The Origin of the Colour Bimodality in the Scatter of the Stellar-to-Halo Mass Relation

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Recent observations reveal that there is a strong bimodality in the scatter around the galaxy stellar-to-halo mass relation (SHMR): at a given halo mass, galaxies with a higher stellar mass tend to be blue indicating a higher specific star formation rate, while galaxies having a lower stellar mass tend to be red and quiescent; or at a given stellar mass, blue galaxies tend to live in halos with lower mass while red galaxies tend to have massive host halo. This has important implications for abundance matching and halo occupancy models commonly used in cosmological studies, but its physical origin remains debated. The SIMBA cosmological galaxy formation simulation successfully reproduces these observations, enabling us to investigate the physical driver behind this phenomenon. We show that the offset from the mean SHMR is strongly correlated with both halo formation time when half the halo mass assembled, as well as galaxy transition time defined as when the stellar doubling time becomes longer than 10 Gyr. Moreover, these two quantities are anti-correlated: early formed halos tend to host late transition galaxies corresponding to blue galaxies today, and vice versa, particularly for halo masses $11.5 \lesssim \log M_{\text{halo}} \lesssim 12.8 M_{\odot}$ and galaxy stellar masses $\log M_{*} \geq 10 M_{\odot}$. Prior to their transition time, galaxies lie on the SHMR for blue galaxies. Early transition galaxies, hosted by late formed halos, have their stellar mass growth almost ceased owing to AGN feedback even though their host halos continue to accrete mass, which moves these galaxies off the blue SHMR towards the red one creating the SHMR bimodality. We then investigate why early formed halos tend to host late transition galaxies. We find two key interconnected

times: the gas-to-stellar domination time when the galaxy's cold gas mass becomes smaller than its stellar mass, and the black hole (BH) jet ignition time governed by the BH Eddington ratio. Both show strong linear correlations with the galaxy transition time. Early formed halos have higher cold gas fractions (defined by cold gas mass in central galaxy with respect to the host halo mass) with a lower stellar-to-halo mass growth ratio before the transition time compared to the median or late forming halos; this allows them to sustain their stellar growth longer. Eventually, the continued growth fed by the cold gas reservoir allows them to surpass the galaxies with early transition times. Conversely, galaxies hosted by late formed halos have less cold gas with high stellar-to-halo mass growth ratios. Hence the Eddington rate becomes low earlier on, which triggers AGN into an energetic jet mode that heats gas, rapidly truncates further accretion and also stops star formation. These processes thus conspire to create the SHMR bimodality. In SIMBA, the cold gas evolution occurs naturally owing to the interplay of accretion and star formation feedback, while the AGN feedback transitions from a radiative mode at high Eddington ratios that is ineffective at quenching, to a jet mode at low Eddington ratios that suppresses star formation. SIMBA further includes X-ray feedback that drives the last remaining cold gas out, completing the quenching and strengthening the SHMR bimodality.

1 Introduction

Galaxies are formed inside dark matter halos, whose gravitational influence attracts gas that eventually condenses and cools. This drives star formation and supermassive black hole growth, which

release energy in the form of supernovae and active galactic nuclei (AGN) feedback that self-regulates galaxy growth. Without such feedback, early models demonstrated that halos would form too many stars, and massive halos would host vigorously star-forming galaxies, in contradiction to observations^{1–3}.

The galaxy stellar-to-halo mass relation (SHMR) represents a fundamental barometer for accretion and feedback processes in galaxy formation⁴. At low masses, the efficiency of star formation is low, increasing towards a peak of $\sim 25\%$ (the ratio between stellar mass and total baryon mass) in $M_{\text{halo}} \approx 10^{12} M_{\odot}$ halos, and then dropping again to higher masses^{5,6}. The origin of this has been explored in both physical models using semi-analytic^{7–9} and hydrodynamic^{10–12} techniques, as well as empirical models using abundance matching^{13,14}, halo occupation distributions^{15,16} (HOD), and conditional stellar mass functions^{17,18}. Physically-based galaxy formation models generally invoke star formation feedback to explain the SHMR below M^* , and AGN feedback to explain the high-mass inefficiency¹⁹.

Although the galaxy colour bimodality has been known and studied for a long time^{20–22}, only recently, a new clue to the origin of the SHMR comes from observations of a bimodality in the scatter around the mean SHMR^{23–25} at $z = 0$: At a given halo mass, red galaxies with low specific star formation rate ($\text{sSFR} \equiv \text{SFR}/M_*$) tend to have lower stellar mass than blue galaxies with higher sSFR; or alternatively, at a given stellar mass, red galaxies tend to live in more massive halos. Using the Sloan Digital Sky Survey group catalogue²⁶, it was found that early-formed halos²⁷ tend to host central galaxies with a higher stellar mass²⁸. This provides new constraints on

how galaxies populate halos, and suggests the existence of *assembly bias*, i.e. the dependence of galaxy properties on halo formation time.

