The Merger History of Massive Galaxies: Observations and Theory

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How/when do galaxies form/evolve?

Some questions

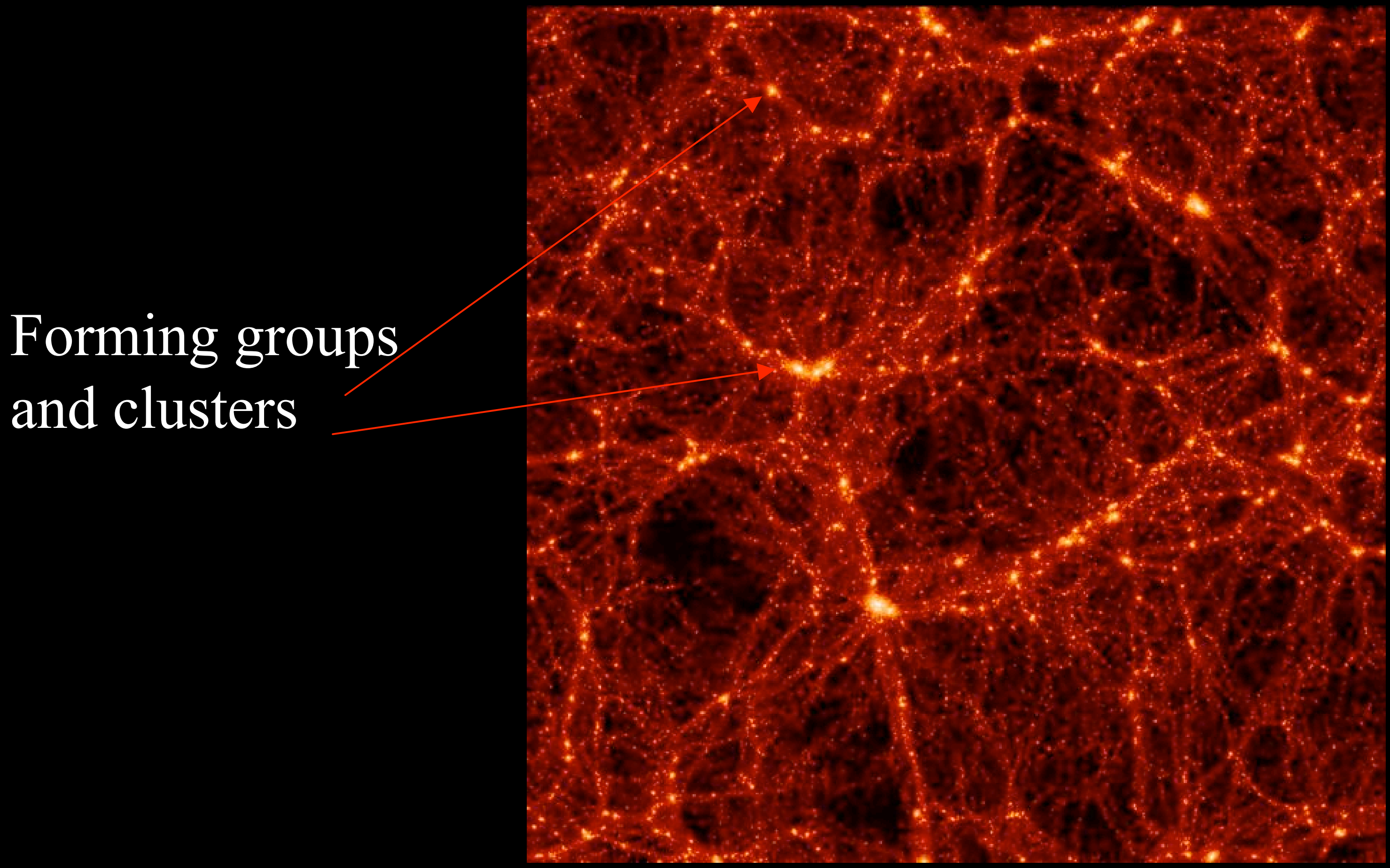
a. Do galaxies evolve by themselves? That is, without much influence from other galaxies or 'environment'

b. What is the role of galaxy mergers and interactions in the evolution of galaxies?

c. When do galaxies form their stars, as opposed to their mass? Is this distinction important?

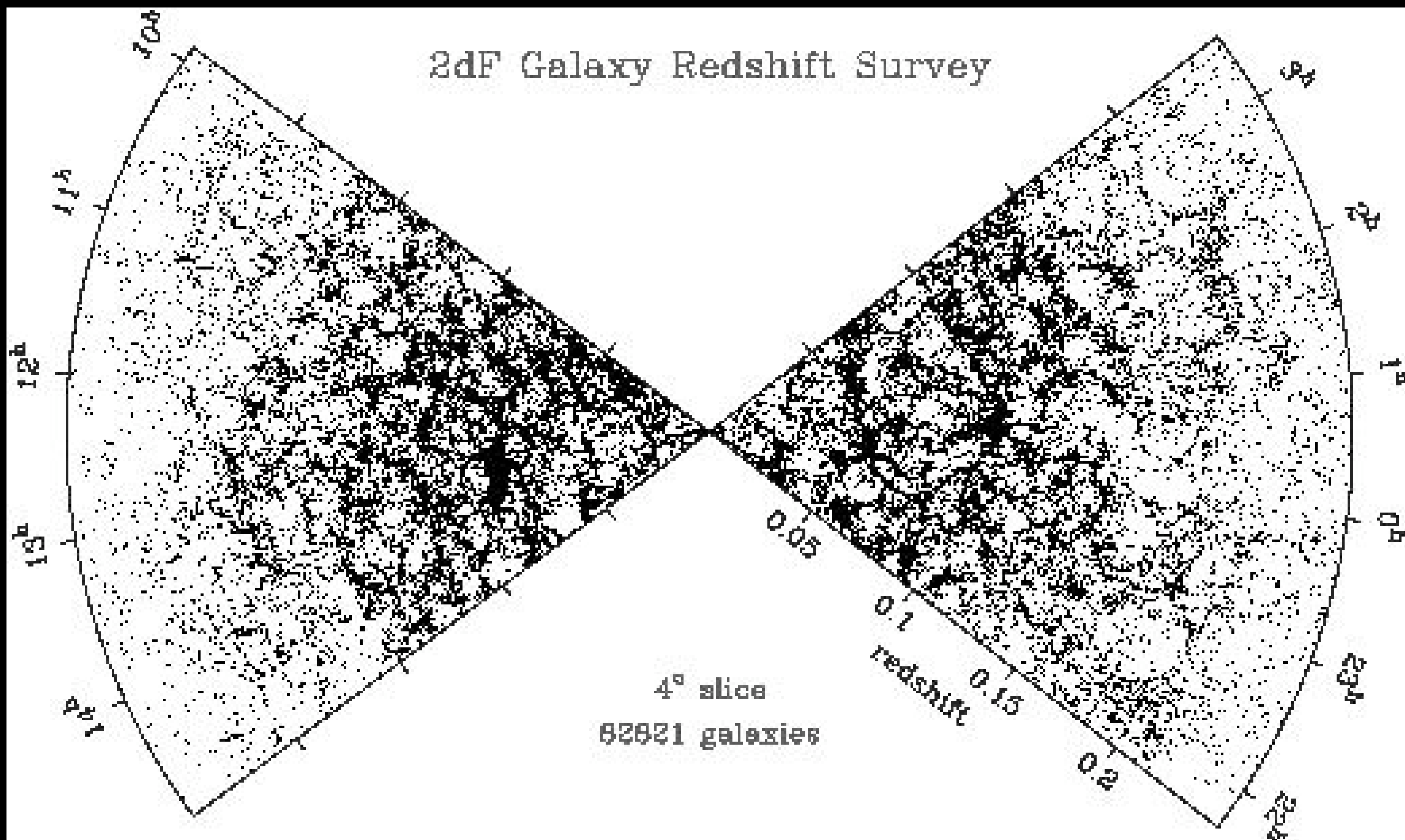
d. Does the environment of a galaxy significantly change its evolution outside of direct galaxy-galaxy encounters?

Within Cold Dark Matter theory galaxies strongly cluster



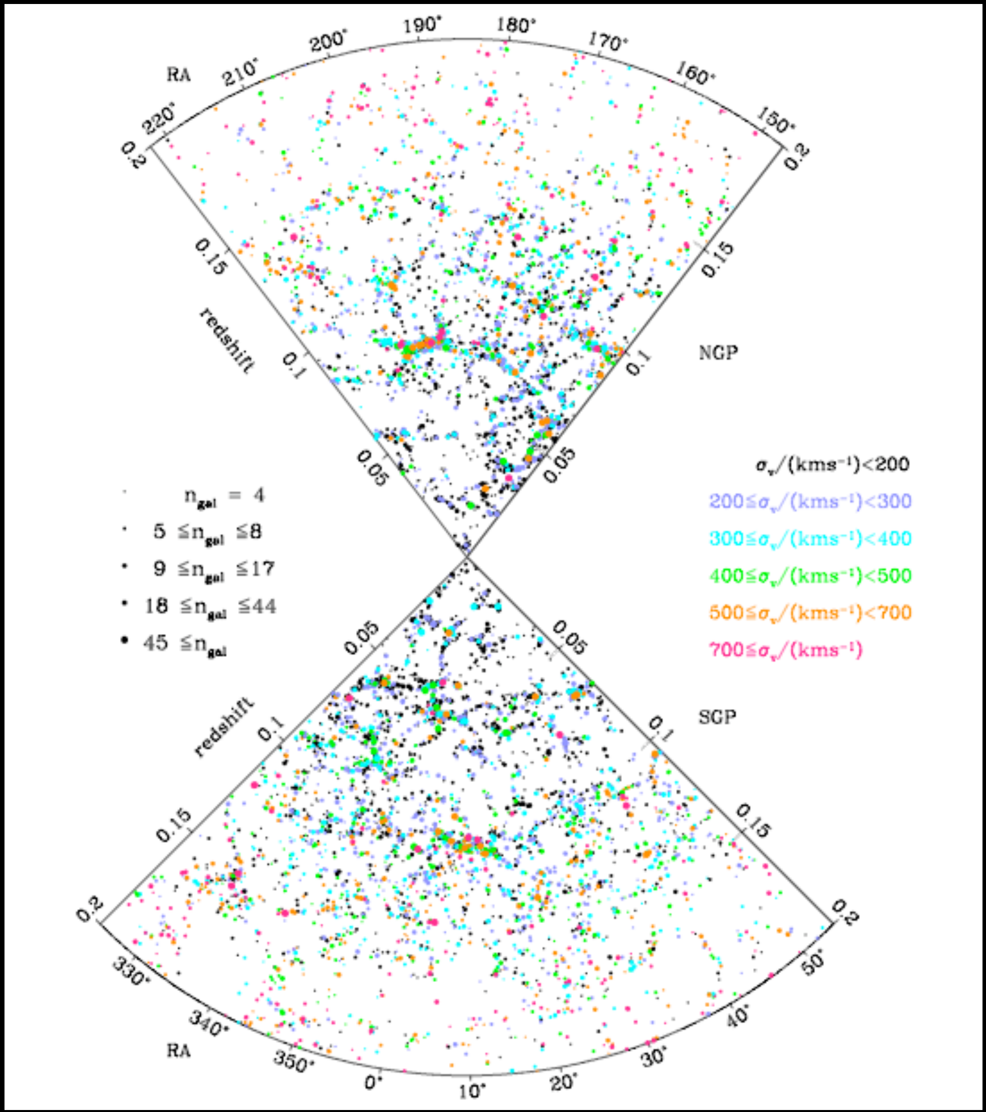
Virgo consortium simulation (Jenkins et al. 1998)

This clustering is directly observable and agrees with CDM models to a high degree



Type of structure found at low redshifts up to z~0.2 in the 2dFGRS and in Sloan

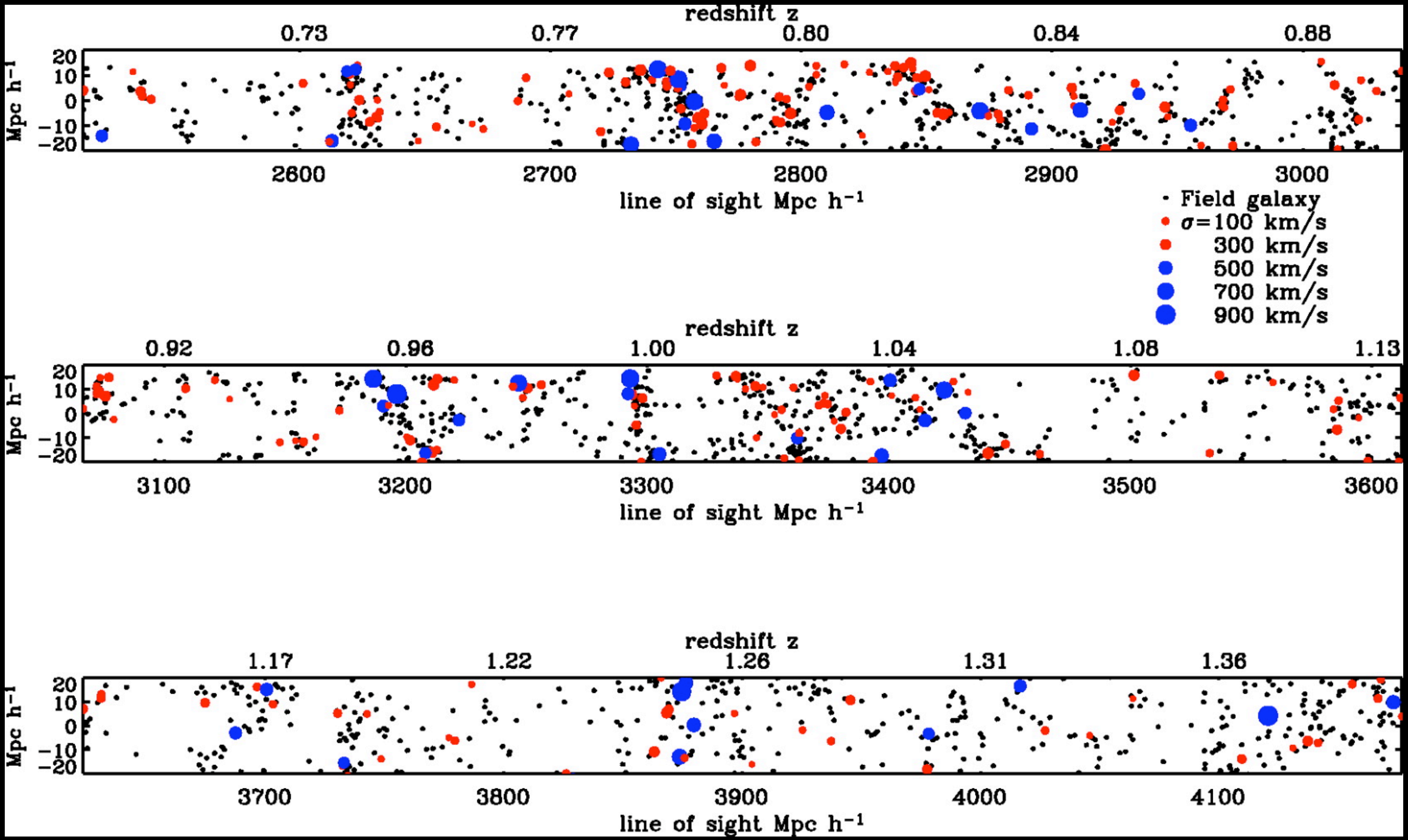
Most of this clustering is due to clusters/groups



Eke et al. (2004)

Galaxy groups in the 2dFGRS

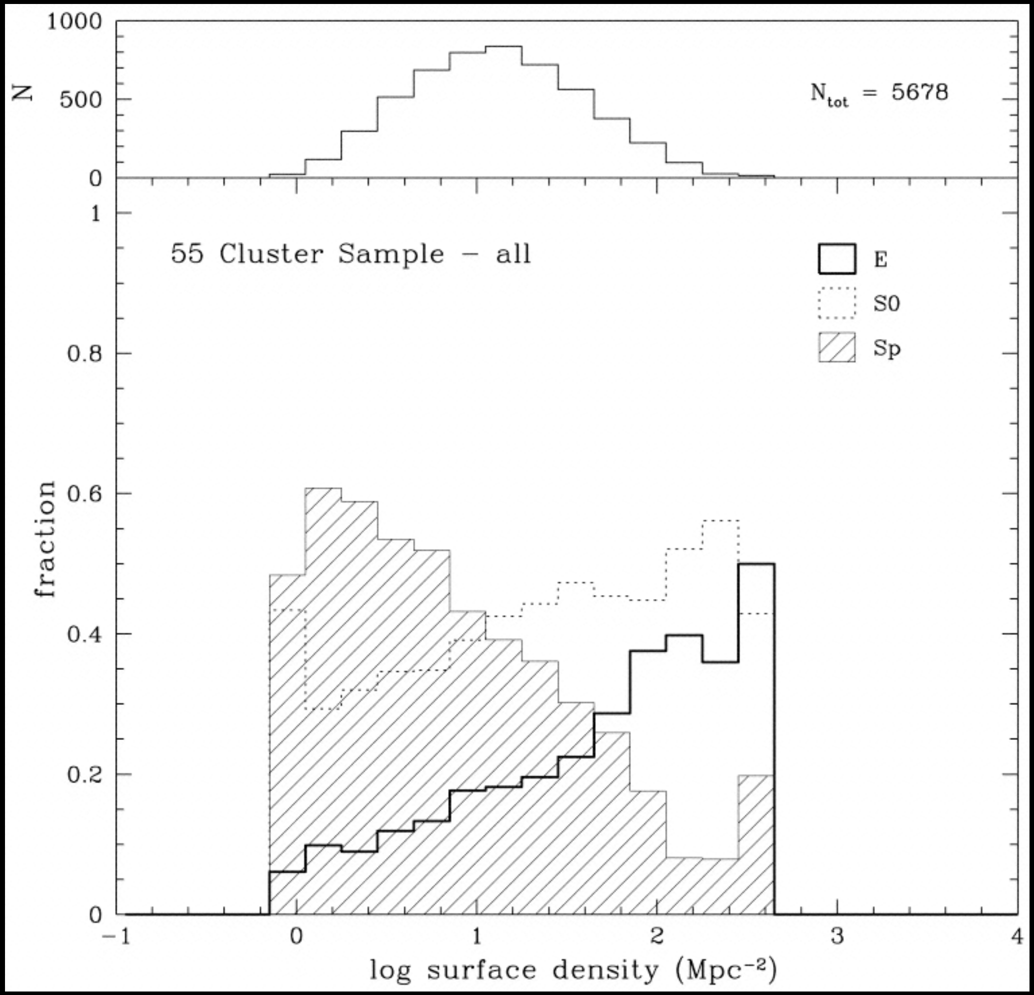
Galaxies exist in different environments at all redshifts thus far studied



Gerke et al. (2005)

What types of galaxies exist in different environments?

