
Galaxy Mergers at z > 1
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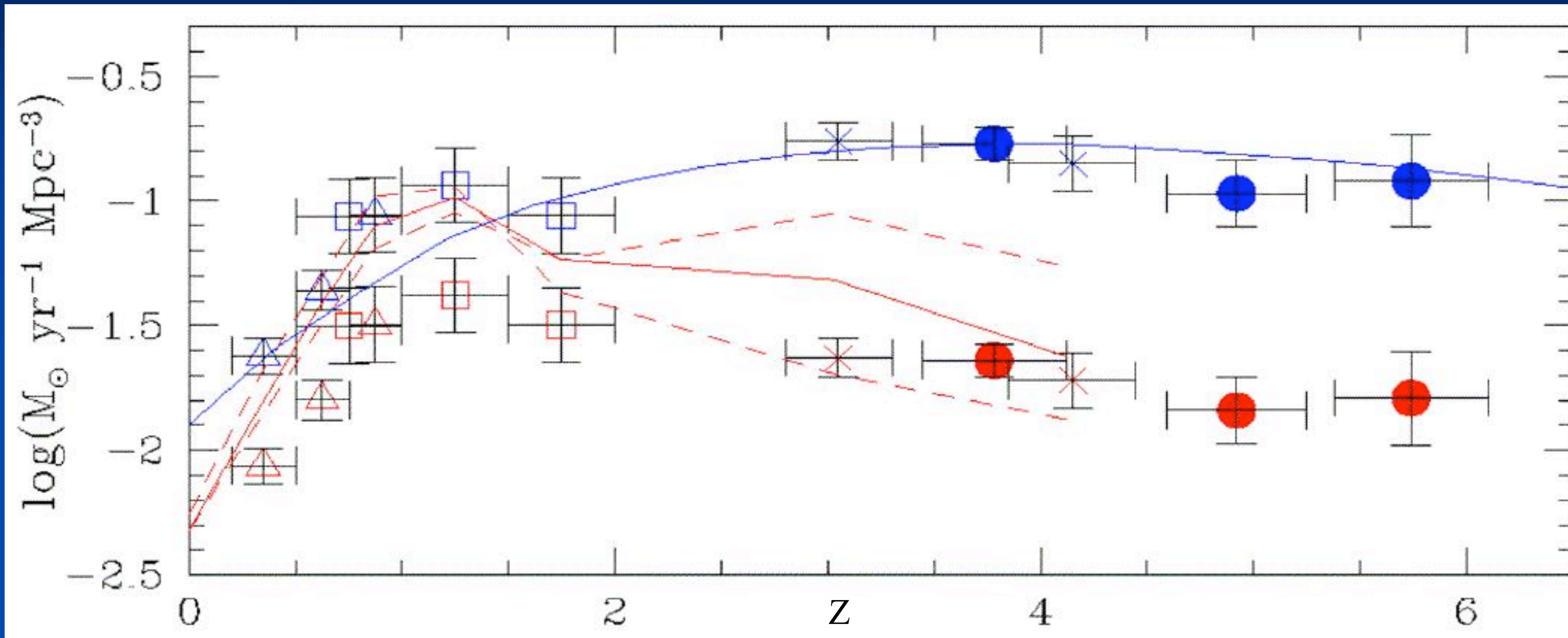
WHAT DO WE KNOW CONCERNING GALAXY FORMATION



Giavalisco et al. (2004)

Star formation is observed to be more common in the past than today – qualitatively consistent with old stellar populations in the nearby universe

This tells us *when* galaxies formed, but not *how*

Do galaxies form through mergers?

I will argue yes (for some)

Galaxy mergers vary however with

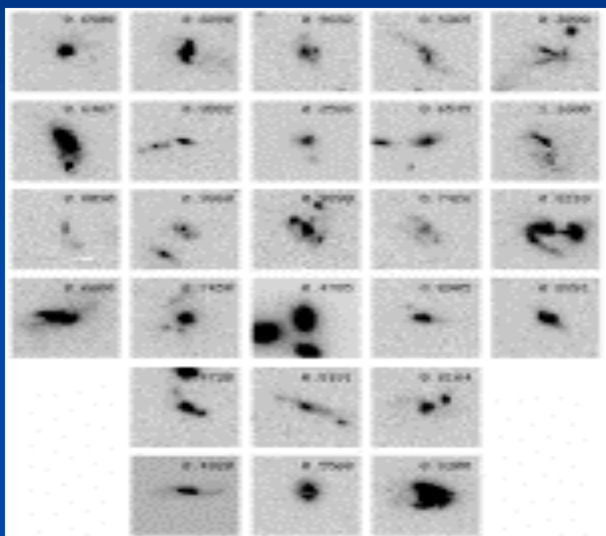
1. Redshift (time)
2. Stellar Mass

..and the merger fraction is not equal to the merger rate

also, galaxy interactions are not the same as galaxy mergers

How do you find galaxy mergers/interactions?

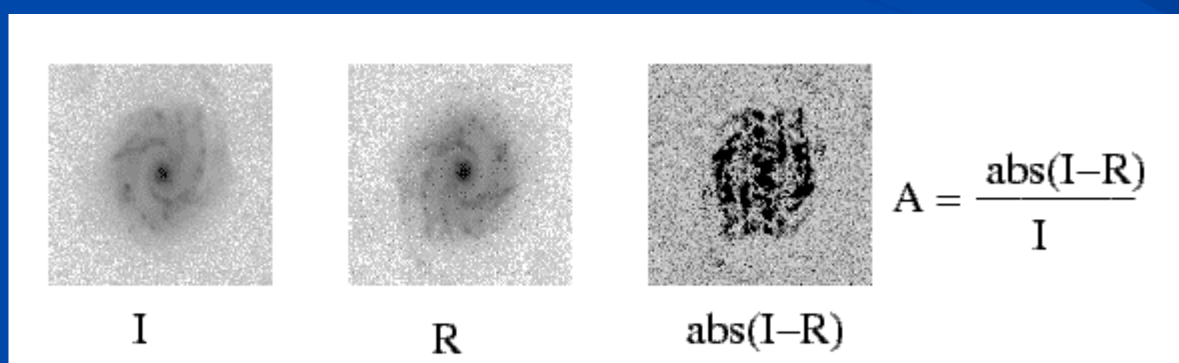
1. Traditional method for finding mergers is to use pairs



LeFevre et al. (2000)

2. Evolution of galaxy clustering

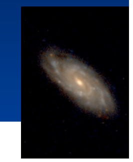
3. Morphological method finds objects that have already merged

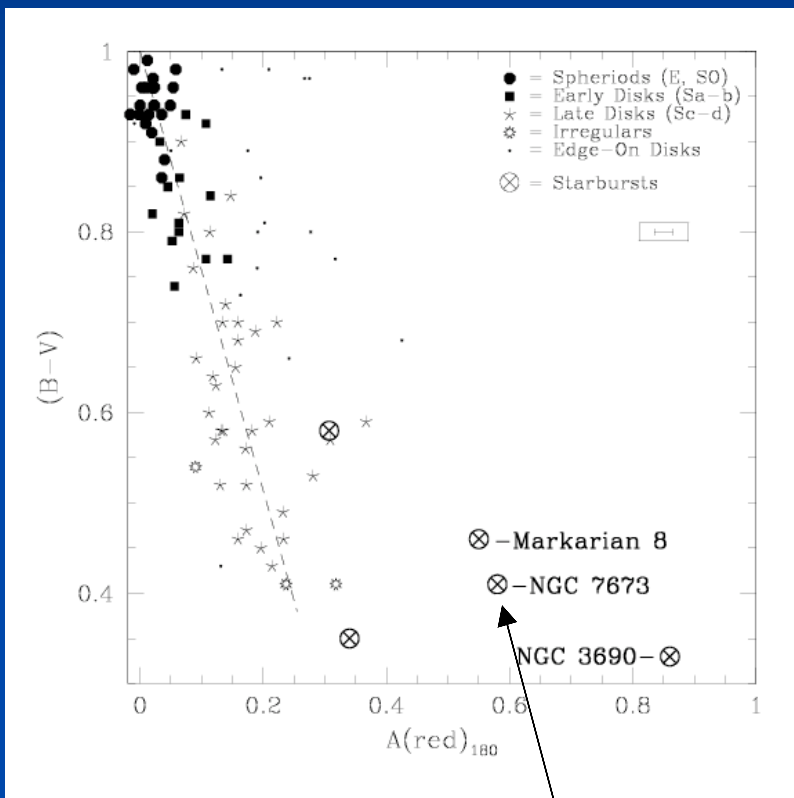


Rotate and subtract and image and quantify the residuals as a number e.g., CAS

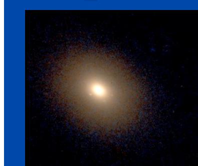
We can use the value of the asymmetry index to determine whether a galaxy is undergoing a merger

