AMAZE and LSD: Metallicity and Dynamical Evolution of Galaxies in the Early Universe

Roberto Maiolino[1]
Filippo Mannucci[2]
Giovanni Cresci[2]
Alessio Gnerucci[3]
Paulina Troncoso[1]
Alessandro Marconi[3]
Francesco Calura[4]
Andrea Cimatti[5]
Filomena Cocchia[1]
Adriano Fontana[1]
Gianluigi Granato[6]
Andrea Grazian[1]
Francesca Matteucci[7]
Taro Nagao[8]
Laura Pentericci[1]
Antonio Pipino[9]
Lucia Pozzetti[10]
Guido Risaliti[2]
Laura Silva[6]

[1] INAF–Osservatorio Astronomico di Roma, Monte Porzio Catone, Italy
[2] INAF–Osservatorio Astrofisico di Arcetri, Firenze, Italy
[3] Dipartimento di Fisica e Astronomia, Università degli Studi di Firenze, Italy
[4] Jeremiah Horrocks Institute for Astrophysics and Supercomputing, University of Central Lancashire, Preston, United Kingdom
[5] Dipartimento di Astronomia, Università di Bologna, Italy
[6] INAF–Osservatorio Astronomico di Trieste, Italy
[7] Dipartimento di Fisica, Università di Trieste, Italy
[8] Graduate School of Science and Engineering, Ehime University, Japan
[9] Department of Physics and Astronomy, University of California Los Angeles, USA
[10] INAF–Osservatorio Astronomico di Bologna, Italy

The metal content in galaxies provides important information on the physical processes responsible for galaxy formation, but little was known for galaxies at $z > 3$, when the Universe was less than 15 % of its current age. We report on our metallicity survey of galaxies at $z > 3$ using SINFONI at the VLT. We find that at $z > 3$, low-mass galaxies obey the same fundamental relation between metallicity, mass and star formation rate as at $0 < z < 2.5$; however, at $z > 3$ massive galaxies deviate from this relation, being more metal-poor. In some of these massive galaxies we can even map the gas metallicity. We find that galaxies at $z \sim 3.3$ have regular rotation, though highly turbulent, and inverted abundance gradients relative to local galaxies, with lower abundances near the centre, close to the most active regions of star formation. Overall the results suggest that prominent inflow of pristine gas is responsible for the strong chemical evolution observed in galaxies at $z > 3$.

The chemical enrichment that we observe in local galaxies has been produced by the nucleosynthesis of stars formed over their cosmic lives. Such enrichment has been modulated by the inflow of pristine gas (which both boosts star formation and dilutes the gas metallicity), enriched gas outflows (driven by the star formation activity itself or by active galactic nuclei [AGNs]) and gas exchange during galaxy merging events. The shape of the initial mass function of star formation also plays an important role, since different stellar masses inject into the interstellar medium different amounts of chemical elements. Clearly, the metal content of galaxies is an important tracer of their star formation history and of the main physical processes involved in galaxy evolution. Indeed, the metallicity of local and distant galaxies is one of the most important tools to constrain galaxy evolutionary models.

Clear observational evidence of a connection between the content of metals and star formation history is given by the tight three-dimensional correlation between metallicity, stellar mass and star formation rate (dubbed Fundamental Metallicity Relation, FMR, Mannucci et al., 2010), as illustrated in Figure 1. More specifically, the gas metallicity is observed to increase as a function of the stellar mass (at a given star formation rate [SFR]) and to decrease with the SFR (at a given stellar mass). Galaxies show a very small metallicity scatter of 0.05 dex around this surface and this suggests that the bulk of galaxy formation occurs through a smooth, long-standing equilibrium between star formation, gas inflow and outflow. Distant galaxies, out to $z < 2.5$, appear to obey the same fundamental relation between metallicity, mass and SFR observed in local galaxies. This finding suggests that the same mechanisms of galaxy formation are at work at any epoch in the redshift interval $0 < z < 2.5$.

Until recently, little was known about the metallicity of galaxies at $z > 3$, due to the difficulty of detecting the optical nebular lines (redshifted into the near-infrared) required to measure the metallicity in these faint systems. However, this is a crucial epoch of very fast galaxy evolution, just before the peak of cosmic star formation, which requires thorough investigation to understand the formation of primeval galaxies properly.

