

Stellar Mass and Velocity Functions of Galaxies: Backward evolution & the fate of Milky Way siblings

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ABSTRACT

Context. In the recent years, Stellar Mass Functions of both star forming and quiescent galaxies have been observed at different redshifts in various fields. In addition, Star Formation Rate distributions (e.g. in the form of far infrared luminosity functions) were also obtained. Taken together, they offer complementary pieces of information concerning the evolution of galaxies.

Aims. We attempt in this paper to check the consistency of the observed stellar mass functions, SFR functions and the cosmic star formation rate density with simple backward evolutionary models.

Methods. Starting from observed Stellar Mass Functions for star-forming galaxies, we use backwards models to predict the evolution of a number of quantities, such as the SFR function, the cosmic SFR density and the Velocity Function. The velocity being a parameter attached to a galaxy during its history (contrary to the stellar mass), this approach allows us to quantify the number density evolution of galaxies of a given velocity, e.g. of the Milky Way siblings.

Results. Observations suggest that the Stellar Mass Function of star forming galaxies is constant between redshift 0 and 1. In order to reproduce this result, we must quench star formation in a number of star forming galaxies. The Stellar Mass Function of these “quenched” galaxies is consistent with available data concerning the increase in the population of quiescent galaxies in the same redshift interval. The Stellar Mass Function of quiescent galaxies is then mainly determined by the distribution of active galaxies that must stop star formation, with a modest mass redistribution during mergers. The cosmic SFR density, and the evolution of the SFR functions are relatively well recovered, although they provide some clue for a small evolution of the Stellar Mass Function of star forming galaxies at the lowest redshifts. We thus consider that we have obtained in a simple way a relatively consistent picture of the evolution of galaxies at intermediate redshifts. We note that if this picture is correct, 50% of the Milky-Way sisters (galaxies with the same velocity as our Galaxy, i.e. 220 km/s) have quenched their star formation since redshift 1 (and an even larger fraction for larger velocities). We discuss the processes that might be responsible for this transformation.

Key words. Galaxies:mass function - Galaxies:high-redshift - Galaxies:formation - Galaxies:evolution

1. Introduction

In the last few years, the analysis of many deep fields together with improvements in techniques such as SED-fitting have enabled many studies of the Stellar Mass Function (SMF) of galaxies at both low and high redshifts (e.g. Bell et al. 2003, 2007, Borch et al. 2006, Bundy et al. 2005, 2006, Arnouts et al. 2007, Vergani et al. 2008, Perez-Gonzalez et al. 2008, Pozzetti et al. 2009, Ilbert et al. 2009). One of the somewhat surprising result is that it is generally found that the SMF of star forming galaxies (selected on the basis of color, morphology or spectroscopy) has not evolved much between redshift about unity and the present time (e.g. Bell et al. 2007, Cowie et al. 2008, Vergani et al. 2008, Pozzetti et al. 2009). The analysis of the evolution of the Luminosity Function had already suggested that the stellar mass of blue galaxies is constant, while the one of red galaxies increases with time (Faber et al. 2007).

Since star formation is undergoing in such galaxies, the stellar mass in each of them is bound to increase. This maintained status quo of the SMF thus indicates that a number of massive star forming galaxies must evolve towards early type, or at least quiescent galaxies (through quenching of their star formation), as noted in Bell et al. (2007) and Arnouts et al. (2007), while they are replaced by lower mass galaxies gaining mass with time (see also Pozzetti et al. 2009). This type of scenario was also advanced in Brown et al. (2007) to explain the doubling

of the stellar mass in red galaxies over the past 8 Gyrs. Such a quenching is also constrained by the evolution of the co-moving Star Formation Rate (SFR) density, i.e. the SFR averaged over representative volumes of the universe, dropping by a factor 6 to 10 between redshift 1 and 0 (see the compilations of Wilkins et al. 2008 and Hopkins and Beacom 2006).

It is reasonable to think that even at “intermediate” redshifts (defined broadly as $0 < z < 1$), star formation takes place in “normal” star forming galaxies, such as the precursors to present day disk-galaxies and the Milky Way. Smooth SFR histories are known to be realistic and capture enough of the physics of such galaxies (see e.g. models in Boissier & Prantzos 1999, 2000). This is especially suggested by the facts that we see star formation at intermediate redshift in rotating disks that should have formed through smooth accretion (e.g. Shapiro et al. 2008) and that most of the galaxies forming the bulk of the infra-red emission at redshift unity look like undisturbed disk galaxies (e.g. Bell 2005, Melbourne et al. 2005, Lotz et al. 2008). The tightness of the SFR-Stellar Mass relationship also suggests that the evolution is mostly driven by smooth evolution and not starbursts (Noeske 2009, Noeske et al. 2007). The kinematics and morphology are more disturbed at high redshift than in the local universe but this fact is still consistent with minor merger and gas accretion (e.g. Ziegler et al. 2009) although this is still debated (e.g. Neichel et al. 2008). Finally, it has also been shown that models of the chemical and spectro-photometric evolution of the Milky

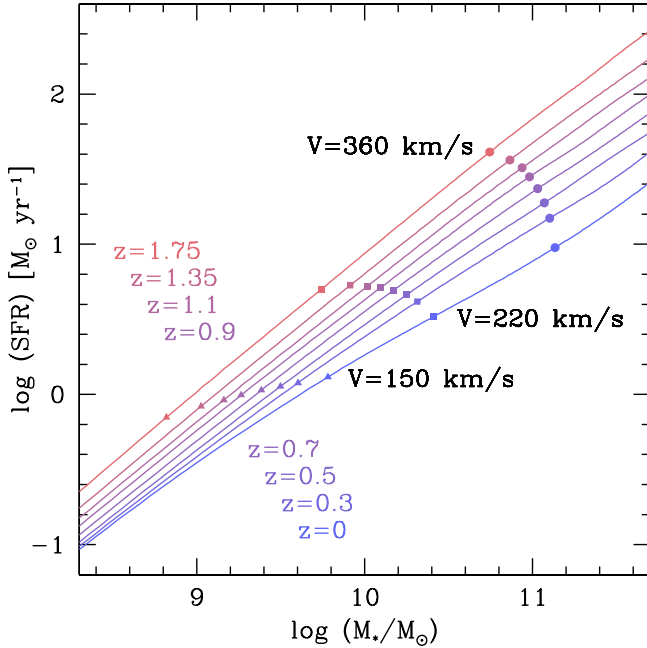


Fig. 1. Redshift evolution of the SFR - Stellar Mass relationship in the backward models. Symbols (triangles, squares, circles) show the values for three velocities (150, 220, 360 km/s).

Way and nearby disk galaxies, when rolled backwards, fit in a very reasonable way the properties of redshift ~ 0.7 star forming galaxies (Buat et al. 2008).

In this paper, we propose to combine such models with the information from the SMF in order to compute the evolution of the “Velocity Function”, with the advantage that the velocity tags a galaxy, while the stellar mass evolves with redshift when star formation takes place (e.g. Noeske 2009 mentions the intrinsic difficulty in comparing galaxies of a given stellar mass at different redshifts). This allows us to check the global consistency of the SMF, the SFR of individual galaxies, the cosmic SFR density and simple models of galactic evolution. It is then possible to derive the fraction of galaxies that were similar to the Milky Way (the “Milky Way siblings”) and that must have quenched their star formation during the second half of the history of the universe. We acknowledge that this approach is simplistic but we think it is worth performing it since it allows us to step back and have a global look at all the important data of the problem (Stellar Mass Functions of quiescent and star forming galaxies, SFR functions, cosmic SFR density) in a simple, educational framework, while many studies focus only on some of these aspects (with however interesting exceptions as e.g. Hopkins et al. 2009 or Bell et al. 2007).

In section 2, we present the “backward” models of the evolution of star forming galaxies that we use. In section 3, we compute the velocity function and its evolution assuming a constant SMF, as suggested by the observations. In section 4, the consequences of our simple assumptions are discussed. In section 5, a summary of our work is proposed.

