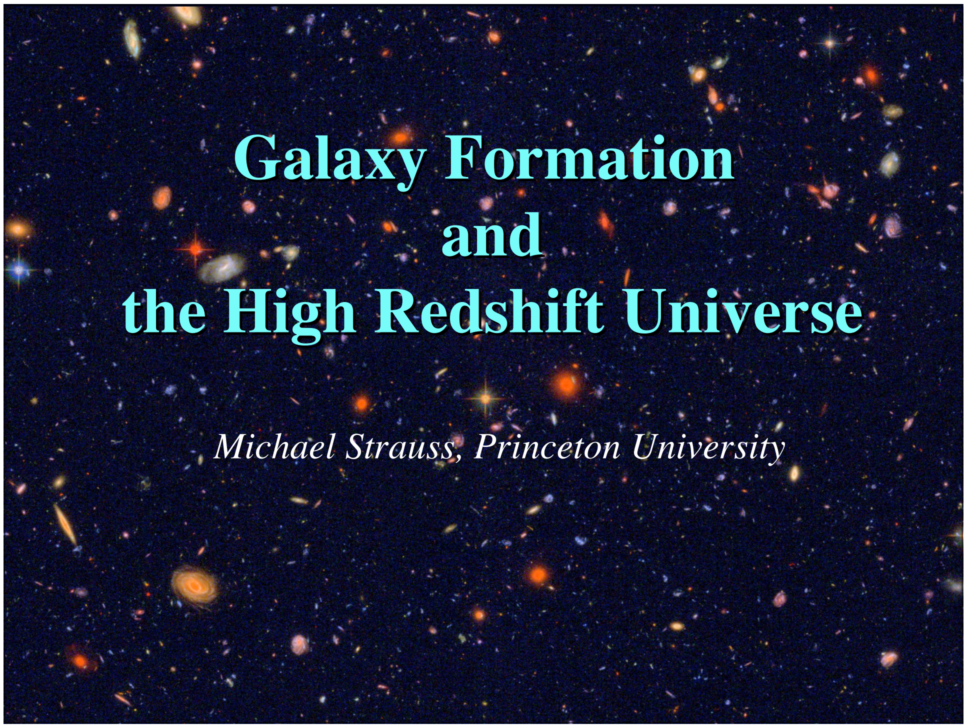

We used to ask:

- What is the epoch of galaxy formation?
- What does a primeval galaxy look like?

This is still true!

THE ASTROPHYSICAL JOURNAL, **192**:251–259, 1974 September 1

SEARCH FOR PRIMEVAL GALAXIES

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Joseph Henry Laboratories, Physics Department, Princeton University
Received 1974 February 15

ABSTRACT

Most models for galaxy formation in an evolving Universe include a high-luminosity epoch of bright star formation at a redshift of $2 < z < 100$. These objects could have escaped detection on deep red photographic plates if they are extended (~ 100 arcsec^2) and fade into the sky background. This paper reports an unsuccessful search for extended red objects, in apparently blank regions of the sky. A special photometer with high red sensitivity was used to compare the sky brightness in two halves of a circular aperture. Search beams between 17″ and 40″ diameter were used, and altogether 2.0×10^4 arcseconds^2 were searched. With 90 percent confidence, there was no object in the area searched with a flux greater than 38×10^{-29} ergs cm^{-2} s^{-1} Hz^{-1} in our bandpass of 6200–8900 Å. Furthermore, fluctuations on a scale of 26″ were smaller than 6×10^{-29} ergs cm^{-2} s^{-1} Hz^{-1}. The results constrain the luminosity and number density of primeval galaxies in the standard model.

Subject headings: cosmology — galaxies

$z>1$ was *really* high redshift when I was a grad student!

3C 324—AN EXTREMELY DISTANT CLUSTER RADIO GALAXY

ApJ, 280, L9 (1984)

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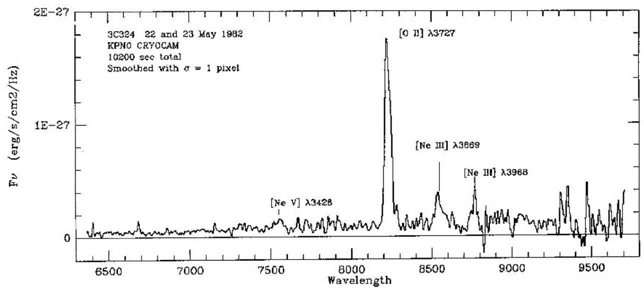
Received 1983 November 10; accepted 1984 January 10

