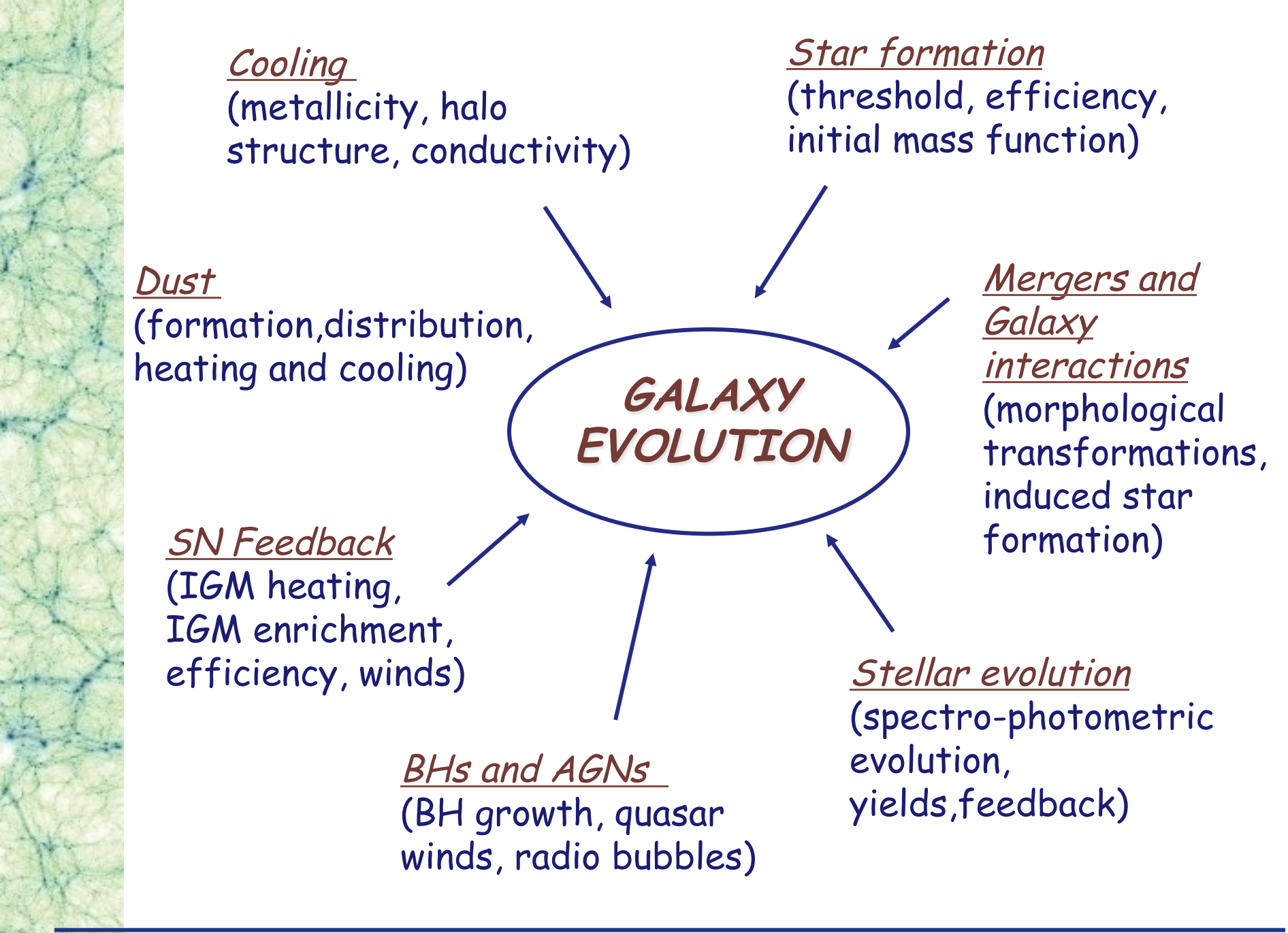
A theoretical overview of galaxy evolution