2. Backward evolutionary models

Following the “backward” approach of Silk & Bouwens (1999), we make the assumption that the properties of star forming galaxies at high redshift can be inferred by rolling backward

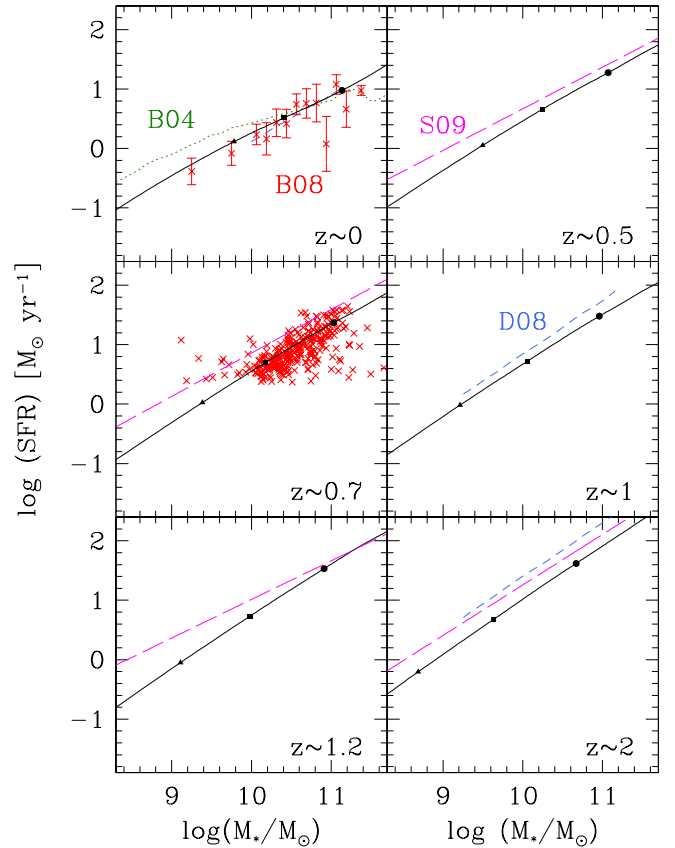


Fig. 2. Observed SFR - Stellar Mass relationship at various redshifts, compared to the models (solid line with the same symbols as in Fig. 1). Blue dashed lines (D08): observational trends reported by Davé (2008) on the basis of Elbaz et al. (2007) and Daddi et al. (2007). Dotted line (B04): Brinchmann et al. (2004). Crosses (B08): Buat et al. (2008). Magenta Long-Dashed lines (S09): Santini et al. (2009).

models of the evolution of well studied present day disk galaxies. This is motivated especially by Buat et al. (2008), showing that such backward models reproduce the average specific SFR - Stellar Mass relationships observed in galaxies at redshift 0 and 0.7.

In the present work, we use the same basic models and we remind below their main ingredients. These models are based on the grid proposed in Boissier & Prantzos (1999) and Boissier & Prantzos (2000) for the Milky Way and nearby spiral galaxies, calibrated to reproduce many observed trends in the local universe (e.g. colour-magnitudes diagrams, luminosity-metallicity relationship, gas fractions, colour and metallicity gradients). A comparison of this grid with the properties of galaxies at redshifts lower than 1 was proposed in Boissier & Prantzos (2001). Note that we changed the Initial Mass Function (IMF) from Kroupa et al. (1993) to Kroupa (2001), motivated by the fact that this IMF is closer to the one used in general in studies of the SMF. It is also providing a better fit to the UV surface brightness profiles of some of the SINGS galaxies (Muñoz Mateos et al., in preparation). The change affects mostly the most massive stars (thus the UV emission and metallicity output), leaving the SFR, gas, stellar mass evolution changed by less than about 20%. This number is below

the typical uncertainty that we can expect in our models. Indeed the calibrations used to measure stellar masses or SFR on which are based the models can easily be changed by a factor 1.5 to 2, for instance adopting different IMFs (e.g. Bell et al. 2007). The efficiency of the star formation law, a basic ingredient of the model is also varying within a factor 2 between galaxies (e.g. Kennicutt et al. 1998). As a result, we do not expect such models to give results to a better accuracy than a factor 2.

The grid of models was constructed adopting various circular velocity (V) and various values of the spin parameter (λ) measuring the specific angular momentum of the galaxy. With simple scaling relationships, this allowed the reproduction of the observed ranges of stellar masses and sizes of disk galaxies (the used scaling relationships imply that galaxies with larger velocities are more massive, and galaxies with larger spin parameter have larger spatial extent). For each couple of values of the parameters (λ , V), the corresponding model provides one unique history of the galaxy that includes the evolution of the SFR and of the stellar mass, resulting from the combination of a star formation law (see e.g. Kennicutt 1998, Boissier et al. 2003) and the accretion of cold gas at a rate chosen to reproduce the observations in nearby galaxies. For simplicity and following Buat et al. (2008), we adopt here the average value of the spin parameter ($\lambda=0.05$), and concentrate on the dependences on stellar mass (the mass of a galaxy depends on the circular velocity as $M \propto V^3$). A distribution of spin parameter would create a small dispersion around the main trends shown in the paper as a function of the stellar mass. The fact that the mass is the main intrinsic parameter of the evolution of galaxies was already found in “local” studies (e.g. Gavazzi et al. 1996) and confirmed in the recent years at high redshift (e.g. Noeske 2009). Thus, in this paper, for a given velocity, we have one star formation history, that can be seen in Fig. 6 of Buat et al. (2008). For high velocities, the SFR presents a rapid rise followed by an exponentially declining star formation rate. For $V = 220$ km/s (corresponding to the case of our Milky Way) the history is similar with a modest decline (in agreement with the observational constraints available in our Galaxy). Going to even smaller velocity (towards less massive galaxies), the SFR gently rises with time. Summarizing in simple words, the stars are formed earlier in galaxies with large velocities than in those with low velocities. We stress that these SFR Histories are not especially picked for this work. On the contrary, they result from the assumptions that one has to make to reproduce among others the distribution of metallicity in the Solar Neighborhood G-dwarf stars (Boissier & Prantzos, 1999) implying a long time-scale for the formation of our Galaxy, the colors and metallicity (Boissier & Prantzos 2000), the star formation efficiency and gas fractions (Boissier et al. 2001) of nearby galaxies, especially as a function of the luminosity or the stellar mass. Of course, the evolution might be more complicated than in these models, and there is no unique solution, however the general trends of these star formation histories are robust in view of the constraints involved.

Since Stellar Mass and SFR play a central role in our analysis, we show in Fig. 1 the relation between these two quantities in our models for various redshifts. The redshifts are chosen to correspond to the data of Ilbert et al. (2009) and Arnouts et al. (2007) to which we compare our results later in the paper. Note that the dependence of the various quantities on the circular velocity were initially computed only for a few points. These relations were interpolated on a finer grid and smoothed in order to avoid oscillations or artificial breaks due to the limited number of computed points. This allows us to present a smooth curve in this plot and the others in the remaining of the paper.

As mentioned earlier, there are evidences that these simple models capture enough of the properties of star forming galaxies up to redshift ~ 0.7 (Boissier & Prantzos 2001, Buat et al. 2008). We present in Fig. 2 in addition the relationship between the stellar mass and SFR for a set of redshifts for which various observations are available. This simple comparison shows that up to redshift 1, the model reproduces quite well the average trends found in observations, with serious departures starting only to be present at redshifts larger than 1. Especially at redshift ~ 2 , for galaxies more massive than $10^{10} M_{\odot}$ (for which observations are available), the models tend to underestimate the actual SFR for a given stellar mass. This difference between observations and models was found by other authors (e.g. Davé 2008, Santini et al. 2009) using semi-analytical or hydrodynamical models. Davé (2008) suggests that a solution might be a modification of the IMF with redshift. As noted by Santini et al. (2009), Khochfar & Silk (2009) propose that the star formation efficiency in high redshift galaxies is higher owing to cold gas accretion. Neither of these effects (probably still to be debated) are included in our models, and our strongest conclusions will be limited to redshifts lower than about unity, where they are not needed.

The various quantities presented in the paper assume a Kroupa (2001) IMF, and a ($H_0=70$, $\Omega_M=0.3$, $\Omega_{\Lambda}=0.7$) cosmology.

3. Derivation of the velocity function

The SMF of star forming galaxies has little evolved between redshift 1 and redshift 0. In Fig. 3, we present the observed SMF of Bell et al. (2003) at redshift 0 (with two different definitions of the star forming sample, based on either color or concentration); and those from Ilbert et al. (2009), Arnouts et al. (2007), and Borch et al. (2006) in various redshift bins (restricted to $z < 1$). This figure confirms that the evolution of the SMF for Star Forming galaxies, if any, is quite small (lower than 0.2 dex) with respect to the difference between the various studies that can reach about 0.5 dex.

Taking into account this dispersion and lack of clear evolution, we believe it is educational to adopt the assumption that the SMF is indeed constant with redshift, by defining an Average Mass Function (AMF) as the average value among the curves shown in Fig. 3 (unweighted average of $\log(\Phi(M_*))$ after converting each work to the Kroupa et al. 2001 IMF). This AMF is shown in the figure as the thick curve. Note that many other determinations of the SMF exist, and we limited ourselves to a few representative cases. Especially, Bell et al. (2003) is often used as a local reference, and the SMF by Borch et al. (2006) were measured following the same methods at higher redshifts. Ilbert et al. (2009) and Arnouts et al. (2007) propose two slightly different approaches in identical redshift bins, and procure a good example of the dispersion that can be found in the data due to e.g. cosmic variance or differences in the adopted methods. Note that Hopkins et al. (2009) also chose these two last studies for their analysis for the same reasons. Inspection of Fig. 3 thus shows that the AMF at each stellar mass has a typical uncertainty of 0.2 dex.

