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The history and mass content of cluster galaxies in the EAGLE simulation

Cristóbal Sifón[1], ...
[1] *Instituto de Física, Pontificia Universidad Católica de Valparaíso, Casilla 4059, Valparaíso, Chile*

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ABSTRACT
We explore the mass content of cluster galaxies in the EAGLE cosmological hydrodynamical simulation.

We explore changes in satellite stellar mass/halo mass as a function of (the observationally accessible) distance from host/nearest cluster, as well as the more physical change as a function of time for the same satellites.

We identify the progenitors of $z = 0$ satellites as **some population of centrals at some earlier time**, and find **the following problems arise when interpreting differences between present-day satellites with present-day centrals**

1 WISH/THOUGHT LIST

are all quantities in the HBT catalogs in units of h, or is the value of h already included?

(Given in the order they came to my head)

(i) Explore what difference does it make where did the satellite come from, by binning as a function of cluster-centric distance but also, for galaxies not part of the cluster, by host mass (probably do not need groups less massive than $10^{12}\,h^{-1}\,\mathrm{M}_\odot$, as that's already the mass of the Milky Way). Another way is, for galaxies not part of a massive cluster, to see how far they are to a massive cluster and what is their host mass. For a given distance to a massive cluster, does the mass relation change with host mass? We may need to control by distance from host center as well, and then it may become too noisy...
(ii) try to find a good definition for subhalo size using the density profiles. Perhaps differences between our measurements and EAGLE are caused by a model error?
(iii) Plot stellar-to-total mass *ratios* as a function of cluster-centric distance.
(iv) When plotting "distance to nearest cluster" as opposed to distance to *host* cluster, should
(v) Use some definition of "phase-space distance", similar to the bins in Fig 1 of Muzzin+14.

1.1 Literature notes

(i) Rhee et al. (2017): weak preprocessing in general (< 30% mass loss prior to entering cluster). Mass lost up to 1st pericenter ~20-30%, constant with time (Fig 4)

1.2 New thoughts emerging from my HBT+ exploration:

(i) To see what produces changes (especially fluctuations) in mass, should look at the location of the (sub)halo and its neighbors. It's probably that their spiraling into each other or so.

2 INTRODUCTION

Over time, galaxies evolvoe and co-evolve as they are pulled together by gravity and form larger gravitationally-bound systems such as groups and clusters of galaxies, and eventually merge into larger galaxies. This hierarchical formation scenario is widely supported by simulations of structure formation (e.g., **?**) and observations (e.g., **?**). Galaxies, in turn, reside in dark matter subhaloes, which interact gravitationally to form ever larger subhaloes and haloes (where subhaloess

In this paper, we study the demographics and evolution of satellite galaxies and their host haloes in detail, paying particular attention to the transfer of mass from galaxies to their host groups and clusters,

In this paper we refer generically to "galaxy groups" as all galaxy associations more massive than $M_{200\mathrm{m}} = 10^{11}\,\mathrm{M}_\odot$, and to "clusters" as the subset of those groups which have $M_{200\mathrm{m}} > 10^{13}\,\mathrm{M}_\odot$. (This is a more relaxed definition of "cluster" than usual.) Throughout, we refer to masses $M_{\Delta m}$ ($M_{\Delta c}$) as the mass containing Δ times the mean (critical) density of the Universe at the group redshift. Where appropriate, we adopt the cosmology used in the EAGLE simulations, with **parameters...** Throughout, we use log to refer to base 10-logarithm.

3 SIMULATION

We use the Evolution and Assembly of Galaxies and their Environment (EAGLE) simulations (Schaye et al. 2015; Crain et al. 2015). EAGLE is a suite of cosmological hydrodynamical simulations with varying box sizes, resolutions, and baryonic feedback prescriptions. The simulation we use here is labelled `RefL0100N1504` and has a box size of $(100\,h^{-1}\,\mathrm{Mpc})^3$, with N particles and mass resolutions of X,Y,Z for dark matter, gas and stars, respectively. Our study is based on the upgraded Hierarchical Bound Tree (HBT+, Han et al. 2018) post-processing of EAGLE, in which subhaloes are found ... .