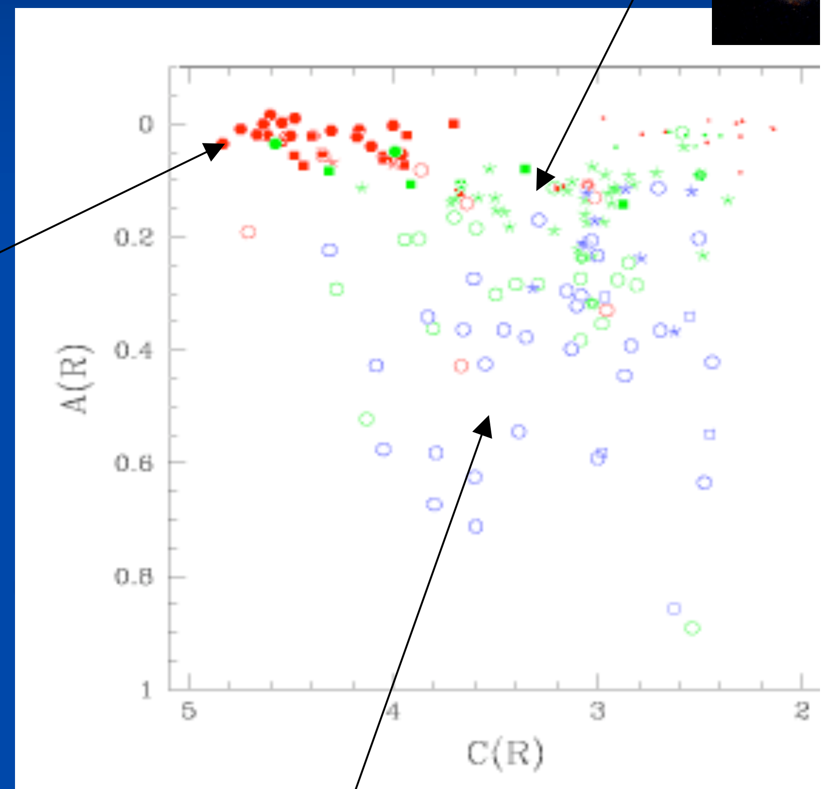
Disk galaxies





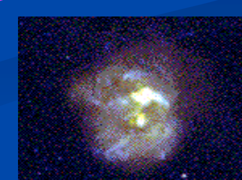
Ellipticals



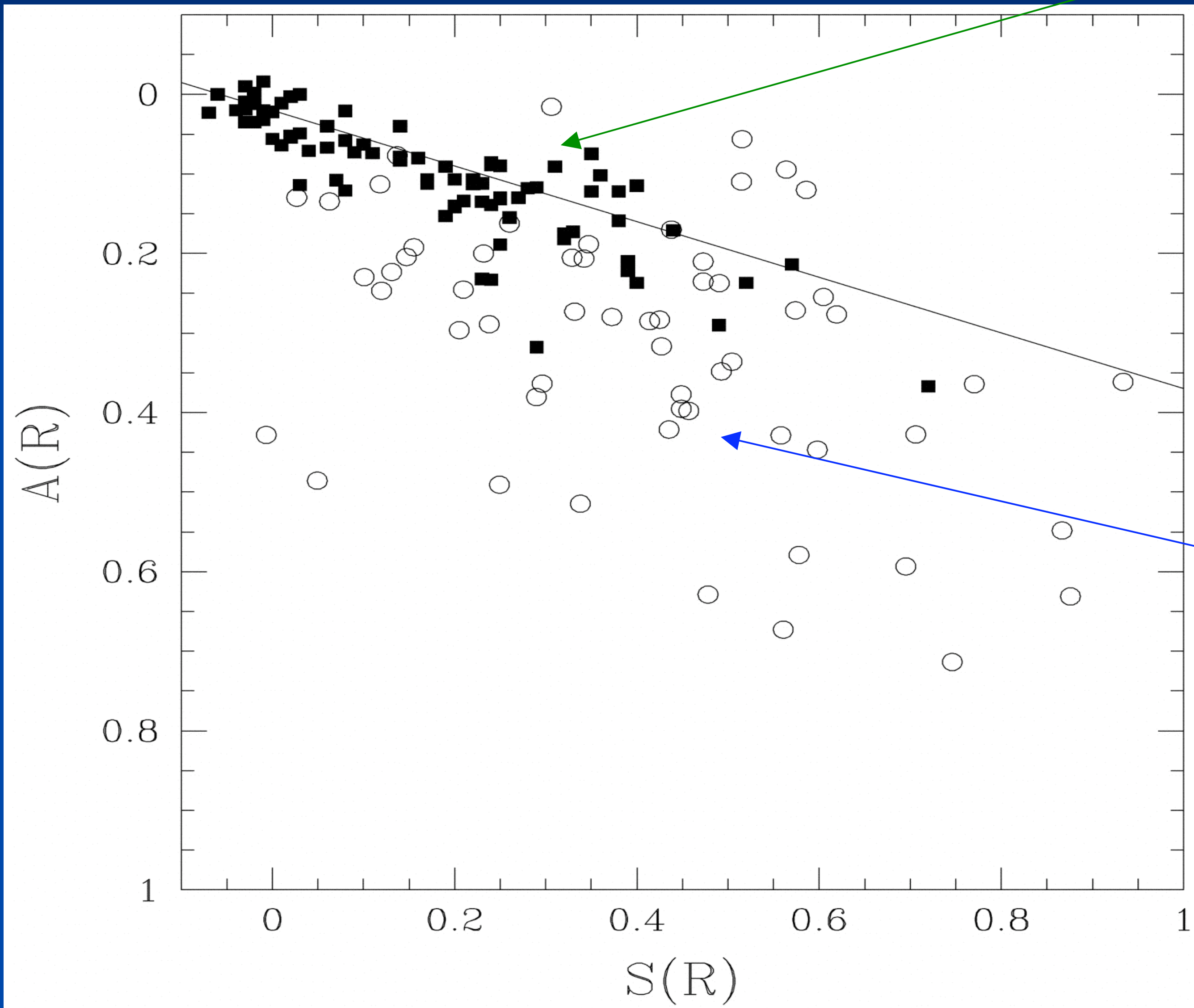


High A(R) galaxies are mergers

High A galaxies with blue colours are merger induced starbursts



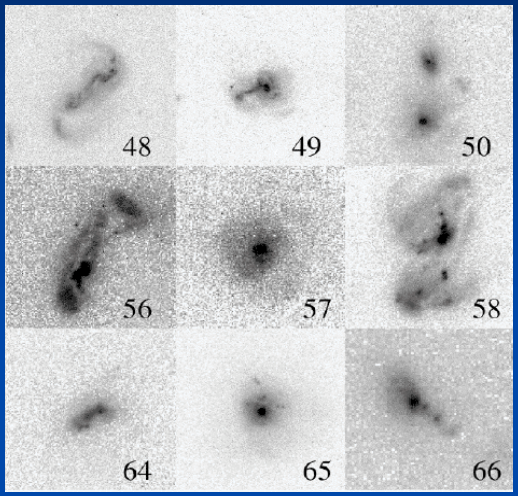
How to identify a merger – asymmetries



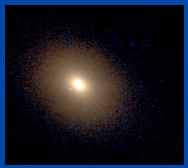
Clumpy light produces asymmetries for normal star forming galaxies

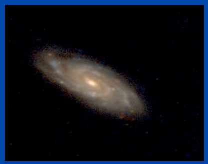
Mergers (open circles) have asymmetries too high for their clumpiness values: produced by bulk asymmetries not small scale ones