The morphological distribution in differing environments may reveal the physical processes responsible for galaxy evolution



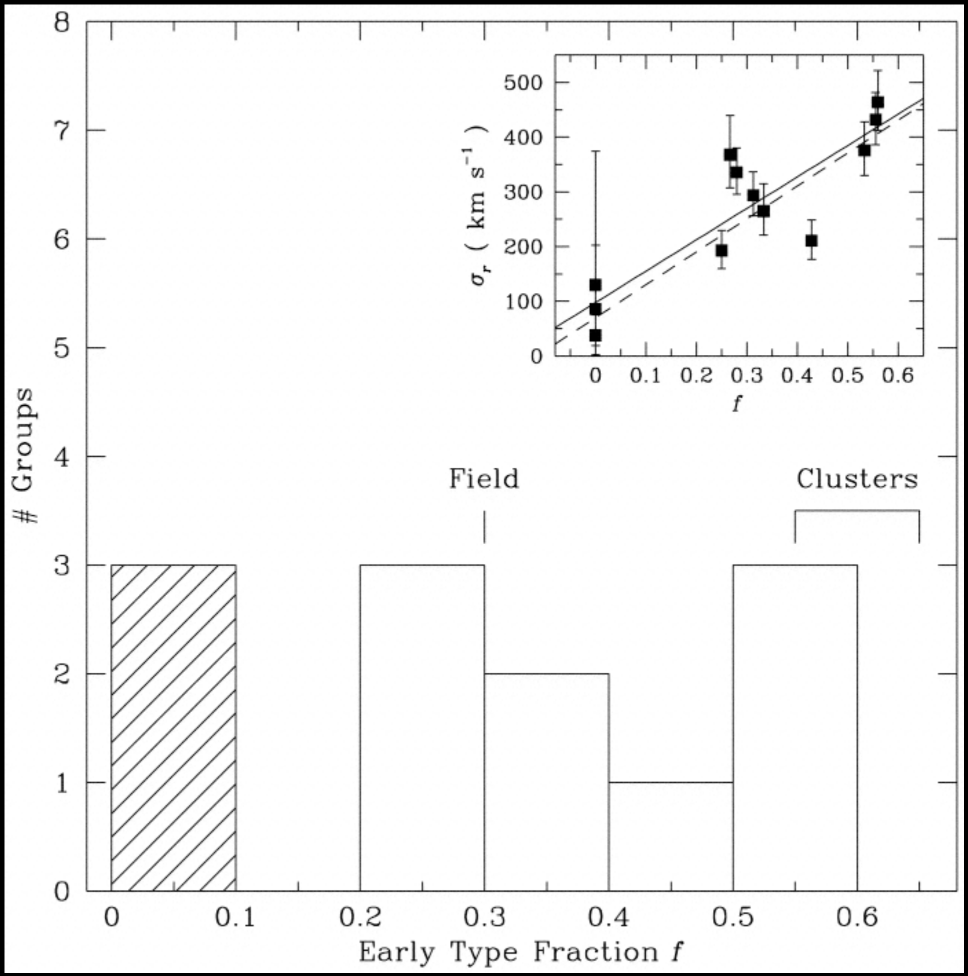
Dressler (1980)

Morphology/density relation: higher fraction of late type galaxies in lower density environments

Some groups still have a large total early type fraction

These early types are found among the higher velocity dispersion groups

Most of the‘red’ galaxies are found towards the centers of groups



Zabludoff & Mulchaey (1998)

How do galaxies form/evolve in different environments?

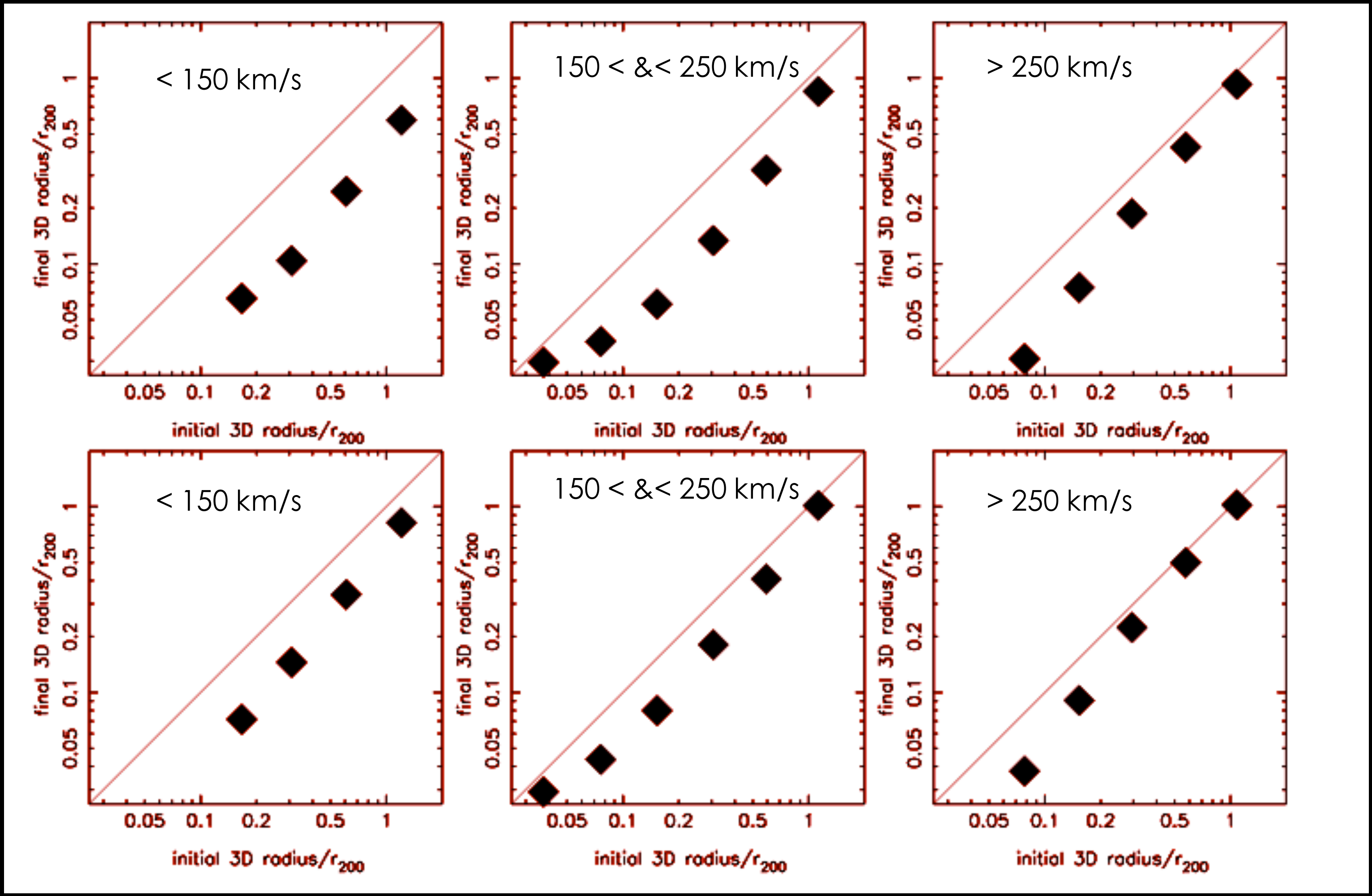
Possible Physical Processes

- Mergers - two or more galaxies colliding to form a more massive system - should be common in groups
- Harassment - high speed galaxy interactions removing mass (Moore et al. 1999) - unlikely to be important at low relative velocities
- Strangulation - removal of hot gas - halts star formation, more common in denser environments
- Ram pressure stripping - removing gas from disks due to traveling in an intragroup/cluster medium, depends upon (group σ)^2 - also halts star formation
- Non-gravitational processes (AGN, SNe) - likely important, hard to constrain observationally

Galaxy Mergers

- Should be common in average dense environments - dynamical friction time-scale evolves as $(\sigma)^3$
- ~250 km/s upper limit for dragging galaxies into center of a group over a Hubble time
- Low redshift merger rate expected to be low, around 2% of galaxies in groups merge per Gyr
- At higher redshift the mass density increases as $H^2 \sim (1+z)^3$. Results in a higher merger rate of $\sqrt{(\rho)} \sim (1+z)^{1.5}$

Evolution of cluster galaxies due to dynamical friction



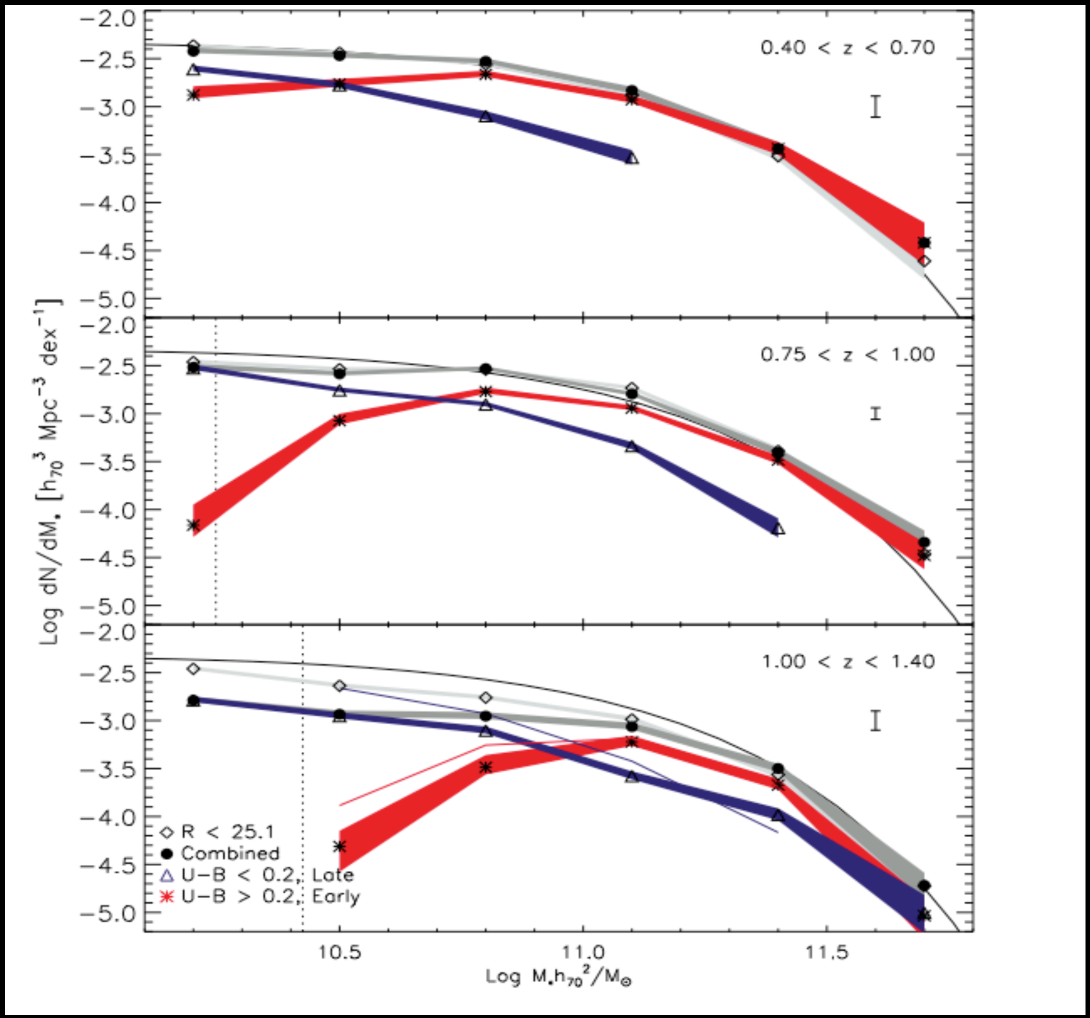
Initial position decreases by a factor of two over 5 Gyrs

Carlberg (2004)

Mergers are unlikely a dominant process at z < 1

When do galaxies form?

Stellar mass function at z < 1.4



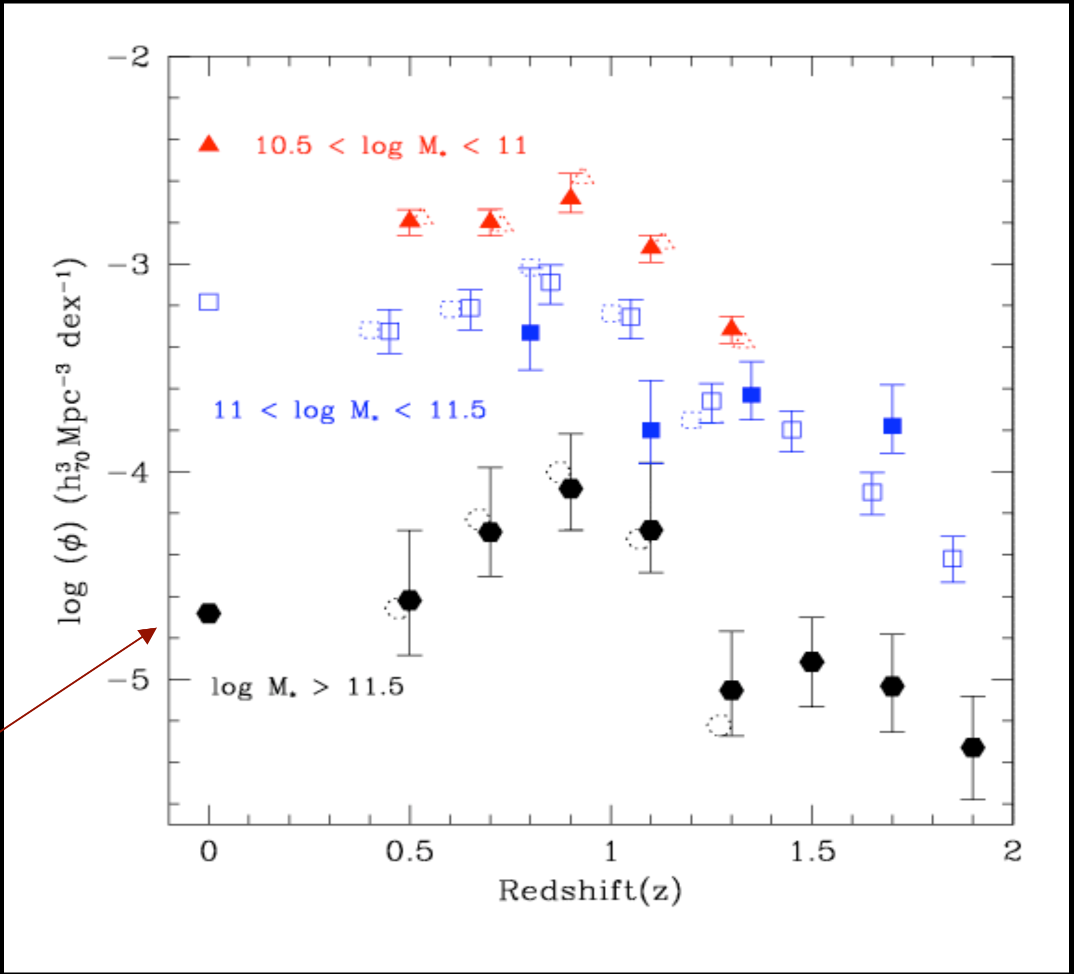
At higher redshifts results not so clear

Bundy et al. (2006)

Nearly all massive galaxies are formed by z~1 - 1.5

Results from Palomar Observatory Wide-Field Infrared Survey (POWIR) +DEEP2 Redshifts

(Conselice et al. 2007)



