CENTRO DE ASTRO-INGENIERIA UC

Environmental effects on semi-analytic galaxies: tidal and ram pressure stripping in clusters

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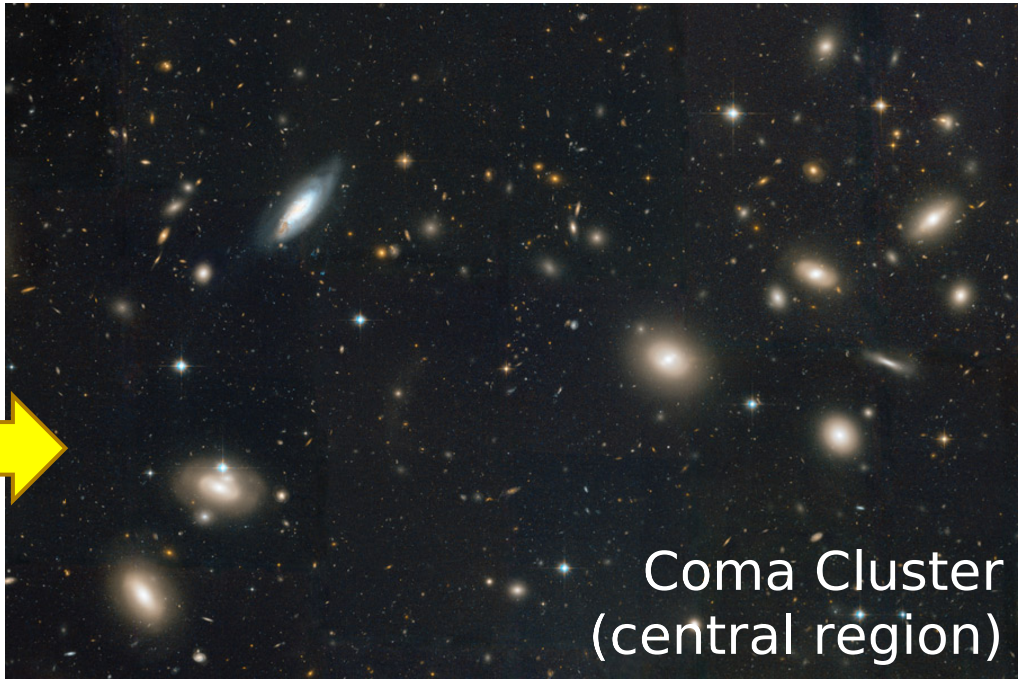
Galaxies and environment

Properties of galaxies depend on the environment in which they reside



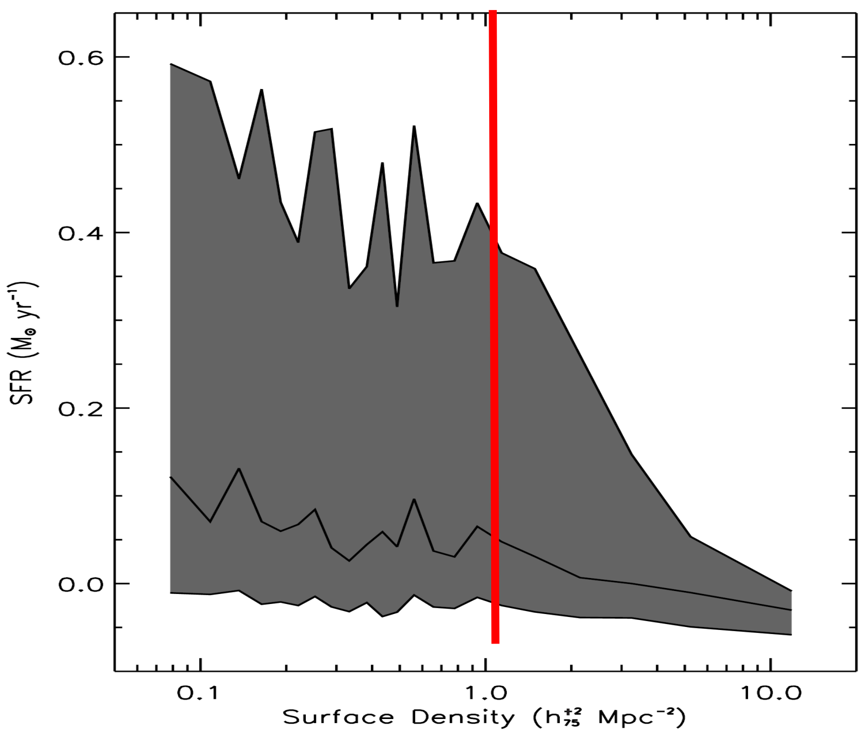
The level of star formation activity in galaxy groups is known to be suppressed relative to the field.

High density regions in the local Universe host mostly early type galaxies characterized by a lower level of SF activity than the field (mostly late-type galaxies)

SFR-density relation

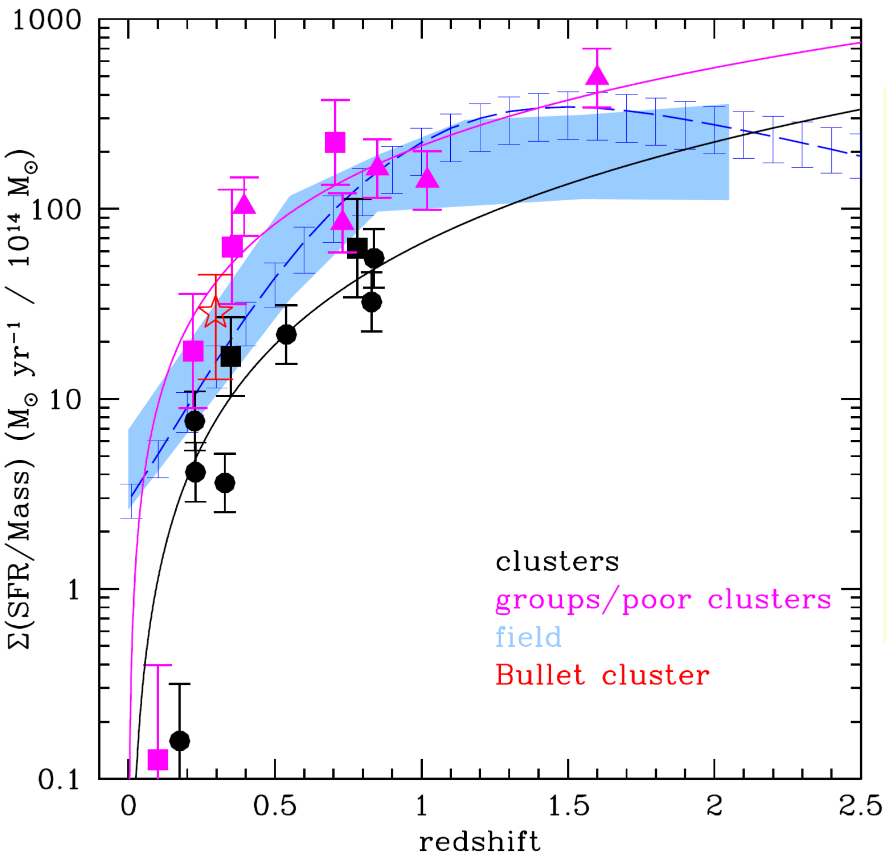
(Hashimoto et al. 1998; Lewis et al. 2002; Gómez et al. 2003)

"Break" at gx surface density of 1 h^2_{75} Mpc^{-2} corresponds to clustercentric radii ~2-3 R_{vir}, where the distribution of SFRs in cluster gx begins to differ from that of the field population.



The Σ(SFR)/*M*–z relation (Popesso et al. 2012)

Evolution of the SF activity per halo mass up to z ~= 1.6 as seen by *Herschel*



Comparison of the **Σ(SFR)/*M*–z** relation of galaxy systems (**groups / poor clusters** and **clusters**) with the corresponding relation for **field galaxies**

Groups / poor clusters:
$10^{13}\,M_\odot < M_{200} < 3 \times 10^{14}\,M_\odot$

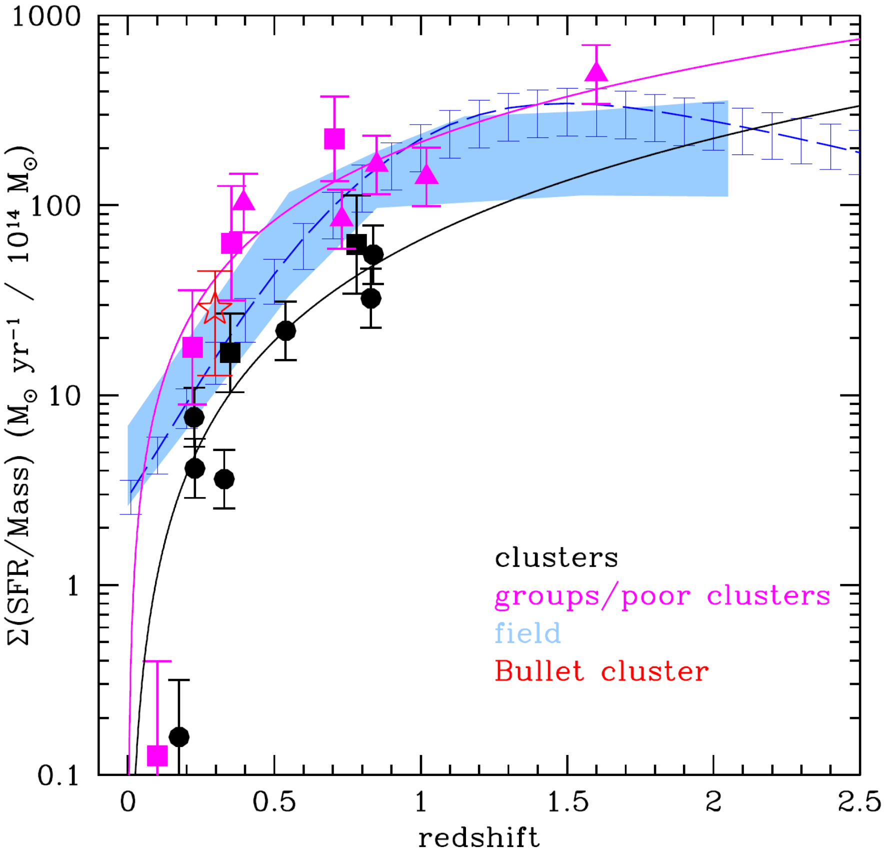
Clusters: $M_{200} \geq 3 \times 10^{14}\,M_\odot$.

