Modeling the formation of cluster galaxies: recent progress and challenges

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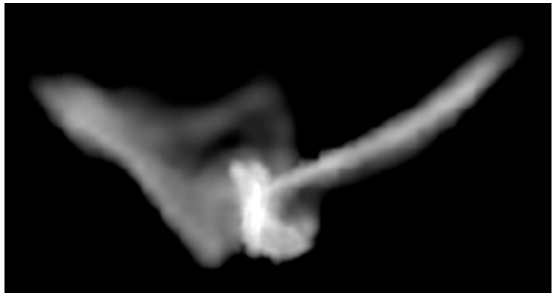
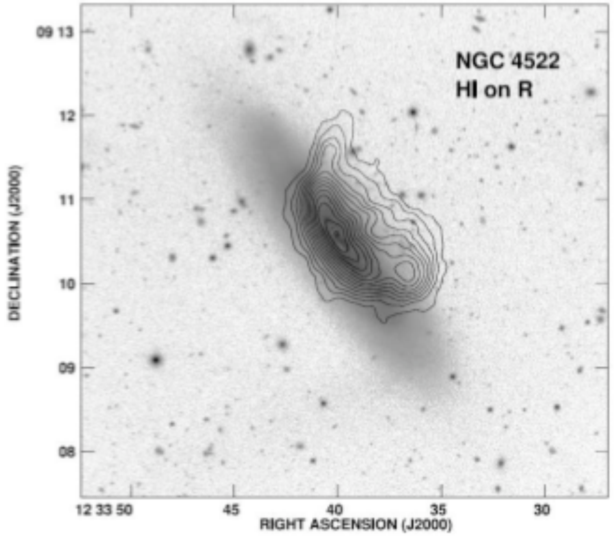
OSSERVATORIO ASTRONOMICO TRIESTE

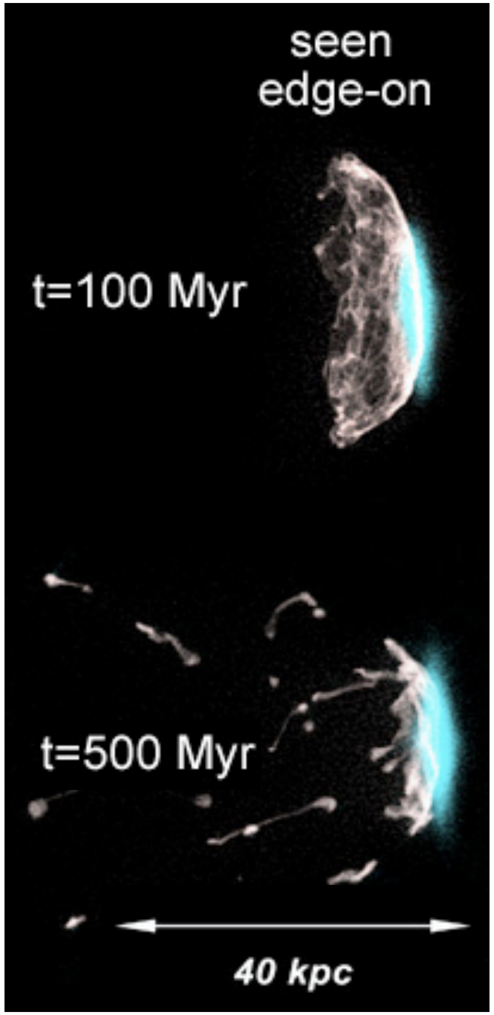
"Nurture"

Moore et al. 1996





Kenney et al. 2004



Kronberger et al. 2008

(i) Interaction with other cluster members and/or with the cluster potential
(ii) Interactions with the hot gas that permeates massive galaxy systems.
The influence of these processes and their characteristic time-scales have been studied using detailed numerical simulations.

Physical mechanisms

Galaxy mergers:
e.g. Negroponte & White '82, Barnes & Hernquist '91, '92, '96 Mihos & Hernquist '94, '96,

WHERE : field + low velocity dispersion groups
WHAT : strong internal dynamical response

Harassment:
e.g. Spitzer & Baade '51, Richstone '76, Farouki & Shapiro '81, Moore et al. '96, Moore et al. '98

WHERE : in massive clusters
WHAT : some damage but less than mergers – at least on luminous members

Gas stripping:
e.g. Gunn & Gott '72, Cowie & Songaila '77, Nulsen '82, Quilis et al. '00

WHERE : very central regions of clusters
WHAT : suppression of SF, indirect influence on morphology

Strangulation:
e.g. Larson, Tinsley & Caldwell '80, Balogh, Navarro & Morris '00

WHERE : any "larger" structure
WHAT : suppression of SF, indirect influence (time-scale longer than gas stripping?)

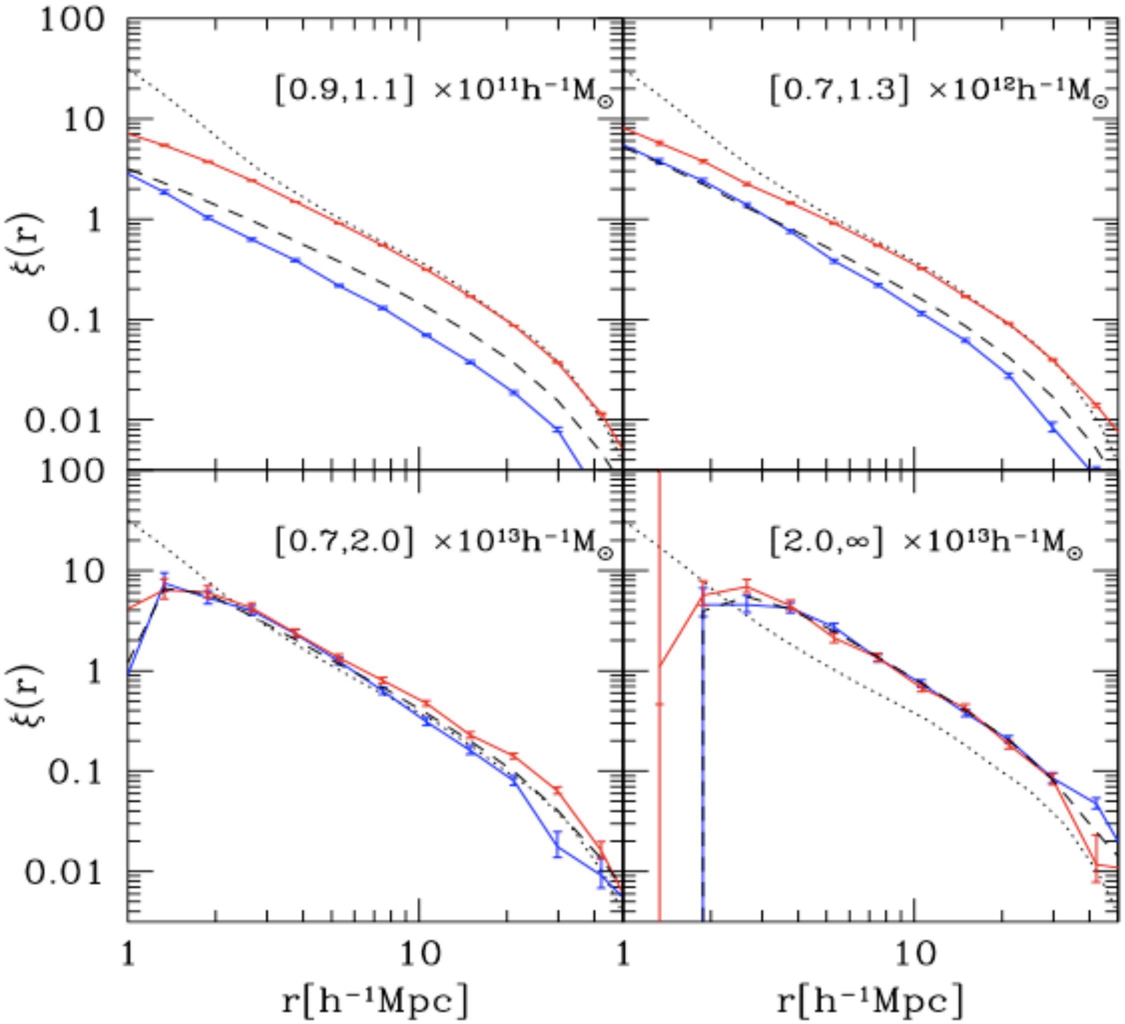
AGN heating:
e.g. Churazov et al. '01, Brueggen et al. '02, Della Vecchia et al. '04, Sijacki & Springel '06