As stellar mass is obviously evolving in star forming galaxies, the fact that the SMF is roughly constant for $0 < z < 1$ is actually hiding a real evolution. To get rid from this difficulty, we compute a model Velocity Function where the velocity is ac-

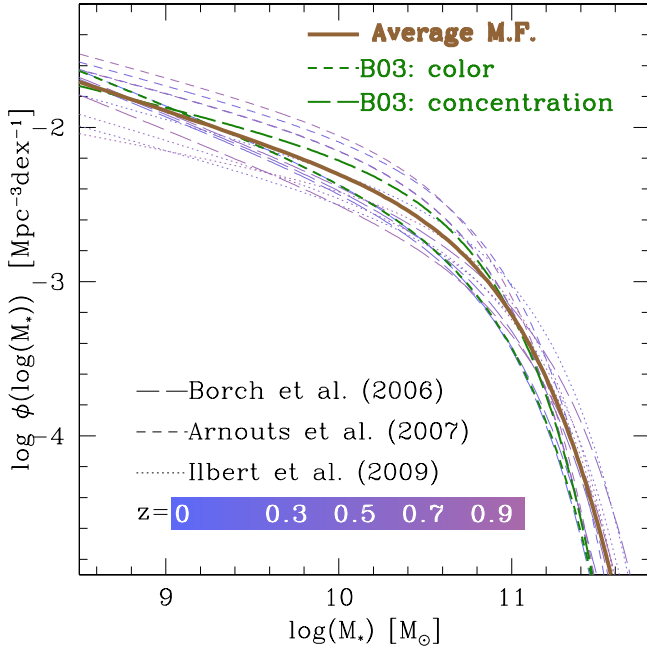


Fig. 3. Stellar Mass Functions for star forming galaxies from Bell et al. (2003) (redshift 0, bold dashed curves for both the color-selected sample and the concentration-selected one), Ilbert et al. (2009) as dotted curves, Arnouts et al. (2007) as short-dashed curves and Borch et al. (2006) as long-dashed curves (between redshifts 0 and 1). The resulting Average Mass Function (AMF) is shown as the bold solid curve.

tually the parameter of the simple model presented in section 2, and thus does not evolve. The Velocity Function is computed as:

$$\phi(V) = \frac{dN}{dV} = AMF(M) \times \frac{dM}{dV}. \quad (1)$$

In this equation, $AMF(M)$ is the Average Mass Function defined above, and the factor dM/dV is obtained for each redshift by numerically deriving the velocity- stellar mass relationships of the models shown in Fig. 4: for each redshift, there is a one-to-one correspondence between the stellar mass and the velocity.

By definition, at redshift 0, the circular velocity can be identified with the observed rotational velocity. We thus compare in Fig. 5 the Velocity Function obtained for redshift 0 with the rotational velocity functions for spirals observationally derived by Gonzalez et al. (2000). They obtained their functions by combining various empirical luminosity functions and tully-fisher relationships available at that time. Taking into account the scatter they obtained for different inputs (about 0.4 dex at $V=220$ km/s), and the scatter around the AMF (different studies and different redshifts cover a range of 0.5 dex), the agreement between our redshift 0 model Velocity Function and the ones in Gonzalez et al. (2000) is reasonable. We also show the Velocity Functions obtained if we replace the AMF by the redshift 0 observed Stellar Mass Functions from Bell et al. (2003), giving an idea of the uncertainty (the scatter in Fig. 3 is larger than the difference obtained using the AMF or Bell et al. functions)

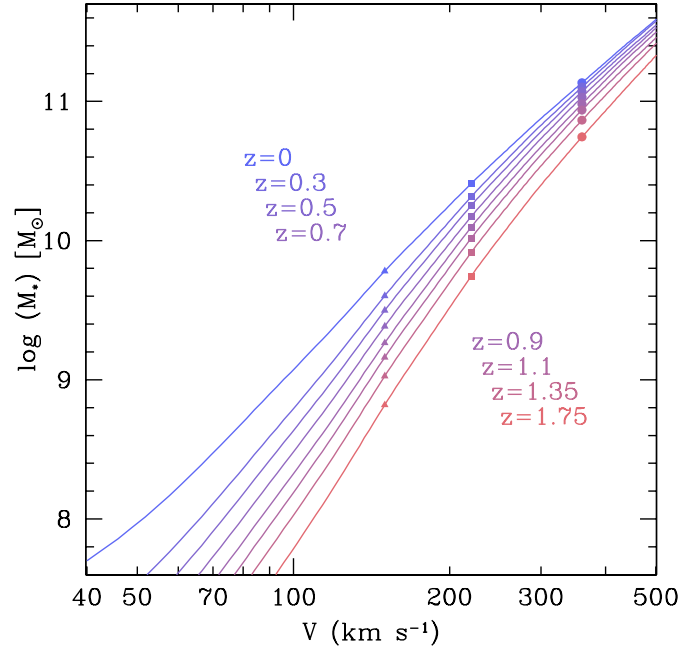


Fig. 4. Stellar mass - velocity relationship in the models (same color and symbol-coding as in Fig. 1).

4. Cosmic evolutions

4.1. Evolution of the velocity and SFR functions

In the previous section, we derived from the combination of observations (a constant stellar mass function, the AMF), and the stellar mass-velocity relationship of simple models the velocity function at various redshifts. From this distribution at each redshift, many quantities and their distribution can be computed using the models. Fig. 6 shows the evolution of the model velocity function in the top left panel. The “SFR function” evolution is shown in the top right panel, and the bottom panels shows the evolution of the contribution to the cosmic SFR density by galaxies of various stellar mass (left) and SFR (right). These panels illustrate that at higher redshift, the cosmic SFR density is dominated by galaxies of larger SFR in our models. It is also dominated by galaxies of larger stellar masses at larger redshift, although the effect is smaller. The peak of the contribution to the cosmic SFR density moves from $\log(M/M_\odot) \sim 10.6$ (redshift 1.75) to $\log(M/M_\odot) \sim 10.3$ (redshift 0). In the following, we study some interesting details of the evolution summarized in this figure.

These results (and those in the remaining of the paper) have been obtained assuming that the Stellar Mass Function of star forming galaxies is constant with time, while their Velocity Function changes. Before studying in details the consequences of our assumption, we first try to see whether the opposite assumption is acceptable. We thus assume that the Velocity Function is constant (we adopt the velocity function found at redshift 0 above, and shown in Fig. 5), and compute the evolution of the Stellar Mass Function then implied by the model stellar mass-velocity relationship. The results for redshift lower than 1 are shown in Fig. 7, together with the area occupied by the Star Forming Galaxies Stellar Mass functions observed in the same redshift interval by Ilbert et al. (2009), Arnouts et al. (2007) and Borch et al. (2006). We find a systematic decrease of the computed Stellar Mass Function with red-

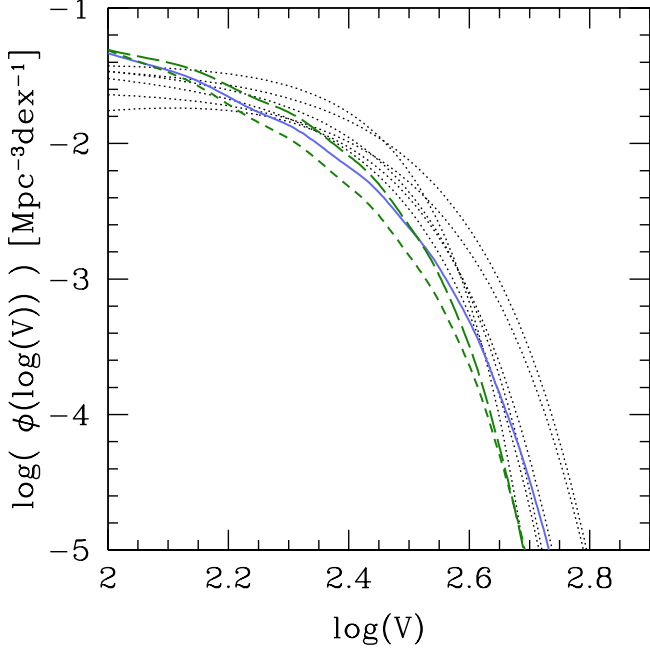


Fig. 5. Spiral galaxies Velocity Function at redshift zero, derived from the AMF using our models (solid line), compared to velocity functions empirically derived in the local universe by Gonzalez et al. (2000), using various observational sets (dotted lines). The dashed curves show the Velocity Functions obtained if the Bell et al. (2003) redshift 0 functions (shown in Fig. 3) are used instead of the AMF.

