Satellite Galaxies as Signposts of Environmental Effects

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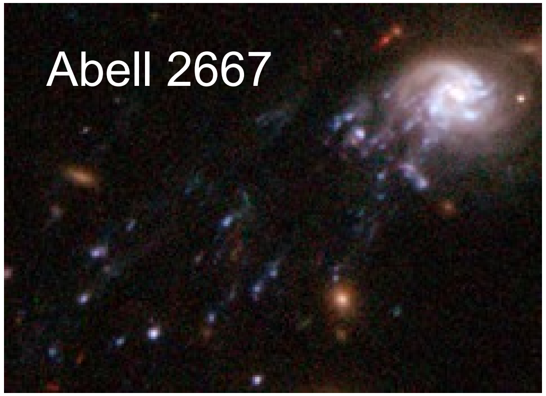
The Central - Satellite Distinction

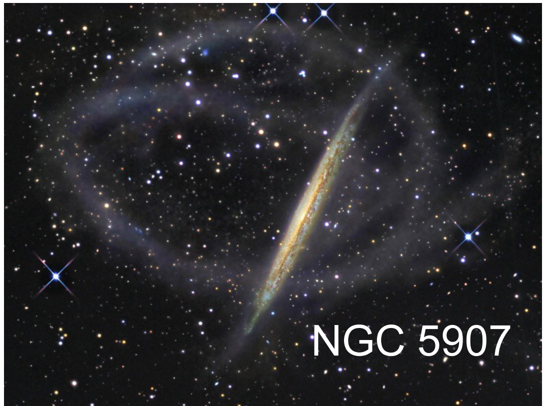
- **Definition**: out of the galaxies residing in the same group/cluster, the **central** is the most massive located in the group/cluster centre, and the remaining ones are defined **satellites**;

- **A major disadvantage:** satellites orbit within their environment, and interact with the local ICM, their peers and the potential well of their group/cluster;

- **The satellite erosion processes:**

  - Strangulation: slow removal of hot gas (Larson et al. '80)
  - Ram pressure stripping: fast removal of hot/cold gas (Gunn & Gott 1972)
  - Tidal stripping: removal of stars
  - Harassment, due to fast encounters (Moore et al. 1998)
  - Mergers with the central galaxy





Cortese et al. (2007)
Martinez-Delgado et al. (2008)

The Goal

- Use the **observed properties** of satellite galaxies to address:

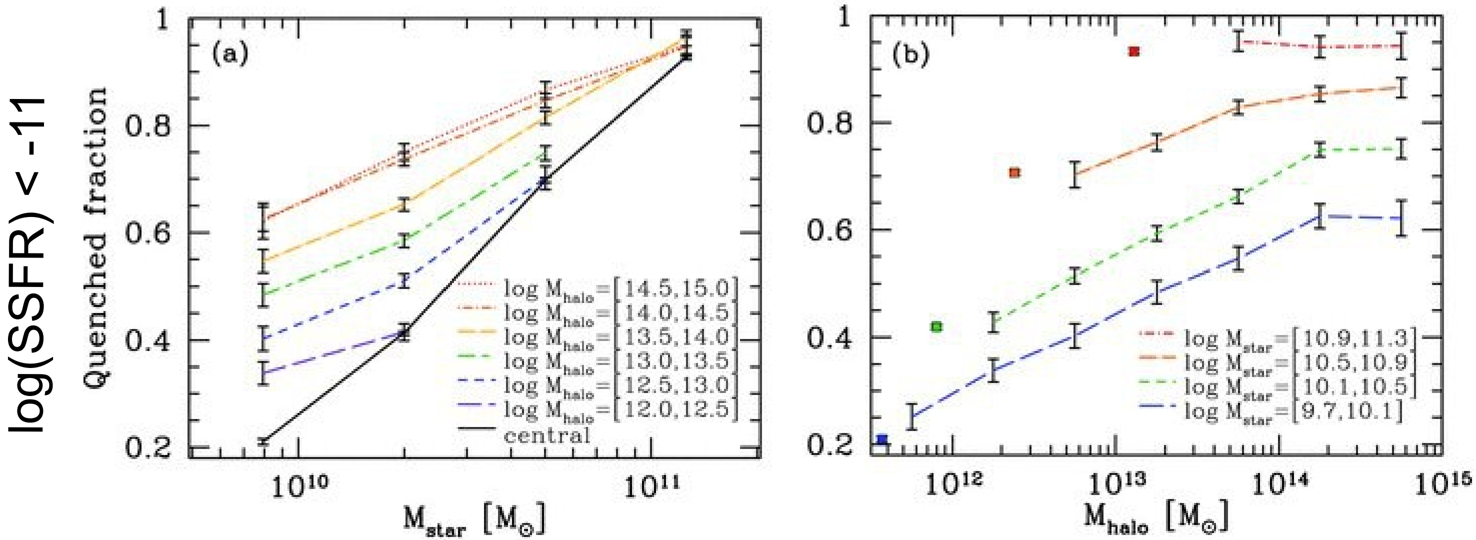
  - the time scales of quenching
  - their amplitude
  - their dependence on stellar mass (M*), halo mass (M_h) and cluster-centric distance
  - their dependence on redshift

- Compare the observed satellites with **the predictions of simulations and semi-analytic models** of galaxy formation and evolution to constrain the physics (and recipes) of environmental effects

Lessons learnt at z ~ 0

- **Strangulation: the facts**

1) The fraction of quenched satellites

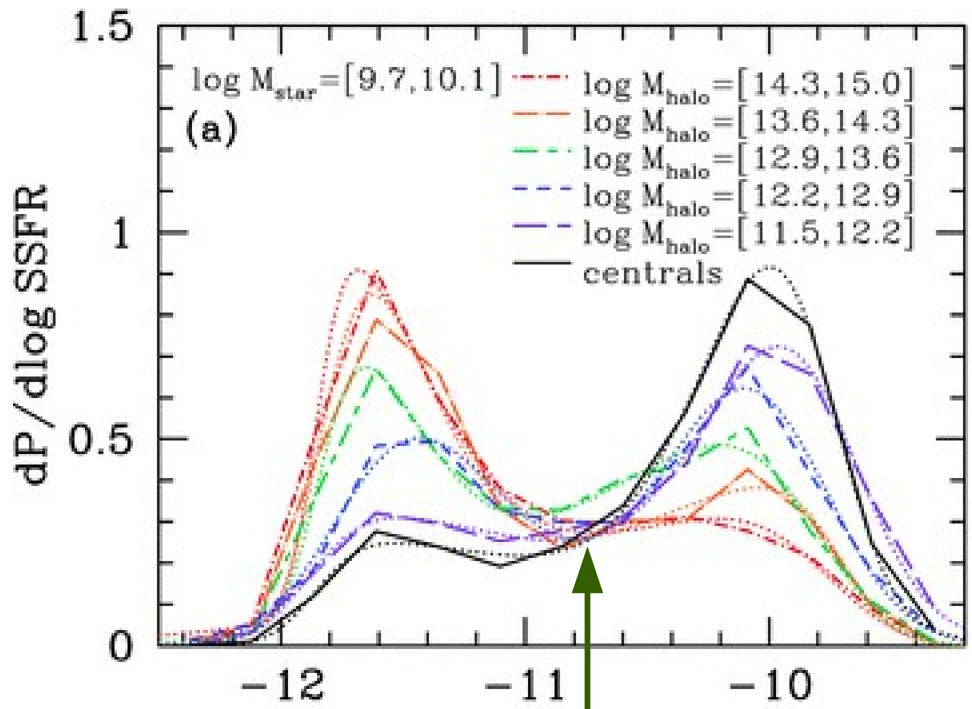


Wetzel et al. (2012)

