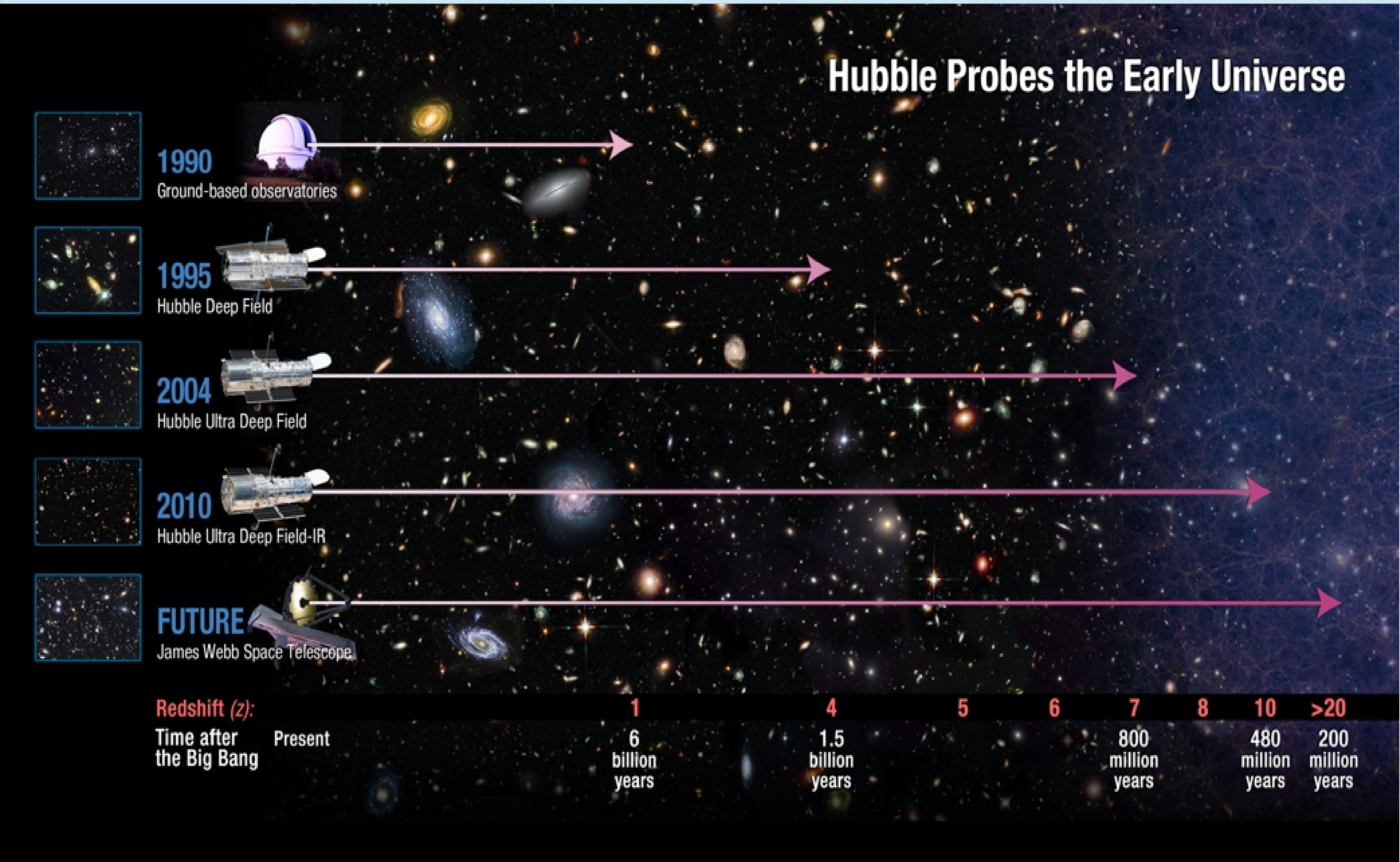
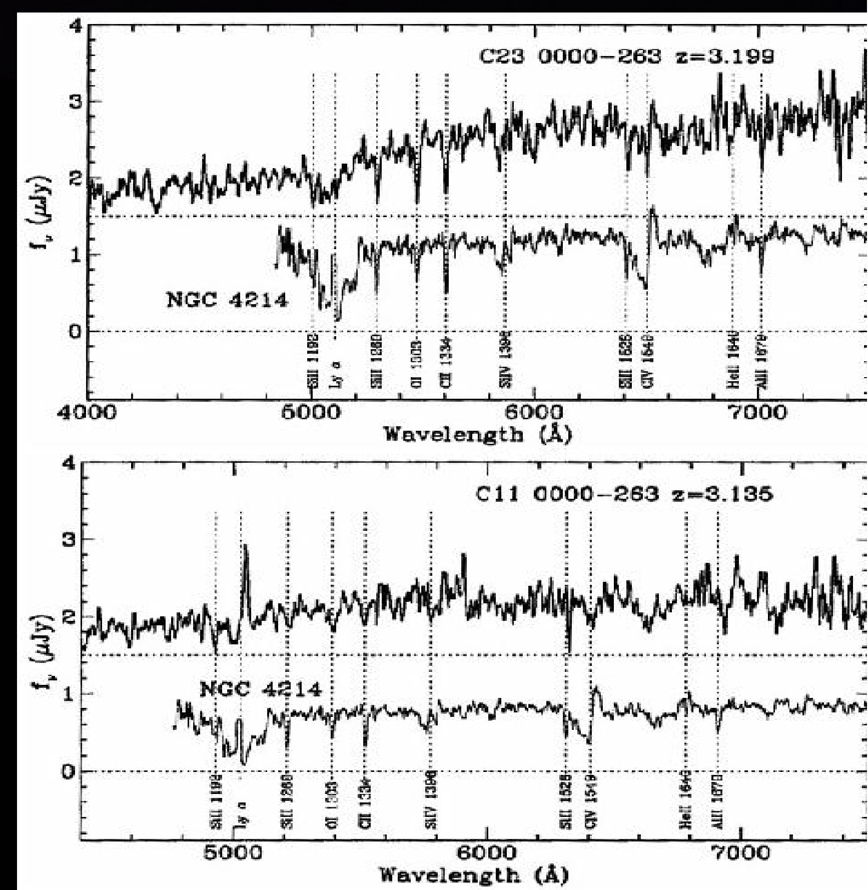
GALAXY EVOLUTION ACROSS COSMIC TIME

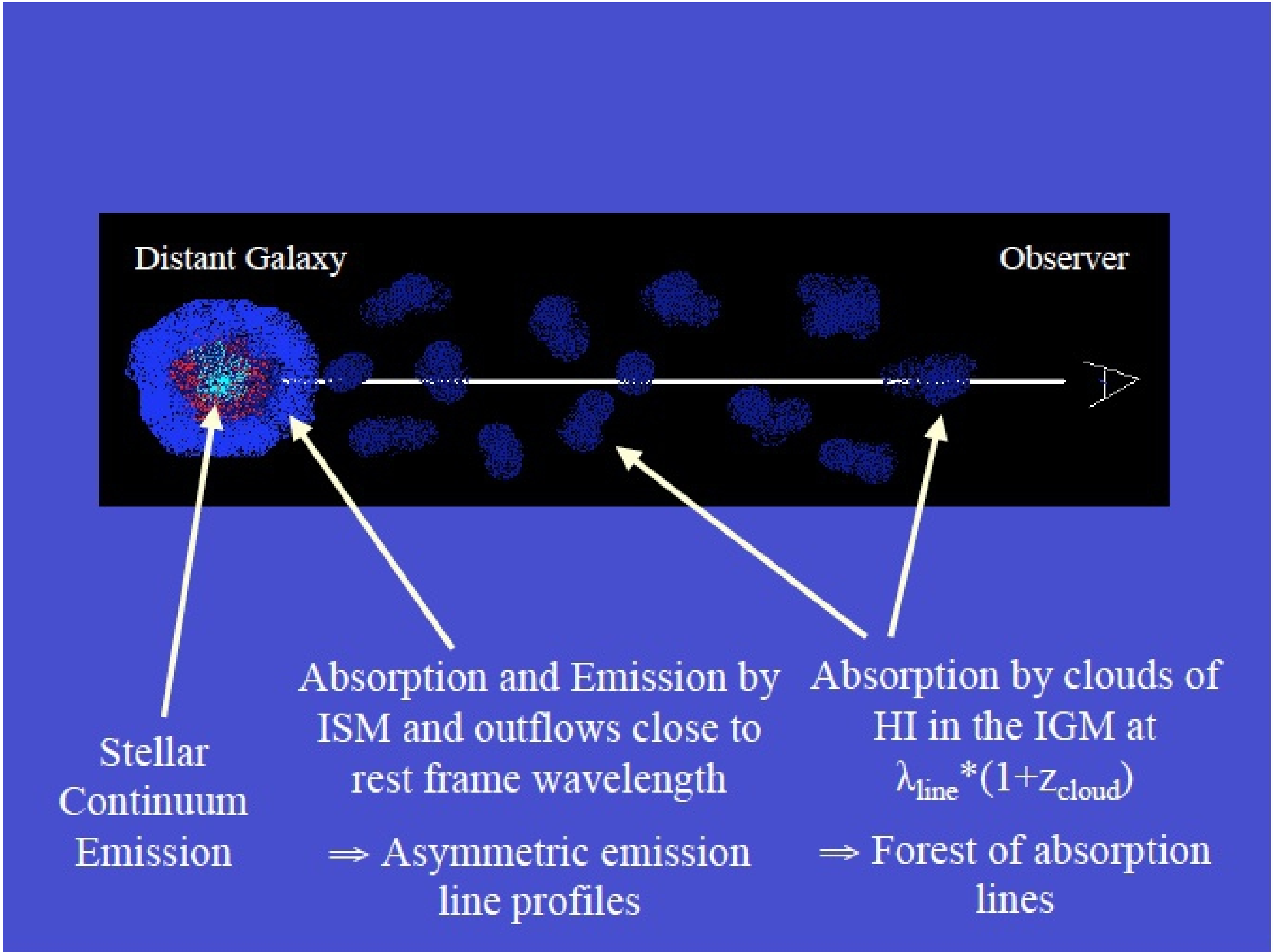


Hubble Ultra Deep Field
Hubble Space Telescope • Advanced Camera for Surveys

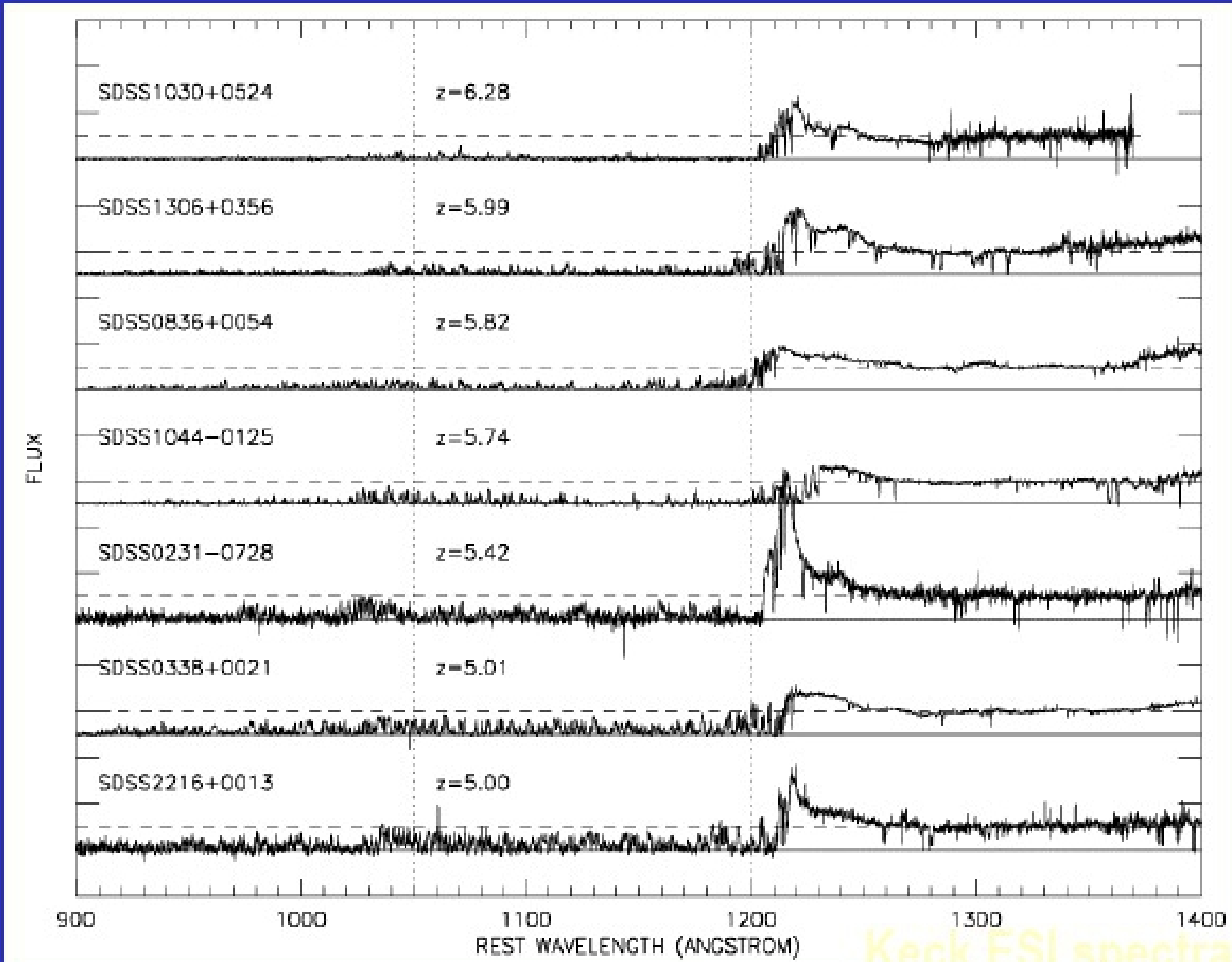
NASA, ESA, S. Beckwith (STScI) and the HUDF Team STScI-PRC04-07a



Finding high redshift galaxies:
1) The Lyman Break Technique

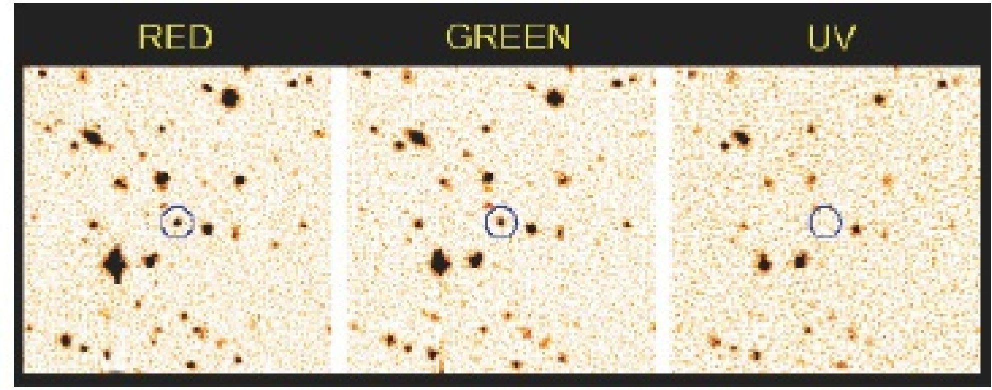


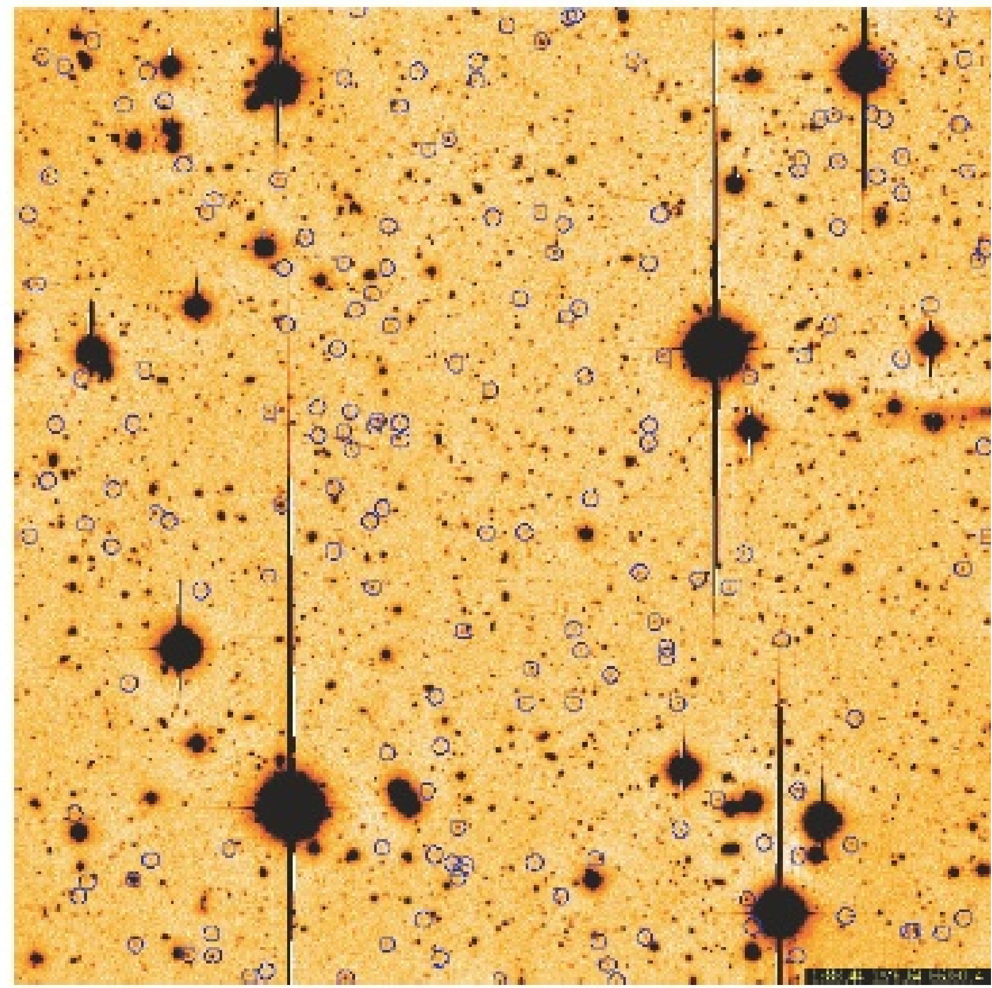
Intergalactic absorption provides a huge marker at high z



Lyman break galaxies

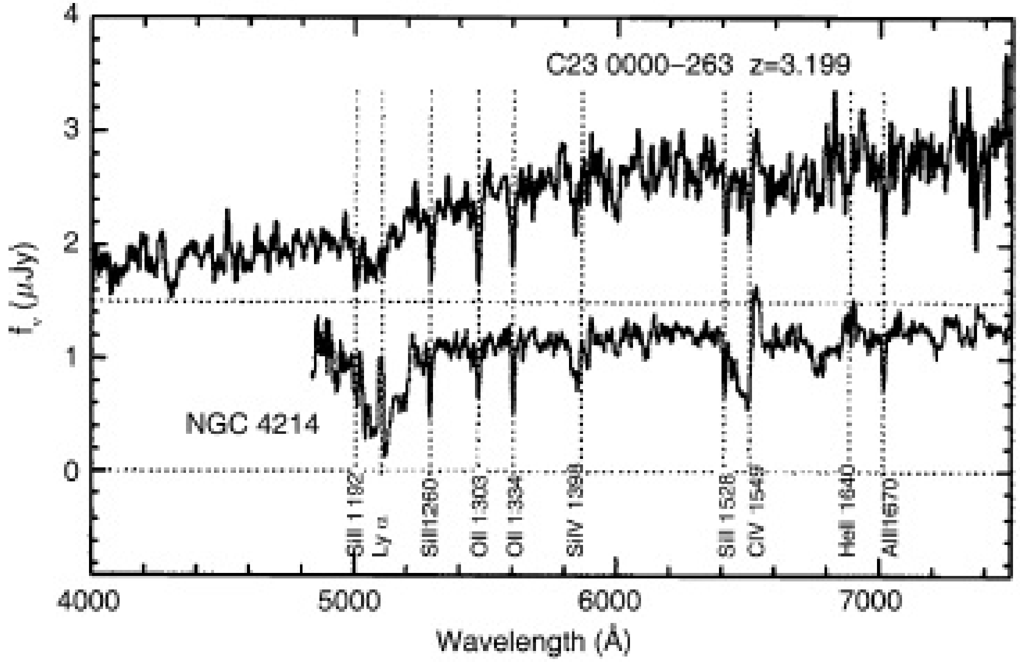
- Galaxy is visible in the two longer wavelength filters.
- Due to young stellar population, galaxy appears blue in these two filters.
- Expect galaxy to be brighter at shorter wavelengths, but it disappears or "drops out" due to absorption shortward of Ly α.
- Called Lyman break or drop out galaxies.
- Very effective technique to find large numbers of high z galaxies.
- Select z of interest by choosing filter bands.
- First done with U-band, so Lyman break often refers to galaxies found at $z \sim 3$.

