Populations of Galaxies and their Formation at z < 7

Christopher J. Conselice
(Caltech)

Facing the Future: A Festival for Frank Bash

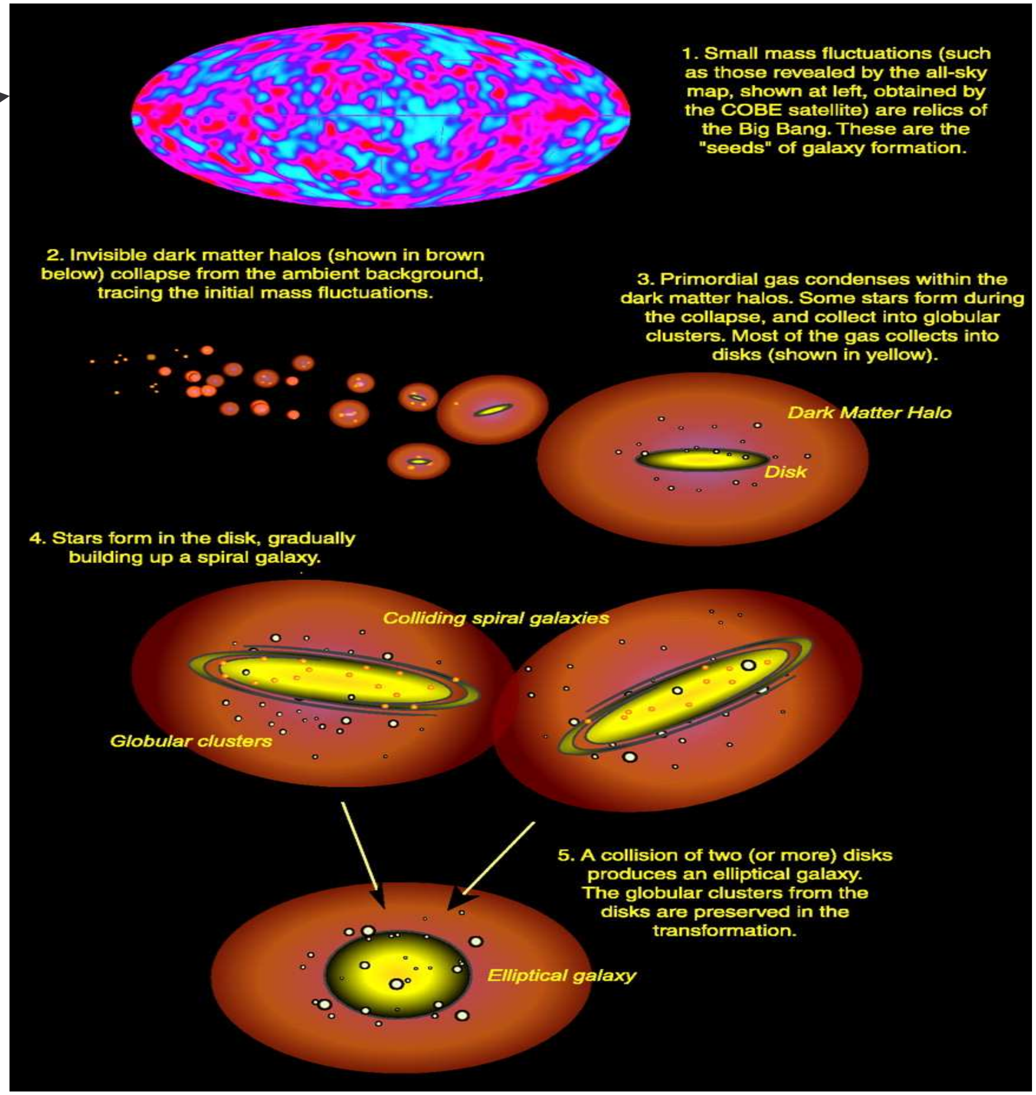
Austin, October 18, 2003

Motivation

The basic idea behind galaxy formation – objects start small and grow by merging

CMB

Low–mass galaxies



Star formation

mergers

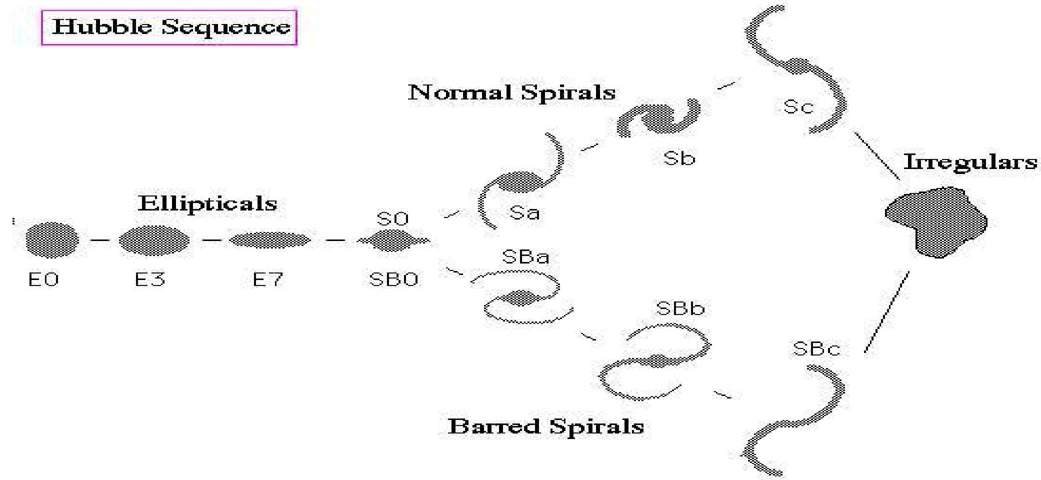
Specific questions and our understanding of them

	grade
1. When did the first galaxies form?	C
2. When did the bulk of the galaxy population form?	B
3. What physically drove the formation of galaxies?	B
4. What is the end product of galaxy evolution at $z = 0$?	A
5. How well do models predict these observations?	B

Key: A = understand with good confidence
B = known something, but more to be done or outstanding problems
C = have little or no observations

Nearby Universe

98% of all nearby bright galaxies can be placed into a Hubble type



Hubble types are the z = 0 final state of bright galaxy evolution

Ellipticals have old stellar populations, spirals have both old and young components while irregulars are dominated by young stars

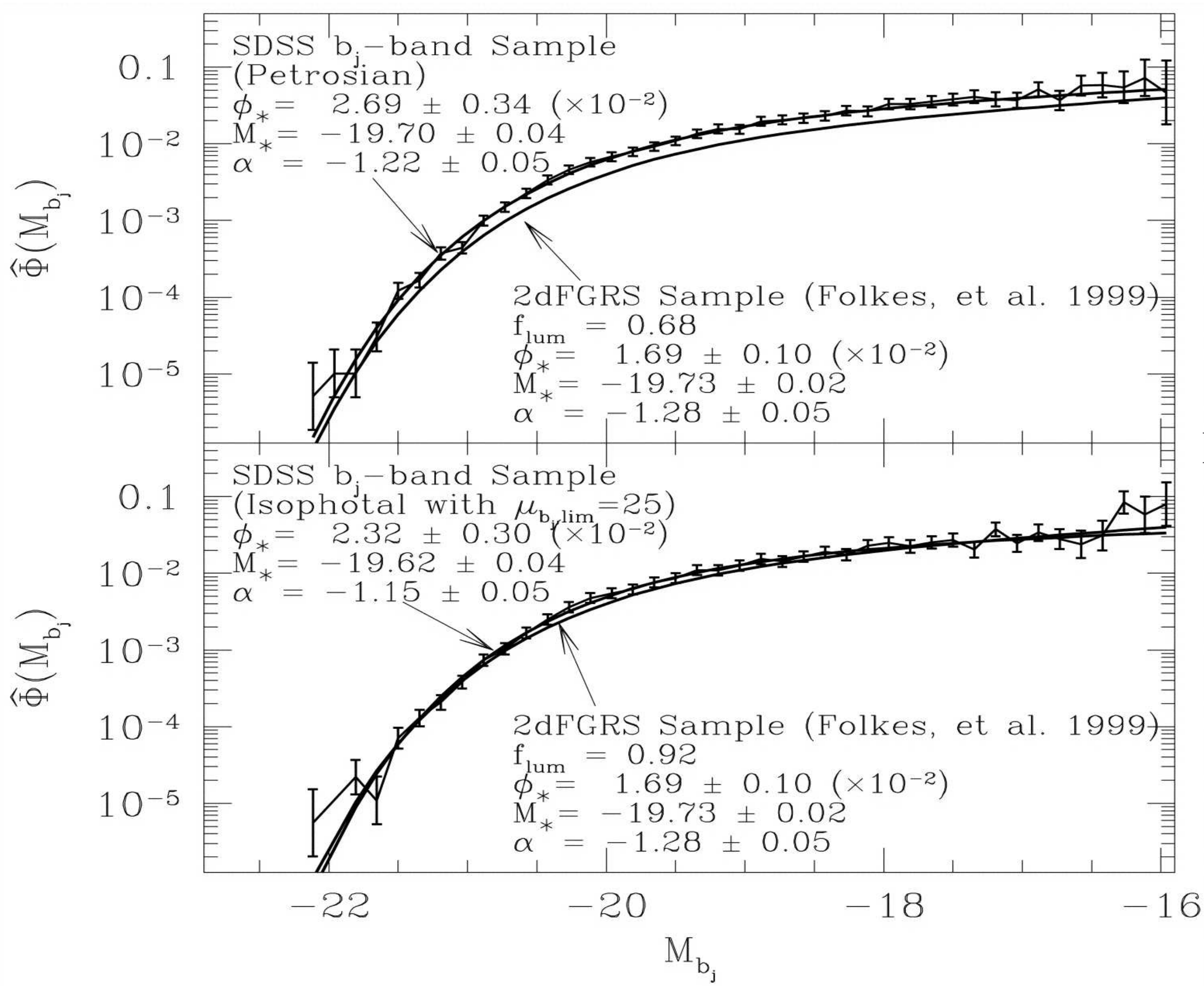



Old stars

Young stars

A significant amount of star formation must have occurred in the past for Es, but young stars clearly exist in spirals

Luminosity Function of Nearby Galaxies from SDSS

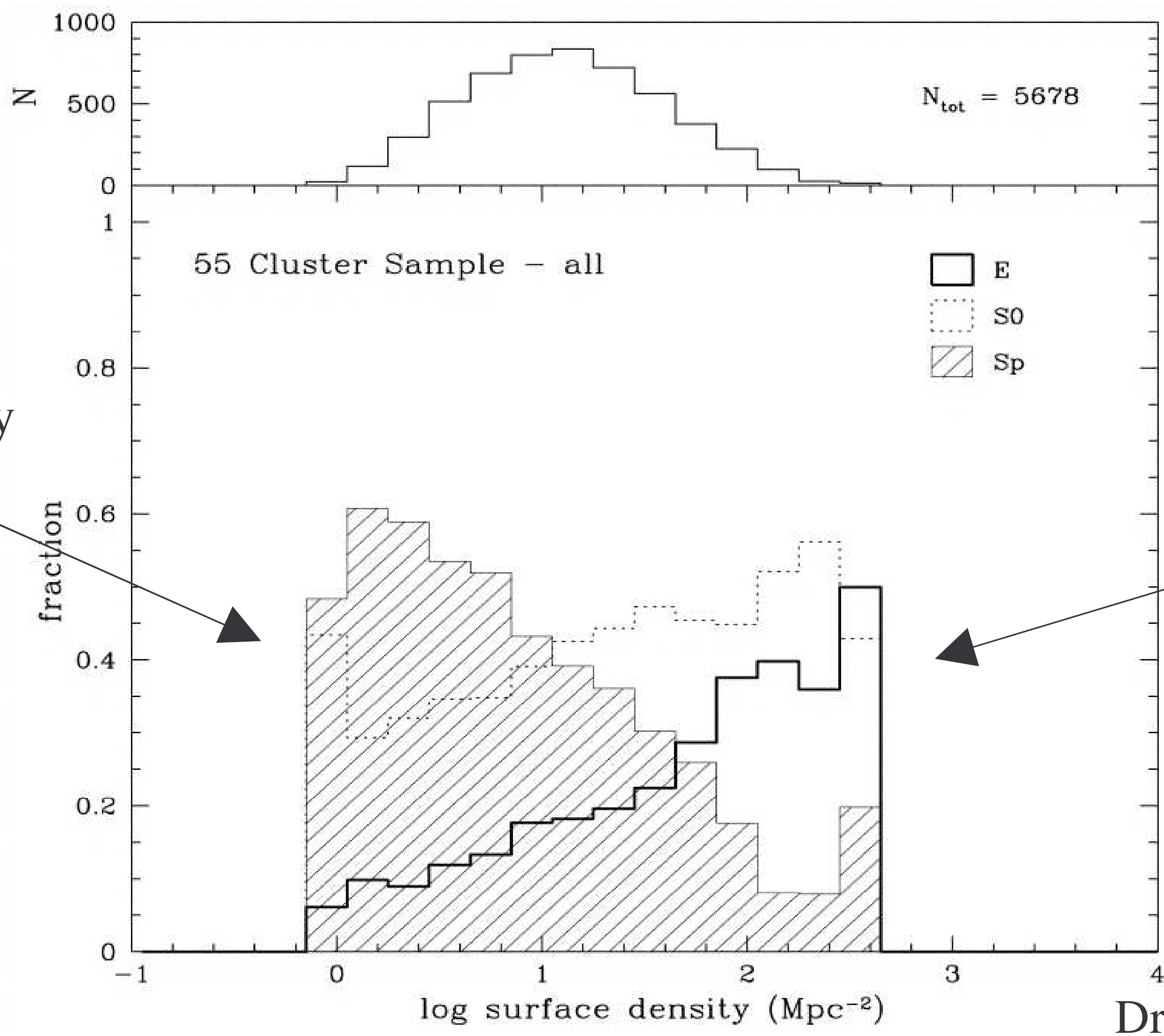


Blanton et al. (2001)

There are many more faint galaxies than brighter galaxies

Different galaxies are found in different environments: the morphological density relationship

Spirals in lower density areas



Ellipticals in dense areas

Dressler et al. (1997)

Why do galaxies form differently in different environments?

