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Shaping massive galaxies: their morphology and kinematics at $z = 1 - 3$

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Abstract

Massive ($M_* \geq 10^{11}\mathrm{M}_\odot$) galaxies at high redshift ($z \geq 1.5$) remain mysterious objects. Their extremely small sizes (effective radii of 1–2 kpc) make them as dense as modern globular clusters. It is thought that a highly dissipational merger is needed to create such compact galaxies. Within this proceedings, we discuss this issue, along with state-of-the-art morphological and kinematic observations of these objects. In the present day Universe massive galaxies contain large sizes, and harbour old and metal-rich stellar populations. In order to explore their development, we present near-IR IFU observations with SINFONI@VLT for ten massive galaxies at $z \sim 1.4$ solely selected by their high stellar mass which allows us to retrieve velocity dispersions, kinematic maps and dynamical masses. We combine this with data from the GOODS NICMOS Survey, the largest sample of massive galaxies (80 objects) with high-resolution imaging at high redshift ($1.7 < z < 3$) acquired to date. As a result, we show how massive galaxy morphology changes possibly result through elusive minor merging.

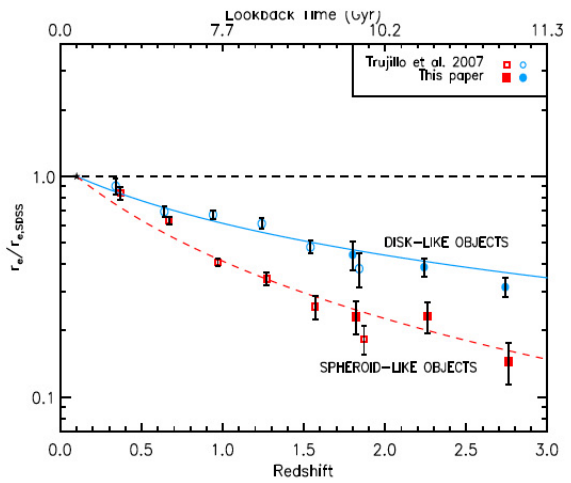
1 Introduction

Our knowledge of massive galaxies at high redshift has broadened in the last few years (for a comprehensive review on this topic see Ignacio Trujillo's review in this proceedings volume). Many photometric ([17, 47, 48, 49, 14, 7] amongst many others) and spectroscopic [30, 51, 13, 10, 41, 40] studies have reported the main characteristics of the galaxy population. This picture is confirmed by the latest observations with adaptive optics [11] and WFC3 [46, 44], apart from deep stacking [52] and theoretical work [55]. Latest results indicate that massive compact galaxies display a variety of star forming properties and are not only composed of quiescent systems as previously thought [42, 1, 50, 12]. By investigating stellar densities for the most massive galaxies at both high and low redshifts we are potentially examining the properties of the precursors of massive spheroids in the Local Universe [2, 28].

Several mechanisms have been argued as possible evolutionary paths for these objects to grow, and thus to match their massive local counterparts, namely major merging [15, 3, 33, 19], minor merging [38, 6, 34] and AGN puffing-up [23, 24]. Due to the insufficient number of major mergers from $z \sim 3$ ($N_m = 1.7 \pm 0.5$ according to [3]) and the measured values of the velocity dispersions for massive galaxies [13], the most likely agent to shape these galaxies is the continuous bombardment by minor satellites. At the same time, this provides a natural explanation for how massive galaxies could maintain a level of star formation, as they are continuously fed with pristine gas from these satellites.

One question yet to be answered is how these compact and massive objects were first formed. The origin of these galaxies should be through a very dissipative process, such as gas-rich mergers in order to produce a compact and massive remnant as a final product. Due to their high gas mass fraction (and thus huge induced star formation) these events should be detected in the sub-millimeter range. The so-called sub-millimeter-galaxies fulfill this criteria, and at the same time they posses the right number densities to account for being progenitors of the massive compact population. Ricciardelli and collaborators in [43] were the first to photometrically test this scenario using a set of HST ACS and NICMOS imaging from the parent sample of [35]. They found a combination of small sizes with a series of morphologies (disks, mergers, compact galaxies) that are consistent with the hypothesis that disk galaxy mergers are the precursors of the ultra-compact massive galaxy population.

The problem arises when one wants to study how these galaxies assembled their mass, and at the same time change their properties to match their local Universe counterparts. It is clear that, while both disks and spheroids decrease dramatically in their size since $z \sim 3$ (Figure 1 left side and [7]), the number fraction of different types switches in comparison with the local Universe (Fig. 1 right side, data taken from POWIR [15] and GNS [16] surveys). However, all these result are based on deep photometry, but ideally one would want to use high signal-to-noise spectroscopy to carefully study how this morphological change is taking place. Due to the high redshifts of the relevant galaxies, up to now very few objects have been observed kinematically. Spatial information is also desirable, as minor features around, or within the outskirts, of the main galaxy can reveal signals of possible minor merging. To facilitate this situation our group performed a series of 3D spectroscopic observations in a sample of massive galaxies at high redshift [8].



