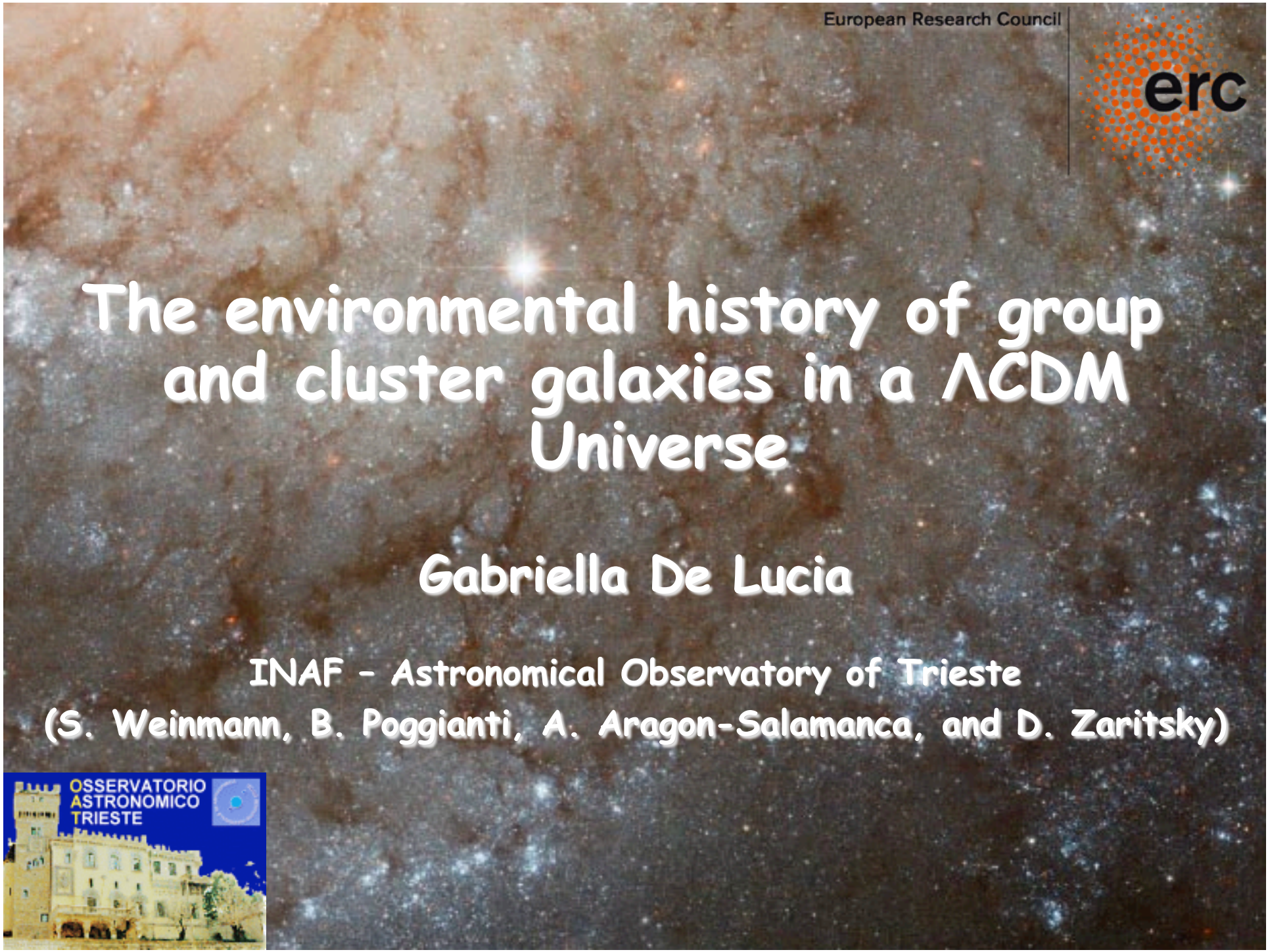
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The environmental history of group and cluster galaxies in a ΛCDM Universe
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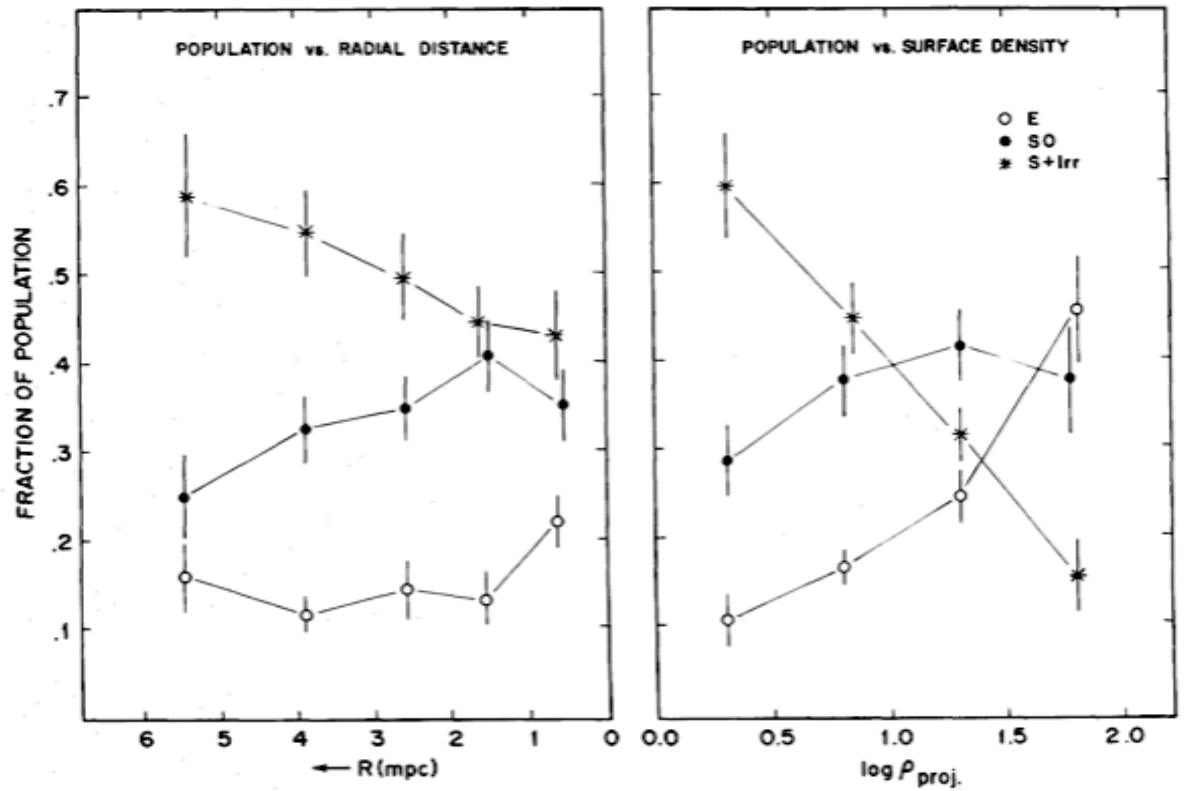
The "nature" vs "nurture" debate

