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The evolution of massive galaxies: improving the determination of physical properties of high redshift galaxies

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Abstract

The basics of our current knowledge about the formation of massive galaxies will be presented, jointly with some key open questions. We will also describe how we are trying to improve our understanding of galaxy formation and evolution by obtaining more robust estimations of properties such as the stellar mass, age of the stellar populations, and SFRs of high redshift (z = 1–4) massive galaxies. In this context, we present the main results of our research about the assembly of galaxies at $z < 4$ based on the data obtained by the deepest *Spitzer* surveys carried out with IRAC and MIPS during the cryogenic mission. Analyzing SFR and stellar mass functions in several redshift bins at $0 < z < 4$, we have found and quantified that galaxies formed following a downsizing scenario, with the most massive systems assembling early in the lifetime of the Universe and very quick (i.e., with very high star formation efficiencies, and a significant amount of obscured starbursts), while less massive systems assembled later and/or more slowly. However, *Spitzer* has left several open questions that still hamper our current understanding about the formation and evolution of galaxies. I will discuss three of these results and how future facilities such as *Herschel*, ALMA, E-ELT or JWST can lead to a more robust and detailed (with higher spatial resolution and depth) characterization of how galaxies formed in the early Universe: (1) the mid-to-far IR colors of galaxies evolve with redshift, departing considerably from the typical values observed in the local Universe, specially at $z >$ 1.5–2.0; (2) the IMF might not be universal, evolving to a top-heavy IMF at $z > 1.5$; (3) obscured AGN may be ubiquitous in high-z galaxies, playing a significant role in the downsizing scenario.

1 Introduction

The current paradigm of galaxy formation establishes that the baryons closely follow the evolution of the Cold Dark Matter halos in cosmological simulations such as those found in [64] (see also [4, 13]). This means that the star formation started within the cooling gas clouds in merging dark matter halos, after a slow early collapse regulated by feedback processes. This early star formation formed relatively small disk systems that later merged in larger (i.e., more massive) spheroidal systems [26]. This hierarchical scenario for galaxy formation is quite different from the classical view of the problem, where merging gas clouds would suffer a monolithic collapse and cooling, producing (maybe very violent) star formation. Feedback processes would remove the remaining gas and stop the star formation, leaving an spheroidal galaxy which would then evolve passively, maybe accreting a star-forming disk at some time after the main collapse.

The hierarchical scenario for galaxy formation is based on the ΛCDM models (e.g. [64]) and simulations of galaxy mergers (e.g. [42]). These models have been very successful in reproducing several observational data, specially at low redshift. For example, ΛCDM models do a fantastic job in reproducing the Cosmic Microwave Background (CMB) spectrum [62, 61, 24]. Another remarkable success of these models is the predictions about the Large Scale Structure of the Universe, which shows a filamentary shape with the presence of clusters, groups and voids (see, e.g., the data in the 2dF survey published in [14]). In addition, the current paradigm of a hierarchical scenario for galaxy formation is also supported by the observations of galaxy mergers at different cosmological distances (e.g. [69, 48]), and the increase of the fraction of galaxies undergoing mergers as we move to higher redshifts (e.g. [41, 15, 7, 44, 43]).

In this review presented in the 2010 "Sociedad Española de Astronomía" (SEA, Spanish Astronomical Society) Meeting held in Madrid (Spain), we discussed some of the results demonstrating that we still do not fully understand galaxy formation, and the paradigm currently presents significant aspects that must be improved. In addition, we describe how we are trying to improve our understanding of galaxy formation and evolution by obtaining more robust estimations of the main properties of high-z galaxies.

2 Challenges to the current paradigm of galaxy formation

2.1 Downsizing mass assembly vs. hierarchical scenario

The hierarchical models still have severe drawbacks in several aspects. For example, the local near-infrared (NIR) luminosity function, or the stellar mass function, closely linked to that, is not well reproduced by the current models of galaxy formation both at the faint and bright ends, i.e., the light and heavy ends of the stellar mass function. One of the latest K-band local luminosity functions published with UKIDSS data by [63] shows that there is a "satellite problem" in the models, which predict many more low-mass galaxies than what is actually observed. On the bright end, models tend also to overpredict the number of massive galaxies observed in the local Universe, although they are getting closer to the observations after taking into account quenching mechanisms (e.g. [23]).