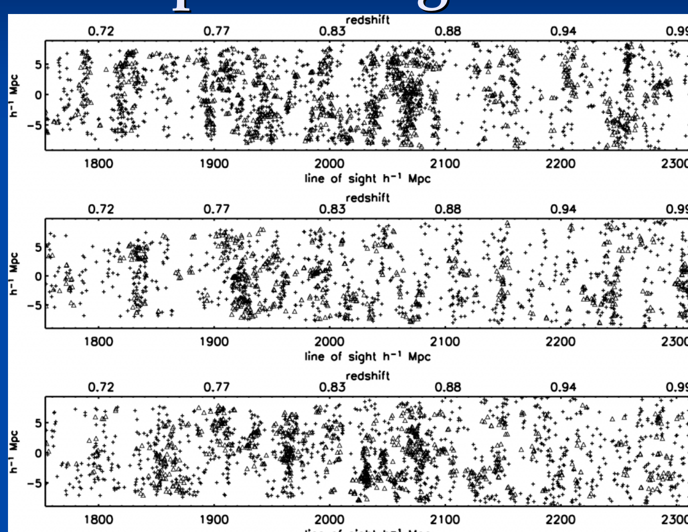
ABSTRACT

The strong radio source 3C 324 is identified with a faint cluster galaxy, with $V \approx 22.6$. Our new CCD spectroscopic data yield an emission-line redshift, $z_e = 1.2063$. The emission spectrum is narrow-line and shows a characteristic low-ionization level. The strong [O II] line is both spatially and velocity resolved in 3C 324; a speculative hypothesis on its origin in a rotating and possibly captured gas disk or an infalling galaxy is advanced. The detection of a cluster around 3C 324 is discussed.

Subj

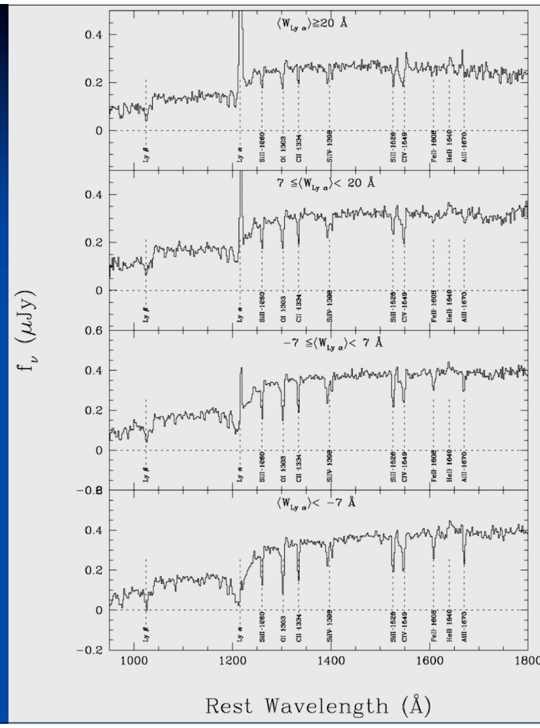


Now we are studying huge samples at high z

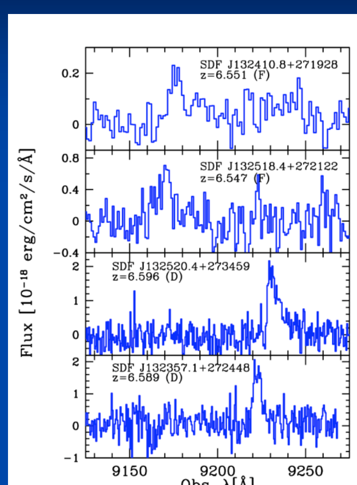


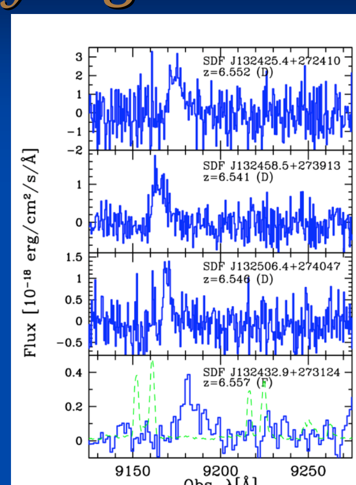
Coil et al. 2005, DEEP2 redshift survey

Steidel et al. 2003: Composite spectra of ~200 galaxies in each bin, at z~3.



