Relevant Material for Lecture 12

"Galaxies: Structure, Dynamics, and Evolution"

9. Evolution with redshift - $z > 1.5$

At high redshifts, life gets tougher. The restframe optical, in which we select galaxies at $z = 0$ and to $z = 1.3$, is shifted into the Near-IR. There are several ways of solving this:

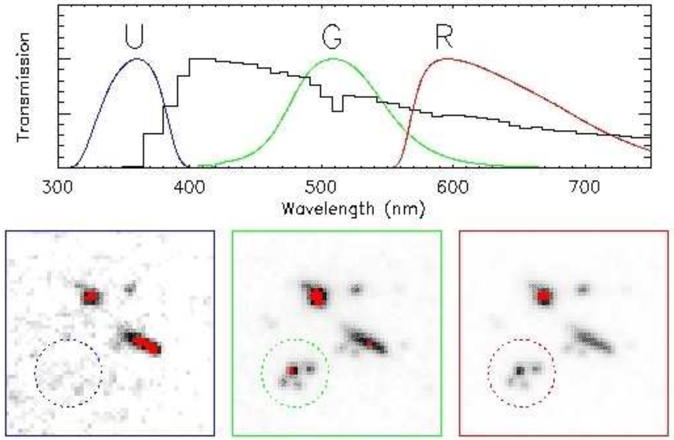
1) Observe galaxies in the observers optical - which is the rest-frame UV

2) Suffer and observe galaxies in the restframe optical - the near-ir

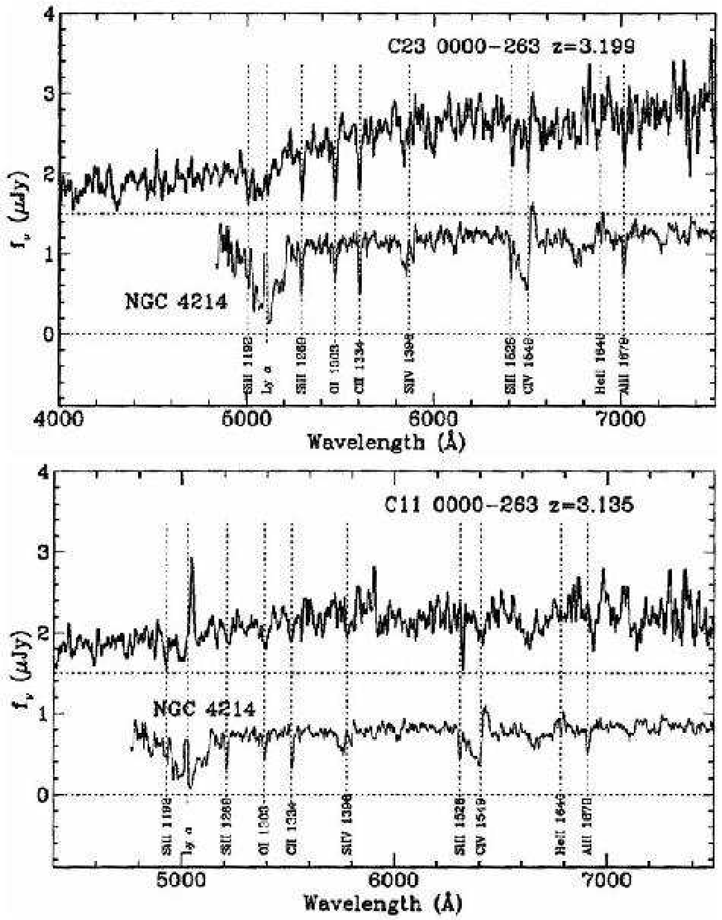
3) Use other methods - for example, radio emission, submm emission, etc.

All methods have advantages and disadvantages. I am showing some examples below.

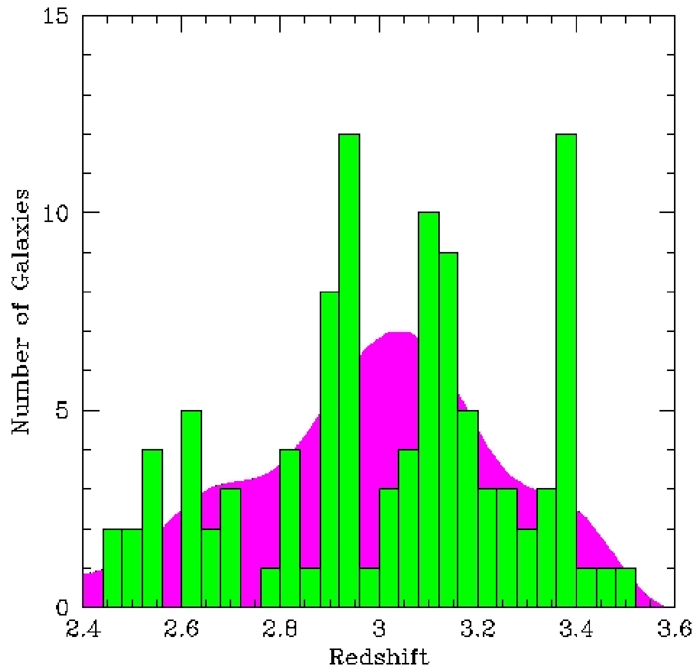
Selection in the rest-frame UV



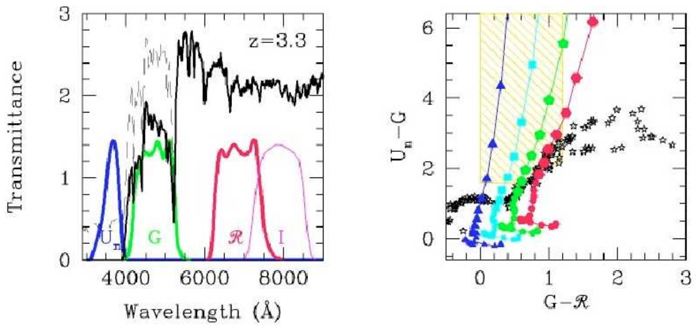
If we take a star burst spectrum (with a young age - dominated by O and B stars), and shift it to high redshift, we expect that the Lyman Break falls redward of the U filter. Such a galaxy is blue in the $g - r$ color, and red in $u - g$. When we select such galaxies we find the spectrum below



These are observed spectra of a U-dropout galaxy taken with the Keck telescope (Steidel et al. 1996a,b, 2003) - clearly at high redshift. Also shown are the spectra of local star burst galaxies - note how similar they are



This is the redshift distribution of galaxies selected as "U-dropouts".

