Stellar Populations at Higher Redshifts

Tadayuki Kodama

National Astronomical Obseravtory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan
email: kodama@optik.mtk.nao.ac.jp

Abstract. We will review some recent advances in understanding the evolution of stellar populations in galaxies at relatively higher redshifts ($z \gtrsim 0.5$). We will focus on "mass assembly", "down-sizing" and "high-z zoo" which have been among the most major topics and have seen great observational achievements in the past few years. In particular, wide-field near-infrared surveys, large spectroscopic surveys, and the Spitzer observations at infrared wavelengths, have unveiled underlying stellar masses and dusty star formation in high-z galaxies, which have been crucial in making such recent progresses.

Keywords. galaxies: evolution, galaxies: formation, galaxies: luminosity function, mass function, galaxies: stellar content, galaxies: high-redshift, galaxies: clusters: general, cosmology: large-scale structure of universe

1. Introduction

The current theoretical picture of structure formation in the Universe is the bottom-up growth of large systems by assembly of many building blocks. Figs. 1 show theoretical predictions for cluster formation on the left and galaxy formation on the right. Cluster scale assembly can be directly observed by wide-field imaging of distant clusters (eg., PISCES, Kodama *et al.* 2005). We can identify lots of filaments and clumps in and around distant clusters as predicted by numerical simulations. However, when it comes to galaxies where baryon physics come into play, the fundamental picture of hierarchical formation has not been fully tested yet.

We will concentrate on the following three major issues on galaxy formation and evolution from observers point of view.

(*a*) When are the massive galaxies assembled? Is it consistent with hierarchical models?

(*b*) What is the origin of down-sizing? Is it consistent with the bottom-up picture?

(*c*) What is the sampling bias in high-z galaxies? How can we overcome this problem?

2. Mass assembly

The first important issue is the epoch of assembly of massive galaxies, as it directly tests the hierarchical picture of galaxy formation. In the hierarchical models, stellar mass function (SMF) of galaxies is expected to change dramatically with redshift (e.g. Kauffmann & Charlot 1998), because massive galaxies are end products of successive mergers of building blocks and therefore they tend to be assembled late in the relatively recent past. Do we really see this change in SMF in the real Universe?

There have been tremendous efforts put in this critical test, and in fact, many wide-field near-infrared (NIR) surveys (e.g., K20 (52 arcmin^2); GOODS-MUSIC (160 arcmin^2); UKIDSS (0.6 deg^2)) were conducted and have quantified the evolution in SMFs (or K-band luminosity functions, hereafter KLFs) as a function of redshift. These wide-field surveys demonstrate that there is no significant evolution at the massive end of SMFs or the amount of evolution is consistent with pure passive evolution at the bright end of

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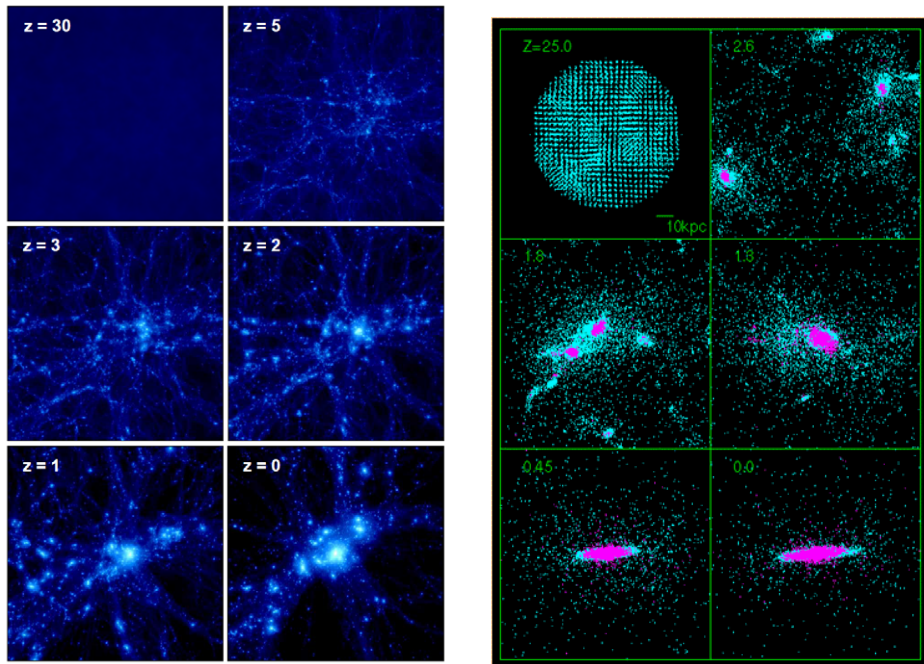
Figure 1. *left panel:* Dark matter evolution on a cluster scale predicted by νGC simulation by Nagashima *et al.* (2005). Mass of the cluster is $6\times10^{14}\mathrm{M}_\odot$ at $z = 0$. *right panel:* A SPH simulation of a Milky-Way type galaxy formation by Bekki & Chiba (2001).

