The SINS and zC-SINF Surveys: The Growth of Massive Galaxies at $z \sim 2$ through Detailed Kinematics and Star Formation with SINFONI

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In recent years, major advances have been made in our understanding of the early stages of galaxy formation and evolution. Remarkable progress has come from spatially– and spectrally–resolved studies of galaxies beyond $z \sim 1$ with SINFONI at the VLT, when the Universe was less than 40% of its present age. Here we report on key insights from our SINFONI observations of over 100 massive $z \sim 2$ star-forming galaxies, resolving the kinematics, physical, and star formation properties on scales of ~ 1–5 kiloparsecs.

The $z \sim 2$ Universe, at lookback times of ~ 10 billion years, is now known to represent a critical epoch in the mass assembly of galaxies. During this era, both the cosmic star formation rate and the luminous quasar space density were at their peak. The assembly of galaxies is correspondingly rapid, with the total stellar mass density in galaxies increasing from ~ 15% of its current value at $z \sim 3$ to ~ 50–75% at $z \sim 1$. The multitude of multi-wavelength imaging surveys and large optical spectroscopic campaigns carried out over the past decade have set the stage for detailed spatially-resolved studies of individual galaxies. Such studies are essential to pin down the actual processes that drive early galaxy evolution and to address key questions such as: What is the relative importance of mergers versus smooth infall in the accretion of mass? What is the connection between bulge and disc formation? What is the interplay between angular momentum, dissipation and feedback processes? Is star formation at high redshift mostly driven by major mergers between galaxies of comparable mass, as in present-day galaxies with similarly high star formation rates?

Recent observational and theoretical findings indicate that the majority of $z \sim 1$–3 massive star-forming galaxies appear to be continuously fed by gas that promotes star formation, rather than occasionally undergoing starbursts as a result of major mergers. Some of the most convincing evidence has come from spatially-resolved ionised gas kinematics with SINFONI, which have revealed large clumpy rotating discs at $z \sim 2$ with high star formation rates (SFR ~ 100 $M_{\odot}$/yr), without any sign of ongoing merging (e.g., Förster Schreiber et al., 2009). In parallel, multi-wavelength galaxy surveys have shown that the star formation rate correlates tightly with stellar mass M_* and that the SFR versus M_* relation steadily declines from $z \sim 2.5$ to $z \sim 0$, arguing against a