WHERE : centre of massive groups/clusters
WHAT : suppression of cooling flows

Cannibalism:
e.g. Ostriker & Tremaine '75, White '76, Makumuth & Richstone '84, Merritt '85

WHERE : groups and clusters
WHAT : formation of BCGs?

"Nature"



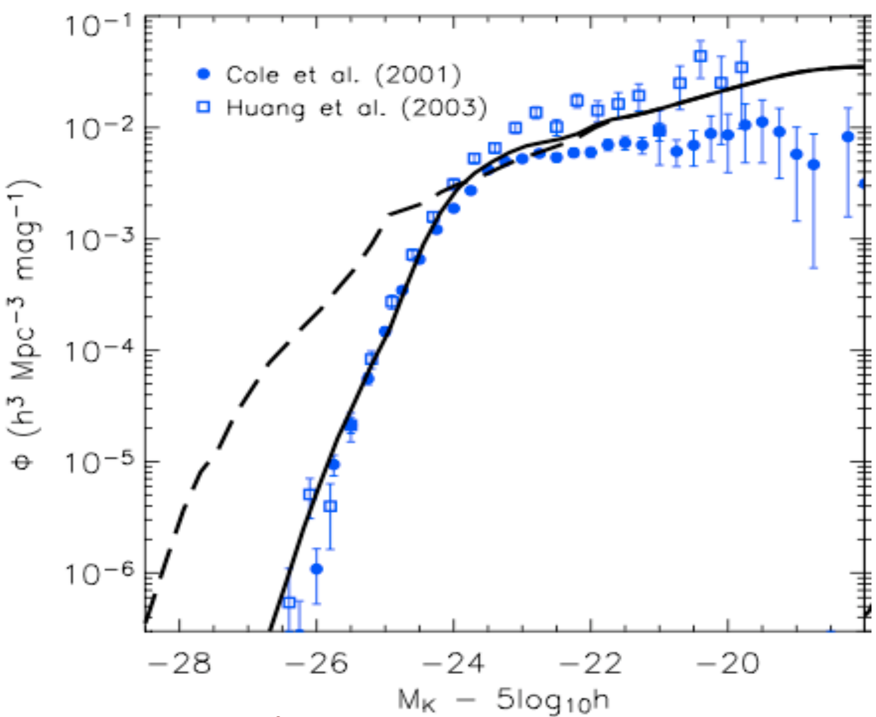
Gao et al. 2005

Recent numerical work has shown that halo properties (e.g. spin, concentration, shape) show environmental dependencies: haloes in over-dense regions form statistically earlier and merge more rapidly than haloes in regions of the Universe with average density.

Note that, at face value, these results invalidate the basic assumption of the HOD approach, i.e. that the galaxy content of a dark matter halo depends only on its mass.

The "radio-mode" feedback

An crucial ingredient to avoid an excess of massive galaxies, and to keep the stellar populations of these galaxies old. Ensemble-averaged power sufficient to offset cooling, but not clear how this happens.

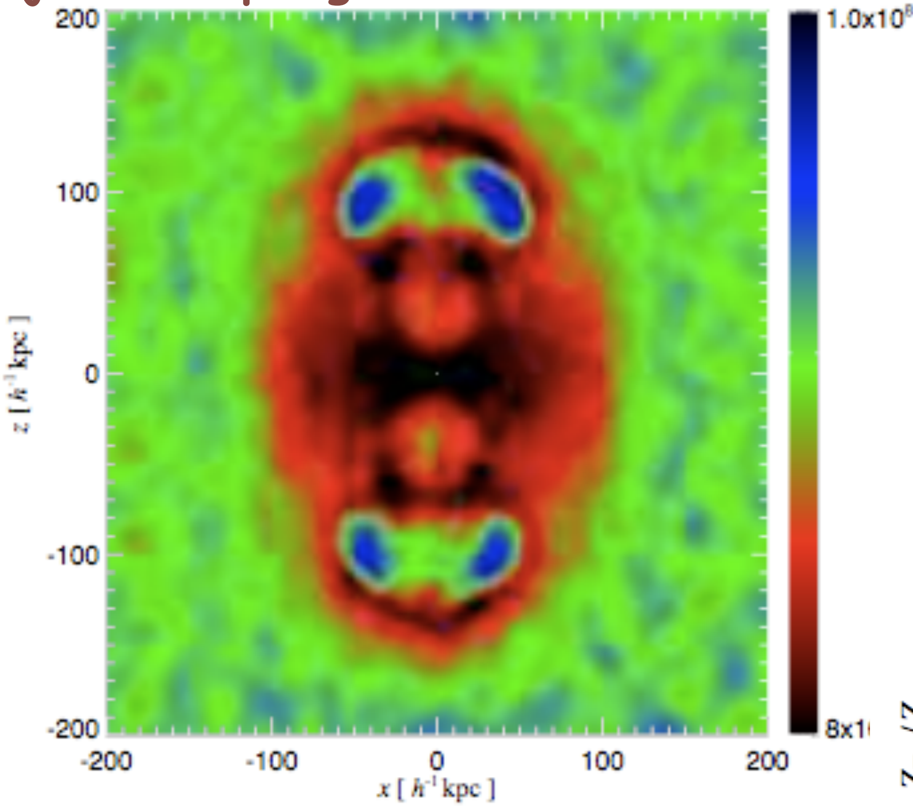


Croton et al. 2006

Radio galaxies regulate the cooling flows? (Tabor & Binney 1993)
Supported by X-ray observations and demographics of radio-loud galaxies (Best et al. 2007)