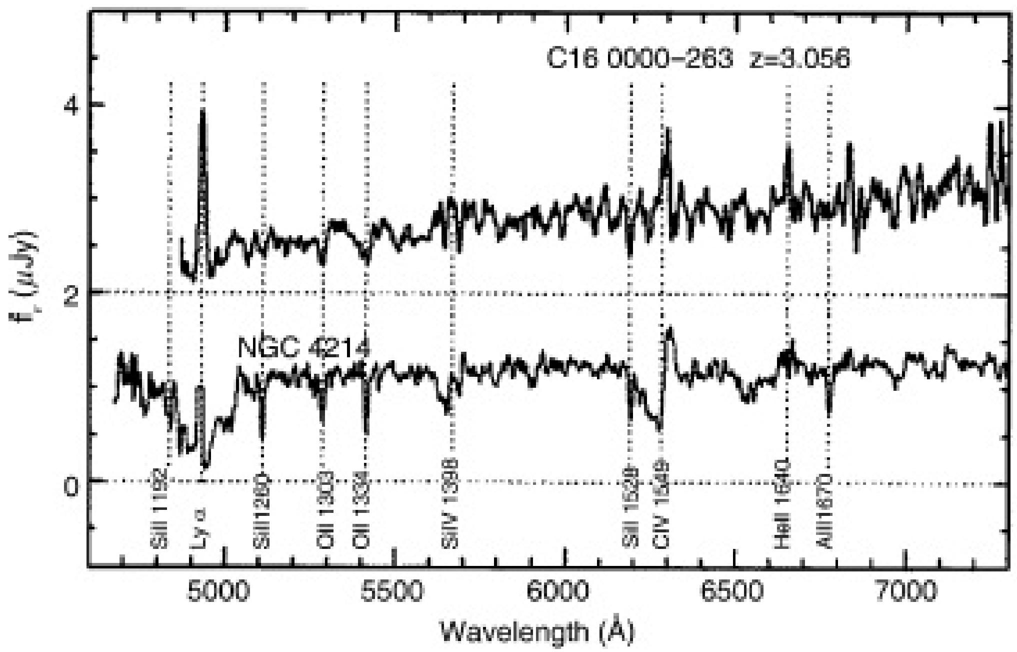




Lyman break galaxies

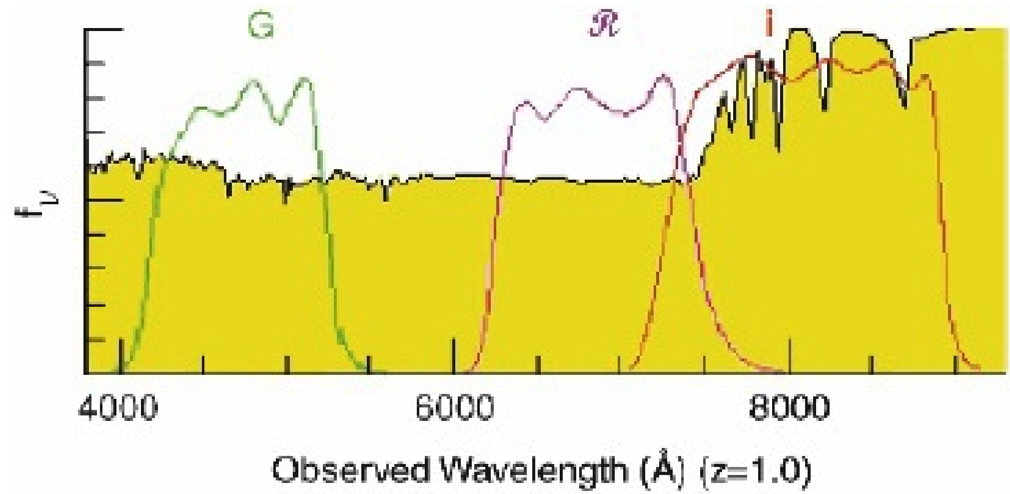
- Redshifts can be confirmed spectroscopically.
- Spectrum also reveals galaxy type.
- Tend to find star forming galaxies.
- Spectra are (typically) very similar to nearby star forming galaxies.
- Many of the galaxies lack a Ly α emission line.

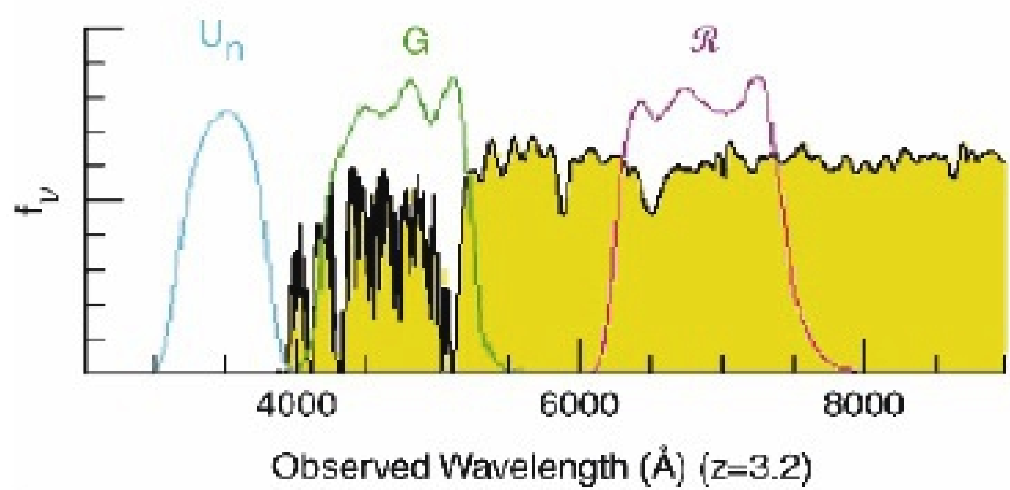




2) Photometric redshifts

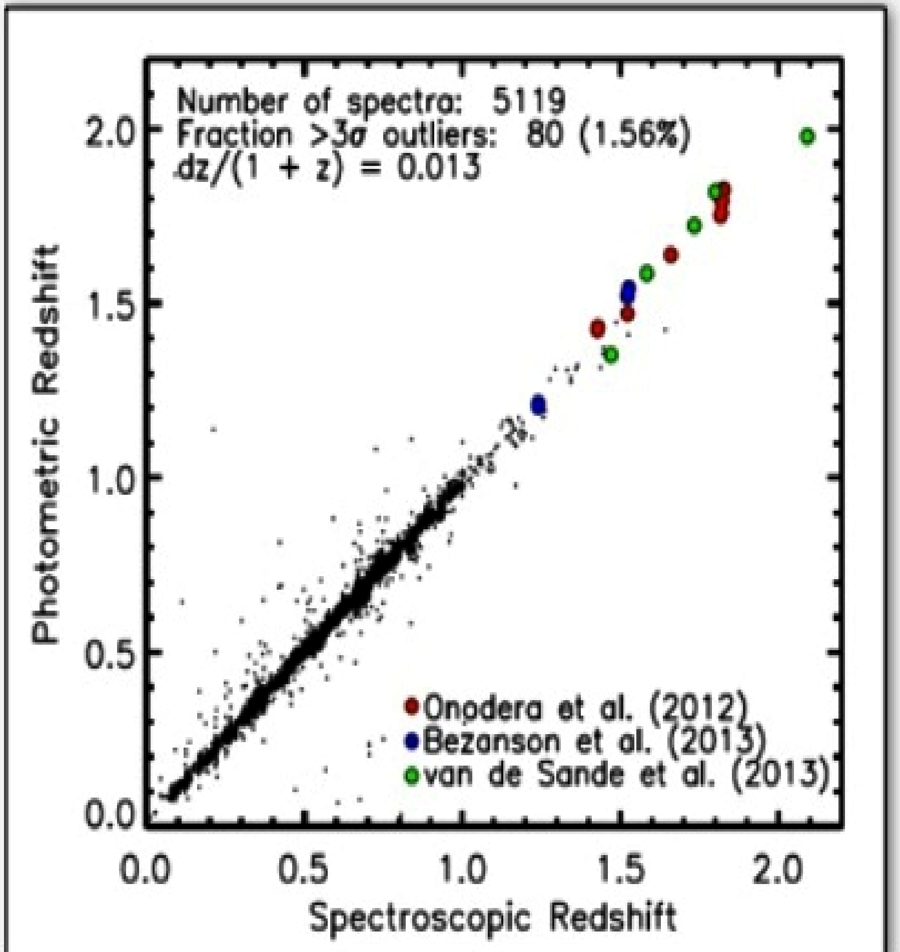
- Galaxies tend to have spectral features at the Lyman edge (~1000 Å) and at the Balmer edge (~4000 Å).
- Using photometry in multiple bands, preferably covering the optical and NIR, one can use these features to determine the galaxy redshift.
- The overall shape is determined by the galaxy type, so one fits for redshift and galaxy type simultaneously.





Catalog Overview

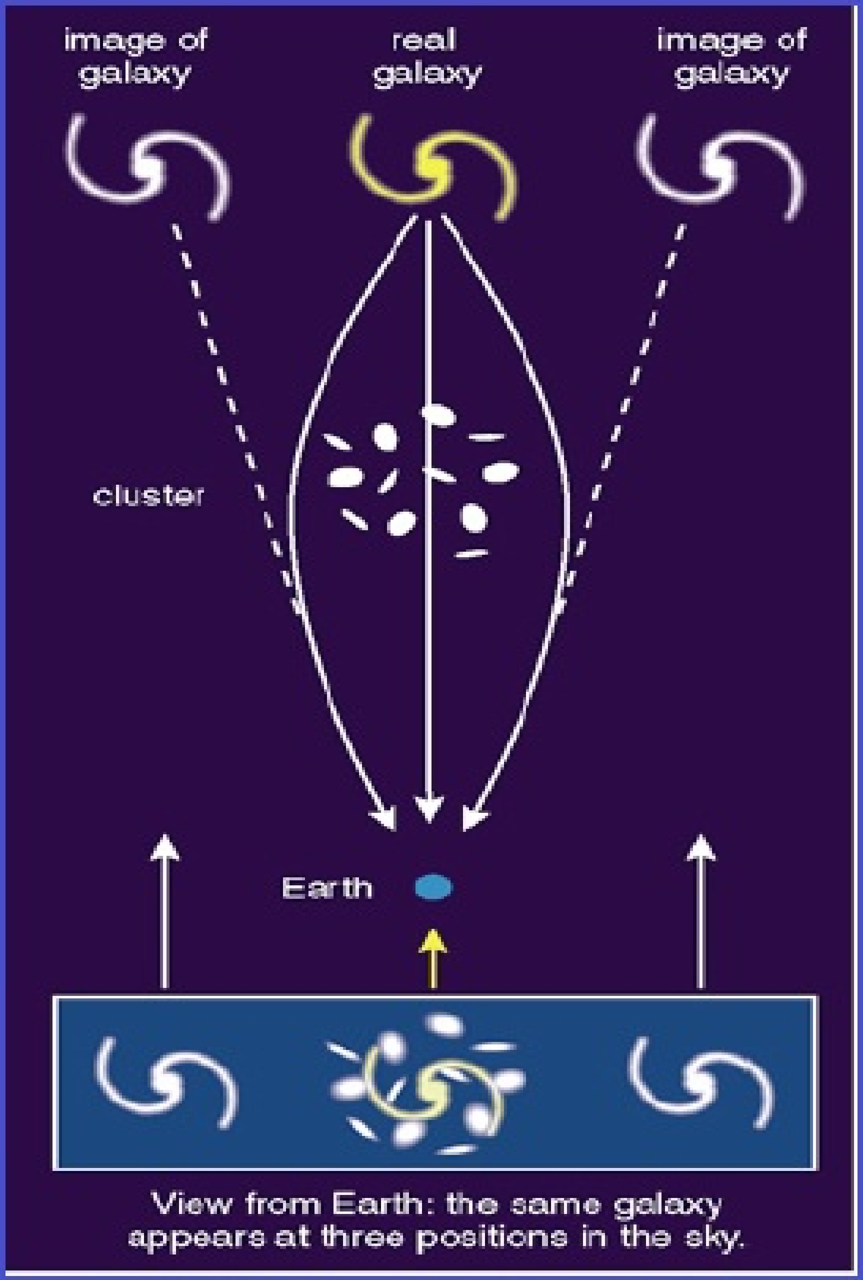
The current catalog release, v4.1 is a Ks-selected catalog of the COSMOS field based on the imaging from the DR1 UltraVISTA release. The catalog covers a total area of 1.62 deg^2, and has photometry in 30 bands including the GALEX, Subaru, CFHT, UltraVISTA, and Spitzer imaging. The 90% completeness limit of the survey is Ks,tot = 23.4 AB. Photometry has been determined in a color aperture by PSF matching all bands, including additional source-fitting for the large-PSF space-based imaging such as GALEX and IRAC/MIPS.



Photometric Redshifts

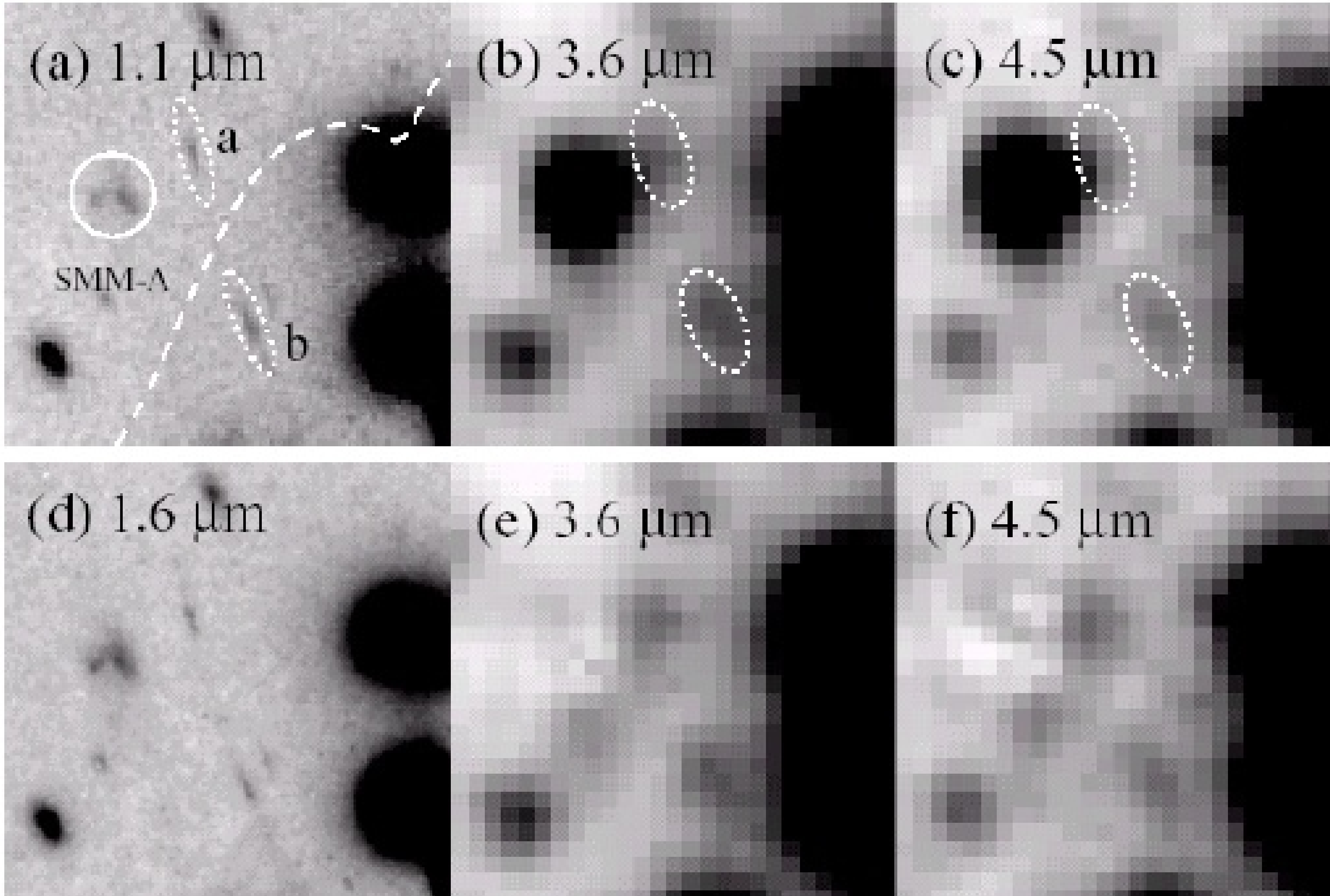
Photometric redshifts for galaxies have been calculated using the EAZY code. The agreement between the photometric redshifts and spectroscopic redshifts from the literature such as zCOSMOS is excellent, with an outlier fraction of 1.56% and an RMS of dz/(1+z) = 0.013.

