

Galaxies: Structure, Dynamics, and Evolution

Analysis of Galaxy Stellar Populations

“What can we learn about galaxies by
putting together a large survey of galaxies in
the nearby universe”

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 + Gas Cycle

May 4: Galaxy Evolution at $z > 1.5$

May 11: Galaxy Evolution at $z > 6$. / Review for Final Exam

Problem Set 4

Due on April 27

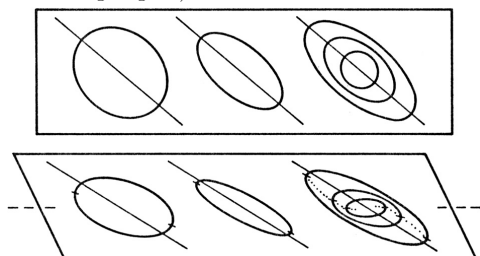
Galaxies: Structure, Dynamics, and Evolution

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 $5 \times 10^{10} M_\odot$, is entirely composed of stars with $1 M_\odot$, and has approximate dimensions of $2 \text{ kpc} \times 2 \text{ kpc} \times 2 \text{ kpc}$. 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 $1.5 h^{-1} \text{ Mpc}$? [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 $0.01 h^3 \text{ Mpc}^{-3}$. The correlation length r_0 is $5h^{-1} \text{ Mpc}$.

- a) Why does the density and the correlation length depend on h ($= H_0 / (100 \text{ km/s/Mpc})$)
 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.

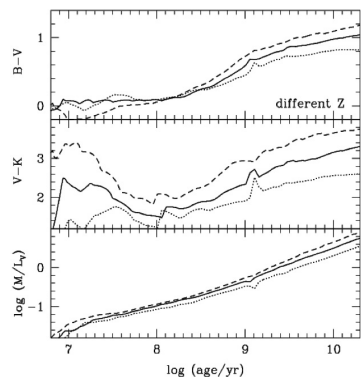
Problem Set 6

Due on May 11

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

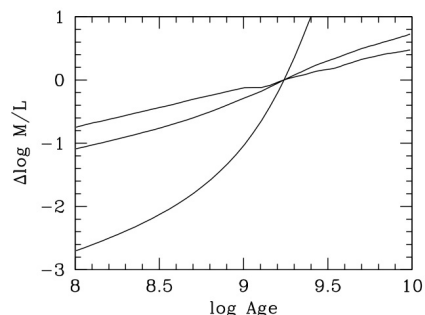
Here is Problem Set 6. The entire problem set will be due before class on Monday, May 11 (email them to Wout and include GSD in the subject line). Be sure to pay extra attention to problem 1, as your solution to that problem will be checked carefully and used in determining your homework grade.

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):



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 according 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-

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

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

Presentation of Solutions to Problems

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

What can learn about the formation and evolution of galaxies from the stars we find in these galaxies?

Ideally, we would use the observed stars to reconstruct the history of star formation in a galaxy.

We would like to determine the function:
SFR(t)

where t is time.

Generally, this area of study is divided into two subfields:

1) Resolved Stellar Population Analyses

Can measure the luminosity and color of individual stars in the nearby object

Useful for studies of Nearby Galaxies and Star Clusters

2) Integrated (Unresolved) Stellar Population Analyses

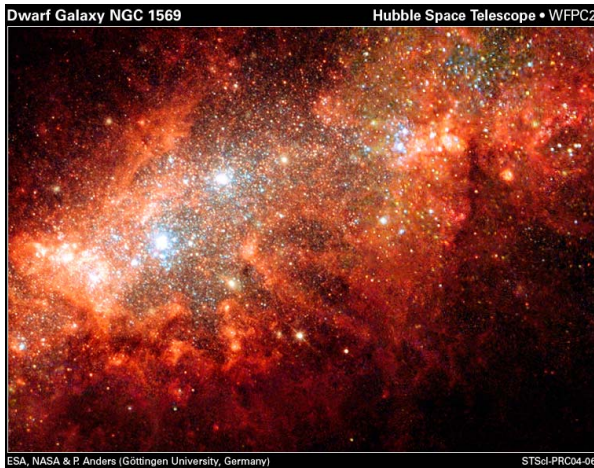
One cannot resolve the light from individual stars and they all blend together.

Used in Studying Distant Galaxies (galaxies greater than a few Mpc away)

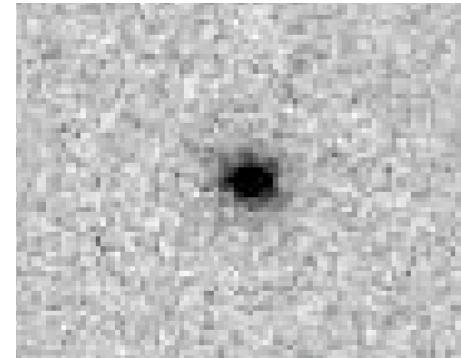
2) Integrated Stellar Population Analyses

If one cannot resolve out the individual stars, one must look at the total spectrum coming from all stars in a galaxy.

The Problem



“What you’d like to get”



“What you get”

(George Hau)

WHAT CAN WE MEASURE?

Broad-band colours (B-V, J-K, etc).

Surface brightness fluctuations (sometimes)

Spectroscopic features (absorption lines)

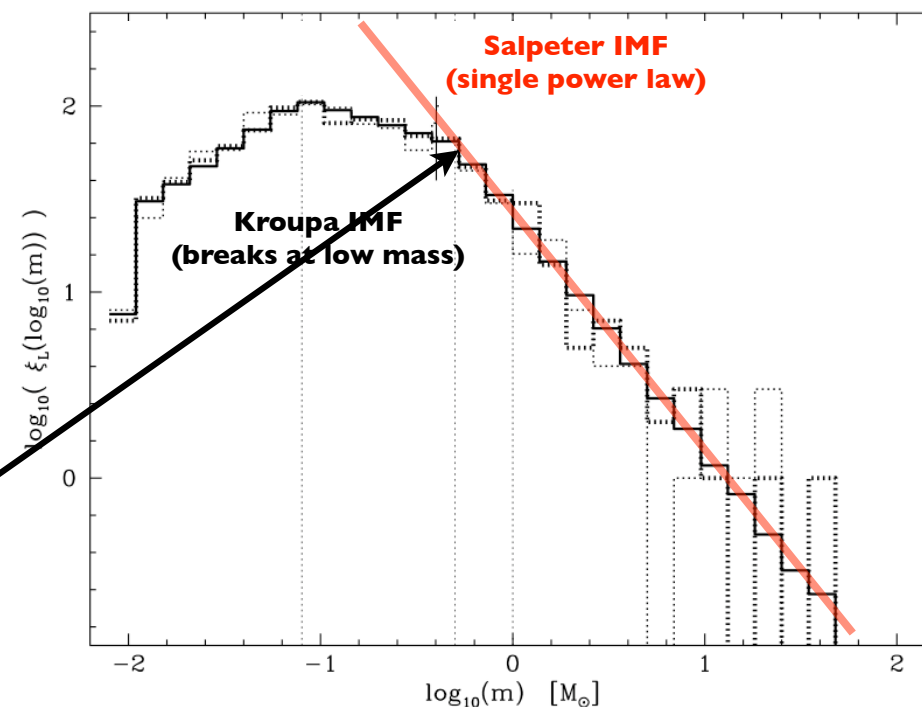
Credit: Russell Smith

2) Integrated Stellar Population Analyses

One attempts to model the observed spectrum using the following inputs:

1) **Stellar Initial Mass Function $\phi(m)$:**
Defines the Fraction of Forming Stars as a function of the stellar mass m . Appears to be well described by the Salpeter power-law function $m^{-2.35}$ at intermediate to high masses.

At masses lower than 1 solar mass, the power law turns over.



2) **Metallicity and abundance ratios of the stars which are forming:**

Metallicity can have a significant impact on the light emitted by stars, making them appear redder. It can also slow down the evolution of stars somewhat.

2) Integrated Stellar Population Analyses

Other inputs to stellar population analyses:

3) Detailed Stellar Evolution Models:

While most phases of stellar evolution seem to be well understood, other rarer phases of stellar evolution like the horizontal branch evolution or the asymptotic giant branch evolution are less well understood. This can make the predictions of the models uncertain.

4) Spectra of Stars at a given temperature, metallicity, surface gravity.

One can calculate the spectra of stars theoretically from stellar atmosphere modelling. However, the predictions from theory often differ from observations -- suggesting that one may want to use real spectra of actual stars. The challenge with using real

2) Integrated Stellar Population Analyses

Other inputs to stellar population analyses:

5) Star Formation History of Galaxies

This is the typical input that people assume changes from galaxy to galaxy.

The simplest model is single burst stellar population models... where one assumes all the stars in a galaxy formed at a single point in the past.

Such models can work well for describing the stellar populations of elliptical galaxies and globular clusters, where most of the stars were first formed long ago in the past.

Another simple model is to assume that stars in a galaxy formed at a fixed constant rate with time.

Such models can work well for describing the stellar populations of late spiral and irregular galaxies.

One can try to parameterize all star formation histories between a constant star formation model and a fixed burst in the past adopting an exponentially declining star formation rate:

$$e^{-t/\tau}$$

where τ is the time scale on which the star-formation rate of some galaxy declines with time.

Note that $\tau = 0$ corresponds to a simple stellar population (all stars formed at some time in the past) while $\tau = \infty$ corresponds to a constant star formation model.

2) Integrated Stellar Population Analyses

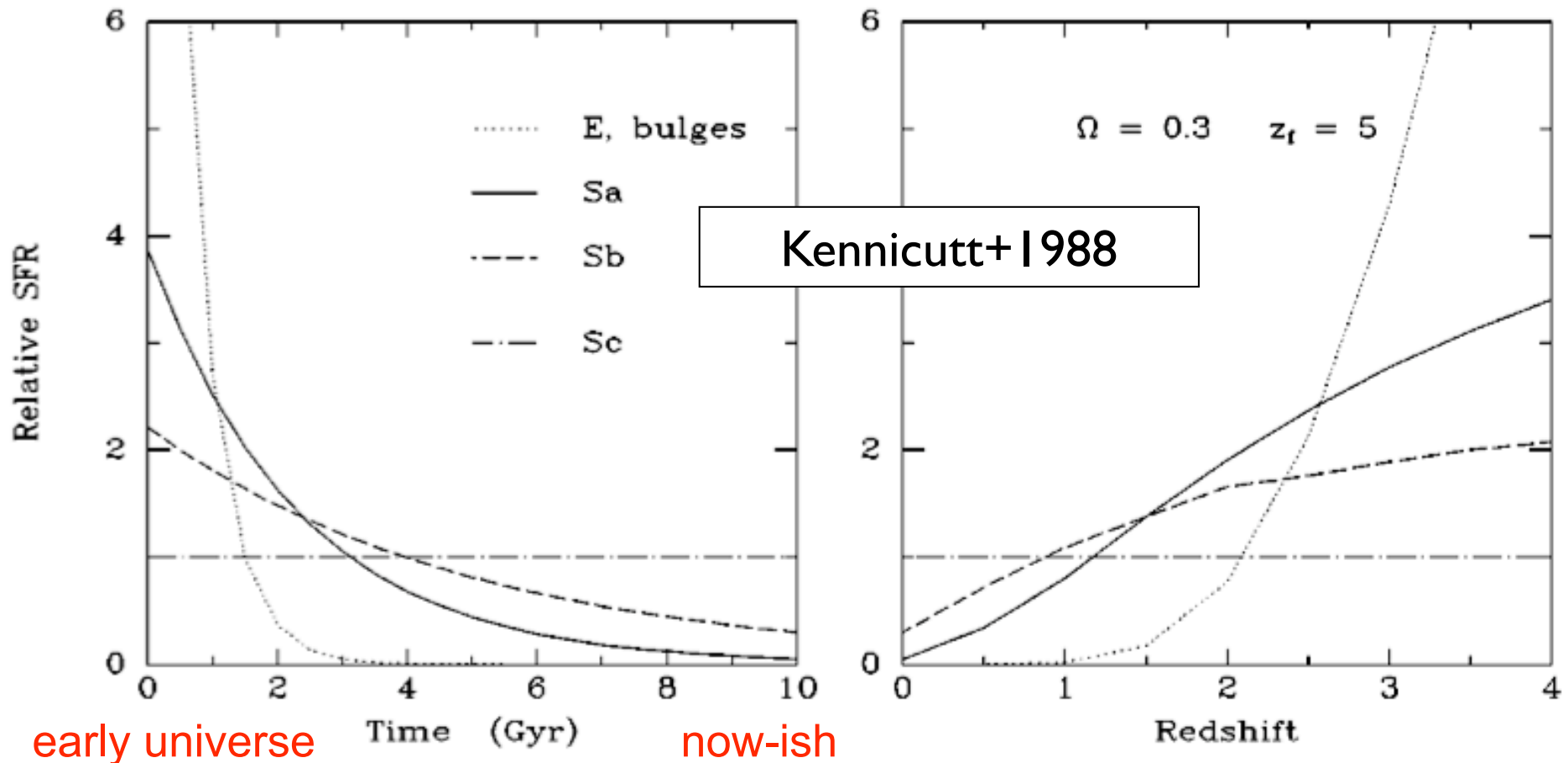
Other inputs to stellar population analyses:

5) Star Formation History of Galaxies

One can try to parameterize all star formation histories between a constant star formation model and a fixed burst in the past adopting an exponentially declining star formation rate:

$$e^{-t/\tau}$$

where τ is the time scale on which the star-formation rate of some galaxy declines with time.



Age-Metallicity Degeneracy

A wide variety of different ages and metallicities for a stellar population produce approximately the same integrated spectrum:

It can therefore be quite challenging to determine both the age and metallicity of a galaxy uniquely with just **color information**.

To break the degeneracy, high S/N **spectra** are required!

