What drives galaxy formation: galaxy mass or environment?

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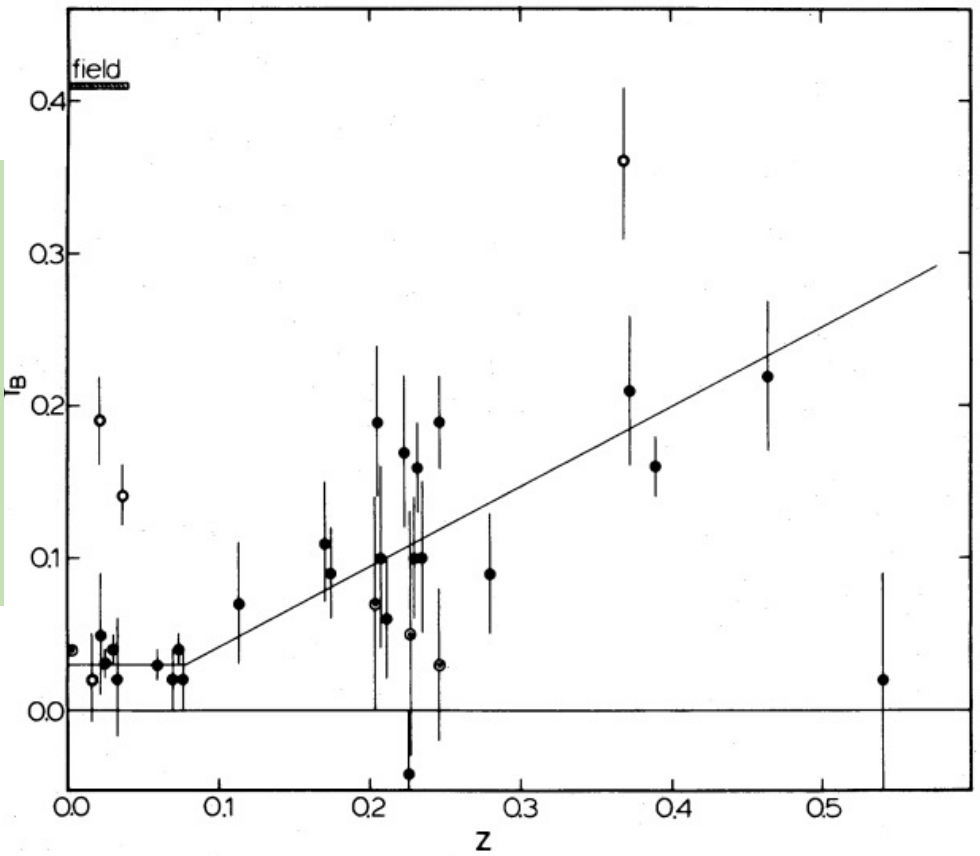
What drives galaxy formation?

- Is galaxy mass or environment more important in determining galaxy properties? “Data must speak first….”
- What does this mean for theoretical models?
- How do we define galaxy environment to compare with observations?

Durham University

Properties that depend on environment



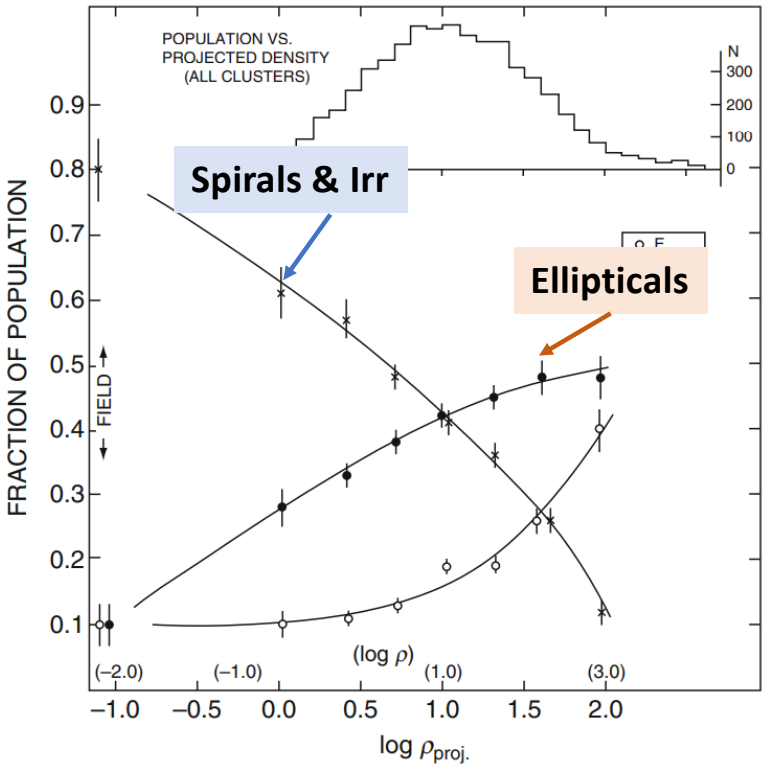
Fraction of blue galaxies

redshift

- The fraction of blue galaxies in clusters
- Higher redshift clusters have more blue galaxies
- Is infall population evolving with redshift?
- Transformation within clusters?

Butcher & Oemler 1978

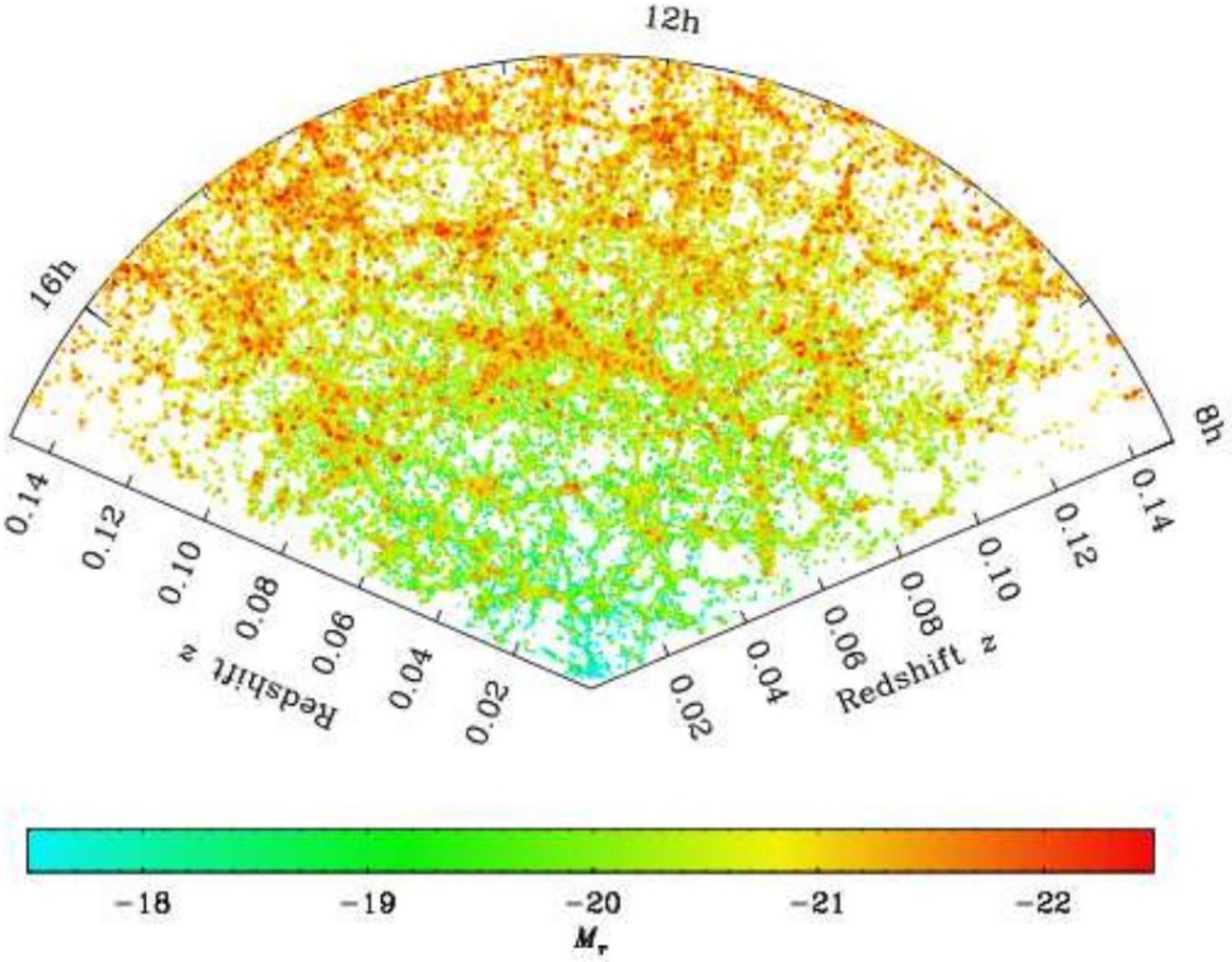
Properties that depend on environment



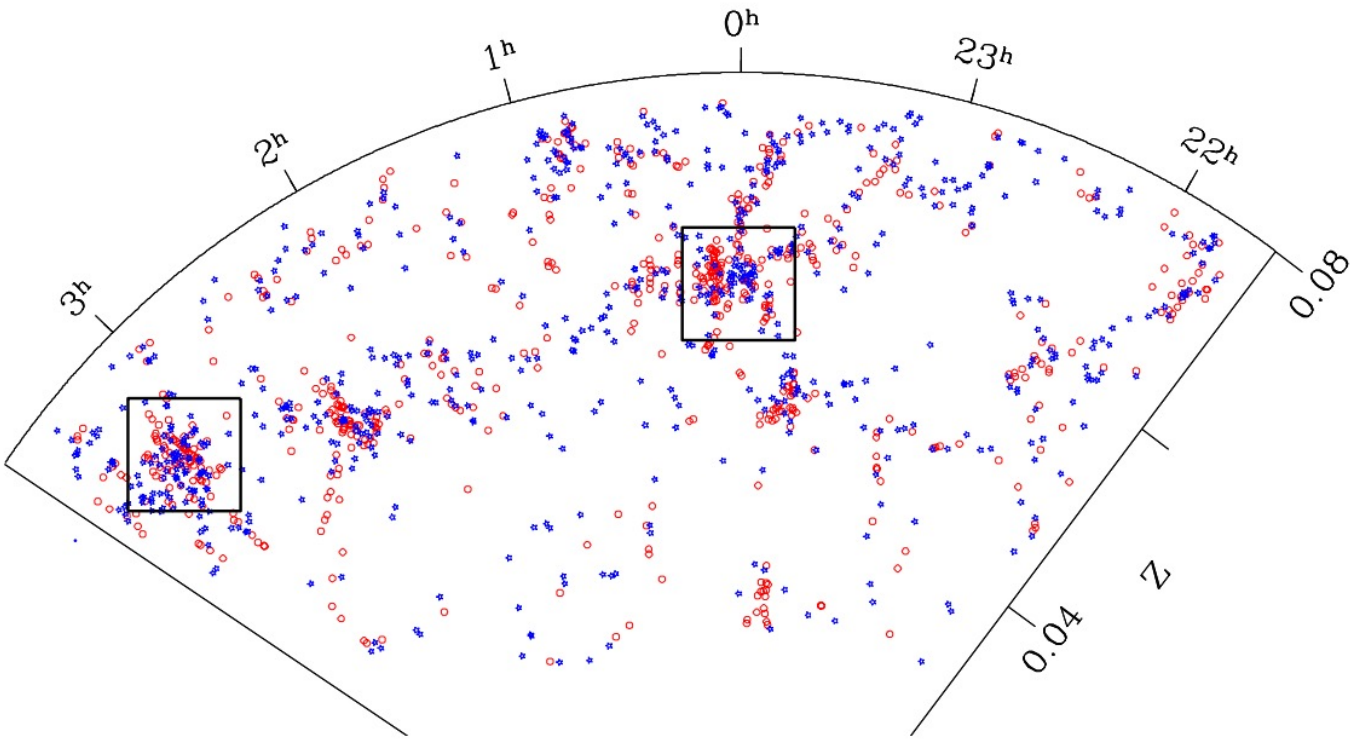
Projected current density

- Variation of morphological type with local density inside clusters
- Fraction of Early type galaxies increases with local density
- Expressed in terms of local density but “seen” as showing a dependence on “birth” density

