Galaxies: Structure, Dynamics, and Evolution

“Evolution of Galaxies with Redshift: What are the Most Salient issues?”

“How do galaxies look at the earliest times?”

Layout of the Course

Lectures

Feb 2: Course Introduction, Overview, and Galaxy Formation Basics
Feb 9: Disk Galaxies (I)
Feb 12: Disk Galaxies (II)
Feb 16: Disk Galaxies (III) / Collisionless Stellar Dynamics
Feb 23: Collisionless Stellar Dynamics + Vlasov/Jeans Equations
Feb 26: Vlasov/Jeans Equations / Elliptical Galaxies (I)
Mar 9: Elliptical Galaxies (II)
Mar 23: Dark Matter Halos
Mar 30: Connecting Galaxies to Dark Matter Halos
Apr 13: Galaxy Stellar Populations + Lessons from Galaxies at z<0.2
Apr 20: Lessons from Galaxy Samples at z<0.2 + Evolution with Redshift
Apr 23: Evolution of Galaxies with Redshift + Pushing to z>1.5
May 4: Gas Cycle + Galaxy Evolution at z>6
May 11: Galaxy Evolution with JWST / Review for Final Exam

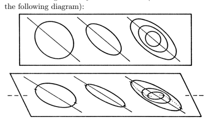
Problem Set 4

Due on April 27

Galaxies: Structure, Dynamics, and Evolution
Problem Set 4
Instructor: Dr. Bouwens

Here is Problem Set 4. The entire problem set will be due before class on Monday, April 27 (email them to Wout and include GSD in the subject line). Be sure to pay extra attention to problem 6, as your solution to that problem will be checked carefully and used in determining your homework grade.

1. Determine the impact of projection effects on the apparent isophotal twist (for elliptical galaxies). Consider two ellipses with their major axis oriented 45 degrees away from some line (that line would be horizontal on the following diagram):



Suppose that the axial ratio is 1.15 for the one ellipse (similar to the leftmost ellipse shown in the above figure) and 2.8 for the other ellipse (similar to the center ellipse shown in the above figure). Suppose that we are viewing the ellipses face on and then we rotate the ellipses by 60 degrees about an axis (parallel to the aforementioned line) so that the ellipses are viewed almost edge on. What ellipticity would we measure for each of our two ellipses? What would be the apparent position angle of the major axis of each ellipse relative to aforementioned line?

2. (a) Derive the enclosed mass M(< r) for the NFW profile $\rho(r) = \rho_s/[(r/r_s)(1+r/r_s)^2]$. Use $r/(1+r)^2 = 1/(r+1) - 1/(1+r)^2$
(b) Use this to show $\rho_s = \frac{200}{3}\rho_{cr}(z)\frac{c^3}{\ln(1+c)-c/(1+c)}$ given our parameterization $\rho(r) = \frac{\rho_s}{(r/r_s)(1+r/r_s)^2}$
(c) Derive the circular velocity as a function of radius for an NFW profile.

3. Consider the collapse of a uniform cloud of stars initially at rest. Assume the cloud has a total mass of 5×10^{10} $M_\odot$, is entirely composed of stars with 1 $M_\odot$, and has approximate dimensions of 2 kpc $\times$ 2 kpc $\times$ 2 kpc. Assume that the collapse finishes in one free fall time, $1/\sqrt{G\rho}$. What is the time scale for violent relaxation? [Approximate order-of-magnitude estimates are fine for this first step.] If the system were instead in equilibrium (i.e., not undergoing collapse), what relaxation time scale would we estimate for stars in this system using the equations we derived in Lecture #5? How do these time scales compare?

4. Determine what the b_n normalization factor in the Sersic law must be such that the integral of the surface brightness profile $10^{b_n[(R/R_e)^{1/n}-1]}$ over all radii is equal to one. What is this normalization factor in the case $n = 1$ and $n = 4$?

5. Look at the angular correlation functions for luminous galaxies $-22 < M_{UV,AB} < -21$ and lower luminosity galaxies $-19 < M_{UV,AB} < -18$ (shown in the last lecture). What is the ratio of bias factors for these galaxies at a scale of 1.5 h^{-1} Mpc? [Make your best guess for the bias factors based on the figure shown in lecture.]

6. Derive the Fundamental Plane that one would find if the mass-to-light ratio is a function of mass only $M/L = M^{0.25}$ and more generally $M/L = M^{\gamma}$. (The Fundamental Plane is the relation of the form $R_e \propto \sigma^{\alpha}\mu_e^{\beta}$ where R_e is the half-light radius.) Assume that the galaxies are homologous, i.e., they have similar density profiles, but scaled up or down with respect to each other. Note that the assumption of homology results in the following relation: $\sigma^2 \propto M/R_e$.

7. The number density of galaxies is about 0.01 h^3 Mpc^{-3}. The correlation length r_0 is $5h^{-1}$ Mpc.
a) Why does the density and the correlation length depend on h (= H_0/ (100 km/s/Mpc))
b) The correlation function gives the relative excess of galaxies at a given radius. Calculate the integrated correlation function, i.e., the excess from within a radius smaller than r.
c) Now combine this with the average number density to estimate the radius r within which each galaxy has on average 1 neighbor.
d) What would this radius be if the galaxies are not correlated?

Problem Set 5

Due on May 4

Galaxies: Structure, Dynamics, and Evolution
Problem Set 5
Instructor: Dr. Bouwens

Here is Problem Set 5. The entire problem set will be due before class on Monday, May 4 (email them to Wout and include GSD in the subject line). Be sure to pay extra attention to problem 1, as your solution to that problem will be checked carefully and used in determining your homework grade.

1. We can see from the figure from Springel et al. that about 30-40% of the mass of a halo is in subhalos. This appears quite different from the situation in clusters, where the light is dominated by the ensemble of regular cluster galaxies, and NOT by the brightest cluster galaxy. Can you think of an explanation ?

2. One result which has been found in the astronomical literature (Adelberger 2005) is that the observed clustering of quasars does not depend on the luminosity of the quasar. What does this suggest about the relationship between the quasar luminosity and the mass of the underlying halo in which it lives. Can you think of any physical reason why this might be the case?

3. Approximate the rotation curve of UGC 4325 by a straight line, through (0 arcsec, 0 km/s) and (60 arcsec, 110 km/s). What is the best fitting NFW model ? This would be the model for which $\chi^2 = \int (V_{obs} - V_{model})^2 dr$ is minimized.
4. Images of the bulge show that it has a very regular appearance. However, we have seen that the halo is quite irregular, with stellar streams, etc. Why might the bulge be so regular, whereas the halo is irregular? Be quantitative.

5. Assume that red galaxies form in random bursts from $t = 0.4$ Gyr to $t = T_b$ where T_b is 1 Gyr and 8 Gyr and t is the time after the Big Bang. Calculate the scatter in the color $U-V$ magnitude that one would derive for a population of such galaxies, assuming $U - V = 0.65\log_{10}\text{time} + b$ where b is some constant. The current age of the universe is 13.7 Gyr.

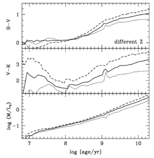
Problem Set 6

Due on May 11

Galaxies: Structure, Dynamics, and Evolution
Problem Set 6
Instructor: Dr. Bouwens

Here is Problem Set 6. The entire problem set will be due before class on Monday, May 11 (email them to Wout and include GSD in the subject line). Be sure to pay extra attention to problem 1, as your solution to that problem will be checked carefully and used in determining your homework grade.

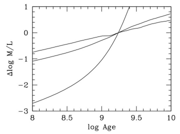
1. Evolution of the mass-to-light ratio. (a) The mass-to-light ratio is roughly a power-law with time. Measure by hand the coefficient α for the mass-to-light ratio $M/L = t^\alpha$ for the V band from the following figure shown in lecture (choose the middle line):



(b) The $B-V$ and $V-K$ color of a SSP (simple stellar population) depend more or less linearly on $\log t$ for ages about 10^8 years. Determine this dependence from the figure shown above (take the middle line again). Use the result to derive the coefficient α for the mass-to-light ratio dependence on time for the B band and the K band.

(c) Use the following figure (also shown in lecture) to derive α for the U-band (the U band curve is the steepest one):

1



2. (a) Assume that the time dependence of the mass-to-light ratio derived in problem #1 for all t below 10^{10} years. The equations above were derived for single burst stellar populations. Now assume a population with constant star formation. Calculate the evolution of the M/L ratio with time T for the U, B, V and K band. Do this by calculating the light from a populations formed at a time interval t, $t+dt$, and then integrating from $t=0$ to $t=T$, where T varies from 1 to 10 Gyr. The only thing we care about is the dependence of the M/L ratio with time, not the absolute value of the M/L ratio.
(b) Use the results obtained in (a) to derive the dependence of the $U-B$, $B-V$, and $V-K$ colors with time. Compare these numbers to the time dependence of the same colors for an SSP.

