Towards a precise understanding of galaxy formation through the second-order effect on the galaxy-stellar-to-halo-mass relation

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Outline for section 1

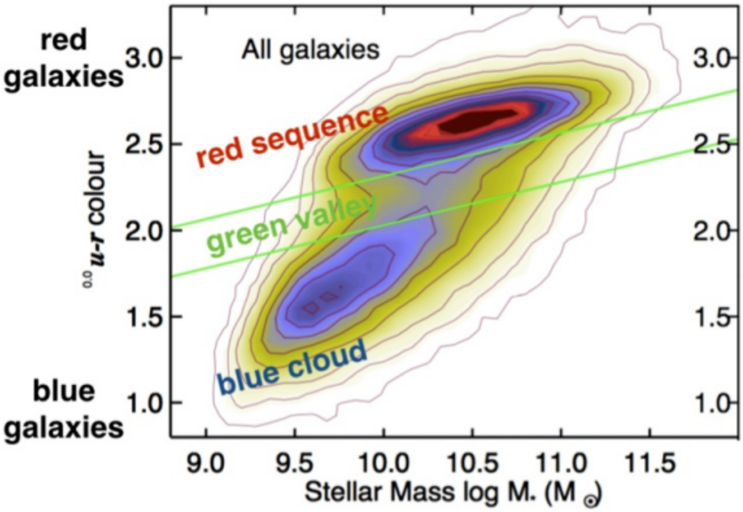
Introduction

The SIMBA simulation

The Origin of the colour bimodality in SHMR relation, (Cui, Dave, Peacock, Angles-Alcazar and Yang, 2021)

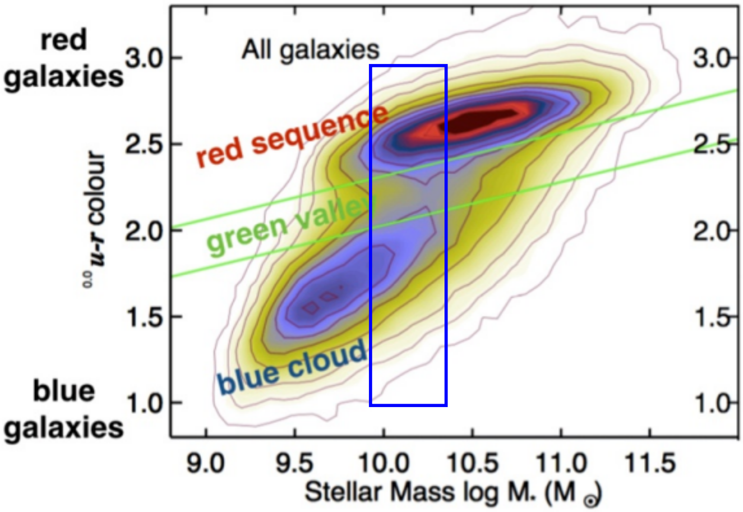
Conclusion

Galaxy colour bimodality with galaxy – halo relation



The old problem of colour-bimodality is solved by quenching galaxies with different mechanisms! – SN and AGN feedback.

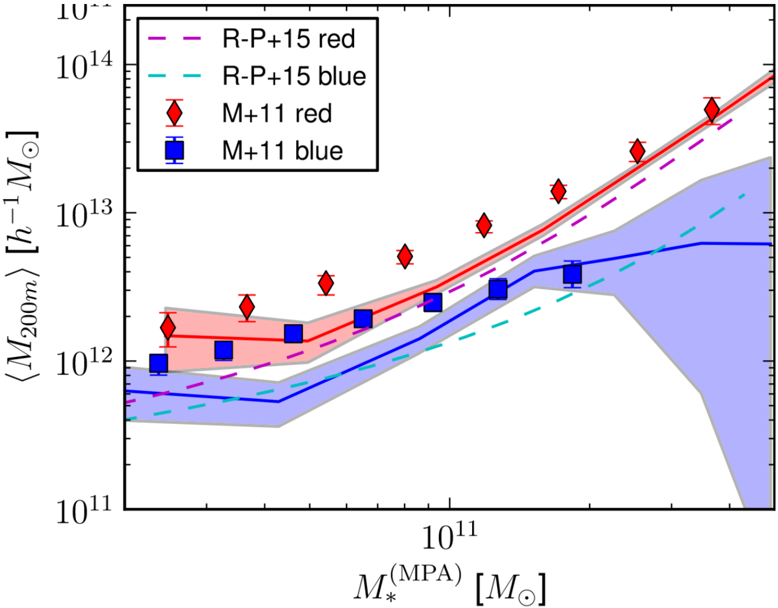
Galaxy colour bimodality with galaxy – halo relation



The old problem of colour-bimodality is solved by quenching galaxies with different mechanisms! – SN and AGN feedback.

A further step question – why the galaxies at the same mass have different quenching history?

