Gas accretion in galaxies as a function of halo mass and redshift

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ABSTRACT

Inflow of fresh gas in galaxies is essential to explain the scaling relation between stellar mass and star-formation rate (SFR) and the observed bimodality of the galactic population. Main sequence galaxies are continuously replenished of gas from outside, while for red sequence galaxies this supply is shut down. Therefore the conditions under which galaxies can accrete are of vital importance for theories of galactic evolution. The classic argument of comparing cooling time and free fall time of halos results in a halo virial mass range for effective gas accretion $\sim 10^9 - 10^{12} M_\odot$, not strongly dependent on redshift. More accurate descriptions predict an upper mass threshold of $\sim 6 \times 10^{11} M_\odot$ at $z = 0$, but, significantly, higher values for $z \gtrsim 2$, due to the fact that at that stage of cosmic history streams of cold gas could flow through halos even if they were not cooling efficiently. This results in massive starbursts at $z \gtrsim 2$. We compared data from two different datasets of galaxies, the first from SDSS survey that contains galaxies at $z \sim 0$ and the second from 3D-HST survey which extends up to $z = 3$. We constrained the halo mass thresholds for gas inflow and found that at $z \gtrsim 2$ the upper threshold must be higher, as predicted by most recent theories.

Key words: galaxies: SFR – galaxies: evolution – galaxies: halos

1 INTRODUCTION

Surveys of galaxies such as SDSS and 3DHST show an evident bimodality in the galactic properties: many of them live on a line in the $log(M_{star}) - log(SFR)$ diagram, usually referred as galactic main sequence, summarized by (Bouché et al.,2010):

$$SFR(M_{star}, z) = 150 \cdot M_{star,11}^{0.8} (1+z)^{2.7} M_\odot \mathrm{yr}^{-1} \quad (1)$$

this galaxies are blue and gas-rich, symptom of current star formation. On the other side, especially at high stellar masses, many galaxies are much redder, void of interstellar gas and dust, and are not forming new stars. The first family includes mostly disk-like galaxies, while the second one giant ellipticals, which often host AGNs. Various attempts have been made to explain this bimodality in a unified model of galactic evolution. The gas availability is the key factor (Bouché et al., 2010; Lilly et al., 2013; Almeida et al., 2014). Gas initially resides outside the virial radius of dark matter halos, and enters them at a cosmological rate given by (Bouché et al., 2010):

$$\dot{M}_{halo} \simeq 510 \left(\frac{M_{halo}}{10^{12} M_\odot}\right)^{1.1} \left(\frac{1+z}{3.2}\right)^{2.2} \quad (2)$$

When gas flows to the central disk it drives star formation. The system will reach a stationary state, in which the gas consumed by star formation is replenished by cosmic inflow (Bouché et al., 2010). Details of this model, called *open-box*, will be presented in the next section. In the opposite situation in which gas accretion is suppressed star formation will quickly estinguish the gas reservoir of the galaxy, which will then evolve according to the *closed box* model to become red and "dead" (Dekel & Birnboim, 2006; Lilly et al., 2013). Gas is prevented to inflow to the center of the halo whether the halo mass is too little or too high: in both cases gas can not cool enough within the dynamical time-scale of the halo (Rees & Ostriker, 1977). The condition of collapse is:

$$\frac{t_{cool}}{t_{ff}} = 20 \cdot T_6 \cdot \Lambda_{-23}^{-1}(T) \cdot (1+z)^{-3/2} \lesssim 1 \quad (3)$$

where Λ is the cooling function and T is the virial temperature, $T_{vir} \propto M_{halo}/R_{vir}$. This condition holds within halo mass range $\approx 10^9 - 10^{12} M_\odot$ (we neglect metal line cooling). The lower threshold is determined by UV background and by SN feedback (Bouché et al., 2010), which rise the temperature of the gas over 10^4 K and prevent efficient cooling. The upper threshold is due to ambient gas heating owing to gravitational structure formation via the formation of virial shocks. Gas post-shock temperature increases with the speed of the fall and therefore with the potential well's depth, which scales with mass. A more solid criterion for critical shock stability is balance between the cooling rate and the post-shock compression rate, rather than the dynamical time (Birnboim & Dekel, 2002; Dekel & Birnboim, 2006). Post-shock compression restores the pressure supporting the shock against gravitational collapse. The predicted halo mass upper threshold for cooling is $6 \times 10^{11} M_\odot$ at $z = 0$ (Dekel & Birnboim, 2006). Below this mass gas is not shocked to virial temperature and streams of cold gas can flow to the central parts of the halo and feed the disk. Interestingly, cosmological hydrodynamic simulations for spherical halos show that at $z \gtrsim 2$ streams of cold gas can penetrate even shock-heated halos (Fig. 1, Dekel & Birnboim, 2006). If this is true, an enhanced star formation should be in principle observable in galaxies at high redshift.