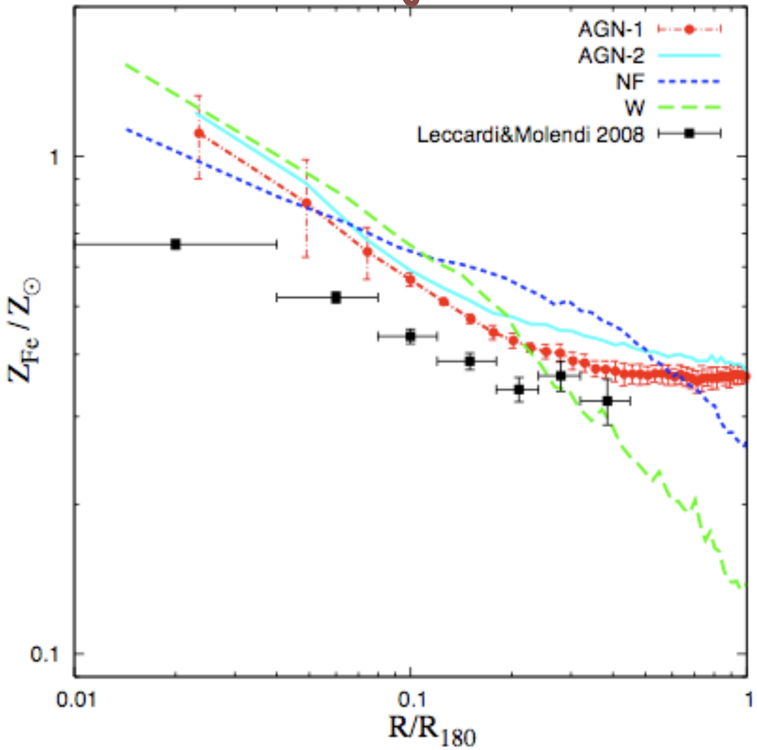
The "radio-mode" feedback

Sijacki & Springel 2006



Detailed simulations are carried out by different groups. These have shown that the outcome of this feedback mode depends critically on a number of unknown parameters (e.g. duty cycle, gas viscosity, geometry of the energy injection)

Fabjan et al. 2009

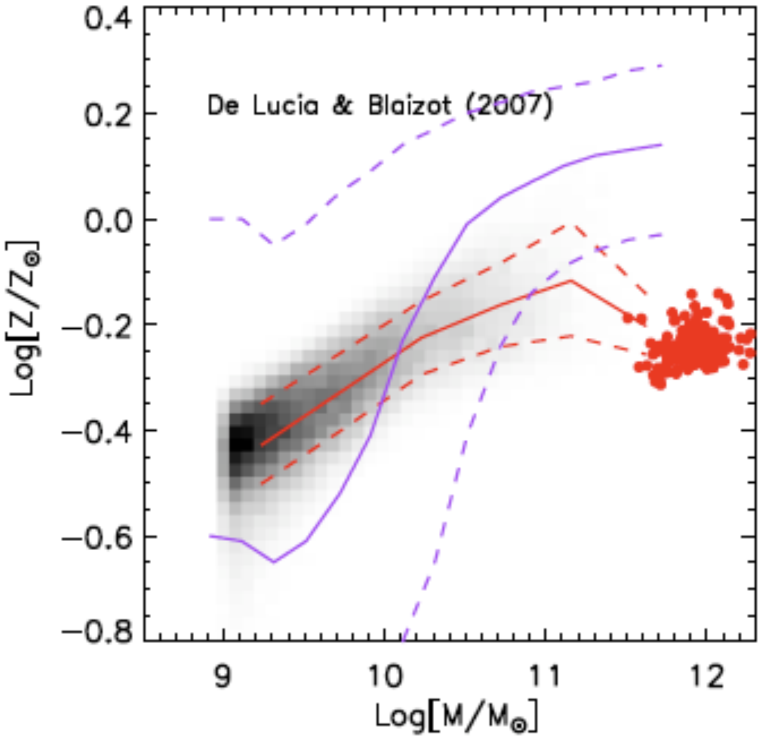


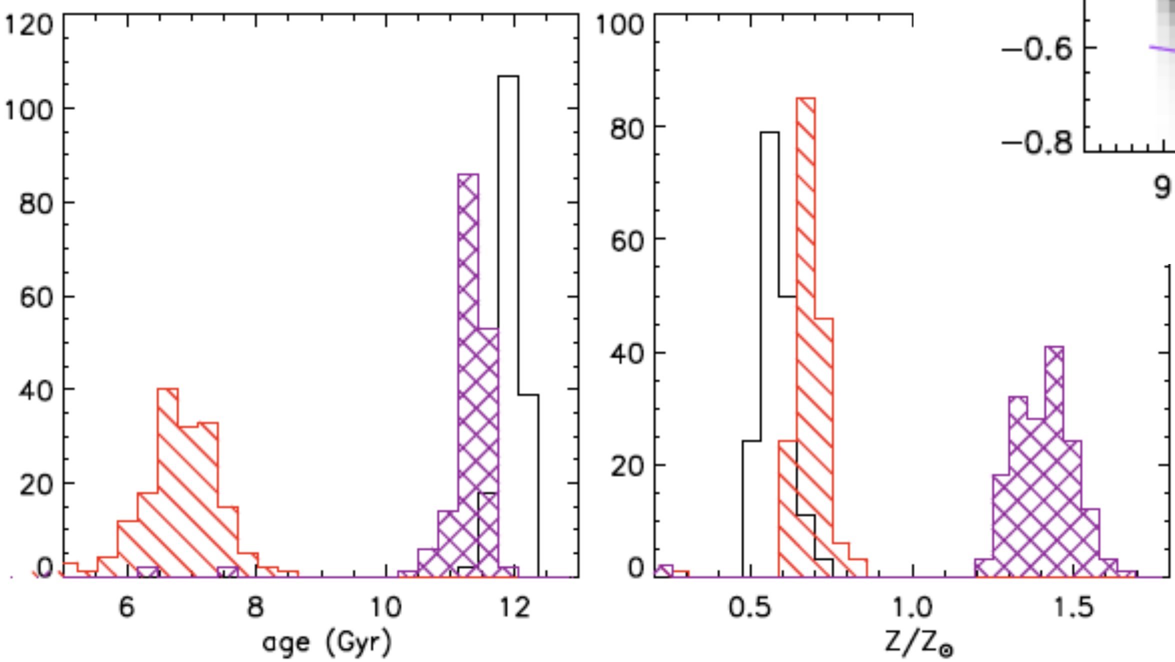
Current numerical implementations result in an efficient extraction of enriched gas from star forming regions at high-z. This leads affects e.g. the metallicity pattern of the ICM

The stellar metallicity of BCGs

De Lucia & Borgani 2012

While current models successfully reproduce the old stellar populations observed for massive galaxies, they all fail in reproducing their observed chemical abundances. This appears to be the case also in hydrodynamical simulations (**McCarthy et al. 2010**).



