The role of environment in the evolution of massive galaxies

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Prelude

- Galaxy evolution is driven by **stellar mass**, **M_*** (a proxy for internal secular evolution and AGN feedback), and by **environment**, which is parameterized with:
  - local number density and/or **M_h**, the mass of the dark matter halo embedding a group/cluster of galaxies;
  - galaxy hierarchy, i.e. group/cluster galaxies are distinguished between one **central** (the most massive) galaxy and **satellites**.

- Centrals experience different **environmental effects** wrt satellites:

Mergers +
ICM accretion =

Mass growth

Strangulation +
Ram pressure +
Tidal stripping +
Harassment =

Quenching of star-formation
Mass loss

Environmental Effects in a Nutshell

- **Strangulation**: slow removal of the hot gas halo of a satellite (reservoir for future star formation) upon accretion onto a group/cluster (Larson et al. 1980).

- **Ram-pressure stripping**: fast removal of the diffuse interstellar medium (ionized and neutral) of a satellite due to its interaction with the intra-group or intra-cluster medium (ICM; Gunn & Gott 1972).
  The fraction of stripped gas increases with the ICM density (generally higher in the core of a galaxy group/cluster), the satellite orbital velocity (V^2) and M_h of the host group/cluster (Bekki 2009, Kapferer et al. 2009).

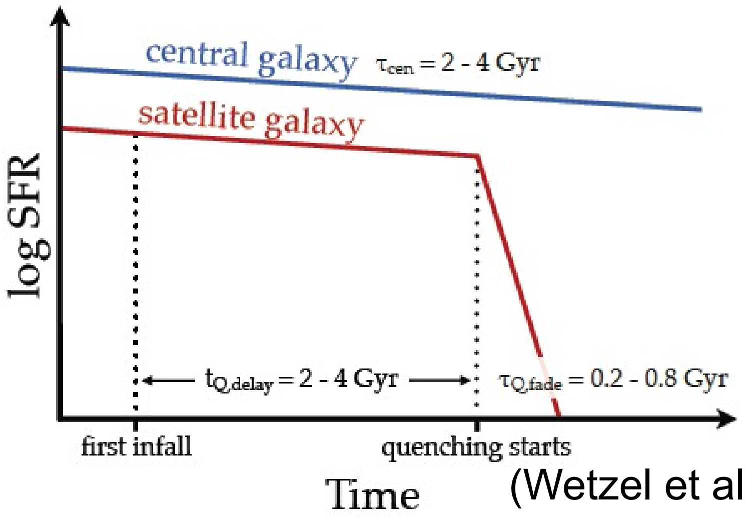
- **Tidal stripping**: removal of stars and gas from a satellite as a result of its tidal interactions with the gravitational potential of its host group/cluster and/or of its central galaxy (Villalobos et al. 2012, Chang et al. 2013).

- **Harassment**: loss of gas and stars undergone by low surface brightness satellites during fast and close encounters with brighter cluster galaxies (Moore et al. 1996, 1998).

The “Delayed-Then-Rapid” Quenching Scenario

Proposed by Wetzel et al. (2013) in order to explain the observed properties of satellites:

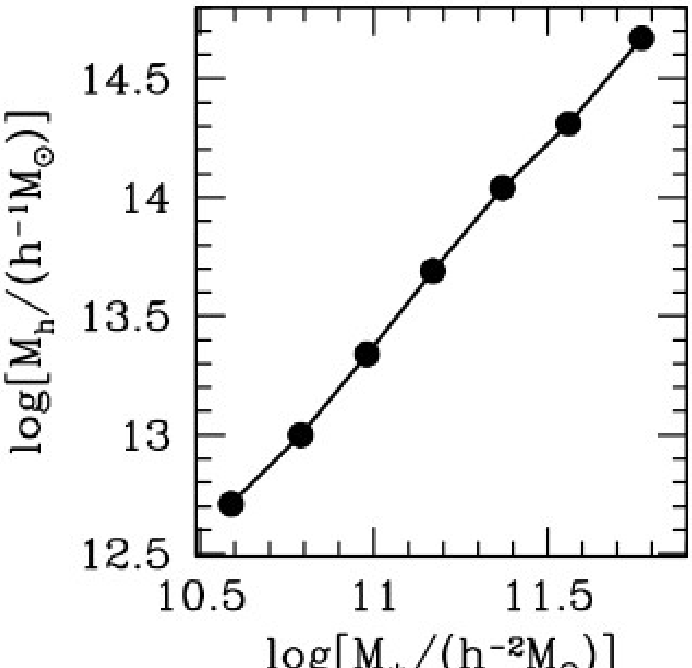
- Low mass galaxies and those residing now in more massive environments were accreted earlier.
- Upon accretion satellites keep forming stars for 2 – 4 Gyr, this time scale being shorter for more massive galaxies, still independent of M_h. In this period satellites also are deprived of their hot gas halo (strangulation).
- Once quenching of star formation has started (via ram pressure), the e-folding time over which the star formation rate decreases is < 1 Gyr.
- About 50% of low mass passive satellites ($M^* < 10^{10}$ M_o) in clusters were quenched in another smaller host halo (group) before infalling into the cluster. This is also known as *group preprocessing*.