Cole et al. (2001)
z~0 comparison

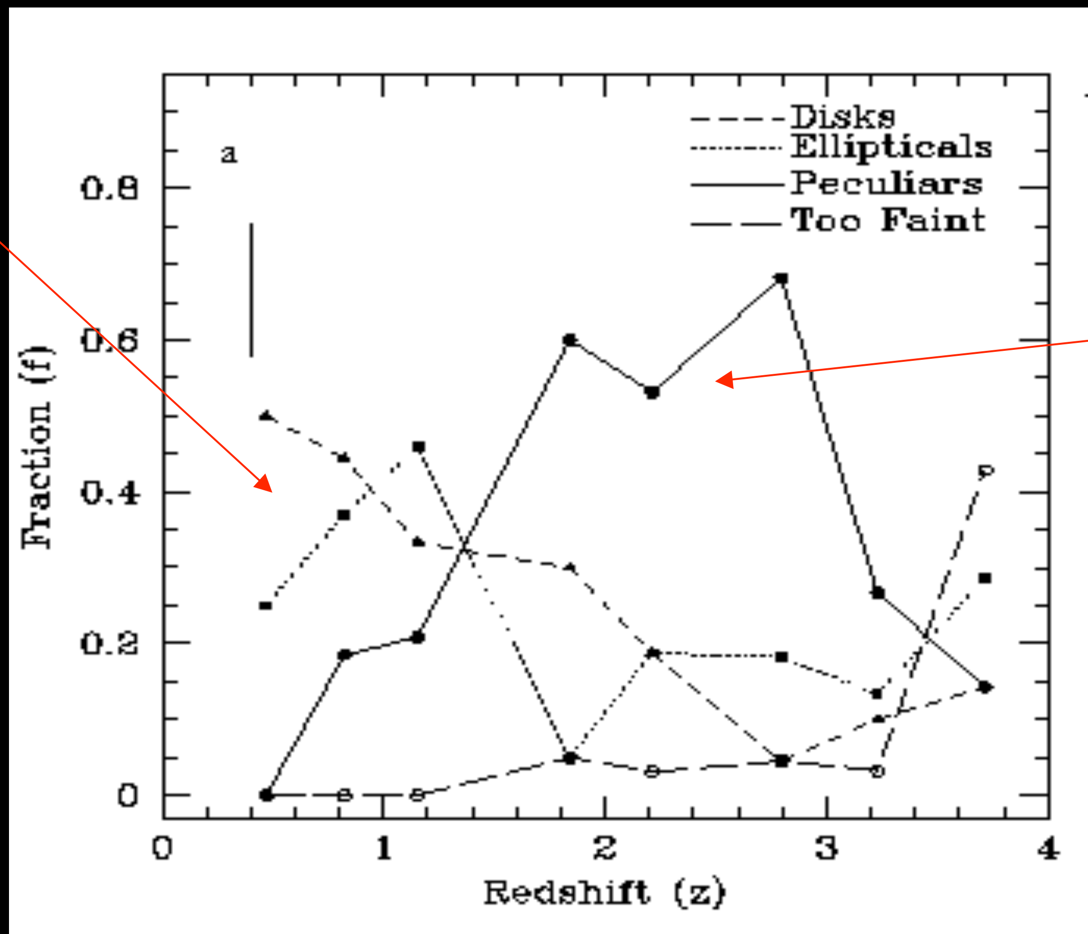
Massive galaxies must form at > 1.5

How do galaxies form?

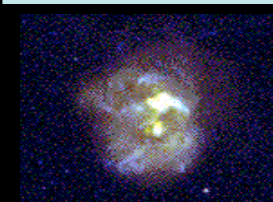
Connect the high and low redshift universe with structure

<u>Evolution of co-moving number densities to z~2 in HDF-N</u>

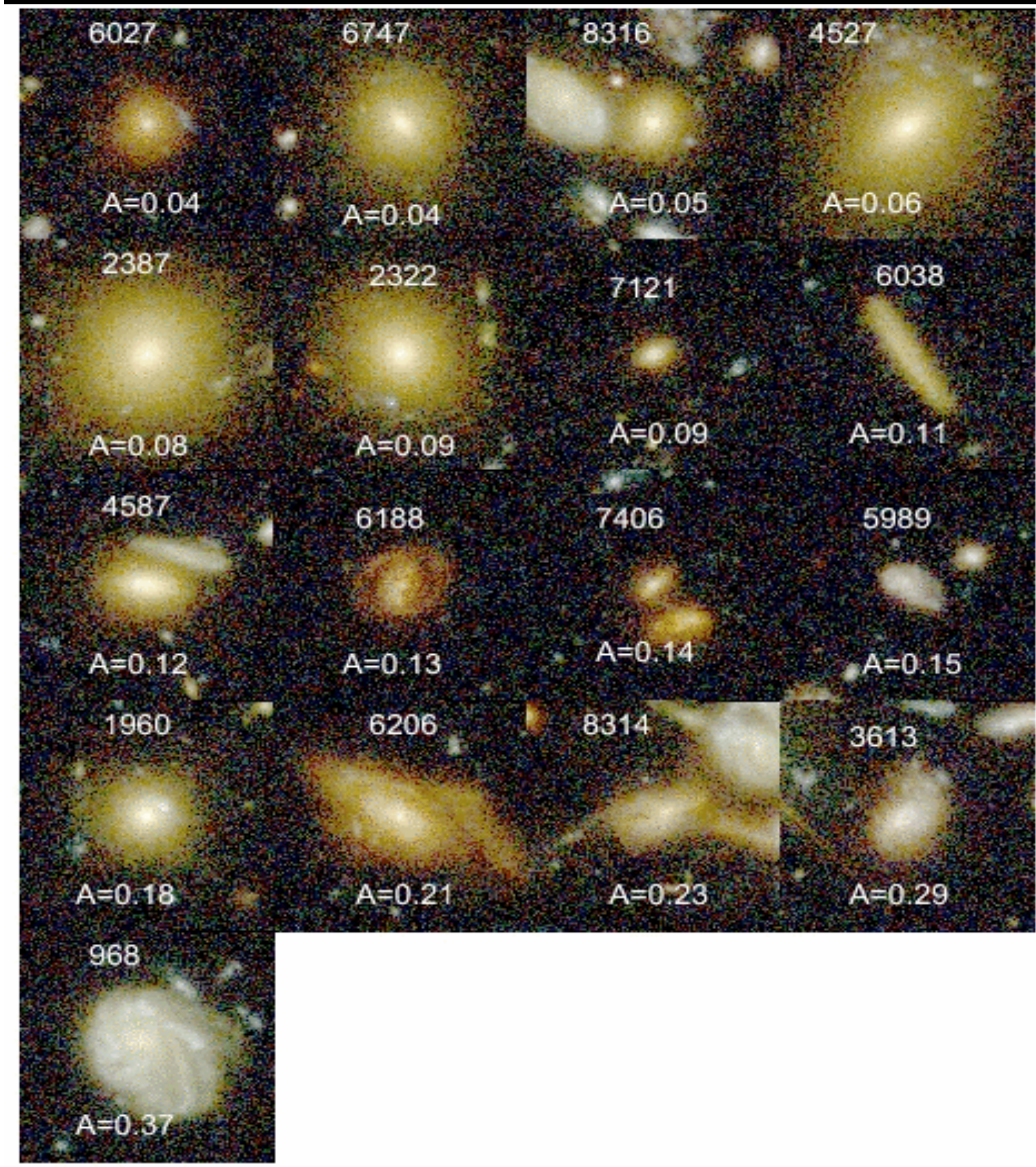
Spirals
and ellipticals
more common
today



Peculiars more
common
at high redshift



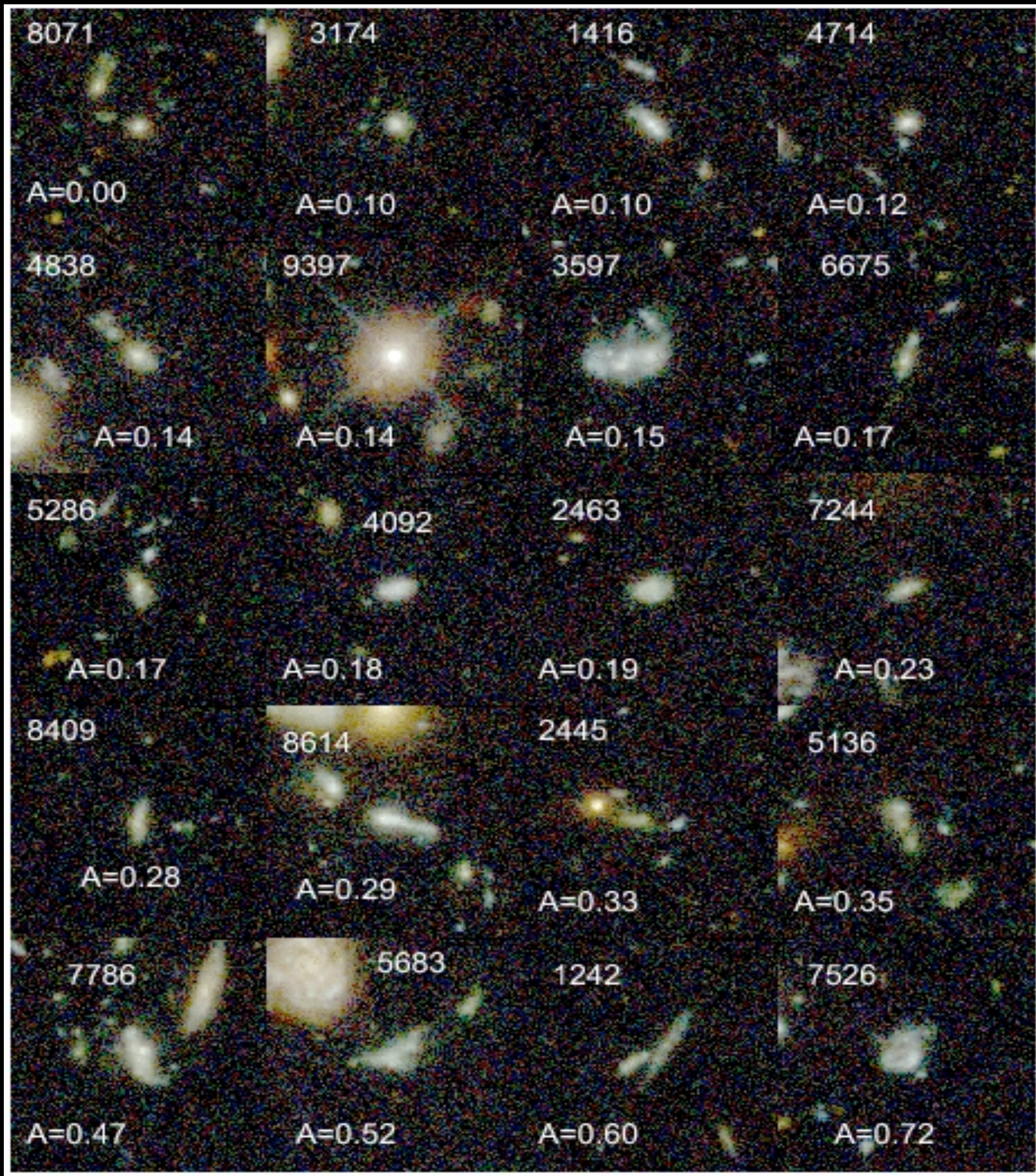
Conselice, Blackburne, Papovich (2005)



Hubble Ultra Deep Field

Galaxies in the nearby universe at z < 1 are smooth and show few signs of merging activity

Conselice et al. (2008)



Hubble Ultra Deep Field

Galaxies at z > 1.5 often show distorted structures

Are these galaxies undergoing mergers?

Conselice et al. (2008)

What does the history of galaxy interactions look like?

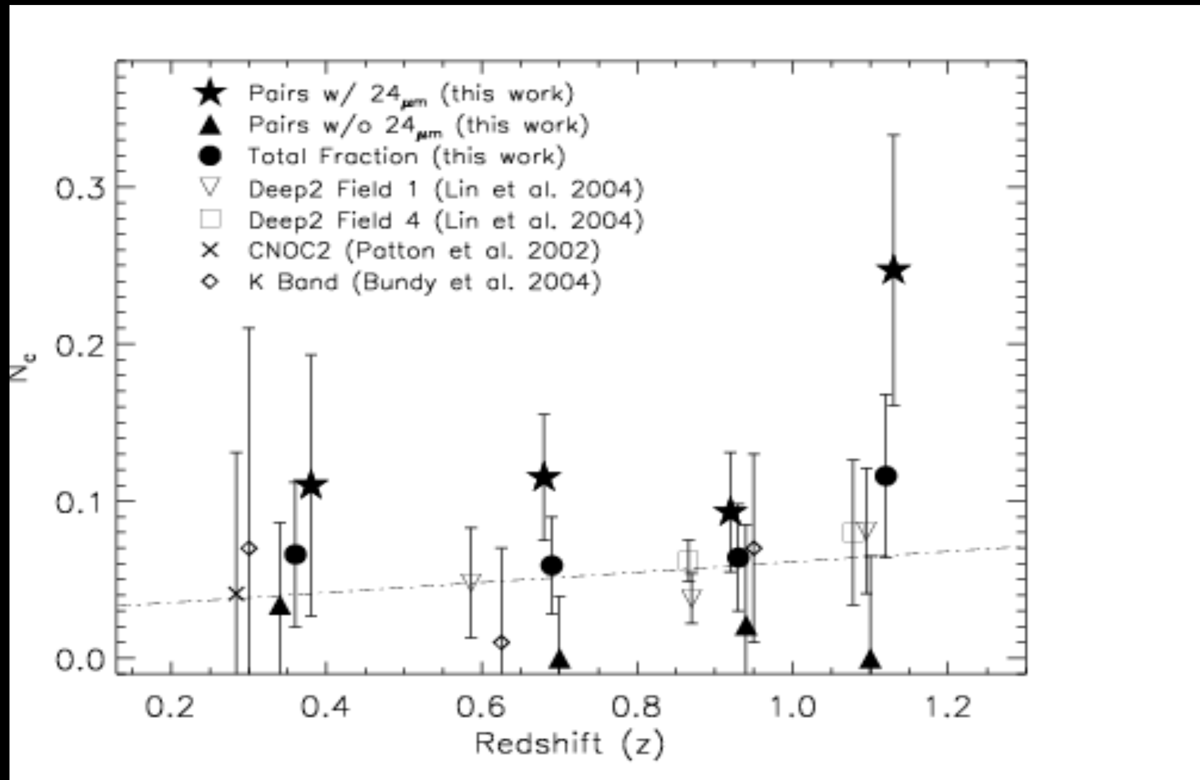
Important for understanding:

Feedback

Star Formation

Black Hole Formation and AGN triggering

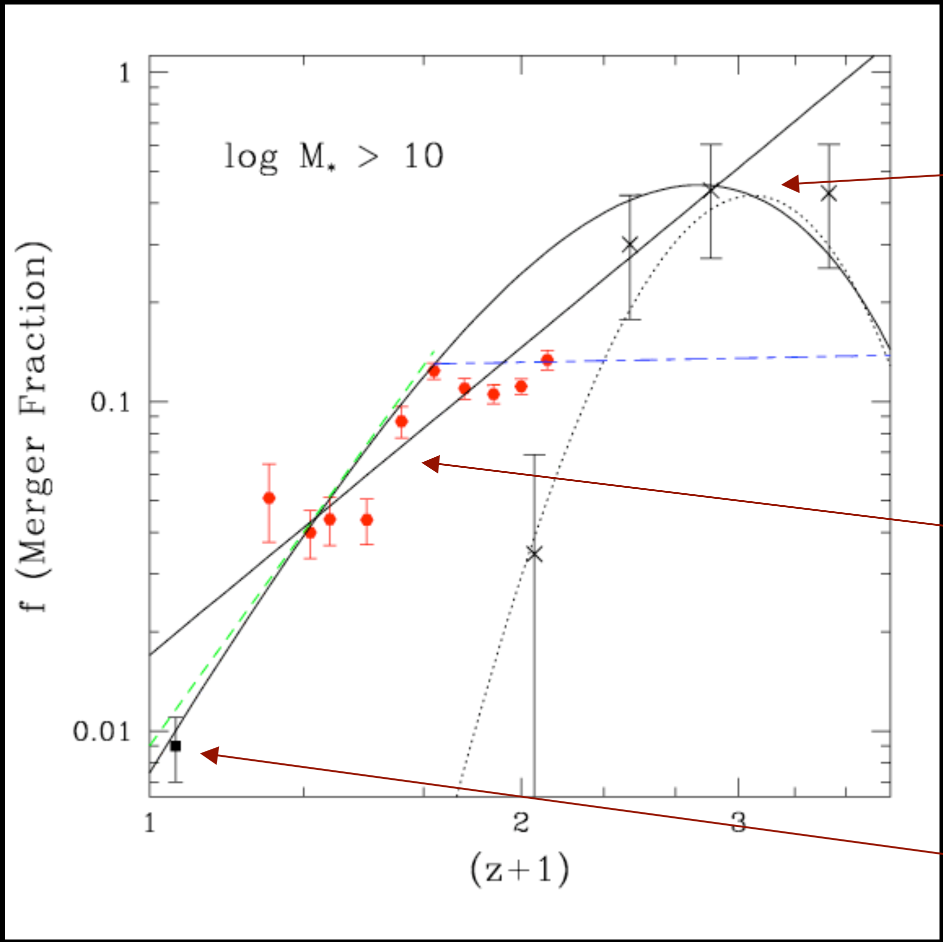
Galaxy assembly



Bridge et al. (2007)

Does not show much evolution to z = 1

Detailed Merger History at z < 3



UDF+HDF (z = 1 - 3)