3) Gravitational Lensing



To get even more sensitivity we can add a second cosmic telescope to our ground telescope

Spitzer Detection of Lensed z~6.8 Pair



IRAC flux densities: $f_\nu(3.6\mu m) = 1.2 \pm 0.3\ \mu Jy$

$f_\nu(4.5\mu m) = 1.0 \pm 0.2\ \mu Jy$

SED Implies Established Stellar Population @ z~7

Key parameters:

SFR = 2.6 $M_\odot$ yr^{-1}

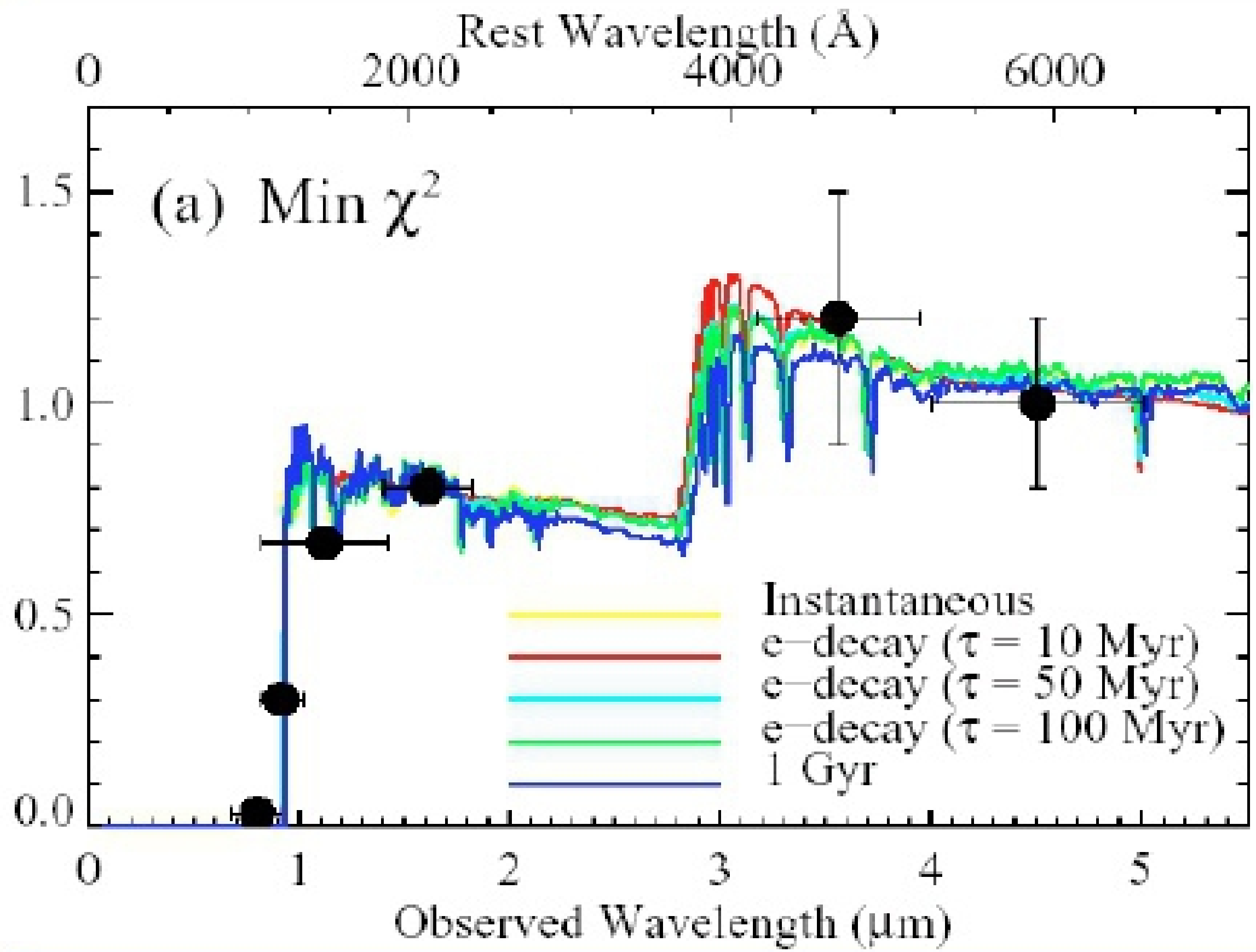
M_{star} ~ 5-10 10^8 $M_\odot$

z ~ 6.8 ± 0.1

age 40 – 450 Myr
($7 < z_F < 12$)

Age > e-folding SF time ⇒ **more luminous during active phase?**

(Egami et al 2005, Ap J 618, L5)



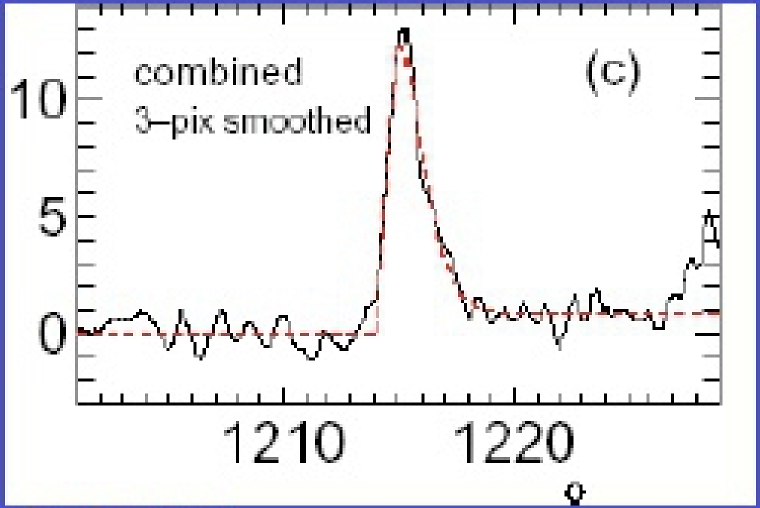
Given small search area, such sources may be very common

4) High z Lyman α Surveys

Origin: ionizing flux absorbed by H gas → Lyα photons

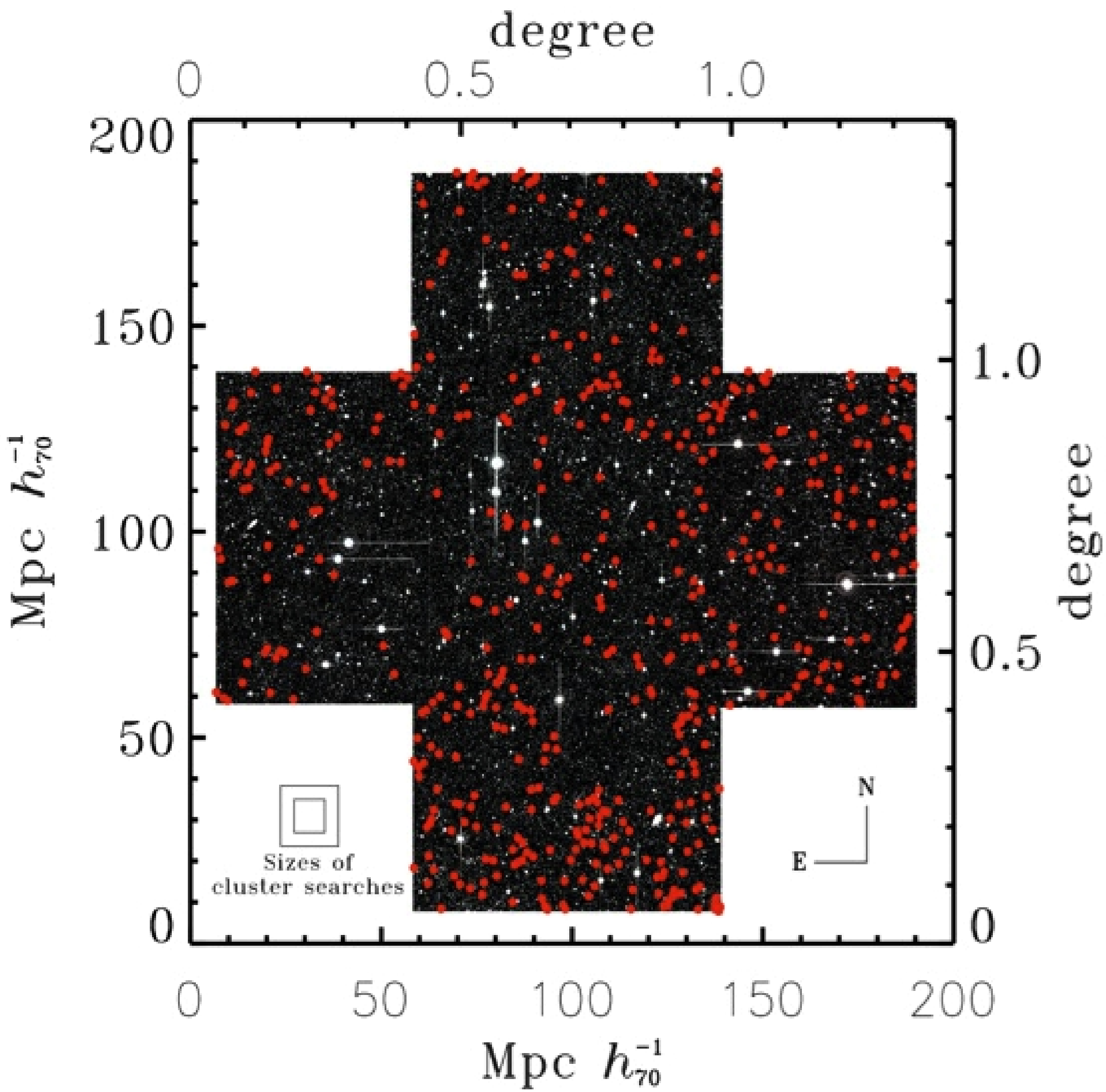
Efficient: < 6-7% of young galaxy light may emerge in Lα depending on IMF, metallicity etc.

1 $M_\odot$ yr^{-1} = 1.5 10^{42} ergs sec^{-1} (Kennicutt 1998)



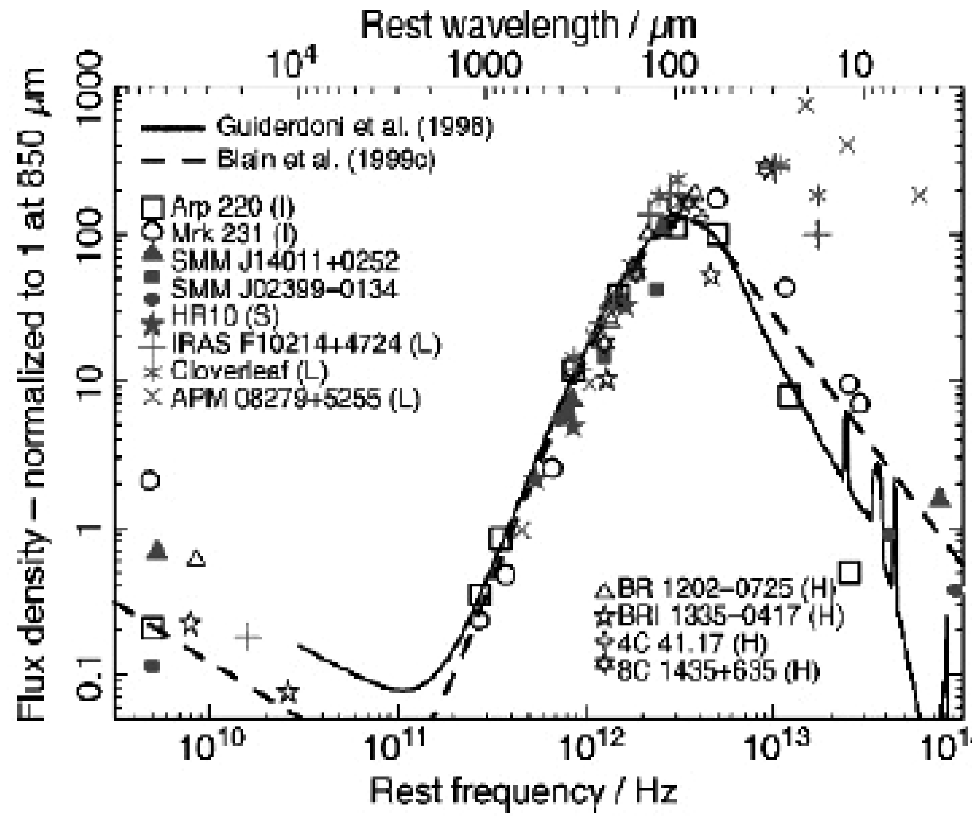
Complementary techniques:

- nb ($f_\alpha < 10^{-17}$ cgs, $L_\alpha < 5.\ 10^{42}$ cgs, SFR~3 $M_\odot$ yr^{-1}, V~2. 10^5 Mpc^3)
- lensed spectra ($f_\alpha < 3.10^{-19}$, $L_\alpha < 10^{41}$, SFR~0.1 $M_\odot$ yr^{-1}, V <50 Mpc^3)



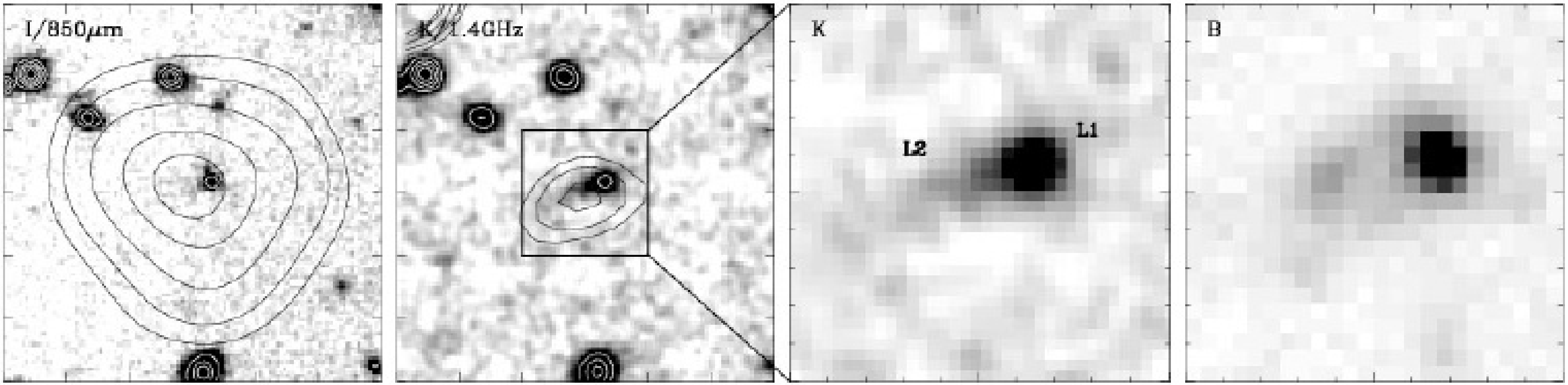
\scriptsize{9} {\bf Lyman Alpha Emitters at redshift $z = 5.9$} Red dots show the locations of Lyman Alpha Emitter candidates detected in narrowband-wideband image ratios. Large Scale Structure is apparent in the form of clusters and voids in the LAE locations. Plot from Ouchi et *al*. (2005) \protect \cite{ouchi05}, adapted by Kevin Bandura

5) Sub-mm galaxies



- Sub-mm telescopes (SCUBA) operating at 0.4-1.3 mm mainly see dust at 20-40 K.
- Spectrum $S_\upsilon \sim \upsilon^{2+\beta}$ with $1 < \beta < 2$. Redshift increases rest-frame υ and increasing spectrum leads to a negative K-correction.
- For $z_{max} > z > 1$, flux stays constant or increases.
- What sets z_{max}? For dust at 40 K and $\lambda \sim 0.85$ mm, $z_{max} \sim 8$.