Similarity of the field and the groups (SFR)/*M*–*z* relations suggests that a SF quenching effect is taking place mostly after galaxies enter the cluster environment, and not in groups before they merge into more massive structures, as would be predicted by the pre-processing scenario (Zabludoff & Mulchaey 1998; Kodama et al. 2001; Balogh et al. 2011).

We can therefore consider the field and group (SFR)/M–z relation as indicating the normal galaxy evolution, and the cluster (SFR)/M–z relation as the accelerated evolution experienced by galaxies following their accretion to more massive structures, as individuals or in groups.

The Σ(SFR)/*M*–*z* relation (Popesso et al. 2012)

Σ(SFR)/*M*–*z* relation of galaxy systems and field galaxies



At *z* > 0.2, group and field galaxies show comparable Σ(SFR)/*M*.

Clusters have lower Σ(SFR)/*M* than field galaxy halos at all *z*.

This confirms earlier indications (Finn et al. 2005; Bai et al. 2007; Koyama et al. 2010) that **Σ(SFR)/*M* is lower for systems of higher mass**, and show for the first time that **this is true at all redshifts from *z* ~ 0 to *z* ~ 0.9.**

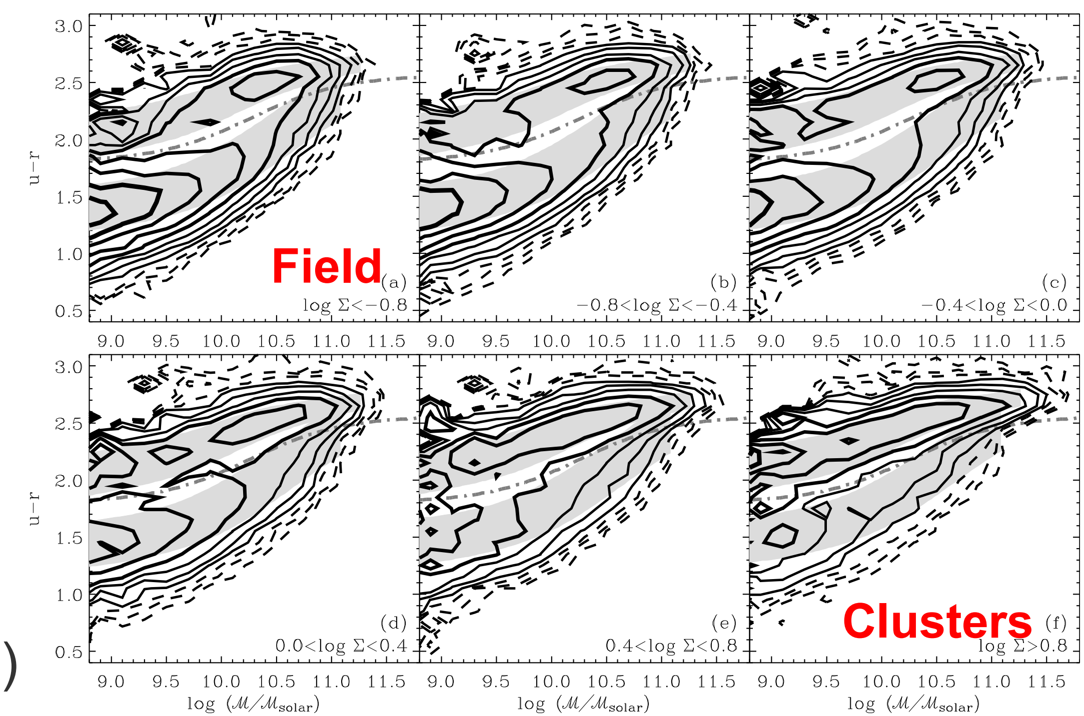
Bimodality in galaxy colours

In the local universe, galaxies form two well defined sequences in colour-magnitude space.

Red sequence	bulge-dominated, passive systems
Blue cloud	star-forming discs

Morphology-density relation:

in denser environments the population consists predominantly of elliptical galaxies (Dressler 1980; Whitmore et al. 1993)



Baldry et al. (2006)

Quenching process that would operate only in the cluster environment

Processes happening preferentially in high-density environments that **remove gas from galaxies**, suppressing their SF and/or altering their morphology:

(1) Galaxy–galaxy interactions and mergers: “harassment” (Moore et al. 1996; Perez et al. 2006a,b)

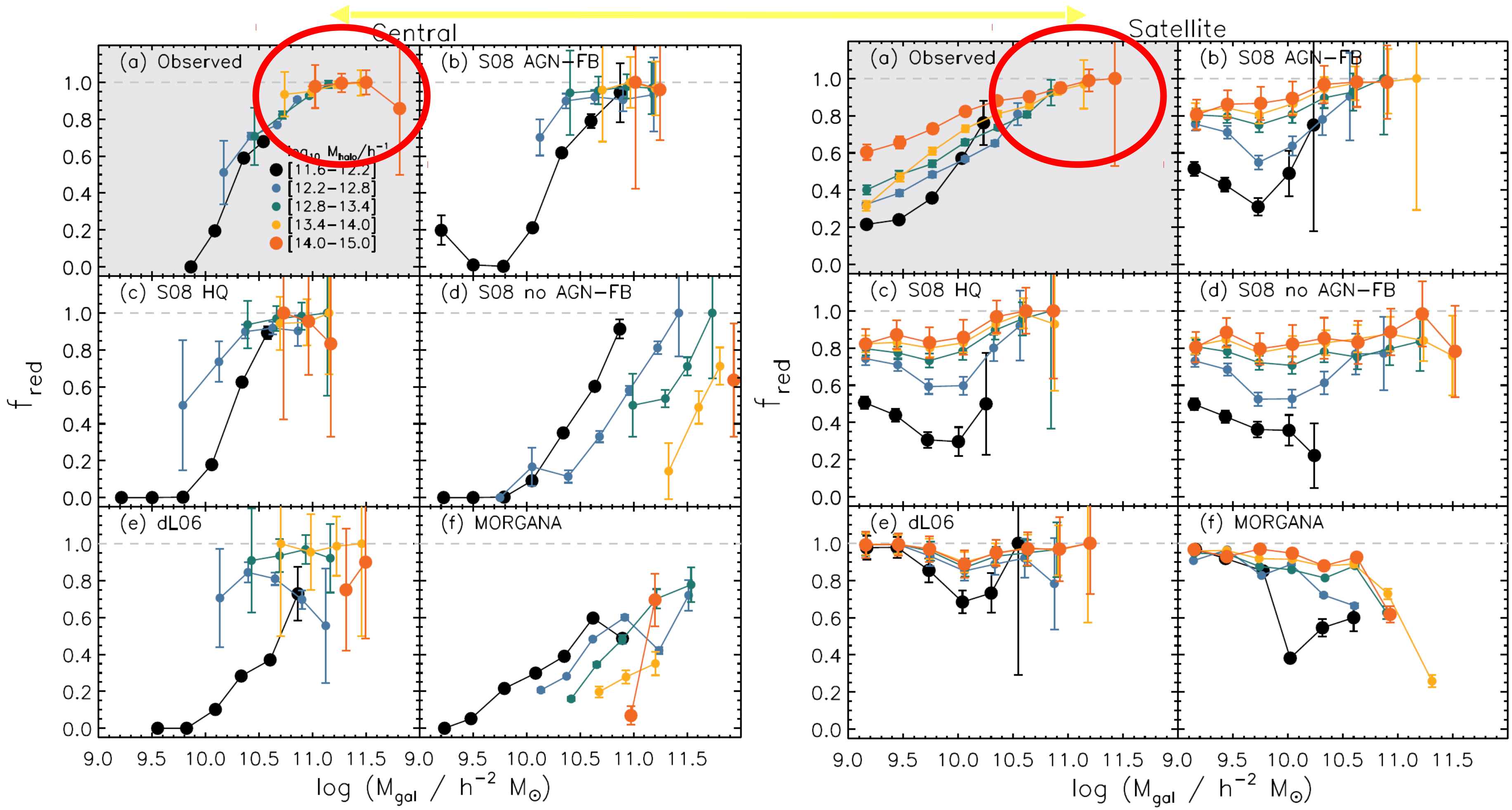
(2) Removal of the hot diffuse gas halo of a galaxy after its infall into a group or cluster: “strangulation” (Larson, Tinsley & Caldwell 1980; Balogh, Navarro & Morris 2000; Kawata & Mulchaey 2008).

