Challenges in Panchromatic Modelling with Next Generation Facilities
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Modelling the emission of passive galaxies at z∼3

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Abstract. Early-type galaxies (ETGs) are of crucial importance to trace back the galaxy mass assembly across cosmic time, yet their formation and quenching remain remarkably elusive. The discoveries of massive, dead galaxies at ever-growing redshifts provided compelling evidence to push their formation up to redshift $>4-5$ when the Universe was barely 1 Gyr old. In this talk I will present our results on the ages of a new sample of ETGs at $z\sim3$, built by exploiting HST WFC3/G141 rest-frame optical/near-UV grism spectroscopy to study the nature of 10 passive galaxy candidates at $2.5<z<3.5$ in COSMOS.

This work is part of a PhD project aimed at quantifying the parent space density of distant *genuine* passive galaxies. I will also discuss the importance of multi-wavelength data in clarifying the degree of contamination by dusty star-forming galaxies affecting the color selection.

Keywords. Galaxies: evolution , Galaxies: elliptical and lenticular, cD, Galaxies: high-redshift

1. Introduction

The early formation and quenching of massive galaxies are still to be clarified by modern astrophysics. Passively Evolving Galaxies (PEGs) have been shown to host the bulk of the stellar mass in the local Universe (Baldry *et al.* (2004); Renzini & Peng 2015), thus representing good candidates to trace back the galaxy mass assembly. The larger their stellar mass, the earlier their formation. Specifically, archaeological studies of ETGs at $z\sim0$ estimated the formation of the most massive galaxies to be at $z\gtrsim4$ with Star Formation Histories (SFHs) characterized by strong and narrow peaks in Star Formation Rate (SFR) (e.g. Thomas *et al.* 2010). So, how fast is their mass growth and quenching? How many already passive galaxies can we expect to find as early as $z\sim3$? Populations of compact quiescent galaxies have been found at progressively higher redshifts ($1<z<3$) (Franx *et al.* 2003; Cimatti *et al.* 2004; Kriek *et al.* 2006; Straatman *et al.* 2014). Nonetheless, they are described as rare objects at $z>3$ by current number densities and mass functions at the high-mass end (Muzzin *et al.* 2013; Davidzon *et al.* 2017). These mass functions, however, heavily rely on galaxy colors to establish their passiveness, therefore a spectroscopic confirmation of photometric candidates is crucial to alleviate the uncertainty on the level of their star-formation.

While photometric identification of passive galaxy candidates is already probing $3<z<4$ range, spectroscopic confirmation of such objects is struggling at breaking the $z\sim3$ barrier with current facilities. Individual high-z spectra where acquired for a few galaxies placed at z $\gtrsim$ 3 (Gobat *et al.* 2012; Glazebrook *et al.* 2017; Newman *et al.* 2018; Schreiber *et al.* 2018), the latter work showing MOSFIRE spectra of 4 objects, in the ZFOURGE catalog, with moderately evolved stellar populations (Balmer Breaks) at 3.2 < z < 3.7. The degree of contamination of the UVJ color selection by dusty star-forming galaxies was reported to be of 21% and the number density of quiescent galaxies of $(1.4 \pm 0.3) \times 10^{-5} Mpc^{-3}$, one dex higher than what hydrodynamical simulations and semi-analytic models predict (Qin *et al.* 2017a,b; Wellons *et al.* 2015; Davé *et al.* 2016) at $3 < z < 4$ and $log(M_{\star}/M_{\odot}) > 10.5$. Here we tackle this issue by studying the HST grism spectra of a pilot sample of 10 passive galaxy candidates at z ∼ 3.

2. Data and Methods

The sample consists of the most massive ($\mathrm{logM}_{\star} > 10.7$, $H_{AB} < 22$) 10 passive galaxy candidates with photometric redshifts within $2.5 < z_{phot} < 3.5$ in the COSMOS field. The selection as passive was performed on the basis of their rest-frame UVJ (Williams *et al.* 2009) colors, excluding galaxies with observed (B-z) and (z-K) colors (also known as the BzK selection) indicative of star-forming objects (Daddi *et al.* 2004). A fraction (50%) of the sample is sBzK-uncertain, i.e. formally classified as star-forming but with S/N in the B-band (and in some cases z-band) not sufficient to reject a passive nature. Additional criteria were the absence of 24μm detections in the McCracken *et al.* 2010 catalog and the lack of acceptable SED fits for dusty starburst solutions to broad-band photometry (from B to IRAC). Our HST program (P.I. E. Daddi) was designed to get WFC3/IR low resolution (R = 130) G141 slitless spectra, for a total of 17 orbits, including F160W ancillary imaging. The data were reduced and analized by means of the `grizli` software package†. The spectra were optimally extracted (Horne *et al.* 1986) and fitted with the composite stellar populations (CSPs) from Bruzual & Charlot 2003 templates, using four different SFHs to account for diverse modes of star-formation, namely allowing for a constant SFR, exponentially declining, delayed exponentially declining and a truncated SFH. We apply the Calzetti *et al.* 2000 extinction law and Salpeter IMF. Best fit templates are evaluated by their goodness of fit.