- The fraction of quenched satellites increases with M_* and, at fixed M_*, with M_h. Its dependence on M_h weakens at $\log(M_*) > 10$

  cf. also Balogh et al. (2004), Hogg et al. (2004), Blanton et al. (2005), Weinmann et al. (2006), van den Bosch et al. (2008)

2) The distribution of satellite Specific SFRs



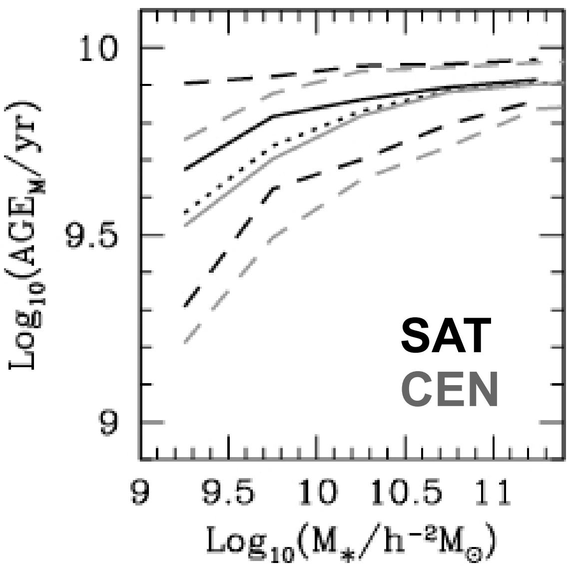
Wetzel et al. (2012)

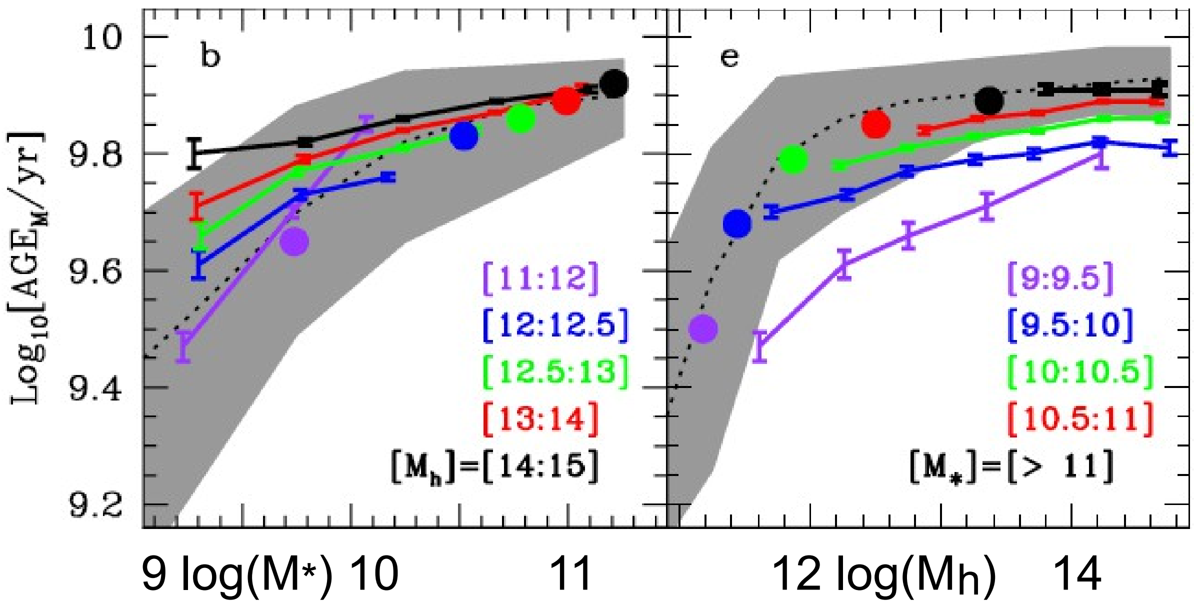
green valley

- Satellites of different M* in different environments show a similar bimodal distribution in SSFR with a constant break (or green valley) at log(SSFR) ~ -11

  cf. Balogh et al. (2004), Poggianti et al. (2008), Lewis et al. (2002) Gomez et al. (2003), Kauffmann et al. (2004), Tanaka et al. (2004)

3) The mean age of stars in satellite galaxies





Pasquali et al. (2010)

- Satellites are older than centrals at fixed M*: Δ(age) ~ 1.5 Gyr at log(M*) ~ 9.5
- Satellites at log(M*) < 10 show noticeable (age – M*) and (age – Mh) relations
- The age of the more massive satellites depends more on M* than Mh

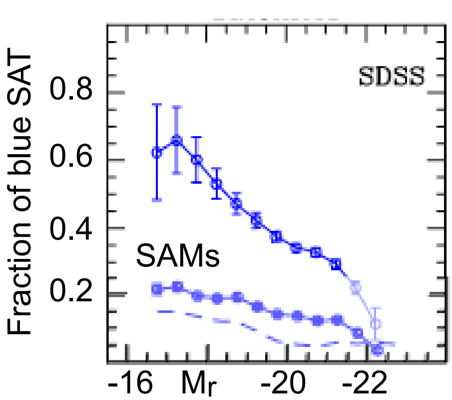
cf. also Gallazzi et al. (2005), Jimenez et al. (2007), Bernardi (2009)

Strangulation: suggested scenario

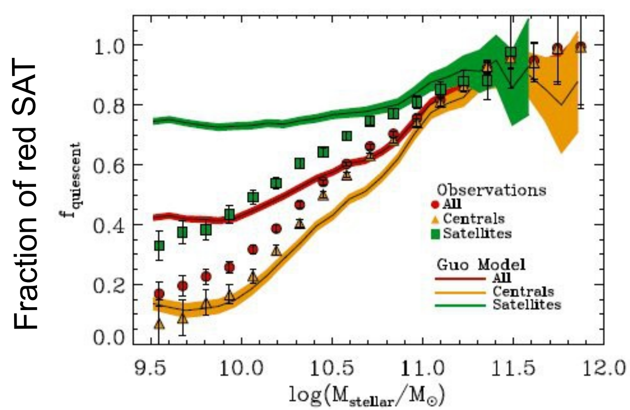
- More massive satellites had their first infall later than less massive satellites
- Satellites keep forming stars for 2 – 4 Gyr after their first infall, aka delay of quenching, independent of M_h
- The quenching of the star formation lasts itself less than 1 Gyr (Wetzel et al. 2012)