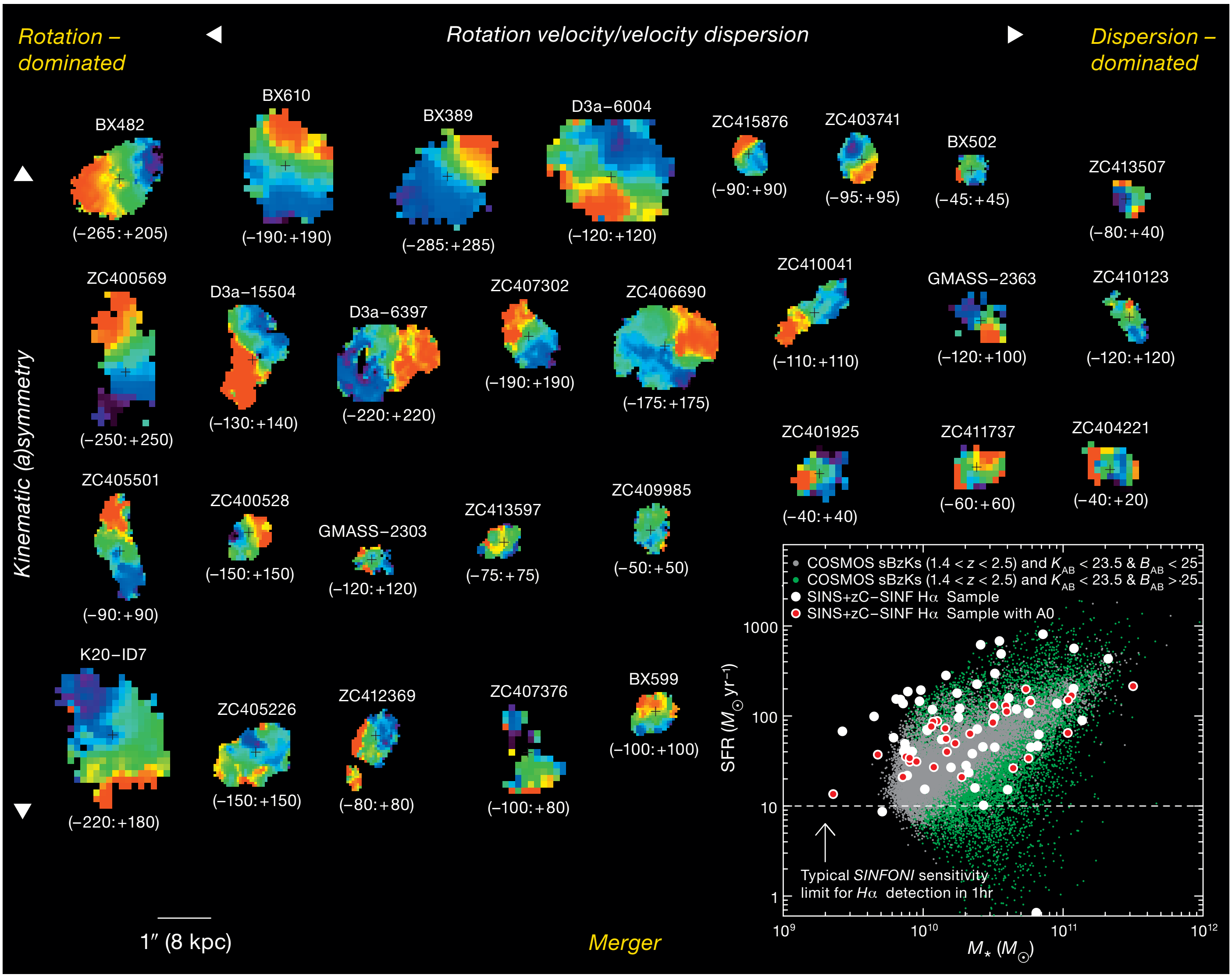

Figure 1. Velocity fields for 29 of the 110 galaxies observed with SINFONI as part of the SINS and on-going zC-SINF large programme. Blue to red colours correspond to regions of the galaxies that are approaching and receding relative to the systemic or bulk velocity of each galaxy as a whole. The minimum and maximum relative velocities are labelled for each galaxy (in km/s). All sources are shown on the same angular scale; the white bar at the bottom left corresponds to 1 arcsecond, or about 8 kpc at $z = 2$. The inset (adapted from Mancini et al., 2011) shows the distribution of all targets (white-filled circles) and the AO sample of 29 targets (red-filled circles) in the stellar mass versus star formation rate plane.

dominant bursty, major-merger-driven star formation mode (e.g., Daddi et al., 2007). Moreover, observations of (sub)millimetre CO line emission in non-major merging star-forming galaxies at $z \sim 1$–3 have uncovered large molecular gas reservoirs, implying gas-to-baryonic mass fractions of ~ 50% and requiring continuous replenishment to maintain the observed star formation (e.g., Tacconi et al., 2010).

This new empirical evidence matches remarkably well with state-of-the-art cosmological simulations, within the now mature Cold Dark Matter paradigm, in which galaxies form as baryonic gas condenses at the centre of collapsing dark matter haloes. In these simulations, massive galaxies acquire a large fraction of their baryonic mass via steady gas accretion along narrow, cold streams and/or a rapid series of minor mergers. These mechanisms sustain elevated star formation rates over much longer timescales than violent, dissipative major mergers. Under these conditions, the net angular momentum is largely preserved as matter is accreted onto galaxies, and discs can survive. Along with continuous replenishment of gas, dynamical processes within galaxies can drive the evolution of discs and the rapid formation of bulges.

