Cluster Galaxies: Why Are They Different? Why Should You Care?

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Santa Fe Cosmology Workshop
July 9, 2012

Perseus Cluster (SDSS) – R. Lupton

Outline

- Characterizing cluster galaxies
- Transformation mechanisms
- Synthesis

Characterizing cluster galaxies

Characterizing cluster galaxies

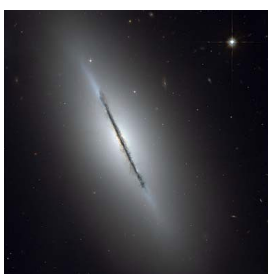
- Morphology
- Luminosity
- Star formation
- Gas content
- AGN activity
- Color
- Metallicity
- Internal kinematics

Morphology

Morphology-density relation (Dressler 1980):

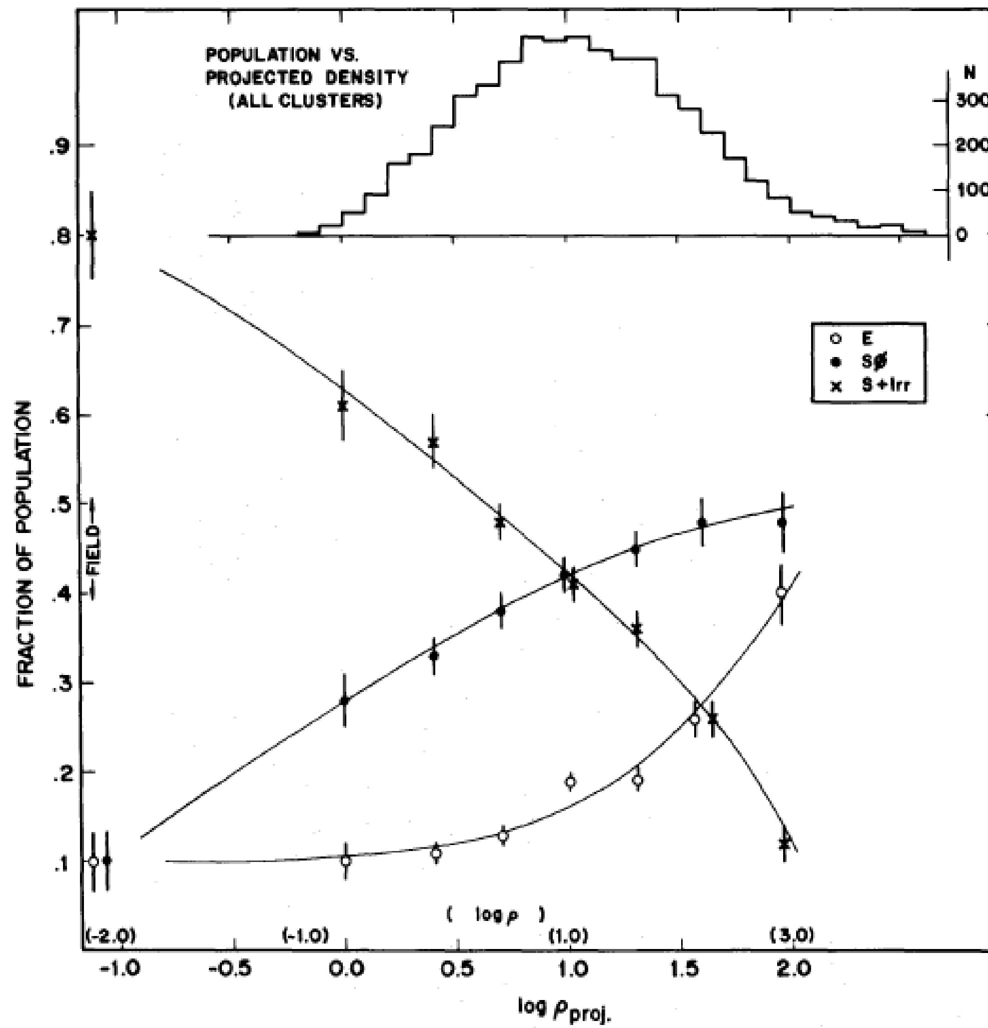
- Early-type (E+S0) fraction is higher in clusters than in the field

Elliptical



S0 (spheroidal, lenticular)

Spiral

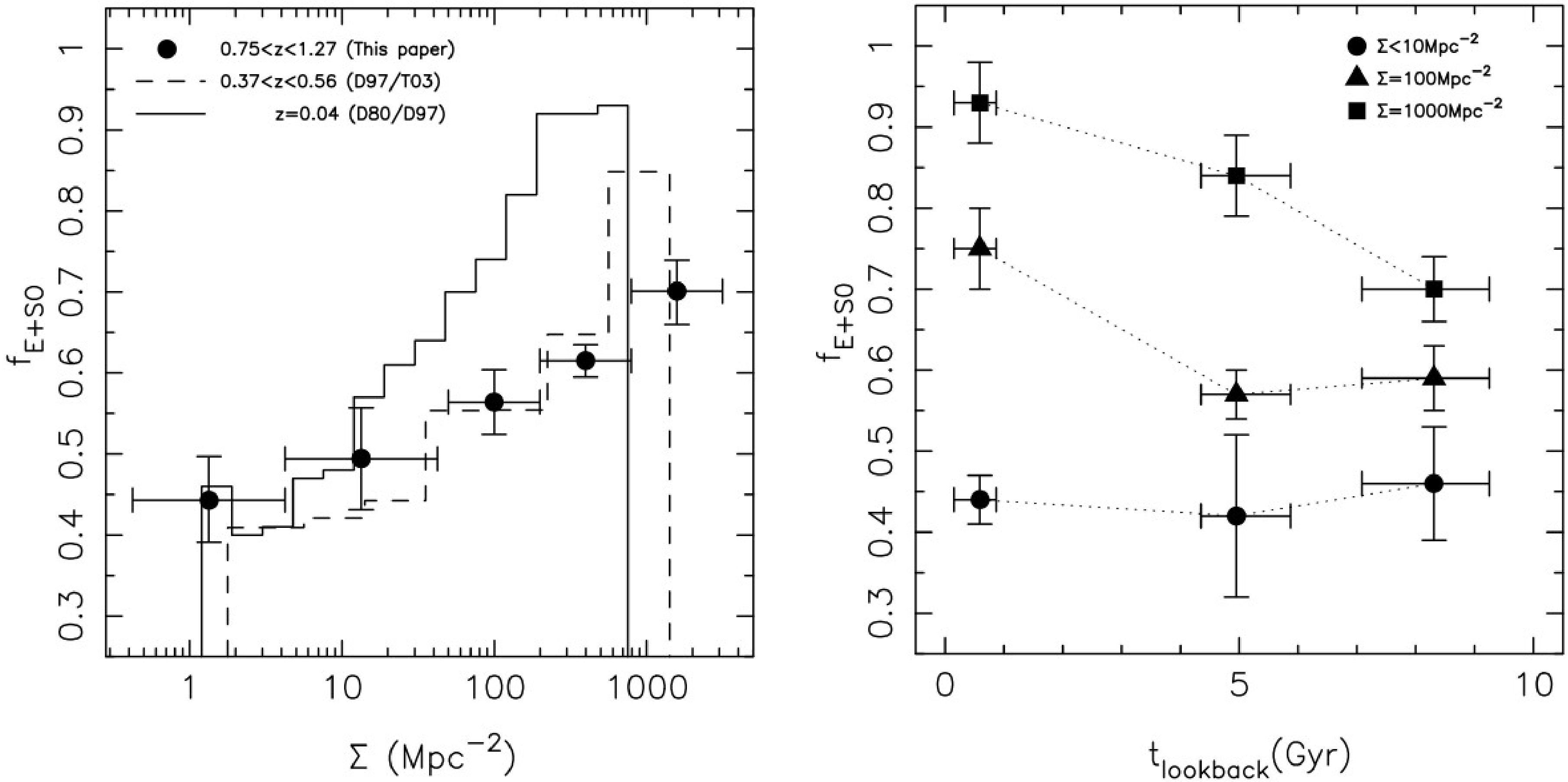


(galaxies Mpc^{-2})

Hubble Heritage

Morphology

Morphology-density relation is already in place by z ~ 1; evolution in early-type fraction only in groups/clusters (Dressler et al. 1997; Smith et al. 2005)



Smith et al. (2005)

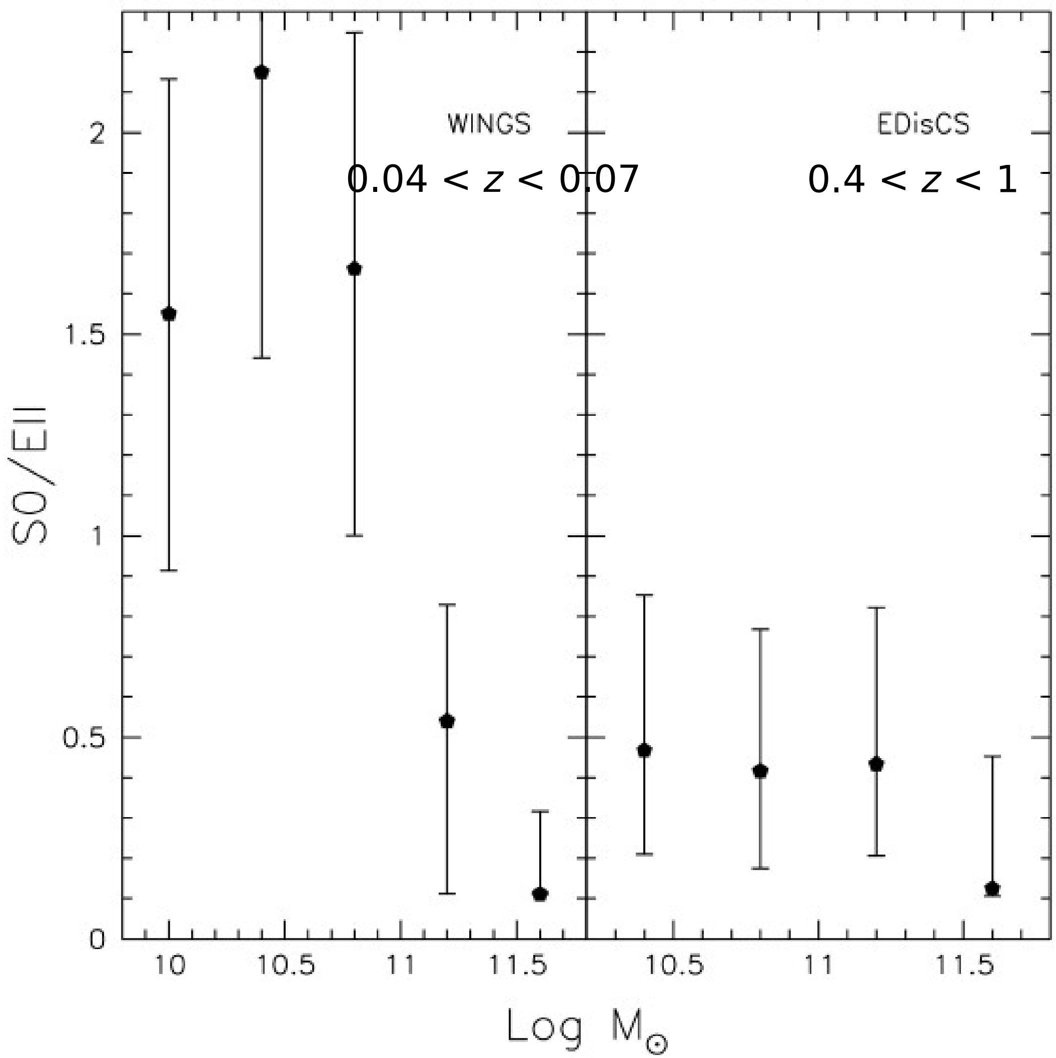
Morphology

Evolution of early-type fraction driven by increase in S0 population with time since z ~ 0.5

(Dressler et al. 1997; Vulcani et al. 2011)

No further evolution in S0/E up to z ~ 1

(Postman et al. 2005)



Vulcani et al. (2011)

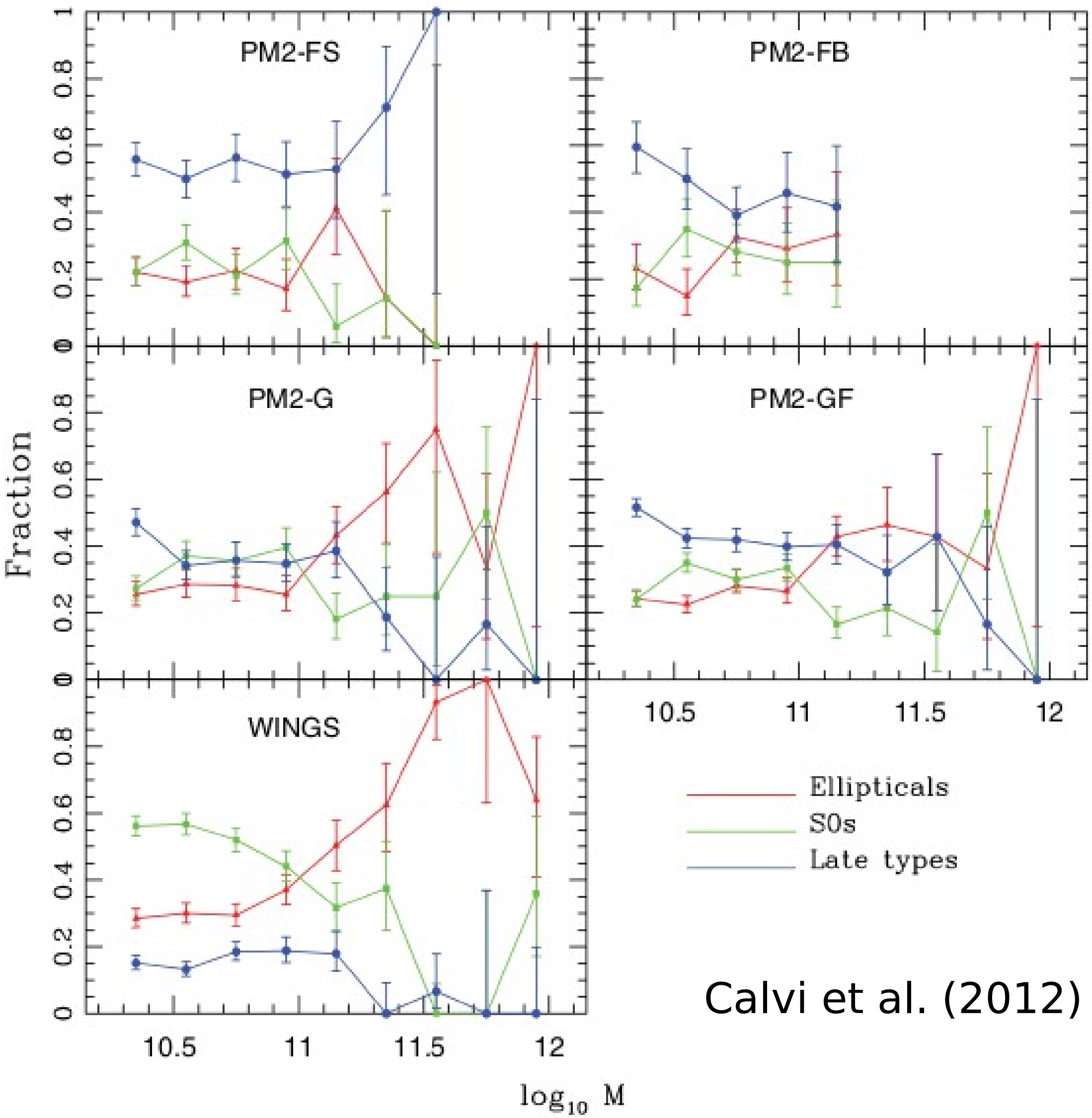
Morphology

Morphology-density relation is not an artifact of varying stellar mass in different environments