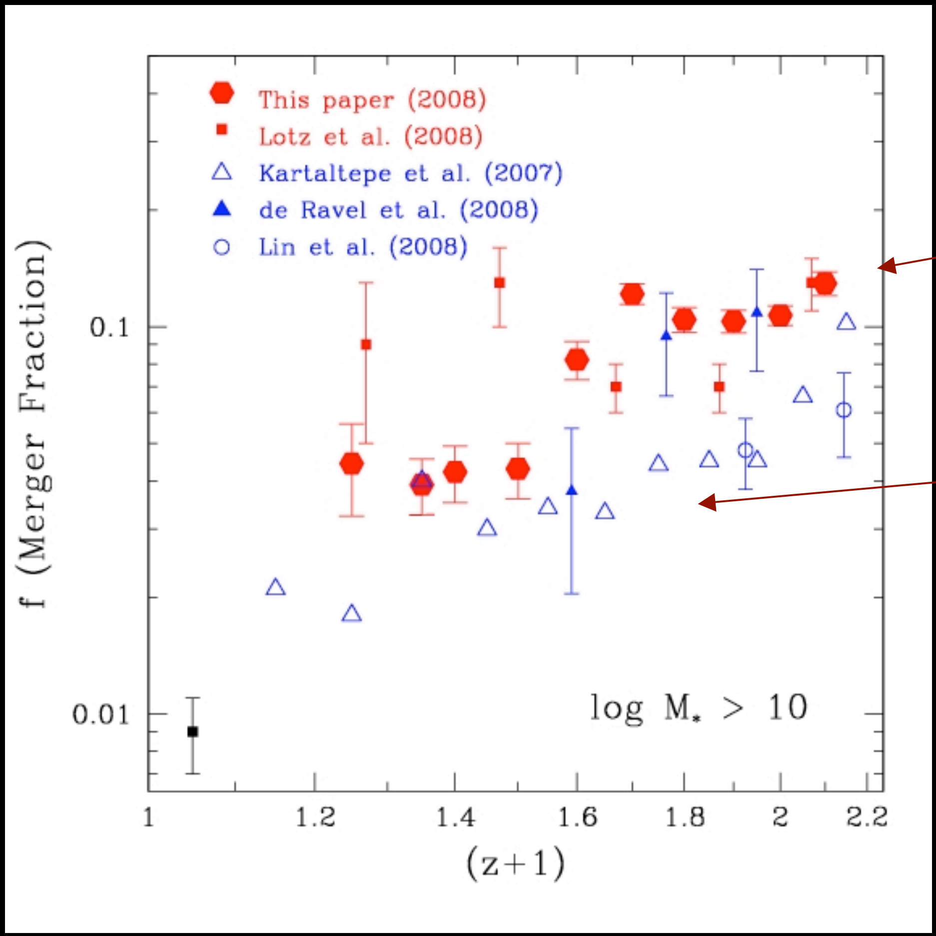
EGS+COSMOS (z = 0.2 - 1.2)

Millennium Galaxy Catalog (z = 0)

Evolves as (1+z)^3 to z = 1.5

Conselice et al. (2009)

Comparing structural and pair merger measures



Red points - structure mergers

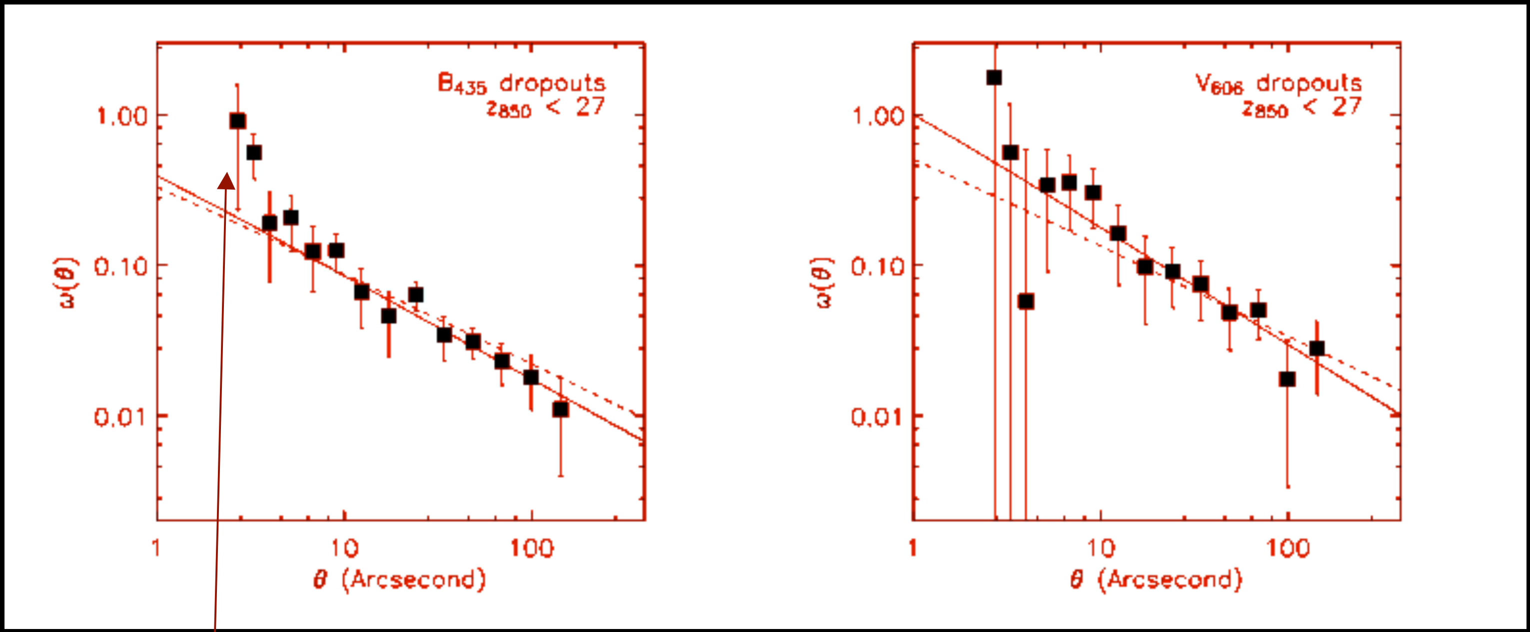
Blue points - pair fractions

Time-scales for pairs to merge are shorter than structural method time sensitivity - <u>merger rates are the same</u>

Galaxies at the highest redshifts

$z = 4 - 6$

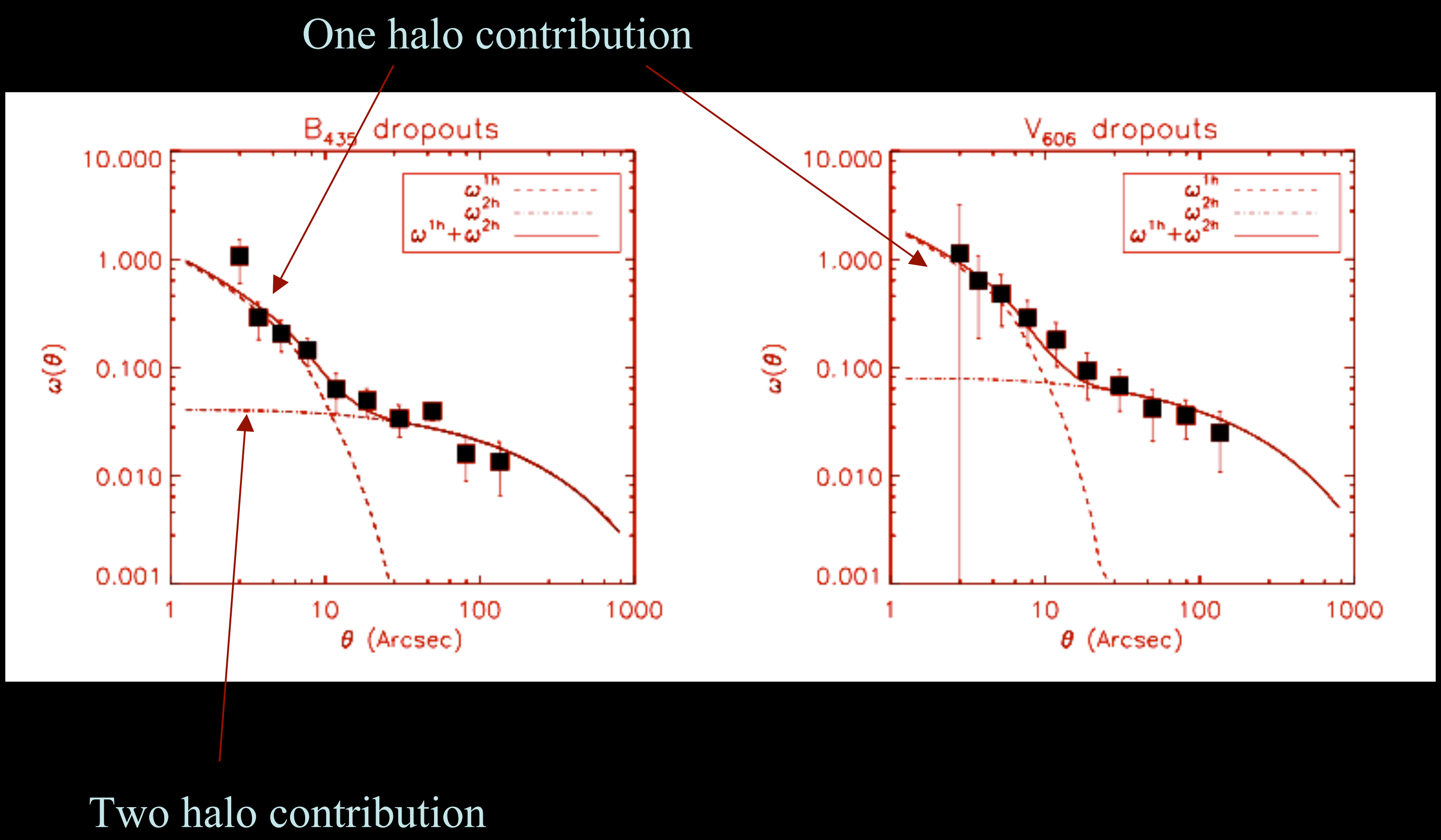
Angular correlation function w(Θ) for B (z~4) and V (z~5) drop-outs in the GOODS fields



Lee et al. (2005)

A large departure from the fit power-law form at separations < 10 arcsec

This excess at small scales can be accounted for by multiple galaxies in the same halo



Halo occupation distributions

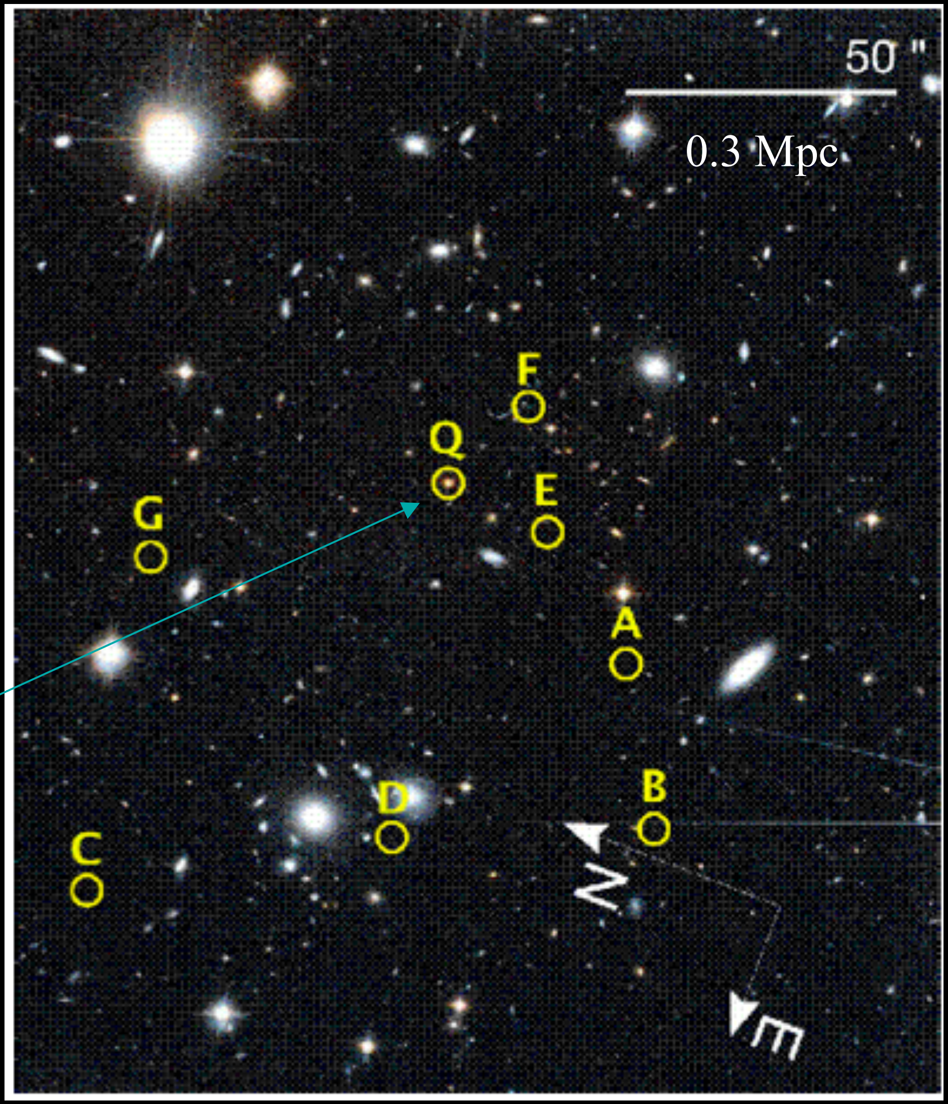
Do different environments exist at high redshifts?

Likely…

Find clustering at the highest redshifts we can probe

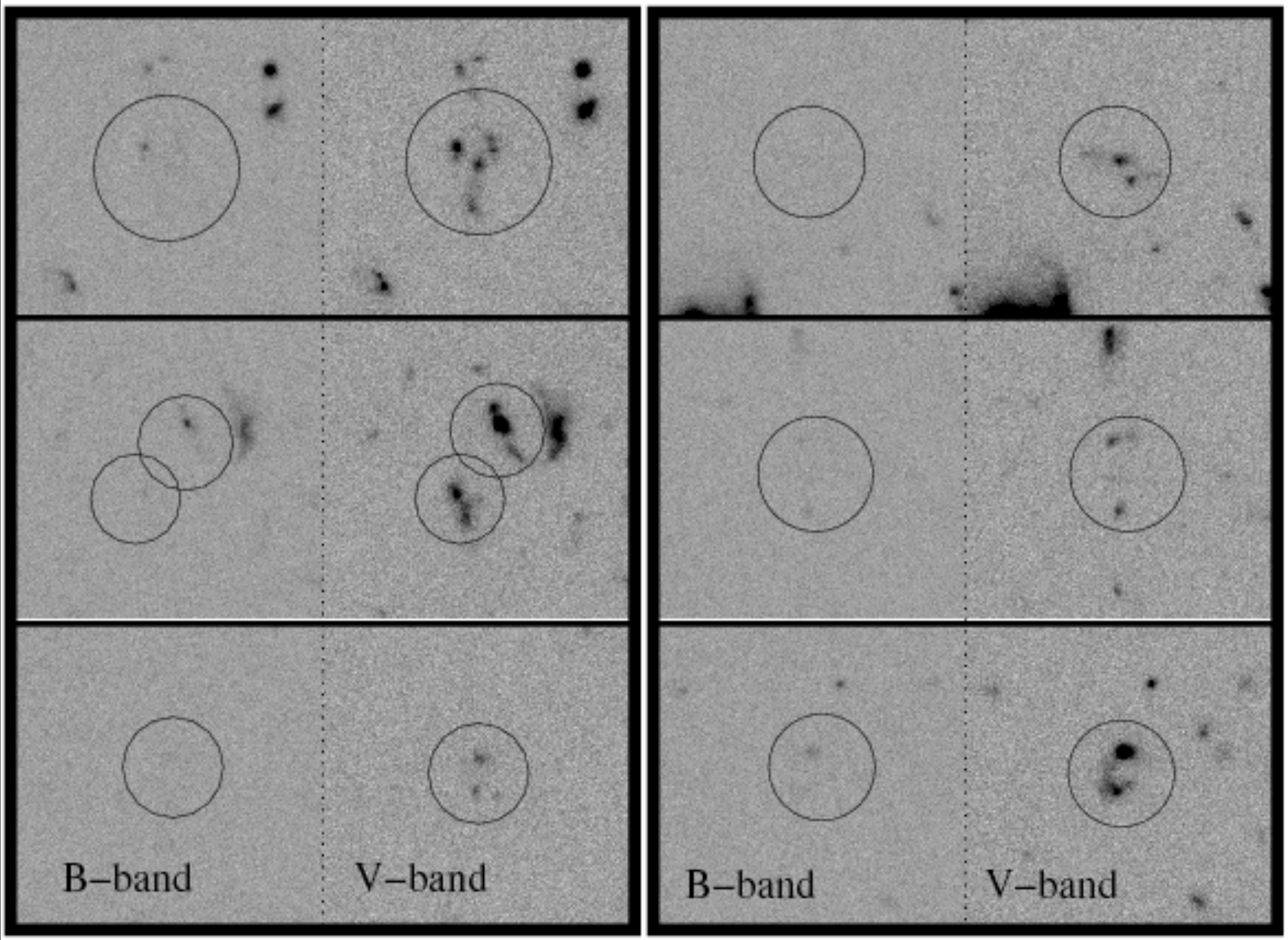
z~6 Sloan QSO

Labeled systems are at similar redshifts based on (i-z) colors



Zheng et al. (2005)