In this work we used a simple model of galactic evolution in order to link the halo mass thresholds for gas accretion to observables, in particular the stellar mass and SFR. We used this model to study whether the threshold is higher at $z \gtrsim 2$ than at $z = 0$.

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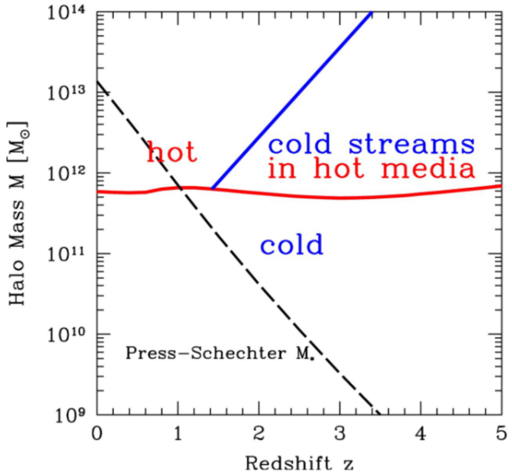

Figure 1. Penetration of streams of cold gas in dark matter halos as a function of virial mass and redshift, based on cosmological hydrodynamic simulations in spherical symmetry by Dekel & Birnboim (2006). At $z = 0$ streams can feed the central disk only if the halo mass is $\lesssim 6 \times 10^{11}$, while at $z \gtrsim 2$ cold streams can flow even in massive halos.

2 MODELS OF GALACTIC EVOLUTION

This section is based mostly on the works by Bouché et al. (2010) and Lilly et al. (2013). It is well known that for most of the galaxies SFR is proportional to the gas content (Kennicut-Schmidt model):

$$SFR(t) = \frac{\epsilon}{\tau_{dyn}} M_{gas}(t) \tag{4}$$

where ϵ is a dimensionless star formation efficiency parameter related to the physics of giant molecular cloud and we will take ~ 0.02, while τ_{dyn} is the dynamical time:

$$\tau_{dyn} = 2 \times 10^7 \left(\frac{R_{1/2}}{4\ \mathrm{kpc}}\right) \left(\frac{V_c}{200\ \mathrm{km/s}}\right)^{-1} \tag{5}$$

In the simple *closed box* model gas is consumed by newborn stars according to:

$$\frac{dM_{gas}}{dt}(t) = -SFR(t) = -\frac{\epsilon}{\tau_{dyn}} M_{gas}(t) \tag{6}$$

The gas content in the ISM falls exponentially, and SFR with it.

In the *open box* model inflows and outflows of gas from the galaxy are taken into account. We make the assumption that the only important source of gas outflow is due to SN type II explosions, and that the rate of explosions is proportional to the SFR: this is justified by the fact that very massive stars are short lived.

$$\dot{M}^{out}_{gas}(t,,) = \eta SFR(t) \tag{7}$$

η is the fraction of mass ejected by each SN type II event and it is set to 0.5. We will also assume that a fraction R of the gas consumed by star formation is returned to the ISM by stellar wind instead of being locked into stars and stellar remnants. A reasonable value for R is 0.4. The gas reservoir will evolve according to:

$$\begin{aligned} \frac{dM_{gas}}{dt}(t) &= \dot{M}^{in}_{gas}(t,,) - \dot{M}^{out}_{gas}(t,,) - (1-R)SFR(t,..) \\ &= \dot{M}^{in}_{gas}(t,,) - (1+\eta-R)\epsilon' M_{gas}(t) \end{aligned} \tag{8}$$