(Calvi et al. 2012)

In clusters, S0s dominate at low masses, ellipticals at high masses

(Vulcani et al. 2011)



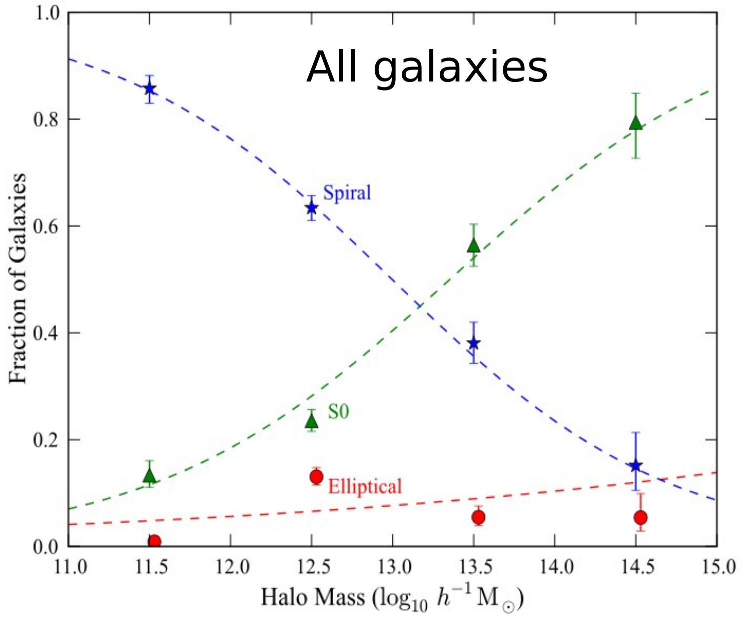
Calvi et al. (2012)

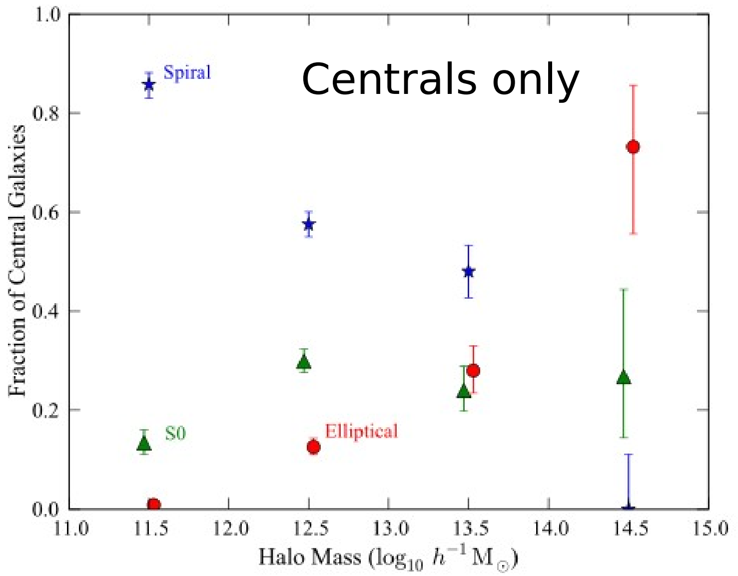
Morphology

Spiral and S0 fractions vary strongly with parent halo mass; elliptical fraction roughly constant

EXCEPT for central galaxies: elliptical fraction strong function of halo mass

(Wilman & Erwin 2012)

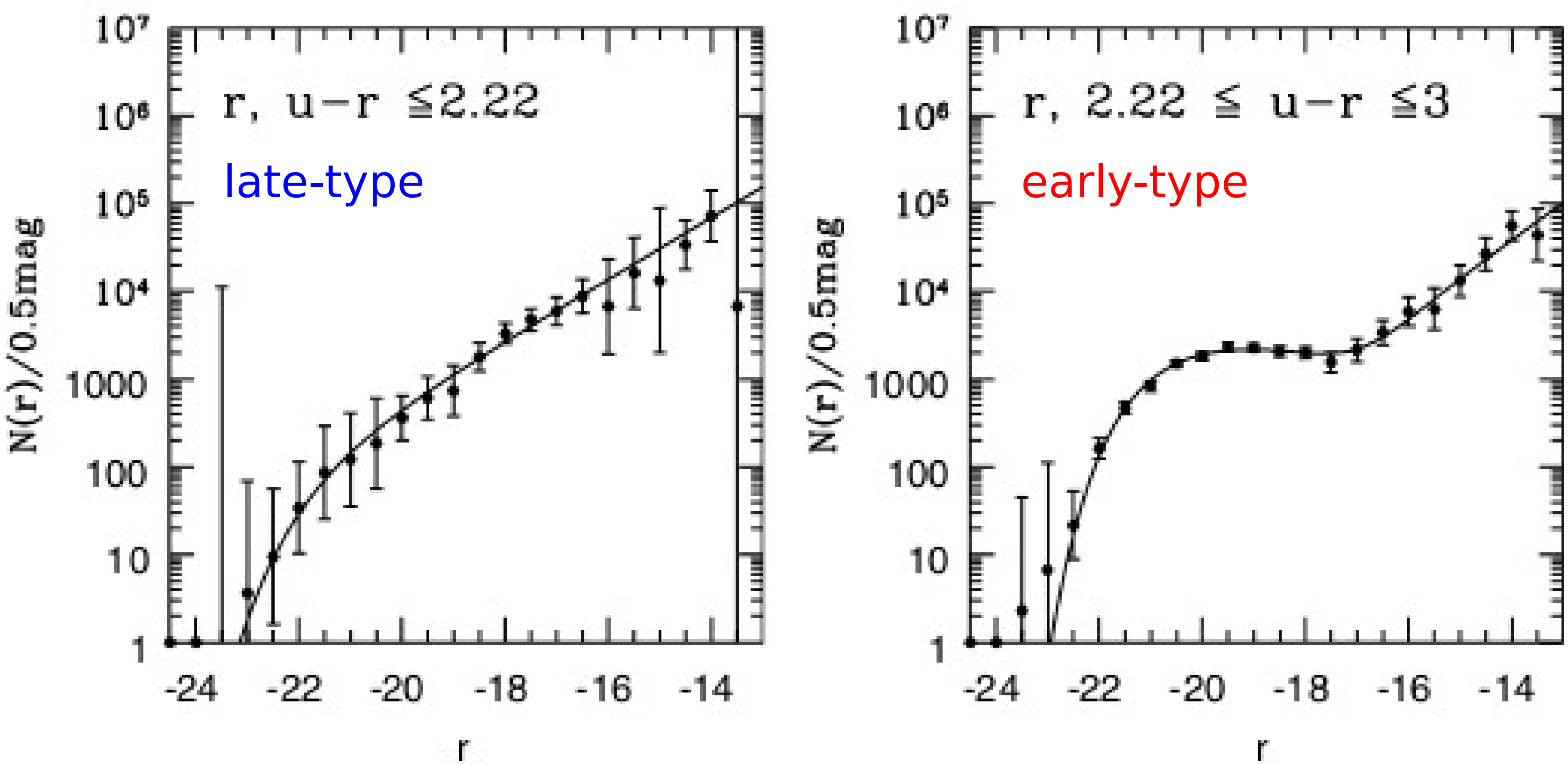




Luminosity function

Late-type luminosity function (LF) in clusters resembles field

Early-type LF shows upturn at low luminosities



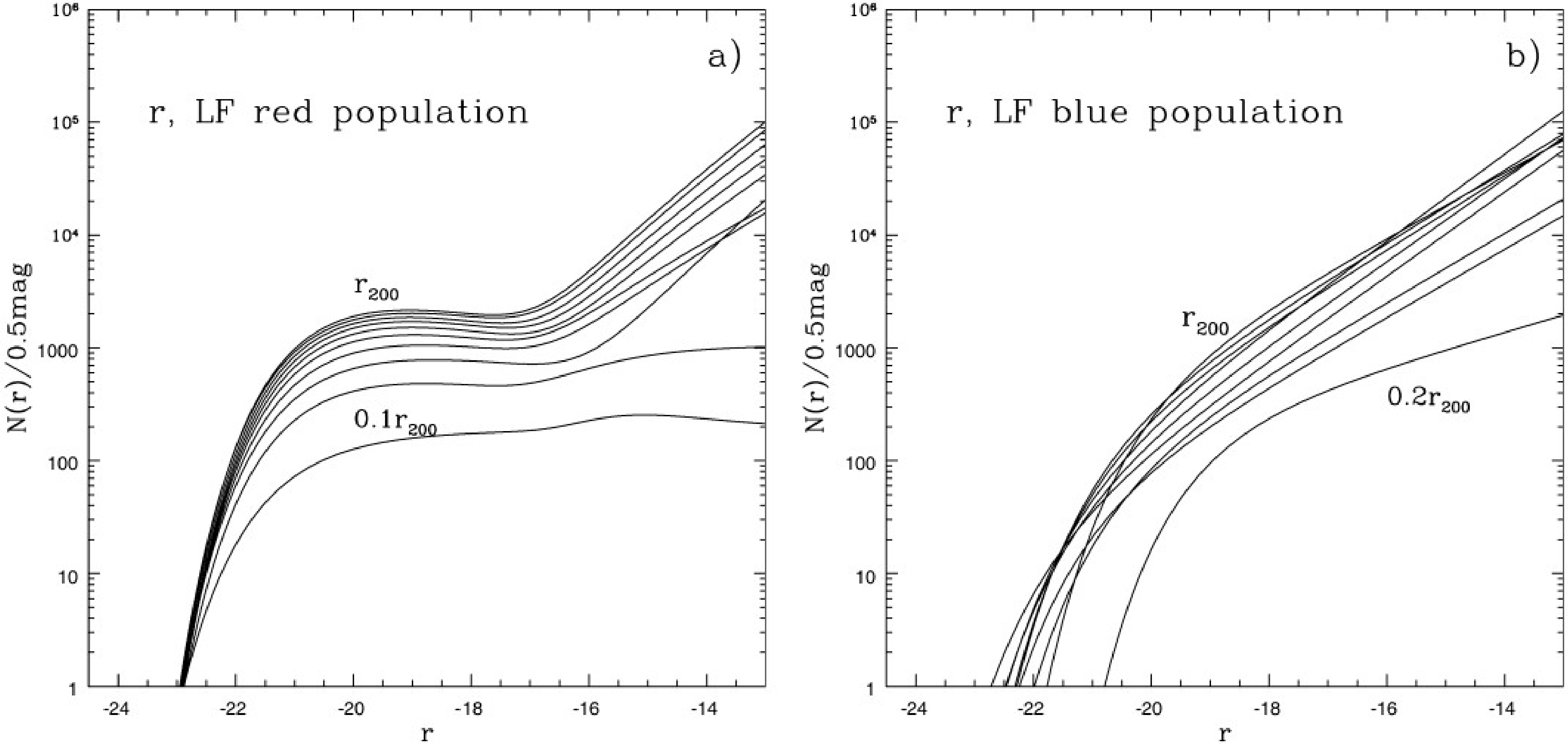
⟵ intrinsically brighter

Popesso et al. (2005)

Luminosity function

Most of the early-type dwarfs are outside cluster centers

(Popesso et al. 2006)



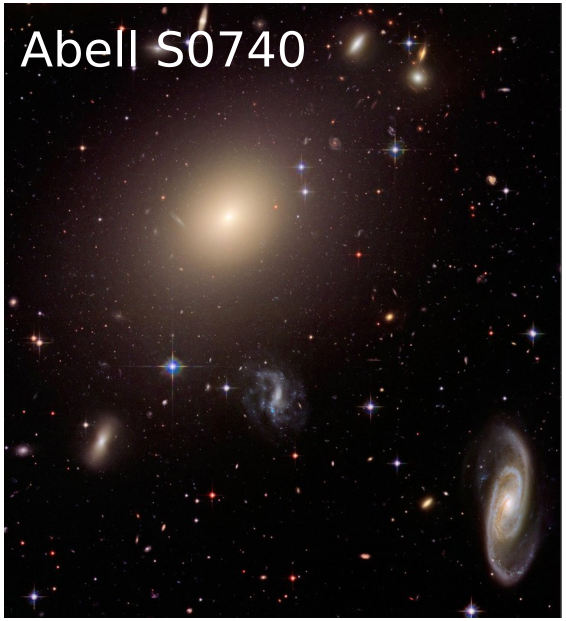
Popesso et al. (2006)

Brightest cluster galaxies (BCGs)

The most massive galaxies are ellipticals located at cluster/group centers

Appear to form in a different way than "normal" cluster galaxies:

- Magnitude gap, density of close satellites (Tremaine 1990)
- BCGs often offset from X-ray centroids, have nonzero relative velocities (Beers & Geller 1983)
- Properties insensitive to global kinematic properties of clusters (Zabludoff et al. 1990)