The SINS and zC-SINF SINFONI surveys

Galaxies at $z \sim 1$–3 are faint, their projected angular sizes are small, and important spectral diagnostic features that are emitted in the rest-frame optical are redshifted into the near-infrared bands, 1.0–2.5 μm. The advent of cryogenic near-infrared integral field spectroscopy on 8-metre-class telescopes, along with adaptive optics (AO), has opened up new avenues by making distant galaxies accessible to detailed spatially- and spectrally-resolved studies. The high sensitivity of SINFONI, mounted on Yepun (Unit Telescope 4; UT4) at the VLT, has allowed ground-breaking studies including those led by our team, providing unprecedented insights into the dynamical evolution of massive star-forming galaxies, the connection between bulge and disc formation, and the mechanisms driving star formation, angular momentum, feedback, and metal enrichment at $z \sim 2$.

Given the unique opportunities afforded by SINFONI, we have conducted the SINS survey to map the kinematic, star formation, and physical properties of high-redshift galaxies. SINS was the first and largest survey with full 2D mapping of the ionised gas kinematics and morphologies of 80 galaxies at $z \sim 1.3–2.6$ (Förster Schreiber et al., 2009). The SINFONI data were mostly collected as part of the Max-Planck-Institut für extraterrestrische Physik's (MPE) SPIFFI and PARSEC Guaranteed Time Observations. The galaxies are resolved on typical seeing-limited angular scales of about 0.6 arcseconds, corresponding to 4–5 kiloparsecs (kpc) at $z \sim 2$, and as small as 0.1–0.2 arcseconds, or 1–1.5 kpc, for the dozen objects also observed with AO. We are continuing this effort through a SINFONI large programme (LP) in collaboration with zCOSMOS team members, capitalising on two major ESO VLT programmes: SINS with SINFONI and zCOSMOS, the VIMOS optical spectroscopic campaign in the 2-square-degree COSMOS field (Lilly et al., 2007; Lilly et al., 2008). With ~ 6000 objects confirmed at $1.4 < z < 2.5$ across the widest multiwavelength cosmological survey field, zCOSMOS offers the best opportunity to significantly expand the SINS sample. SINFONI data have been taken in natural seeing for 30 $z \sim 2$ zCOSMOS targets, the "zC-SINF" sample (Mancini et al., 2011), out of which the best and most representative subset is now being observed with AO.

Together, the SINS and zC-SINF samples comprise 110 $z \sim 2$ galaxies with SINFONI integral field spectroscopy, which parallels existing near-infrared long-slit spectroscopic surveys. Once our LP is completed, the full AO sample will include nearly 30 objects, surpassing any other sample of this kind at $z \sim 2$. The galaxies cover roughly two orders of magnitude in stellar mass and star formation rate ($\sim 3 \times 10^9 – 3 \times 10^{11}\ M_\odot$ and ~ 10–800 $M_\odot$/yr), probing the bulk of massive, actively star-forming galaxies in the range $1.4 < z < 2.5$ (Figure 1, inset). The samples shown in this figure cover well the region occupied by the bulk of the massive star-forming population at $z \sim 2$, here taken from photometrically-selected candidates in the COSMOS field (small green and white dots). For the vast majority of the galaxies, the Hα recombination line was the main feature of interest. The Hα line (and the neighbouring [N II] forbidden lines) predominantly trace star-forming regions. The SINFONI seeing-limited and AO datasets are highly complementary and provide, respectively, the overview of the kinematics and emission line properties on ~ 4–5 kpc scales and, for selected objects, a sharper view allowing the characterisation of the processes at play through ~ 1 kpc-scale signatures (see Figure 1). In what follows, we highlight some of the key outcomes from SINS and initial results from our LP, with half the AO data taken to date.