Are the observed trends the end product of physical processes coming into play only after the galaxies have become part of a "group" or of a "cluster"? Or are they established before these events take place?



R [Mpc]

projected density

Dressler 1980

"There are some indications of a correlation between the characteristic type and compactness, the density of cluster diminishing as the most frequent type advances along the sequence of classification"

"The Realm of Nebulae", E. Hubble 1936

An ill posed problem:

✓ If we live in a hierarchical Universe, as we believe, then galaxies have experienced a sequence of different environments during their lifetimes. So nature and nurture are inevitably and heavily intertwined.

✓ Many numerical studies focused on the role of "nurture" (a plethora of physical processes can contribute to change the level of star formation activity and/or morphology of galaxies in high-density regions).

✓ "Nature" was believed to play a minor role up to about one decade ago. More recent numerical simulations, however, have shown that halo properties (e.g. spin, formation time, concentration) depend on the environment. This is bound to leave an "imprinting" on the properties of galaxies that live in different environments.

✓ One important missing ingredient is a detailed characterization and quantification of the "environmental history" that galaxies experienced during their lifetimes.

Tools and data

✓ A publicly available catalogue of galaxy merger tree obtained applying a semi-analytic model (De Lucia & Blaizot 2007) to a large cosmological simulation (the Millennium Simulation, Springel et al. 2005).

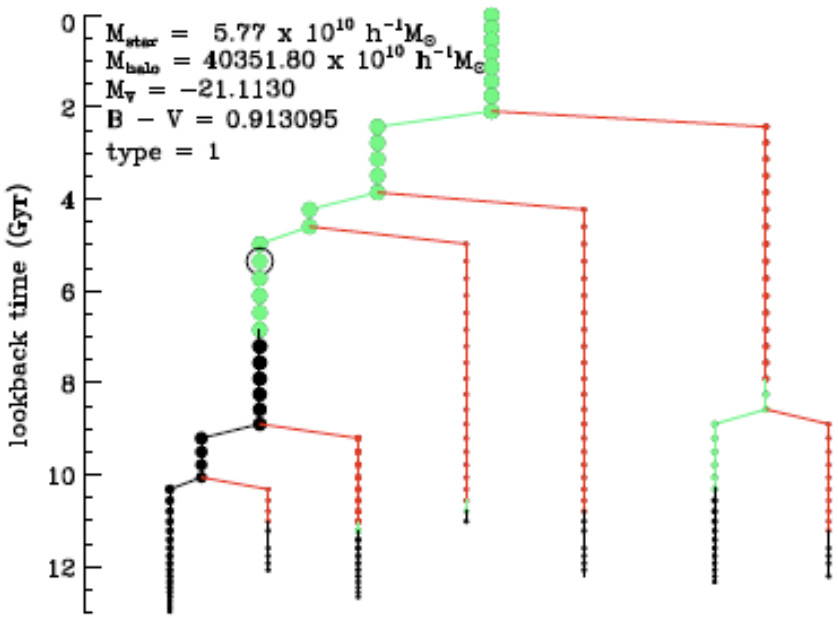
✓ Note that the model is not without problems (see e.g. talk by Monaco and Cucciati), but we are only using the galaxy merger trees and the mass of galaxies (results are robust when using different models).

✓ A cluster catalogue based on SDSS DR4 and the C4 cluster catalogue (von der Linden et al. 2007), and a group catalogue based on DR4 (Yang et al. 2007).

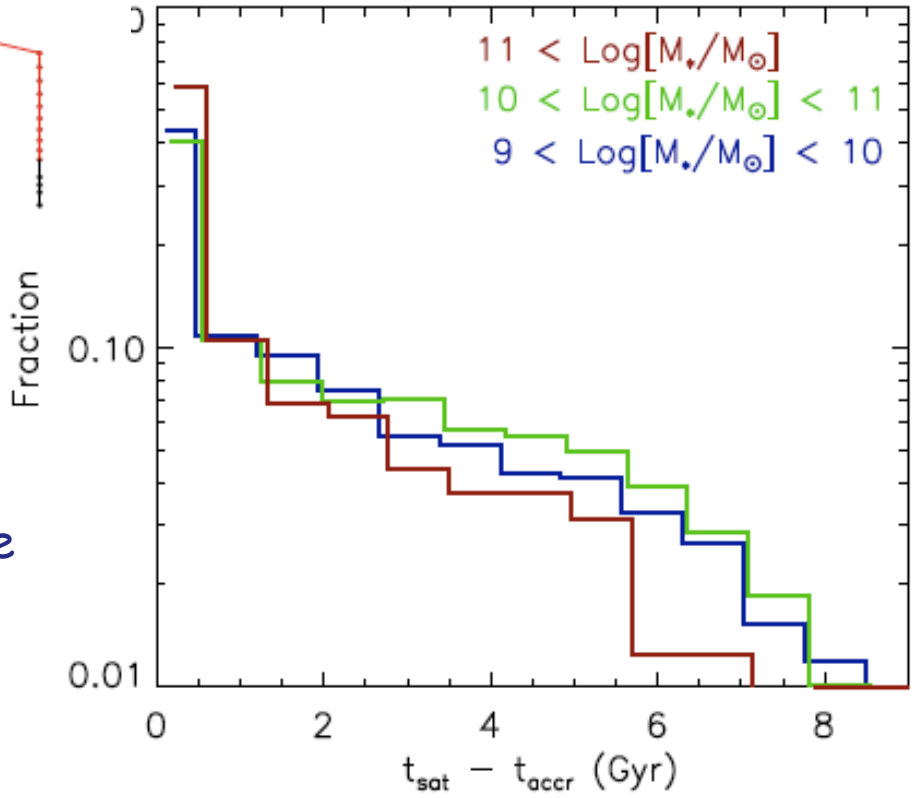
✓ Up-to-date measurements of stellar masses and specific star formation rates obtained by matching the original catalogue to DR7 MPA/JHU data.