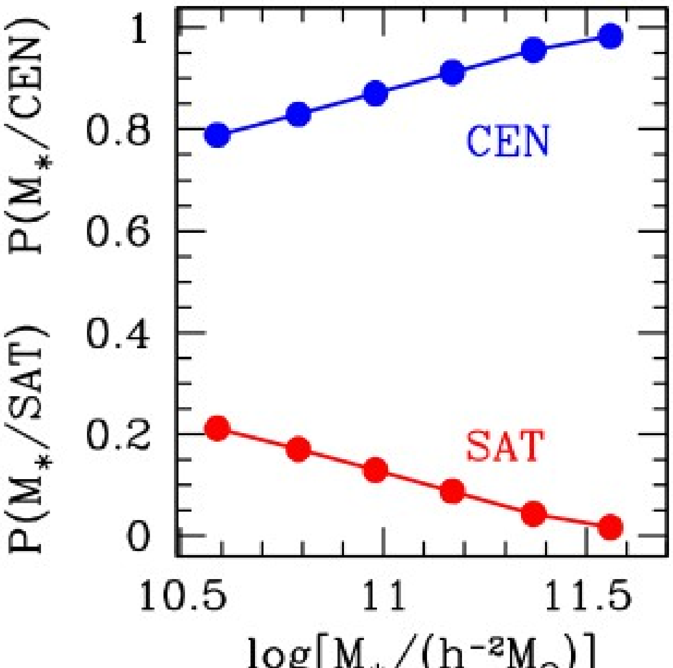


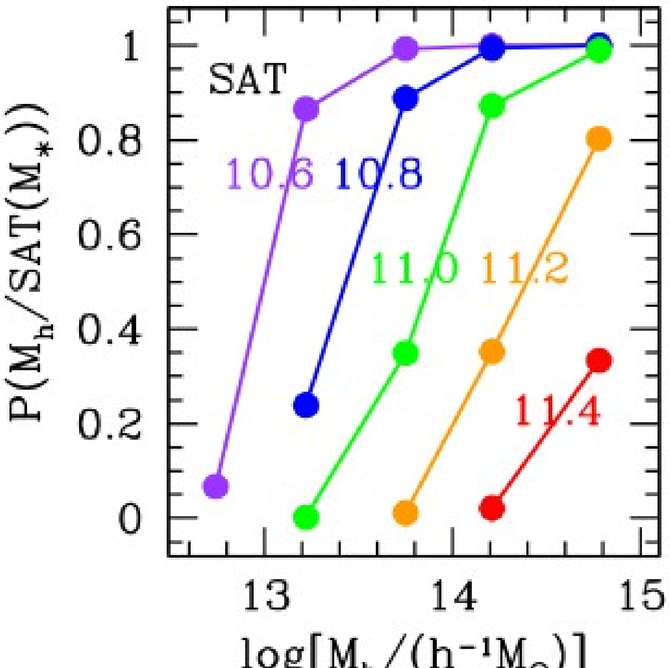
(Wetzel et al. 2013)

Massive galaxies' demography

- Working selection: $\log(M_*/h^{-2} M_\odot) \geq 10.5$.
- Data: DR7 group catalogue by Yang et al. (2005, 2007), based on a group-finder algorithm that makes use of the traditional FOF method and the conditional luminosity function. The latter assigns to a total luminosity (stellar mass) of a galaxy group a mass and virial radius of the dark matter halo associated with it. In these groups, galaxies are split between central and satellite galaxies.