Kinematic diversity of $z \sim 2$ galaxies

One of the first and foremost results from SINS and zC-SINF is the kinematic diversity among massive star-forming galaxies at $z \sim 2$, illustrated in Figure 1. Velocity fields and velocity dispersion maps are measured from the shift in observed wavelength and the width of the Hα line across the sources. The galaxies shown in Figure 1 are approximately sorted from left to right according to whether their kinematics are rotation-dominated or dispersion-dominated, and from top to bottom according to whether they are disc-like or merger-like. All 29 objects have, or will have, SINFONI + AO observations. For 18 of the galaxies, the velocity fields are extracted from the existing AO data, with typical resolution of ~ 1–2 kpc; for the others, the seeing-limited data are shown, with resolutions of ~ 4–5 kpc. The classification in the kinematic parameter space is based on: (1) the degree of symmetry of the kinematics: from regular kinematics characteristic of ordered disc rotation to irregular kinematics indicative of mergers, quantified for many objects through kinemetry (e.g., Shapiro et al., 2008); and (2) the dominant source of dynamical support, quantified through the ratio of rotational or orbital velocity v_{rot} to intrinsic velocity dispersion σ_0.

About one third of the galaxies are rotation-dominated yet turbulent discs, another third are major mergers with disturbed kinematics, and the remaining third are typically compact systems with velocity dispersion-dominated kinematics. The fraction of rotation-dominated discs appears to increase at higher masses and, among the larger, more luminous systems, discs account for around two thirds while major mergers represent a minority. The existence of large rotating discs among the massive actively star-forming $z \sim 2$ population was a surprise, and is consistent with smoother but efficient mass accretion mechanisms playing an important role along with merging events.

Properties and evolution of $z \sim 2$ discs

A remarkable finding from our studies is that $z \sim 2$ discs are characterised by large intrinsic velocity dispersions ~ 30–90 km/s, implying low $v_{rot}/\sigma_0 \sim 2–6$, and high gas-to-baryonic mass fractions of ~ 50 %. Although their sizes and specific angular momenta are comparable, the $z \sim 2$ discs are thus geometrically thicker, more turbulent, and more gas-rich than their $z \sim 0$ counterparts. Furthermore, many of the $z \sim 2$ discs exhibit irregular Hα morphologies, and our SINFONI + AO observations resolve luminous kpc-sized clumps in several of the discs (Genzel et al., 2011). Similar clumps are also seen in the rest-optical continuum light tracing the bulk of stars in five discs for which we obtained sensitive Hubble Space Telescope (HST) NICMOS/NIC2 *H*-band imaging (Förster Schreiber et al., 2011). The clumps have large inferred masses of $\sim 10^8 – 5 \times 10^9$ $M_\odot$, typically a few percent and up to ~ 20 % of the mass of the host galaxy.

In a detailed study of several of our best-resolved SINS galaxies, our SINFONI data revealed the presence of turbulent rotating star-forming outer rings/discs and central bulge/inner disc components. The mass fractions of the central bulge/inner disc relative to the total dynamical mass appear to scale with the global stellar and chemical evolutionary stage of the galaxies (Figure 2; Genzel et al., 2008). This trend suggests a gradual buildup of the inner disc and bulge via internal processes that drive gas and stars inwards, without major mergers. For two of these discs, for which high-resolution Hubble Space Telescope (HST) imaging is available, radial variations in stellar age of individual clumps are inferred from age-sensitive indicators: the Hα line-to-continuum flux ratio for the one object with SINFONI + AO and HST NIC2 observations (Figure 3), and the restframe ultraviolet-to-optical colours for the other with HST NIC2 *H*-band and ACS *i*-band imaging available (Förster Schreiber et al., 2011). The trends are such that the clumps closest to the centre of the galaxies appear older.