Quenching process that would operate only in the cluster environment

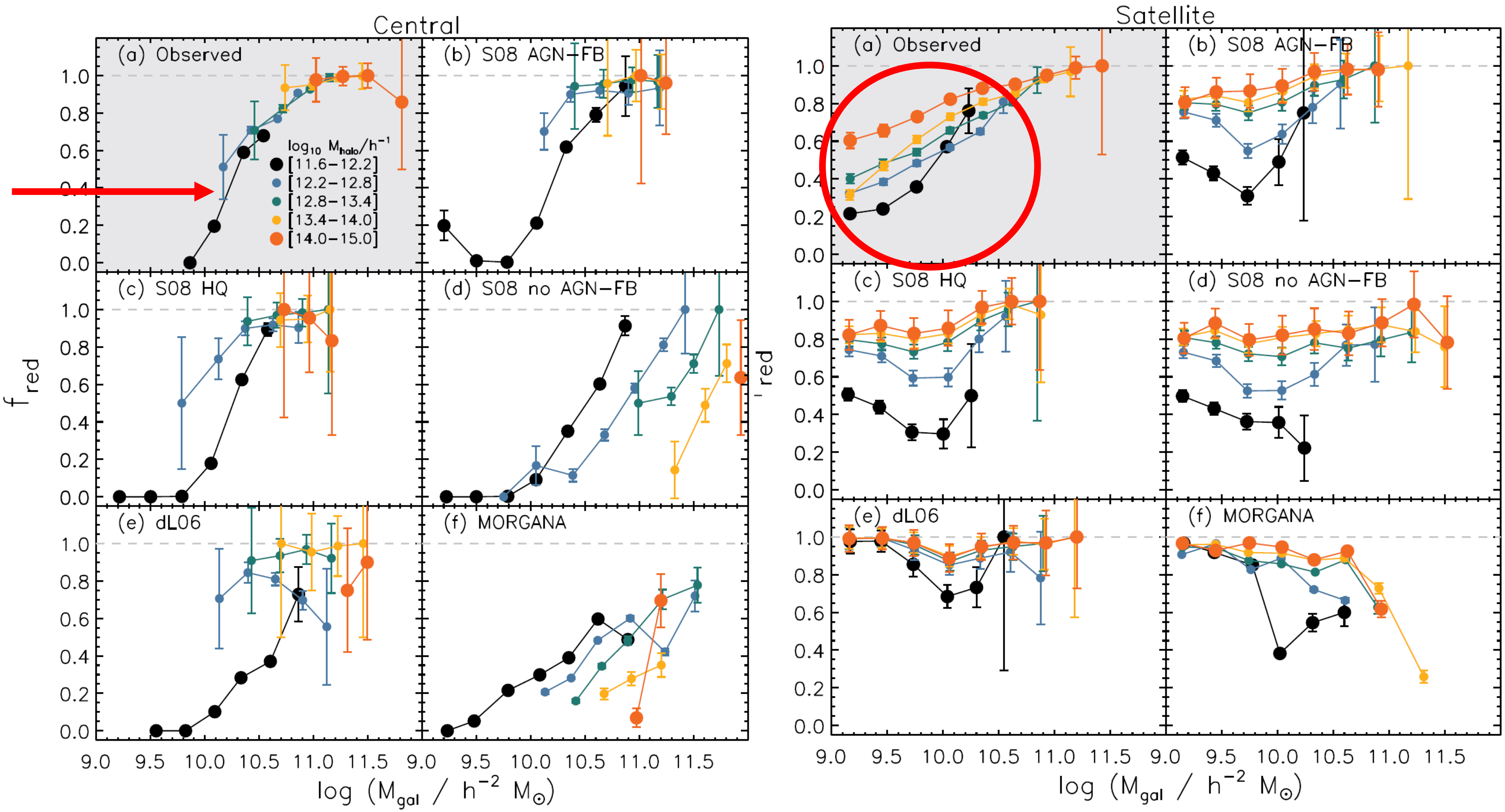
Strangulation:

- **How quickly does it proceed?**
  - Immediately upon accretion onto a larger system?
  - On a longer timescale?
- **Which physical mechanism causes it?**
  - Instant shock heating?
  - Tidal interactions with the halo potential?
  - Ram pressure stripping?

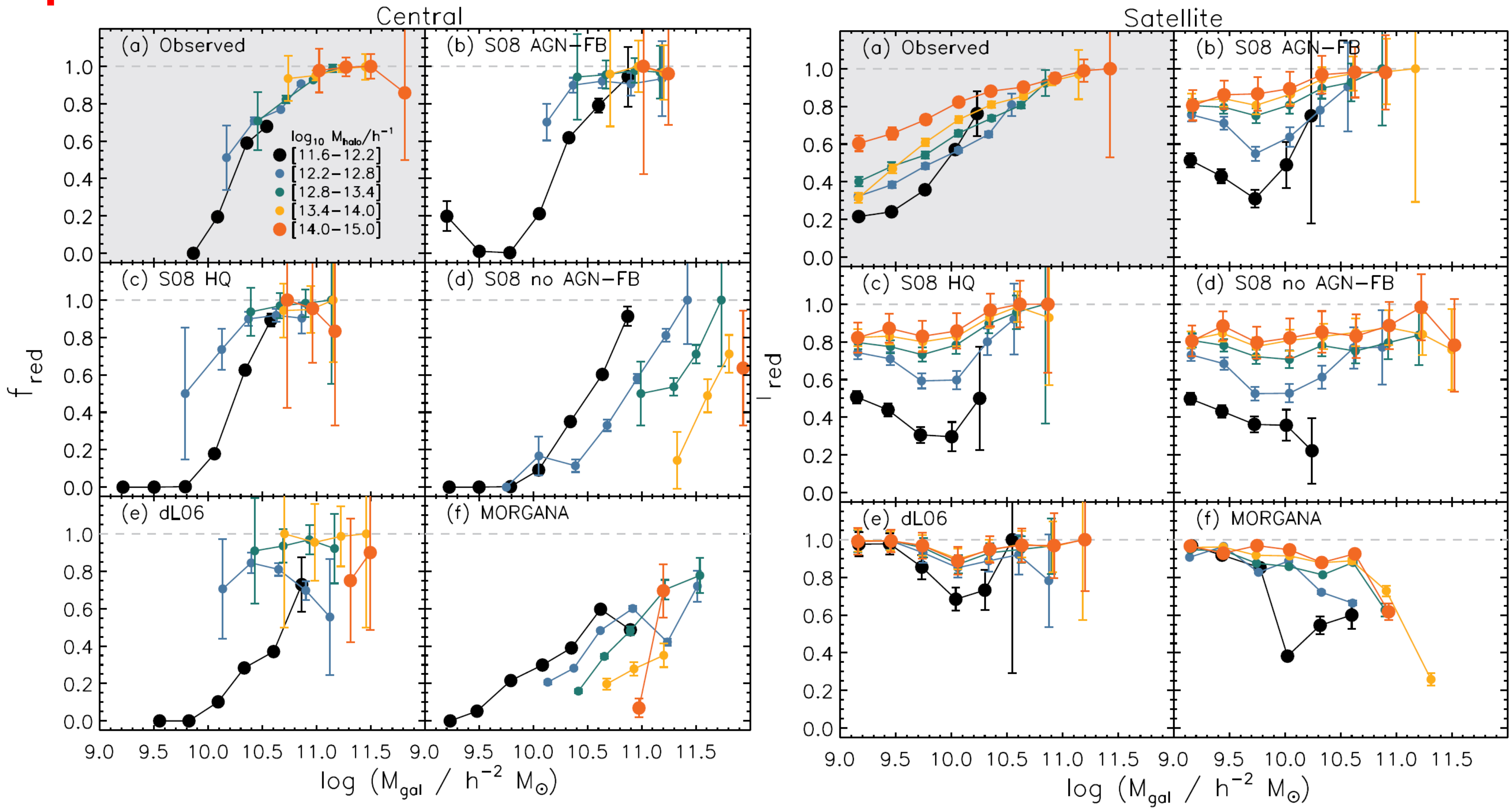
Observed satellite galaxies show an f_{red} dependence that is very similar to that of centrals <u>for massive galaxies</u> (M_{gx} >~$10^{10.5}\,h^{-2}\,M_{\odot}$), with no significant dependence of f_{red} on halo mass (environment) for fixed stellar mass (e.g. Kimm et al. 2009)



For <u>intermediate and low mass</u> satellites, f_{red} shows some dependence on both galaxy stellar mass and halo mass, but does not show the very **sharp drop** over intermediate halo masses (11.5 <~log M_{halo} <~ 12.5 h^{-1} $M_\odot$) seen in the central population.



In the semi-analytic models (Somerville08; Croton06/DeLucia06; MORGANA) f_{red} for the satellites **does not have a strong enough dependence on M_{gal} at fixed halo mass → satellite overquenching problem**



Quenching process that would operate only in the cluster environment

Strangulation:

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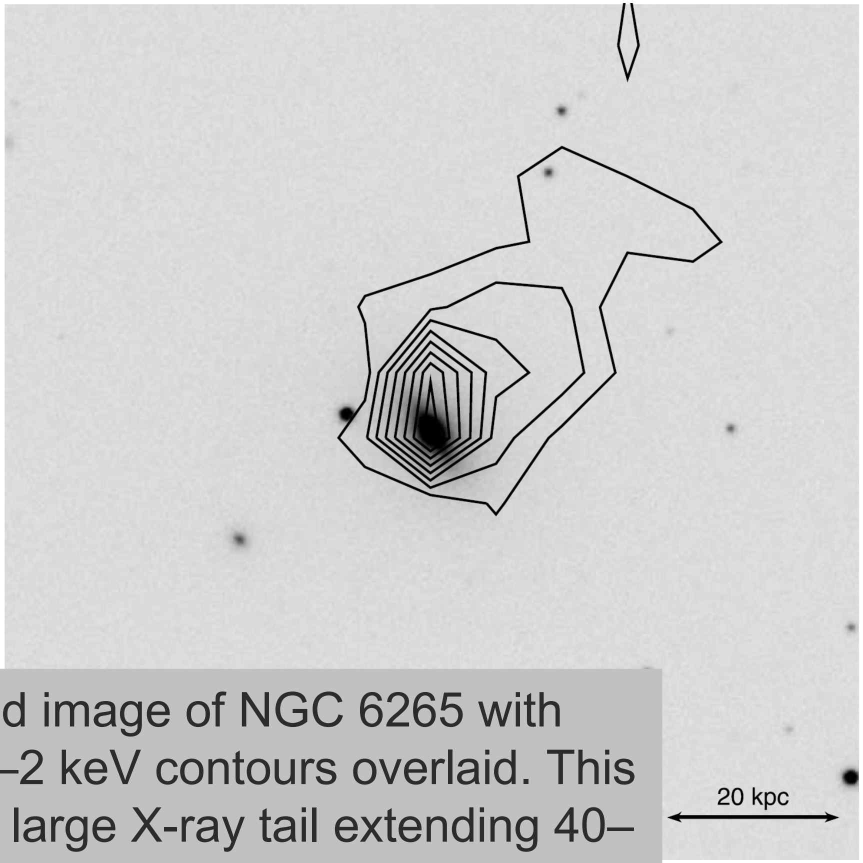
Gradual removal of hot gas

Large fraction of near-IR-bright, early-type galaxies in groups (Jeltema et al. 2008) and also in clusters (Sun et al. 2007) have extended X-ray emission, indicating that they retain significant hot gas halos even in these dense environments.