3. An important assumption in the analysis of unresolved stellar population is that of a universal initial mass function. What would be the impact if this assumption were not true? Consider two cases: the first being a Salpeter IMF with cut-offs at 0.1 $M_\odot$ and 100 $M_\odot$ and the second being a Salpeter IMF with cut-offs at 0.1 $M_\odot$ and 1 $M_\odot$.
(a) Assume that a galaxy formed stars acording to the two IMFs described. Very qualitatively, what would the SEDs of galaxies look like like 10 Myr later and 11 Gyr later? How similar are the SEDs of galaxies in the two cases at the later time?
(b) How do the SEDs of galaxies evolve in the case of the first IMF vs. the second IMF? How accurately could one determine the time since the instan-

2

taneous burst of star formation in the two cases?
(c) Let's suppose that the true IMF of a galaxy corresponded to the second case, but let's suppose one assumed it was the first case. How might it impact one's estimates of the total mass locked up in stars based on the observed SED? How might it impact one's estimates on the total metals ejected as a result of supernovae in the formed stars? Describe each case.

4. Use a modern stellar population synthesis code to predict galaxy spectra. In this problem you will use the Flexible Stellar Population Synthesis (FSPS) code through its Python interface (`python-fsps`). Start early, as installation and setup may take some time.

(a) Consider a simple stellar population (SSP), in which all stars form instantaneously at $t=0$. Using FSPS, generate spectra for a population with the following parameters:

- Star formation history: instantaneous burst (SSP)
- Metallicity: $Z \approx 0.004$ (subsolar)
- Initial mass function: Salpeter
- No dust attenuation and no nebular emission

Compute spectra over a range of ages from 10^6 to 10^{10} years, using logarithmically spaced time steps (e.g., ~ 100 steps). Plot the spectrum at approximately 10^7, 10^8, 10^9, and 10^{10} years on the same wavelength range.

Briefly describe how the spectral shape evolves with time.

(b) Using the same model, compute the absolute magnitudes in the V and I bands as a function of time over the range 10^6 to 10^{10} years.

From these results, determine the absolute magnitude in the I band, M_I, either directly or using

$$M_I = M_V - (V - I).$$

Plot M_I as a function of $\log_{10}(t/\text{yr})$.

Using the stellar mass of the population and the I-band luminosity, determine how the mass-to-light ratio evolves with time. Assume a power-law form

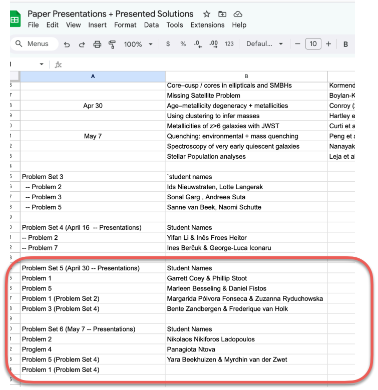
$$\frac{M}{L_I} \propto t^\alpha.$$

3

Presentation of Solutions to Problems

~7.5% of course grade involves presenting a solution to a problem

~16 students from class need to present

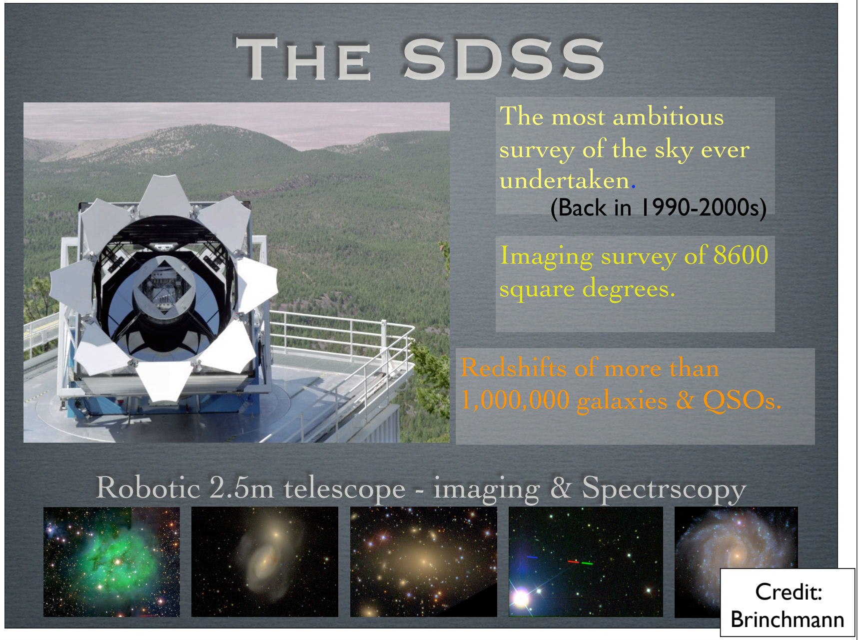


A	B	
	Core–cusp / cores in ellipticals and SMBHs	Kormend
	Missing Satellite Problem	Boylan-K
Apr 30	Age–metallicity degeneracy + metallicities	Conroy (
	Using clustering to infer masses	Hartley e
	Metallicities of z>6 galaxies with JWST	Curti et a
May 7	Quenching: environmental + mass quenching	Peng et a
	Spectroscopy of very early quiescent galaxies	Nanayak
	Stellar Population analyses	Leja et al
Problem Set 3	`student names	
-- Problem 2	Ids Nieuwstraten, Lotte Langerak	
-- Problem 3	Sonal Garg , Andreea Suta	
-- Problem 5	Sanne van Beek, Naomi Schutte	
Problem Set 4 (April 16 -- Presentations)	Student Names	
-- Problem 2	Yifan Li & Inês Froes Heitor	
-- Problem 7	Ines Berčuk & George-Luca Iconaru	
Problem Set 5 (April 30 -- Presentations)	Student Names	
Problem 1	Garrett Coey & Phillip Stoot	
Problem 5	Marleen Besseling & Daniel Fistos	
Problem 1 (Problem Set 2)	Margarida Pólvora Fonseca & Zuzanna Ryduchowska	
Problem 3 (Problem Set 4)	Bente Zandbergen & Frederique van Holk	
Problem Set 6 (May 7 -- Presentations)	Student Names	
Problem 2	Nikolaos Nikiforos Ladopoulos	
Proglem 4	Panagiota Ntova	
Problem 5 (Problem Set 4)	Yara Beekhuizen & Myrdhin van der Zwet	
Problem 1 (Problem Set 4)		

Feb 19: Board Work + Problem Set 1
Mar 12: Board Work + Problem Set 2
Mar 26: Problem Set 3 / Paper Presentations (3 slots)
Apr 2: Problem Set 3 (cont'd) / Paper Presentations (6 slots)
Apr 16: Problem Set 4 / Paper Presentations (3 slots)
Apr 30: Problem Set 5 / Paper Presentations (3 slots)
May 7: Problem Set 6 / Paper Presentations (3 slots)

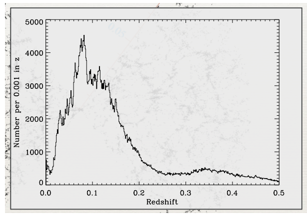
First, let's review the important material from last week

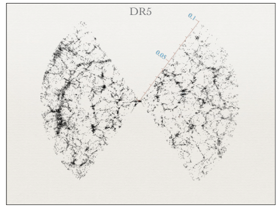
What can we learn about the structure, formation and evolution of galaxies by putting together a large survey of galaxies in the nearby universe?



Credit: Brinchmann

There are spectra, colors, luminosities for 100,000s of galaxies in the nearby universe such as we have from the Sloan Digital Sky Survey.





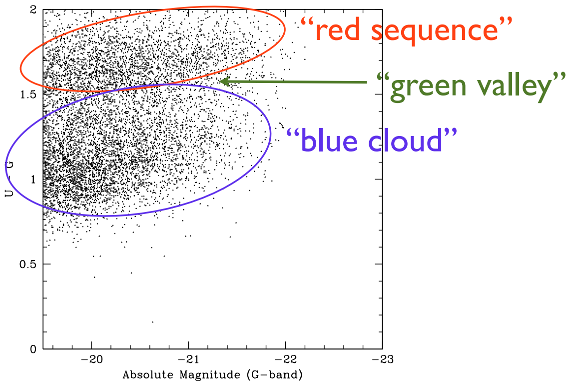
What general conclusions can we draw about galaxies from these observations?

Galaxies in the nearby universe can be divided into two types:

Galaxies whose colors lie on "red sequence"

Galaxies whose colors lie within the "blue cloud"

color



luminosity

There is a clear ***bimodality*** to the distribution!

What is the distinction between galaxies in the red sequence and the blue cloud?

It would appear to be whether the galaxies are still actively undergoing star formation or not.