The discrepancies between the predictions of current galaxy formation models based on the ΛCDM paradigm and the data are more obvious as we move to higher redshifts. In the last decade, several papers found compelling evidence that the formation of galaxies follows a downsizing scenario [16, 35, 33, 38, 52, 53, 5, 6, 2]. In this theory, the most massive galaxies formed first in the history of the Universe, thus having the oldest stellar populations seen today. The formation of less massive systems continued at lower redshifts. This finding is indeed extremely challenging for models of galaxy formation based on the ΛCDM matter paradigm. Indeed, the downsizing scenario contradicts, at least at first sight, the predictions of a hierarchical assembly of the stellar mass in galaxies, i.e., the most massive galaxies do not seem to be the result of multiple mergers occurring in a extended period along the Hubble time [4, 13]; see also [26, 28].

Downsizing implies that most of the star formation in the most massive galaxies happened quick and stopped for some reason in early times. This means that there should be massive passively evolving galaxies at high redshift. Indeed, the deep NIR data which started to be taken early this century was able to detect a population of galaxies which are very faint at optical wavelengths, but bright in the NIR. Different types of these galaxies have been denominated with various names: Extremely Red Objects (EROs, [72]), Distant Red Galaxies (DRGS, [31]), *BzK* galaxies [18], etc... All of them are characterized for very steep spectral energy distributions (SEDs) in the rest-frame optical, which can be caused by evolved stellar populations or very extincted starbursts. Moreover, all of them have been found to be galaxies at redshift larger than unity. *Spitzer*/MIPS data revealed that at least half of these red galaxies at high-z are indeed forming large amounts of stars in very obscured star-forming knots [50], but another half is completely consistent with an evolved stellar population [12]. This means that a fair number of galaxies must have formed most of their stars at even higher redshifts. It also means that there should be a mechanism responsible for the quenching of the star formation.

Thanks to *Spitzer* data, we were able to quantify the downsizing scenario. In [53], we studied the evolution of the stellar mass function (SMF) from $z = 0$ to $z = 4$, using a NIR/stellar mass-selected galaxy sample. Our work coped with 3 significant biases found in previous estimations of the SMF based on optical data: (1) very red galaxies at $z > 1$ are commonly missed by optical surveys, but easily detected in NIR surveys such as ours (e.g., massive galaxies at $z \sim 2$ such as DRGs or BzK objects); (2) stellar mass estimates are more robust when having rest-frame NIR fluxes, which are dominated by the stars that contribute the most to the global stellar mass of a galaxy (see [29]); and (3) our high-quality IRAC data was extremely deep, deeper than any other previous survey in the NIR with ground-based telescopes (see [71]).

We also analyzed the evolution of the specific SFR (SFR per stellar mass unit) of the Universe, calculated by dividing the average values of the SFR density [36] by our stellar mass density estimates. The specific SFR of the Universe monotonically increases as we move to higher redshifts. When we considered the evolution of the specific SFR for different stellar mass intervals, we clearly saw that the most massive galaxies ($M > 10^{11.7}$ $M_\odot$) presented very large specific SFRs at high-z. These galaxies exhibited values of the SFR that are so large that they could double their stellar mass in just 0.1 Gyr at $z = 3$–4. As we move to lower redshifts, their specific SFRs decreased considerably, by a factor of 10 from $z \sim 4$ to $z \sim 2.5$ (1.5 Gyr), and by 100 times from $z \sim 4$ to $z \sim 1.5$ (in 3 Gyr), in agreement with the results from [50]. For smaller masses, the evolution was weaker. The evolution at $z < 1$ was similar for all the mass intervals, as already noted by [74].