The origin of the SHMR scatter has been investigated theoretically, with sometimes contradictory results. Semi-empirical modelling found that at low masses, processes that delay star formation without invoking overly strong supernova-driven outflows could explain the high $M_* - M_h$ ratios of blue centrals as compared to those of the scarcer red centrals²⁹. Semi-analytic models (SAMs) find that, at fixed halo mass, older halos tend to host more massive galaxies, which is explained by the central galaxies in early-formed halos having more time to accrete and form stars³⁰. However, this contradicts observational indications that galaxies lying above the median are blue and have younger formation times. In the EAGLE simulation¹¹, the SHMR scatter was found to correlate strongly with the halo formation history³¹, as characterised by the redshift at which half its mass is assembled. Furthermore, the scatter in the SHMR anti-correlates with the mean age of the galaxy stellar population, such that galaxies with a higher stellar mass at fixed halo mass are younger³². While this qualitatively agrees with observations, the physical processes leading to this bimodality remain unclear.

In this paper, we seek to understand the cause of the SHMR bimodality using the state of the art SIMBA simulation³³, described in the Methods section. SIMBA reproduces many key observations including the stellar mass function up to high redshifts, the fraction of present-day quenched galaxies as a function of mass³³ and the bimodality in the sSFR function³⁴. We demonstrate here that SIMBA also reproduces the observed SHMR bimodality for central galaxies. We then inves-

tigate the physical origin of this phenomenon by comparing galaxy and halo formation times via a new metric, the *transition time*, when a galaxy goes from fast-growing to slow-growing. The transition time is in turn driven by a declining cold gas content owing primarily to the jet-mode AGN feedback in SIMBA.

2 The colour bimodality in the SHMR

Fig. 1 shows the SHMR in SIMBA. The simulated galaxy points are coloured by their $g - r$ colour, with star-forming systems generally bluer. The medians of red-sequence and star-forming galaxies, separated in the same way as observations²³¹, are shown with magenta and cyan dashed lines, with the error bars showing the $16^{th} - 84^{th}$ percentiles.² We note here that using a separation based on $sSFR$ ($\log sSFR[Gyr^{-1}] = -2$) yields a similar result. We adopt the same halo mass definition as in observations – M_{200m} , the mass enclosing $200\times$ the mean density – and we correct for minor differences in cosmological parameters. Observations are shown with halo masses based on weak lensing²⁵ and satellite kinematics²³. SIMBA clearly reproduces the bimodality in the SHMR relation, with values that are consistent with observations across the entire mass range probed.

In Fig. 2, we show the same SHMR as Fig.1, but colour-coding to halo formation time (z_F ; defined as the redshift at half mass) in the left-hand panel and galaxy transition time (z_T which

¹The separation line has a slightly lower slope compared to ²³. This is because the massive galaxies in SIMBA include the intra-cluster light which has much younger age than the BCG ³⁵

²We note here that the error bars estimated with percentiles are very large and this error is different to the errors in the observational results.

Figure 1: The SHMR at $z = 0$ from the SIMBA simulation compared to observational results. The simulated galaxies are binned by galaxy and halo masses with the median $g-r$ colour in each bin shown by the colour bar. The cyan and magenta symbols are the median values for blue and red galaxies respectively, with error bar showing the $16^{th} - 84^{th}$ percentiles. Observational results^{23,25} are presented with different symbols and colours indicated in the legend.

Figure 2: The SHMR from the SIMBA simulation. Galaxies are binned in stellar and halo mass with the median halo formation redshift (left) and galaxy transition redshift (right) indicated by the colour bar to the right. Lines of different colours show median values for the transition and formation redshift ranges indicated in the legends, with error bars showing $16^{th} - 84^{th}$ percentiles. Median lines for red and blue galaxies are also included for comparison. Note that the dotted magenta and cyan lines are the linear fitting results with the fitting parameters are shown in table 1.

	a	b
red galaxy	0.966	-1.765
blue galaxy	1.197	-4.233

Table 1: The parameters of the fitting function ($\log M_{halo} = a \log M_* + b$) for the median red and blue galaxies in the SHMR.