There are other factors which are important (dust, metallicity), but they only change the picture slightly.

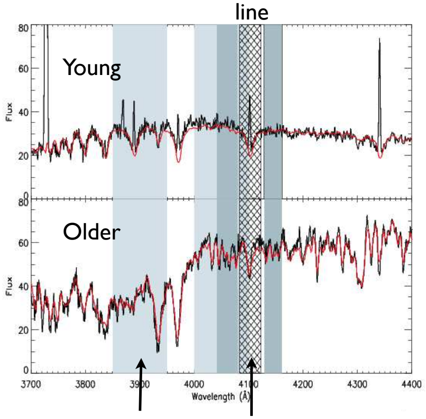
Systematic Analysis of >100,000 Galaxy Spectra from the Sloan Digital Sky Survey

Two features that were used extensively were the Hδ line and the magnitude of the 4000 Angstrom break $D_n(4000)$

Hδ line

Hδ line emission; $D_n(4000)$ small

Hδ line absorption; $D_n(4000)$ large



Almost no 4000 Angstrom break

Measurable 4000 Angstrom break

Dn(4000) break measured by comparing these two spectral regions

How do the spectral properties of galaxies, i.e., $D_n(4000)$ and Hδ, depend on their mass?

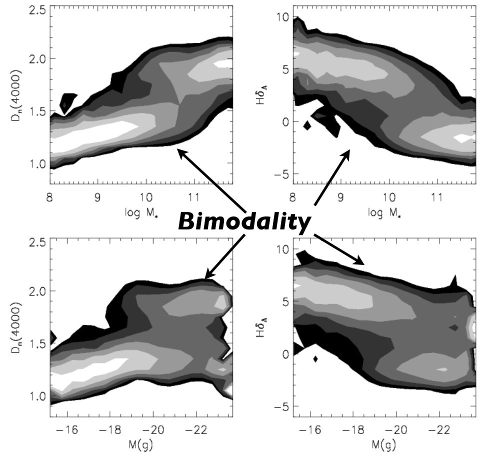


Figure 1. Conditional density distributions showing trends in the stellar age indicators $D_n(4000)$ and $H\delta_A$ as functions of the logarithm of stellar mass and of g-band absolute magnitude. Galaxies have been weighted by $1/V_{max}$ and the bivariate distribution function has been normalized to a fixed number of galaxies in each bin of log M_* or $M(g)$. Here and in all subsequent contour plots, each contour represents a factor of 2 change in density.

what is striking is a ***bimodality*** in the distribution

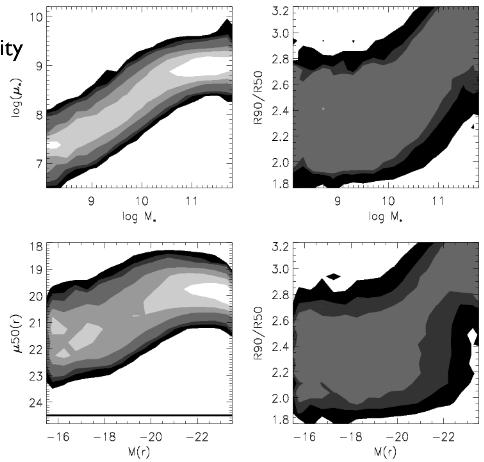
it occurs around a solar mass of 3×10^{10} M_{solar}

galaxies that are less massive than 3×10^{10} M_{solar} show low $D_n(4000)$

galaxies that are more massive than 3×10^{10} M_{solar} have high $D_n(4000)$

The structural properties of galaxies also depend on their mass

μ_* = surface density of stars = M_* / radius^2



"concentration of light"

R90 / R50 = radius containing 90% of light / radius containing 50% of light

related to the Sersic index of galaxies

low mass galaxies have exponential disks while high mass galaxies have $r^{1/4}$ profiles

Figure 8. Conditional density distributions showing trends in the structural parameters μ_*, $\mu_{1/2}$ and $C = R90/R50$ as a function the logarithm of stellar mass and as a function of r-band absolute magnitude. Galaxies have been weighted by $1/V_{max}$ and the bivariate distribution function has been normalized to a fixed number of galaxies in each bin of log M_* and of r-band absolute magnitude. The line in the bottom left-hand panel indicates the surface brightness completeness limit of the SDSS survey.

There is a good connection between the Spectral Properties of Galaxies ($D_n(4000)$ and Hδ) and Structural Properties (μ^* and R_{90}/R_{50})

$D_n(4000)$ correlates well with surface density of stars and also with the concentration R_{90}/R_{50} .

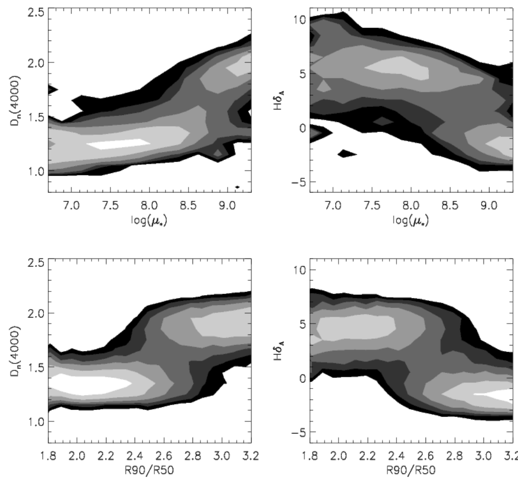


Figure 12. Conditional density distributions showing trends in the stellar age indicators $D_n(4000)$ and $H\delta_A$ as functions of the logarithm of the surface mass density μ_* and of the concentration index C.

Why is there a bimodality?

Galaxies exist in one of two states:

ALIVE and star-forming (fueled by cold gas)

↓ "quenching" ↓

DEAD and non-star-forming (only have hot gas left -- which cannot cool)

We saw that many of the properties of galaxies depend on their stellar mass. Is there an additional dependence on their environment?

Yes: here are the $D_n(4000)$, specific star formation rates (SFR/M*), stellar mass density μ_*, and concentration parameters $C = R_{90}/R_{50}$ we looked at before:

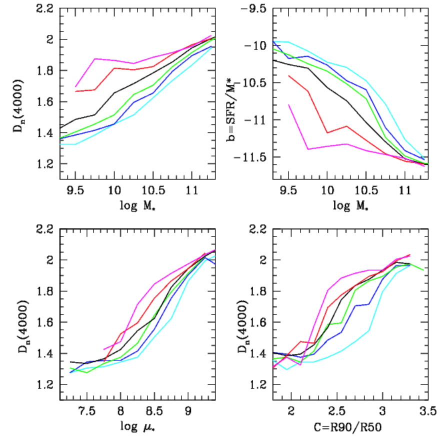


Figure 7. Top: the median relations between $D_n(4000)$ and SFR/M_* are plotted as a function of stellar mass for five different bins in density, colour-coded as in Fig. 5. Bottom: the median relations between $D_n(4000)$ and μ_* (left) and C (right).

Cyan = lowest density environment
Blue = 2nd lowest density environment
Green = 3rd lowest density environment
Black = 3rd highest density environment
Red = 2nd highest density environment
Magenta = highest density environment

Low mass galaxies in high density environments are more likely to have stopped forming stars

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Relationship between the Gas-Phase Metallicity in a Galaxy and Its Mass

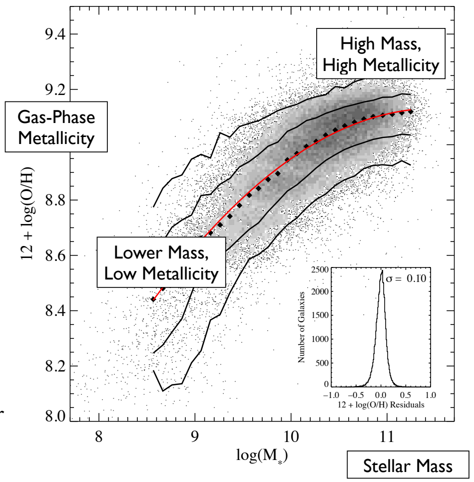
Two primary explanations for this:

1) Low Mass Galaxies Form Stars Less Efficiently

As such, only a small percentage of the gas turns into SNe (which adds more metals to the mix)

2) Metals can escape more easily from low-mass galaxies due to SNe winds

The escape velocity for lower mass galaxies is lower and hence it is easier for metals to escape from such galaxies due to SNe winds



Tremonti+2004

How have the properties of galaxies changed over the past 10 billlion years?

Can investigate by creating large samples of galaxies over the redshift range z~0 to z~1 to study them in the same way as at z~0.