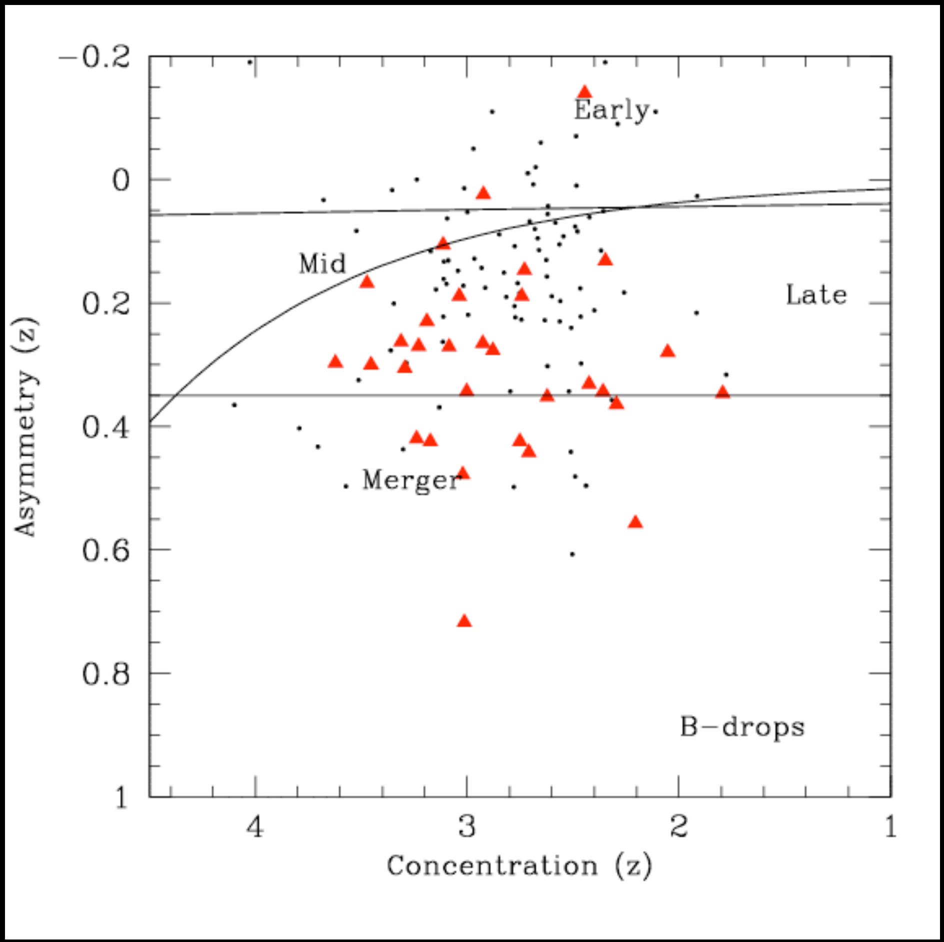
There are also LBGs in pairs



B-drops in the Hubble UDF

Conselice et al. (2009)

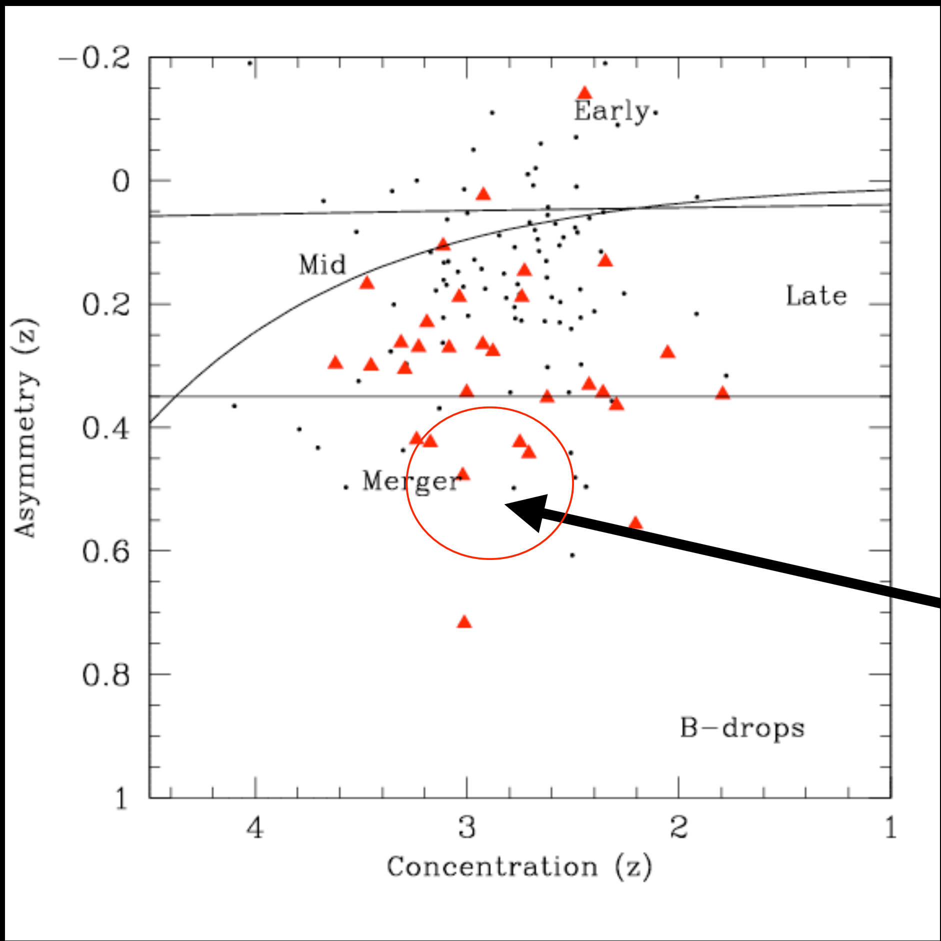
A diversity in galaxy structure for z = 4-6 galaxies

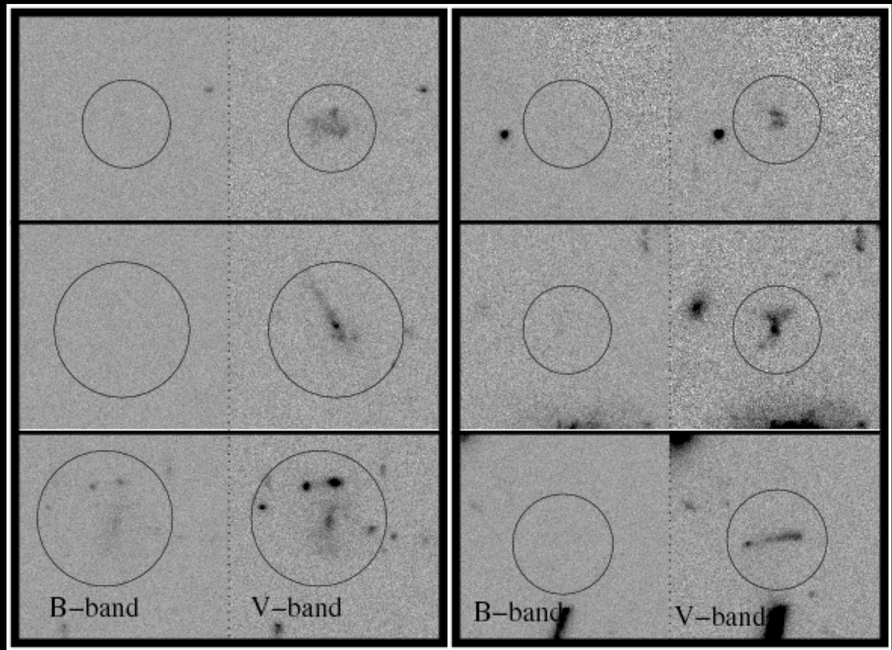


Measurement of the CAS parameters on the drops utilizing the z-band UDF image

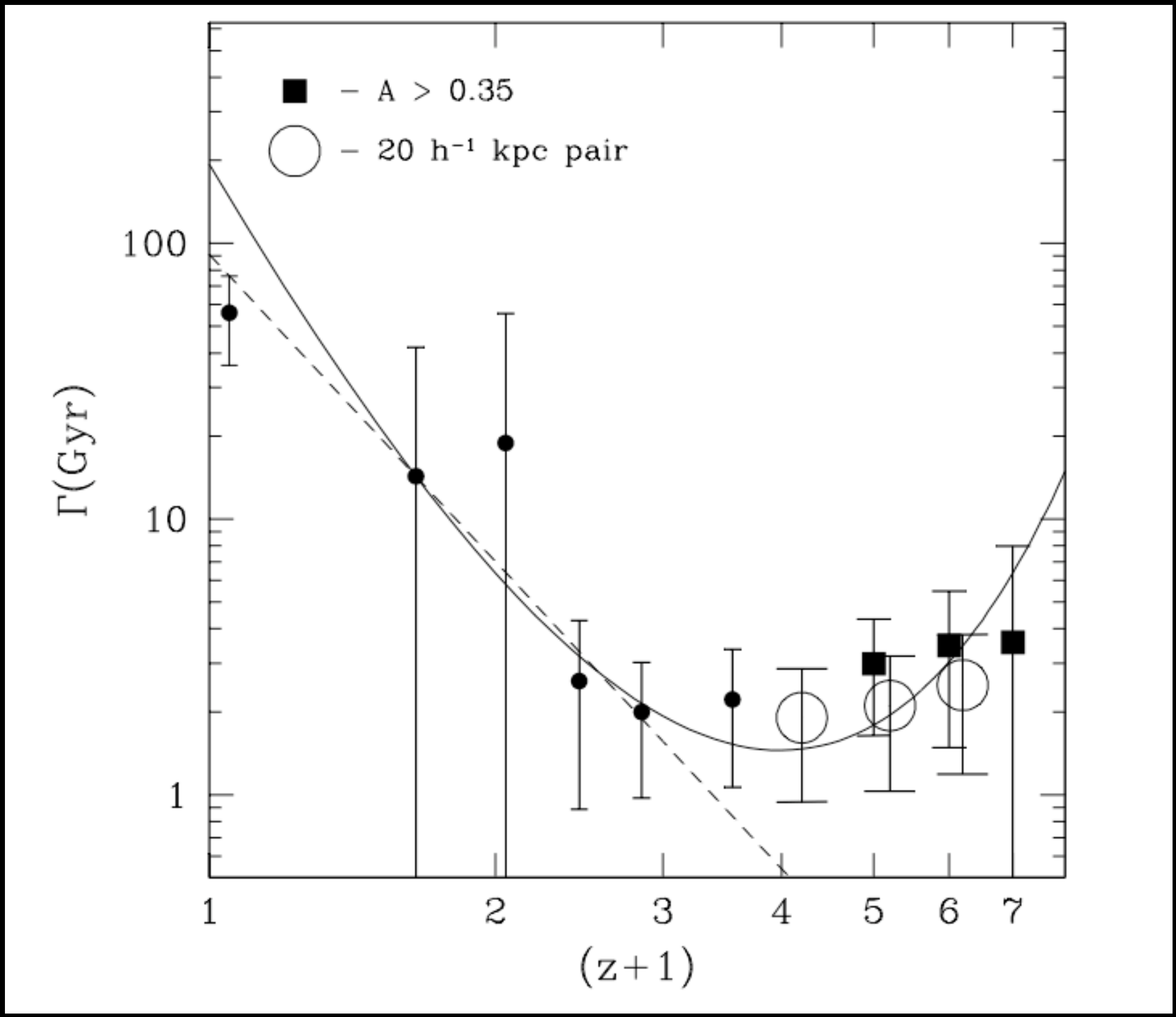
It appears, based on a simple concentration asymmetry diagram, that a diversity of galaxy structure exists at z~4-6