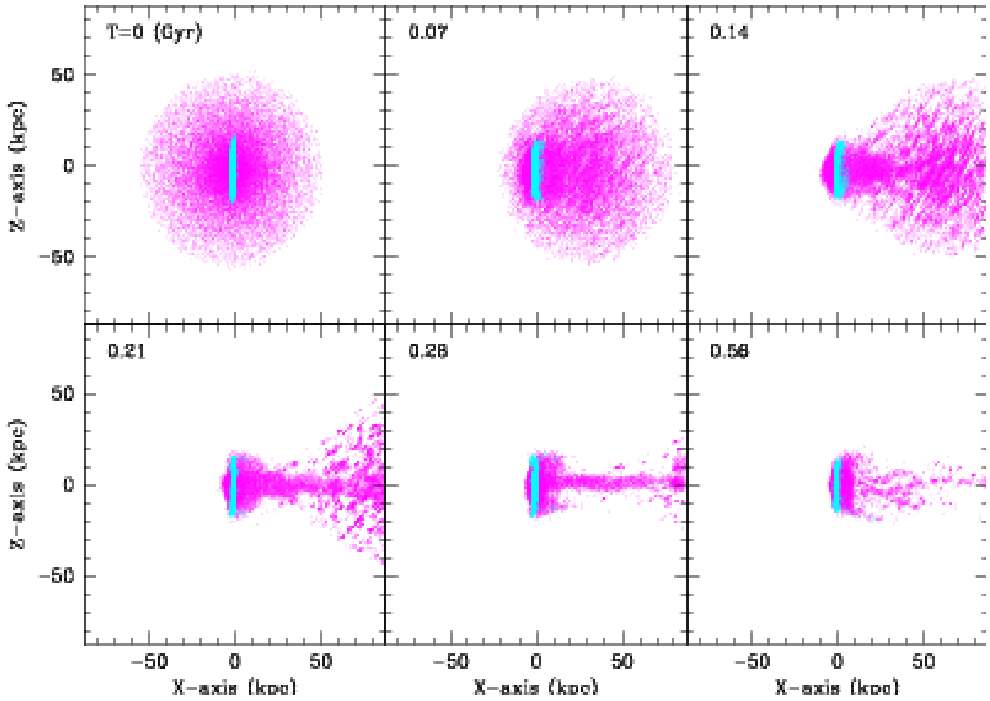


SDSS *r*-band image of NGC 6265 with *Chandra* 0.5–2 keV contours overlaid. This galaxy has a large X-ray tail extending 40–50 kpc

Jeltema et al. (2008)

Gradual removal of hot gas

From hydrodynamic simulations: hot gas halos of satellites are <u>not stripped instantly</u> (McCarthy et al. 2008; Bekki 2009).



Bekki (2009)

Satellite galaxies can keep up to 30% of the initial hot halo gas for up to 10 Gyr.

RPS of halo gas is much more effective than that of disk gas

In SAM: Font et al. (2008, hot gas only)

Environmental effects on hot gas: ram pressure and tidal stripping

Effects on **satellite's hot halo** of:

- **Tidal stripping (TS)**
  Interaction with the cluster potential

- **Ram pressure stripping (RPS)**
  Ram pressure forces due to satellite's motion through the intracluster medium (ICM)

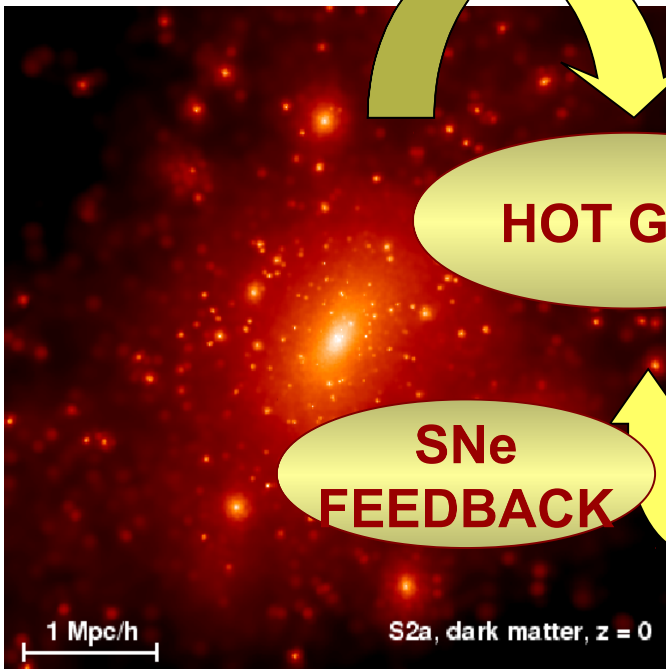
$$P_{\rm ram} = \rho_{\rm ICM}(r)\, v_{\rm rel}^2$$

Implemented on a semi-analytic model of galaxy formation

We explore this questions using a semi-analytic model of galaxy formation

Sagitario semi-analytic model (Tecce et al. 2013)

This code is a major revision and update of SAG (Cora 2006; Lagos, Cora & Padilla 2008; Tecce et al. 2010)



$$M_{\text{hot}} = \Omega_b M_{\text{vir}} - \sum_i \left(M_{\text{star}}^{(i)} + M_{\text{cold}}^{(i)} + M_{\text{BH}}^{(i)} + M_{\text{hot}}^{(i)} \right)$$

HOT GAS

$$\frac{dM_{\text{cool}}}{dt} = 4\,\pi\, r_{\text{cool}}^2 \frac{dr_{\text{cool}}}{dt}$$

$$t_{\text{cool}}(r) = \frac{3}{2} \frac{k\,T\,\rho_g(r)}{\mu\, m_p\, n_e^2(r)\, \Lambda(T,Z)}$$

COLD GAS

SNe FEEDBACK

STARS

$$\frac{dM_{\text{¿}}}{dt} = \alpha \frac{\left(M_{\text{cold}} - M_{\text{crit}}\right)}{t_{\text{dyn}}}$$

$$\Delta m_{\text{BG,Q}} = f_{\text{BH}} \frac{M_{\text{sat}}}{M_{\text{central}}} \frac{m_{\text{cold}}}{1 + \left(200\ \text{km s}^{-1} / V_{\text{vir}}\right)^2}$$

$$\Delta M_{\text{reheat}} = \frac{4}{3} \varepsilon \frac{\eta_{\text{SNCC}}\, E_{\text{SNCC}}}{V_{\text{vir}}^2} \Delta M_{\text{¿}}$$

$$\dot{m}_{\text{BG,R}} = \kappa_{\text{AGN}} \left(\frac{m_{\text{BH}}}{10^8\, M_o}\right) \left(\frac{f_{\text{hot}}}{0.1}\right) \left(\frac{V_{\text{vir}}}{200\ \text{km s}^{-1}}\right)^2$$

BH

AGN FEEDBACK

$$\dot{m}'_{\text{cool}} = \dot{m}_{\text{cool}} - \frac{L_{\text{BH}}}{1/2\, V_{\text{vir}}^2}$$

Metals:

Low mass stars

Marigo (2001)

Simple degenerate model (Lia et al. 2002)

SNe CC

SNe Ia

Portinari et al. (1998)

Iwamoto et al. (1999)

Stellar life time:

Padovani & Matteucci (1993)

TS implementation

If the base simulation had ultra-high resolution: just follow the subhaloes recording their position, velocity and bound mass...
Problem: need good mass resolution and frequent simulation outputs

Type 2 (orphan) galaxies: if they are assumed to be completely stripped of DM – gas, if resolution is not high enough model is indistinguishable from instant stripping!