Galaxies in dense environments, i.e., clusters, are ellipticals

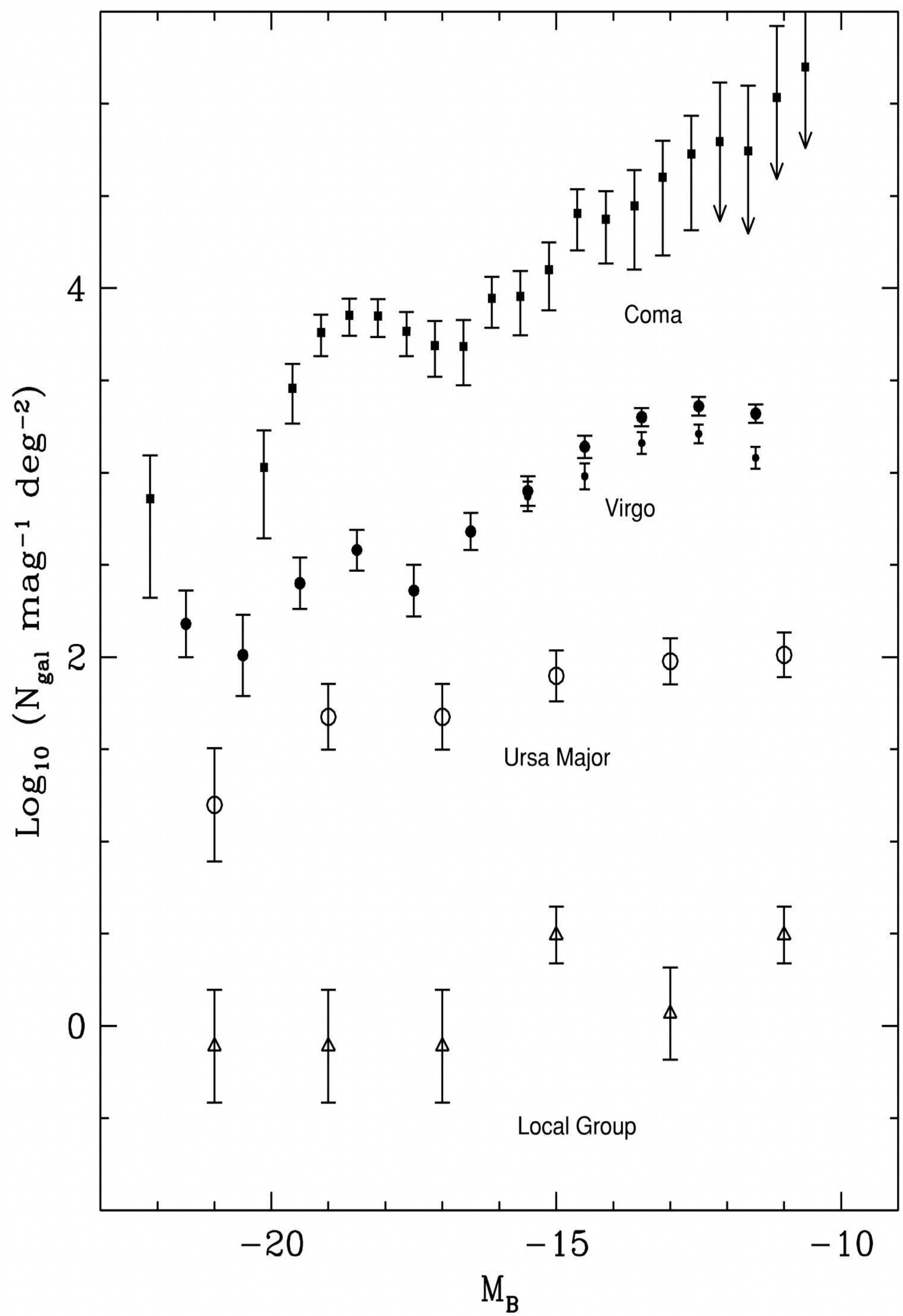
HST image of cluster Abell 2218 at z = 0.16

Relationship holds out to z~1.3, highest redshift cluster

Another clue towards galaxy formation:

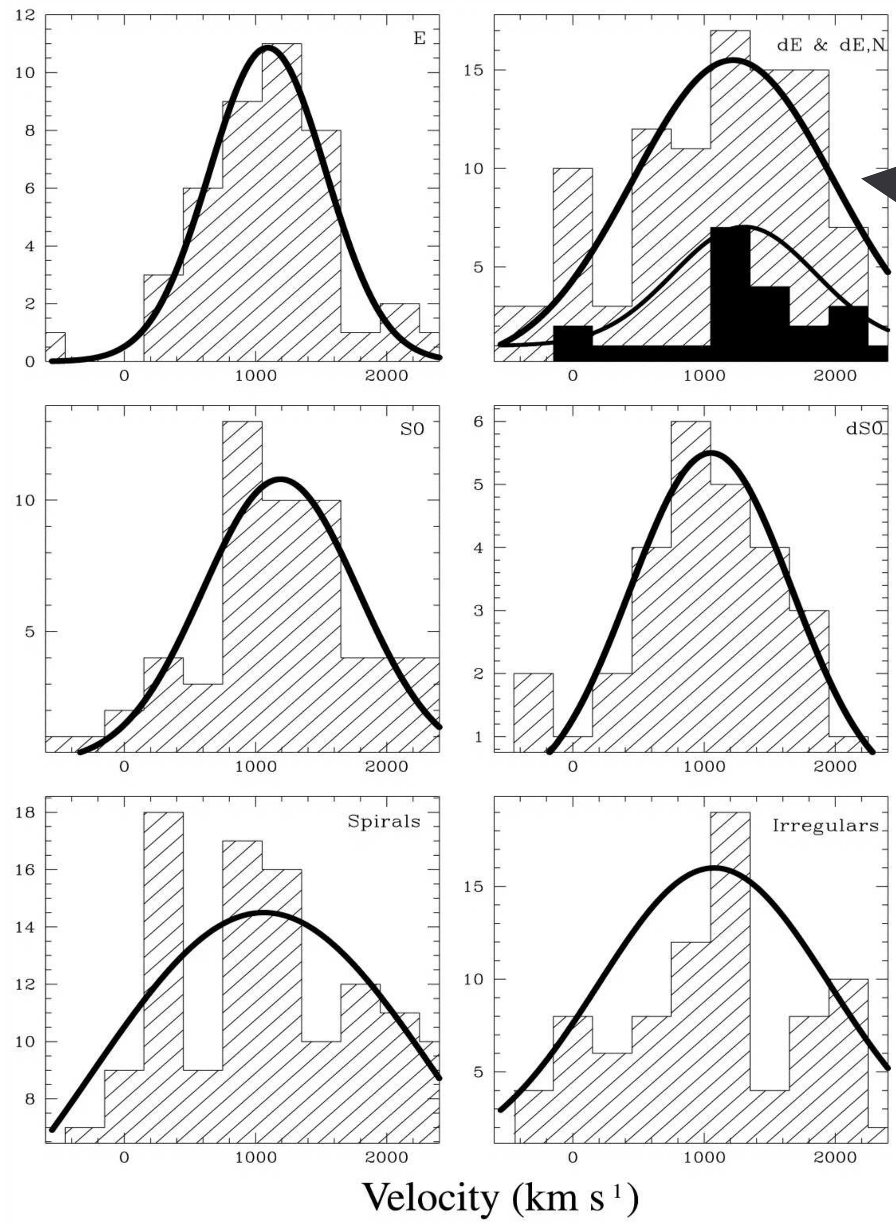
Denser areas also have more faint galaxies

Does environment influence the formation of fainter galaxies as well?



Likely, yes.

Velocity distributions suggest that not all faint galaxies formed at the same time



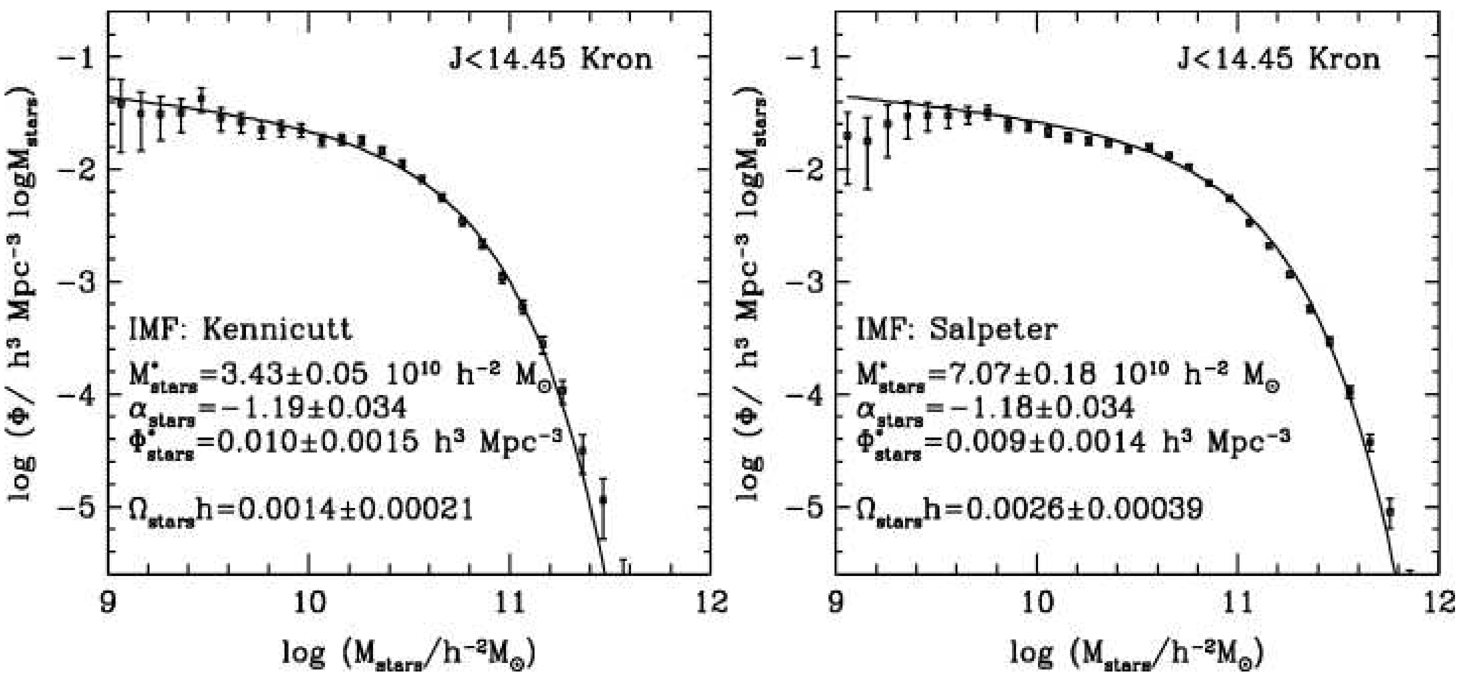
Low–mass galaxies

A broader distribution and substructure suggests an infall formation

Conselice et al. (2001)

How many stars are there in the universe?

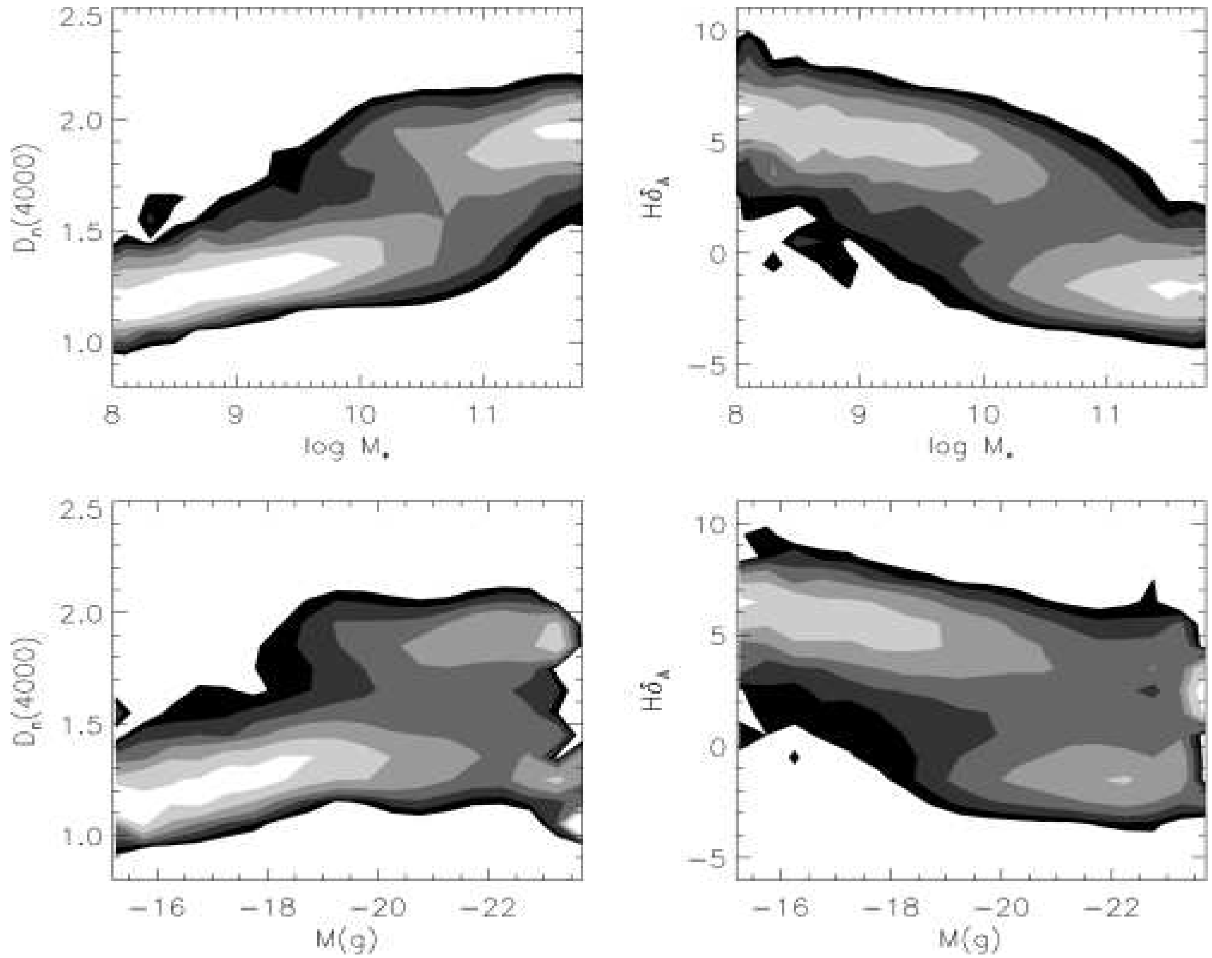
Integrated mass function at z = 0: Integrated history z = 0 – 1000