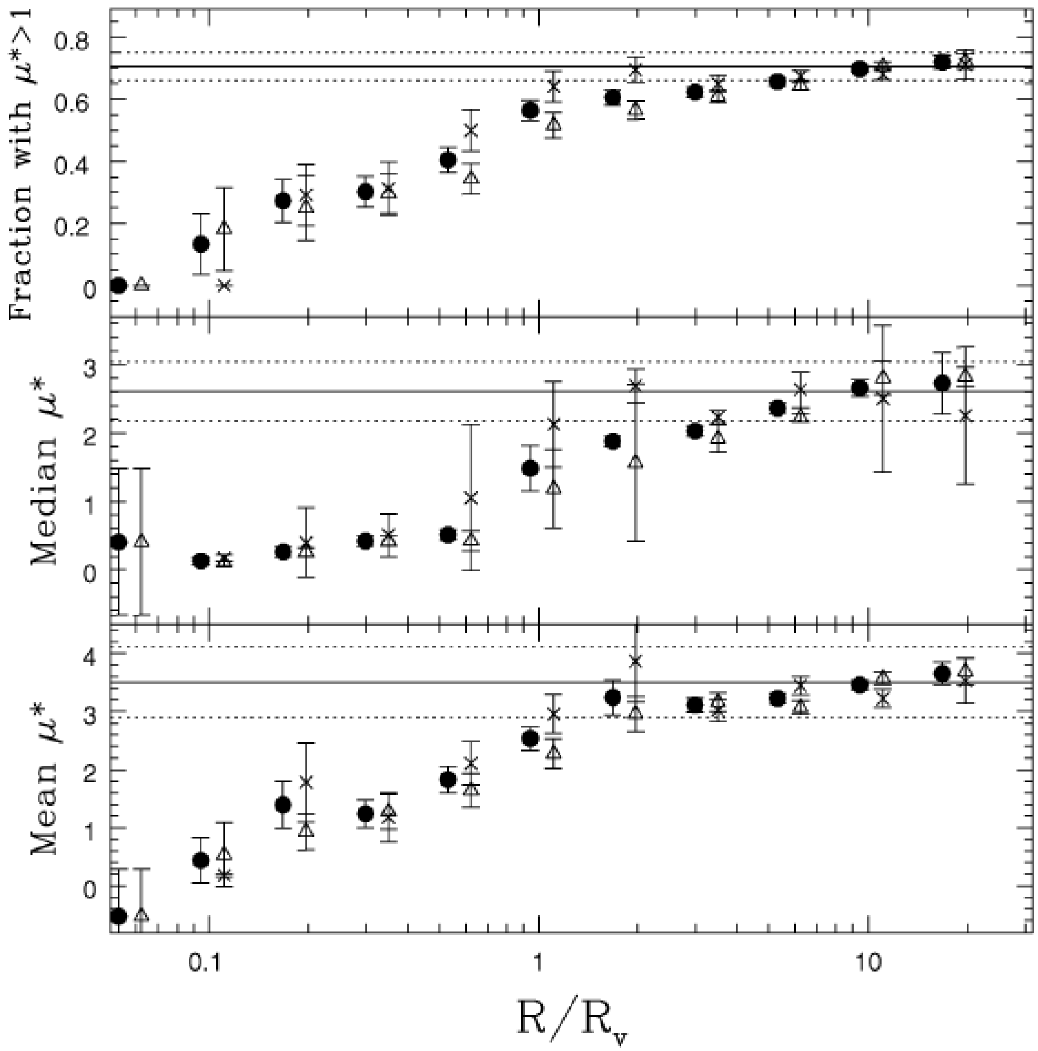


Hubble Heritage

Star formation

Star formation rate (SFR)-density relation (Balogh et al. 1997; Lewis et al. 2002; Gomez et al. 2003):

- ⟨SFR⟩ is much lower in clusters than in the field
- SFR suppression decreases with cluster-centric radius
- Significant suppression even beyond virial radius



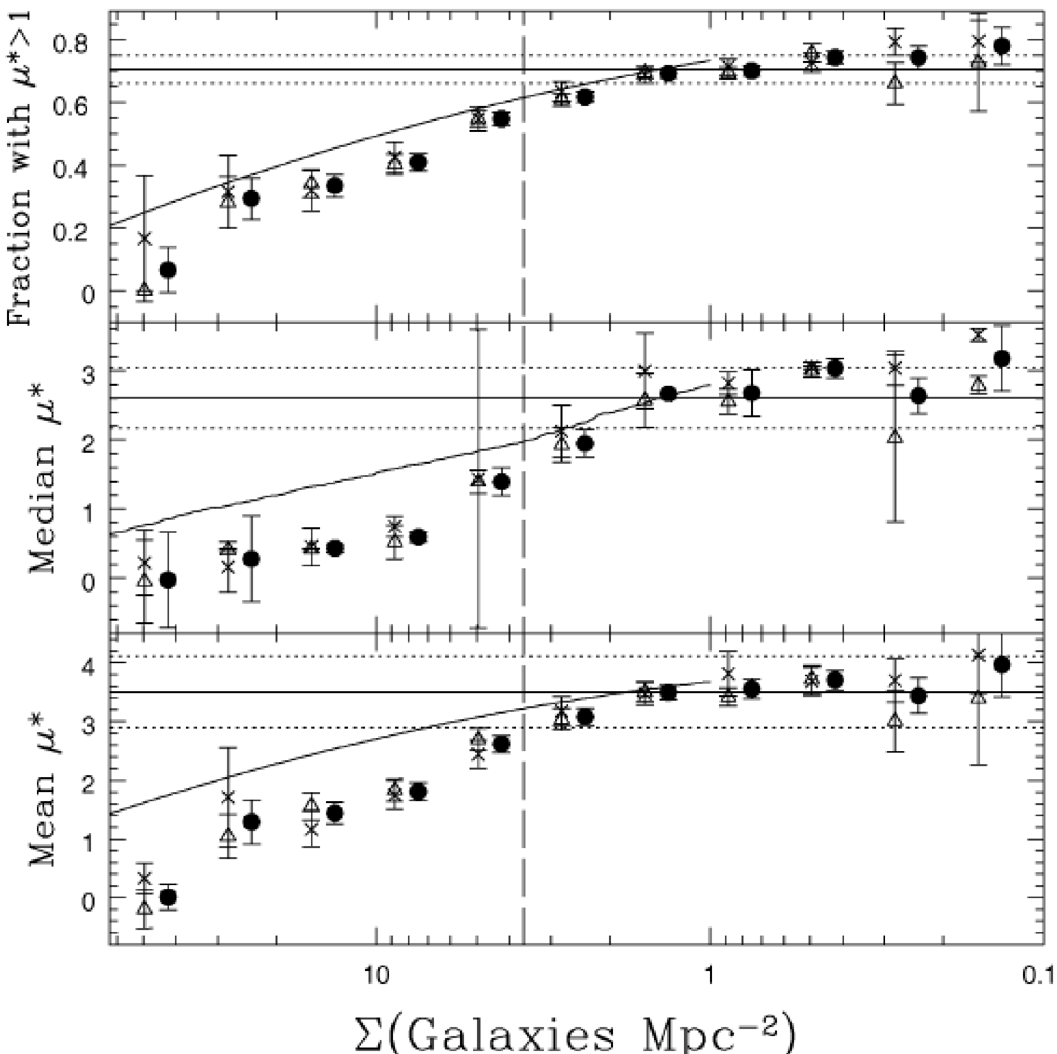
Lewis et al. (2002)

Star formation

SFR suppression in all high-density regions, not just clusters

Appears to be separate from morphology-density relation

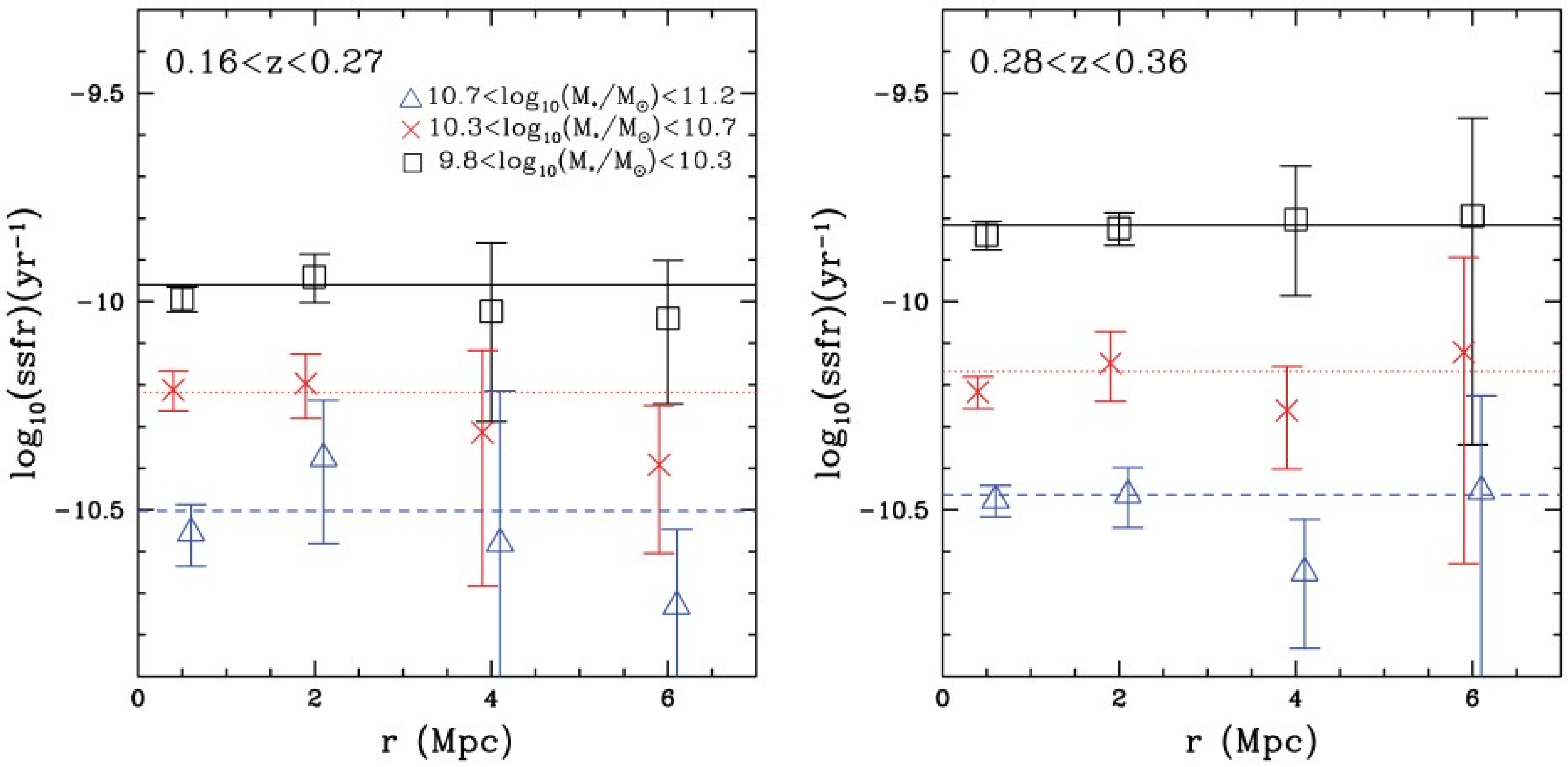
(Lewis et al. 2002)



Lewis et al. (2002)

Star formation

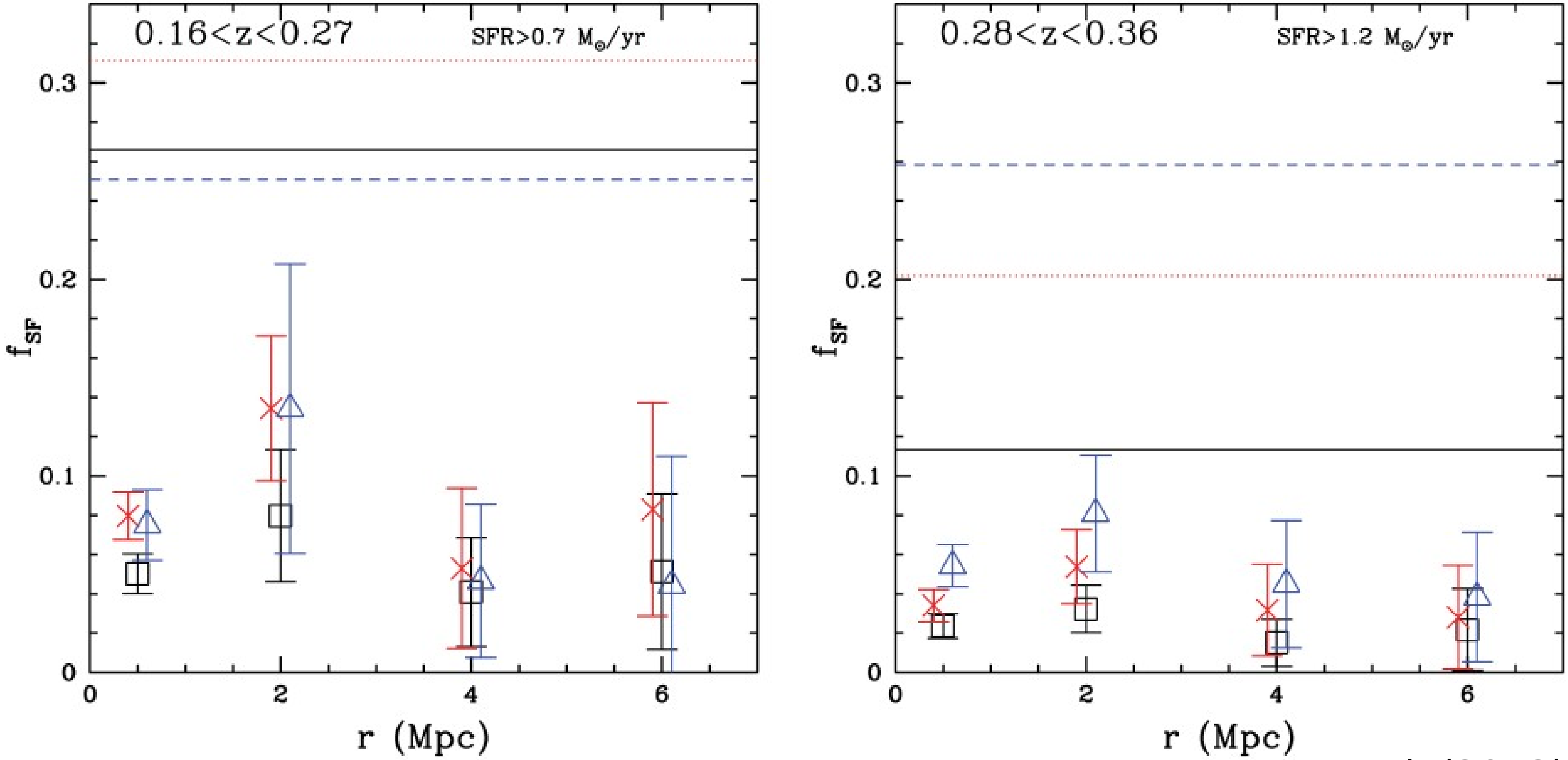
Specific SFR does not seem to differ between clusters and field, but does decline with increasing stellar mass
(Lu et al. 2012)



Lu et al. (2012)

Star formation

Total fraction of galaxies with detectable star formation is suppressed well outside virial radius (Lu et al. 2012)