Dressler 1980



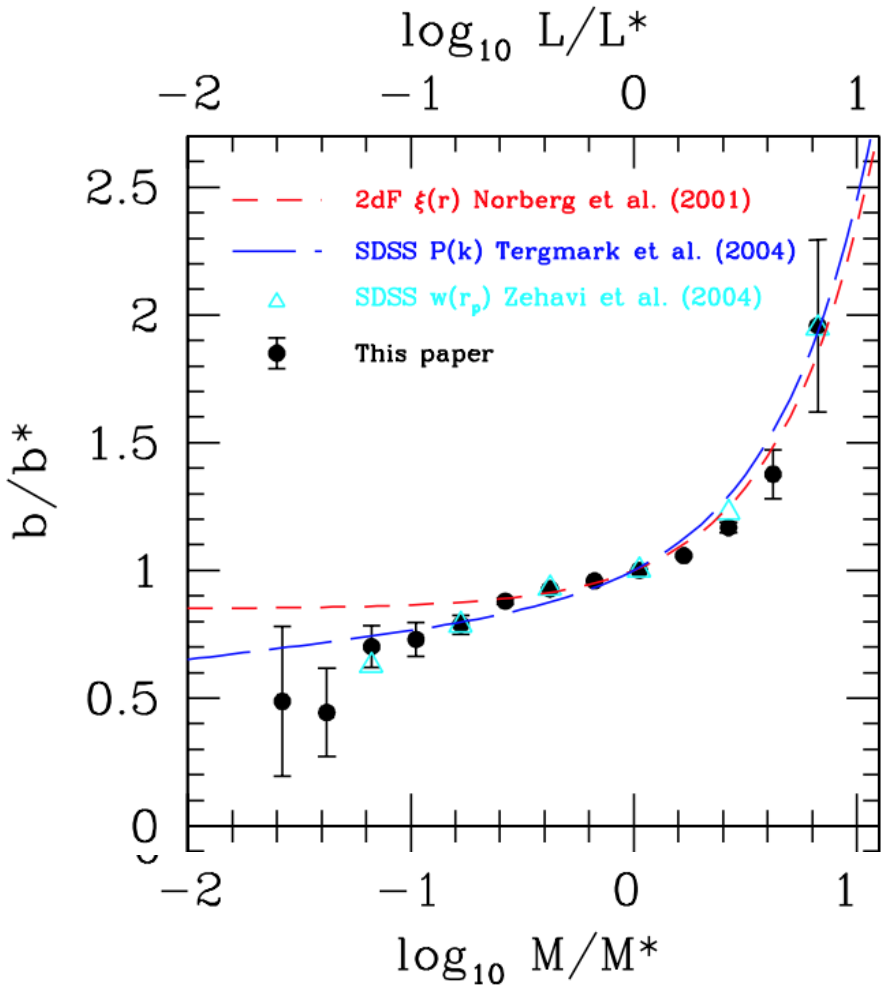
- SDSS Main Galaxy Sample
- Probe wide range of environments
- Large enough to subdivide by intrinsic galaxy properties
- Dependencies on M*: e.g. mass-metallicity relation
- Galactic conformity
- Bright galaxies more strongly clustered
- Zehavi et al. 2011



(a) $-18.0 \geq M_{b_J} - 5\log_{10} h \geq -19.0$

Passive spectral type **active spectral type**

- 2-degree field Galaxy Redshift Survey
- Spectral types assigned using PCA Madgwick et al. 2001, 2002
- Galaxies with more passive spectra more strongly clustered
- Norberg et al. 2002



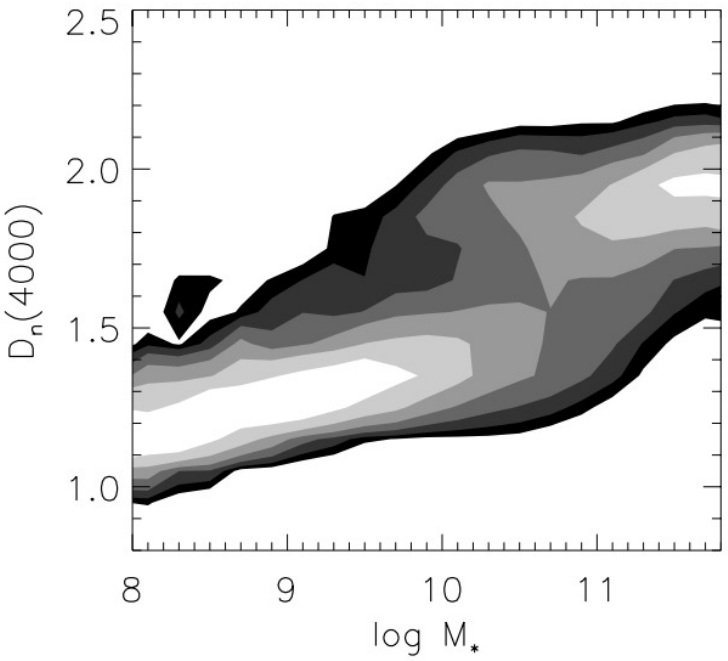
Properties that depend on galaxy mass – galaxy clustering

Li et al. 2006

See also:
Zehavi et al. 2005, 2011, Norberg et al. 2001, 2002

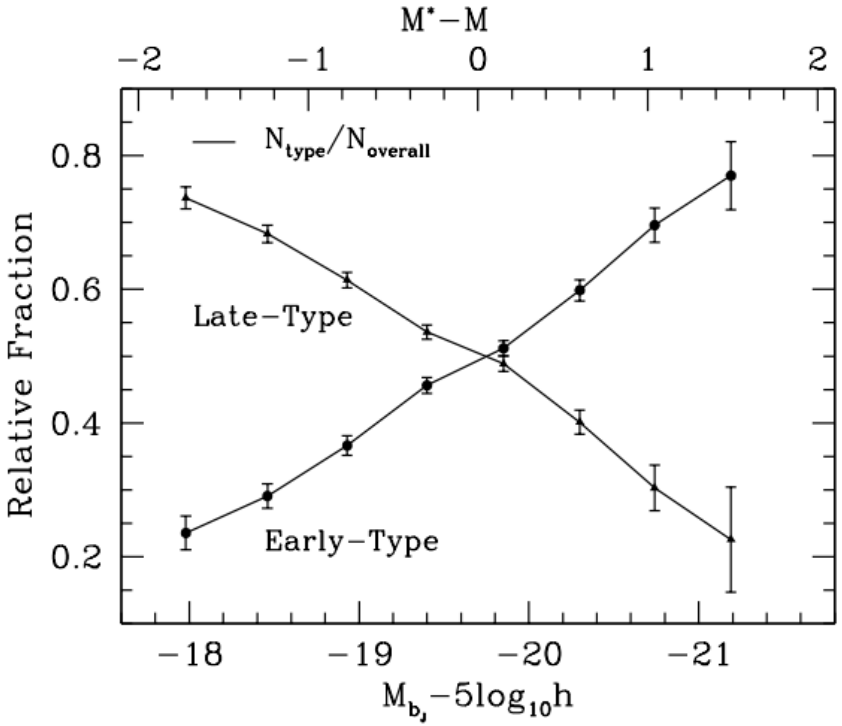
Properties that depend on galaxy mass

Variation of age of stellar populations with mass

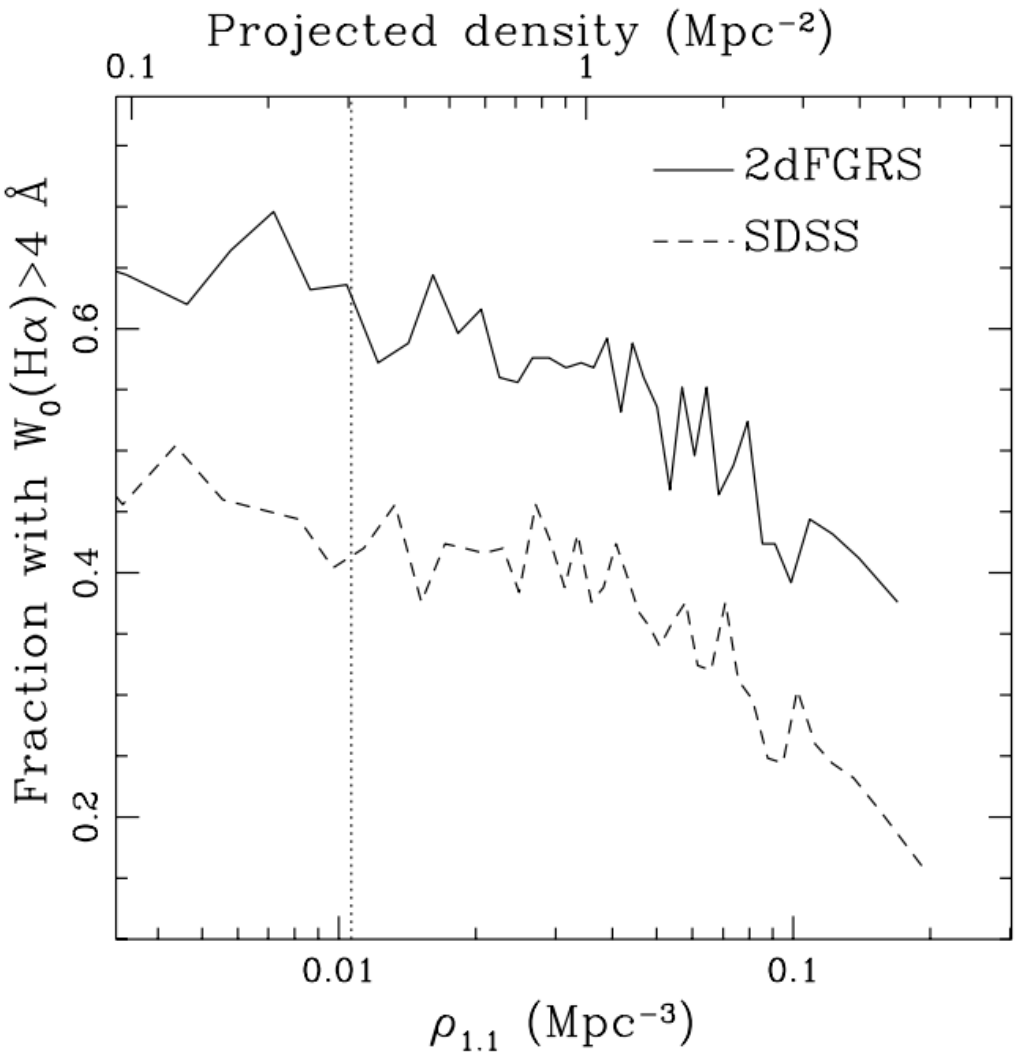


Kauffmann et al. 2003

Variation of spectral type with luminosity

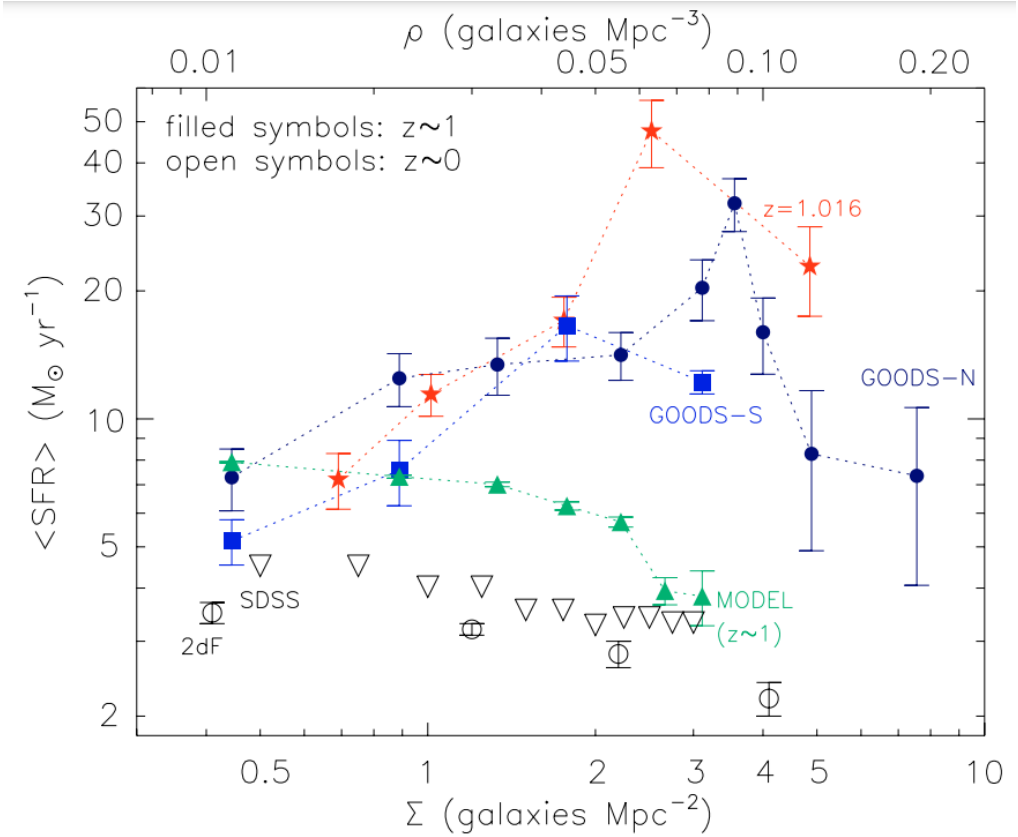


Norberg et al. 2002; Madgwick et al. 2001



- Study of SFRs in groups and low density environments
- Decline in SFR with increasing density
- Similar results in 2dFGRS and SDSS
- Balogh et al 2003 (see also Lewis et al 2002)

