UNVEILING OLD MASSIVE SPHEROIDAL GALAXIES IN THE YOUNG UNIVERSE

VERY DEEP VLT SPECTROSCOPY HAS UNVEILED THE EXISTENCE OF OLD AND MASSIVE SPHEROIDAL GALAXIES WHEN THE UNIVERSE WAS STILL YOUNG, THUS SHOWING THAT MASSIVE GALAXIES FORMED EARLIER AND FASTER THAN HAS BEEN EXPECTED FROM CURRENT THEORIES OF GALAXY FORMATION.

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UNDERSTANDING THE PHYSICS and tracing the cosmic history of galaxy mass assembly is one of the main open questions of galaxy formation and evolution. Despite the tremendous progress in observational cosmology, the accuracy in the estimate of cosmological parameters and the successful convergence on the ΛCDM cosmological model, the mechanisms leading to the birth and the evolution of galaxies are still poorly known.

The generally accepted framework of galaxy formation is known as hierarchical merging. In the early Universe, small mass density fluctuations (such those observed with WMAP) trigger gravitational instability and dark matter halos begin to collapse from the ambient background. Each dark matter halo contains a fraction of baryonic matter. This pristine baryonic gas starts to condense and, through its cooling, the first disks form at the center of dark matter halos. Star formation converts cold gas into luminous stars and chemical enrichment and feedback effects also start to play a relevant role (e.g. through supernova explosions). Galaxies assemble and increase their mass gradually through the merging of dark matter halos, and a collision between two or more disk galaxies is thought to produce a spheroidal galaxy. In this scenario, the young Universe is expected to be populated by small mass objects which are the first to form, whereas the most massive galaxies are the last product of the "merging tree" evolution.

The empirical approach adopted by astronomers to investigate galaxy formation and evolution is to search for and to study the populations of distant galaxies. Samples selected in the optical bands allow us to cull star-forming galaxies where the redshifted ultraviolet (UV) radiation is dominated by hot, massive and short-lived stars. However, optical samples are affected by severe biases due to the strong influence of dust extinction in the UV and to the wide range of shapes that spectral energy distributions (SEDs) have in the UV depending on the level of star formation activity and the age of the galaxy.

At longer wavelengths, the above problems are alleviated, as the rest-frame optical and, even better, the near-infrared radiation is dominated by low mass, long-lived stars (with a lifetime comparable to the age of the Universe). Also, the shapes of the SEDs in the optical/near-IR are very similar for all galaxy types, and the effects of dust extinction become less severe. In addition, the rest-frame optical/near-IR luminosity is known to correlate with the galaxy mass. The above advantages make galaxy samples selected in the near- (e.g. *K*-band at 2.2 µm) or, even better, in the mid-IR (e.g. ~4–8 µm, now possible with the Spitzer Space Telescope) more suitable than optical samples to investigate galaxy evolution and, particularly, the history of galaxy mass assembly, because they allow us to observe the rest-frame optical and near-IR for high redshift galaxies.

Recent results based on *K*-selected samples consistently show that from z~0 to z~1 there is a mild evolution of the global stellar mass density in the Universe (e.g. Fontana et al. 2004 and references therein; Glazebrook et al. 2004). This suggests that most stellar mass was already in place and most galaxies completed their mass assembly by z~1, i.e. when the Universe was about 5.9 Gyr old (H_o=70 km/s/Mpc, with $h_{70}=H_o/70$, Ω_M=0.3 and Ω_Λ=0.7 are adopted throughout the article). However, the evolution is poorly known at higher redshifts ($z > 1$). In this context, the formation and evolution of E/S0 galaxies play a particularly relevant role because in the present-day Universe (13.7 Gyr old), up to 75% of the stellar mass is locked up in these galaxies with spheroidal morphology. While it is now generally accepted that the number density of field massive E/S0 systems remains rather constant out to $z \sim 1$, it is still unknown whether the paucity of spheroidal galaxies at $z > 1$ is a real effect of galaxy evolution or an observational bias.