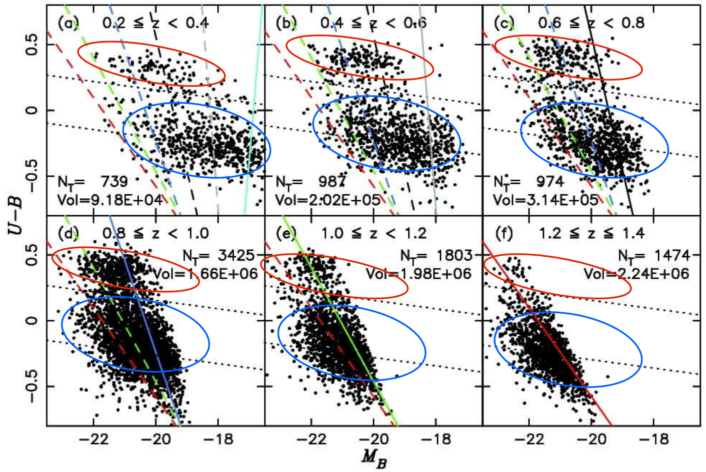
How to collect such samples?

1) Use powerful spectrographs like DEIMOS on Keck to obtain spectroscopy of many sources on a field simultaneously

(Still Samples not as Large as at z~0)

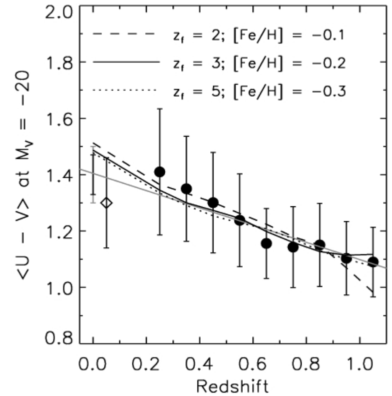
2) Take images of an area on the sky at multiple wavelengths and then estimate redshifts for sources from the measured fluxes:

One of the most interesting aspects of the evolution of galaxies with cosmic time are changes to the "red sequence" and "blue cloud":



One can see the existence of the red-sequence out to z~1

How do the colors of galaxies in the red sequence change with redshift?

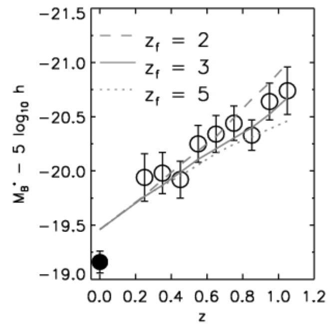


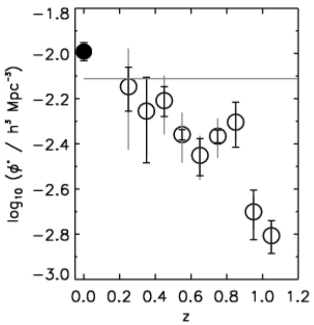
"Red sequence" galaxies are becoming bluer, as one moves to higher redshift. This is what one would expect if they formed almost all of their stars a long time ago. Since the colors of galaxies change as a power law, one can try to use the evolution in color to determine when red sequence galaxies formed their stars.

Parameterizing the evolution of the luminosity function of "red sequence" galaxies using the Schechter function,

$$\phi(L) = \phi^* e^{-L/L^*} (L/L^*)^{\alpha}$$

how do the individual parameters evolve?



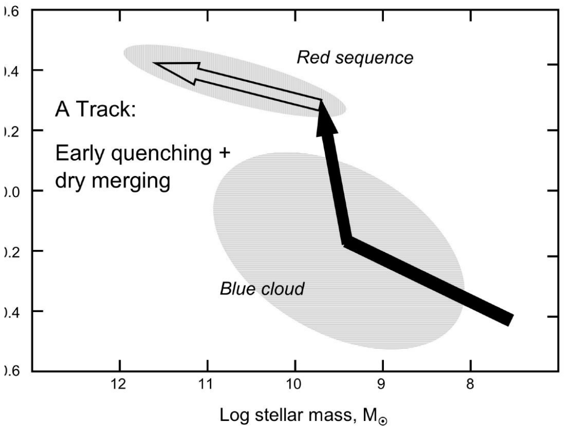


How would you interpret these trends?

NOW new material for this week

How might galaxies move from the blue cloud to red sequence?

There are many possibilities!



The above are scenarios outlined in Faber et al. based on DEEP2 results

What is quenching?

A galaxy is "quenched" when it stops forming stars. It appears that most quenched galaxies never form stars again.

How does quenching happen?

It is unknown. Maybe due to energy coming from black holes at the center of a galaxy heating up the gas in and around a galaxy.

Observationally, by noting which galaxies are quenched and which are not, we can determine the factors which led to "quenching":

1) Mass Quenching -- When galaxies become more massive, "quenching" is more likely to happen

(could be due to increased important of AGN in the most massive galaxies)

2) Environmental Quenching -- When galaxies are in dense environments (nearby many other galaxies), "quenching" is more likely to happen

(could occur as galaxies become satellites in more massive halos and lose their gas supply)

REMINDER: What is a dry merger?

There appear to be two different classes of elliptical galaxies.
They form in two different ways.

Case #1: "Wet" Mergers
(e.g., between two spiral galaxies)

(tends to occur more frequently for lower mass galaxies, when galaxy evolution less advanced)

Galaxy (with gas) →  ← Galaxy (with gas)

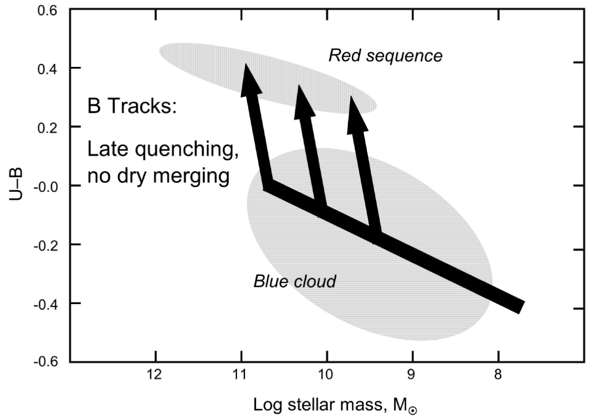
Case #2: "Dry" Mergers
(e.g., between two elliptical galaxies)

(frequently occurs after many previous mergers, when the mass is higher)

Galaxy (without gas) →  ← Galaxy (without gas)

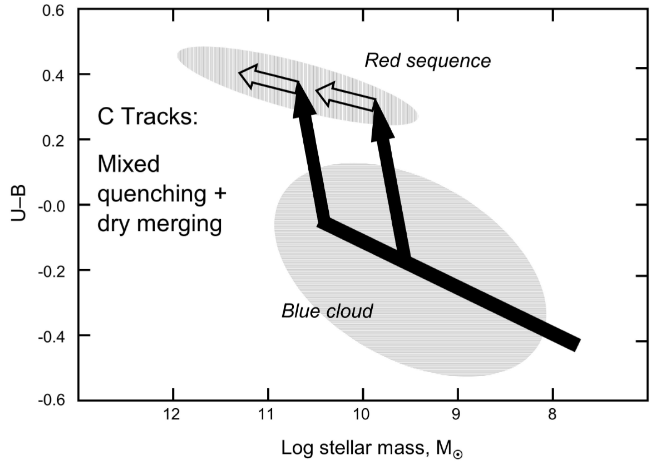
How might galaxies move from the blue cloud to red sequence?

There are many possibilities!



How might galaxies move from the blue cloud to red sequence?

There are many possibilities!



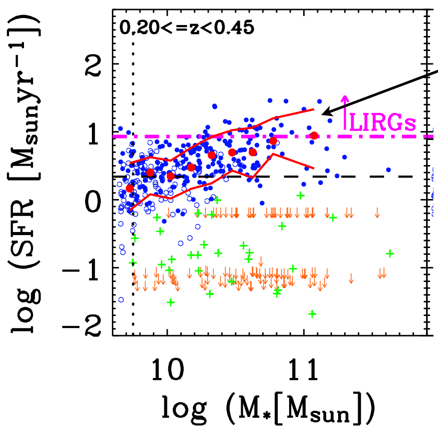
Besides this movement of galaxies from the blue cloud to the red sequence, how does star formation proceed on the blue cloud?

How do galaxies grow when they exist in the blue cloud?

Let's look at evolution of SFR and stellar mass relation for blue cloud

Let's look at evolution of SFR and stellar mass relation for blue cloud

Clear relationship between the star formation rate and the stellar mass of a galaxy...