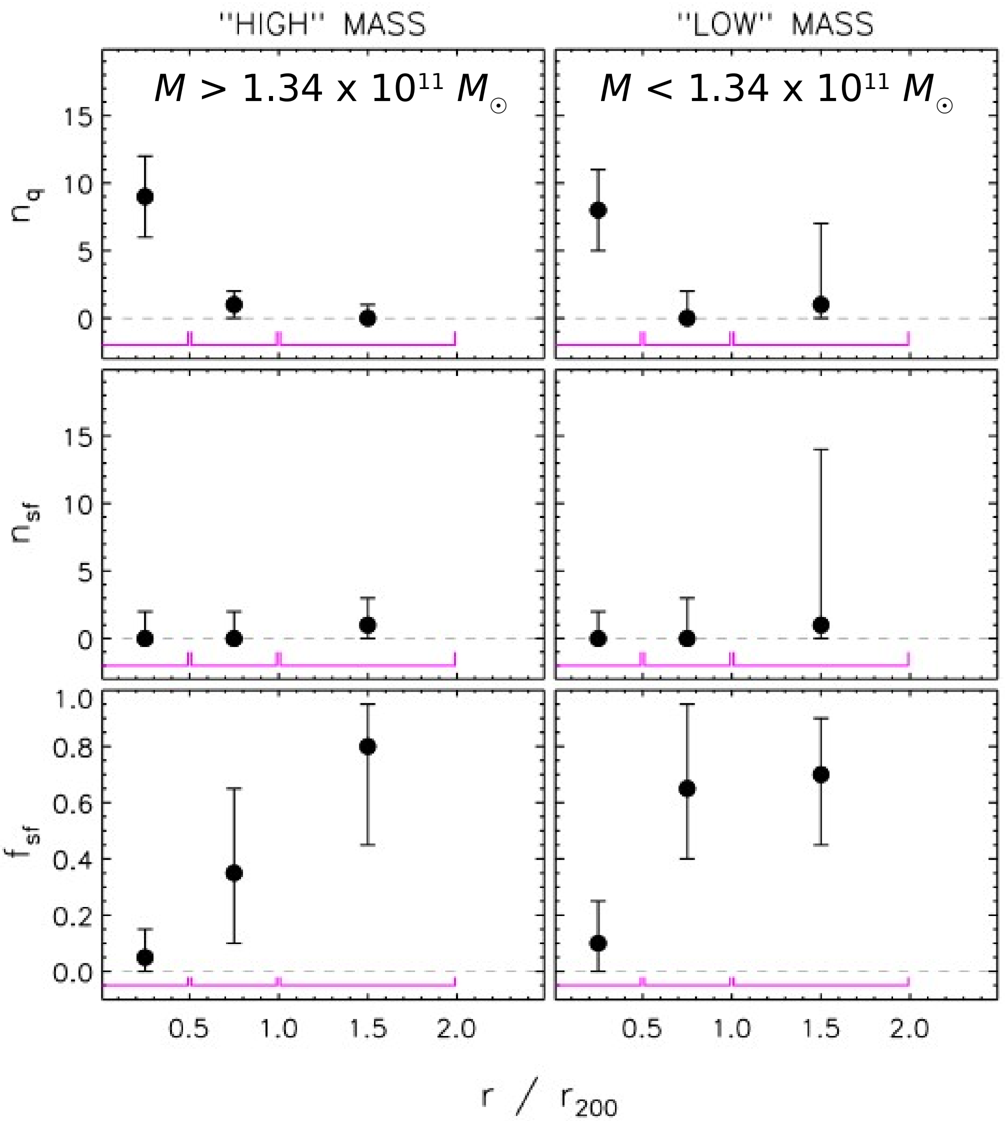


Lu et al. (2012)

Star formation

SFR-density relation appears to have been established as early as z ~ 2

(Chuter et al. 2011; Raichoor & Andreon 2012; Quadri et al. 2012)

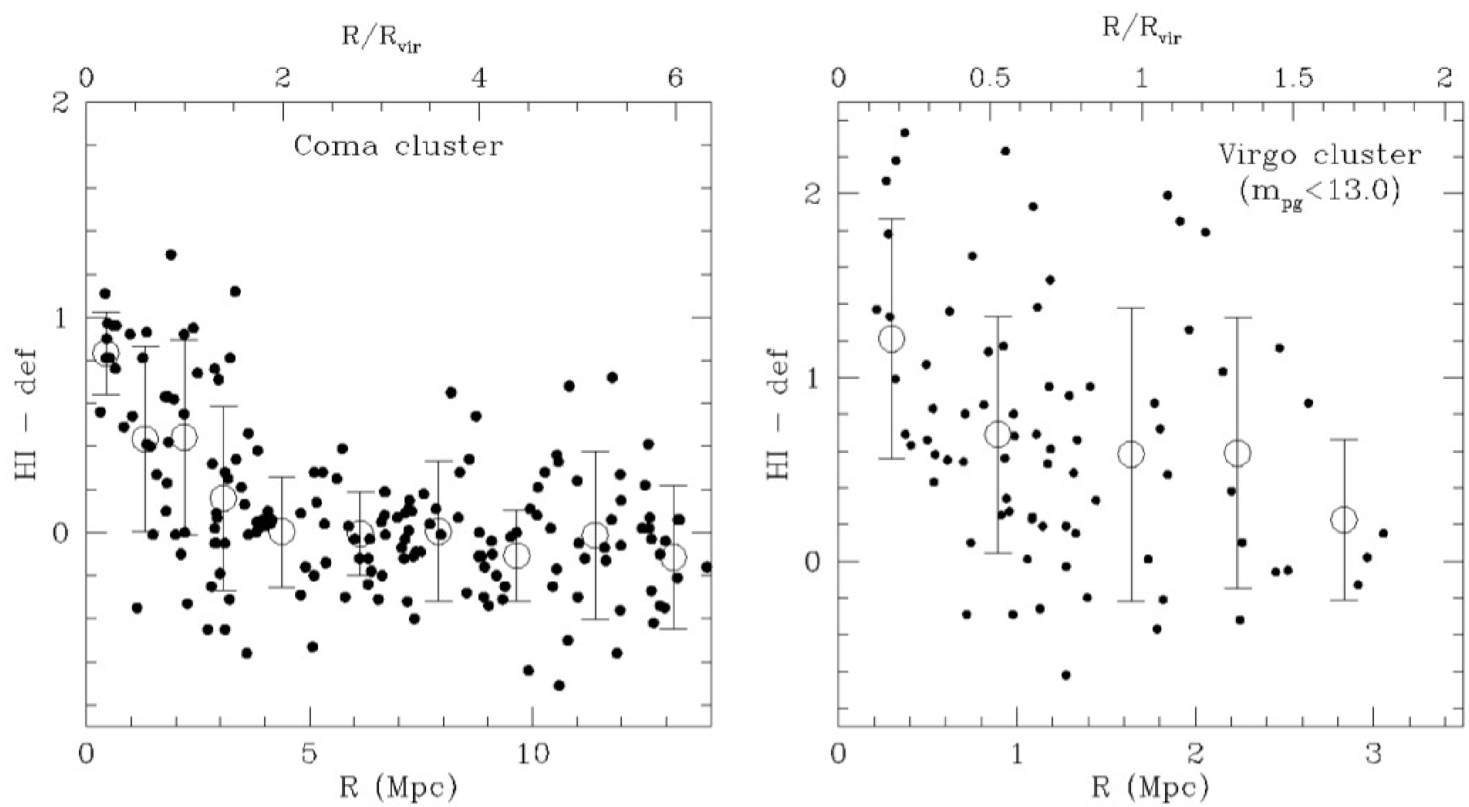


JKCS 041 (Raichoor & Andreon 2012)

Gas content

Late-type galaxies are HI deficient at low redshift, but not H_2 deficient (Giovanelli & Haynes 1985; Boselli et al. 1997)

HI deficiency not seen in all clusters – e.g. A1367 (Scott et al. 2010)



Boselli & Gavazzi (2006)

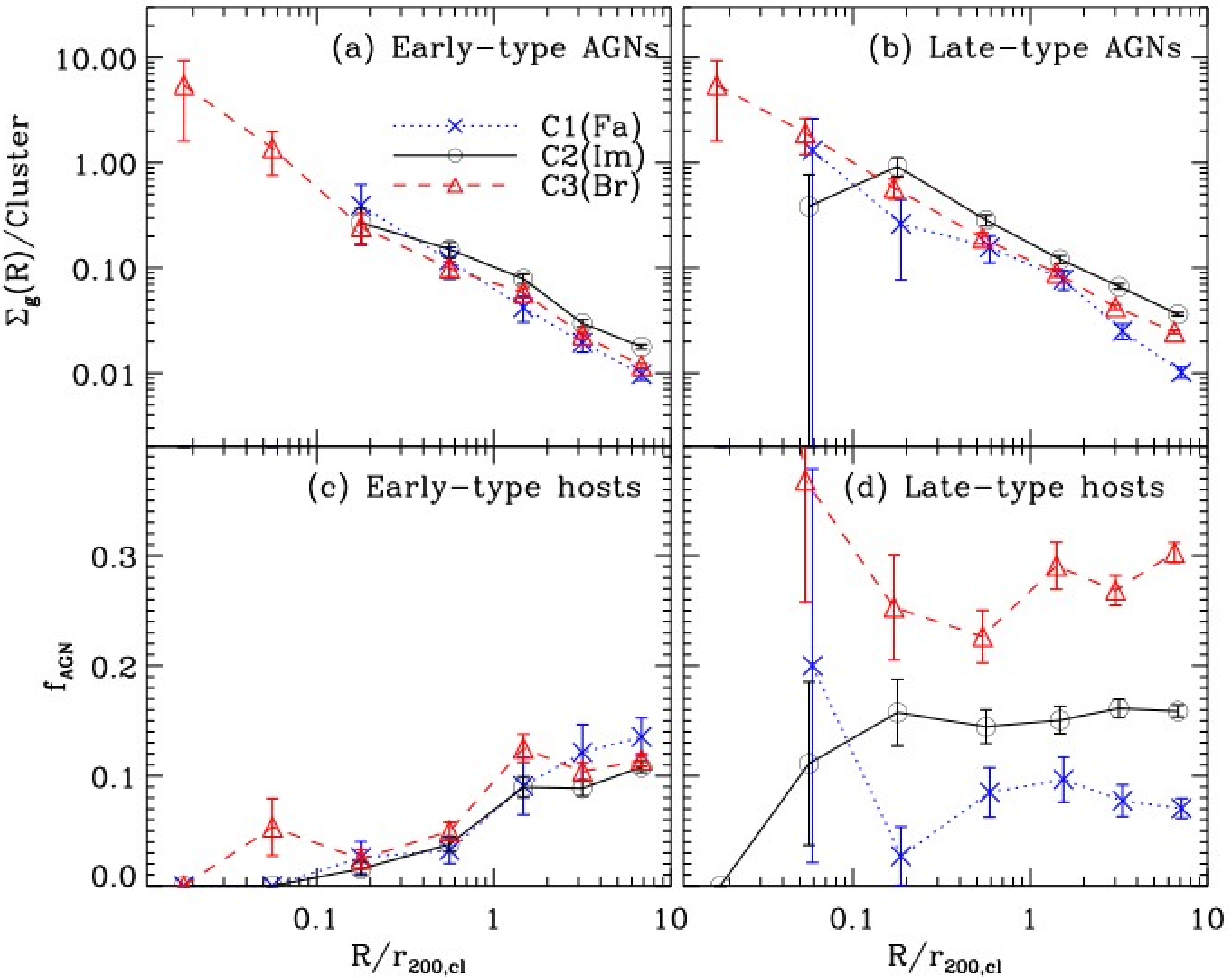
AGN activity

AGN activity is reduced significantly relative to the field

(Hwang et al. 2012)

AGN fraction tends to be higher for S0s than ellipticals

(Wilman & Erwin 2012)



Hwang et al. (2012)

Summary of Part I

- Cluster galaxies at $z = 0$ are predominantly low-luminosity S0s and high-luminosity ellipticals.
- At higher z, spiral fraction increases, and S0 fraction decreases. Elliptical fraction remains constant.
- Star formation rate is suppressed beyond virial radius, but specific rate is same in clusters and field.
- Evidence for deficient HI/HII gas content and reduced early-type AGN fraction in clusters.

Transformation mechanisms

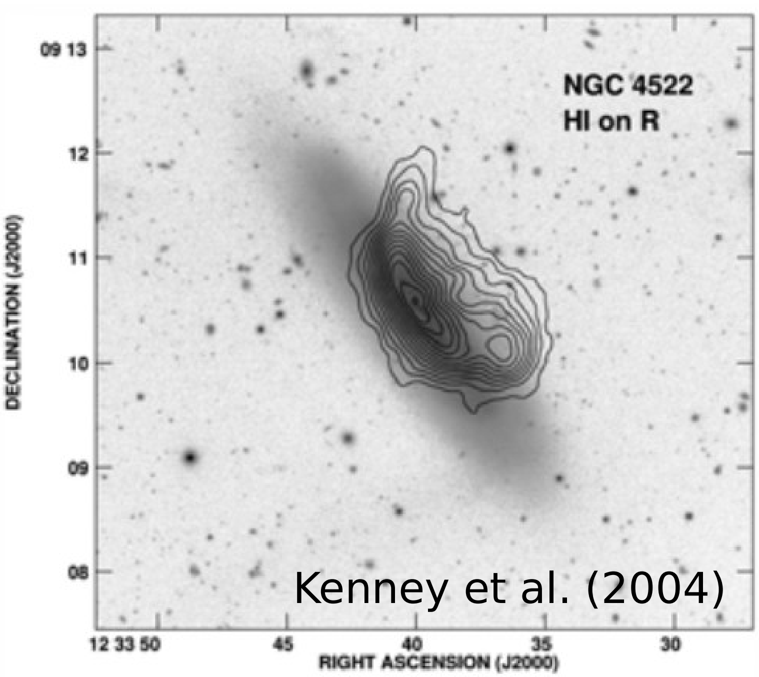
Transformation mechanisms

- Ram pressure stripping and strangulation
- Tidal stripping and harassment
- Galaxy mergers
- AGN feedback
- Dynamical friction
- Viscous stripping
- Evaporation