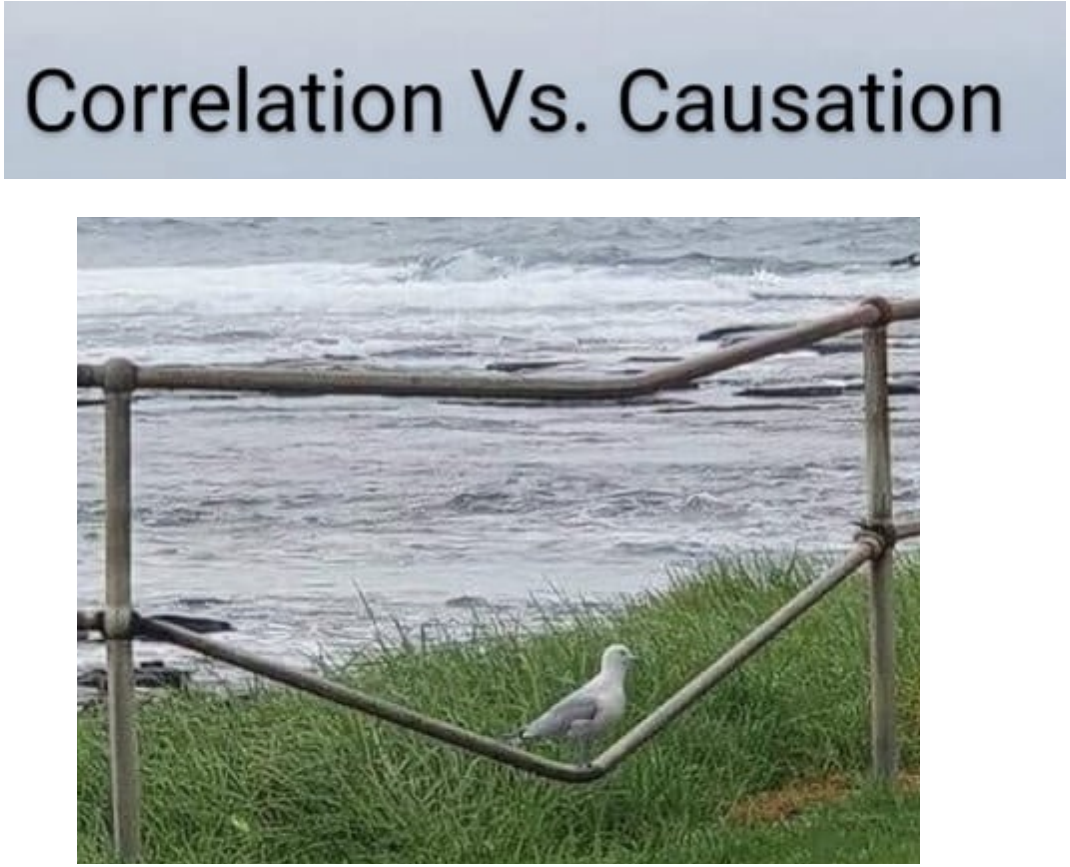
Dependence of SFR on environment



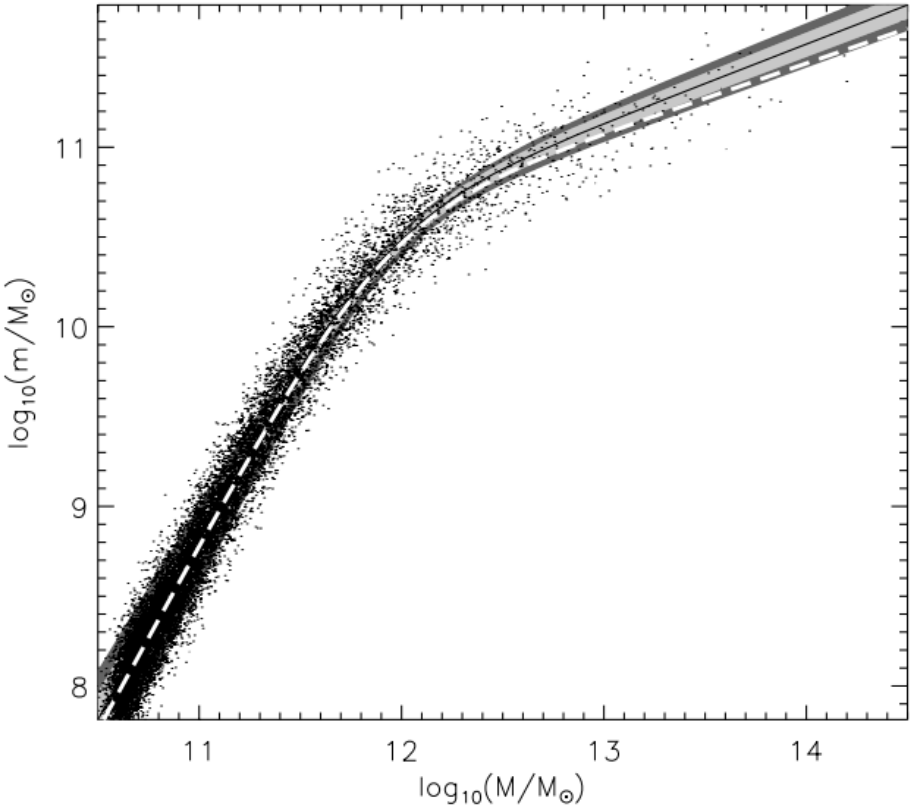
- Measurement of SFR vs galaxy local density
- At z=0, higher SFR in galaxies in low density environments
- This trend reverses at high redshift
- Elbaz et al 2007
- See recent view on this in Lemaux, Cucciati et al. 2022

How do we interpret trends with galaxy mass or galaxy environment in theoretical models?

Is it really galaxy mass that matters?



Halo mass is a primary driver: M* correlates with Mhalo



- Galaxies form in DM halos: White & Rees 1978
- Abundance match galaxies drawn from observationally inferred stellar mass function with mass ranked halos from N-body simulation
- Moster et al. 2010
- See also Kravtsov et al. 2004, Vale & Ostriker 2006

Monte Carlo dark matter halo merger trees

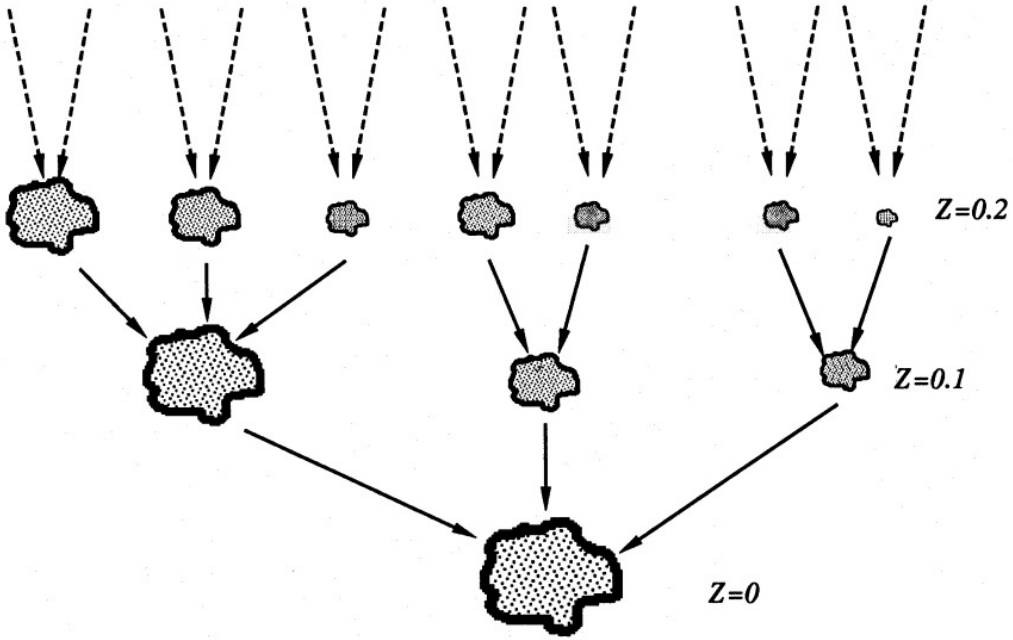


Figure 1. A schematic representation of a halo merging history 'tree'.

Kauffmann & White 1993

- Extended Press-Schechter theory gives probability of halo at one redshift being part of another at different redshifts
- Monte Carlo schemes to build merger histories
- e.g. Kauffmann & White 1993, Somerville & Kolatt 1999, Cole et al. 2000.

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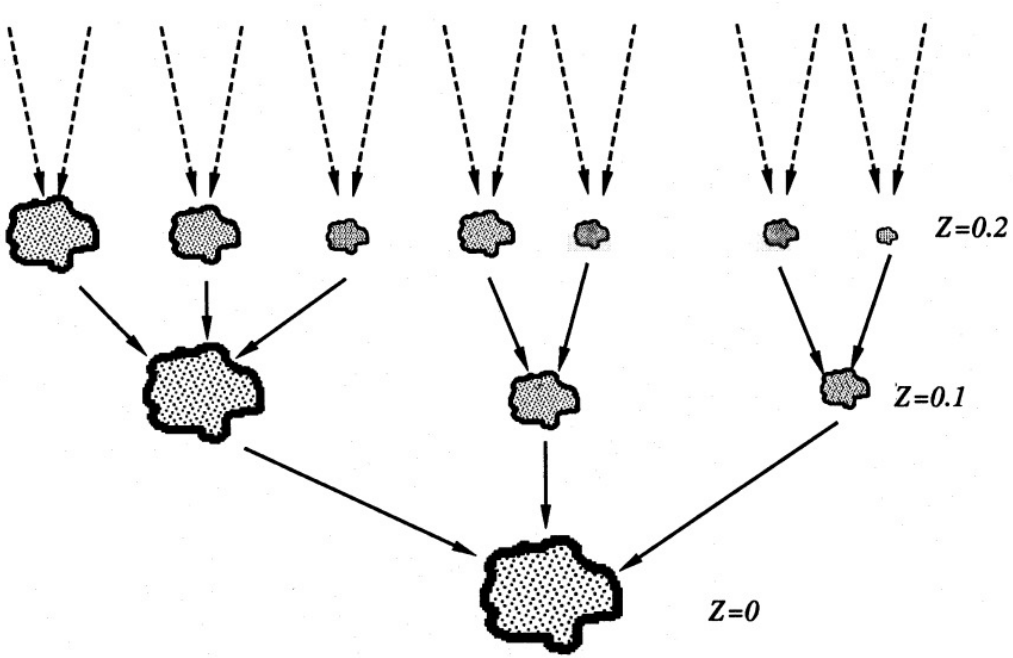

