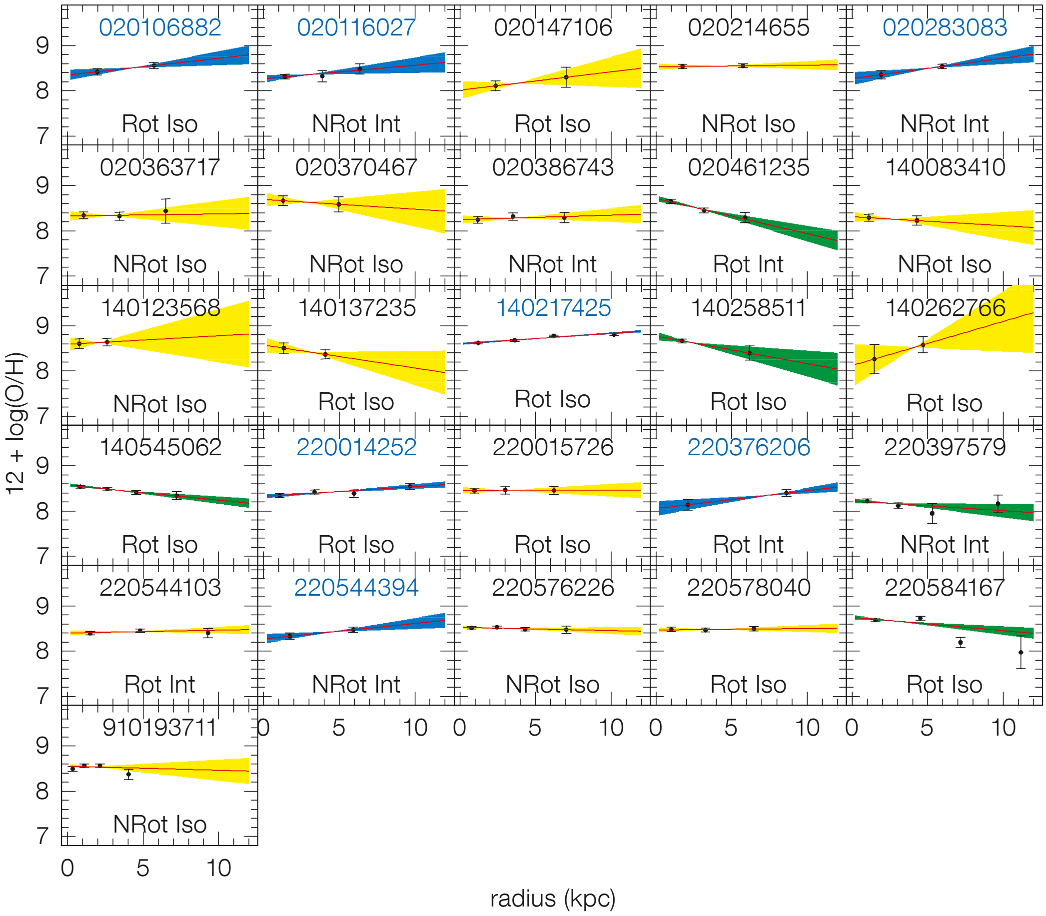

Figure 5. Metallicity gradients for 26 MASSIV galaxies. The yellow/blue/green regions represent the 1σ errors associated to the gradients (red lines). Blue (green) labels indicate the galaxies for which the gradient is positive (negative) with a high confidence level. For each galaxy the dynamical (Rot = rotating disc, NRot = no rotation) and environment (Iso = isolated, Int = interacting) classes are indicated.

the main mechanism responsible for a significant infall of metal-poor gas onto the galaxy centre.

The other mechanism put forward to explain the high occurrence of positive metallicity gradients in $z \sim 3$ isolated discs is cold accretion (Cresci et al., 2010). However this occurrence drops to about 15–20 % at $z \sim 1.2$ (Queyrel et al., 2012) and is almost equal to zero in the local Universe. If cold accretion is the main process able to explain the positive metallicity gradient in high-z isolated discs, this mechanism does not dominate the galaxy assembly at lower redshifts ($z < 2$).

To conclude, all the results obtained so far from the MASSIV survey favour a scenario in which the mass assembly of star-forming galaxies is progressively shifting from a predominance of smooth cold gas accretion to a predominance of merging as cosmic time evolves, with a transition epoch around $z \sim 1$–1.5.

Next steps

The SINFONI observations are now completed. The full exploitation of the unique MASSIV dataset is underway, looking forward to further new and exciting discoveries. In the short term, doubling the statistics in the highest redshift range ($z > 1.2$) will allow us to better probe the dominant mechanisms at play in the overall process of galaxy assembly. New observations of MASSIV galaxies at the VLT with X-shooter and SINFONI are already planned to address specific questions, such as the ubiquity of positive metallicity gradients and the level of gas turbulence in high-z discs. In the longer term, taking the census of the cold gas content and dynamics in MASSIV galaxies with the Atacama Large Millimeter/submillimeter Array (ALMA) will be the obvious step towards a full description of the galaxy growth in the young Universe.

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Links

[1] MASSIV database : http://cosmosdb.lambrate.inaf.it/VVDS-SINFONI/