Now *z~6* is *really* high redshift





Kashikawa et al. 2006; spectroscopy of Lyman α galaxies at z=6.5

HST, Spitzer and high-redshift galaxies

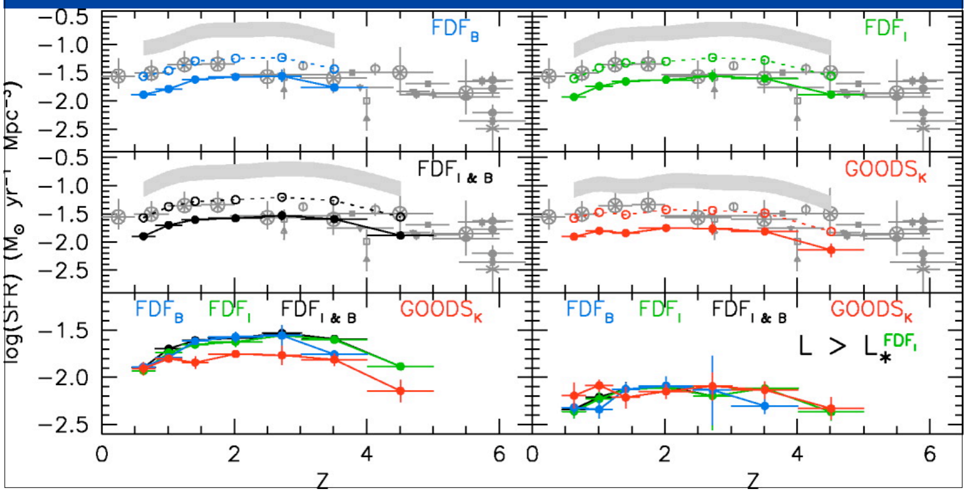
- At increasingly high redshifts, HST/ACS is observing the rest-frame UV, and therefore is sensitive to recent star formation.
- To observe the bulk of the stellar mass, one wants to observe at $\lambda_{rest} > 5000$-10,000 Å; at redshift 3, this is 2-3 microns. Spitzer IRAC is exactly what we want.
- Spitzer also allows us to find dust-enshrouded galaxies, and to do spectroscopy in the mid-infrared, a brand-new capability at high redshift.

The GOODS Survey

- *Great Observatories Origins Deep Survey*: 320 arcmin^2 in *BViz* with ACS, plus 3.6, 4.5, 5.8, and 8 microns with IRAC and 24 microns with MIPS, plus Chandra, to depths within 1 magnitude of the Hubble Deep Field.
- This is just what we want: multiple bands in both HST and IRAC, going deep enough to study galaxies all the way to z~6.
- Extensive ground-based follow-up with spectroscopy and JHK imaging.

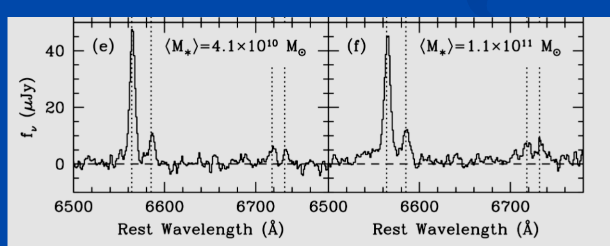
The History of Star Formation

Gabasch et al. 2004: Star formation rate from 1500 Å luminosity density (Madau diagram). Correction for dust extinction is large and uncertain! SFR from Spitzer may be more robust (Papovich et al. 2006)



Ways to measure star formation rate

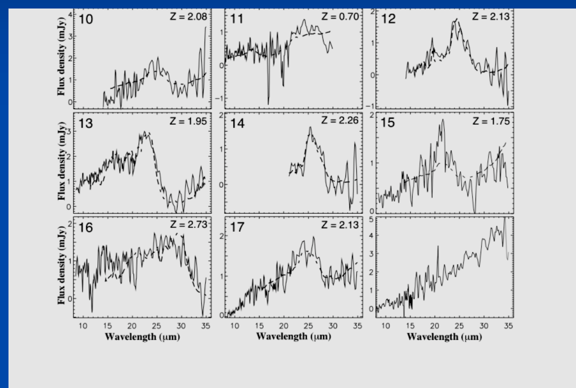
- Rest-frame UV luminosity is strongly affected by extinction (but it can be corrected for… Look at 24 microns for galaxies with heavy extinction.
- Hα can be observed in near-IR at z~3



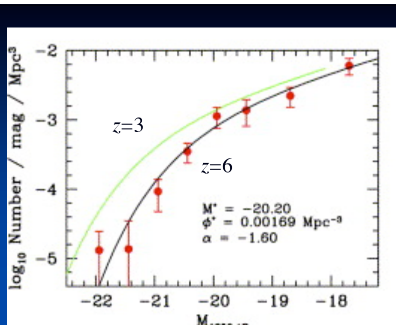
Erb et al. 2006

Alternative measures from X-ray, radio (e.g., Reddy and Steidel 2004) give consistent results.

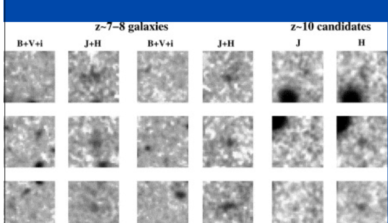
Houck et al. 2005

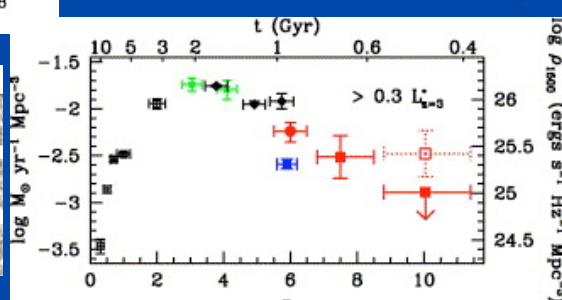


Another approach is PAH emission from IRS spectroscopy (which yields redshifts too!).