✓ N.B. This is work in preparation. Comments are welcome!

Method and definitions

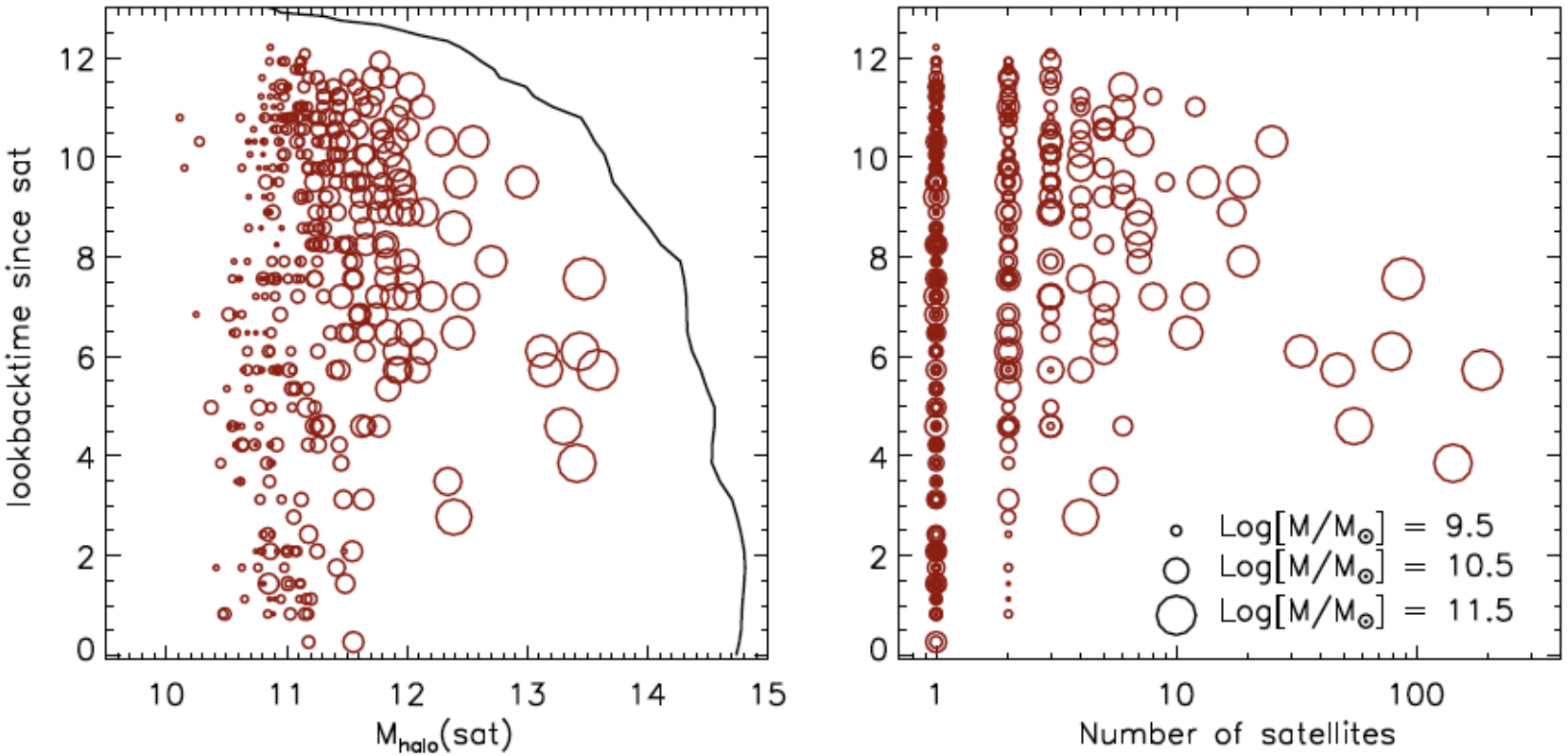


By construction, T_{sat}-$T_{clust} \geq 0$.
For 40-60% of the galaxies the two events happen at the same time. A larger fraction of the massive galaxies are accreted as centrals.