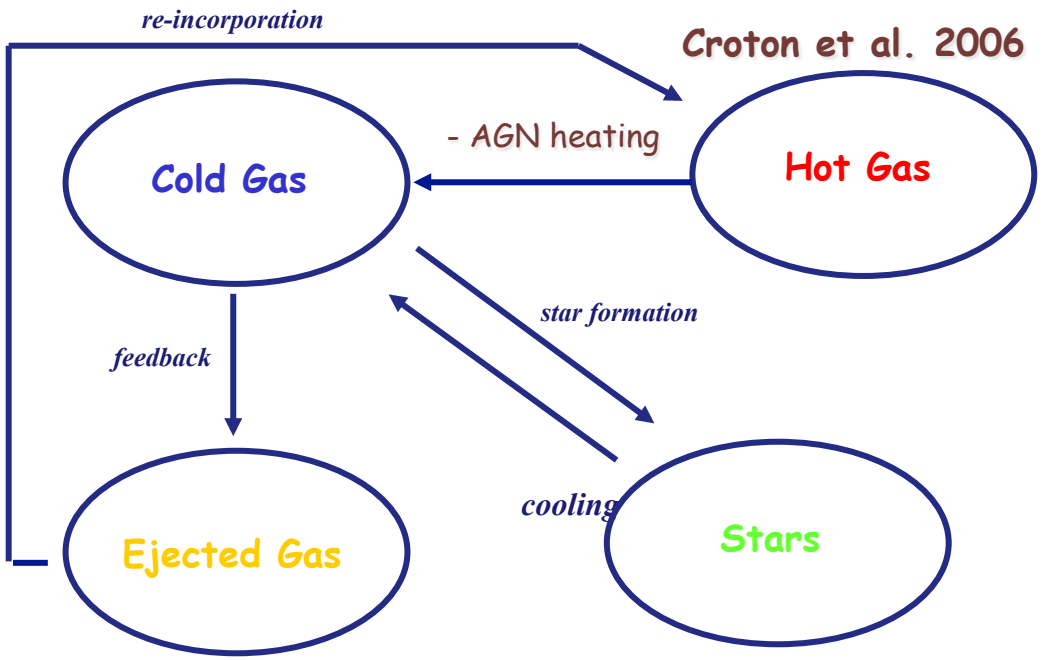
Gabriella De Lucia

INAF – Astronomical Observatory of Trieste

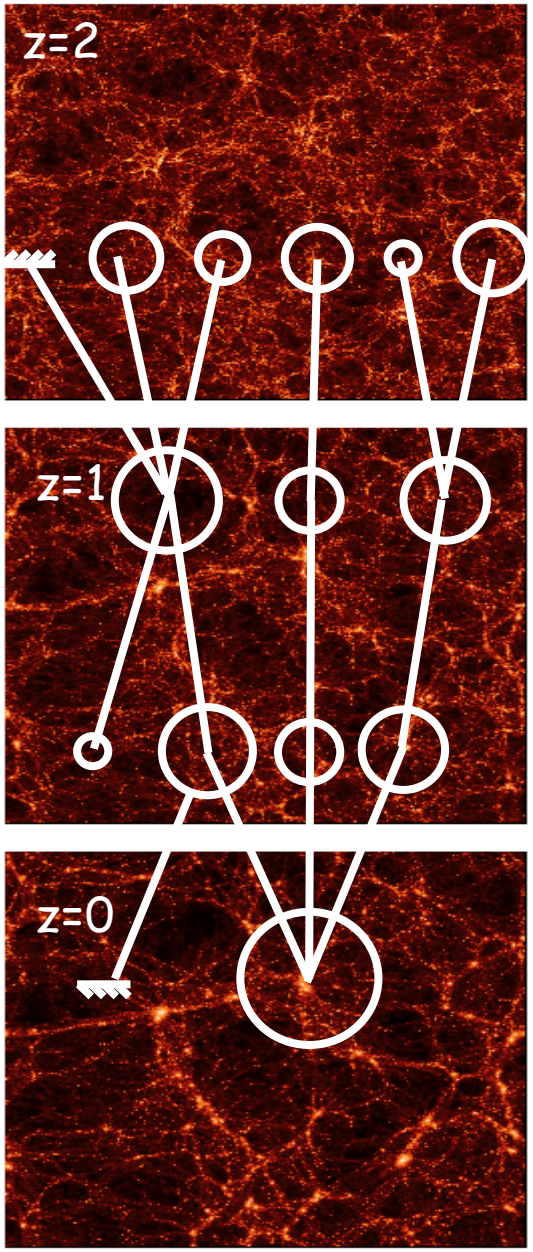

Cooling
(metallicity, halo structure, conductivity)
Star formation
(threshold, efficiency, initial mass function)
Dust
(formation,distribution, heating and cooling)
Mergers and Galaxy interactions
(morphological transformations, induced star formation)
GALAXY EVOLUTION
SN Feedback
(IGM heating, IGM enrichment, efficiency, winds)
Stellar evolution
(spectro-photometric evolution, yields,feedback)
BHs and AGNs
(BH growth, quasar winds, radio bubbles)

Theoretical methods to study GF

Semi-analytic models
(simple but physically and observationally motivated prescriptions, large dynamic range, Fast, no "spatial resolution")



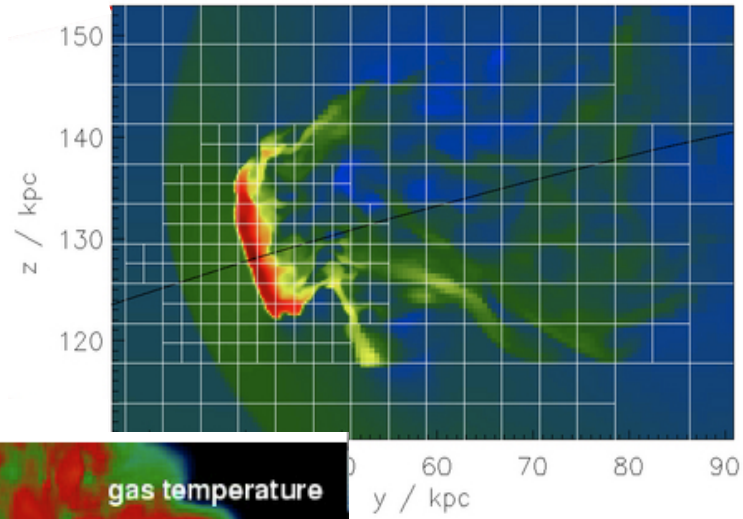
De Lucia, Kauffmann & White, 2004



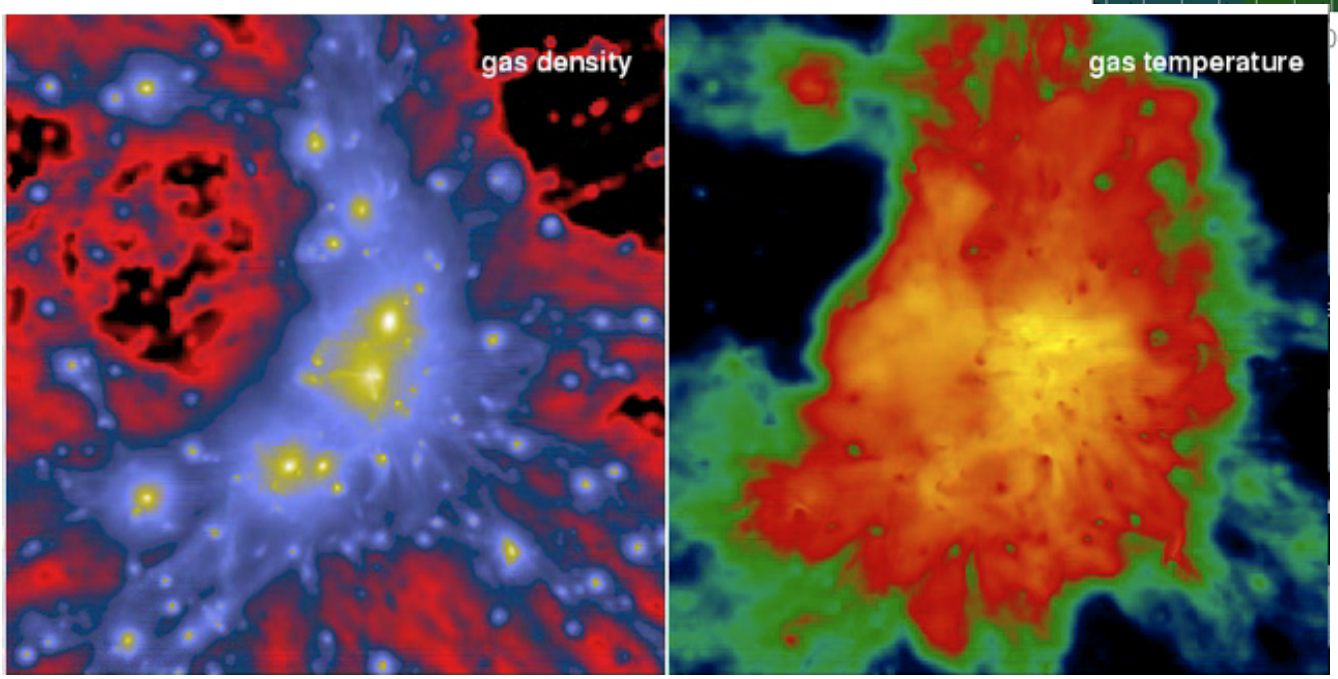
Kauffmann et al., 1999

Theoretical methods to study GF

Roediger & Brueggen 2007



Hydrodynamical simulations
(explicit description of gas dynamics, limited mass and spatial resolution, computational time, "sub-grid" physics)



Courtesy:
Volker Springel

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?)