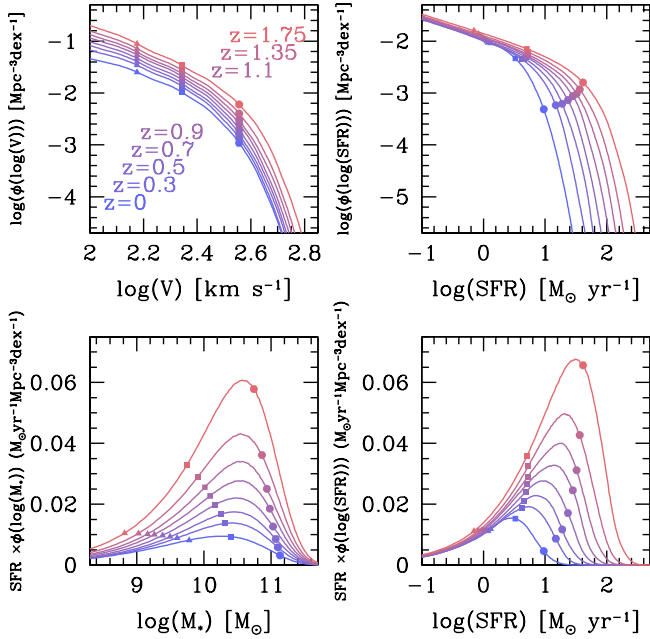


Fig. 6. Redshift evolution of the modeled velocity distribution (top-left panel), SFR function (top-right panel) and contribution to the cosmic SFR density (bottom) of galaxies of a given stellar mass (left) or SFR (right), assuming a constant stellar Mass function (the AMF, shown in Fig. 3). The redshifts and symbols are the same as in Fig. 1.

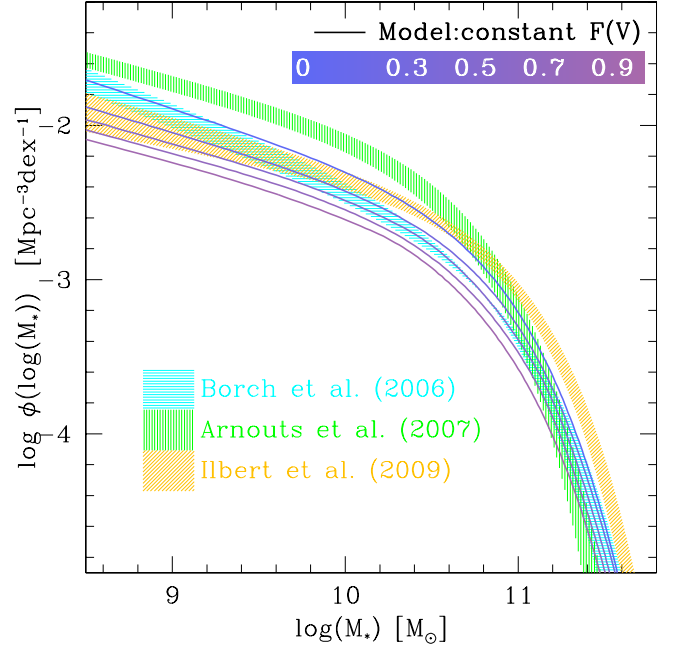


Fig. 7. Predictions at redshifts 0, 0.3, 0.5, 0.7, 0.9 for the Stellar Mass Function of star forming galaxies assuming a constant Velocity Function (lines), compared to the observed ranges by Ilbert et al. (2009), Arnouts et al. (2007) and Borch et al. (2006) in the same redshift intervals.

shift. For $\log(M/M_\odot) = 10.5 - 11$, the decrease with respect to the redshift 0 value reaches 0.4 dex at redshift ~ 1 . This number is not very far from the dispersion found among the observational studies. However, this dispersion is largely due to systematic differences between the various studies. Within the individual studies of Ilbert et al. (2009), Arnouts et al. (2007), and Borch et al. (2006), Fig 7 shows that the evolution of the SMF is smaller than ~ 0.2 dex, a much lower value than the change we expect under the assumption of a constant Velocity Function. We thus conclude that the evolution of the star-forming galaxies Velocity Function is clearly established.

4.2. Build-up of the “quiescent” stellar mass function

The model velocity function for star-forming galaxies shown in Fig. 6 evolves with redshift, with a larger number of star forming galaxies at higher redshift for any given velocity. It is another way to say that, at a given velocity, a fraction of galaxies have quenched their star formation between the redshift probed and now. We computed the velocity function with a $\Delta z = 0.2$ step in redshift. The difference between functions at different steps is the velocity function of galaxies that have quenched their star formation rate in this redshift interval and is shown in the top panel of Fig. 8 (normalised to be expressed as a flux). Combining it with the stellar Mass-Velocity relation at the beginning of each redshift interval (assuming the quenching is instantaneous at the beginning of the bin, since the stellar mass evolves little in such small redshift interval), we can compute the Quenched stellar Mass Function in each interval (bottom panel). This function is normalized by the time elapsed within each redshift bin, so that it is actually a number density flux from star forming galaxies to quiescent ones. These numbers can be compared to e.g. Pozzetti et al. (2009) who found a red sequence growth rate

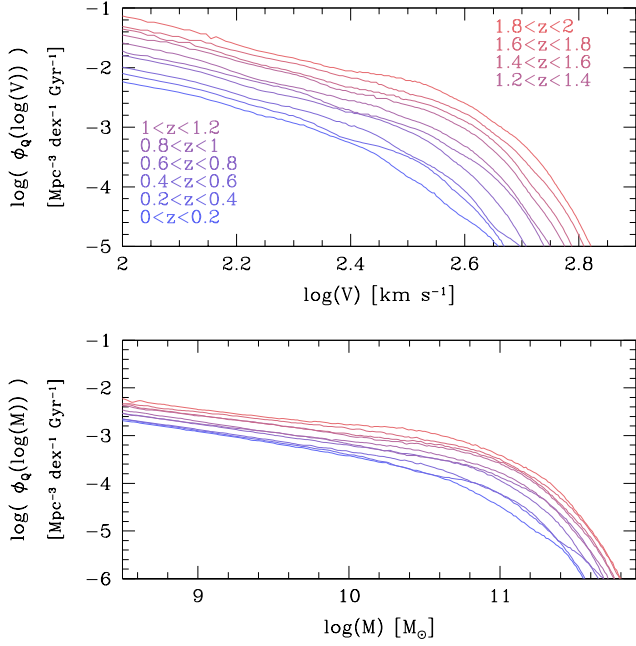


Fig. 8. Velocity (top) and stellar Mass Functions (bottom) of galaxies that “Quenched” their star formation within redshift bins of $\Delta z = 0.2$, as predicted in our model. The functions are normalised by the time elapsed within the corresponding redshift bins so that they correspond to number density fluxes.

of a few 10^{-4} gal $\text{Mpc}^{-3} \text{Gyr}^{-1} \text{dex}^{-1}$ for $\log(M/M_\odot) < 11$ in the redshift range 0.3 to 0.9. With the quenched flux estimated above, it is easy to compute the cumulated Quenched stellar Mass Function between two redshifts. This is done in Fig. 9, between redshift 1.1 (beyond this point, the models start to be unreliable, see section 2) and several redshifts for which we compare the results of our model to the increase in the quiescent stellar mass function of Ilbert et al. (2009) and Arnouts et al. (2007). Considering the uncertainties in the derivation of stellar mass functions (especially at high redshift, see in the figure the difference between the two observational studies), the agreement is good above $\sim 3 \cdot 10^{10} M_\odot$, i.e. the increase in the observed stellar mass function of quiescent galaxies is well compatible with the number of star forming galaxies that must quench their star formation in order to obtain their about constant stellar mass function, within a few tens of dex, i.e. our uncertainties (see also Bell et al. 2007 for a simple approach, and Pozzetti et al 2009). Below and around $10^{10} M_\odot$, the model predicts a much larger number of quenched galaxies and a steeper slope than the differential evolution obtained in the observational studies. This results directly from the assumption that the SMF of star forming galaxies does not evolve, even at low stellar mass where it is not observed at high redshift (in this regime, the model is a mere extrapolation). To obtain less quiescent galaxies with stellar masses in the range $10^9 - 10^{10} M_\odot$, we would need a change in the number of low-mass star forming galaxies with redshift. Only future observations bringing constraints on the low-mass end of the stellar mass function of star forming galaxies at intermediate redshift will allow us to check if it is the case. Pozzetti et al. (2009) computed the number evolution of quiescent galaxies in three stellar mass ranges between redshifts ~ 0.25 and 0.9. In Fig. 10, we show their data and compare them to the predictions of our model (solid curves, integrating the cumulative quenched stellar mass