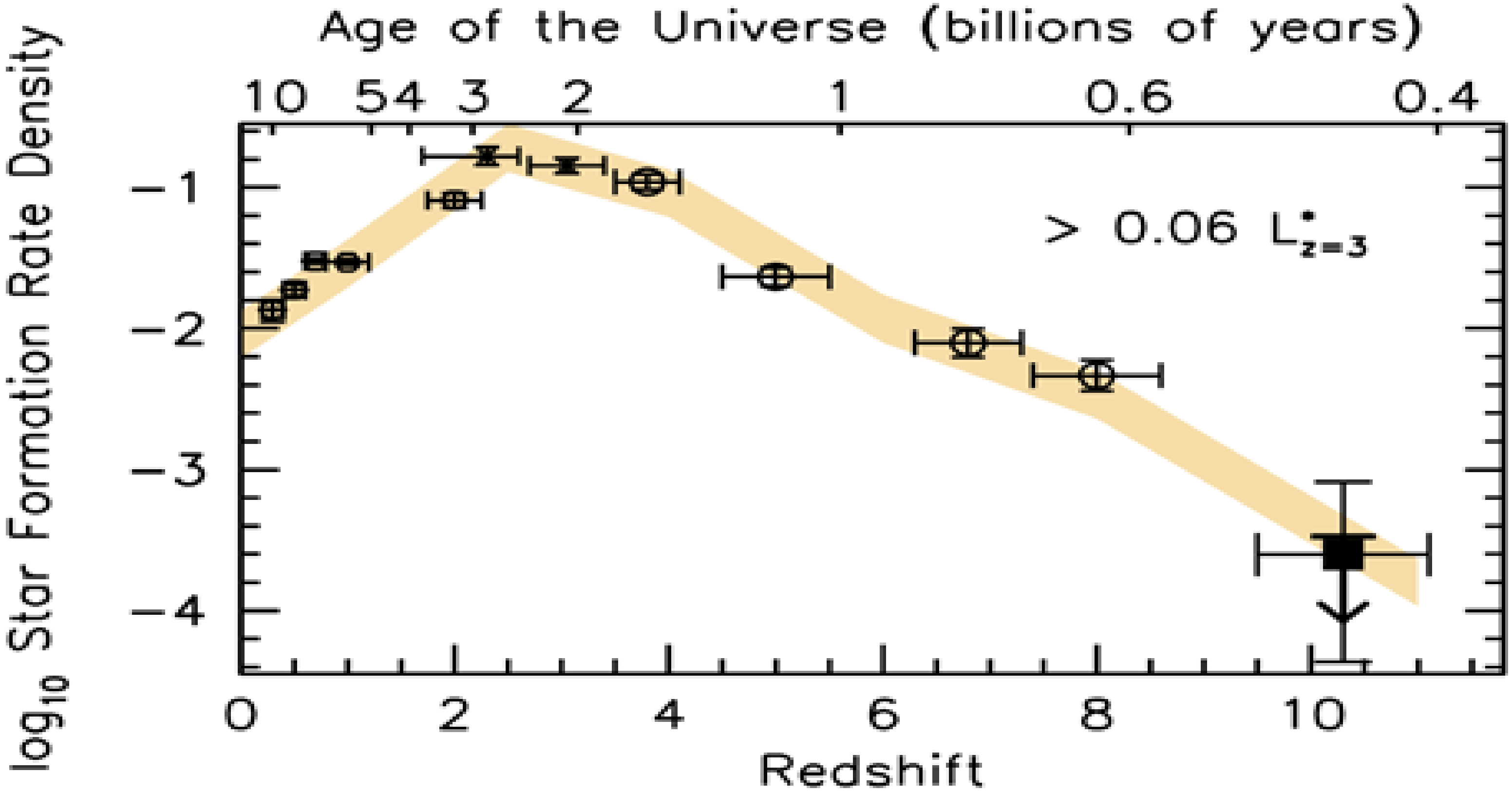
Sub-mm galaxies



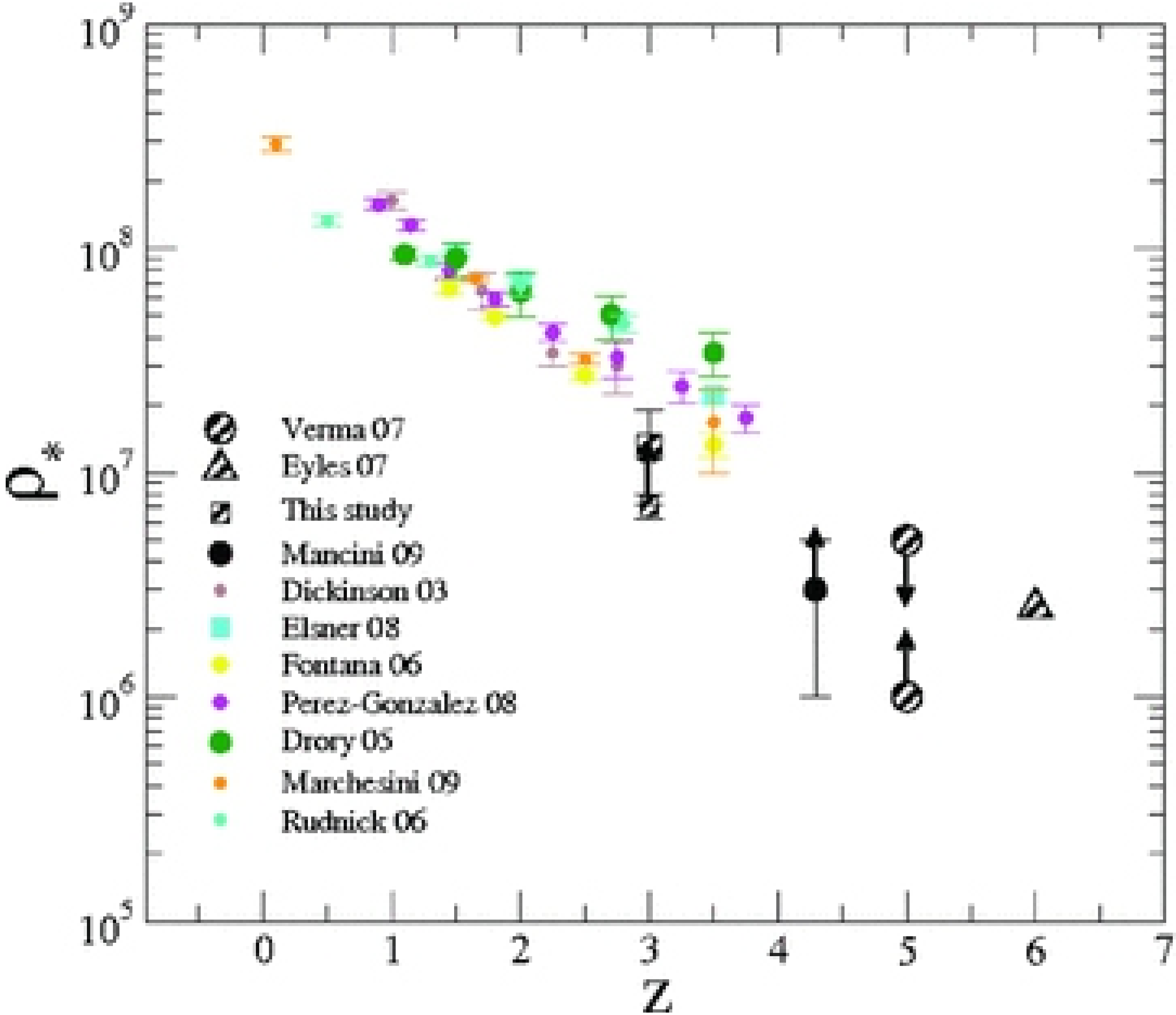
- SCUBA positions good to ~15" making optical identification difficult.
- Counterparts identified in radio with VLA (1.4 GHz, 1") and then in optical.
- Redshifts from optical or a sort of photo-z from radio/sub-mm flux ratio.
- Median $z \sim 2.5$. Galaxy masses $\sim 10^{11}\ M_{\rm Sun} \sim 10\times$ mass of LBGs.
- From mass, number density, and optical morphology, sub-mm galaxies are thought to be ellipticals in the process of formation.
- Many sub-mm have AGN revealed in X-rays, but X-ray/sub-mm ratio is low suggesting galaxies are dominated by star formation.

What are the main things learned from empirical studies of high redshift galaxies?

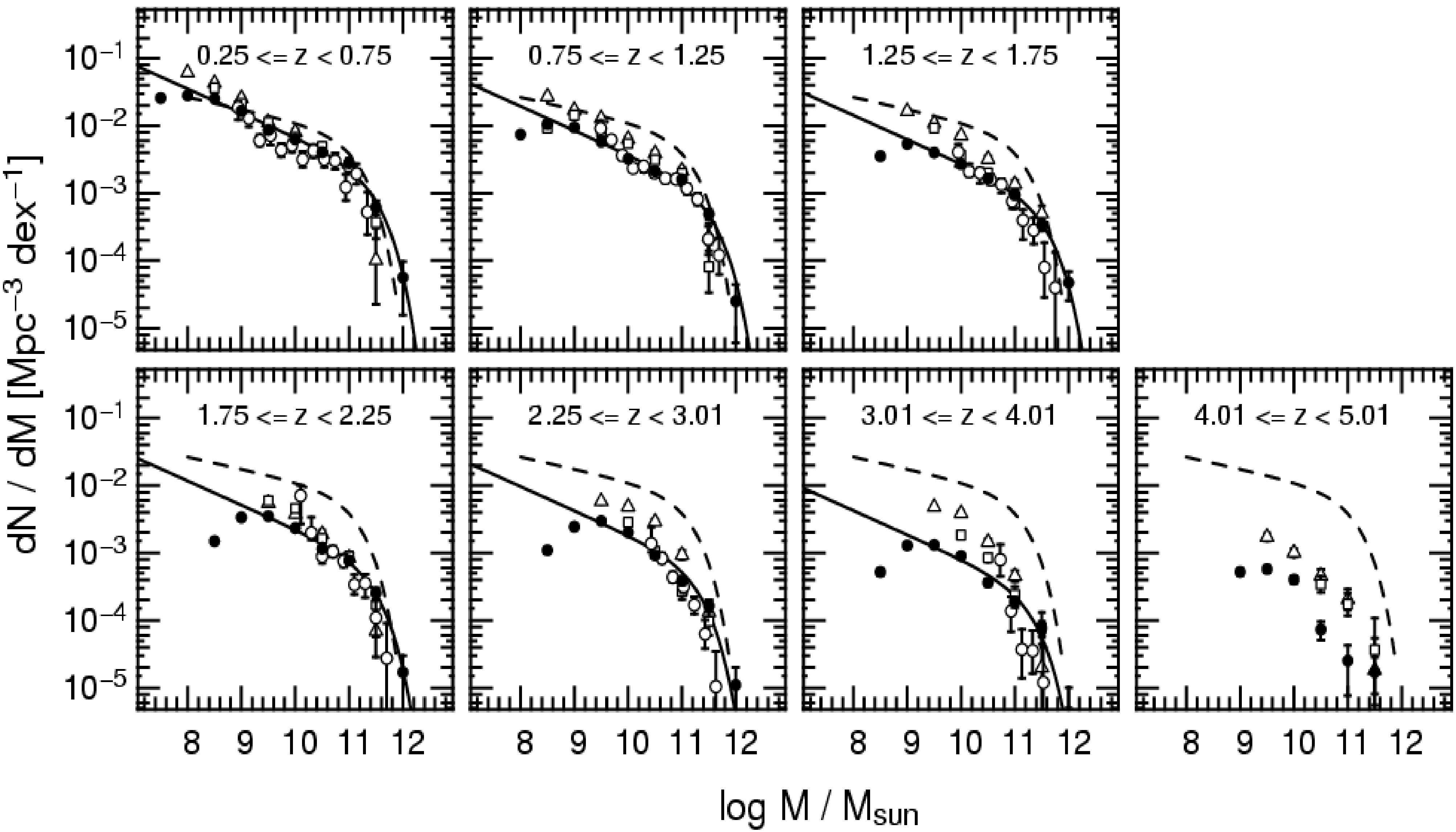
1) Rise and fall of the integrated star formation rate density in galaxies, with a peak at redshifts 2-3



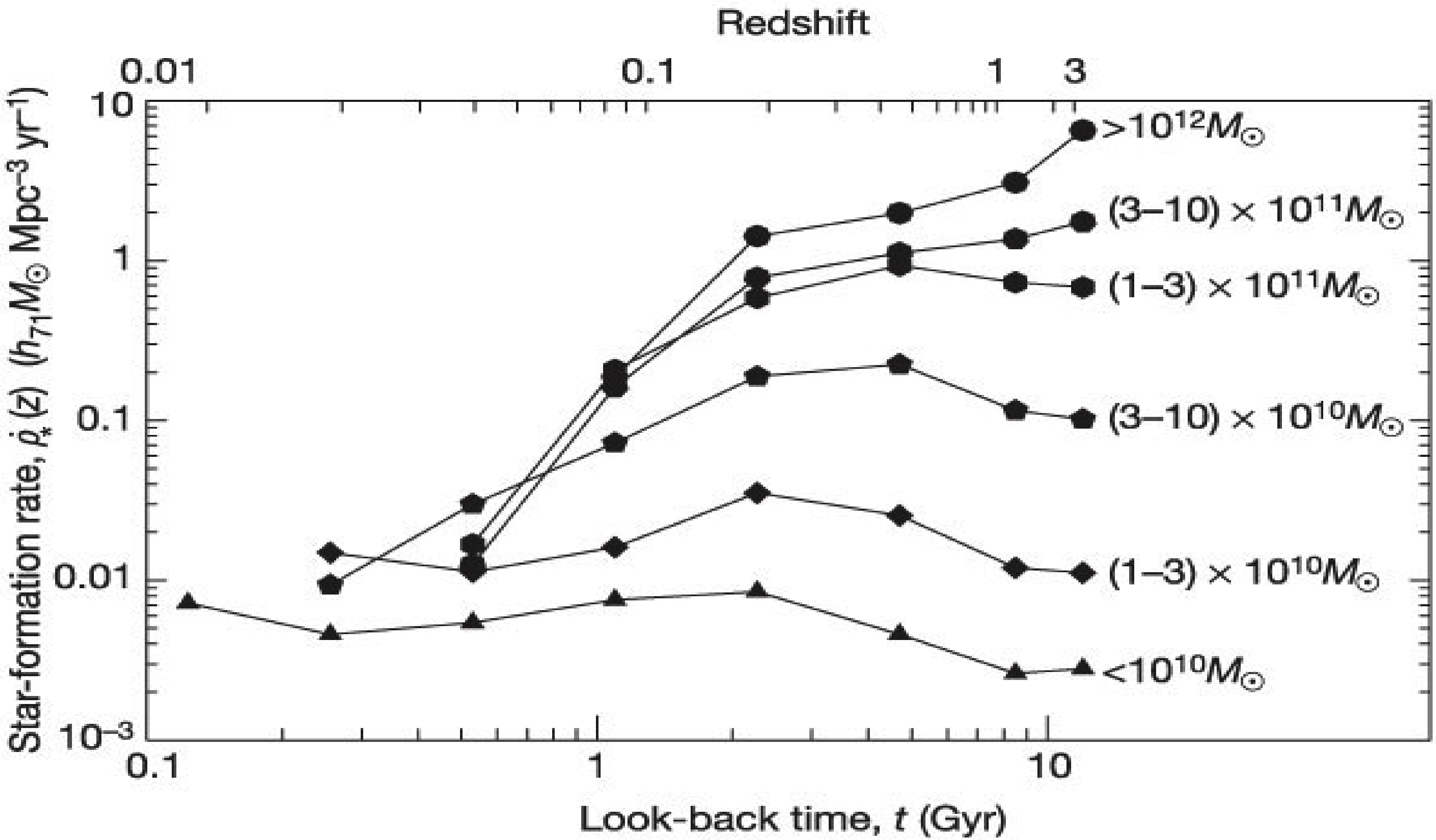
Buildup of the cosmic density of stars in galaxies



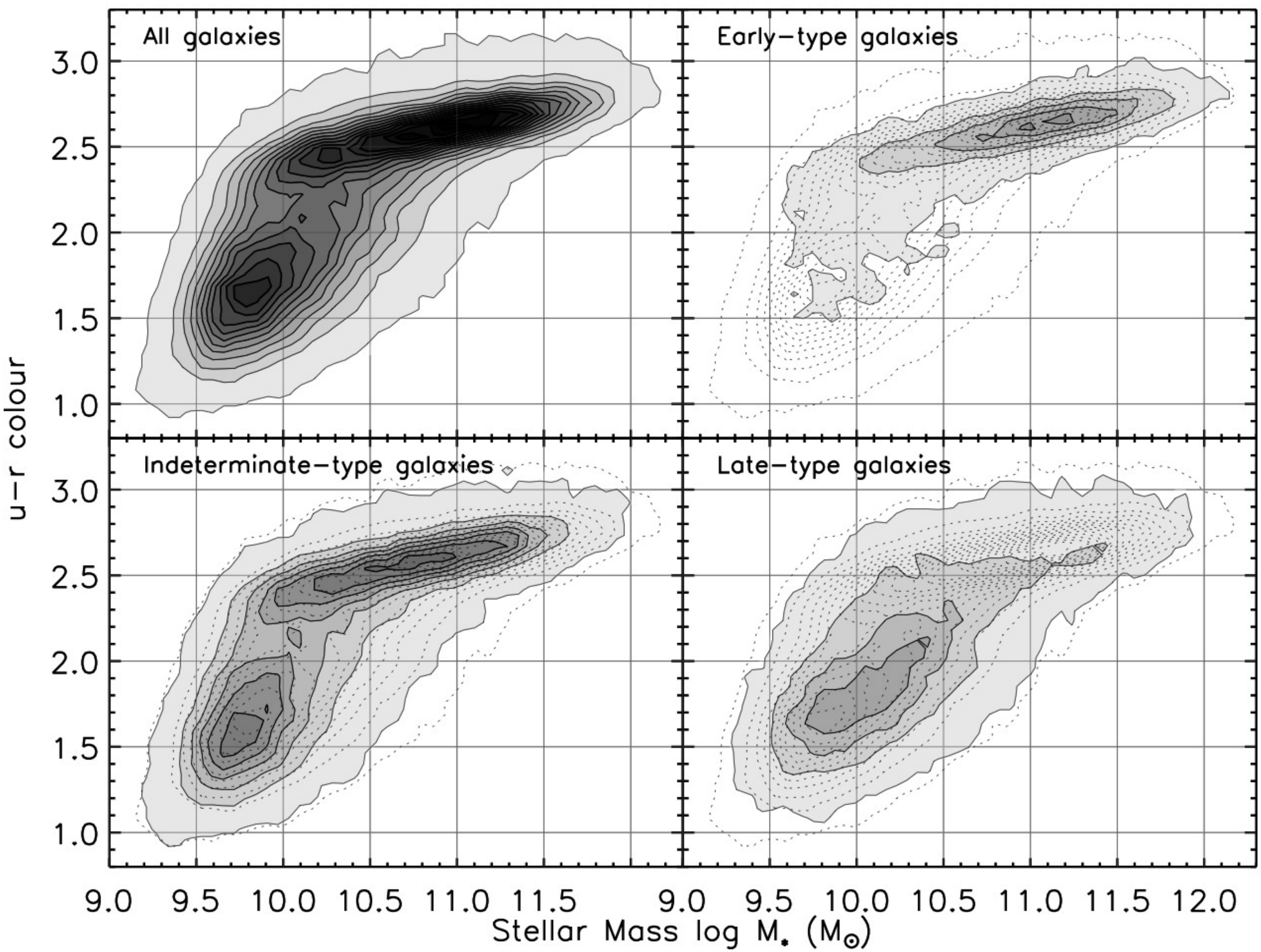
Evolution of the Stellar Mass Function to High Redshifts
(note recent rapid evolution at low mass end)



This is consistent with the star formation histories of galaxies as a function of mass inferred from studying their stellar populations at low redshifts



Colour Bimodality in Galaxy Population at z=0



Bimodality persists at higher redshifts

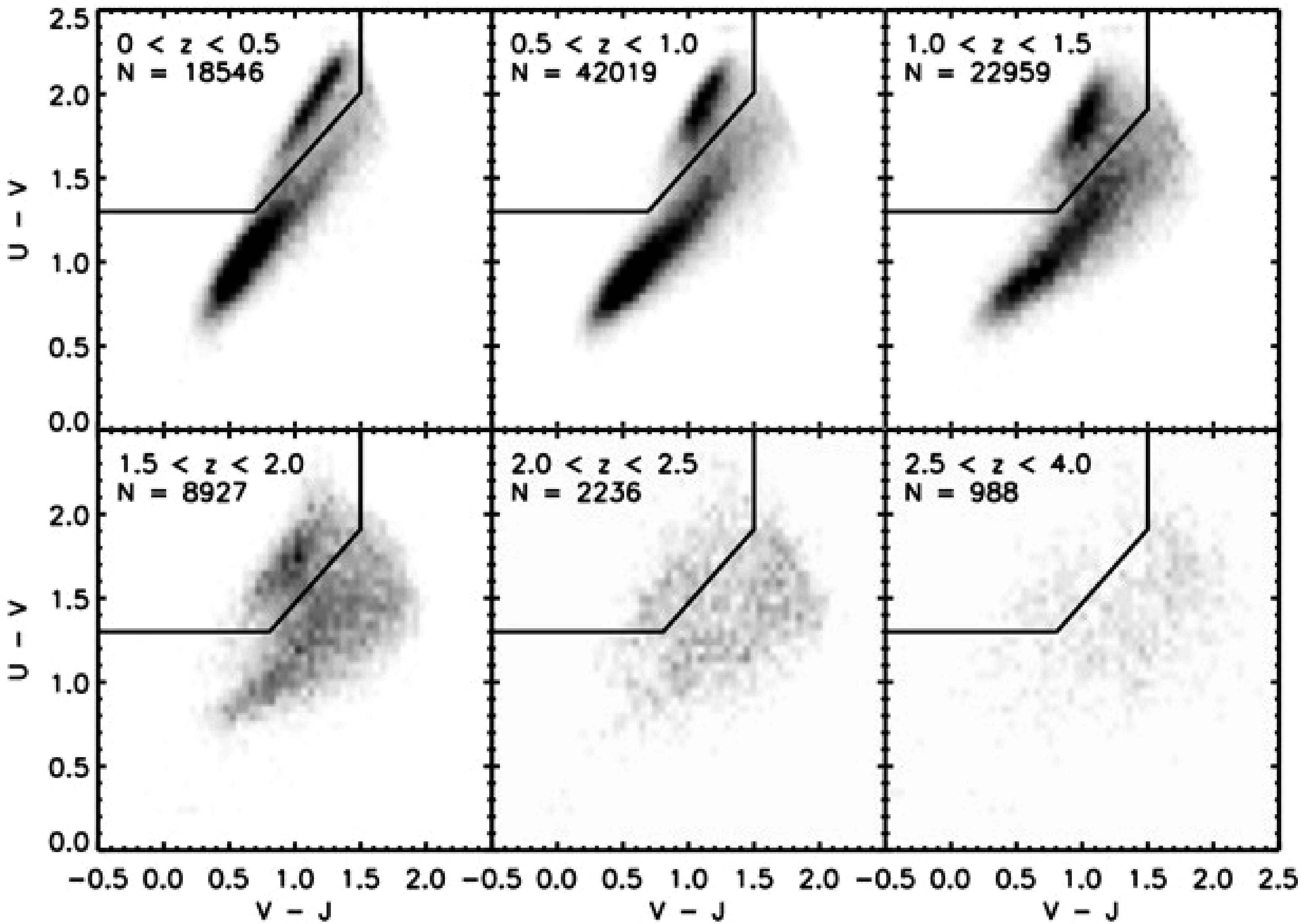
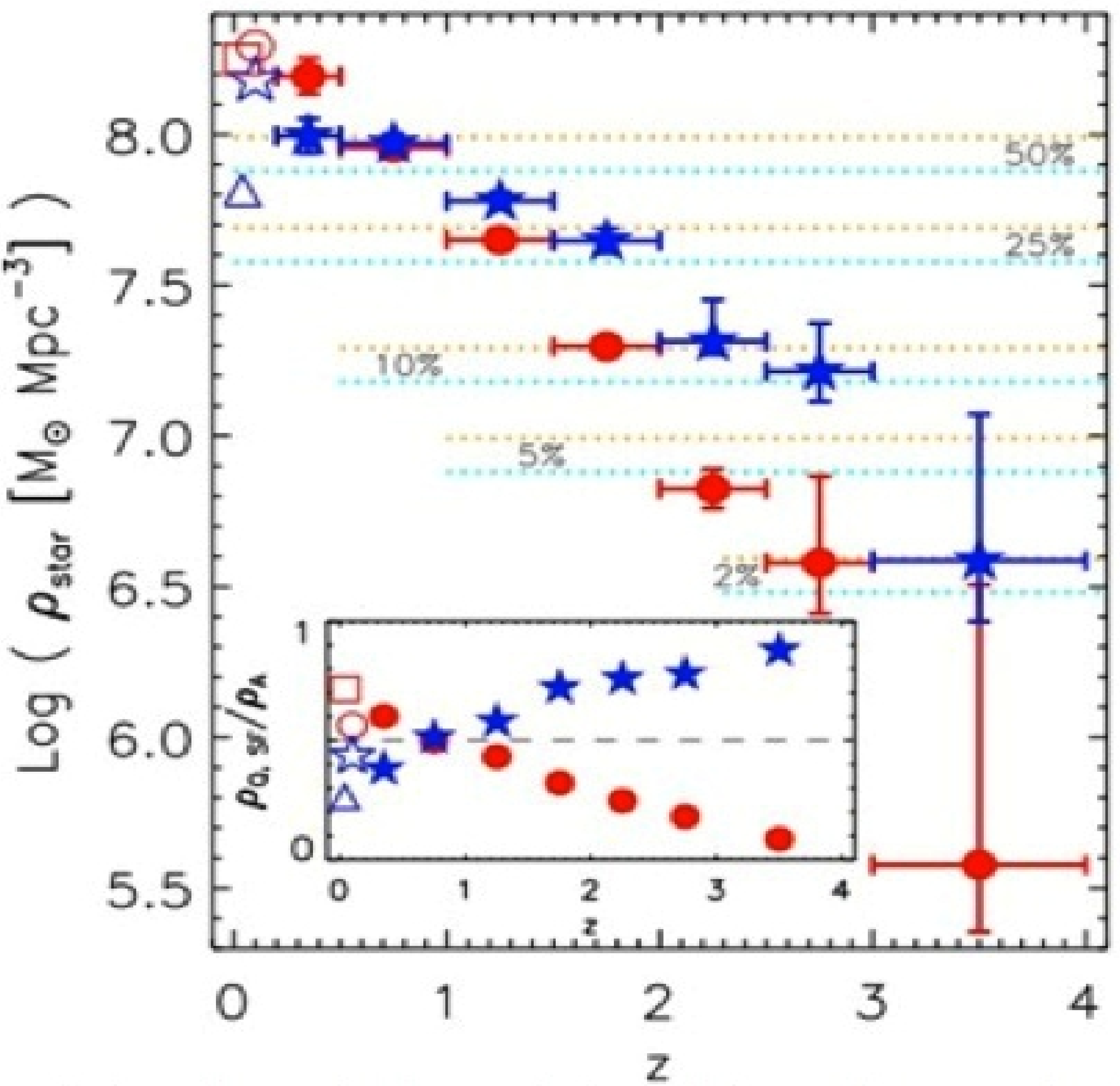