One must look at the properties of specific absorption lines to break the degeneracy

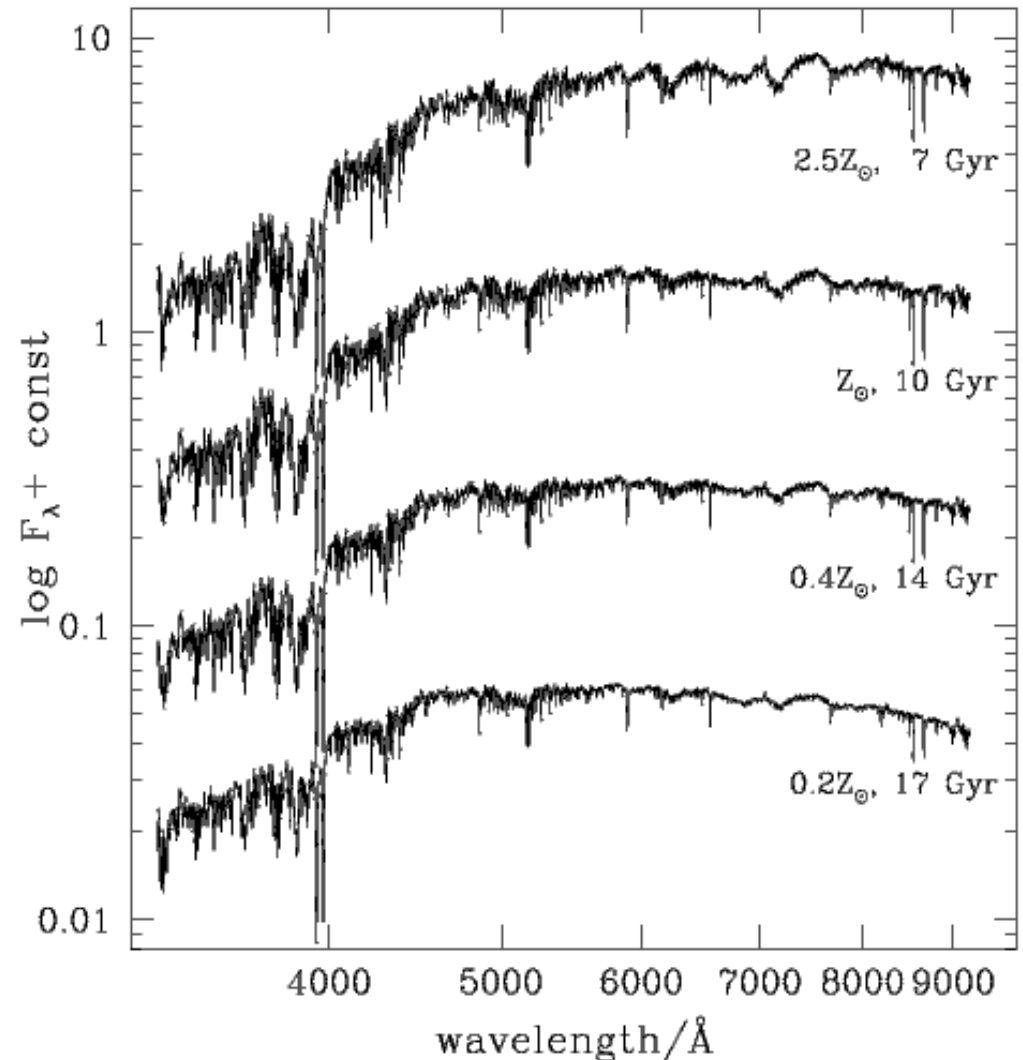
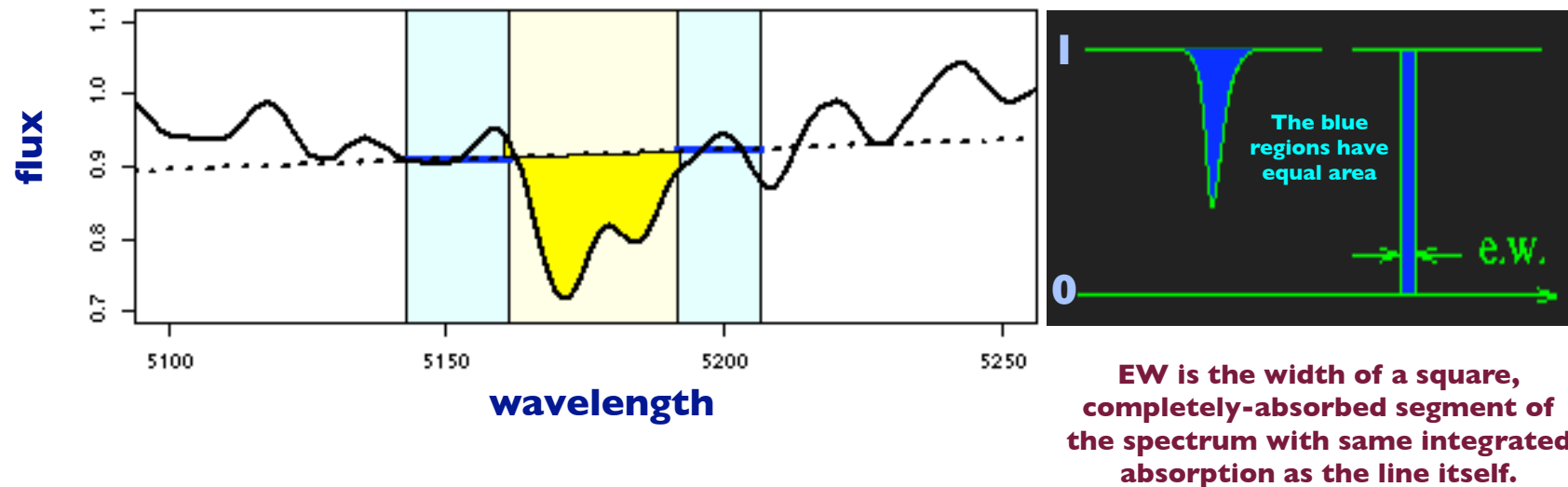


Figure 10. Spectra of the standard SSP model of Section 3 at different ages for different metallicities, as indicated. The prominent metallic features show a clear strengthening from the most metal-poor to the most metal-rich models, even though the shape of the spectral continuum is roughly similar in all models.

Breaking the Age-Metallicity Degeneracy with Spectra

Line indices (e.g. “Lick” indices)



We have seen that the degeneracy-breaking power of spectra is localised to particular features.

So define “indices” which isolate these features and so carry most of the information in the spectra.

Cannot see “true” continuum. Use neighbouring region to define “pseudo-continua”.

Express absorbed flux as an equivalent width.

Credit: Russell Smith

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

THE SDSS



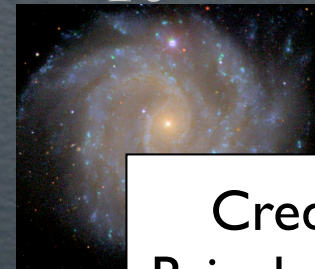
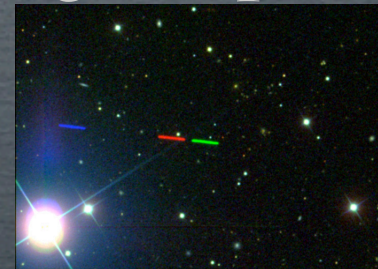
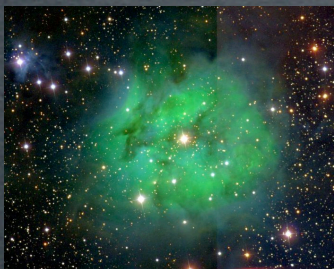
The most ambitious survey of the sky ever undertaken.

(Back in 1990-2000s)

Imaging survey of 8600 square degrees.

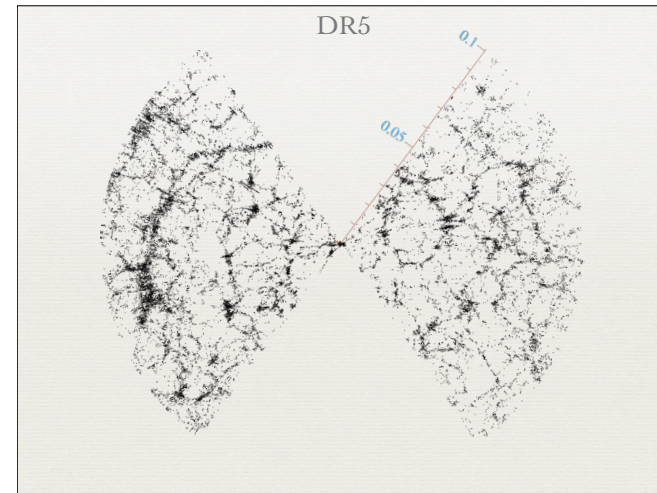
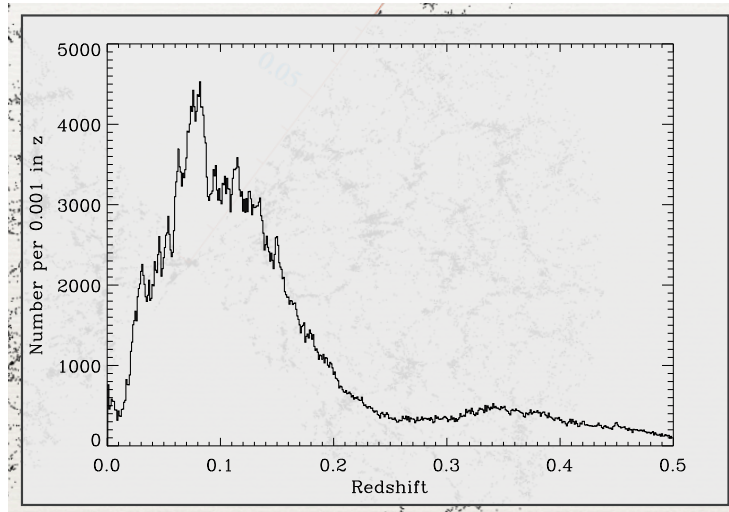
Redshifts of more than 1,000,000 galaxies & QSOs.

Robotic 2.5m telescope - imaging & Spectroscopy



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.

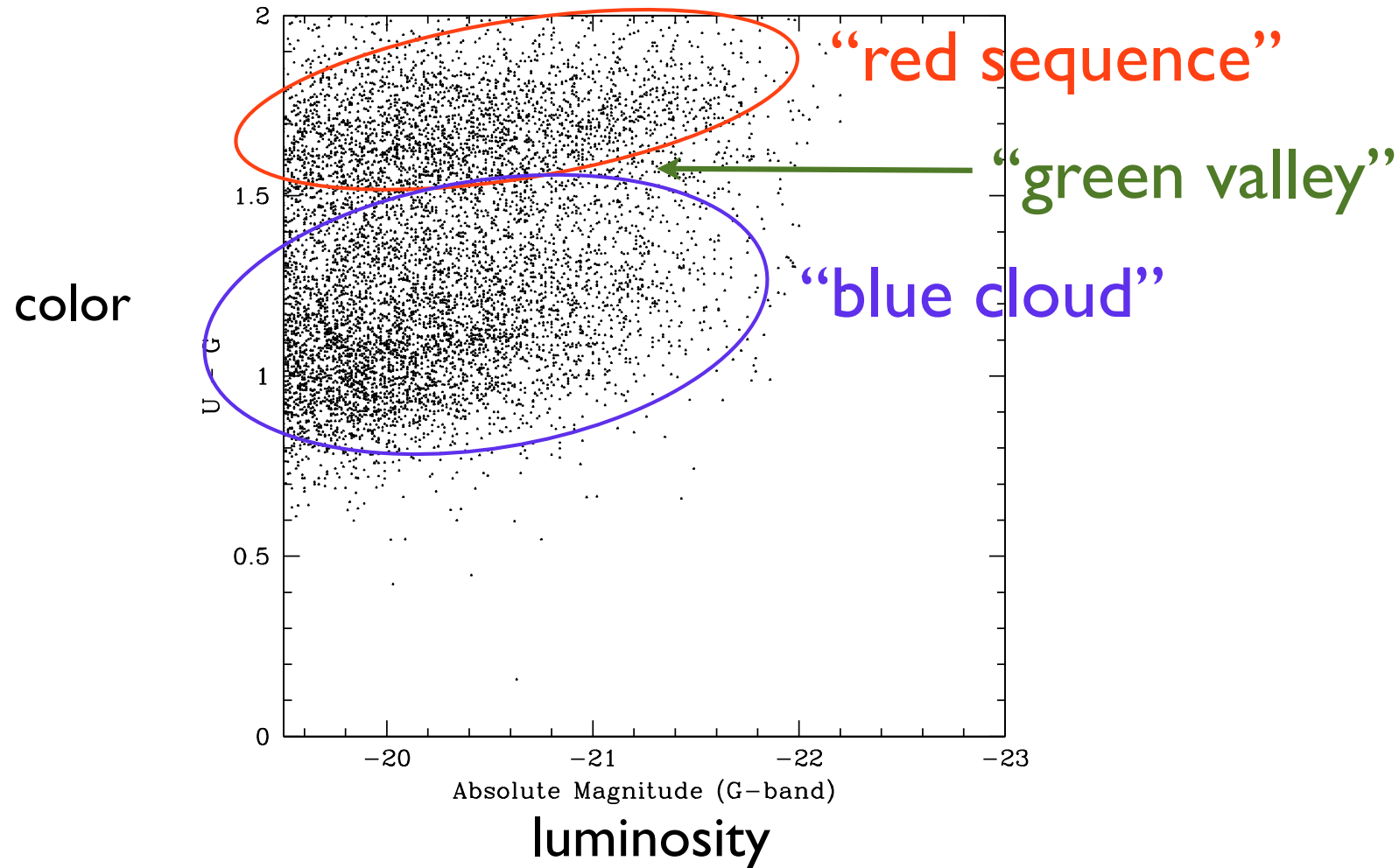


What general conclusions can we draw about galaxies from these observations?

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”



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.