Ram pressure stripping

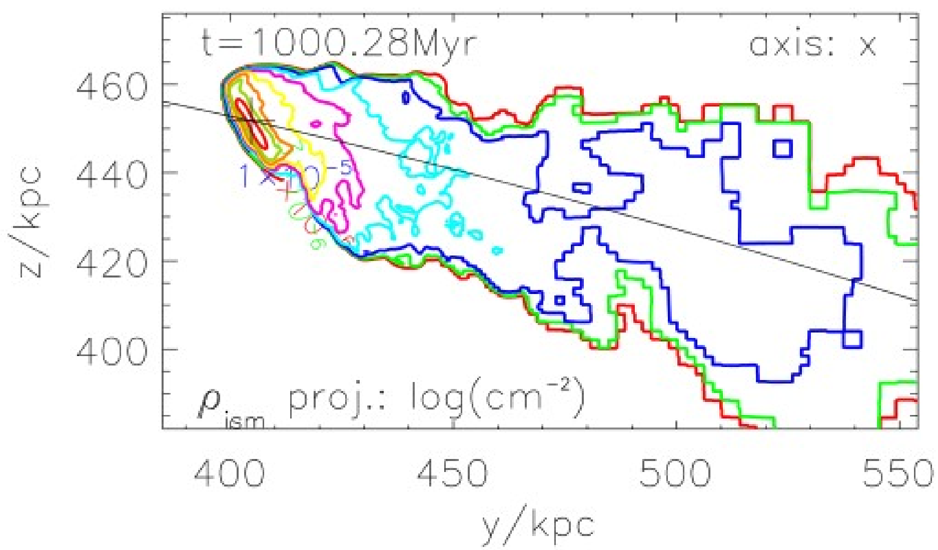
Passage through intracluster medium (ICM) removes gas due to effective wind pressure, leaves stars/dark matter alone (Gunn & Gott 1972):

$$\nabla P_{\mathrm{ram}} = \nabla(\rho_{\mathrm{ICM}} v_{\mathrm{gal}}{}^2) \quad \text{vs.} \quad \rho_{\mathrm{gal}} \nabla \phi_{\mathrm{gal}}$$



Kenney et al. (2004)

Gas wakes ~ 50 – 100 kpc

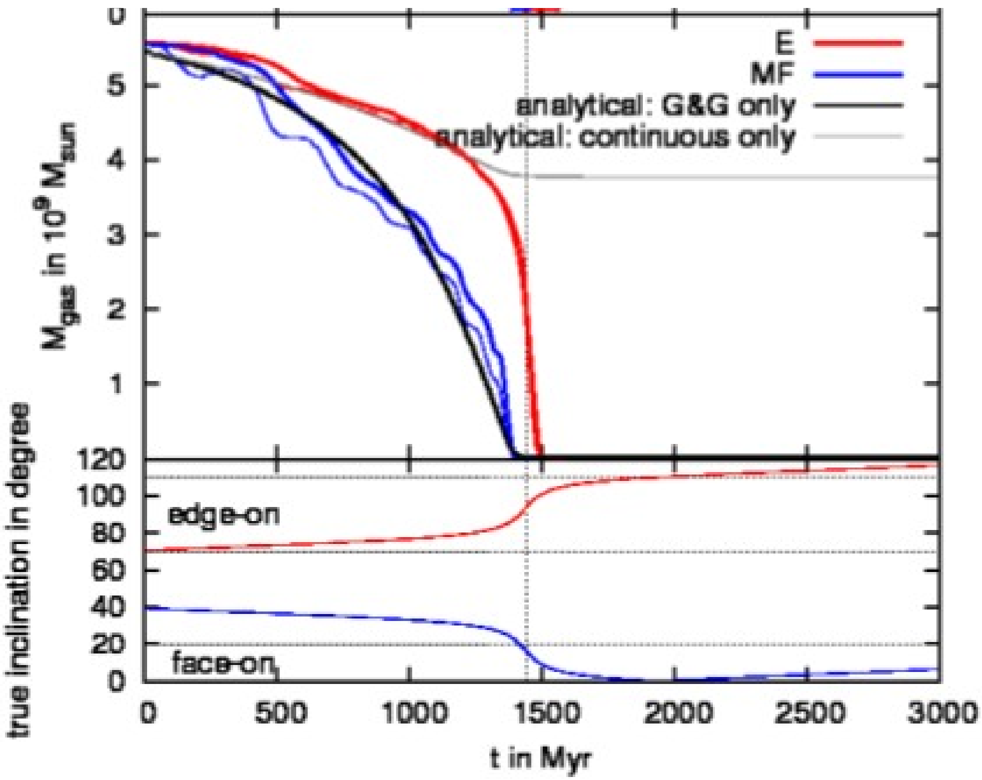


Roediger & Brüggen (2008)

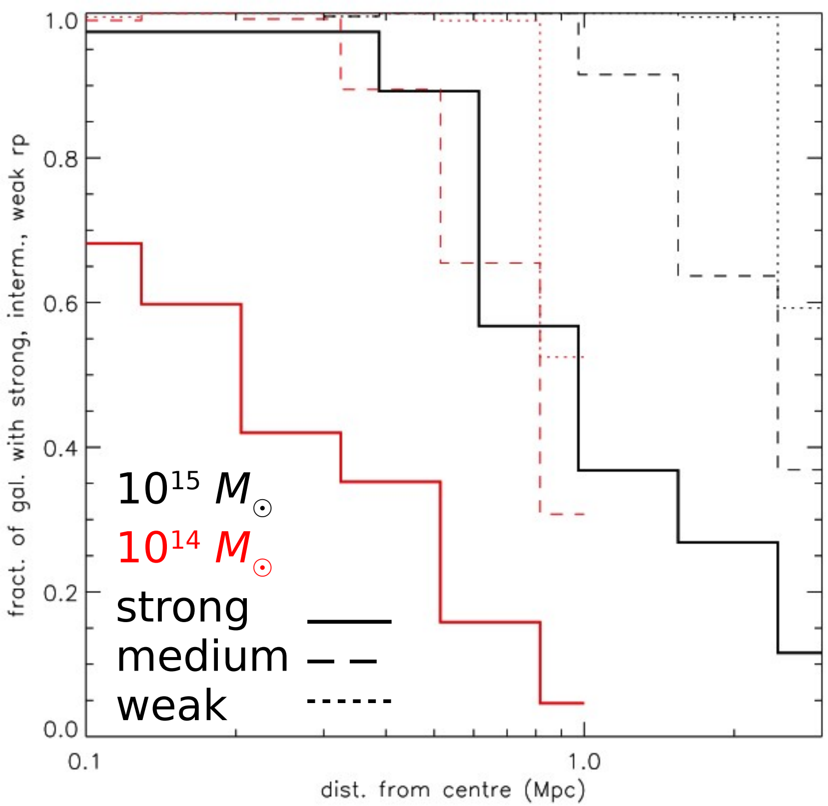
Ram pressure stripping

Gunn & Gott criterion underestimates mass loss for edge-on galaxies

Most galaxies experience strong stripping at some point



Roediger & Brüggen (2007)



Brüggen & De Lucia (2008)

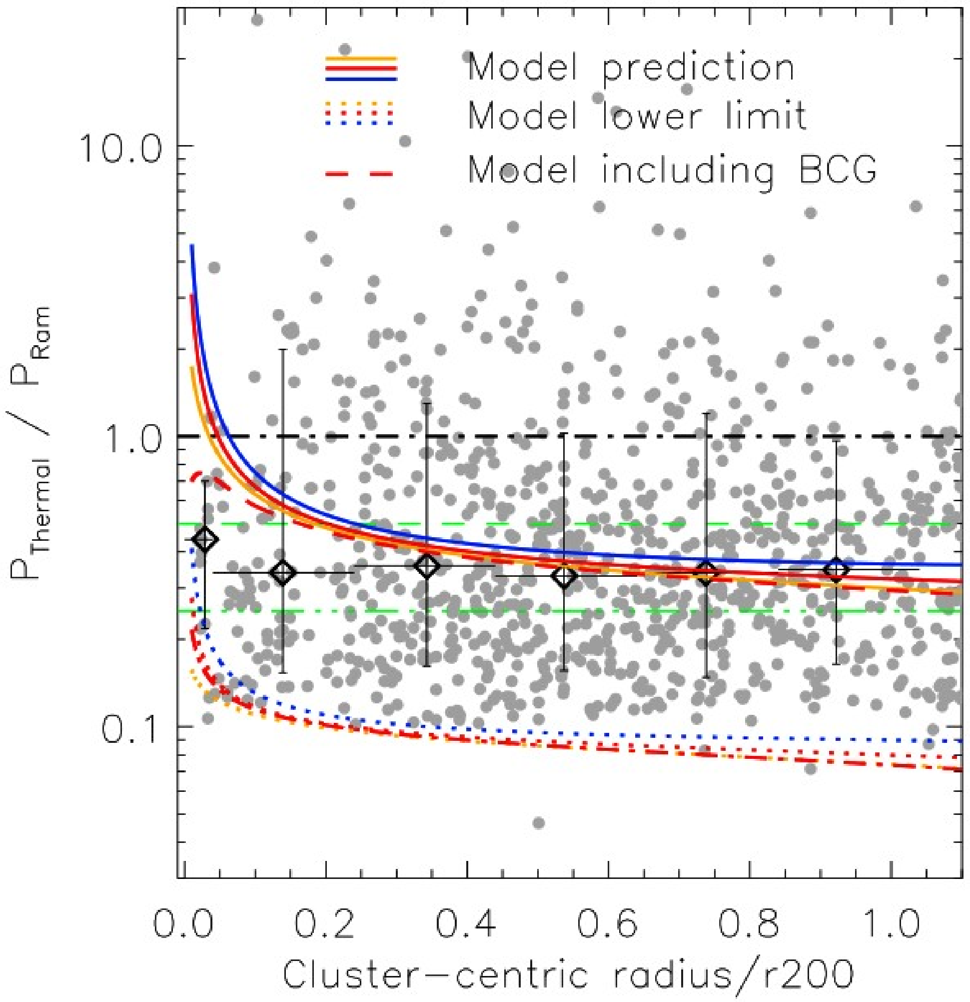
Strangulation

Removal of weakly bound hot gas from galaxies reduces fuel for eventual star formation (Larson et al. 1980)

Competition between ram pressure and confinement pressure typically favors ram pressure in groups

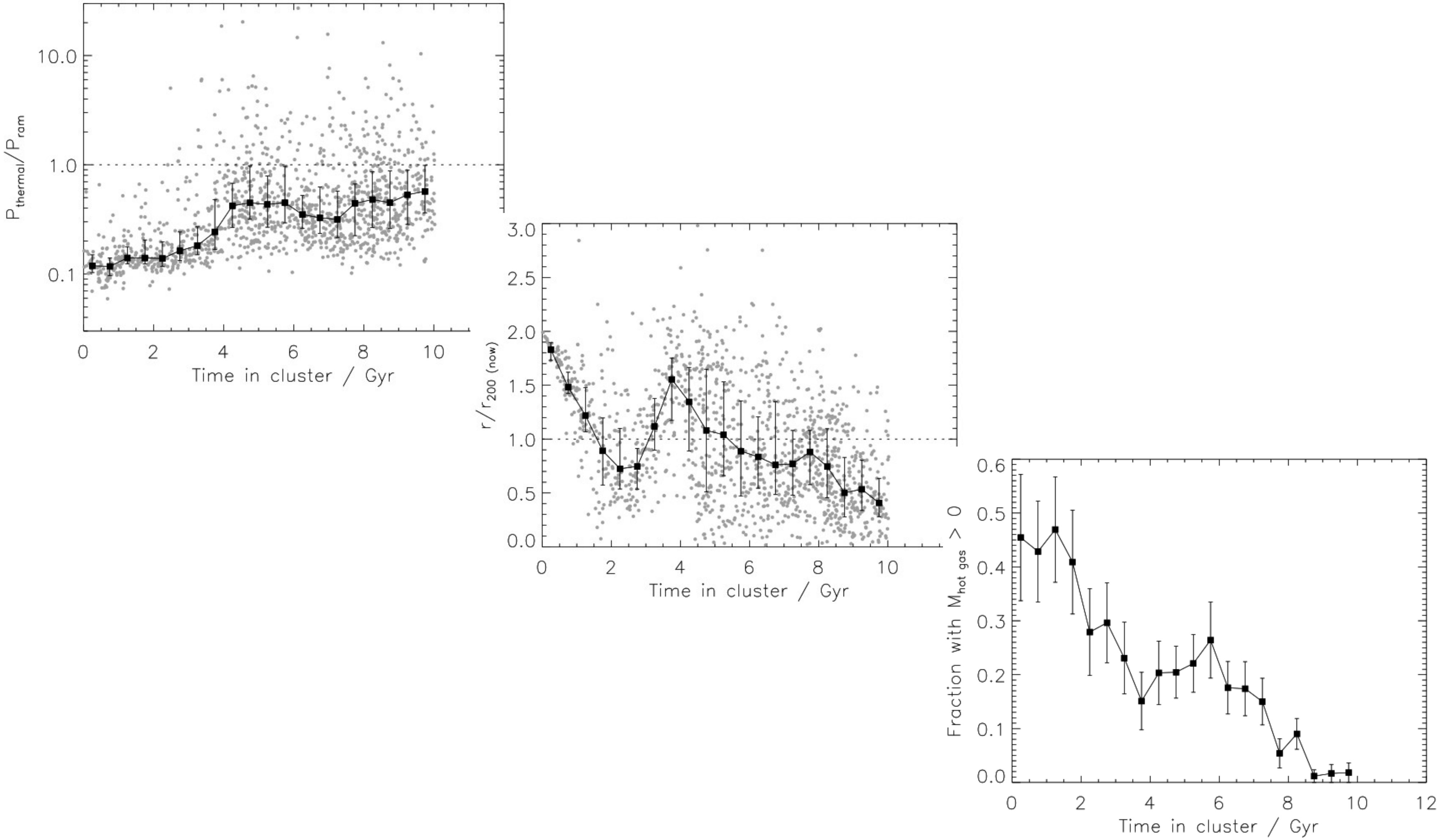
Distribution of pressure ratio is independent of parent halo mass

(Bahe et al. 2012)



Bahe et al. (2012)

Strangulation



Bahe et al. (2012)