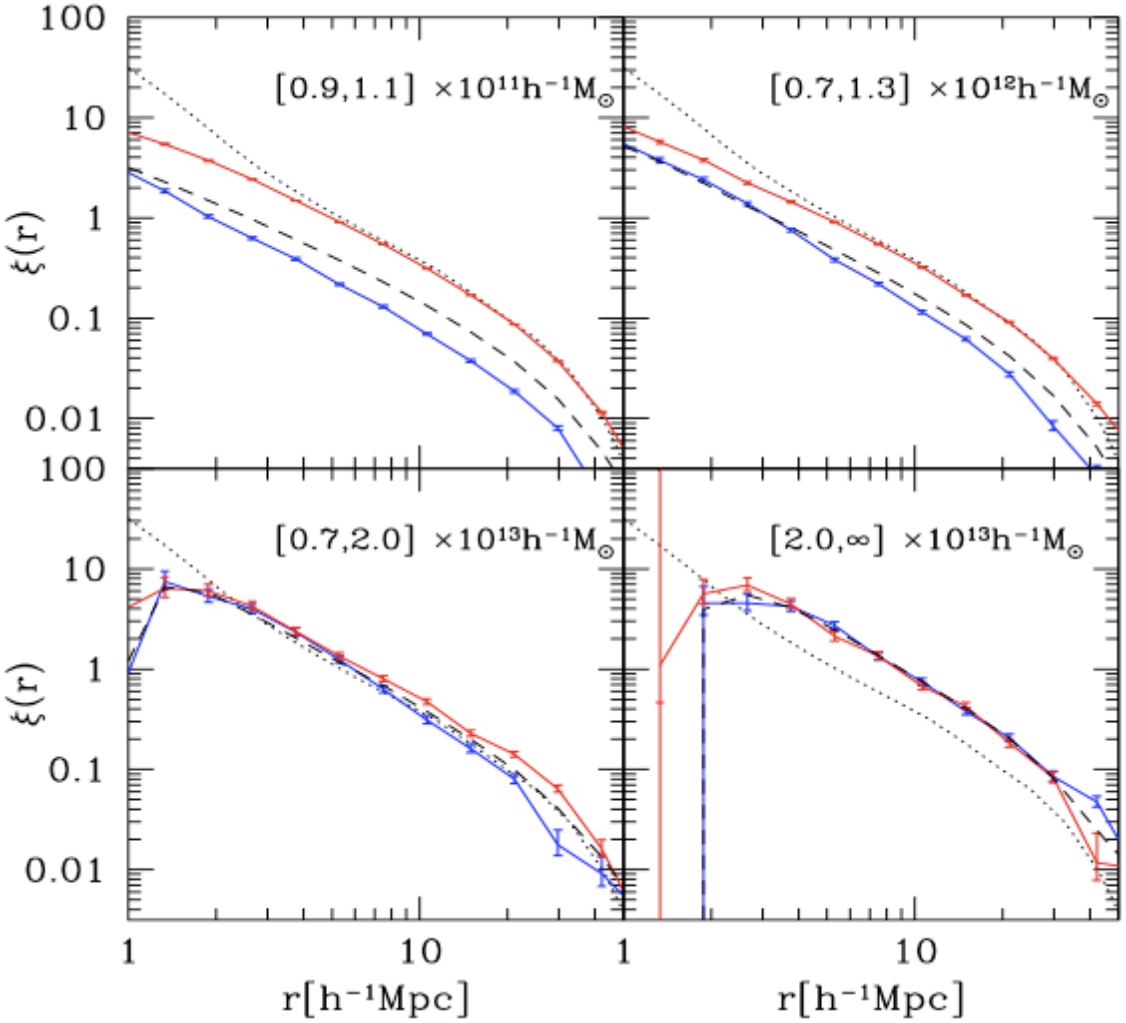
AGN heating:
e.g. Churazov et al. '01, Brueggen et al. '02, Della Vecchia et al. '04, Sijacki & Springel '06

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.

Central and satellite galaxies

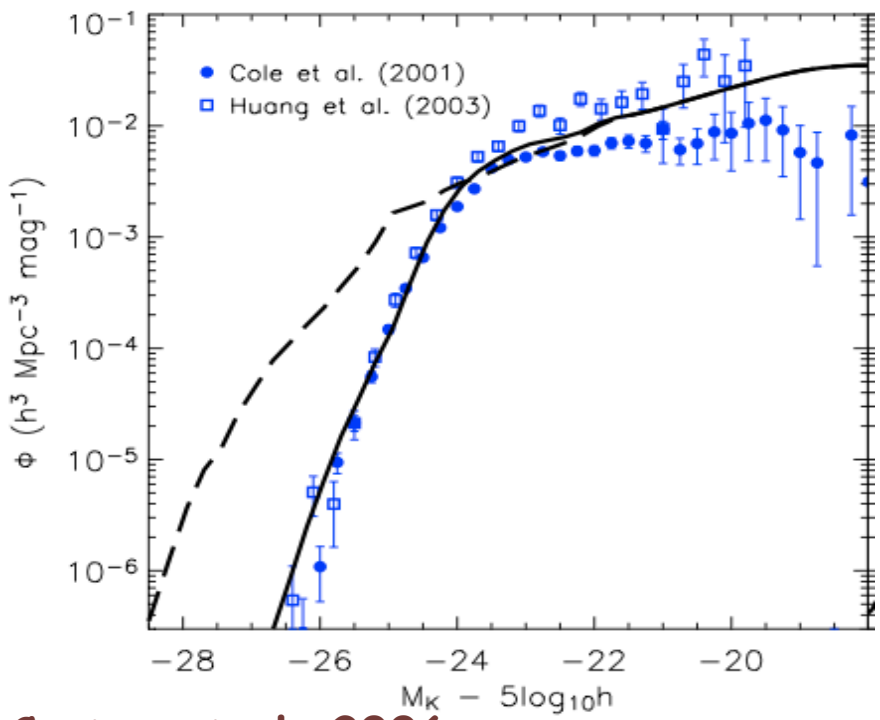
Credit: NASA/JPL-Caltech/GSFC/SDSS

The distinction is obvious (and convenient) from the theoretical point of view. Observationally speaking, it is "easy" for clusters (not always, e.g. Coma), but often very difficult (maybe inappropriate?) for lower mass systems.

Note that with the aid of numerical simulations, this distinction is now routinely applied to observational data (also not just for galaxy clusters)

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.



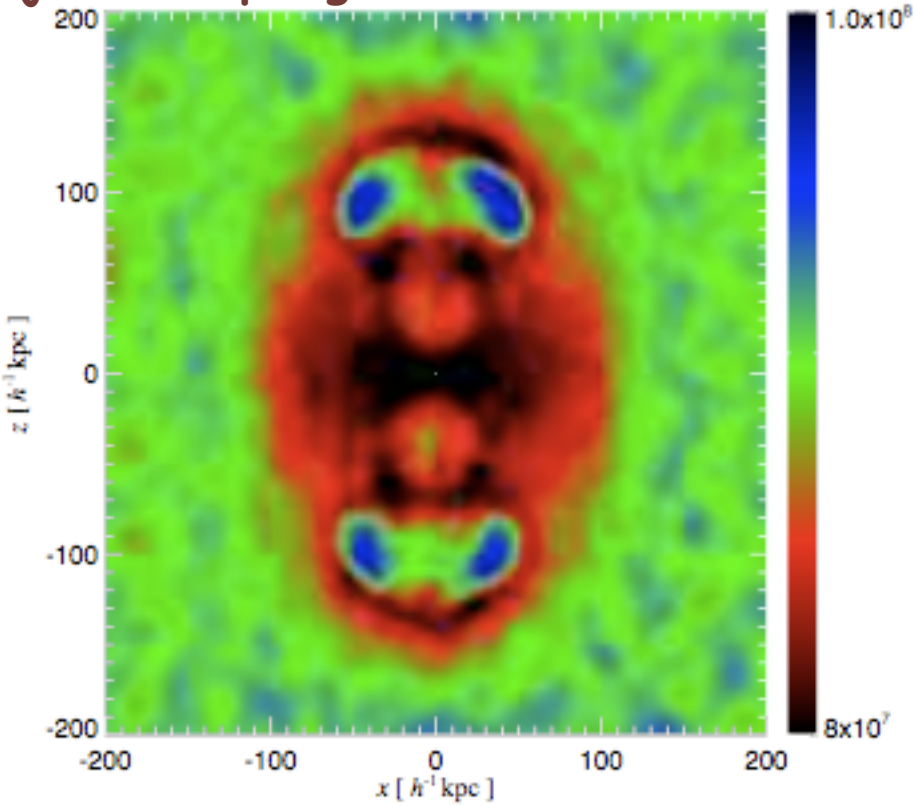
Croton et al. 2006


The Perseus Cluster's X-Ray Skull
Credit: A. Fabian et al.