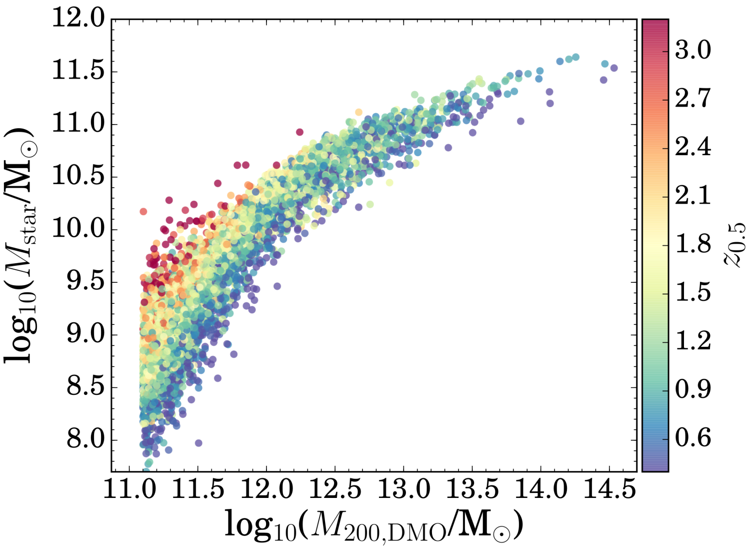
Galaxy – halo relations



At the same halo mass, blue galaxies have higher stellar mass compared to red galaxies.
At the same stellar mass, blue galaxies tend to live in low mass halos while red galaxies tend to be in higher mass halos.

Mandelbaum et al. 2016
See Zu et al. 2021 for similar conclusion at higher halo mass end.

How can we understand this?



Matthee et al. 2017, see also Zehavi et al. 2018.

At the same halo mass, early-formed halos tend to host (blue) galaxies with higher stellar mass, while low mass (red) galaxies tend to live in late-formed halos.
Contradicting to what we expect!!
To understand this, we need simulations/models to reproduce this colour bimodality in SHMR first. SIMBA, to my knowledge, is the first simulation to show very good agreement with the observations on this.

Outline for section 2

The SIMBA run: basic information

- The simulation code is based on GIZMO (Hopkins 2015, 2017), MUFASA model (Dave et al. 2016) with a new advanced BH model (Angles-Alcazar et al. 2017) and a dust model (Li et al. 2019). See next slide for details.
- Other input physics: $\mathrm{GRACKLE}$-3 for gas radiative cooling and photoionization heating, Haardt & Madau (2012) ionizing background with self-shielding, an H_2-based star formation rate, 11 elements are tracked with chemical enrichment from Type II supernovae (SNe), Type Ia SNe, and Asymptotic Giant Branch (AGB) stars, stellar feedback with mass loading factor follows Angles-Alcazar et al. (2017b).

The SIMBA simulation (Dave et al. 2019): the advanced BH model

Two types of BH accretion:

- the torque-limited accretion model for cold gas (T$<10^5$ K, Angles-Alcazar et al. 2015, 2017)
- Bondi-Hoyle-Lyttleton accretion model for hot gas (T$>10^5$ K)

Three BH ("kinetic") feedback models:

- 'Radiative feedback' ('thermal feedback') in high Eddington ratios $f_{Edd} \gtrsim 0.2$ with a wind speed of 1000 km/s.
- Jet feedback in low $f_{Edd} \lesssim 0.2$ ejects the hot gas in collimated jets with a wind speed 8000 km/s.
- X-ray feedback, energy input from X-rays off the accretion disc following Choi et al. (2012), for galaxies in jet-mode with gas fraction $f_{gas} < 0.2$. Directly increasing the gas's temperature for non-ISM gas; Half energy into a radial outwards kick and half to heat for ISM gas.

The SIMBA simulation (Dave et al. 2019): the dust model (Li et al. 2019)

- Dust is passively advocated following the gas particles.
- It has the same physical properties with a fixed radius a $=0.1$ μm.
- Dust is produced by condensation of metals from eject of SNe and AGB stars.
- Once dust grains are produced, they can grow by accreting gas phase metals.
- Dust will be destroyed instantaneously in the process of hot winds (for example AGN X-ray heating or jets) and star formation, with all dust mass and metals being returned to the gaseous phase.

The SIMBA simulation suite (Dave et al. 2019)