Spread in the relation is only 0.3 dex

Suggests that SFR is proportion to stellar mass

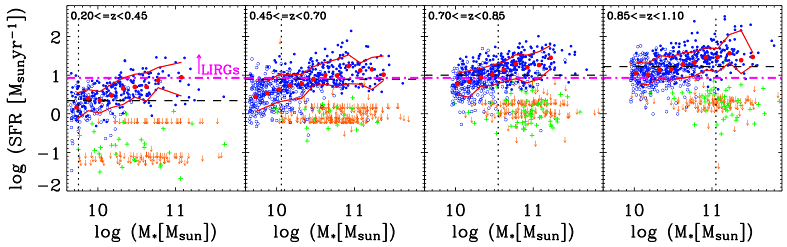
called "main sequence of star formation" for galaxies

Implies exponential growth of galaxies

Noekse+2007; Salim+2006

Let's look at evolution of SFR and stellar mass relation for blue cloud

Clear relationship between the star formation rate and the stellar mass of a galaxy...



Constant of proportionality between the star formation rate and stellar mass evolves with redshift...

Galaxies form stars for a given stellar mass at high redshift...

Noekse+2007; Salim+2006

Let's look at evolution of SFR and stellar mass relation for blue cloud

How are the SFRs and stellar masses derived?

Deriving the Star Formation Rate in Distant Galaxies

One of the best measures of how quickly galaxies are growing is the star formation rate (since it measures the growth in the stellar mass).

How is the star formation rate estimated?

1. Using the Hα emission line fluxes. Hot O stars produce a lot of radiation at wavelengths blueward of 912 Angstroms. This radiation ionizes hydrogen gas and results in large ionized bubbles surrounding star-forming regions in galaxies. These ionized bubbles produce Hα emission. One challenge is that dust extinction can attenuate the Hα emission in galaxies and requires correction. Fortunately, one can use Hβ emission from galaxies to estimate this extinction, since the ratio of fluxes in Hα to Hβ is almost the same under a variety of conditions. After correction for dust extinction, one can directly estimate the dust extinction from Hα fluxes.

Deriving the Star Formation Rate in Distant Galaxies

2. Using the UV light Hot O and B stars in galaxies produce a lot of UV light in general. One can use this UV light to estimate the star formation rate in distant galaxies. However, dust extinction can be a key challenge, as even a small amount of dust extinction can attenuate most of the UV light.

3. Using the far-IR emission. If most of the light from young stars is absorbed by dust and then re-emitted, that light will come out with a blackbody structure at 1000 microns. With telescopes like Spitzer or Herschel or submm telescopes on the ground, one can measure this light directly for galaxies (but generally only for the most extreme systems). By measuring the total energy output in the IR, one can try to estimate the star formation rate. One drawback of this technique is that other energy sources can also heat the dust, e.g., quasars or even lower mass stars.

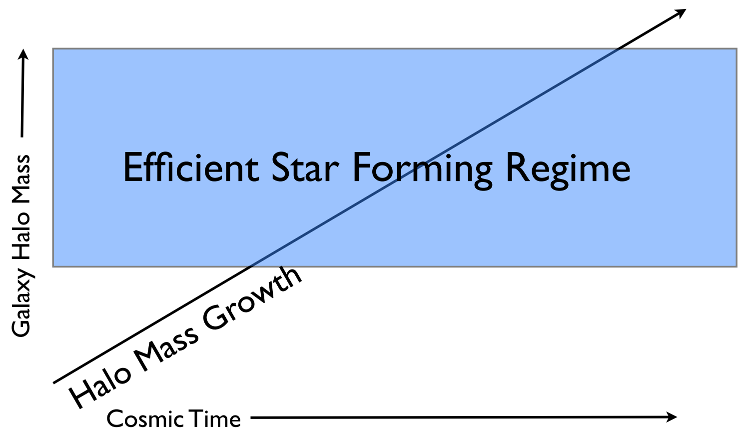
Deriving the Star Formation Rate in Distant Galaxies

4. Using the radio emission. Synchrotron emission from electrons in supernovae explosions produce significant radio emission in star forming galaxies. Since supernovae explosions are proportional to the star-formation rate, one can use light in the radio as a probe of the star formation rate. The correlation of the radio emission with the far-IR emission is remarkably good and not totally understood. Very deep observations are required.

5. Using x-ray emission. One biproduct of star formation in galaxies is the production of high-mass x-ray binaries, which emit prolifically at x-ray wavelengths and can be used as a probe of the star formation rate in distant galaxies. Very deep data are required to use this technique.

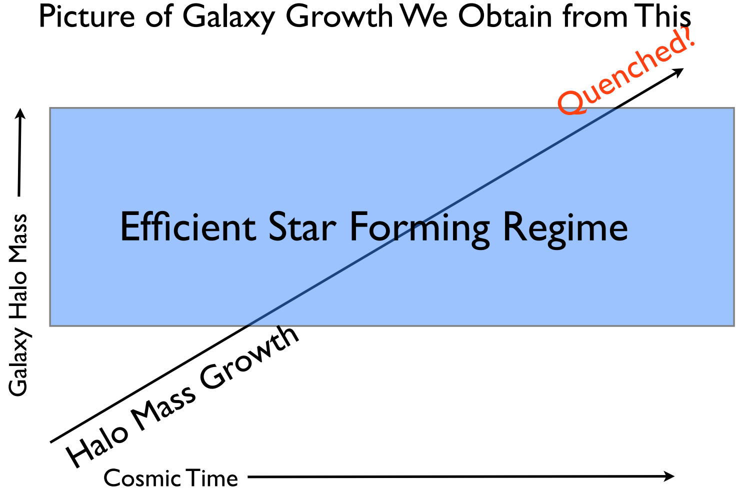
When using the far-IR emission, radio emission, or x-ray emission to derive star formation rates, one must be careful that an AGN is not present, since it can produce a similar or even stronger signal.

Picture of Galaxy Growth We Obtain from This



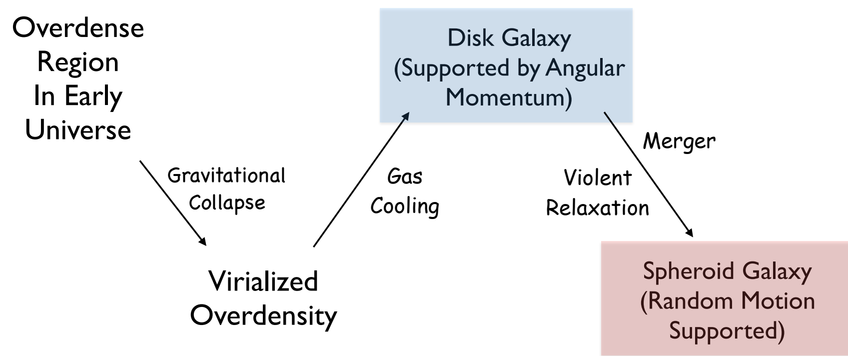
Noekse+2007; Salim+2006

Picture of Galaxy Growth We Obtain from This



Noekse+2007; Salim+2006

Galaxy Formation: Major Steps



How can estimate the stellar masses of individual galaxies?

Through stellar population modelling:

Measure the fluxes of galaxies at a large number of wavelengths and then find the stellar population model (age of stellar population, metallicity, current star formation rate) that best fits the fluxes.

Flux Measurements in K band or with Spitzer are particularly essential.

From Shapley et al.

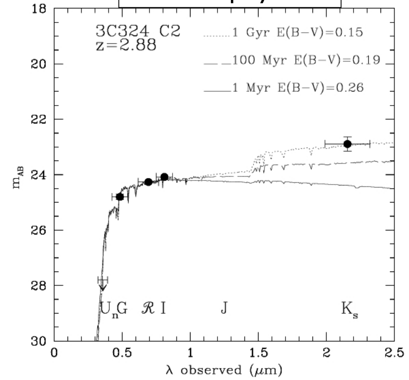
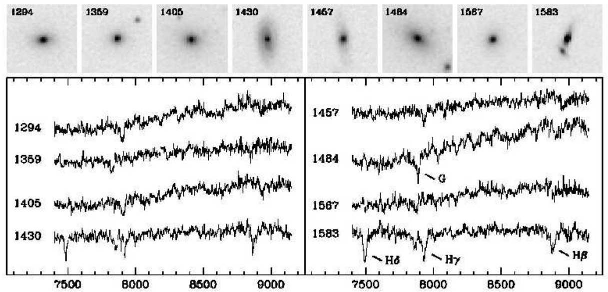


FIG. 6.—Age-dust degeneracy. The points indicate the observed SED of 3C 324–C2, an LBG at $z = 2.880$. Shown with the points are BC96 constant star formation models of different ages, modified by the amount of dust extinction required to reproduce the observed $G-\mathcal{R}$ color. The dotted line is 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.*]

How accurate are mass measurements of distant galaxies based on their flux measurements?

These mass measurements can be checked directly for early-type galaxies by measuring their velocity dispersions. This requires long integrations on distant galaxies, i.e., >10 hour integration times with 10 meter telescopes.

One example is shown below from elliptical galaxies in cluster at z=0.8:



Franx 1993; van Dokkum et al. 1996, 1998; van der Wel et al. 2003

most galaxies is the the brightest cluster

Recall the following diagram from the lecture on elliptical galaxies:

This illustrates how one measures the velocity dispersion.