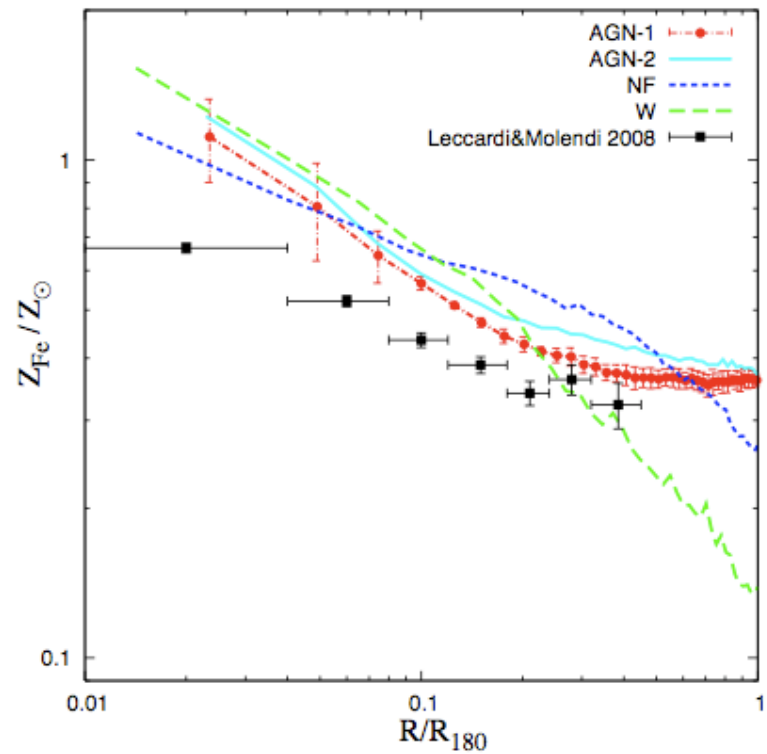
Radio galaxies regulate the cooling flows? (Tabor & Binney 1993) Supported by X-ray observations and demographics of radio-loud galaxies (Best et al. 2007)

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)



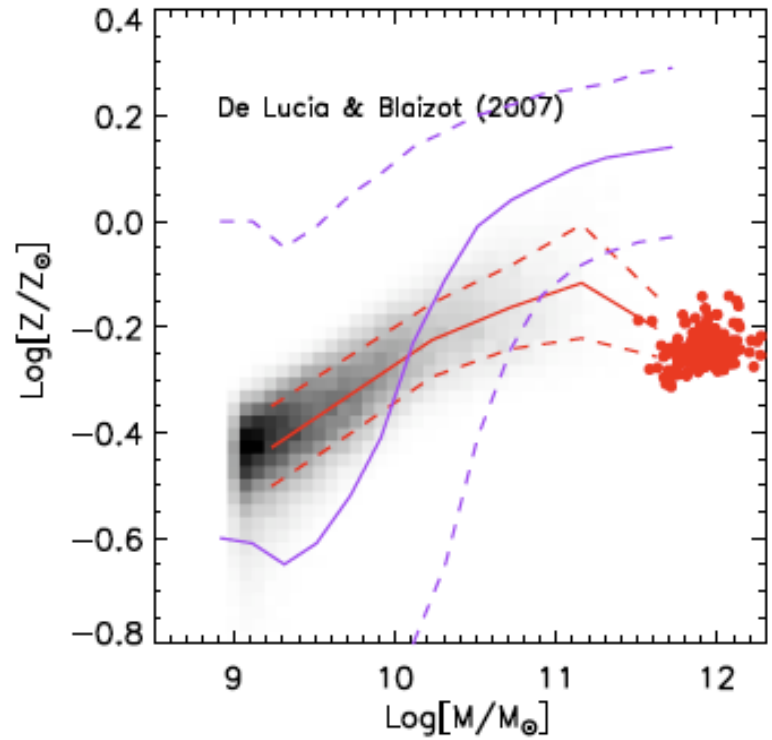
Current numerical implementations result in an efficient extraction of enriched gas from star forming regions at high-z. This leads affects e.g. the metallicity pattern of the ICM

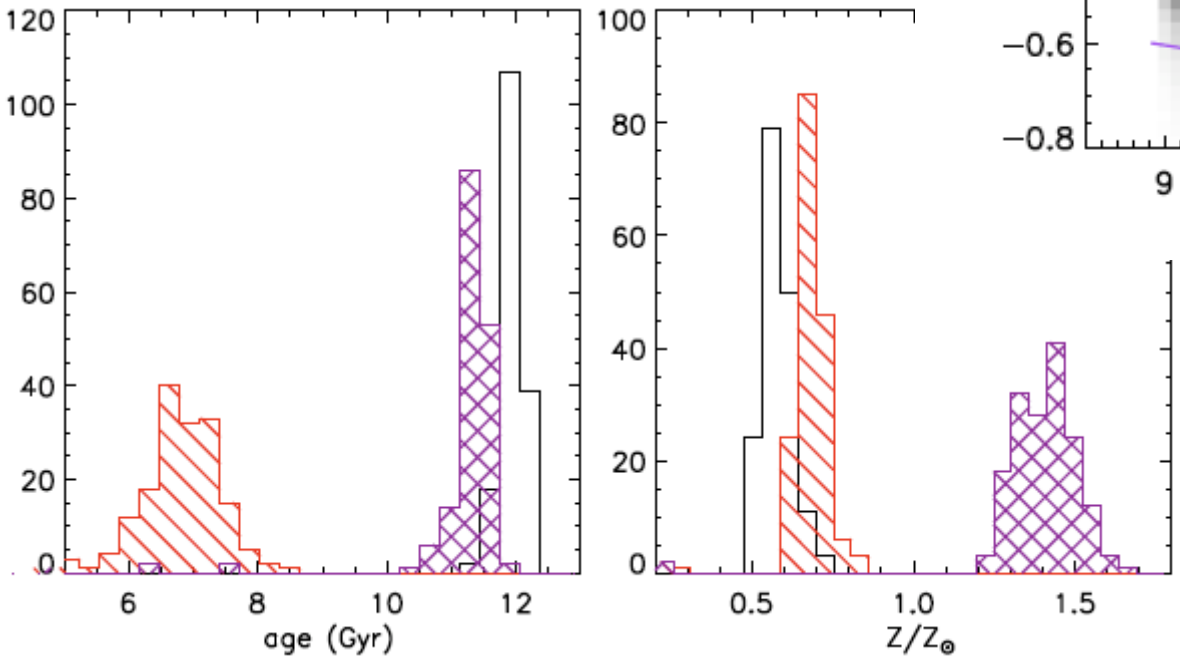
Fabjan et al. 2009, Planelles et al. 2014

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 (e.g. McCarthy et al. 2010, Planelles et al. 2014).