These results are in remarkable agreement with theoretical arguments and recent numerical simulations, which indicate that gas-rich turbulent discs as observed at $z \sim 2$ can fragment via disc instabilities into very massive, kpc-scale star-forming clumps. These massive clumps can migrate inwards through dynamical friction and clump–clump interactions, and coalesce at the centre if they survive the disruptive effects of stellar feedback and tidal torques. Along with instability-driven inflow through the gas-rich discs, clump migration could contribute to the formation of nascent bulges. With the large intrinsic velocity dispersions and high gas mass fractions of $z \sim 2$ discs, dynamical friction and viscous inflow processes proceed on timescales of less than one billion years, at least an order of magnitude faster than in present-day disc galaxies (e.g., Genzel et al., 2008).

Vigorous star formation feedback in clumps

With our most recent SINFONI + AO datasets, we have discovered broad Hα (and

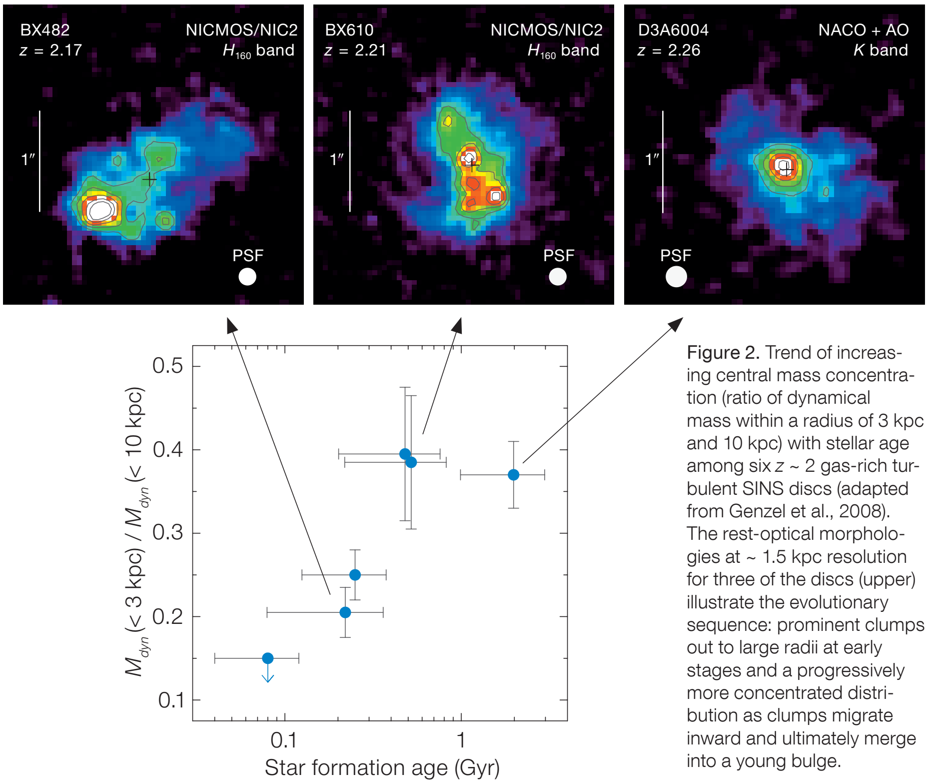

Figure 2. Trend of increasing central mass concentration (ratio of dynamical mass within a radius of 3 kpc and 10 kpc) with stellar age among six $z \sim 2$ gas-rich turbulent SINS discs (adapted from Genzel et al., 2008). The rest-optical morphologies at ~ 1.5 kpc resolution for three of the discs (upper) illustrate the evolutionary sequence: prominent clumps out to large radii at early stages and a progressively more concentrated distribution as clumps migrate inward and ultimately merge into a young bulge.