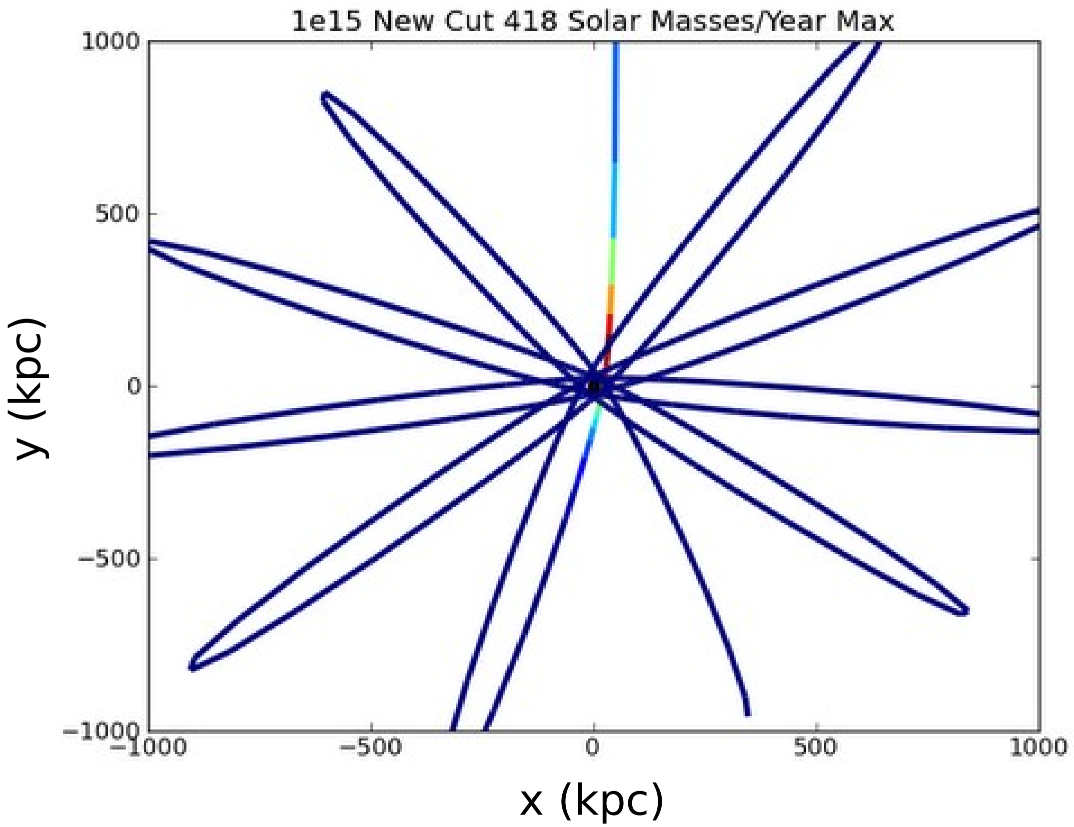
Tidal stripping

Tidal stripping removes weakly bound material at edge of galaxy when background potential gradient is large (Byrd & Valtonen 1990; Gnedin 2003)

Competition among:

- Compactness of galaxy
- Potential gradient
- Orbital speed

Most effective during first orbit on infall into cluster



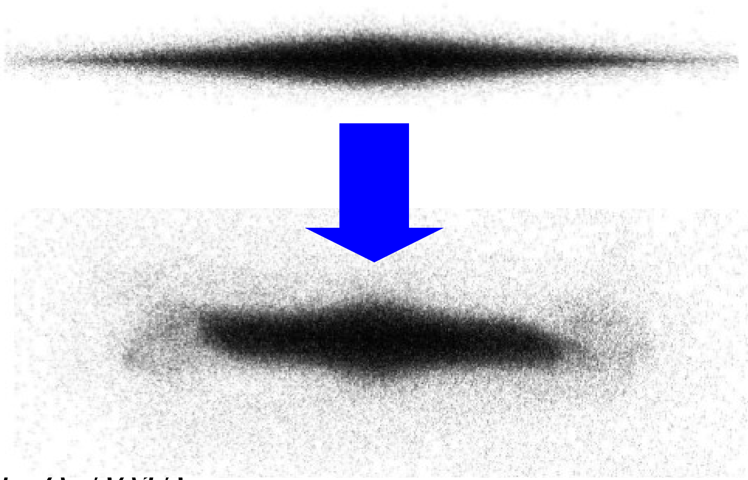
R. Chamberlain

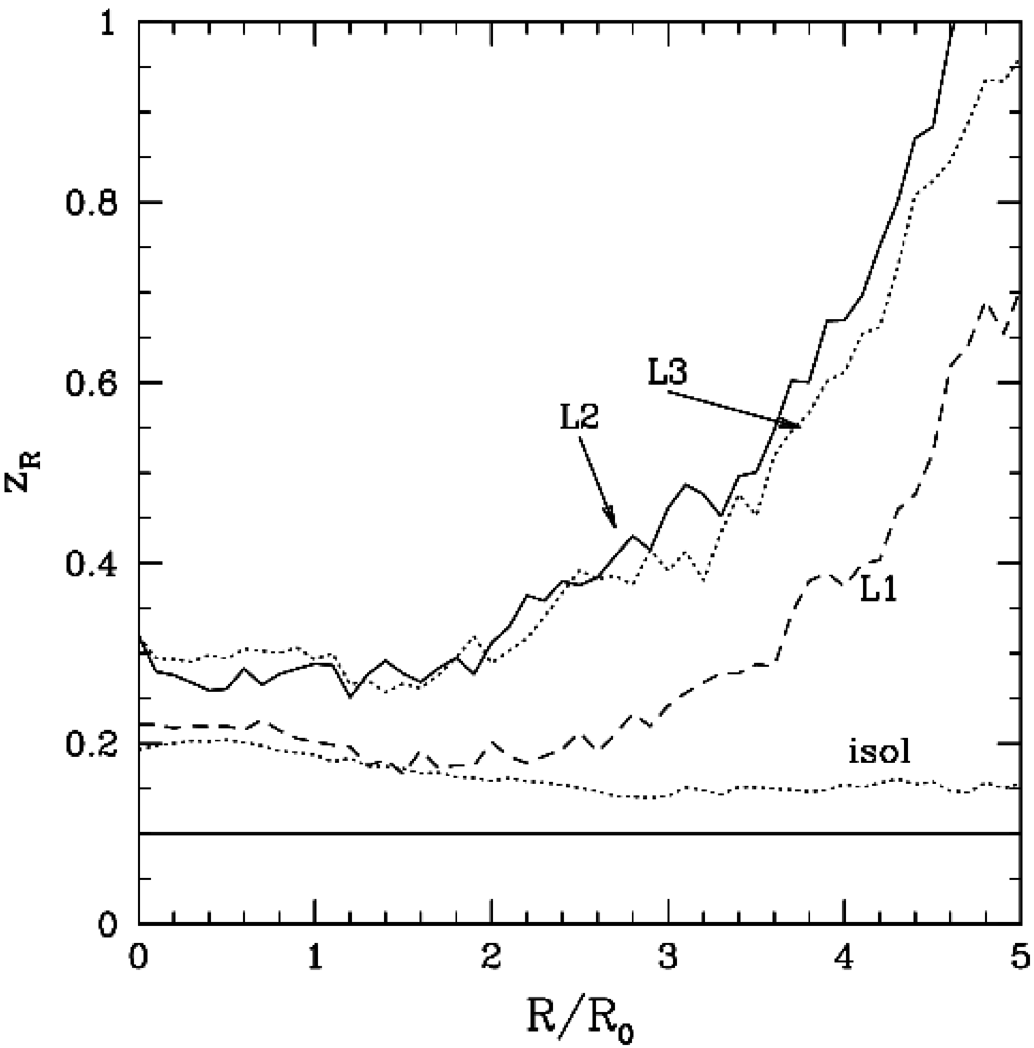
Tidal stripping

Maximum density encountered along orbit determines where density profile is truncated:

$$\rho_{tidal} \sim 2 \times 10^{-3}\, M_\odot\, \mathrm{pc}^{-3}$$

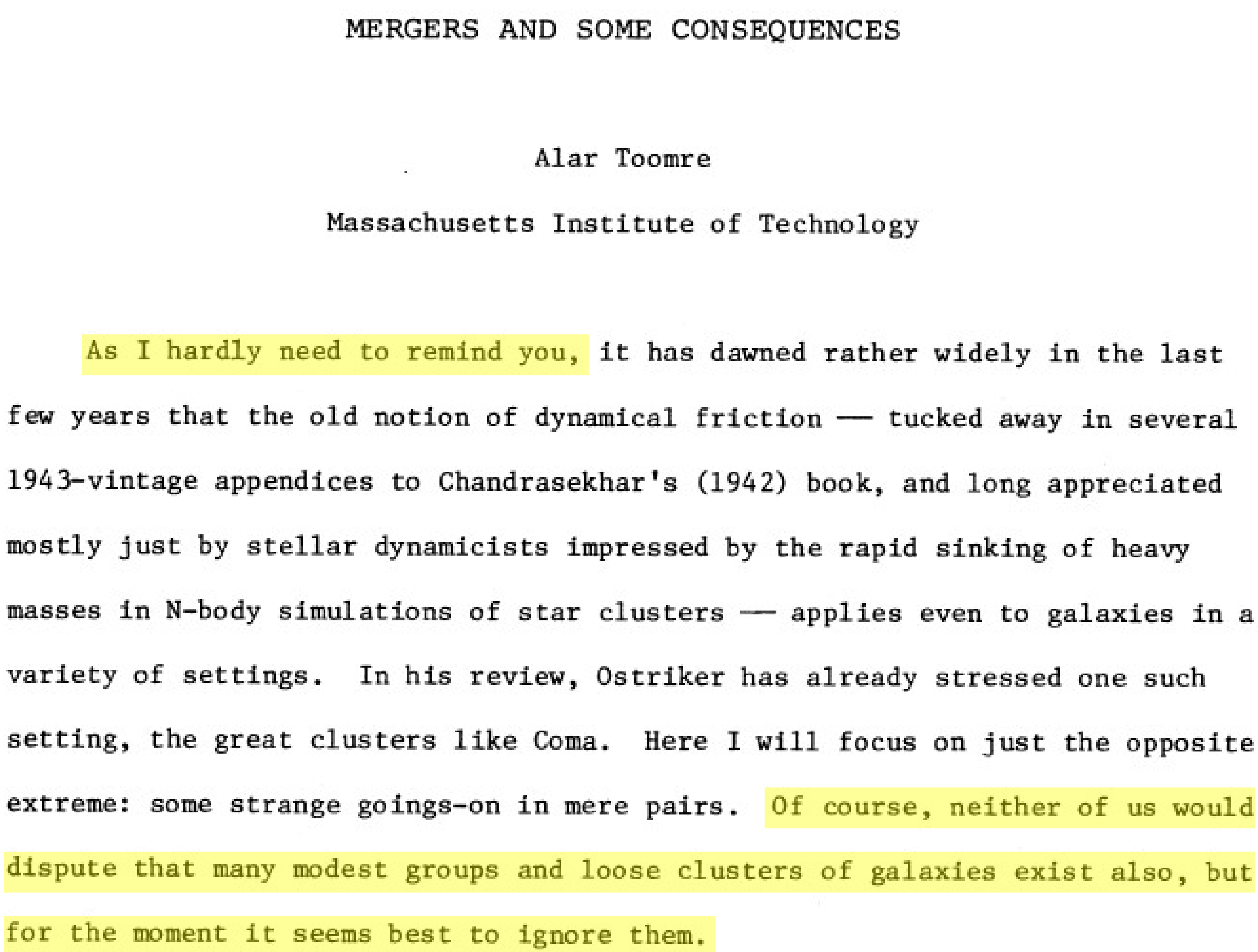
Heating (not destruction) of disks: spiral ⟶ S0





Gnedin (2003)

Galaxy mergers

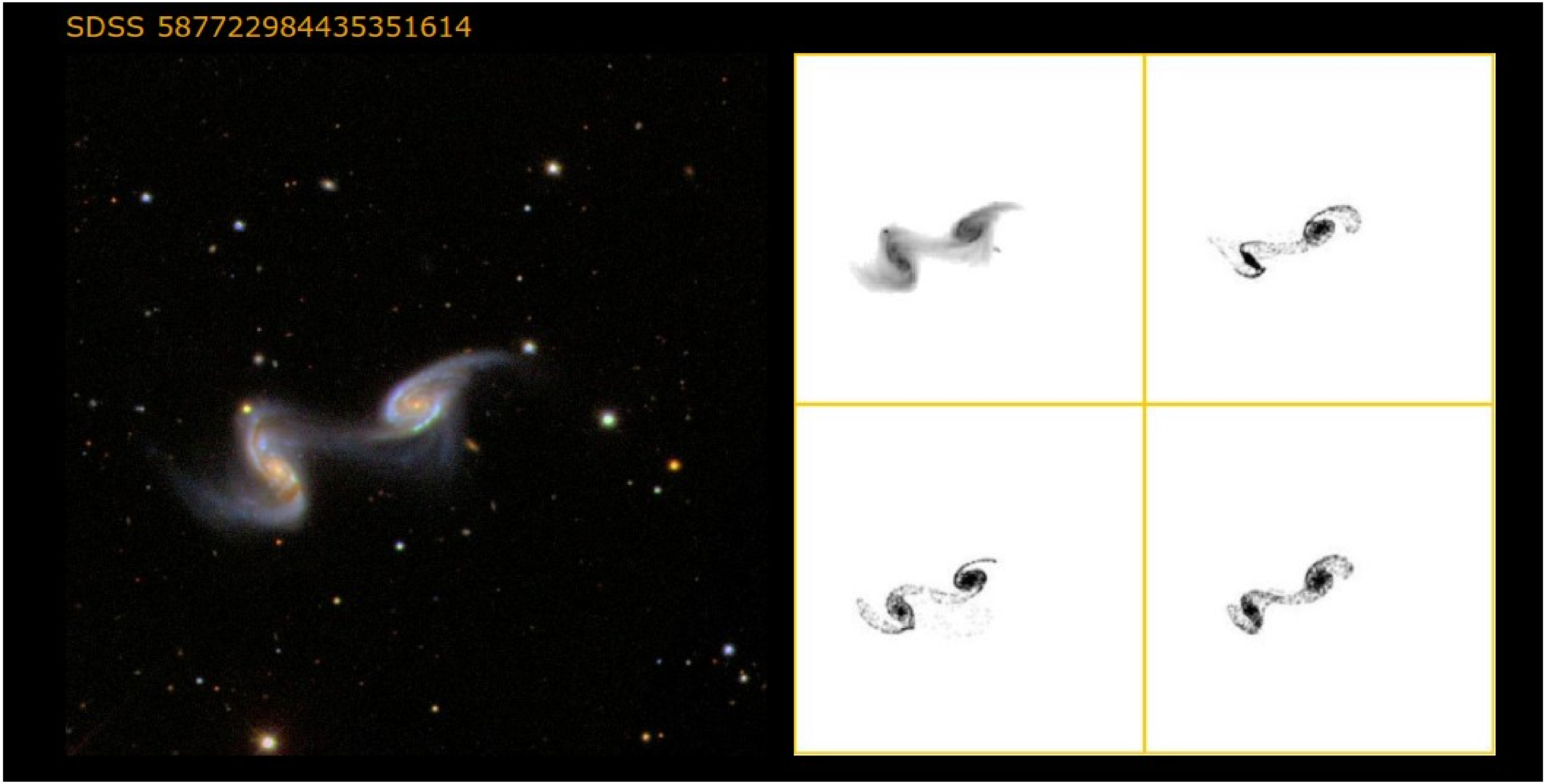

MERGERS AND SOME CONSEQUENCES

Alar Toomre

Massachusetts Institute of Technology

As I hardly need to remind you, it has dawned rather widely in the last few years that the old notion of dynamical friction — tucked away in several 1943-vintage appendices to Chandrasekhar's (1942) book, and long appreciated mostly just by stellar dynamicists impressed by the rapid sinking of heavy masses in N-body simulations of star clusters — applies even to galaxies in a variety of settings. In his review, Ostriker has already stressed one such setting, the great clusters like Coma. Here I will focus on just the opposite extreme: some strange goings-on in mere pairs. Of course, neither of us would dispute that many modest groups and loose clusters of galaxies exist also, but for the moment it seems best to ignore them.