Mergers deviate by more than three sigma from S-A relationship

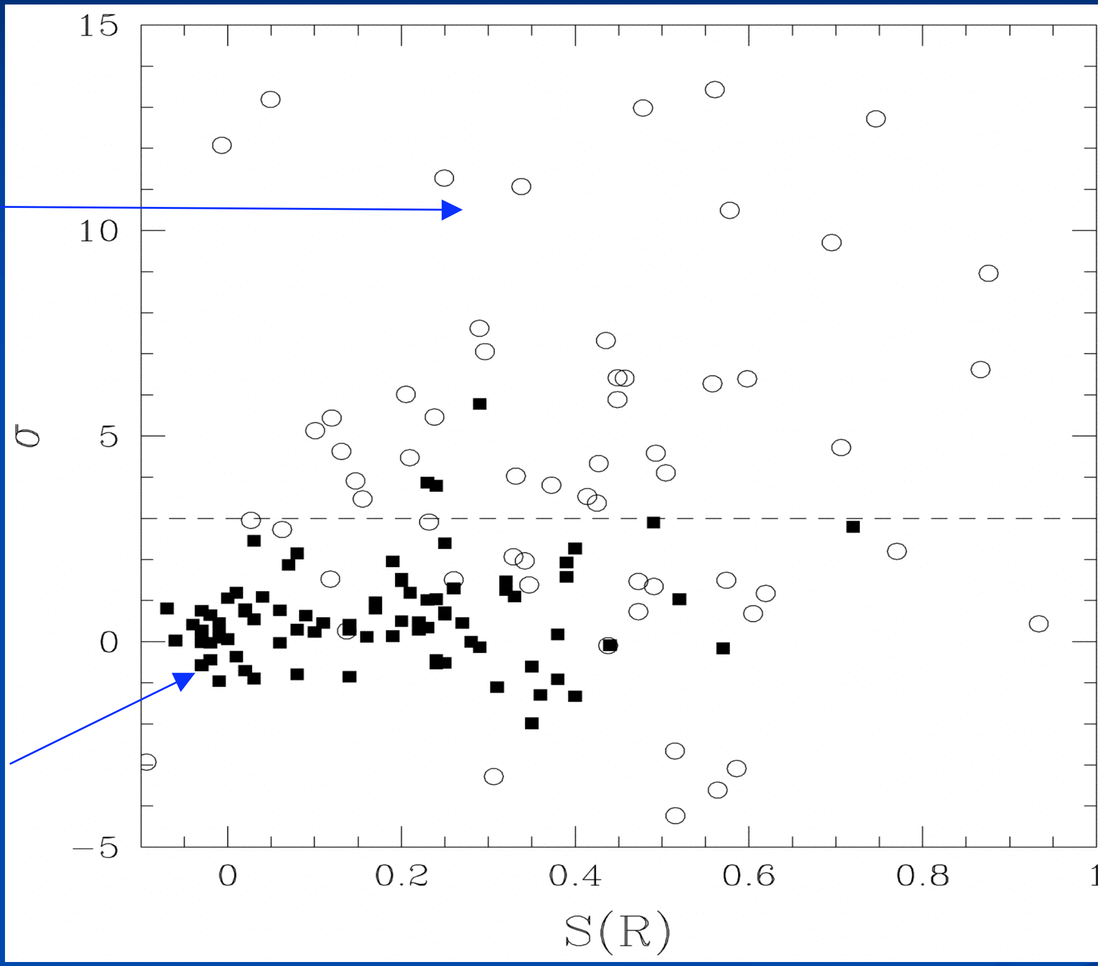


mergers

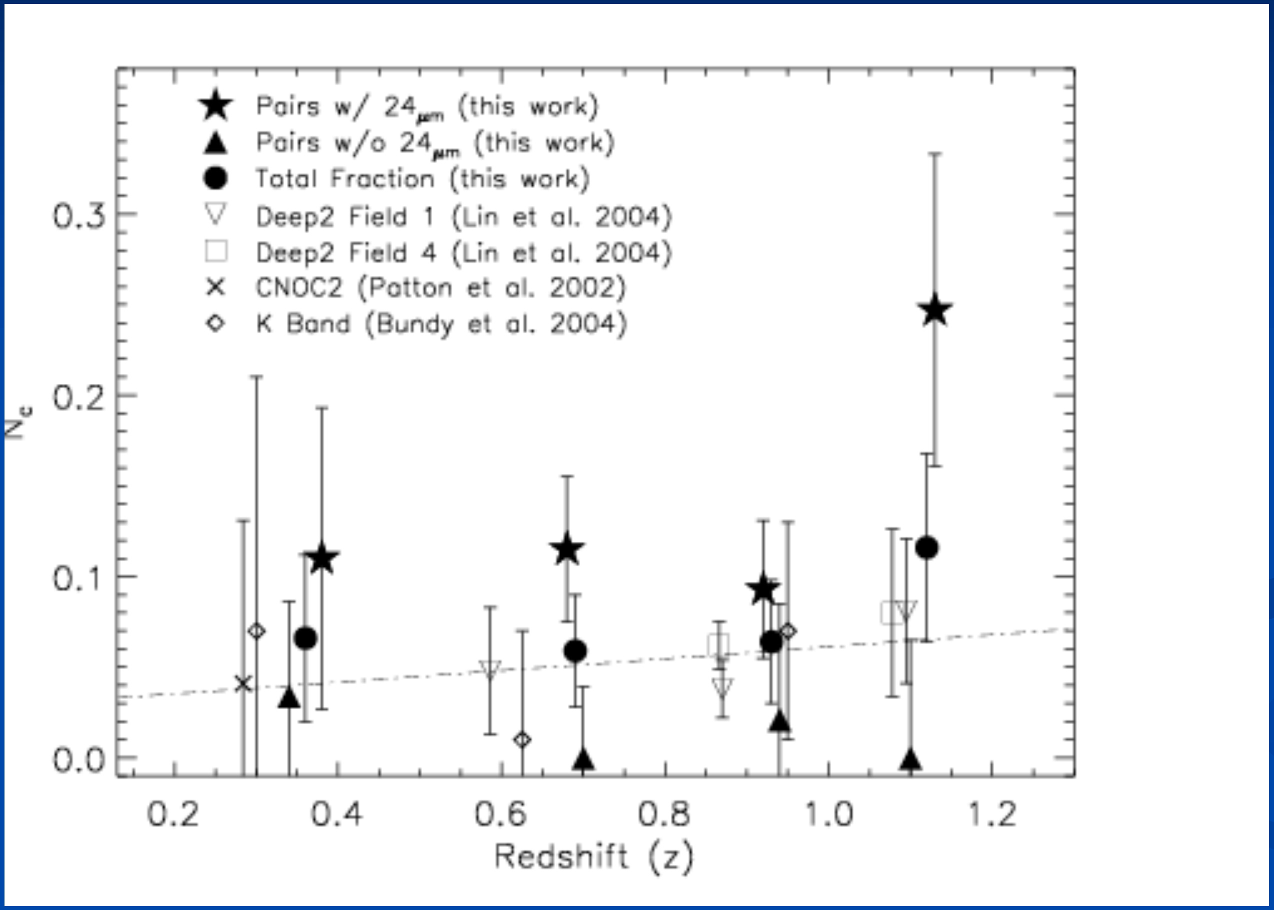




Normal galaxies



What does the history of galaxy interactions look like?



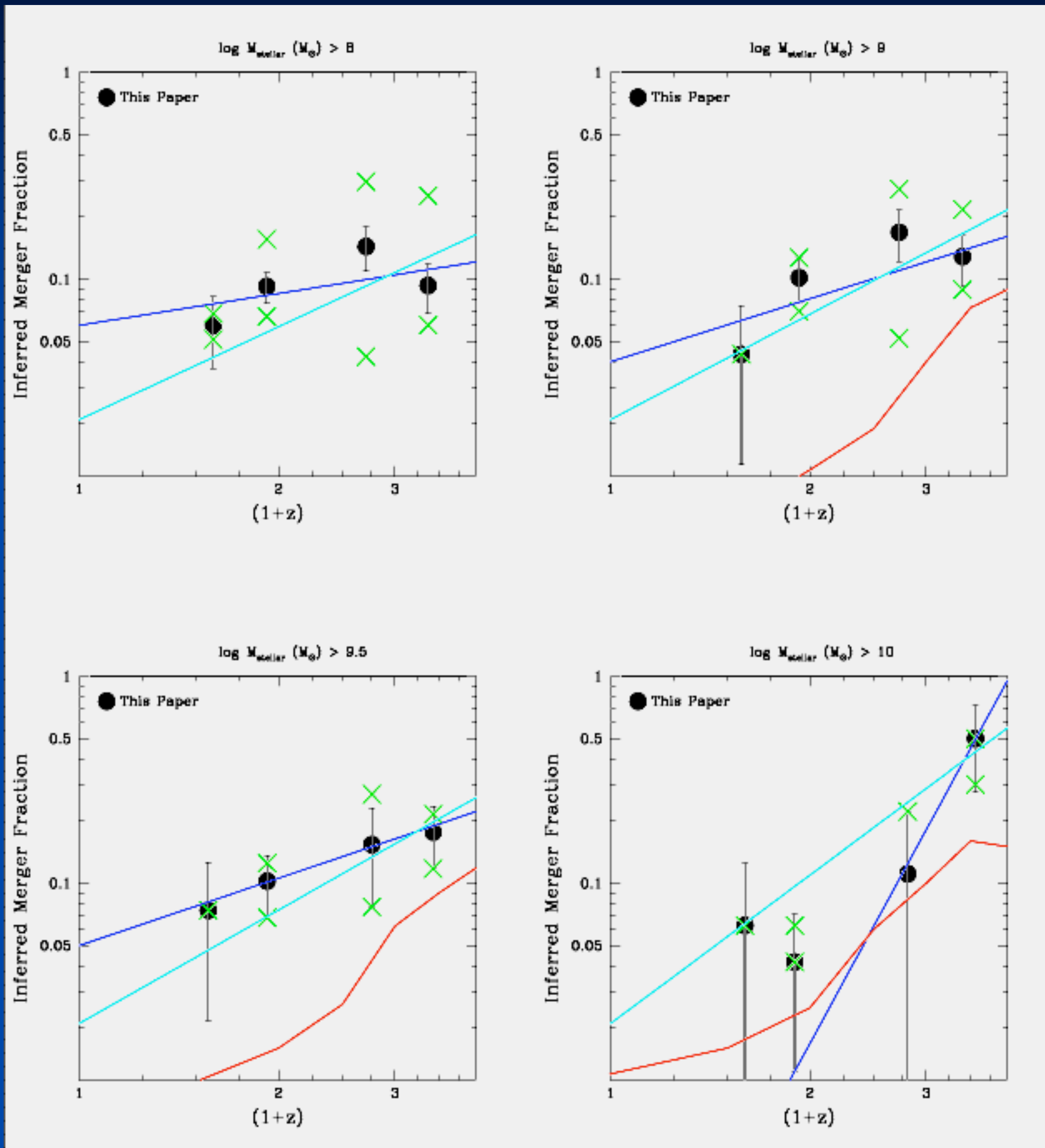
e.g., LeFevr
and Lin
talks

Bridge et al. 2007

Can characterize merger history by looking for physical pairs

Does not show much evolution to z = 1

What about at higher redshift?