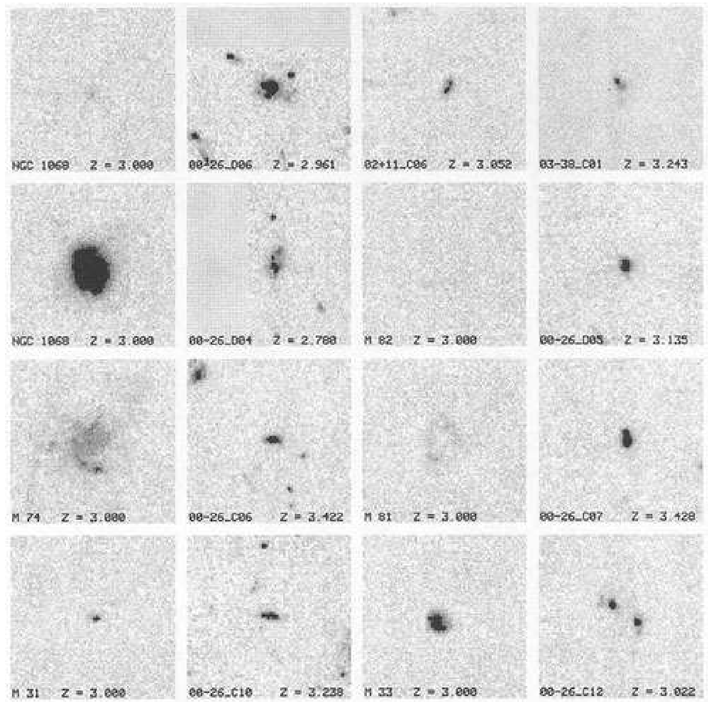


How to interpret ?

We have to calculate over what redshift range we *expect* to find these galaxies. Then we divide the number of galaxies found by the number of galaxies truely found in the sample.

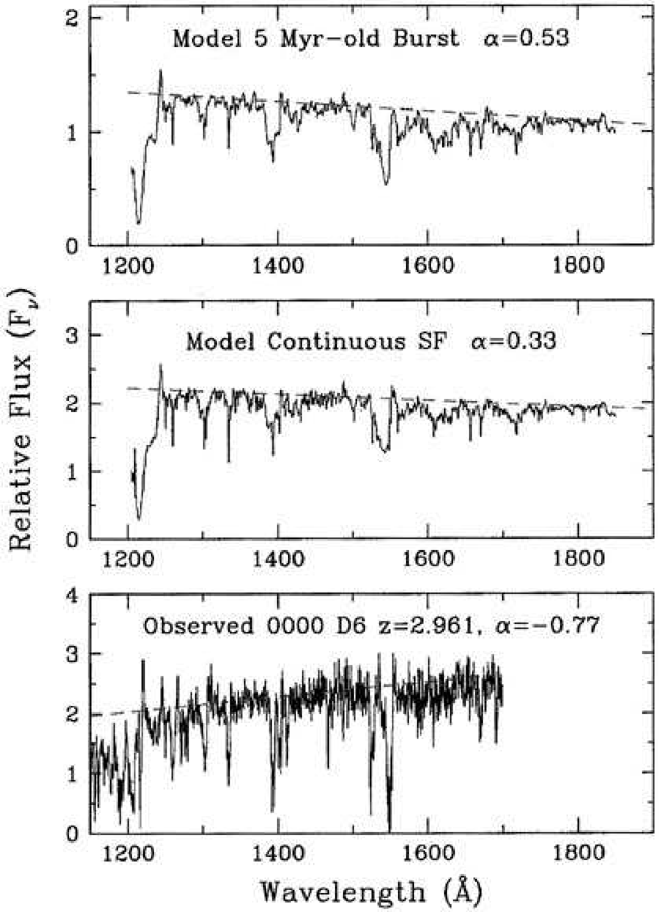
The right hand figure shows the U-G and G-R colors for galaxies with different colors. The yellow box is the selection area in which we define U-dropouts to lie. The blue galaxies are indicated by the blue lines, at each redshift interval of 0.1, a blue triangle is shown. As can be seen, the blue galaxies are found at many redshifts. This does not hold for the green or red galaxies, which are much redder (due to age or dust). Hence we can find red galaxies over a small redshift interval, but blue galaxies over a much larger.

Overall, one finds that the density of the (bright) Lyman breaks at $z = 3$ is about 1.6 10^{-2} h^3 Mpc^{-3}. Comparable to that of nearby galaxies ! However, if we were to put nearby galaxies at high redshift, we would not detect anything !



WFPC2+F606W images of LLGs and local galaxies as HST would observe them if placed at $z = 3$. We had to boost their surface brightness 100x to detect them in 5 hr except NGC 1068, shown before and after the boost. Panels are 7 arcsec in size and $q0 = 0.1$.

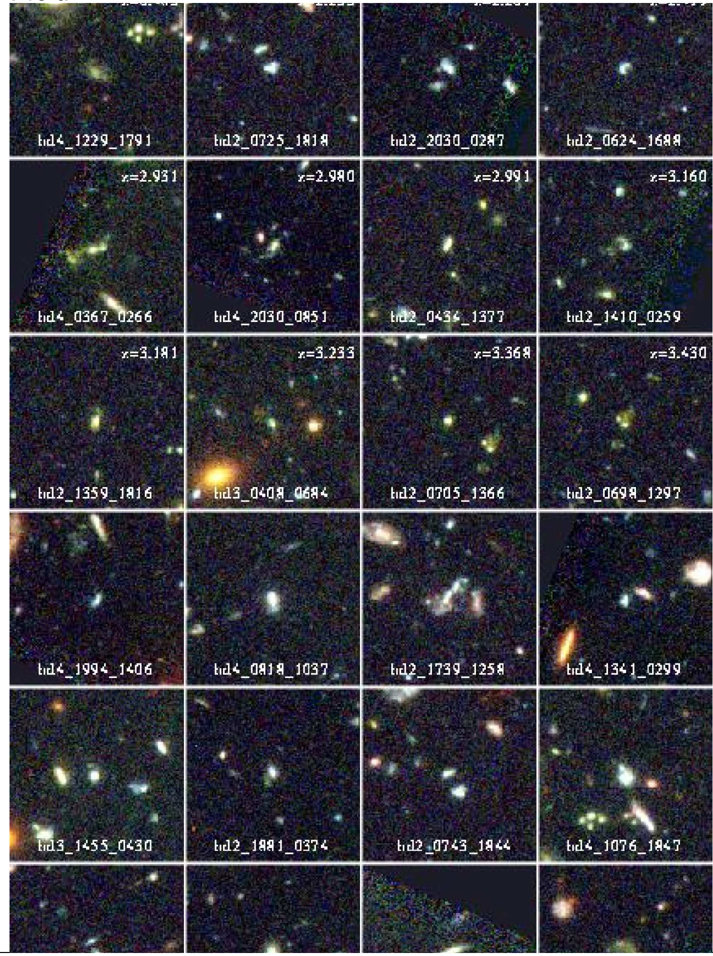
Hence Lybreaks are very different from nearby galaxies: the same number densities, (number per Mega parsec) but much smaller, and forming stars at much higher rates.