Galaxy mergers



http://mergers.galaxyzoo.org

Galaxy mergers

Mergers tend to destroy disks (Toomre 1977), but are rare in clusters (Richstone & Malamuth 1983):

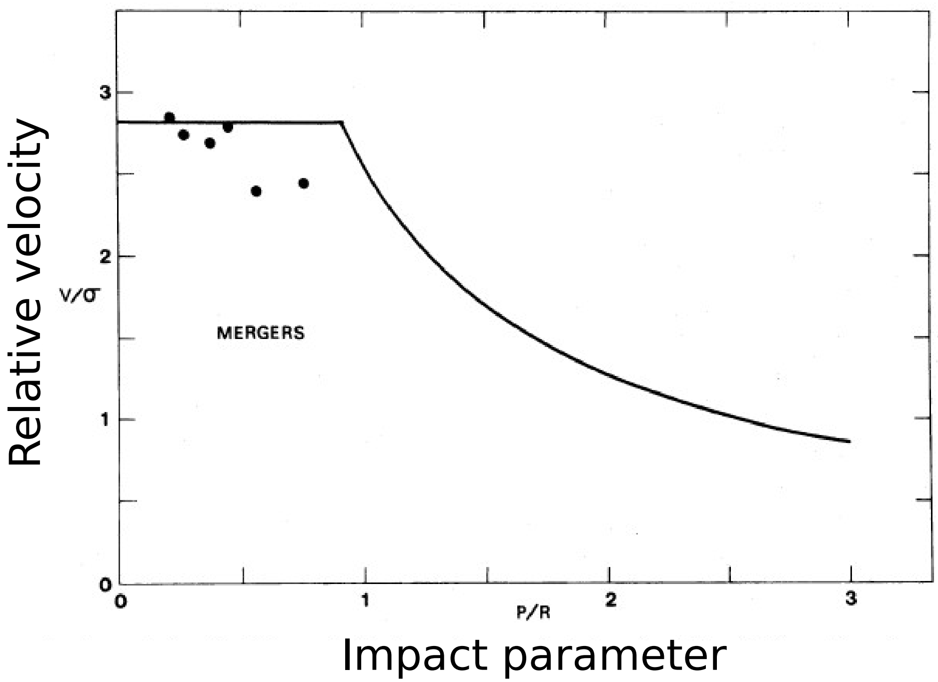
$$t_{\rm merge} \sim [f_{\rm merge}(\sigma) n_{\rm gal} r_{\rm tidal}{}^2 \sigma]^{-1} > t_{\rm Hubble}$$

Tidally ejected material comes from all radii; returning tidal tails may re-form a weak stellar disk

(Mihos 2004)

Groups are a more suitable environment

(Zabludoff & Mulchaey 1998)



Richstone & Malamuth (1983)

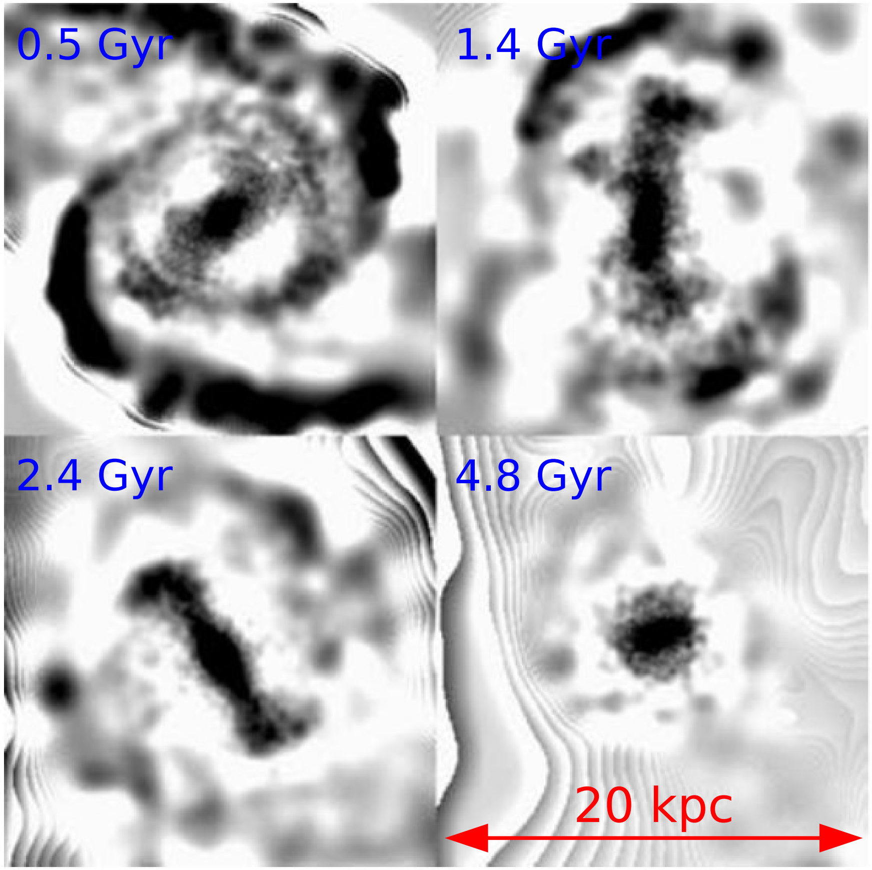
Harassment

Repeated high-speed galaxy-galaxy interactions can drive morphological transformation (Moore et al. 1996)

Important throughout cluster until cluster tide has truncated disk

Like other processes, tends to produce S0-like galaxies rather than ellipticals

Can trigger bar instabilities that actually enhance star formation



Mastropietro et al. (2005)

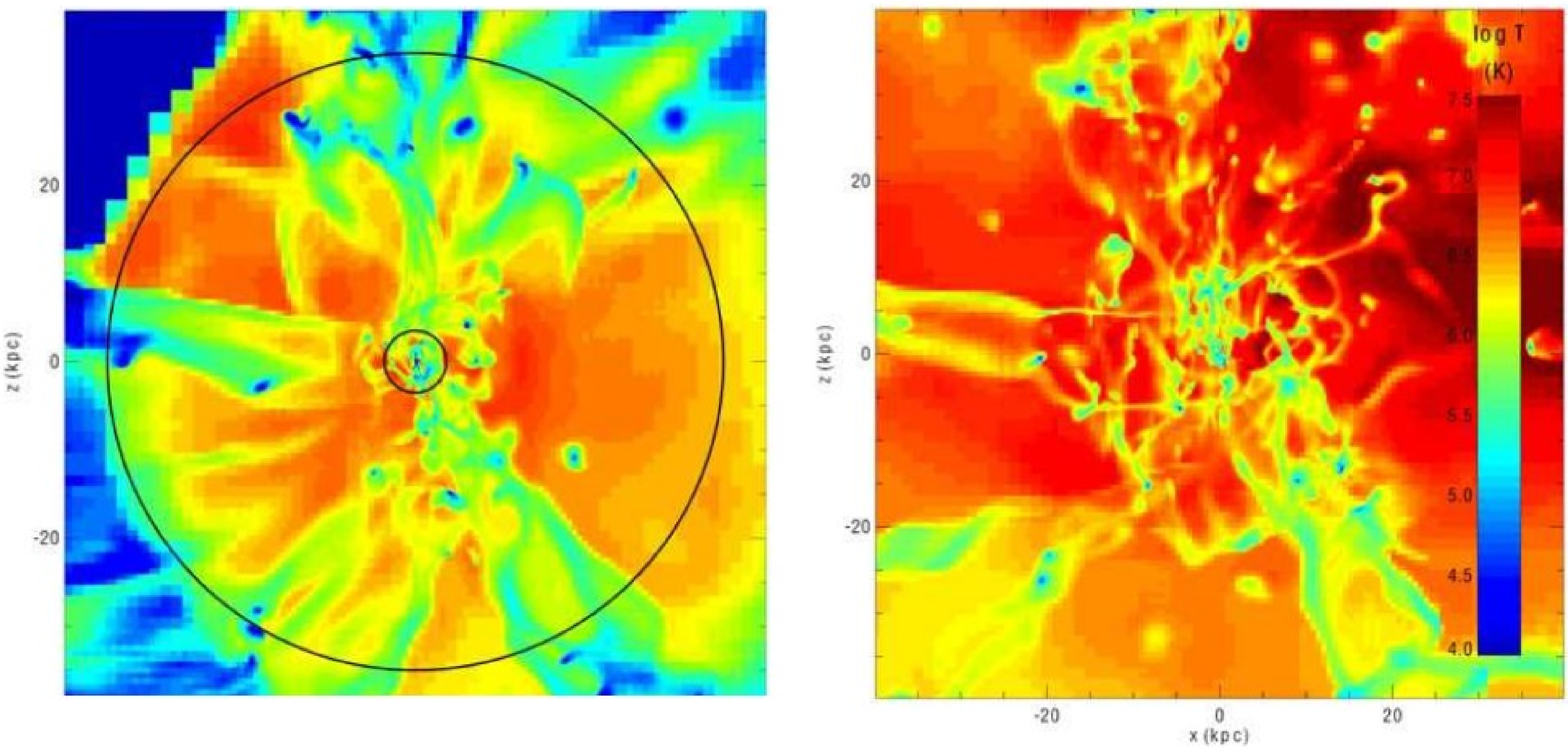
AGN feedback

AGN feedback removes cold gas

Has biggest effects at high redshift, when potentials shallow

without feedback

with feedback



Dubois et al. (2012)

AGN feedback

Early AGN feedback can drive gas loss that reduces SFR in BCG progenitors

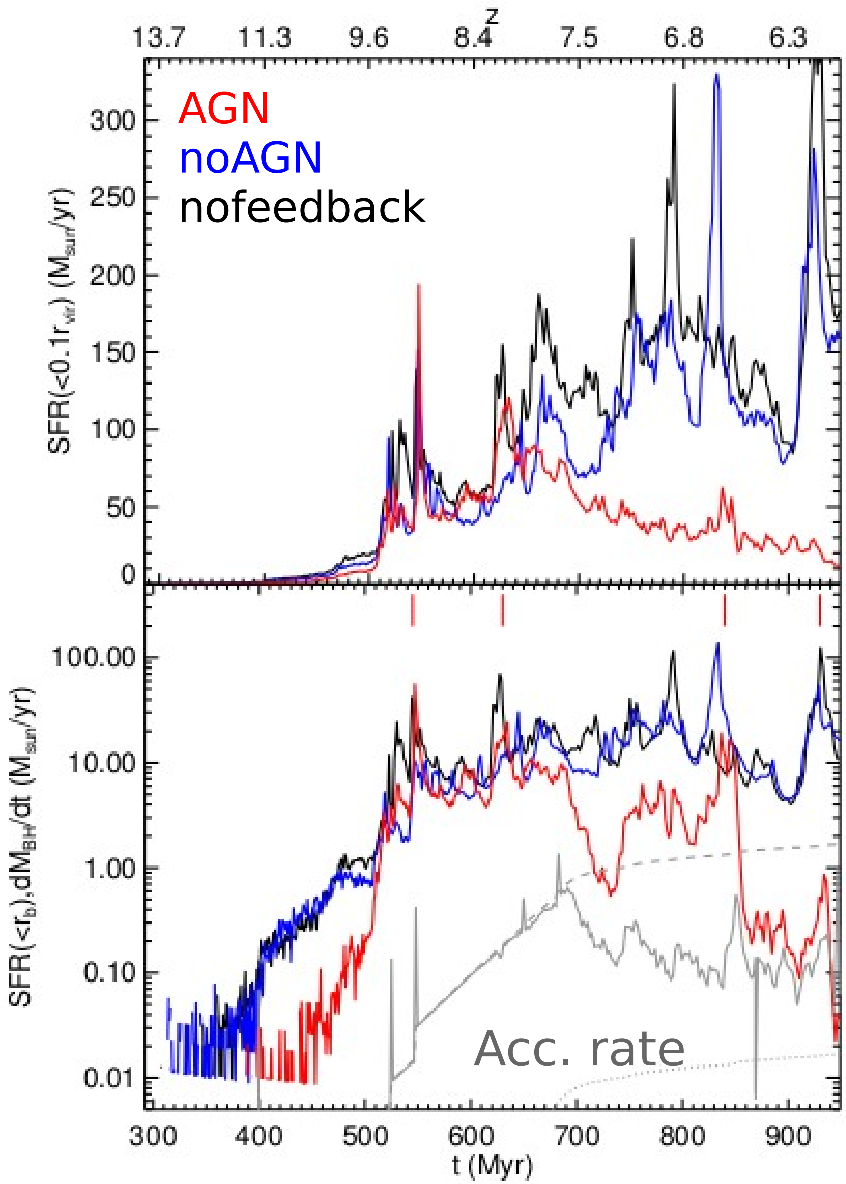
Significant (~ 35%) effect on dark matter density profile