characterises when the galaxy transitions from a growth mode to a quiescent mode, see Method section for details) in the right-hand panel. We present linear fits results to the median red/blue galaxies (magenta and cyan dotted lines, respectively) in Fig. 2, with parameters listed in Table 1. Note that Fig. 2 shows the $M_* - M_{halo}$ plane as in Fig. 1, thus the data is binned in galaxy stellar mass instead of halo mass. However, as shown in the Supplement (8), binning in halo mass yields similar results. Therefore, the SHMR from SIMBA does not have the inversion problem^{13,36} at least in halo mass range $11.5 \lesssim \log M_{halo} \lesssim 12.8 M_\odot$. Also note that we use a Friends-of-Friends (FoF) halo mass M_{FoF} instead of M_{200m} in this figure and later on, in order to avoid pseudo halo growth introduced in the overdensity method³⁷. There is very little difference between the two mass definitions at $z = 0$. Thus, there are only subtle differences of the median lines of red and blue galaxies between the two halo definitions. Finally, note it is clear that the median line for red galaxies is basically in agreement with the median lines of halos that are formed in $0.5 \leq z < 1$ and of galaxies that have transition time in $1 \leq z < 1.5$, while the median line for blue galaxies corresponds to one redshift bin higher and lower for halo formation time and galaxy transition time respectively. It is naturally thought galaxies at their transition time have blue colour. To quantify the time scale for the galaxy to become red, we further investigate the galaxy $g - r$ colour evolution in Supplement 7, and show that galaxy needs about 5 Gyr from its transition time to have a $g - r$ colour of 0.65.

It has been argued that the halo formation time gives rise to the scatter in the SHMR^{31,38}. We see the same behaviour from SIMBA in the top panel of Fig. 2: Halos with a higher formation redshift have higher M_* at a given M_{halo} . However, this does not directly answer why one sees a

bimodality in colour (or equivalently, sSFR). It is not inherently obvious why halos that formed early should host bluer galaxies today; indeed, one could argue that they should have used up their gas earlier and ended up redder. To connect to galaxy colour, we must consider the galaxy mass accretion history, which more directly drives with galaxy colour and hence the bimodality.

To investigate this, the SHMR from SIMBA is redisplayed in the right panel of Fig. 2 with the galaxies coloured by their transition time. Since galaxies must have cold gas with star formation to be blue, it is not surprising that the blue galaxies correspond to late transition galaxies ($z_T < 1$), while red galaxies correspond to early transition galaxies ($z_T \geq 1.5$). More interestingly, the scatter in SHMR is strongly correlated with the galaxy transition time. However, z_T shows a reversed trend compared to z_F : early transition galaxies tend to live in late formed halos while late transition galaxies are in early formed halos at the bottom of the $M_* - M_{halo}$ plane. This connects more directly with the observational result that blue (late transition) galaxies tend to have higher stellar mass at a given halo mass.

We note here that the right panel of Fig. 2 also indicates a picture of ‘downsizing’³⁹, i.e. massive galaxies evolve faster and reach their peak of star formation earlier than low-mass galaxies. Most of the massive galaxies ($M_* \gtrsim 10^{11} M_\odot$) in SIMBA have transitioned before $z \sim 1.5$, while the galaxies with lower stellar masses are dominated by late transition galaxies. We note that our results are in agreement with the EAGLE simulation⁴⁰ on the correlation between the scatter on SHMR and halo formation time, especially at intermediate and low halo mass range: galaxies at a given halo mass with higher stellar masses typically have their host halo formed earlier. In

contrast, EAGLE predicts that at a given stellar mass the late-formed halos host galaxies with a higher sSFR, which is opposite to our results shown in Fig. 2. Our explanation is as follows. For a given $z = 0$ halo mass, the earlier-forming halos have a long period at high redshift where their halo mass exceeds that of the later-forming halos. These earlier-forming halos can thus host a late transition galaxy, which also has a longer time for continuing star formation to support its growth, resulting in a higher stellar mass³⁰. To proof this hypothesis, we need to investigate the evolution of the SHMR, which is presented in the following section 3.

3 The evolution of the SHMR

Even in the quiescent state, i.e. well after transition, galaxies can still grow via merging and residual star formation. Although we do not explicitly separate the in-situ and ex-situ growth when computing the transition time, the fast growth phase is dominated by in-situ growth, while ex-situ growth only becomes important for massive quiescent galaxies^{41,42}. To see what effect this has on the SHMR, Fig. 3 shows the median evolutionary tracks of the SHMR separated into different halo mass bins marked by the vertical dotted lines, and three colour regions separated by the fitted median lines of red/blue galaxies from Fig. 2. Hence the SHMR plane is separated into 15 zones by the dotted and dashed lines. The median $[M_{halo}, M_*]$ in each zone is marked by the coloured star: blue for these lying above the fitting line for blue galaxies (early formed halo with late transition galaxies); red for these below the fitting line for red galaxies (late formed halo with early transition galaxies) and green for these in between. We track the median $[M_{halo}, M_*]$ for all the galaxies within each zone back in time, shown as the coloured lines with the redshift indicated in the colour

Figure 3: The SHMR at $z = 0$ again but shown M_{halo} in axis. Galaxies are separated into 3 different regions (blue, green and red) by the median red and blue galaxy lines from Fig. 2 and into different halo mass bins. The median stellar mass and halo mass in each zone is marked with a star symbol. The median SHMR evolution track of each zone is shown by the colourful curves (dotted for blue region; solid for green region and dashed for red region) with the redshift is shown in the colour bar. The median galaxy transition times are marked with squares. We further highlight the results from two halo mass bins with thick lines.

bar. The median galaxy transition times are also shown as square symbols with the same colour. We further use thick lines to highlight two interesting halo mass regions: $12.2 < \log M_{halo} \leq 12.5$ and $12.5 < \log M_{halo} \leq 12.8$ which each include all 3 regions. We note that here we use the reversed SHMR plane, i.e. M_{halo} versus M_* , because studying the evolution in the same stellar mass bin with different halo masses will entangle with the halo formation time – massive halos tends to have late formation time.