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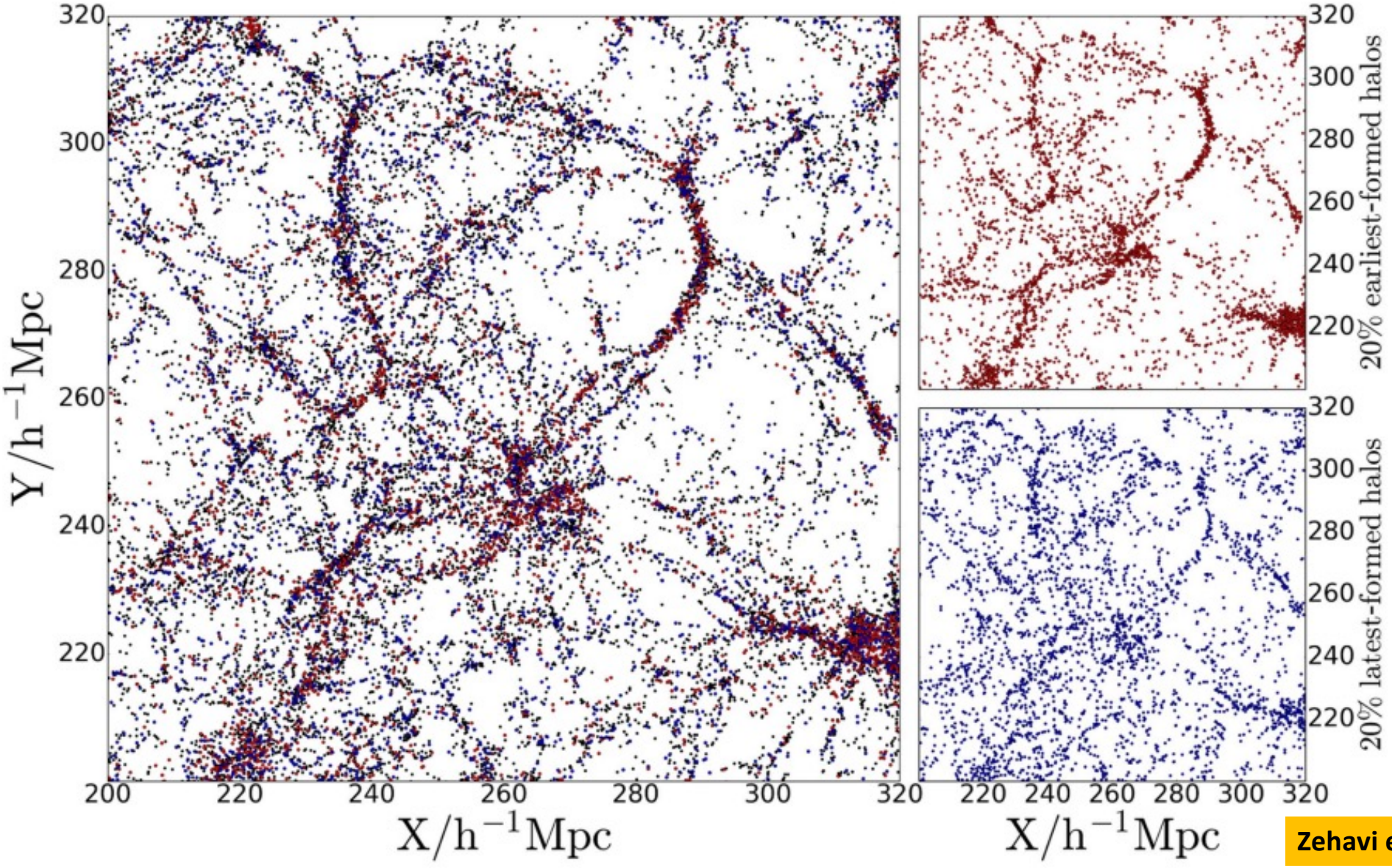
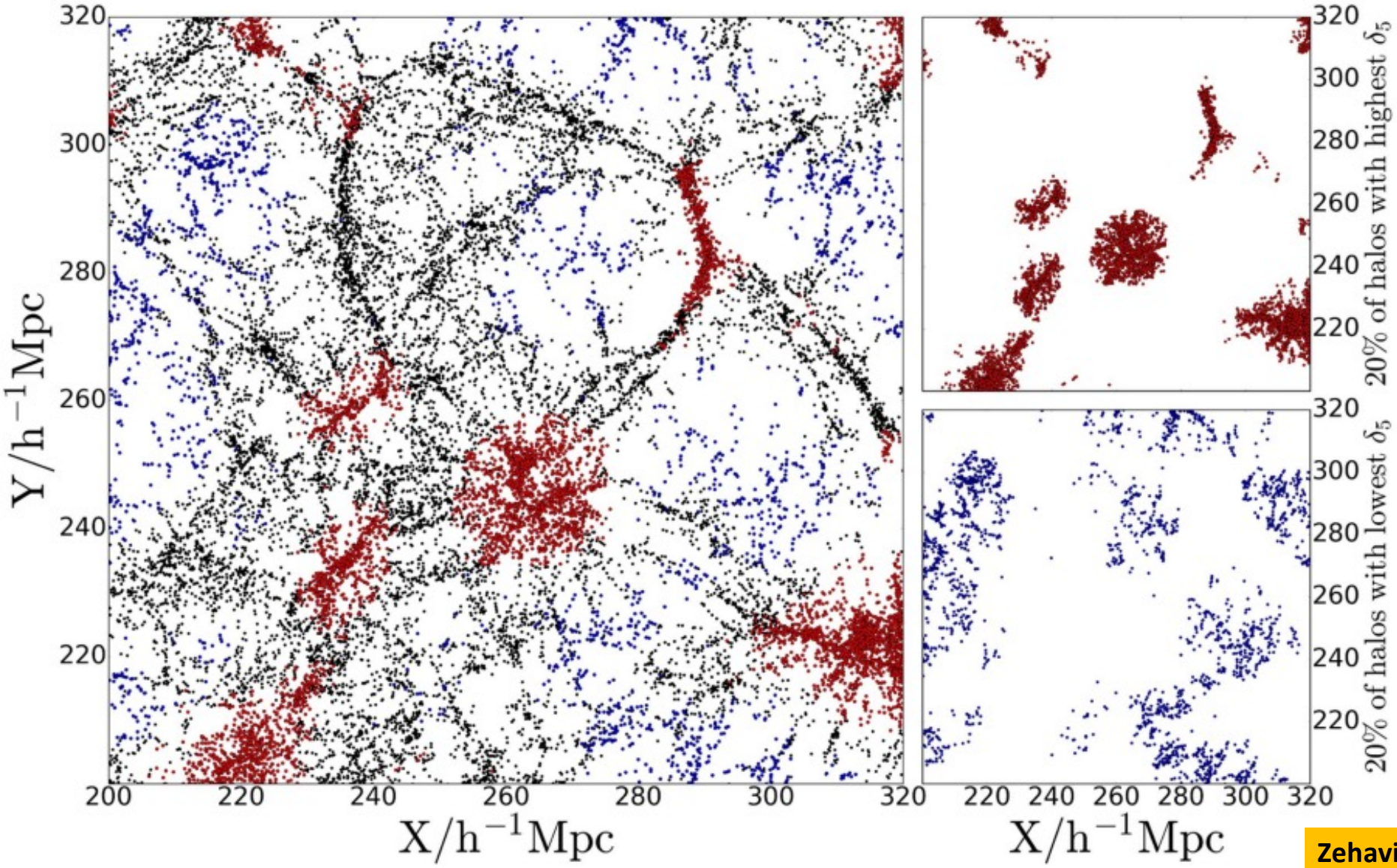
But is halo mass all you need?

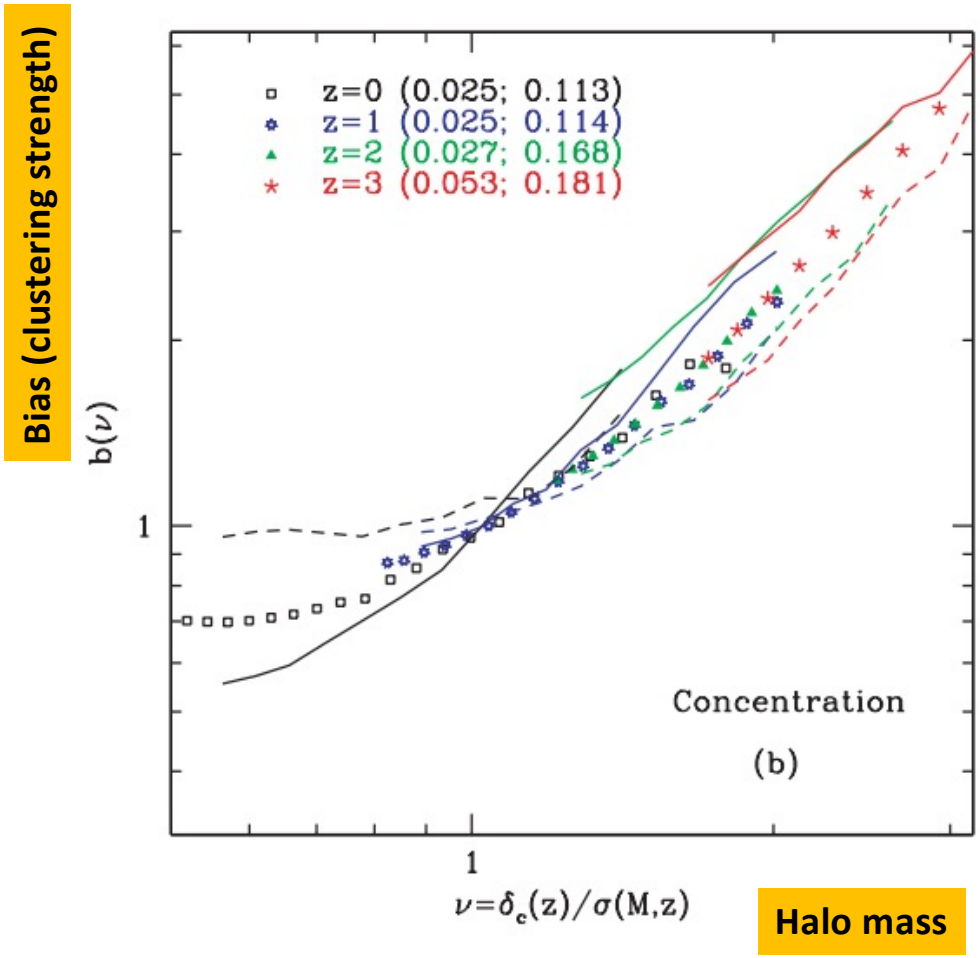


Zehavi et al. 2018



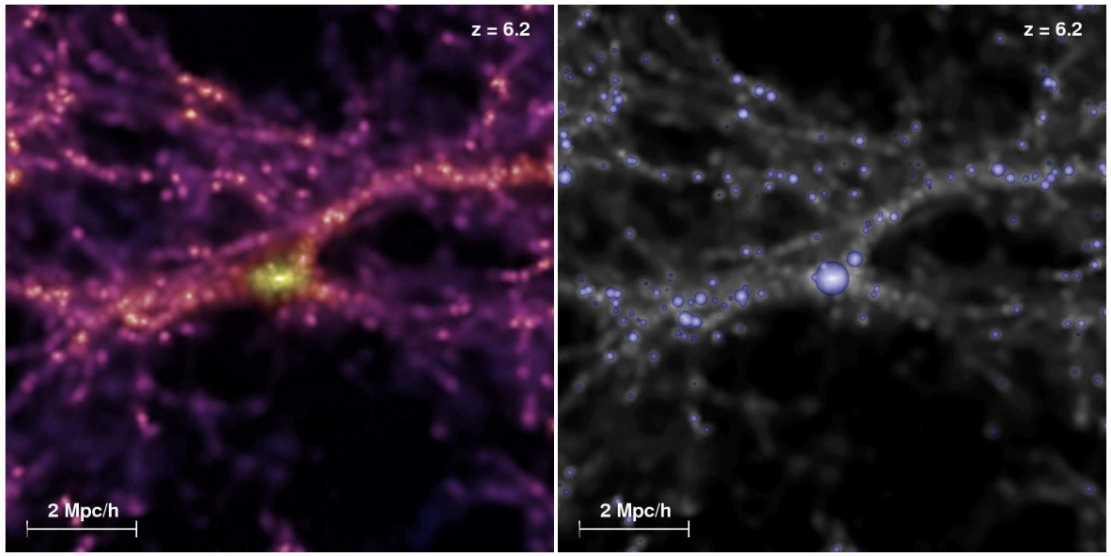
Zehavi et al. 2018

Halo assembly bias



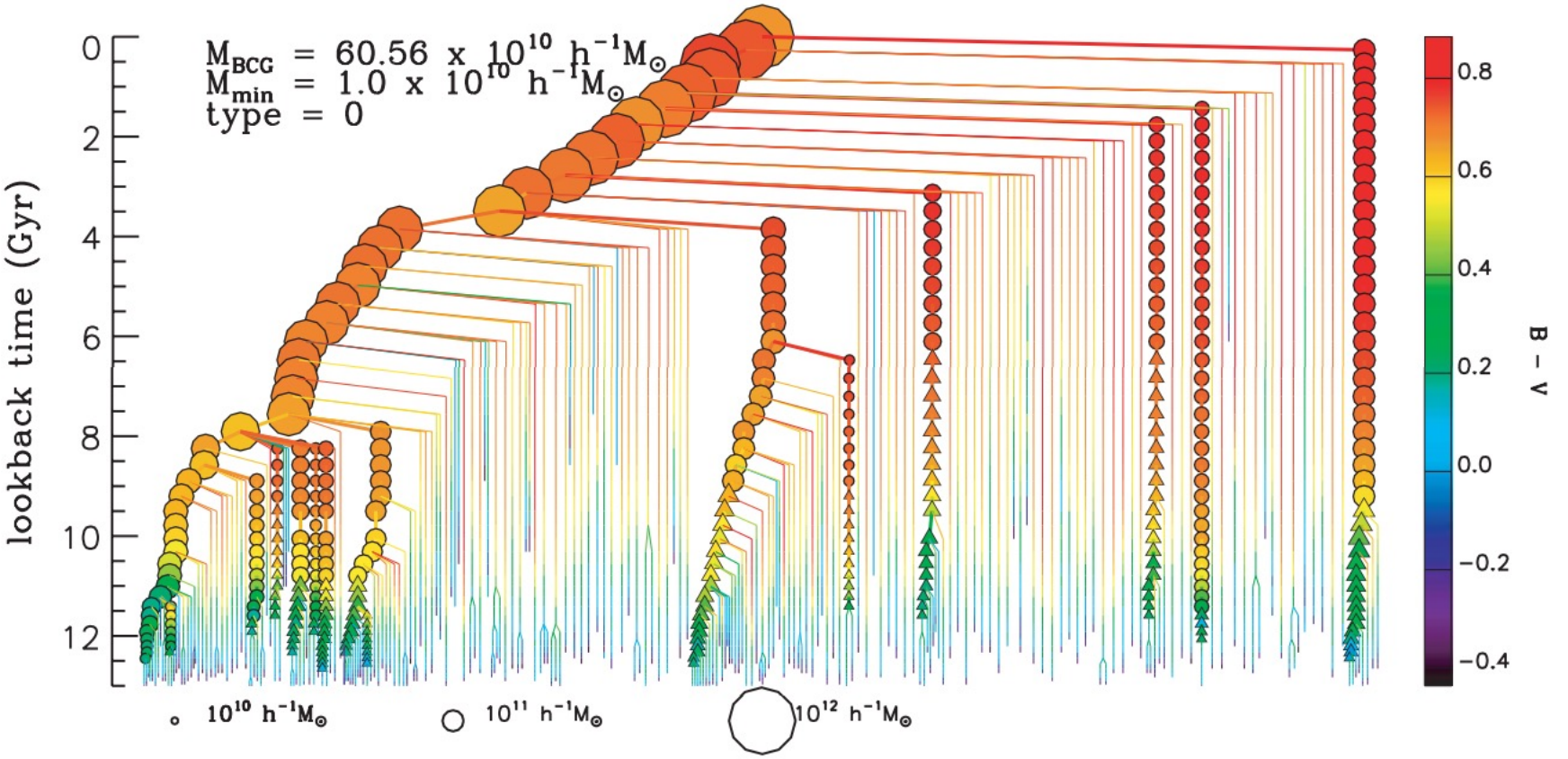
- Halo clustering depends on mass and: formation time, concentration, spin, substructure fraction
- Breaks basic assumption underpinning HOD and SHAM
- Gao et al. 2005, 2007, Weschler et al. 2006, Croton et al. 2007