Table: Planck 2016 concordant cosmology Parameters

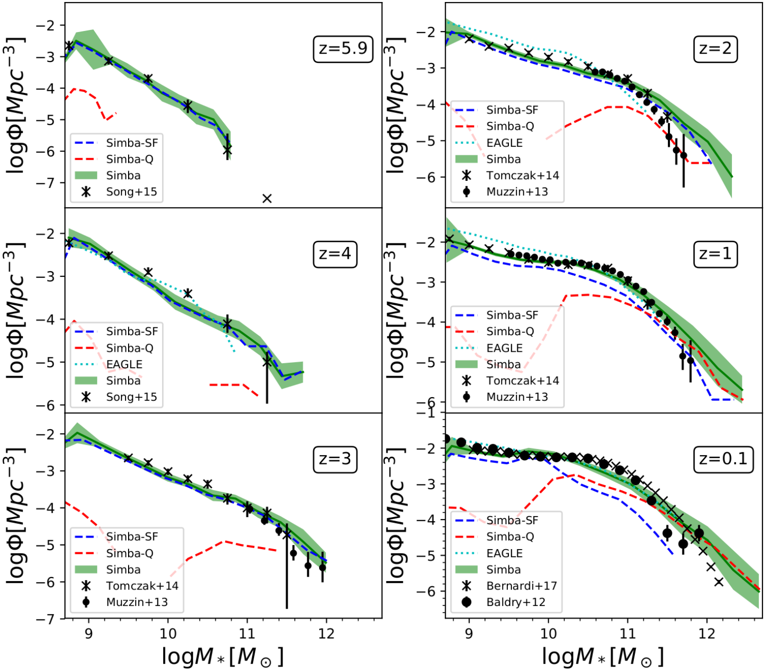
Parameter	Value	Description
Ω_M	0.3	Total Matter density parameter
Ω_B	0.048	Baryon density parameter
Ω_Λ	0.7	Cosmological Constant density parameter
h	0.68	Hubble constant in units of 100 km/s/Mpc
σ_8	0.82	Normalization of Power spectrum
n_s	0.97	Power index
z_{init}	250	Initial redshift of the simulations

Table: The simulation runs

Name	L_{box} [Mpc/h]	m_{gas} $[M_\odot]$	m_{DM} $[M_\odot]$	z_{end}
m100n1024[2]	100	1.82e7	9.6e7	0
m50n512	50	1.82e7	9.6e7	0
m50n512 - No-X	50	1.82e7	9.6e7	0
m50n512 - No-Jet	50	1.82e7	9.6e7	0
m50n512 - No-AGN	50	1.82e7	9.6e7	0
m50n1024	50	2.28e6	1.2e7	1
m25n1024	25	2.85e5	1.5e6	2
m12.5n1024	12.5	3.56e4	1.88e5	5

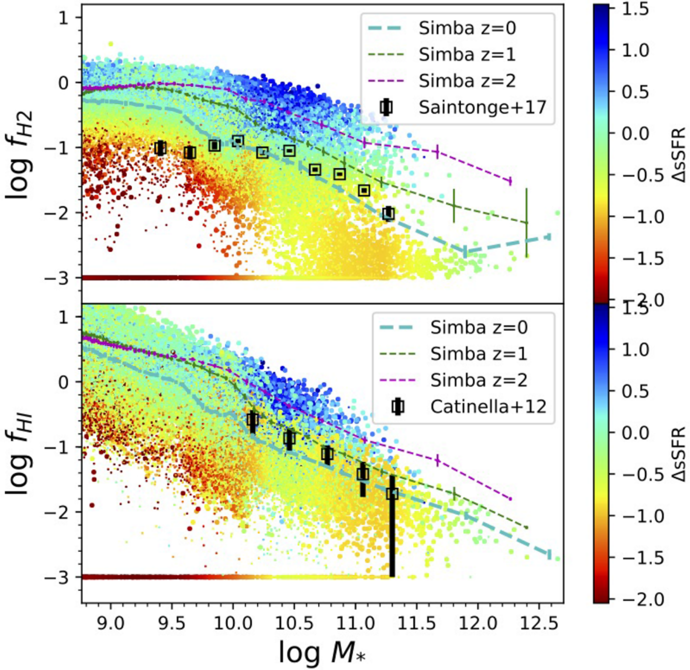
[2] The SIMBA simulation

The SIMBA simulation: Comparisons with observations



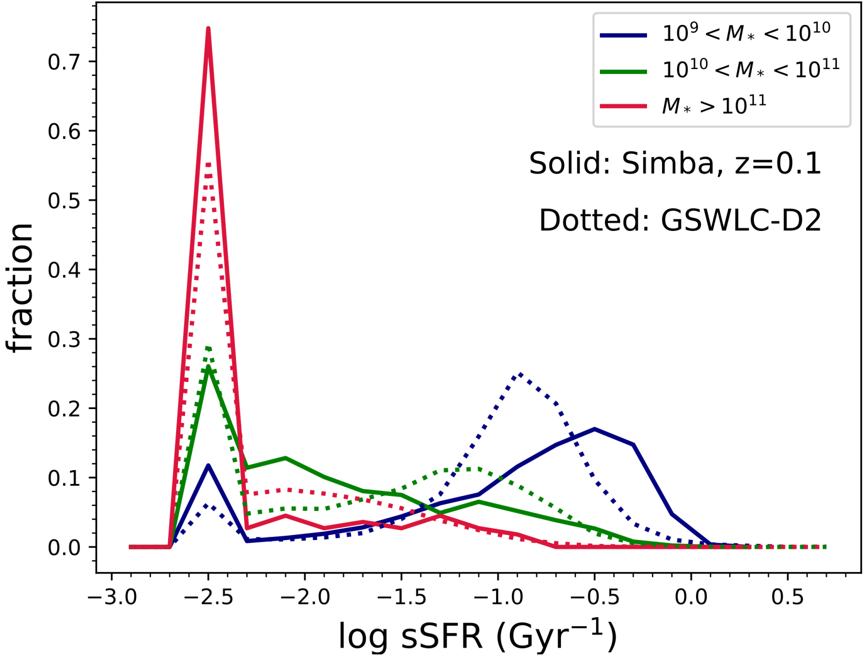
The galaxy stellar mass function, Dave et al. 2019