FIG.1. UVJ color-color diagram at various redshifts for galaxies more massive than the 95% mass-completeness limits. The bimodality in the galaxy population is clearly visible up to z=2. The cuts used to separate star forming from quiescent galaxies for the SMFs are shown as the solid lines.

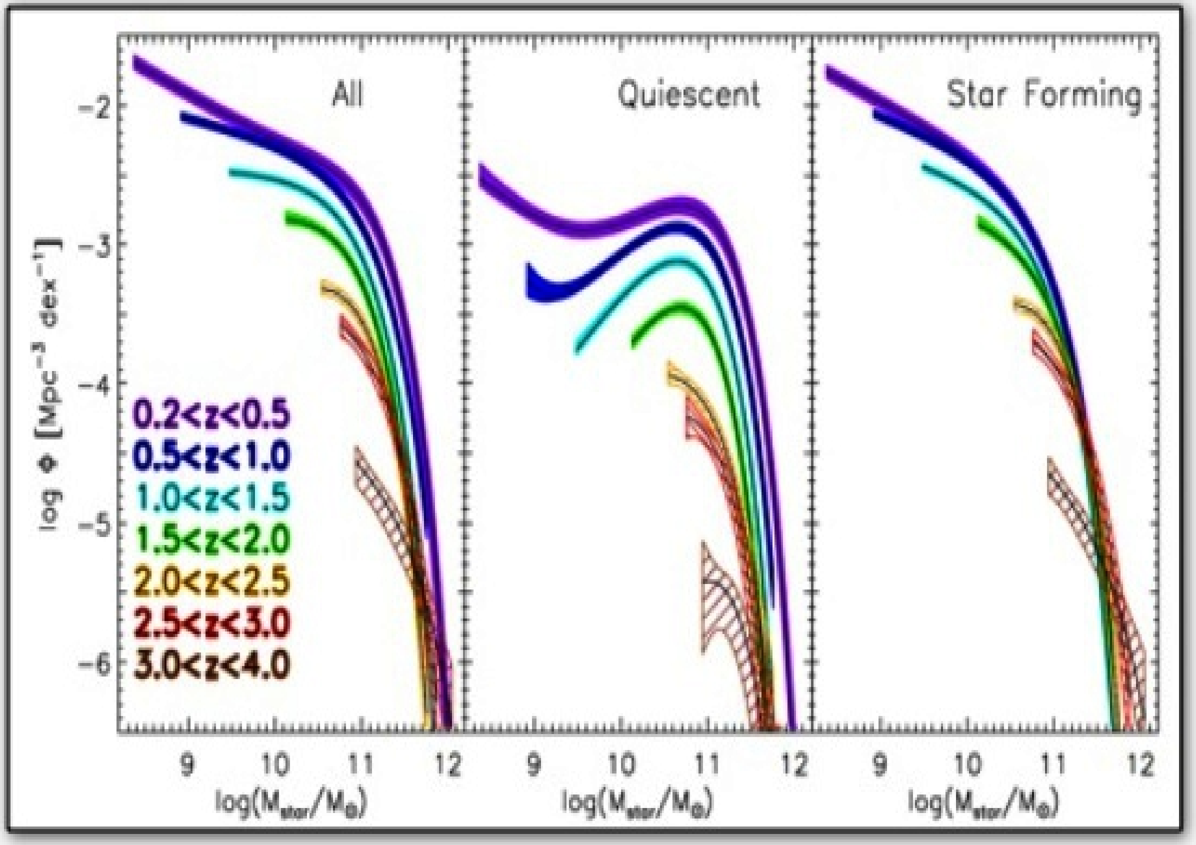
Stellar mass density in the red sequence drops faster than that in the blue cloud



Most of the evolution is at the low mass end for both classes....

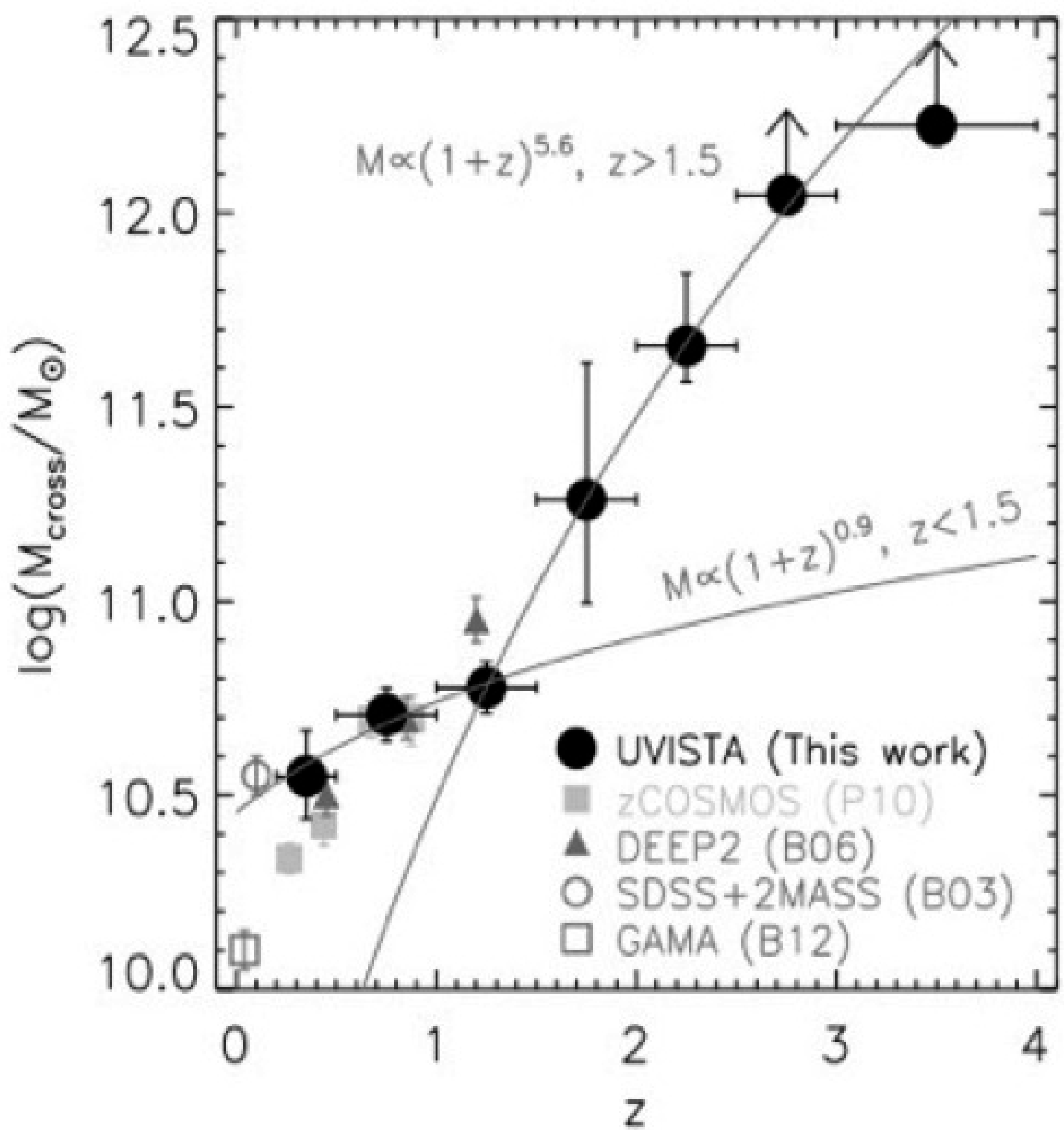
Stellar Masses

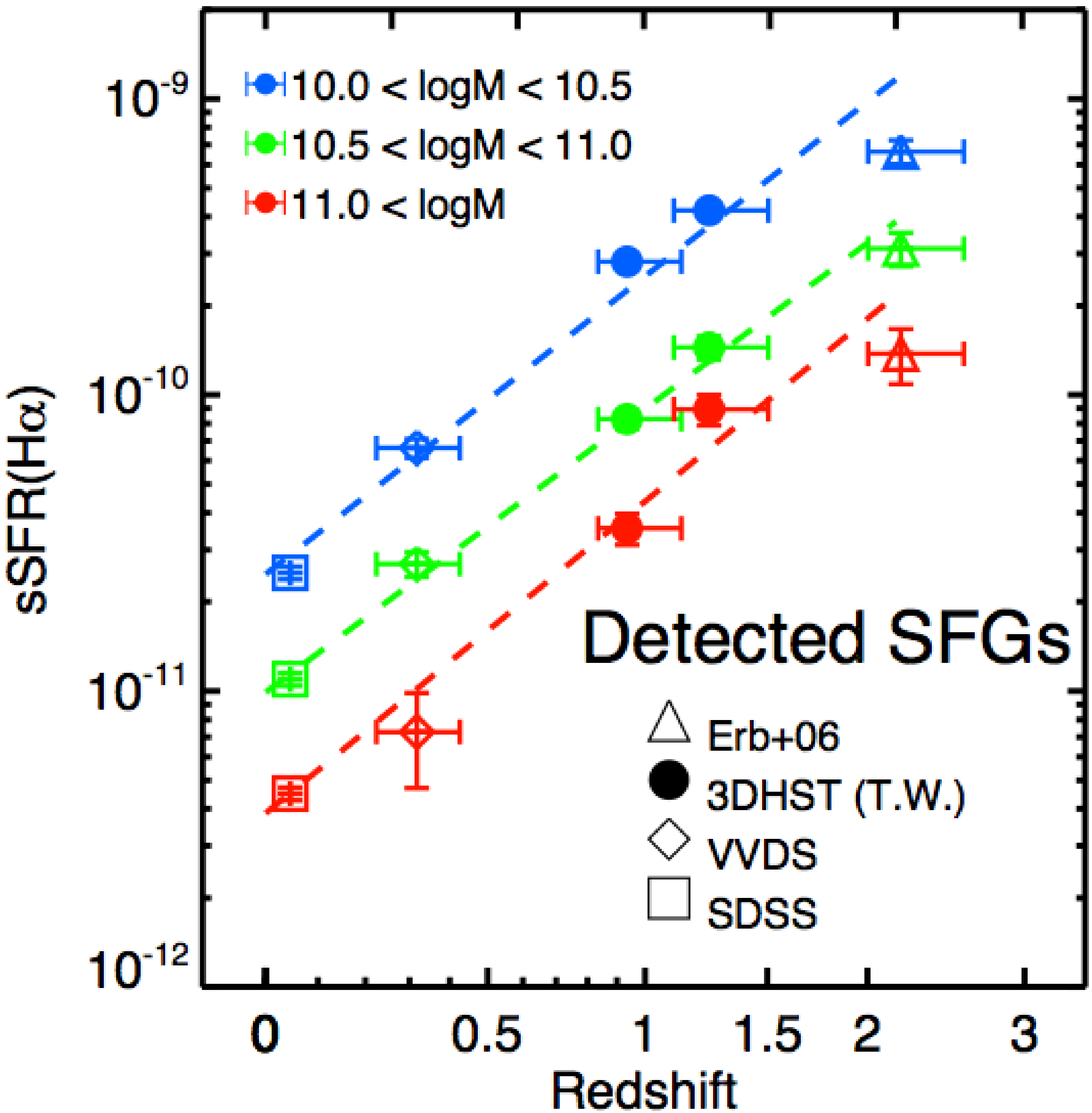
Stellar masses and other population parameters are calculated for all galaxies using the FAST code. These are determined from fitting the SEDs of the galaxies to models such as Bruzual & Charlot (2003) and Maraston (2005). FAST also outputs stellar population parameters such as ages and star formation rates. All of the best-fit SEDs from the FAST fits are available in the data products page.



Evolution of the stellar mass at which quiescent galaxies dominate over star-forming galaxies

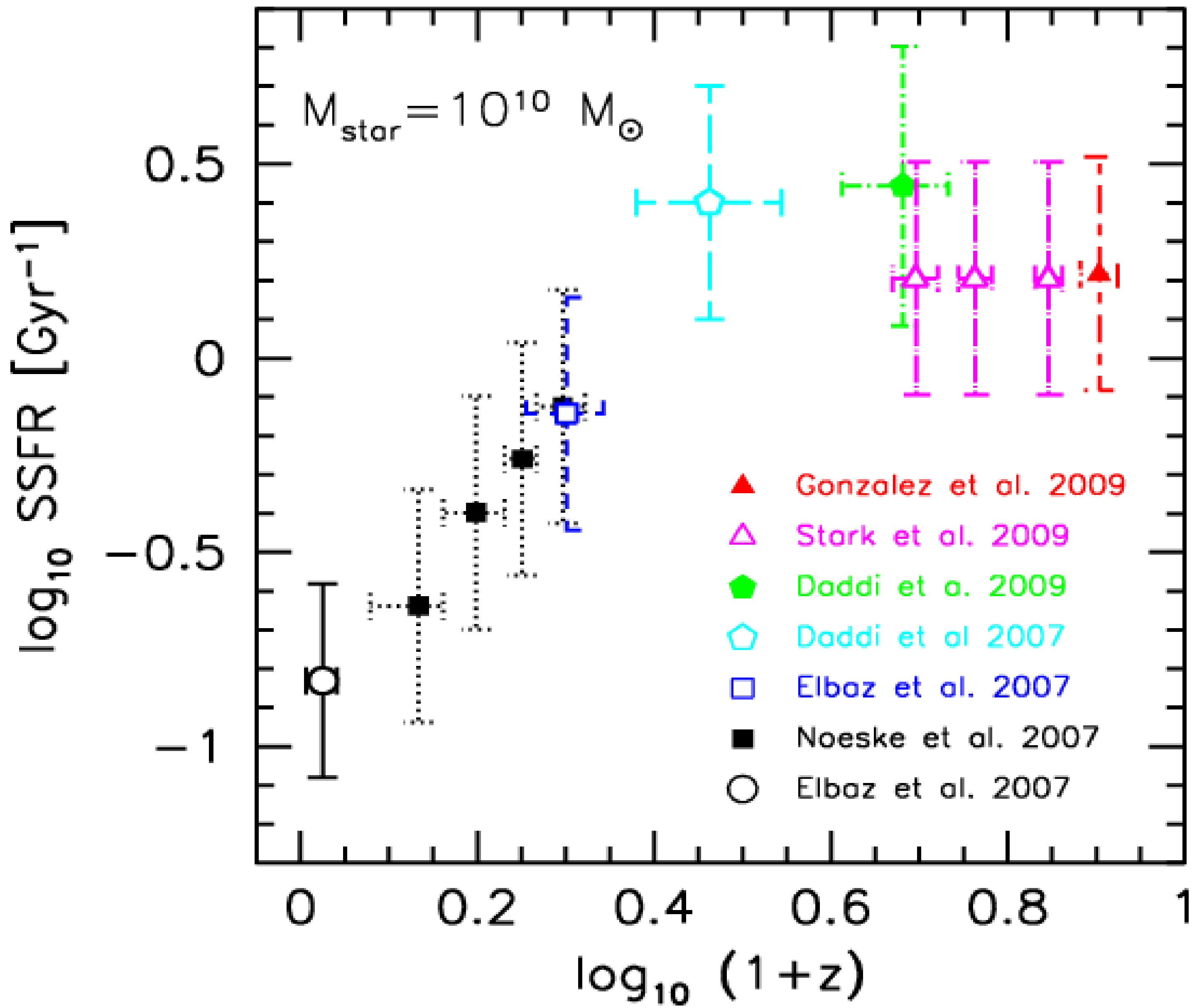
FIG.6. The M_{star} at which quiescent galaxies dominate over star-forming galaxies (M_{cross}) as a function of redshift. Measurements from other surveys are shown and agree reasonably well with the UltraVISTA measurement. Quiescent galaxies dominate the high-mass end of the SMF up to z~1.5. Thereafter star-forming galaxies quickly become dominant at all M_{star}.