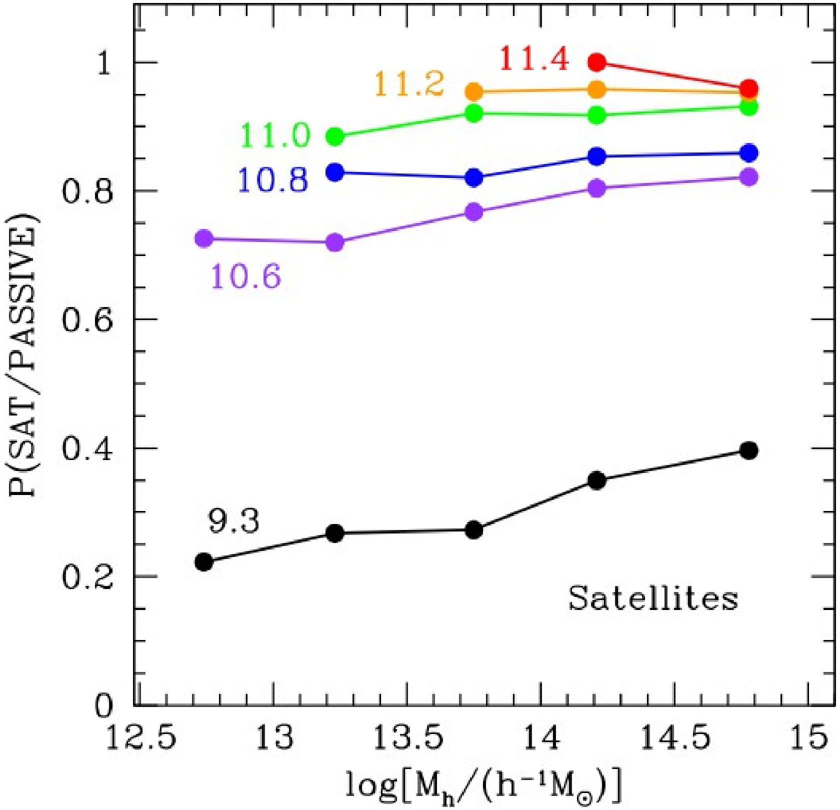




Properties of Massive Satellites vs Environment

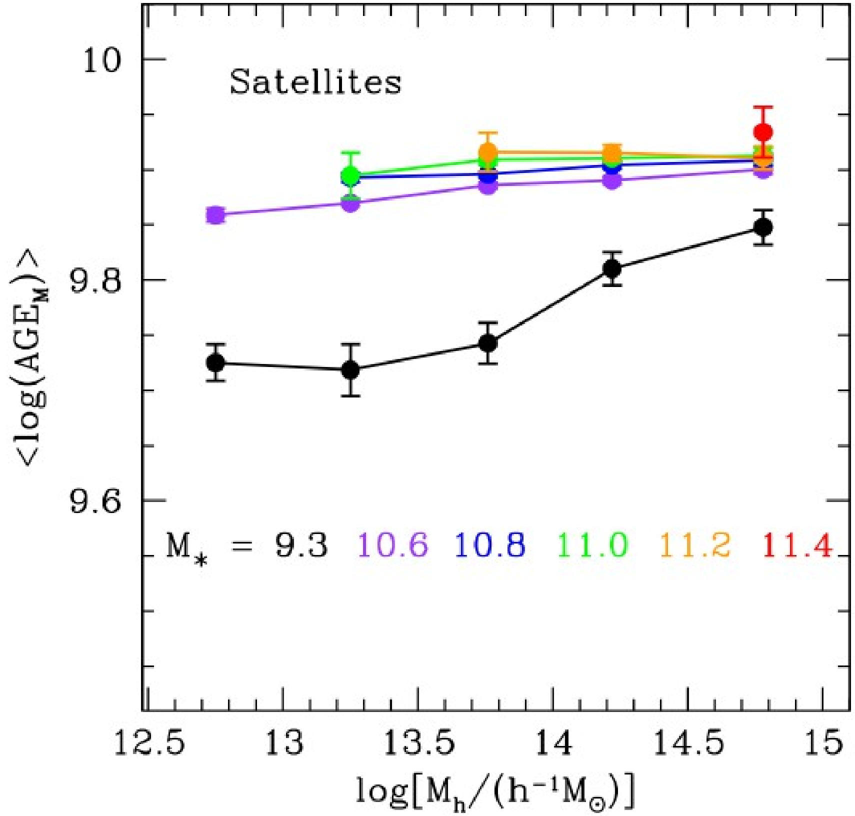
- Fractions of passive satellites with $\log(SSFR/yr^{-1}) < -11$:

  between 80% and 100%, with little or no dependence on M_h.
  (Balogh et al. '04; Blanton et al. '05; van den Bosch et al. '08, Wetzel et al. '12)



- Average, mass-weighted age of stellar populations:

  old stars with age ≈ 8 Gyr, independent of environment.
  (Gallazzi et al. '05; Jimenez et al. '07; Bernardi '09; Pasquali et al. '10; Gallazzi et al. '15)

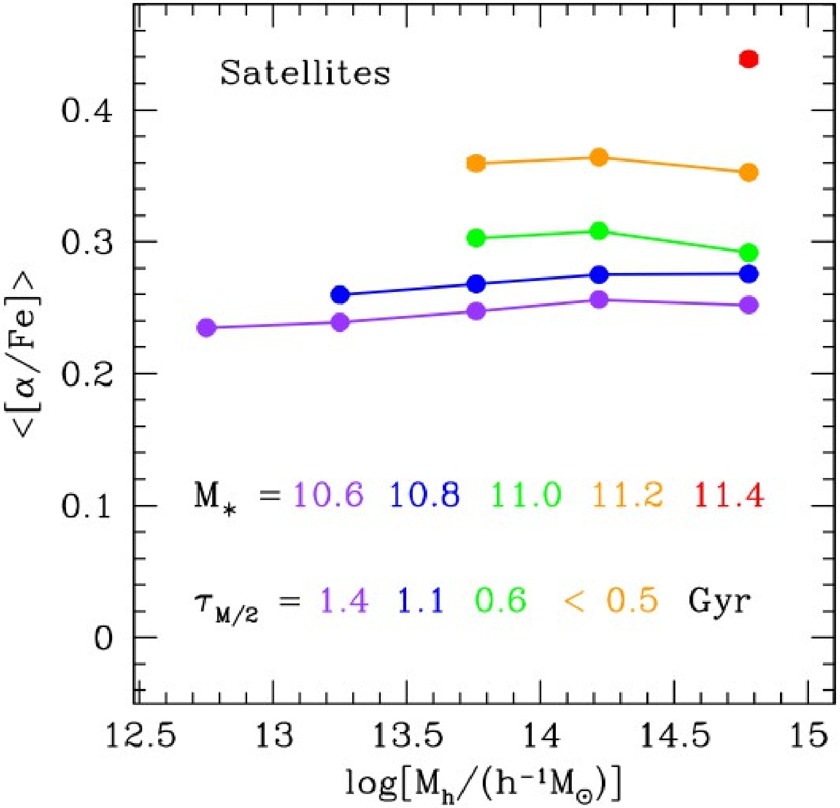


- Average [α/Fe]:

  clear dependence on M*, but no significant changes as a function of Mh.