The SIMBA simulation: Comparisons with observations



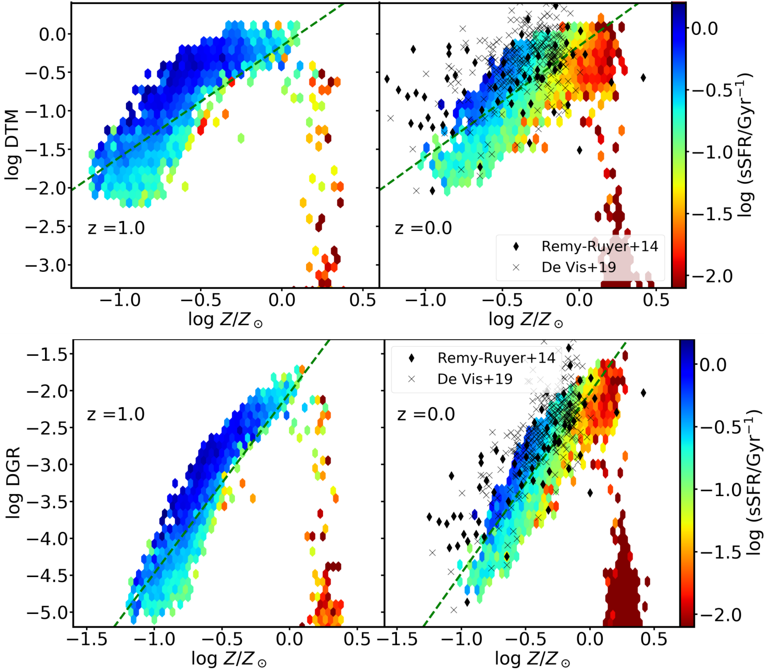
The galaxy gas mass fractions, Dave et al. 2019

The SIMBA simulation: Comparisons with observations



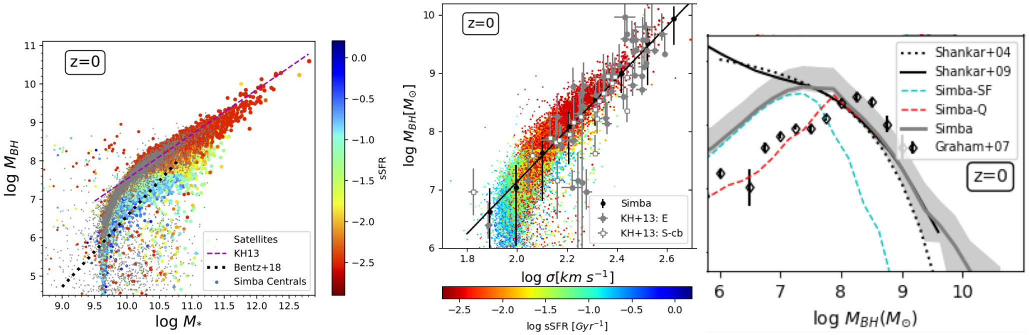
The bi-modality of galaxies, Dave et al. 2019

The SIMBA simulation: Comparisons with observations



The dust relations, Li et al. 2019

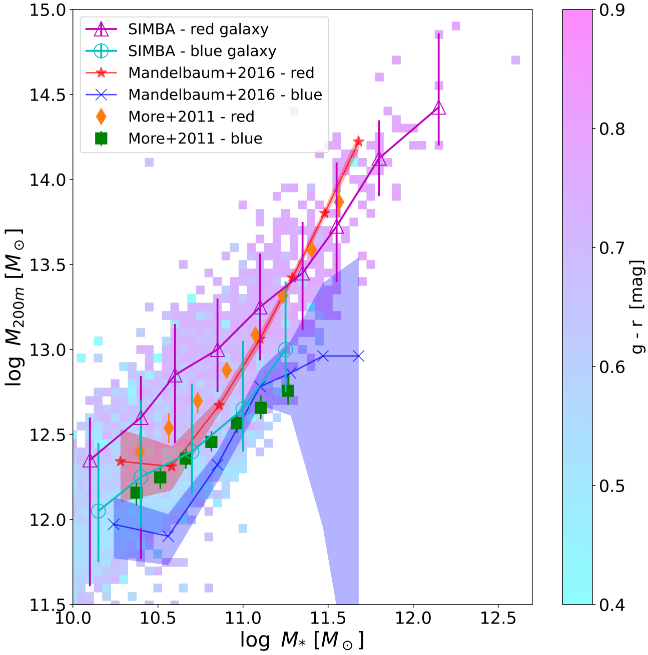
The SIMBA simulation: Comparisons with observations