N-body + semi-analytical models



- High resolution N-body simulation with many outputs e.g. 50-200
- Run halo/subhalo finder and tree builder
- Halo merger trees with environmental effects
- Kauffmann et al. 1999; Benson et al. 2000; Springel et al. 2005

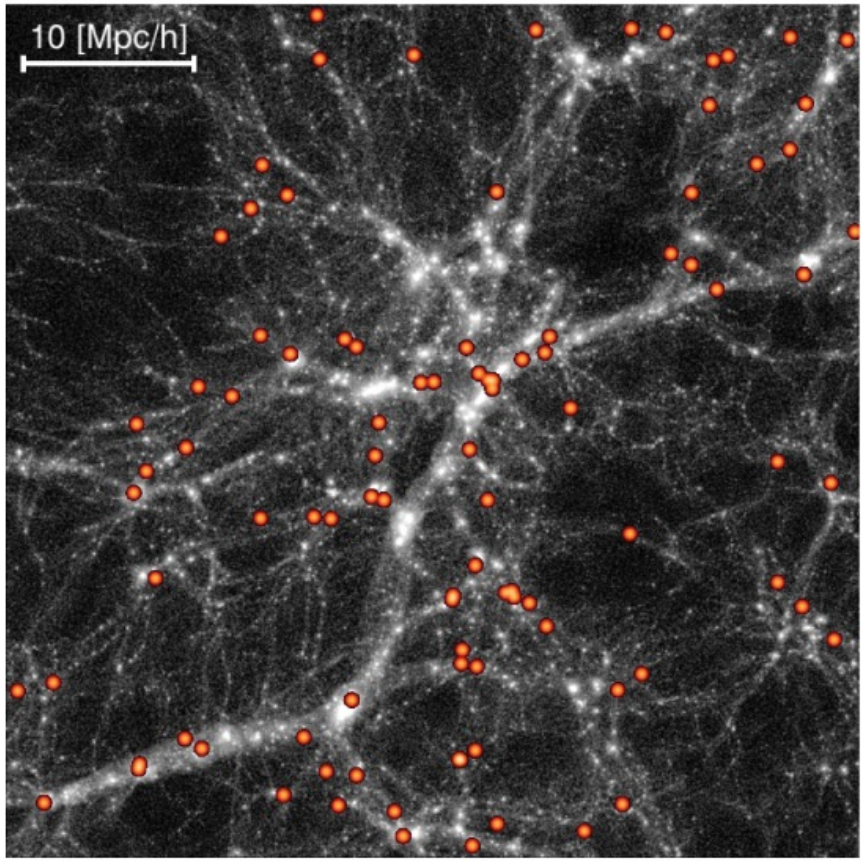
N-body merger tree – example for a BCG



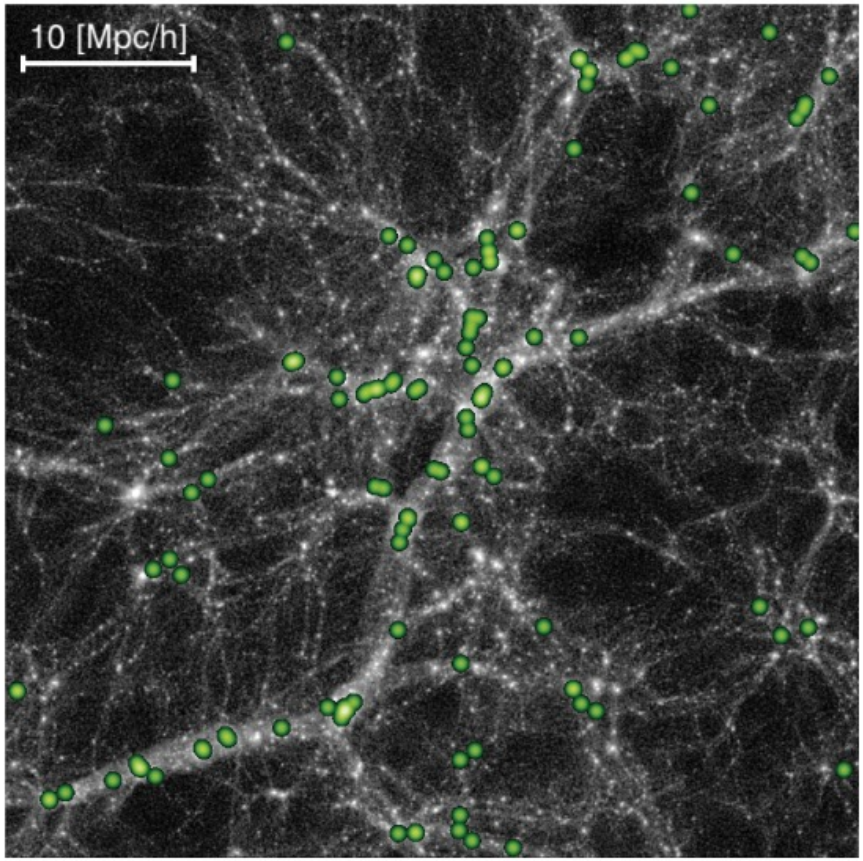
De Lucia & Blaizot 2006

Some model predictions for environmental effects

N-body + semi-analytical model



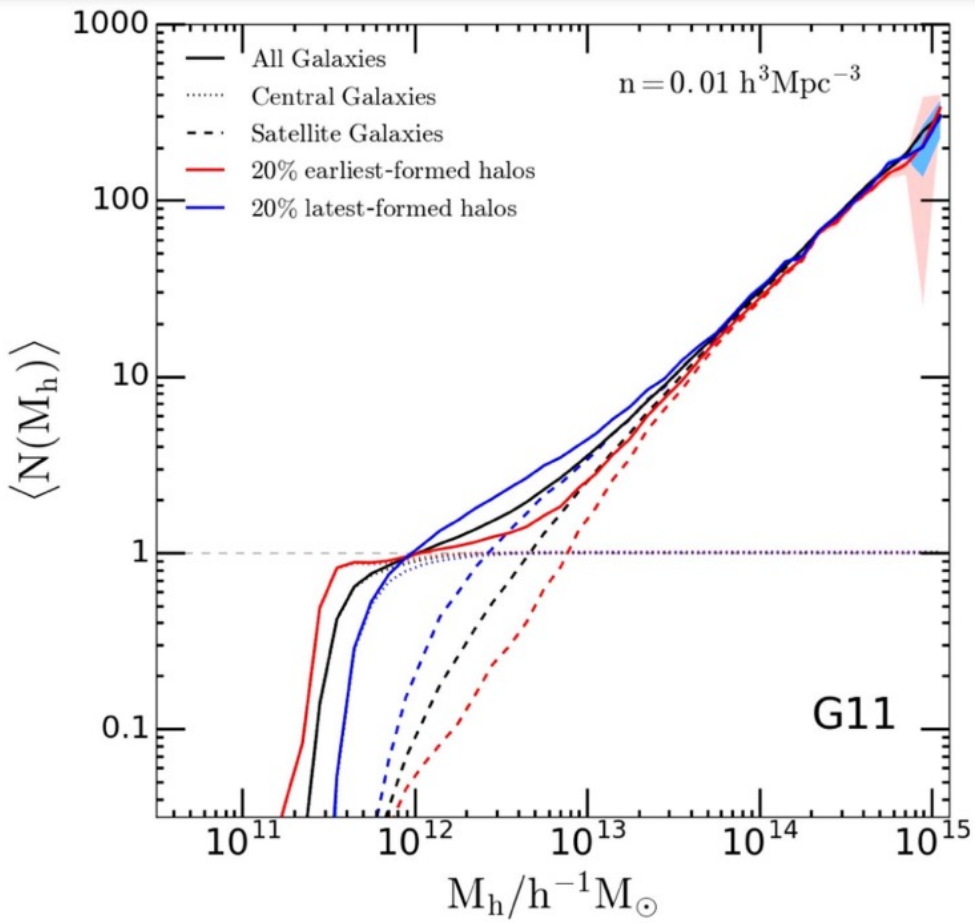
H-alpha selection ~ SFR



H-band ~ stellar mass

Orsi et al. 2010

Halo assembly and the galaxy content of halos

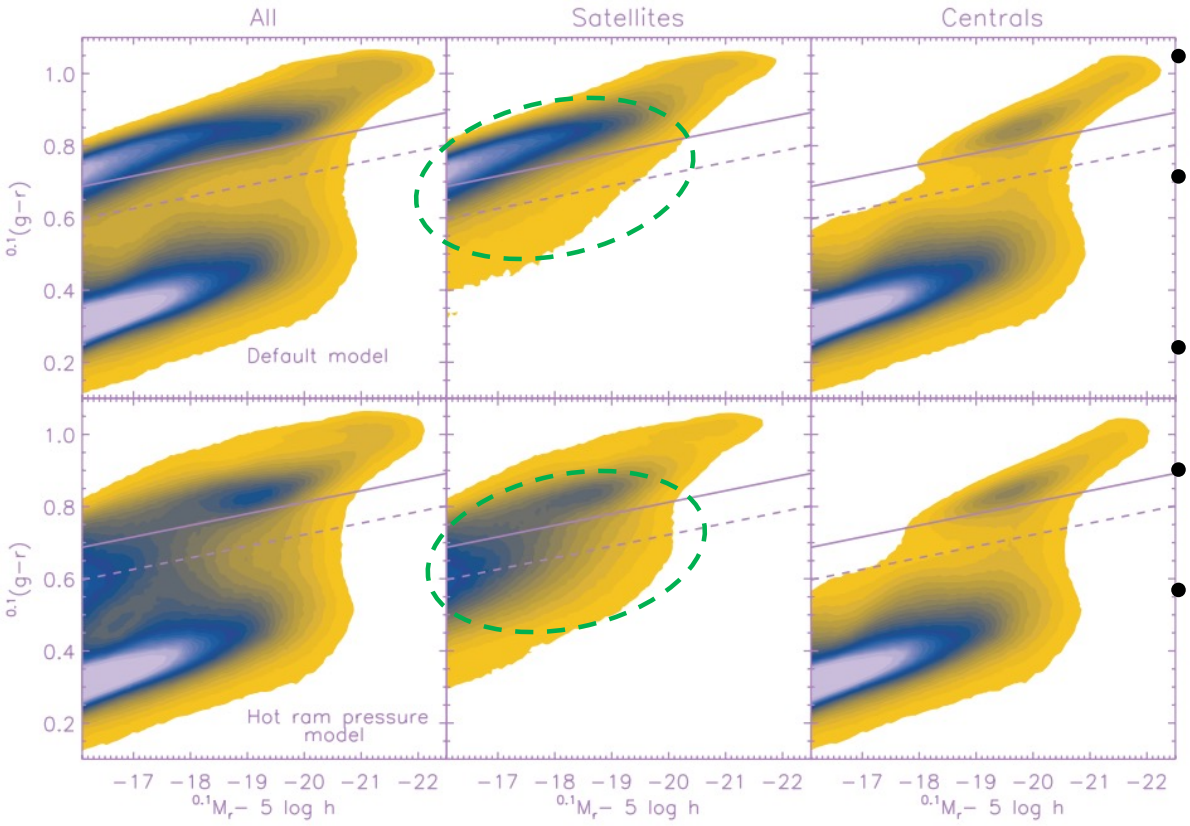


- Predictions from a physical model
- Plotted as mean number of galaxies as function of halo mass
- Occupancy depends on halo formation time as well as mass
- Zehavi et al. 2018