This equation is self regulated: the system will reach equilibrium when the timescale associated with gas consumption is comparable or shorter than the timescale of gas accretion. At equilibrium the only factor that determines the SFR is the rate of inflow of cold gas:

$$SFR^{eq} = \dot{M}_{gas,in} \frac{1}{(1+\eta-R)} \tag{9}$$

The gas supply from the halo to the central galaxy is regulated by an efficiency parameter:

$$\dot{M}^{in}_{gas} = \zeta f_b \dot{M}_{halo} \tag{10}$$

where $f_b \sim 0.15$ is the baryonic fraction. Often in literature ζ is set 0 or 1 whether halo mass falls between the two thresholds for effective cooling M^{min}_{halo} and M^{max}_{halo}. More complex models express ζ as convolution of different continuous terms, depending both on mass and redshift (Davé et al., 2012). We will explore this option later.

Galaxies that are continuously accreting gas and that reached equilibrium between the inflow rate and the outflow and consumption rate are those lying on the main sequence. The slope of the main sequence is determined by $\dot{M}_{halo} \propto M^{1.1}_{halo}$, while it's turning points by ζ.

3 METHODS, OBSERVATIONS

We used two different datasets of galaxies: the first is from the SDSS survey, and consists of photometric measurements in five different optical bands (u,g,r,i,z) for 92483 galaxies at low redshift ($z < 0.08$). To extract the stellar masses and SFR we used *CIGALE* (Code Investigating GALaxy Emission) software (https://cigale.lam.fr/). For each galaxy *CIGALE* fits the 5 spectral points with a spectral model for single stellar population, exponential star formation history (which offers high flexibility) and Calzetti law for dust absorption. *CIGALE* fitting algorithm runs over the space of model parameters and returns the values corresponding to the best χ^2.

For galaxies at high redshift we used 3D-HST catalogue (https://irsa.ipac.caltech.edu/data/COSMOS/spectra/3D-HST/3dhst_readme_v4.1.5.pdf). It contains optical spectra for 18745 galaxies, ranging from $z \sim 0.5$ to $z \sim 3$. The analyzing software is called *FAST* and works as *CIGALE*.

To constrain M^{min}_{halo} and M^{max}_{halo} we first linked them to the predicted SFR vs M_{star} curves: if $\zeta = 1$, equations (2), (9) and (10) combined will define a scaling law between SFR and M_{halo} that holds between the two thresholds. To link M_{halo} and M_{star} we applied the open box model: we initialized halos at different masses and evolved them numerically following equation (2). The inflowing gas rate is determined by (10). The gas reservoir of the galaxy is regulated by (8), which in turns gives at every time SFR and M_{star}. A full analytic solution is presented in Lilly et al., 2013. Fig. 2 shows the evolution over cosmic time of different dark matter halo and galaxy systems. Predicted curves in the SFR-M_{star} diagrams are obtained from the evolutionary paths of galaxies by joining the points at equal cosmic time, as shown in Fig. 3. We compared the model lines for different lower and upper mass thresholds with the experimental points from SDSS at $z = 0$, as shown in Fig. 4. We found that the best fit corresponds to $M^{min}_{halo} = 10^{9.5} M_\odot$ and $M^{max}_{halo} = 10^{11.6} M_\odot$ ($\tilde{\chi}^2 = 0.3$, 18 d.o.f.). For 3D-HST galaxies we first selected only those at redshift > 2 and then performed the same test: best fit corresponds to $M^{min}_{halo} = 10^{10} M_\odot$ and $M^{max}_{halo} = 10^{13} M_\odot$ ($\tilde{\chi}^2 = 1.9$, 18 d.o.f.). The experimental points and fitted curve are shown in Fig. 5.