KLFs up to redshift of 1–1.5 (e.g. Pozzetti *et al.* 2003; Drory *et al.* 2005; Fontana *et al.* 2006; Cirasuolo *et al.* 2006). Combined with the fact that SED of massive galaxies evolve passively in general at $z < 1$ (Section 3) hence the assumption of passive evolution is justified independently, it can be concluded that the majority of the massive galaxies seen today had already been assembled by $z =$1–1.5, namely the first 1/2–1/3 of the age of the present-day Universe. There is a caution, however, that the brightest cluster galaxies (such as cD) sitting in the deepest potential wells of massive clusters may have a different story and they may be still growing by further accretion/mergers even at $z < 1$ (Aragón-Salamanca *et al.* 1998). We should also note that some studies (e.g., van Dokkum 2005; Bell *et al.* 2004; Faber *et al.* 2005) claim much later assembly of massive galaxies by major mergers of gas poor systems ('dry merger') at $z < 1$.

What about higher redshifts? Beyond $z = 2$, an efficient way of tracing stellar mass is to search for distant red galaxies (DRGs, Franx *et al.* 2003), with a single colour cut of $J - K > 2.3$. Such surveys have been conducted intensively (e.g., van Dokkum *et al.* 2003; 2004; 2006; Förster Schreiber *et al.* 2004; Papovich et al 2006), and what they found is that there are a large number of very massive galaxies, more massive than $10^{11}\mathrm{M}_\odot$ in stellar mass, and that DRGs host almost 80% of the entire stellar mass at $2 < z < 3$. However, the co-moving number density of such massive galaxies starts to decrease with redshift beyond $z = 1.5$ or so, as is shown in some recent deep surveys at NIR and Spitzer bands (Drory *et al.* 2005; Fontana *et al.* 2006). Decline in the number of massive galaxies is also reported in proto-clusters (Kodama *et al.* 2007). As shown in Fig. 3, the massive end ($\mathrm{M_{stars}} > 10^{11}\mathrm{M}_\odot$) of the red sequence of galaxies in proto-clusters seems to grow rapidly between $z = 3$ and 2. These are indirect pieces of evidence that massive galaxies start to break down into building blocks and are yet at the stage of assembly
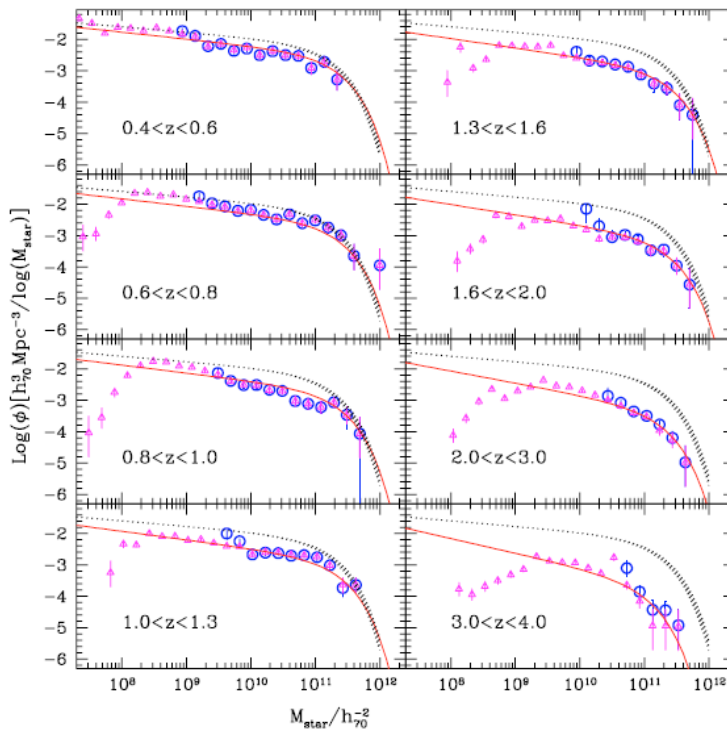
Figure 2. Evolution of stellar mass function with redshift derived from the GOODS-MUSIC survey (Fontana *et al.* 2006).