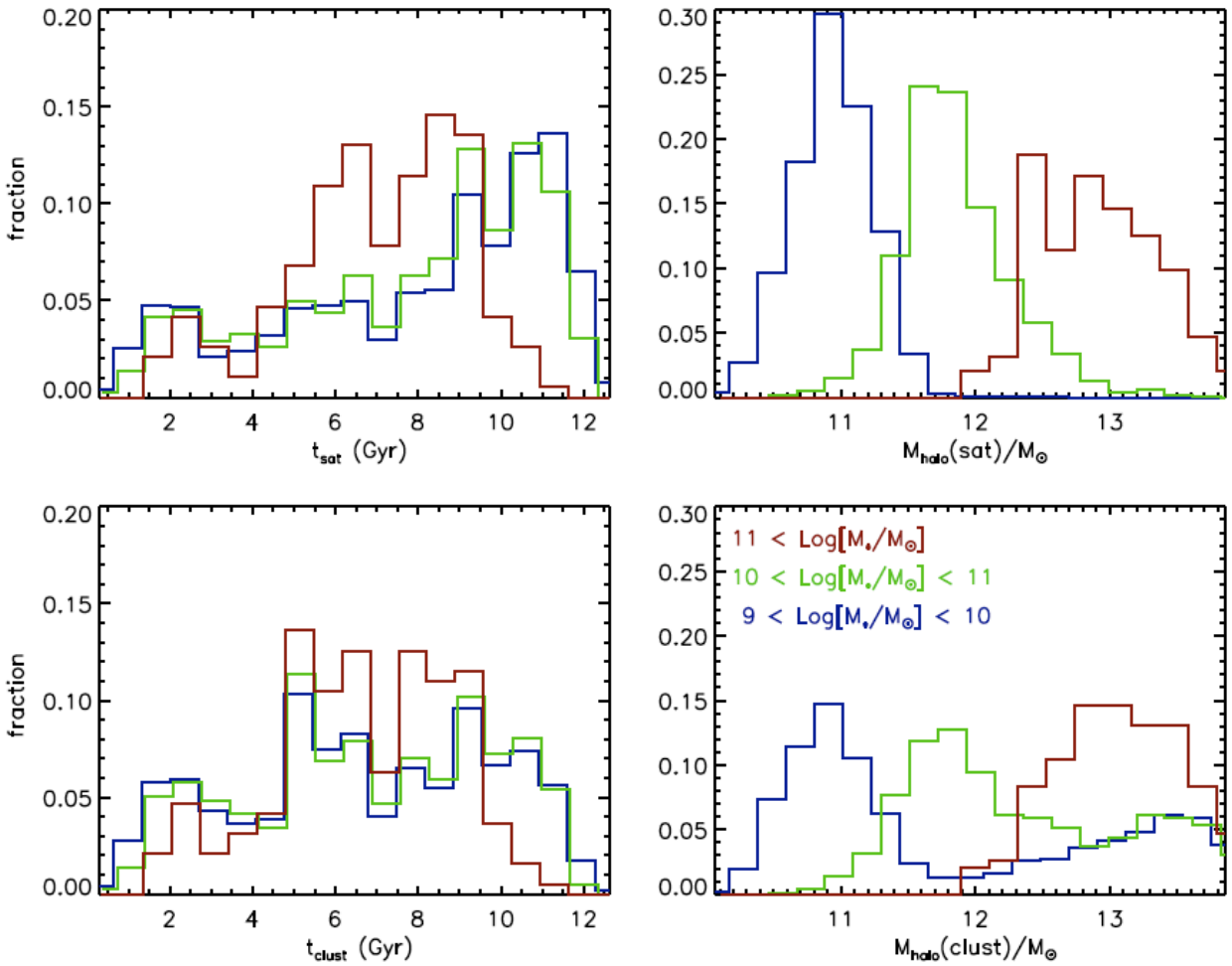
Galaxy history = tracing the main progenitor at each redshift
Two critical times:
(i) T_{sat}: the galaxy becomes satellite of a more massive halo
(ii) T_{clust}: the galaxy falls on the main progenitor of final cluster

The history of cluster galaxies



Galaxies with small stellar mass become satellites at all times, while the (few) most massive galaxies tend to become satellite later, and they are typically accreted when sitting in relatively massive haloes.
N.B. Down to ~4Gyr (z=0.4) the cluster mass grows significantly through the accretion of few relatively massive structures. At lower z, it grows mostly through small structure and diffuse accretion.

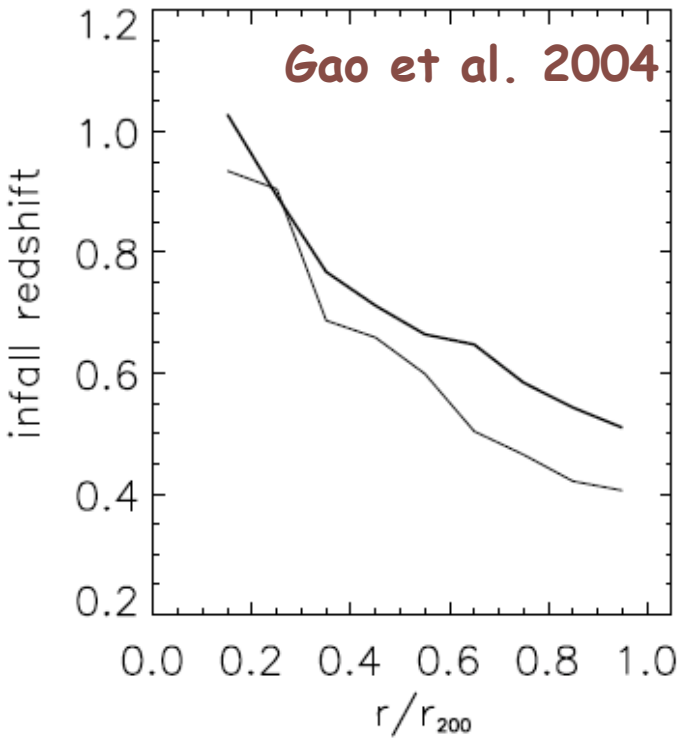
The history of cluster galaxies



Strong correlation between galaxy mass and parent halo mass at T_{sat}. "Bimodal" distribution for low-intermediate mass galaxies at T_{clust}. The two peaks are made up of galaxies accreted as centrals and galaxies accreted when satellites.