Asymmetric Galaxies





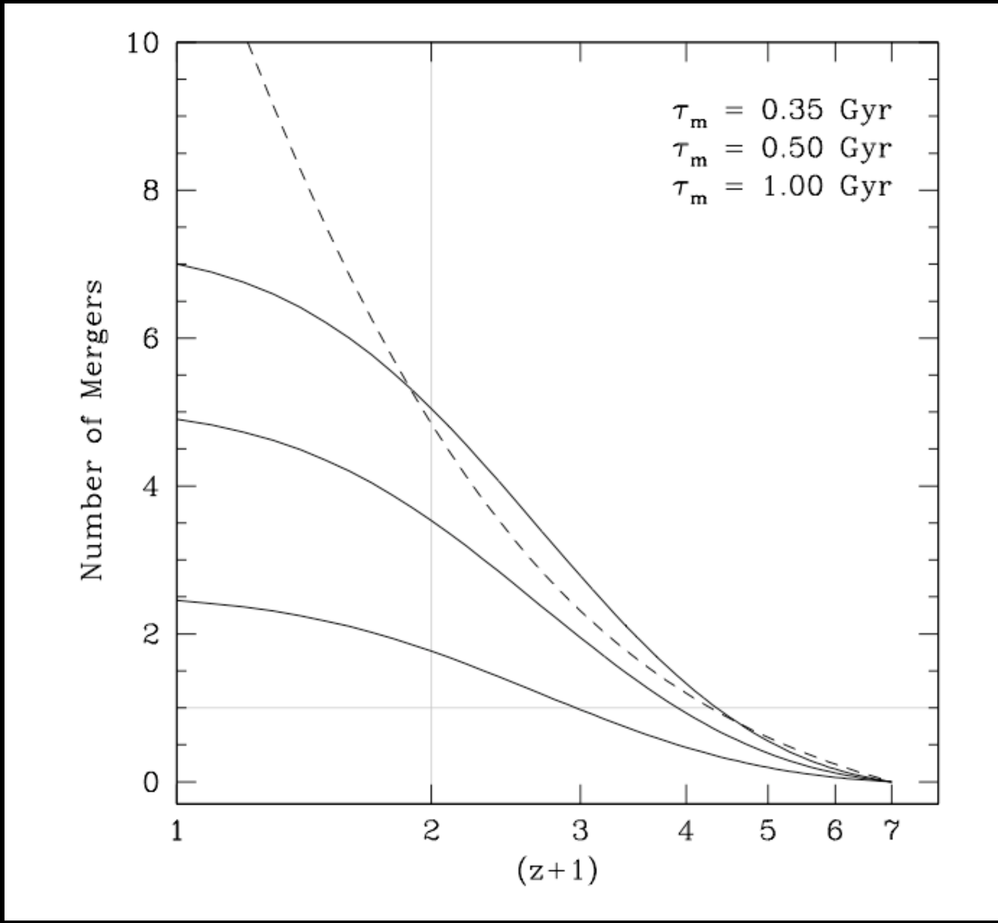
The galaxy merger rate history to z = 6



For galaxies with log M > 10

Gamma = tau/f or average time between mergers

The cummulative merger history at z < 6 for log M > 10 galaxies

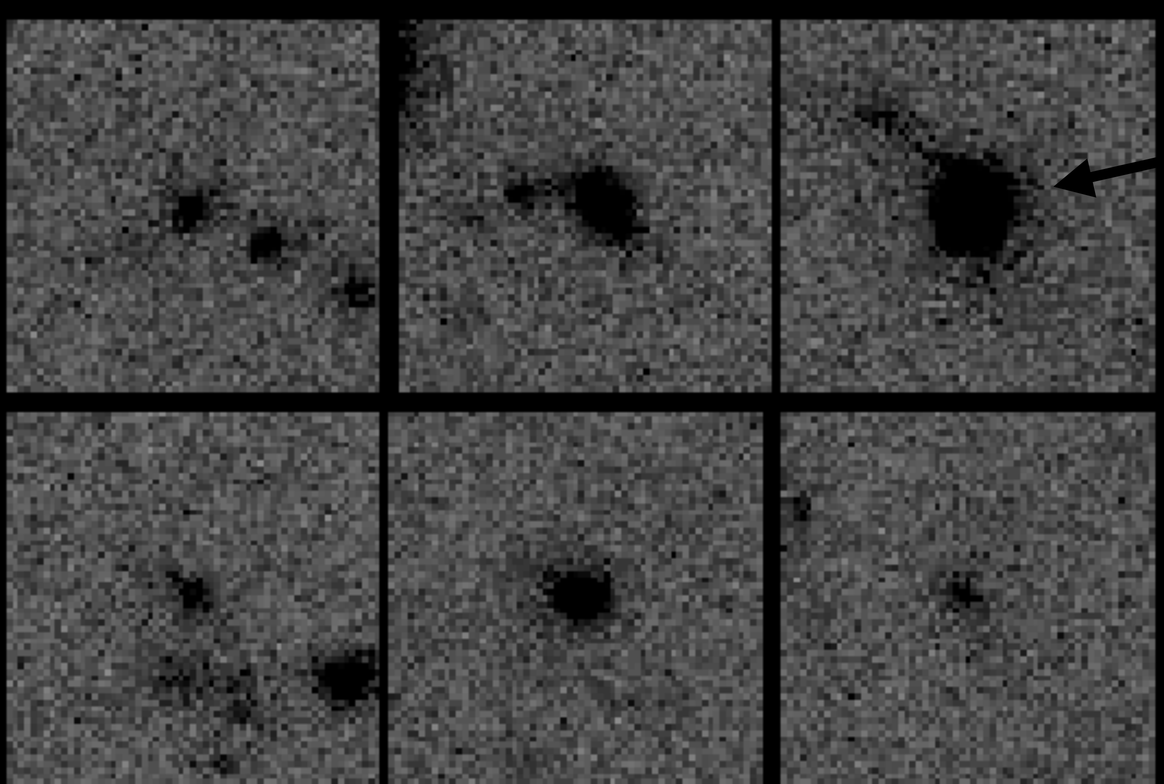


Total number of mergers Depends upon the time-scale for merging

Tau = 0.6 Gyr - best estimate based on models and empirical results

Total number of mergers:
<u>~0.9 at z < 1</u> and
<u>~4.2 at z < 6</u>

High concentration galaxies



SBM03#1 at
z = 5.83, with
a stellar mass
= 1-6 * 10^{10} M_0

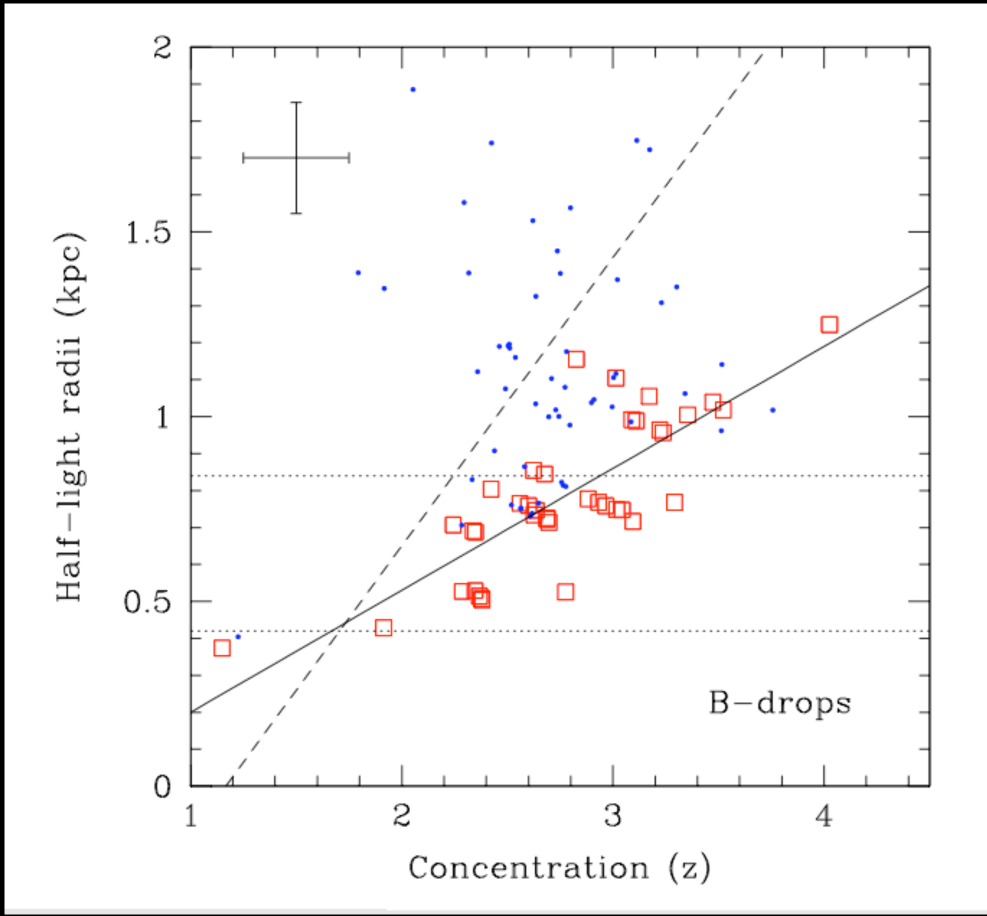
Eyles et al. (2005); Yan et al. (2005)

Evidence for
an early formation?

C > 3 galaxies are nearly always early types at z = 0

Not the case at z~6, but some evidence for relaxed structure

The concentration index correlates with size

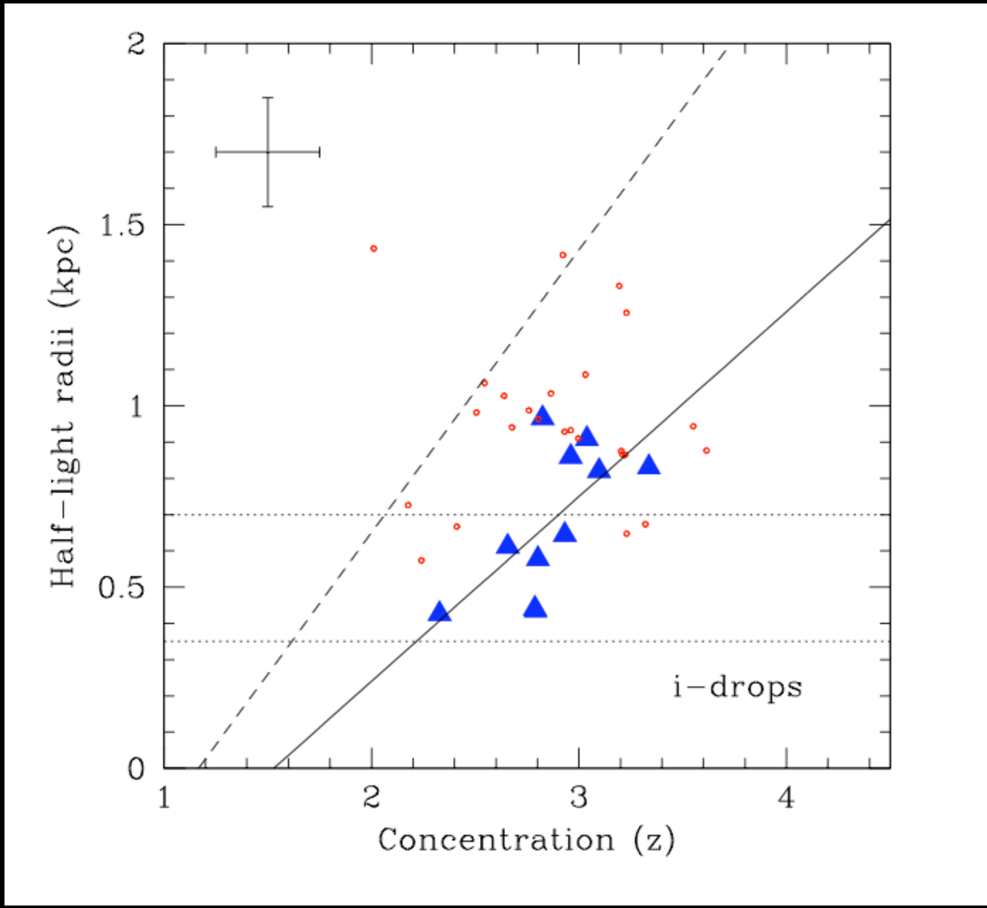


B-drops (red)

Relationship is such that more concentrated objects are larger

Evidence that galaxy structure is stable or virialized by z ~ 6

The concentration index correlates with size



i-drops (blue)

Last merger > 0.5-1 Gyr

Implies that these galaxies are the earliest 'monolithic' collapse galaxies. However, cannot rule out earlier merging At z > 10.

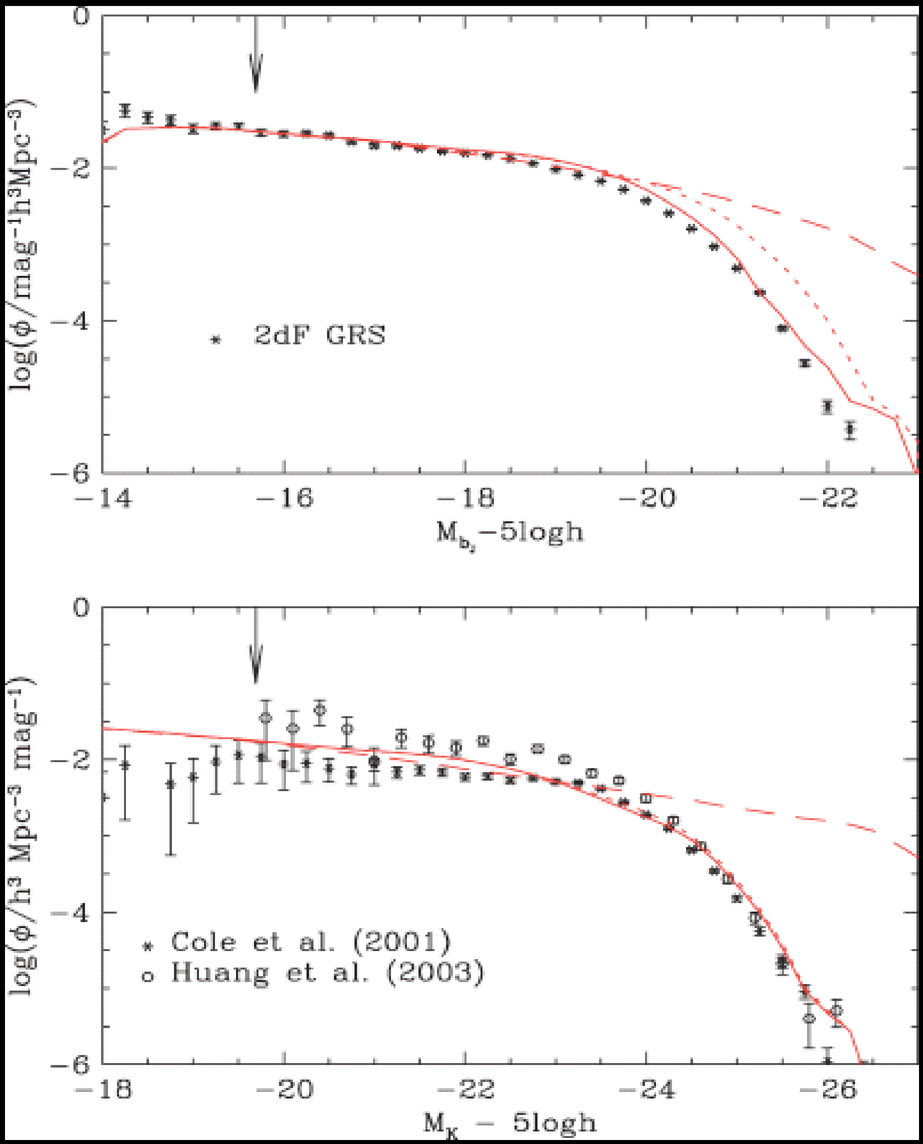
Holds out to z~5-6

Conselice et al. (2009)

Direct test of the ΛCDM model of galaxy formation

One future test of Lambda CDM will come from direct measurements of the merger history of galaxies

Why : Cold dark matter is becoming the accepted model for galaxy formation, yet in a sense it is difficult model to test, and its basic prescription should be directly tested – galaxy formation through merging.



Bower et al. (2006)

With added physics and feedback, LCDM models can match *some* z = 0 galaxy properties very well

Including:

Luminosity functions

Mass functions

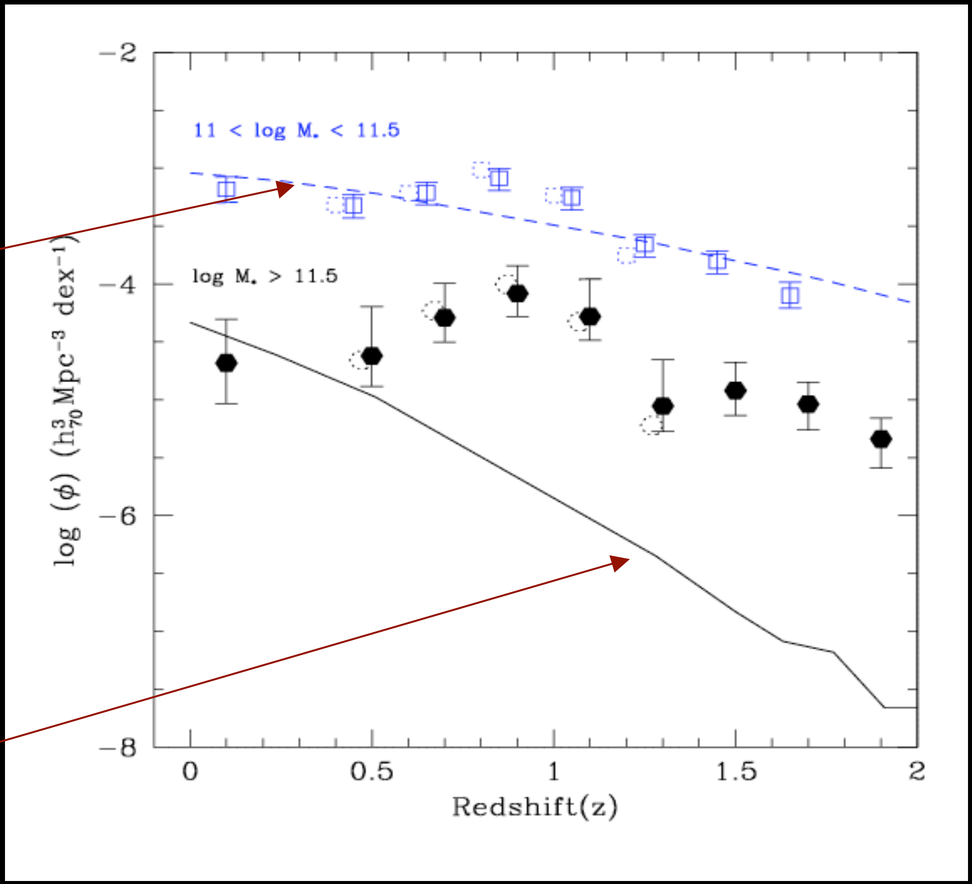
Galaxy colors and distributions

Scaling relations: Tully-Fisher, etc.

There are too many massive galaxies in comparison to models

Millennium simulation

Prediction for 11 < log M < 11.5

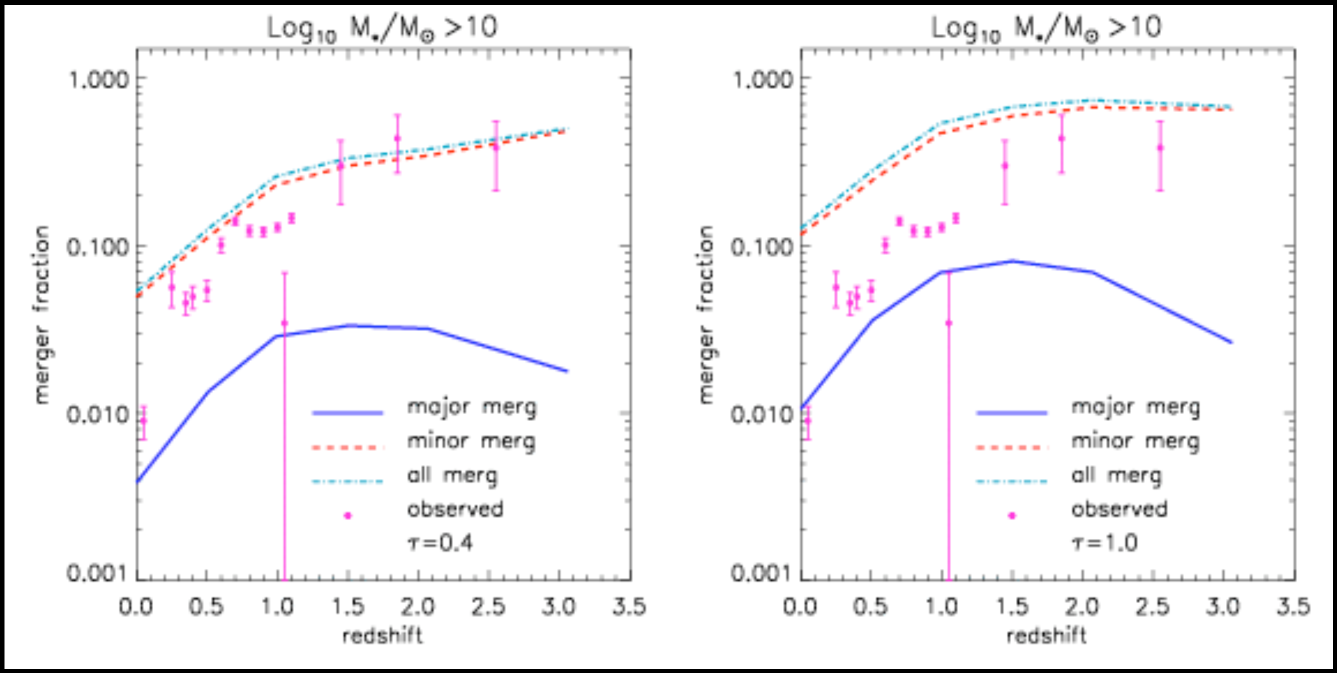


Prediction for log M > 11.5

Conselice et al. (2007)

Vast under prediction in models compared to observations

Different Lambda+CDM model predictions of the merger rate

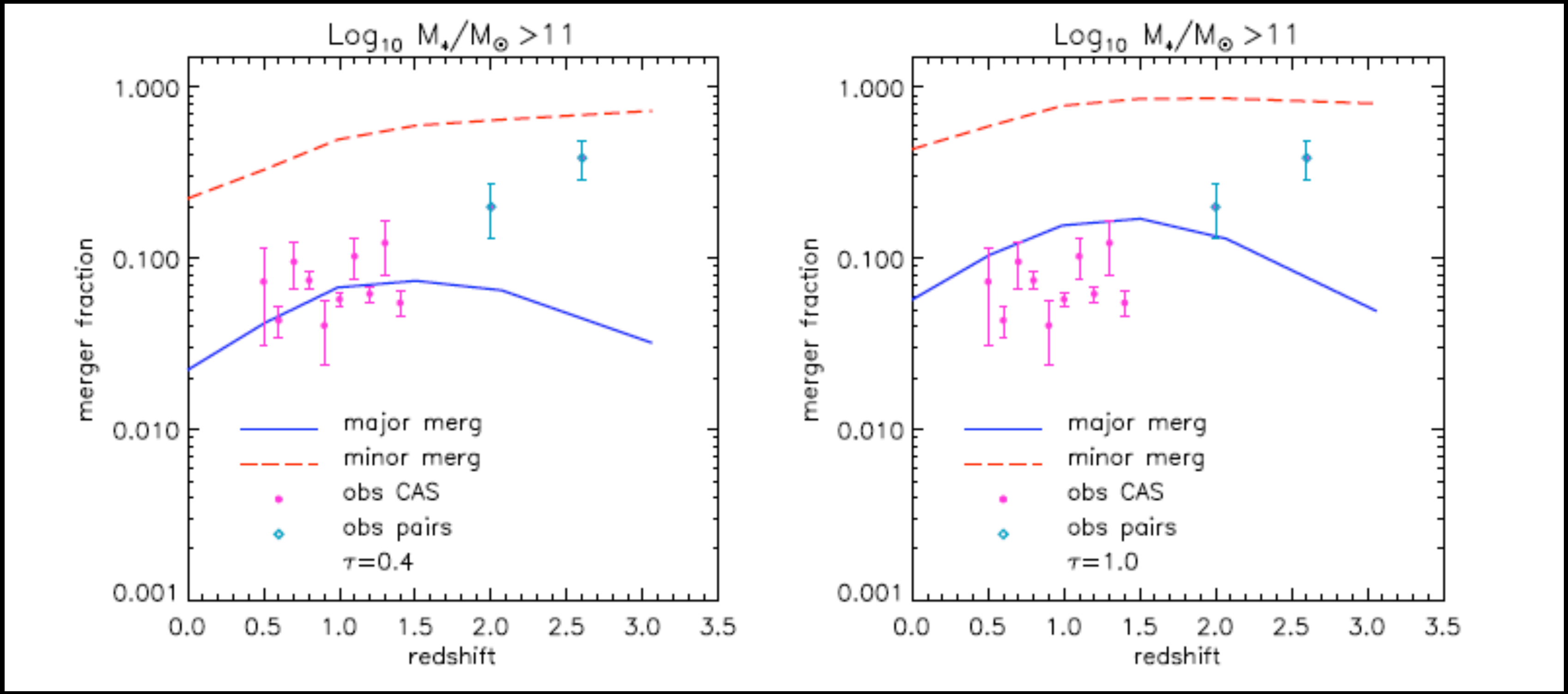


The merger history is a new and fundamental feature that must be modeled correctly

Is problem with galaxy or dark matter physics?