Addressing this problem is difficult because for $z > 1.3$ these galaxies become very faint in the optical and lack strong spectral features observable in optical spectra. This makes such objects among the most difficult targets to identify even with the

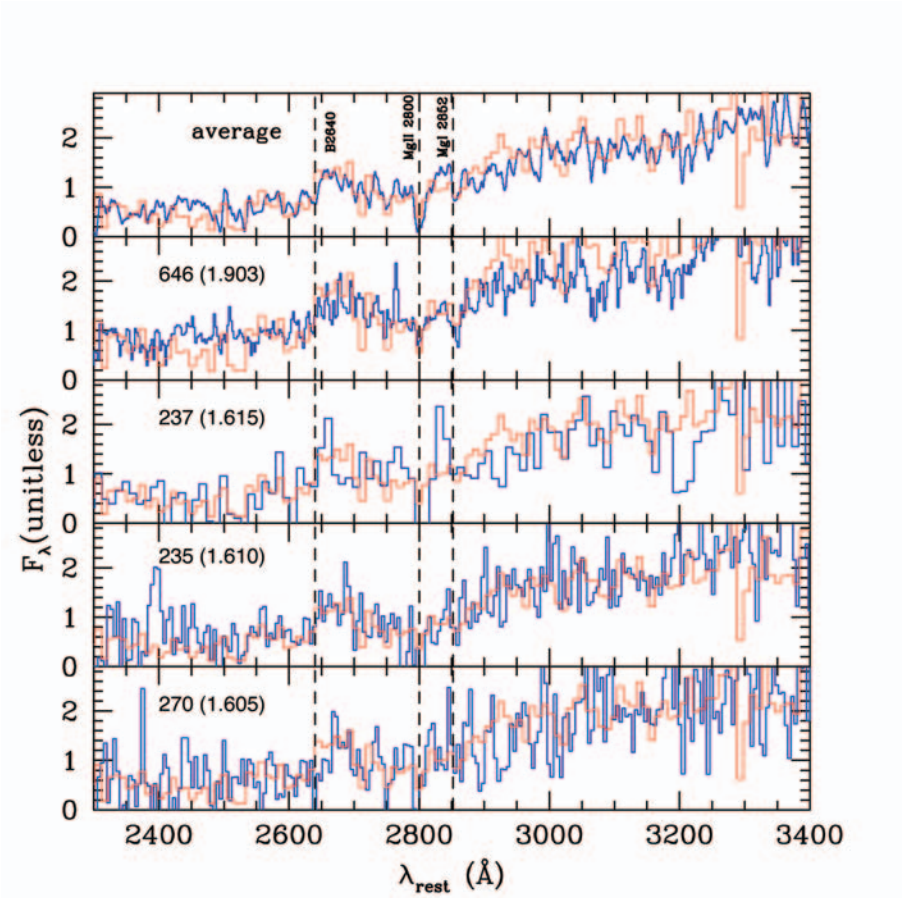

Figure 1: From top to bottom: the average spectrum of the four old galaxies ($z_{average}$=1.68) and the individual spectra. The red line is the spectrum of the old galaxy LBDS 53w091 (Dunlop et al. 1996; z=1.55) used to search for spectra with a similar continuum shape. Weak features in individual spectra (e.g. Mg II λ2800 and the 2640 Å continuum break, B2640) become clearly visible in the average spectrum.

largest optical telescopes. Indeed, while star-forming galaxies and quasars are now routinely found up to $z \sim 6.5$, the most distant spectroscopically confirmed old spheroid is still a radio–selected object at $z = 1.55$ discovered almost a decade ago (Dunlop et al. 1996).

Searching for the oldest galaxies at high redshift

One way of addressing the question of massive and spheroidal galaxy formation is to search for the farthest and oldest galaxies with masses comparable to the most massive galaxies in the present-day Universe (10^{11-12} $M_\odot$), and to use them as the "fossil" tracers of the most remote events of galaxy formation.