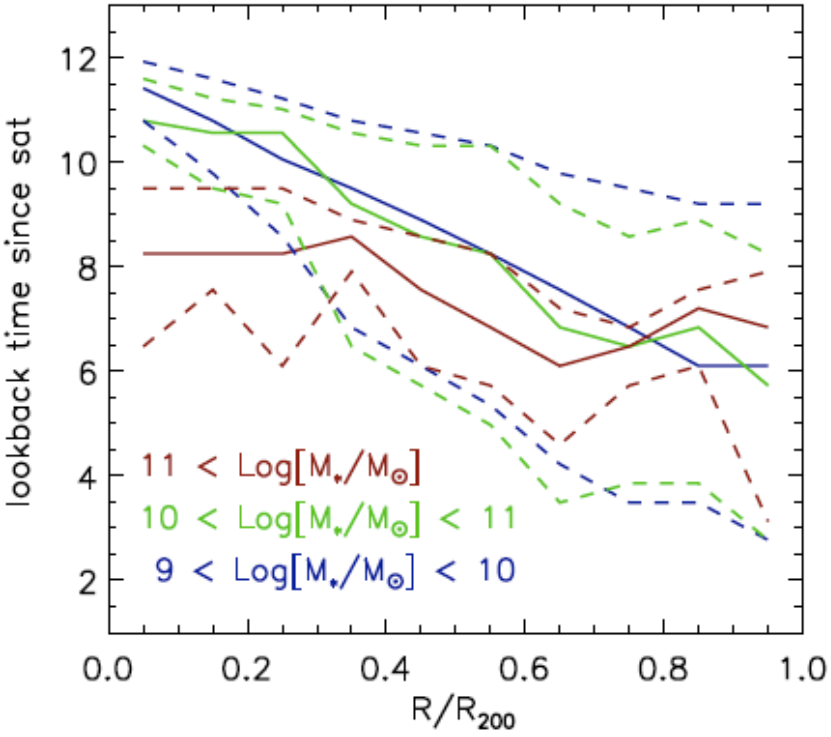
~48% of the galaxies in the lowest mass bin were accreted as satellites; ~43% for intermediate galaxies and ~23% of the most massive ones

Radial dependency

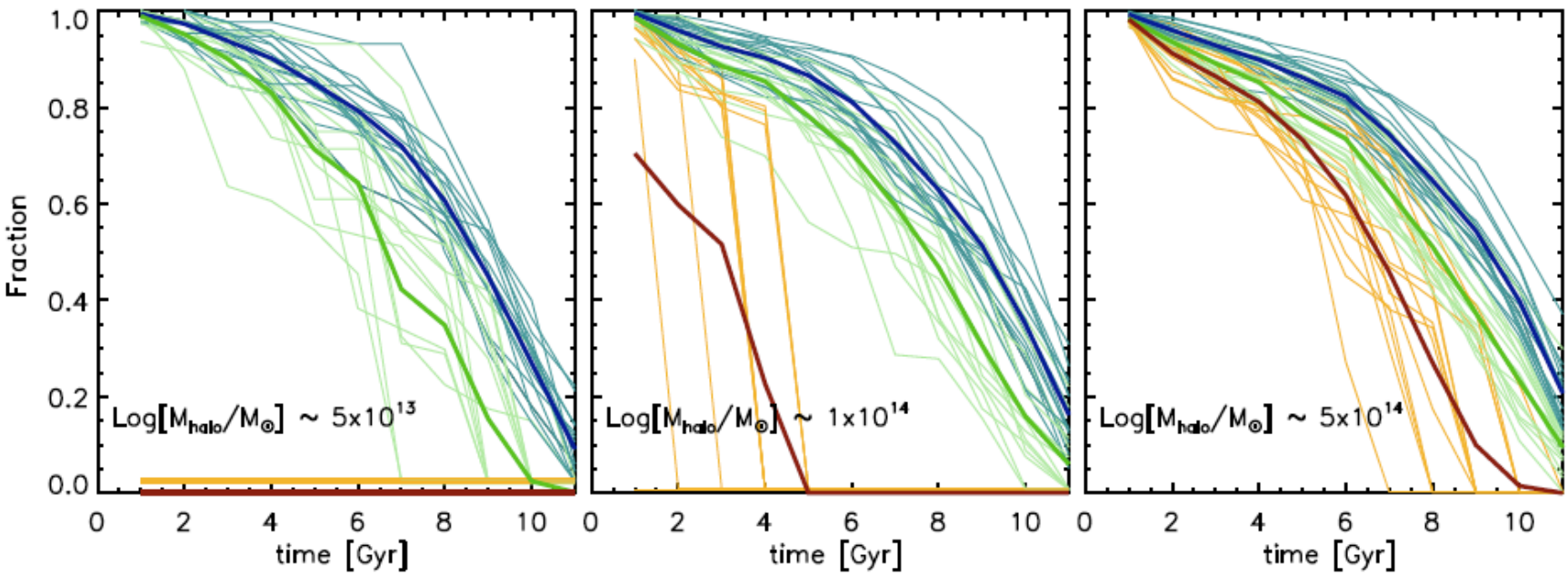


This correlation is also found for cluster galaxies. Therefore, a radial dependence of galaxy properties is (at least in part) natural consequence of the fact that galaxy mixing is incomplete during cluster assembly.

Haloes accreted onto the main progenitor of their parent halo at early times had relatively short orbital periods and have suffered from dynamical friction and tidal stripping for longer times with respect to haloes of similar mass but accreted later.