The AMAZE and LSD surveys

We have undertaken two major projects using the near-infrared integral field spectrograph SINFONI at the VLT. AMAZE (Assessing the Mass-Abundances redshift [*Z*] Evolution) is an ESO large programme that was awarded 180 hours of observations. It consists of deep SINFONI, seeing-limited, integral field spectroscopy of about 30 star-forming galaxies (Lyman-break selected), most of which are at $3.0 < z < 3.7$ and a few them at $4.2 < z < 5.2$. In the following we will focus on the sample at $z \sim 3.3$. For these galaxies the nebular lines [O II] 3727 Å and [Ne III] 3869 Å are redshifted into the *H*-band, while Hβ and [O III] 5007 Å are redshifted into the *K*-band. The flux ratio of these lines allows us to measure the gas metallicity, as discussed in Maiolino et al. (2008).

LSD (Lyman-break galaxies Stellar population and Dynamics) is a companion programme that was awarded 70 hours of observations with SINFONI, assisted by the adaptive optics module, so as to achieve a much higher angular resolution relative to the seeing-limited observations. The sample consists of eight Lyman-break galaxies at $z \sim 3.3$ selected to have a nearby bright star, which is required to guide the adaptive optics system.

In both projects the line emission (especially the strongest one, [O III] 5007 Å) is generally spatially resolved by our data.

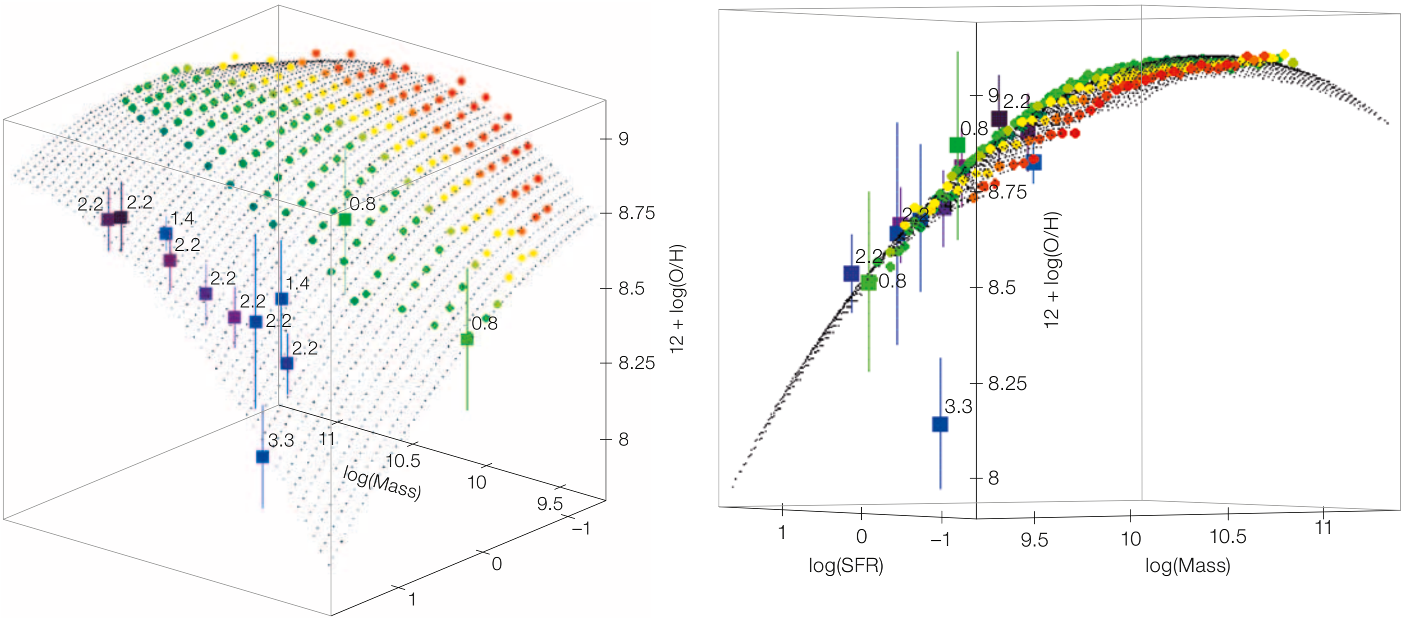

Figure 1. Two views of the fundamental metallicity relation (FMR) between mass, star formation rate and metallicity for local galaxies are shown. The small points, with different colours, indicate different star formation rates. Squares with error bars indicate the average location of distant star-forming galaxies at different redshifts (the latter indicated by the number associated with each point). The point at $z \sim 3.3$ deviating from the FMR was obtained with the first preliminary set of 17 galaxies from AMAZE and LSD. From Mannucci et al. (2010).