Conselice et al. (2003)

Can fit merger fraction evoluti
as a powerlaw

$$fm = f0 * (1 + z)^{m}$$

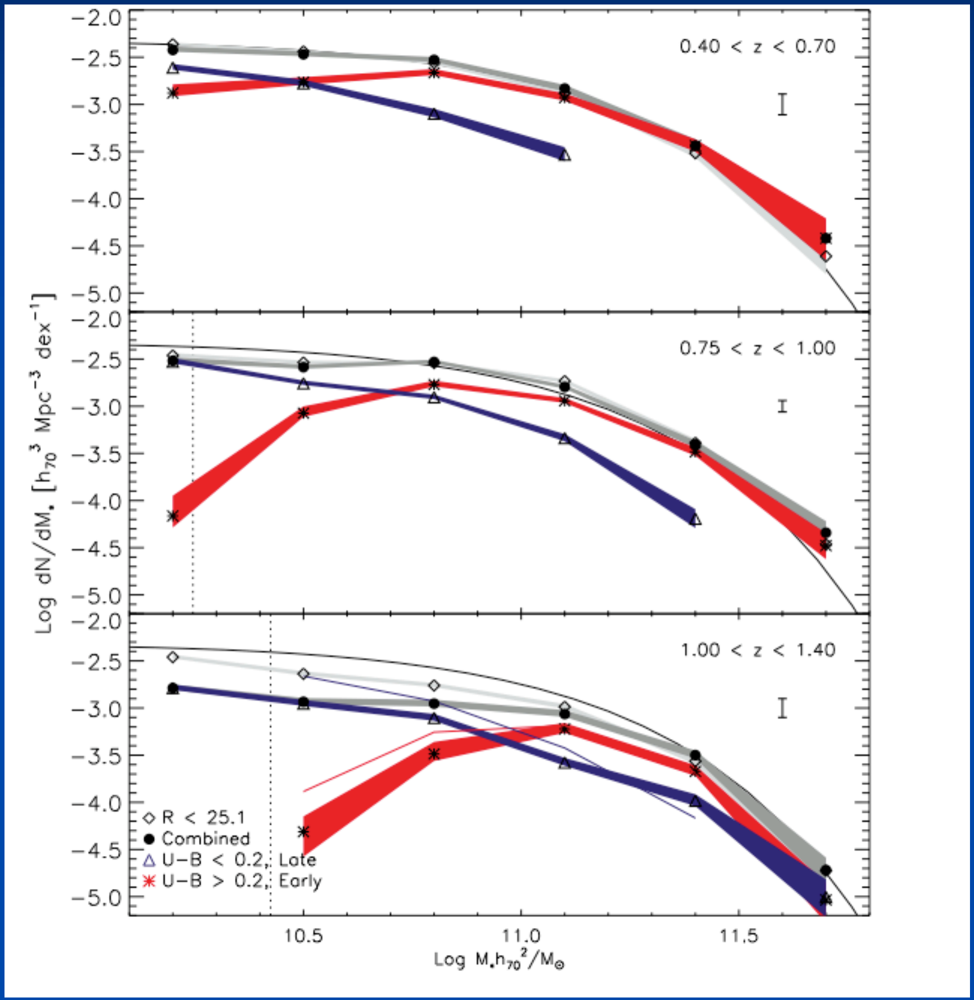
From z ~0 to z~3

For objects with Mb > -21 or
log (Mstellar) < 10 ---- m ~

For objects with Mb < -21 or
log (Mstellar) > 10 ---- m ~

More mergers at
higher (z > 1.5)
redshifts

Stellar Mass Functions



The stellar mass function can
be computed at redshifts up to z~1.4

Using the large area Palomar/DEEP
fields ~2 sq. degree, we find
that the most massive galaxies are
already formed by z~1

The slope of the mass function reve
the total stellar mass density, and ho
it has evolved

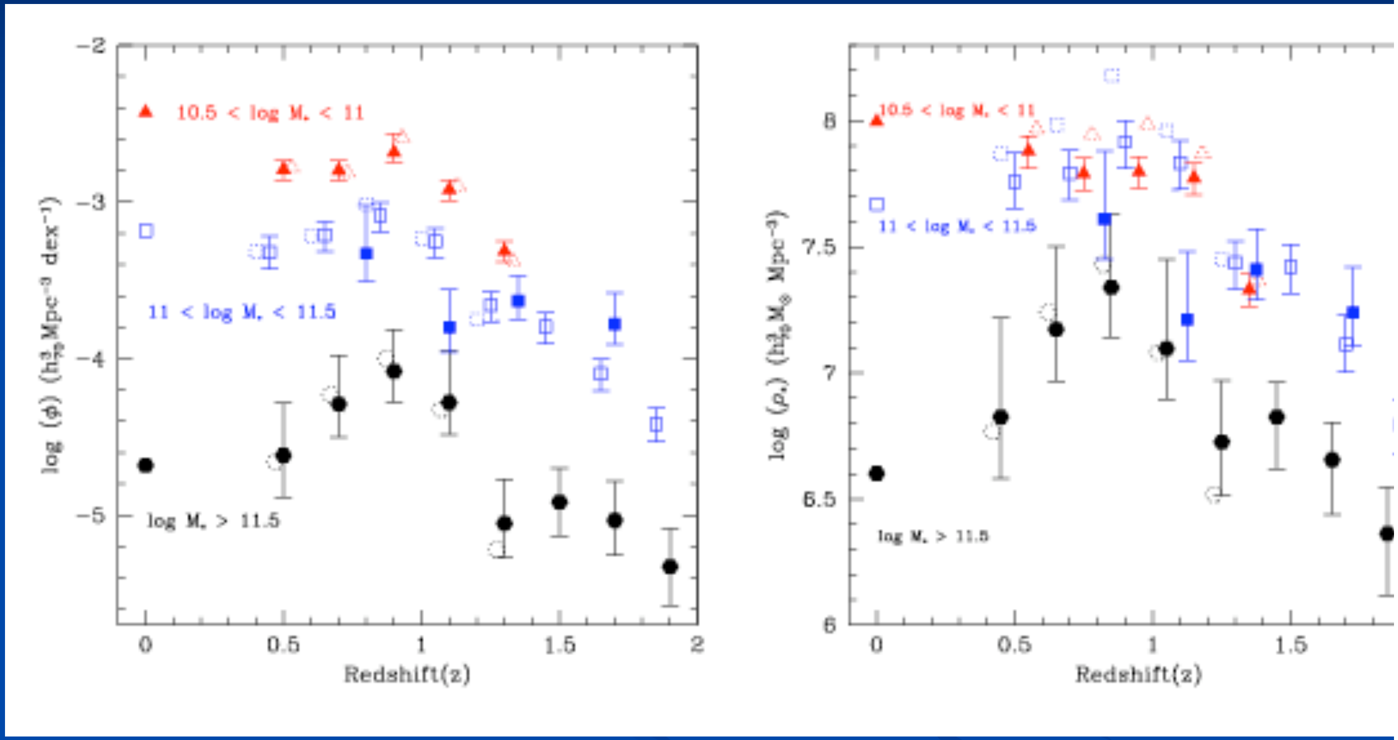
Bundy et al. (2006)

Evolution of the number densities for galaxies of various masses

The most massive galaxies are formed by z~1.5

11 < log M < 11.5 systems grow by a factor of ~5 since z~1.5

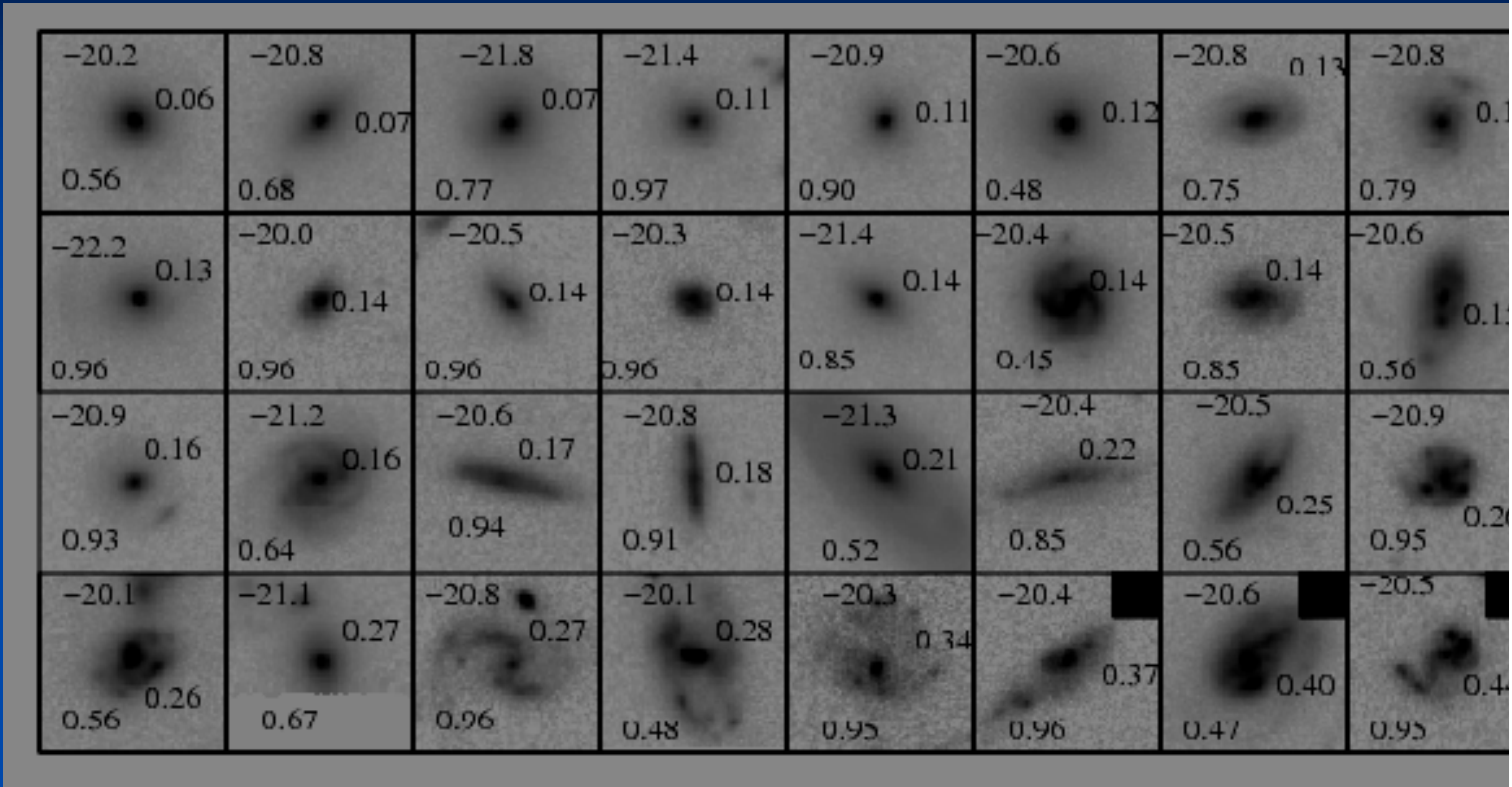
10.5 < log M < 11 systems grown by a factor of ~12 since z~1.5