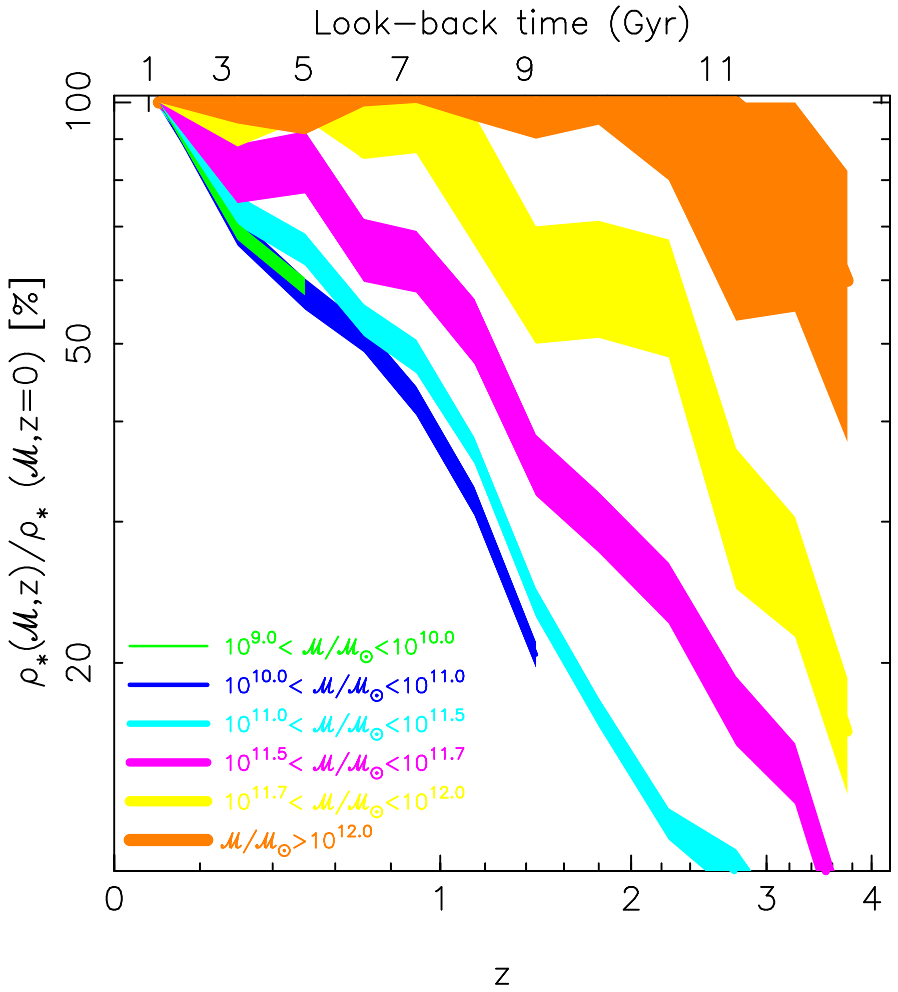

Figure 1: Fraction of the local stellar mass density already assembled at a given redshift for several mass intervals (adapted from [53]). Other papers presenting similar results are [66, 2, 47].

In Fig. 1 (see [53]), we demonstrate that the most massive systems ($M > 10^{12}$ M$_\odot$) formed first (they assembled more than 80% of their total stellar mass before $z = 3$) and very rapidly (about 40% of their mass was assembled in 1 Gyr between and $z = 4$ and $z = 3$). Systems with masses $10^{11.7} < M < 10^{12.0}$ M$_\odot$ assembled their mass more slowly: from $z \sim 4$ to $z \sim 2.5$ (1.5 Gyr), they assembled around 50% of their stars, and then evolved more slowly to reach the local density at low redshifts. Less massive galaxies assembled their mass at even a slower speed, reaching the local density at very recent epochs. This plot shows the rapid recent evolution of the galaxies with masses $M \sim 10^{10.5}$ M$_\odot$, which assembled 30% of their mass in the last 3 Gyr. Our results in [53] pointed out to a dual galaxy formation scenario: a quasi-monolithic and rapid collapse of the most massive galaxies, which ceased to form stars at a certain epoch, and a more hierarchical and timely relaxed assembly for less massive systems. This scenario has only been reproduced by galaxy formation models introducing early star formation in very massive halos that is quenched for some reason at high-redshift (see, e.g., [17, 9]). The most accepted quenching mechanisms are AGN feedback and supernova winds.