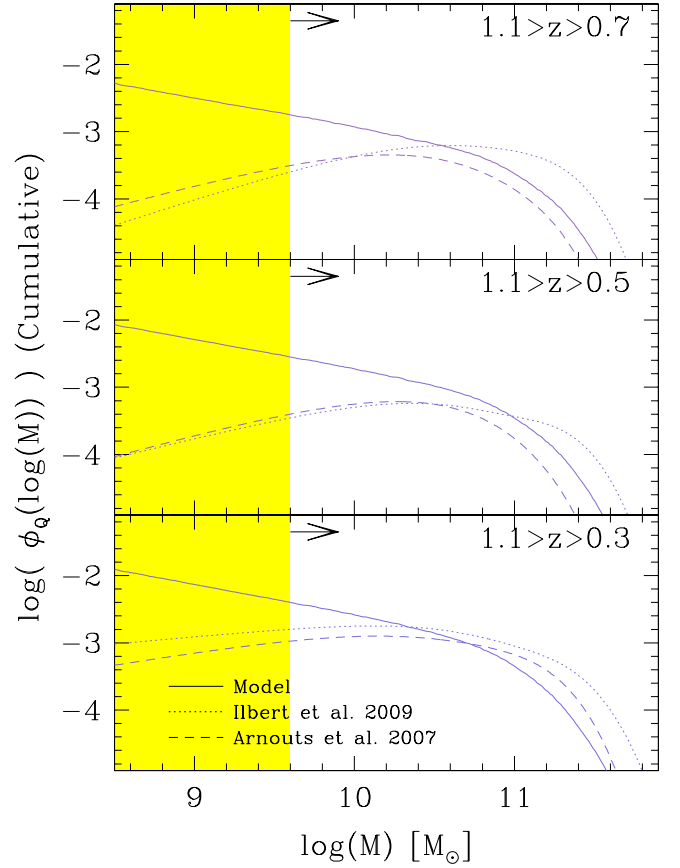


Fig. 9. The cumulated quenched stellar mass function since $z=1.1$ in our simple model is compared to the increase of the observed stellar mass function of quiescent galaxies in Ilbert et al. (2009) and Arnouts et al. (2007). The comparison is meaningful only out of the shaded area, on the side indicated by the arrow (the limit corresponds to $\log(M)=9.6$, the lower stellar mass used in Ilbert et al. (2009) at redshift 1.1, that we use as reference).

function such as the ones shown in Fig. 9 in the same stellar mass bins). We also show our computations of the same numbers using the observed stellar Mass Functions of Arnouts et al. (2007) and Ilbert et al. (2009), allowing to estimate the uncertainty on these numbers by comparing the various studies. When considering the top panels, one has to take into consideration the fact that a number of quiescent galaxies are “formed” beyond redshift 1.1, while the model only shows the one formed by quenching after this epoch. For this reason, the two thin lines show the sum of the newly quenched galaxies (model) and of the quiescent galaxies already existing at redshift 1.1, taking the data of Ilbert et al. (2009) or Arnouts et al. (2007). We also show in the bottom panels the relative number evolution with respect to $z \sim 0.9$. On the massive galaxies side, the quenching forms a small number of quiescent galaxies with respect to the number already present at $z=0.9$: massive galaxies are already in place at this redshift. The model predict a small increase of the number density in this stellar mass range, consistent with the estimations of a quasi constant number-density. Moving to the intermediate stellar mass bin ($10^{10.5-11} M_\odot$), we predict a larger increase in the number of quenched galaxies, consistent with the data. We note however a large dispersion: the model tend to underpredict the evolution with respect to Pozzetti et al. (2009), but overpredict it

with respect to Ilbert et al. (2009) or Arnouts et al. (2007). In the lower mass bin, the model is roughly consistent with the various studies when no normalisation is done (top panel of fig. 10). In the bottom panel, two of the observational works are found below the model curve but this is mostly due to the $z=0.9$ point. The figure suggests that most of the low-mass quiescent galaxies are formed between redshifts 1.1 and 0 through quenching of the star formation of star-forming galaxies.

4.3. On the role of mergers

Fig. 9 shows that the star formation quenching inferred from the model reproduces relatively well the observed increase on the massive side of the SMF for quiescent galaxies (even if uncertainties due to poor statistics are large). It overpredicts the quiescent SMF on the low mass-side (even if at the lowest stellar masses, the models are extrapolations, the slope seems larger than the one observationally found). How would those results be affected if in addition to the quenching itself, the mass is redistributed through mergers? A complete answer would need a full treatment of the Halo Occupation Distribution and is beyond the scope of this paper. However, we attempt to illustrate what could happen in two simple cases shown in Fig. 11. We thus start from the modeled Stellar Mass Function of quenched galaxies between redshifts 1.1 and 0.3 (within the mass range 10^8 to $10^{12} M_\odot$). We then assume two merging scenarios, redistributing the mass in different ways: - Case 1: Each quenched galaxy merge with another one, the mass of each merging galaxy being taken randomly from the initial distribution with lower mass limit $10^8 M_\odot$ (mergers - random mass curve in Fig. 11), resulting in an average mass ratio of 0.14 for a final $10^{11} M_\odot$ galaxy. - Case 2: Each galaxy suffers one major merger in the redshift interval, computed by assuming that each galaxy merge with a galaxy of identical mass (same mass curve). Jogee et al. (2009) estimated that 68 % of galaxies with stellar masses larger than $2.5 \cdot 10^{10} M_\odot$ have undergone a merger of mass ratio larger than 1/10 over lookback times of 3 to 7 Gyrs. Including stellar masses as low as $10^9 M_\odot$, they found that 84 % of galaxies have undergone one merger. Thus Case 1 may not be very far from the truth. Case 2 is highly biased in favor of major mergers given the results from various studies. For instance, Jogee et al. (2009) found that 16 % of galaxies have undergone a major merger over lookback times 3-7 Gyrs. Based on galaxy pairs, de Ravel et al. (2009) found that 22 % of galaxies have undergone a major merger since $z \sim 0.9$. López-Sanjuan et al. (2009) found that 8 % of galaxies more massive than $10^{10} M_\odot$ have undergone a merger since $z \sim 1$.

Case 1 shows that a small number of minor mergers have almost no effect on the stellar mass function. Making e.g. \sim ten minor mergers (an extreme case) rather than 1 would have an impact on the results however they would depend on the lower mass limit adopted for the computation, while the SMF is increasingly uncertain towards low masses.

Case 2 shows what happens if each galaxy goes through one major merger. In this case, the shape of the quenched stellar Mass Function is modestly changed at low and intermediate mass where the number of galaxy at a given stellar mass is slightly reduced. Only the high-mass end of the distribution is significantly changed. In particular, major mergers seems to be the only way to build the more massive quiescent galaxies.

As seen earlier, the slope found in the intermediate/low mass range of the diagram is quite steep in the model with respect to the observations of Ilbert et al. (2009) or Arnouts et al. (2007). Fig. 11 shows that simple merger models do not help to solve the problem.

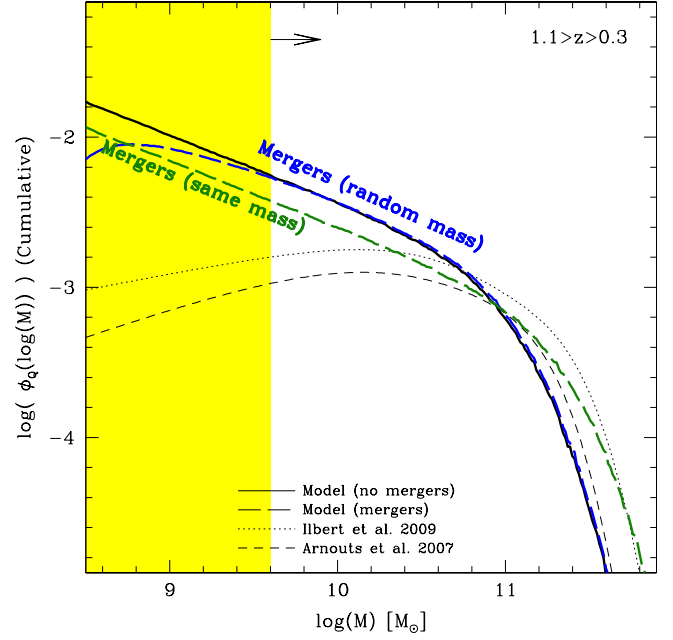


Fig. 11. The increase of the observed stellar mass function of quiescent galaxies in Ilbert et al. (2009) and Arnouts et al. (2007) is compared to monte-carlo realization of the cumulated quenched mass function between $z=1.1$ and $z=0.3$. One realisation (black solid line) shows the same as Fig. 9 (i.e. result obtained by quenching star-forming galaxies by the right amount to keep a constant stellar Mass Function) while others show the potential effect of various merger scenario on the mass function (see text).