This picture is also supported by the observed [α/Fe] vs M_h
→ Anna Gallazzi's talk

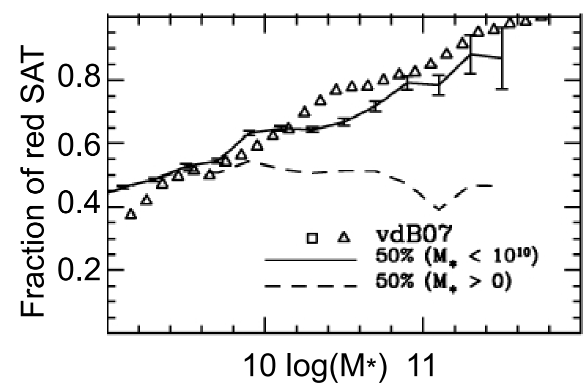
- The models' view → Michaela Hirschmann's talk



Instantaneous removal of hot gas: 80% of SAT are quenched (Weinmann et al. '06)



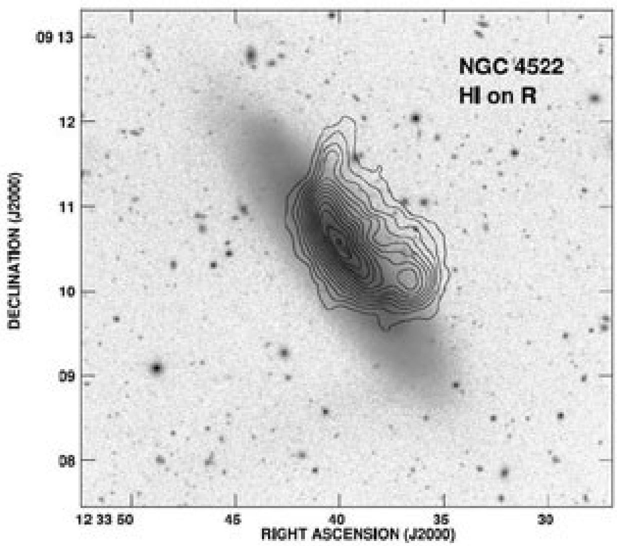
Removal of hot gas depends on M_h (Guo et al. '11, De Lucia et al. '12, Hirschmann et al. '14)

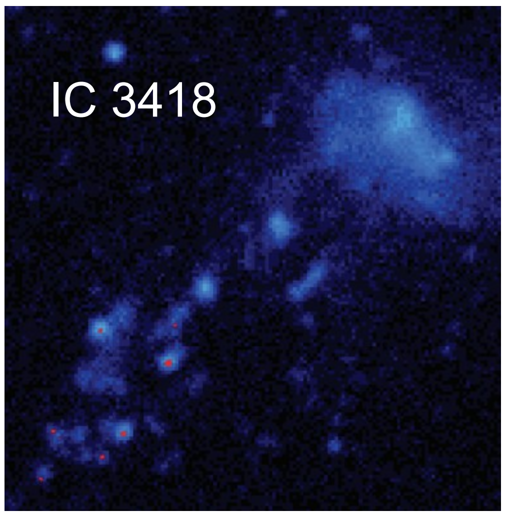


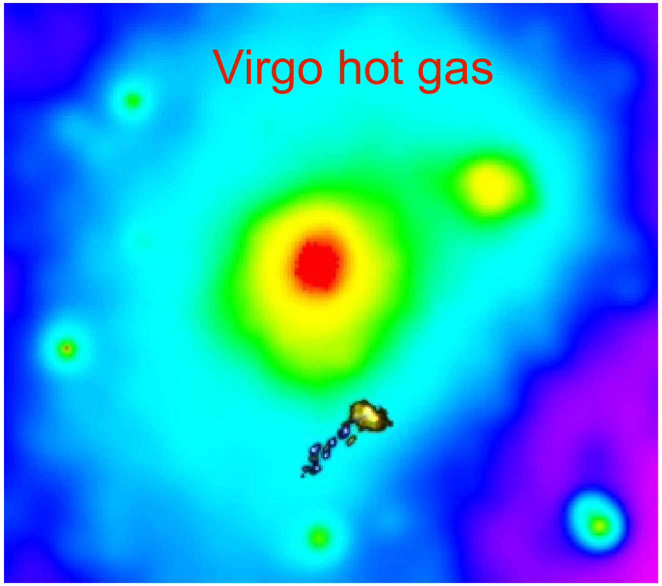
Gas stripping in 3 Gyr + 50% SAT at $M^* < 10^{10}$ disrupted (Kang & van den Bosch '08)

Ram-pressure stripping: the facts

1) Direct detection







Kenney et al. (2004, 2014), Vollmer et al. (2004)

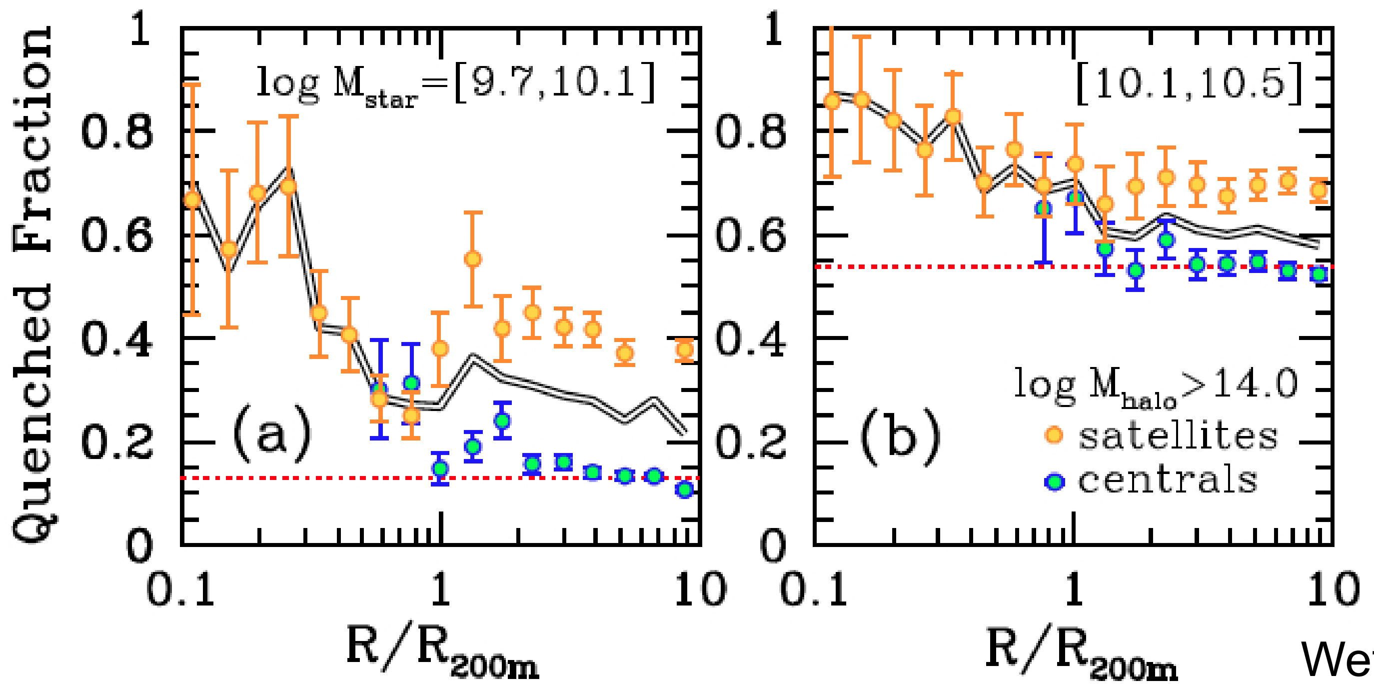
- The fraction of gas stripped from a satellite increases with the orbital velocity of the galaxy, the density of the ICM and the halo mass M_h of the environment