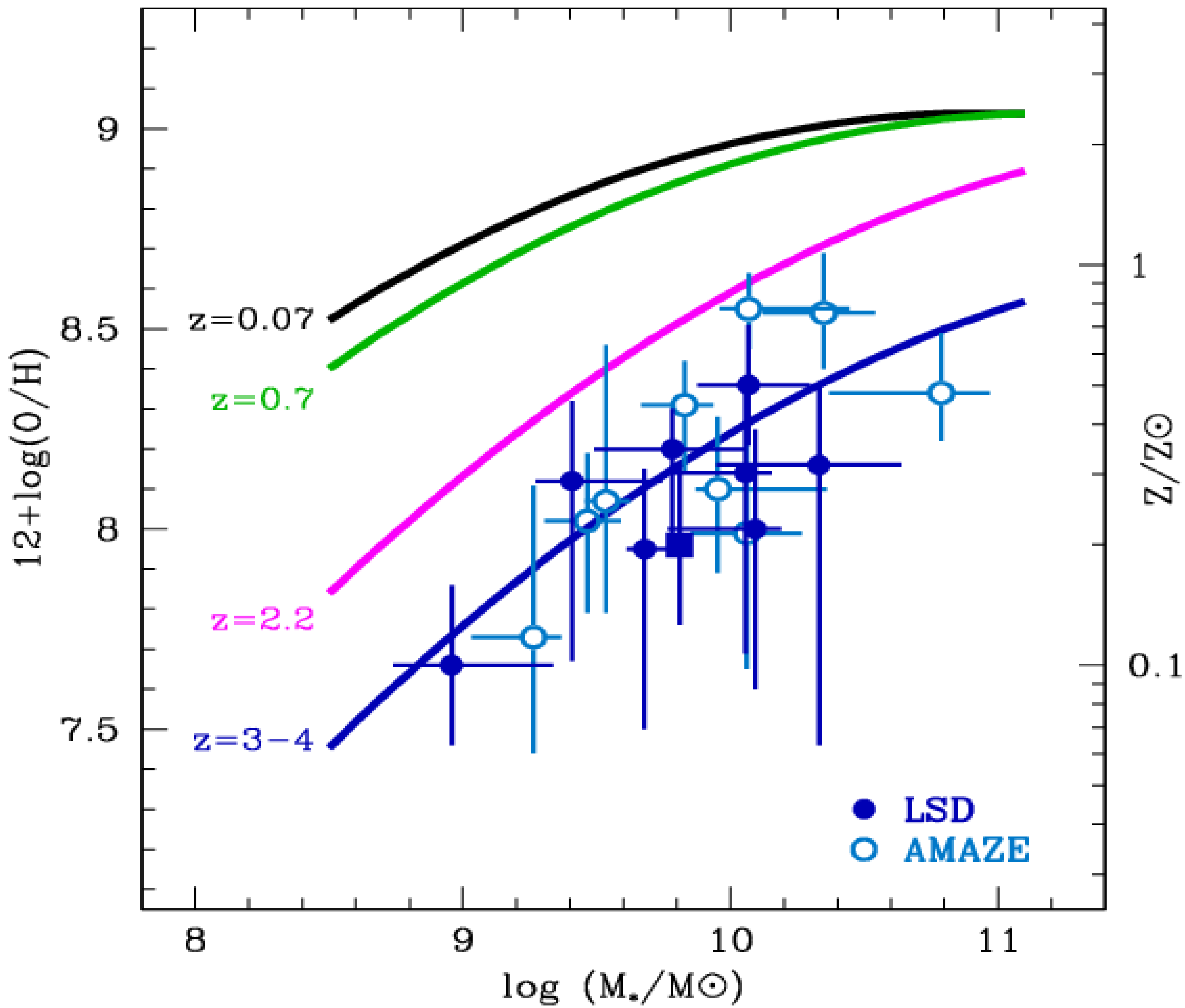


Evolution in star formation rate per unit mass (specific SFR) for star-forming galaxies

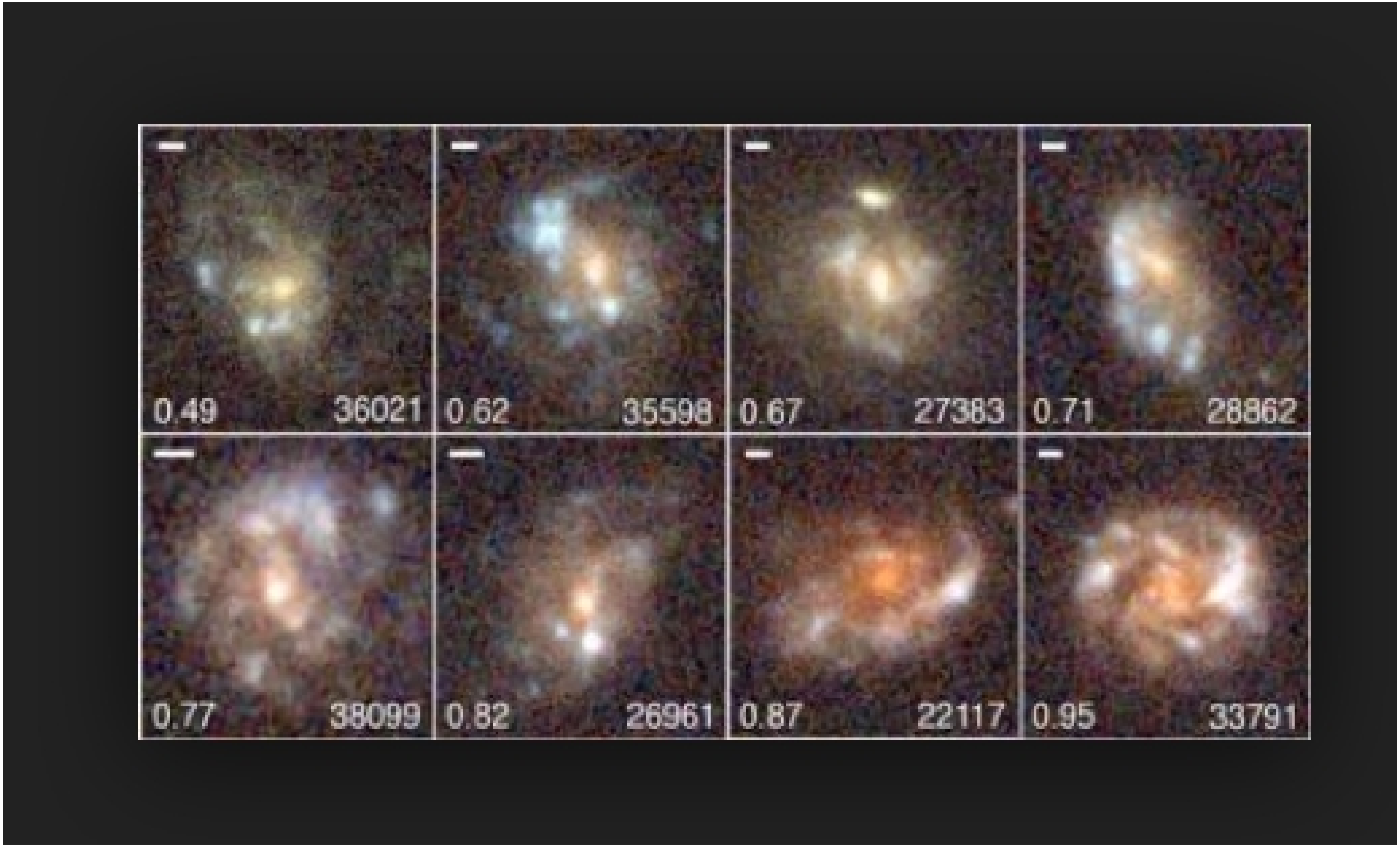
Evidence for flattening in sSFR at fixed M* beyond z=2?



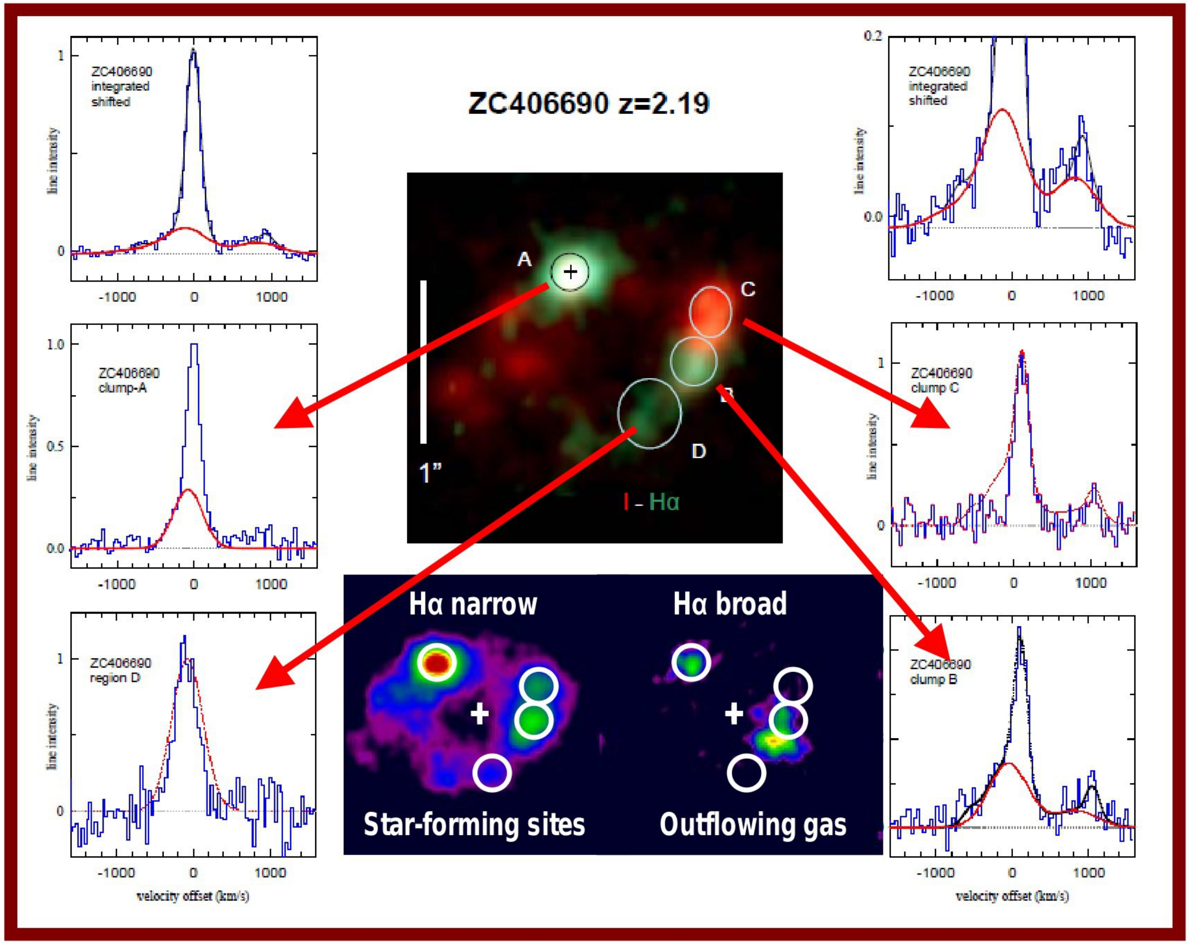
At fixed stellar mass, the gas metallicities of galaxies are lower at higher redshifts

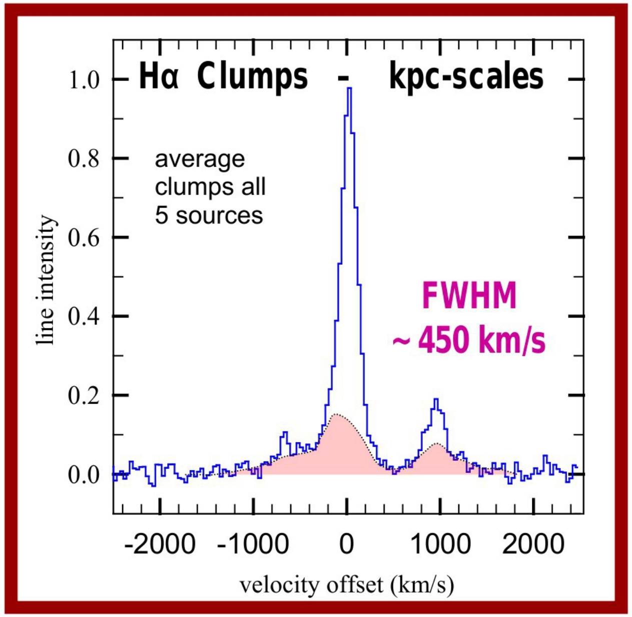


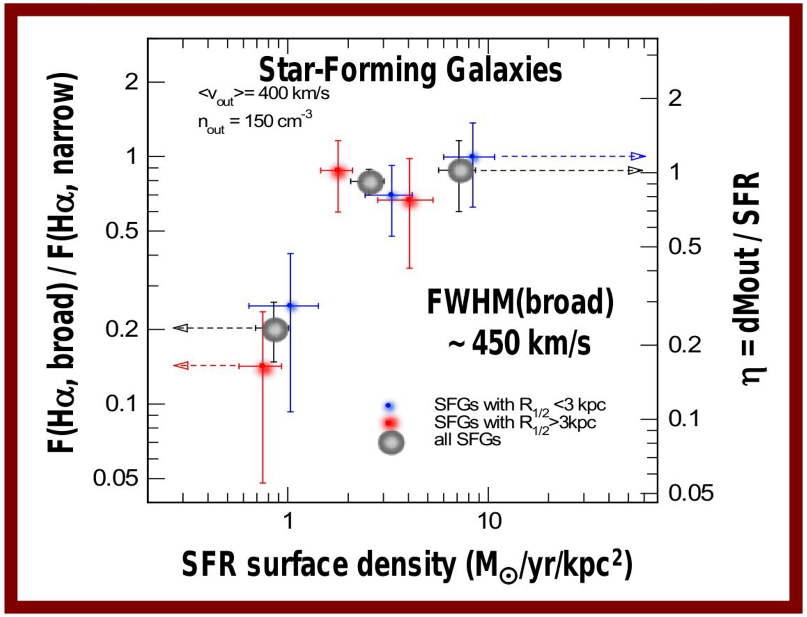
High redshift star-forming galaxies have clumpier morphologies than nearby spiral galaxies



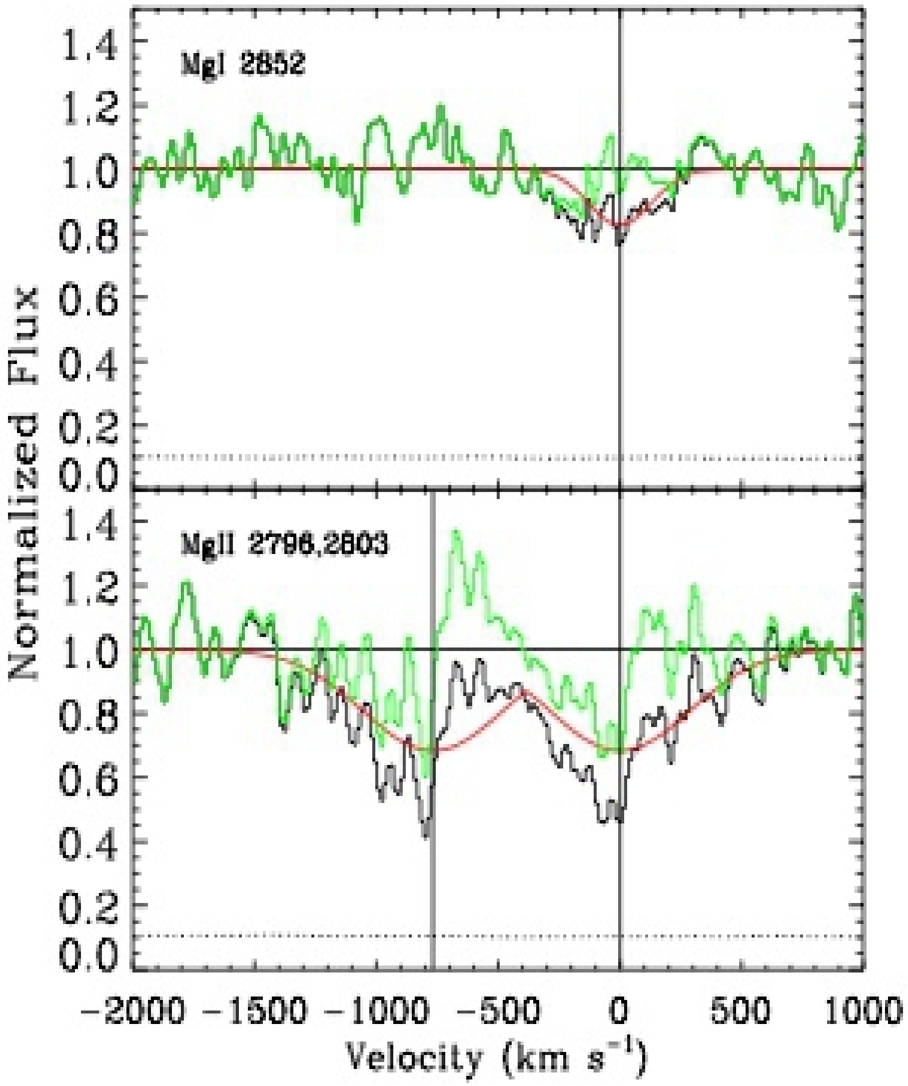
These giant clumps of young stars drive outflows of gas – in the high redshift Universe, this is a UBIQUITOUS phenomenon (at low redshifts, much more rare)