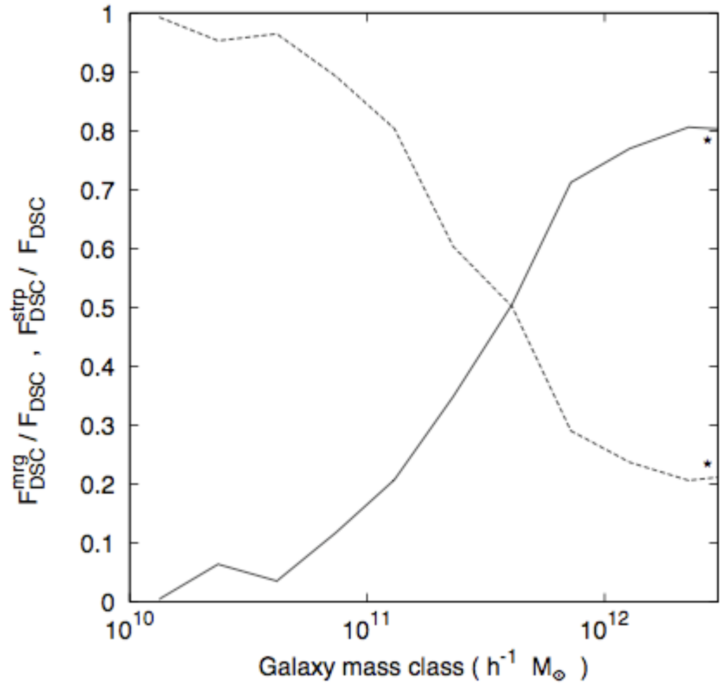


Switching off the radio mode would increase only slightly the metallicity of these galaxies, and make them significantly younger.

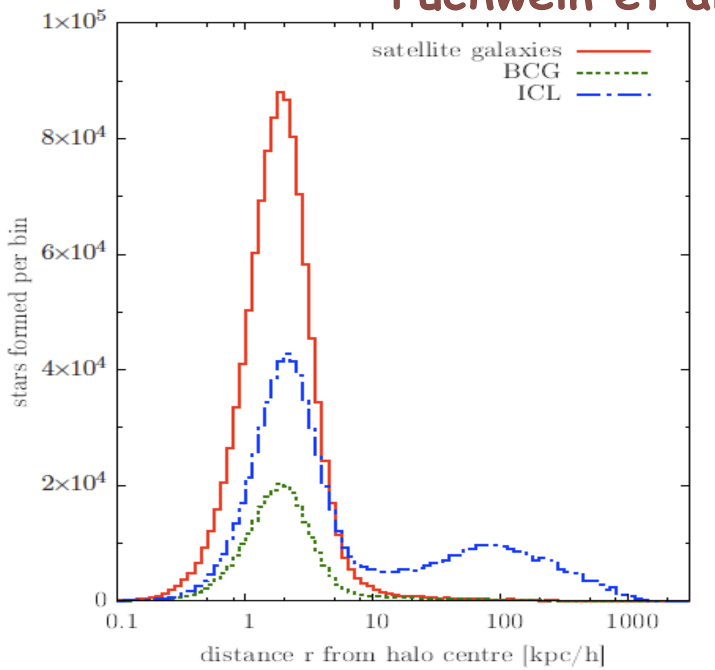
The diffuse stellar component

Formation of DSC parallels that of the BCGs. In hydro simulations, most of it comes from particles unbound during mergers, with a minor fraction coming from tidal stripping of satellites. Unfortunately, simulation results do not converge: increasing resolution leads to increasing ICL fractions.