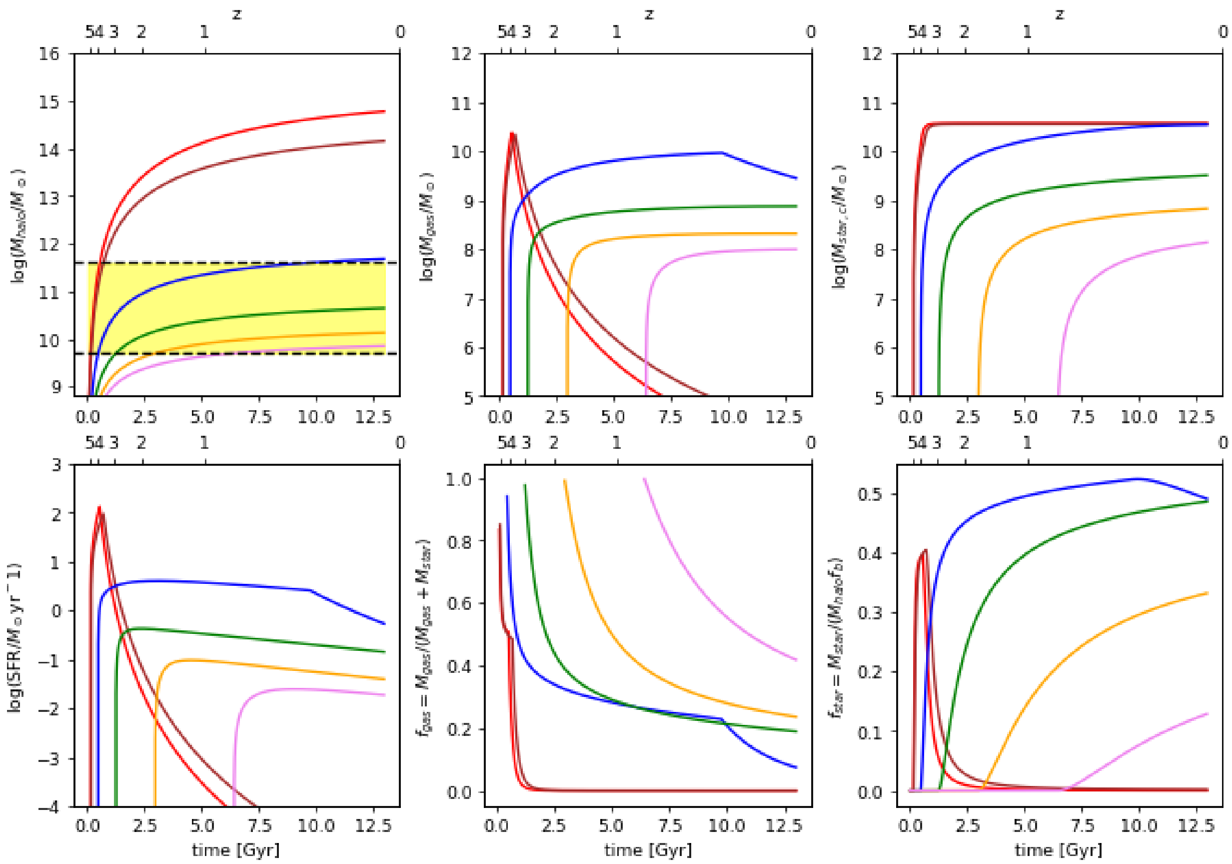

Figure 2. Evolutionary tracks of galaxy properties over cosmic time for different halos and fiducial values $M_{halo}^{min} = 10^{9.5} M_\odot$, $M_{halo}^{max} = 10^{11.6} M_\odot$. The halos are initialized with the same mass but at different times, which is the same as starting an initial mass distribution at time 0. Gas accretion and star formation begin when the halo mass reaches the lower threshold mass. The older and most massive halos will exceed the upper threshold too, at that point gas inflow will be suppressed and SFR will fall down exponentially. In this model the fate of galaxies is determined uniquely by the age of the DM halo, or equivalently by it's initial mass.