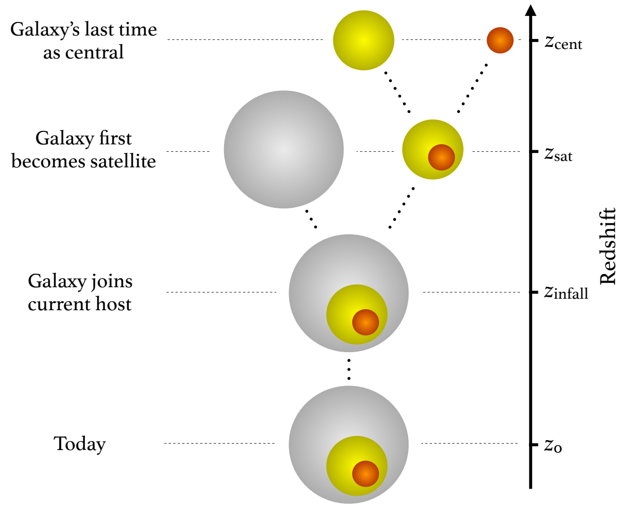

Figure 1. Schematic figure showing the relevant times we consider in this work. The brown circle represents a galaxy of interest, which is a satellite at redshift z_0, part of a host group shown in grey. We identify the last redshift (earliest time) at which the brown satellite was hosted by the grey host as $z_{\rm infall}$. The last time at which the brown satellite was a central galaxy is labelled $z_{\rm cent}$. When the brown satellite fell into the grey host (identified at present with `GroupID`), it may in fact have already been part of another group, shown in green. If this is the case, then $z_{\rm cent} \neq z_{\rm infall}$. We identify $t_{\rm cent}$ and $t_{\rm sat}$ separately because a small fraction of subhaloes are labelled as satellites and later re-labelled as centrals, in which case $t_{\rm cent} > t_{\rm sat}$.

Here, we consider all subhaloes with masses $m_{\rm sub} \geq XXX{\rm M}_\odot$ residing in haloes with masses $M_{\rm host} \geq 10^{11}{\rm M}_\odot$.

3.1 Mass definitions

Throughout this work we speak of 'subhaloes' as all dark matter haloes that inhabit a larger halo, including central subhaloes; and of 'galaxies' as the subset of subhaloes which contain at least one star particle. Total masses of both subhaloes and galaxies are defined as the total mass of all bound particles (i.e., the sum of all dark matter, gas, star, and black hole particles, defined in HBT+ as `Mbound`), and stellar masses are similarly defined as the total mass in all bound star particles according to HBT+. Central and satellite subhaloes are hosted within a 'host halo', whose total mass is defined as an over-density mass M_Δ, where in this work $\Delta = \{200, 500\}$, and the over-density is with respect to either the mean density (denoted, e.g., $M_{\rm 200m}$) or the critical density (e.g., $M_{\rm 200c}$), both defined at the corresponding redshift.

We compare the different mass definitions, and show the relative contribution of each to their host halo, in **??**. ...

We show the mass functions for subhaloes and galaxies in Figure 2.

- plot mass functions for different host mass definitions (Mbound, M200Mean, etc) and for subhaloes
- show plots comparing those masses directly