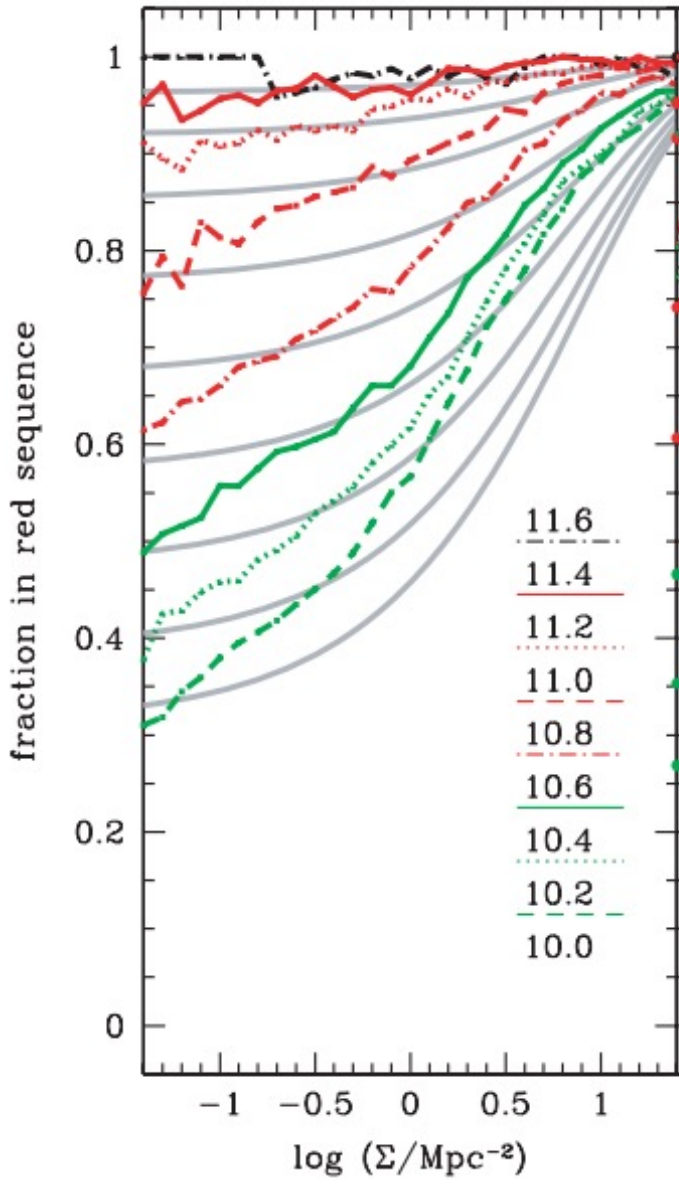
Bimodality: centrals vs satellites

Stripping on infall

Gradual stripping



- Central galaxies can accrete cooling gas
- Satellites can lose all hot gas in strangulation or gradually through ram pressure stripping
- Gradual stripping, bluer satellite colours
- Font et al. 2008, Weinmann et al 2006. Guo et al. 2011,
- But see Hirschmann et al 2016, De Lucia et al. 2019 for view that SNe feedback model is more important

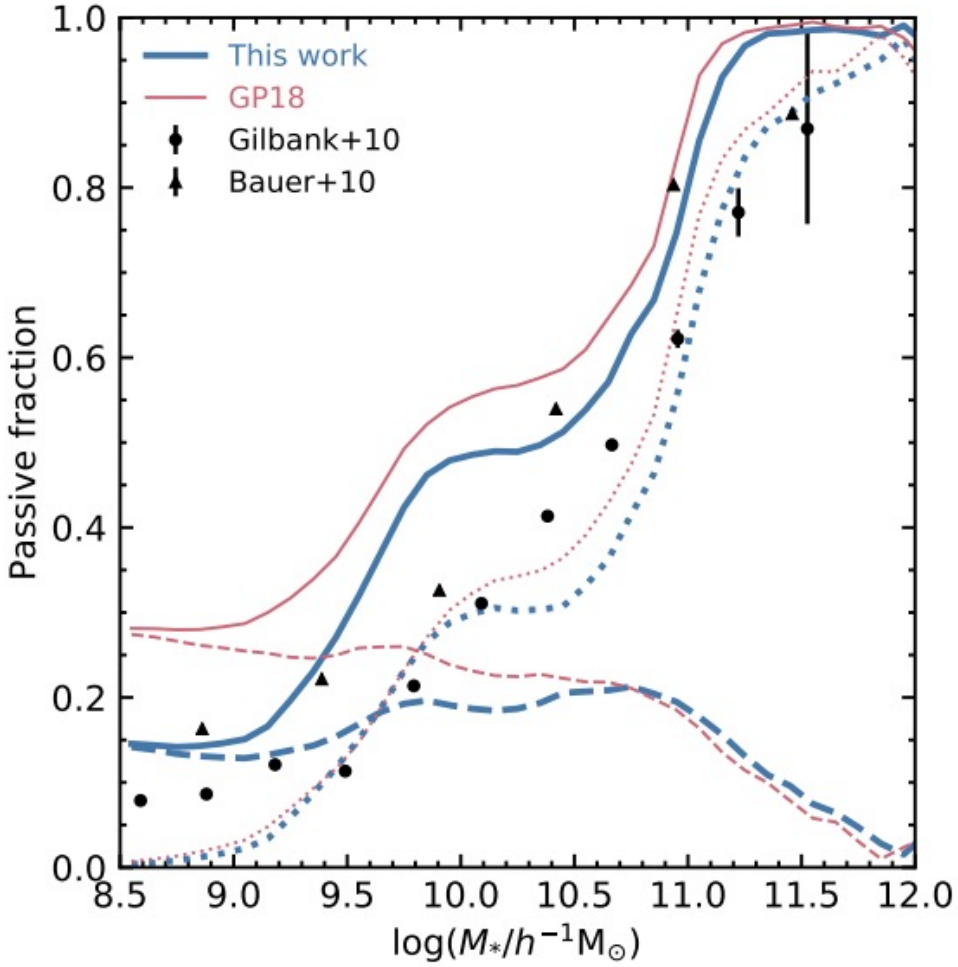


Passive fraction

- Passive fraction in terms stellar mass and density
- Grey curves fits to results from SDSS
- Coloured lines: Bower et al. 2006 GALFORM

Baldry et al. 2006

Quenched or passive fraction at z=1

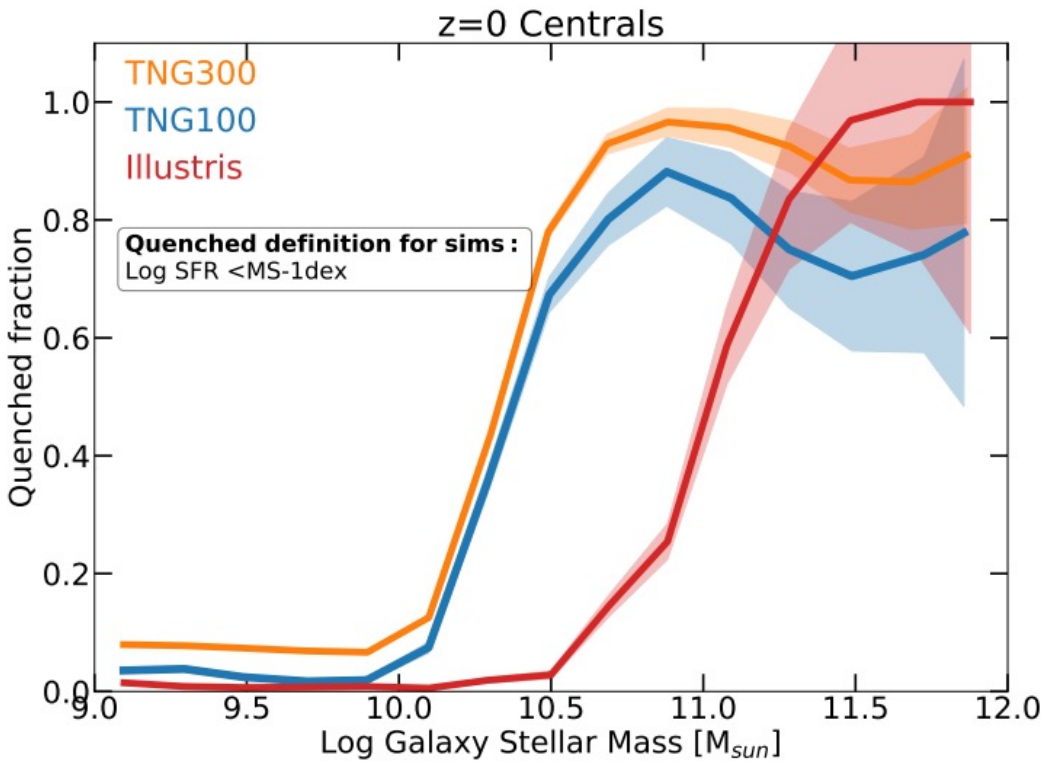


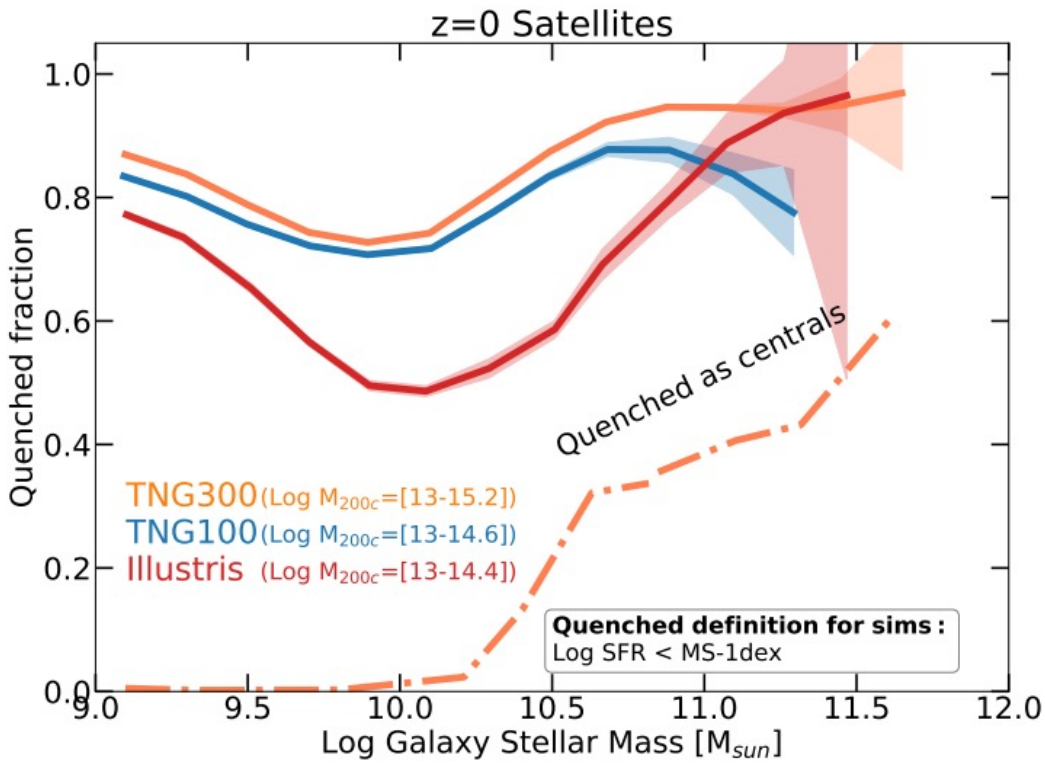
- DASHED = satellites
- DOTTED = centrals
- SOLID = all

- Gradual ram pressure stripping key for satellite passive fraction – would be much higher with stripping on infall
- But – sensitive to SNe feedback model
- AGN suppression of cooling for higher mass centrals