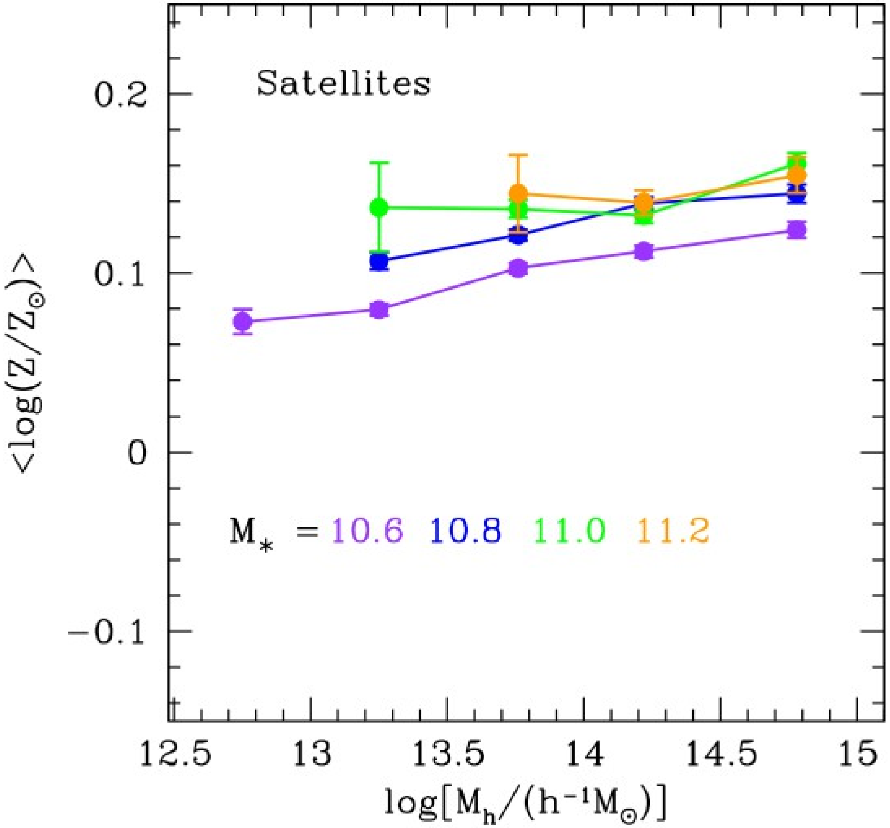
  τ(M/2) decreases by a factor of 2 at higher M*; at fixed M* the scatter in τ due to environment is ~0.1 Gyr.

  (de la Rosa et al. '11; Gallazzi et al. '15)



- Average stellar metallicity:

  mild dependence on Mh for M* < 10.8
  possibly due to tidal stripping.
  (Pasquali et al. '10; Gallazzi et al. '15)



Properties of Massive Centrals vs Environment

Bona-fide Early-Type Centrals (ETCs), when separated in M_h ($M_h < 12.5$: isolated, $M_h > 12.5$: in groups) show that:

ETCs in groups are younger than isolated ETCs by 1 Gyr.

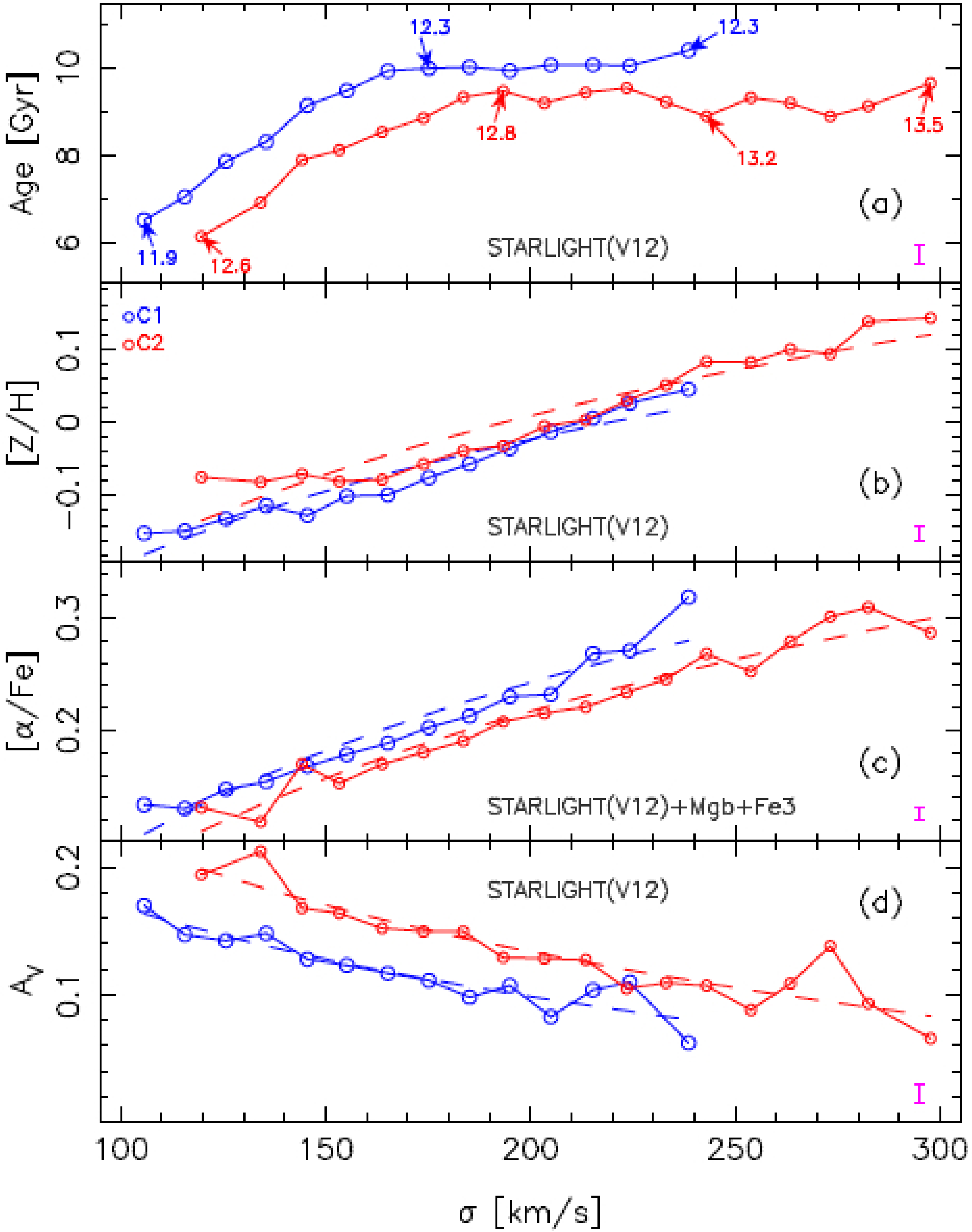
ETCs in groups are metal-richer than isolated ETCs by 0.02 dex in [Z/H].