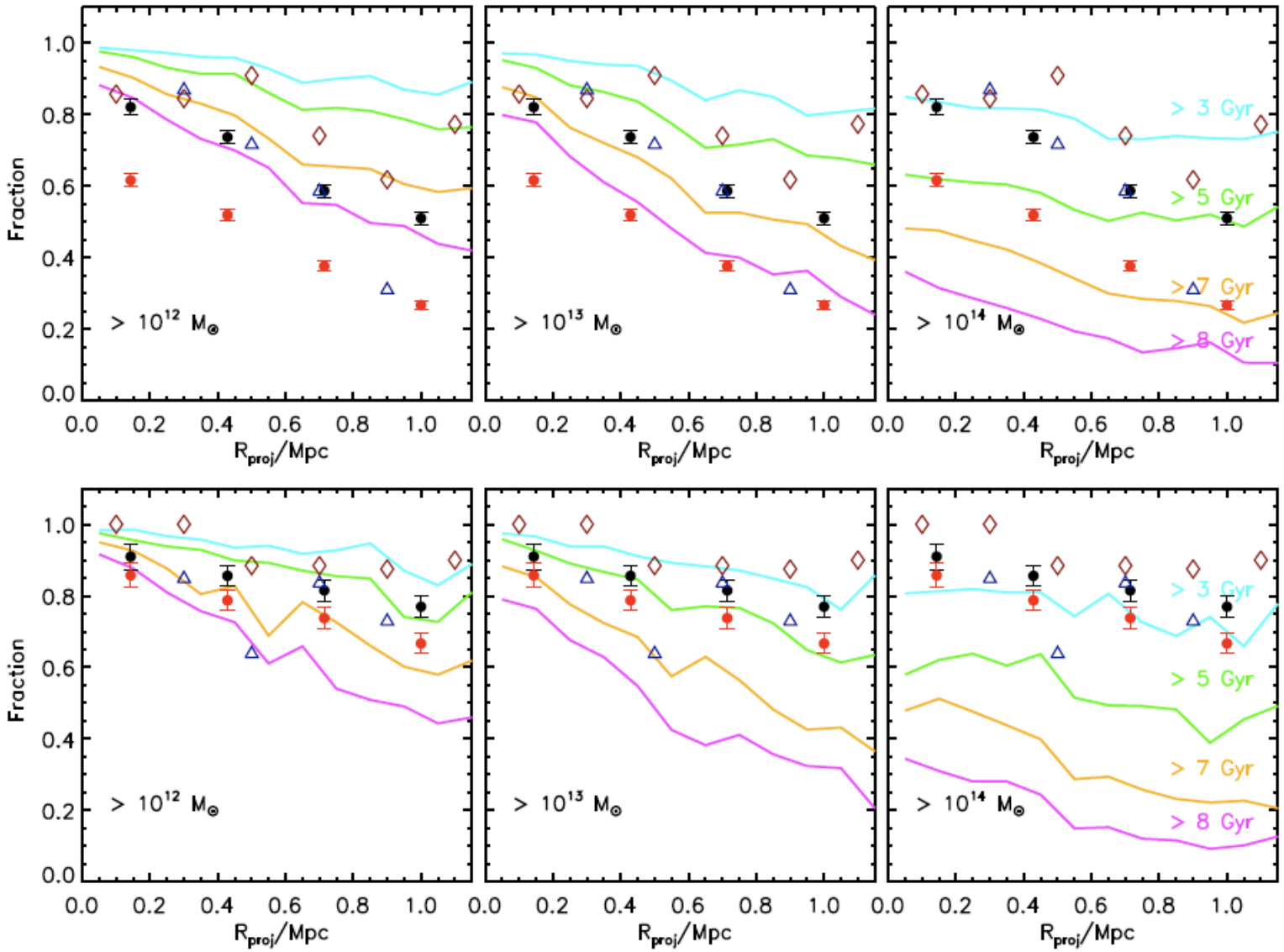
A "history bias"



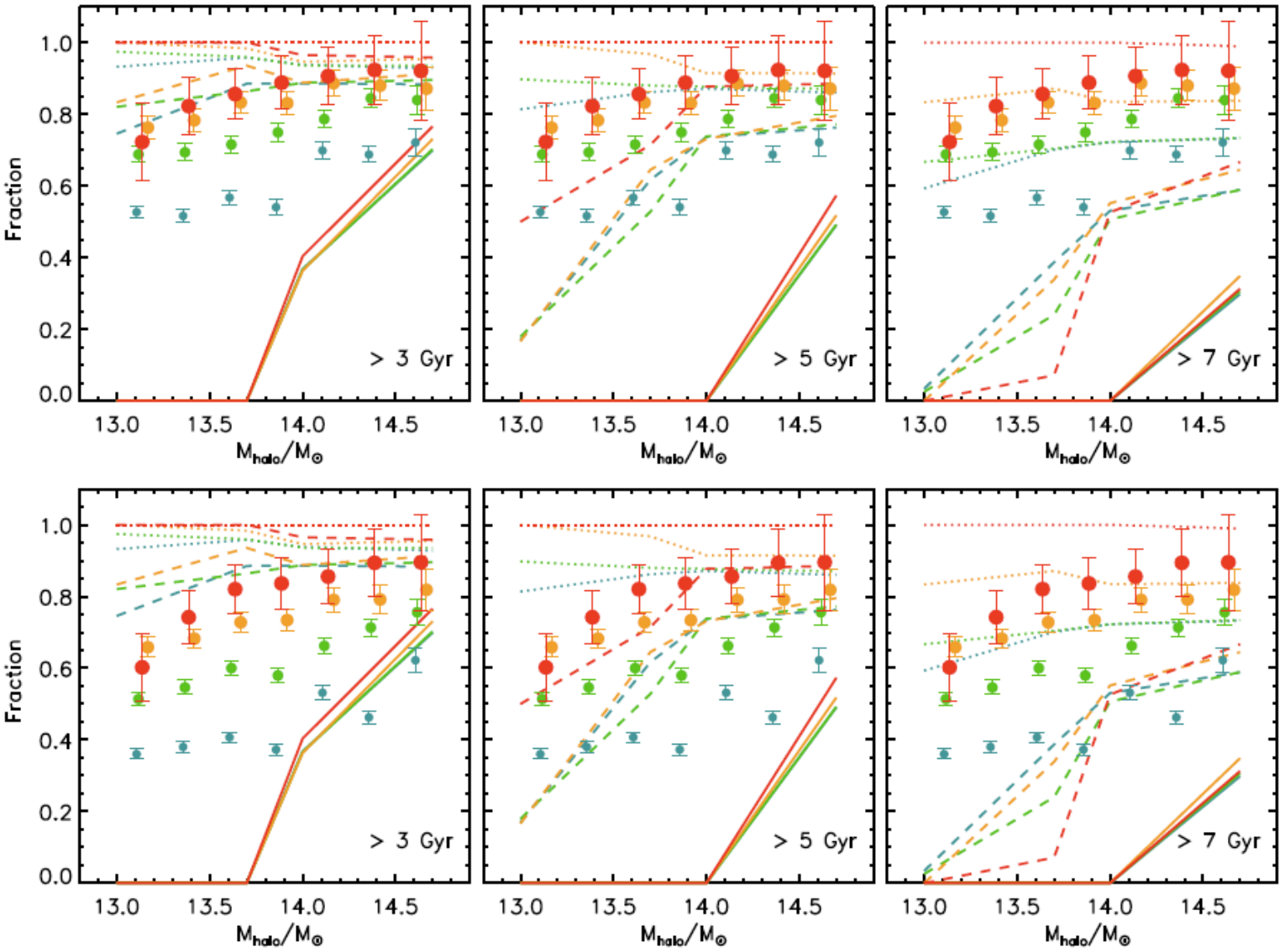
As a consequence of structure formation: the fraction of galaxies that have resided in haloes more massive than M_{halo} for a time longer than T_{halo} decreases when considering more massive haloes and longer time.