The BH-galaxy scaling relations, Dave et al. 2019 & Thomas et al. 2019

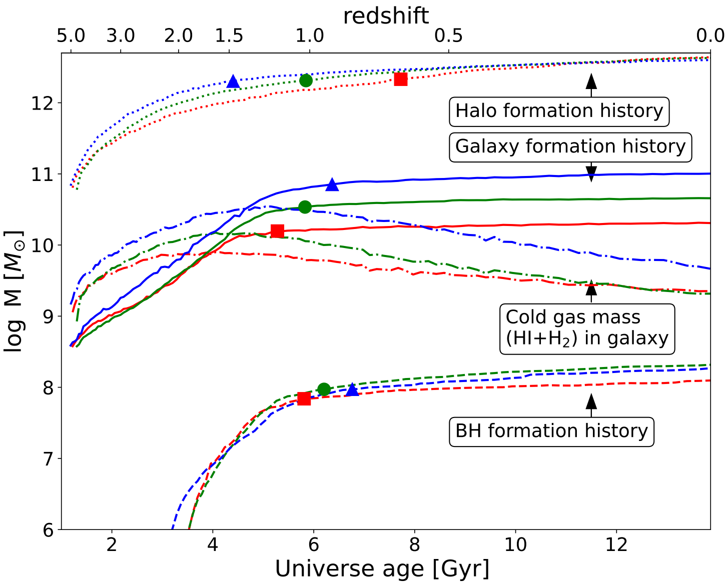
Outline for section 3

SIMBA vs Observation.



The same threshold for separating red and blue galaxies is adopted following More et al. 2011.
Using sSFR cut gives the same result.
Note the errorbar from SIMBA simulation is $16^{th} - 84^{th}$ percentile, not the same as observational errors.
Only central galaxies.

The anti-correlation between Z_T and Z_F

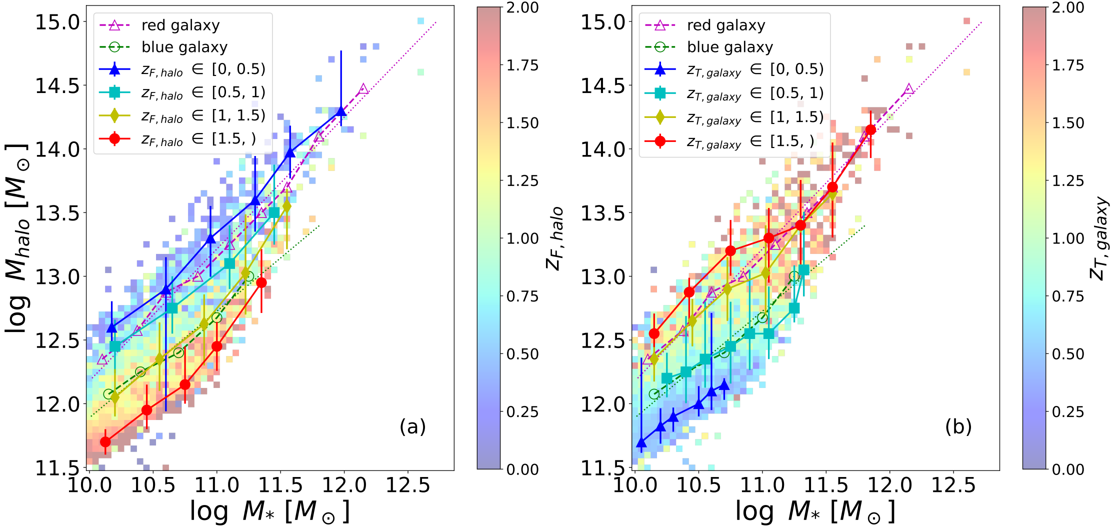


Halo formation time: Z_F, when the halo accreted half of its final mass.

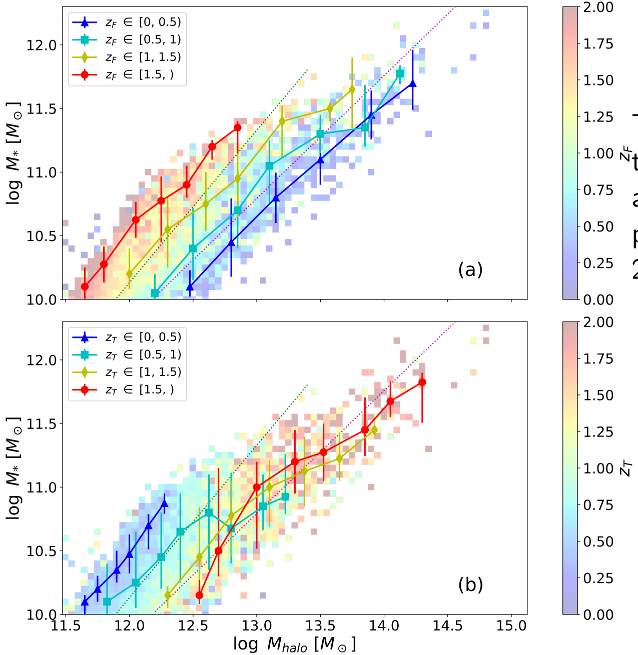
Galaxy transition time: Z_T, when the galaxy transform from fast growth mode to quiet mode, $d\log M_*/dt[Gyr] < 0.1$.