UV luminosity function at z=3, and z=6, from photometrically selected galaxies from GOODS (Bouwens et al. 2006). The star formation rate is finally falling off…



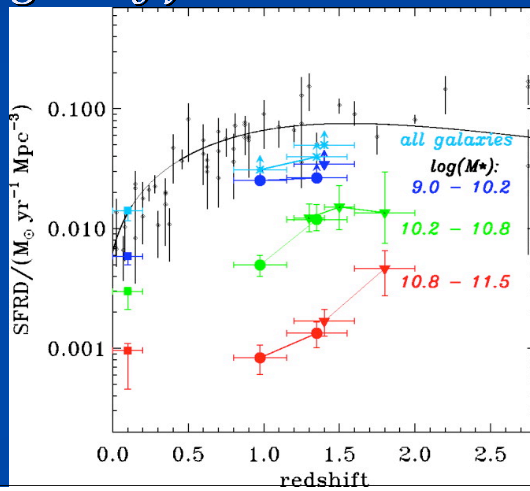


Bouwens et al. 2006, the Madau diagram pushed to astonishingly high (photometric) redshift.

Cosmic downsizing: the star formation in higher-mass objects took place at earlier times. *There is no one epoch of galaxy formation*

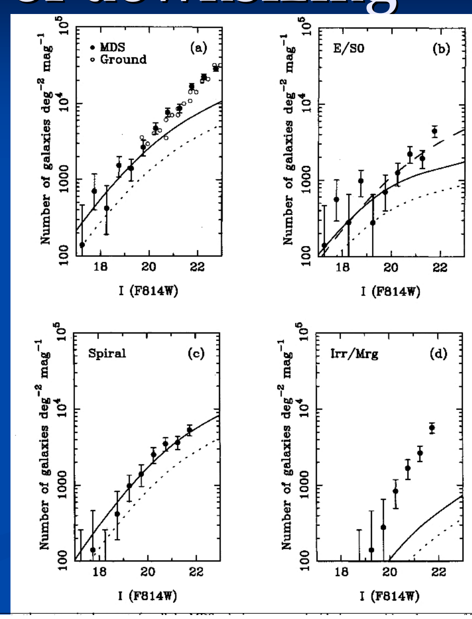
Juneau et al. 2005 (from GDDS): star formation rate (from [OII], UV light) shows different functional dependence for different mass galaxies.

High-mass, red galaxies evolve little since z~1, and contain most of the present-day stellar density

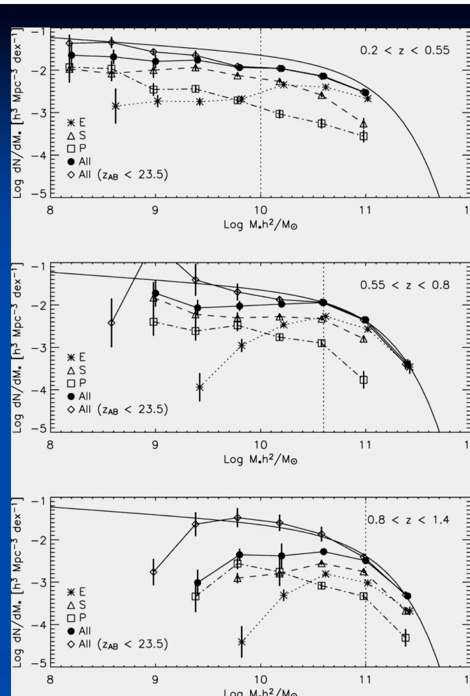


An early hint of downsizing

Glazebrook et al. 1995, HST medium-deep survey: the number counts of ellipticals and spirals follows the no-evolution predictions, while dwarf/irregular/merging galaxies show a dramatic excess at faint magnitudes.