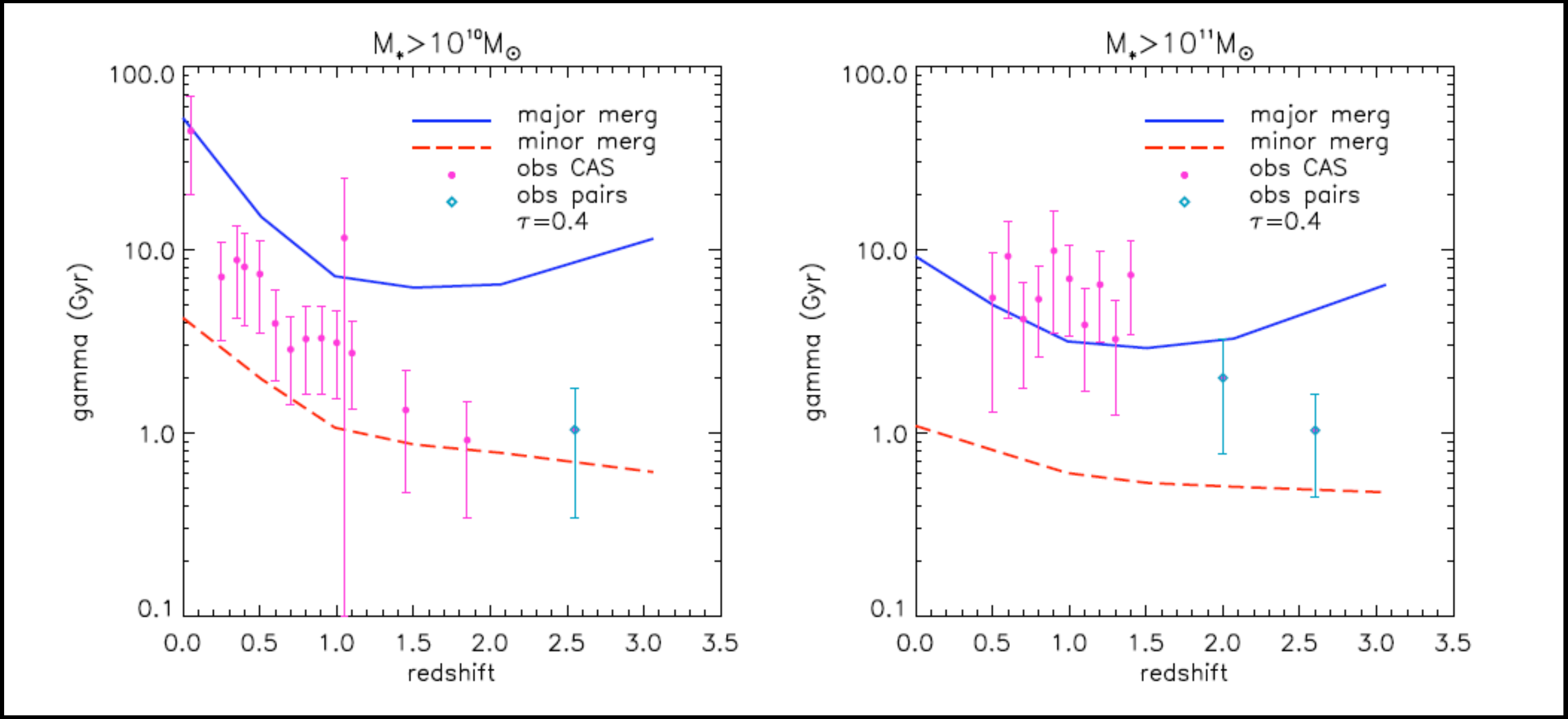
Bertone & Conselice (2009)

Problem continues for the highest masses at high redshifts

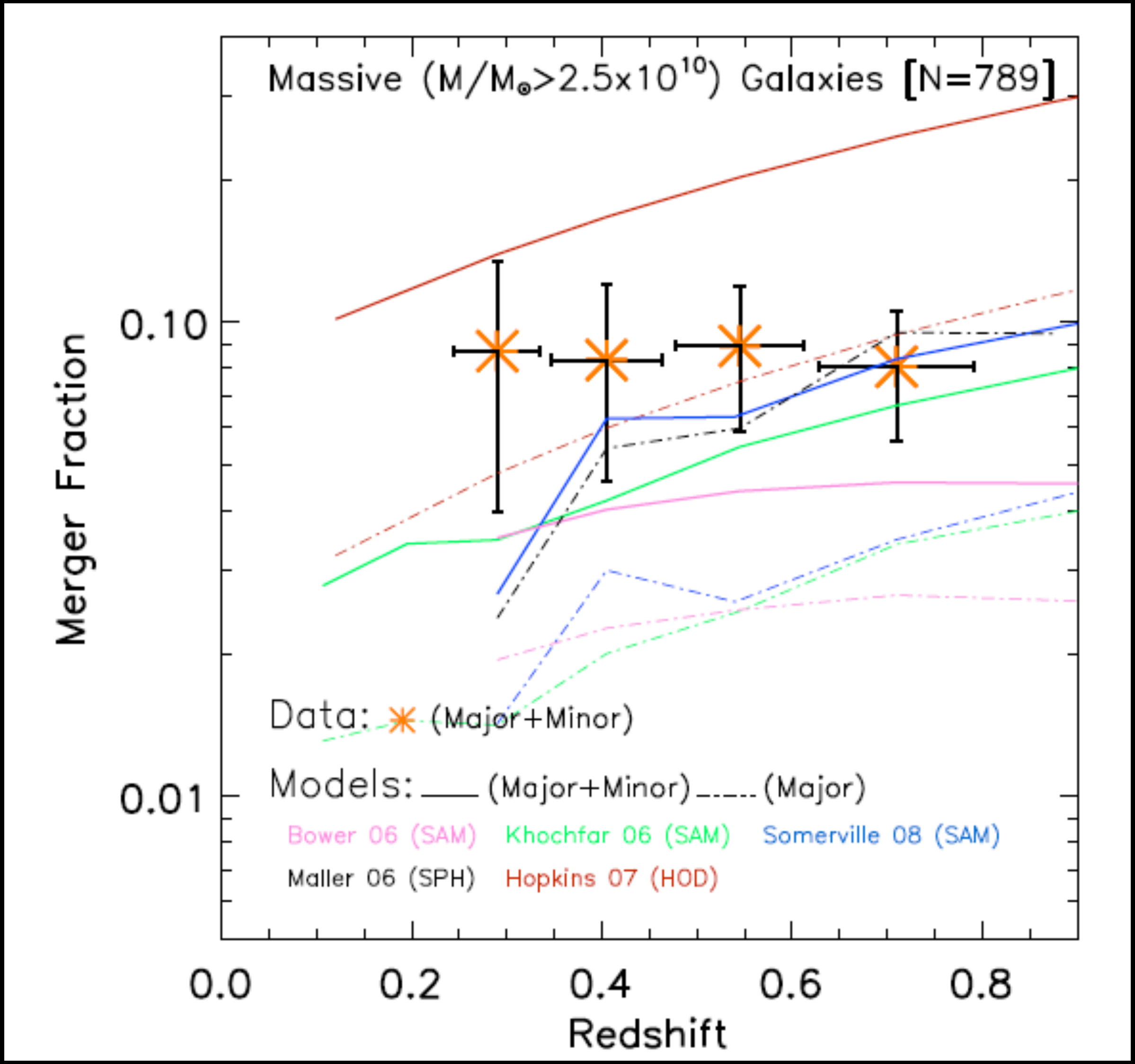


Observational method must be sensitive to > 1:10 mergers and/or have a time-scale of > 5 Gyr to match prediction.

Galaxy Merger Rates : gamma = merger time-scale/f_m



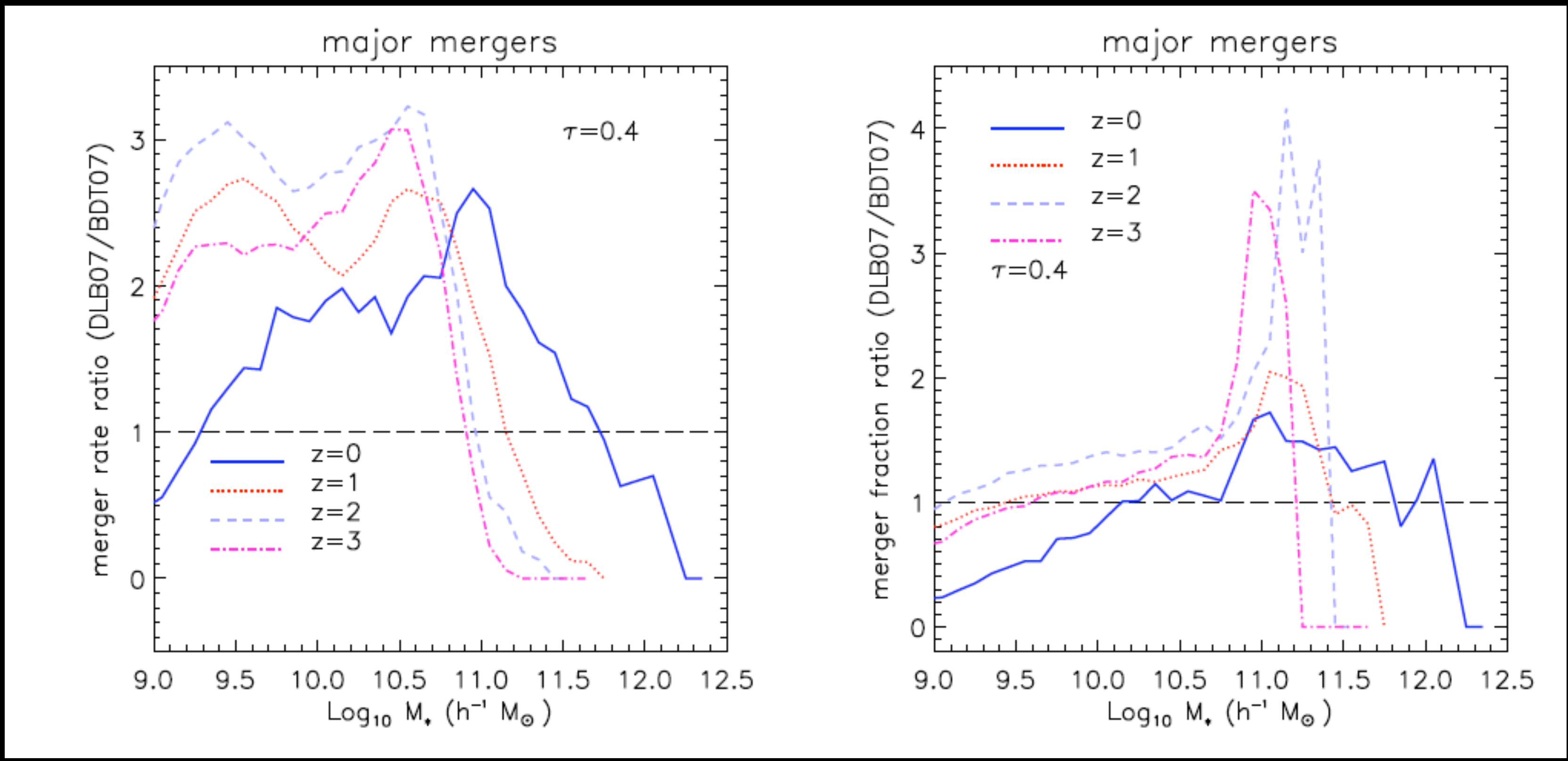
Merger fractions based on visual measures - find similar results



Galaxy sims do not predict enough mergers

Jogee et al. (2009)

Different star formation physics, give different merger histories



Bertone & Conselice (2009)

Ratio of merger rates and fractions for De Lucia et al. (2007) and Bertone et al. (2007). Both use the Millennium simulation, and only differ in terms of how SN feedback is implemented.

GOODS NICMOS Survey (GNS)

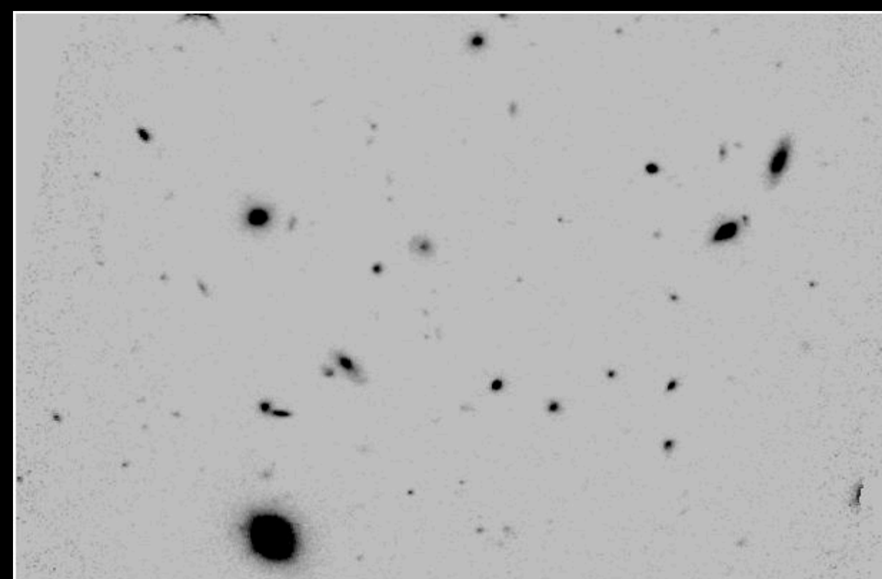
We must probe in the NIR to study structures at z > 1.