One assumption that has been implicitly done is that mergers do not enhance star formation. If it was not the case, a fraction of star forming galaxies would have larger SFR than deduced from the models, and the result of the fusion would have a larger stellar mass than the one described in the basic approach of this section. However, Robaina et al. (2009) showed recently that the additional SFR due to mergers is very modest (and then even more significant for the additional stellar mass). de Ravel et al. (2009) found a net star formation enhancement in merging pairs of only 25 %. This modest enhancement is also consistent with the merger simulations of Di Matteo et al. (2007). Note that in fact, we do not exclude at this level the possibility of mergers being related to the quenching itself. The merging of two star forming galaxies of similar mass may result in the quenching of their star formation, for instance through AGN formation and feedback (e.g. Sanders et al. 1988, Springel et al. 2005). This case would be exactly similar in our approach to two star-forming galaxies quenching their star formation, and having their masses added together to form a new galaxy (Case 2 above).

In summary, in this section, we only discussed about the shape of the mass distribution of quiescent galaxies, and the possible impact of mergers on it. Our conclusion is that the stellar Mass Function of galaxies quenched at redshift lower than 1.1 originates from the shape of the SMF of star forming galaxies. Mergers only bring modest adjustment to the quenched stellar Mass Function by re-distributing part of the mass. They probably may play an important role at most at the high-mass end of the Mass Function.

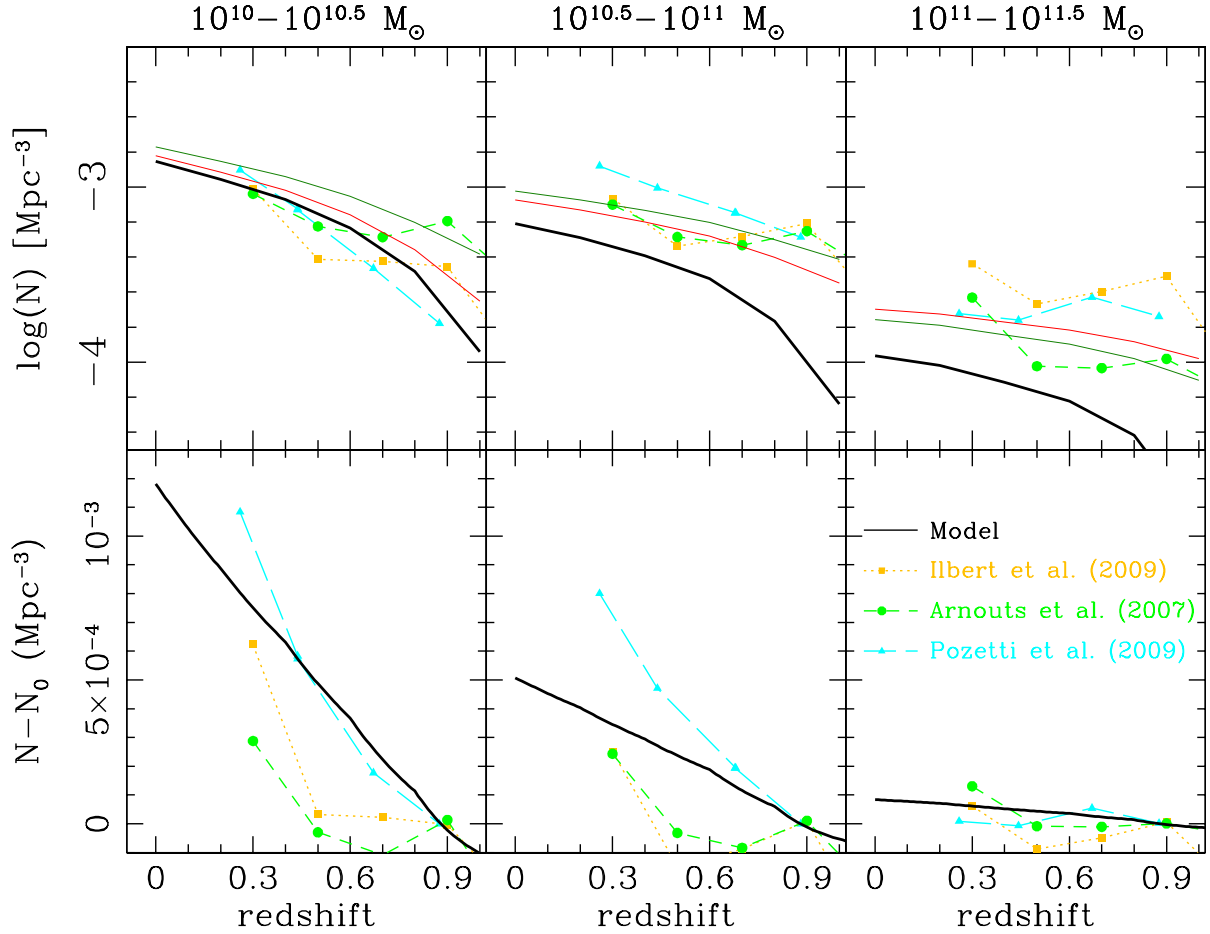


Fig. 10. *Top:* Modeled evolution of the number density of quiescent galaxies (solid curves) in three stellar mass bins (left to right: $10^{10}-10^{10.5} M_{\odot}$, $10^{10.5}-10^{11} M_{\odot}$ and $10^{11}-10^{11.5} M_{\odot}$) cumulated since redshift 1.1, compared to the data of Pozzetti et al. (2009) for the same mass ranges as the long dashed curves with triangles. We integrated within the same mass bins the observed stellar mass functions of Ilbert et al. (2009) and Arnouts et al. (2007), respectively the dotted with squares and dashed with circles curves). We also show as two thin solid curves how the model curve is shifted if we add to the newly quenched galaxies the number of quiescent galaxies already present at $z=1.1$ according to the observed Stellar Mass Functions of Ilbert et al. (2009) and Arnouts et al. (2007). *Bottom:* Differential number density evolution in the same mass ranges (N_0 is the number density at redshift 0.9 in both the data and the model). See section 4.2 for details.

4.4. Cosmic SFR density

In the last decade, many studies have put constraints on the cosmic SFR density history. A compilation can be found in Hopkins & Beacom (2006). In a more recent work, Wilkins et al. (2008) derived the cosmic SFR density history from a compilation of measurements of the cosmic stellar density at various redshifts. These two approaches give close results in the redshift range in which we are interested, the latter one producing a smaller drop in the cosmic SFR density between redshift 1 and 0 (a factor of about 6 versus 10). We decided to use as a reference the results of Wilkins et al. (2008) for two main reasons: first it is based on measurements of mass densities, more consistent with our starting points of stellar mass functions than SFR measurements. Second, any evolution that we need to impose in our model to reproduce this trend is likely to be a lower limit on the actual evolution.

In Fig. 12, we reproduce the evolution provided by Wilkins et al. (2008) with their 1 and 3σ dispersion determination as the solid curve and shaded areas. We overplot the cosmic history of the SFR density obtained with the model ve-

locity function derived at various redshift as explained before, in combination with the velocity-SFR relation from the models (triangles). Concentrating on the redshifts lower than 1 where we are confident in the models, we note that the points are within the shaded area determining the compilation of data from Wilkins et al. (2008) even if the drop in SFR is not as large as usually considered (factor of ~ 3 rather than 6 since redshift 1). This is mostly due to the fact that our AMF produces a relatively large cosmic SFR density at redshift 0. We also present in the figure the cosmic SFR density if the observed Stellar Mass Function of Bell et al. (2003), derived at redshift zero is used rather than the AMF (dots). Very similar results are found, especially the fact that our redshift 0 point is relatively high. This indicates a small inconsistency between the SMF of local star forming galaxies, the SFR-Stellar mass relationship, and the cosmic SFR density measurements, the basic observables used to compute the redshift 0 point.

In this figure, we also attempt to relax the assumption of a constant stellar mass function, and we use for each redshift shown the mass functions derived for this redshift by Ilbert et al. (2009) (open circles) and Arnouts et al. (2007) (open

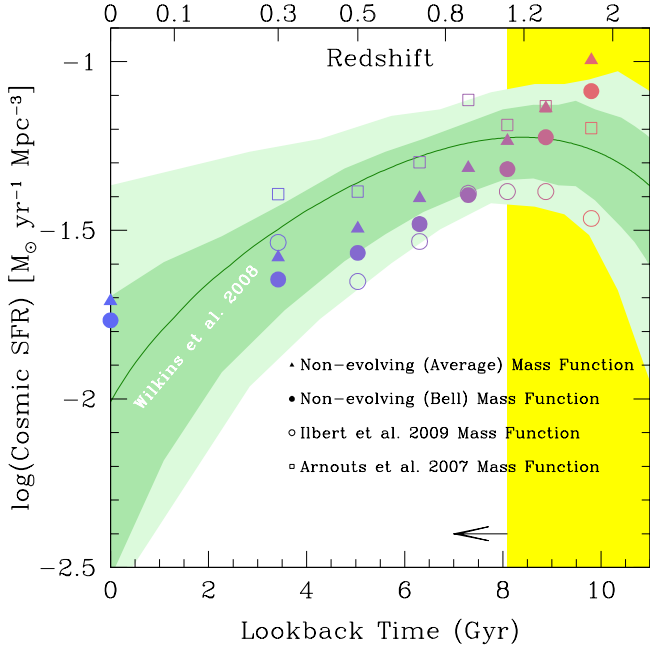


Fig. 12. Cosmic star formation rate density histories. The observational trend from Wilkins et al. (2008) is compared to model predictions assuming a constant SMF (filled circles assuming the Bell et al. (2003) stellar Mass Function for a color-selected sample, filled triangles assuming the AMF), or using for each redshift the SMF observed at this redshift by Ilbert et al. (2009) (open circles) or Arnouts et al. (2007) (open squares). In the vertically shaded area ($z > 1.1$), the results from the models are mere extrapolations showing the limits of our approach beyond this redshift.

squares) in place of the AMF. The general trend is similar to the one obtained with the AMF, but introducing deviations around it. These deviations correspond to the scatter in the observed stellar mass functions. The approach consisting in using the AMF allows us to focus on general trends, and filters out the peculiarities of individual studies (e.g. the effects of cosmic variance).