Similarly, the stellar mass function of galaxies of different morphologies is a strong function of redshift, with a dramatic increase at low masses since z=1.
Bundy et al. 2005

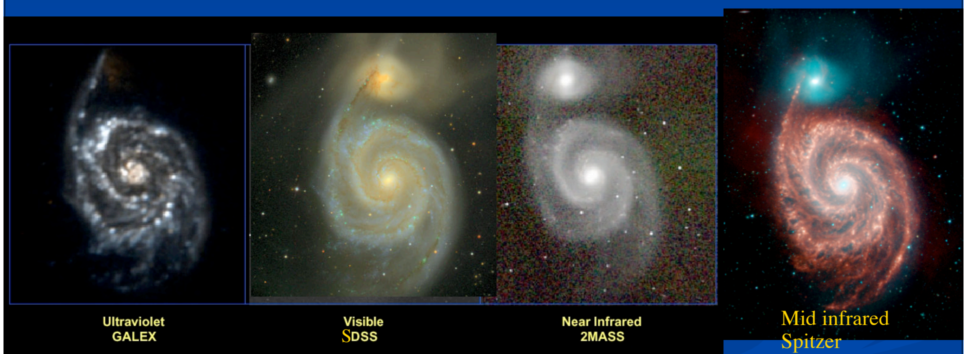


So what about galaxy morphologies?

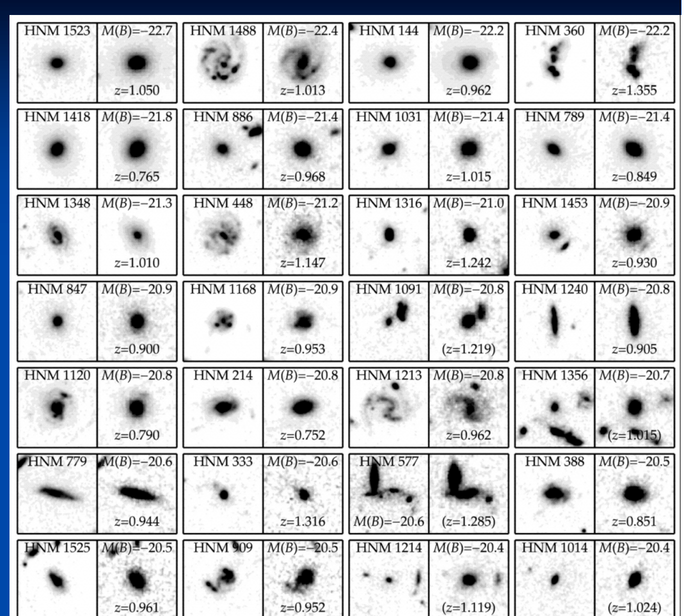
The Hubble Ultra-Deep Field is stunning; it is showing us ***UV*** morphology for highest-redshift galaxies

Colorized by Hogg et al, following Lupton et al.

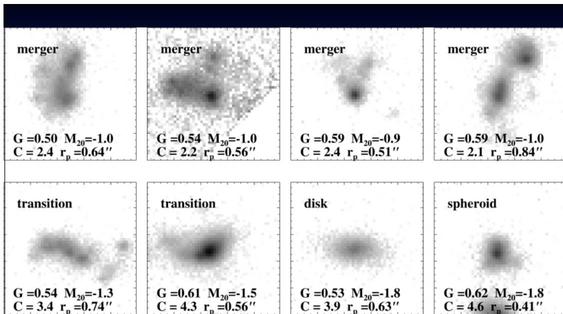
The morphologies of galaxies are a strong function of wavelength!



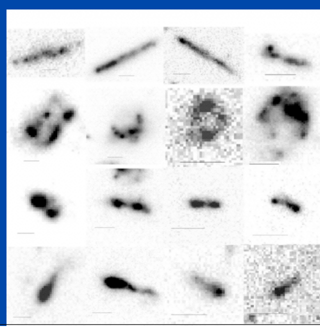
Comparison of galaxy morphologies in GOODS in rest-frame UV (ACS) and optical (NICMOS) at z~1.
Papovich et al. 2005

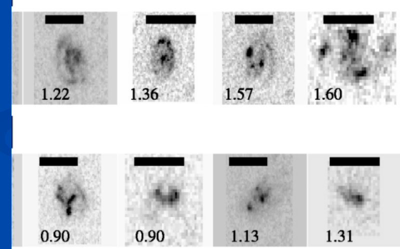


Is there a Hubble Sequence at *z*>1.5?



Lotz et al. 2005; some galaxies at z=4 have "recognizable" morphologies…



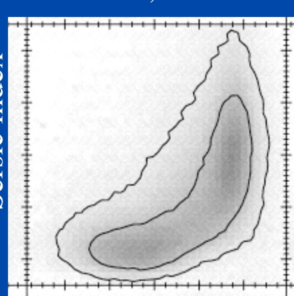


while others have truly "weird" shapes (Elmegreen et al. 2005; Conselice et al. 2004)

What does galaxy morphology tell us anyway?

At the present day, the distribution of galaxies is strongly ***bimodal*** in broad photometric and stellar population properties. But the detailed properties of disks, bars, spiral arms, etc, have not been put on the same scheme, or studied with as large uniform samples.