at $z > 1.5$. Some direct pieces of evidence of mass assembly or mergers in action are also reported in high resolution imaging of distant galaxies. For example, the central radio galaxy in a proto-cluster at $z \sim 2.16$ turns out to be consisting of many building blocks by HST/ACS imaging (Miley *et al.* 2006). It is interesting to note such an era of rapid growth of massive galaxies coincides with the peak of the submm phase and the peak of the cosmic star formation rate (e.g., Chapman *et al.* 2005; Bouwens *et al.* 2005). Therefore, massive galaxies are just forming during this epoch by vigorous star formation and assembly.

Such relatively early formation of massive galaxies ($z > 1.5$), however, can be a serious problem for the hierarchical galaxy formation models. Cimatti *et al.* (2005) showed that the fraction of massive galaxies in a semi-analytic model (De Lucia *et al.* 2006) decreases much faster than what is observed even below redshift of unity. However, some other recent models seem to do a better job, not only at $z \sim 1$ but even at higher redshifts. Fontana *et al.* (2006) compared the observed SMFs with various model predictions. There are at least two models which can reproduce the observed stellar mass density and the SMFs at high redshifts. One is the new Durham semi-analytic model (Bower *et al.* 2006) which has now taken AGN feedback into account. And the other is the hydro-dynamical simulation by Nagamine *et al.* (2005). Both models have succeeded in reproducing enough number of massive galaxies at high redshifts.
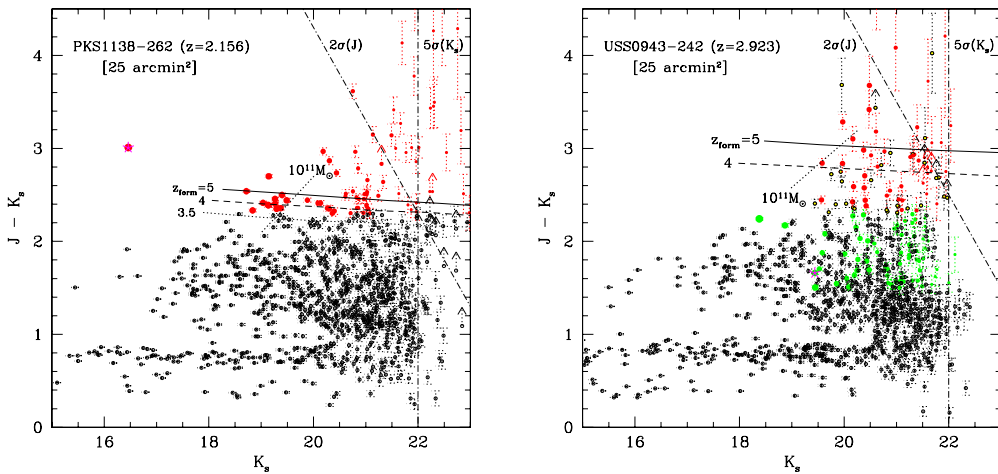
Figure 3. Near-infrared colour-magnitude diagrams of proto-clusters at $z \sim 2$ (*left*) and at $z \sim 3$ (*right*) (Kodama *et al.* 2007). The predicted location of the colour-magnitude sequence is shown in the case of passive evolution with various formation redshifts (Kodama *et al.* 1998). The iso-stellar mass lines at 10^{11} $M_\odot$ are also shown. See Kodama *et al.* (2007) for further details.