Baryon fraction reduced by 30%

Disturbance of nearby filaments

Supernova feedback is very inefficient

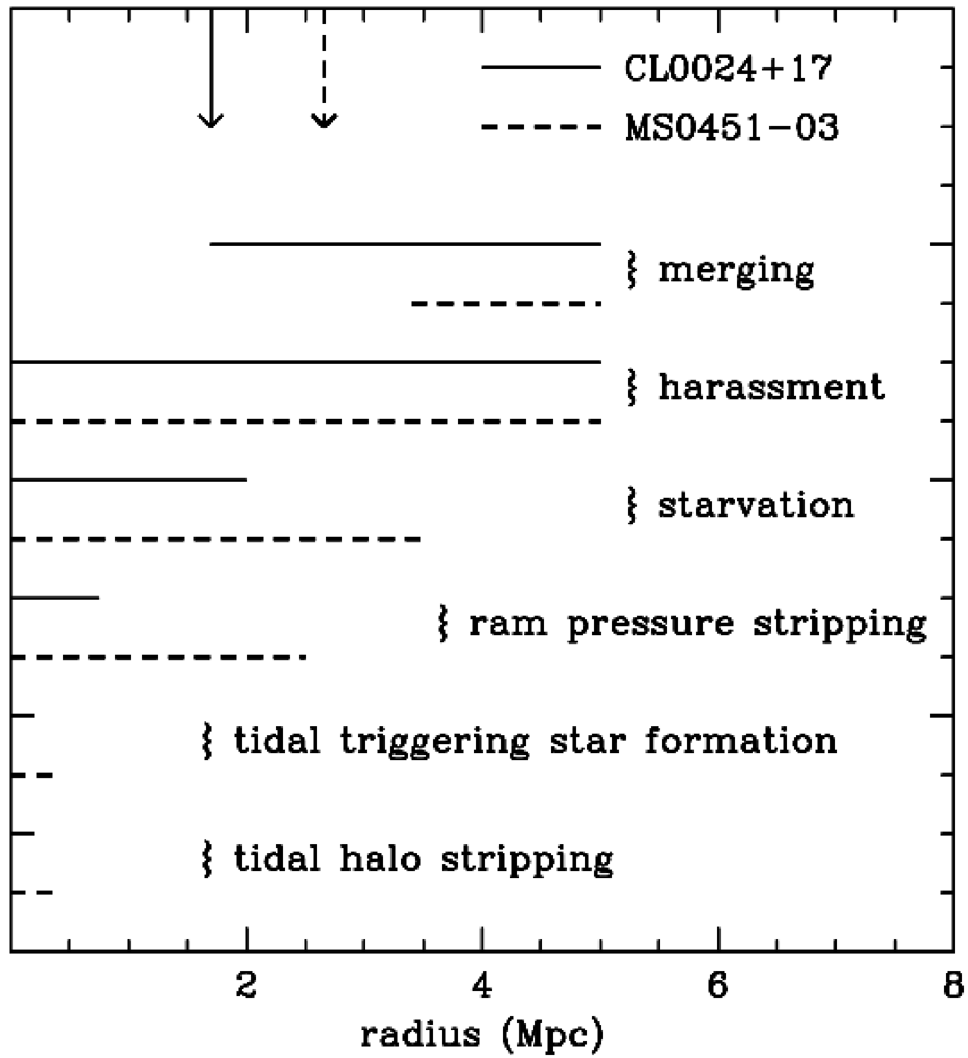
(Dubois et al. 2012)



Dubois et al. (2012)

Synthesis

Location of action



Moran et al. (2007)

Synthesis

Galaxy mergers and harassment drive morphological transformation from spiral to S0 in groups/cluster infall regions (**preprocessing**).

Ram pressure stripping removes HI and HII gas as galaxies orbit within cluster; cluster tidal field strips dark matter halo (**downsizing**). (Question: what about H_2?)

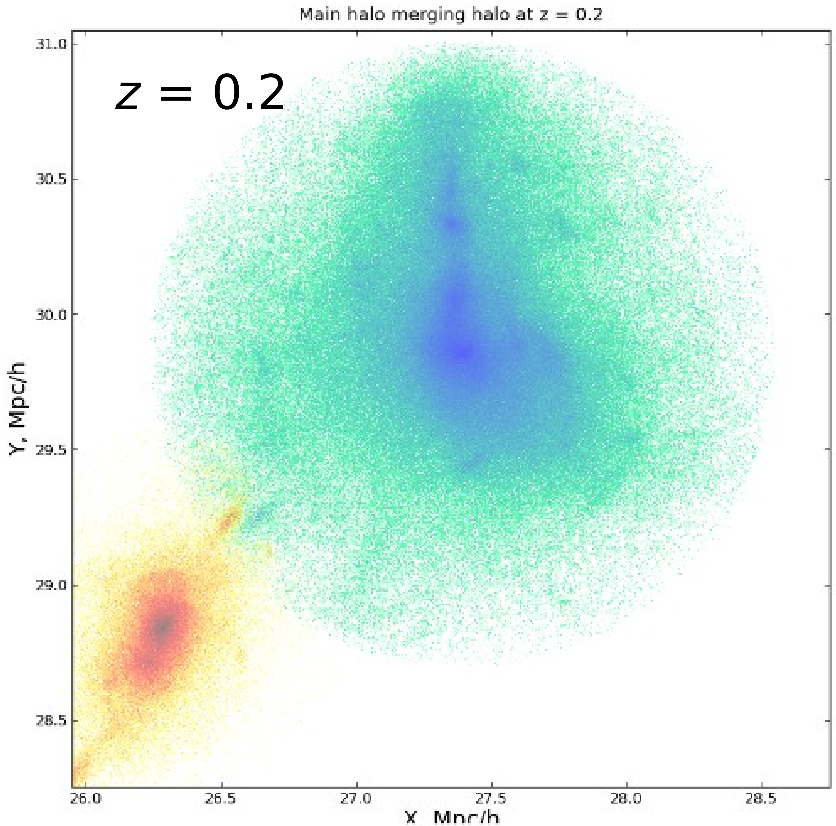
The earliest galaxies (in most massive halos) hosted AGN that limited their star formation by z ~ 2 (**mass quenching**). (Question: why don't AGN limit star formation today?)

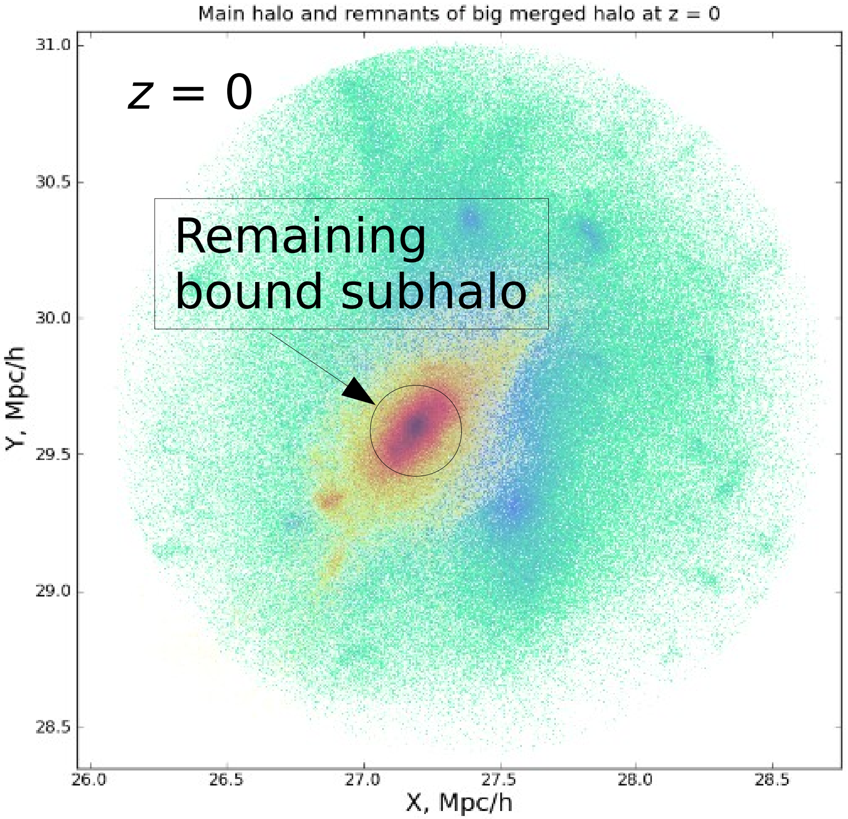
They were BCGs of groups that built the clusters. Today we know them as cluster ellipticals. The ones on radial orbits merged to form cluster BCGs.

Variable preprocessing

The degree of preprocessing may depend on location within a group – least bound galaxies are stripped first

Previous group members form coherent substructure (Cohn 2012)





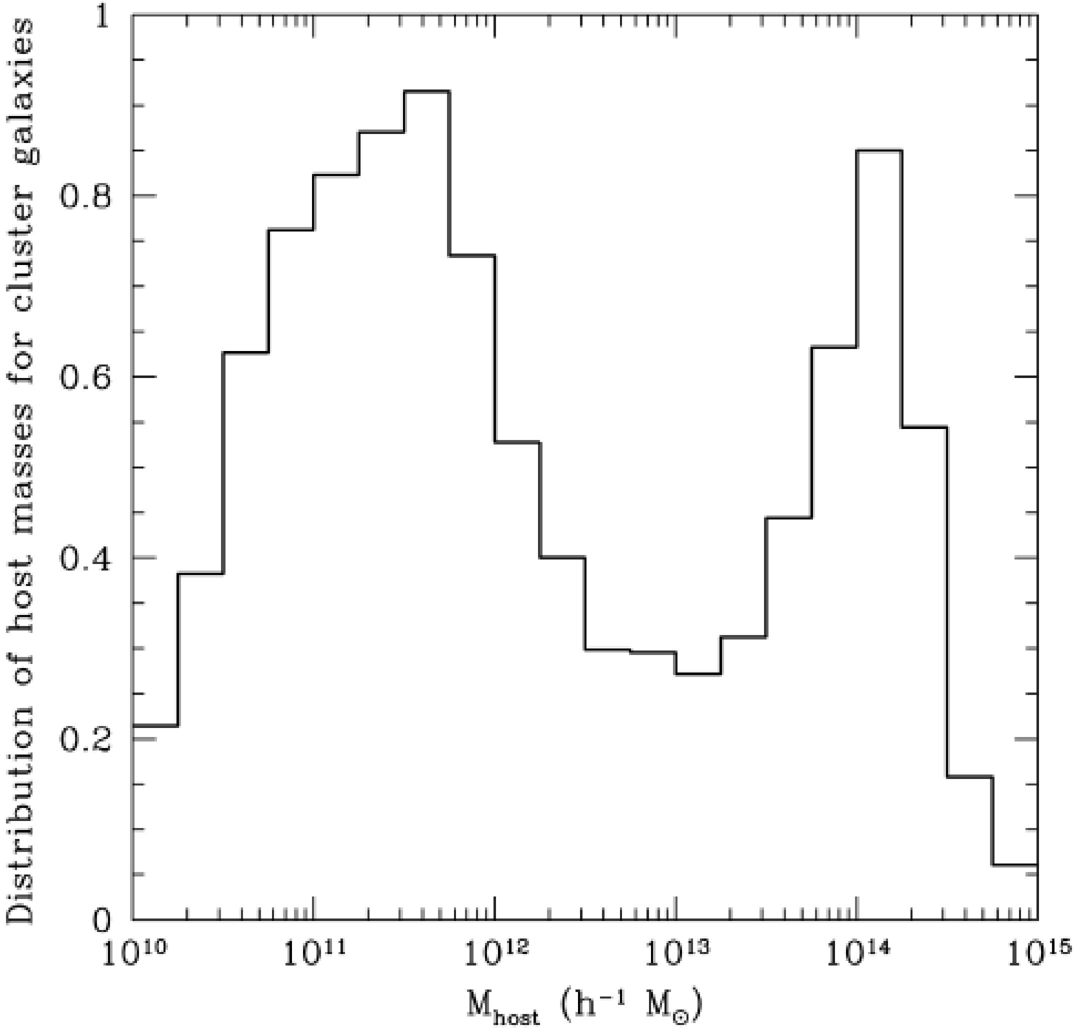
R. Vijayaraghavan

Does preprocessing really happen?

Berrier et al. (2009) claim no – 70% of galaxies fall into clusters directly from field (assume halo :: galaxy)

Totally opposite result obtained using semi-analytic model with merger tree (McGee et al. 2009)

Crucial question: what fraction of the halos that accrete onto clusters actually host galaxies of a given mass?



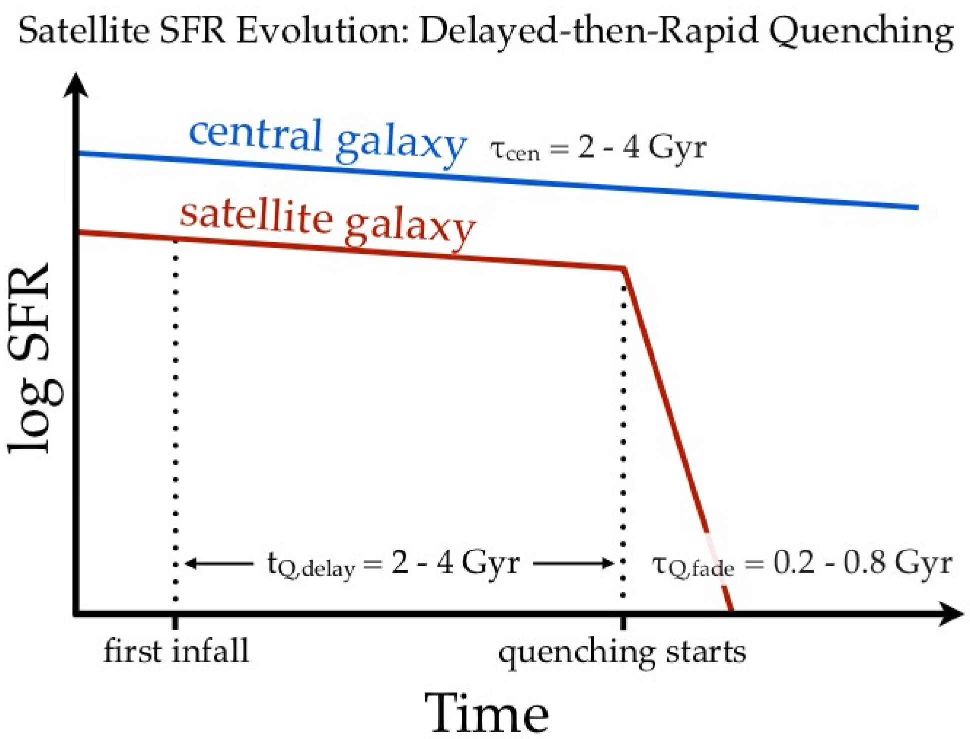
Constraining quenching timescale

Use observed SFR of central galaxies at $z \sim 0.5$ to establish initial conditions for subhalos in N-body simulations

Constrain quenching timescale by fitting SFR distribution of satellites at $z = 0$

Galaxies continue to form stars while in groups, so mass rank = luminosity rank

This allows subhalo abundance matching (SHAM) to work



Wetzel et al. (2012)

Cosmology

Galaxy- and cluster-based cosmological probes require accurate predictions of galaxy distributions for different cosmologies.

Simulations cannot yet (ever?) do this self-consistently.

Therefore we “paint” galaxies onto *N*-body simulations.

Painting schemes are calibrated using observations.

How do we know these work at high redshift?

Summary of Part II

- A combination of processes acts to transform spirals into S0s, reduce their masses, and suppress star formation.
- This is likely to involve some form of preprocessing in groups and filaments.
- Understanding the effects of these processes is crucial to establishing the reliability of methods for “painting” galaxies onto *N*-body simulations.