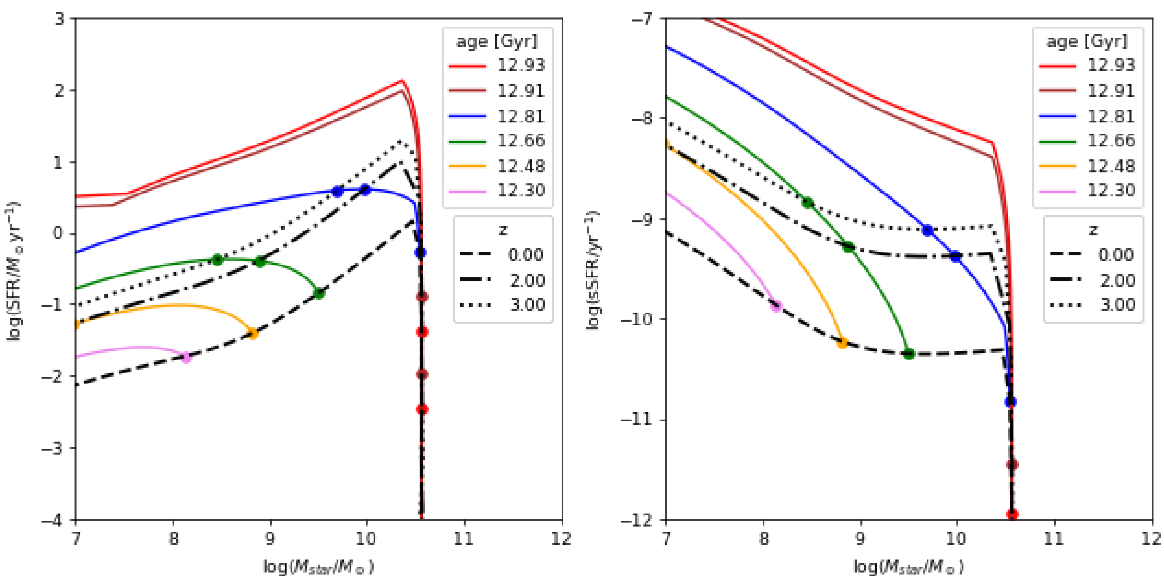

Figure 3. On the left the evolutionary tracks of SFR and M_{star} for the same systems of Fig. 2. The predicted SFR vs M_{star} curves are obtained simply by joining the points at equal cosmic time, and are shown for three different redshifts. On the right the same curves are plotted for the specific star formation rate $sSFR = SFR/M_{star}$.