Black-hole jet-on time t_{jeton}, when the jet mode AGN feedback is turned on. This is characterised with the $f_{Edd} < 0.2$, $d\log M_\bullet/dt[Gyr] < 0.9$.

The anti-correlation between Z_T and Z_F

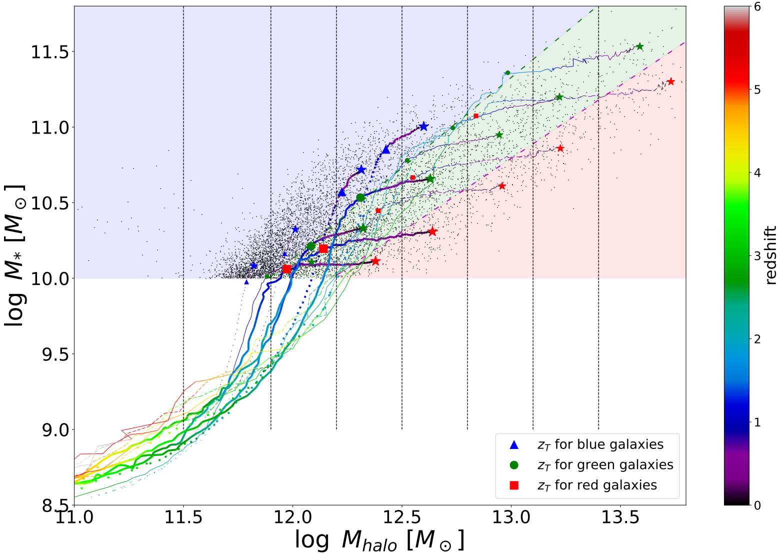


The anti-correlation between Z_T and Z_F



The same as previous figure, just to highlight here these quantities are not suffering the inverse problem (see Moster et al. 2018, 2020 for details.)

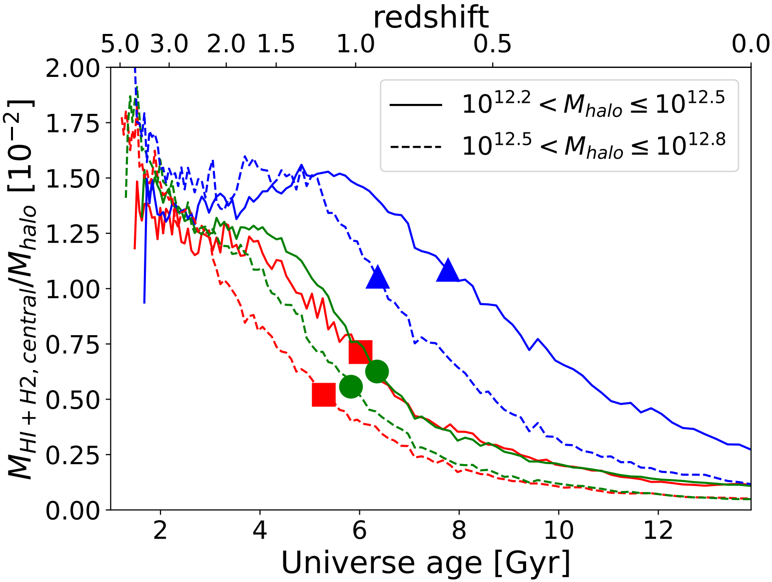
Tracking the evolution of the SHMR



The median value of each region at z=0 is marked with a star. Colour lines show the median value of the galaxy progenitors at corresponding redshift. Triangles (blue), circles (mixed/green) and squares (red) indicate the median galaxy transition redshifts.

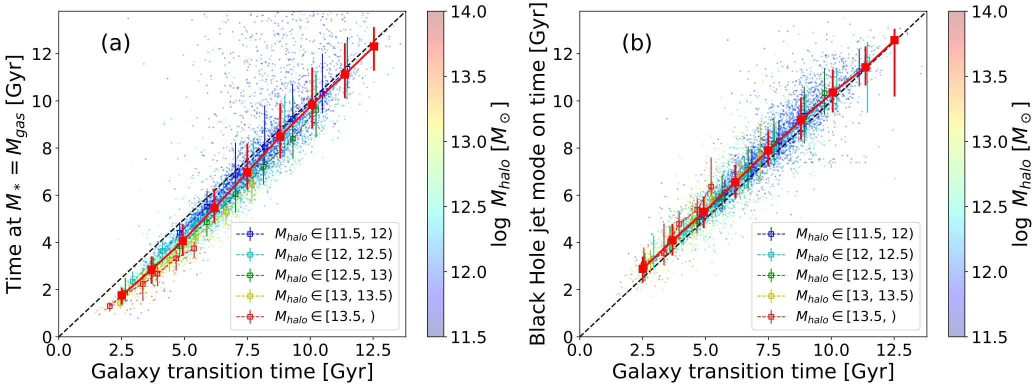
Prior to the transition time, the lower the final M_*, the higher the slope (fast stellar growth). After the transition time, galaxies in red region have a longer time to grow their halo mass, ended in the lower-right portion of this SHMR plane.