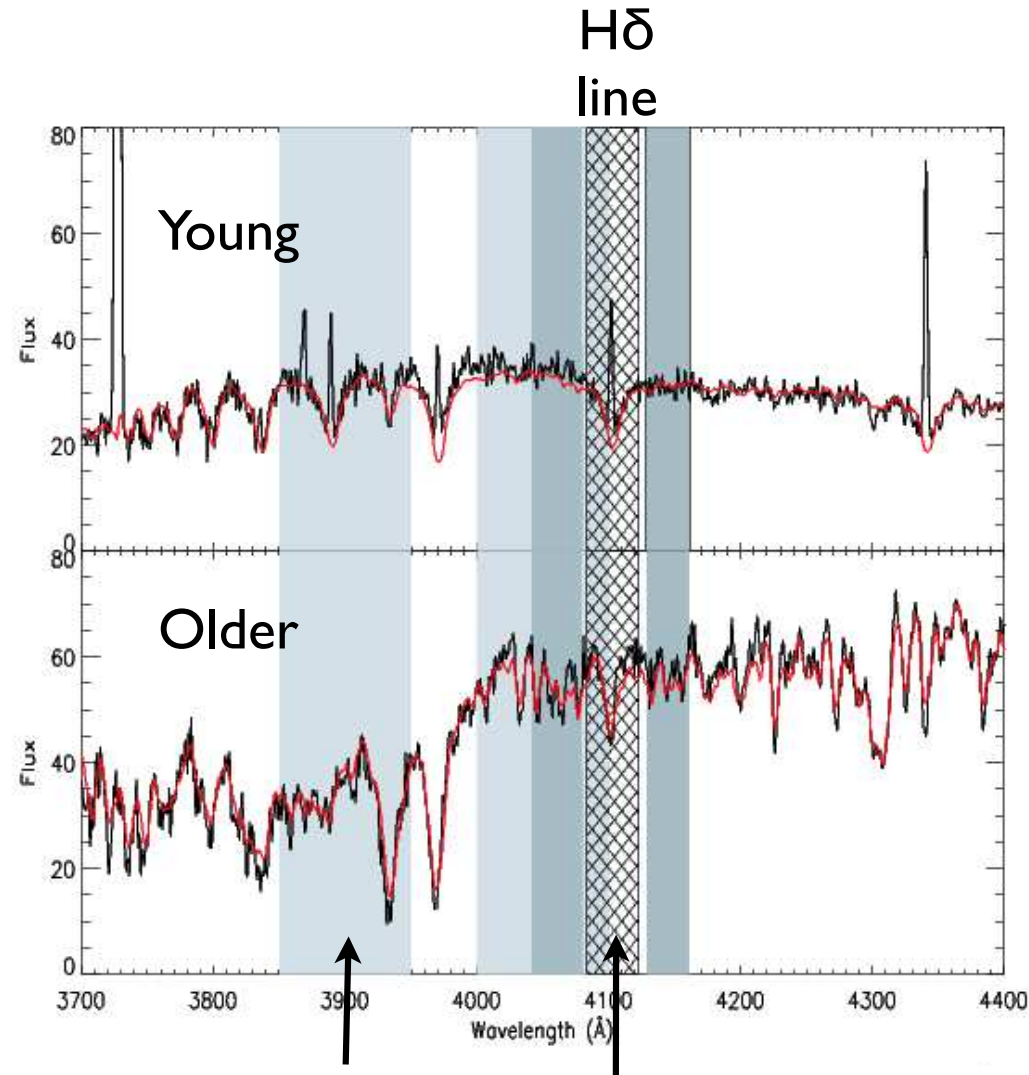
There are other factors which are important (dust, metallicity), but they only change the picture slightly.

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

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

H δ line emission;
 $D_n(4000)$ small

H δ line absorption;
 $D_n(4000)$ large



Almost no
4000
Angstrom
break

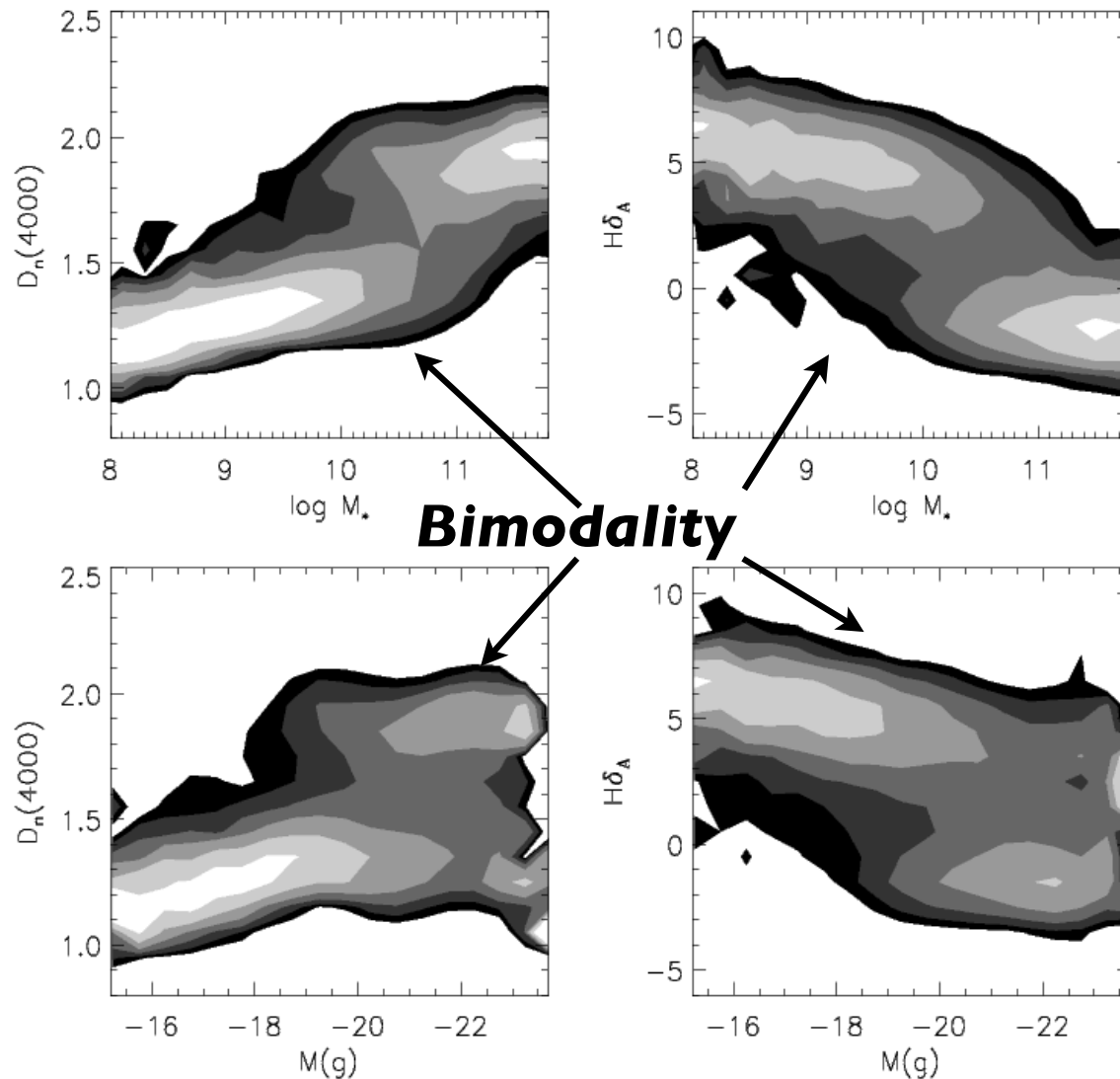
Measurable
4000
Angstrom
break

$D_n(4000)$ break measured by
comparing these two spectral regions

NOW new material for this
week

How do the properties of galaxies depend on their stellar mass?

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



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

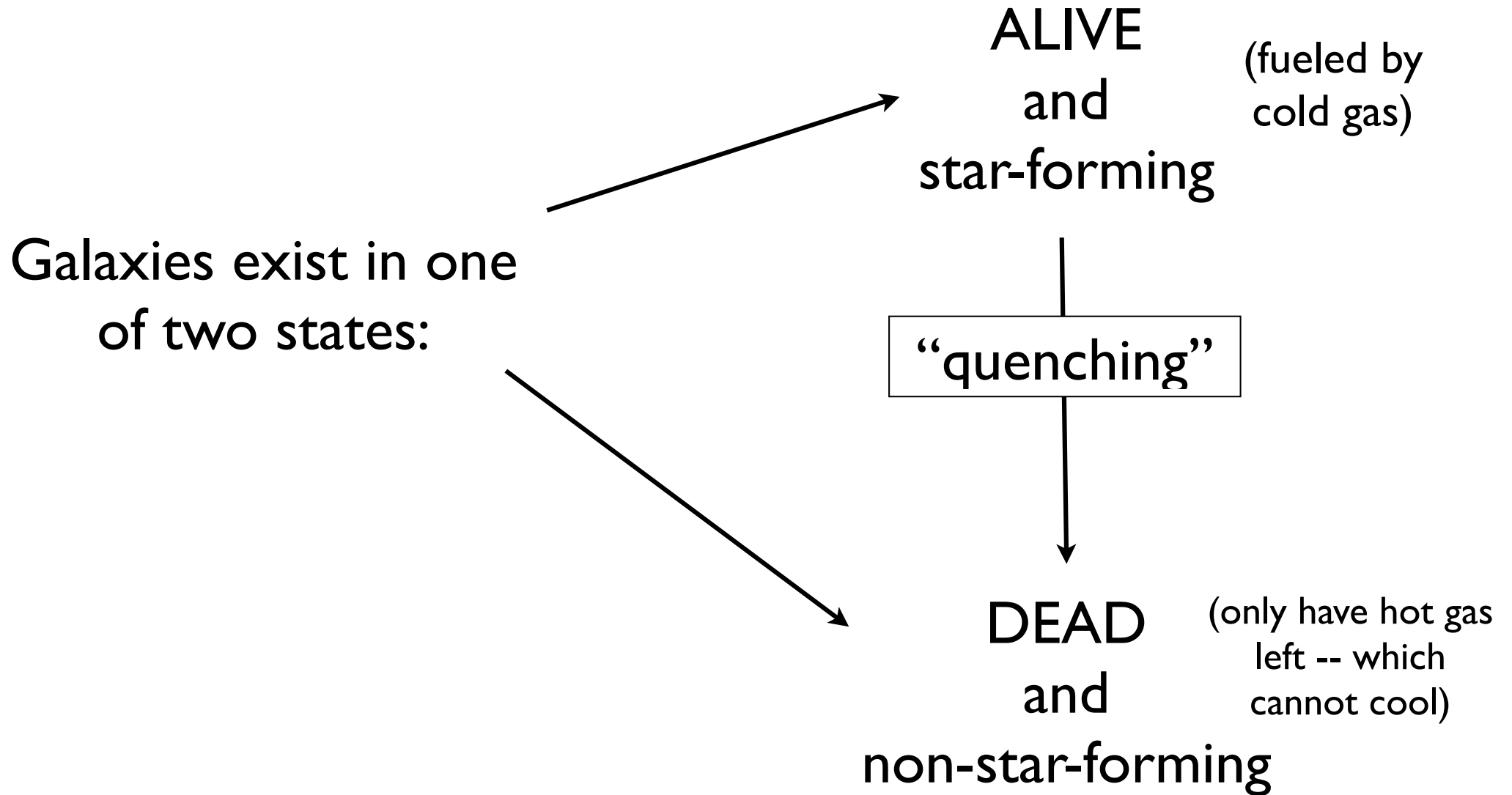
it occurs around a solar mass of $3 \times 10^{10} M_{\text{solar}}$

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

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

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 $1/V_{\text{max}}$ 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.

Why is there a bimodality?



This can also be seen in the following figure showing distribution of galaxies vs. $D_n(4000)$

Fraction

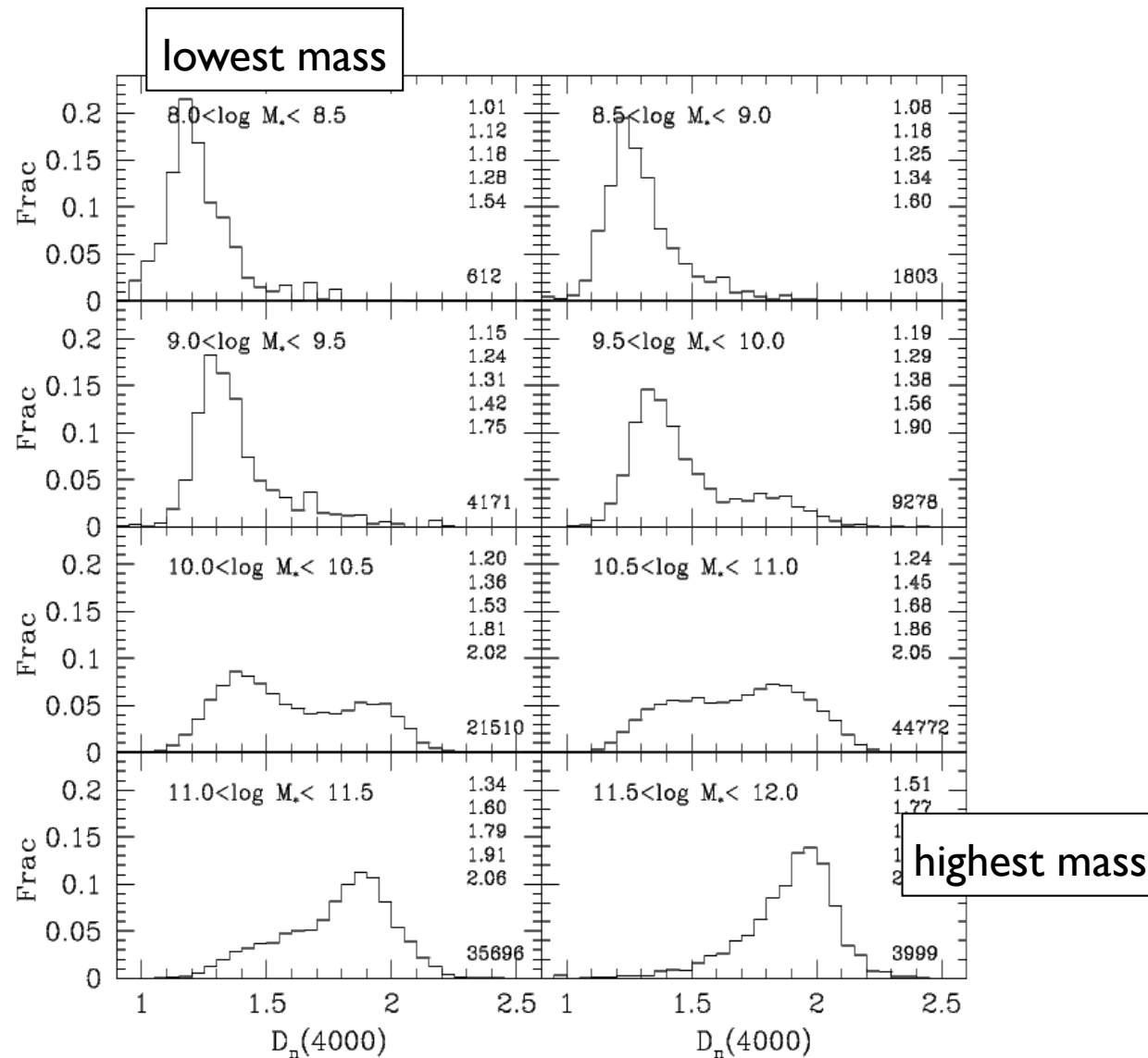
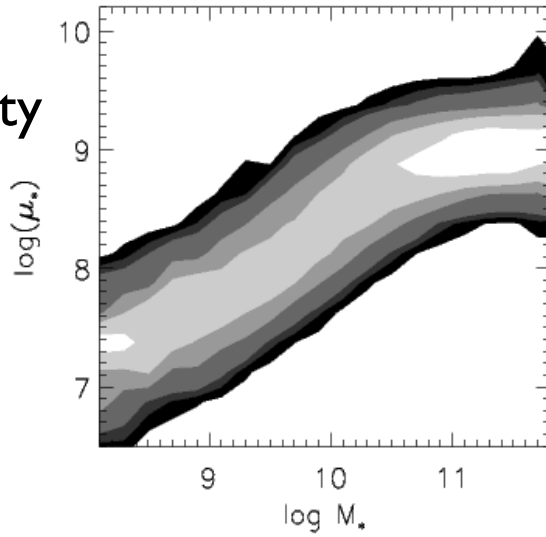