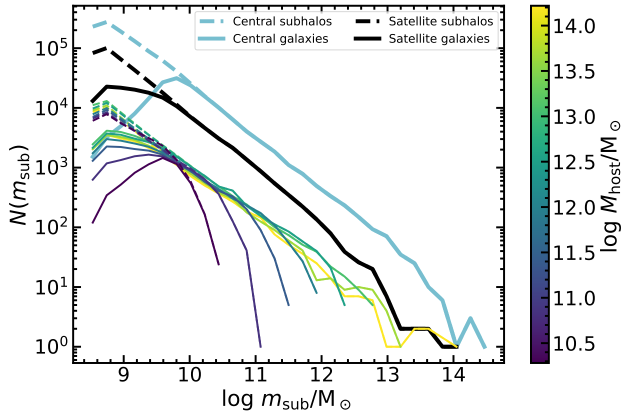

Figure 2. Total mass function of central (cyan) and satellite (black) subhaloes (dashed) and galaxies (solid). The thinner, colored lines show the satellite subhalo mass function split into different host halo masses. The rapid drop in each colored curve happens as subhalo masses approach their host halo mass, as the latter is always larger. **Our analysis throughout refers to subhaloes with $\log m_{\rm sub} \geq 9.7$, identified by the vertical dotted line.** Here, $M_{\rm host} = M_{\rm 200m}$.

4 PRESENT-DAY CLUSTER GALAXIES IN EAGLE

- make a plot similar to Figure 3 but showing how this depends on the subhalo-to-host mass ratio (e.g., with different lines, or normalizing an axis or both axes)
- also make a plot with total-to-stellar mass ratio as a function of cluster-centric distance (also showing the effect of host halo mass)
- also have a look at scatter in mtot vs. mstar

4.1 The relations between total and stellar mass

Figure 3 shows the stellar-to-halo mass relation (SHMR) and the halo-to-stellar mass relation (HSMR)[1] Central and satellite galaxies clearly follow different relations. This result has been seen for a long time in simulations and originates in the severe tidal stripping suffered by satellite galaxies (moreover, with time, some of the stripped mass will be accreted by the central subhalo).

We also show two observational results for comparison: the central HSMR by van Uitert et al. (2016), and the satellite HSMR by Sifón et al. (2018). There is general agreement between the observational results and EAGLE, with perhaps some evidence for larger total satellite masses at large stellar masses in EAGLE compared to observations, which Sifón et al. (2018) showed is also seen in the SUBFIND subhalo catalogue of EAGLE ()

Figure 4 shows the dependence of the HSMR on host halo mass. As seen in the right panel, there is a slight dependence of the HSMR with host halo mass, with more massive haloes hosting satellites with a lower total-to-stellar mass ratio (i.e., a lower dark matter fraction). This can easily be understood by the effect of tidal stripping from the host halo, which is more severe in more massive hosts and affects dark matter more strongly than stellar mass (e.g.,). The left panel shows the same relations but separated by the ratio of satellite-to-host mass,

$$\mu \equiv \frac{m_{\rm sub}}{M_{\rm host}}\,. \tag{1}$$

[1] Note that due to intrinsic scatter, one cannot be obtained by simply inverting the other.

The HSMR depends more strongly with μ than $M_{\rm host}$ alone. **Why?**

To highlight this, we show the HSMR as a function of the distance from the subhaloes to the host halo centre of mass in ??.

4.2 Subhalo disruption

Recently, it has become apparent that most, if not all, disruption of subhaloes in N-body simulations is a result of numerical noise or other artefacts of the simulation, rather than it being the consequence of physical effects (van den Bosch et al. 2018; van den Bosch & Ogiya 2018). In this section, we present demographics of disrupted subhaloes in EAGLE; in Section 6 we discuss the implications of their demographics for comparisons with observational measurements.

?? shows the fraction of disrupted subhaloes as a function of host mass. Use Frank's papers as reference - are things consistent? do we learn anything?

5 THE EVOLUTION OF CLUSTER GALAXIES

- reproduce the 2d histograms in Figure 3 but now show tracks for a few subhaloes, i.e., how do they move along this plane as they are accreted and orbit the cluster?
- show something like the fraction of subhaloes that were centrals at infall (i.e., $t_{\rm cent} = t_{\rm infall}$) as a function of halo mass, subhalo mass, and infall time.
- follow up the 4-panel shmr figure with relations with time. Perhaps we can find a time when central and satellite galaxies had the same HSMR? What are the roles of stripping and star formation in this evolution?

Notes on Figure 5.