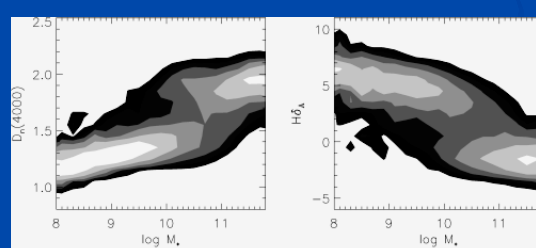
Sersic index



g-r

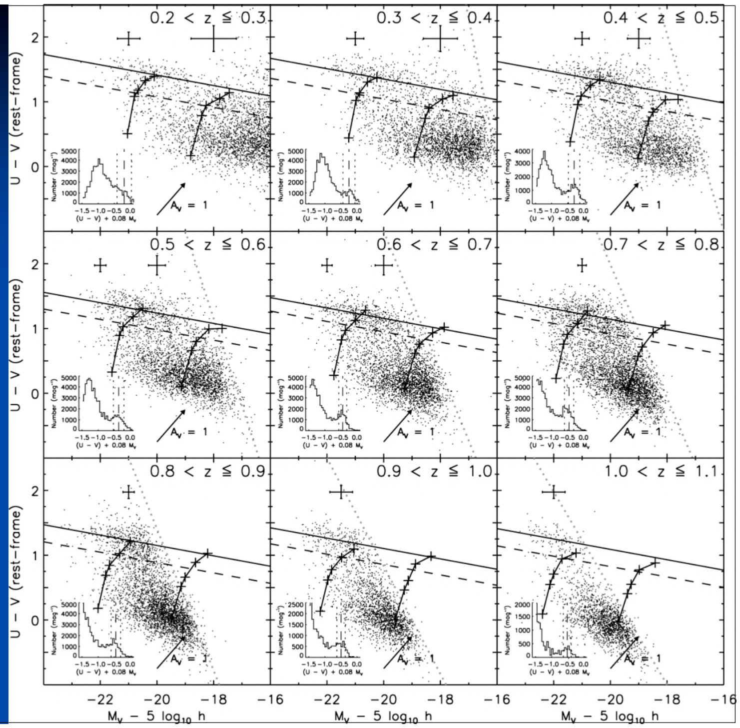
Blanton et al. 2004

Population age indicators



Stellar mass

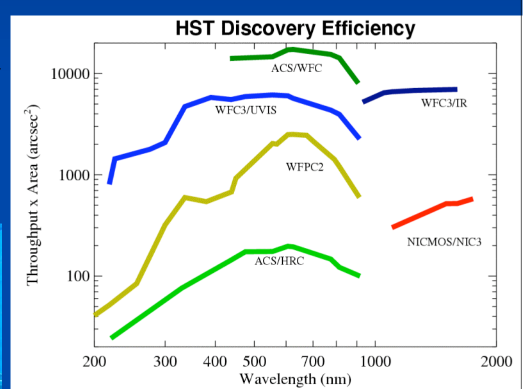
Kauffmann et al. 2003



Bell et al. 2004
The color-magnitude diagram for galaxies in different redshift bins: the bimodality existed at $z \sim 1$.

We need morphologies of high-redshift galaxies in the rest-frame optical!

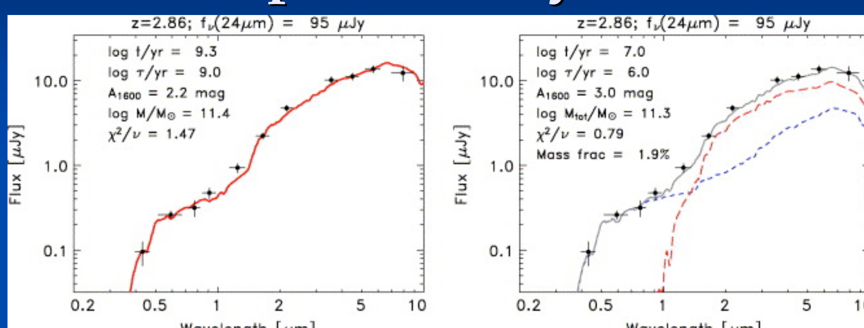
HST's WFC3 is exactly what we need: wide field sensitivity in J and H, with high angular resolution.