The points at redshift larger than 1 can be considered as extrapolations in which we have little confidence since the models are less and less reliable when moving at larger redshifts. The points show that our basic assumptions overpredict the cosmic SFR density at redshift 1.75 by a few tens of dex. Since the models underpredict the individual SFR in galaxies towards these redshifts but the cosmic SFR density is over-predicted, this means that our other assumption (the consistency of the SMF) cannot be applied at these redshifts. Indeed, the points computed with the SMF of Ilbert et al. (2009) and Arnouts et al. (2007) are in better agreement with the Wilkins et al. (2008) data.

A good way to understand the cosmic SFR density evolution is to look in Fig. 13 at the star forming galaxies SFR functions at each redshift for which they were observationally derived in Bell et al. (2007), Le Floc'h et al. (2005), and Rodighiero et al. (2009). The infra-red luminosity functions from the two last papers were converted into SFR functions assuming $\log(SFR) = \log(L/L_\odot) - 9.97$ (Buat et al. 08). Note that other references are available in the infrared but we show Rodighiero et al. (2009) and Le Floc'h et al. (2005) for convenience as they are given for the same redshift bins, of interest for us. The latter study found a slightly smaller number of very

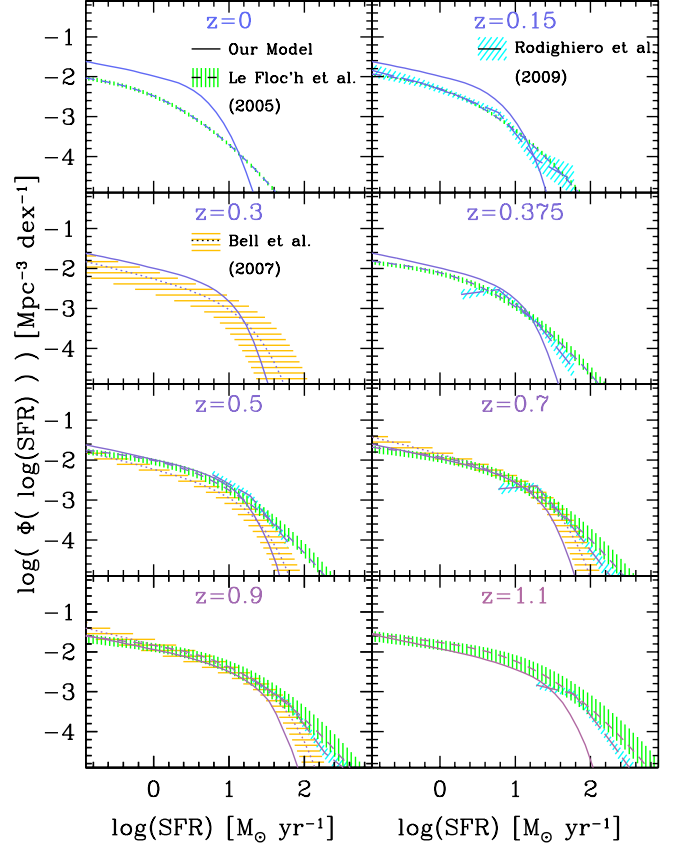


Fig. 13. Models SFR Functions at various redshifts compared to observations of Bell et al. (2007) and to the infrared luminosity functions observed by Le Floc'h et al. (2005), and Rodighiero et al. (2009) converted into SFR functions assuming $\log(SFR) = \log(L/L_\odot) - 9.97$ (Buat et al. 08).

luminous galaxies than the former, as did Magnelli et al. (2009). For redshifts above 0.3, the modeled SFR functions are consistent with the data, especially for intermediate star formation rates (a few to a few tens $M_\odot \text{yr}^{-1}$) dominating the cosmic SFR density (see Fig. 6). The shape of the function is not evolving much, but is shifted towards higher SFR when moving to larger redshifts, both in the observations and the models (as normal disk galaxies had larger amount of gas and SFR in the past). The models distribution has a sharper drop at high SFR than the observations (especially at high redshift), what may indicate that we are missing a small number of galaxies with enhanced activity with respect to the models. This is also the case when comparing our models to Ilbert et al. (2009) or Pozzetti et al. (2009). We do not reproduce the “active” fraction of galaxies observed by these studies. However, because of the shape of the SFR function, such galaxies cannot dominate the cosmic SFR density, although they may contribute slightly to its evolution. To estimate this contribution, we use the Le Floc'h et al. (2005) data to compute the fraction of the cosmic SFR density coming from galaxies with SFR higher than $10 M_\odot \text{yr}^{-1}$ and that are not predicted by the models (i.e. computing the difference between the model and observed contributions to the cosmic SFR density above this SFR with respect to the total one). This fraction is equal to 13, 19, 23, 31 and 38 % at redshift 0.375, 0.5, 0.7, 0.9, and 1.1. This discrepancy was found in other simple models (e.g. Daddi

et al. 2007, Davé et al. 2008). Part of the difference could be due to an enhancement of star formation during interactions that are not included in our approach. Actually, the recent studies of Robaina et al. (2009) and Jogee et al. (2009) suggest that major interactions trigger extra star formation. They contribute to less than 10 % to the cosmic SFR density, but are responsible for some of the galaxies with the largest SFR as revealed by their infra-red luminosity. This results is also recovered by the empirical models of Hopkins et al. (2009). Even so, our approach is still meaningful since these galaxies do not represent the bulk of the contribution to the cosmic SFR density.

We have seen above that the model is on the upper side of the cosmic SFR density at low redshift, thus predicting an evolution with redshift on the weaker side of the one allowed by the data. It is interesting to note that the modeled SFR functions at low redshift ($z < 0.3$ panels in Fig. 13) also overestimate the number of galaxies with intermediate SFR, around a few $M_{\odot} \text{yr}^{-1}$ (dominating the cosmic SFR density at this redshift) by up to 0.6 dex (almost a factor 4). This difference explains the excess in the cosmic SFR density obtained at low redshift in the models. The Stellar Mass-SFR relationship is relatively easy to construct and different data sets provide very similar results for this amount of star formation (top left panel of Fig. 2: the average values are well within 0.2 dex of each other). The only other way to overestimate the cosmic SFR density and the SFR function in our approach is to over-estimate the Stellar Mass Function. The AMF that we adopted is however very close to the one measured by Bell et al. (2003) at redshift 0. The most simple solution to this conundrum would be to consider that the local stellar Mass Function reported in Bell et al. (2003) for star forming galaxies overestimates the number of galaxies with intermediate stellar mass (a few $10^{10} M_{\odot} \text{yr}^{-1}$) by a factor 2 to 4; and thus that the SMF in fact does evolve slightly at the lowest redshifts (note that reducing the SMF for all redshifts would lead us to underestimate the cosmic SFR density at redshift ~ 0.5 , thus we do need an evolution). We note that the total observed stellar mass function of Bell et al. (2003) is in good agreement with many other works, and is very probably fine. However, there is an intrinsic difficulty in splitting galaxies in star forming and quiescent ones (see the dispersion at larger redshift between the various studies using various criteria for doing such a thing). Local studies are also very different in nature than higher redshift ones (local volume versus deep field). In summary, a small evolution of the SMF of star-forming galaxies at the lowest redshift could improve the agreement with SFR functions and the drop in the cosmic SFR density. Such an evolution is not visible in current data, what may be due to the combined effect of dispersion and of the intrinsic differences in local studies versus high redshift ones in terms of surveys and separation of the various types of galaxies.