Figure 2. Histograms showing the fraction of galaxies as a function of $D_n(4000)$ in eight different ranges of stellar mass. The numbers in the upper right-hand corner of each panel list, from top to bottom, the fifth, 25th, 50th, 75th and 95th percentiles of the distribution. The number in the lower right-hand corner is the number of galaxies contributing to the histogram.

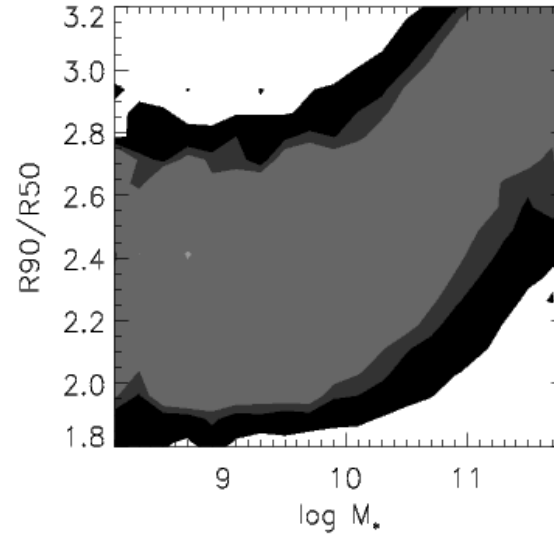
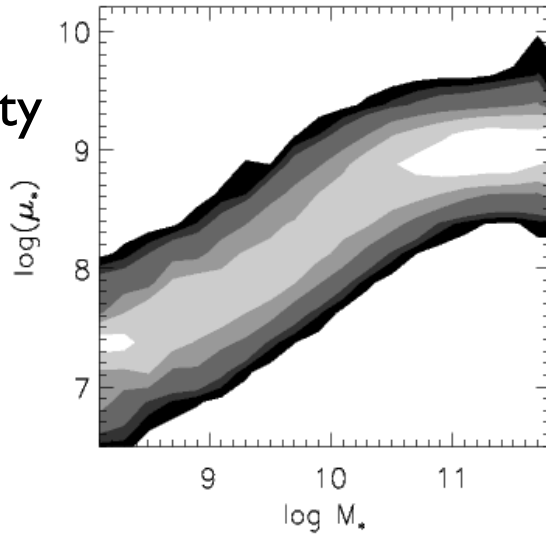
Other structural properties of galaxies also depend on their mass

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



Other structural properties of galaxies also depend on their mass

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



“concentration of light”

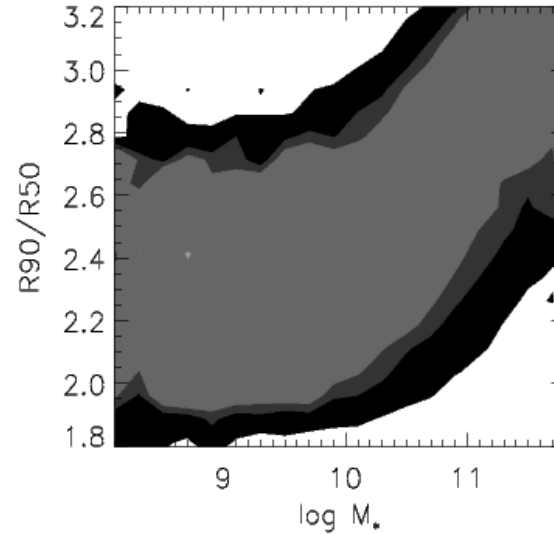
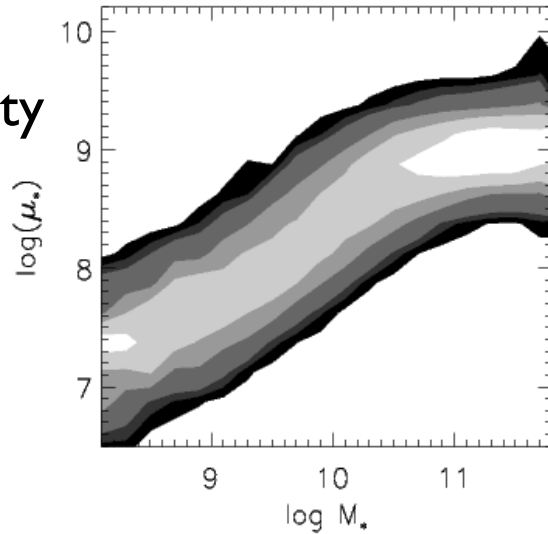
R_{90} / R_{50} = radius containing 90% of light / radius containing 50% of light

related to the Sersic index of galaxies

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

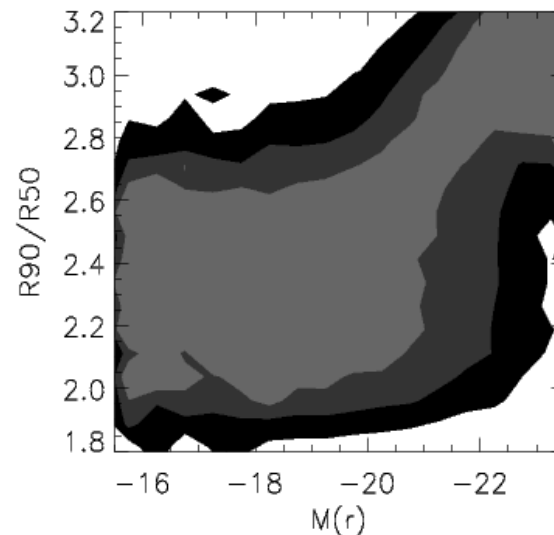
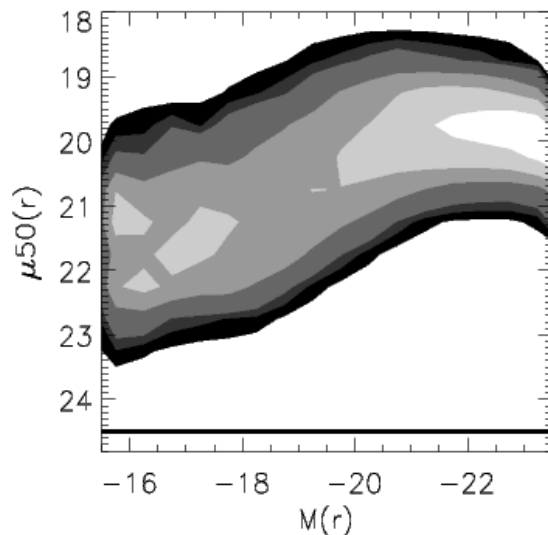
Other structural properties of galaxies also depend on their mass

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 $1/V_{\text{max}}$ 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 $H\delta$) 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} .