ETCs in groups have lower [α/Fe] than isolated ETCs by 0.025 dex.

ETCs in groups have a higher A_V than isolated ETCs by 0.035 mag.

These trends are independent of the galaxies velocity dispersion σ.

La Barbera et al. (2014)



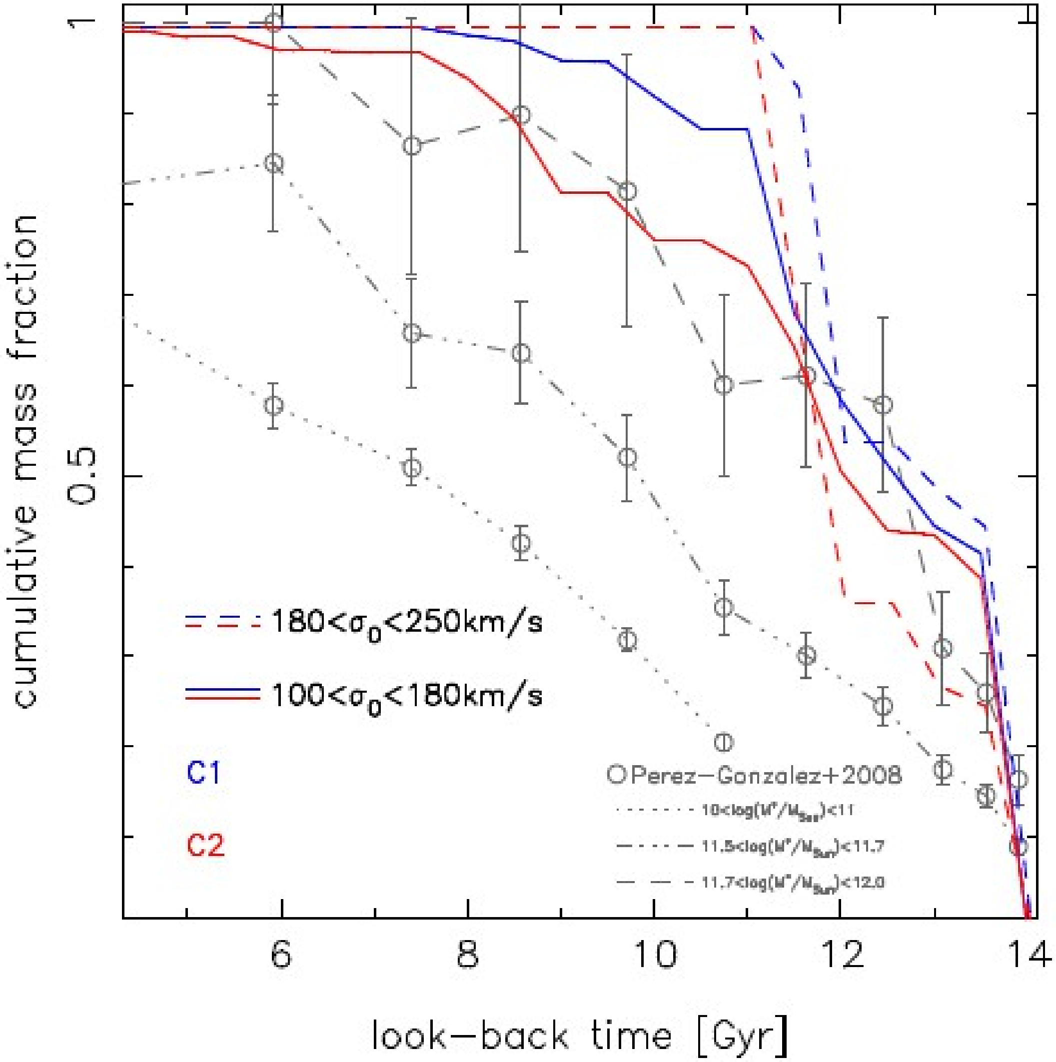
- The star-formation history emerging from the ETCs stacked spectra indicates that:

The bulk of their M* formed at look-back times > 6 Gyr.

ETCs in groups formed their M* over a more extended time scale than isolated ETCs.

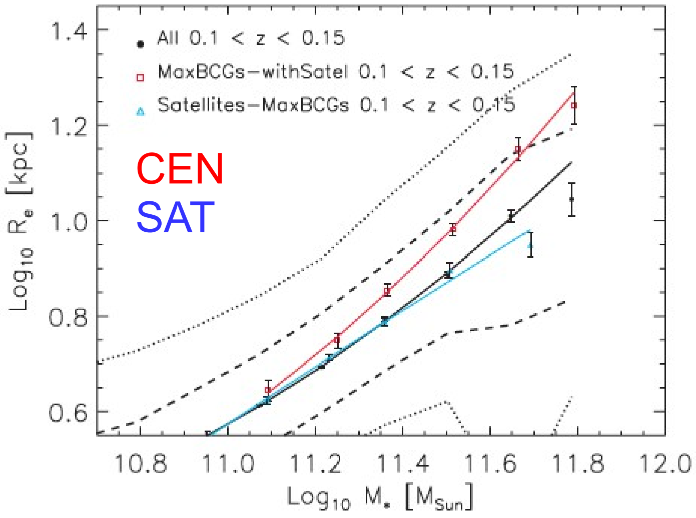
A different assembly time scale is also consistent with the observed difference in [α/Fe] between group/isolated ETCs.

