Formation and Evolution of Galaxy Outskirts
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The build-up of the outskirts of distant star-forming galaxies at $z \sim 2$

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Abstract. In order to constrain – and understand – the growth of galaxies, we present a sample of ~ 30 galaxies at $z \sim 2$ with resolved distribution of stellar mass, star-formation rate, and dust attenuation on scales of ~ 1 kpc. We find that low- and intermediate-mass galaxies grow self-similarly, doubling their stellar mass in the centers and outskirts with the same pace. More massive galaxies ($\sim 10^{11}$ $M_{\odot}$) have a reduced star-formation activity in their center: they grow mostly in the outskirts (inside-out quenching / formation). Similar trends are find in cosmological zoom-in simulations, highlighting that high stellar mass densities are formed in a gas-rich compaction phase. This nuclear 'starburst' phase is followed by a suppressed star-formation activity in the center, resulting in growth of the outskirts. All in all, we put forward that we witness at $z \sim 2$ the dissipative formation of $z = 0$ M* early-type galaxies.

Keywords. galaxies: bulges, galaxies: elliptical and lenticular, cD, galaxies: evolution, galaxies: formation, galaxies: fundamental parameters, galaxies: high-redshift, galaxies: structure

1. Introduction

Observations of the galaxy population encompassing the last 12 billion years of cosmic time have constrained the mass functions of star-forming and quiescent galaxies, showing that the knee of the mass functions of star-forming galaxies (SFGs) remains roughly constant at $\sim 10^{10.8}$ $M_{\odot}$, while the number density of quiescent galaxies increases by more than a factor of 10 from redshift $z \sim 2$ to today (e.g., Ilbert *et al.* 2013; Muzzin *et al.* 2013). Already by $z \sim 1.5$, the quiescent galaxies are dominating the high-mass end of the galaxy population.

Furthermore, observations have revealed that SFGs form their stars on a tight (~ 0.3 dex scatter), nearly linear relation between stellar mass ($M_{\star}$) and star-formation rate (SFR), the so called 'main sequence' (MS; e.g., Brinchmann *et al.* 2004; Noeske *et al.* 2007; Speagle *et al.* 2014). A simple continuity argument directly implies that high-mass SFGs at $z \sim 2$, which form star at a rate of ~ 200 $M_{\odot}$ yr^{-1}, have to cease ('quench') their star-formation soon in order to comply with the constraints from the mass functions and the MS (Renzini 2009; Peng *et al.* 2010).

To shed light the physics govern the evolution of galaxies, namely the growth of galaxies along the MS and the transition from the star-forming to the quiescent state, it is key to understand how the stellar mass and SFR in centers ('bulges') and outskirts ('disks') evolve with cosmic time. As part of the zC-SINF program (Förster Schreiber *et al.* 2014; Genzel *et al.* 2014; Tacchella *et al.* 2015a; Tacchella *et al.* 2015b), we have collected Hubble Space Telescope imaging and adaptive optics Very Large Telescope SINFONI