Following this approach, we recently made use of the database resulting from the completed ESO VLT Large Programme called "K20 survey" (Cimatti et al. 2003). This dataset consists of deep optical spectra obtained with FORS1 and FORS2 for a sample of 546 *K*-selected objects with $K_S < 20$ (Johnson photometric scale) and extracted from an area of 52 arcmin^2. Part of the K20 sample (348 objects) is located in 32 arcmin^2 within the GOODS field (Giavalisco et al. 2004) (hereafter the GOODS/K20 field). The overall spectroscopic redshift (z_{spec}) completeness of the K20 survey is 92%, and multi-band photometry (*BVRIzJHK*$_S$) is also available for all galaxies to derive and characterize their SEDs and to estimate the photometric redshifts (z_{phot}) for galaxies without

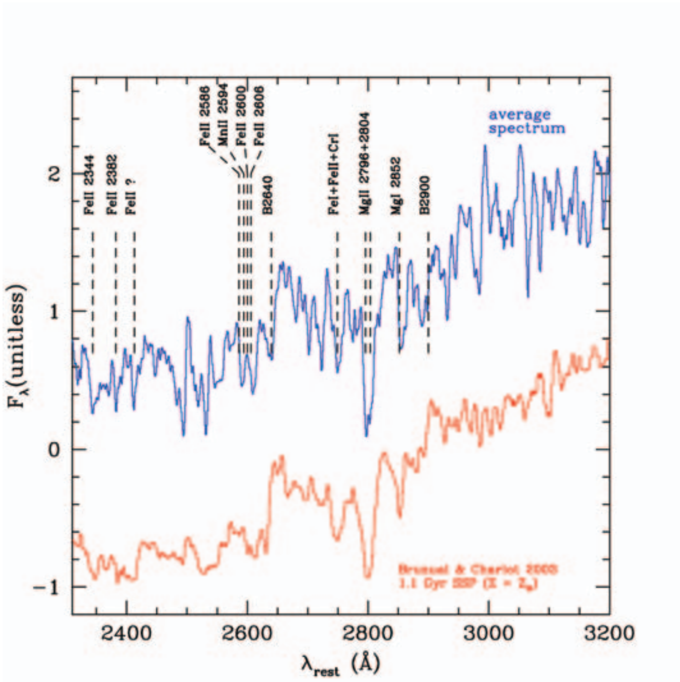

Figure 2: A zoom on the average spectrum (blue), corresponding to 34.4 hours integration time, compared with the synthetic spectrum of a 1.1 Gyr old simple stellar population (SSP) with solar metallicity (Z=Z$_\odot$) and Salpeter IMF (red) (Bruzual & Charlot 2003 models).