- Ram pressure triggers star formation first in the galaxy disk, then in the wake

$\longrightarrow$ Bianca Poggianti's talk

cf. Gunn & Gott (1972), Balogh et al. (2000), Bekki et al. (2002), Hester (2006), McCarthy et al. (2008), Kapferer et al. (2009)

2) Radial gradients in the fraction of quenched satellites

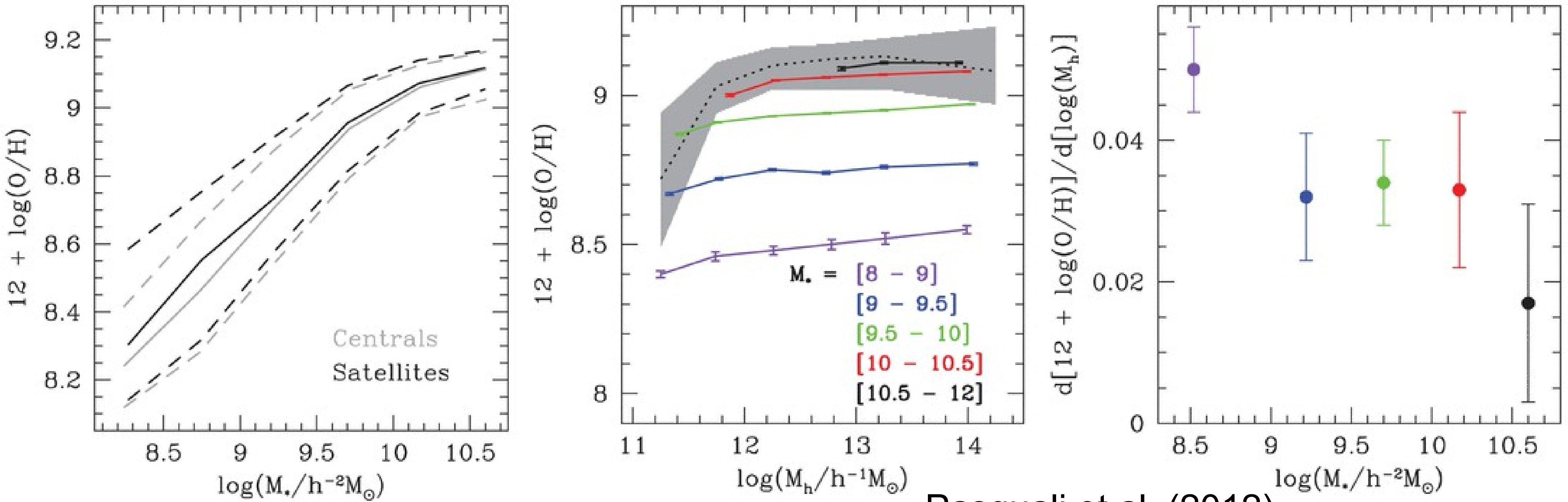


Wetzel et al. (2012)

- The fraction of quenched satellites increases toward the group/cluster centre, where the ram-pressure stripping is more efficient and satellites with earlier infall times are (cf. Hansen et al. 2009, Pasquali et al. 2009, Wang et al. 2009, van den Bosch et al. 2008, von der Linden et al. 2010) ⟶ Anna Cibinel's talk

- The relatively high fraction of quenched satellites at R > R_{vir} may be due to halos being ellipsoidal, satellites moving along elliptical orbits, accretion of galaxy groups, interactions of the infalling satellites with a more-than-thought extended halo (Bahe' et al. 2013, Wetzel et al. 2012)

3) The gas-phase metallicity

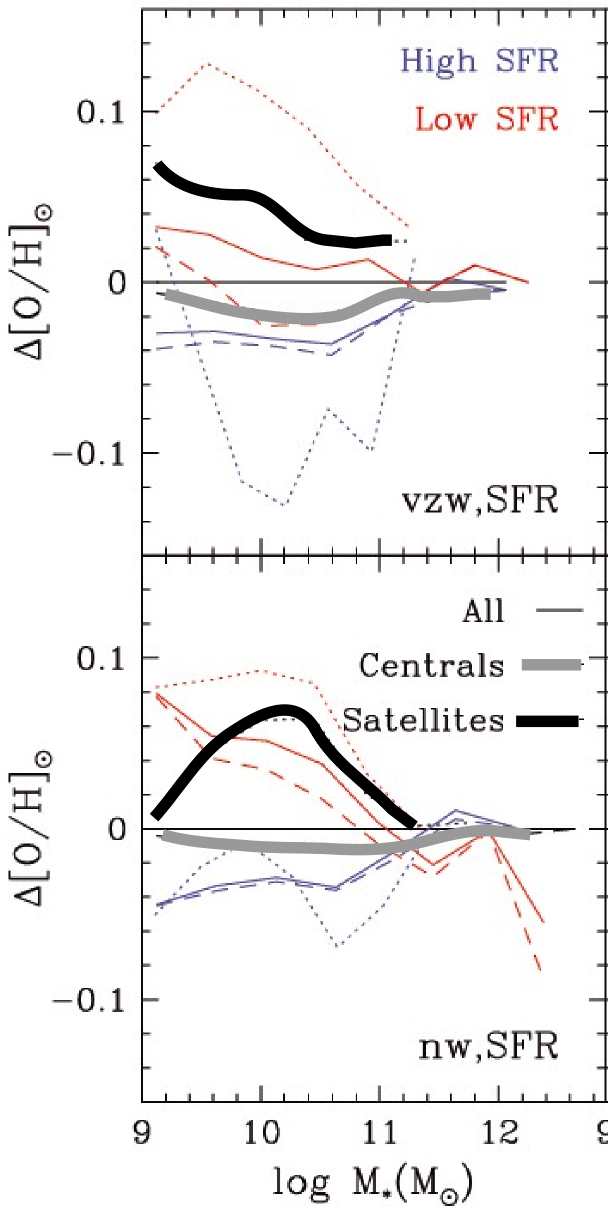


Pasquali et al. (2012)