Data From 2dF redshift survey and 2MASS (Cole et al. 2001)

There is about 10^11 solar masses of stellar mass per every cubic Mpc

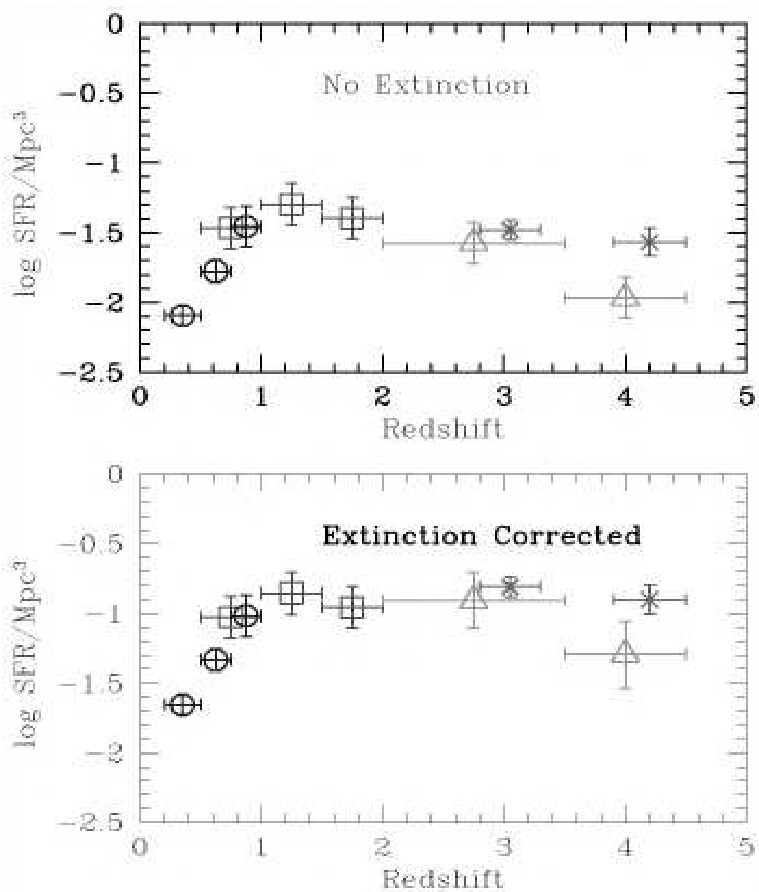
Galaxy formation is still ongoing – for low mass systems



Kauffmann et al. (2003)

SDSS study of 100,000 galaxies shows that lower mass galaxies are still forming while massive ones are largely old

When did galaxies form?



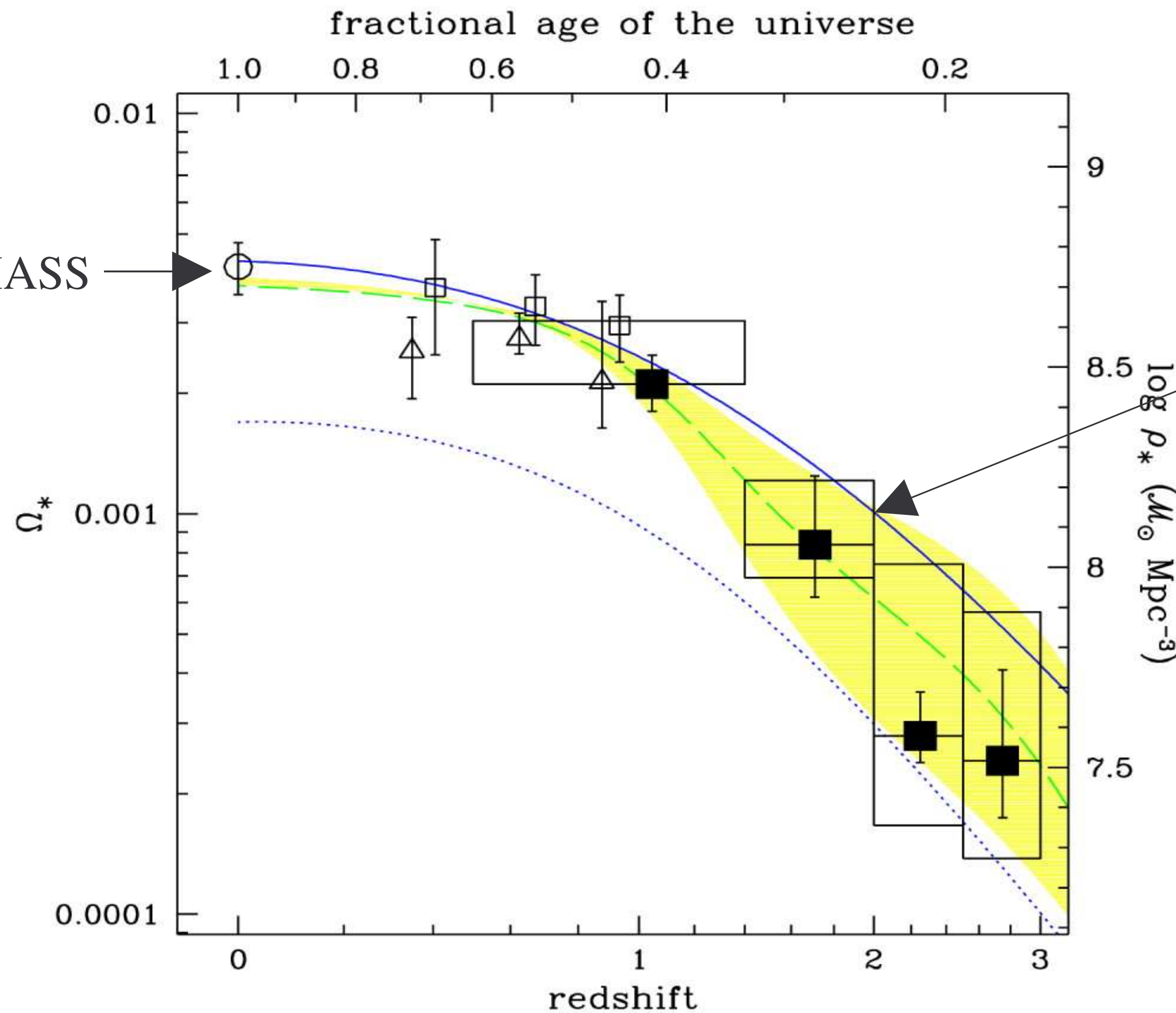
Steidel et al. (1999)

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

How was star formation triggered? Answering this will tell us how galaxies formed

The density of stellar mass as a function of time – integral of SF

Local 2dF/2MASS



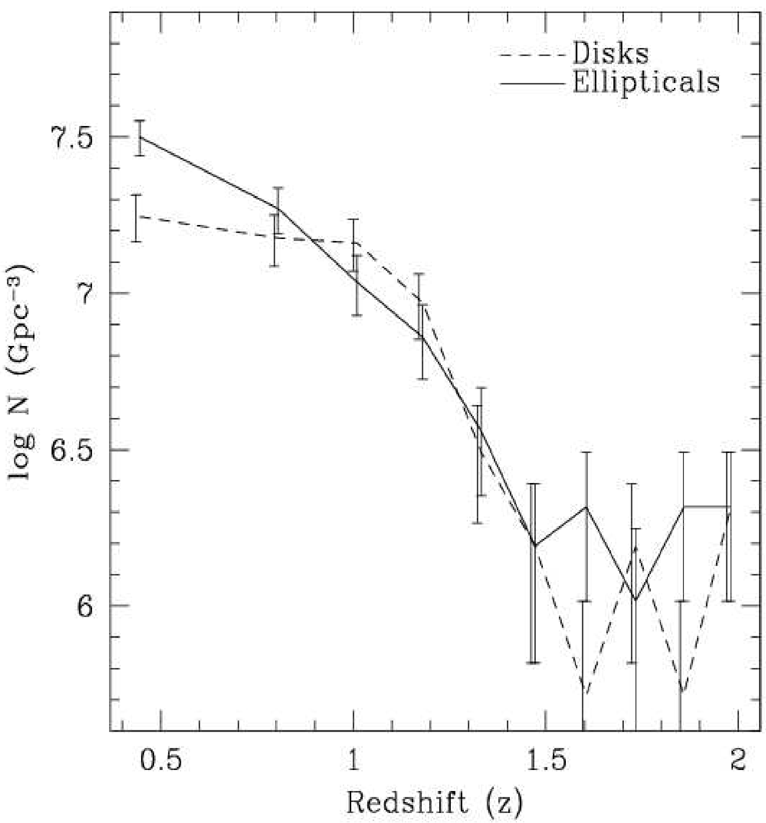
Hubble Deep Field

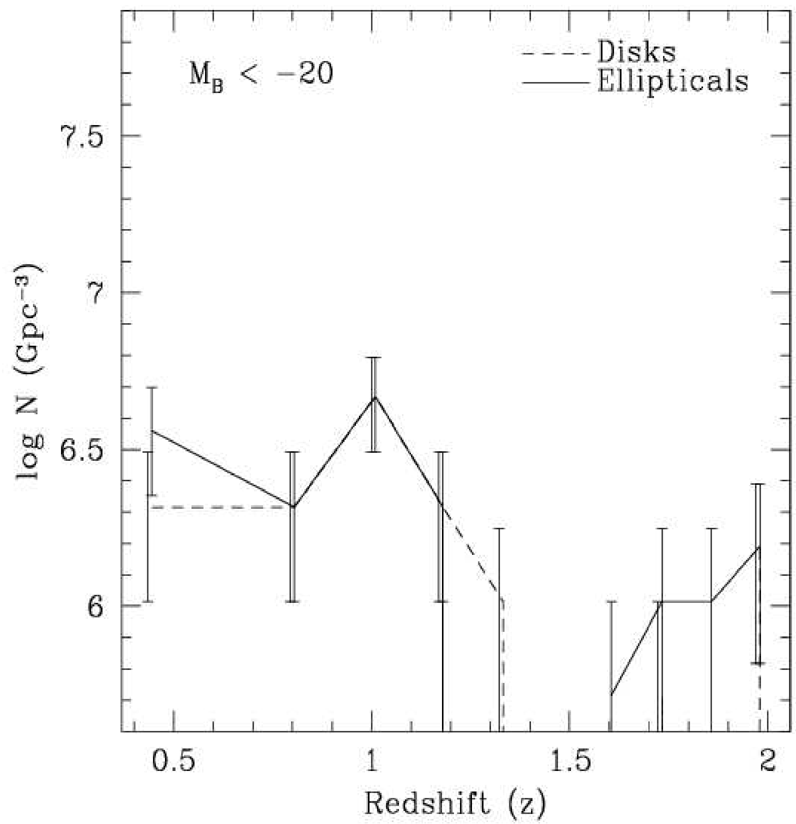
~50% of stellar mass formed at 1 < z < 2

Dickinson et al. (2003)

When did galaxies form into their modern morphological types?

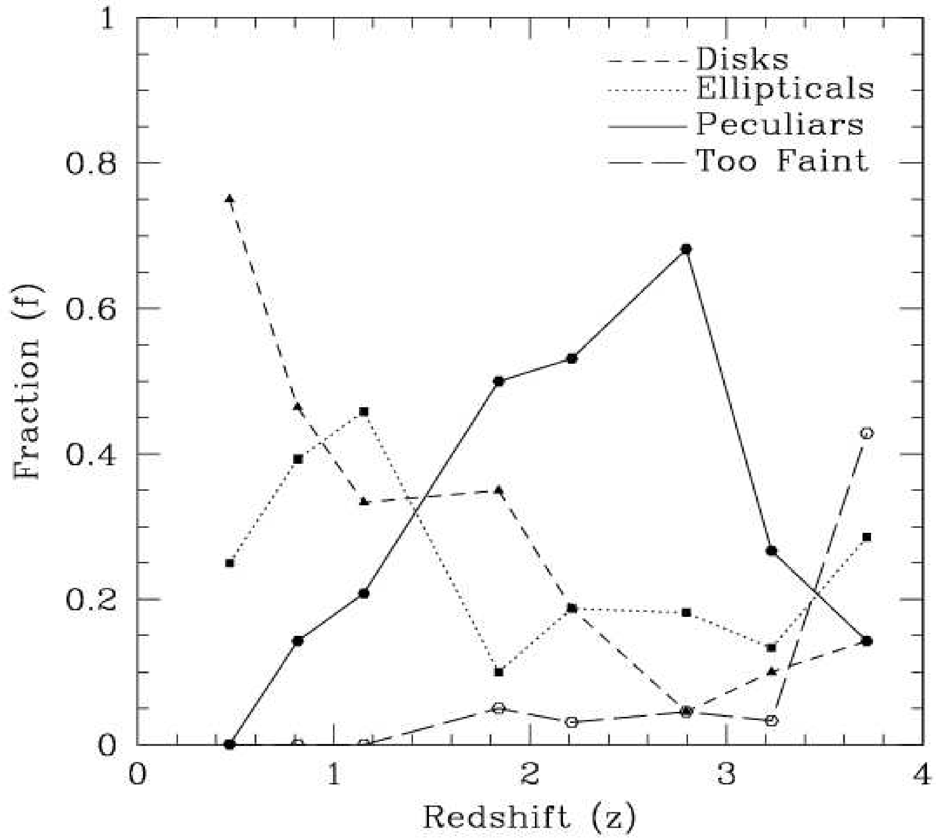
Co−moving density of Hubble Types with redshift in Hubble Deep Fields