Let's go deep in J and H with WFC3 in the GOODS fields

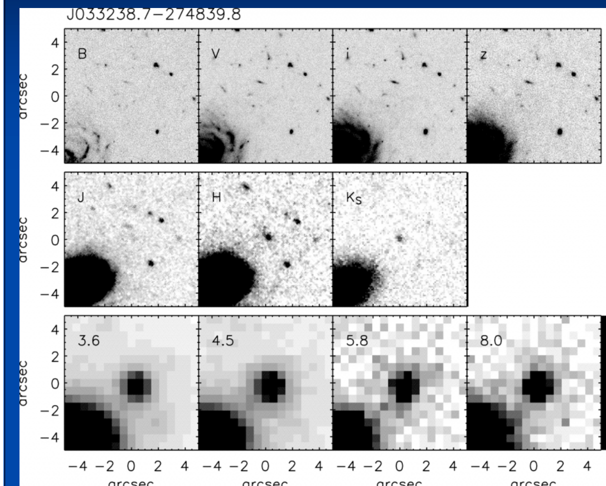
- WFC3 has the resolution to get good galaxy morphologies in rest-frame optical bands for high-redshift galaxies.
- Rest-frame optical from WFC3, plus rest-frame near-IR from Spitzer/IRAC, allows us to determine stellar populations and stellar masses as a function of redshift, and compare directly with the story told by the Madau diagram.
- Good JH photometry is important for getting photometric redshifts in the "redshift desert", $1.3 < z < 2$.
- So, do the stellar populations make any sense?

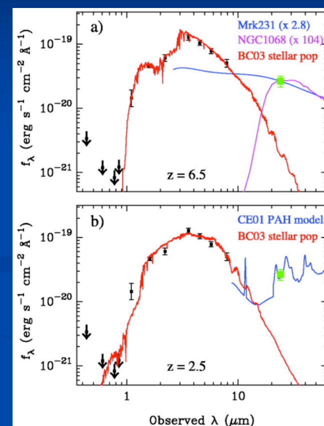
What you can do with 11-band photometry



Papovich et al. 2005: detailed fit to the SED of a z~3 galaxy: two distinct stellar populations?

A massive galaxy at z=6.5??

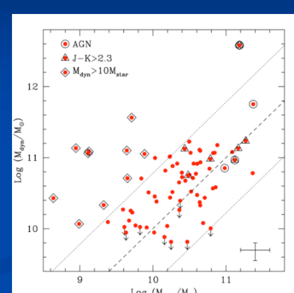




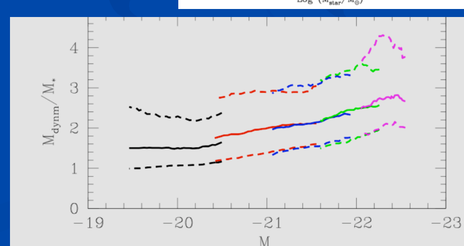
Mobasher et al. 2005. A galaxy with a stellar mass of 6×10^{11} M_{sun}, few $\times10^{8}$ years old??

With resolved emission-line spectra, you can determine a dynamical mass

Erb et al. 2006: dynamical masses are in good agreement with those from stellar populations for many (although not all!) galaxies.



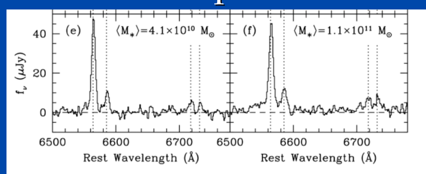
Padmanabhan et al. 2004: ratio of dynamical to stellar mass is well-behaved for z~0 ellipticals.

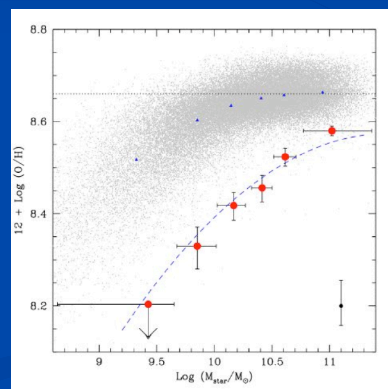


We need more spectra!

Spectra allow us to determine the redshift, the star-formation rate, the metallicity, the dynamics, the stellar populations, AGN components…

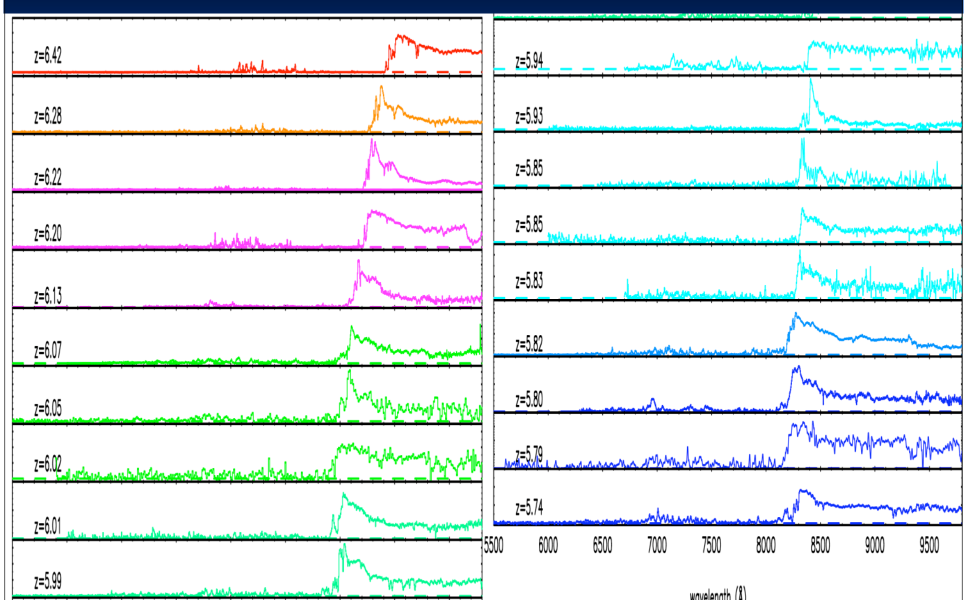
For many of our purposes, near-IR (rest-frame optical), or even mid-IR spectra are ideal.