The spectra look very much like young O stars, with dust (to make them red)

Conclusion: We find a major new population of galaxies by looking in the UV. These galaxies are very different from nearby normal galaxies

Below we show how they look like in the Hubble Deep Field



These Lyman Break galaxies are usually very “clumpy”, irregular, and small.

Many of these galaxies have been found and have measured redshifts. We can measure the clustering of these galaxies. An example is shown below.

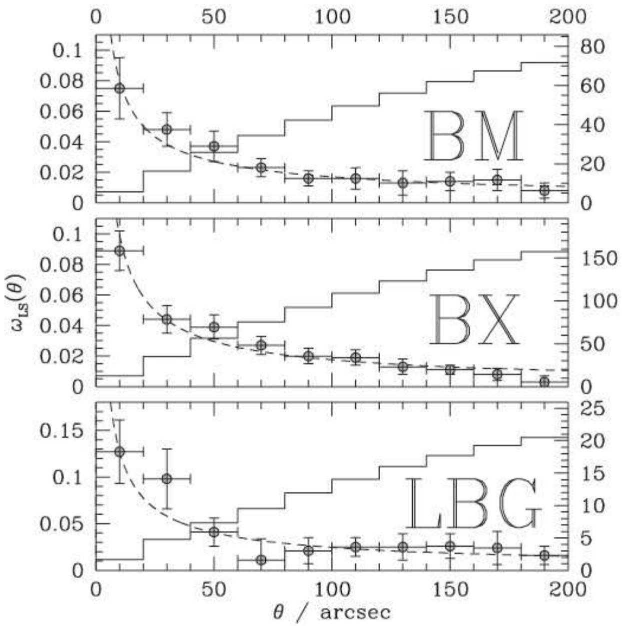


FIG. 3.—Angular correlation functions uncorrected for the integral constraint $\mathcal{I}$. Filled circles with error bars show the measured values of the estimator ω_{LS} for each sample. The dashed line shows the power law $\omega = A\theta^{-\beta}$ that fits the data best. The solid histogram indicates the number of galaxy pairs (/1000) in each angular bin. [*See the electronic edition of the Journal for a color version of this figure.*]

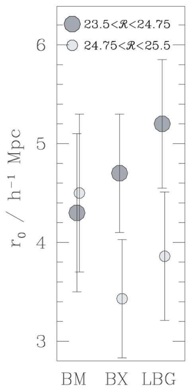
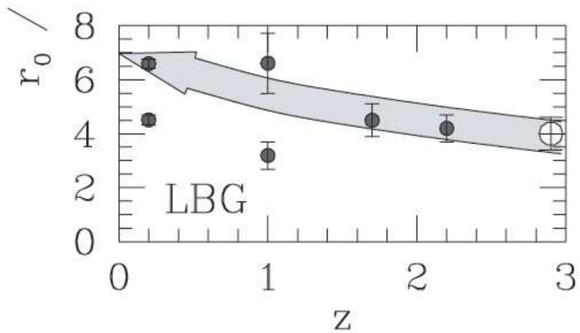


FIG. 5.—Correlation length r_0 for bright and faint subsamples of the BM, BX, and LBG samples.

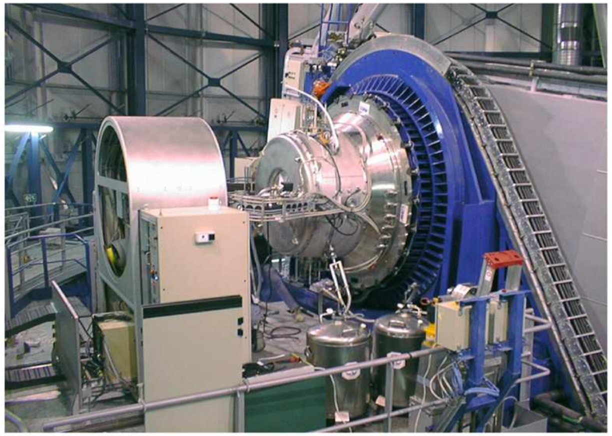
The clustering length of the galaxies is 5Mpc or more ! This is really a very large value at that redshift. Remember that the clustering length is thought to be a signature of the halo in which a galaxy lives. The more massive the halo, the larger the clustering length. We can use models to “predict” the clustering length of the “descendant” halos. Se the figure below



The clustering length is expected to be around 7Mpc, well above the clustering length of normal galaxies in the nearby universe.

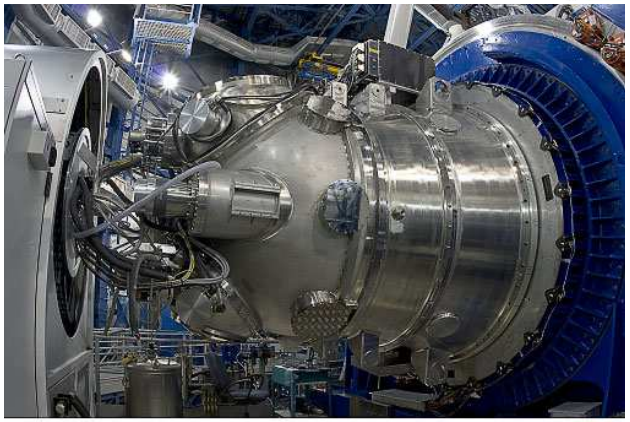
Near-IR selected galaxies to $z = 3$ and above

The logical way to find galaxies equivalent to galaxies in the nearby universe is to look for galaxies based on their rest-frame optical light. The rest-frame optical moves into the Near-IR ($\lambda > 1$ μm) for $z > 1.5$. Hence one should select and study these galaxies in the J, H, K band (depending on their redshift). This has been very hard until 9 years ago, when large Near-IR detectors become available and operational on large telescopes. The first such facility was the 1024x1024 detector on the VLT in ISAAC, working by 1999. It had a field-of-view of 2.5x2.5 arcmin, comparable to HST. Now, the VLT is equipped with Hawk-I, which has a 9 times larger field of 7x7 arcmin. These instruments are gigantic (for a very small detector !)