We consider the orbital evolution of satellite galaxies integrating their orbits in the halo potential, taking into account dynamical friction

$$\frac{\mathrm{d}\vec{v}}{\mathrm{d}t} = -\frac{GM_{\mathrm{sat}}(t)}{r^2} \ln\Lambda \left(\frac{V_c}{v}\right)^2 \left\{\mathrm{erf}\left(\frac{v}{V_c}\right) - \frac{\sqrt{\pi}}{2}\left(\frac{v}{V_c}\right)\exp\left[-\left(\frac{v}{V_c}\right)^2\right]\right\}\vec{e}_v$$

TS implementation

Implementation based in Kimm et al. (2011) and Gan et al. (2010)

- Initial conditions taken from the simulation itself
- Mergers: when the galaxy loses its initial specifc angular momentum
- Satellites of subhaloes can be lost through tidal forces and relocated to the main host halo

In the base model: positions and velocities of type 2 galaxies are traced by following most-bound DM particle. Mergers occur in a dynamical friction timescale

$$t_{\rm friction} = \frac{0.86 f(\epsilon_{\rm orb}) V_c r_c^2}{G M_{\rm sat} \ln \Lambda_C}$$

TS implementation

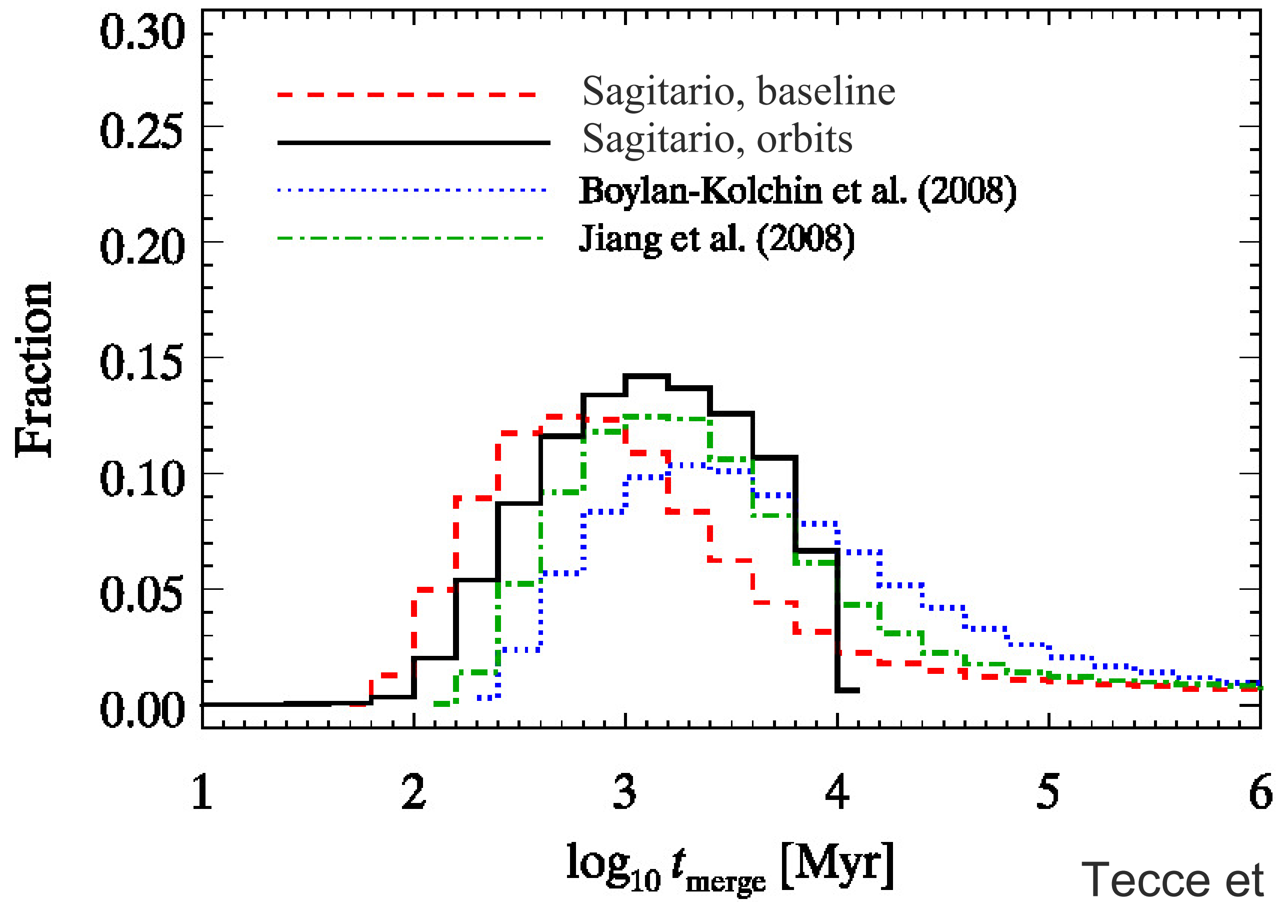
As the galaxy proceeds along its orbit, we calculate the tidal radius

$$r_{\mathrm{t}} = r\left(\frac{M_{\mathrm{DM}}^{\mathrm{sat}}}{M_{\mathrm{DM}}^{\mathrm{central}}(r)}\right)^{2/5}$$

At each timestep, a fraction dt / t_{dyn} of the mass beyond r_t is lost to TS. Remaining mass is assumed to be contained within r_t. Integration stops when a merger occurs or if the remaining mass is < 1% of the initial subhalo mass.

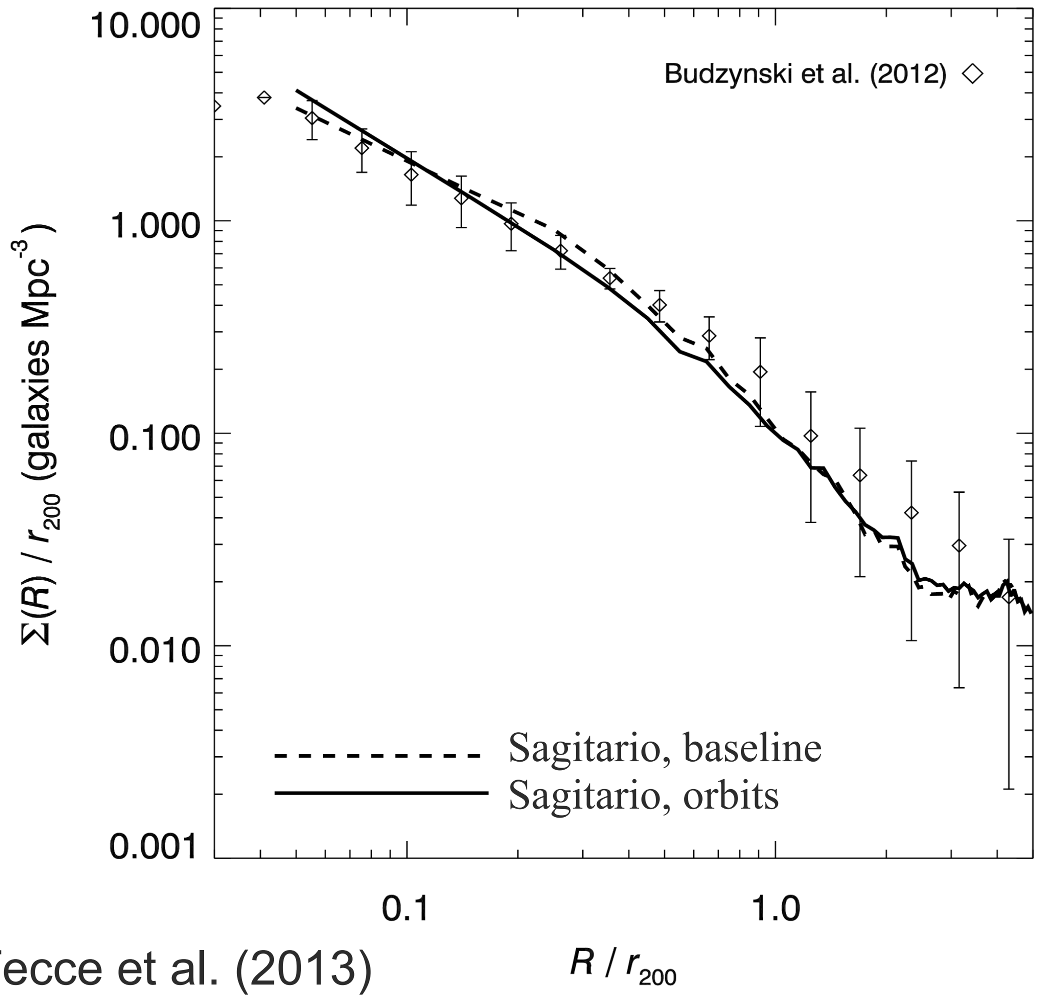
All this can be done only once per merger tree. Positions, velocities, tidal radii and mass loss are stored in postprocessing files.

Galaxy orbits: distribution of merger times



Tecce et al. (2013)

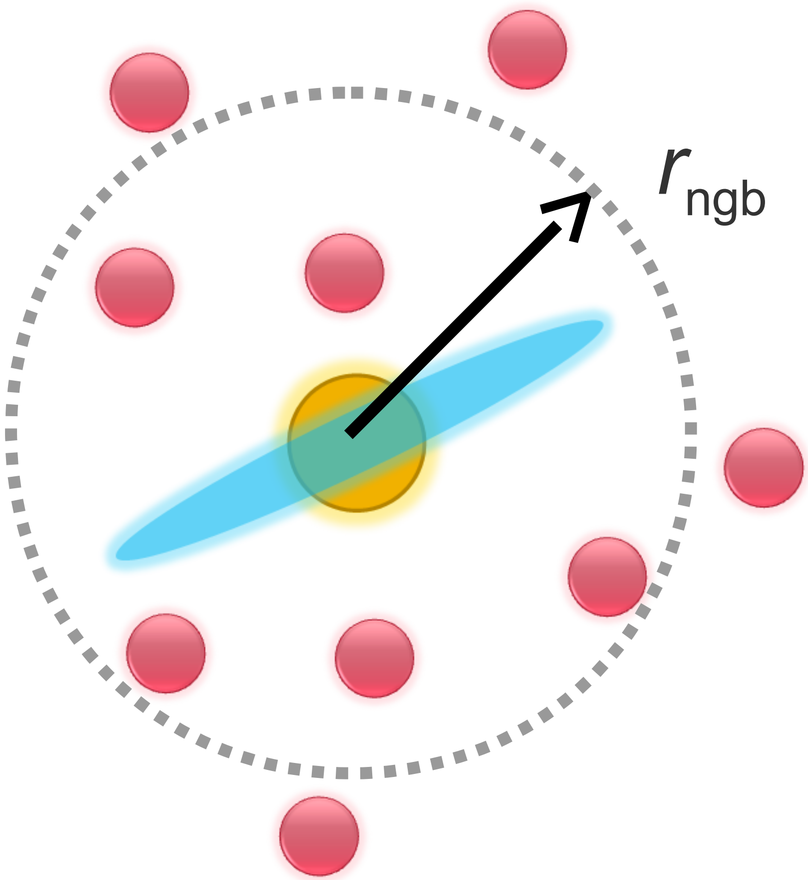
Galaxy orbits: galaxy number density profile



Tecce et al. (2013)

The model with galaxy orbits preserves the good agreement with number density profiles found for models which use DM as tracers of galaxy positions (e.g. Gao et al. 2004; Guo et al. 2011; Tecce et al. 2011)

Determination of RP values



$$P_{\mathrm{ram}} = \rho_{\mathrm{ICM}}(r) v_{\mathrm{rel}}^2$$

We use the method from Tecce et al. (2010): ICM density and relative velocity determined from the gas particles of the underlying simulations

Galaxy positions and velocities are read from the orbits files generated previously.