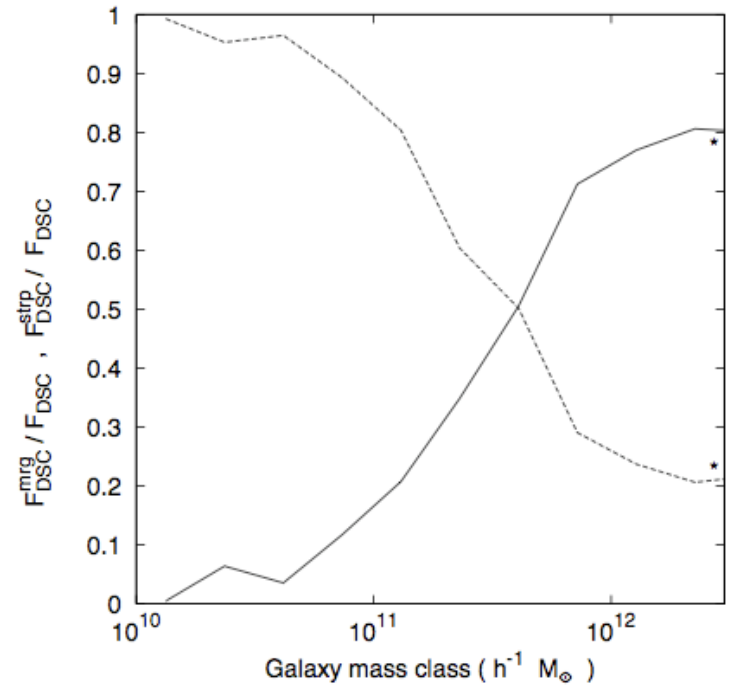


Switching off the radio mode would increase only slightly the metallicity of these galaxies, and make them significantly younger.

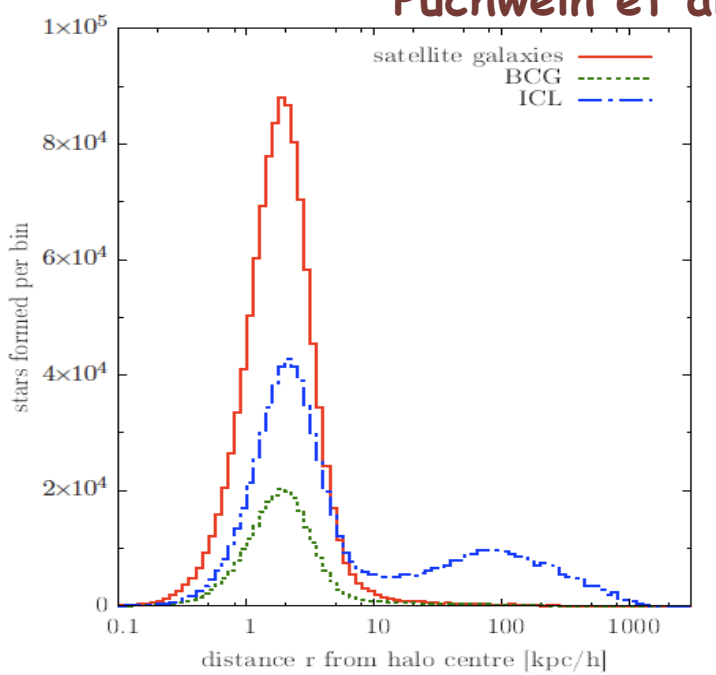
The diffuse stellar component

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).

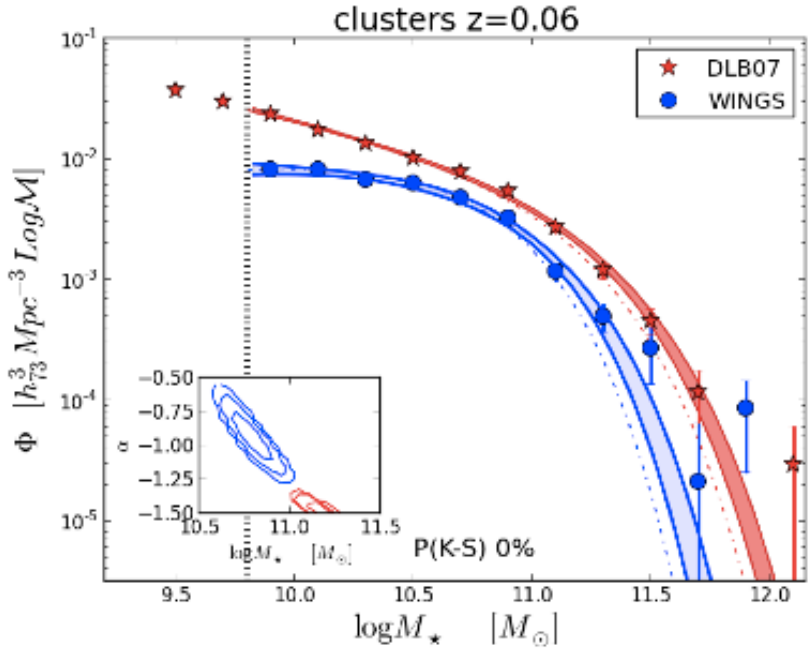
The luminosity function

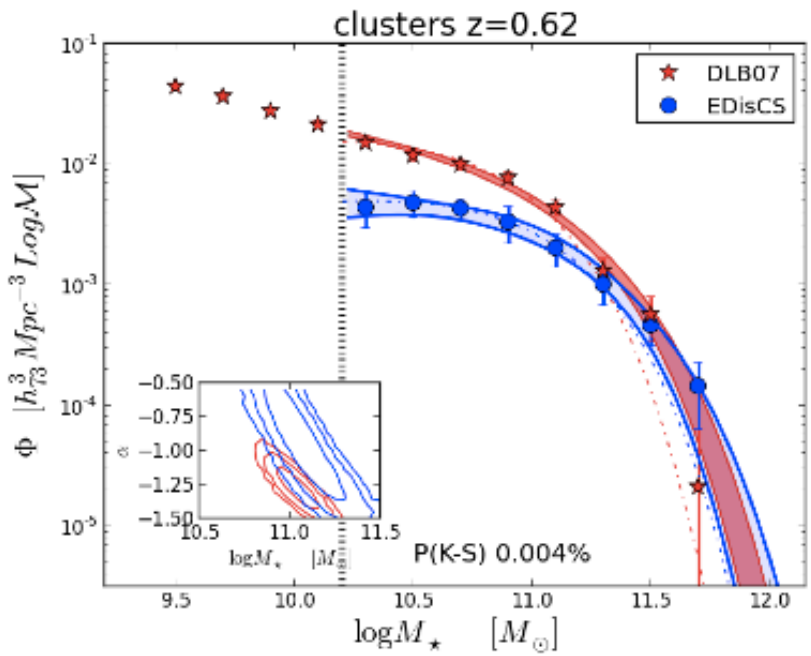
"Simulated sample" obtained projecting simulated haloes and computing velocity dispersions and stellar masses as in the observations.

At low redshift, simulated LF is always above the WINGS LF. At higher z, models agree well with data on the bright end but over-predict the number density of low-mass galaxies.