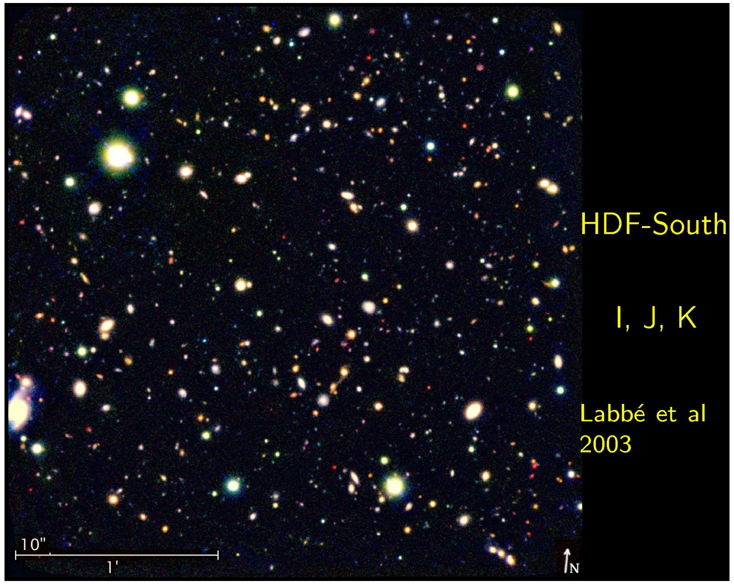
ISAAC mounted on the VLT UT1

ESO PR Photo 46a/98 (26 November 1998) © European Southern Observatory



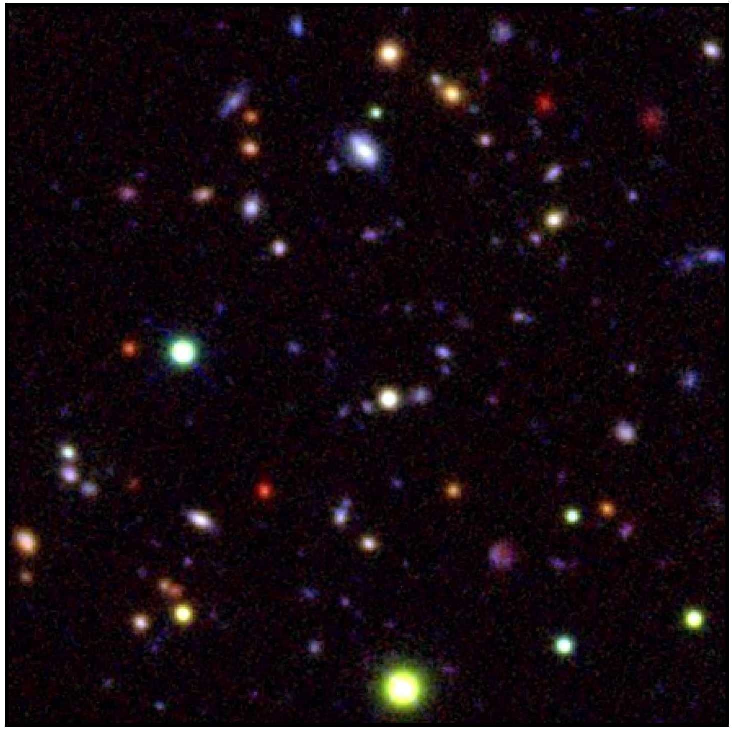
The HAWK-I Instrument at the VLT

Labbe et al. used the instrument to obtain very deep images in J, H, K in the near-ir on the Hubble Deep Field South, and Forster et al. to do the same on the field of the cluster MS1054, as part of the FIRESurvey (Franx et al). It used a total of 200 hours of VLT exposure time.



The striking result is that there are many red galaxies. The picture above shows the field in the I,J,K colors - notice all galaxies that are red: bright in K, low in I and J.

The red galaxies are shown below



This panel shows a zoom-in of the HDFS I,J,K color image. The red galaxies don't emit much at all in the HDFS optical - but a lot in the K.

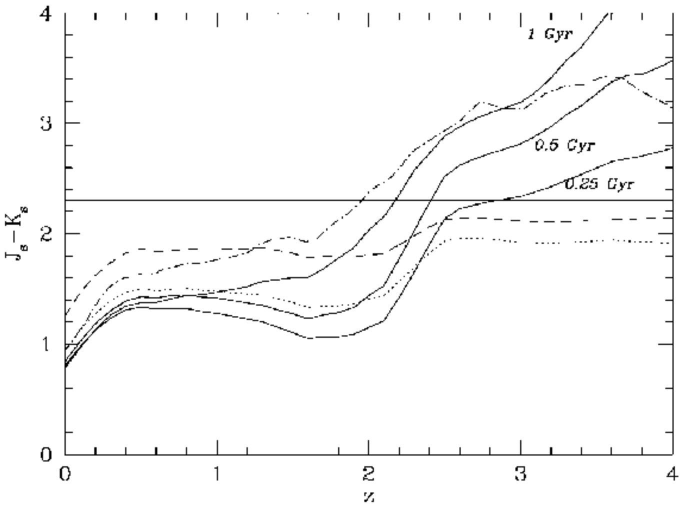


FIG. 1.—J_s-K_s color as a function of redshift for several galaxy spectra. The solid curves indicate single-age stellar populations with ages of 0.25, 0.5, and 1 Gyr. The colors exceed $J_s-K_s = 2.3$ only for $z > 2$ as a result of the Balmer break/4000 Å break moving into the J_s band. The dotted and dashed curves indicate models with continuous star formation with ages and reddenings of 1 Gyr, $E(B-V) = 0.15$ and 100 Myr, $E(B-V) = 0.5$, respectively. Many galaxies with continuous star formation will not reach $J_s-K_s = 2.3$, unless they are even older or have larger reddening. The dash-dotted curve indicates the color evolution of a single-burst population that formed at $z = 5$, and it also satisfies the color criterion above $z = 2$.