- In general, we'd expect $i_{\rm cen} = i_{\rm sat} - 1$, i.e., a subhalo is a central right until it becomes a satellite, after which it is never central again. That's in general not quite what we see.
- The steeper growth of the central subhaloes is not reflected in a comparable decrease in the mass of the most massive subhslaos. Where is all this mass in the last ∼8 Gyr coming from?
- Note that all subhaloes which lose mass abruptly (e.g., yellow, cyan in top row) then regain some mass. This is expected as the subhalo 're-virializes'
- Funny that all centrals *were* satellites at some point (probably only one snapshot?)
- The earliest accreted subhaloes – cyan in row 2 and grey in row 3 – have had multiple severe mass loss episodes, as expected.
- some (potentially) interesting summary plots:

6 APPLICATION TO SATELLITE LENSING MEASUREMENTS

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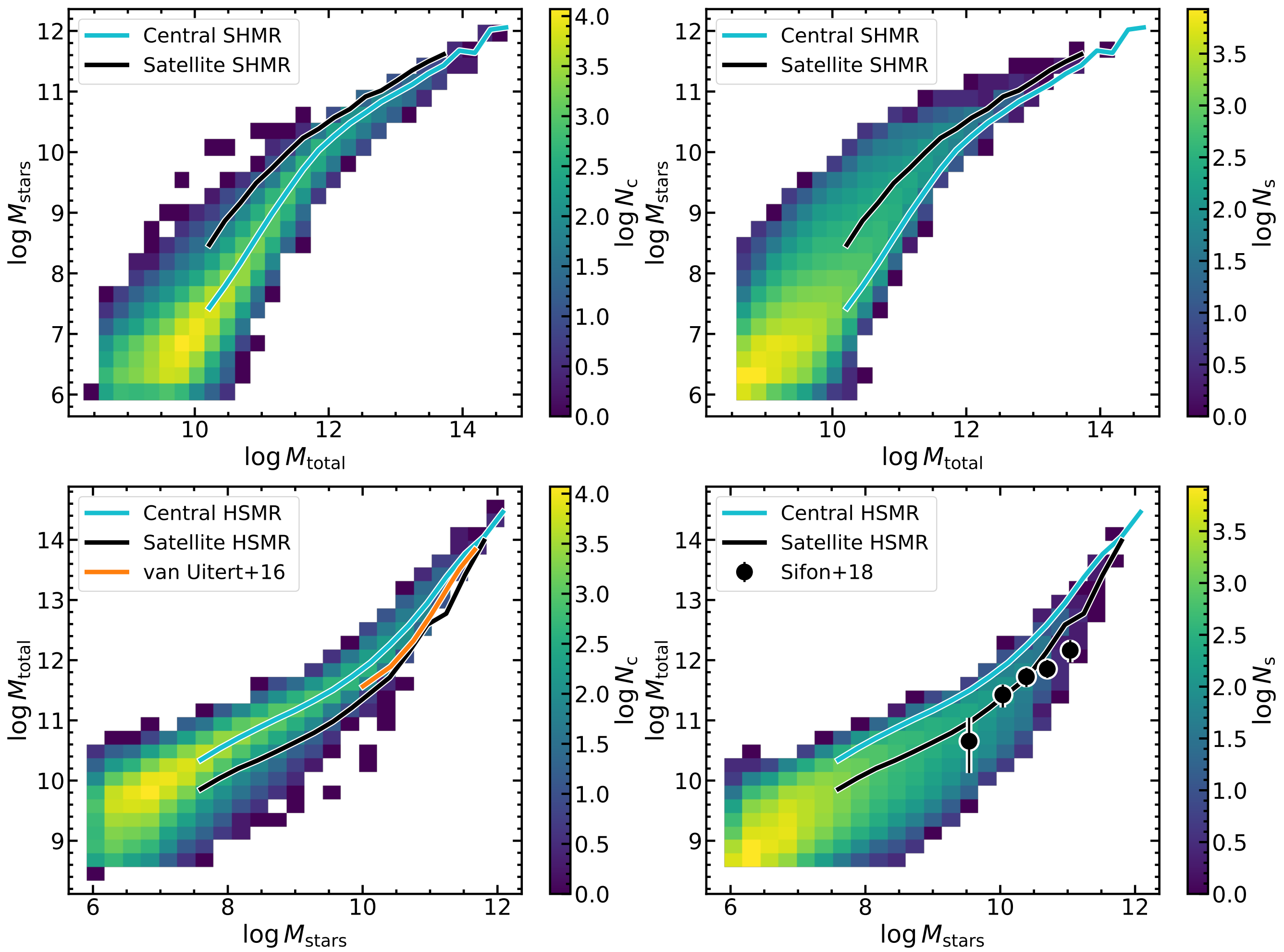