2.2 More proofs of downsizing

Not only the stellar mass assembly of the most massive galaxies seems to follow a downsizing scenario, but also other processes present this behavior. [66] and [45] presented stellar population model fits to absorption line indices and estimations of metallicities for galaxies at low-to-high redshift that were clearly consistent with the downsizing scenario. [66] developed models to constrain the formation of early-type galaxies, finding that the properties of the stellar populations in the most massive galaxies were well reproduced by star formation events at $z \sim 5$ lasting for several hundreds of million years. They also found that less massive systems harbor younger stellar populations and their star formation timescales are also longer. [45] found a correlation between stellar mass and oxygen abundance, being the relationship steeper for higher redshifts. The evolution of the metallicity in light galaxies is stronger relative to heavier systems, which is interpreted as the chemical version of the galaxy downsizing.

As mentioned above, the downsizing scenario also involves larger star formation intensities at high redshift. Indeed, the star formation density of the Universe increases by a factor of 10 from $z = 0$ to $z = 1$, with obscured star formation being more and more dominant as we move back in time (see [52] and references therein), and stays roughly constant up to at least $z = 3$. By comparing the evolution of the cosmic SFR density based on UV and MIR observations, [67] found that the typical attenuation of the star formation in $z < 1$ galaxies is approximately 1 mag, increasing to 2 mag at $z > 1$. [53] also found large specific SFRs for the heaviest galaxies at $z > 2$. Spheroidals and disk galaxies present very similar values of the sSFR at $z \sim 2$, and start to be differentiated below this redshift, when spheroidals saw their sSFR diminish more rapidly (by a factor of 2–3) than disks [54, 10].

The evolution of the AGN also follows a downsizing scenario. [34] showed that the number density and emissivity of the AGN evolve more rapidly for the most luminous AGN. For example, AGN with $L \sim 10^{46}$ erg s^{-1} presented a roughly constant emissivity at z =2–5, and experienced an emissivity decrease of a factor of 100 from $z \sim 2$ down to $z \sim 0$. Comparatively, the number and emissivity of AGN with $L \sim 10^{43-44}$ erg s^{-1} peaked at $z \sim 1$ and then decreased by a factor of 10 in the interval $0 < z < 1$.

2.3 Basic problems in our global picture

In [53], we also obtained cosmic SFR density estimations based on the time derivative of the stellar mass densities, and compared them with literature estimations based on distinct SFR tracers (see Fig. 2). Surprisingly, our estimations of the cosmic SFR density based on the stellar mass density evolution are systematically smaller than the previously published results (as also noted by [58, 36, 8]). A top-heavy IMF (meaning an IMF with relatively