To study this population better, we can select the reddest galaxies, with $J - K > 2.3$ (Franx et al)

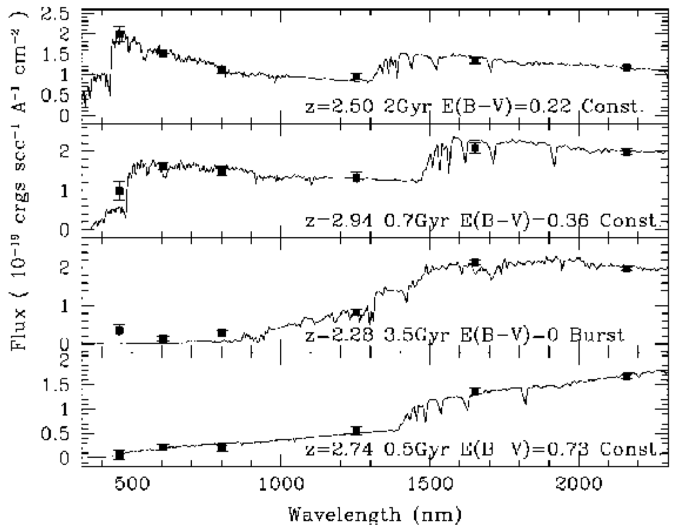


FIG. 3.—SEDs of four galaxies with $J_s-K_s > 2.3$. They span the full range in $I-K_s$ color. All the galaxies show a break between the J_s and K_s bands. The curves show stellar population fits with either constant formation and reddening or unreddened single-age bursts.

Their SEDs look like above. Photometric redshifts, and spectroscopic redshifts for some of them, confirm that they generally lie at redshifts above 2.

Their density is about .0014 Mpc^{-3} - comparable to that of bright Lyman break galaxies.

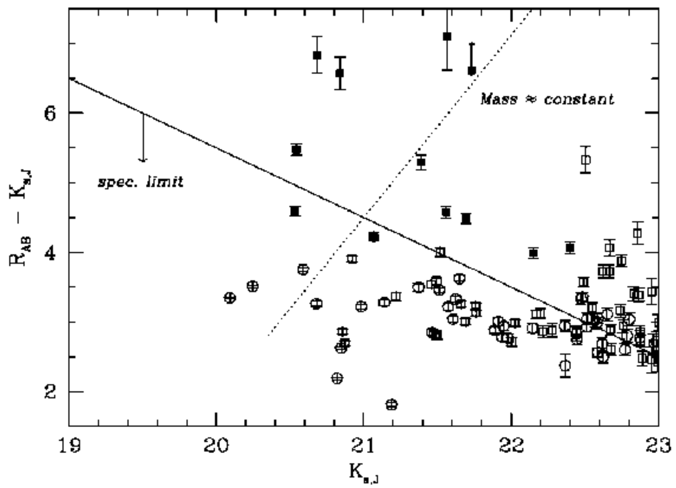


FIG. 4.—$R_{AB}-K_s$ color vs. K_s magnitude for galaxies with $2 < z < 3.5$. The J_s-K_s red galaxies are indicated by filled symbols. Lyman break galaxies are indicated by the circles. The solid line indicates the magnitude limit used for most ground-based spectroscopic studies of Lyman break galaxies of $R_{AB} = 25.5$. Most J_s-K_s red galaxies are missed when this magnitude limit is applied. The dotted line is a track of constant mass for a model with a single-age population. As can be seen, the J_s-K_s red galaxies are slightly less luminous in the K_s band than the brightest Lyman break galaxies in the HDF-S, but their masses may well be comparable or higher.

Since they are red, they are expected to have a higher mass-to-light ratio than the blue Lyman break galaxies. The figure above shows the Lyman-break galaxies and the DRG's (with J-K > 2.3) in the same plot. The DRG's are likely as massive as the Lyman break - or even more massive.

Understanding the galaxy population

How can we understand these galaxy populations of very red galaxies, blue galaxies, and other sorts of galaxies ? The only way forward is again by measuring their stellar masses, and correlation lengths. The stellar masses allows us to compare different types of galaxies at different redshifts, and the correlation lengths allow us to estimate the masses of the halos in which the galaxies reside.

Stellar masses

Optical + Near-IR photometry allows us to estimate the stellar masses. We fit stellar population synthesis models to the photometry, and the best fitting model gives the mass, age, star formation rate. This is uncertain: models are used for this - and the models can be wrong.
An example is shown below (from Shapley et al. 2001)

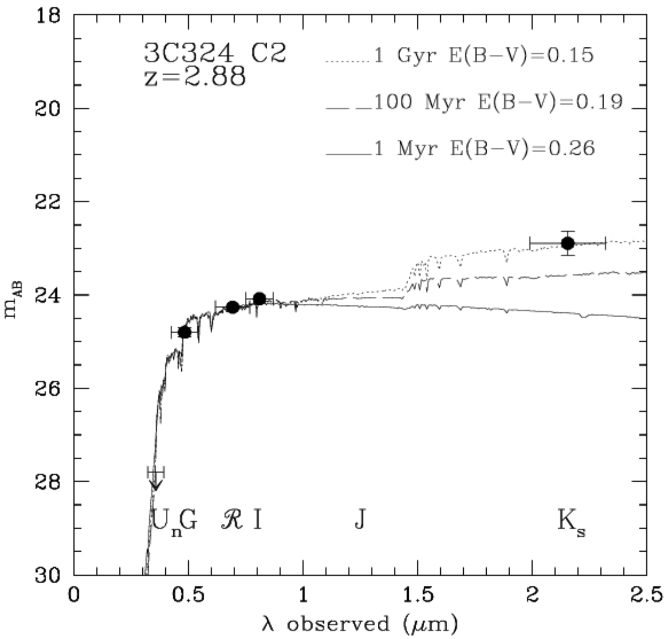
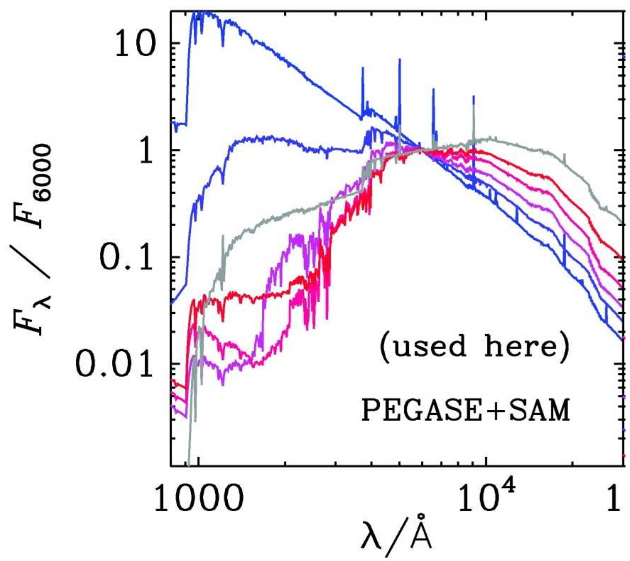