Gonzalez-Perez et al. 2020

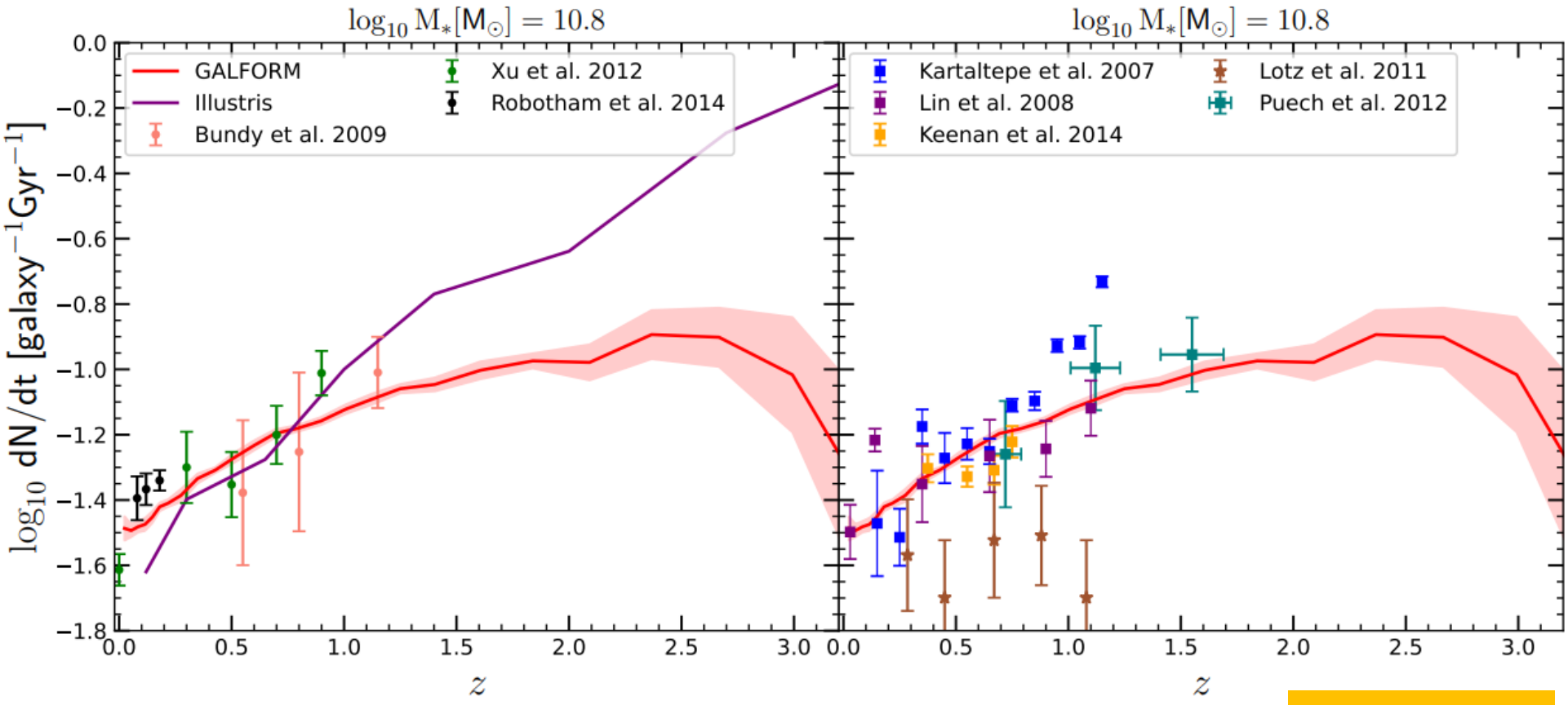
Quenched galaxy fractions vs stellar mass





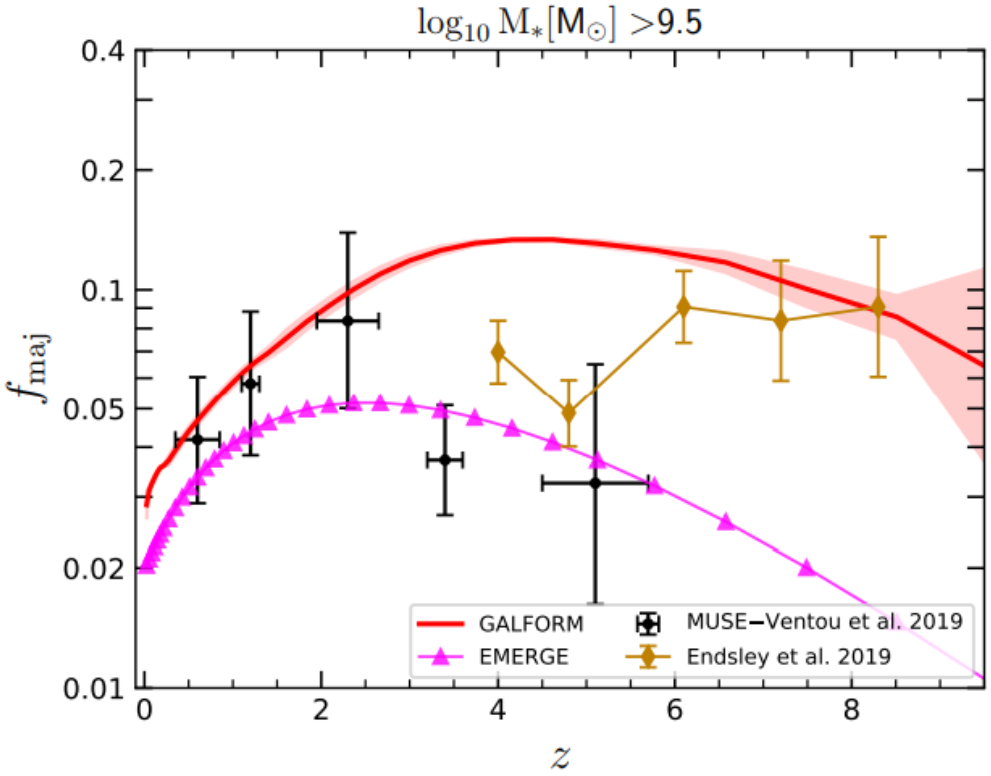
Donnari et al. 2021

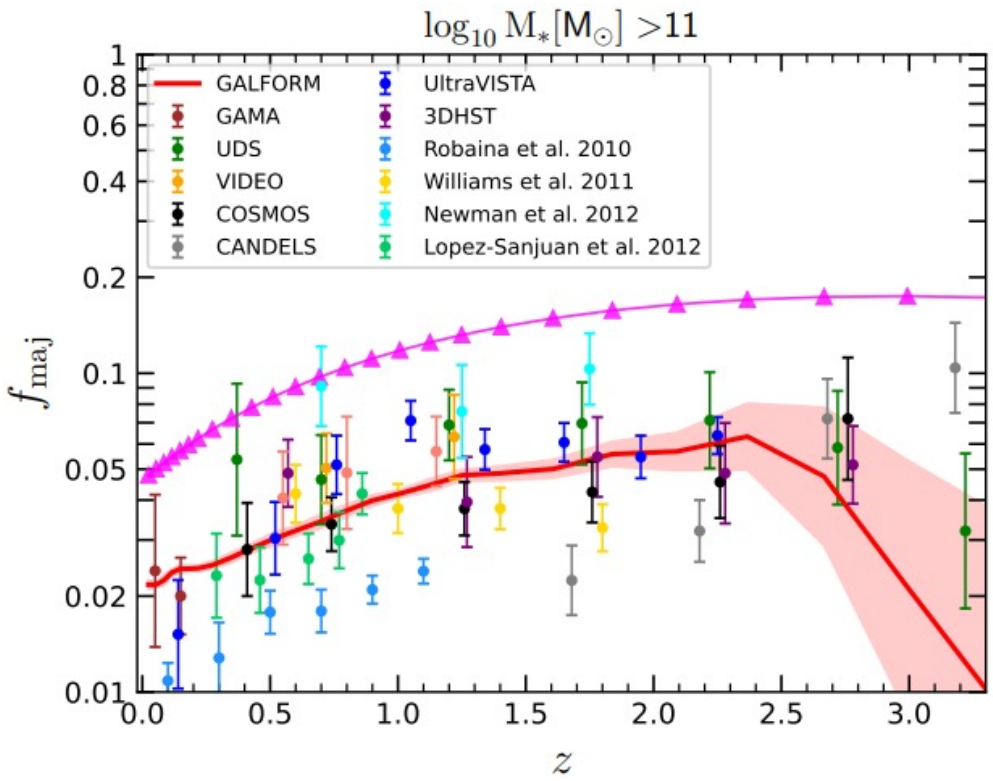
Evolution of the galaxy merger rate: GALFORM (SAM) vs Illustris vs data



Husko et al. 2022

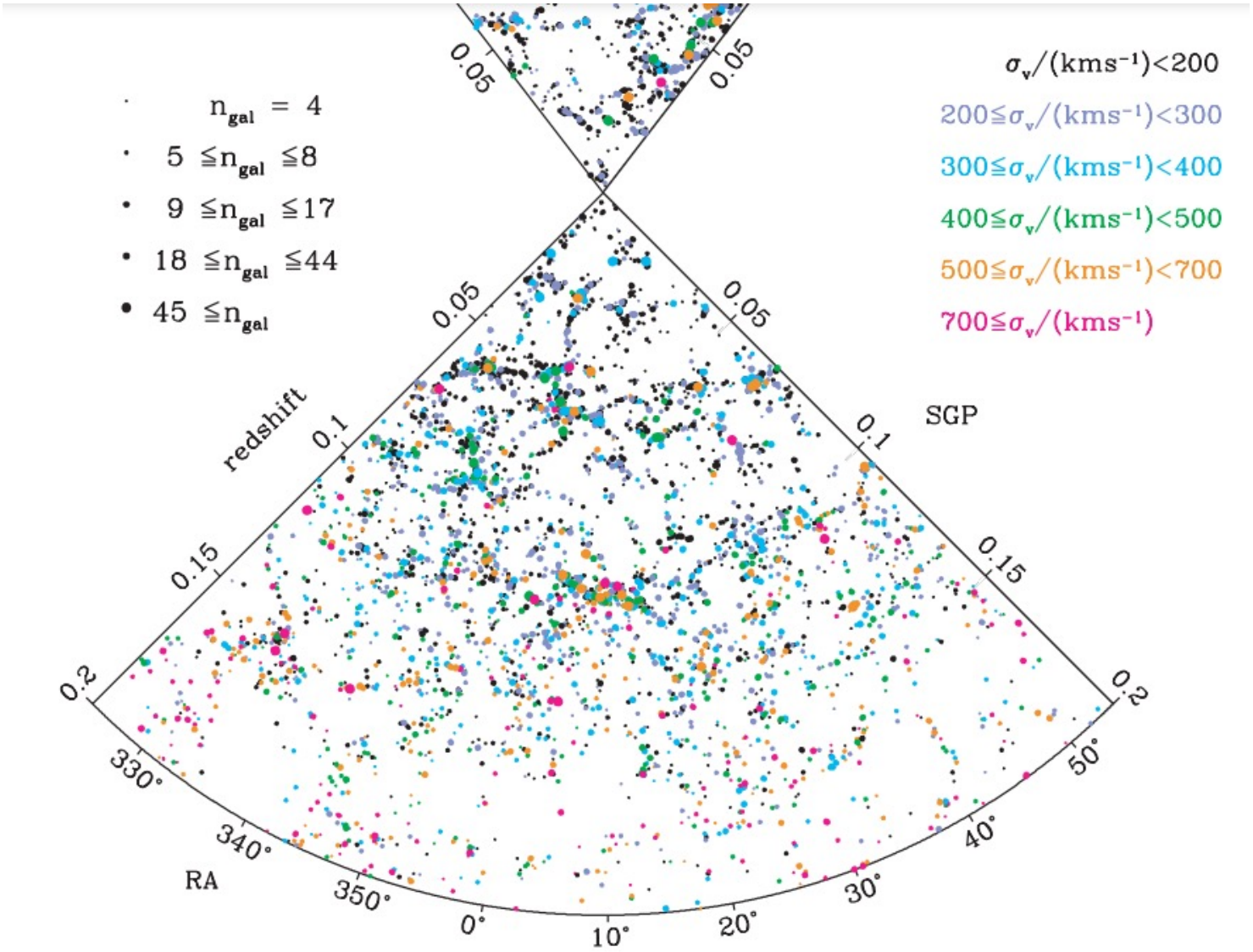
Fraction of major mergers: GALFORM vs EMERGE (emp evol) vs data