RP stripping of gas: two-stage method

$$P_{\mathrm{ram}} = \rho_{\mathrm{ICM}}(r)v_{\mathrm{rel}}^2$$

Gas is removed from the galaxy if the ambient RP exceeds the gravitational restoring force

For the hot gas halo:
(McCarthy et al. 2008)

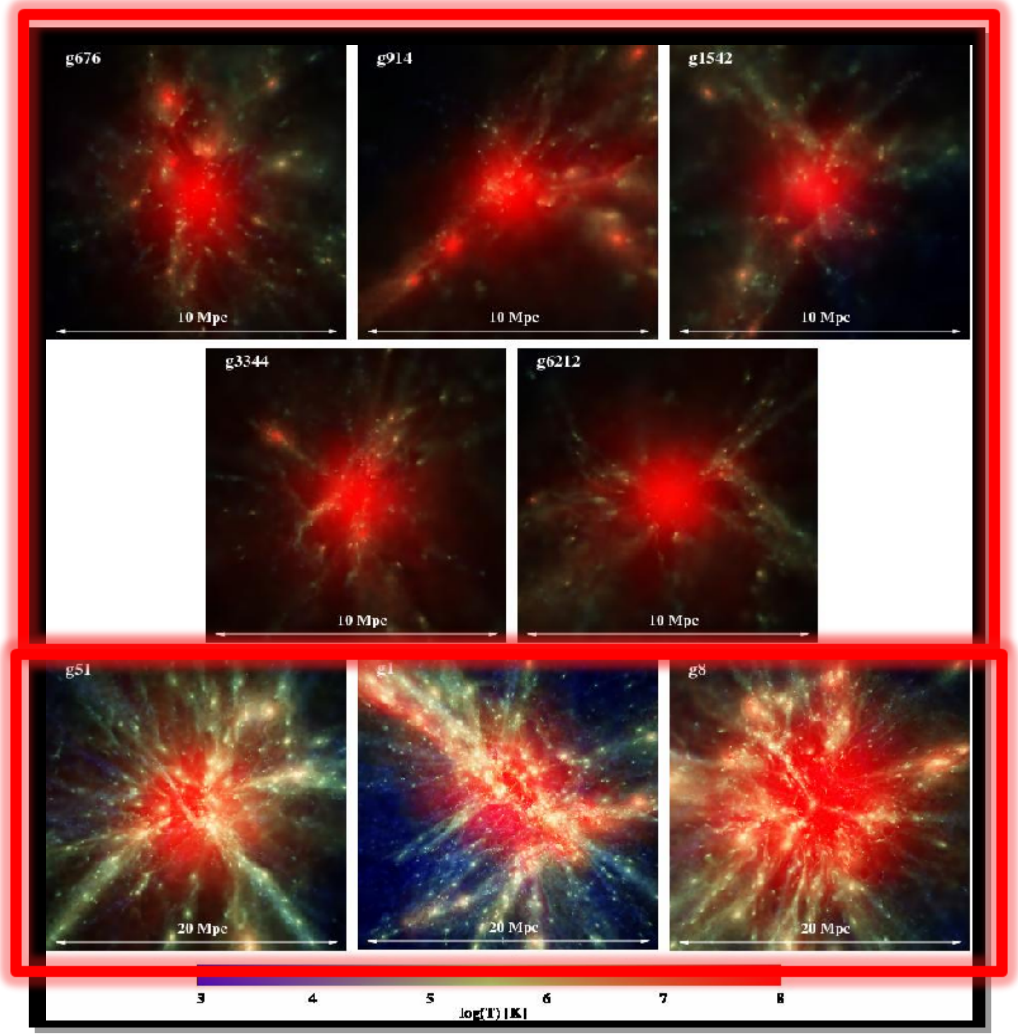
$$\rho_{\mathrm{ICM}}v^2 \geq \alpha_{RP}\frac{G\,M_{\mathrm{sat}}(\mathrm{r}_{\mathrm{sat}})\,\rho_{\mathrm{hot}}(\mathrm{r}_{\mathrm{sat}})}{r_{\mathrm{sat}}}$$

For the cold gas disc:
(Gunn & Gott 1972)

$$\rho_{\mathrm{ICM}}v^2 \geq 2\pi G\Sigma_{\mathrm{disc}}\Sigma_{\mathrm{cold}}$$

RPS of the cold gas disc starts only when the hot gas halo is depleted.

Hydrodynamic simulations of galaxy clusters

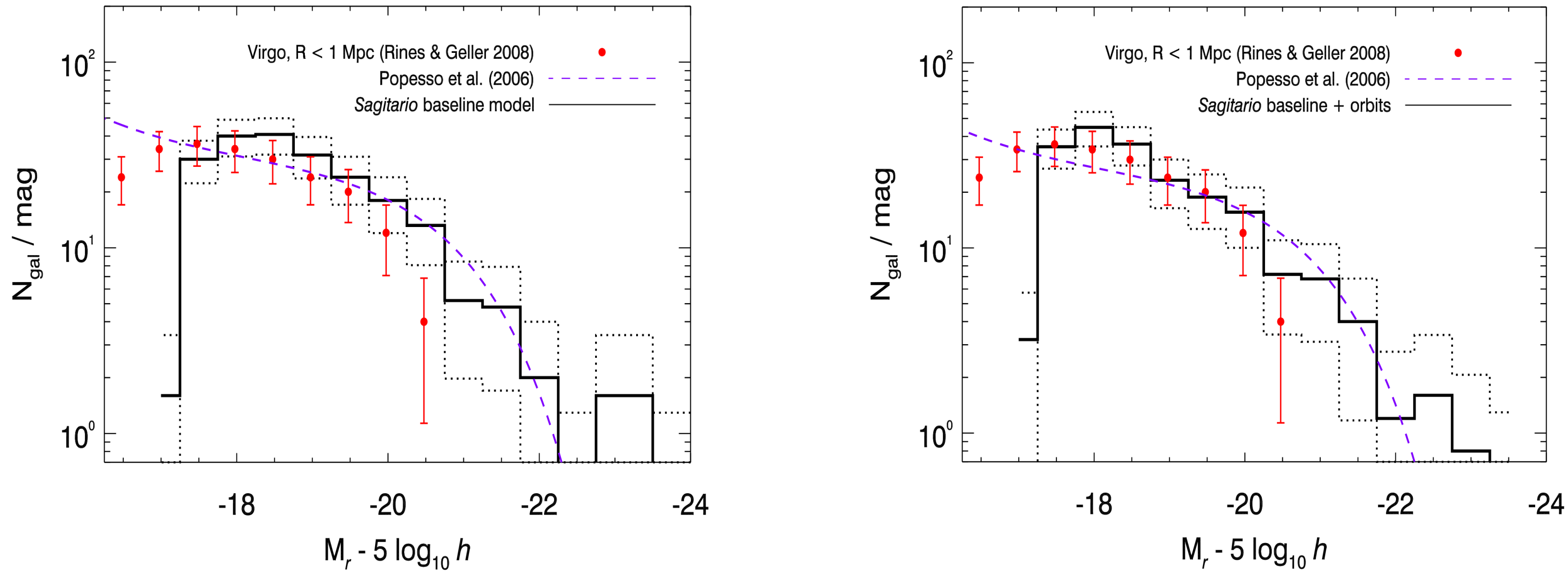


From Dolag et al. (2009), done using GADGET-2

5 regions around clusters of mass $\approx 10^{14}\ h^{-1}\ M_{\odot}$ (G14 clusters)