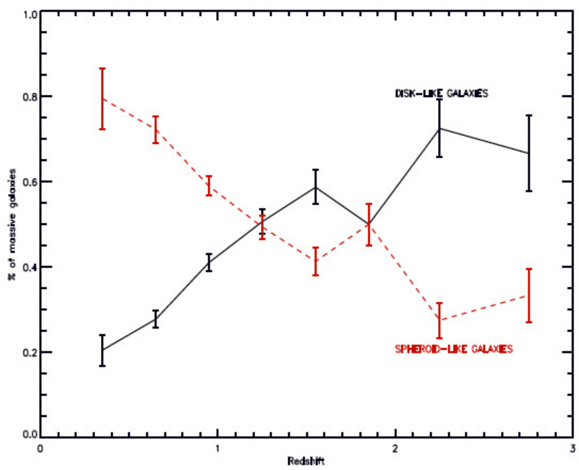


Figure 1: *Left side:* The size evolution of massive galaxies ($M_* > 10^{11}$ $M_\odot$) with redshift [7]. Plotted is the ratio of the median sizes of galaxies in our sample with respect to sizes of nearby galaxies in the SDSS local comparison. The error bars indicate the uncertainty (1σ) at the median position. At a given stellar mass disk-like galaxies at $z \sim 2.3$ are a factor of 2.6 ± 0.3 smaller than present day equal mass systems, and spheroid–like galaxies at the same redshifts are 4.3 ± 0.7 smaller than comparatively massive elliptical galaxies today. *Right side:* Evolution of different morphological types from $0 < z < 3$ using ~ 1000 massive galaxies from [49] and [7]. We also show poissonian error bars on these fractions. The overall tendency towards disk-like galaxies becoming dominant at high redshift is shown. [8].

2 3D spectroscopy observations of massive galaxies

Integral Field Spectroscopy (IFS; aka 3D spectroscopy) is a powerful tool to investigate galaxy kinematics, both at low and high redshifts, using optical and NIR data (see the SAURON Survey [20] or the SINS Survey [25]). When looking at high redshift galaxies, several studies demonstrate an increase of non-circular motions in comparison with the local Universe [31, 32, 53, 53, 21] that may be linked with gas-rich turbulent disks [26], clumpiness and major merging [39] or elusive minor merging and cold gas flows [5]. These works tend to focus on star forming systems that are usually less massive, as more massive galaxies are rarer and shut off their star formation earlier (star formation downsizing [9]), and thus there is a lack of kinematic observations of massive galaxies at high redshfit (with few cases in [29] or [21]).

Here we present a sample of galaxies solely selected by their high stellar mass ($M_* \geq 10^{11} M_\odot$) observed with the SINFONI integral field spectrograph [18, 4] at ESO-VLT. The 10 objects were selected from a large near infrared survey (the Palomar Observatory Wide-field InfraRed survey; POWIR cf. [15]). All components of this sample have $z = 1.36 - 1.41$ to avoid strong OH sky emission lines at the same wavelength. Observations were conducted during 9 nights from June to September 2007 (ESO run ID 079.B-0430(A)) for a total of

1.5 h observation time per object. The instrument was used in seeing limited mode, with a $0.125'' \times 0.25''$ pixel scale ($8'' \times 8''$ field of view) and H grism was utilised (spectral resolution $R \sim 3000$).

We used the ESO pipeline to reduce the data and the PSF stars, and then we constructed our own IDL routines to create kinematic maps, both for Hα and [NII] emission lines. We smoothed the data spatially (using a 2 spaxels gaussian) according to the seeing (mean value $0.56''$). Here we present maps for three of our objects in Fig. 2. We are now finalizing our models to retrieve accurate rotational velocity and velocity dispersion results, with the same formalism presented in [22]. It is important to highlight how much these galaxies appear to rotate. Various caveats however should be taken into account. Emission lines come from ionized gas, and it is not clear to what extent they map the behaviour of the underlying stellar populations. One of the strengthens of our sample is that, being so massive, we can map the continuum of the spectra in our galaxies. We thus know where the main stellar component of our galaxies are, and we compare this with the position of the gas emission. Using this method we find that massive galaxies show disturbances in many cases (e.g., fans of stars, mergers or clumps). But for the majority of cases, remarkably the galaxies show large rotational velocity gradients despite their irregular features, in accordance with the photometric scenario where primordial disks are the bulk of massive galaxies at high-z (see again Fig. 1, right side).