- At fixed M* satellites have a higher gas-phase abundance than centrals. Δ[O/H] = 0.06 dex at log(M*) ~ 8.2
- The gas-phase metallicity of satellites increases with Mh at fixed M*. At log(M*) ~ 9, Δ[O/H] = 0.15 dex in the range 11 < log(Mh) < 14
- Ram-pressure stripping inhibits radial inflows of metal-poor gas

cf. Cooper et al. (2008), Mouhcine et al. (2007), Shields et al. (1991), Skillman et al. (1996), Petropoulou et al. (2011)

3a) Model gas-phase metallicity

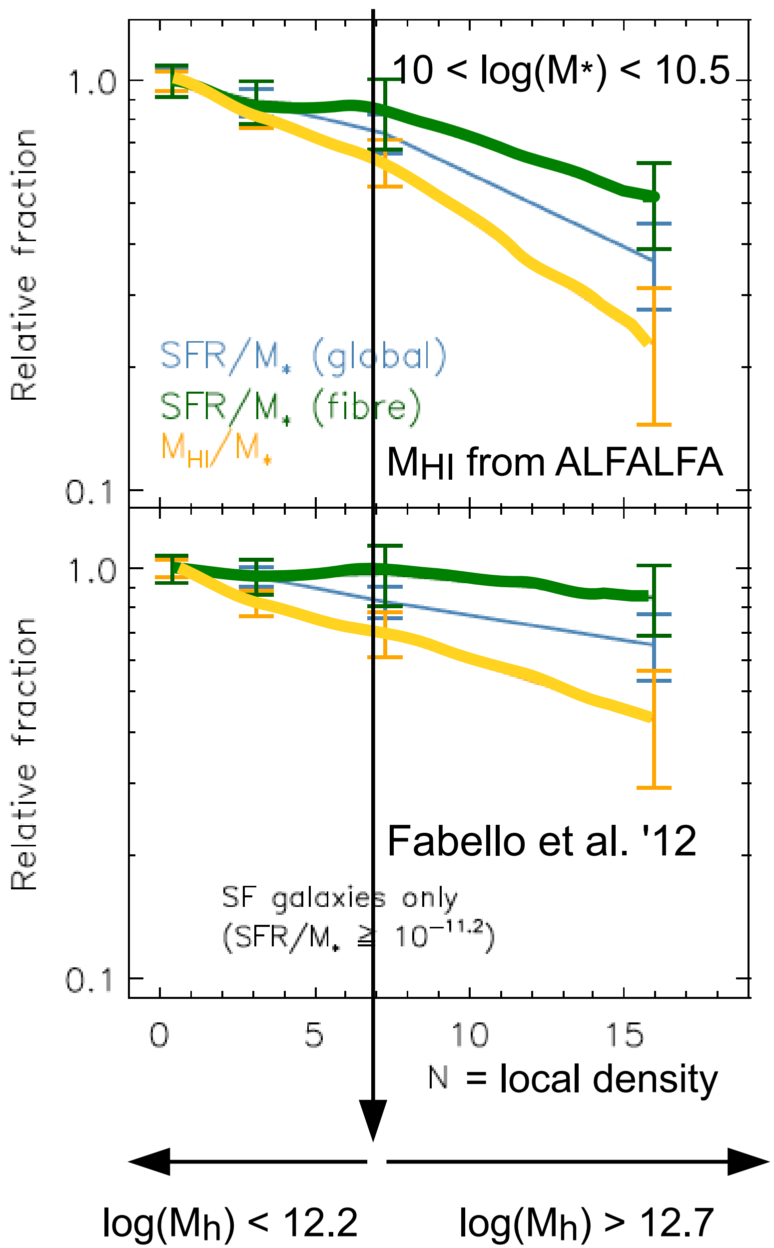


Dave' et al. (2011)

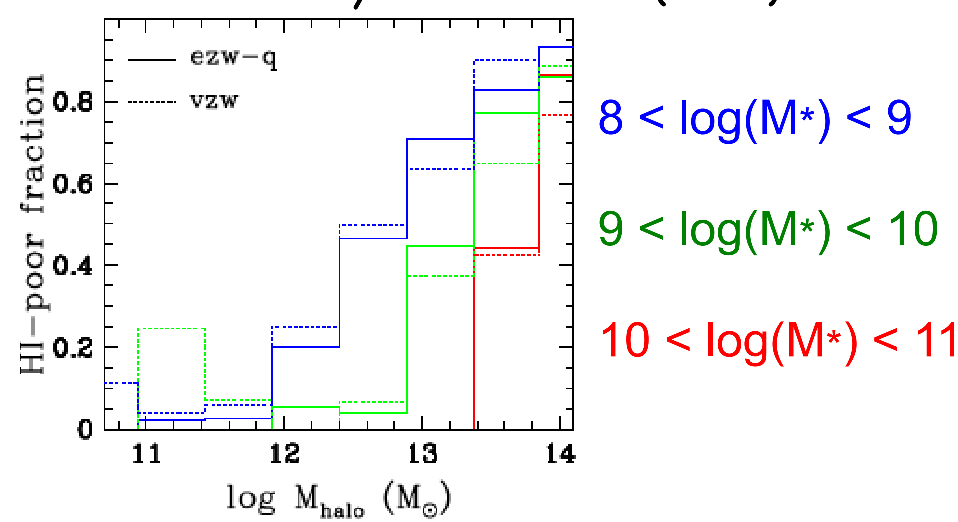
- The simulations performed by Dave' et al. (2011) use GADGET-2 and include ram-pressure stripping, as well as metal-line cooling, metal enrichment from SNeII, SNeI and AGB stars, galactic outflows tied to the SFR

- Switching galactic outflows on/off does not change significantly the offset in [O/H] between central and satellite galaxies.
  This offset is mostly driven by ram-pressure stripping and is consistent with what observed