FIG. 6.—Age-dust degeneracy. The points indicate the observed SED of 3C 324–C2, an LBG at $z = 2.880$. Shown with the points are BC96 constant star formation models of different ages, modified by the amount of dust extinction required to reproduce the observed $G-\mathcal{R}$ color. The dotted line is a 1 Gyr model with $E(B-V) = 0.149$; the dashed line is a 100 Myr model with $E(B-V) = 0.186$; and the solid line is a 1 Myr model with $E(B-V) = 0.263$. All of these models describe the observed optical photometry equally well. However, only the 1 Gyr model successfully describes the observed $\mathcal{R}-K_s$ color. [*See the electronic edition of the Journal for a color version of this figure.*]

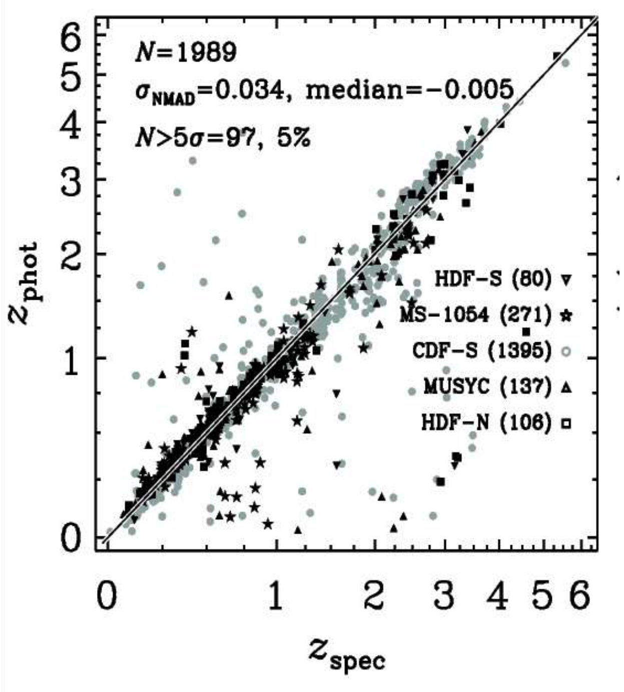
It turns out that the masses are reasonably "stable" if we make changes to the models (like changing the star formation history, metallicity, dust extinction law - all unknown parameters).

We generally find low mass-to-light ratios for Lyman breaks, and high mass-to-light ratios for the red galaxies. The Lyman breaks have typically masses of 10^{10} $M_\odot$, the red galaxies masses at the level of 10^{11} $M_\odot$. There are of course variations - it depends on the brightness of the galaxy too.

van Dokkum et al. applied this technique to all galaxies found in a deep Near-IR imaging survey. Redshifts were not measured with spectroscopy, but from the photometry. This is necessary as it is still very hard to obtain spectroscopy on faint near-ir galaxies. The photometric redshifts are derived from fitting galaxy template spectra to the photometry - while keeping the redshift free as a fitting parameter.



The templates used for the photometric redshift fitting. Note the large variation from blue to red



The comparison of photometric redshifts, and spectroscopic redshifts. The correspondence is generally good, with a scatter of 0.03 in δ z / (1+z). However, this can be misleading: spectroscopy is usually done on bright galaxies at low redshift - and is not done on the "average" population

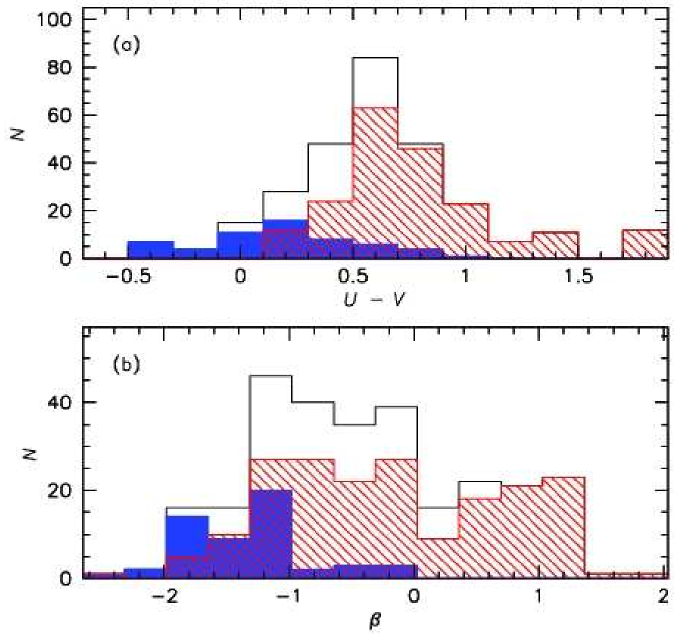


FIG. 2.—Distribution of rest-frame $U - V$ colors (*a*) and rest-frame UV slope β (*b*) for galaxies with $M > 10^{11} M_{\odot}$ and $2 < z_{phot} < 3$. The galaxies show a wide range in rest-frame optical and rest-frame UV colors. Blue histograms indicate galaxies with the colors and luminosities of LBGs; red histograms indicate DRGs.

After the photometric redshifts were derived, all galaxies with photometric redshifts between 2 and 3 were selected. The color distribution is shown above. Blue area is Lyman break galaxies, red area is DRGs (J-K > 2.3)

Notice how wide the distribution is !