A HST NICMOS program to image the most massive galaxies at z > 2 in the GOODS fields (180 HST orbits; PI Conselice)

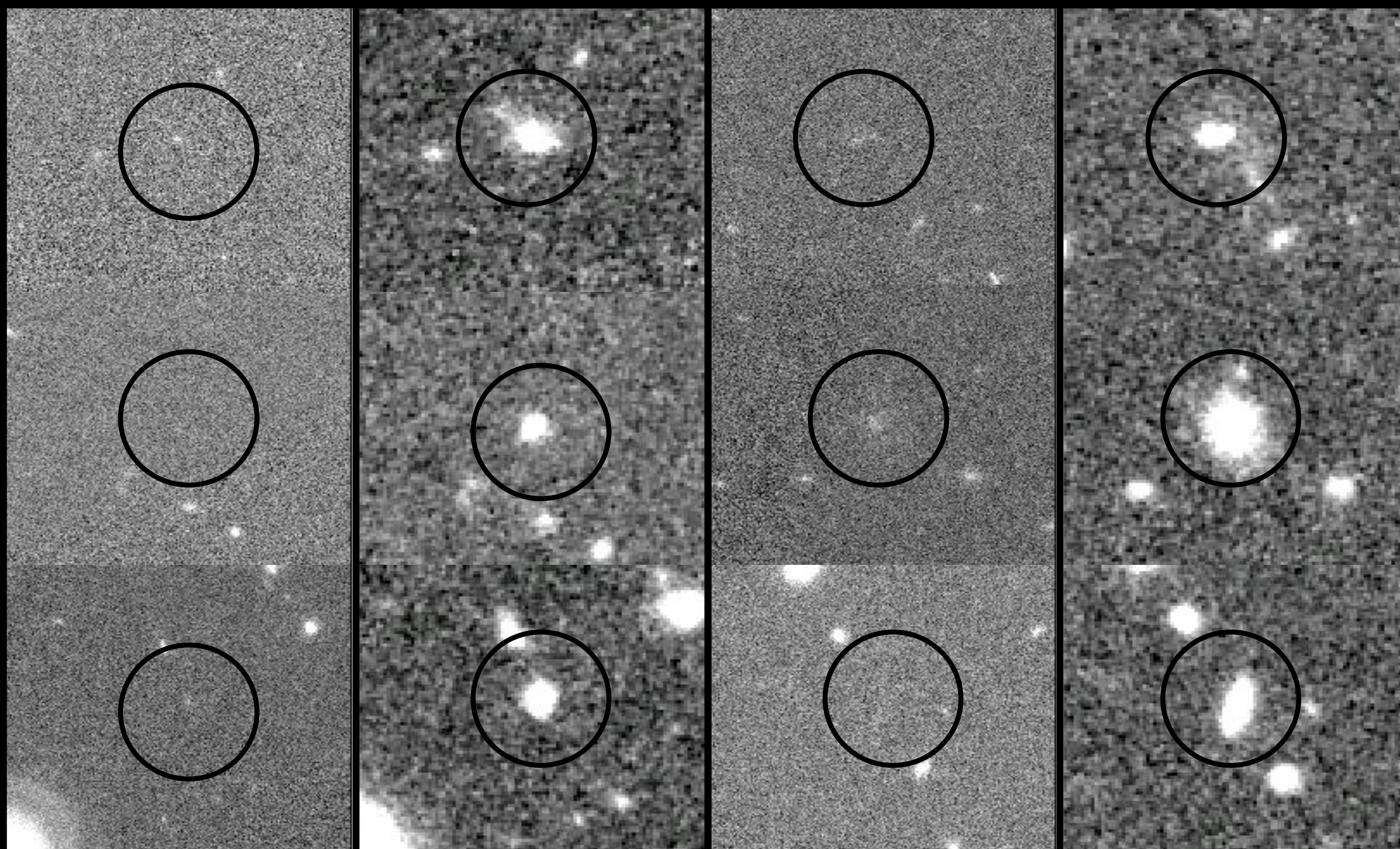
<u>We are examining:</u>

Sizes of massive galaxies at z > 2

Structure and morphologies - merging, etc



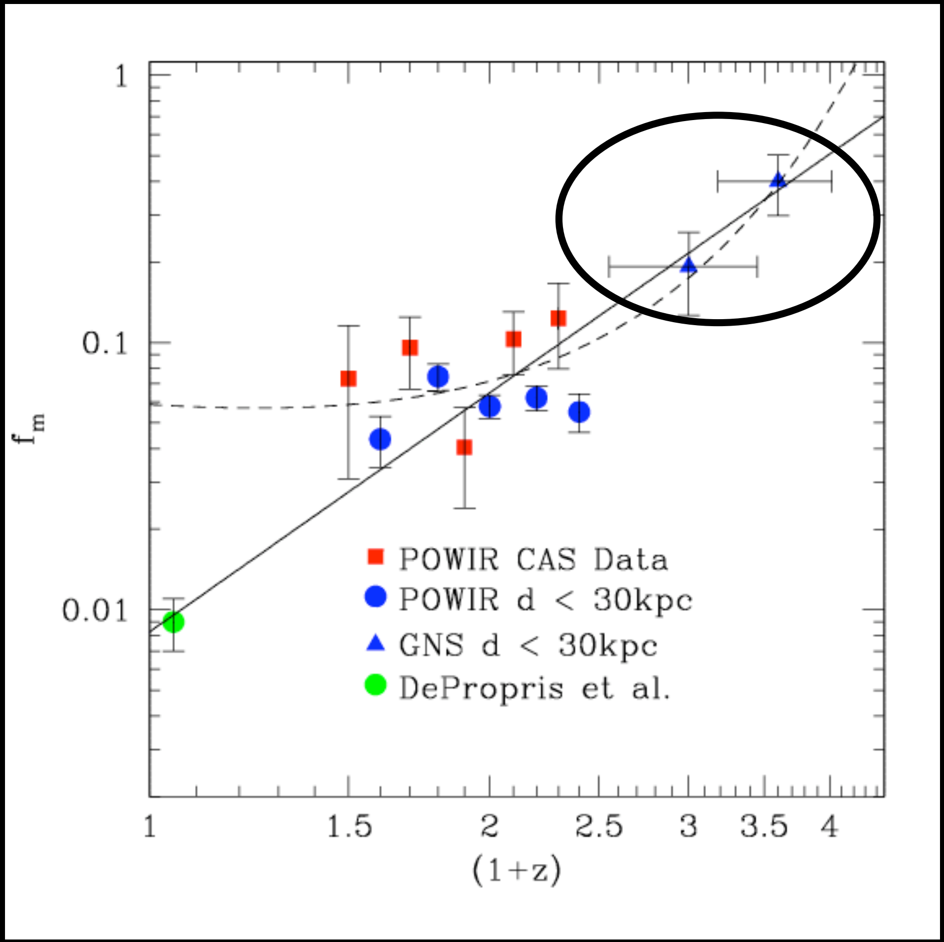
Images of galaxies in the GNS Survey



z-band H-band z-band H-band

log M > 11 and z > 2 systems

A surprisingly high merger fraction for very massive galaxies at z > 2



For log M > 11 systems mergers are an important process in the early universe

Bluck, Conselice, et al. (2009)

See Bluck poster

There is strong evolution in galaxy sizes for massive galaxies at z < 2

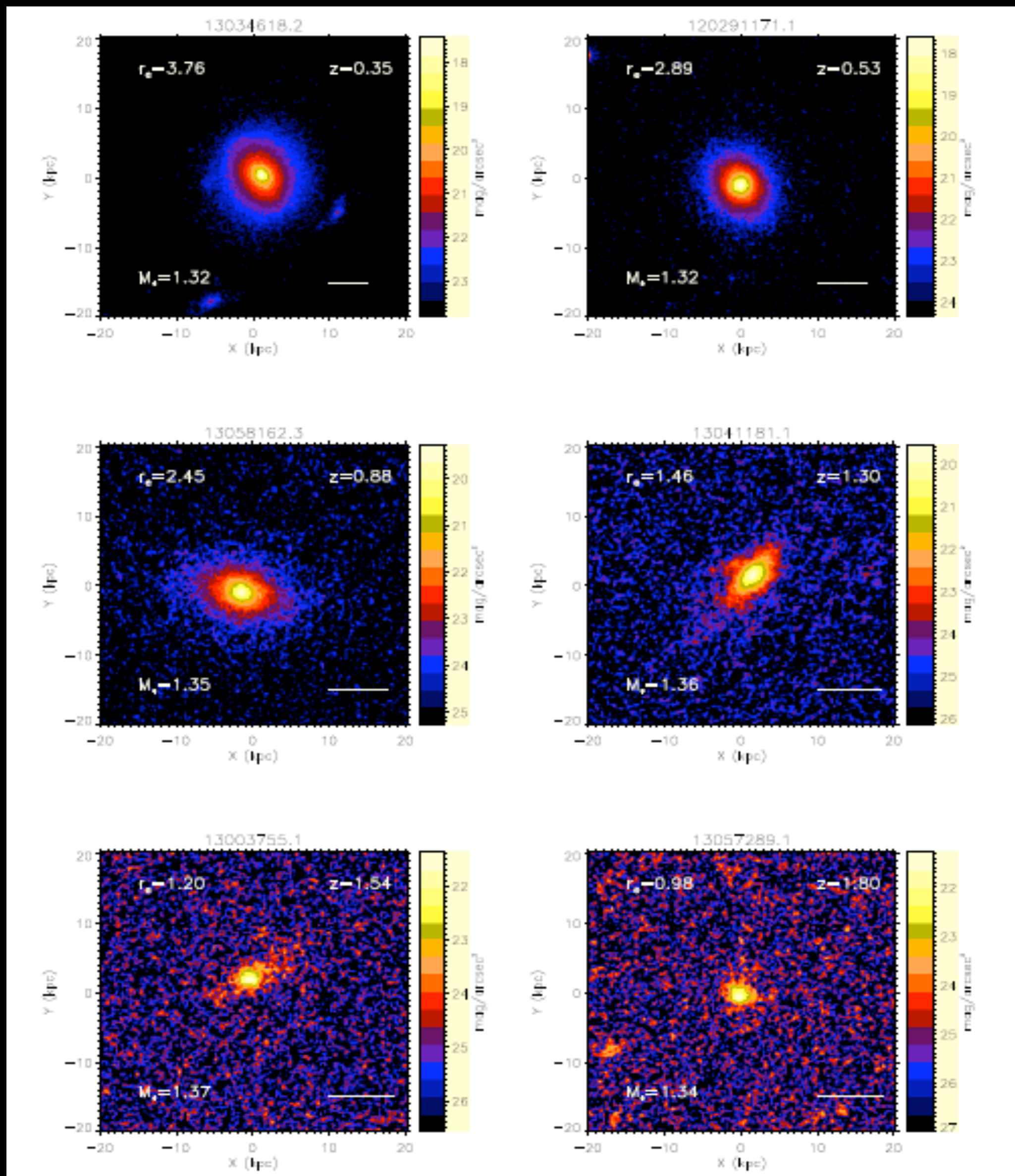
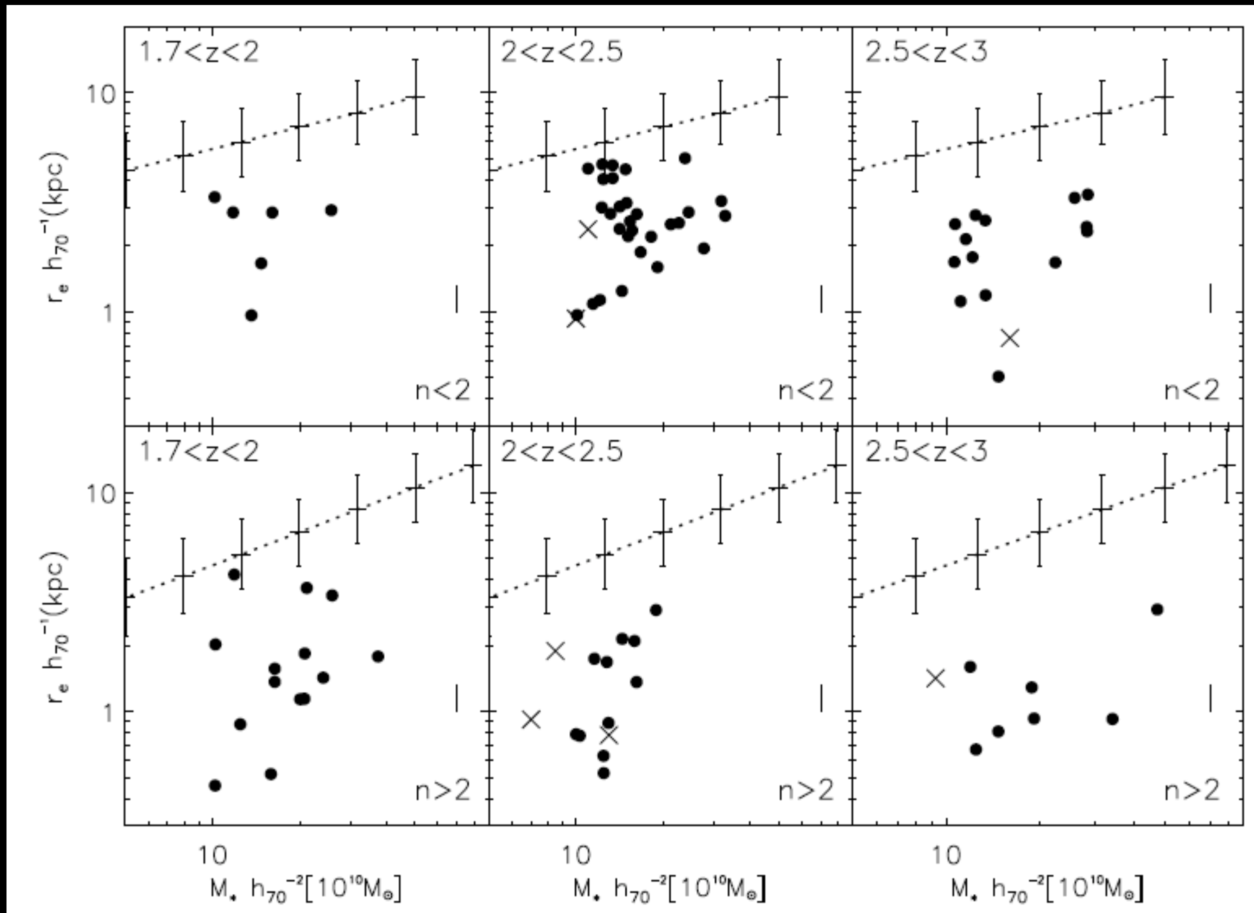


Image shows visually how galaxy size changes with redshift at a constant mass

Trujillo, Conselice et al. (2007)

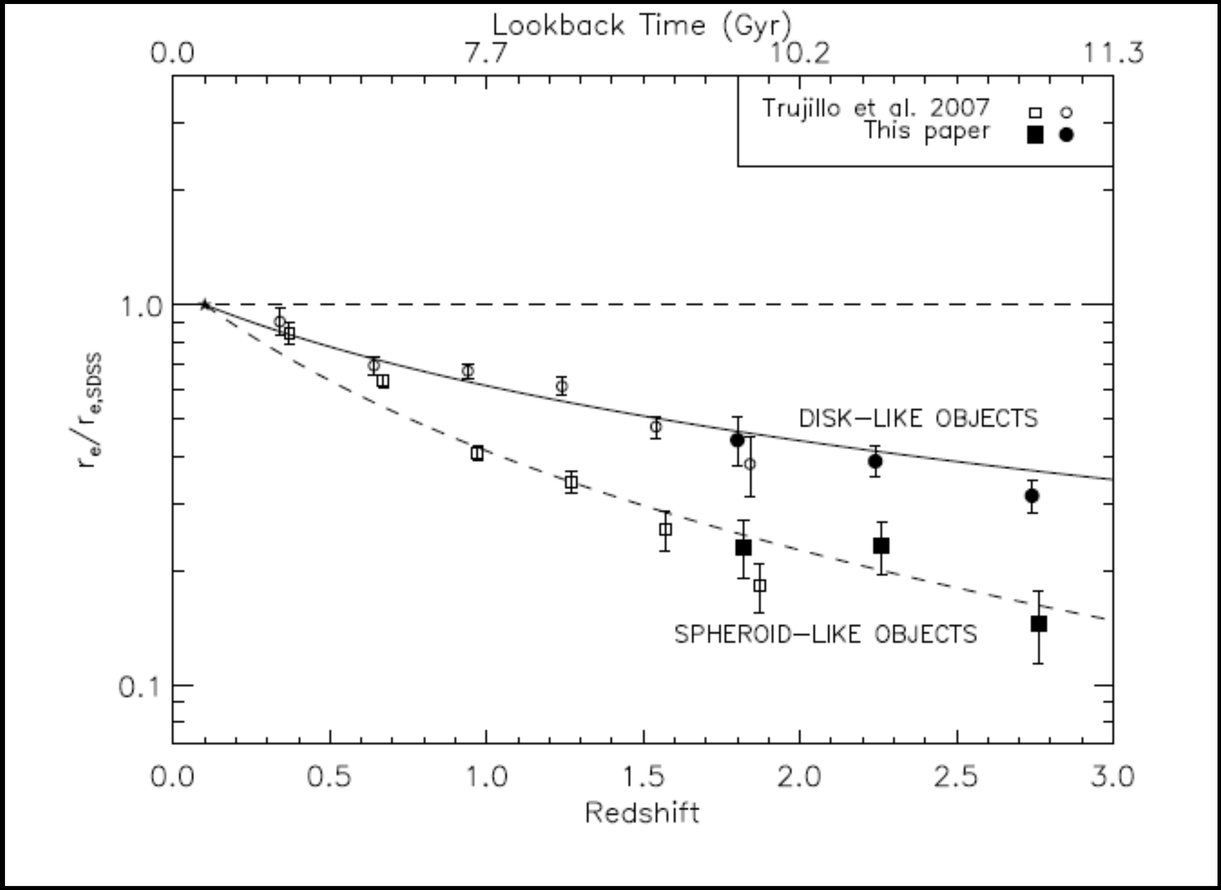
Size evolution for GNS galaxies



Buitrago et al. (2008)

ALL massive galaxies at z > 2 are compact

Galaxy sizes continue to decrease at higher redshifts



Buitrago et al. 2008

Summary

1. Galaxy environment key for understanding galaxy formation - although much of the activity happens in groups.

2. By studying galaxies in terms of masses we can trace directly evolution without recourse to models.

3. Method can be used to determine features of the galaxy population not easily traced through standard parameterizations.

4. Galaxy structure is an extremely powerful tool for uncovering galaxy formation at high redshift.

5. Massive galaxies form by 4-5 mergers since z = 6 - we are also perhaps seeing the earliest galaxy formation

6. CDM models fail to predict the merger history correctly