Before the transition time, the slopes of the tracks in the same halo mass bin are anti-correlated with the final stellar masses – the lower the M_* , the higher the slope. The low slope indicates a relatively fast halo mass growth versus stellar mass growth. This can be easily understand since halo mass growth concurrently brings in a gas supply for star formation. Thus fast halo growth can sustain the galaxy stellar mass growth and results in a massive central galaxy. Furthermore, in the similar stellar mass bin, galaxies in blue regions tend to have the highest slope with the lowest slope for galaxies in red regions. The reason is that galaxies that end up in blue regions have earlier halo formation times, and while the fast halo accretion at very high redshift (generally $\log M_{halo} < 11.5$) accumulates a large gas reservoir, it is inefficient at converting into stars owing to mainly stellar feedback at early epochs. Instead, this gas is lifted via outflows into the halo, to return later as wind recycling that supports their later star formation⁴³; we will return to this when discussing Fig. 6. In contrast, galaxies that end in the red region reach the same stellar mass with a lower halo mass and have consumed much of the already deficient cold gas, lowering star formation and eventually causing the black hole to drop to a low enough Eddington ratio to trigger the jet-mode AGN feedback that enacts galaxy quenching (see further details in the following section

4). This results in a transition time at higher redshift for these galaxies.

After the transition, the stellar mass growth for galaxies in red regions has basically ceased while the halo mass continue to grow and results in a flat growth curve. This basically pushes the SHMR towards massive halos at a given M_* . However, the galaxies in blue region still show some growth in stellar mass which seemingly contradicts our transition definition. These turn out to be a small number of galaxies that happen to have fairly high specific star formation rates, such that they are close to our limit of 0.1 below which we define the galaxy as transitioned. Using a lower threshold would bring the transition time closer to $z = 0$, but it will not qualitatively change the conclusions, so we keep the existing threshold for this work.

We assemble the above trends into a coherent scenario for the bimodality in the SHMR seen in Fig. 1. At early epochs, all galaxies are fast-growing and lie along a similar SHMR. For early-forming halos, they collect lots of cool gas, which then begins baryon cycling to continue to provide fuel for galaxy growth to later epochs, yielding a late transition time. In late-forming halos, the gas supply is less, and the galaxy undergoes an earlier transition time driven by the lower cold gas supply and exacerbated by AGN jet feedback which kicks in at low black hole accretion rates. Once this happens, galaxies grow primarily in halo mass with only meagre stellar growth, separating these red galaxies from the SHMR relation of the star-forming systems. This yields a bimodality where at a fixed halo mass, early formed halos (late transition galaxies) have blue galaxies with higher stellar mass, while late formed halos (early transition galaxies) host red galaxies with lower stellar mass. It further explains the observed trend that the red and blue galaxies

are more widely separated at higher M_{halo} : massive halos tend to have earlier z_{T} and thus more time to grow their halos in comparison with halos that host late transition galaxies. This scenario physically connects halo assembly bias with galaxy mass and colour segregation in the SHMR.

Fig. 3 also has interesting implications for the driver of galaxy quenching. If we assume the transition time is correlated with the quenching time (even though galaxies are still fairly gas-rich at transition), then our results suggest that halo mass cannot be the sole driver of quenching as has been claimed^{44,45}, at least in halo mass $11.5 \lesssim \log M_{\text{halo}} \lesssim 12.8 M_{\odot}$. This is evident because the halo masses at a given transition time for central galaxies are spread out over an order of magnitude, and do not show any characteristic halo mass at which a galaxy enters its quiescent state. However, halo mass still must play a key role, given that centrals in higher mass halos have an earlier transition time and that the fraction of quenched galaxies in high mass halos is significantly higher. If the characteristic halo mass is still used for connecting with galaxy quenching, one solution is that this halo quenching mass is redshift-dependent, i.e. higher characteristic halo mass for quenching at higher redshifts^{46,47}. The anti-correlation between z_{T} and z_{F} and its role in driving the scatter in the SHMR indicates that the halo mass growth history plays a key role in shaping the SHMR.