Cole et al. (2001) z~0 comparison

Conselice et al. (2007

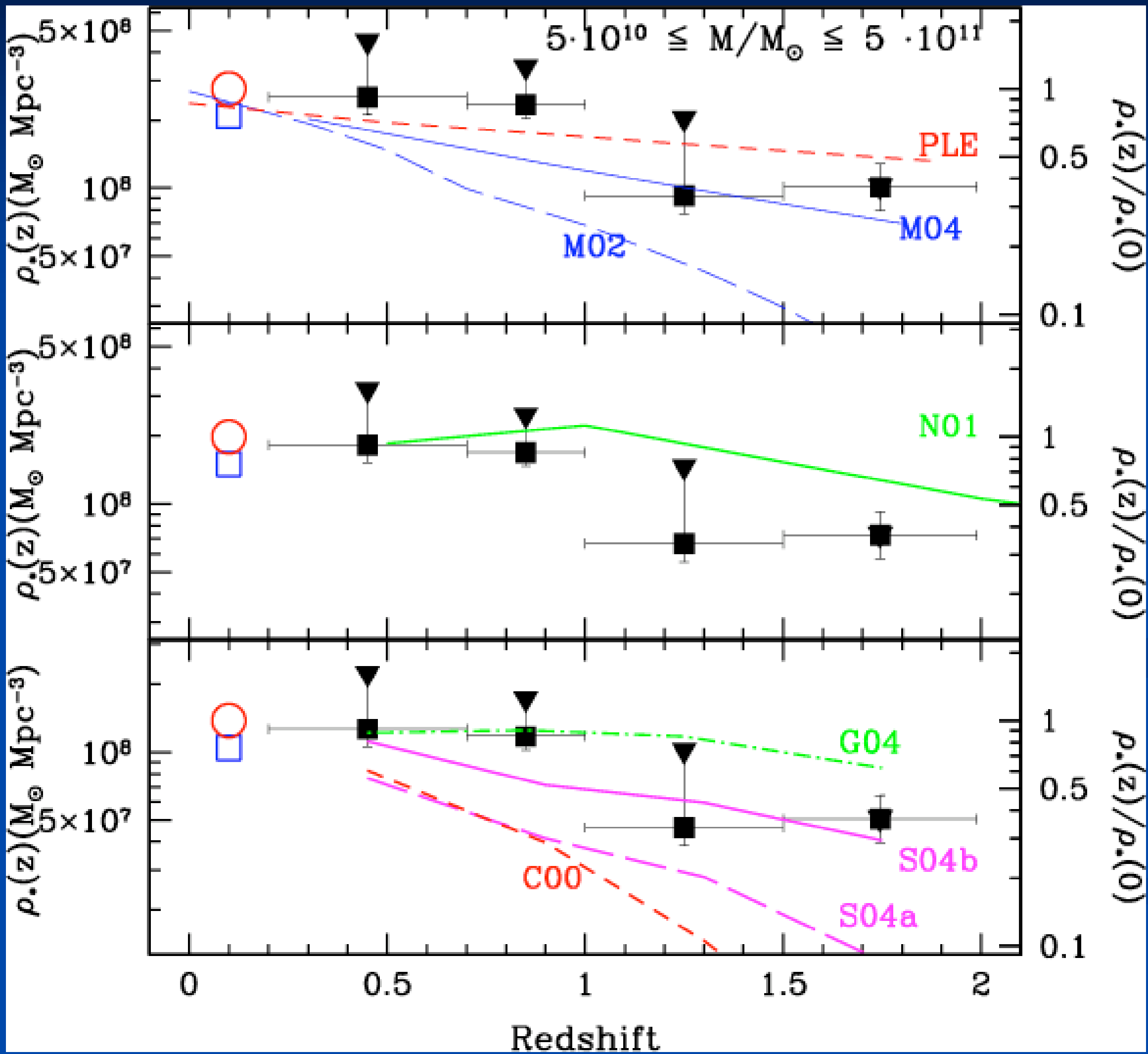
Shown to be the case morphologically as well



Galaxies at z < 1

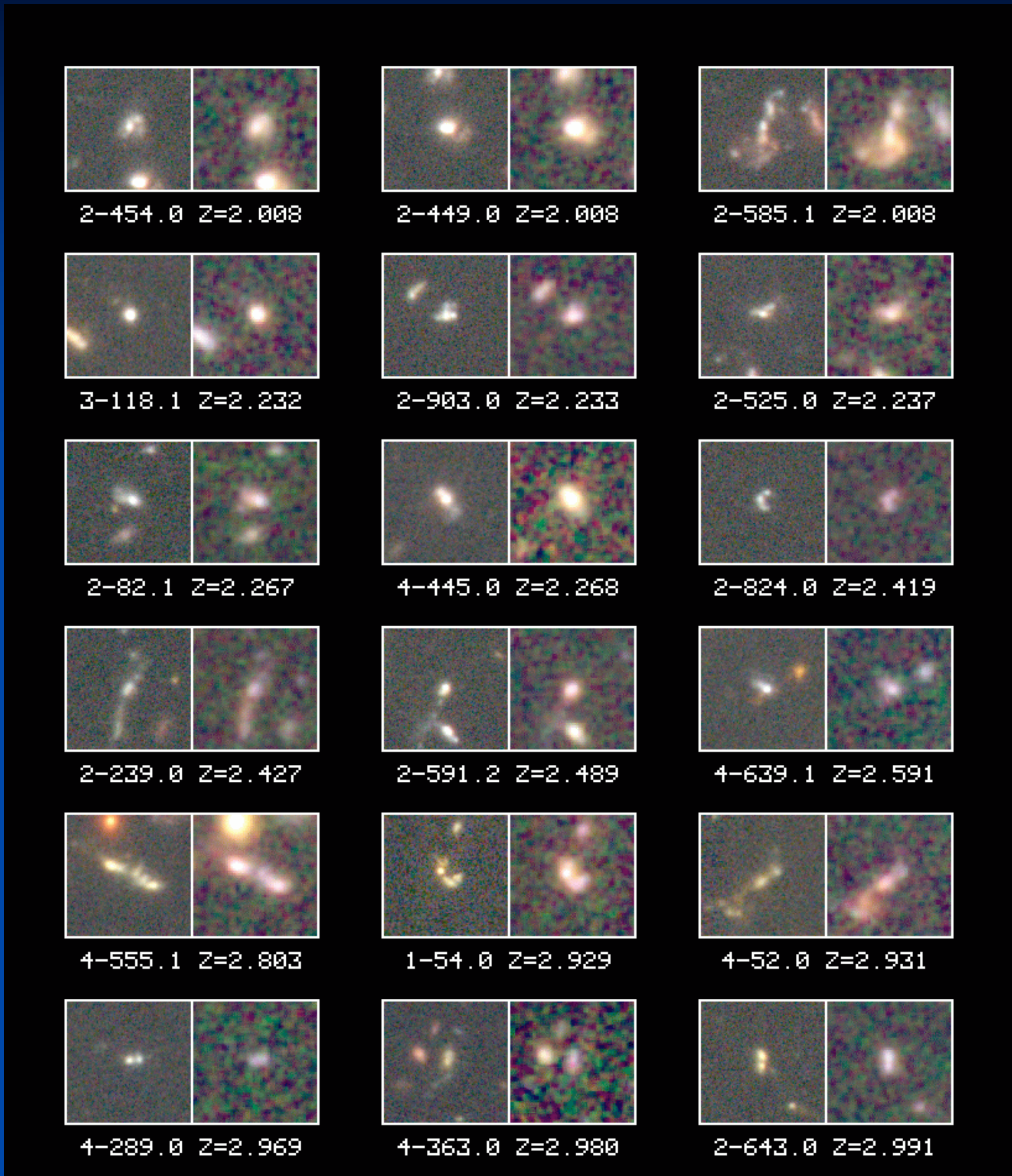
Hubble Sequence in place

WHAT ABOUT AT Z > 1.5?