Murante et al. 2007

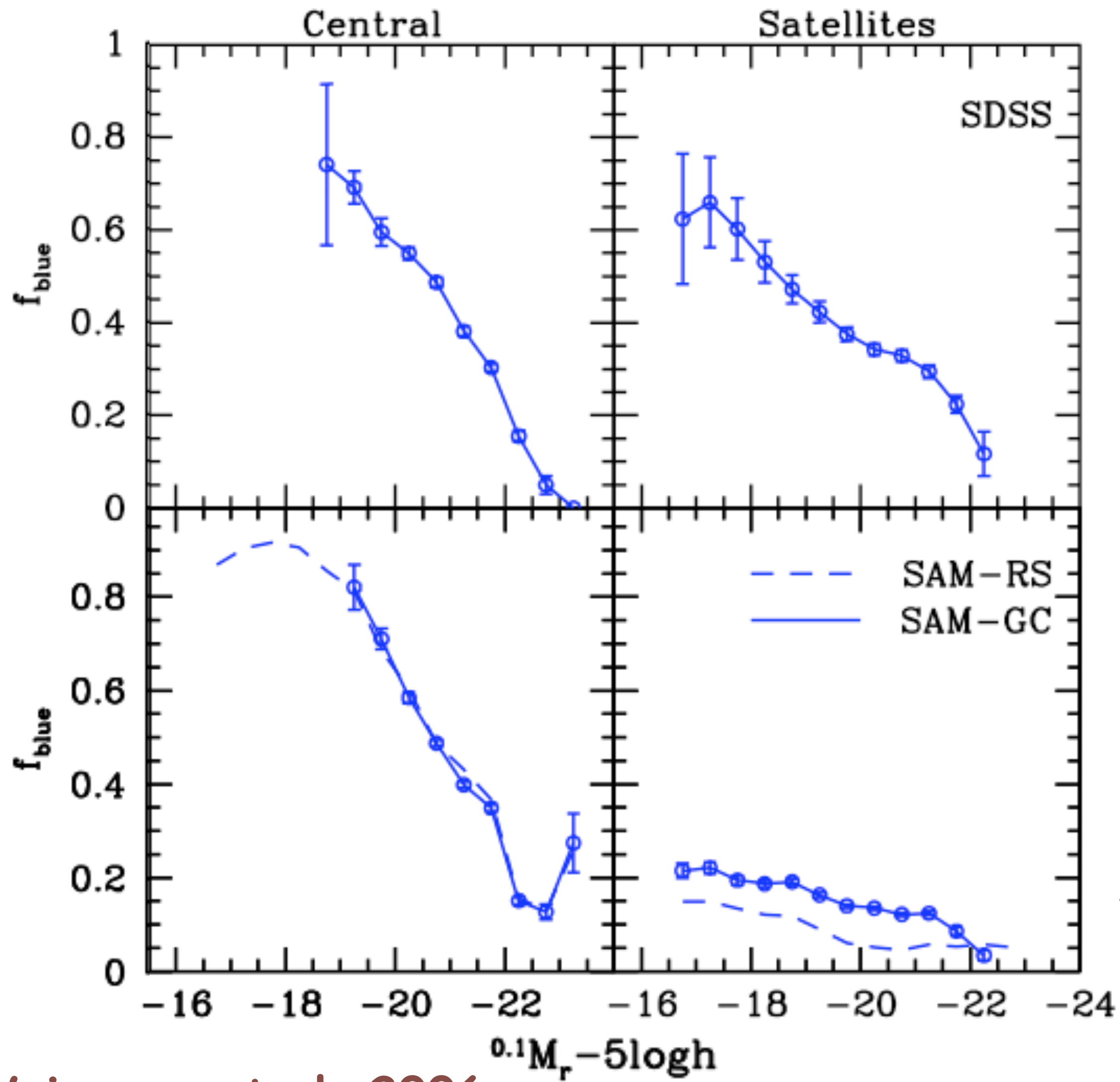


Puchwein et al. 2010



A significant fraction of DSC (up to 30%!) forms in cold gas clouds stripped from infalling structures. Not clear if (and how much of) this `intra-cluster star formation' is just due to spurious numerical effects (e.g. fluid instabilities might be able to destroy these clouds and reduce this contribution).

The satellite galaxy population



Weinmann et al. 2006

The fraction of blue (satellite) galaxies in the models is below the observational data, more so in low-mass haloes.

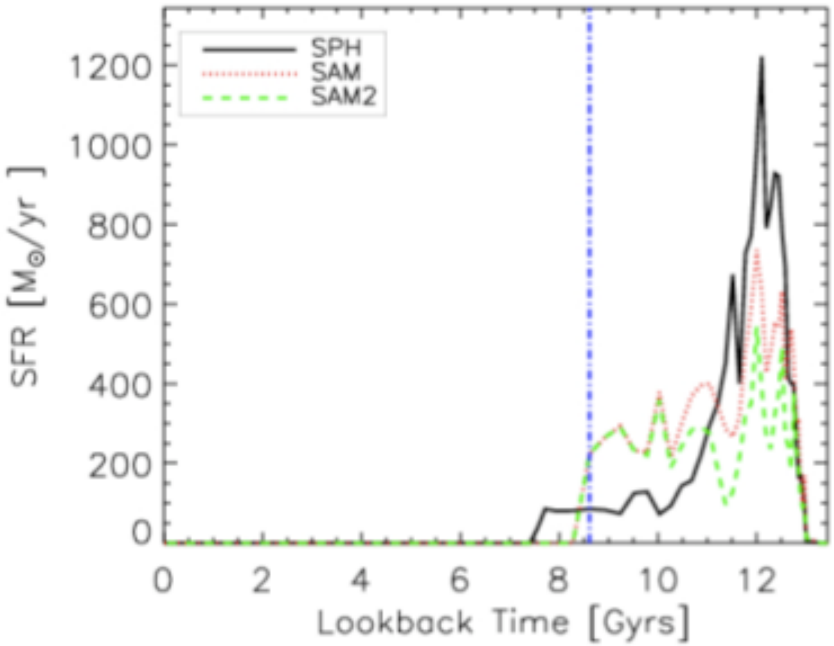
It has been shown that this problem is shared by all models recently published (see e.g. Fontanot et al. 2009).

Is this due to an over-simplified treatment of the "strangulation"?

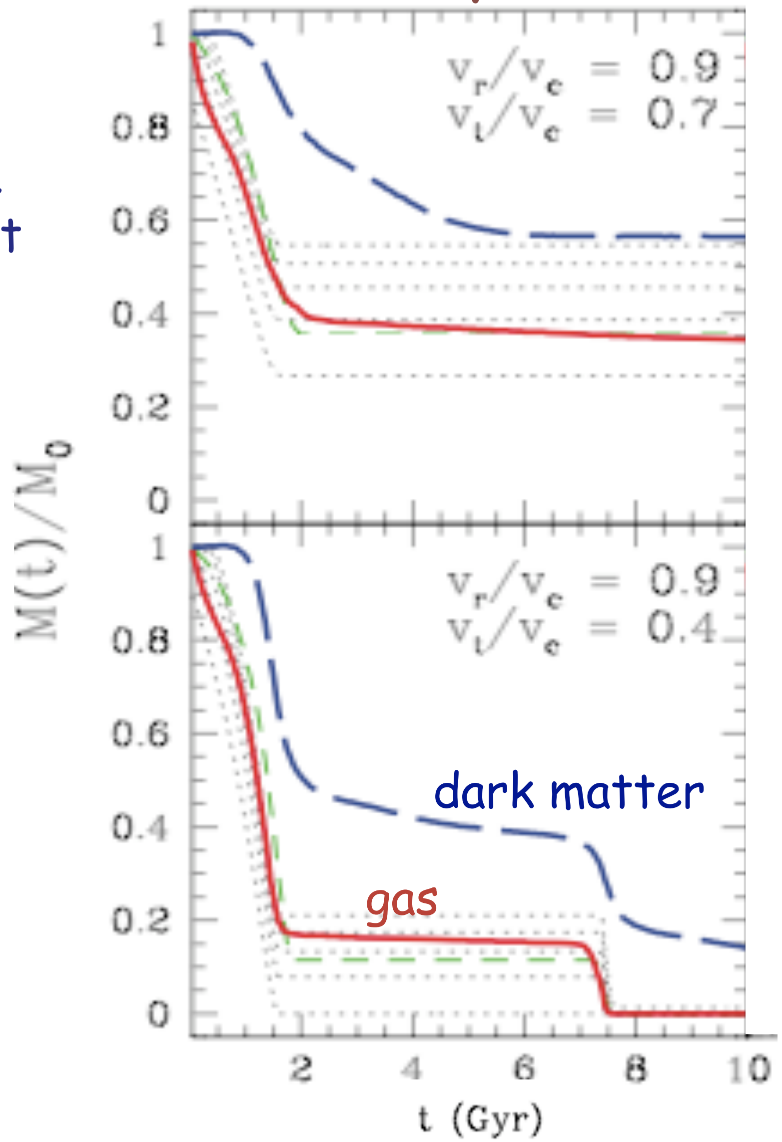
The stripping of the hot reservoir

Strangulation usually assumed to be instantaneous. This implies a fast transition from the active to passive phase (also due to a strong supernovae feedback). Recent studies suggest that the stripping of hot gas occurs on longer time-scales, but results from simulations are not conclusive.