The redshifts of the evolution tracks in Fig. 3 are only qualitatively indicated by the colour bar. Using one fixed halo mass bin $12.5 < \log M_{\text{halo}} \leq 12.8$ from Fig. 3 as an example, we further show the median mass growth history of different components: halo (dotted lines), galaxy (solid), gas (dot-dashed) and black hole (dashed) as a function of the Universe age in Fig. 4. The lines

Figure 4: The median halo mass, galaxy stellar mass, cold gas mass and BH mass in galaxies as a function of redshift for a sample of halos selected to have mass $10^{12.5} < M_{\text{halo}} < 10^{12.8}$ at $z = 0$. As indicated in Fig. 3, halos and galaxy are grouped into red, green blue regions (indicated by different colours). The median formation histories are shown with different lines styles. The stars show the median halo formation time, galaxy transition time and BH jet mode on time.

are colour-coded by final region in SHMR space as in Fig. 3. The stars show the median halo formation time, galaxy transition time, and BH jet-on time (defined below). The stars along the galaxy lines show that halo formation and galaxy transition time are anti-correlated, as we showed earlier.

Fig. 4 shows that the early forming halos (blue) host more massive galaxies, which have a slightly longer growing period, hence a later transition time. This owes to the enhanced cold gas content, defined in SIMBA as the total neutral gas mass ($\text{HI}+\text{H}_2$), at all epochs, which sustains star formation for a longer period. To quantify the correlation between gas evolution with the galaxy transition time, we define a galaxy crossing time when the stellar mass is equal to its cold gas mass ($t_{M_* = M_{\text{gas}}}$). We will explore this time in relation to the transition time below.

Fig. 4 also indicates the median time at which black hole jet feedback turns on in SIMBA (the stars along the BH formation history curves). To explain briefly: there are three AGN feedback modes in SIMBA: A ‘radiative mode’ at high Eddington ratio to drive multiphase winds at velocities of $\sim 1000 \text{ km s}^{-1}$; a ‘jet mode’ at low Eddington ratios $f_{\text{edd}} < 0.2$, where AGNs mostly drive hot gas in collimated jets at high velocities (of order $\sim 10^4 \text{ km s}^{-1}$); and an X-ray heating from black holes. As the Eddington ratio is tightly connect with BH mass growth, the transition from fast BH mass growth (high Eddington ratio) to slow BH mass growth (low Eddington ratio) separates the radiative mode and jet mode AGN feedback. We denote this time as the BH jet-on time (t_{jeton}); see the Method section for the detailed calculation.

Figure 5: Left panel: the relation between galaxy transition time and the time when the galaxy stellar mass is equal to its cold gas mass. Right panel: the relation between the time when jet mode AGN feedback is on and galaxy transition time. Similarly, galaxies are colour coded by their halo mass at $z = 0$ with the medians of different halo mass bins in colourful dashed lines. The black dashed line indicates the 1-to-1 relation. The red line with error bars shows the median values of all halos and $16^{\text{th}} - 84^{\text{th}}$ percentiles after binning in galaxy transition time.

4 The cause of galaxy transition

We have qualitatively argued that the galaxy transition time is driven by cold gas supply and AGN jet feedback in previous section. To quantify these effects and understand the physical connection between them, we now examine the cold gas content evolution and the time of AGN jet turn-on in relation to the transition time of galaxies.

In Fig. 5, we explore the relationships between these various times. In the left panel we show the $t_{M_*=M_{\text{gas}}}$ as a function of the galaxy transition time (t_{T}), while in the right panel we

show t_{jeton} versus t_T . Remarkably, both $t_{M_* = M_{gas}} - t_T$ and $t_{jeton} - t_T$ nearly follow a one-to-one relation (dashed lines in Fig. 5), confirming the driving role of these aspects in setting the galaxy transition time. This is in agreement with the expulsion of efficiently cooling gas from the CGM as a crucial step in quenching a galaxy⁴⁸. While the galaxy SFR correlates with the cold gas mass⁴⁹, the fact that t_T is proportional to $t_{M_* = M_{gas}}$ is a non-trivial consequence of the upward trend of increasing cold gas mass at early times, tightly connected with halo formation time, and a downward trend of decreasing cold gas mass at late times, which can be driven by depletion by star formation, heating/outflows by feedback, and/or virial shock heating⁵⁰. Indeed, the lower gas fraction connects to a low Eddington ratio that results the jet mode AGN feedback, which quenches the galaxy⁵¹. This is presented in the right panel – jet mode AGN feedback is the key for galaxy quenching in SIMBA. Note that there is a ~ 0.5 Gyr delay between $t_{M_* = M_{gas}}$ and the transition time for massive halos indicated by red and yellow dashed lines, in agreement with Fig. 4, indicating that galaxy transition requires a lower gas fraction. For low-mass halos or late transition galaxies, although the median line follows a one-to-one relation, there are many galaxies with transition time $t_T < t_{M_* = M_{gas}}$. This could be because the threshold for determining the transition time is still high for these low-mass late transition galaxies, as discussed in reference to Fig. 3. In any case, we emphasise that SIMBA’s success in reproducing the SHMR scatter owes to quenching feedback that kicks in when the cold gas content drops to low values, which in SIMBA’s case triggers the AGN jet feedback.