Thick Black Line is Observed Spectrum

Dotted lines are spectra of stars smoothed along the line of sight to obtain a match with the observed spectrum

Fitting the Velocity Dispersion

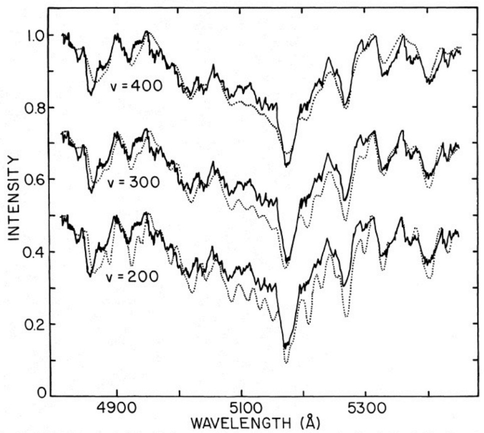


FIG. 3.—NGC 4472 compared with standard star HR 1805 (K3 III), broadened by various line-of-sight velocities (*dotted line*)

Galaxies in the intermediate to high-redshift z>1.5 universe

Observing galaxies at high redshifts z>1.5 is more challenging that at later times

At optical wavelengths, we only see the UV light from the distant galaxies

i.e., we only see the regions in distant galaxies which are actively star-forming...

To see the predominantly older and longer lived lower mass stars, we need to survey the sky in the near-infrared. This is more challenging, due to technological issues... brightness of sky in near-infrared, etc.

How does one identify large numbers of galaxies at z>1.5?

1. Select them at optical wavelength, i.e., in the rest-frame UV
2. Select them at near-infrared wavelength, i.e., in the rest-frame optical
3. Select them by their brightness at some other wavelength, i.e., radio, near-infrared, mm wavelengths

Each selection technique has its advantages and disadvantages.

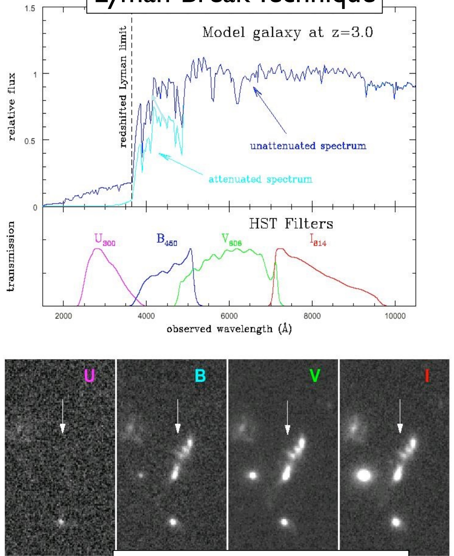
Let's begin by talking about selecting z>1.5 galaxies at optical wavelengths (i.e., in the rest-frame UV)

We can take advantage of neutral hydrogen in the distant universe which absorbs light in galaxies blueward of 1216 Angstroms (Lyman Alpha)

This introduces a very sharp break in the spectrum -- which is a very characteristic feature that is easy to identify in looking at light in broad-band images.

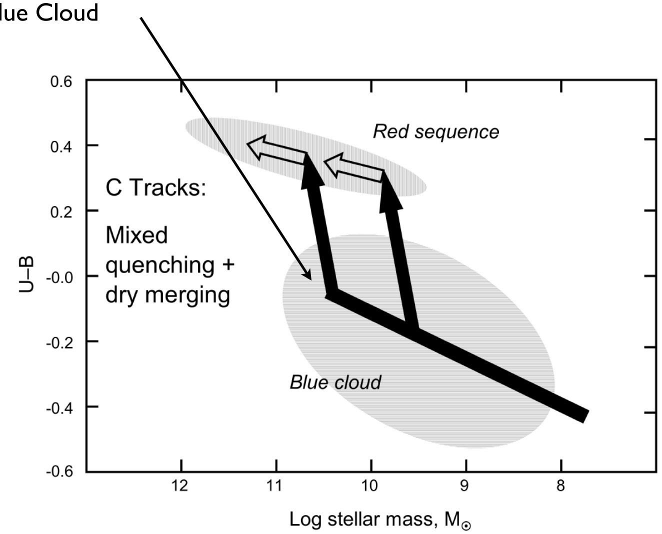
Expect very Red U-B colors and Blue B-V colors

Lyman-Break Technique



Credit: Dickinson 1999

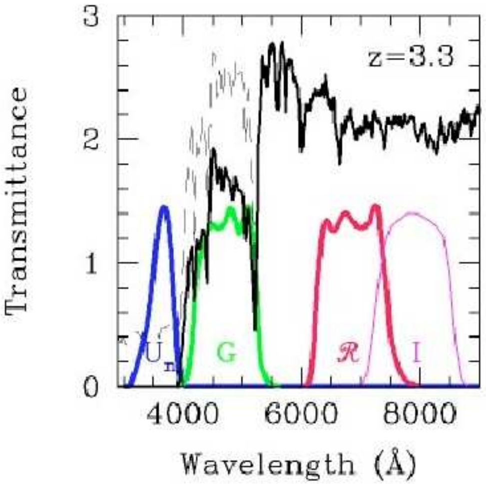
Lyman-Break Galaxies are Galaxies in the Early Universe on the Blue Cloud



How might one hope to isolate z~3 galaxies in color-color space using such a selection?

Looking at the spectrum to the right relative to the filters, we would expect the Un - G color to be red.

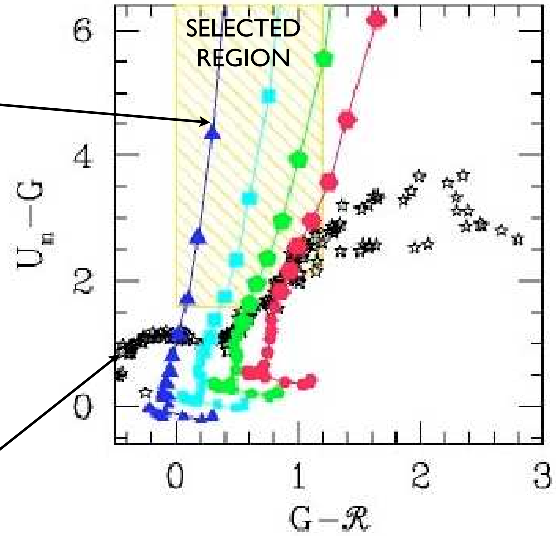
The G-R color should be blue.



How does such a selection look like in color-color space?

tracks show the expected colors of star-forming galaxies with a variety of dust reddening

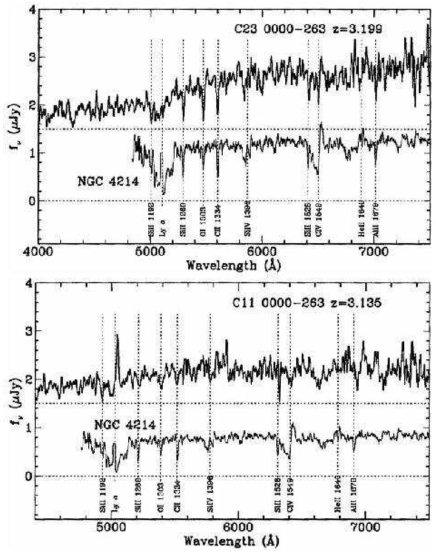
colors of nearby stars



Do galaxies selected using the Lyman-Break Galaxy selection technique have the desired redshifts?

Find out using the large telescopes like the 10-meter Keck Telescopes in Hawaii…

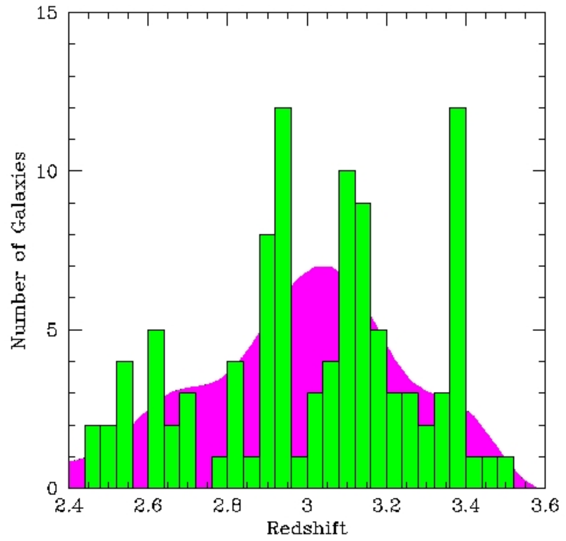
When one takes deep spectra at optical wavelengths of Lyman-Break selected galaxies ("U-Dropouts"), one finds the spectra to the right:



Notice how similar the spectra are to spectra taken of starburst (actively star-forming) galaxies in the nearby universe.