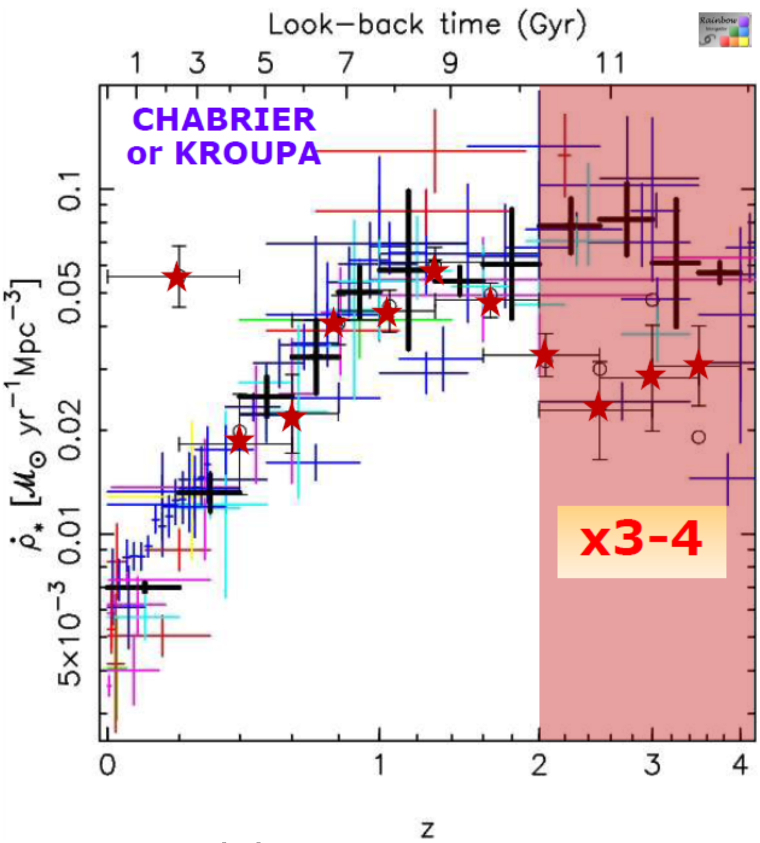

Figure 2: Figure adapted from [53] comparing two independent estimations of the cosmic SFR density up to $z = 4$. Direct estimations of the SFR density with different tracers are shown with color bars. A weighted average has been calculated and is shown with thick black bars. These estimations are compared with the values obtained from the time derivative of the evolution of the stellar mass function (red stars). All the data refers to a Chabrier or Kroupa IMF, which produces both estimations to agree well up to $z \sim 1.5$. A Salpeter IMF produced a systematic offset for all redshifts. The Kroupa/Chabrier IMF is not able to reconcile both SFR density estimations at $z > 1.5$, which differ by a factor of 3–4. Possible explanations are discussed in the text, including an evolution of the IMF.

more massive stars compared to the amount of low-mass stars than the typical ratio observed followed by a Salpeter or Kroupa IMF) at high redshifts (i.e., an evolution of the IMF) could solve the mismatch. The discrepancy could also be explained if the SFRs estimated (with different tracers: UV, IR, and sub-mm emission) for the massive galaxies at $z > 1$ were overestimated due to, for example, the presence of a strong obscured AGN in most of these sources [19], which would imply that a significant fraction of their UV or IR emission arises from the AGN, i.e., it is not linked to star formation. An evolution of the IMF at high redshift has been discussed in a dozen of papers in the last 2 years (e.g. [22, 70]).

Other basic problems that the current models have difficulties in reproducing are: (1) the significant size evolution of the most massive galaxies from $z \sim 2$ to $z = 0$, specially for spheroids [68]; (2) the dynamics of galaxies at $z \sim 2$, a population which seems to be dominated by disks and not by mergers (e.g. [30]), although the number of observations is still reduced and possibly biased; (3) the dynamical studies of the molecular gas for typical star-forming $z \sim 2$ galaxies, which seem to be also dominated by rotating disks and present SFR efficiencies comparable to local spirals, rather than to those of sub-mm galaxies [20, 21, 65, 32]; and (4) although AGN have been claimed to be the main responsible for star formation quenching in the downsizing theory by both observers and modellers [60, 59, 17, 49, 37], no direct evidence exists, and, at least at $z < 1.5$, some observations point against this link (e.g. [1, 74]). The situation might be different at higher redshifts, where downsizing is more pronounced, and obscured AGN have been claimed to be ubiquitous [19].