Saro et al. 2010

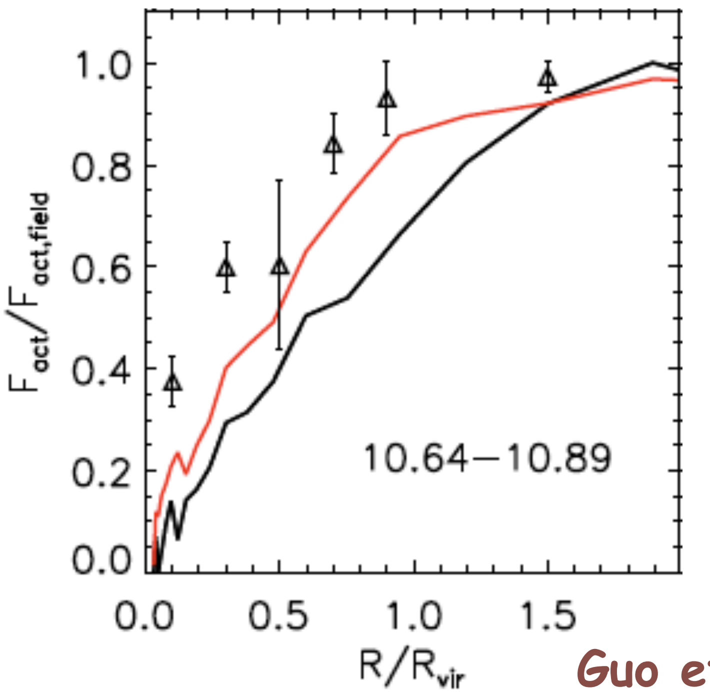


McCarthy et al. 2008



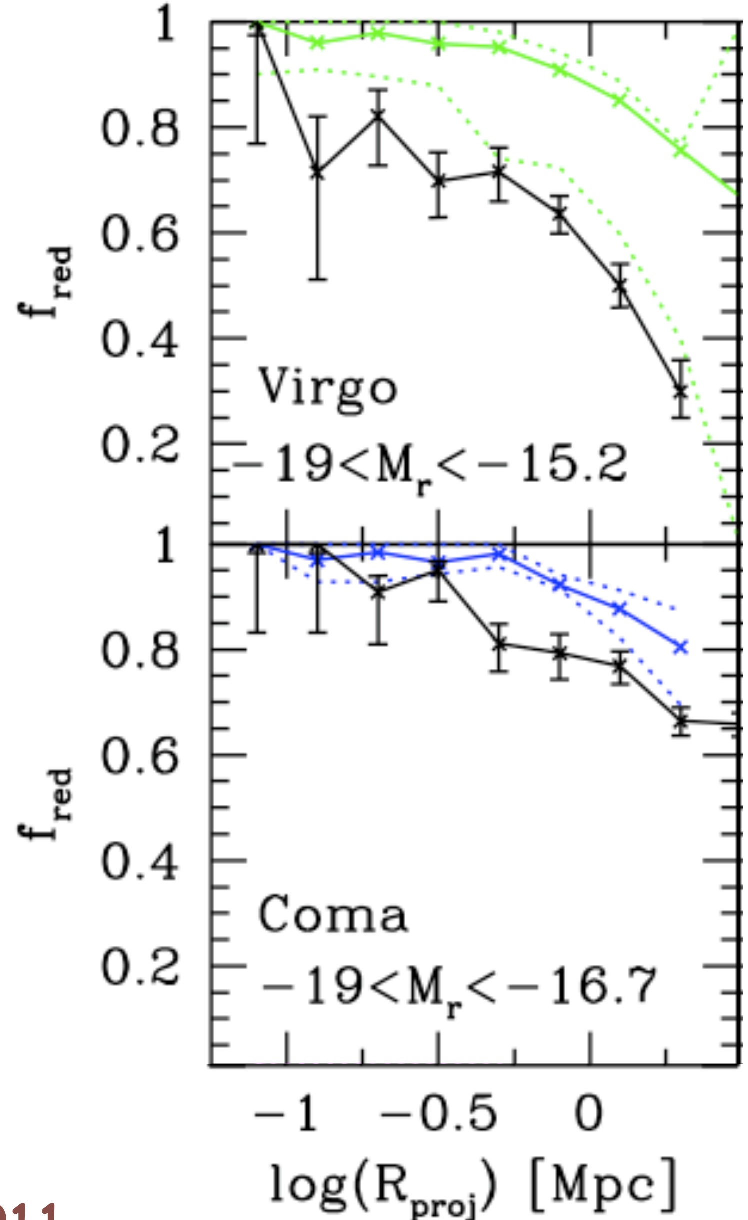
The colours of satellites

More recent models assume a non-instantaneous stripping of hot material. This material can cool on satellite galaxies and keep their star formation on for longer times making them bluer. This improves the agreement with observational data which is, however, not very good yet.