3 Other important results and conclusions

Our group has performed several other studies focused on massive galaxies at high redshift, as we exploit the GOODS NICMOS Survey (GNS; P.I. Conselice, see for a full description [16] and visit http://www.nottingham.ac.uk/astronomy/gns for a list of investigations based on these data and/or to download all the available imaging). In brief, GNS is a large HST program consisting of 180 orbits (60 pointings, 3 orbits per pointing) using the NICMOS3 camera as a NIR infrared counterpart of the GOODS fields. It is optimized to obtain deep photometry of as many massive galaxies as possible. The limiting magnitude is $H = 26.8(5\sigma)$ which is 2 magnitudes fainter than best ground-based observations. Another advantage is the superb HST resolution ($0.1''$/pix with a PSF FWHM $= 0.3''$).

Highlighting the lastest findings [27] have studied the environmental properties for all the galaxies in this sample. Regarding the massive galaxies, no dependency has been found between local density and galaxy size. [37] address the galaxy mass function within the GNS, finding that massive galaxies are largely already in place at redshifts as high as $z = 3$, and also describe how lower massive galaxy populations grow, reaching completeness limits as low as $M_* = 10^{9.5}$ up to the same redshift limit. Furthermore, we pay special attention to probing the star formation history of the massive galaxies, as we mentioned in the introduction. This is a controversial issue, as some authors claim these are quiescent objects [30], whereas others find just the opposite trend [42]. We conducted a number of projects with multi-wavelength coverage, focussing mainly in the far-infrared, in order to have a panchromatic and holistic approach: [1] (Spitzer & ACS), [50] (BLAST & LABOCA) and [12] (using Herschel data from the HerMES survey). Massive galaxies are forming stars at high rates, particularly

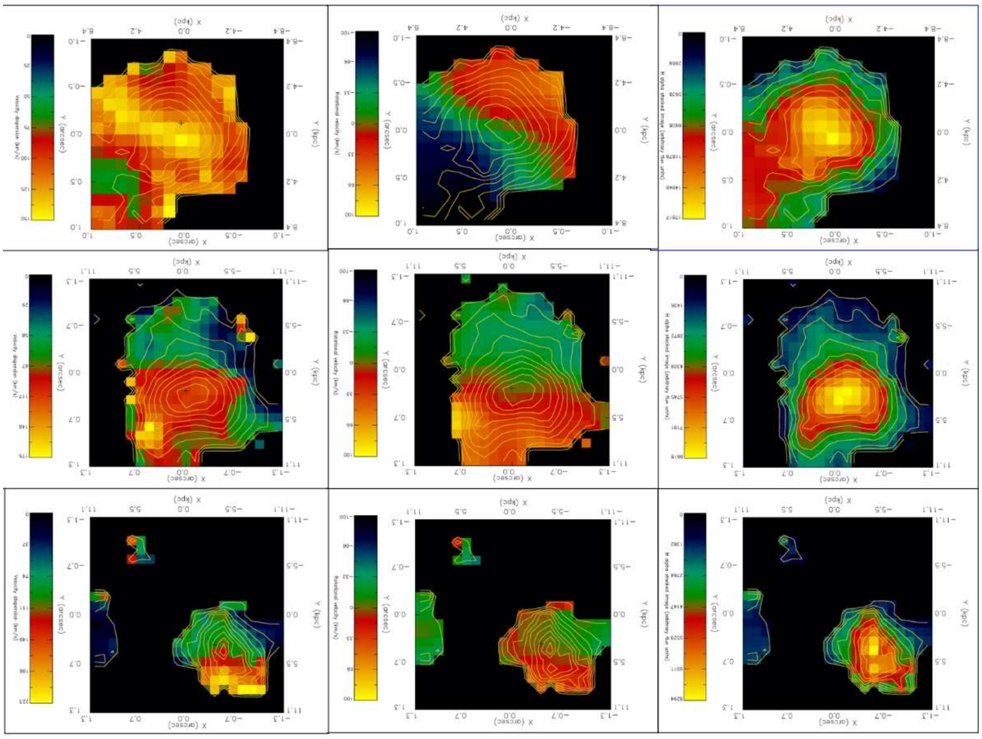


Figure 2: We show flux, rotational velocity and velocity dispersion maps (columns) for three different massive galaxies (rows) with high rotational velocities using 3D spectroscopy [8]. All the pixels shown are above $S/N = 3$. Previous Fig. 1 (right side) suggests a trend towards a majority of disk-like massive objects as redshift increases. This information is based only on photometrical analysis. To fully test this evolution we need to explore the kinematics of massive galaxies.

many compact massive galaxies have SFR of $\sim 100\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$ with SPIRE derived sSFR of $\sim 0.67\,\mathrm{Gyr}^{-1}$.

In conclusion, redshifts $z = 1-3$ are key for understanding how massive galaxies evolve. We discussed several probes in this contribution concerning how these galaxies form, and their possible links with the submillimeter galaxy population, how they change structurally using deep photometry and 3D observations, and finally by using their star formation rates. The GOODS NICMOS Survey which aims to probe massive galaxies at these redshifts is an ideal introduction to the next generation HST surveys which will reveal more information about these puzzling and important objects.

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