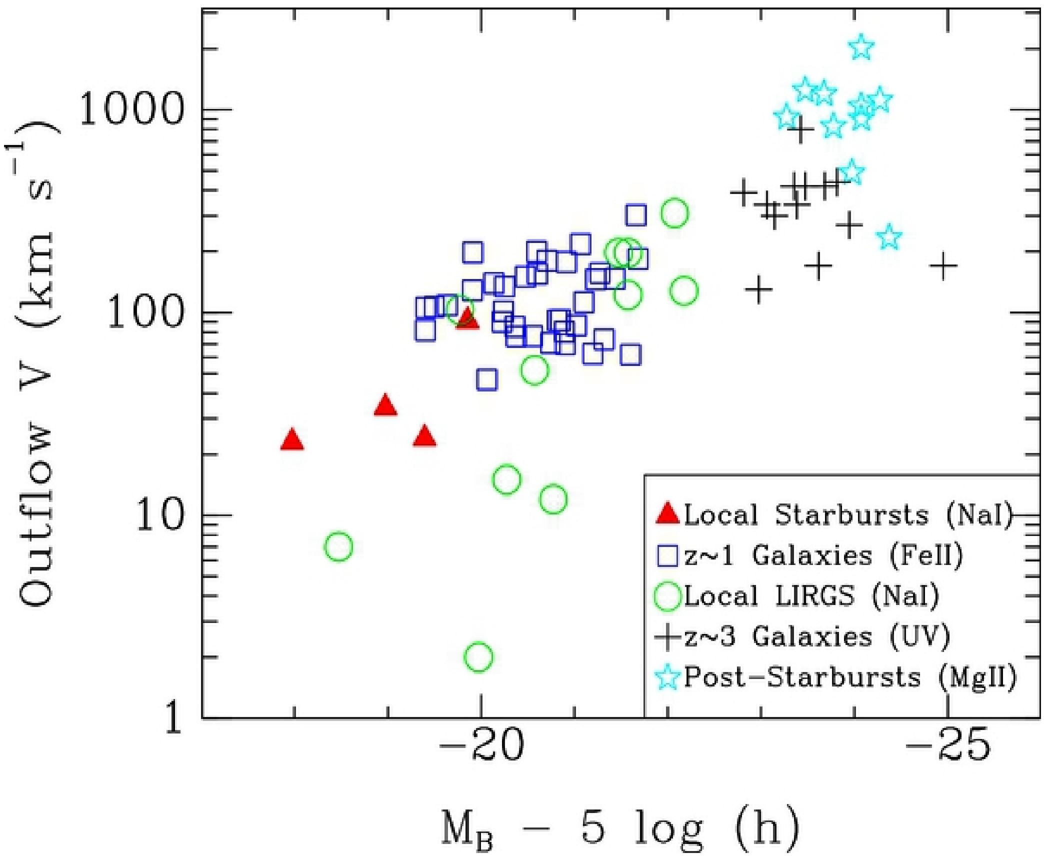




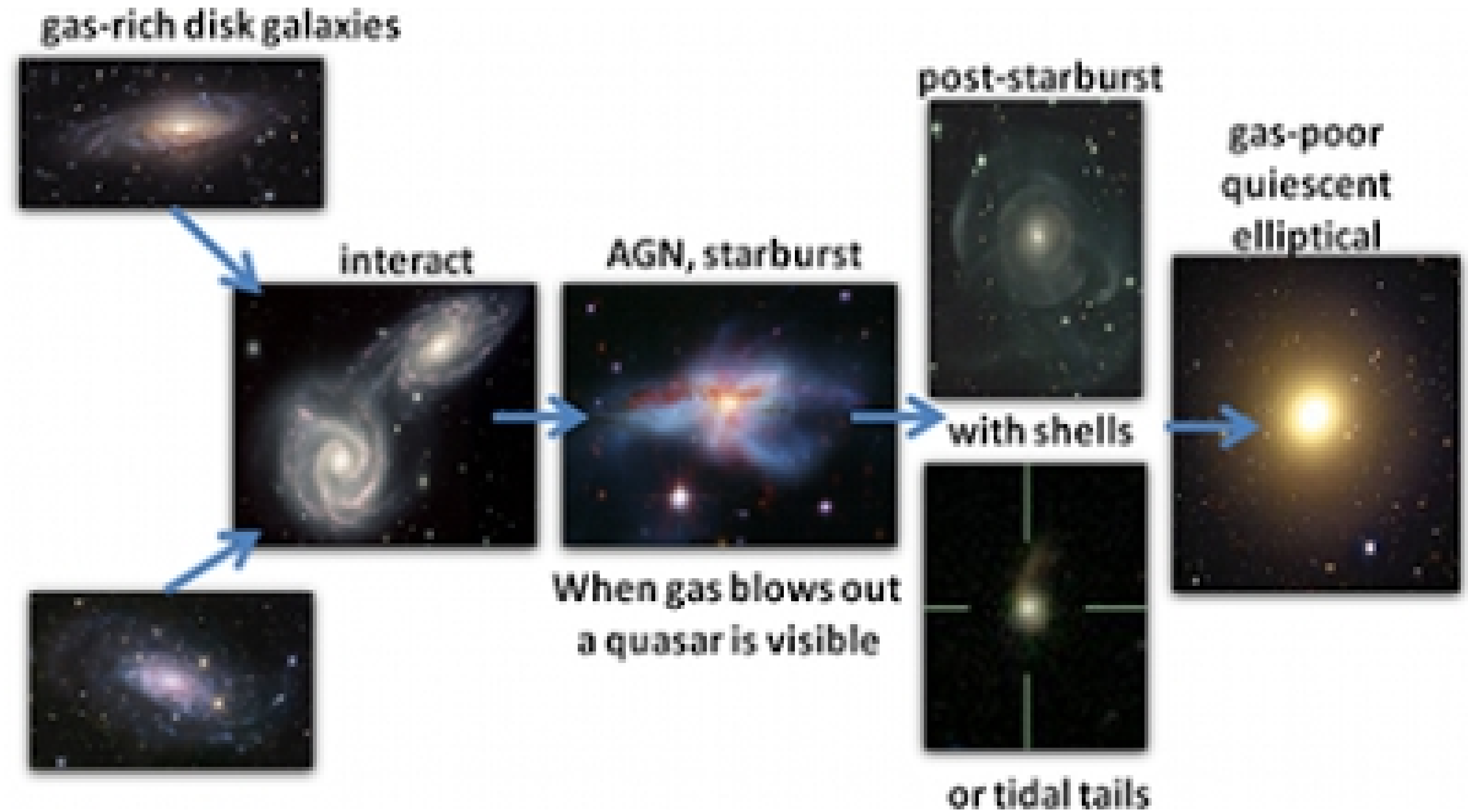


Outflows traced by interstellar absorption lines

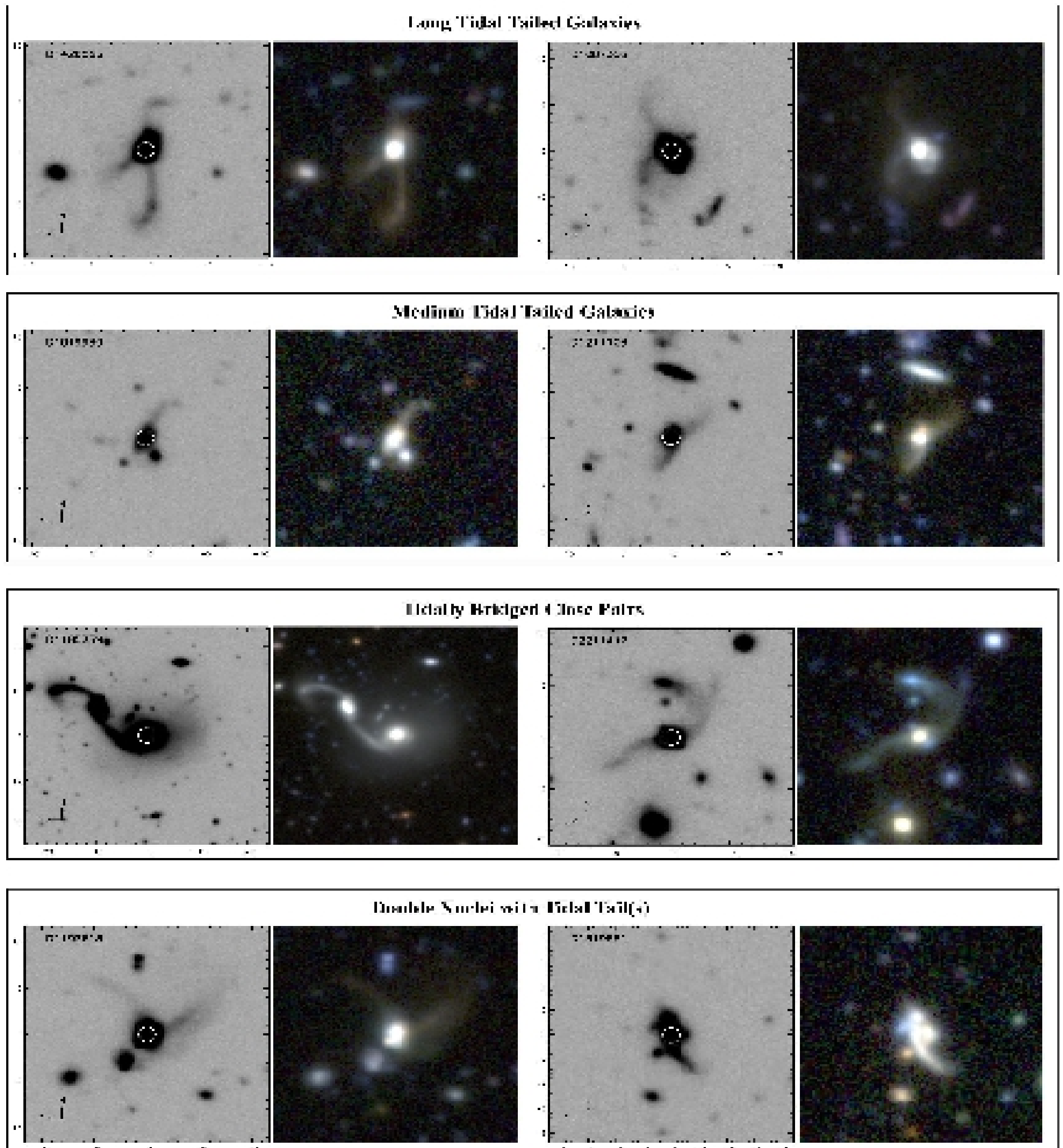


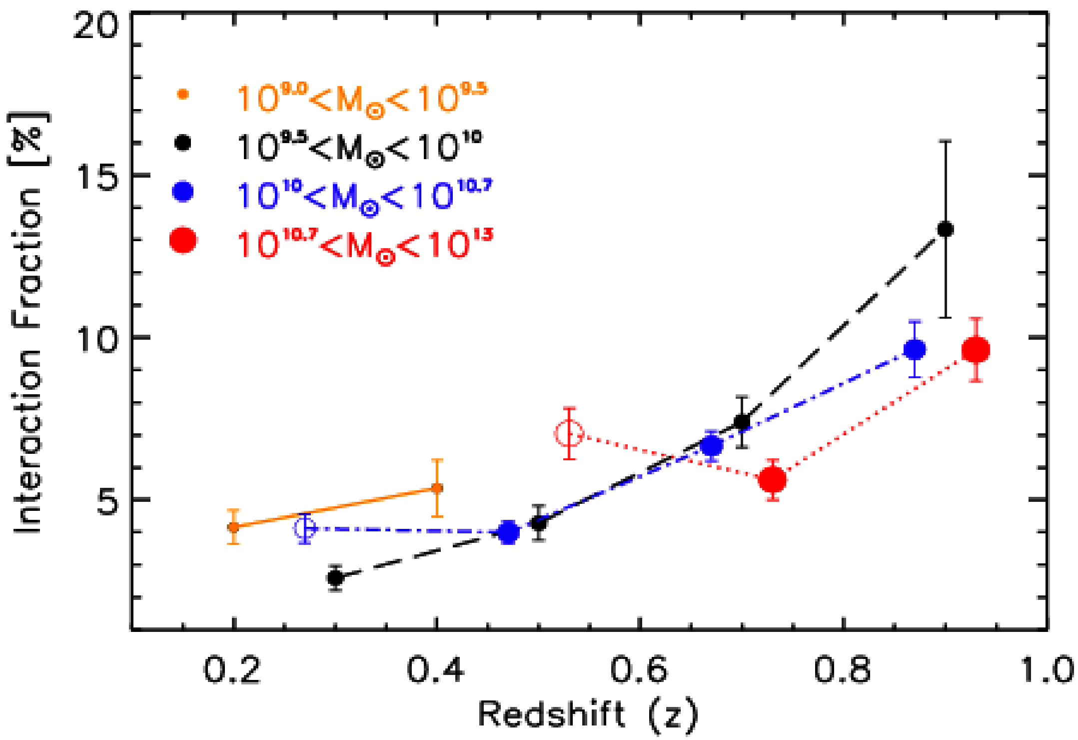


Why are high redshift galaxies more actively star-forming than nearby galaxies?
One possible scenario....

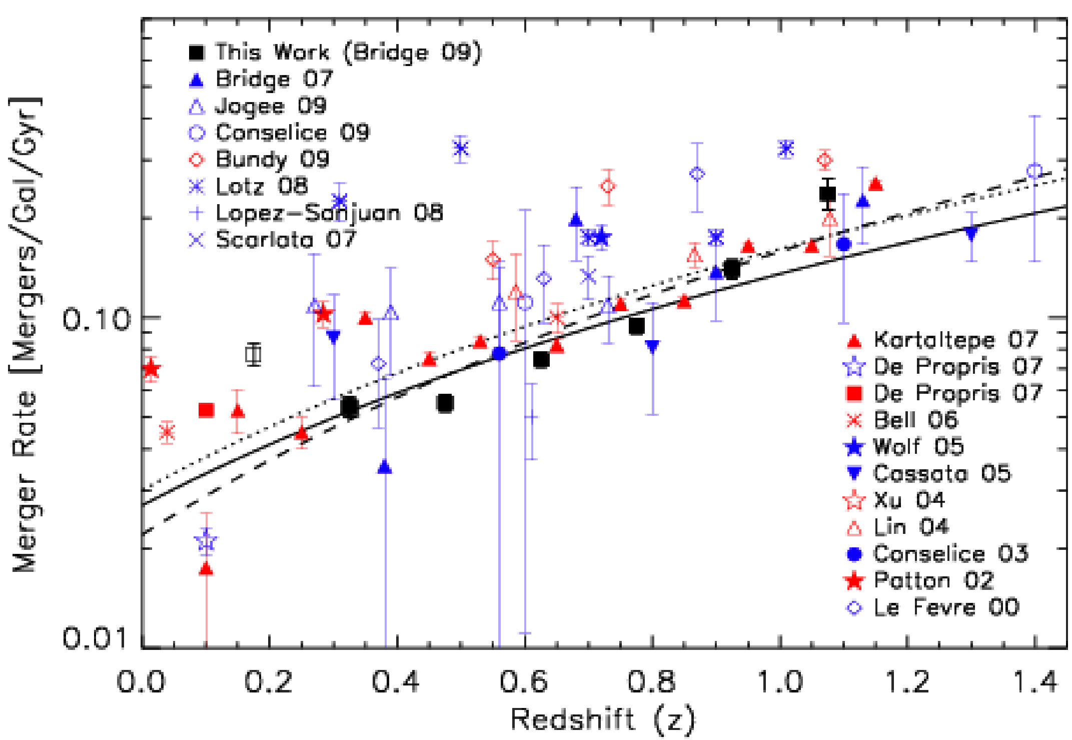


HST images allow empirical estimates of the evolution of galaxy merger rates with redshift.





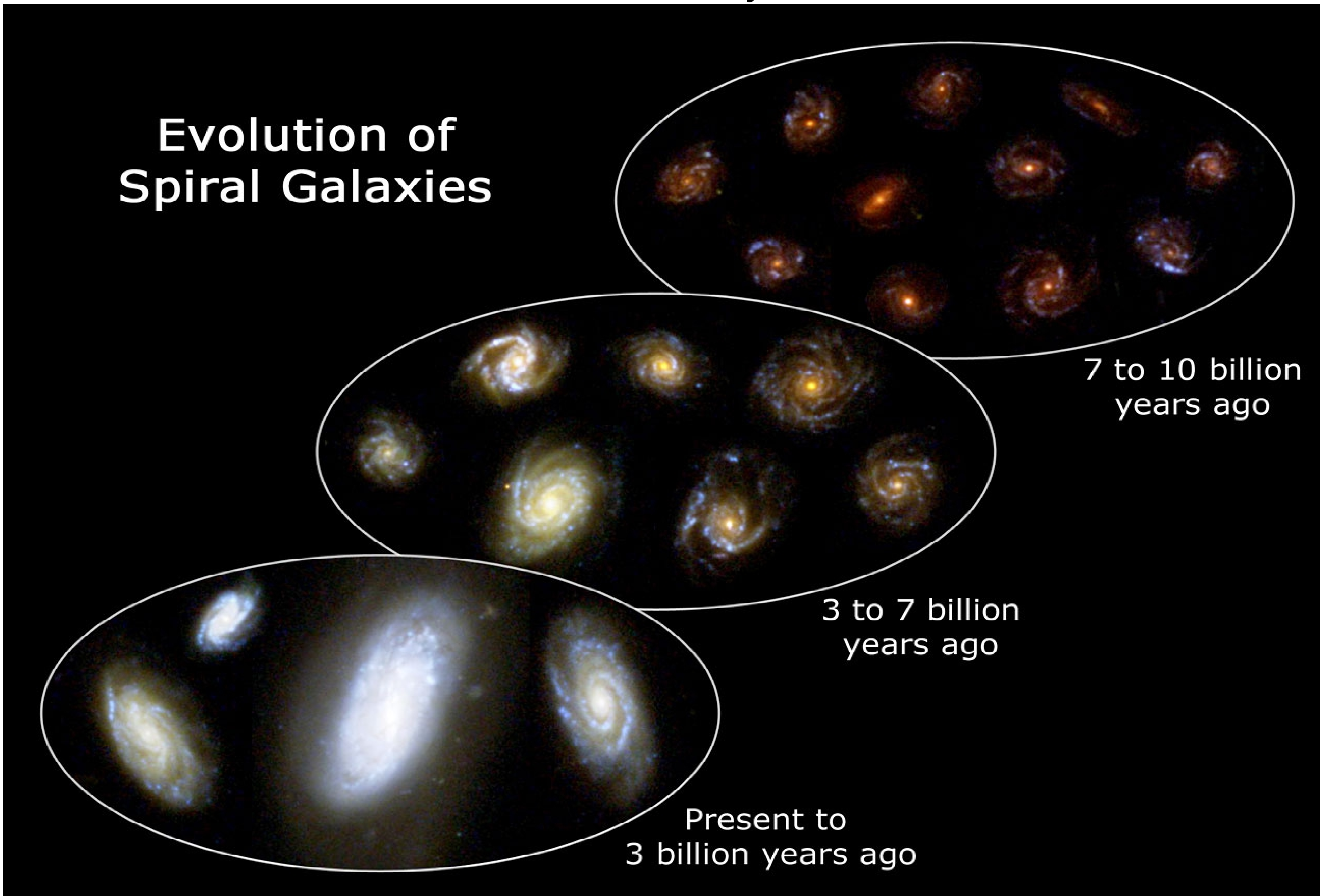
Fraction of galaxies that are visibly interacting.