3. Down-sizing

Let us now turn to less massive galaxies. It was first noted by Cowie *et al.* (1996) that massive galaxies are the oldest and less massive galaxies tend to be younger or have extended star formation. They named this phenomenon "down-sizing" as star formation activities propagate from massive systems to less massive systems as time progresses. Recent surveys have confirmed that this trend extends to much fainter magnitudes. Kauffmann *et al.* (2003) showed using the SDSS data that massive galaxies are red and old while less massive galaxies tend to be blue and younger. This trend is also seen at higher redshifts. Galaxies at $z \sim 1$ show a very similar bimodal distribution on the colour-magnitude diagram (Kodama *et al.* 2004). Massive end is almost completely dominated by red old galaxies while the low mass end is exclusively dominated by blue galaxies and the transition occurs at around a few times $10^{10} M_\odot$ in stellar mass.

There have been many papers since then which confirms the down-sizing picture from various aspects. These includes a fundamental plane analysis of early-type galaxies at $z \sim 1$ (e.g., Treu *et al.* 2005; van der Wel *et al.* 2005), chemical enrichment of gas in HII regions at $z \sim 2$ (e.g., Erb *et al.* 2006), and Mg/Fe ratio of local early-type galaxies (e.g., Thomas *et al.* 2002). All these results indicate clearly that less massive galaxies have had more extended star formation history compared to massive, older galaxies. The most convincing case has recently come from Bundy *et al.* (2006) based on ~8,000 galaxies with spectroscopic redshifts between $0.4 < z < 1.4$ taken by the DEEP2 survey (Davis *et al.* 2001). As reproduced in Fig. 4, SMFs of red and blue galaxies are shown separately as a function of redshift. They find again that massive end is dominated by red galaxies, while low mass end is dominated by blue galaxies at all redshifts. What is interesting here is that the critical mass that separates the red and the blue populations actually shifts to lower mass as we go to lower redshift as illustrated by the arrow. This is the true "down-sizing" seen as a function of time, and star formation is truncated from massive galaxies to low mass galaxies as time progresses.

What if the down-sizing is now seen as a function of environment? Based on the wide-field data on cluster outskirts, Tanaka *et al.* (2005) has shown similar diagrams but
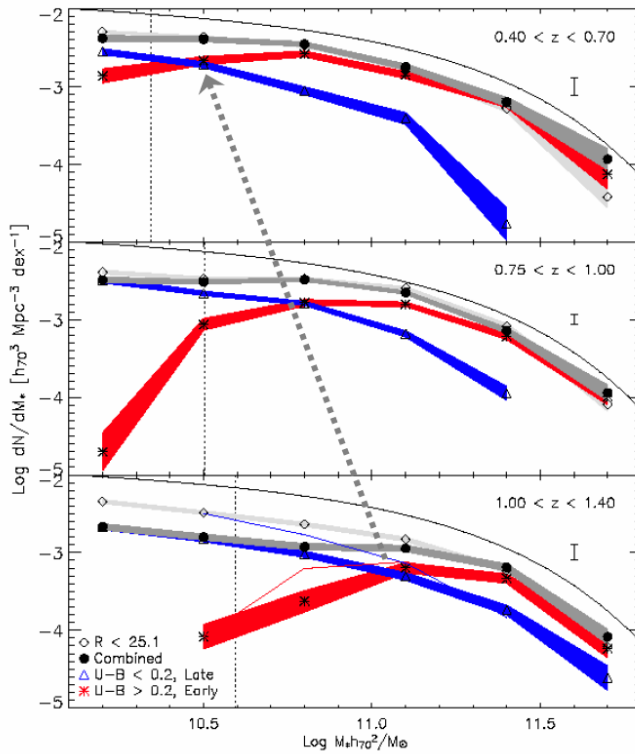
Figure 4. "Down-sizing" evolution in star formation of galaxies from the DEEP2 spectroscopic survey (Bundy *et al.* 2006). Red, Blue, and grey curves are stellar mass functions of red, blue and total galaxies, respectively, as indicated in the bottom panel. An arrow indicates how the dividing mass between red and blue populations shifts to lower masses as time progresses.