Central ETGs in groups can grow in M* via gas accretion during interactions and mergers with gas-richer satellites.

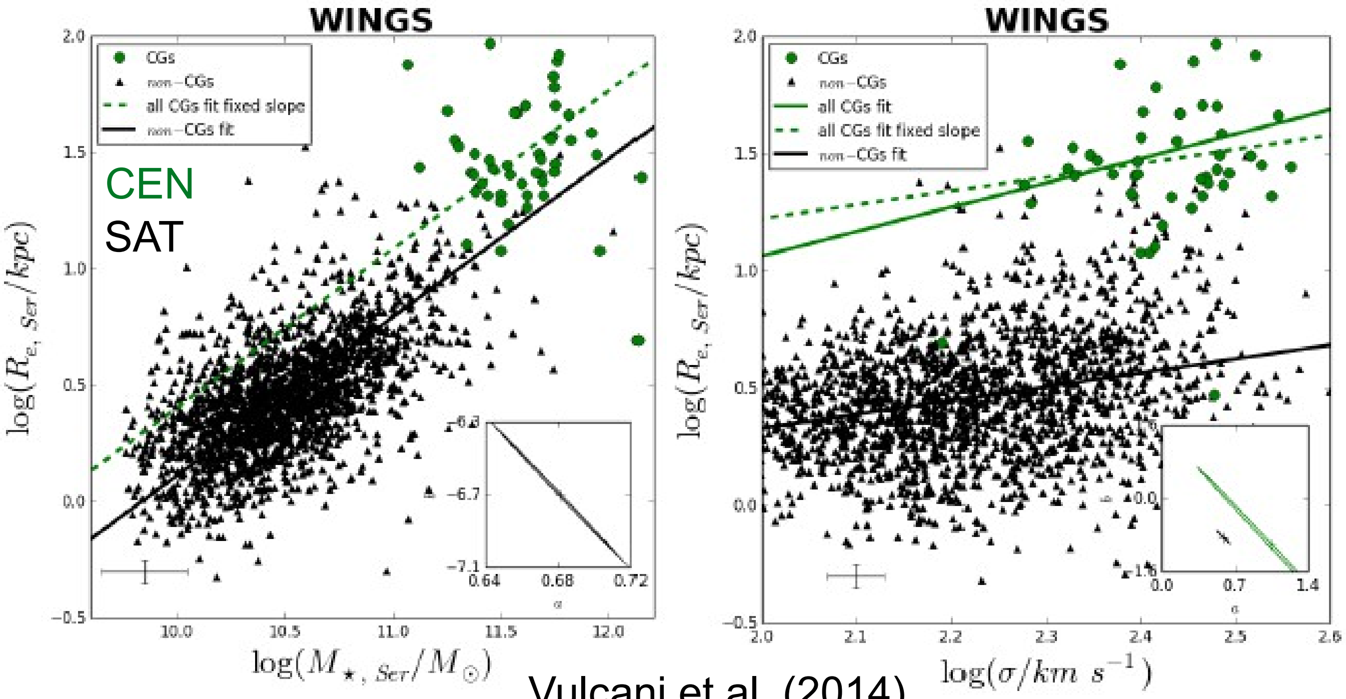


La Barbera et al. (2014)

Sizes of early-type central galaxies:



Bernardi (2009)



Vulcani et al. (2014)

Environment: clusters with $\log(M_h/M_o) \geq 14$.

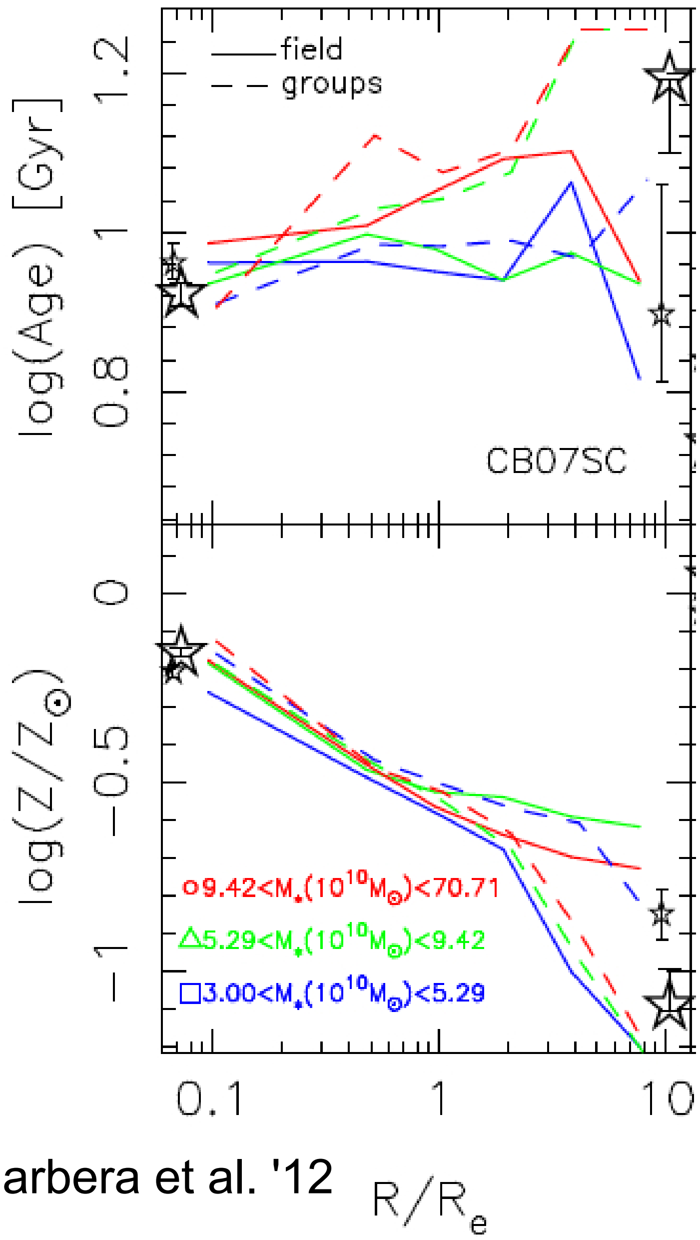
Sizes: R_e from de Vaucouleur profiles or double Sersic profiles.