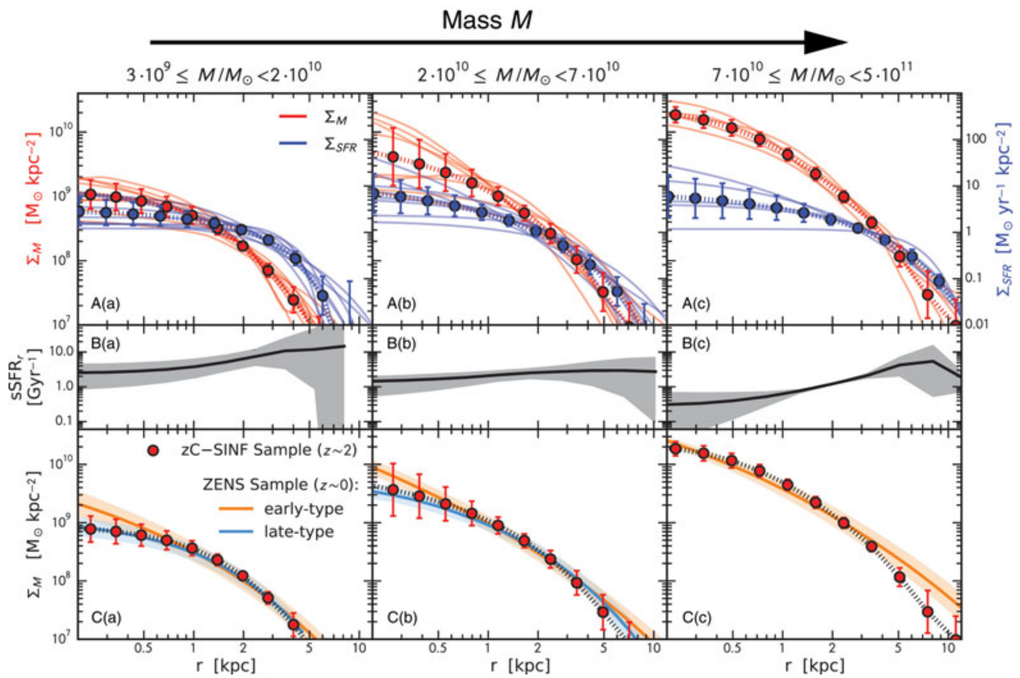

Figure 1. Observed stellar mass and star-formation rate surface density distributions of $z \sim 2$ galaxies. The three columns of (a) to (c) show results for the three bins of stellar mass. Upper row (A): The stellar surface mass density profiles (red) and SFR surface density profiles (blue). Thin lines represent individual galaxies; the mean values are given by the solid circles (with error bars indicating the 1σ scatter). Middle row (B): The mean sSFR profiles. Bottom row (C): The average stellar mass profiles our $z \sim 2$ SFGs (red points with dashed line) overplotted on the average profiles for the mass-matched samples of $z = 0$ galaxies (colors indicate morphological types). Figure adopted from Tacchella *et al.* (2015b).

integral field spectroscopy for ~ 30 $z \sim 2$ SFGs in order to constrain the distribution of stellar mass, dust attenuation, SFR (on timescales of 10^7 yr from Hα and 10^8 yr from UV) and gas kinematics on resolved scales of ~ 1 kpc within *individual* galaxies.

2. Resolved Distribution of Star-Formation and Stellar Mass

In Tacchella *et al.* (2015b) we compare locally within galaxies the stellar mass and SFR surface densities (Fig. 1). We find that the SFR density profiles for galaxies at all masses ($3 \times 10^9 - 3 \times 10^{11}$) are well represented with an exponential disk, whereas the stellar mass density profiles are denser at higher masses: the Sérsic index increases from $n \approx 1$ at lower masses ($\sim 10^9 - 10^{10.5}$ $M_\odot$) to $n \approx 3.3$ at higher masses ($\sim 10^{11} M_\odot$).

Lower mass galaxies have flat sSFR profiles (sSFR$_r$ $= \Sigma_{\rm SFR}/\Sigma_{\rm M}$), indicating that they are doubling their stellar mass at all radii with the same pace (self-similar growth). This can also been seen when comparing high-z galaxies with local galaxies in the plane of central (within 1 kpc) stellar mass density (Σ_1) and total stellar mass: galaxies increase Σ_1 concurrently with their total mass following a tight, nearly redshift-invariant relation.

The massive, $z \sim 2$ SFGs have similar central stellar mass densities as the $z \sim 0$, quiescent early-type galaxies (a few times $\sim 10^{10}$ $M_\odot$ kpc^{-2}), only missing some mass in the outskirts. Therefore, they should reduce the star formation in their centers within a few hundred Myr, while they can keep forming stars in their outskirts for another $2-$

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4 Gyr. Indeed, these massive galaxies have rising sSFR profiles toward the outskirts, with $\mathrm{sSFR}^{-1} \geqslant t_{\mathrm{H}}$ in their centers, indicating heavily star-forming outskirts around quiescent centers. The bulk of the growth happens for these galaxies in their outskirts (inside-out quenching / inside-out growth). Furthermore, the presence of a bulge component argue for a gas-rich, dissipative bulge formation process at even earlier epochs, which is consistent with the properties of typical $z \sim 0$ early-type galaxies, namely fast-rotating kinematics with disk-like isophotes, steep nuclear light profiles, and steep metallicity gradients.

3. The Perspective from Simulations

To constrain the physical processes behind the observed trends, we analyse a set of cosmological zoom-in simulations (see Ceverino *et al.* 2014). Consistent with observations, we find that galaxies grow self-similarly at low masses, and inside-out at late comic epoch and high masses (Tacchella *et al.* 2016a). The simulated galaxies form their high central stellar mass densities by gas-driven compaction phases, in which a dissipative inflow happens when the gas fraction is high and the angular momentum of the gas is low (Dekel & Burkert 2014; Zolotov *et al.* 2015). This compaction phase marks the onset of gas depletion in the center, during which the central gas is exhausted due to SFR and outflow, while the inflow from the disk is suppressed. Galaxies show the signature of inside-out quenching, where the SFR first reduces in the center, and then the outskirts can be replenished by fresh gas accompanied by new star formation.

We link this evolutionary sequence to the evolution of galaxies about the MS (Tacchella *et al.* 2016b). We find that galaxies oscillate about the MS ridge on timescales of $\sim 0.4\, t_{\mathrm{H}}$. Galaxies on the upper envelope of the MS have high central gas densities, forming most of the stars in their bulge regions, while galaxies at the lower envelope form most of their stars in the outskirts. The self-regulated nature of these mechanisms can explain the confinement of SFGs into a MS narrower than ± 0.3 dex. A halo above the critical mass for virial shock heating, $\sim 10^{11.5}\ M_{\odot}$, helps suppressing the replenishment and makes long-term quenching possible.

Adding the pictures of the observations and simulations together, we put forward that our observations of the massive $z \sim 2$ galaxies reveal the dissipative formation of $z = 0$ M* early-type galaxies.

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