Co−moving density drops rapidly at z > 1, even when considering only bright galaxies.
Hubble sequence appears to form at z~1.5

Evolution in the relative fraction of types out to z ~ 4 in the HDFs

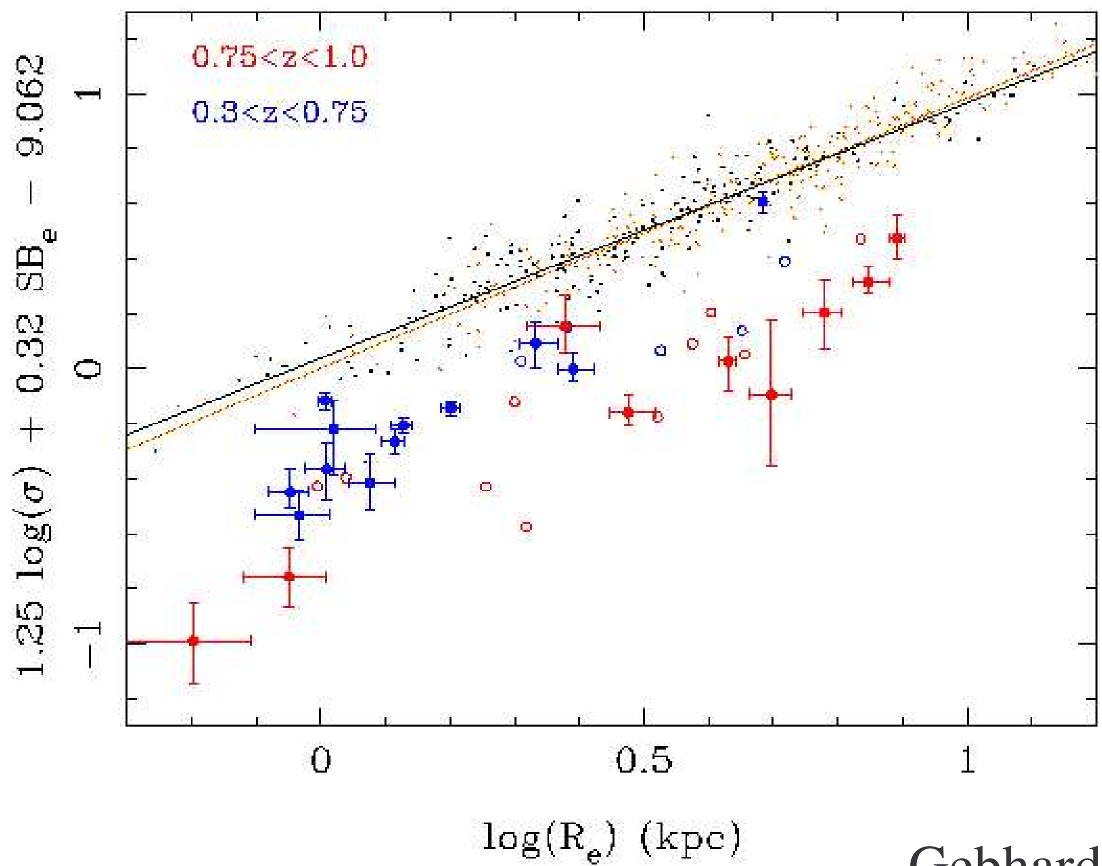


As the relative fraction of ellipticals/spirals declines, the fraction of peculiars rises.

Scaling relationships for normal galaxies: Evolution from z ~ 1

Reveals evolution of relationship between dark matter halos and stellar components

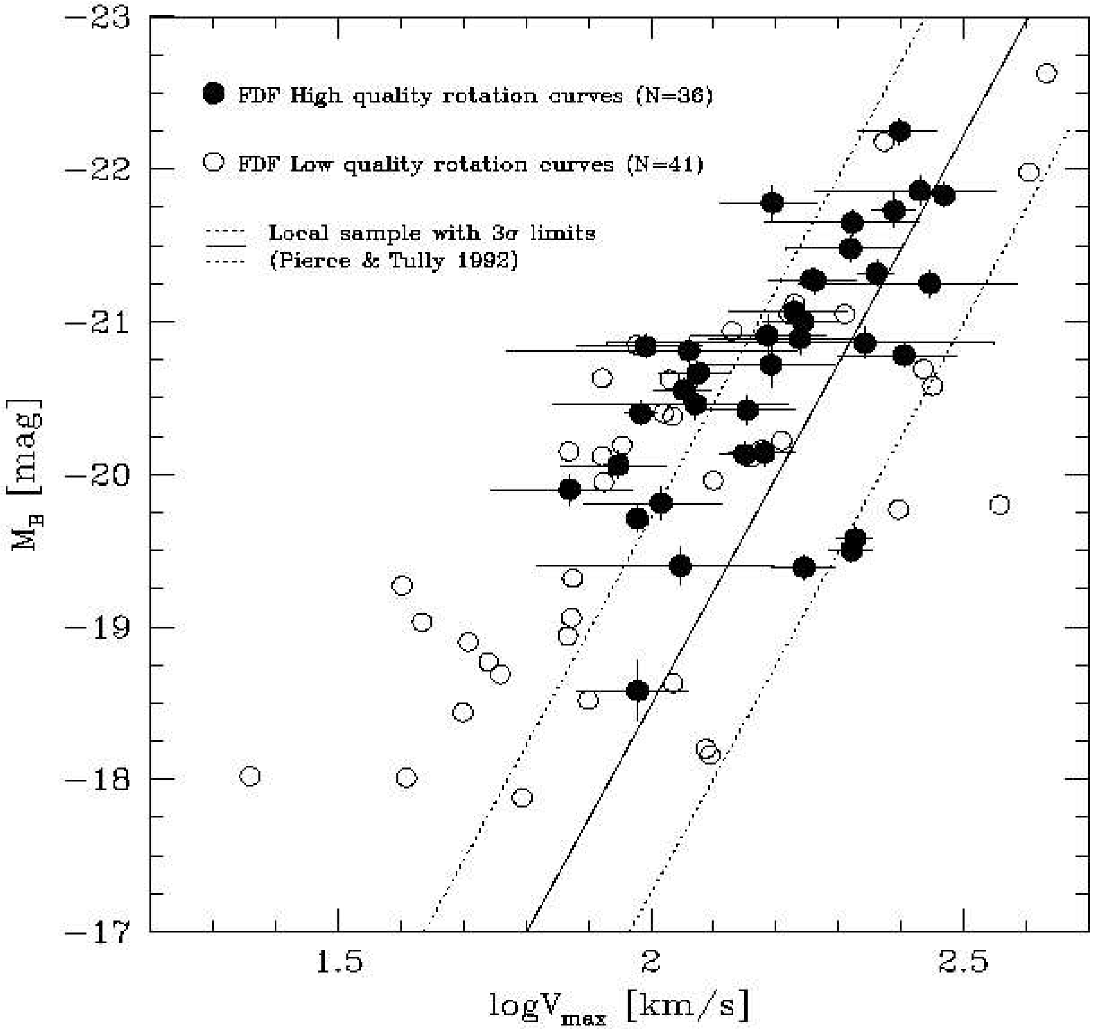
Ellipticals: Fundamental Plane



Gebhardt et al. (2003)

Spirals: The Tully–Fisher relationship

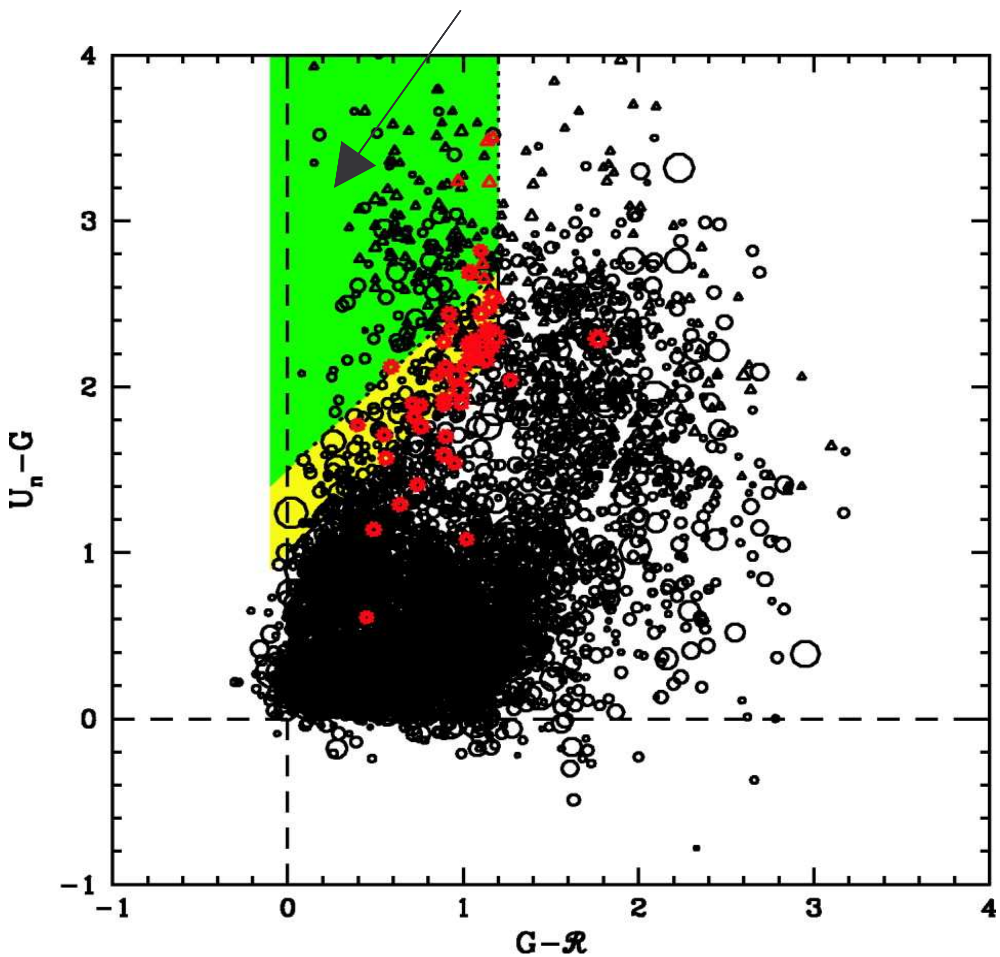
Dark halos are established by z~1, with modest amounts of stellar evolution since then

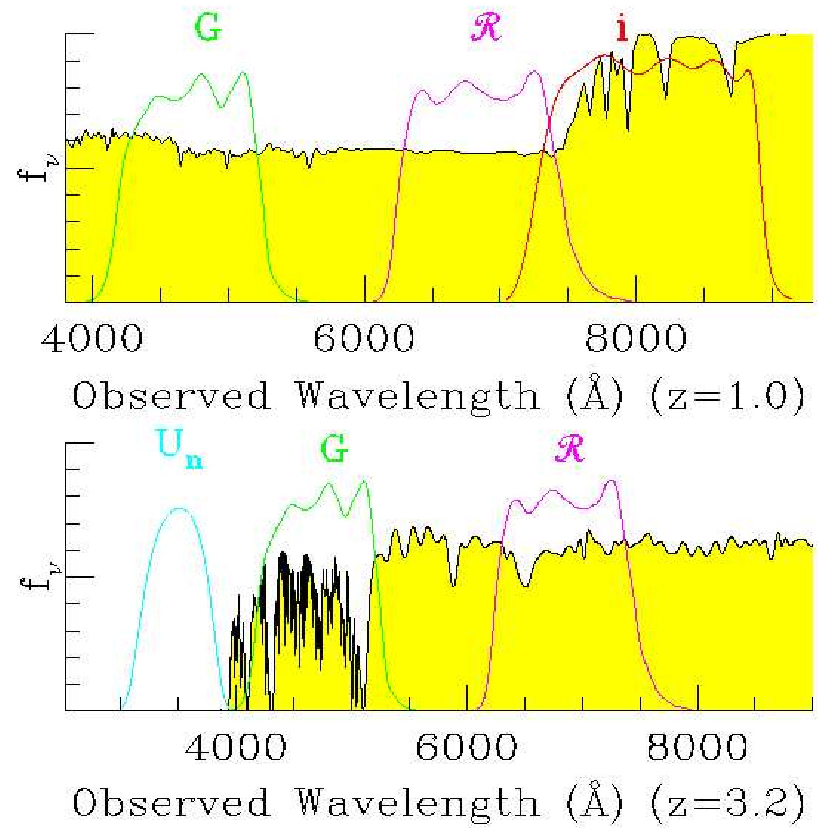


Bohm et al. (2003)

Galaxies at z > 1.5 – The key to galaxy formation

Galaxies at z > 2.5 occupy unique regions of colors space





Lyman–break technique – finds starbursts at z > 2.5

Properties of high redshift galaxies

LBGs at $2.5 < z < 4$ are clustered, have low stellar masses and are undergoing intense star formation

What could these galaxies be, and are they most of the galaxy population at high redshift? No.