Figure 3. The stellar-to-halo mass relations (SHMR, top panels) and halo-to-stellar mass relations (HSMR, bottom panels) for central (left panels) and satellite (right panels) cluster galaxies in EAGLE. Color scales represent the log of the number of central and satellite galaxies, respectively, and lines are the means in each panel, as labelled, and are only shown where the samples are complete in the independent (i.e., x-axis) variable. Central total masses refer to M_{200m}, while subhalo masses are total HBT+ masses. The central HSMR is compared to that derived from KiDS data by van Uitert et al. (2016), while the satellite HSMR to that measured in MENeaCS clusters by Sifón et al. (2018).

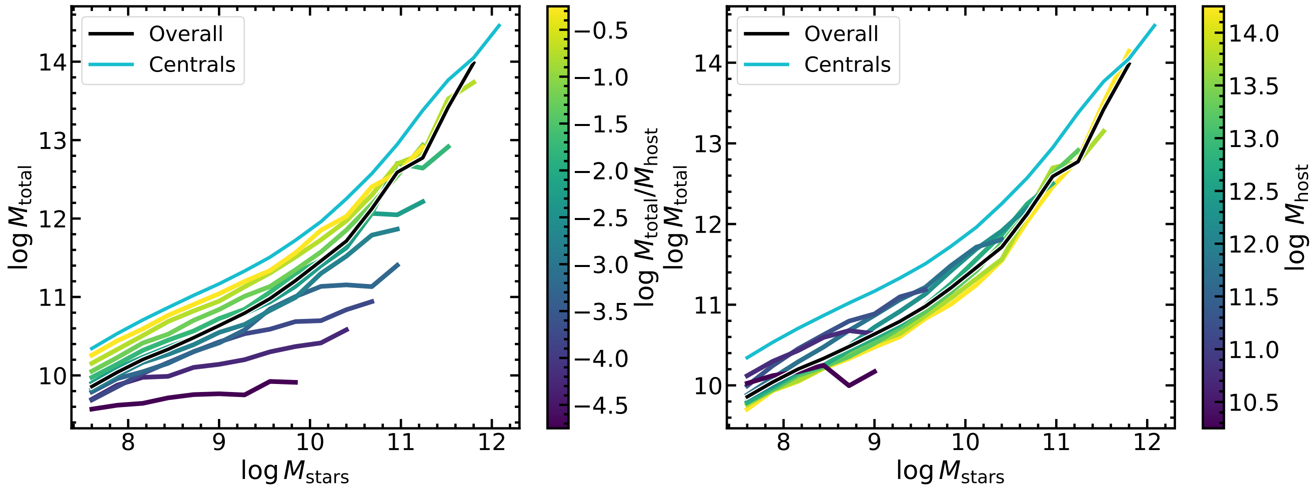

Figure 4. The dependence of the halo-to-stellar mass relation on subhalo-to-host mass ratio (left) and on host halo mass (right). The black line shows the HSMR averaged over all subhaloes, while the cyan line shows the HSMR of centrals for reference. Mass definitions are as in Figure 3. **check number of particles/destruction rate vs. mu**