4) The HI mass

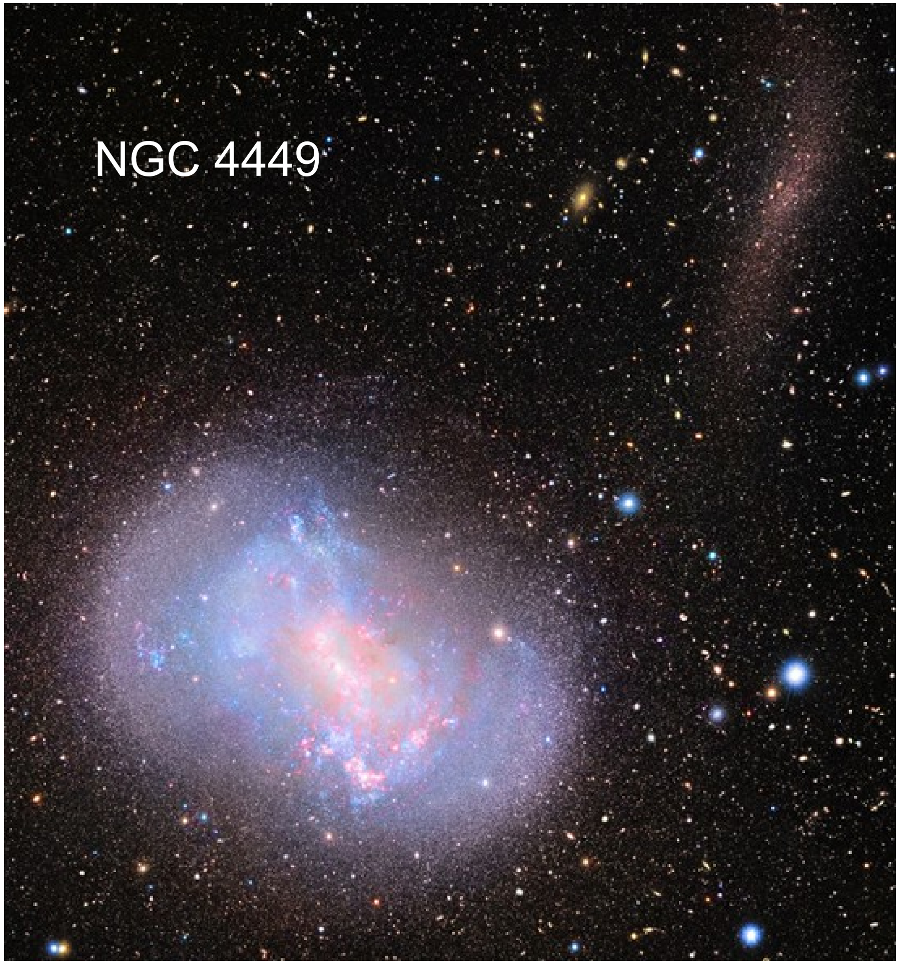


- The fraction of galaxies with detected M_{HI} declines with N more rapidly than the fraction of galaxies with measured SFR $\rightarrow$ Eva Busekool's & Ryan Cybulski's talks
- This trend is evidence for ram-pressure stripping of cold gas from the outer disks of galaxies with log(M*) < 10.5
- Ram-pressure stripping is at work in environments more massive than $\log(M_h) \sim 13$ (Fabello et al. 2012; see also Gavazzi et al. 2013)
- The simulations by Dave' et al. (2013) show:



Tidal stripping or stellar mass loss

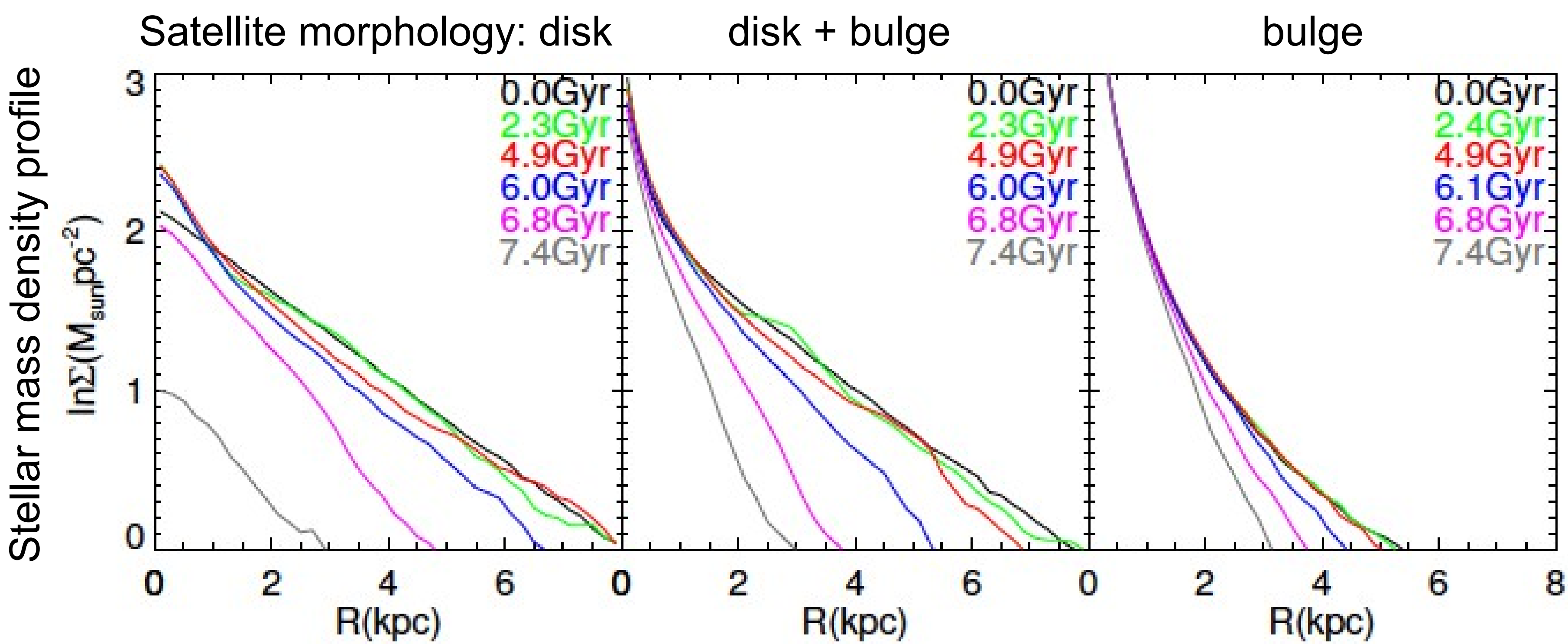
1) Direct detection



Martinez-Delgado et al. (2012)

Duc (2013)