Fontana et al. 2004

Mass density for the most massive galaxies drops quickly at z > 1



Dickinson et al. (2000)

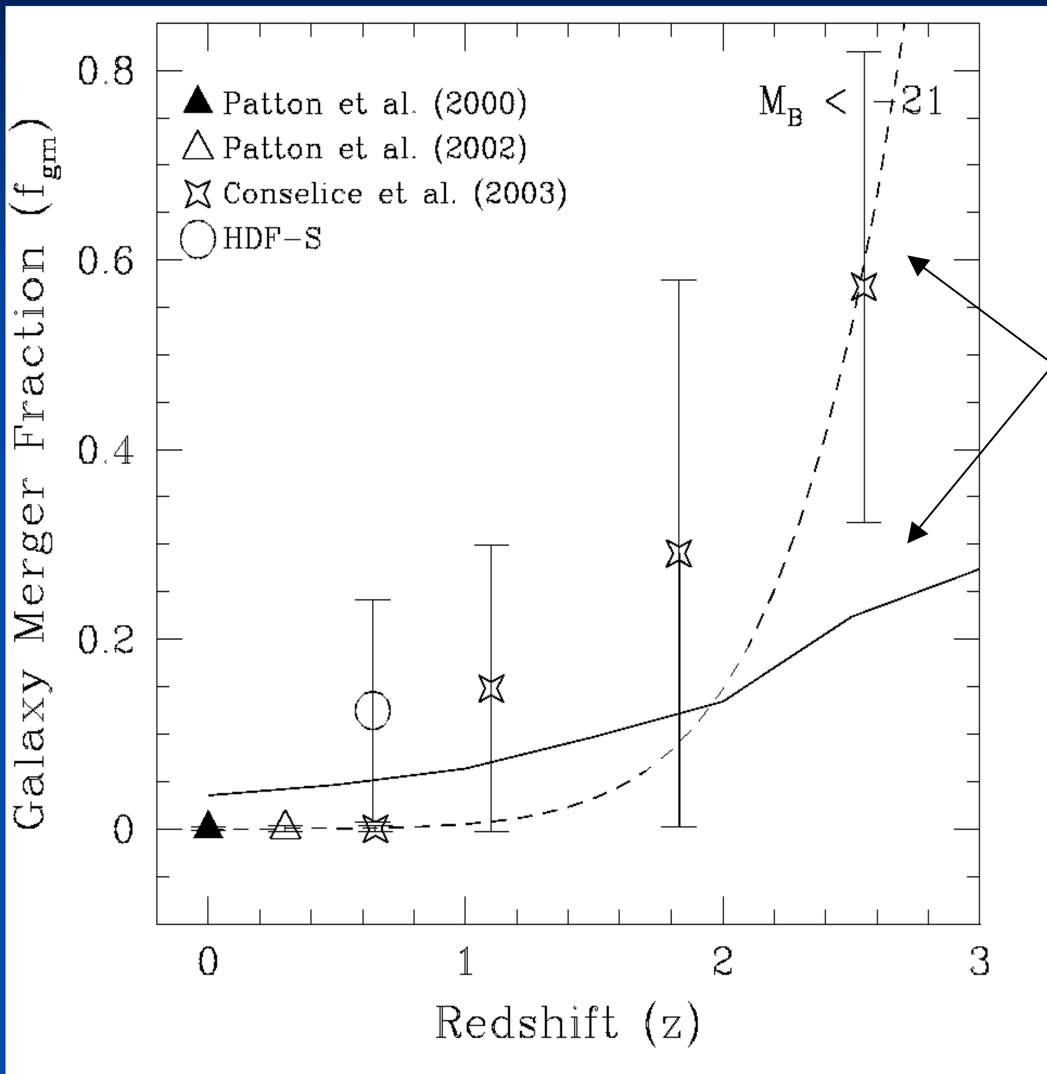
Galaxies at z > 2 in HDF-N

Rest-frame optical view
with NICMOS

The most massive galaxies at z > 2 appear very peculia

These systems appear to be merging

Can use the number of mergers at various redshifts to determine the history of merging



CDM semi-analytic model predictions from Benson et al. (2002

Merger fractions computed as a function of redshift and upper magnitude limit

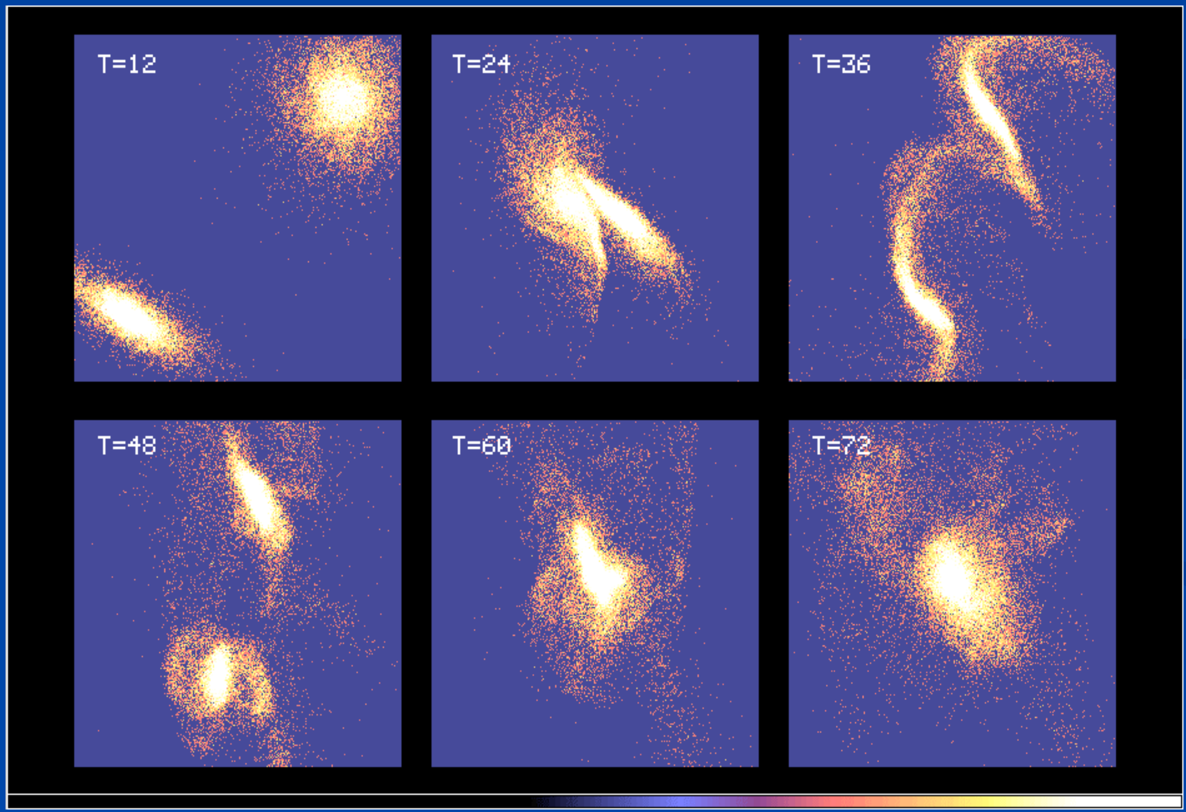
The brightest and most massive galaxies are those undergoing the most merging at high redshift with 60% involved in a merger

Conselice et al. (2003); Conselice (2006)

N-Body models: Useful for verifying that mergers can be identified morphologically, and for establishing mass and time-scale sensitivity

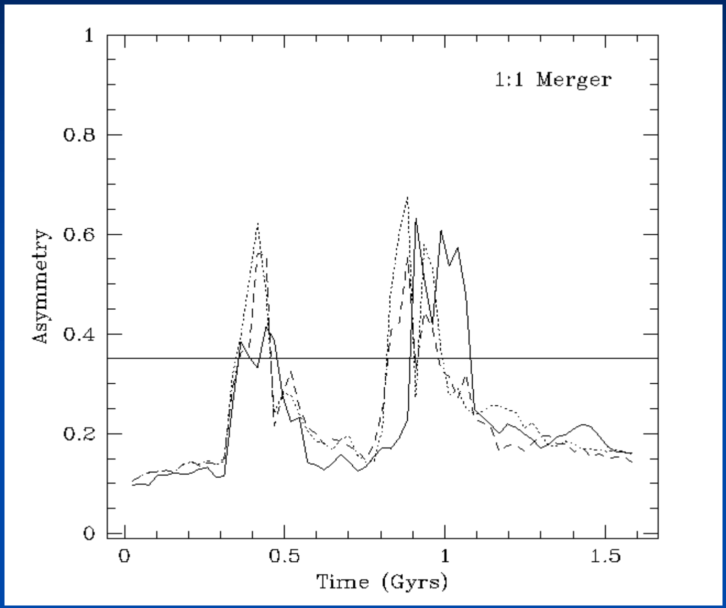
1:1 merger simulation

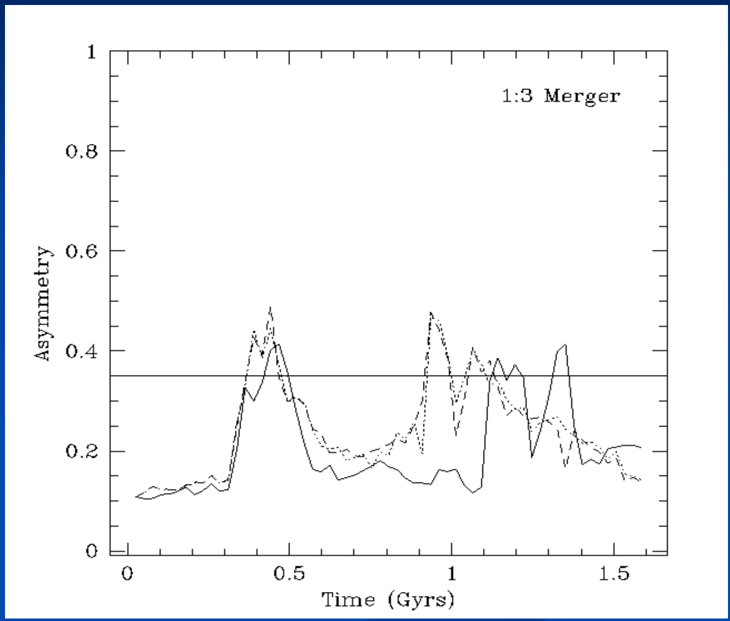
From
C. Mihos



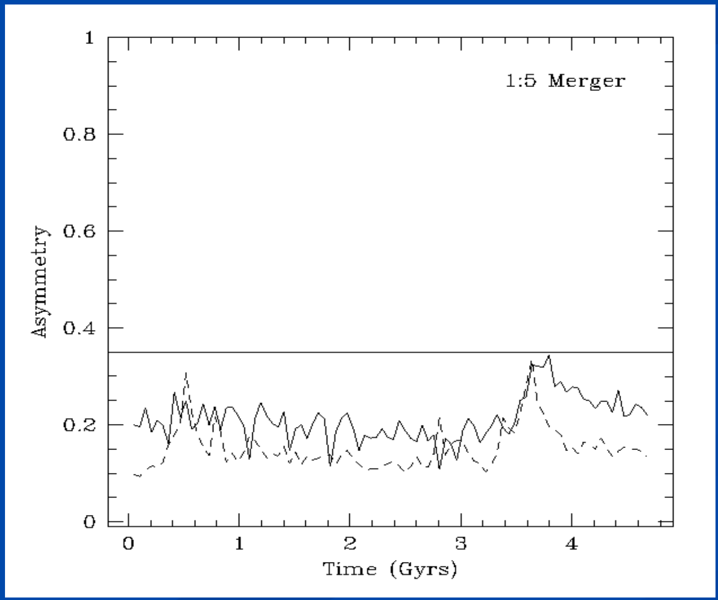
Total time of simulation is roughly 1.5 Gyrs