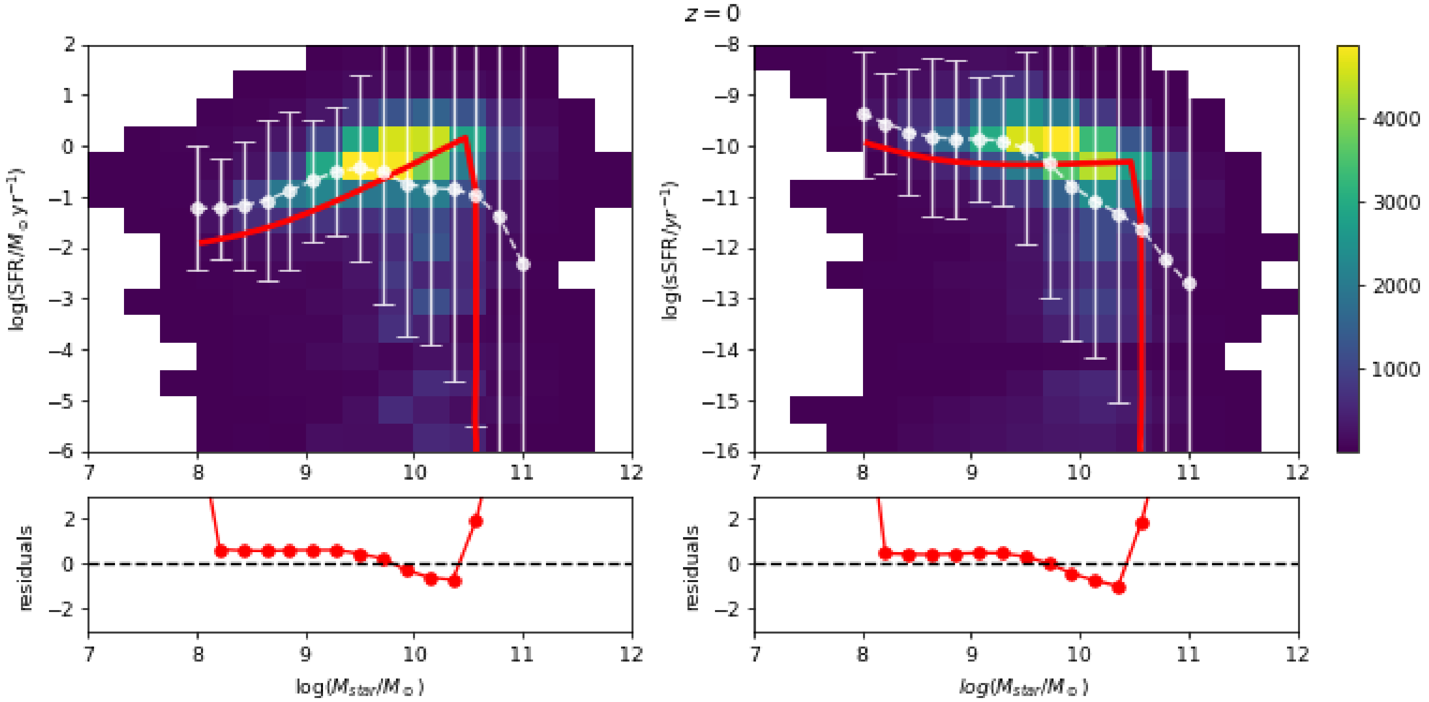

Figure 4. Distribution of stellar masses vs SFR (left) and of stellar masses vs sSFR (right) for the SDSS dataset, obtained by *CIGALE* software as discussed in Sec.3. All galaxies are at $z \sim 0$. Medians and dispersion are plotted in white and the best fit model in red. The scatter in log space of SFR and sSFR being quite high, medians and half the differences between 84^{th} and 16^{th} percentiles are more representatives of means and standard deviations, because less subject to outliers. Best fit values for M_{halo}^{min} and M_{halo}^{max} are $10^9 M_\odot$ and $10^{11.6} M_\odot$ respectively.