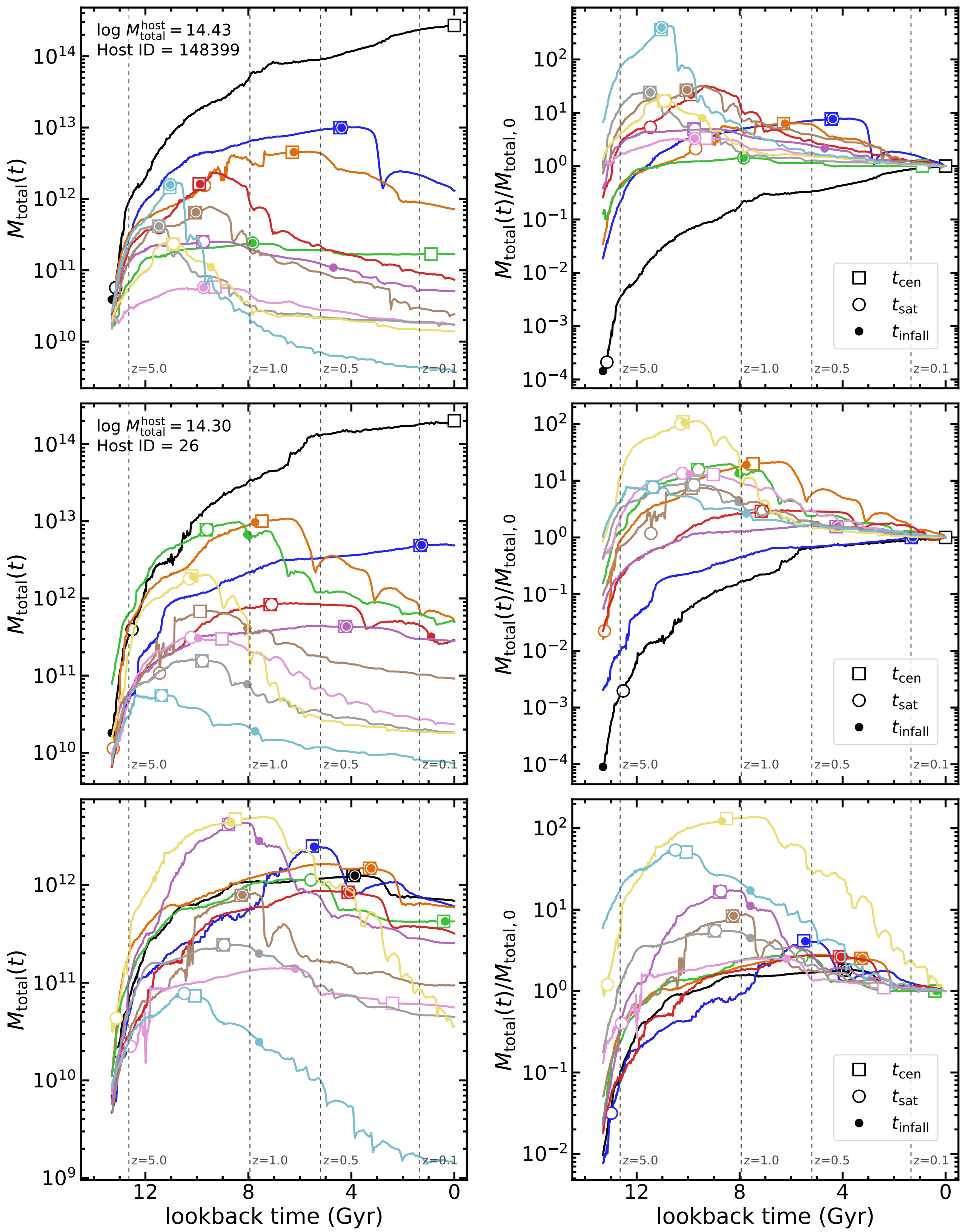

Figure 5. The evolution of the total mass of the 11 most massive subhaloes (i.e., the central plus the ten most massive satellite subhaloes) in the three most massive haloes in EAGLE. Empty squares, empty circles, and filled circles correspond to the first time a subhalo became a satellite ($t_{\rm sat}$), the last time it became a central ($t_{\rm cen}$), and the time of infall to its current host ($t_{\rm infall}$), respectively. The left panel shows mass as a function of lookback time, while the right panel is normalized by present-day mass. Each subhalo has the same color in the left and right panels.