Evolution of the asymmetry parameter in 1:1, 1:2 and 1:5 mass ratio mergers



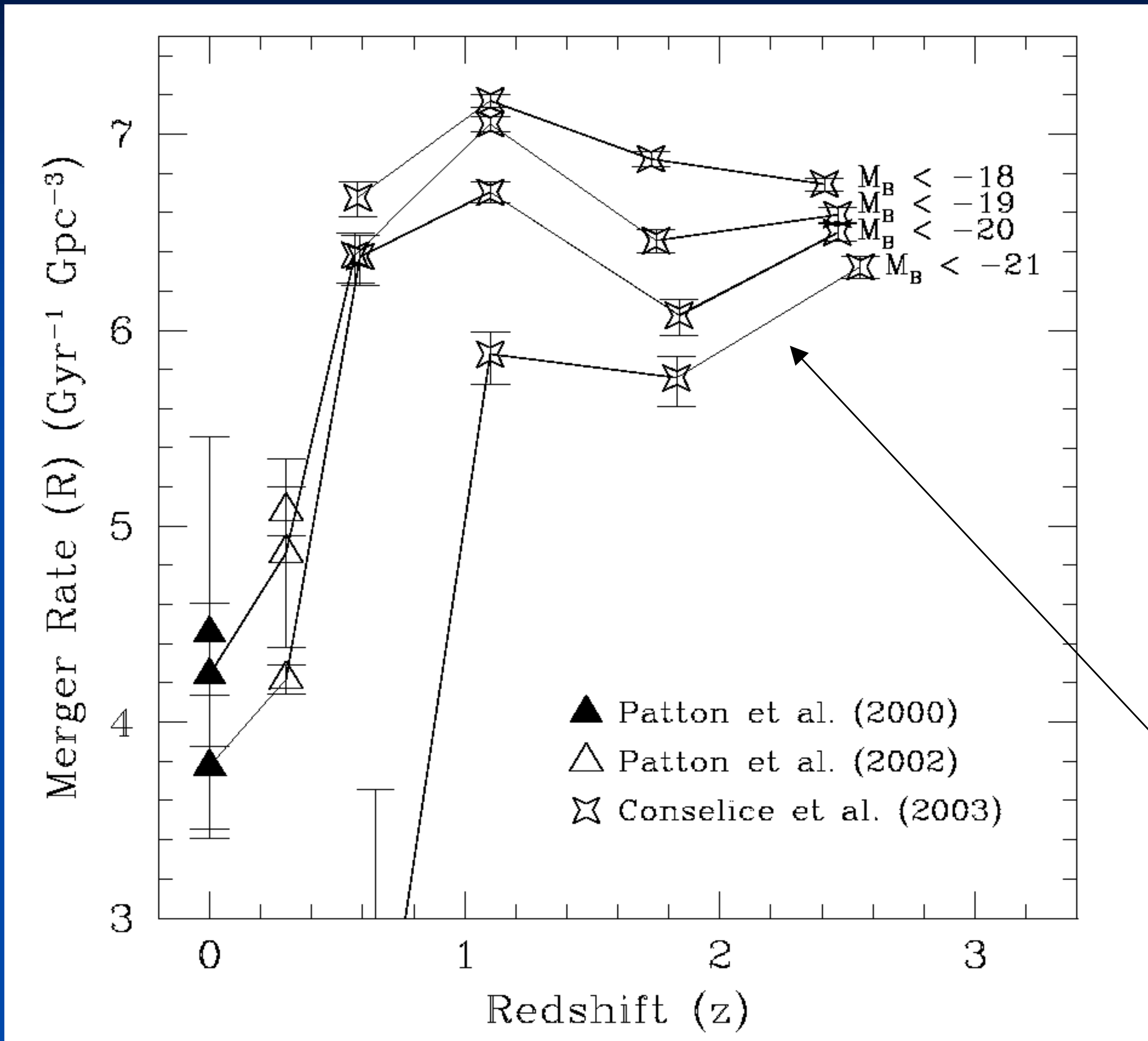


Only simulated mergers with mass ratios of 3:1 or less produces an asymmetry signal



A merging galaxy remains asymmetric enough to be counted as a merger for 300 Myrs – places a time scale on the merger process

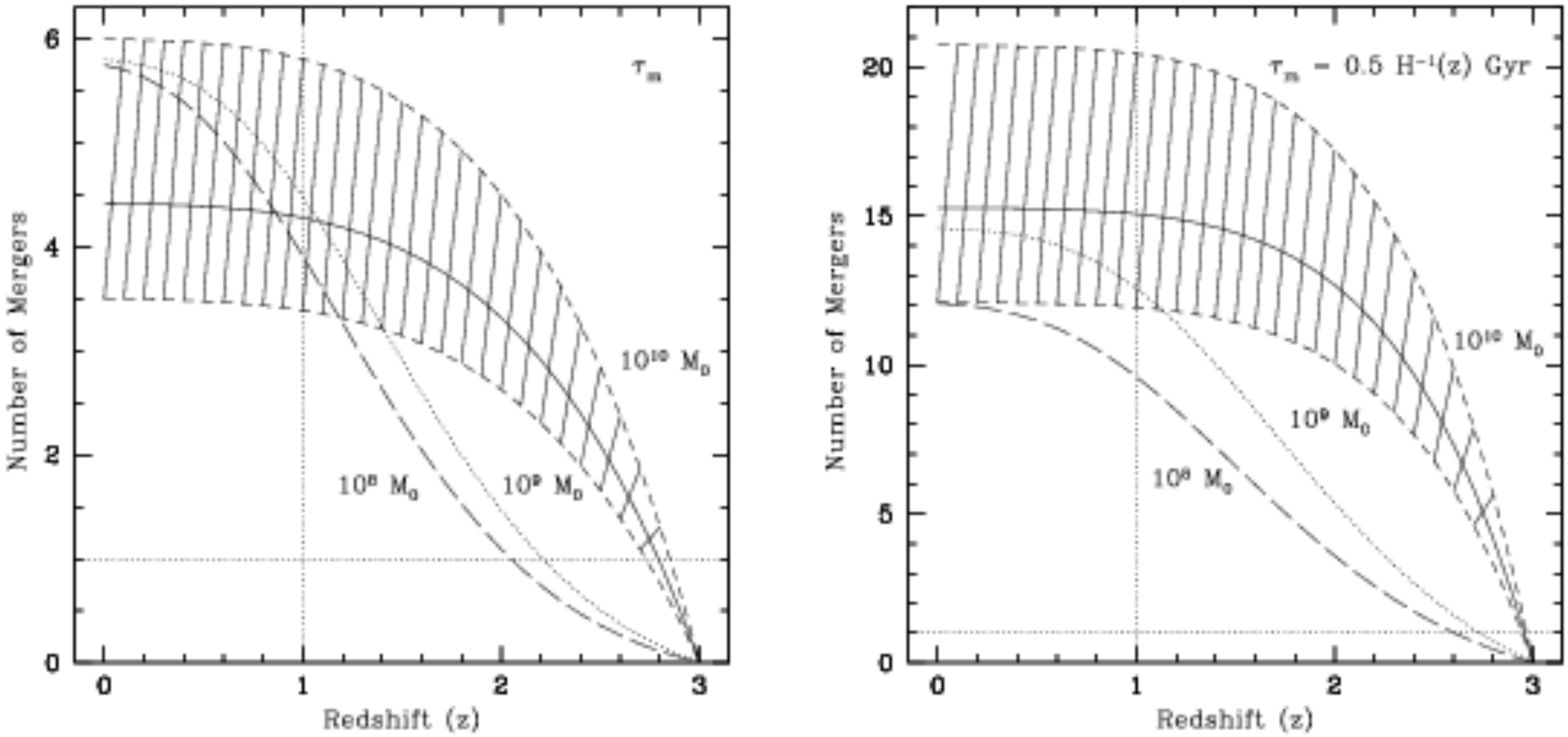
Merger Rates



From the merger time scale, we can compute the merger rate – that is the number densities of mergers occurring pe unit time as a function c redshift

Merger rate is high at z > 1, but declines rapidly at lower redshifts. Consistent with an early formation of galaxies and a lambda dominated universe