The origin of the colour bimodality: The intrisic reason



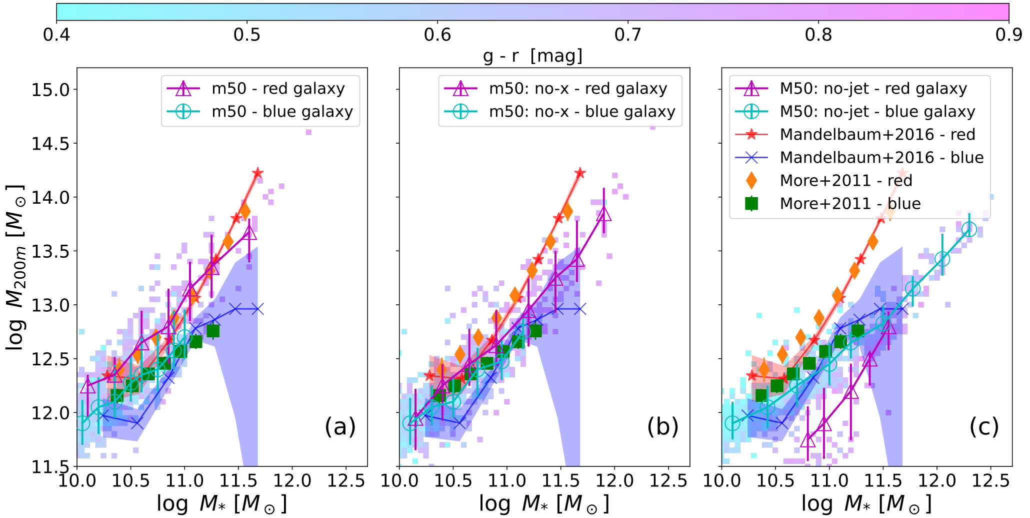
Gas fraction evolution. Reminder: Blue galaxies tends to live in early-formed halos. Higher gas fraction is the key to sustain star formation and delay jet-mode AGN feedback (responsible for quenching galaxies) in SIMBA (see next slide). Early-formed halos have higher gas fraction!

The origin of the colour bimodality: The physical driver of galaxy transition



Left panel shows the connection between gas content with galaxy transition time; right panel highlights the jet-mode AGN feedback in SIMBA is responsible for quenching galaxies.

The origin of the colour bimodality: Enhancing the galaxy colour separation



X-ray feedback in SIMBA is for completely shutdown the star formation.

Outline for section 4

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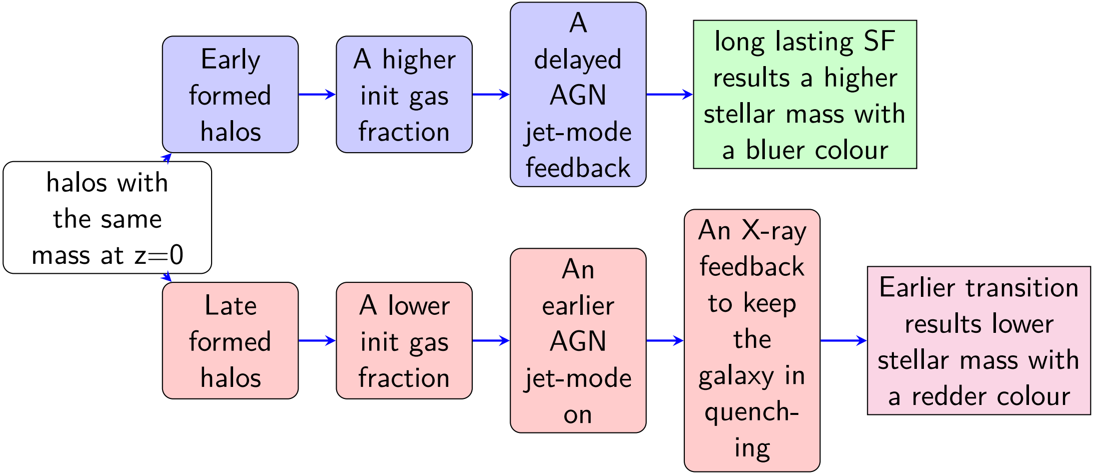
Conclusion

Conclusion


halos with the same mass at z=0
Early formed halos
A higher init gas fraction
A delayed AGN jet-mode feedback
long lasting SF results a higher stellar mass with a bluer colour
Late formed halos
A lower init gas fraction
An earlier AGN jet-mode on
An X-ray feedback to keep the galaxy in quench-ing
Earlier transition results lower stellar mass with a redder colour

Conclusion

The SIMBA simulation[3] reproduced the observed colour bimodality in the SHMR. It further revealed the anti-correlation between halo formation time and galaxy transition time.