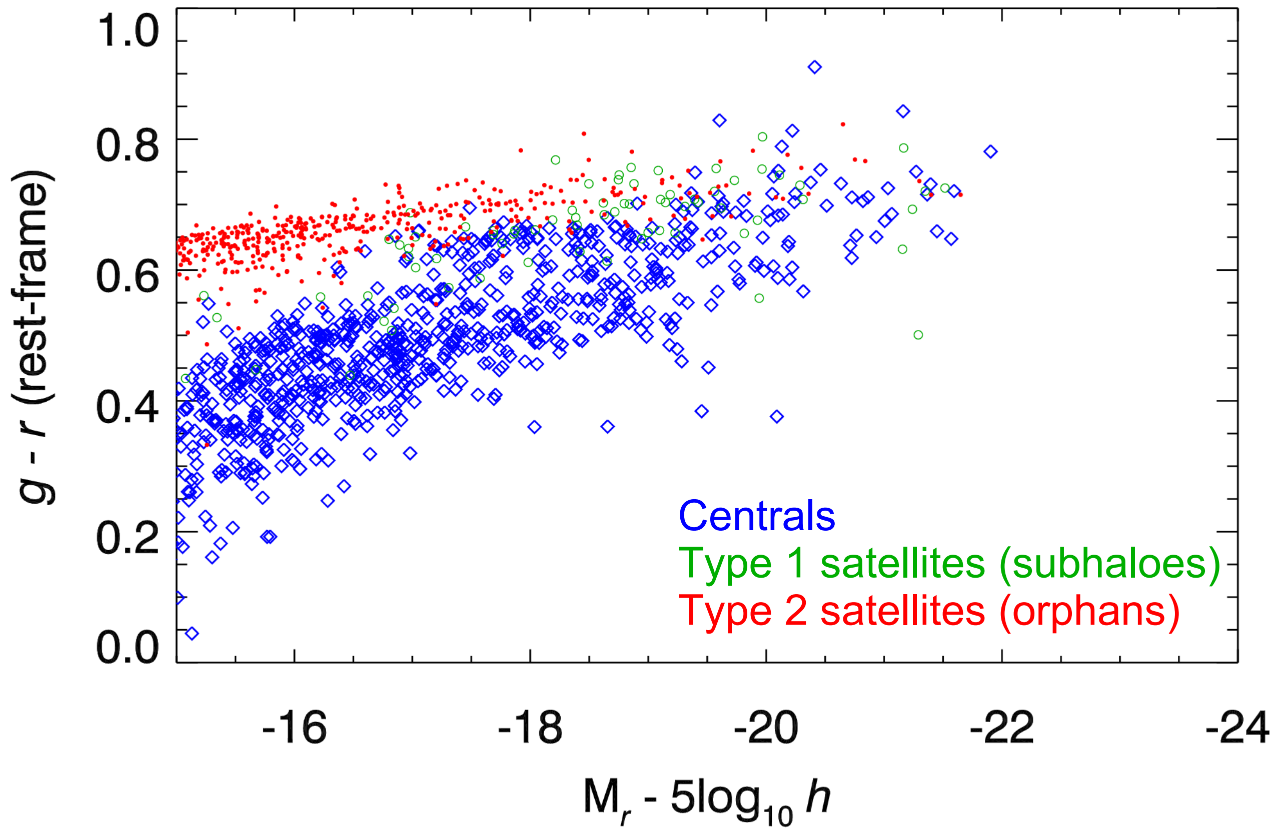
3 regions around clusters of mass $\approx 10^{15}\ h^{-1}\ M_{\odot}$ (G15 clusters)

Results: luminosity functions (base model, with and without orbits)



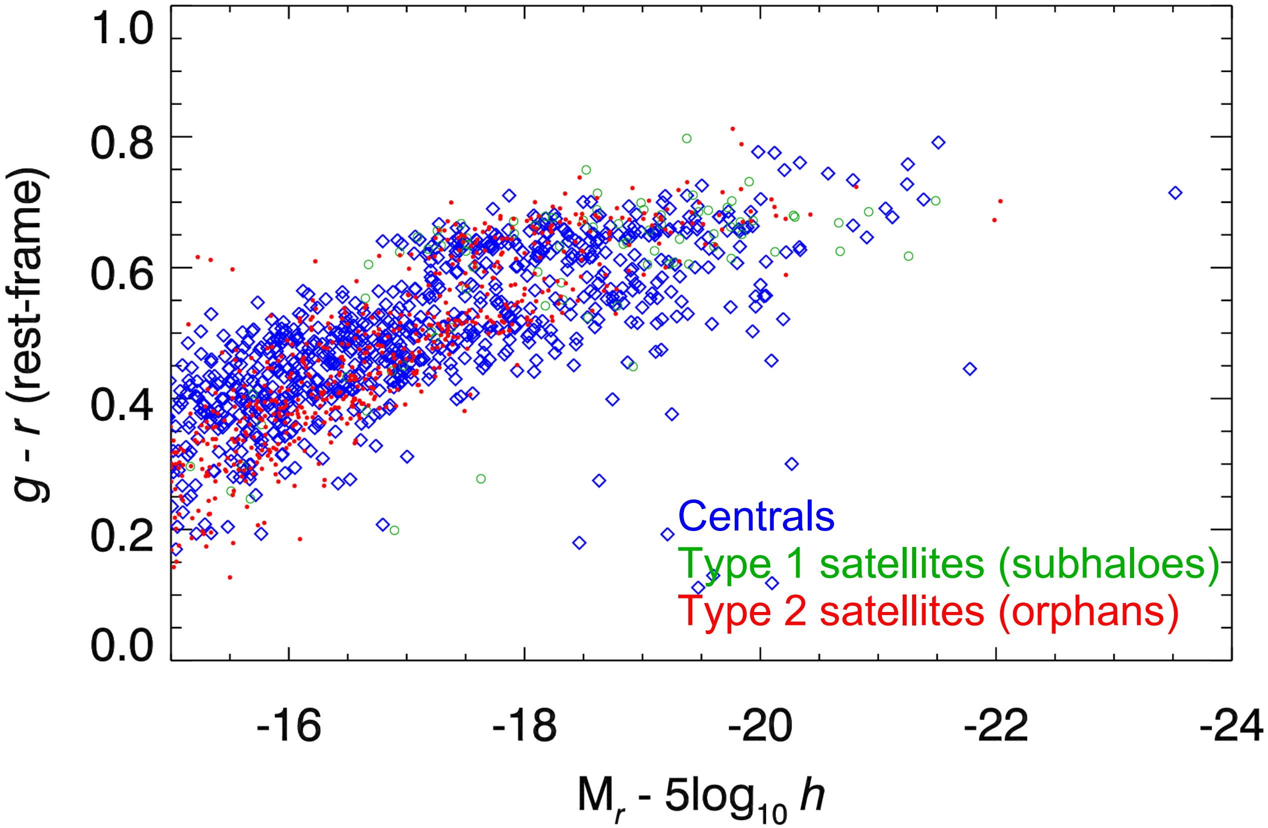
Baseline + orbits model has 25% more galaxies at z = 0 (consistent with latest merger times findings of Villalobos et al. 2013) but has roughly the same number of galaxies with $M_{stellar} > 10^9\, h^{-1}\, M_\odot$ *(effect of tidal stripping of the stellar content).*