3. Results

We find 8 passive galaxies with moderately evolved stellar populations showing evidence of Balmer/4000 Åbreaks and low values of dust extinction, 3 of which are placed at z $\gtrsim$ 3 (Fig. 1). The determination of the significance for the secondary solution is currently work in progress. The remainder 2 candidates (ID266486 and ID581181) show best-fit solutions consistent with being star-forming interlopers. These two objects have 24 μm Spizter/MIPS > 4σ detections in the Super-Deblended catalog by Jin *et al.* 2018, further supporting this picture. No further detections from 100 μm to 1.4 GHz (Spitzer/Herschel/SCUBA-2/AzTEC/MAMBO/VLA) are present for our sources. The fit results can be found in Table 1. The measured spectroscopic redshifts agree with the z_{phot} of the parent sample with the calibration by Strazzullo *et al.* 2015, given their uncertainty of $\frac{\delta z}{1+z} = 0.06$ (see Fig. 2).

4. Future Perspectives

A further improvement to be undertaken is the simultaneous fit of both spectra and photometry, fully exploiting the wavelength coverage of the COSMOS field. We will also check for any X-ray detections and ultimately derive the number density of the early passive population. Moreover, these galaxies offer an unique opportunity to extend the work of Gobat *et al.* 2018 on individual high-z quiescent galaxies. The goal will be to

† https://github.com/gbrammer/grizli

Table 1. Targets' characteristics and Simple Stellar Population equivalent best fit age. Stellar masses were derived using the Chabrier 2003 IMF.

ID	z	log($M_\star$)	t_{SSP} [Gyr]
20600	$2.841^{+0.021}_{-0.018}$	11.0	0.5
402009	$2.667^{+0.015}_{-0.002}$	11.1	0.6
266486	$2.666^{+0.046}_{-0.021}$	11.4	0.1
21292	$2.557^{+0.005}_{-0.005}$	11.2	0.7
93434	$3.124^{+0.003}_{-0.003}$	11.0	0.5
581181	$2.393^{+0.011}_{-0.000}$	11.0	0.6
316710	$2.998^{+0.002}_{-0.003}$	11.0	0.5
248503	$2.801^{+0.005}_{-0.002}$	10.9	0.3
227846	$2.665^{+0.007}_{-0.007}$	10.9	0.1
169603	$3.230^{+0.007}_{-0.006}$	10.7	0.3

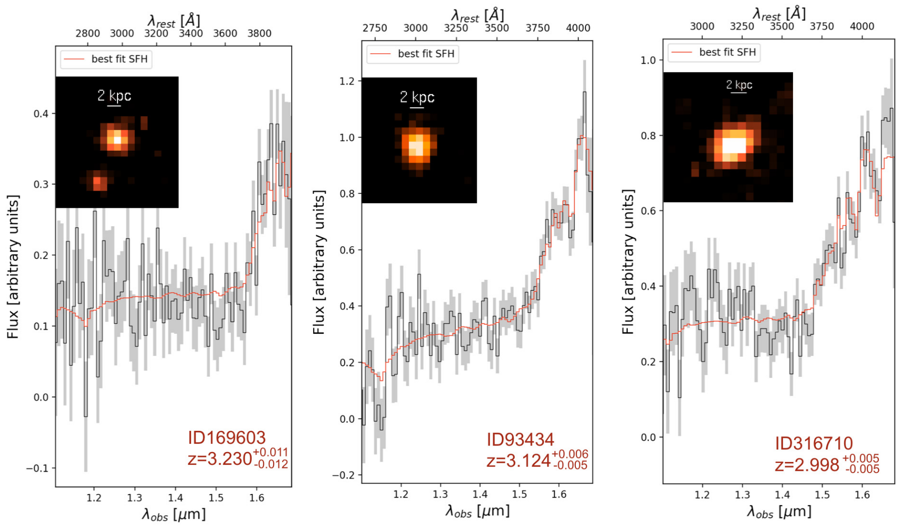

Figure 1. HST spectra are shown for our z∼3 objects. Red curves: best fit CSPs from BC03. Cutouts from HST/WFC3 F160W imaging are reported.