Note the large halo-to-halo scatter that can explain (at least in part) the scatter measured for some properties of the galaxy populations of groups and clusters.

Radial trends for passive/red fractions



Mass trends for passive/red fractions



Where and how galaxies are quenched?

Rough halo mass/timescale that reproduces both the passive fractions as a function of cluster centric distance and as a function of halo mass:

~5-7 Gyr in haloes more massive than 10^{13} M_{sun}

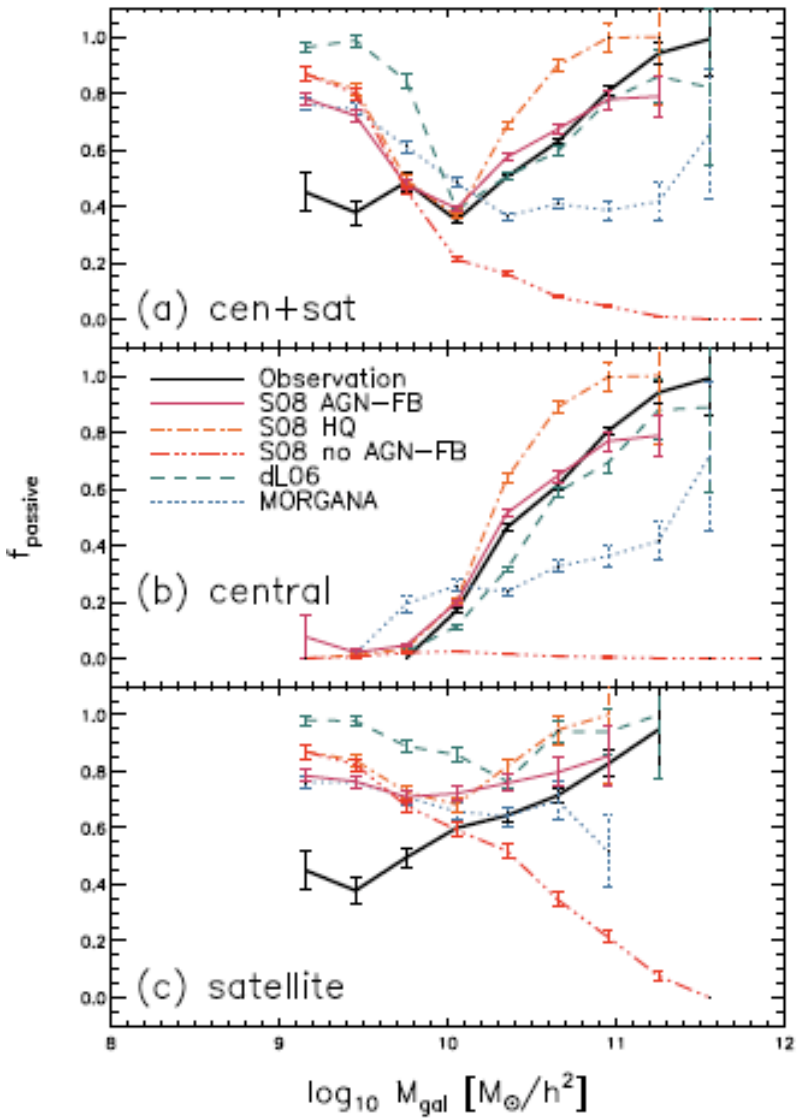
But "mass quenching" ($\log(M/M_{sun}) > 10.5$) and "environment" quenching ($\log(M/M_{sun}) < 10.5$)...

One can define a "probability to be quenched by environment":

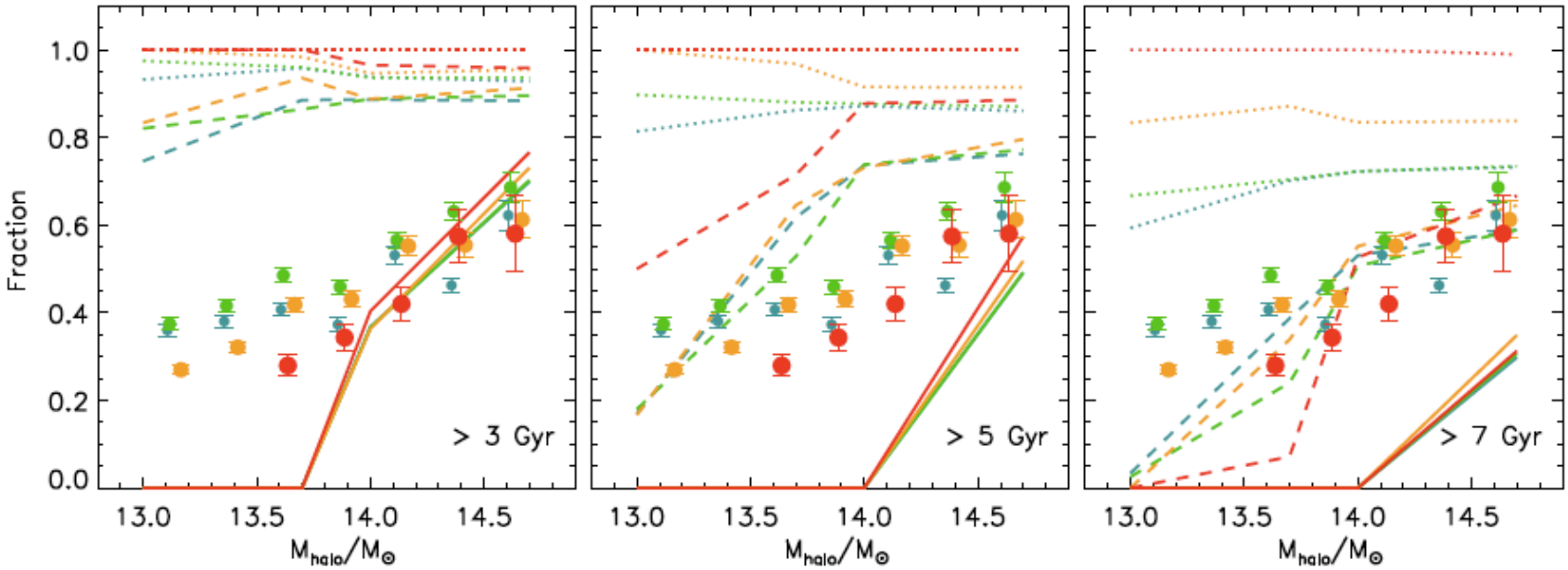
f(r|sat) – f(r|cent) / f(b|cent)