The projected spatial resolution is typically about 5 kpc (seeing ~ 0.6 arcseconds) for the AMAZE data and about 1.5 kpc for the (nearly) diffraction-limited data in LSD (point spread function [PSF] ~ 0.2 arcseconds). Also in both samples extensive multiband photometry (including Spitzer data) allowed us to constrain the stellar masses tightly. The star formation rate is inferred by using both the Hβ luminosity and spectral energy distribution (SED) broadband fitting, generally obtaining consistent results.

A detailed description of these two programmes, as well as preliminary results, is given in Maiolino et al. (2008) and in Mannucci et al. (2009). Additional results have been, or are being published in five additional papers (Gnerucci et al., 2010; Cresci et al., 2010; Troncoso et al., 2010; Troncoso et al., in prep.; Gnerucci et al., in prep.), while follow-up observations are delivering additional results. It is beyond the scope of this paper to give an extensive overview of the various results. Here we only show some of the main highlights that have been obtained by these programmes so far.

Chemical upsizing at $z > 3$

The AMAZE and LSD samples span more than two orders of magnitude in stellar mass ($M_{\star} \sim 10^{9}$–10^{11} $M_{\odot}$) and over an order of magnitude in star formation rate

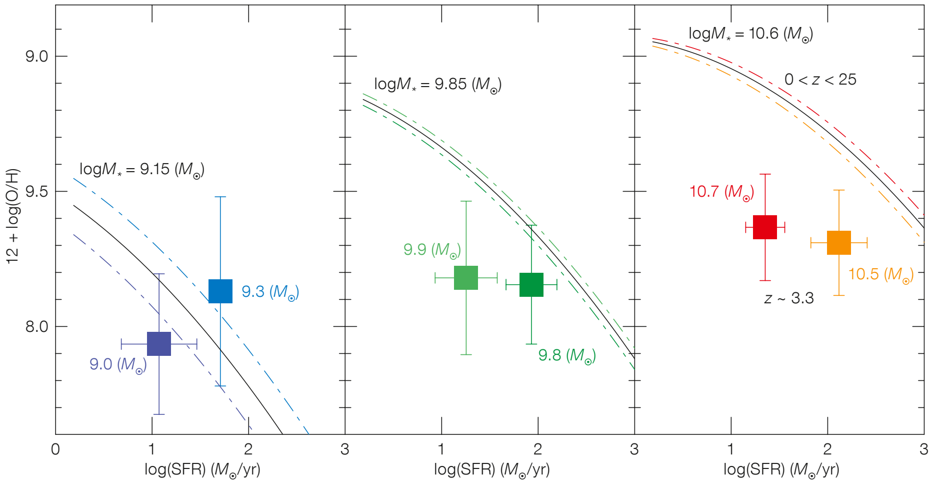

Figure 2. Metallicity versus star formation rate in galaxies at $0 < z < 2.5$ on the FMR (lines) and in galaxies at $z \sim 3.3$ (squares) is shown for three different stellar mass ranges. Within each panel different colours give the metallicity values at exactly the same average stellar mass for galaxies both at $0 < z < 2.5$ and at $z \sim 3.3$. Note that while the metallicity of low-mass galaxies at $z \sim 3.3$ is consistent with local galaxies, massive galaxies at $z \sim 3.3$ are significantly more metal-poor relative to their local counterparts. From Troncoso et al. (2010).