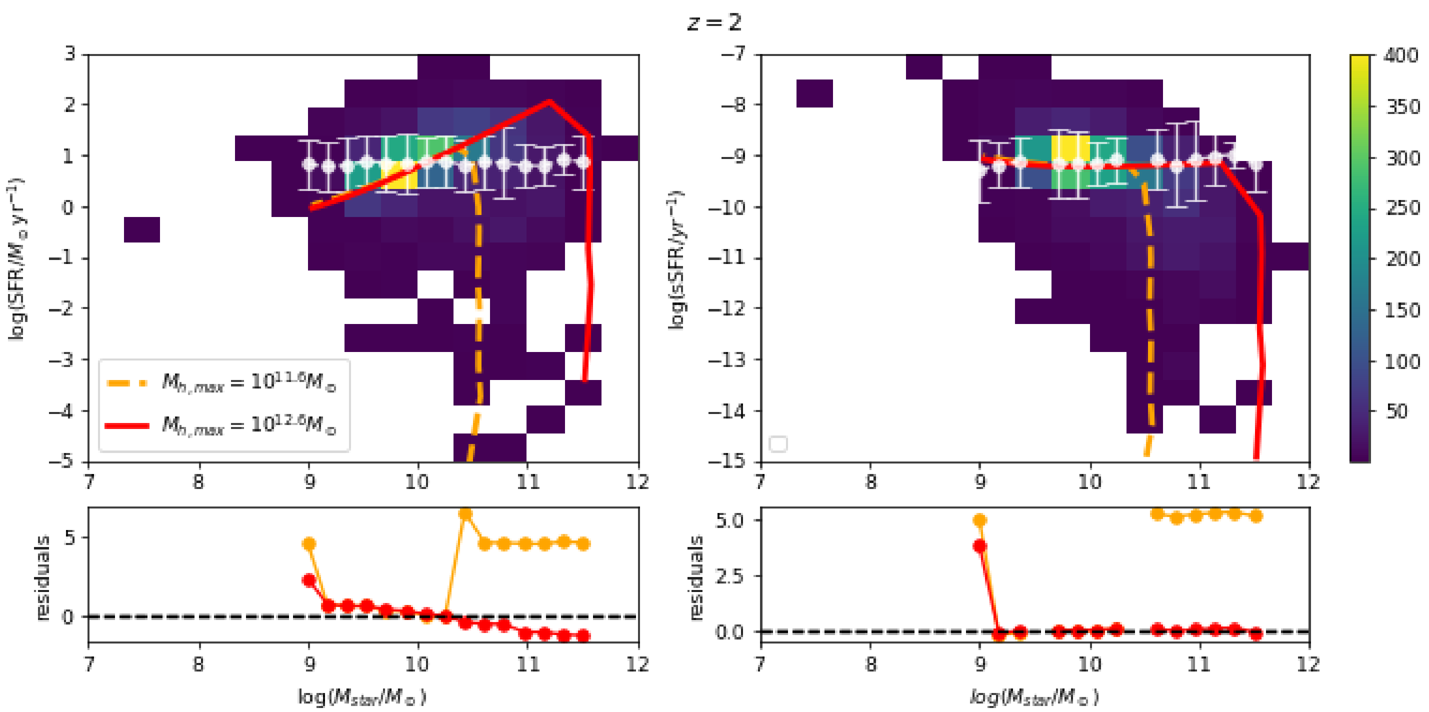

Figure 5. Distribution of galactic masses and SFR, sSFR for the 3DHST dataset. Galaxies are at $2 < z < 3$. Medians and dispersion are plotted in white and the best fit model in red. This fit has an upper halo mass threshold $10^{12.6} M_\odot$ much higher than the one found for $z = 0$. The model with threshold $10^{11.6} M_\odot$ is plot in orange for comparison. The difference between the two fits is relevant at high masses. No galaxies are present below stellar mass of $10^9 M_\odot$ because of selection effects.

4 DISCUSSION

The open box model is very simple nevertheless it remarkably reproduces the features in the $M_{star} - SFR$ and $M_{star} - sSFR$ diagrams. Lower and upper halo mass thresholds play a very important role in this model, especially because they determine the turning points of the main sequence (Dekel & Birnboim, 2006; Almeida et al.,2014). Once halo mass exceeds the upper threshold the central disk stops accreting gas, star formation is hampered and the galaxy will become a red giant elliptical.

We show that at redshift $z = 2$ the observed SFR of galaxies of high mass is too high to be compatible with the best upper threshold at $z = 0$, $M_{halo}^{max} = 10^{11.6} M_\odot$. Although in the standard picture (Ostriker & Rees, 1977) halos this massive are expected to be too hot to cool efficiently, some process must be at work injecting cold gas in the disk. Dekel and Birnboim simulations of cold streams in hot halos, Fig. 1, offer a solution to this problem. The upper threshold mass they found at $z \sim 2$ of $\sim 10^{13} M_\odot$ is similar to our upper threshold.

It must be stated clearly that our galactic evolution model is subject to many oversimplifying assumptions: many processes other than SN type II may contribute to $\dot{M}_{gas}^{out}$ term in equation (8): for example SN type I, AGNs or Ram pressure stripping are all processes that can potentially eject high quantity of gas out of the galaxy. We also assumed ϵ, η and R fixed, but in principle they could change with galactic mass and redshift. Including this parameters as free parameters of the model would however over complicate the problem, adding a lot of degeneracy in the fit. Moreover changing ϵ, η and R would not change the scaling relationships. Another factor we have completely neglected is the effect of galactic mergers during cosmic history. However this simplification is reasonable, since studies show that mergers account for only $\sim 10\%$ of galactic growth (Almeida et al.,2014).

For what concerns the suppression of cold gas streams the top-hat model we adopted for ζ in eq. (10) is useful but certainly not realistic. An interesting analysis was performed by Davé et al., 2012. They modelled ζ as convolution of four different preventive feedback terms: ζ_{photo} and ζ_{winds} regard the effect of photo-heating and winds on inflowing gas and operate below $M_\gamma \sim 3 \times 10^9 M_\odot$ (today), or $\sim$ few $\times 10^8 M_\odot$ (at higher redshift). ζ_{quench} includes whatever process(es) prevents cooling flows and it's effective above a quenching mass threshold $M_q \sim 10^{12} M_\odot$, that could be higher at high redshift. This term might include feedback from energetic sources in galaxies, such like AGNs, or dynamical friction, (Dekel & Birnboim, 2006). ζ_{grav} describes the suppression of inflow in hot halos when gravitational structure forms due to virial shocks (Davé et al., 2013):

$$\zeta_{grav} = 0.47 \cdot \left(\frac{1+z}{4}\right)^{0.38} \left(\frac{M_{halo}}{10^{12} M_\odot}\right)^{-0.25} \tag{11}$$

We checked if this model for ζ, Fig. 6, was consistent with SDSS and 3D-HST data, and we found it is ($\tilde{\chi}^2 = 0.47$, 20 d.o.f. and $\tilde{\chi}^2 = 2.4$, 20 d.o.f. for SDSS and 3D-HST data respectively). It predicts that at high redshift the halo mass range for effective gas accretion is broader than at $z = 0$, coherently with previous results.