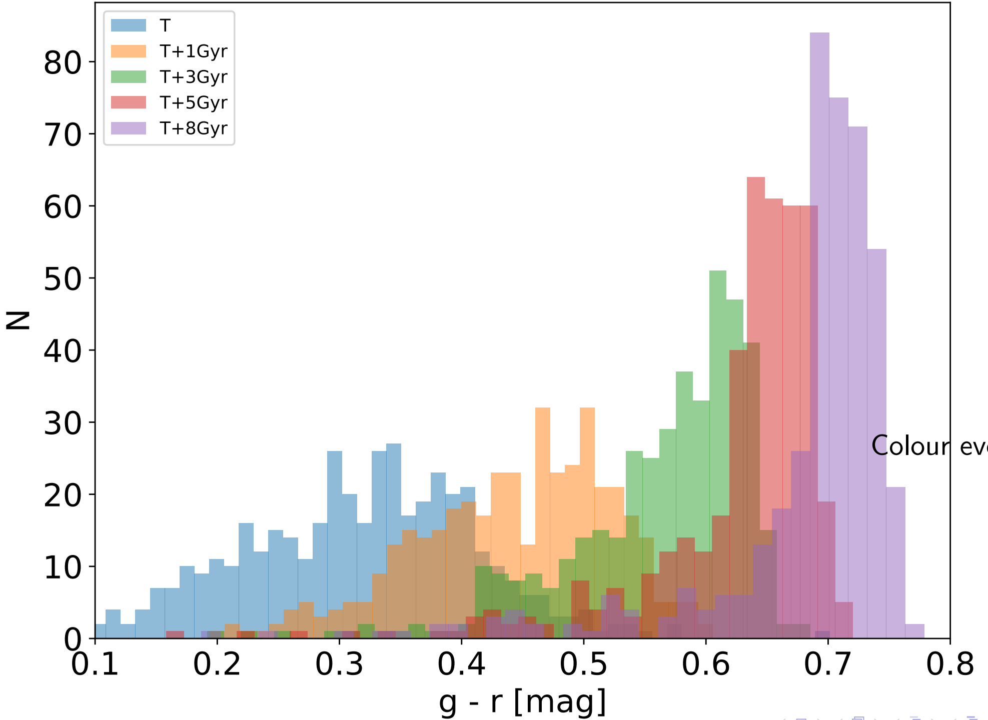
The origin of the colour bimodality in SIMBA simulation can be explained with:

- The intrinsic driver – halo assemble bias: early-formed halos tends to host a higher gas fraction.
- The physical driver – galaxy transition: the gas content does not only serve as the reservoir for galaxy formation, but also connected with the jet-mode AGN feedback in SIMBA which is the key feature to quench galaxy.
- An additional enhancer: X-ray feedback. the separation between red and blue galaxies is almost mixed without the X-ray feedback.

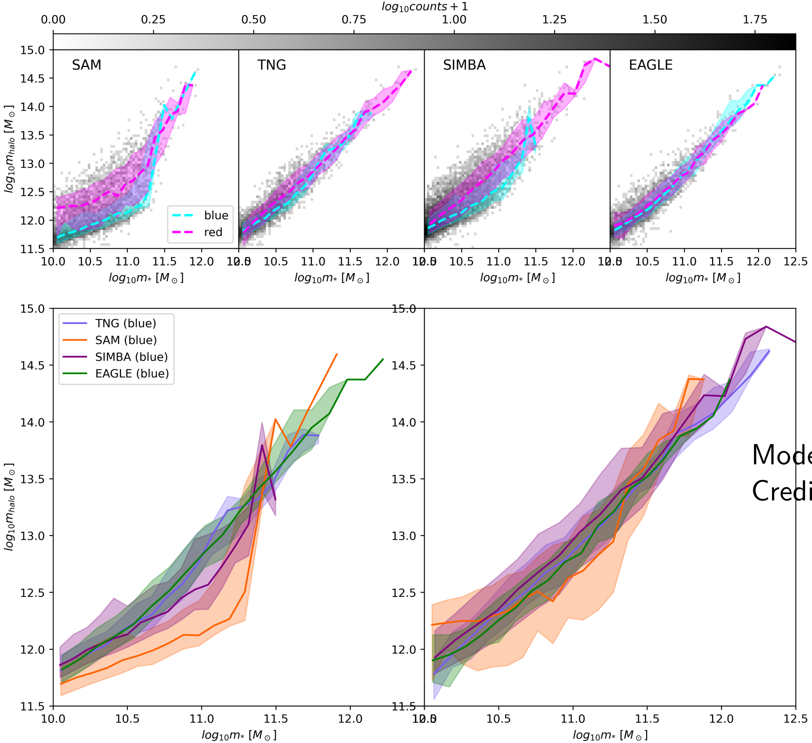
The scatter in SHMR is meaningful. And it leads to a precise understanding of the SHMR.

Acknowledgements:

[3] http://simba.roe.ac.uk/



Colour evolution.



Model comparisons.
Credit: Austen Gabrielpillai