van den Bosch et al. 2008

Kimm et al. 2009



The environmental quenching efficiency

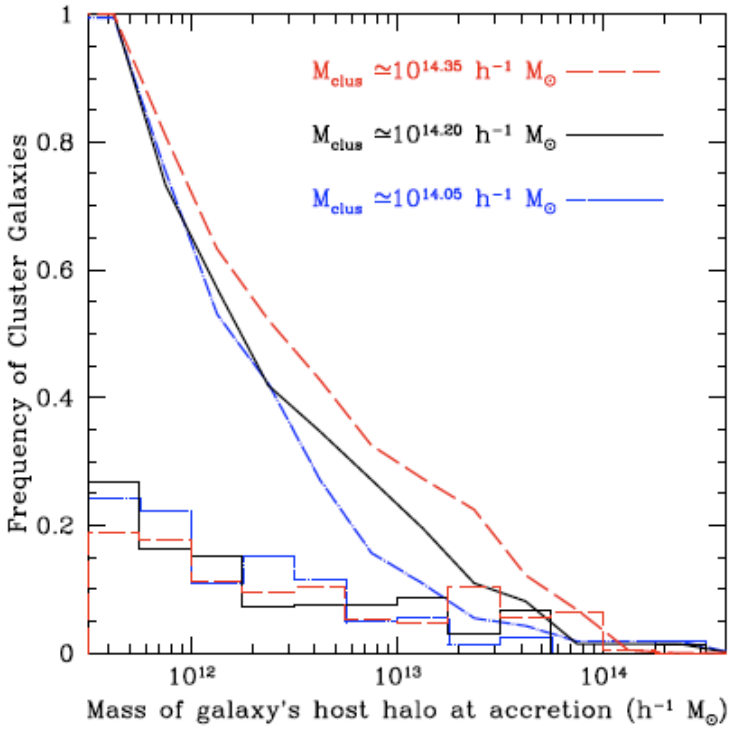


van den Bosch et al. (2008) find that "satellite quenching affects roughly 40 per cent of all galaxies that are still blue at their accretion time, roughtly independent of their stellar mass".

The fraction of satellite affected by environment varies (albeit weakly) with halo mass, increasing from ~40% to ~60% over the halo mass range considered.

Critical environment given by 10^{13} M_{sun} haloes over 5-7 Gyr time-scale

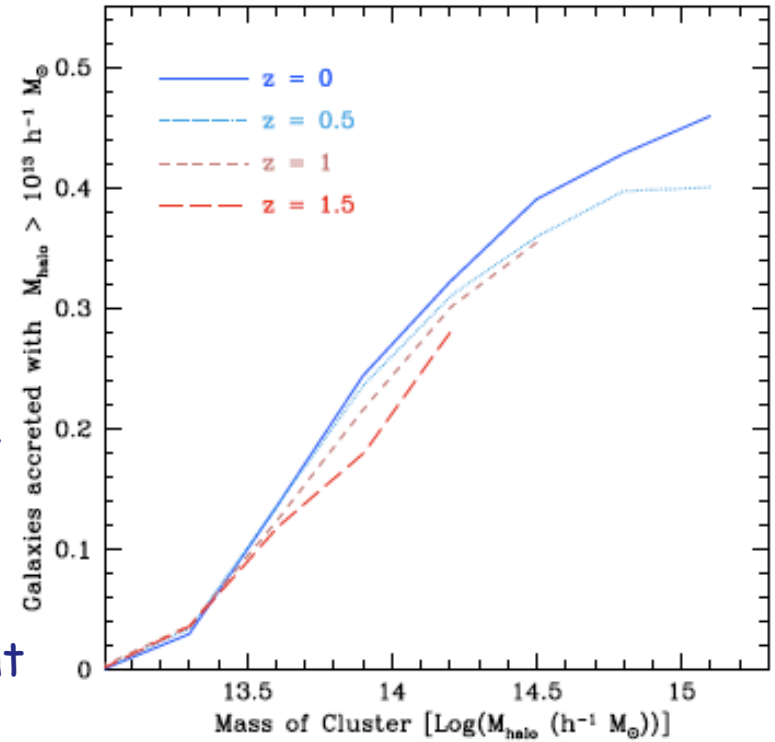
Is pre-processing in groups important?



Berrier et al. 2009

For haloes with mass ~10^{14} M_{sun}, Berrier et al. estimate that less than ~12% of galaxies were accreted in haloes with 5 or more galaxies while McGee et al. find that ~30% of galaxies accreted in haloes with mass larger than $10^{13} M_{sun}$

McGee et al. 2009



Main reason for disagreement is the use of two different "events" corresponding to the "accretion".
Pre-processing might play an important role. Important to study the environment corresponding to 10^{13} M_{sun} haloes.

A few more thoughts

✓ Caveat: our models are known to over-predict the numbers of low to intermediate mass galaxies, but we are using fractions….

✓ Note that our results are valid on "average", but there is a large cluster to cluster variation, and in reality suppression of activity probably occurs in a "probabilistic" fashion

✓ The ~10^13 Msun environment is important but very few numerical studies have been dedicated to this mass regime (but see Villalobos et al. submitted)

✓ Limited our analysis to the low-z Universe. High redshift data are going to add strong constraints on the time-scale and environment of galaxy transformations (work in progress…)

✓ We have worked in a "theory space" (mass of the halo). Need to extend the analysis using observer-like definitions of environment (work in progress…).