1. Lyman−alpha galaxies

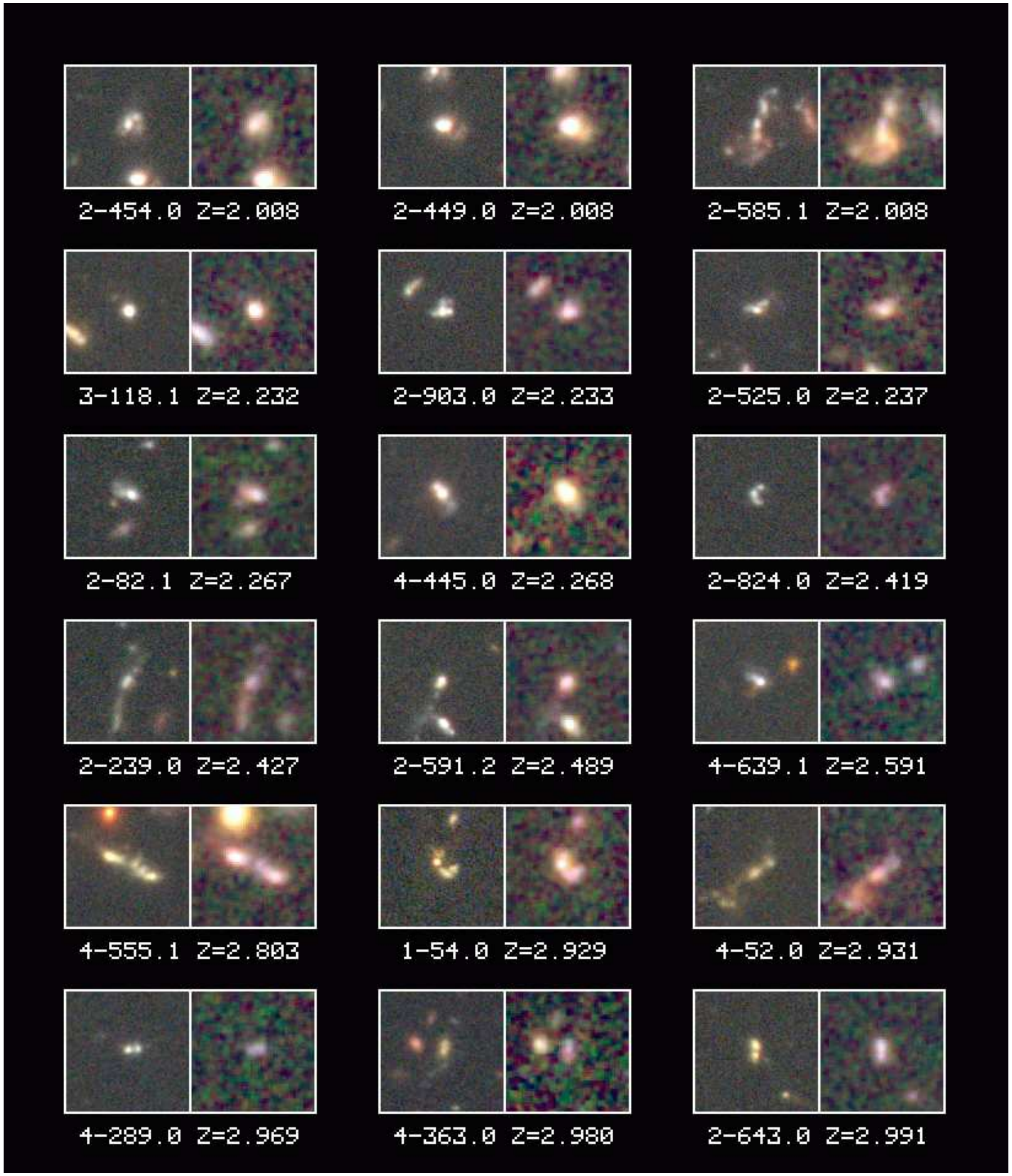
2. K−selected ’older’ galaxies

3. Sub−mm sources

4. QSO absorption line systems

(2 and 3 →) see Andrew’s talk

Can investigate how galaxies form by studying these systems individually



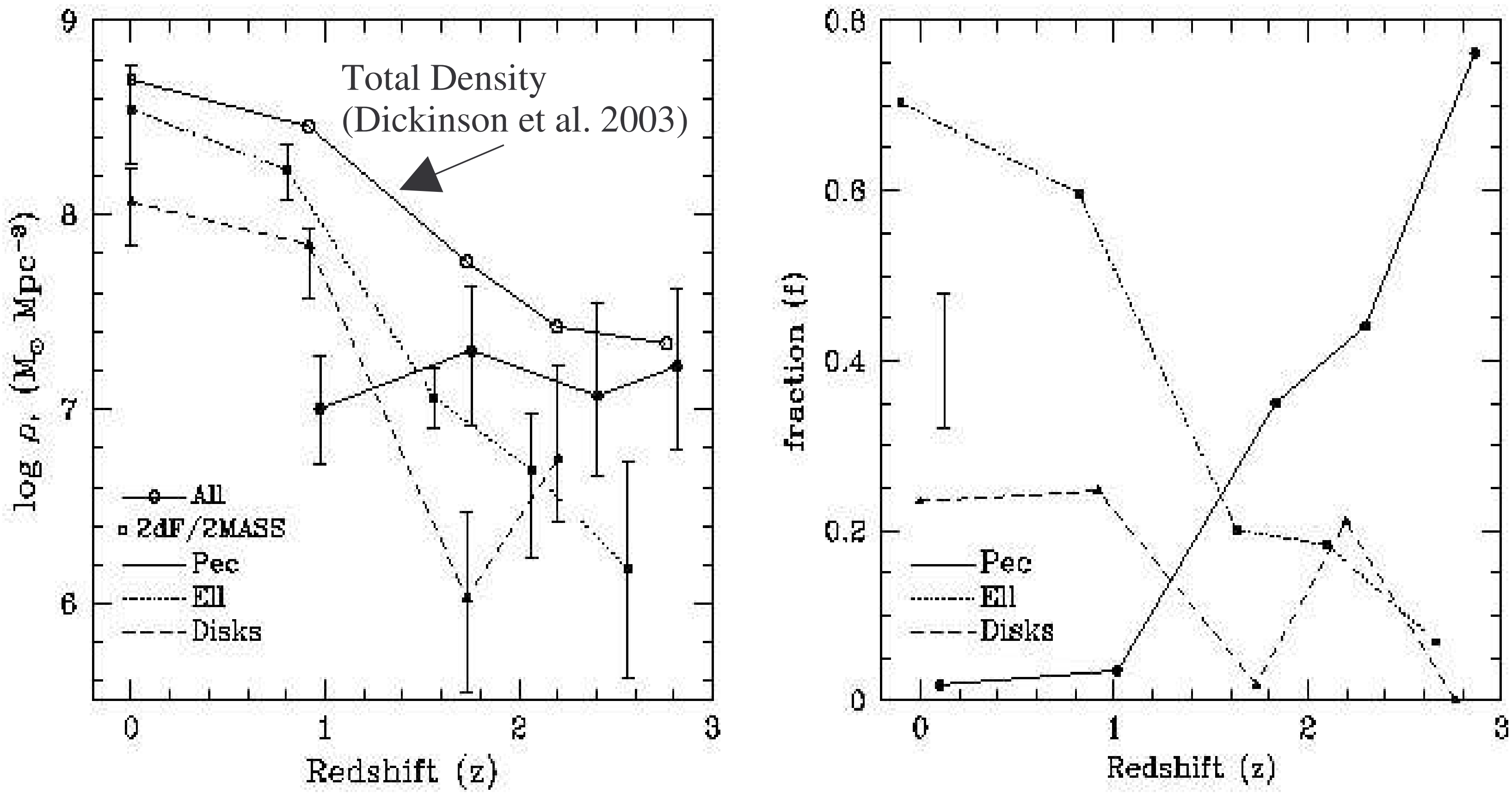
Dickinson et al. (2003)

1st step – Lyman Break galaxies

Some Examples of individual galaxies in the HDF seen at high redshift at observed optical and near infrared morphologies.

The morphological evolution of galaxies is critical for understanding their formation

The Evolution of Stars in Galaxies – where does stellar mass form?

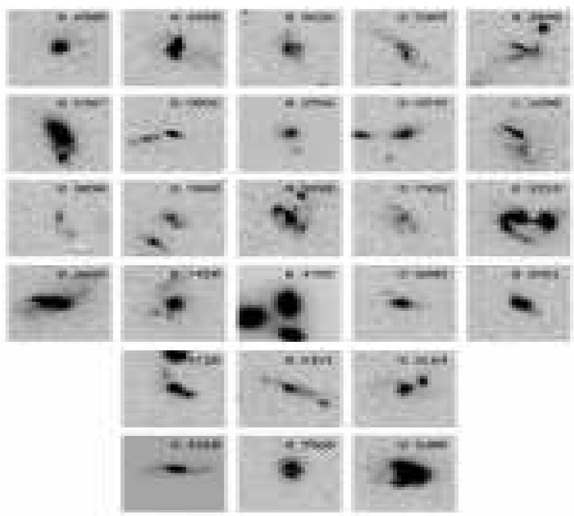


Stellar mass densities and fraction of stellar mass in various forms out to z ~ 3.

What is the importance of peculiars in galaxy formation?

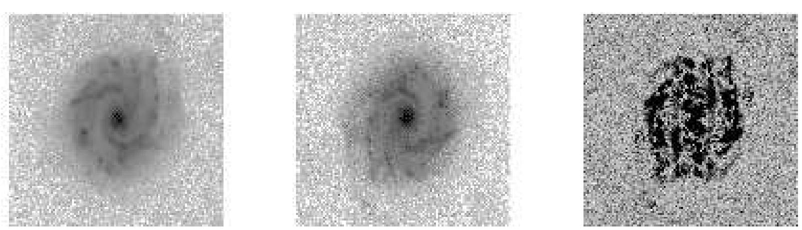
Are they mergers as assumed?

Traditional method for finding mergers is to use pairs



LeFevre et al. (2000)

Morphological method finds objects that have already merged

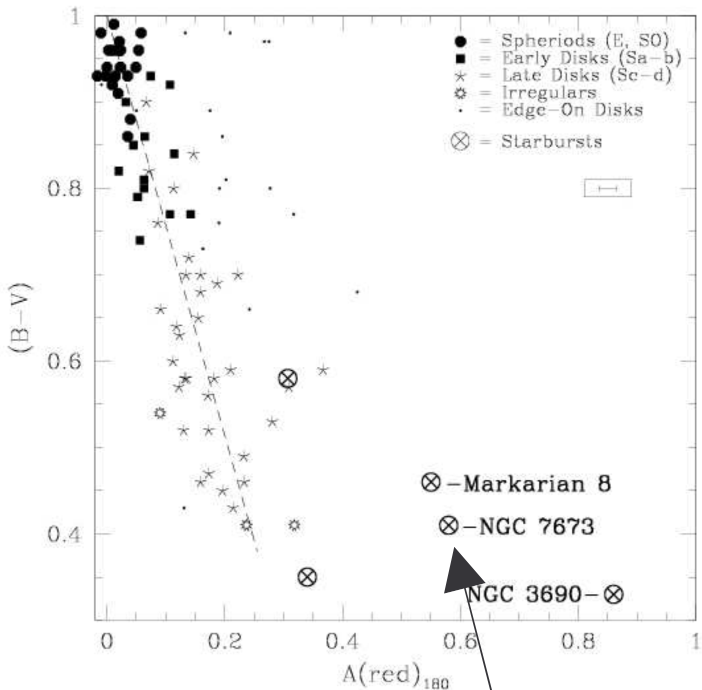


I R abs(I–R)

$$A = \frac{abs(I-R)}{I}$$

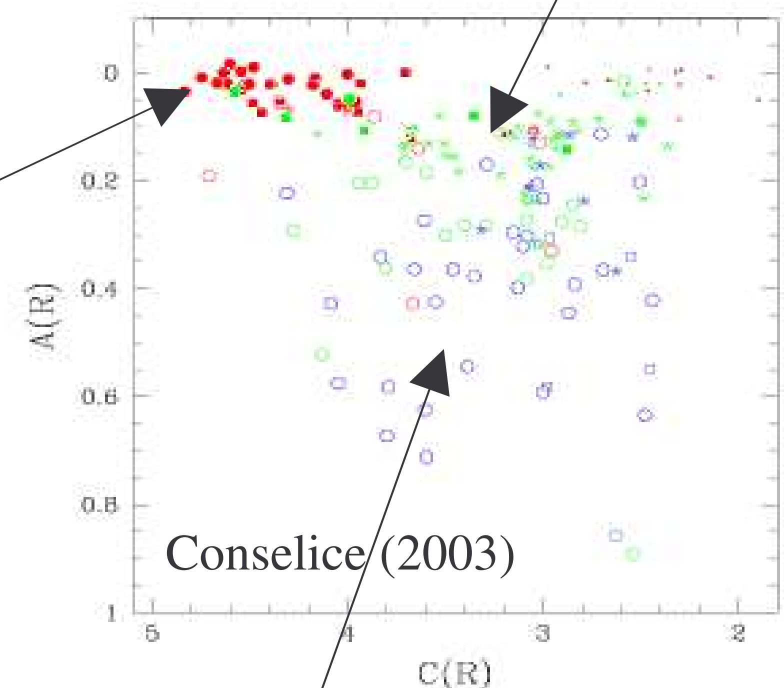
Rotate and subtract and image and quantify the residuals as a number