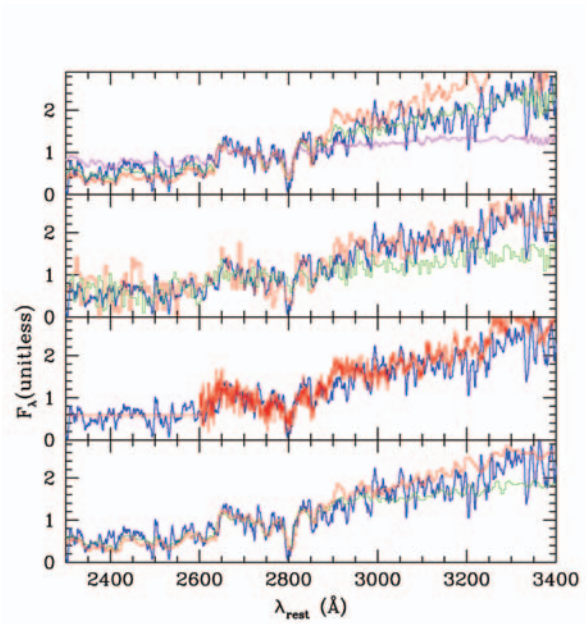

Figure 3: The average spectrum (blue) compared to a set of template spectra. From bottom: F2 V (green) and F5 V (red) stellar spectra with Z=Z$_\odot$, the composite spectrum (red) of 726 luminous red galaxies at $0.47 < z < 0.55$ selected from the SDSS (available only for λ>2600 Å), the average spectra of z~1 old (red) and dusty star-forming (green) EROs, Bruzual & Charlot (2003) SSP synthetic spectra (Z=Z$_\odot$, Salpeter IMF) with ages of 0.5 Gyr (magenta), 1.1 Gyr (green) and 3.0 Gyr (red).

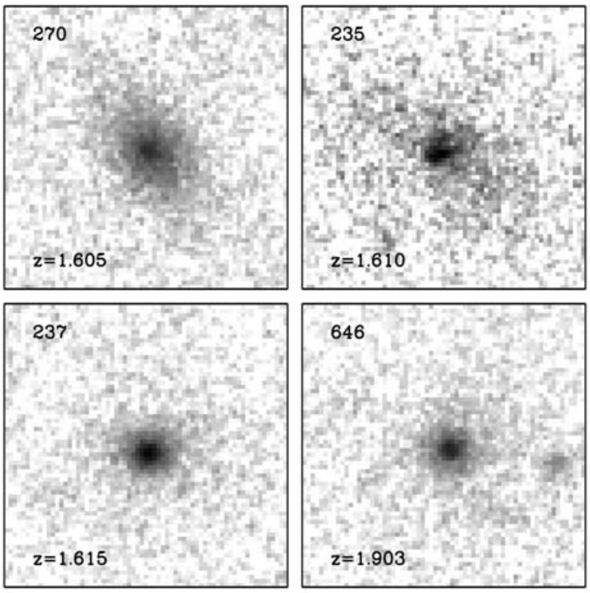

Figure 4: Images of the four galaxies taken with the *Hubble Space Telescope* + ACS through the F850LP filter (from GOODS data) which samples the rest-frame ~3000-3500 Å for $1.6 < z < 1.9$. The images are in logarithmic grey–scale and their size is 2″×2″, corresponding to ~17×17 kpc for the average redshift z=1.7 and the adopted cosmology.

spectroscopic redshifts. We complemented the K20 survey database with the ESO/GOODS public spectroscopy to increase the z_{spec} completeness to 94% (Vanzella et al. 2004). For the GOODS/K20 field it was also possible to complement VLT spectroscopy with deep imaging obtained using the *Hubble Space Telescope* equipped with the Advanced Camera for Surveys (ACS) (*BViz* bands) and publicly released by the GOODS HST *Treasury Program* (Giavalisco et al. 2004).

In order to investigate the evolution of distant massive galaxies, the available spectra within the GOODS/K20 field were then used to search for galaxies at $z > 1.5$ with the continuum UV spectra expected in case of old stellar populations. We spectroscopically identified four galaxies with $18 \le K_S \le 19$ and $1.6 \le z_{spec} \le 1.9$ which have rest-frame mid-UV spectra with shapes and continuum breaks compatible with being dominated by old stars and $R–K_S \ge 6$ (Cimatti et al. 2004) (i.e. the colour expected at $z > 1.5$ for old passively evolving galaxies due to the combination of old stellar populations and k-correction effects).

The spectra were obtained with FORS2 (MXU mode), grisms 200I (R(1″) ~ 400) (ID 237) and 300I (R(1″) ~ 600) (IDs 235, 270, 646), 1.0″ wide slit and ≤ 1″ seeing conditions (see Cimatti et al. 2003 for details on the observation techniques and data reduction). The integrations times were 3 hours for ID 237, 7.8 hours for IDs 235 and 270. For ID 646, the ESO/GOODS public spectrum (8 hours) was co-added to our K20 spectrum (7.8 hours), thus providing a very deep spectrum with 15.8 hours integration time. Figure 1 shows the spectra of the individual objects. A fairly precise determination of the redshift was possible based on absorption features and the overall continuum spectral shape.