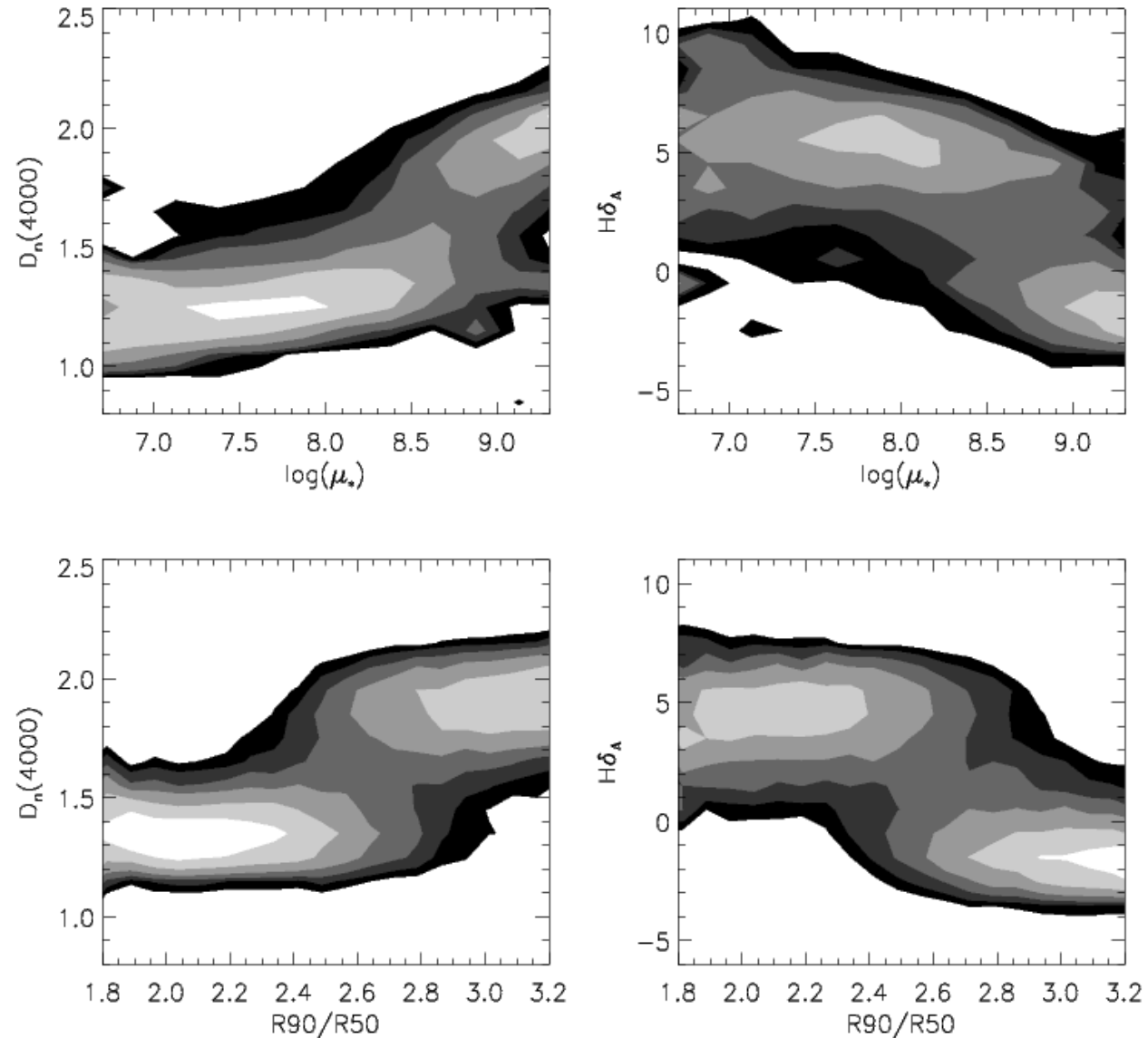


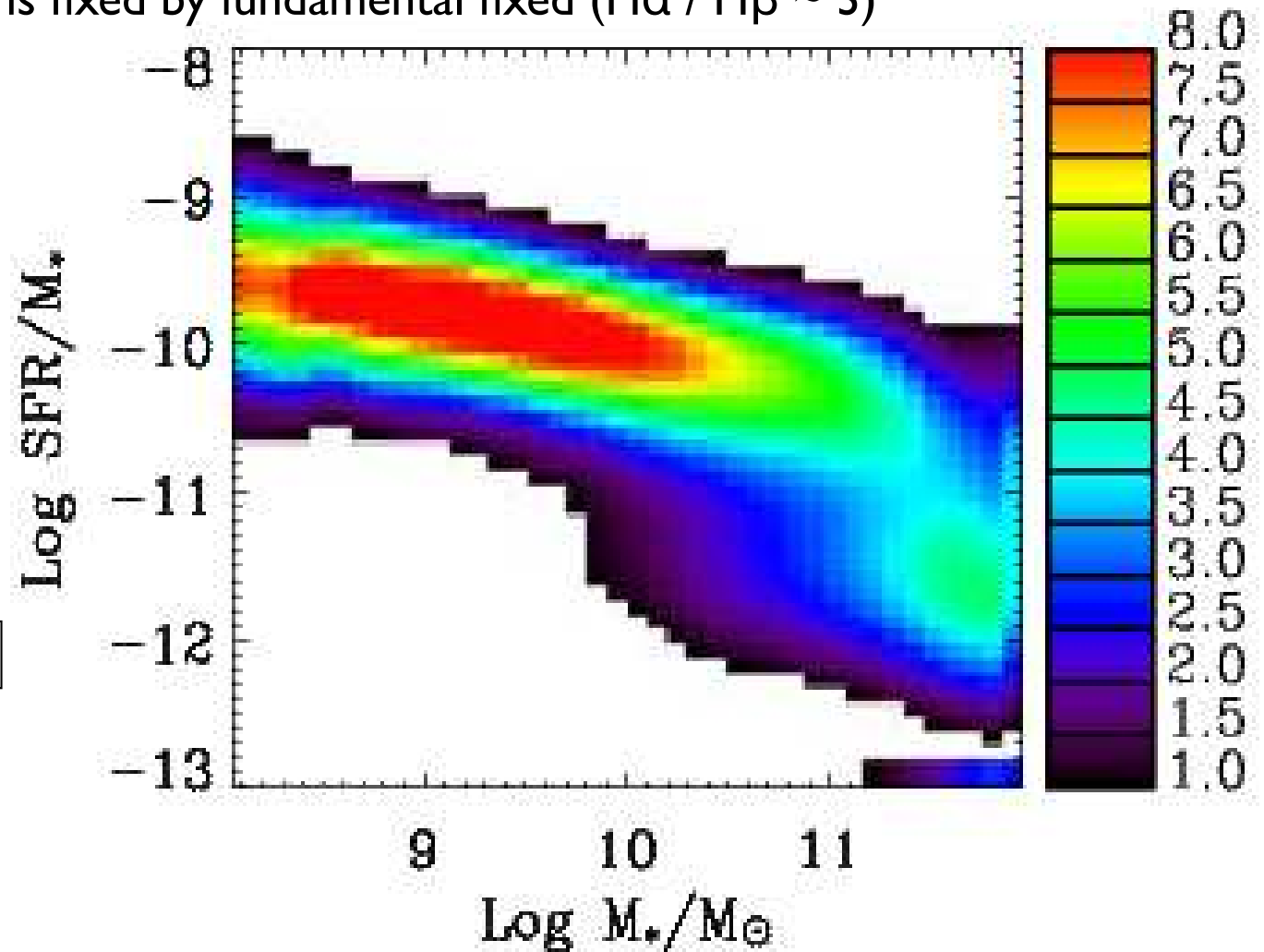
Figure 12. Conditional density distributions showing trends in the stellar age indicators $D_n(4000)$ and $H\delta_A$ as functions of the logarithm of the surface mass density μ_* and of the concentration index C .

Can compute the star formation rate for galaxies in the nearby universe from the strength of H α , H β lines

and correcting for extinction realizing that intrinsic ratio of H α , H β is fixed by fundamental fixed (H α / H β \sim 3)

Specific Star Formation
Rate
= Star Formation Rate /
M* (stellar mass)

Brinchmann et al. 2004



Galaxies with lower stellar mass tend to be star-forming, whereas galaxies with higher stellar masses appear to have stopped forming stars.

Very massive galaxies formed most of their stars long ago in the past!

How do the properties of galaxies depend on their environment?

This question (and the previous one) connects to a long-standing debate:

**LONG-STANDING DEBATE:
Nature vs. Nurture**

“NATURE”: Do galaxies have their observed properties simply as a result of properties inherent to themselves (e.g., their mass or angular momentum)?

“NURTURE”: Of do galaxies have their observed properties more as a result of their interactions with galaxies that surround them?

Dependence of Galaxy Properties on their Environment

You have seen that the properties of galaxies appear to depend on their environment, i.e., elliptical galaxies are more common in clusters.

However, it would be nice to quantify the role that the environment has.

So, what is environment and how can we quantify it?

We can quantify it in terms of the local density of galaxies around a specific galaxies.

To do this, we count the # of neighboring galaxies within a given distance.

Analysis as in Kauffmann+2004 (but also see Blanton+2003, Hogg+2004

“What fraction of galaxies have fewer than N nearby neighbors?”

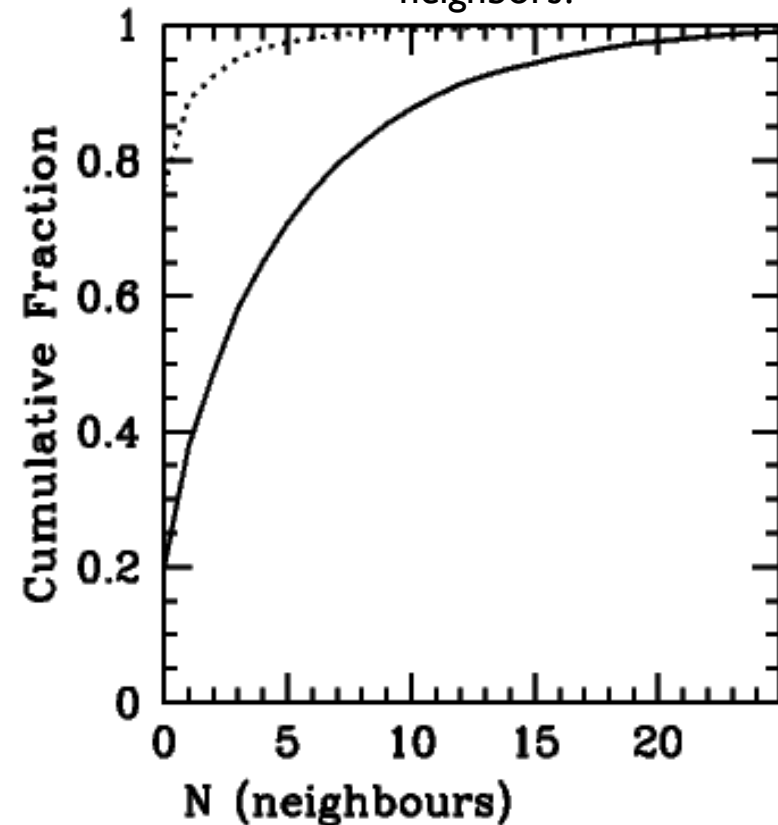


Figure 1. The cumulative fraction of galaxies with counts less than N for the target sample (solid curve) and for a random sample (dotted curve).

Criteria for a Neighboring Galaxy:

<2 Mpc projected separation (plane of sky),
<500 km s⁻¹ (along line of sight)

What does the color - stellar mass relation look like in low and high density environments?

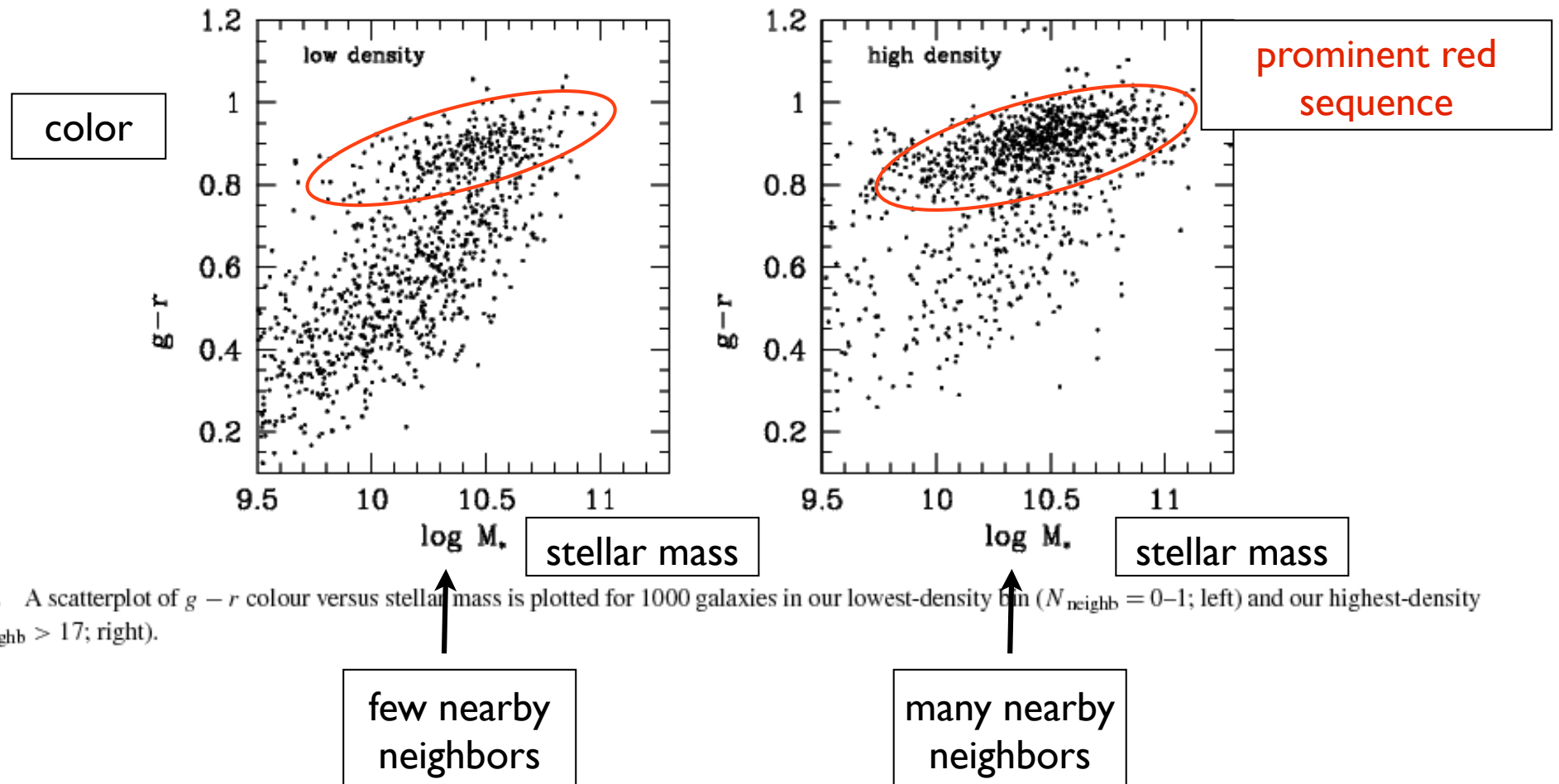


Figure 6. A scatterplot of $g - r$ colour versus stellar mass is plotted for 1000 galaxies in our lowest-density bin ($N_{\text{neighb}} = 0-1$; left) and our highest-density bin ($N_{\text{neighb}} > 17$; right).

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

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 before:

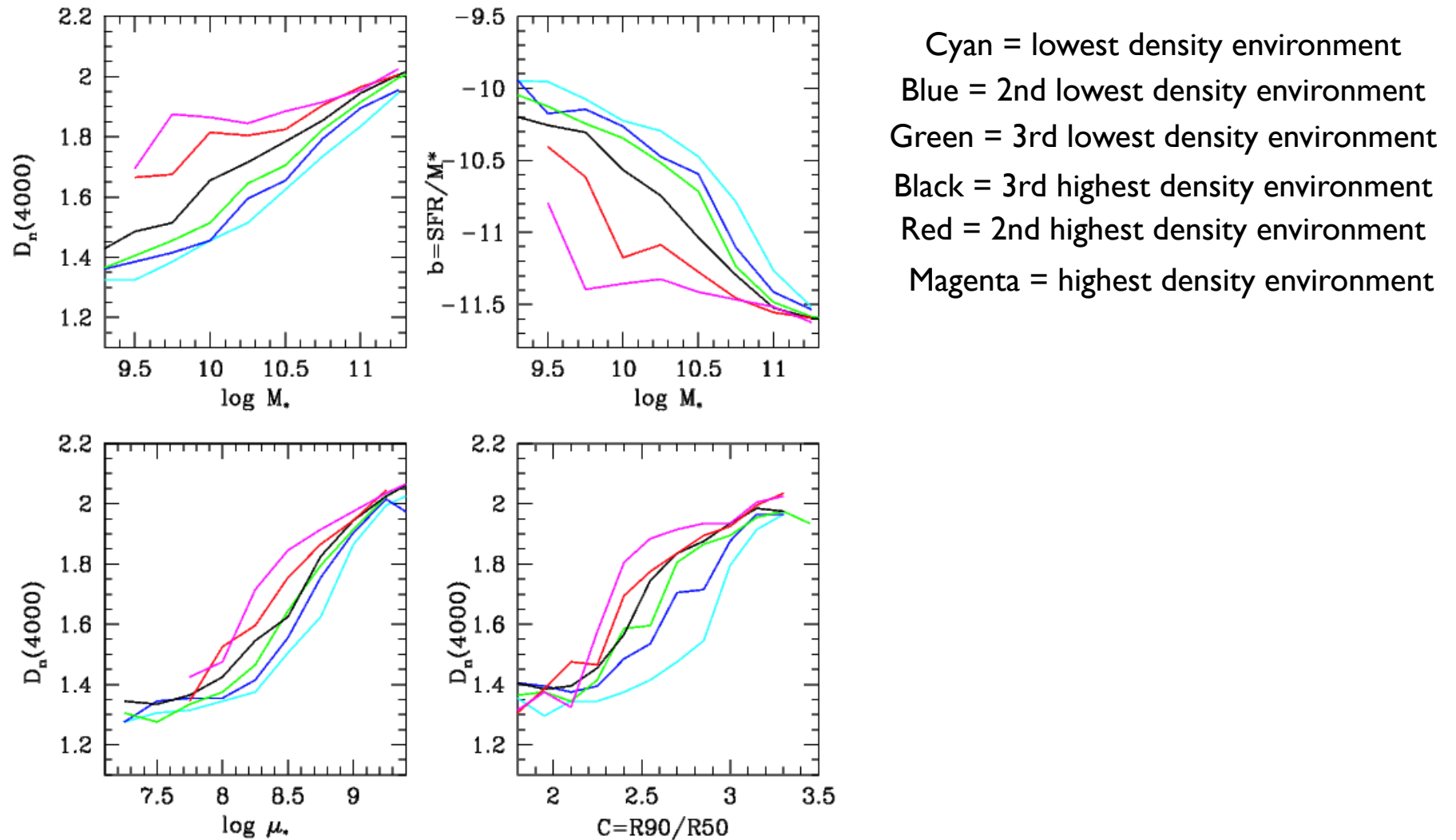


Figure 7. Top: the median relations between $D_n(4000)$ and SFR/M_* are plotted as a function of stellar mass for five different bins in density, colour-coded as in Fig. 5. Bottom: the median relations between $D_n(4000)$ and μ_* (left) and C (right).