Early-type centrals are more extended than early-type satellites of the same M_* or σ : size growth driven by minor mergers.

(Bernardi 2009; Hyde & Bernardi 2009; Hirschmann et al. 2015; Lauer et al. 2007; Liu et al. 2008; Naab et al. 2009; Nipoti et al. 2012; Oser et al. 2012; Trujillo et al. 2011)

Properties of the Whole Population of Massive Galaxies

- Age and metallicity radial gradients in early-type galaxies (La Barbera et al. 2012):



La Barbera et al. '12

Computed by comparing colour profiles with population synthesis models.

Environment: groups with $\log(M_h/M_o)$ ~ 13.9 and field.

AGE: group ETGs exhibit positive gradients, with their outskirts been older than their central regions; field ETGs have flatter or null gradients.

METALLICITY: gradients of group and field ETGs are negative. Gradients of group ETGs steepen in the galaxy outskirts.

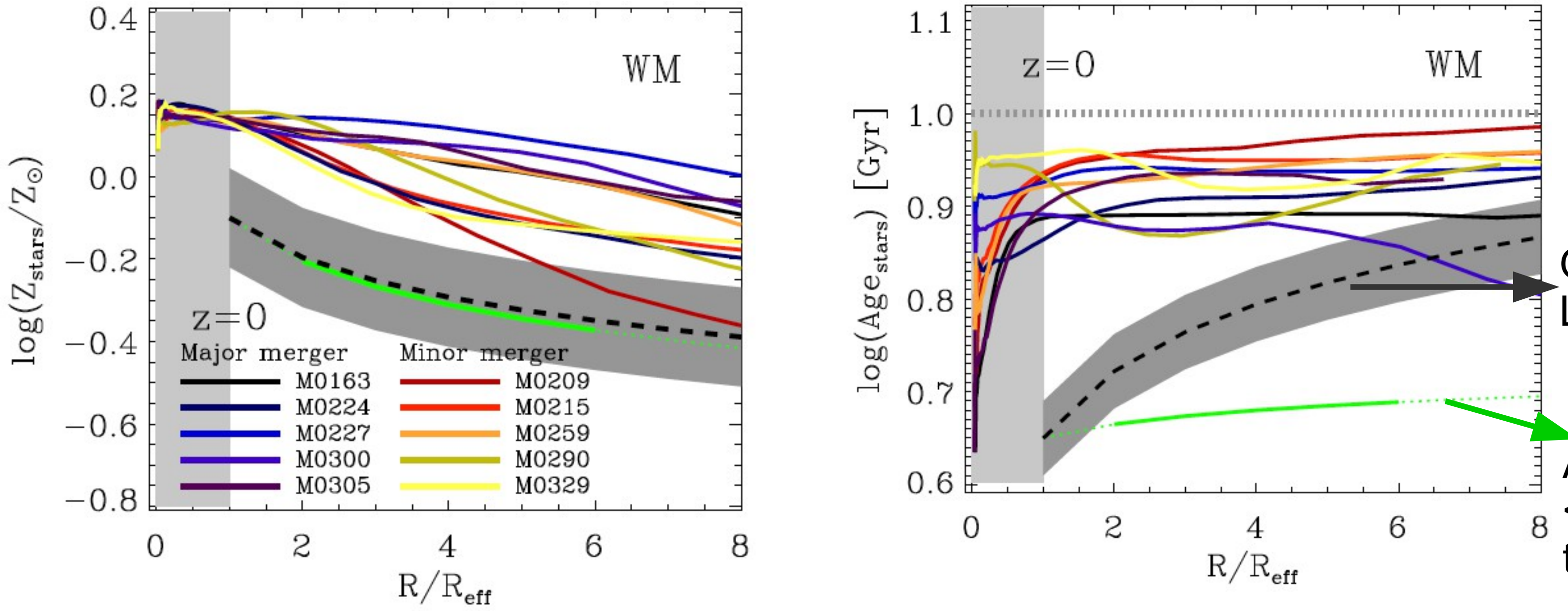
MODELS: different population models change the strength of these gradients but not the general conclusions.

CAUSE: ETGs outskirts build up through mergers with low mass systems, old and metal poor.

(Greene et al. '13 and '15; Hirschmann et al. '15; Lackner et al. '12; Naab et al. '09; Oser et al. '12; Pastorello et al. '14)

Comparison with Simulations

- Cosmological simulations of massive galaxies which feature major/minor mergers, metal cooling, SNII/I and AGB enrichment, galactic winds (Hirschmann et al. 2015):



Observations from La Barbera et al.'12

Average simulated <gradient>, scaled to observations

- ➔ Simulated ages and metallicities are offset from observations, possibly because of the recipe for galactic winds and the fact that simulated galaxies are satellites.
- ➔ Simulated <gradient> in Z is in good agreement with observations; simulated <gradient> in Age is positive but shallower than observed.
- ➔ Both simulated <gradients> are driven by galaxies which have assembled most of their mass through minor mergers (up to 10, of mass ratio < 1:4) since z ~ 2.