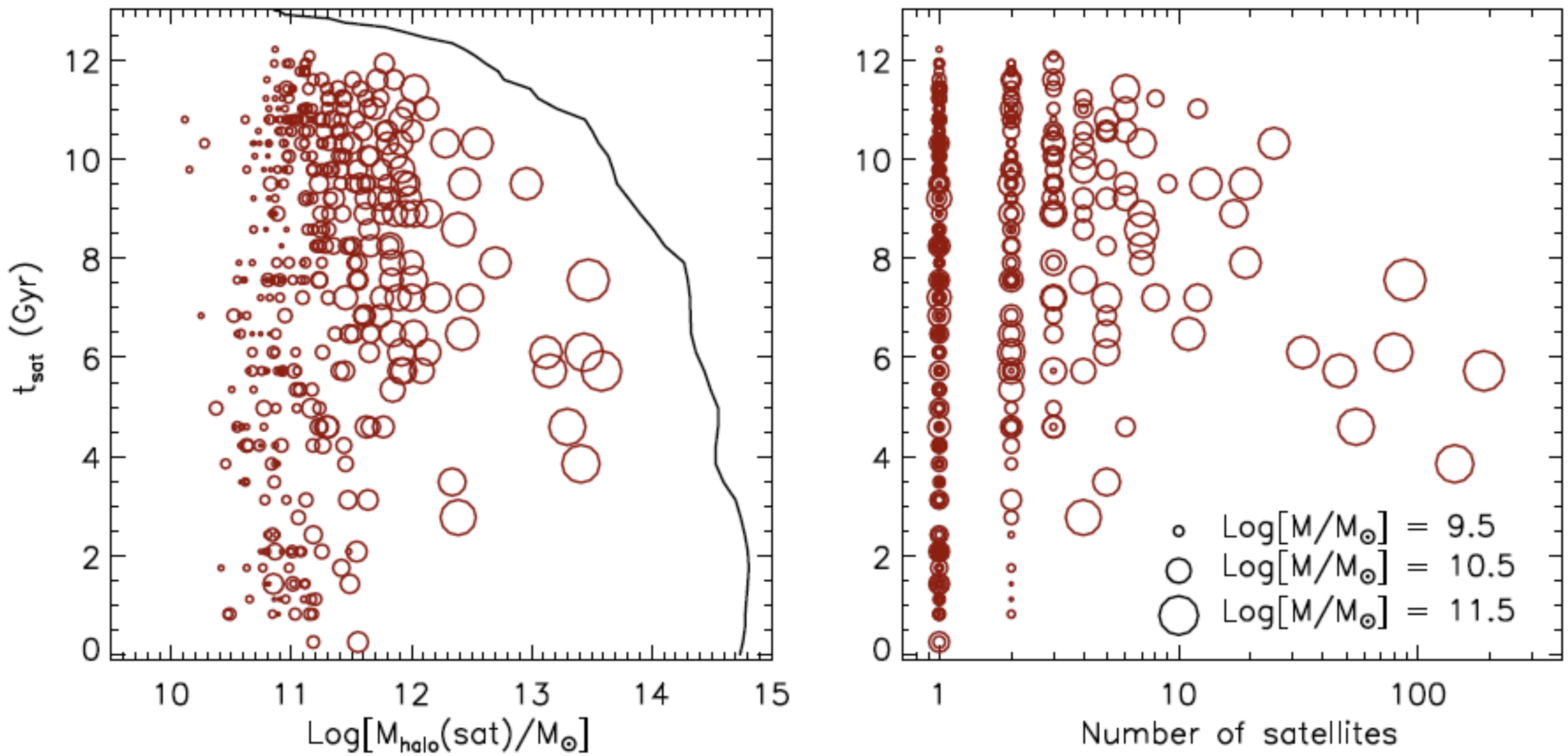
Guo et al. 2011

Weinmann et al. 2011



The history of cluster galaxies

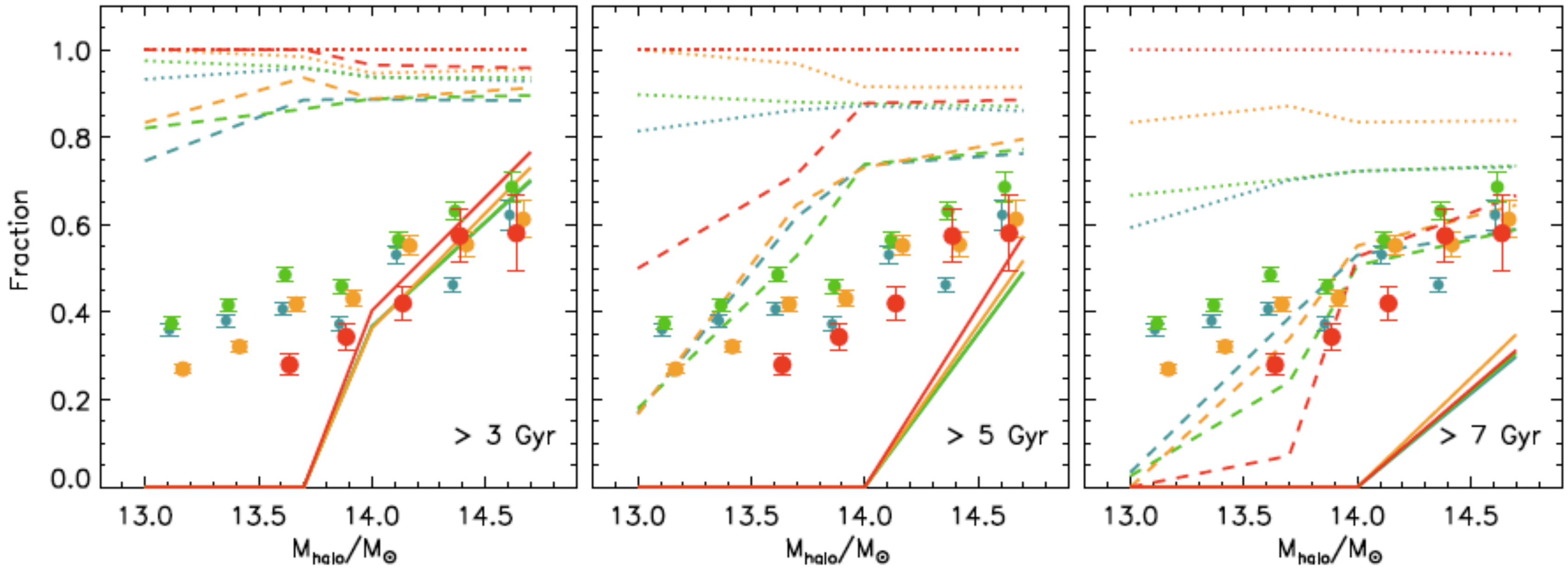
De Lucia et al. 2012



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 ~4 Gyr (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 environmental quenching efficiency

De Lucia et al. 2012



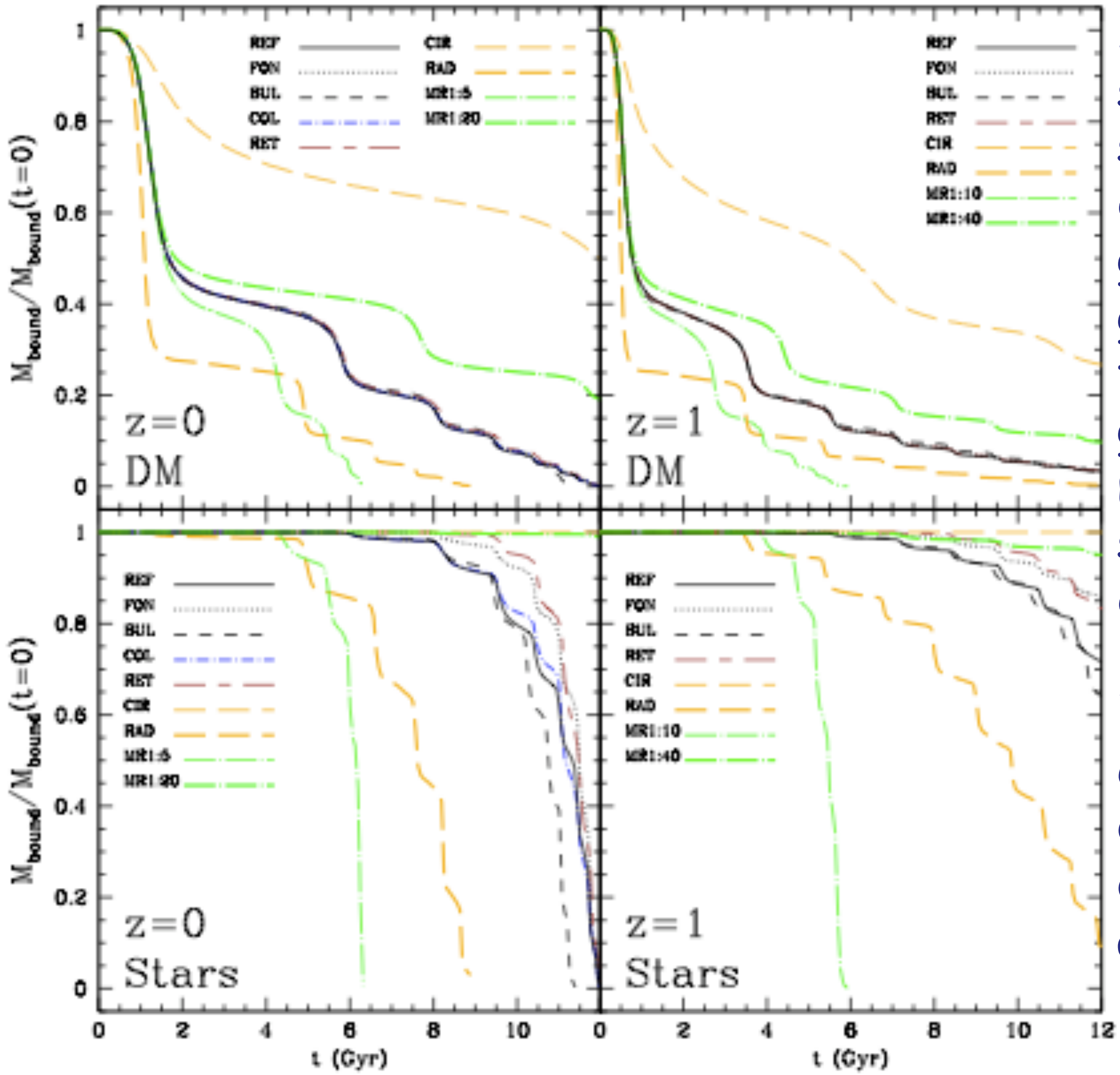
Define a "probability to be quenched by environment":