Ages and formation epochs

In order to increase the signal-to-noise ratio and to perform a detailed spectral analysis, we co-added the spectra of the four galaxies and obtained an average spectrum corresponding to 34.4 hours of integration time. The co-added spectrum (Figs. 1–3) shows a mid-UV continuum shape, breaks and absorption lines that are intermediate between those of a F2 V and a F5 V star. It is also very similar to the average spectrum of z~1 old Extremely Red Objects (EROs) (Cimatti et al. 2003), and slightly bluer than that of the z~0.5 Sloan Digital Sky Survey (SDSS) red luminous galaxies and of the z=1.55 old galaxy LBDS 53w091 (Dunlop et al. 1996). However, it is different in shape and slope from the average spectrum of z~1 dusty star-forming EROs (Cimatti et al. 2003).

The observed average spectrum was compared through a χ^2 fitting to a library of synthetic template spectra of "simple stellar populations" (SSPs) with a range of ages of 0.1–3.0 Gyr with assumed metallicities Z= 0.4×, 1.0×, and 2.5×$Z_\odot$. In the case of solar metallicity, the ranges of ages acceptable at 95% confidence level are $1.0^{+0.5}_{-0.1}$ Gyr and $1.4^{+0.5}_{-0.4}$ Gyr for SSP models of Bruzual & Charlot (2003) and Jimenez et al. (2004) respectively (see also Fig. 3, top panel). Ages ~50% younger or older are also acceptable for $Z=2.5\,Z_\odot$ or $Z=0.4\,Z_\odot$ respectively. The 2640 Å and 2900 Å continuum break amplitudes measured on the average spectrum are B2640=1.8±0.1 and B2900=1.2±0.1. These values are consistent with the ones expected in SSP models for ages around 1–1.5 Gyr and solar metallicity. For instance, the SSP model spectrum shown in Fig. 2 has B2640=1.84 and B2900=1.27.

An average age of about 1–2 Gyr ($Z=Z_\odot$) at $<z>$~1.7 implies that the onset of the star formation occurred not later than at z~2.5–3.4 (z~2–2.5 for $Z=2.5\,Z_\odot$). These are strict lower limits because they follow from assuming "instantaneous bursts", whereas a more realistic, prolonged star formation activity would push the bulk of their star formation to an earlier cosmic epoch. As an illustrative example, the photometric SED of ID 646 (z=1.903) can be reproduced (without dust) with either a ~1 Gyr old instantaneous burst occurred at z~2.7, or with a ~2 Gyr old stellar population with a star formation rate declining with $exp(-t/\tau)$ ($\tau = 0.3$ Gyr). In the latter case, the star formation onset would be pushed to z~4 and half of the stars would be formed by z~3.6.

The morphology of the old galaxies

In addition to spectroscopy, the nature of these galaxies was investigated with the *Hubble Space Telescope*+ACS (*Advanced Camera for Surveys*) imaging from the GOODS public *Treasury Program* (Giavalisco et al. 2004). On visual inspection, the galaxies have rather compact morphologies with most of the flux coming from the central regions. A quantitative analysis of their surface brightness profiles show that objects ID 237 and ID 646 have the steep profiles typical of elliptical galaxies, object ID 270 is better reproduced by a somewhat flatter profile, whereas ID 235 has a profile between a disk and spheroid. These two latter galaxies may be bulge-dominated spirals but no bulge/disk decomposition was attempted due to the faintness and small angular size of these galaxies. Ground-based near-infrared images taken under 0.5″ seeing conditions with the ESO VLT+ISAAC through the K_S filter (rest-frame ~6000–8000 Å) show very compact morphologies for all four galaxies, but no surface brightness fitting was done. The bottom line is that the surface brightness distribution of these galaxies is typical of elliptical/ early-type galaxies.