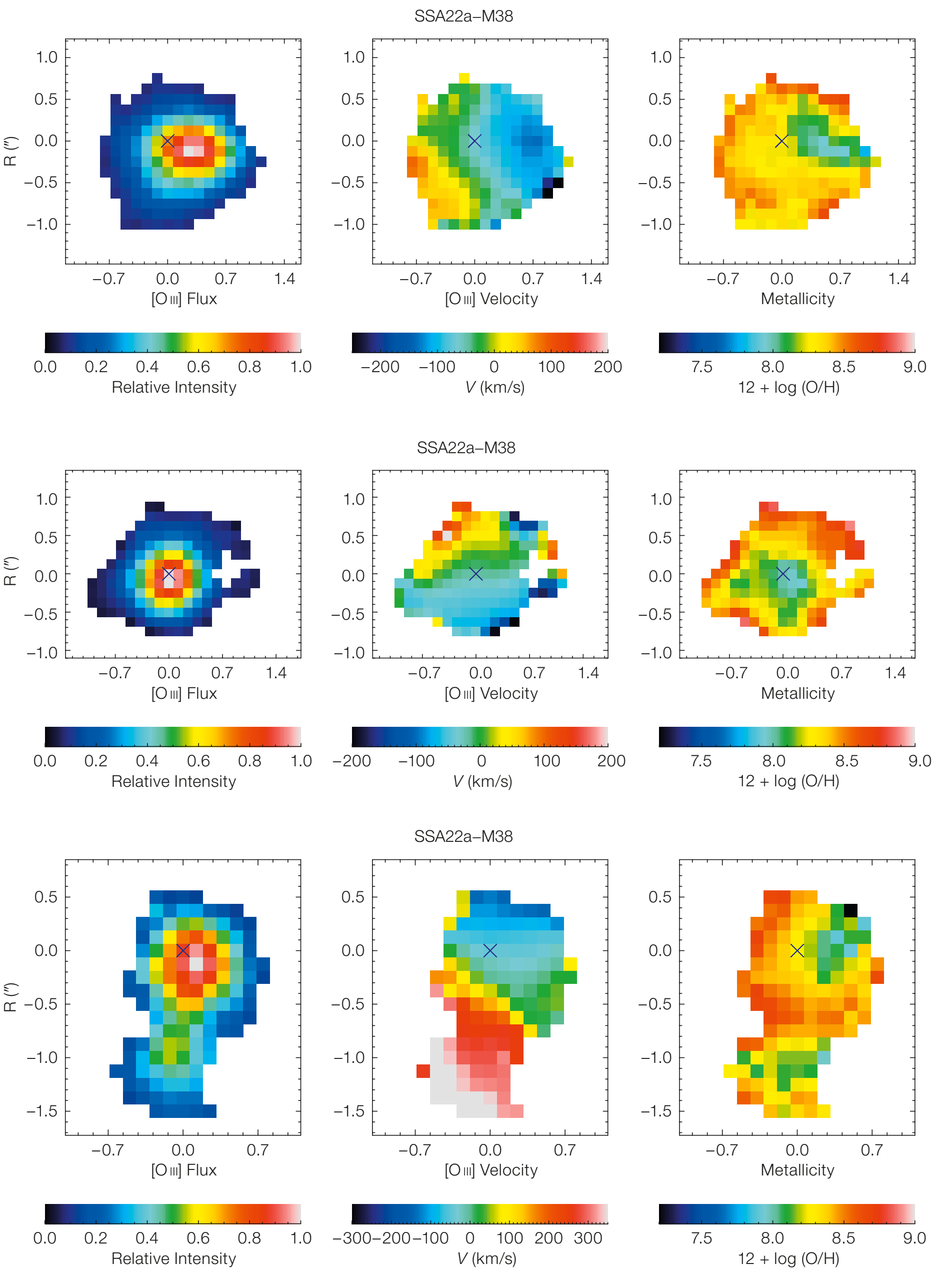

Figure 3. [O III] flux, velocity field and metallicity maps for three massive galaxies at $z \sim 3.3$ characterised by regular rotation patterns. The metallicity has a minimum close to the central peak of star formation (as traced by the maximum of Hβ emission). From Cresci et al. (2010).

(SFR ~ 30–300 $M_\odot$/yr). Therefore, the metallicity inferred from the SINFONI spectra allows us to obtain information on the mass–SFR–metallicity relation (FMR) at $z \sim 3.3$. Figure 1 shows the location of galaxies at $z \sim 3.3$ obtained from the average of the first set of 17 galaxies observed in AMAZE and LSD, showing that galaxies at $z \sim 3.3$ clearly deviate from the FMR.