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



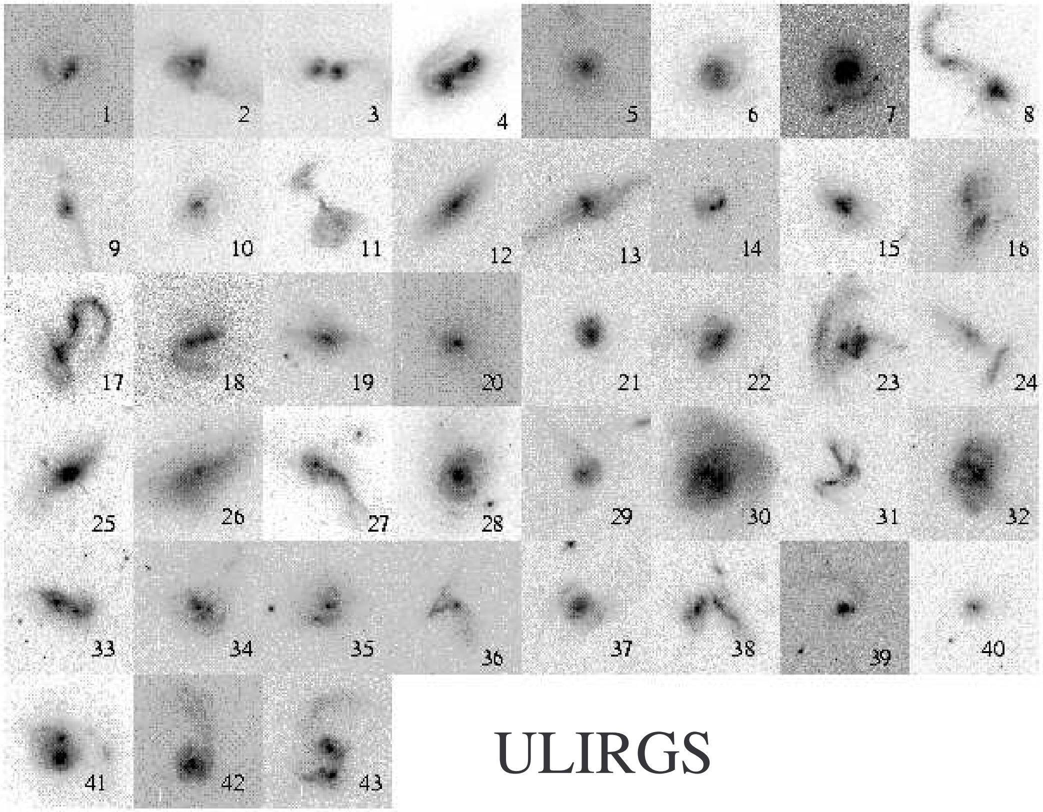
Ellipticals

Disk Galaxies



High A galaxies with blue colors are merger induced starbursts

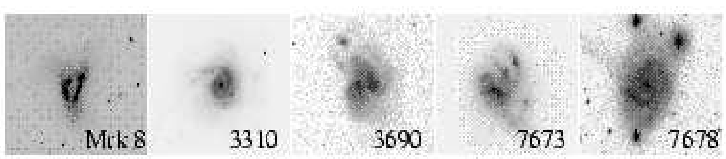
High A(R) galaxies are ULIRGs



ULIRGS

Some of the high asymmetry ULIRGs and starbursts

Most are mergers in progress

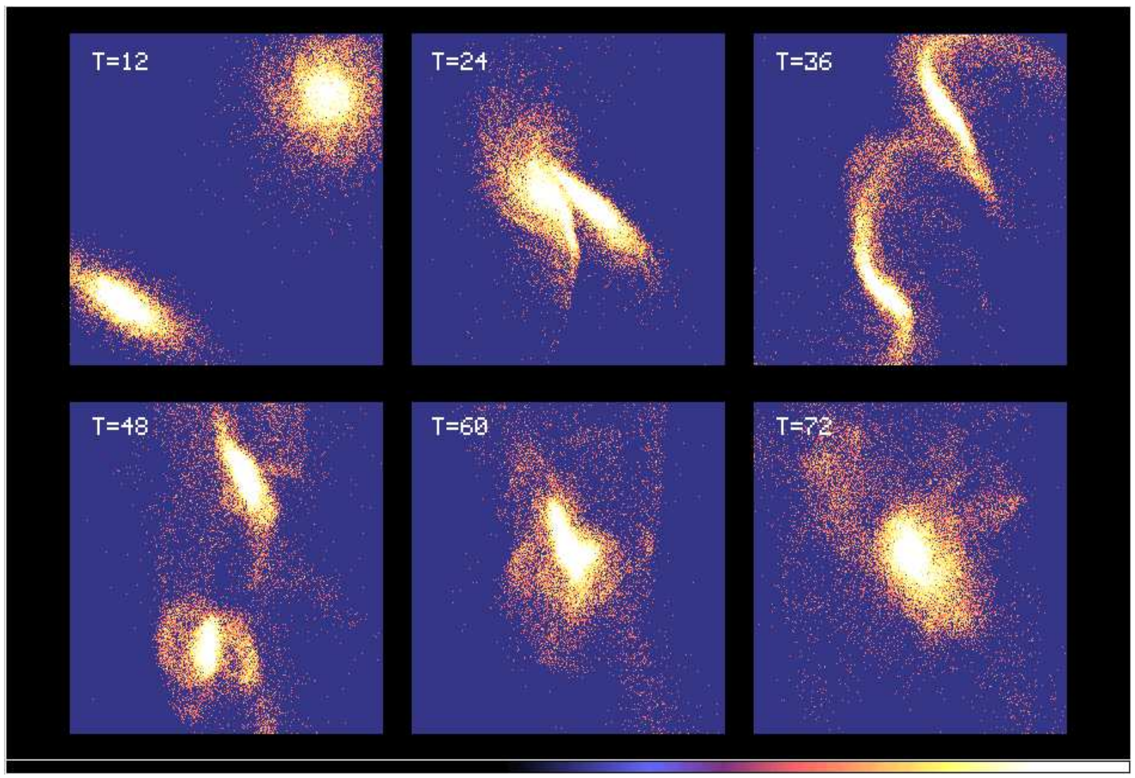


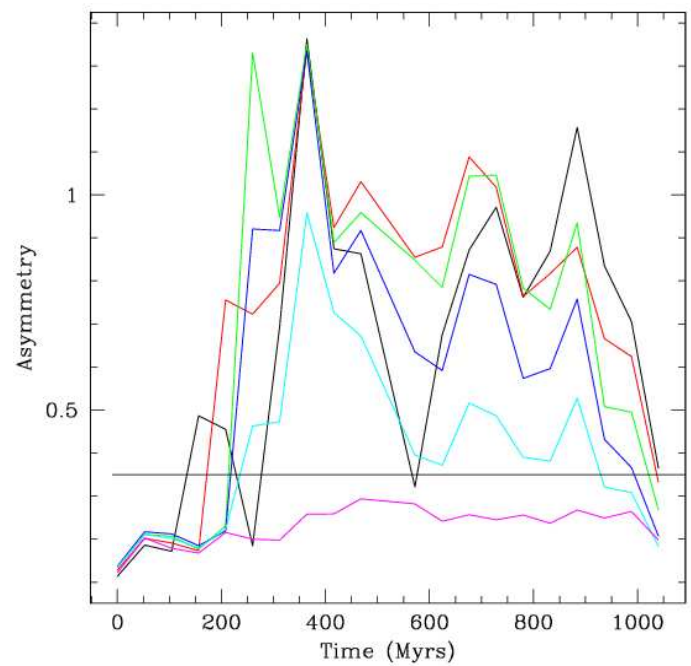
Starbursts

How long does a merger stay identifiable as a merger under the asymmetry technique? Can compute by using N–body simulations of the merger process from C. Mihos.

Different colors are for different inclinations – pink is for face on

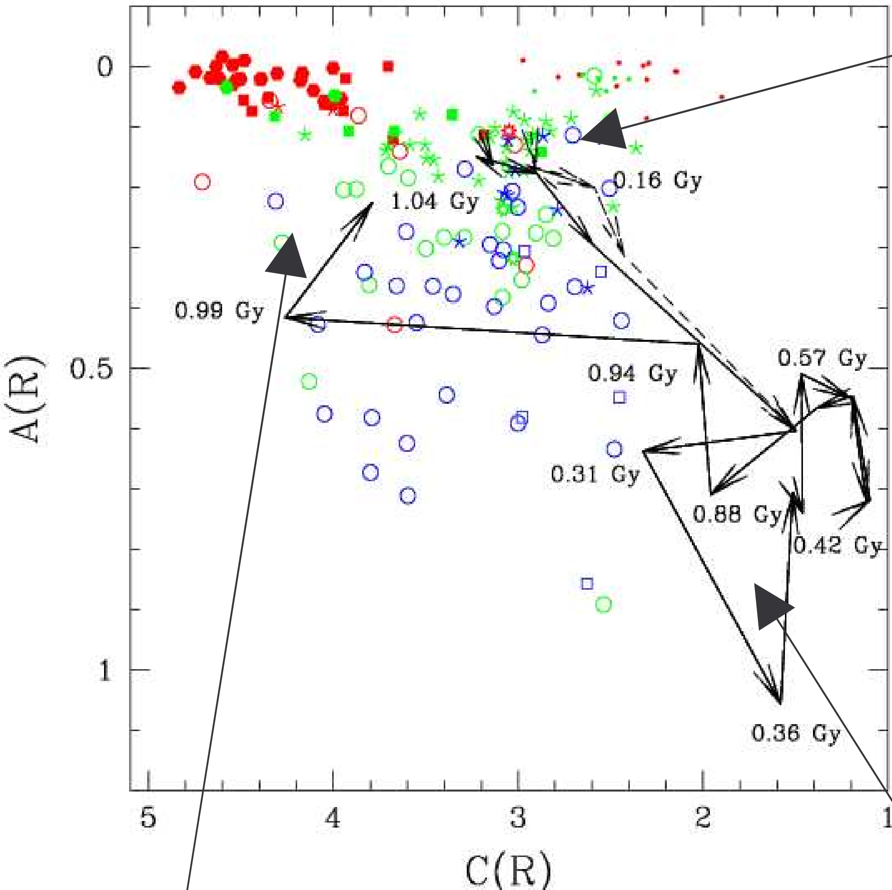
1:1 merger asymmetry simulation





<u>Result</u>– Asymmetry method identifies galaxies undergoing mergers for ~ 800 Myrs

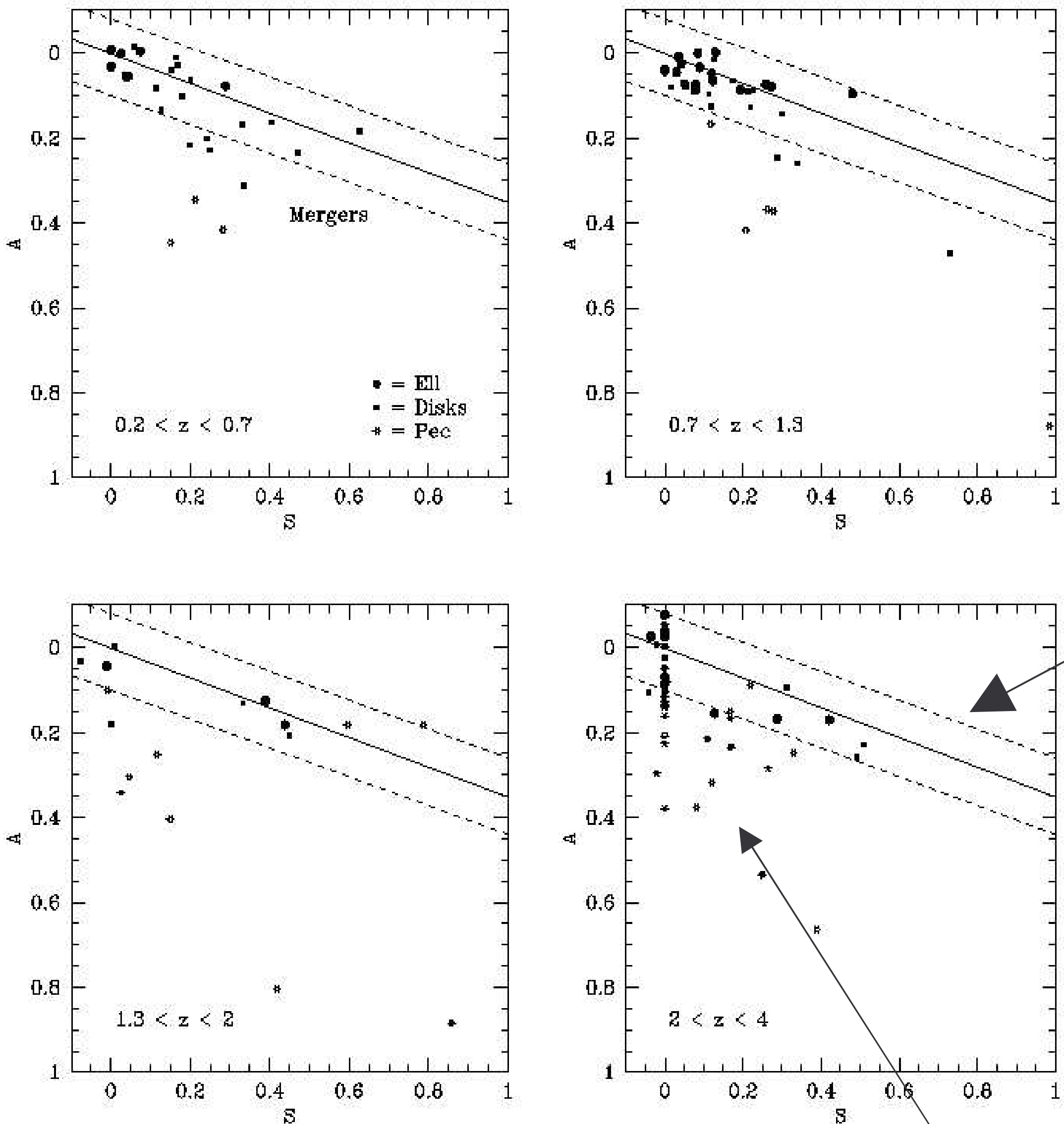
Merger beings with two disk galaxies of equal mass



Evolution of the asymmetry and concentration index for the Mihos N−body simulations.

Merger becomes highly asymmetric

Merger ends as a concentrated low asymmetry object.