Stellar masses and main implications

Besides pushing the identification of the highest redshift elliptical galaxy to z~1.9, these objects provide new and enlightening clues on massive galaxy formation and on the evolution of the mass assembly.

In order to estimate the stellar masses of the identified galaxies, their multi-band photometric SEDs were successfully fitted without the need for dust extinction, and using a library of simple stellar population (SSP) models with a wide range of ages, $Z=Z_\odot$ and Salpeter IMF. This procedure yielded best-

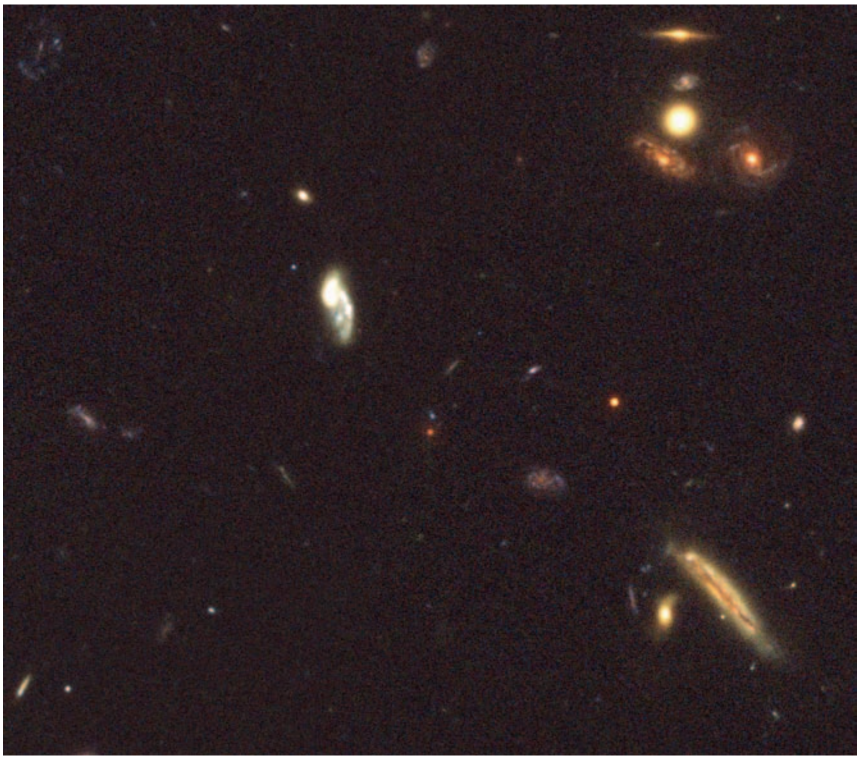

Figure 5: Zoomed image of the GOODS/K20 field (40×40 arcsec) centered on the highest redshift galaxy in the sample (ID 646; z=1.903). The colors are representative of the real galaxy colors, and it is evident that ID 646 is the reddest object in the field compared to the other faint galaxies. The red colors are due to the old stars contained in this evolved galaxy. This image was obtained with the public GOODS HST + ACS data in *bviz* bands (courtesy of R. Fosbury, ESO/ST-ECF, and P. Rosati, ESO).

fitting ages of 1.0–1.7 Gyr (consistent with the spectral analysis), the mass-to-light ratios and hence the stellar mass of each galaxy, which results in the range of 1–3 10^{11} h_{70}^{-2} $M_\odot$. With stellar masses $M_* > 10^{11}$ h_{70}^{-2} $M_\odot$, these systems would rank among the most massive galaxies in the present-day universe, suggesting that they were fully assembled already at this early epoch.