The excess of low-to-intermediate mass galaxies is a well known problem that affects all published semi-analytic models. It originates from an excess of central galaxies with Vcirc ~100-200 km/s (Fontanot et al. 2009)

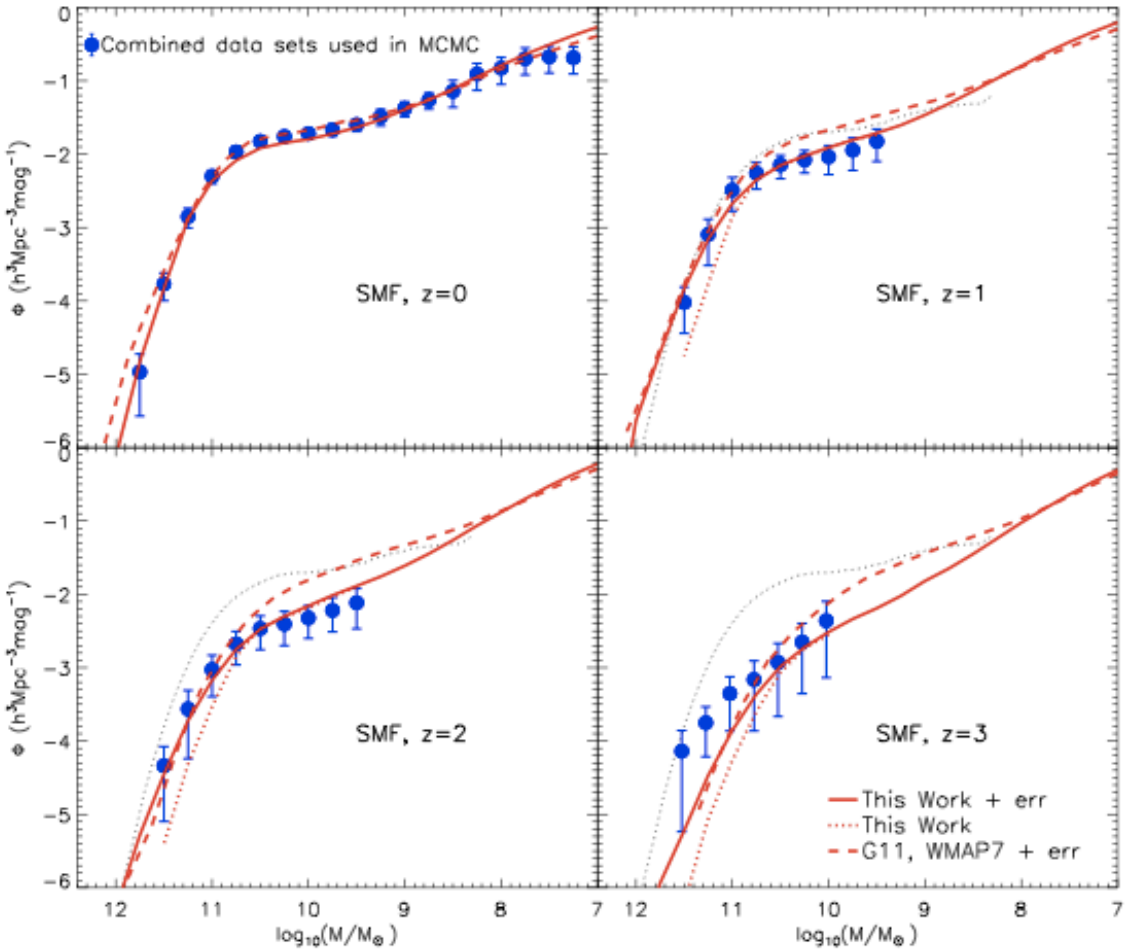
Vulcani et al. 2014





A problem with gas re-incorporation?

Henriques et al. 2013

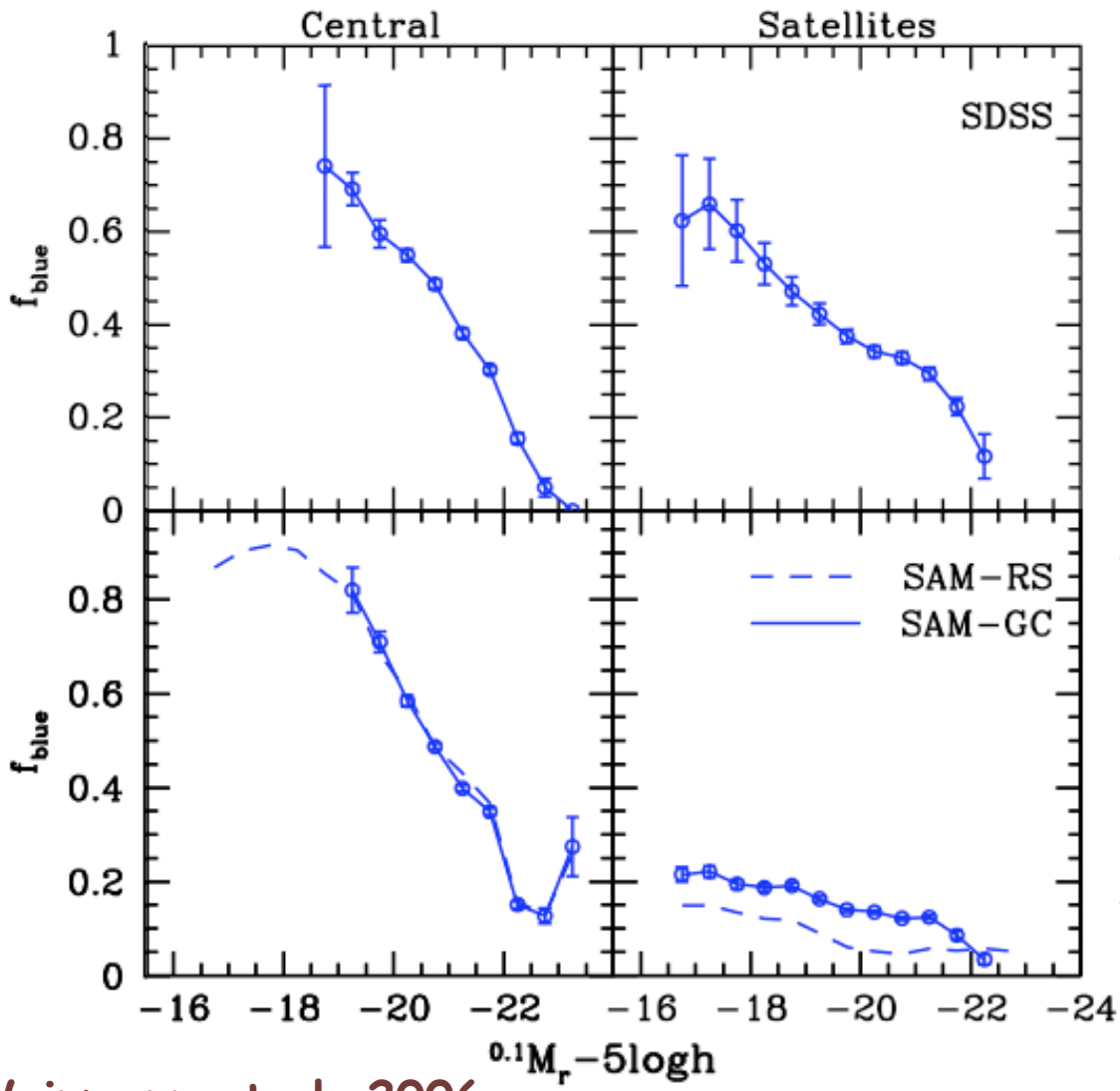


Use Monte Carlo Markov Chain to find the model that "best-fit" a given set of z=0 observational data (in this case MF and LF at four redshifts).