With this understanding, we can now answer the key question: why do early formed halos tend to host late transition galaxies? Using the same highlighted halo mass bins in Fig. 3, we

Figure 6: The median central gas fraction evolution. The two selected halo mass bins are indicated in the legend. Different colourful lines are for the results in different colour regions in Fig. 3. The median galaxy transition times are marked as square in the curves.

present the median cold gas fraction (note that it is defined as the cold gas mass in the central galaxy divided by the host halo mass) evolution in Fig. 6. Different coloured lines represent the results from different regions. Solid lines are for the lower halo mass bin while the dashed lines are for the higher halo mass bin.

The galaxies in blue region are hosted by early formed halos, i.e. more massive at high redshifts than their counterparts, and their galaxy gas fraction is higher⁵² than these galaxies in green or red regions for several Gyr prior to their transition time. The gas fractions are still slightly higher for galaxies in blue region after the transition time, even at $z = 0$. This high gas fraction is the key for the galaxy to maintain its star formation and also the high Eddington ratio so the AGN feedback stays in radiative mode. Winds from neither supernova nor the radiative mode AGN feedback are efficient to eject the gas far out. Given the relatively higher halo mass at high redshift, it will cold down and fall into the central galaxy again. In contrast, galaxies in red region with lower gas more easily reach the Eddington ratio limit of a few percent to trigger the jet mode AGN feedback which has an order of magnitude higher wind speed than the radiative mode AGN feedback. This can further decrease the deficient cold gas and cease the star formation. We further note that the gas fractions are somewhat higher in the low halo mass bin than the high halo mass bin for all three regions, since higher halo masses host more massive galaxies with weaker winds that result in more effective conversion of gas into stars⁵³.

Since there are three AGN feedback models in SIMBA, we can also experimentally investigate the effects of the three feedback models by turning them off one-by-one in smaller SIMBA

cosmological simulations with 50 Mpc/h boxsize. In section 9, we show the simulation without X-ray feedback has its median red galaxy line much closer to the median blue galaxy line compared to the full feedback model. This means the X-ray feedback is particularly essential for the colour bimodality in the SHMR. This is consistent with X-ray feedback being important for fully shutting down star formation in the ISM^{33,54}.

5 conclusion

To summarise, we have used the state-of-the-art hydrodynamic simulation SIMBA to understand how galaxies form a colour (or sSFR) bimodality in the scatter of the SHMR. Introducing the idea of galaxy transition time between growth and quiescent modes, we find that in the halo mass range $11.5 \lesssim \log M_{halo} \lesssim 12.8 M_{\odot}$, the main driver is that after the transition time, the halo growth outpaces stellar growth, leading to such earlier transition galaxies lying further below the mean SHMR. In contrast, late transition galaxies gain stellar mass (via both star formation and mergers) outpacing their halo growth, which lifts them above the mean SHMR at later time. The transition time is, in turn, governed by the cold gas content of the galaxy. Early-forming halos retain a higher gas fraction that sustains their star formation. Late-forming halos conversely have a lower cold gas fractions, so consume and/or expel their cold gas earlier and easier. This in turn triggers the jet mode AGN feedback which, together with X-ray AGN feedback, shuts down the star formation. This leads to an anti-correlation between the transition time and halo mass and formation time, which reveals itself as a colour bimodality in the SHMR. While we have used the SIMBA simulation to illustrate these physical effects, its quantitative agreement with observations suggests that even

if the details of SIMBA’s feedback models are not fully correct, the phenomenological scenario outlined above is likely to drive the observed colour and mass bimodality in the SHMR.

6 Methods

The Simba simulation. The $100 h^{-1}$ Mpc SIMBA simulation⁵⁵ is used for this study. SIMBA is based on the MUFASA simulation⁵⁶ with its sub-resolution star formation and stellar feedback prescriptions, with galactic wind scalings taken from the FIRE simulations^{57,58}. SIMBA further includes two models of black hole growth prescriptions: the torque-limited accretion model from cold gas^{59,60} and Bondi accretion from hot gas. AGN feedback is modelled via kinetic bipolar outflows, the strength of which depends on the BH accretion rate, separated into ‘radiative mode’ at high Eddington ratios and ‘jet mode’ at low Eddington ratios, as well as X-ray heating. This simulation is tuned to reproduce the stellar mass function up to redshift ~ 6 . It furthermore reproduces the quenched fractions and the main sequence of star-forming galaxies at various M_* ³³, the observed black hole mass - galaxy stellar mass and velocity dispersion relations⁶¹, and many other galaxy properties. Furthermore, a smaller box (50 Mpc/h) simulation with different feedback models are also used to investigate the effects of different AGN feedback.