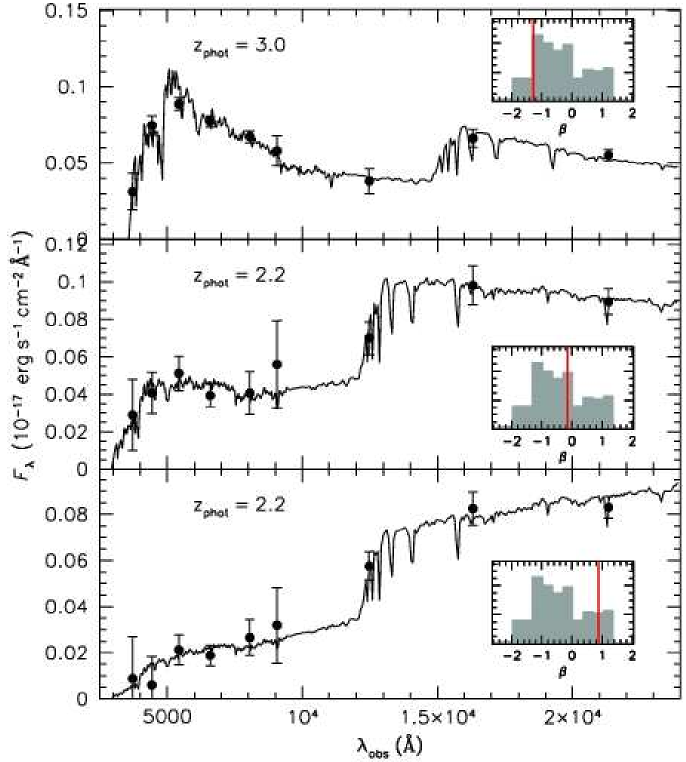


FIG. 3.—SEDs of three MUSYC galaxies with different rest-frame UV slope β. Overplotted are the best-fitting Bruzual & Charlot (2003) models. From top to bottom, the galaxies have $\beta = -1.3, -0.2$, and 0.9 respectively. The blue rest-frame UV SED of the top object is typical for LBGs. The slope of the middle galaxy is close to the median value of the full sample.

The SED shapes in the UV also vary by large amounts. The main result is that more than 50% of the galaxies are red ! These galaxies dominate the population at the massive end ($M > 10^{11} M_{\odot}$).

Star formation

At the same time, we wish to measure star formation rates, so that we can see how the stars are being formed in the universe. Star formation rates are generally measured in various ways:

1) Hα emission lines. O stars emit a lot of photons below 912 Angstrom. These photons ionize the hydrogen gas around the stars. This ionized hydrogen gas emits Hα emission (6563 Angstrom). The problem is, that dust around the stars will reduce the emission. Hence this needs to be corrected for. This can be done using the Hβ line (4861 Angstrom). The intrinsic ratio of Hβ over Hα does not vary much. Hence any observed reduction of the ratio is due to dust (Hβ gets extincted more). These H β measurements are very hard - and they don't correct for UV photons being absorbed.

2) UV emission. Young stars (O and B) emit a lot of UV flux. This is a reasonable measure of the star formation rate (not so good as Hα, because more older stars contribute, and because extinction is harder to correct for.) The main problem is that a bit of extinction will wipe out the UV light very effectively. This problem is huge in the UV.

3) IR emission. Most of the light from star formation comes out in the mid-ir, as most emission is extincted by dust, the dust is heated, and emits in the IR (peaking at 60-200 μm). With telescopes like Spitzer we can measure the emission in the mid-IR (although with great trouble at observers wavelengths longer than 24

μm.

4) Radio. A not-so-well relation exists between the emission in the mid-IR, and synchrotron relation. The correlation is very good, indicating that radio can be used. Very, very deep data are needed to do this.

5) Xray. Young stars emit Xrays. These can be measured with satellites like Chandra. The problem is that galaxies are faint in the Xray.

A problem with all these methods is that Active Galactic Nuclei can also emit a lot of light in all these wavelengths. And that is not star formation !

When we add all the indicators together, we can estimate the star formation rate density of the universe. It looks like below:

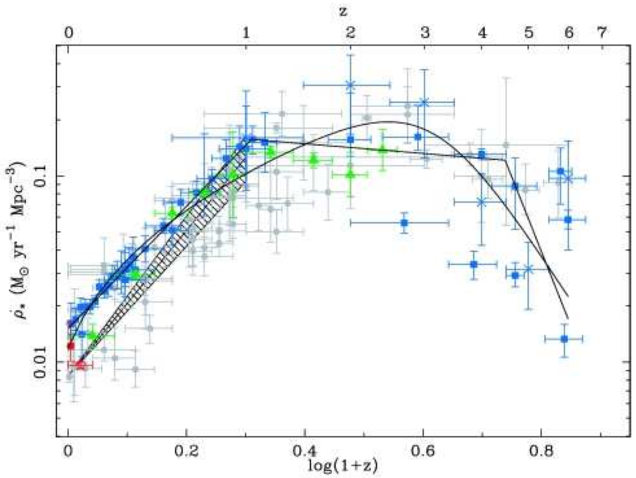


FIG. 1.—Evolution of SFR density with redshift. Data shown here have been scaled, assuming the SalA IMF. The gray points are from the compilation of Hopkins (2004). The hatched region is the FIR (24 μm) SFH from Le Floc'h et al. (2005). The green triangles are FIR (24 μm) data from Pérez-González et al. (2005). The open red star at $z = 0.05$ is based on radio (1.4 GHz) data from Mauch (2005). The filled red circle at $z = 0.01$ is the Hα estimate from Hanish et al. (2006). The blue squares are UV data from Baldry et al. (2005), Wolf et al. (2003), Arnouts et al. (2005), Bouwens et al. (2003a, 2003b, 2005a), Bunker et al. (2004), and Ouchi et al. (2004). The blue crosses are the UDF estimates from Thompson et al. (2006). Note that these have been scaled to the SalA IMF, assuming they were originally estimated using a uniform Salpeter (1955) IMF. The solid lines are the best-fitting parametric forms (see text for details of which data are used in the fitting). Although the FIR SFH of Le Floc'h et al. (2005) is not used directly in the fitting, it has been used to effectively obscuration-correct the UV data to the values shown, which are used in the fitting. Note that the top logarithmic scale is labeled with redshift values, not $(1 + z)$.

The star formation rate increases rapidly from $z = 0$ to $z = 1$, and then flattens out. At higher redshift, it decreases again.