investigate whether the fast rise in the molecular gas fraction in ETGs from $z \sim 0$ to $z \sim 1.8$ steepens, remains flat or inverts when looking at higher lookback times (Fig. 3). The addition of photometric data in the 1.1mm regime (ALMA and NOEMA) will allow us to estimate the dust mass, M_{dust}, from the FIR flux taking advantage of the optically thin Rayleigh-Jeans tail of thermal dust emission as in Magdis *et al.* 2011 and Scoville 2013. This will allow us to estimate M_{dust} by fitting the 260 GHz fluxes with templates of dust grain emission (Draine & Li 2007) by varying the mean intensity of the radiation field $< U >$ and the dust temperature (T_{dust}) as in Béthermin *et al.* 2015; and to put a first constraint on the gas mass by assuming a reasonable gas-to-dust ratio (G/D) conversion (Galametz *et al.* 2011; Magdis *et al.* 2011; Magdis *et al.* 2012a; Gobat *et al.* 2012) and a gas-metallicity phase close to the solar value given the high stellar masses of our sample (see Table 1). The clarification of the high-z trend could have important implications in determining whether the quenching mechanisms that acted on these galaxies were efficient or not at removing the pre-existing fuel for star formation.

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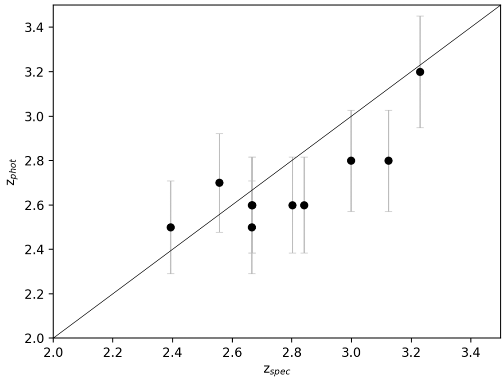

Figure 2. Comparison between spectroscopic and photometric redshifts of our sample, which confirm the appropriateness of our adopted photometric redshift calibration from Strazzullo *et al.* 2015. Degeneracies are not yet explored.

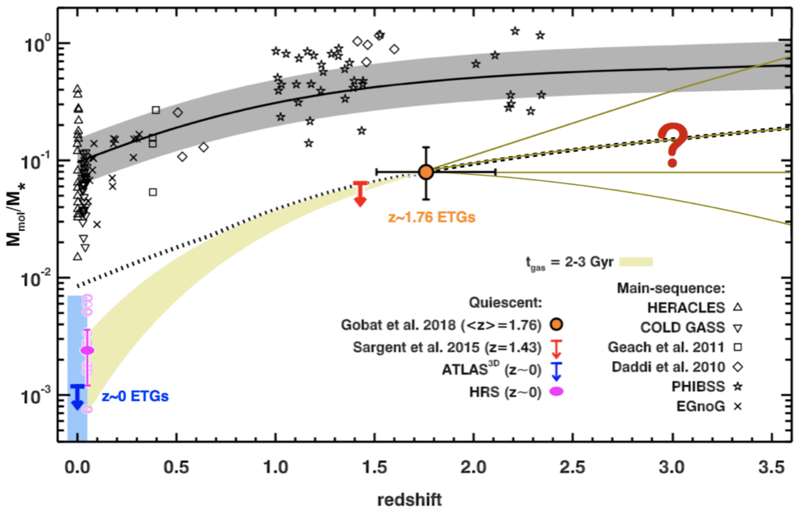

Figure 3. Evolution of molecular gas fraction $M_{mol}/M_{\star}$ as a function of redshift for main sequence and quiescent galaxies. The reference sample of 977 ETGs at $< z >\sim 1.76$ is marked as an orange dot. The solid line shows the the evolution of an average MS galaxy with stellar mass $5 \times 10^{10} M_{\odot}$. The red dashed curve shows the dust fraction evolution (traced by molecular gas) offset by a factor of 6 and for the median stellar mass of the Gobat *et al.* 2018 sample.

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Discussion

MANATARI: By what redshift should the passive galaxies form their stellar mass?

D'EUGENIO: Typically $z \sim 4$, but it depends on the underlying Star Formation History. Here we are sensitive to the last episode of star formation, so the bulk of the stellar mass could have formed even earlier.

CARNALL: Have you considered the implied OII fluxes you should see for your best-fitting solutions for your HST grim data? This could help you discriminate between dusty and passive.

D'EUGENIO: No, not yet but it is a nice suggestion. Thank you.

CEVERINO: A comment: The color selection may miss an important population of high-z, post-starburst galaxies with bluer colours, according to cosmological simulations (Ceverino, Klessen & Glover 2000).

D'EUGENIO: We are not looking for post-starburst galaxies but for galaxies with several hundred Myr of quiescence so, in this sense, the color selection might allow us to be conservative.