Claim a modification in the re-incorporation timescales (that should vary inversely with the halo mass). Note that also other parameters have changed wrt previous model.

Note: some parameters assume extreme values. Not all problems with satellite galaxies are solved. Modification of re-incorporation timescales should be physically justified.

The colours of satellite galaxies



Weinmann et al. 2006

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

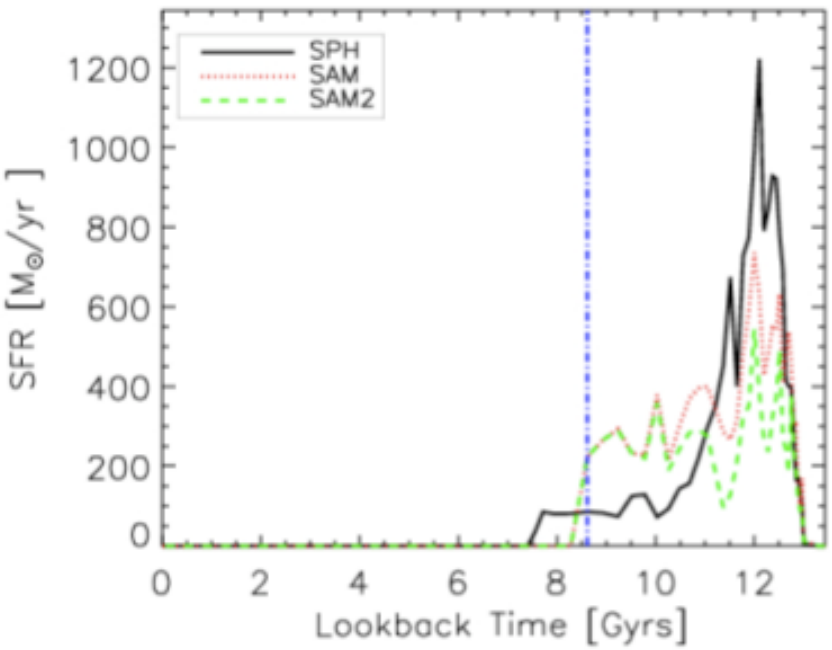
Again, this problem is shared by all models recently published (see e.g. Fontanot et al. 2009).