Halos are identified on the fly during the simulation run using a 3D friends-of-friends (FoF) algorithm with a linking length of 0.2 times the mean inter-particle spacing. The halo masses in this paper are the FoF halo mass, except for Fig. 1 where we computed M_{200m} in order to be consistent with observational comparisons. Galaxies are identified using a 6D phase-space galaxy

finder within each dark matter halo in the YT-based package CAESAR. Many galaxy properties are computed after the identification. The galaxy magnitudes in SDSS g and r bands are computed using the `pyloser` package, which employs the FSPS stellar population synthesis code to compute spectral energy distributions and includes line-of-sight extinction based on the self-consistently evolved dust content in SIMBA. The simulated galaxies are further separated into red and blue by their $g - r$ colour as in observations²³. Finally, galaxies and halos are linked with their progenitors through matching their unique particle IDs. As we only focus on the central galaxy and its host halo in this study, the merger history is built based on the main progenitors of $z = 0$ halos.

data statement Our SIMBA simulation snapshots with halo and galaxy catalogues are publicly available online at <http://simba.roe.ac.uk/>. The detailed analysis pipeline scripts are available in the authors github repository: <http://github.io/> (to be updated).

Halo formation, galaxy transition and jet mode AGN feedback ignition times. As illustrated in Fig. 4, the histories of galaxy formation and halo formation are rather different while the BH formation history shares some similarity with the galaxy formation history. Individual halos or galaxies basically have very similar growth histories as the medians. We use the commonly-adopted half-mass redshift, when the halo accreted half of its $z = 0$ mass, for the halo formation time. We have calculated the halo formation time both by interpolation of the data points and from the data smoothed with the Savitzky-Golay filter⁶² which has been integrated in SCIPY^{63,64}. The two methods give a consistent result. Galaxy mass accretion histories can be generally characterised by two processes: a fast growing period in its early phase and a constant/quiescent period after

the transition. Therefore, it is natural to choose the connecting point between the two periods as their transition time. We first fit the galaxy formation history with a step function by joining an error function term (for the fast growing period) and a linear term (for the constant period). We note here that we simply use the total stellar mass of galaxies as they evolve without considering in-situ/ex-situ growth modes or rejuvenation processes. The advantages of this simply treatment are (1) we do not need a separate explanation for the scatter in the two phases; (2) it is very hard to separate in-situ and ex-sit growths in observation. Then, we get the galaxy transition time T through the slope of the fitting curve, as the time when

$$\frac{d \log M_*}{dt[\text{Gyr}]} < 0.1. \quad (1)$$

We note here that this definition is similar to a threshold in sSFR, but it is based on a much longer time baseline, and it includes stellar mass brought in by mergers. Our conclusions are not affected by the choice of this threshold, which only produces a systematic shift in the transition time.

The BH mass growth history can also be roughly separated into fast growing period in its early phase and a constant period later on. The is consistent with two modes of BH accretion in SIMBA. Furthermore, this also correlates with the radiative and jet mode AGN feedback which is dominated in high Eddington ratio in the fast BH mass growing and in low Eddington ratio ($f_{\text{Edd}} < 0.02$) in the constant period, respectively. To directly link the BH mass change with the Eddington ratio, we use equation 11 from ⁶¹ to correlate the Eddington ratio with the BH mass growth rate and determine the jet mode feedback ignition time:

$$\frac{d \log M_\bullet}{dt[\text{Gyr}]} < 0.9. \quad (2)$$

7 Supplement – colour evolution

Although we show the median line for blue galaxies is roughly consistent with the galaxies in transition time bin $0.5 \leq z < 1$ and the median line for red galaxies has their transition time between $z = 1$ and 1.5 in Fig. 2. It is interesting to know how long the galaxy takes for changing its colour into red. We select the early transition galaxies which have their transition time less than 3.8 Gyr of the Universe age. In Fig. 7, we show the $g - r$ colour distribution of these galaxies at their transition time and 1, 3, 5, 10 Gyr after the transition time in different colours. To reach the $g - r \approx 0.65$, the galaxy needs about 5 Gyr. Note that for this simple estimation, we don't separate the galaxy samples by its stellar mass, which may play a role. Furthermore, this estimation is roughly consistent with our previous results.

8 Supplement – the inversion problem

It has been noted^{13,36} that binning the data in halo mass vs. stellar mass can result in reversed trends. It is worth investigating here whether our results shown in Fig. 2 are caused by this inversion problem. In Fig. 8, we represent the results in Fig. 2 but in reversed axes, thus the binning is done in halo mass instead of stellar mass. It is clear that the median lines for different halo formation times are basically unchanged. This is also true for the median lines in different galaxy transition time bins in lower halo mass range $11.5 < \log M_{halo} \lesssim 12.8$. While at more massive halo mass range, there is a reverse trend, i.e. late transition galaxies tend to lie below the early transition galaxies. However, it is not clear whether this is due a limit number of sample data points: very

Figure 7: The $g-r$ colour distributions for galaxies at the transition time and after. Only galaxies which have their transition time + 10 Gyr less than the Universe age are selected. This plot indicates that the galaxy needs about 5 Gyr after its transition time to reach a red colour ($g-r \gtrsim 0.65$).