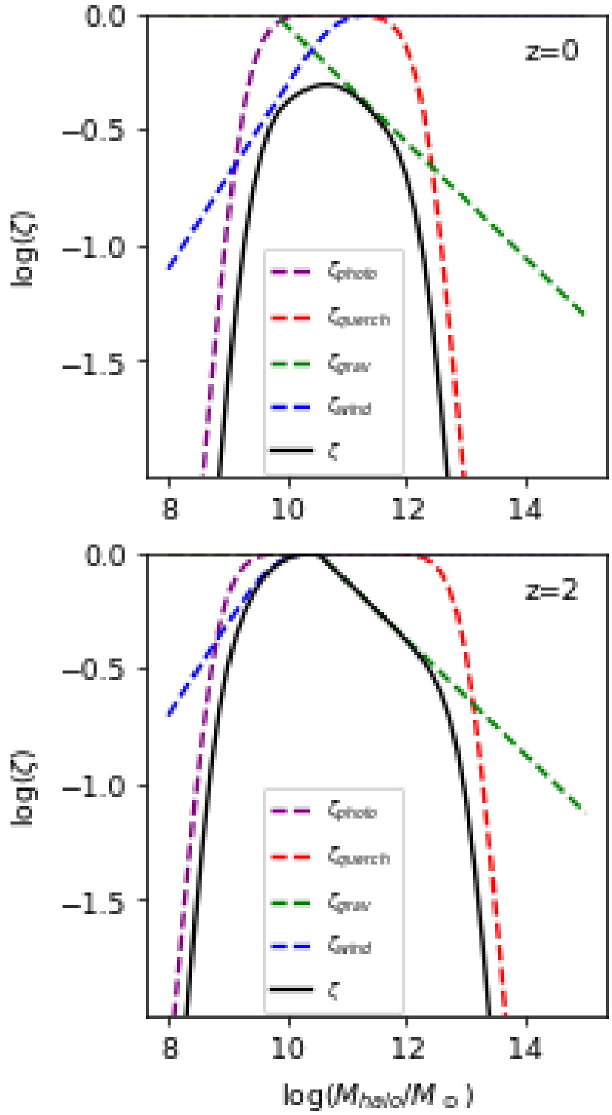

Figure 6. ζ preventive feedback parameter modelled following Davé et al., 2013. ζ_{grav} follows equation (11). ζ_{photo} is parametrized as $[1 + 1/3(M/M_\gamma)^{-2}]^{-1.5}$, ζ_{quench} as $[1+(M/M_q)^2]^{-1.5}$, with $M_q = 10^{12} M_\odot$ at $z = 0$ and $10^{13} M_\odot$ at $z = 2$, and ζ_{wind} as $[1 + 1/3(M/M_w)^{-2}]^{-0.2}$, with $M_w = 10^{11} M_\odot$ at $z = 0$ and $10^{11} M_\odot$ at $z = 2$. These values and their parametrizations are fairly arbitrary, they are intended only to reproduce general trends.

5 CONCLUSION

In the gas-regulated model of galaxy formation inflows of gas from the halo to the central disk sustain a constant SFR and define the main sequence. The turning points of main sequence are set by a lower and an upper mass threshold, the first determined by feedback from UV background or galactic winds, the second one by virial shock-heating, both preventing efficient cooling. At $z = 0$ gas supply to galactic disks is completely suppressed in dark matter halos more massive than $10^{11.6} M_\odot$, that are shock-heated and can not cool. At $z \gtrsim 2$ cold gas streams can penetrate even in massive hot halos.

Further analysis should include metallicity, that is available for many SDSS catalogue galaxies. The open box model can predict the evolution of metal content of the ISM over cosmic time (Lilly et al., 2013; Davé et al., 2012). This could be used to put more constraints to gas accretion.

The evolution model could be refined also by allowing gas inflow to be intermittent rather than continuous. This better describes accretion by clumpy gas streams compared to a constant in-falling rate.

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