2) Simulations of tidal stripping for a central-satellite pair

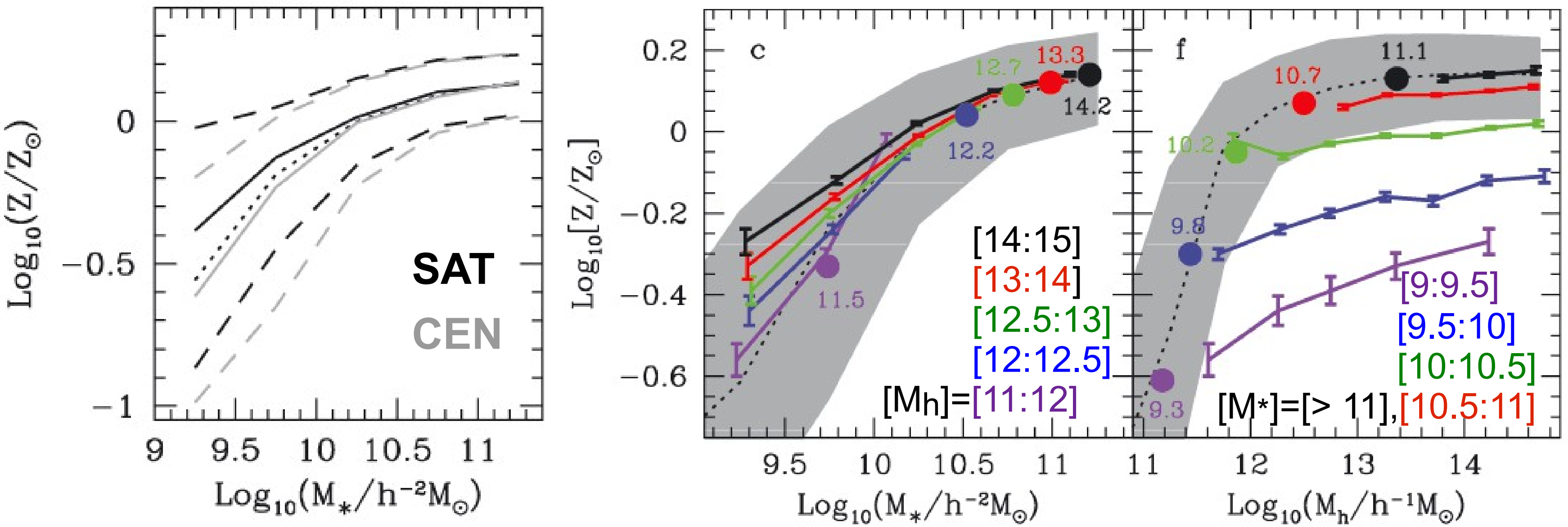


Chang et al. (2012)

- Stellar mass loss starts ony after 80% - 90% of the satellite darrk matter halo has been removed

- At fixed M*, stellar mass loss mainly depends on the satellite morphology; the satellite orbit and the morphology of the central play a 2nd order effect (Chang et al. 2012)

3) The stellar metallicity

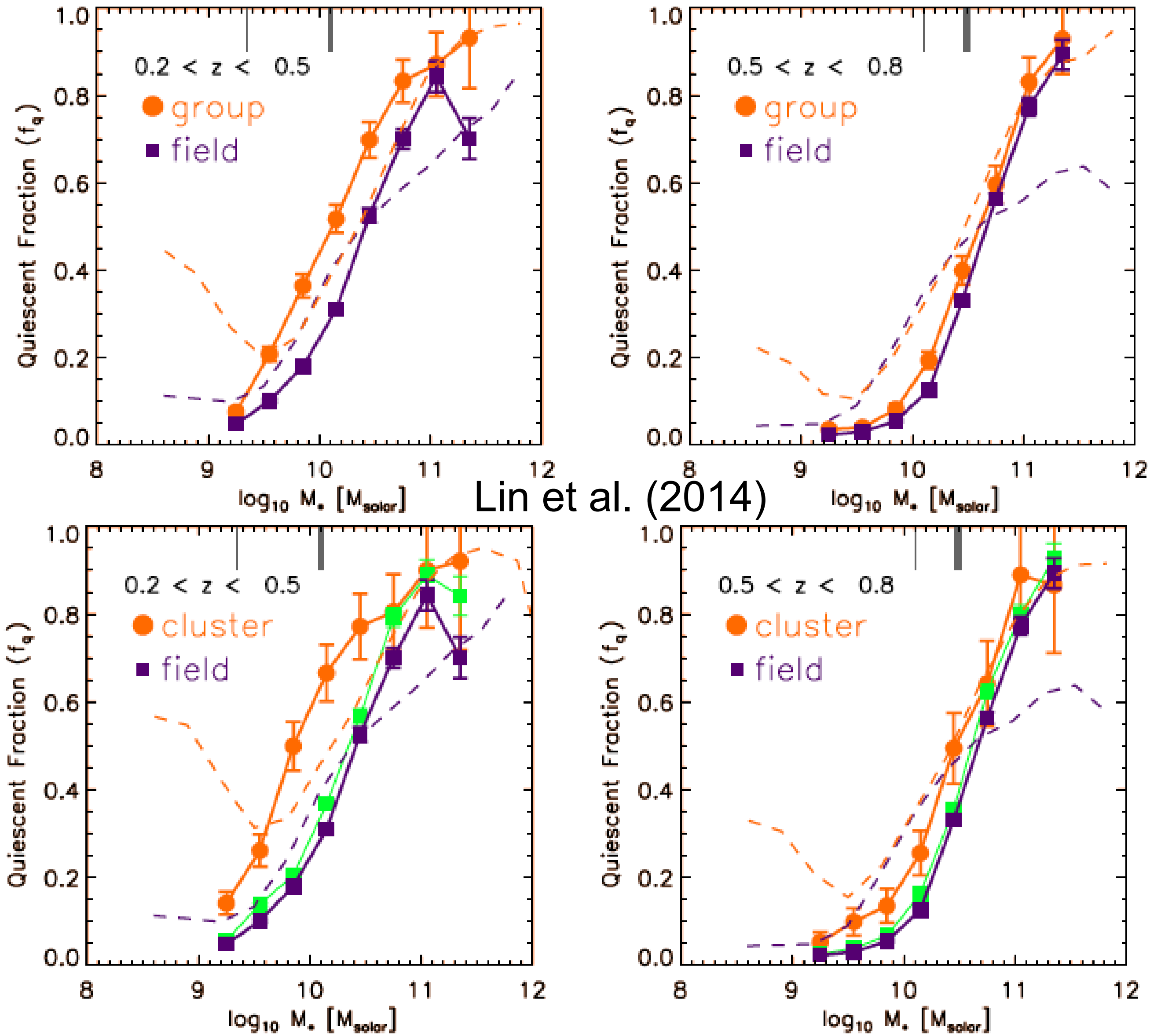


Pasquali et al. (2010)

- Satellites get metal-richer than centrals as their M* decreases. $\Delta[Z/Z_O]$ ~ 0.2 dex at log(M*) ~ 9
- The stellar metallicity of satellites at log(M*) < 10 increases with Mh. This is evidence for tidal stripping and early redshifts of infall
- See Anna Gallazzi's talk for an update
- SAMs of Wang et al. (2008) predict that satellites and centrals have similar metallicity

Environmental effects at high redshift

At intermediate redshifts: 0.2 < z < 0.8



Lin et al. (2014)

The fraction of quiescent galaxies decreases with at higher z, but is larger in groups/clusters than in the field

The fraction of quiescent galaxies is higher in clusters than in groups

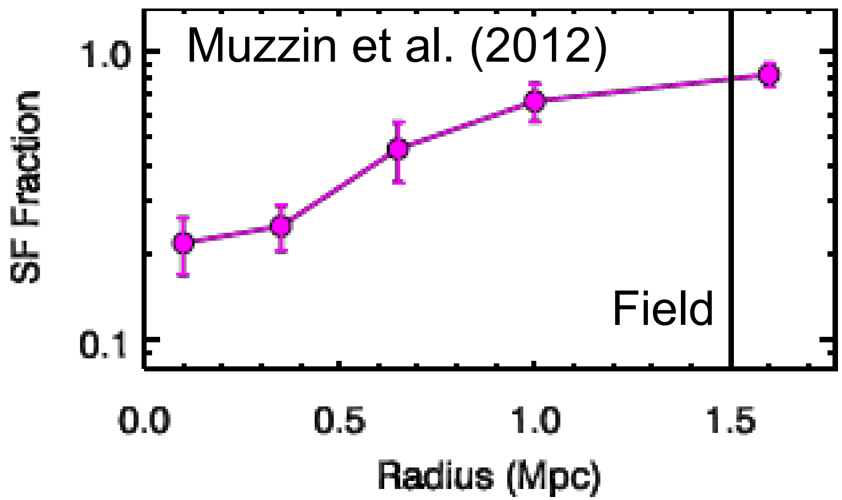
The fraction of quiescent galaxies at these z is smaller than at z ~ 0