Erb et al. 2006: metallicity-mass relationship is dramatically lower at high z…

19 quasars with z>5.7, 10^9 yrs after the Big Bang

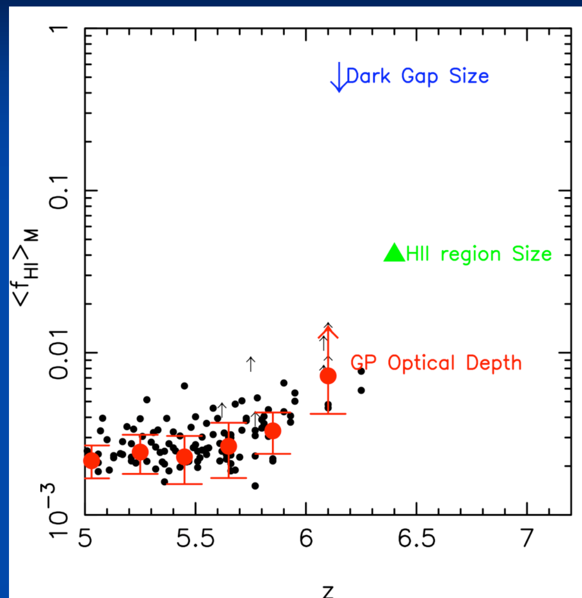


The end of reionization…

Limits on the (mass-weighted) neutral hydrogen fraction as a function of redshift…

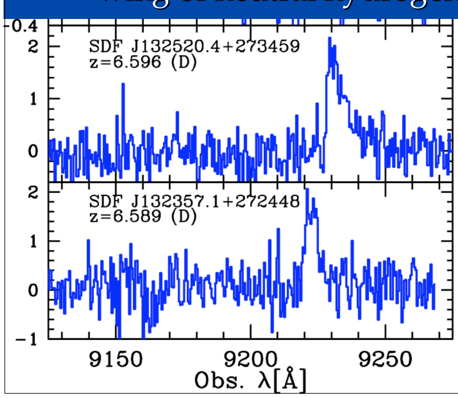
We claim a *measurement* of 0.05 at *z*=6.4.

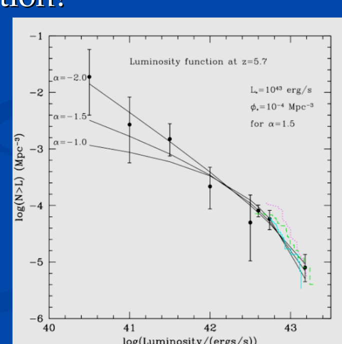
WMAP claims 50% ionized fraction at *z*~10. So the reionization process is *not* like a phase transition.



The state of the IGM should have an effect on the observed properties of z~6 galaxies

- Might formation of dwarf galaxies be suppressed (Loeb and Wyithe)?
- Might Lyα emission be suppressed by the damping wing of neutral hydrogen absorption?





Kashikawa et al. 2006; Malhotra & Rhoads 2004

Big Questions, Big Projects

- Covering a fair fraction of the GOODS fields with WFC3 in J and H to get rest-frame optical morphologies, and real SEDs at z=1-2. Does it make sense to do slitless spectroscopy with WFC3 in NIR?
- GOODS is still cosmic-variance limited for many populations of galaxies. Larger areas (10 deg^2 ?) would allow measurement of a true global star formation rate with redshift.
- One can never have enough spectroscopy. Optical and near-IR spectroscopy will be from the ground, but Spitzer IRS spectra are a new resource we are just beginning to use and understand, and we won't have them much longer…

- We are just starting to study the physical properties (e.g., stellar populations) of galaxies at the reionization epoch, z~6.
- We are asking questions at high redshift that are still unknown, or are only now getting properly addressed, at low redshift (e.g., mass-metallicity relation, relation between stellar and dynamical masses, the physical nature of the Hubble sequence, properties of young star-forming galaxies at low redshift). All this suggests further work at z~0, with COS, and surveys like SDSS, 2MASS.
- Images and science results from the Great Observatories are truly inspirational to the general public, more so, perhaps, than the manned missions. We need to communicate this fact to the folks at NASA!