Results: colour-magnitude



Baseline model + orbits + cold gas RP

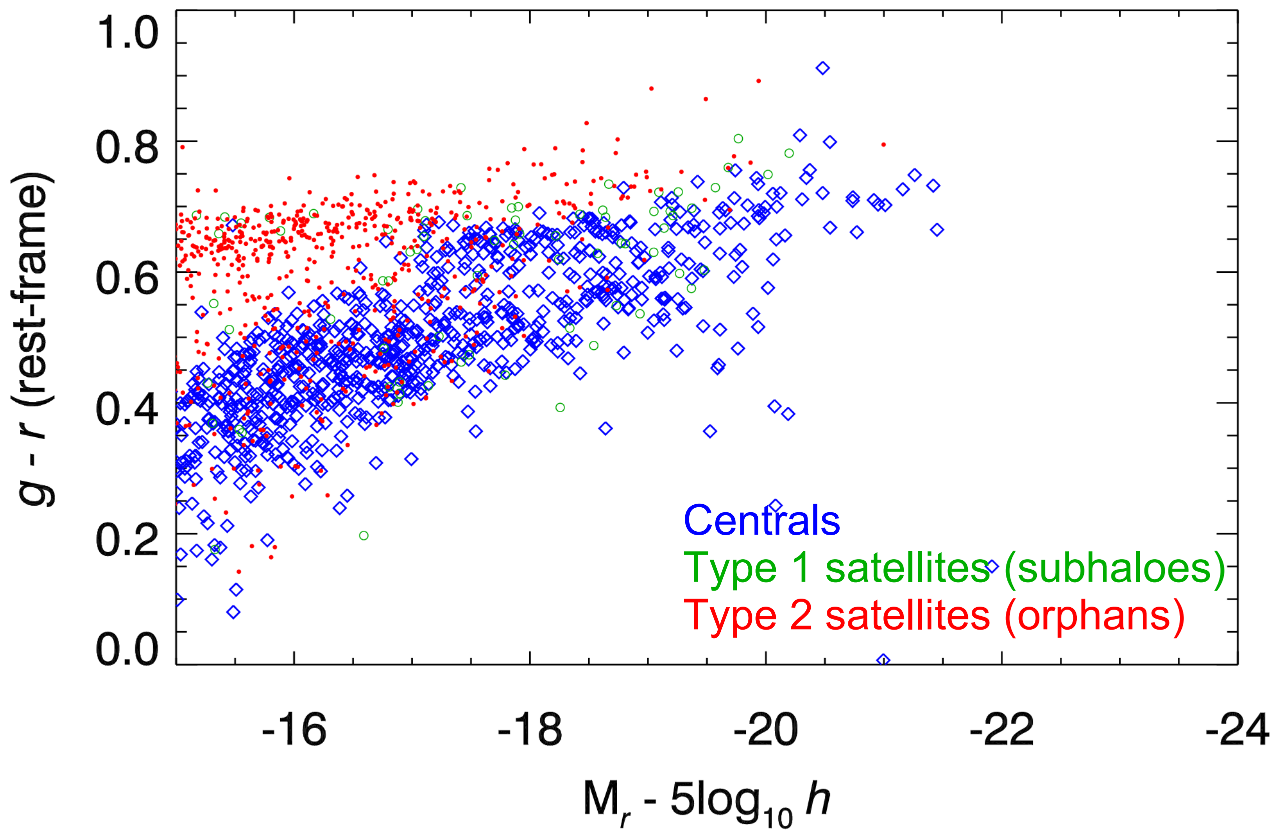
Results: colour-magnitude



Satellite cooling enabled, no environmental effects

Results: colour-magnitude

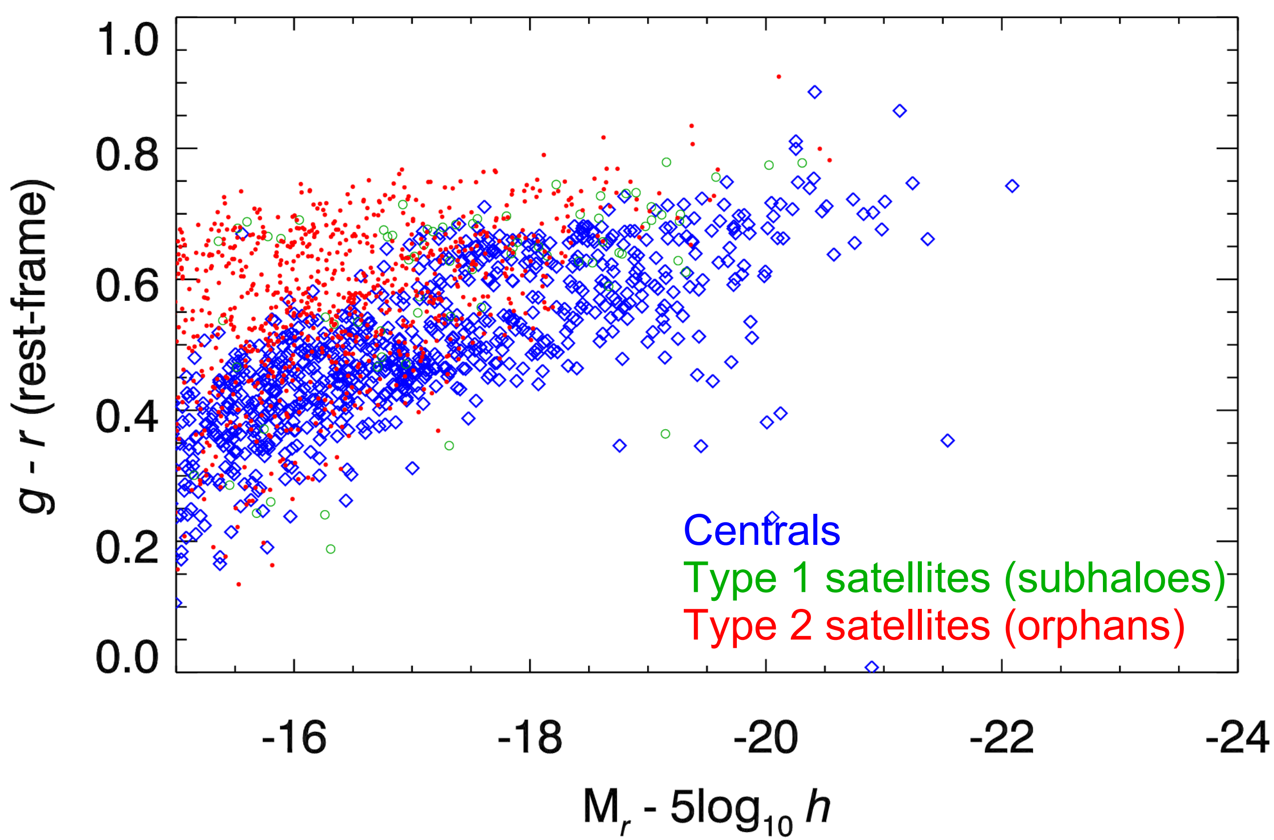
$\alpha_{RP} = 2$



Full model (satellite cooling + TS + RPS)

Results: colour-magnitude

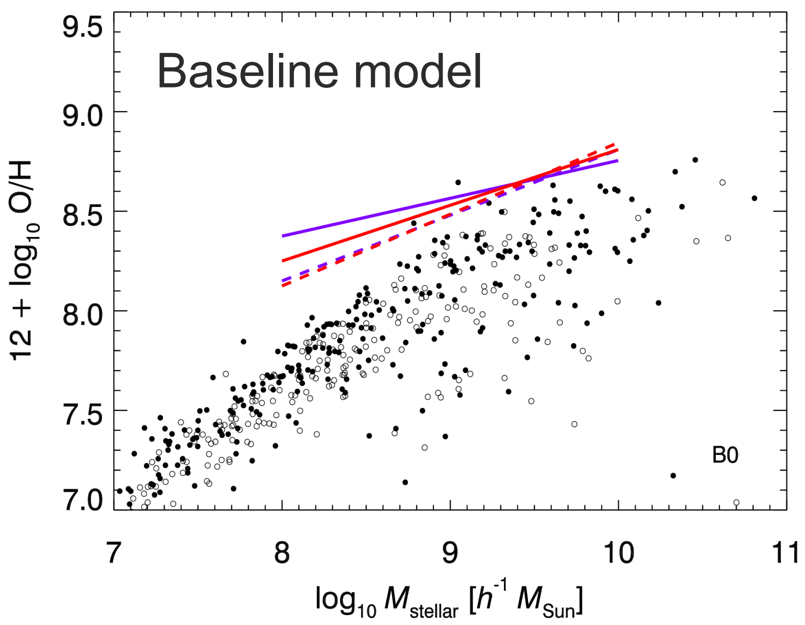
$\alpha_{RP}=10$

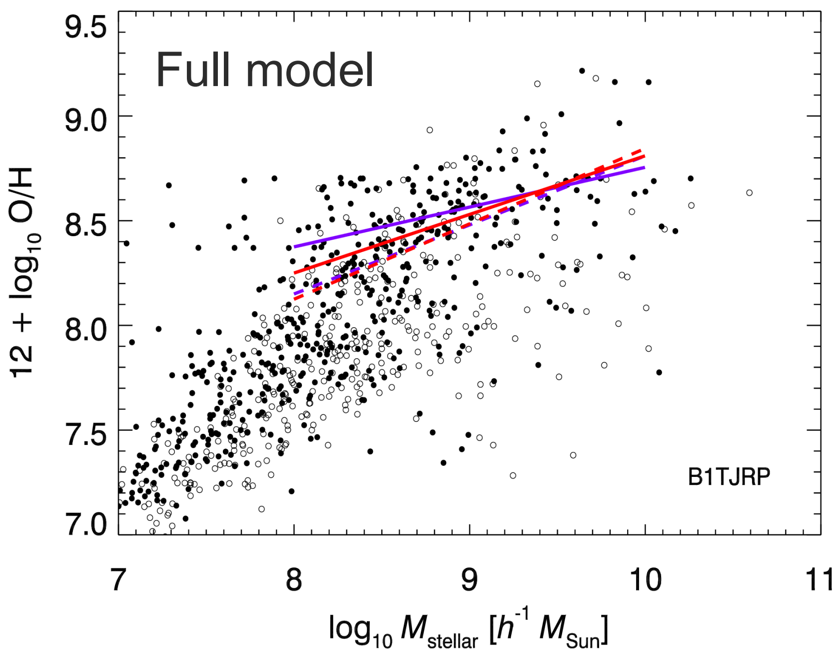


Full model (satellite cooling + TS + RPS)

Results: mass-metallicity

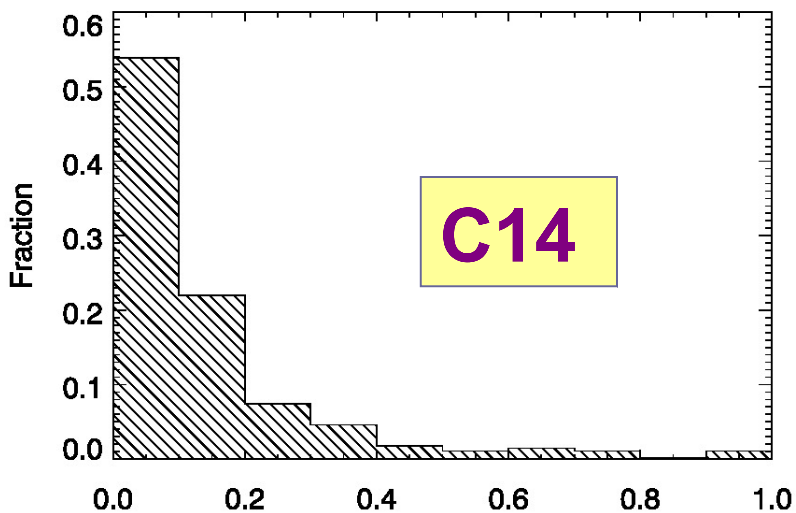
Cold gas metallicity vs stellar mass for cluster galaxies





Lines: mean observed relations from Petropoulou et al. (2012)

Which is the dominant effect?



$$r^{sat}_{strip,hot} / r^{sat}_{DM}$$

Defined by TS

Defined by comparing TS and RP

Almost all galaxies have

$$r_{strip,RP} < r_{strip,TS}$$

More than 50% of the galaxies have small ratios

$$r^{sat}_{strip,hot} / r^{sat}_{DM} < 0.2$$

Ram pressure stripping is the dominant effect on the gradual removal of hot gas

Conclusions

Sagitario improves the modelling of environmental effects on galaxy groups and clusters: particularly necessary for low mass systems (~< 10^{14} $M_{\odot}$) for which instant halo stripping is a bad approximation.

Orbits integration shows good agreement with previous results obtained when using DM as a tracer.

Over 50% of galaxies in low-mass clusters lose completely their hot gas haloes, and are affected by RPS of their cold gas phase (and TS of cold gas and stars).

Sagitario offers and excellent basis for the study of evolution of chemical properties of galaxies and ICM.

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