In Figure 2 (from Troncoso et al., 2010a) we exploit the full AMAZE and LSD final samples. The solid and dashed lines show a cut of the FMR (i.e. the metallicity–SFR relation) at three different values of stellar mass. The AMAZE+LSD data at $z \sim 3.3$ are shown with solid squares that, for sake of clarity, give the average of the data in bins of mass and SFR. Low-mass galaxies ($M_\star \sim 10^{9.2}\,M_\odot$, leftmost panel) have a metallicity in line with the expectation of the relation observed at $0 < z < 2.5$, indicating that these low-mass galaxies at $z \sim 3.3$ are very much like local galaxies and suggesting that they are regulated by the same evolutionary processes. However, massive galaxies at $z \sim 3.3$, especially at $M_\star \sim 10^{10.7}\,M_\odot$ (rightmost panel), are significantly more metal-poor than galaxies at $0 < z < 2.5$ with the same SFR. Taken at face value, this result seems to imply that massive galaxies at $z \sim 3.3$ are in an earlier evolutionary stage relative to their low-mass counterparts, in the sense that they have still to reach the metallicity–mass–SFR relation characterising galaxies at low-z. This is in contrast with the expectations of downsizing scenarios, where massive galaxies should evolve faster and at earlier epochs relative to low-mass systems.

There are a few possible scenarios that could explain the deviation of massive galaxies at $z \sim 3.3$ from the FMR observed at $0 < z < 2.5$. An excess of pristine cold gas inflow in massive galaxies, at such early epochs, may significantly dilute the gas metallicity. Alternatively, galaxy mergers may drive gas from the outer, low metallicity regions into the central parts of massive galaxies, hence diluting the metallicity of star-forming regions. The latter scenario can be investigated by studying the dynamical properties of these systems, as inferred by our SINFONI data.

Massive rotating discs at $z > 3$

The two-dimensional spectroscopic information delivered by SINFONI allows us to trace the kinematics of the galaxies at $z \sim 3.3$ in our sample, by measuring the velocity shift of the brightest line, [O III] 5007 Å. About 30 % of the galaxies in our sample show ordered rotational motions (Gnerucci et al., 2010a). A few examples of such rotating systems are shown in Figure 3, where the central panels show the rotation curve, along with the [O III] flux map (leftmost panels).

In relation to the chemical upsizing result discussed above, we find that there is no correlation between the dynamical prop-

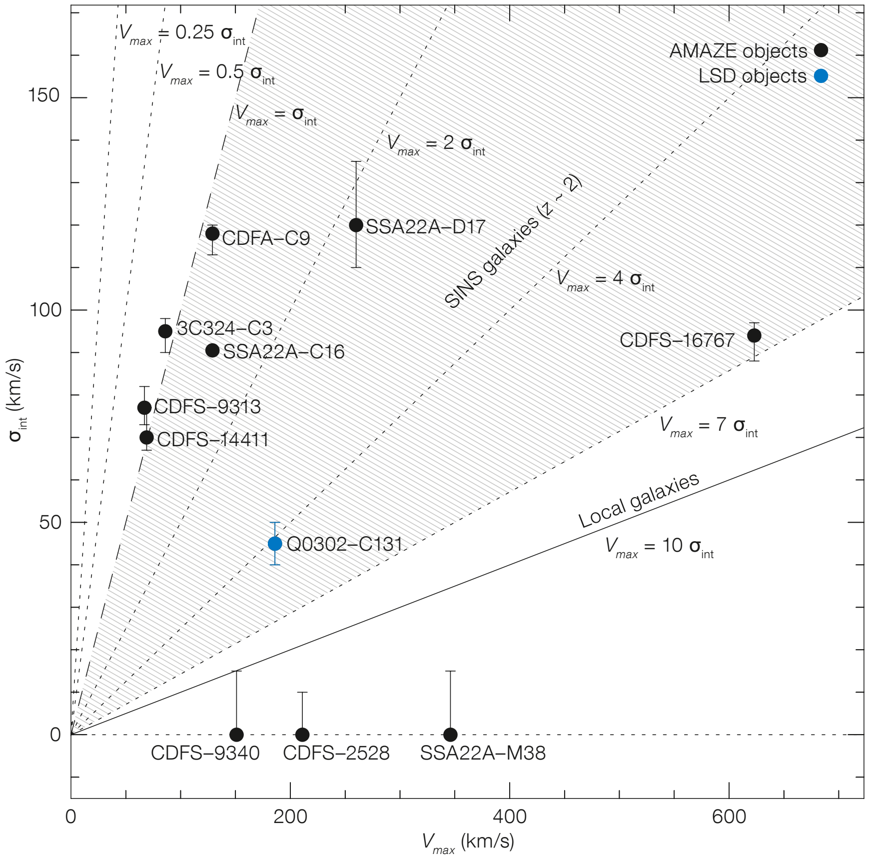

Figure 4. Velocity dispersion (σ) versus rotational velocity (V_{max}) is shown for disc galaxies at $z \sim 3.3$ with a regular rotation pattern. The solid line shows the relation $V_{max}/\sigma = 10$ typical of local galaxies. Note that discs at $z \sim 3.3$ are much more turbulent than local galaxies, many of them having $V_{max}/\sigma \sim 1$. From Gnerucci et al. (2010).