Husko et al. 2021

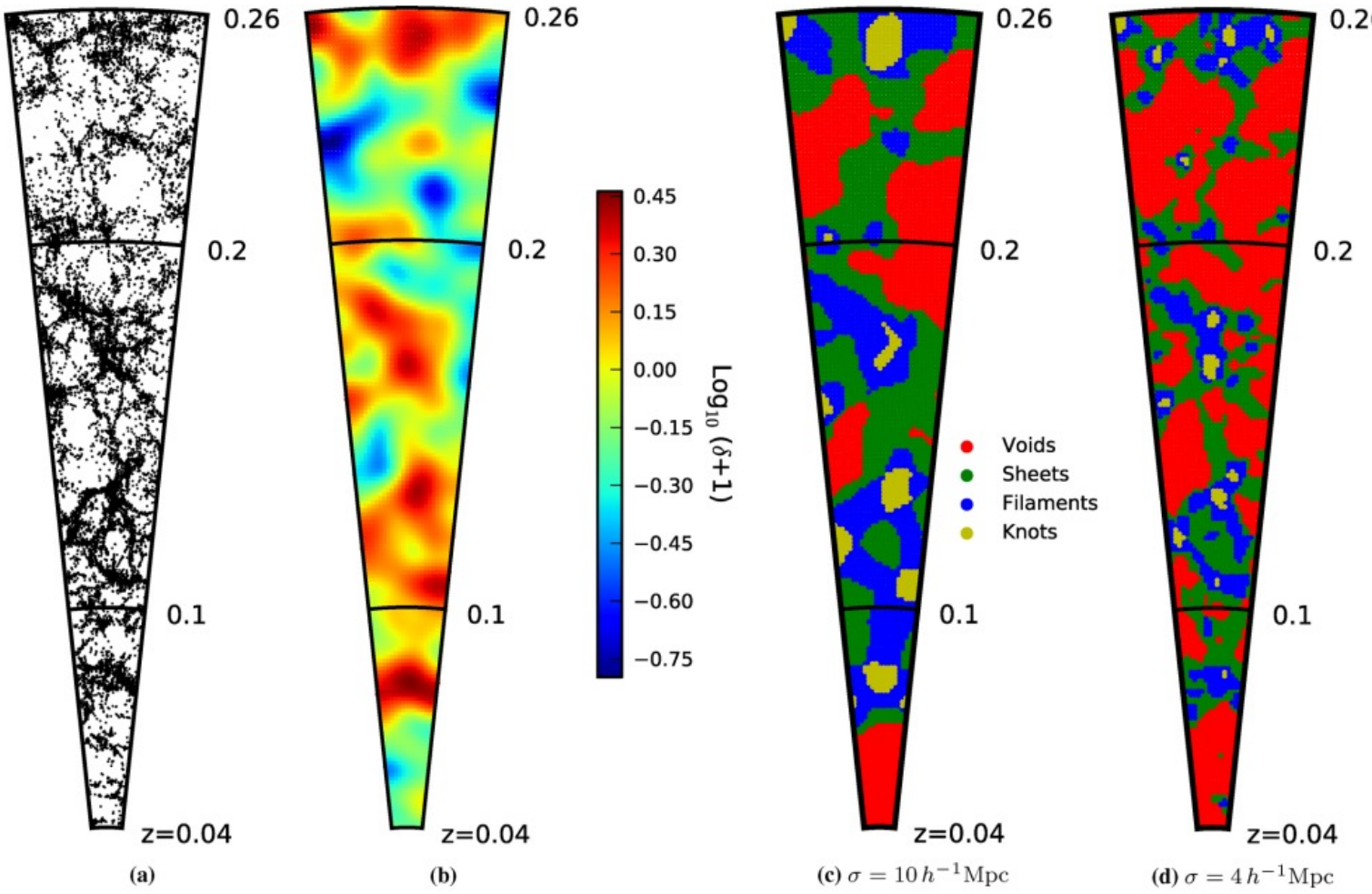
How can we define environment?



Percolation galaxy group finding

- Run anisotropic FOF on galaxies
- Test on mocks to find best proxy for halo mass, in terms of systematic offset & scatter
- Connection to dark matter halos

- E.g. Eke et al. 2004, Yang et al. 2006

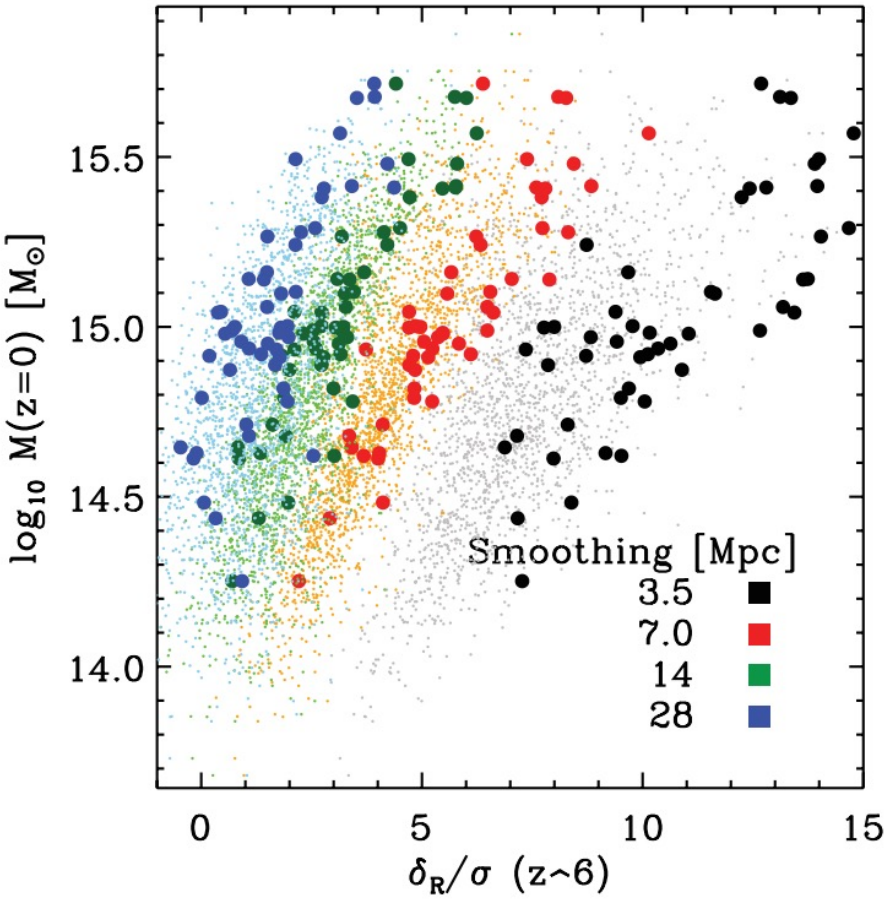


Various Density measures:

- **Distance to nth nearest neighbour**
- **Smooth over volume**
- **Tidal tensor / NEXUS**

Cautun et al. 2013, Eardley et al. 2015

Larger scale environment and descendant mass



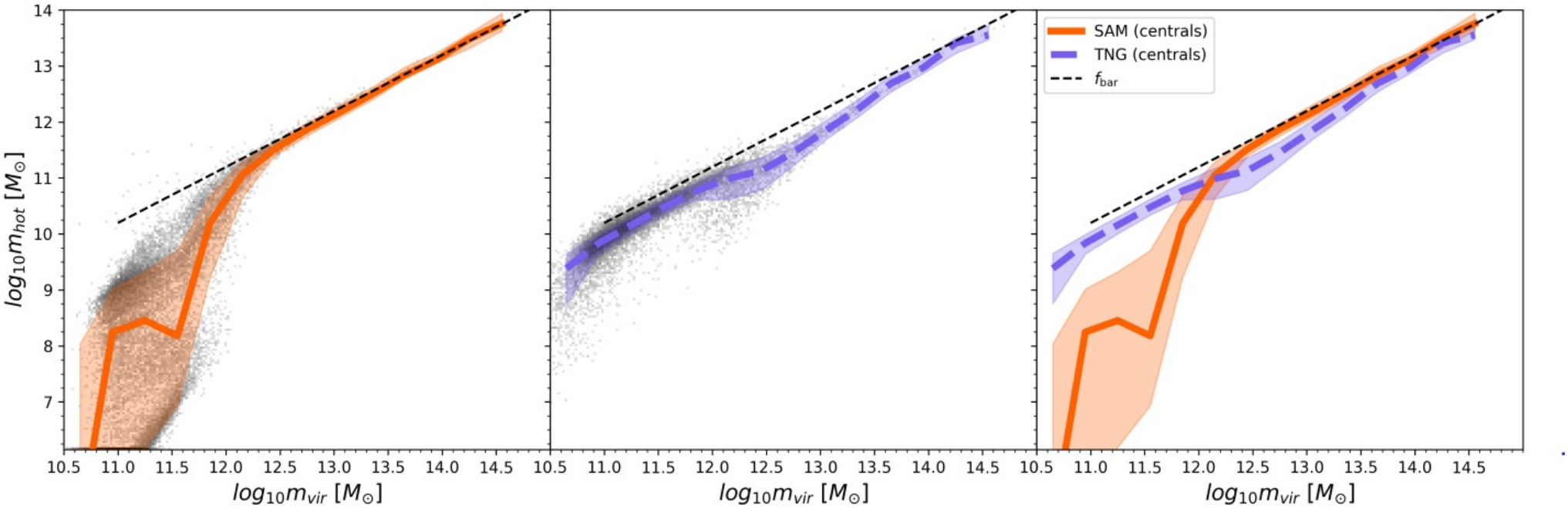
- Wide range of z=0 mass for halos that host QSOs at z=6
- Hard to predict z=0 descendant mass from z=6 halo mass
- Correlation of final mass with local overdensity at z=6
- Ties in with analysing overdensities at high z e.g. Lyman-alpha emitters to find protoclusters.

Angulo et al 2012

Summary

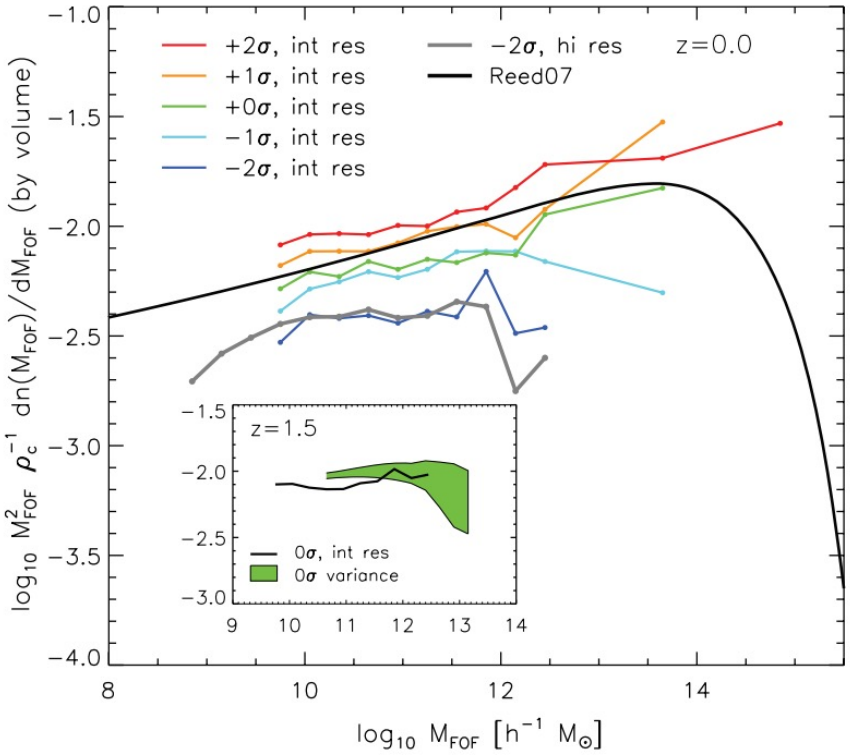
- Many galaxy properties correlate with stellar mass
- Galaxy mass closely related to halo mass
- Halo mass primary driver of galaxy properties
- N-body merger trees + SAMs capture environmental effects *within* halo due to halo formation history
- Need extended models or gas simulations to capture beyond halo effects
- Many ways of defining environment – some more appealing from a theoretical view, others match what can be done in observations: can apply to realistic mock catalogue which match selection and evolution in galaxy number density.

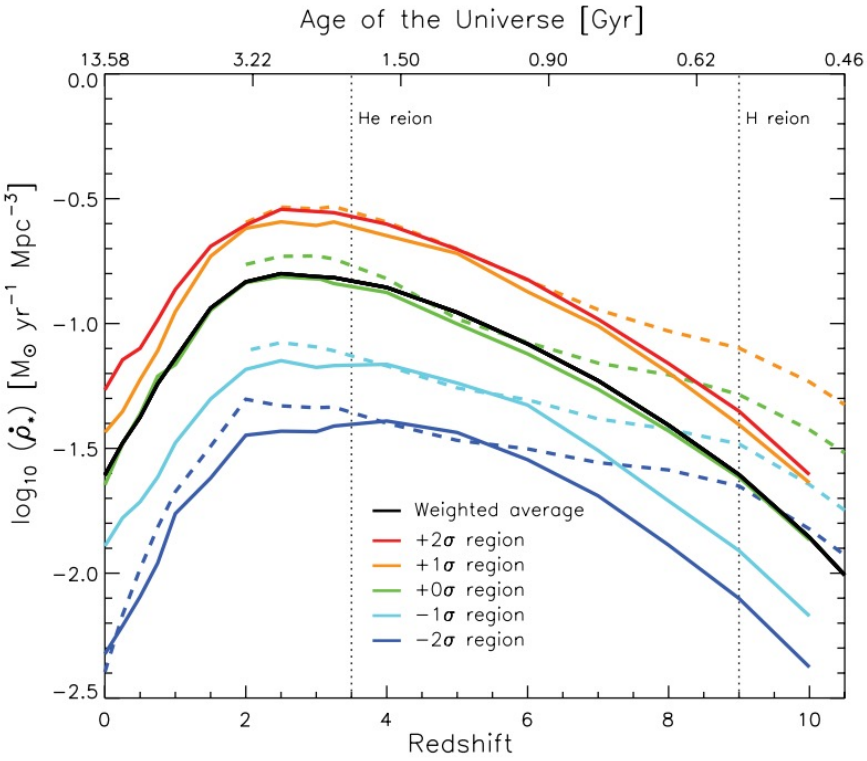
Santa Cruz SAM compared with IllustrisTNG – I.



Gabrielpillai et al. 2022

Environmental effects – local overdensity





Crain et al. 2009