4.5. On the fate of the Milky Way siblings

Fig. 14 shows the number evolution of star forming galaxies of a given velocity. This is different from number evolution of galaxies of a given stellar mass (what is more often shown) because the mass of a star forming galaxies evolves with time (e.g. Noeske 2009). In our approach, the velocity is attached to a galaxy. We show it for massive galaxies ($V=360 \text{ km/s}$, top panel) and for intermediate mass galaxies, similar to the Milky Way ($V=220 \text{ km/s}$, bottom panel). This figure shows clearly that the number of galaxies with a given velocity has declined since redshift 1. The $V = 220 \text{ km/s}$ galaxies have declined by a factor about 2 since redshift 1. Thus statistically, half of the Milky

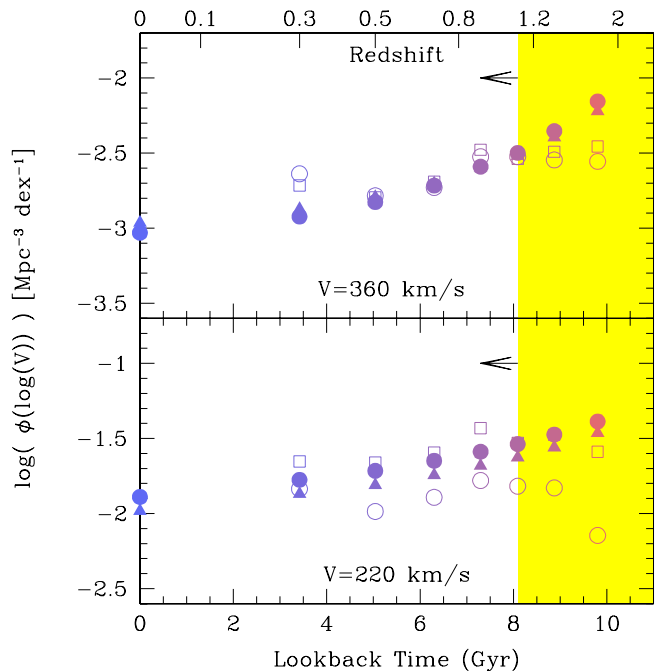


Fig. 14. Evolution of the number of Milky-Way type spirals ($V=220 \text{ km/s}$, bottom) and more massive galaxies ($V=360 \text{ km/s}$, top) with redshift. Symbols are the same as in Fig. 12.

Way siblings at redshift 1 have disappeared since then ! The fraction of more massive galaxies having survived is even lower. Note that given the discussion above, these numbers are probably lower limits: if as suggested by the SFR function, the SMF does evolve, and especially is lower by a factor 2-4 at redshift zero, the evolution given above should be multiplied by a similar quantity.

Beyond redshift ~ 1 , once again our results are extrapolations that should be treated with caution. Especially, the trend obtained with a constant stellar Mass Function for star forming galaxies, and the one adopting observed functions start to differ (this is similar to what is found with the cosmic SFR density in the previous section). The number of galaxies with $V = 220 \text{ km/s}$ is found to decline with increasing redshifts when we use the stellar Mass Functions from Ilbert et al. (2009) (and flatten with Arnouts et al. 2007), indicating that we may reach another era when the stellar Mass Function of star forming galaxies is not constant with time, as this population is building up.

What are the processes and loci of the transformation of half of the Milky Way sisters between redshift 1 and 0 ? Many suggestions can be found in the literature. For instance, Pozzetti et al. (2009) propose that the transformation could be driven by several processes (aging of the stellar population, exhaustion of the gas reservoir, gas stripping, AGN feedback, truncation of gas accretion via infall or satellites, starvation or strangulation) but they do not clearly identify it. Bolzonella et al. (2009) find some clues that the transformation is accelerated in over-dense regions. However the environment is only roughly defined (5th neighbor). They propose viable mechanism as merging processes triggering AGNs (but see discussion on mergers below) and propose finally strangulation (halo-gas stripping due to gravitational interaction with e.g. groups haloes). On the other hand, Cowie & Barger (2008) found an effect of environment (traced by the projected nearest neighbor) only in massive galaxies (above $10^{11} M_{\odot}$), while we definitively

need an effect below. Martig et al. (2009) proposed the process of “Morphological Quenching” of the star formation, occurring when disks become dominated by a stellar spheroid stabilizing the disk against star formation. In this scenario, the spheroid can be built via major, minor merger or disk instabilities. Although an interesting process, this does not allow by itself to easily predict which fraction of disks are going to turn red and dead.

Whatever process is responsible for quenching star formation, it cannot have happened only in clusters of galaxies that encompass a much smaller fraction of galaxies than the one we need to quench (point also noted in Bolzonella et al. 2009). Based on merger models, Koda et al. (2009) suggest that 70 % of galaxies with halo mass in the range $5 \times 10^{10} - 10^{12} M_{\odot}$ have not suffered a merger with mass ratio larger than 0.05 since redshift 1. This point is also consistent with the results of Oesch et al. (2009) indicating that mergers cannot drive the morphological transformation at redshift less than unity. Observationally, Robaina et al. (2009) and Jogee et al. (2009) found relatively low rates of major mergers. Thus major mergers cannot explain the number decrease of Milky Way galaxies (50%) or more massive galaxies.

In conclusion, this major event in the history of a downsizing universe, consisting in the halt of star formation in previously star forming galaxies (then becoming quiescent galaxies) must be a common phenomenon occurring on an intermediate scale, not specifically related to clusters or major mergers. May be we should look at the scales of groups to find the culprit (see also Tran et al. 2009 and references within). Several elements reinforce us in adopting groups as prime suspects, firstly the fact that the number of galaxies in groups (55% in Eke et al. 2004) is large enough to be consistent with the large fraction of galaxies that must quench their star formation. More-over, Star Formation is suppressed on the scales of groups according to Lewis et al. (2002) who found that the SFR depends on local density, regardless of the richness of groups or clusters. Kilborn et al. (2009) recently studied HI in groups and conclude that transformation is taking place in groups in which galaxies loose gas through tidal stripping during galaxy-galaxy or galaxy-group interaction. Tanaka et al. (2007, 2009) also suggest that galaxy-galaxy interactions in groups play a major role in the built-up of the red sequence on the basis of a detailed spectroscopic analysis of galaxies embedded in filaments around two clusters at redshift 0.55 and 1.24. Finally, Gavazzi et al. (work in preparation) found that the red sequence is already formed in groups (as it is in clusters, but not among isolated galaxies).

5. Conclusions

This paper presents an original and educational approach to work with Stellar Mass Function of star forming galaxies. The main point consists in combining observed Stellar Mass Functions with simple backward evolutionary models (assuming a smooth evolution driven by star formation in a galactic disk fuelled by cold accretion) to obtain modeled velocity functions at various redshifts. The big advantage of the velocity is that it is a model parameter attached to a galaxy, contrary to stellar mass, which evolves with star formation. In the framework of such models, for a given velocity, the Star Formation History and the Stellar Mass history are known. Galaxies with large velocities are the precursor of today’s massive star forming galaxies (in the absence of quenching), with stars having formed at an early epoch. Galaxies with low velocities have been formed on average at later times. These histories are not adhoc models for this paper, but have been shown to be consistent with a large num-

ber of properties of nearby star-forming galaxies. Combining the Velocity Functions and the models, it is possible to compute the model predictions for a large number of quantities and distributions at any redshift (e.g. SFR functions and cosmic SFR density).

At the current time, the empirical stellar mass functions are still rather uncertain (see the scatter between various studies). Assuming that, to the first order, the stellar mass function is constant for star forming galaxies at redshift lower than 1 (in accordance with the data), we obtained several interesting results:

1. A globally consistent picture is obtained in which a large fraction of star forming galaxies quench their activity of star formation between redshift 0 and 1, building up the red sequence. The shape of the quiescent galaxies stellar mass function is recovered above $\sim 3 \times 10^{10} M_{\odot}$. Mergers can only alter it slightly by redistributing the mass among galaxies. At most, their main effect could be seen only on the massive end of the stellar Mass Function.
2. The evolution of the cosmic SFR density falls within the compilation of Wilkins et al. (2008). However, our decrease towards low redshifts is smaller than in the observations. The discrepancy is especially due to our redshift 0 point. This may be related to a small inconsistency between the stellar mass function, SFR function, and stellar mass-SFR relationship of the local universe star forming galaxies.
3. The fraction of galaxies having quenched their star formation is high, in rough agreement with measurements. For example, we conclude that half of the Milky Way siblings (galaxies with circular velocities of 220 km/s) have quenched their star formation since redshift 1, and are then no more star-forming disk such as the Galaxy. This fraction is probably a lower limit since the model cosmic SFR density presents itself a relatively weak evolution with respect to the observed one.
4. The process responsible for this change is not clearly identified today. What is clear is that it is probably not related to cluster physics or to major mergers (which affect galaxies in too small numbers). Groups are our prime suspects because they are numerous enough to have a significant effect on the cosmic evolutions and several studies indicate that transformations are indeed taking place in them.

In the future, we hope that wider, deeper fields and improvement in the analysis of stellar mass functions will allow us to use the method exposed in this paper but on safer grounds. This will allow us to improve our models of galaxy evolution and to get a more complete picture of the cosmic evolution of star-forming galaxies, and their transformation into quiescent ones.

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