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

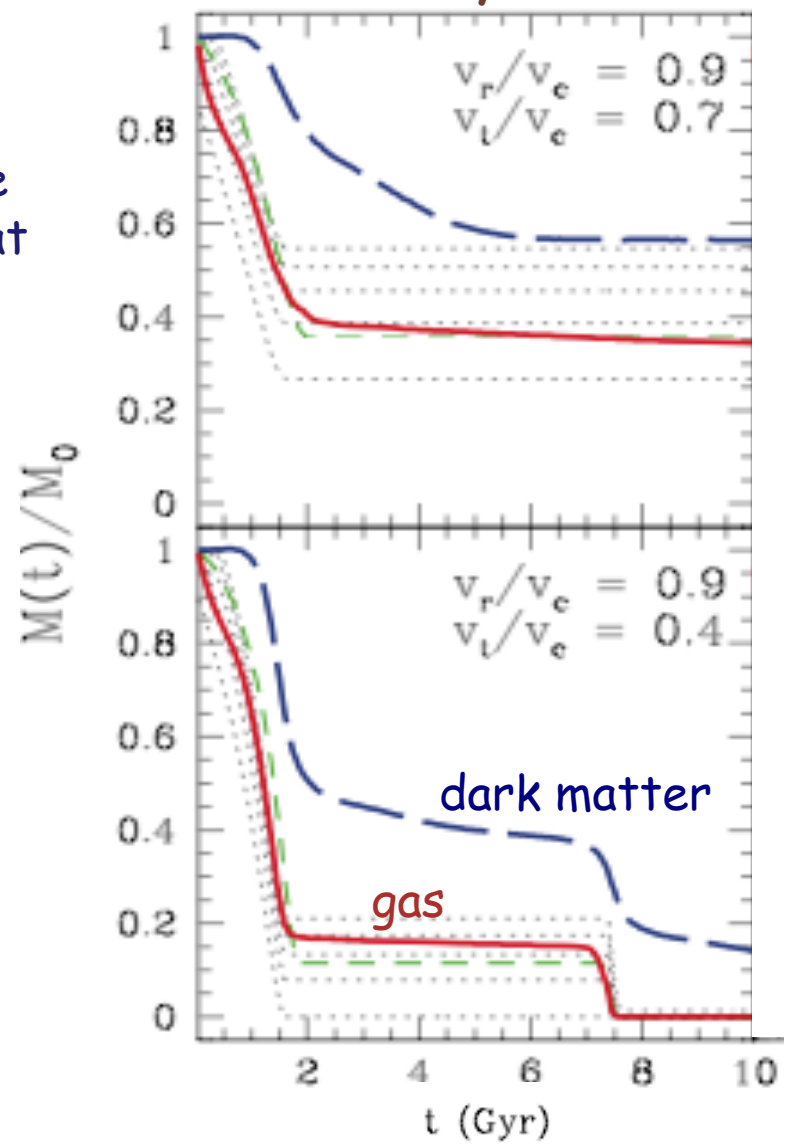
The stripping of the hot reservoir

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

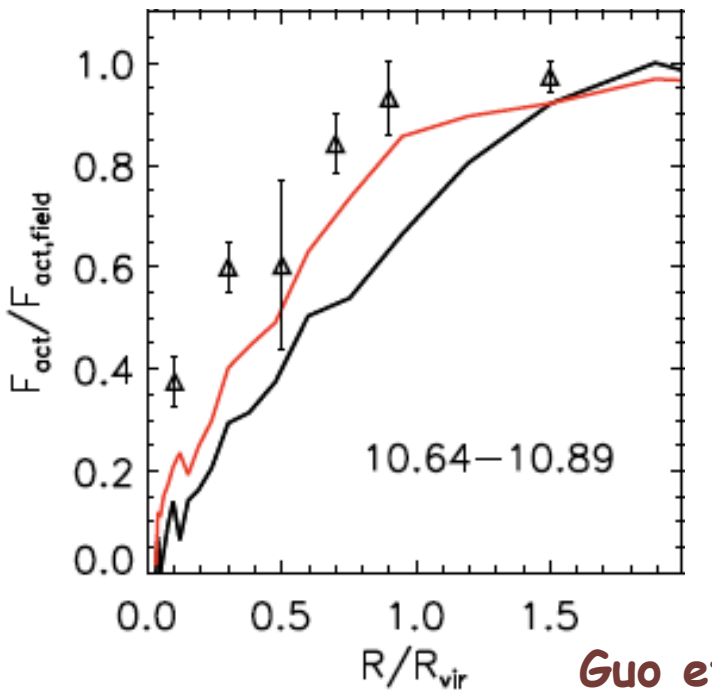


McCarthy et al. 2008



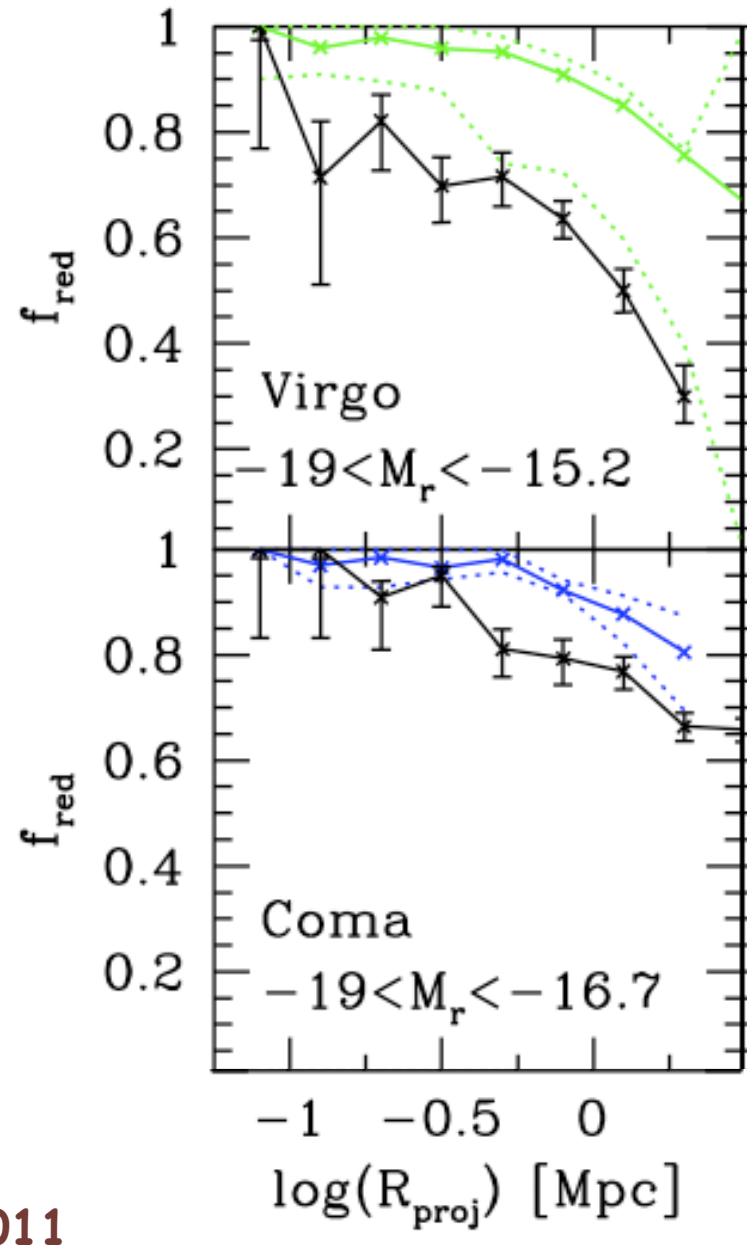
The colours of satellites

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.



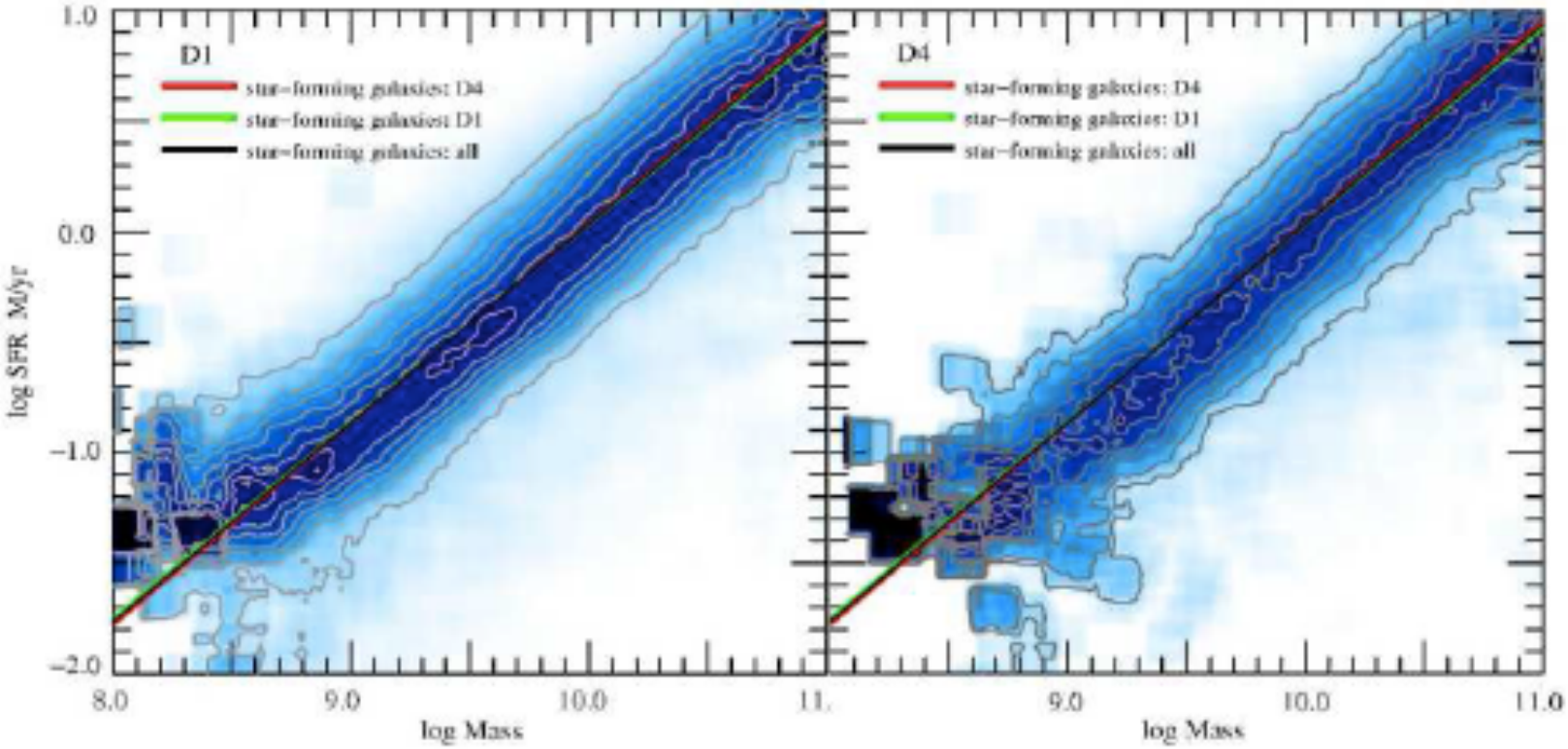
Guo et al. 2011

Weinmann et al. 2011



Satellite and central star forming galaxies

Peng et al. 2010



Star forming satellite galaxies form stars at the same rate as central galaxies. This is a very difficult constraint to satisfy in the models as satellite galaxies are treated in a different way by construction.

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.

✓ 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 (more in general, there is an excess of low and intermediate stellar mass galaxies).

✓ Recent studies argue that a change in the re-incorporation timescales can solve the problem of the excess of low-mass galaxies. However, this model adopts parameters with rather extreme values. In addition, satellite galaxies are still too passive with respect to observational data.

✓ Several recent studies argue for long timescales for the suppression of the star formation in satellite galaxies (satellite galaxies have to behave like centrals for very long times). It is unclear how a gentle mode of strangulation could support cooling and star formation for several Gyr