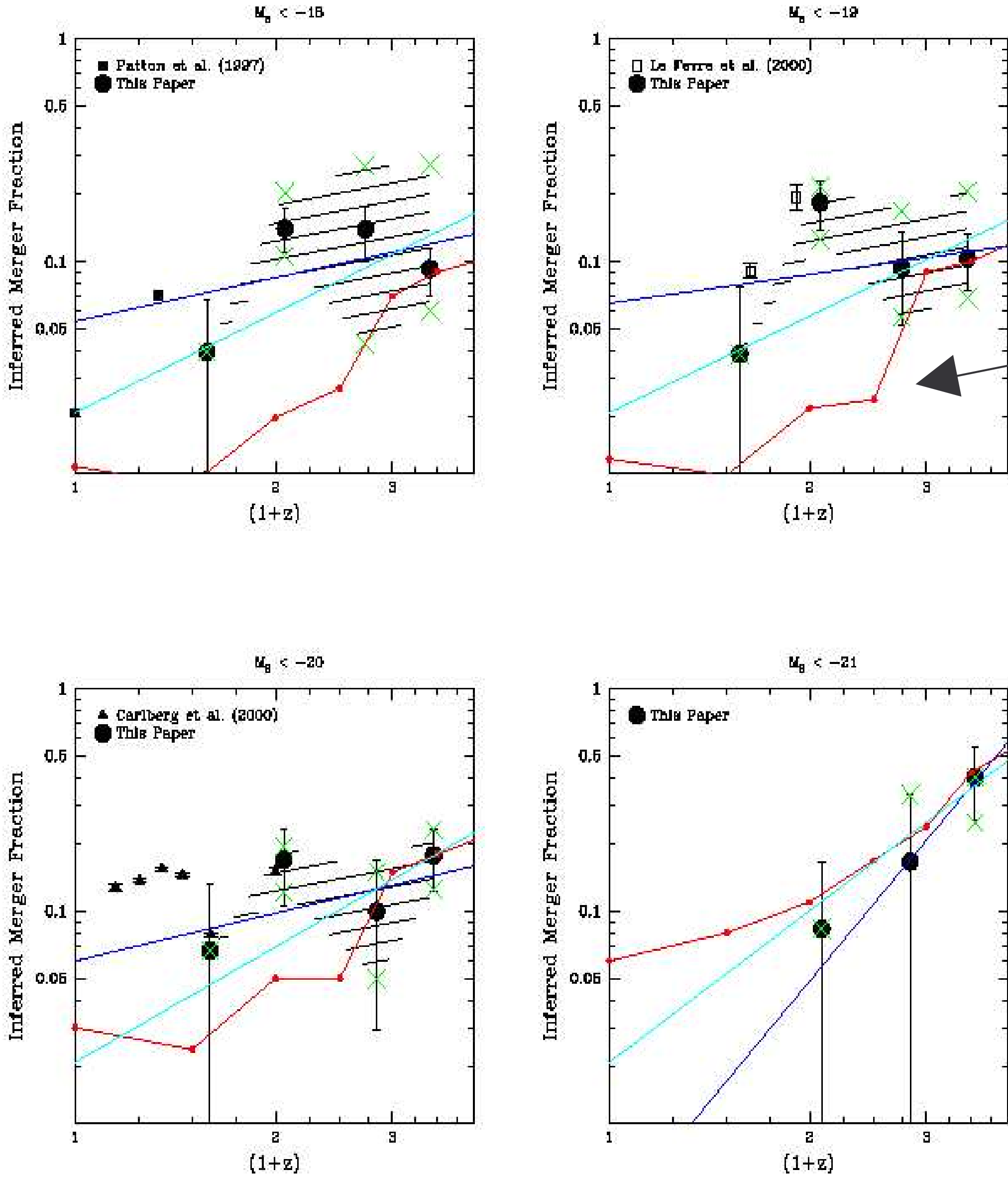


The clumpiness−asymmetry diagram for HDF galaxies at various redshifts and morphologies

Solid and dashed lines are the z=0 relationship between S and A and the 3 sigma scatter

Can use this methodology to find which galaxies are undergoing major mergers

Peculiar galaxies are identified as mergers by this technique



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

CDM semi−analytic model predictions from Benson et al.

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

Blue and cyan lines are two different fits to the asymmetry merger fractions

Conselice et al. (2003)

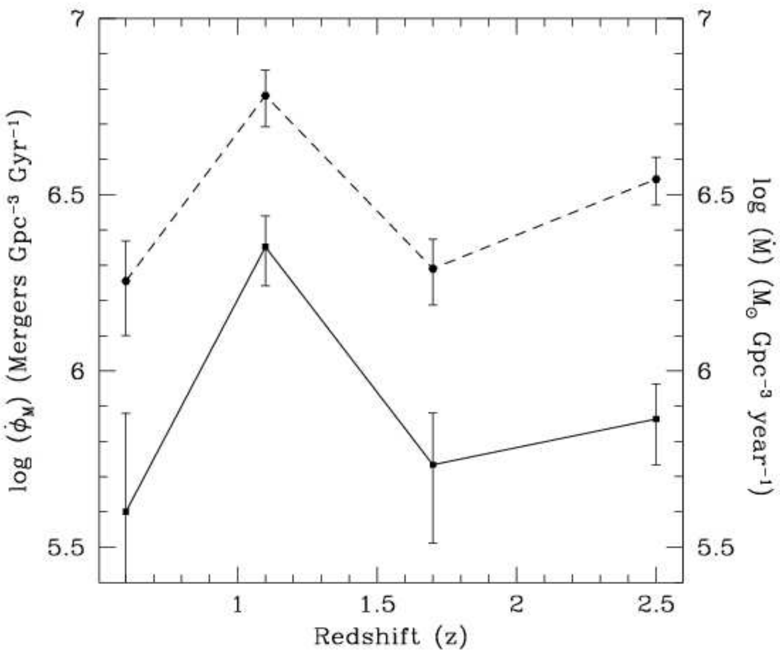
Can fit merger fraction evolution as a powerlaw

$$f_m = f_0 * (1 + z)^m$$

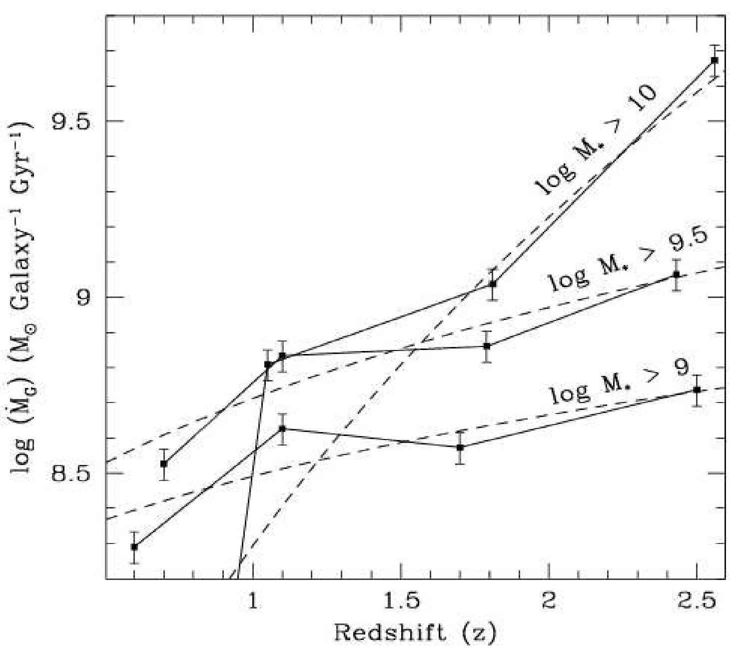
From z ~0 to z~3

For objects with Mb > −21 or log (Mstellar) < 10 ---- m ~1
For objects with Mb < −21 or log (Mstellar) > 10 ---- m ~3.5

<u>Massive galaxies form early</u>



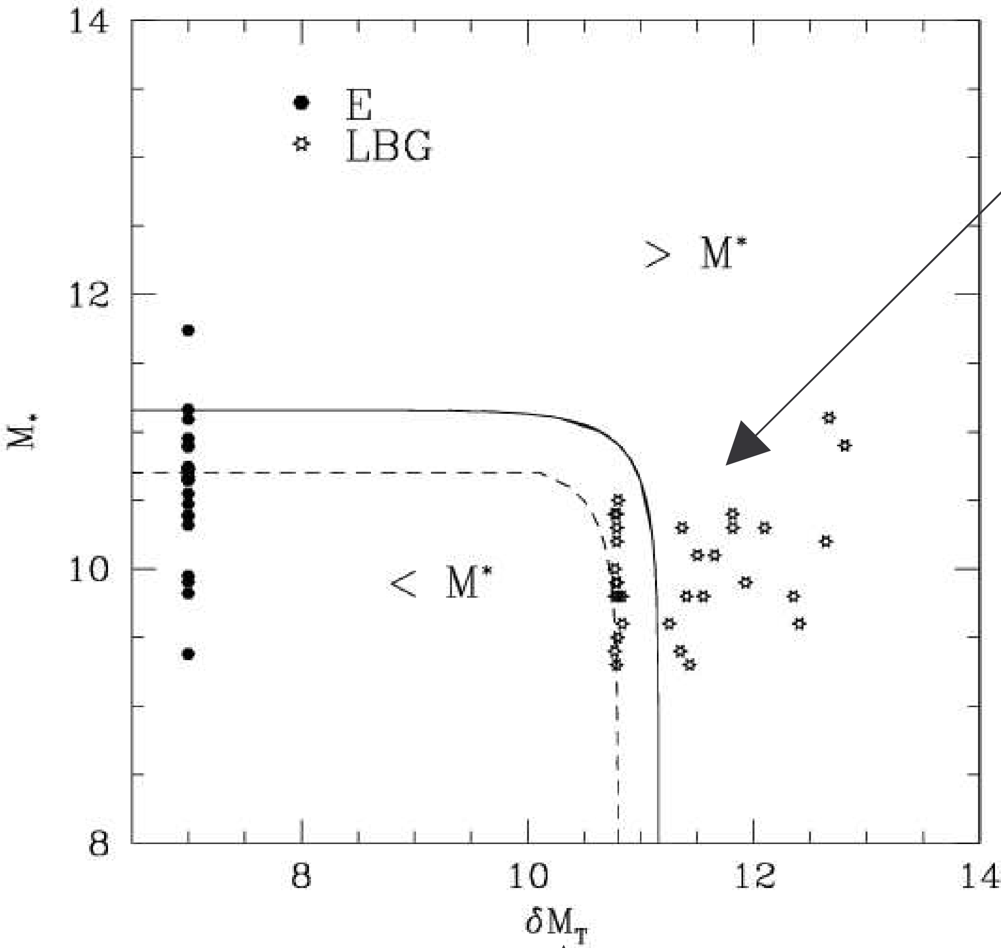
The merger and mass accretion rates can be computed by using the stellar mass estimates from Papovich et al. (2002) and time scales for an 'asymmetry merger' to take place based on N−body simulations of Mihos



Can use this information to calculate the mass accretion rate due to merging as a function of galaxy initial mass

Must include amount of star formation induced as well

Can determine the amount of mass added through star formation and mergers to determine the evolution of high redshift peculiars i.e. Lyman break galaxies:

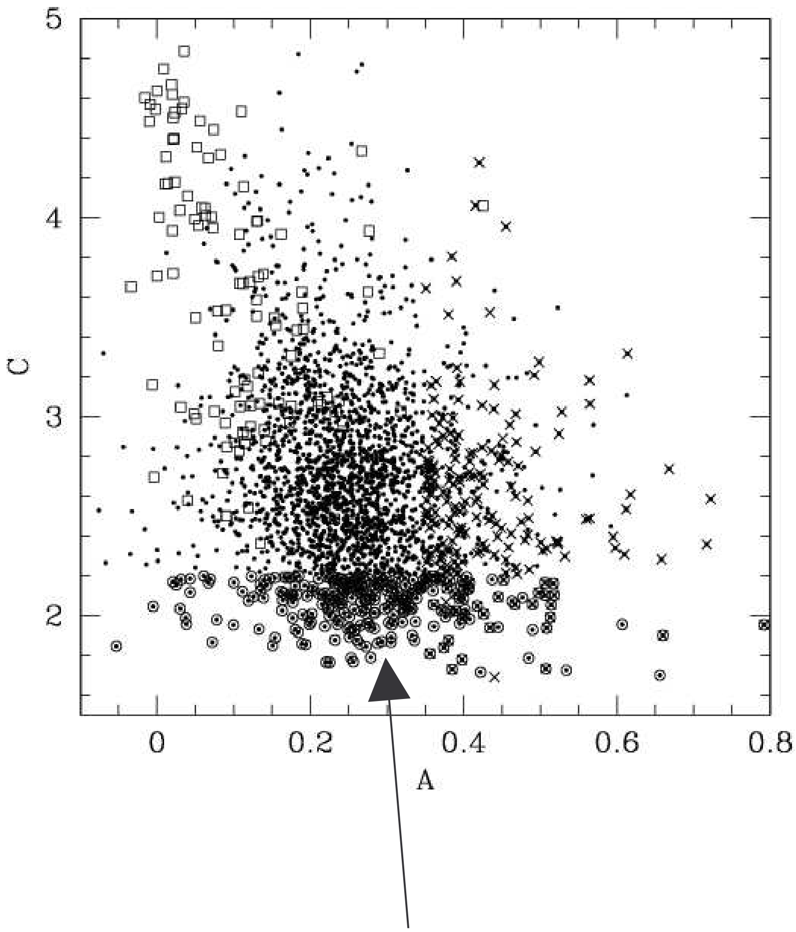


Peculiars at high redshift become as massive as the most massive galaxies at z~ 0

Observed stellar mass

Amount of stellar mass added due to SF induced by mergers + mergers

What about the formation of disk galaxies?