Massive Galaxies and Environment at High Reshifts

- The fraction of quenched massive satellites is > 60% up to *z* ~ 1 and increases with M_* and slightly with M_h.
  (Balogh et al. 2011; Lin et al. 2014; McGee et al. 2011; Mok et al. 2014; Muzzin et al. 2012 & 2014; Poggianti et al. 2006; Vulcani et al. 2010; Wilman et al. 2005)

- At *z* > 1.5, our measurements are biased by cosmic variance and hampered by observations in the infrared; in a number of clusters, the fraction of massive star-forming satellites equals or is somewhat larger than the fraction of passive massive satellites.
  (Hayashi et al. 2010; Strazzullo et al. 2013; Tran et al. 2010)

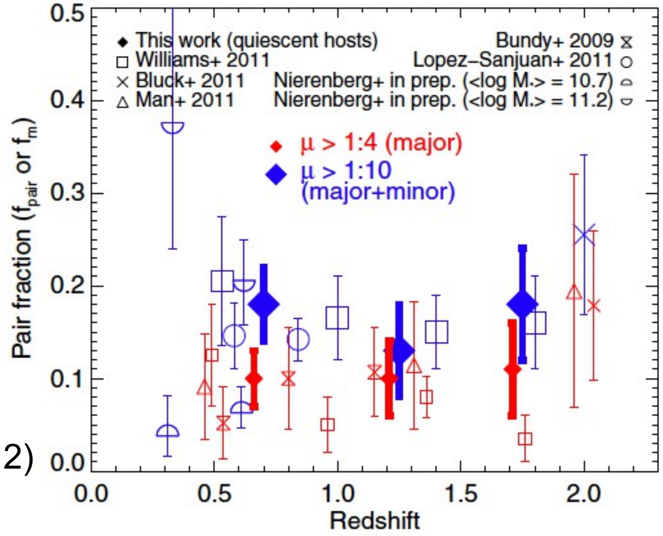
- Up to *z* ~ 0.6, massive central galaxies in massive halos are more extended than satellites of the same M_* or σ.
  Between *z* ~ 0.6 and *z* ~ 0 these galaxies have increased their M_* and R_e by a factor of 2 and 4, respectively, leaving their σ nearly unchanged.
  (Bernardi 2009; Bernardi et al. 2014; Lauer et al. 2007; Valentinuzzi et al. 2010; Vulcani et al. 2014; Zirm et al. 2012)

- This size evolution is part of the more general size growth of massive and quiescent galaxies since *z* ~ 2.
  (Daddi et al. 2005; Ferreras et al. 2009; Trujillo et al. 2006; van Dokkum et al. 2008)

Are there enough satellites out there?

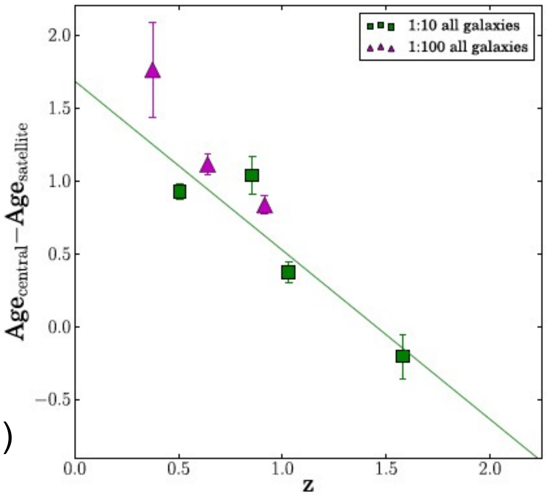
- The fraction of close pairs (massive quiescent galaxy + satellite) is constant with redshift.

  According to Newman et al. (2012), such a fraction can not account for the full size growth of galaxies at *z* ~ 2 via mergers.
  It can instead be sufficient at *z* < 1.



Newman et al. (2012)

- Satellites (logM* > 9) around massive galaxies are coeval (at *z* ~ 2) or younger (at *z* ~ 0) than their central galaxy.
  Their mergers with the central would create outskirts younger and metal-poorer than the inner regions of the central (Marmol-Queralto et al. '13; Pasquali et al. '10).



Marmol-Queralto et al. (2013)

- Cosmological simulations (i.e. Millenium I & II) and SAMs tend to overestimate the number of satellites, which depends on the adopted physics (i.e. SN/AGN feedback and galactic winds; Quilis & Trujillo '12; Hirschmann et al.' 15; Nipoti et al.'11 & '12; Oser et al. '12).

Summary

- The vast majority of massive satellites is passive and old; their observed properties show little dependence on environment, likely because these galaxies can quench their bulk star-formation activity via their secular evolution and/or AGN feedback.

- Massive (early-type) centrals residing in groups/clusters exhibit: *1)* significantly larger R_e than satellites of the same M_* (σ); *2)* a prolonged mass assembly history than their peers in the field. Both properties may be explained with mass accretion via minor mergers.

- Massive galaxies show positive radial gradients in age and negative radial gradients in metallicity, which are consistent with the accretion of small, old and metal-poor satellites. These gradients steepen for massive galaxies in groups, because of a larger number of satellites and an enhanced merging activity?

- Are there enough satellites to explain the size growth of massive & quiescent galaxies via minor mergers since $z \sim 2$ as suggested by simulations? Observations say *“possibly yes”* at $z < 1$ but *“likely no”* at higher redshift.

- Need for dedicated observations of environment at high redshift and for improved physics in simulations and SAMs.