3 Advancing in our understanding of galaxy assembly

Our understanding of the processes involved in the assembly of galaxies from the early Universe to the present will only increase if we are able to get more robust estimations of some key properties of galaxies, such as the stellar masses, stellar population ages, SFRs and extinctions, relationship of those with environment, and, of course, better estimations of the distances to galaxies based on spectroscopic or photometric redshifts. Jointly with this observational effort, we will need better physics in the models, which should give us, for example, more certain emissivities of the stellar populations in the rest-frame NIR (now effected by strong uncertainties due to the little known properties of stellar evolutionary phases such as the thermally-pulsating TP-AGB phase [46, 40]. We will also need a better theoretical understanding of the star formation processes and the role of dust, including a consistent analysis of the stellar radiation and attenuation and the dust properties and emission, the AGN/star formation connection, the processes involved in the star formation quenching or enhancement, the ways in which galaxies might have increased their sizes from $z \sim 2$, etc.

From the observational point of view, in the following years we are going to enjoy several top-of-its-class facilities, such as GTC, ALMA, *Herschel*, *Spitzer* Warm Mission, the *Hubble* WFC3, JWST, or the E-ELT/TMT, which will allow us to advance enormously in our knowledge about galaxy evolution. Here we describe the basic capabilities that these new facilities will offer to enable robust determinations of the most interesting parameters of galaxies:

1. **Redshifts.** The basic property of galaxies in cosmological surveys is the distance. Currently, spectroscopic redshifts can be obtained for sources down to magnitudes of the order of $R, I \sim 25$. This is a strong limitation for studies of high-z galaxies, a good fraction of them being very red and fainter than the spectroscopic limit. For example, only 15–20% of the galaxies in stellar mass selected samples at $z > 1$ in the most targeted fields have spectroscopic redshifts [53]. Indeed, current redshift surveys are strongly biased towards blue galaxies at high-z, which tend to be relatively light in comparison with galaxies such as EROs or DRGs. The latter dominate the heavy end of the stellar mass function but are typically missed by optical spectroscopic surveys. NIR spectrographs such as MOIRCS on Subaru, F2 on Gemini, LUCIFER on LBT,

MOSFIRE on Keck, EMIR on GTC, or KMOS on VLT, or the future instruments on E-ELT, are starting to let us solve this bias of our spectroscopic observations of $z > 1$ galaxies (see, e.g., [39, 73]). In addition, ALMA will open the possibility to obtain redshifts for unbiased samples of UV- and IR-bright star-forming galaxies, both of which must present large amounts of gas, and probe fainter populations which are now beyond the spectroscopic limit due to intrinsic faintness or extinction by dust.

Still, to advance even further in our study of the galaxies at high-z, we will need photometric redshifts to go beyond the spectroscopic limit. To improve those, several surveys are now being carried out or planned to obtain as many photometric points as possible in the spectral energy distributions and thus improve the photo-z determinations and avoid outliers. Among those, we could mention Alhambra, PAU or SHARDS (see below). These are medium-band imaging surveys which will be able to obtain redshifts with uncertainties of a few percent down to very faint magnitudes.

2. **Stellar masses.** Several recent works have shown the advantages of probing the rest-frame NIR to obtain reliable estimates of the stellar mass of galaxies up to $z \sim 4$ and even beyond. For example, [29] showed that including IRAC data in their comparison of observed SEDs to stellar population synthesis models decreased the uncertainties in the stellar masses by up to a factor of 10 (typically, a factor of 2). [27] also reported systematic differences of up to a 70% between estimates of the stellar mass having IRAC data and not having them. These systematics turned to be strongly redshift dependent. Although having rest-frame NIR data has been demonstrated to decrease the uncertainties in the stellar mass determination, these data count with an important problem: stellar population synthesis models are not as robust in the NIR as in the optical. Indeed, recent models published by several authors including the most up-to-date recipes for the inclusion of the TP-AGB phase [46, 11] still differ significantly and even fail to reproduce the global SED from the UV to the NIR [40, 3]. NIR deep imaging surveys with WFC3 and the *Spitzer* Warm Mission (e.g., CANDLES and SEDS), 2D spectra (with current 8–10 meter-class telescopes or E-ELT) to analyze dynamics jointly with spatially resolved stellar population properties, and medium-band ultra-deep imaging surveys such as COSMOS or SHARDS will help in the determination of robust stellar masses.