We can also see that stellar mass density vs. stellar mass relation shows a weak dependence on environment

(color of galaxies in different environments shown as before)

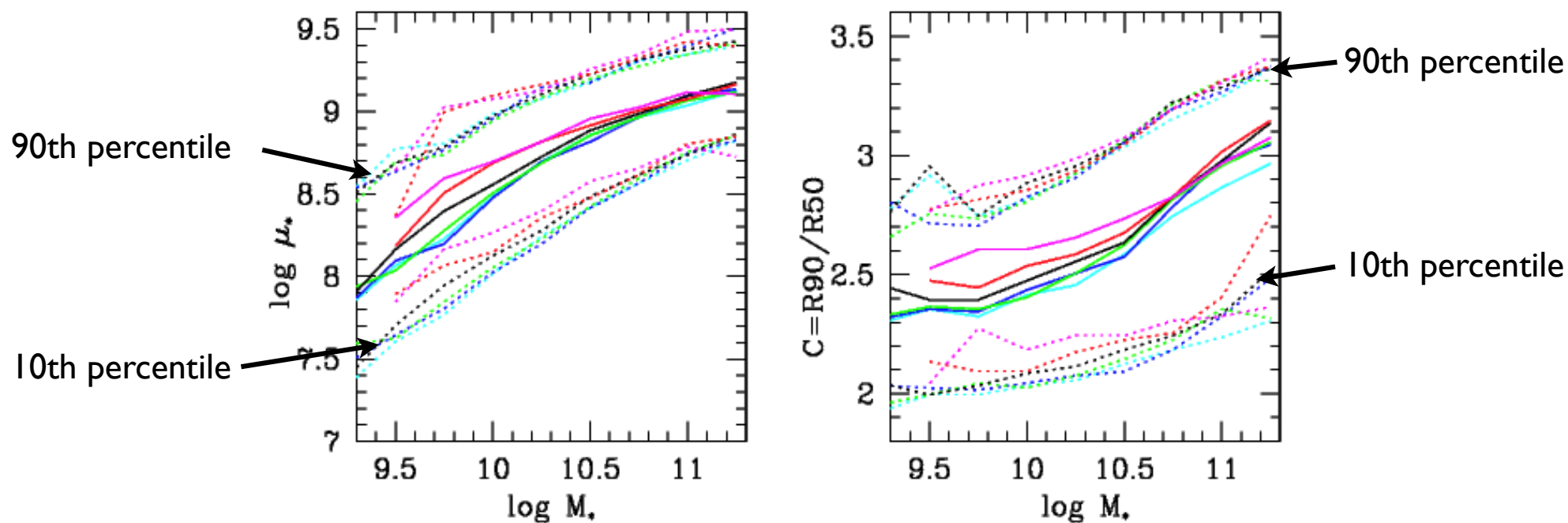
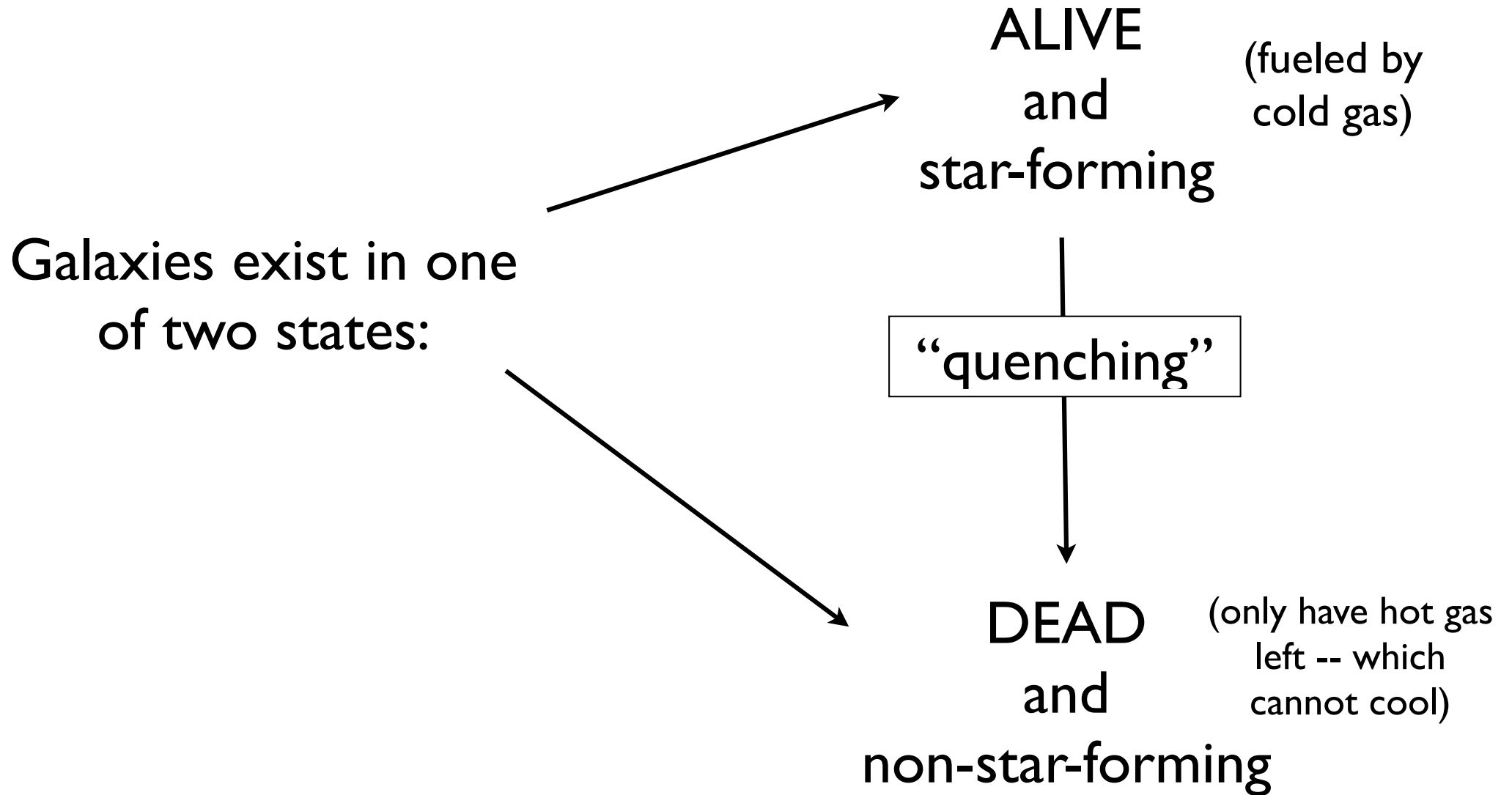


Figure 5. The relations between surface mass density and stellar mass (left) and concentration index and stellar mass (right) are plotted for galaxies in six different density bins as follows: cyan, 0 or 1 neighbour; blue, 2–3 neighbours; green, 4–6 neighbours; black, 7–11 neighbours; red, 12–16 neighbours; magenta, 17 or more neighbours. The solid curves indicate the median value of $\log \mu_*$ or C and a given value of $\log M_*$. The dotted lines indicate the 10th and 90th percentiles of the distributions.

Why is there a bimodality?



from the paper

Main result

- 1) High mass galaxies have nearly formed all their stars
- 2) Galaxies in rich environments have less star formation

These two results suggest that stellar mass *and environment* determine the star formation history. The environment is correlated to the type of halo the galaxy sits in. So maybe it is just 1 parameter which determines the star formation history: the halo mass.

In more massive halos, galaxies have lower star formation. It could be that the correlation with galaxy mass is entirely due to the halo - more massive galaxies are likely to sit in more massive halos.

The physics behind this are under active research right now!

2. Environmental Quenching

Some factor related to the environment of a galaxy is found causes star formation in a galaxy to shut off (perhaps due to the fact that galaxies in dense environments will not be fed by cold gas and thus the star formation would shut off?)

What drives quenching?

I. Mass Quenching

Some factor related to the mass of a galaxy causes star formation in a galaxy to shut off (perhaps due to heat produced from a supermassive black hole in galaxies? which is proportional to the stellar mass)

2. Environmental Quenching

Some factor related to the environment of a galaxy is found causes star formation in a galaxy to shut off (perhaps due to the fact that galaxies in dense environments will not be fed by cold gas and thus the star formation would shut off?)

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

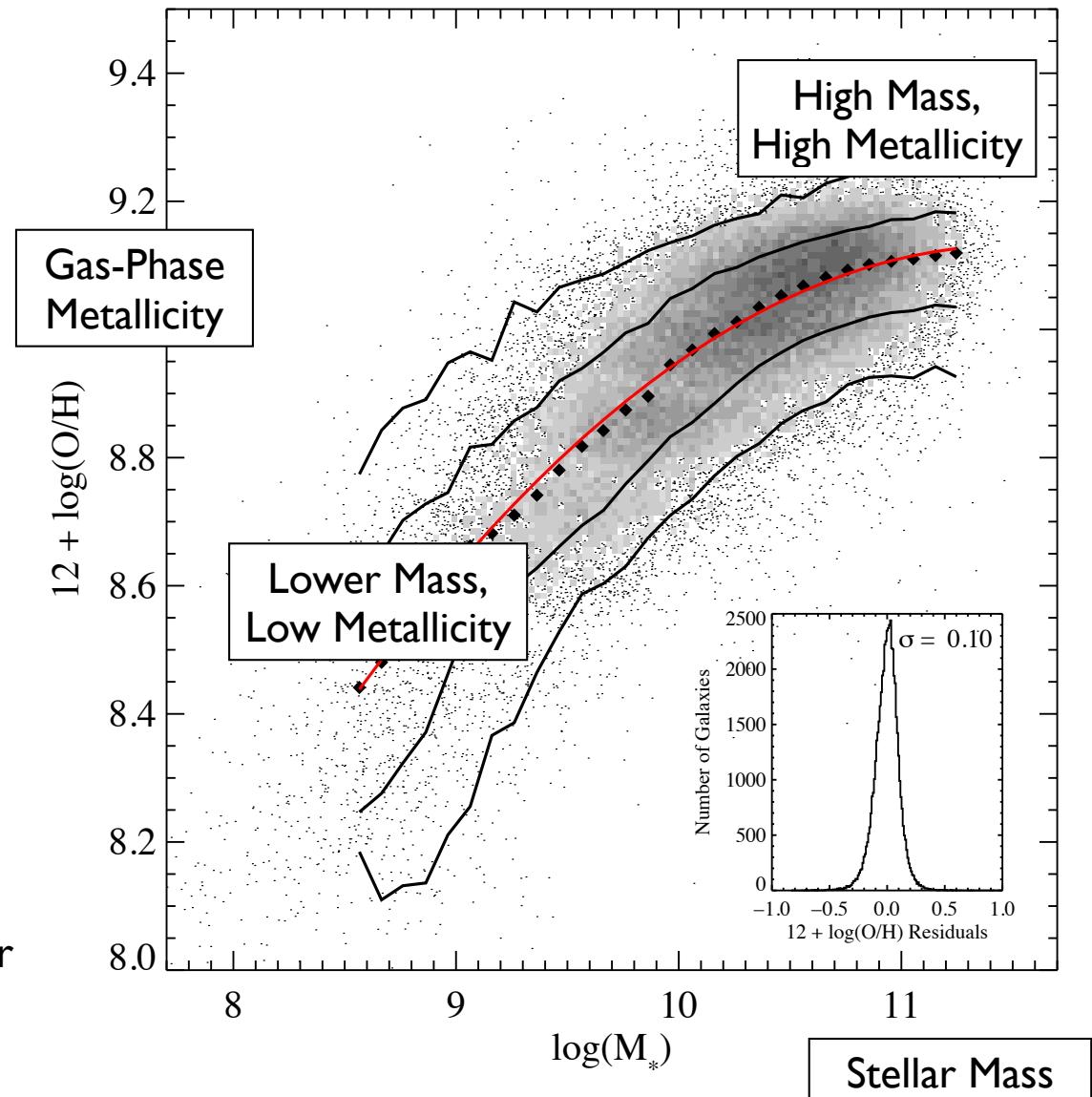
Two primary explanations for this:

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



How do the properties of galaxies change as we move to earlier times in the universe?

Here — I will give the historical perspective:

discuss progress made ~15-20 years ago...

Will give an overview of more recent results at the end
(and also see paper presentations)

While we can understand much from galaxies in the nearby universe, we actually want to understand how they are arrived at their current state

what is their history?

well we can make some estimate of what galaxies looked like from the ages of their stars, i.e., by evolving these stars backwards in time...

however, backwards evolution only works so well, since the age of stars is not the only thing which changes in galaxies...

how can we identify large samples of galaxies in distant universe and study their properties?

one way is to use spectroscopy as we did in studying galaxies in the local universe

but this is expensive... sources 7 billion years in the past are 100x fainter than sources in the nearby universe.

need to integrate 10^4 x longer to reach the same signal to noise as galaxy in local universe.

but telescopes from the 2000s (i.e., ~10-m Keck telescopes in Hawaii) have 16x collecting area as the Sloan Digital Sky Survey telescope...

Not possible to do surveys like the Sloan Digital Sky Survey in the nearby universe...

How can study the properties of galaxies at intermediate cosmic time then?

- 1) Study smaller spectroscopic samples than 10^6 galaxies
- 2) Estimate redshifts and other properties from the photometry (i.e., photometric redshifts)

Both approaches are used a lot these days

Both approaches start by imaging a field at a number of different wavelengths, from optical wavelengths to the near-IR

U, V, I, R, z -- in the optical

Y, J, H, K -- in the IR

3.6, 4.5, 5.8, 8 microns

24, 70, 160 microns

70, 100, 160 microns

250, 350, 500 microns

with Spitzer

with Herschel

Not all bands
are necessary of
course

plus radio, x-ray, UV from GALEX

Surveys usually select galaxies based on light beyond the 4000 Angstrom break, as this correlates better with the stellar mass in a galaxy

As such, surveys of galaxies at $z < 1.5$ often select galaxies based on the light in a redder optical band or a near-IR band.