Figure 8: The same as Fig. 2, but reversed axes with the median lines shown in halo mass bin for the study of the inverse problem.

Figure 9: Similar to Fig. 1, but for the results from a smaller simulation box with the full feedback model (the same as the default simulation set) in the left panel and the one without X-ray feedback in the right panel.

few galaxies with late transition time at this halo mass range in SIMBA. We note here that our main results are thus not driven by the inversion problem.

9 Supplement – The effect of Xray feedback

There are three AGN feedback models in SIMBA. We have verified that the jet mode feedback is directly responsible for ceasing the star formation rate and cause the galaxy transition. It is interesting to quantify the role of X-ray feedback that implemented in SIMBA on the bimodality in the SHMR. Using a series of smaller box simulations (50 Mpc/h) which have different AGN feedback models included, we compared the fiducial run (the same as the SIMBA simulation) in

left panel with the one without X-ray feedback (but all the other feedback models) in right panel. It is clear that the fiducial one shows basically the same results as the full SIMBA run in Fig. 1. Without the X-ray feedback, the median line for blue galaxies is similar. However, the median line for red galaxies is significantly decreased and close to the cyan line. This means that the X-ray feedback, intended to mimic the impact of high energy photons on the inner regions of galaxies⁶⁵, is important to reproduce the colour bimodality in the SHMR. Finally, we also compare to one without both jet mode and X-ray feedback. The red and blue galaxies are reversed in the SHMR. Thus the qualitative trend of the colour bimodality in SIMBA owes to AGN jet feedback, while a quantitative agreement further requires the inclusion of X-ray feedback.

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[Competing Interests] The authors declare that they have no competing financial interests.

Figures

Figure 1

The SHMR at $z = 0$ from the SIMBA simulation compared to observational results. The simulated galaxies are binned by galaxy and halo masses with the median $g-r$ colour in each bin shown by the colour bar. The cyan and magenta symbols are the median values for blue and red galaxies respectively,

with error bar showing the 16th – 84th percentiles. Observational results^{23, 25} are presented with different symbols and colours indicated in the legend.

Figure 2

The SHMR from the SIMBA simulation. Galaxies are binned in stellar and halo mass with the median halo formation redshift (left) and galaxy transition redshift (right) indicated by the colour bar to the right. Lines of different colours show median values for the transition and formation redshift ranges indicated in the legends, with error bars showing 16th – 84th percentiles. Median lines for red and blue galaxies are also included for comparison. Note that the dotted magenta and cyan lines are the linear fitting results with the fitting parameters are shown in table 1.

Figure 3

The SHMR at $z = 0$ again but shown M_{halo} in axis. Galaxies are separated into 3 different regions (blue, green and red) by the median red and blue galaxy lines from Fig. 2 and into different halo mass bins. The median stellar mass and halo mass in each zone is marked with a star symbol. The median SHMR evolution track of each zone is shown by the colourful curves (dotted for blue region; solid for green region and dashed for red region) with the redshift is shown in the colour bar. The median galaxy transition times are marked with squares. We further highlight the results from two halo mass bins with thick lines.

Figure 4

The median halo mass, galaxy stellar mass, cold gas mass and BH mass in galaxies as a function of redshift for a sample of halos selected to have mass $10^{12.5} < M_{\text{halo}} < 10^{12.8}$ at $z = 0$. As indicated in Fig. 3, halos and galaxy are grouped into red, green blue regions (indicated by different colours). The median formation histories are shown with different lines styles. The stars show the median halo formation time, galaxy transition time and BH jet mode on time.

Figure 5

Left panel: the relation between galaxy transition time and the time when the galaxy stellar mass is equal to its cold gas mass. Right panel: the relation between the time when jet mode AGN feedback is on and galaxy transition time. Similarly, galaxies are colour coded by their halo mass at $z = 0$ with the medians of different halo mass bins in colourful dashed lines. The black dashed line indicates the 1-to-1 relation. The red line with error bars shows the median values of all halos and 16th – 84th percentiles after binning in galaxy transition time.

Figure 6

The median central gas fraction evolution. The two selected halo mass bins are indicated in the legend. Different colourful lines are for the results in different colour regions in Fig. 3. The median galaxy transition times are marked as square in the curves.

Figure 7

The $g-r$ colour distributions for galaxies at the transition time and after. Only galaxies which have their transition time + 10 Gyr less than the Universe age are selected. This plot indicates that the galaxy needs about 5 Gyr after its transition time to reach a red colour ($g-r \approx 0.65$).

Figure 8

The same as Fig. 2, but reversed axes with the median lines shown in halo mass bin for the study of the inverse problem.

Figure 9

Similar to Fig. 1, but for the results from a smaller simulation box with the full feedback model (the same as the default simulation set) in the left panel and the one without X-ray feedback in the right panel.