erties of massive galaxies at $z \sim 3.3$ and their deviation from the fundamental metallicity–mass–SFR relation observed at $0 < z < 2.5$. More specifically, among the $z \sim 3.3$ massive galaxies, which are metal-poor relative to the metallicity–mass–SFR relation at $0 < z < 2.5$, we find systems with both irregular kinematics (likely tracing merging systems) and a regular rotation curve, in equal numbers. Therefore, merging cannot be the only process responsible for lowering the gas metallicity in these early galaxies.

From the rotation curve we can also infer dynamical masses, which are in the range $2 \times 10^9 – 2 \times 10^{11}\ M_\odot$. Clearly, some massive rotating discs are already in place at this early epoch in the Universe. However, in contrast to local disc galaxies, at $z \sim 3.3$ rotating discs are much more turbulent. Indeed, as illustrated in Figure 4, the velocity dispersion (σ) is generally comparable with the rotational velocity (V_{max}). More specifically, the average ratio between rotational velocity and velocity dispersion is $\langle V_{max}/\sigma \rangle_{z\,=\,3.3} = 2.2$, to be compared with the value $\langle V_{max}/\sigma \rangle_{z\,=\,0} = 10$ typical of local discs. Galaxies at $z \sim 3.3$ appear to be even more turbulent that those investigated at $z \sim 2$ by the parallel SINFONI programme SINS (Förster Schreiber et al., 2009), which are characterised by $\langle V_{max}/\sigma \rangle_{z\,=\,2} = 4.5$.

The highly turbulent nature of $z \sim 3.3$ discs is likely due to very high gas fractions, which make the discs dynamically unstable. In samples at $1 < z < 2.5$ high gas fractions have been confirmed directly through CO observations (Daddi et al., 2010; Tacconi et al., 2010). At $z \sim 3.3$ we have obtained indirect evidence for high gas fractions (even approaching $f_{gas} = M_{gas}/M_{tot} \sim 0.9$) based on the high surface density of star formation (hence exploiting the Schmidt–Kennicutt relation) and on the comparison between dynamical and stellar masses (Mannucci et al., 2009; Gnerucci et al., 2010; Troncoso et al. in preparation). Such high gas fractions are likely associated with the prominent cold inflows of gas predicted to occur at such early epochs by some theoretical models (e.g., Dekel et al., 2009).

Metallicity gradients and cold flows at $z > 3$

In some galaxies we not only resolve the [O III] 5007 Å emission (used to trace the kinematics), but also the fainter lines of [O II] 3727 Å and Hβ, therefore enabling us to map the metallicity. The rightmost panels in Figure 3 (from Cresci et al., 2010) show the metallicity map for three massive galaxies characterised by regular rotation velocity fields. Surprisingly, in contrast to local galaxies, the minimum metallicity is located close to the central regions. However, the most interesting result is that the minimum metallicity is associated with the peak of Hβ flux, which traces the most active star-forming regions. This result supports the scenario where such massive systems at $z \sim 3.3$ drive major inflows of pristine gas towards their central regions. Such pristine gas both boosts star formation and locally dilutes the pre-existing medium, therefore producing the observed spatial anticorrelation between star formation and gas metallicity.

The same (strong) cold flow scenario can explain, more generally for massive galaxies at $z \sim 3.3$, their reduced metallicity relative to the fundamental metallicity–mass–SFR relation observed at $0 < z < 2.5$, as well as the highly turbulent nature of these systems.

References

Cresci, G. et al. 2010, Nature, 467, 811
Daddi, E. et al. 2010, ApJ, 713, 686
Dekel, A. et al. 2010, Nature, 457, 451
Förster Schreiber, N. M. et al. 2009, ApJ, 706, 1364
Gnerucci, A. et al. 2010, A&A, submitted, arXiv 1007.4180
Maiolino, R. et al. 2008, A&A, 488, 463
Mannucci, F. et al. 2010, MNRAS, 408, 2115
Mannucci, F. et al. 2009, MNRAS, 398, 1915
Tacconi, L. J. et al. 2010, Nature, 463, 781
Troncoso, P. et al. 2010, A&A, submitted