Steidel+1996

What redshift distribution was found for galaxies selected in this way?



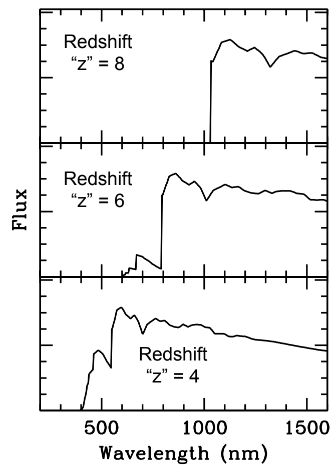
How can we determine which galaxies on deep images come from the most distant galaxies?

There is a sharp break in spectrum of distant galaxies due to neutral hydrogen in the universe.

As the universe expands, this break in the spectrum is shifted to redder wavelengths (“redshifted”)

By looking for sources with breaks at very red wavelengths, we identify the most distant galaxies.

Spectra of Distant Galaxies



Most Distant @ 850 Myr after Big Bang

@ 1000 Myr after Big Bang

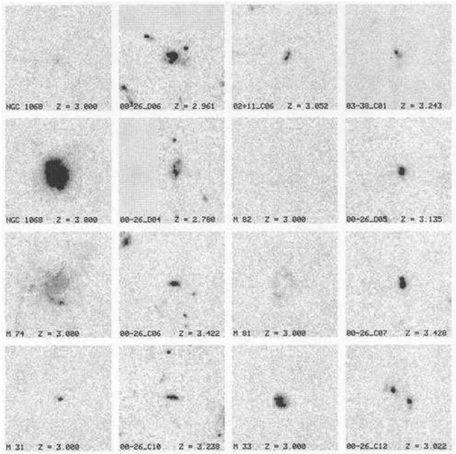
Least Distant @ 1800 Myr after Big Bang

What are the properties of these galaxies that one finds at z~3?

Their volume density is 1.6 x 10^{-2} Mpc^{-3} similar to the density of galaxies in the local universe.

However, z~3 galaxies are much more actively forming stars and have much higher surface brightnesses at rest-frame UV wavelengths.

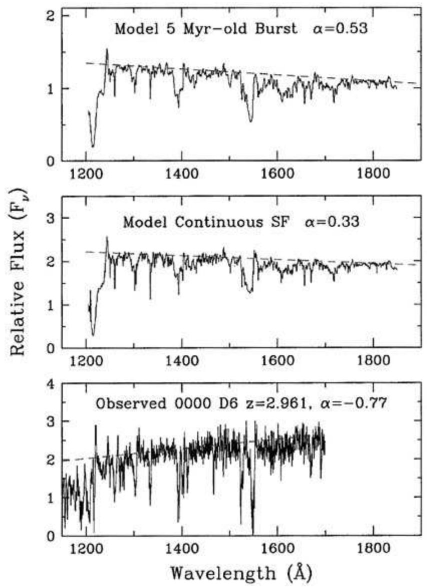
If you would put nearby galaxies at z~3, you wouldn’t see anything.



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.

How do the spectra of these z~3 galaxies compare with the models?

These galaxies appear to be consistent of very young stars, with a small amount of dust present



The newly discovered z~3 population was found to be very different from any galaxy known in the local universe.

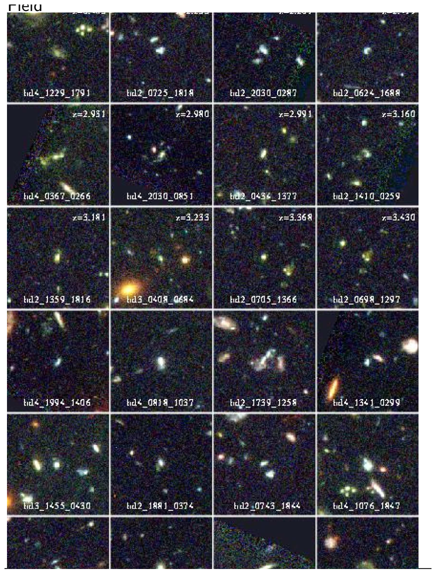
It was a major discovery and revolutionized extragalactic science in 1995-1996.

These galaxies are very irregular, clumpy, and quite small.

Most had sizes of ~1-2 kpc.

This is many times smaller than most bright star-forming galaxies today!

z~3 galaxies in the Hubble Deep Field North



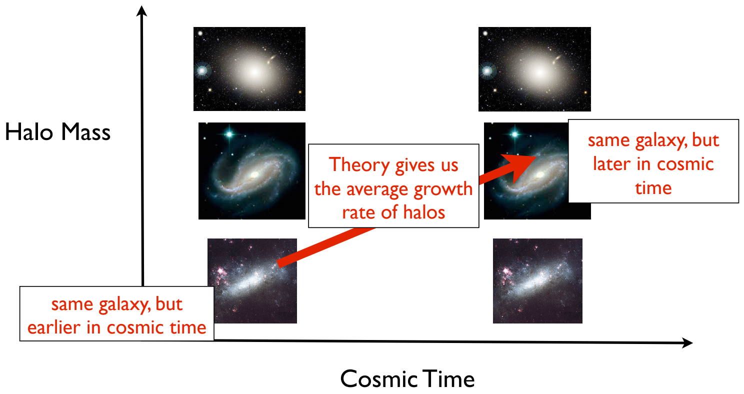
Redshifts allow us to look at the clustering of galaxies in space

This allows us to determine the mass of the dark matter halos in which they live.

RECALL (from Lecture 9)

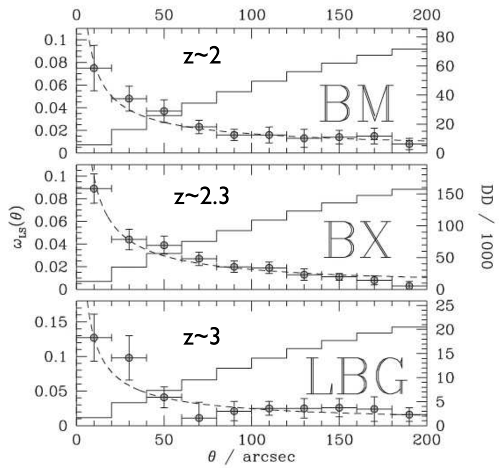
Why is it useful to learn about the dark matter halos in which galaxies live?

It provides us a powerful tool for tracing the same population of galaxies through cosmic time.



Using the spectroscopic redshifts for these galaxies, researchers immediately investigated their spatial distribution to determine their clustering properties.

The correlation functions of these galaxies found at various distances are shown to the right:



What correlation lengths were found for galaxies in these high-redshift samples?

Researchers separated the brighter z~3 galaxies from the fainter z~3 galaxies, in deriving their clustering properties and correlation lengths.

Clustering lengths for these galaxies at in the range ~3-5 Mpc.

From the plot at the right, are the correlation lengths of bright galaxies or faint galaxies larger?

As we can see that the correlation lengths of bright galaxies tend to be larger, this implies they live in more massive halos.

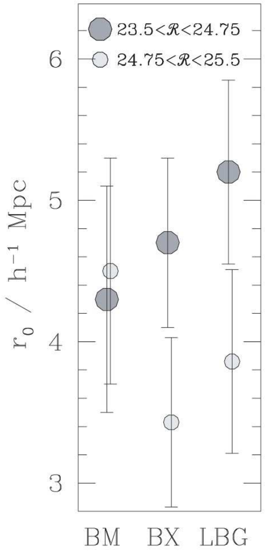
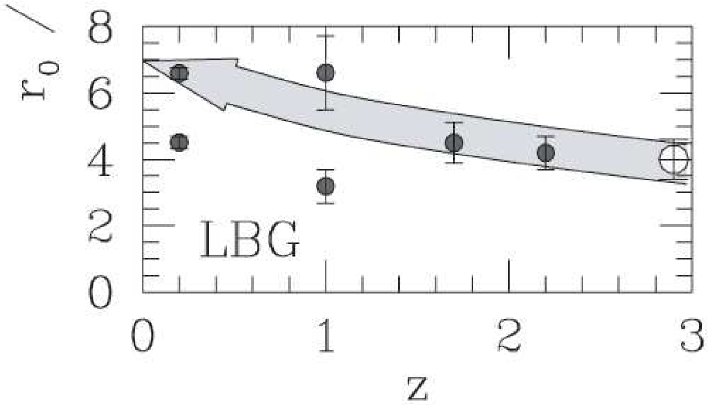


Fig. 5.—Correlation length r_0 for bright and faint subsamples of the BM, BX, and LBG samples.

We can use their measured correlation lengths to determine the mass of the halos they likely live in and connect them with galaxies at lower redshift that they likely become (after evolution).