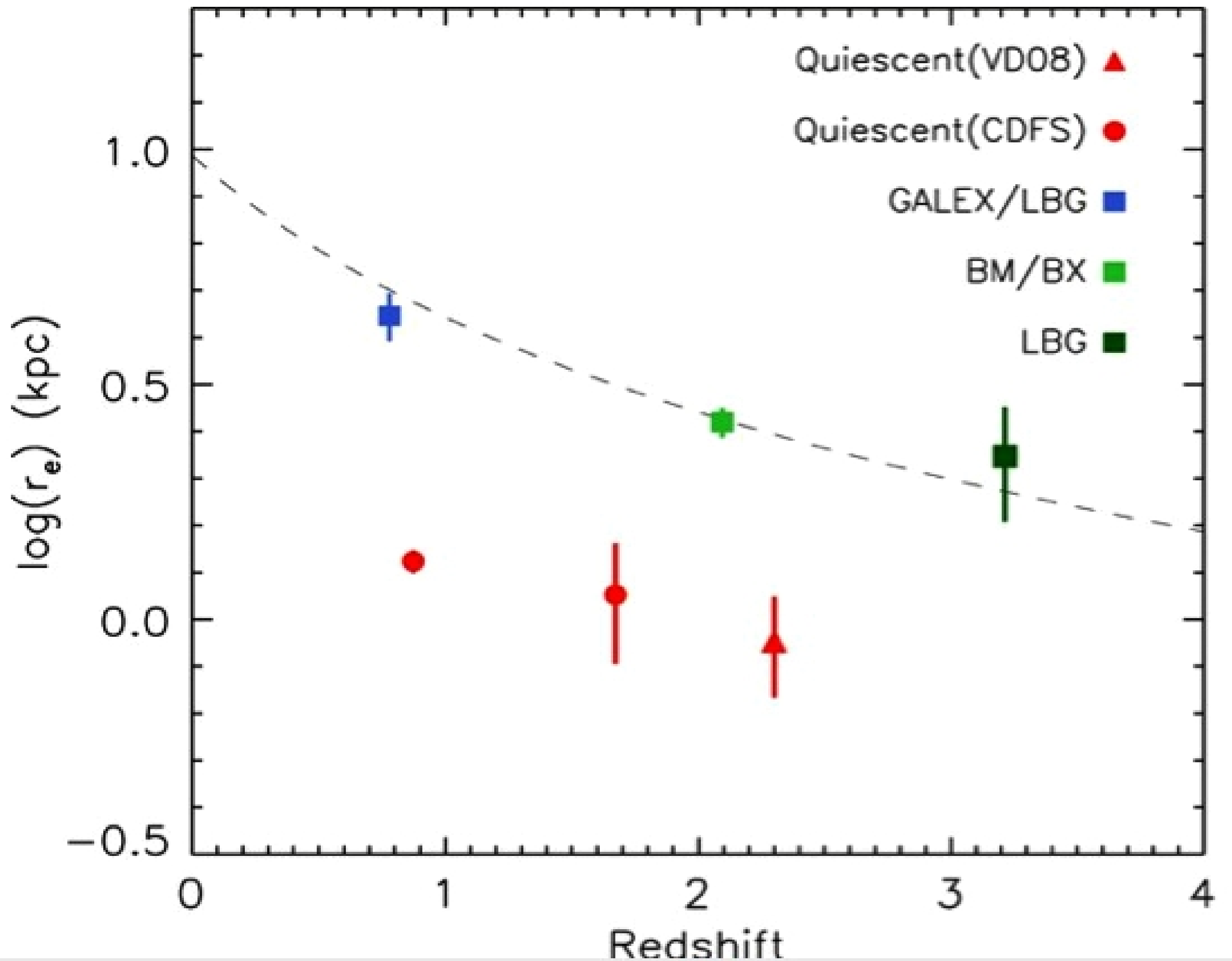
An estimate of the time interval when visible signs of the interaction are present is required to transform to merger rate.

Evolution is very mild.

Nevertheless it is clear from observations that the galaxy population has evolved significantly in size/density.



At fixed stellar mass, both early and late-type galaxies are smaller (more compact) at higher redshifts. **Poorly understood:** if not detectable mergers, what is the main mechanism controlling their growth?

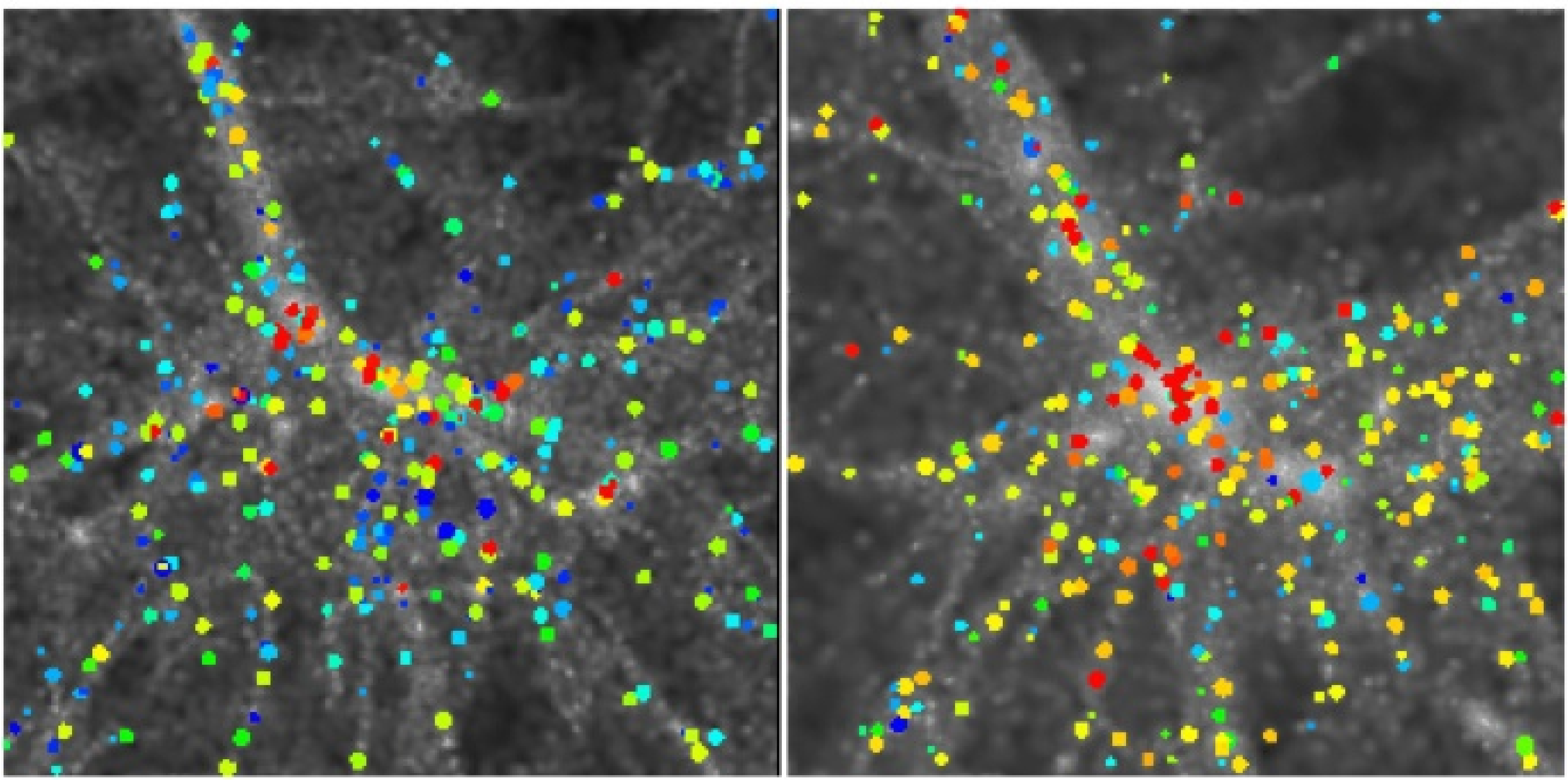


Reset

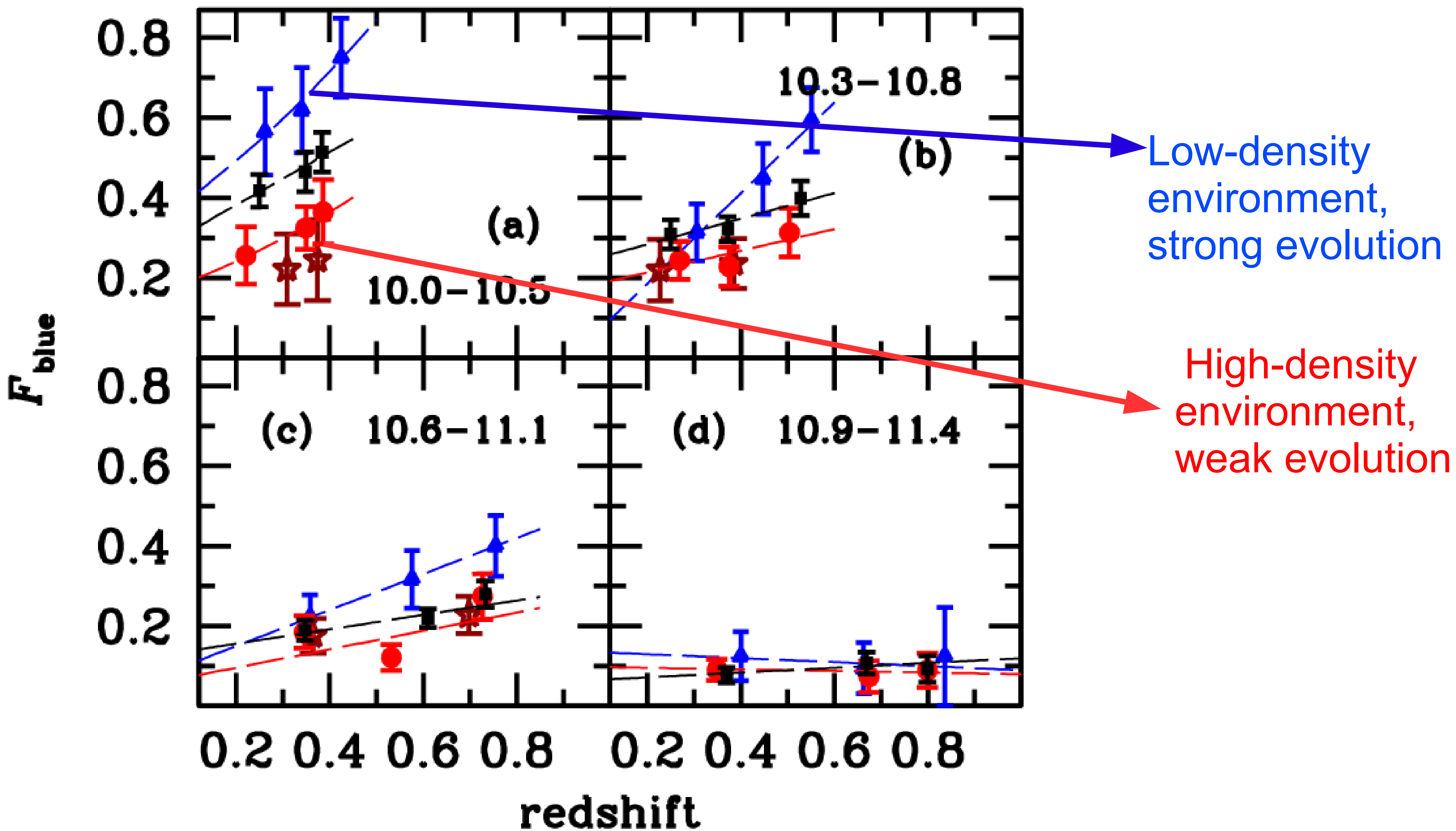
Figure 10. Median sizes of UV-bright galaxies (squares) as a function of redshifts for galaxies with stellar masses $10^{10} < M/M_\odot < 10^{11}$ in GOODS-N field. The red filled circles are quiescent galaxies from CDF-S study with similar mass range and the red triangle is the quiescent sample from van Dokkum et al. (2008b) with median stellar masses of 1.7×10^{11} $M_\odot$. The dashed line shows the best-fitting size evolution to the UV-bright galaxies ($r_e \propto (1+z)^{-1.11\pm0.13}$). The plot indicates that the UV-selected

What about environmental effects? Galaxies in high density regions of the Universe are passive, those in low density environments are actively forming stars. As the Universe evolves, the number density of massive groups and clusters increases.

Is this sufficient to explain the observed evolution in star-forming activity?

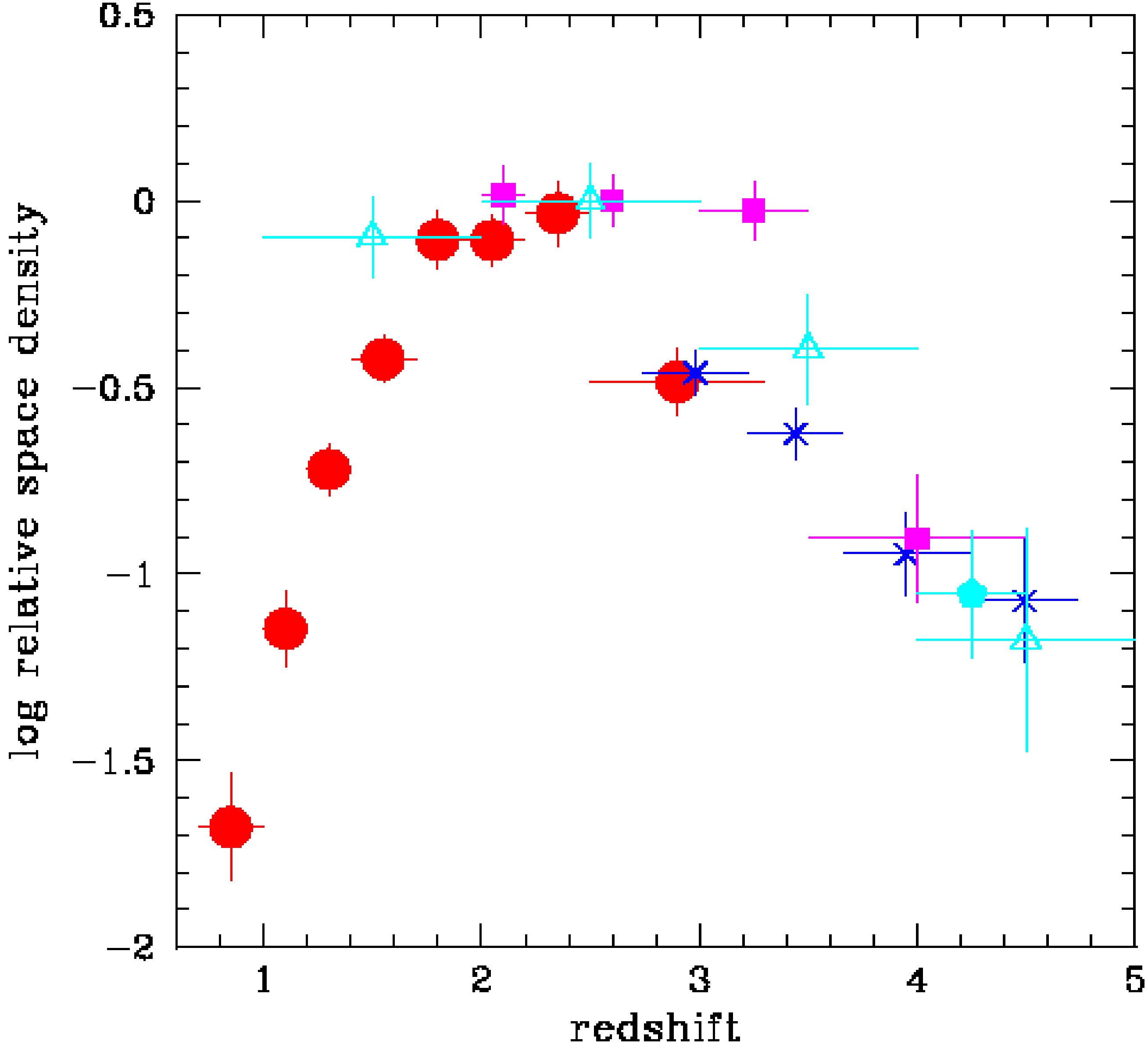


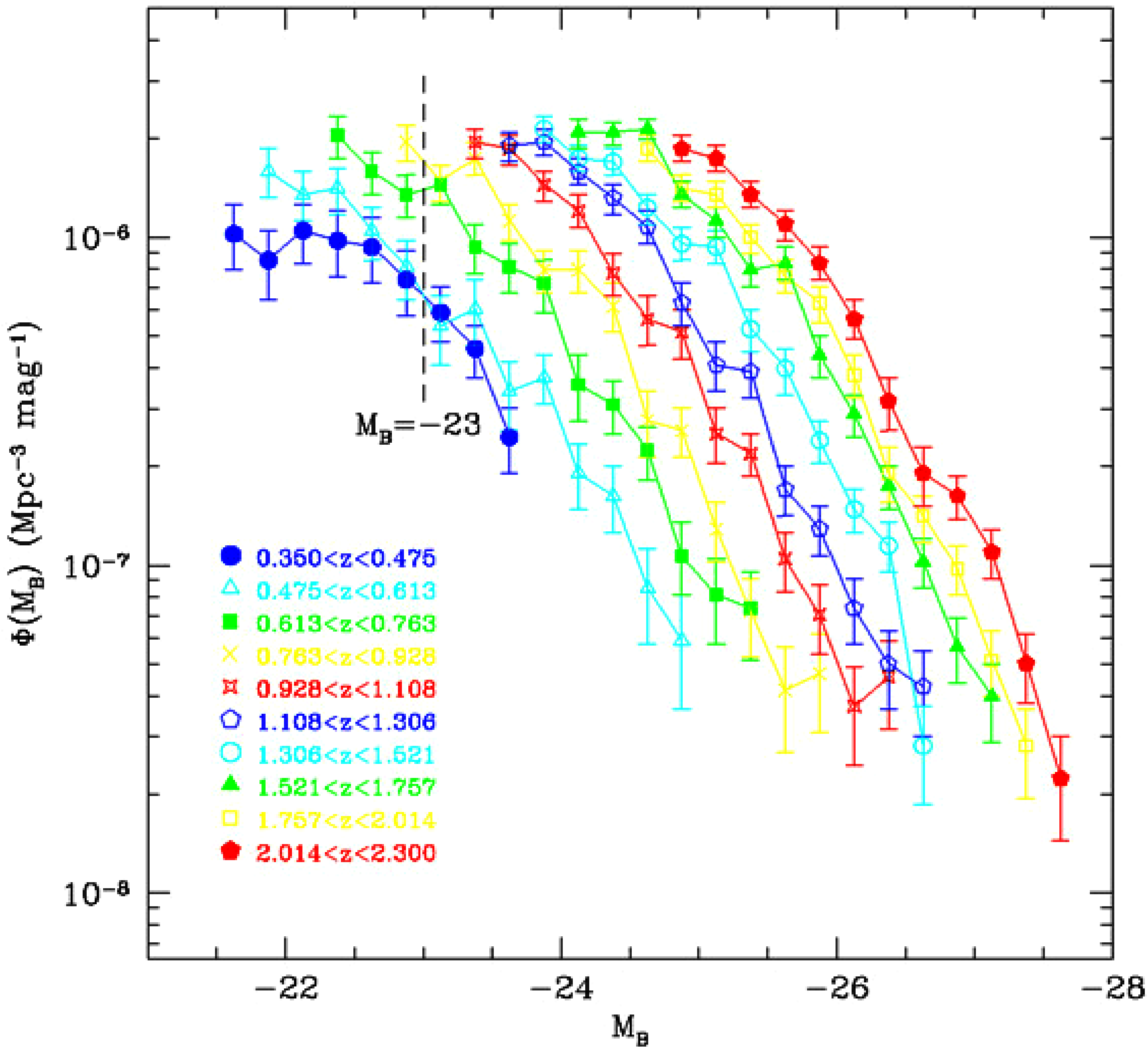
The answer from **observations** is a clear NO. The strongest evolution in star-forming activity is seen for galaxies in low density environments.



Poorly understood: what role do black holes/active galactic nuclei play in regulating galaxy growth?

Number density of galaxies with black holes that are actively accreting mass also exhibits a rise and fall, with a peak at redshifts 2-3, prompting speculation that similar behaviour of the cosmic star formation rate density may be linked.





Φ(M_B) (Mpc^-3 mag^-1)
10^-6
10^-7
10^-8
M_B=−23
0.350<z<0.475
0.475<z<0.613
0.613<z<0.763
0.763<z<0.928
0.928<z<1.108
1.108<z<1.306
1.306<z<1.521
1.521<z<1.757
1.757<z<2.014
2.014<z<2.300
−22
−24
−26
−28
M_B

SUMMARY OF CURRENT SITUATION

Thanks to around 15 years heavy investment of large telescope time in observing high redshift galaxies, evolution of the global properties of the galaxy population (mass, star formation rate, size) is now quite well quantified from z=3-4 to z=0.

Robust constraints on the physical mechanisms responsible for the observed evolution are still few and far between. Not enough work has been done to interpret the observations in the framework of galaxy formation models in the standard LCDM cosmology.

(some thoughts on this to follow in my last lecture next week!)