are now divided into three environmental bins, namely, field, groups and cluster cores (Fig. 5). The red solid and blue dashed curves indicate luminosity functions of the red and the blue galaxies, respectively. The critical mass that separates the red and the blue populations now shifts to lower mass as we go to higher density regions. This is similar to what we see above as a function of redshift. Therefore, the galaxy environment also controls the speed of galaxy evolution, and star formation propagates from high density regions to lower density regions.

Combining the above results based on Figs. 4 and 5, the star formation history of galaxies can be summarised as follows: Star formation is truncated from high-mass systems in high density regions to low-mass systems in low density regions.

Critical question on the down-sizing picture is that how it can be accommodated in the hierarchical galaxy formation scenario which is apparently opposite, namely, early formation of small systems and later formation of massive galaxies would have been expected. However, recent semi-analytic models do reproduce the down-sizing in star formation at least in a qualitative sense (De Lucia *et al.* 2006). In these models, massive galaxies tend to have star formation earlier than less massive ones in consistent with the observations. This is probably because of a strong spatial bias in galaxy formation, in the sense that massive galaxies were formed from higher density peaks at high redshifts which collapsed earlier and had accelerated galaxy formation, while less massive galaxies started from lower density peaks and had delayed formation. There is such an intrinsic
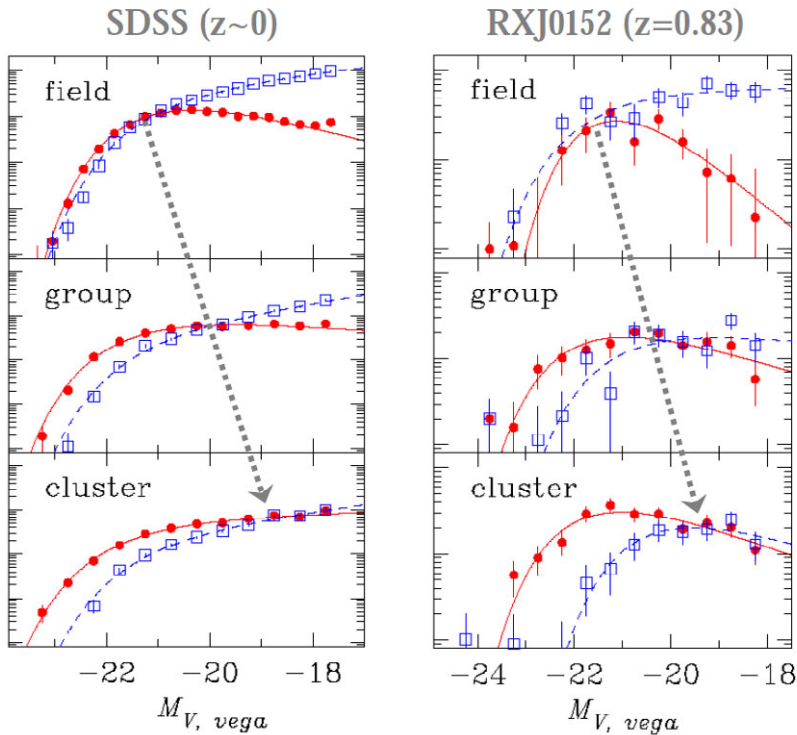
Figure 5. "Down-sizing" seen as a function of environment (Tanaka *et al.* 2005). Filled circles and blue squares show red and blue populations, respectively. Two arrows indicate how the dividing mass between red and blue populations shifts to lower mass as one goes to denser environments.