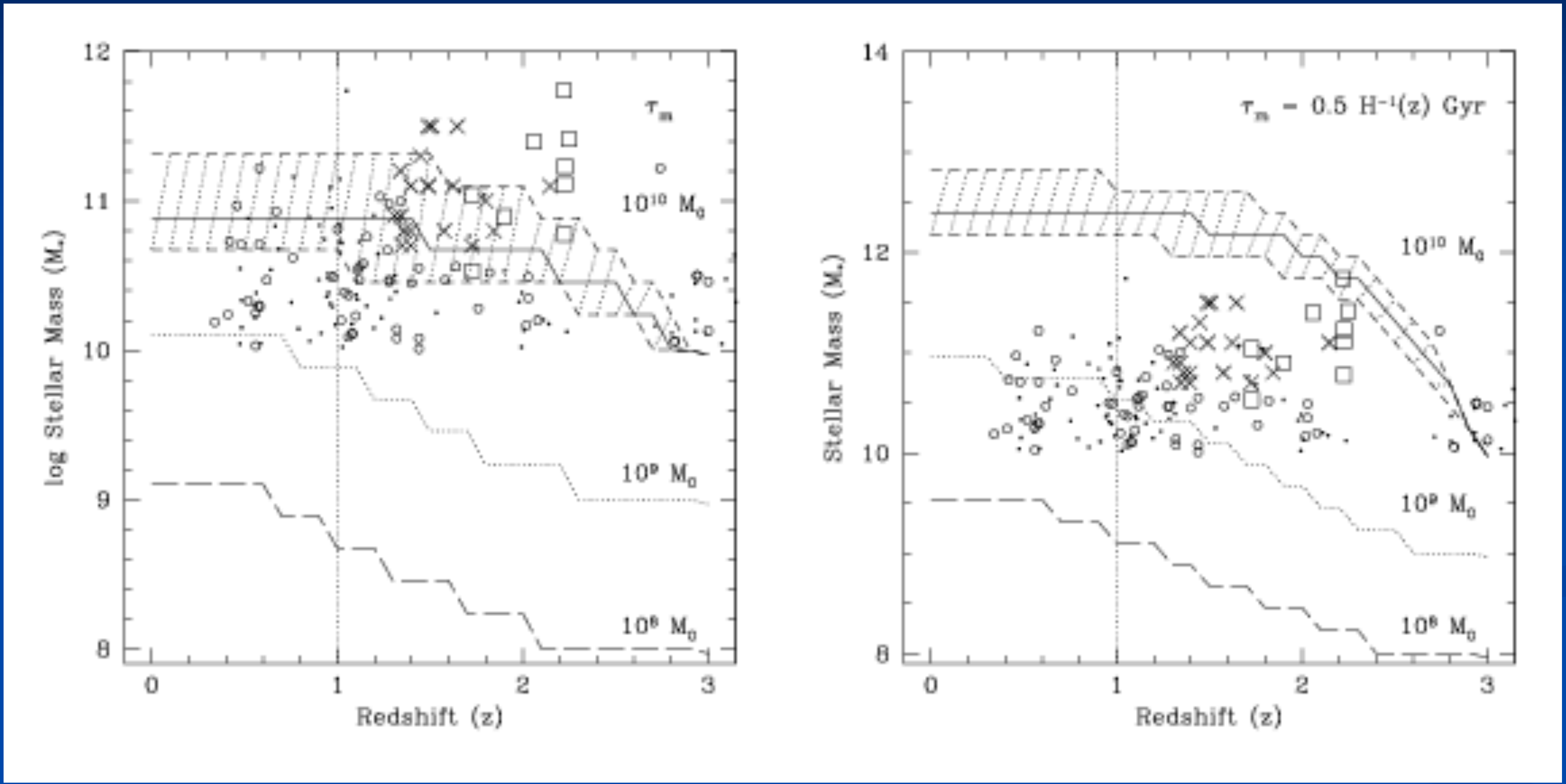
From the merger rate, can calculate the average number of mergers a typical galaxy at z~3 undergoes before it reaches z~0



$$N_{\rm m} = \int_{z_1}^{z_2} \frac{f_{\rm gm}(z)}{\tau_{\rm m}} {\rm dt} = \int_{z_1}^{z_2} t_H \left(\frac{f_0}{\tau_{\rm m}}\right) (1+z)^{\rm m_A - 1} \frac{\rm dz}{{\rm E}(z)}$$

On average, a massive z~3 galaxy undergoes $4.4^{+1.6}_{-0.9}$ major mergers

The mass accretion history can also be calculated by adding in star formation produced by the merger and the mass from the merger

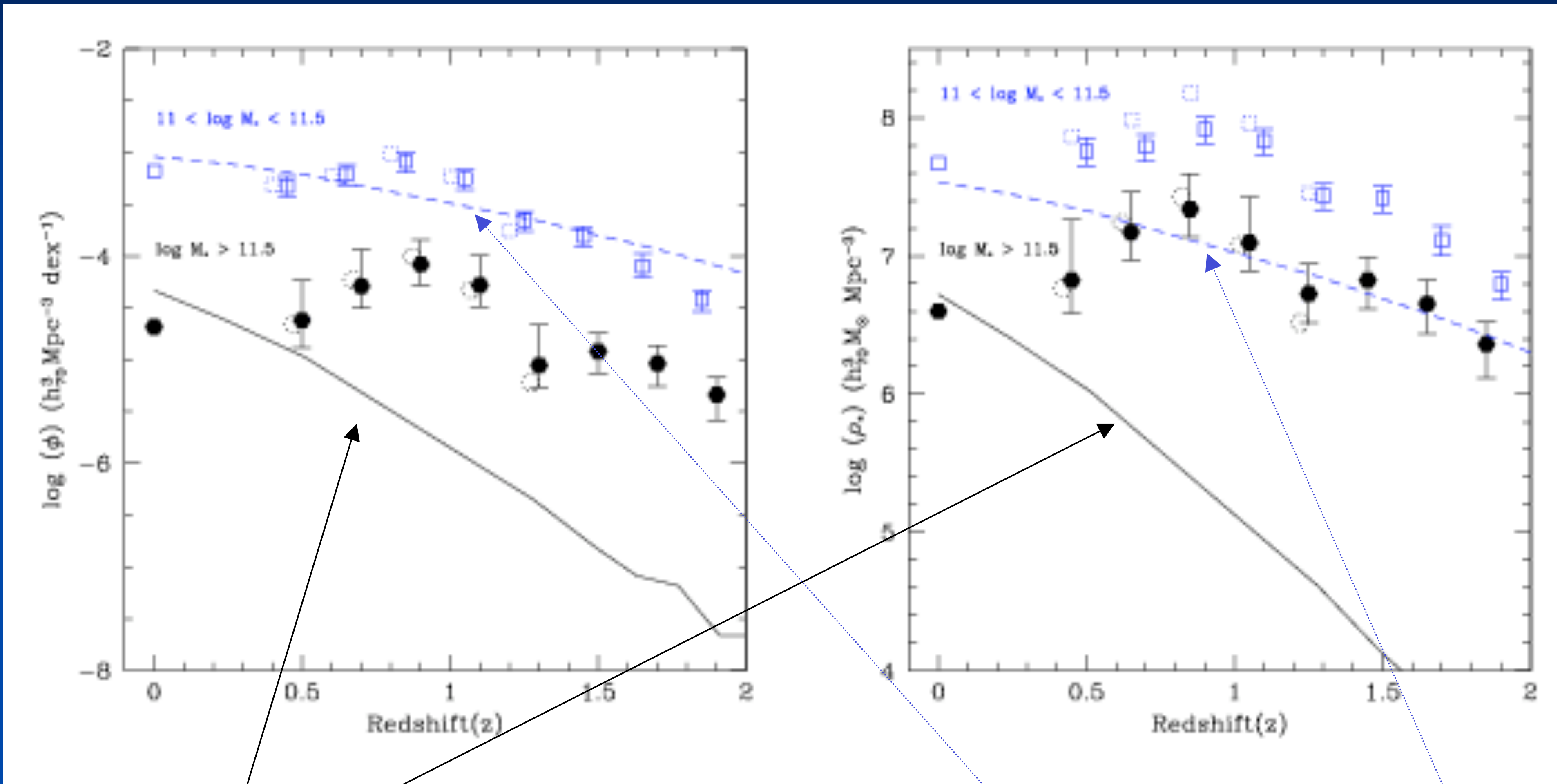


$$\delta M_{msf} = \int_{z_1}^{z_2} \int_0^{t_m} t_H \left(\frac{f_0}{\tau_m}\right) (1+z)^{m_A - 1} \frac{dz}{E(z)} \times \Psi_0 \exp(-t/\tau_{sf}) dt$$

z~3 galaxies increase in mass by a factor of ~10– enough to become today's massive galaxies

Conselice (2006)

Comparison to semi-analytic "Millennium" simulation



Prediction for log M > 11.5

Prediction for 11 < log M < 11.5

Conselice et al. 2007, submitted

In the future…

Must probe higher redshifts to see the bulk of the formation of massive galaxies.

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

We will examine:

Sizes of massive galaxies at $z > 2$

Structure and morphologies - merging, etc

Data being taken now, and is made public immediately

Summary

1. The merger and interaction history for galaxies can be measured using several independent methods

2. Peculiars at high redshift are likely ongoing mergers and massive galaxies appear to form by these mergers at $z > 1.5$, while lower mass galaxies merge at later times - consistent with their later stellar mass formation

3. A typical massive elliptical in today's universe will have undergone 3-5 major mergers since $z \sim 3$

4. Models cannot reproduce the formation of massive galaxies - underprediction of merger rate at high redshift?