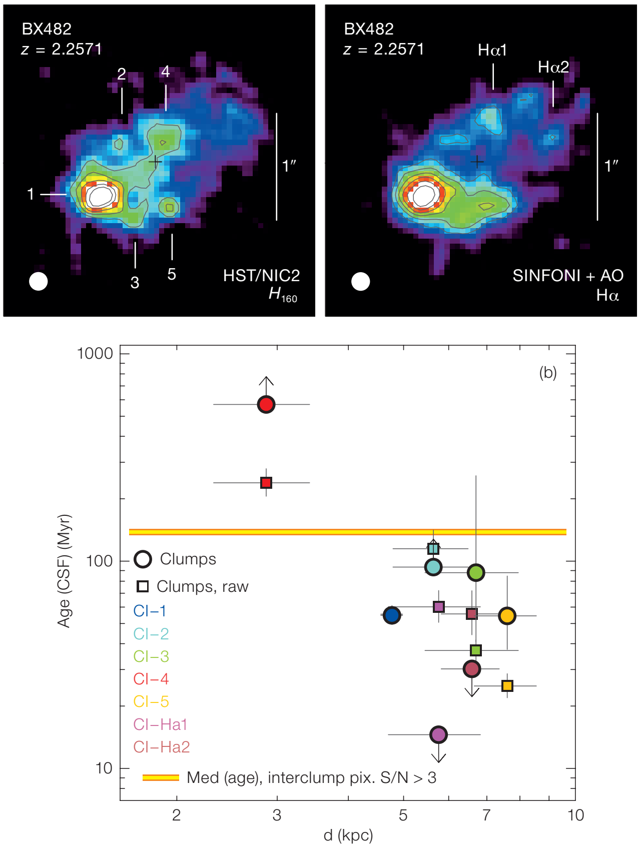

Figure 3. BX 482, a SINS disc galaxy at $z \sim 2$, for which both SINFONI + AO Hα and HST NIC2 *H*-band observations at a resolution of ~ 1.5 kpc are available (Förster Schreiber et al., 2011). For this galaxy, the sets of clumps identified in the optical continuum (upper left) and line (upper right) do not fully overlap, and the Hα line-to-continuum flux ratio (sensitive to age) reveals that the clump closest to the centre is the oldest (lower plot).