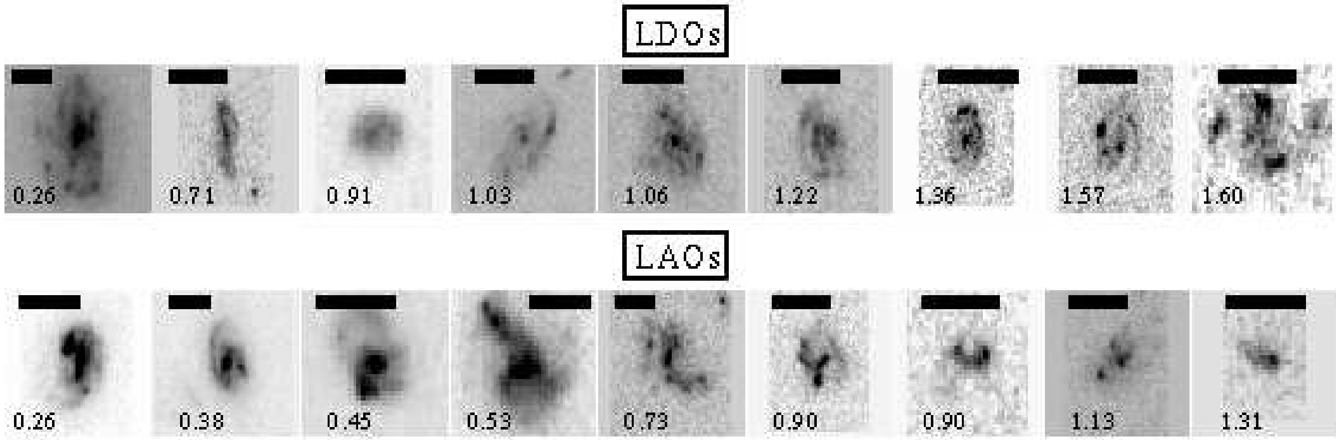
Using GOODS images, there are luminous diffuse objects (LDOs) at z > 1, with large outer HII regions that create un–concentrated galaxies

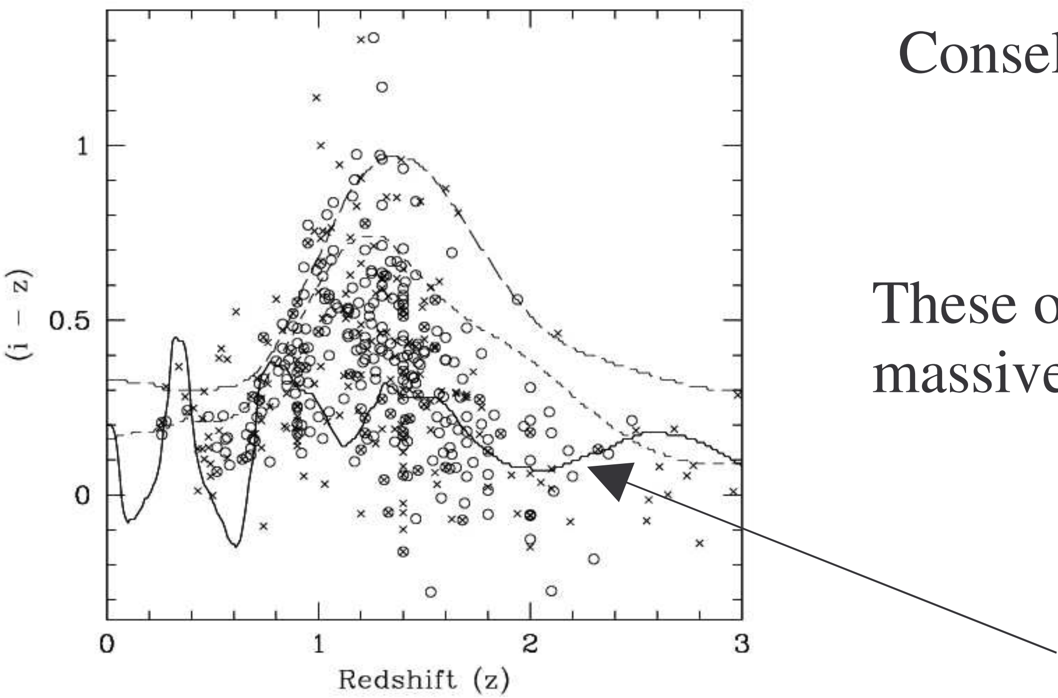
These systems have sizes suggesting they are disks

There are very few at z < 1, but many at 1 < z < 2

LDOs – no local counterparts

What do these look like?

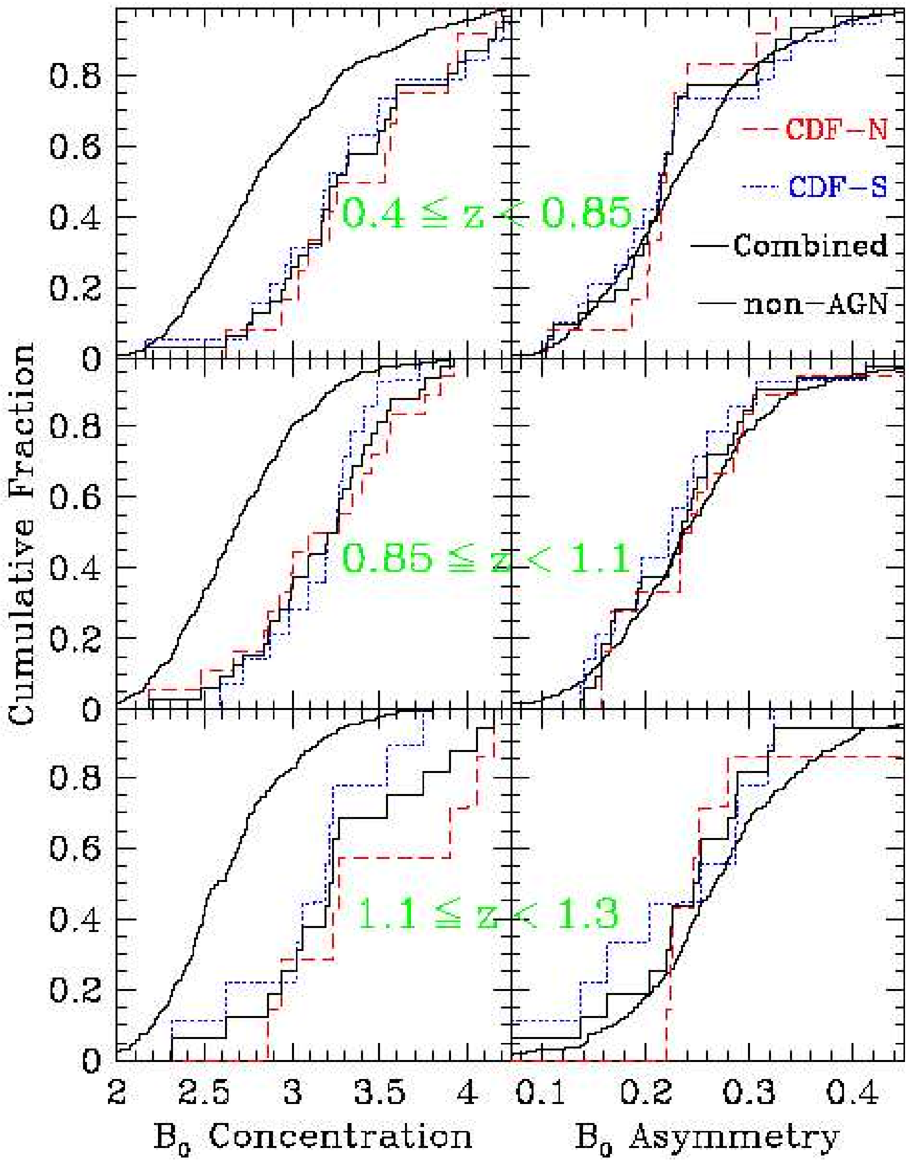




Conselice & GOODS team (2003)

These objects tend to be undergoing massive star formation at z > 1

The role of black holes in galaxy formation

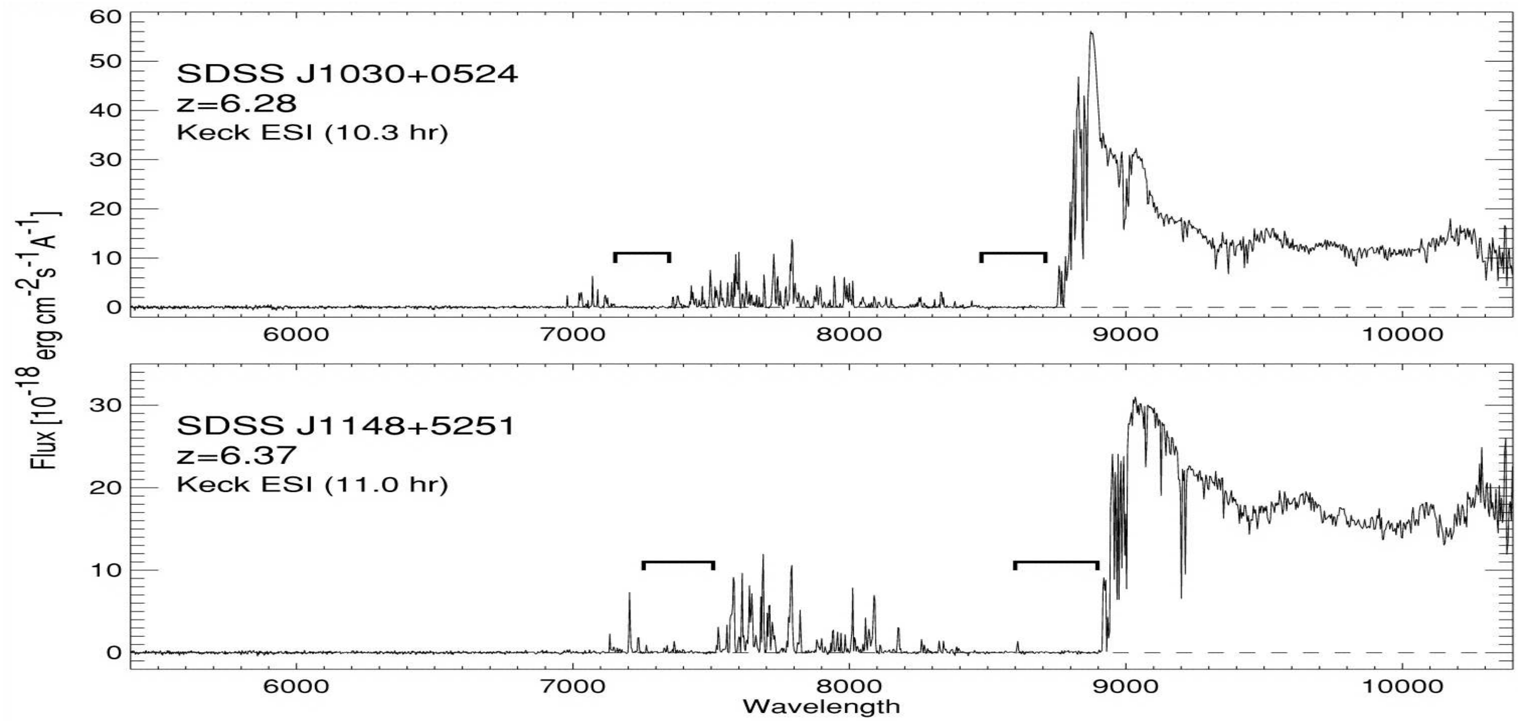


Black holes are in concentrated galaxies – which are more massive systems, out to z~1.3

The presence of merging does not seem to affect the onset or duration of an AGN

Grogin & GOODS team (2003)

Galaxies and QSOs at z > 5 : Birth of the Galaxy Population?



White et al. (2003)

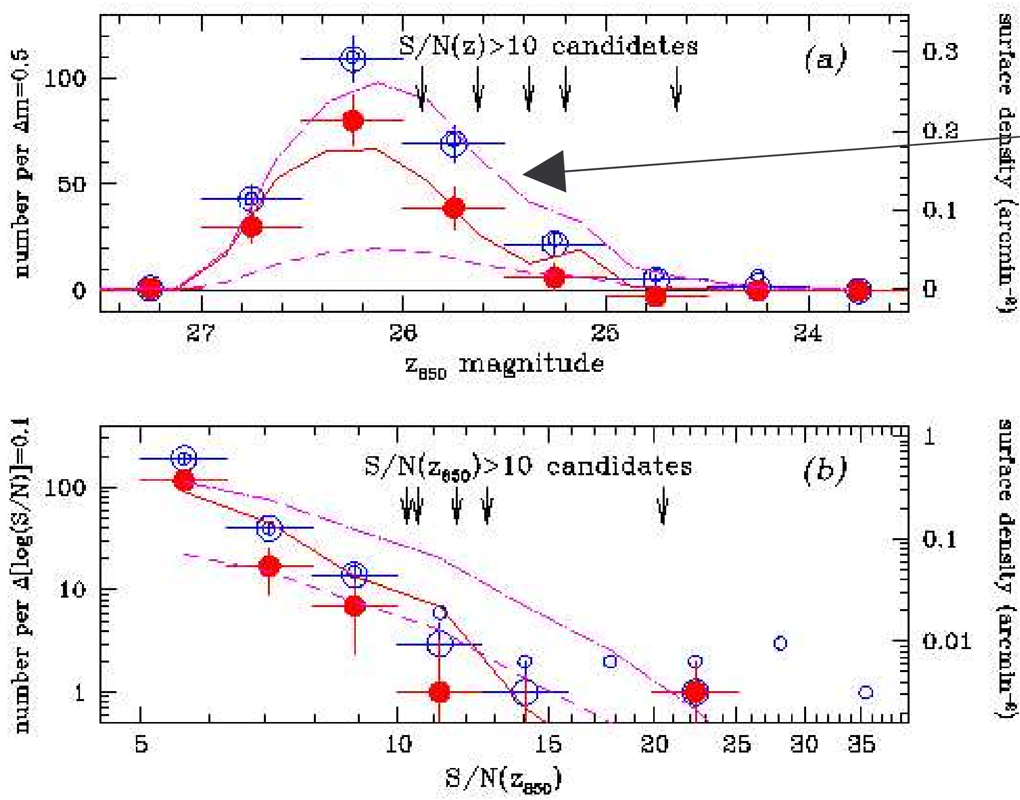
Reionization occurred at z~6 based on spectra of high−z quasars

What produced reionization? We don't know

−Not enough QSOs or X−ray sources at z ~ 6 to ionize universe (Barger et al. 2003)

−Lyman break galaxies could not have ionized universe either (Ferguson et al. 2002)

Galaxies at z > 6 : Faint and Low−mass systems



Predictions based on z~3 LBG luminosity function

Dickinson & GOODS team (2003)

Very few bright or massive systems at z > 6, confirmed also with Lyman−alpha searches (Kodaira et al. 2003)

<u>Consistent with hierarchical idea</u>

Summary

1. Through 2dF, Sloan, and deep pointed observations of clusters we are beginning to understand in detail the z~0 galaxy population.

2. New techniques utilizing 8–10 meter telescopes + HST now allow us to trace the evolution of galaxy populations from z ~ 7 to 0. The integrated stellar mass in the universe increases gradually throughout this time suggesting that galaxy formation does not happen all at once.

3. Galaxies at high redshifts are peculiar and are likely undergoing mergers. The transition from mergers to normal Hubble types occurs at about z~1.5. Calculations show that this picture is consistent with LBGs forming into modern Hubble types.

4. The source(s) of reionization are still unknown. The onset of galaxy formation is also not known with certainty, but likely occurs at z > 7.