bias which can inverse the bottom-up picture. But even so, it is not clear how we can extend star formation in such small systems where SN feedback can easily expel the gas. Extended star formation in these low mass systems would require extremely low star formation efficiency or recurrent star formation by the fall back of once expelled gas.
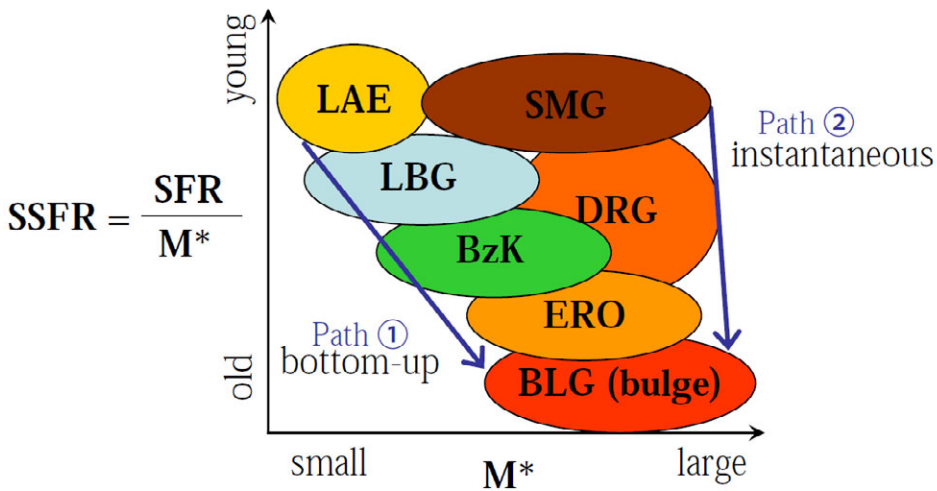
4. High-z zoo

High-z Universe is completely a mess and it is called high-z zoo. There are a wide variety of galaxy populations with three characters, such as LAE, LBG, SMG, DRG, BzK, JHK and so on. Selections of each population are all different and so each sample is biased in some way, and we do not know the evolutionary state of each population nor the evolutionary link between different populations. This situation makes it extremely difficult for us to obtain any general view of high-z galaxies. In order to better understand the galaxy formation, what is needed is to place all these different populations on a single diagram with the common fundamental physical quantities. One of such key diagrams is shown in Fig. 6. We should first construct a stellar mass limited sample, and then measure specific star formation rate (SSFR) of each galaxy. SSFR is the current SFR per unit stellar mass and is very similar to the Kennicutt's birth parameter (1998) and is also directly connected to gas fraction through the Schmidt law (Schmidt 1959; Tinsley 1980). It is therefore a good measure of evolutionary state of a galaxy.