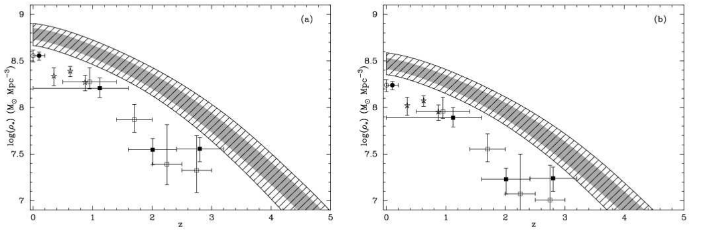


Fig. 5.— Evolution of stellar mass density buildup inferred from the SFH, assuming (*a*) SalA IMF (with $R = 0.40$) and (*b*) BG IMF (with $R = 0.56$). The gray shaded and hatched regions come from, respectively, the 1 and 3 σ confidence regions around the SFH $T = 4$ MeV fits . The details of scaling the data points to our assumed IMFs are given in the text. The open circle is the local stellar density from Cole et al. (2001); the filled circle and filled squares represent the SDSS and FIRES data, respectively, from Rudnick et al. (2003), scaled such that the SDSS measurement is consistent with that from Cole et al. (2001); the open stars are from Brinchmann & Ellis (2000), and the open squares are from Dickinson et al. (2003).

With SED fitting, the mass density of the universe has been determined as well. The points show the results (as obtained in 2006).
A most surprising result follows: the star formation rate history predicts that much more stars are formed than what we see. The drawn lines show the predicted number of stars given the star formation history shown in the previous figure. How can this be ?

1) Maybe our measurements are wrong ?
- do we miss stellar mass ?
- do we overestimate star formation (too much dust correction ?)

2) Maybe the star formation is different ?
- IMF evolves ? More high mass stars, few low mass stars being formed ?

3) The real problem is: we see the formation of massive stars; but we measure the masses of low mass stars in the nearby universe. This is difficult to solve !

This problem is not been solved. People even argue

whether there is a problem...

The highest redshift galaxies

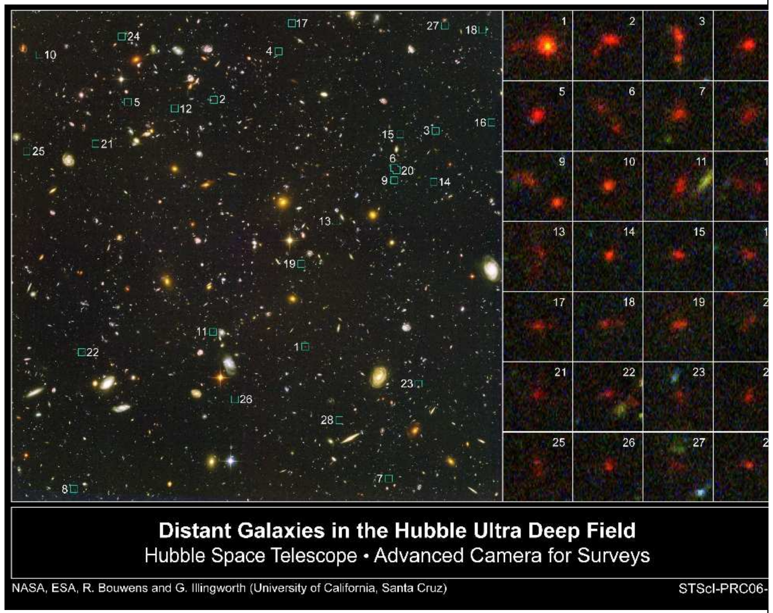
Out to how far can we push it ?

Using the U-dropout technique, we can select $z = 3$ galaxies because they are "dead" in the observers U-band: the U-band samples the restframe wavelength below the Lyman break (912 Å), below which the galaxies emit little, and below which the universe absorbs light.

We can easily use a similar technique to select galaxies at high redshifts. For example, the B-dropouts (red in B-R, blue in R-I) are at redshifts of about 4. The 912 break coincides with B, giving the redshift of 4.

At higher redshifts an additional factor starts to play a role: the universe starts to absorb most of the light below 1216 Å. This is simply due to the fact that it has sufficient neutral hydrogen to absorb significantly at (restframe) 1216 Å, the wavelength of Lyman α. Hence the spectra of $z = 6$ galaxies will be "dead" below 1216 Å, and hence are dead in the I-band (8000 Å, 1216Åhas moved to 8500 Å, above the I band).

Due to the Hubble Ultra Deep Field, we now have identified hundreds of i-dropouts. The ACS camera was very effective in finding these, as it has very high throughput in the i and z band. i-dropouts were selected to have very red i-z colors.



We found a lot of them (see above). Pushing things to higher redshift becomes even harder. The galaxies become less bright, and the near-ir camera on Hubble does not have the same efficiency as ACS. This will be fixed when Hubble gets repaired in May 2009. Only a handful of reliable z-dropouts have been found at $z = 7$. The luminosity density from high redshift galaxies decreases rapidly towards higher redshift:

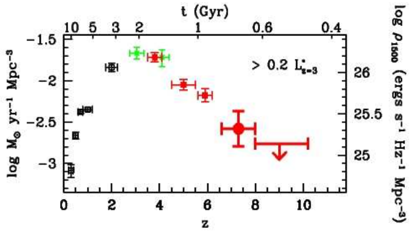


FIG. 8.— The present constraints on the UV luminosity density at $z \gtrsim 7$. At $z \sim 7$, this constraint is shown as a large solid red circle while at $z \sim 9$, it is shown as a 1σ upper limit (*red downward arrow*). These determinations are integrated to $0.2L^*_{z=3}$ to match the approximate faint limits on our $z \gtrsim 7$ galaxy searches. Also shown are the determinations of Schiminovich et al. (2005: *open black squares*), Steidel et al. (1999: *green crosses*), and Bouwens et al. (2007: *solid red squares*) integrated to the same flux limit.

Hence it seems we are really seeing the end of the dark ages ? Many astronomers think that the first stars formed at even higher redshift - maybe z=20-30. These stars would be very different from nearby stars: they contained no metals. Not much is know, of course, but it is often hypothesized that such stars (called "Population III") are very massive, and bright, and end with a very luminous supernova. It is hoped that the successor of Hubble, the James Webb Space Telescope (or JWST) will find them (but we'll see). The JWST is scheduled for launch in 2013, and will operate for at least 5 years.