Amazingly, they match the clustering properties of red sequence (or elliptical) galaxies at lower redshifts.

Near-IR selections of z>2 galaxies

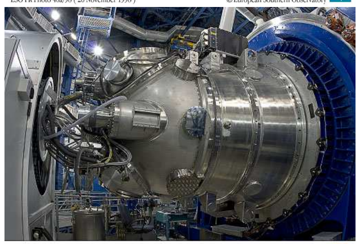
Perhaps, the best way to select older and more evolved galaxies like those that exist in the nearby universe is to search for them at rest-frame optical wavelengths.

This was very hard to do for many years due to high sky brightness at near-infrared wavelengths and the lack of instrumentation to do this well.

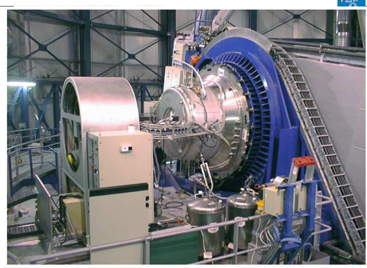
This changed, however, 9 years ago with the introduction of the ISAAC and HAWK-I cameras on the very large telescope.

ESO PR Photo 46a/98 (26 November 1998)

©European Southern Observatory

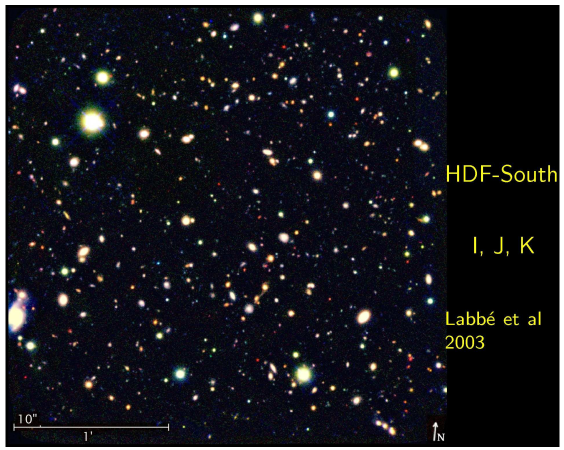


The HAWK-I Instrument at the VLT

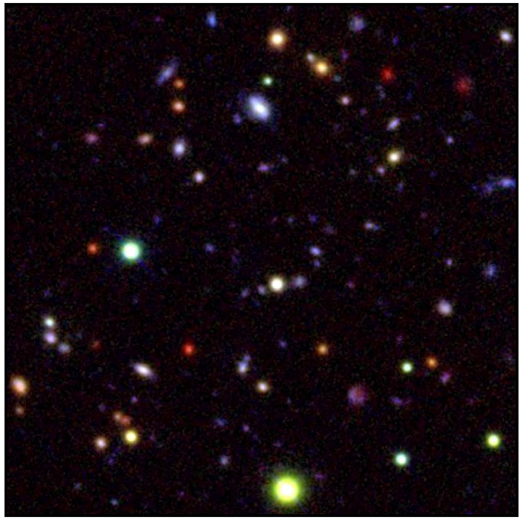


ISAAC mounted on the VLT UT1

Labbe et al. 2003 and Forester-Schreiber et al. used very deep imaging over the HDF South and MS1054 to search for galaxies at z>2. This was part of FIRES survey led by Marijn Franx (200 hours).



Here's a zoom-in on the previous image in the I, J, K bands. Some galaxies are very red in these colors, suggesting they emit almost all of their light in the K band. If these galaxies are at z~2.5, this would be in the rest-frame optical.



How do the SEDs of the galaxies with the very red colors look?

All of them should a break at ~4000 Angstroms (rest frame).

The volume density of these objects is similar to that of the bright Lyman-break galaxies.

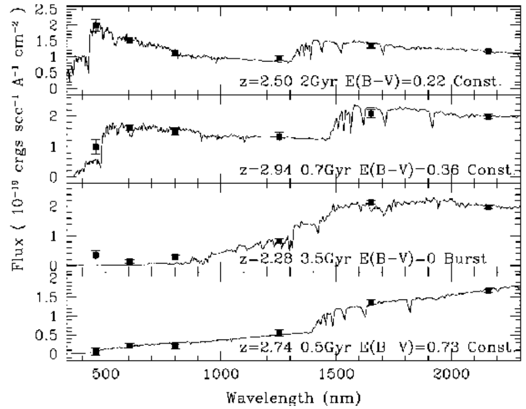
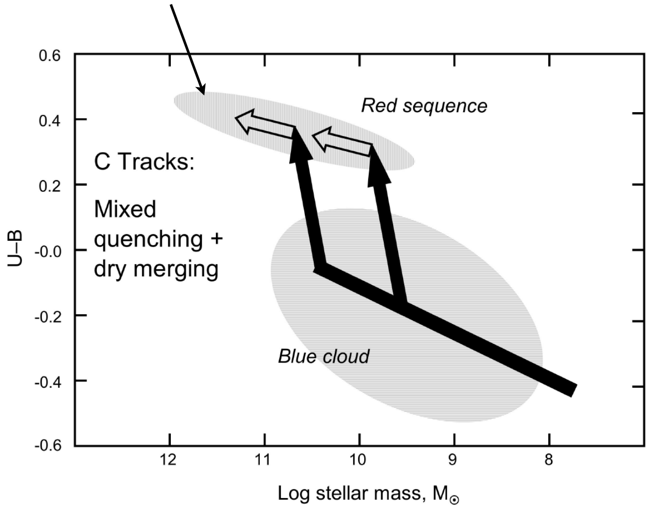


FIG. 3.—SEDs of four galaxies with $J_s - K_s > 2.3$. They span the full range in $I - K_s$ color. All the galaxies show a break between the J_s and K_s bands. The curves show stellar population fits with either constant formation and reddening or unreddened single-age bursts.

Some especially red galaxies that we select with J-K colors are already on the red sequence at z~2.5.

Red-Sequence galaxies are relatively rare though at z~2.5. Almost all galaxies at z~2.5 are in the blue cloud.



How can we gain insight into the properties of these distant galaxies?

From Shapley et al.

How can estimate the stellar masses of individual galaxies?

Through stellar population modelling:

Measure the fluxes of galaxies at a large number of wavelengths and then find the stellar population model (age of stellar population, metallicity, current star formation rate) that best fits the fluxes.

Flux Measurements in K band or with Spitzer are particularly essential.

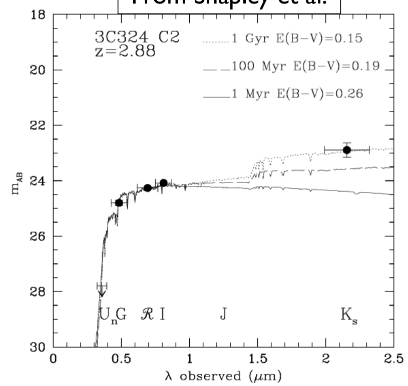


FIG. 6.—Age-dust degeneracy. The points indicate the observed SED of 3C 324–C2, an LBG at $z = 2.880$. Shown with the points are BC96 constant star formation models of different ages, modified by the amount of dust extinction required to reproduce the observed $G - \mathcal{R}$ color. The dotted line 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.*]

Stellar Masses are particularly stable in stellar population fits to the measured fluxes.

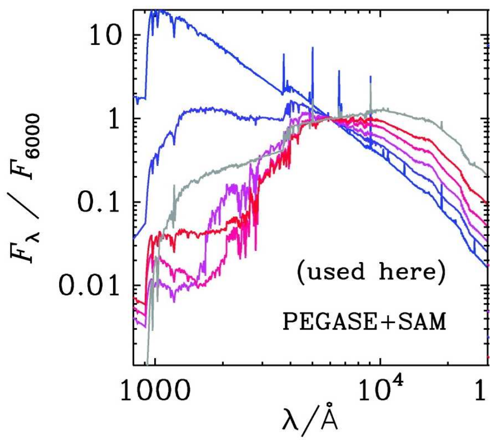
Small changes to the metallicity, age, or other parameters in the stellar population fits do not affect the estimated masses much.

Most Lyman-Break Galaxies at z~3 have masses of $10^{10}\ M_{sol}$, while most "red" galaxies at z~2-3 have masses of $10^{11}\ M_{sol}$.

Photometric Redshift Selections of z>2 Galaxies

A more generic way of selecting z>2 galaxies is by fitting the photometry of z>2 galaxies to SED templates (as shown to the right). You have already seen COMBO-17 using almost an identical technique at z~0 to z~1

van Dokkum applied this technique to all of the galaxies found in the wide-area surveys.



How well did the photometric redshift estimates by van Dokkum compare with the spectroscopic redshifts where they were available?

The scatter in dz/(1+z) is just 0.03.