One of the major uncertainties in making such diagram at high redshifts is the effect of dust extinction on measuring true star formation rates (SFRs). In fact star formation
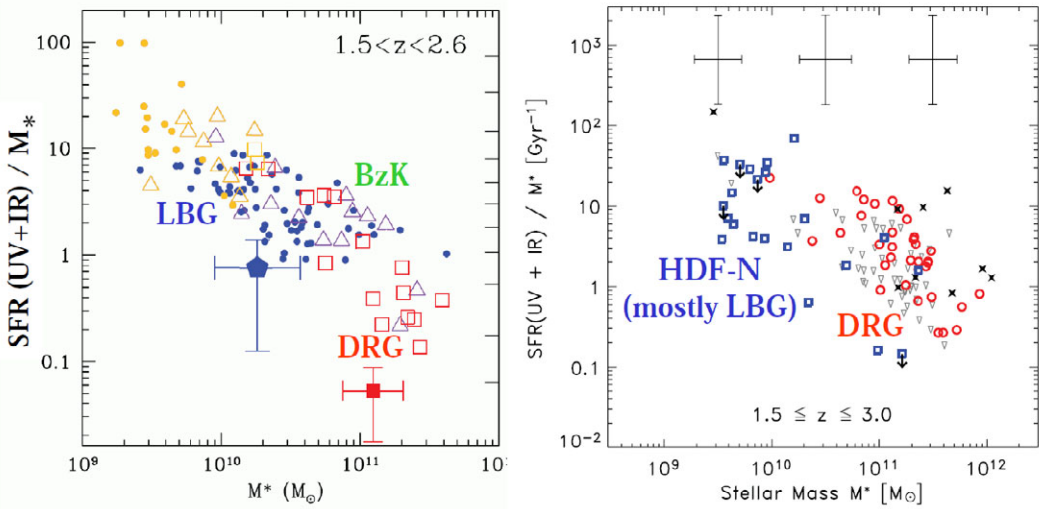
Figure 6. *left panel:* Specific star formation rate (SSFR) as a function of stellar mass of galaxies (Reddy *et al.* 2006). Star formation rates (SFRs) are measured as sums of UV-SFR and infrared-SFR. *right panel:* Similar diagram but from Papovich *et al.* (2006). Different symbols indicate different populations.

Figure 7. Schematic diagram of the "High-z zoo", where a wide variety of 3-character populations have been defined. Neither an evolutionary connection nor inter-relationships are understood well. This diagram sketches the author's personal view of high-z populations on this key diagram showing the specific star formation rates (SSFR) versus stellar masses. Therefore it should be taken carefully. Two arrows indicate two possible paths to form a bulge dominated massive galaxies in the authors view.

is largely hidden in optical surveys at high redshifts, and correction for dust extinction is critically important to derive the cosmic star formation history, for example (e.g., Bouwens *et al.* 2005) Spitzer Telescope observations play a key role here by providing unique information between 3 μm and 24 μm. First of all, the Spitzer bands are essential to accurately estimate stellar masses and photometric redshifts at high-z by SED fitting.

In fact, without the Spitzer data, mass estimates would become very uncertain beyond $z \sim 2$ or so (Fontana *et al.* 2006). Moreover, MIPS 24micron samples PAH features at rest frame 6–9 μm from $z \sim 2$ galaxies which are good measures of dusty star formation rates. Webb *et al.* (2006) actually measured the star formation rates for the MIPS detected DRGs, and found that their average star formation rate is as high as 130 $M_\odot$/yr, and that DRGs contribute 20% of the total SFR density at $z \sim 2$. Furthermore, Spitzer colours can be used to discriminate among passively evolving galaxies, dusty red galaxies, and the galaxies with a significant AGN component (e.g., Wilson *et al.* 2006; Stern *et al.* 2005; Webb *et al.* 2006).

Fig. 6 show the two pioneer works which combine UV star formation and IR star formation derived from the Spitzer data, and they created the ultimate diagrams at $z \sim 2$. Down-sizing is again clearly reproduced on this key diagram even at this high redshift. It is also clear that LBG and DRG are well separated on this diagram, in the sense that DRGs are more massive and more evolved systems than LBGs.

Although it is still too early to show it, we try to summarize the high-z zoo on the schematic diagram shown in Fig. 7. There are apparently two paths to form a massive spheroidal galaxy. One is the gradual bottom-up starting from LAE, evolving to LBG and BzK, and eventually to a bulge dominated massive galaxy. The other path would be an instantaneous early formation of massive galaxy. A galaxy is formed by a strong star burst in a short timescale and is seen as submm galaxies (SMG) during the burst phase. By increasing the sample of galaxies on this ultimate diagram in the near future, and plotting them as a function of redshift, we can eventually make an evolutionary link between different galaxy populations and establish a concrete picture of galaxy formation based purely on observations. That is the way to go.

Acknowledgements

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The speaker (left) talking to Reynier Peletier.