3. **SFRs and extinctions.** Our current SFR estimates are now much more robust than what we had than years ago thanks to the improvements in sensitivity and resolution of the instrumentation and the availability of similar-quality data in several SFR tracers such as the UV, Hα, [OII], and the mid- and far-IR. The MIPS instrument on *Spitzer* have revolutionized the determination of SFRs in galaxies up to $z \sim 3$, allowing to take into account the dust attenuation for hundreds of thousands of galaxies. We also have to keep in mind that the average extinction of galaxies increases as we move to higher redshifts (e.g. [67]). However, SFRs based on 24 μm data alone require a significant extrapolation to obtain a value of the integrated IR luminosity and a SFR from that. Just using *Spitzer* data, several works have shown that SFRs obtained from 24 μm alone are overestimated for the galaxies detected by MIPS at $z > 1.5$, virtually all of

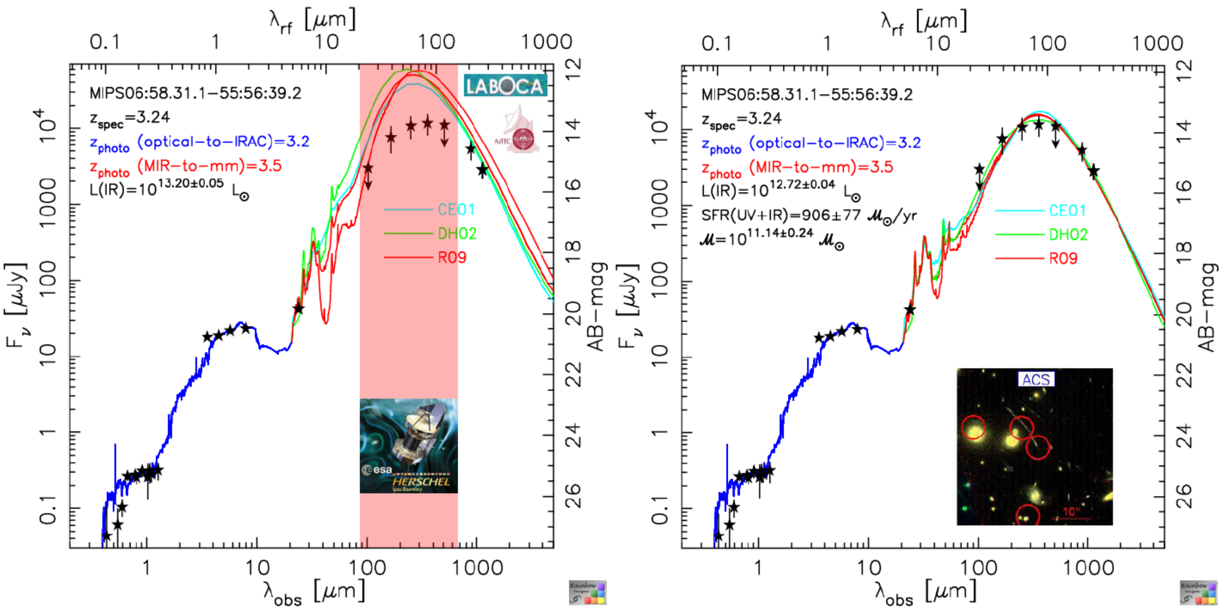

Figure 3: Figure adapted from [55]. The left panel shows the SED of the Southern tip of the arc at $z = 3.24$ in the Bullet cluster. The IR-based SFR has been estimated with the MIPS 24 μm photometric point alone, using three different model libraries. The plot also shows the *Herschel*, LABOCA and AzTEC data at wavelengths between 100 and 1100 μm, demonstrating that MIPS data alone tends to overestimate the IR-based SFR due to an evolution of the typical template of a ULIRG, whose warm-to-cold dust emission ratio is smaller at high-z. In addition, the luminosities inferred with different models differ by factors of 2–3. The right panel shows a fit to all the mid- and far-IR data together, also showing that the scatter in the measurements obtained with different models are considerably decreased.