f(r|sat) – f(r|cent) / f(b|cent) (van den Bosch et al., 2008)

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

The importance of group environment

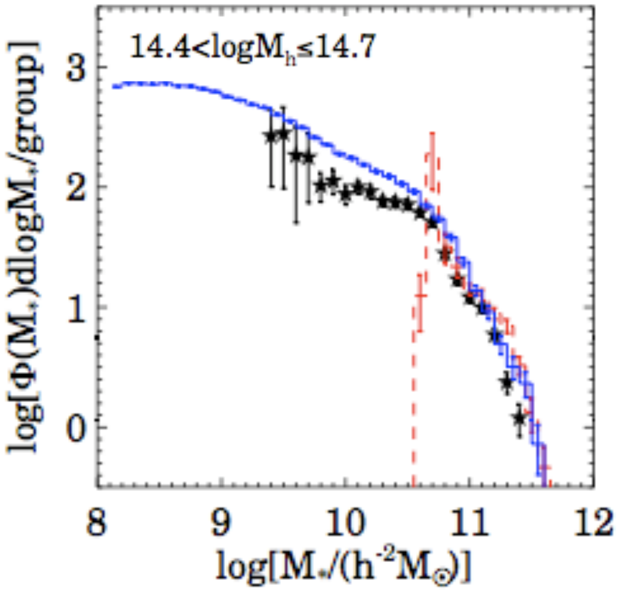


A series of numerical simulations aimed to study the evolution of a disc galaxy within the global tidal field of a group environment. Both the disc galaxy and the group are modelled as multi-component N-body systems composed of dark matter and stars.

Work in progress to evaluate the influence of interactions with other group galaxies, and gas.

Villalobos et al. 2012

Too many satellites

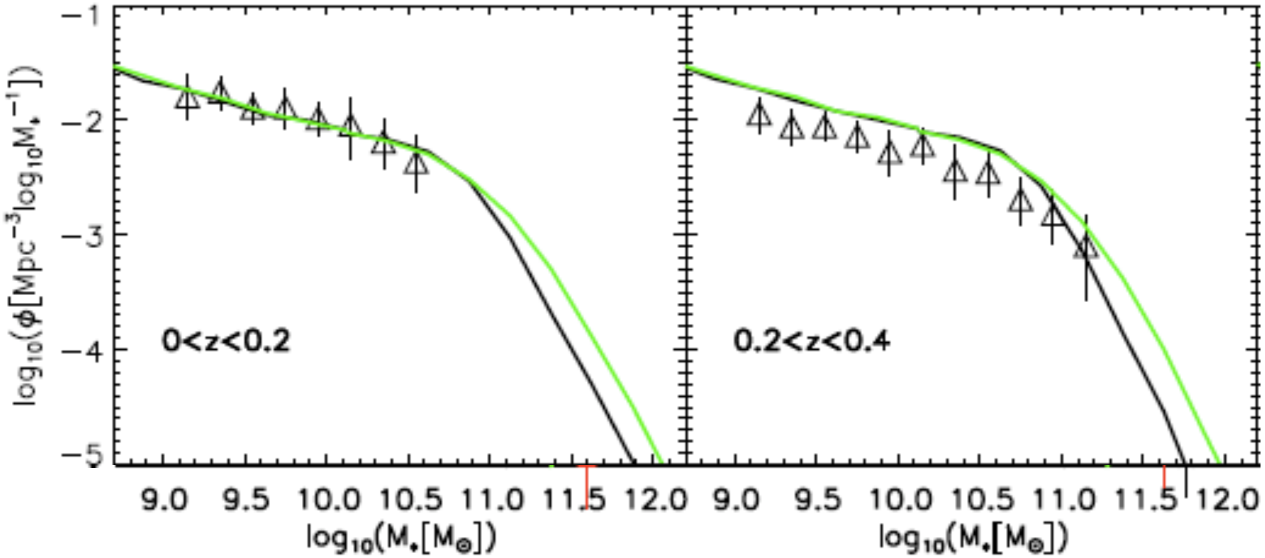


Liu et al. 2010

All models published in the last few years over-predict the number of intermediate-to-low mass galaxies. Some more recent renditions solve this problem in the local Universe by invoking a very efficient SN feedback, but the excess remains at high redshift. Problem originates from an excess of galaxies with Vc~100-200 km/s at higher redshift (**Fontanot et al. 2009**).

Guo et al. 2011

Satellite physics needs to be improved but this is not going to solve this problem (also present in hydro-simulations)



Final remarks – central galaxies

✓ Circumstantial evidence for AGN feedback but this physical process is still included using schematic models, often not very well grounded in the observations. Details (geometry, duty cycle, energy coupling) still need to be understood.

✓ Current implementations are successful in reproducing the observed old ages of brightest cluster galaxies, but not their metal content that appears to be lower than observed. However, only playing with the AGN feedback is not going to solve this problem. Better stellar population estimates for BCGs are needed to constrain the models.

✓ The formation of massive central galaxies is associated with the that of the intra-cluster light. Simulation results have not converged and might be affected by numerical effects. More observational data (distributions, chemical compositions) are coming. Detailed theoretical predictions are needed.

Final remarks – satellite galaxies

- ✓ Current theoretical models (including hydro-dynamical simulations) still have problems in reproducing the number densities and physical properties of the satellite galaxy population

- ✓ (At least some of the) observed trends are naturally explained by the growth of cosmic structure. A more efficient quenching in more massive haloes is not required (i.e. cluster-specific processes are NOT the main drivers for the observed trends).

- ✓ Several recent studies argue for long timescales for the suppression of the star formation in satellite galaxies. It is unclear how a gentle mode of strangulation could support cooling and star formation for several Gyr.

- ✓ The "critical" environment seems to be that of groups of mass 10^{13}Msun. Unfortunately, this is the least studied environment from the numerical viewpoint.