Then, a large number of spectra are taken of all galaxies brighter than flux level in some selection band (probed rest-frame optical light)

The DEEP2 program (Davis et al. 2005; Faber et al. 2006) did such using the power DEIMOS spectrograph on the Keck telescope.

Here is a picture of the DEIMOS spectrograph:



The DEIMOS spectrograph under construction in the UCO/Lick Observatory Instrument Laboratory.

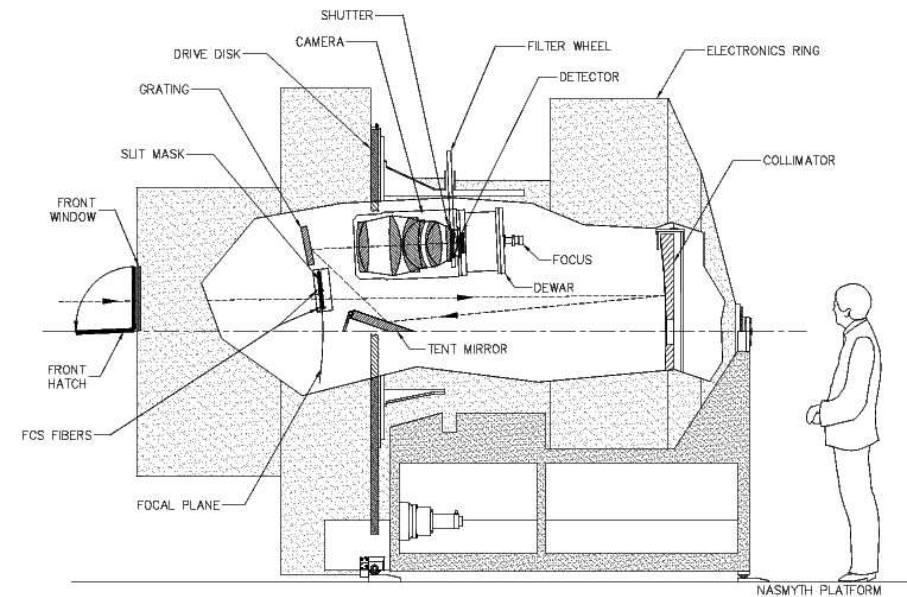


Figure 2. Light path and major optical components.

Biggest element is 1 meter in size!

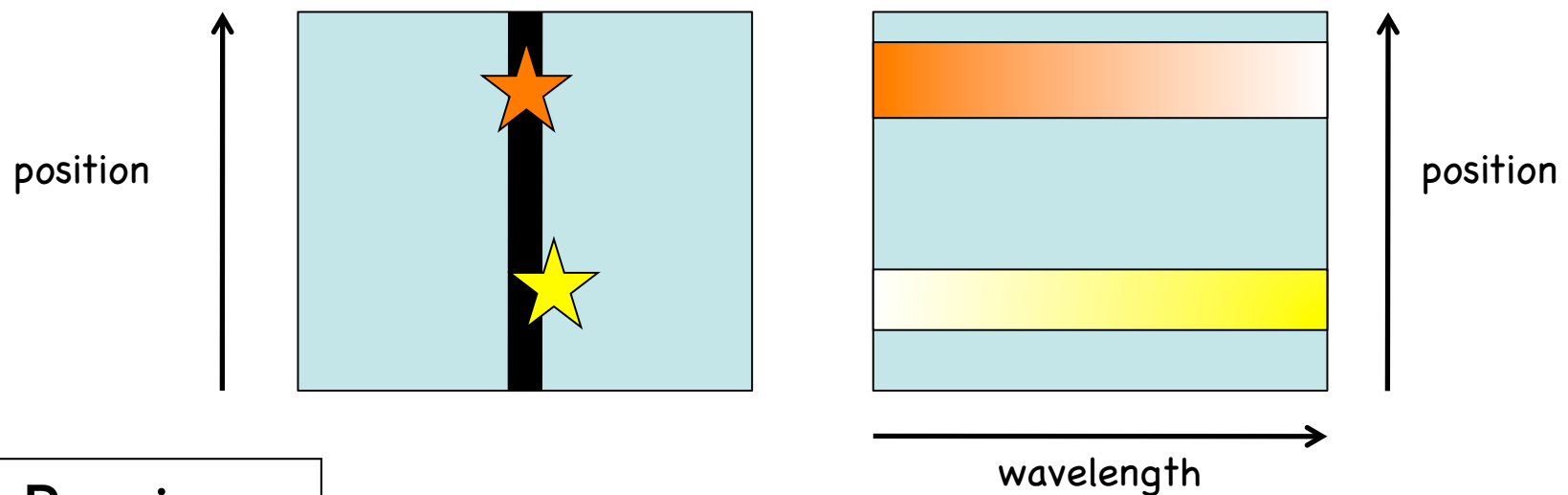
Similar to size of small telescope

Can take 100s of spectra at a time.

Useful feature is high spectral resolution -- which allows us to see between sky lines which are prominent at > 6000 angstroms

How does one use DEIMOS to obtain deep spectra for many sources on a field?

- Make a slit mask and then disperse the light perpendicular to the axis of the slit mask.
- Why using a slit? To keep out as much as background light as possible
- How does the output look like? 2D spectrum



credit: Porciano

Here is the signal on the detector based on a mask:

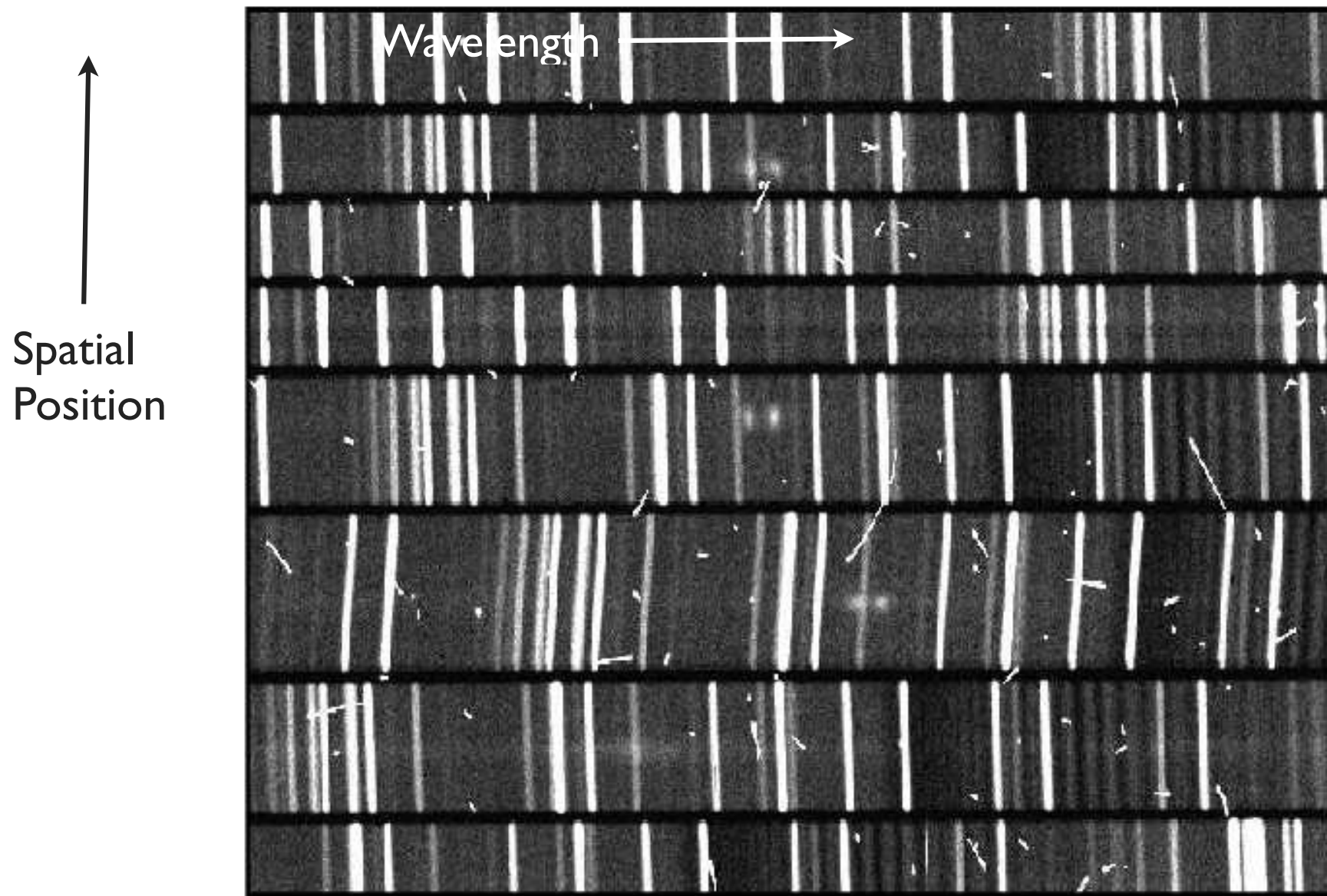
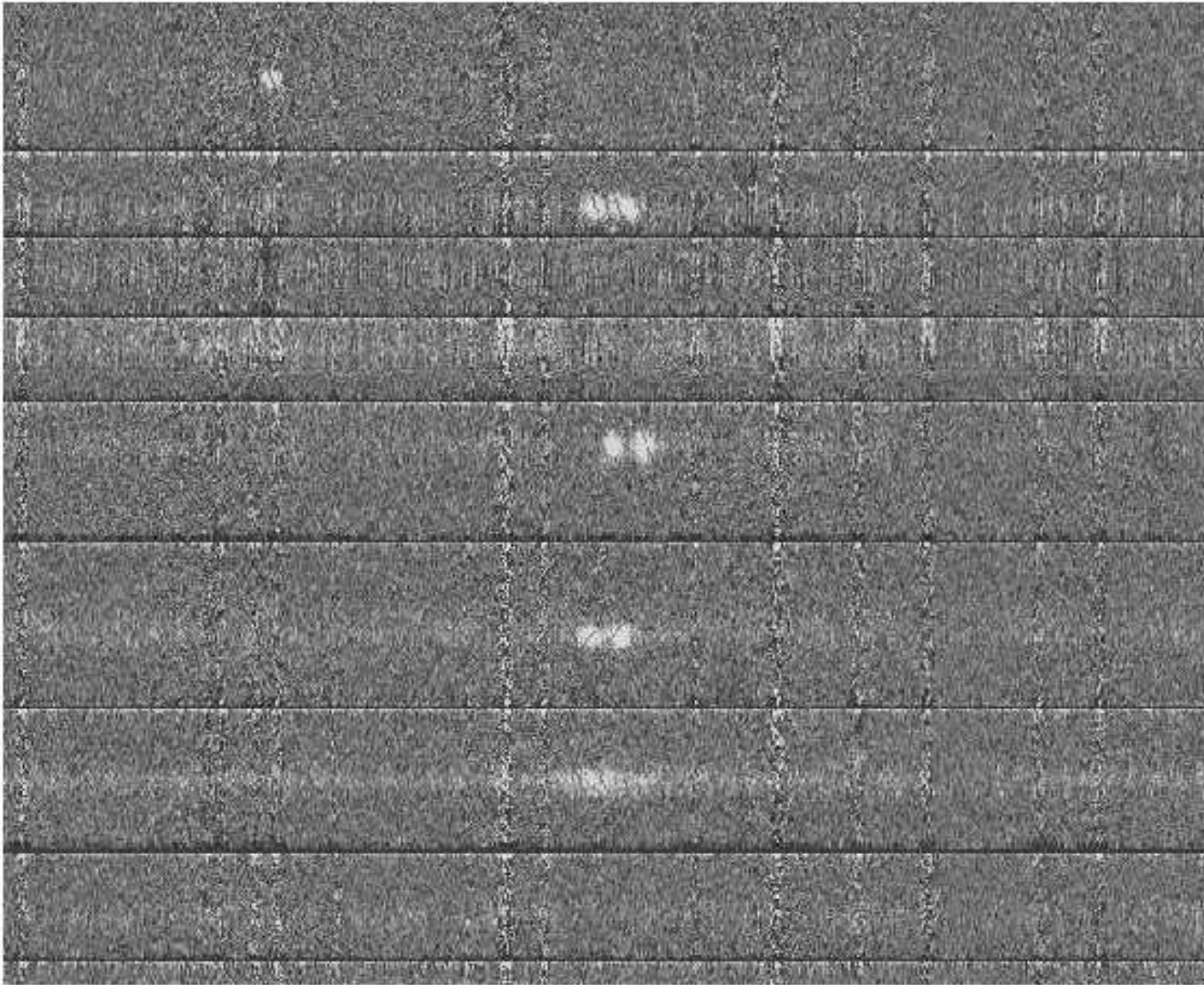


Figure 4. A 700 by 300 pixel section of the coadded raw frames of one mask, with total integration time of one hour. The tilted sky lines indicate the tilt of the individual slitlets. Cosmic rays are prominent, but note as well the sets of double emission lines in the spectra.