them being ULIRGs [51, 57]). This is shown in Fig. 3 (see also [25, 56]. *Herschel* and ALMA data will allow us to take into account this effect (and analyze its importance for low luminosity objects, a good fraction of them being only detectable by MIPS and not by *Herschel*) and improve our knowledge about the extinction properties of high-z sources. JWST will sum up to this effort, allowing the spatial analysis of the different obscured star formation knots.

4. **Stellar ages and SFHs.** The improvements in the determination of stellar masses and SFRs/extinctions will also mean a better estimation of the age of the stellar population and the Star Formation Histories. For that purpose, we will need better quality spectroscopic data (deeper and/OR in 2D), and/or better sampled SEDs using deep medium-band imaging with telescopes/instruments such as GTC/OSIRIS or Subaru/Hyper-Suprime-Cam. In this regard, in this talk we presented the Survey for High-z Absorption Red and Dead Sources (SHARDS, http://guaix.fis.ucm.es/∼pgperez/SHARDS), an ESO/GTC Large Program awarded with 180 hours of GTC/OSIRIS time during 2010-2011. This project consists of a deep imaging survey in 25 medium-band filters

covering the wavelength range between 500 and 950 nm and targeting the GOODS-N field. The main goal of SHARDS is carrying out an unbiased survey of massive galaxies at $z > 1$ and accurately determining the main properties of the stellar populations present in these galaxies through spectro-photometric data with a resolution $R \sim 50$ (typically enough to measure indices such as the Mg index or the D4000 break). The SHARDS data will be also extremely useful for many other scientific projects, such as a detailed study of the properties of AGN at intermediate and high redshift. This survey follows the strategy of previous very successful projects such as COMBO17 or the COSMOS MB Survey, and could be extended in area, depth, and spectral coverage with future telescopes and/or instruments such as Hyper-Suprime-Cam, EMIR, or E-ELT.

4 Conclusions

Here we summarize the main topics treated in this review presented in the 2010 "Sociedad Española de Astronomía" (SEA, Spanish Astronomical Society) Meeting held in Madrid (Spain):

- The current paradigm of galaxy formation (based on the hierarchical assembly of CDM halos) has been very successful in reproducing several observations such as the CMB power spectrum, the LSS, or the ubiquity of galaxy mergers.
- However, the current paradigm still counts with serious problems, for example: (1) the local stellar mass function is not well reproduced at the light and heavy ends; (2) massive galaxies are observed at high redshift, and a significant fraction of them are already dead (i.e., they harbor old stellar populations), while others present very violent star formation events without perturbed dynamics; (3) the evolution of massive galaxies, the metallicity evolution, and the QSO/AGN evolution all follow a downsizing scenario (i.e., anti-hierarchical).
- Therefore, hierarchical events involving mergers and following the ΛCDM behavior and anti-hierarchical (monolithic-like) collapse following a downsizing scenario are both important in galaxy formation. There might be a dependence on stellar mass, in the sense that massive systems seem to assemble following a downsizing scenario while less massive systems may more closely resemble the CDM halo merging process.
- The reconciliation between models and data (at least) needs quenching mechanisms (also delay agents for low mass systems). These mechanisms have been linked to AGN, but we still lack conclusive direct evidence of this process.
- Observationally, we need better estimations of key parameters such as the stellar population ages, stellar masses, SFRs, extinctions, SFHs, more spectroscopic redshifts, better photometric redshifts, etc...
- These requirements will make it necessary to exploit the synergies between the new and future telescopes operating all along the electromagnetic spectrum: GTC, *Herschel*, ALMA, JWST, E-ELT,...

- Moreover, it will be essential to combine all these multi-wavelength data (a vast amount being already in our hands) and analyze them simultaneously in a consistent way with improved stellar, dust, and gas emission models.

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