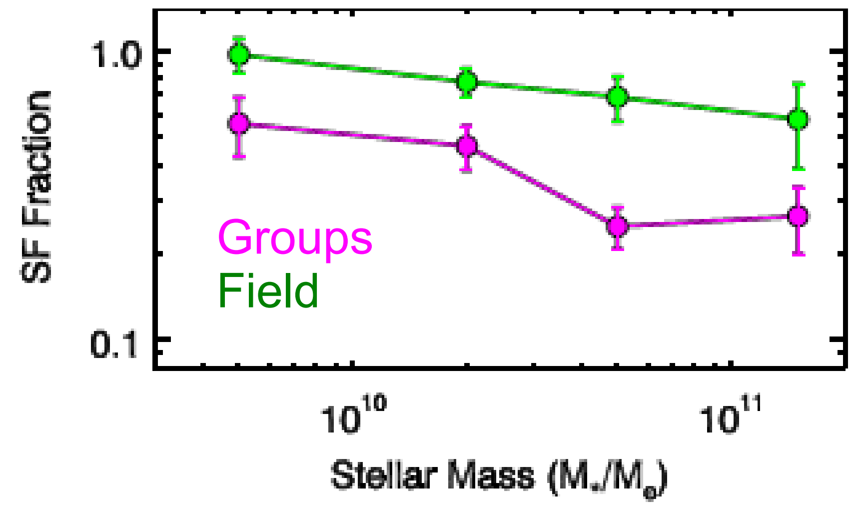
At fixed M*, star-forming galaxies in groups or clusters at these z exhibit a SFR a factor of 2 smaller than those in the field

→ Chris Haines' talk

cf. Lin et al. (2014), McGee et al. (2011), Poggianti et al. (2006), Vulcani et al. (2010), Wilman et al. (2005)

At $z \sim 1$



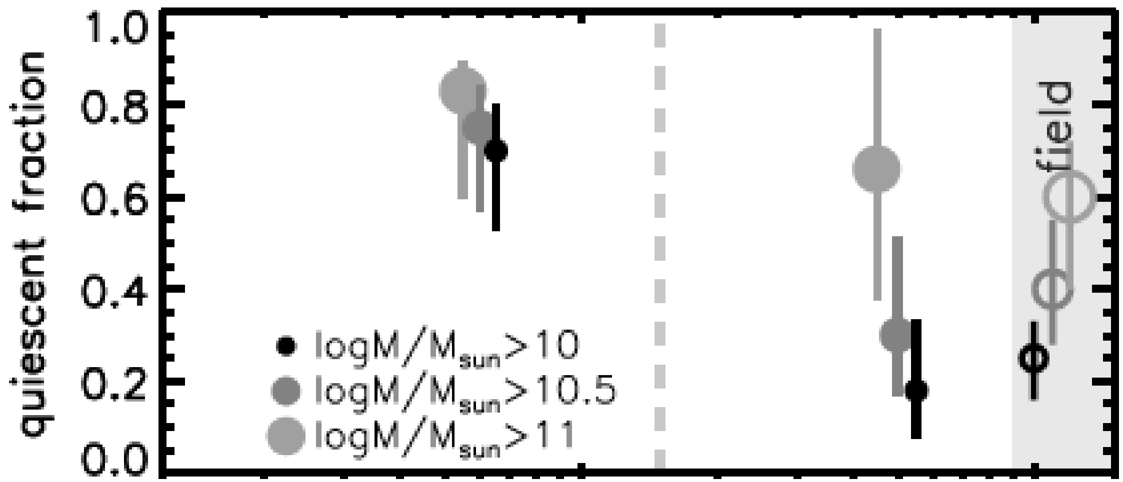


- The fraction of quenched galaxies at $z \sim 1$ is higher in groups (> 50%) than in the field
- The fraction of quenched galaxies at $z \sim 1$ increases at lower cluster-centric distances: evidence for ram-pressure stripping
- The fraction of quenched galaxies at $z \sim 1$ is consistent with a delay < 1 Gyr, plus a short quenching time scale of ~0.25 Gyr

→ Allison Noble's talk

cf. Balogh et al. (2011), Mok et al. (2014), Muzzin et al. (2012, 2014)

At $z \sim 2$



Strazzullo et al. (2013)

- The cluster Cl 1449+0856 at z = 2 exhibits a fraction of quiescent galaxies with log(M*) > 10 that is larger than in the field and increasing at smaller cluster-centric distances (Strazzullo et al. 2013)

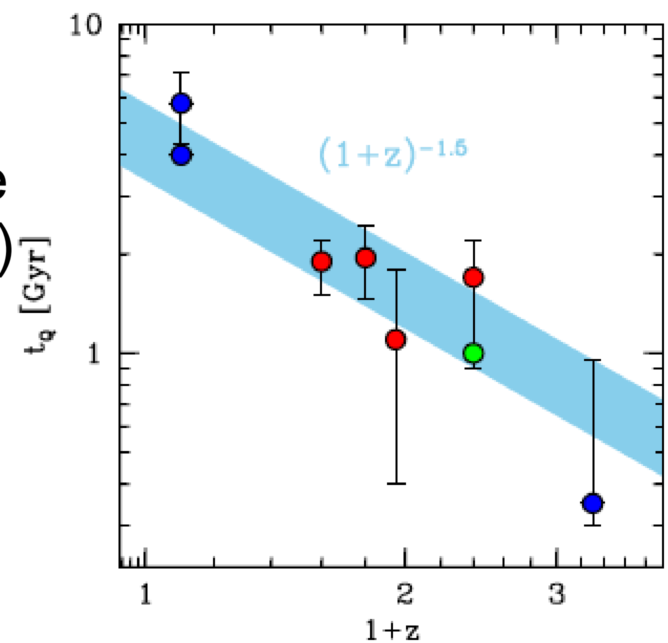
→ Gregory Rudnick's talk

Conclusions

- In the local Universe, the fraction of passive satellites, their SFR distribution, as well as their stellar ages and [α/Fe] abundances are consistent with a delayed-then-rapid quenching of their star formation activity: $\Delta t(\mathrm{SFR}) = 2 - 4$ Gyr $+$ $\Delta t(\mathrm{quenching}) \leq 1$ Gyr

- At $z \sim 1$, the larger fraction of quiescent galaxies in groups/clusters with respect to the field points to a shorter SF delay (≤ 1 Gyr) and a shorter quenching time scale (~0.3 Gyr)

- How to reconcile: the "total" quenching time scale depends on z as $(1 + z)^{-1.5}$, similarly to the Halo dynamical time scale (Tinker & Wetzel '10)
Satellites lose their gas by dynamical friction while crossing their host halo



Tinker & Wetzel (2010)