The number density of such systems turns out to be quite high. Within the comoving volume corresponding to 32 arcmin^2 and $1.5 < z < 1.9$ (40,000 h_{70}^{-3} Mpc^{-3}), their comoving density is about 10^{-4} h_{70}^{-3} Mpc^{-3}, corresponding to a stellar mass density of about 2 10^7 h_{70} $M_\odot$Mpc^{-3}. This is about 10% of the local (z=0) value for masses greater than 10^{11} $M_\odot$, ~20–30% of the total density at $1.5 < z < 2.0$, and a substantial fraction (up to ~50–60%) of the stellar mass density for galaxies with $M^* > 10^{11}$ $M_\odot$ at $1.5 < z < 2.0$ (Fontana et al. 2004; Glazebrook et al. 2004). This mass density is comparable to that of star-forming $M_* > 10^{11}$ $M_\odot$ galaxies at z~2, suggesting that while the most massive galaxies in the local universe are now old objects with no or weak star formation, by z~2 passive and active star-forming massive galaxies co-existed in nearly equal number.

Although more successful than previous models, the most recent realizations of semi-analytic hierarchical merging simulations still severely underpredict the density of such old galaxies: just one old galaxy with $K_S < 20$, $R–K_S < 6$, and $z > 1.5$ is present in the mock catalog for the whole GOODS/CDFS area five times wider (see also Fontana et al. 2004 and Glazebrook et al. 2004). As expected for early-type galaxies, the three galaxies at z~1.61 may trace the underlying large scale structure. In this case, our estimated number density may be somewhat biased toward a high value. On the other hand, the number of such galaxies (and their relative stellar mass density) in our sample is likely to be a lower limit due to the spectroscopic redshift incompleteness. There are indeed up to three more candidate old galaxies in the GOODS/K20 sample with $18.5 \le K_S \le 19.5$, $1.5 \le z_{phot} \le 2.0$, $5.6 \le R–K_S \le 6.8$ and compact HST morphology. Thus, in the GOODS/K20 sample the fraction of old galaxies among the whole $z > 1.5$ galaxy population is 15 ± 8% (spectroscopic redshifts only), or up to 25 ± 11% if also all the 3 additional candidates are counted.

The existence of such old, massive, fully assembled spheroidal galaxies when the Universe was only about one-quarter of its present age and supposed to be dominated by young galaxies with smaller masses, shows that the build-up of massive early-type galaxies occurred earlier and much faster than has been expected from theoretical simulations of galaxy formation. This raises crucial questions on the actual understanding of the processes regulating the birth and evolutionary history of baryonic structures in the Universe. Remaining within the framework of ΛCDM hierarchical merging, one possibility is to find a physical process capable of accelerating and boosting star formation in the most massive dark matter halos, and to rapidly suppress it. This is equivalent to make hierarchical merging mimic the old–fashioned "monolithic" collapse. From the observational point of view, searching for and studying the high-z progenitors of these old galaxies will allow us to understand what mechanisms make it possible to assemble such large masses in a relatively short time.

Populating the "redshift desert"

The redshift range around $1.4 < z < 2.5$ has been traditionally known as the "redshift desert" because of the difficulty of spectroscopically identifying galaxies due to the lack of strong spectral features redshifted in the optical spectra. However, this redshift range is also considered critical because it may represent the cosmic epoch when most star formation activity and galaxy mass assembly took place. Recent work has started to unveil the nature of the galaxies living in the desert. Our results show that, in addition to actively star forming galaxies (Daddi et al. 2004; Steidel et al. 2004), a substantial number of "fossil" systems also already populate this redshift range, and hence remain undetected in surveys biased towards star-forming systems. The luminous/massive star-forming galaxies found at $z > 2$ in the sub-mm (Genzel et al. 2004) and near-infrared (Franx et al. 2003; Daddi et al. 2004) surveys may represent the progenitors of these old and massive systems.

A new VLT Large Programme (*GMASS: the galaxy mass assembly ultra-deep spectroscopic survey;* PI A. Cimatti) has been started in Period 73 with the main aim of tracing the history of galaxy mass assembly at $1 < z < 3$ by means of ultra–deep FORS2 multi-object spectroscopy.

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