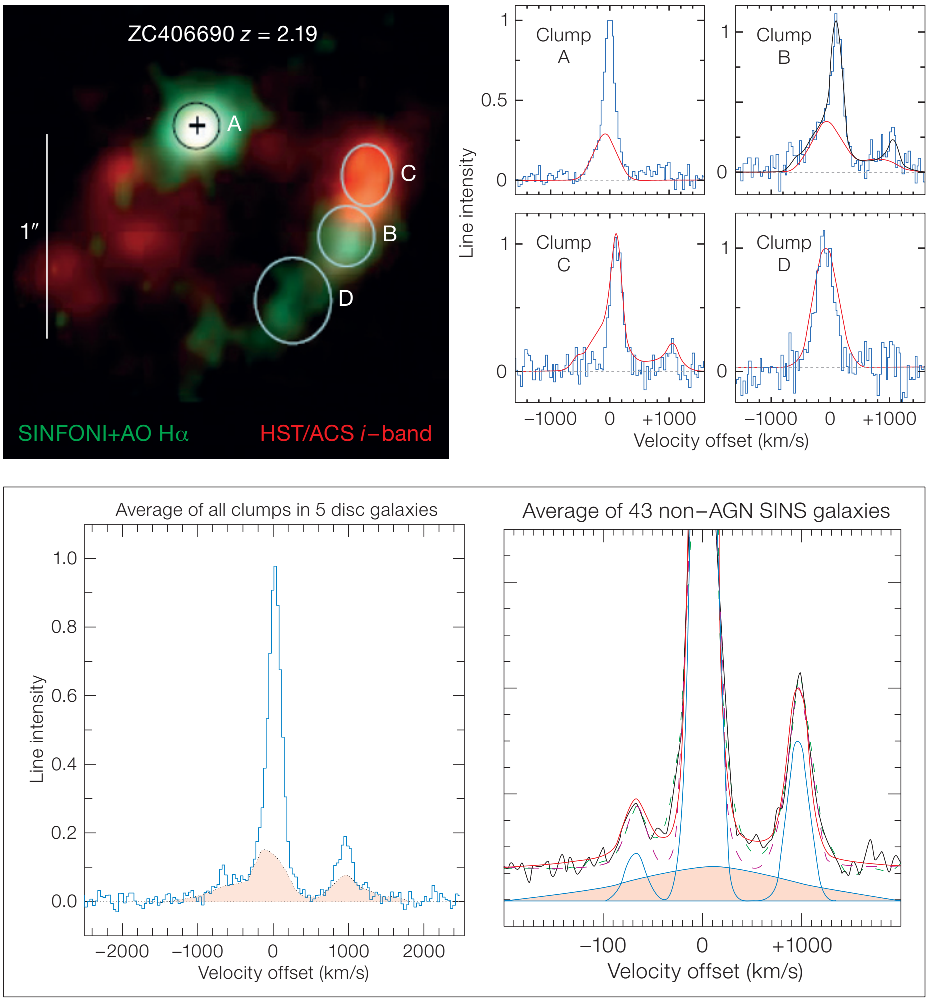

Figure 4. Another example of a kinematically-confirmed disc, for the galaxy ZC406690, with a clumpy star-forming ring in Hα and rest-UV emission as revealed by SINFONI + AO and HST ACS *i*-band observations, respectively (colour-coded in green and red in the composite image, top left). The bright clumps A and B, and region D clearly show a broad emission line component in their spectrum (overplotted as red line in the top right panel), indicative of vigorous star formation driven gas outflows; such a component is undetected in clump C (the red line in this case is the scaled spectrum of clump B). The broad feature is also seen in the average SINFONI + AO spectrum of all clumps in five clumpy discs (bottom panel, left plot) but is undetected in the average of the interclump regions. It is moreover seen in the composite integrated spectrum of star-forming SINS galaxies with best S/N (bottom panel, right plot). Figure adapted from Genzel et al., 2011 and Shapiro et al., 2009.

[N II]) emission components in the spectra of individual bright clumps across several disc galaxies, underneath the narrow component dominated by star formation (Figure 4; Genzel et al., 2011). This ~ 500 km/s-wide component may trace gas outflows driven by the energy and momentum release from massive stars and supernova explosions in the star-forming clumps. In an earlier study, we had detected a similar broad Hα + [N II] component in the high signal-to-noise (S/N) spectrum created by co-adding the spatially-integrated spectra of 43 star-forming SINS galaxies, for an equivalent integration time of about 180 hours (Shapiro et al., 2009). Now, our new SINFONI + AO data provide the first direct evidence for star-formation-driven feedback originating on the small scales of clumps within the discs, pinning down the origins of galactic-scale winds. These winds are ubiquitous at $z \sim 2$, but had so far only been observed on large (> 10 kpc) scales.

The inferred clump mass outflow rates are comparable to or higher than the clump star formation rates, echoing estimates derived from studies of galactic-scale winds at high redshift. Outflow rates largely exceeding the star formation rates suggest that some of the most actively star-forming clumps may lose a large fraction of their gas and be disrupted on very short timescales. Thus, while we found evidence that clumps may be able to migrate inwards and contribute to the early build-up of bulges, vigorous gas outflows could rapidly disrupt some of the more actively star-forming clumps before they reach the centre of the host disc.

Outlook

As we pursue our SINFONI studies and exploit fully the rich SINFONI datasets, we can look forward to further new and exciting discoveries. In the short term, the remaining half of the AO observations planned as part of our SINFONI LP will be crucial to provide a more complete picture, notably: (i) filling in the missing bins in the stellar mass and star formation rate plane; (ii) probing better the different evolutionary stages of early discs; and (iii) unveiling the nature of the compact dispersion-dominated objects. In the longer term, future near-infrared integral field spectroscopic surveys with KMOS at the VLT (Sharples et al., 2010) will substantially augment the current SINFONI seeing-limited samples by factors of ~ 10 or more. AO diffraction-limited capabilities at the VLT will remain essential for integral field spectroscopic as well as imaging follow-up of individual galaxies for more detailed investigations.

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