Here is after the subtraction of the sky lines (after sky subtraction)



Emission lines are clearly visible... but cannot see continuum well
(the continuum requires even longer integration times)

Here are the goals of the DEEP program:

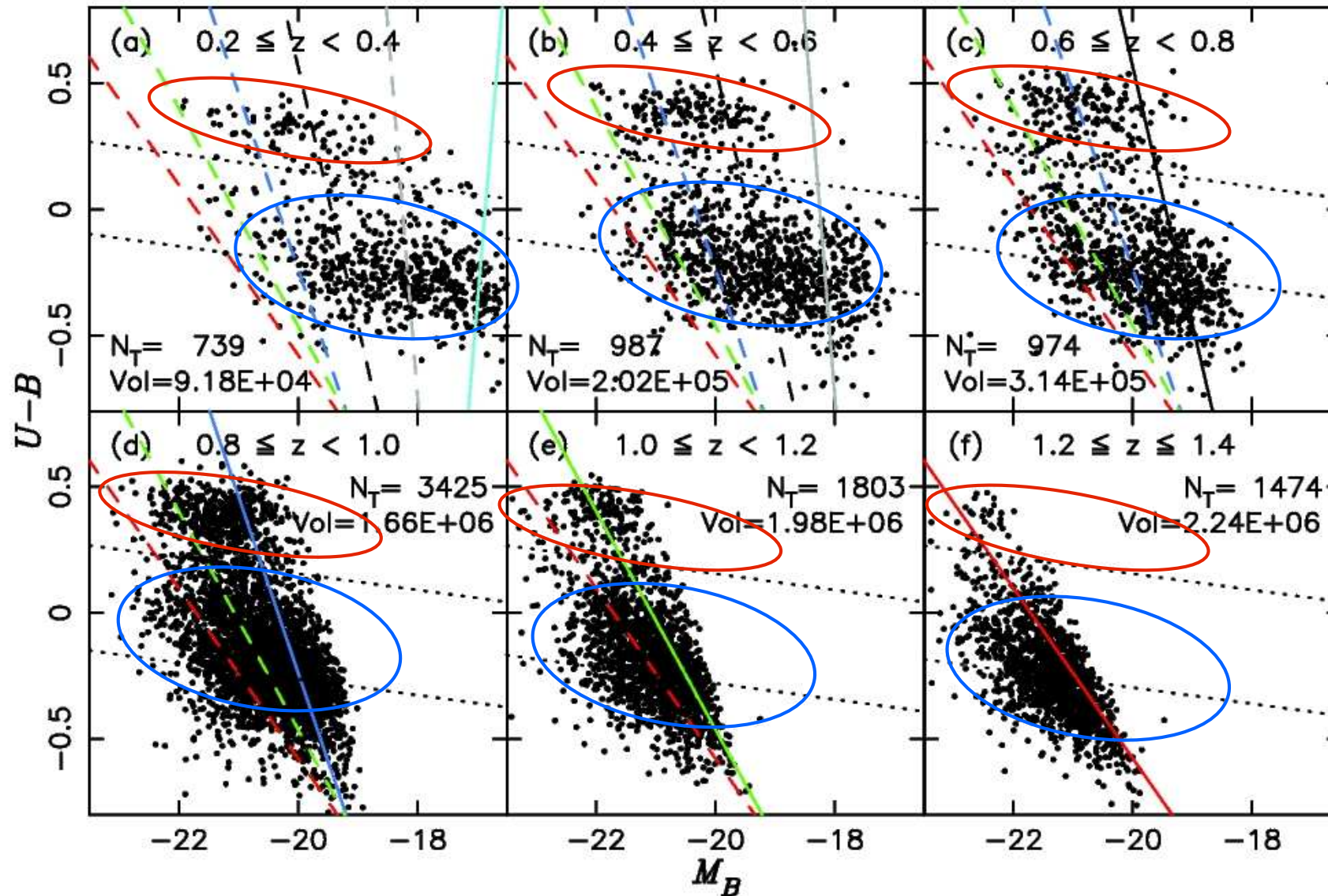
Goal 1: Determine the characteristics of galaxies at $z \sim 1$ and their dependence on environment; e.g. measure the evolution of the “structure function” of galaxies with redshift. DEEP2 will measure a wide variety of parameters of the observed galaxies: not just colors, magnitudes, and redshifts, but also in many cases linewidths or rotation velocities, equivalent widths of emission lines (and thereby such parameters as metallicity and O[II]-derived star formation rates), the ages of stellar populations, etc., etc. The distributions of and correlations between these parameters, along with their evolution to the present epoch, will provide strong constraints on models of galaxy formation and evolution, whether semi-analytic (e.g. Refs. 6,7) or based on N-body simulations (e.g. Refs. 8, 9). An example of this sort of DEEP2 science which is critically dependent on combining ground-based spectroscopy with space-based imaging is the measurement of the “structure function” of galaxies.

Goal 2: Measure the two-point and higher-order correlation functions of galaxies at $z \sim 1$ as a function of other observables. In almost all models of structure formation (e.g., Ref. 13), galaxies are born as highly biased tracers of the mass distribution, but their bias diminishes with time. Spiral galaxies today appear to be weakly biased, if at all, while the clustering of $z \sim 3$ Lyman-break galaxies requires a large bias for any reasonable cosmological model.^{14,15} Galaxies at $z \sim 1$ should have an intermediate degree of bias, with readily observable consequences. With sufficiently dense sampling, determining the higher-order clustering properties of galaxies can yield direct measurements of their biasing.^{16,17} It will be possible to subdivide the 1HS sample as a function of galaxy type, luminosity, etc. and measure the biasing for each sample both in an absolute sense and compared to the other samples. This and other, more sophisticated measures will be explored as part of DEEP2. The 1HS survey is designed to provide a fair sample volume for analysis of LSS statistical behavior, particularly for clustering studies on scales $< 10h^{-1}$ Mpc. The comoving volume surveyed in the 1HS program will exceed that of the LCRS survey,⁴ a survey which has proven to be an outstanding resource for low redshift studies of LSS.

Goal 3: Determine the evolution of the abundance of dark matter halos and clusters as a function of internal velocity, $N(v, z)$. By measuring the linewidths of parent dark matter halos from the galaxies visible within them (as per Goal 1 above), we can use the dark-halo abundance as a function of internal velocity and redshift, $N(v, z)$, to perform a classic cosmological test. It is well known that the volume element $dV/dz d\omega$ (where ω is solid angle) strongly depends on the input cosmological parameters, notably Ω_m and Ω_Λ . Thus, the apparent number of objects with a given linewidth versus redshift is a sensitive test of the volume element—provided the co-moving number density of those objects is known. In practice, the poorly-known evolution of the number density $N(L)$ of galaxies has stymied this test. However, if we have measured real potential-well depths, we can bypass galaxies and count the more easily simulated dark halos directly. This work will require us to study a significant fraction of our galaxies with the high resolution of HST to ensure that these objects are morphologically simple, and thus that their linewidths provide real information about the potential wells of galaxies. Newman & Davis^{19,20} showed that the degree of evolution in the comoving number density of galaxy sized halos at fixed velocity is almost totally independent of cosmology. The observed abundance of such objects, $dN(v)/dz$, thus measures the volume element of the expanding Universe and gives us a powerful handle on the cosmic geometry.

Goal 4: Measure redshift-space distortions due to peculiar velocities at $z \sim 1$. The clustering of galaxies is inherently isotropic in space, with no preferred orientation toward or away from the Milky Way. The observed redshift-space clustering of galaxies, however, is distorted by peculiar velocities, producing features such as the so-called “fingers of God” on virialized scales and a flattening of structure on larger scales. DEIMOS will deliver highly precise redshifts, allowing both of these effects to be readily detectable in our maps (see Ref. 24 for details).

One of the most important results from the DEEP2 program regards the evolution of the “red sequence” and “blue cloud” on the color-luminosity diagram:



One can see the existence of the red-sequence out to $z \sim 1$

This same result was obtained earlier by Bell et al., based on photometric redshifts from the COMBO-17 survey.

COMBO-17 was not based on large numbers of spectroscopic redshifts, but on redshifts estimated from photometry in large numbers of passbands.

17 Filters used by COMBO-17:

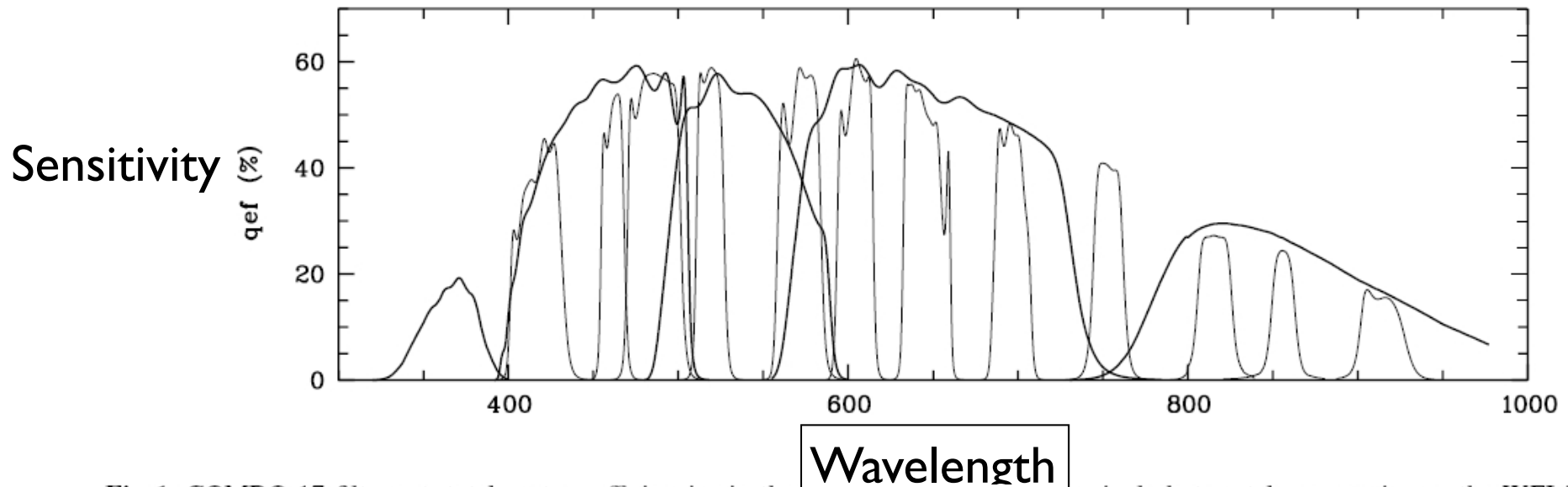
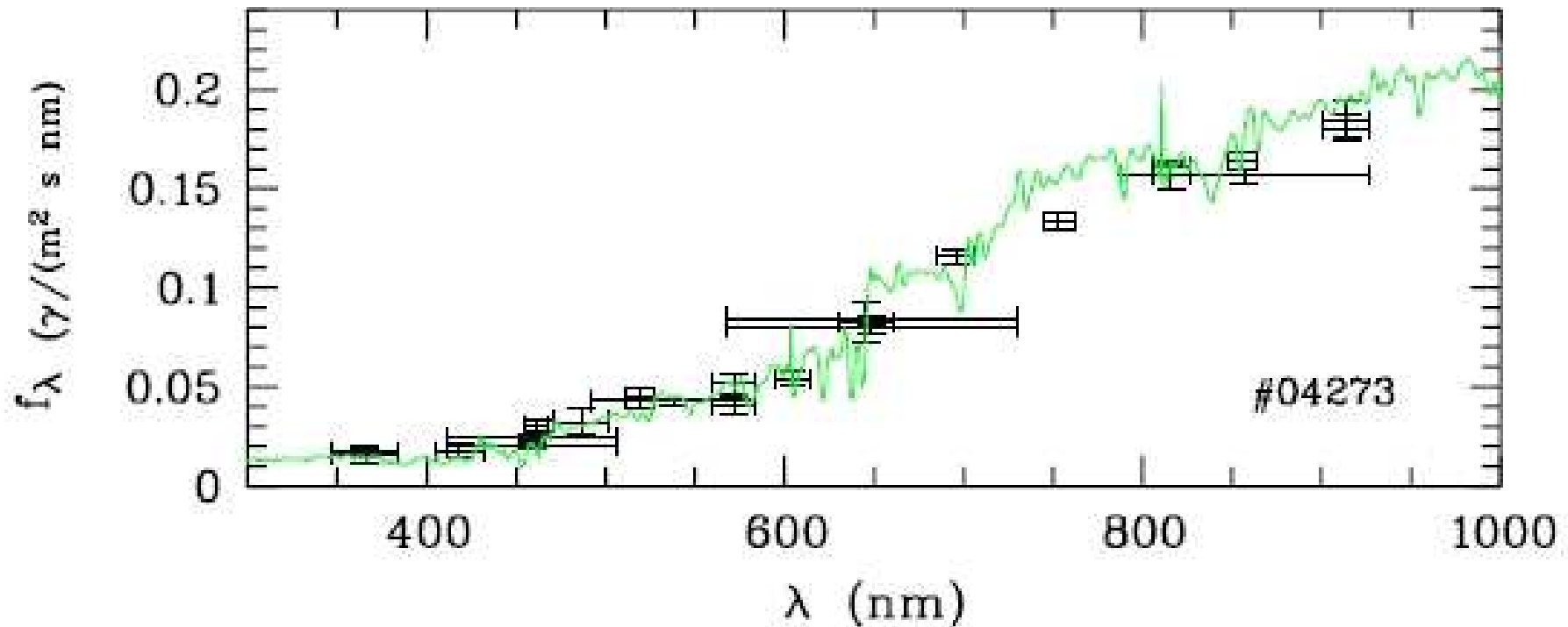


Fig. 1. COMBO-17 filter set: total system efficiencies in the COMBO-17 bands. They include two telescope mirrors, the WFI instrument, CCD detector and an average La Silla atmosphere. Photometric calibrations of such datasets are best achieved with spectrophotometric standards inside the target field.

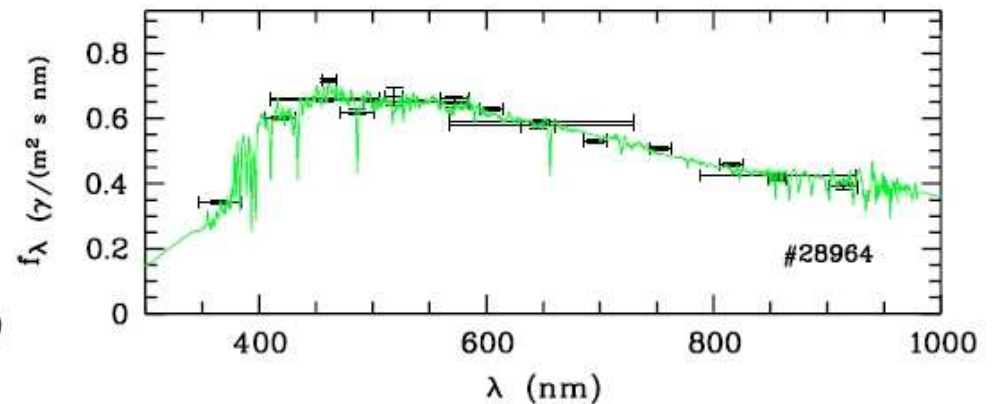
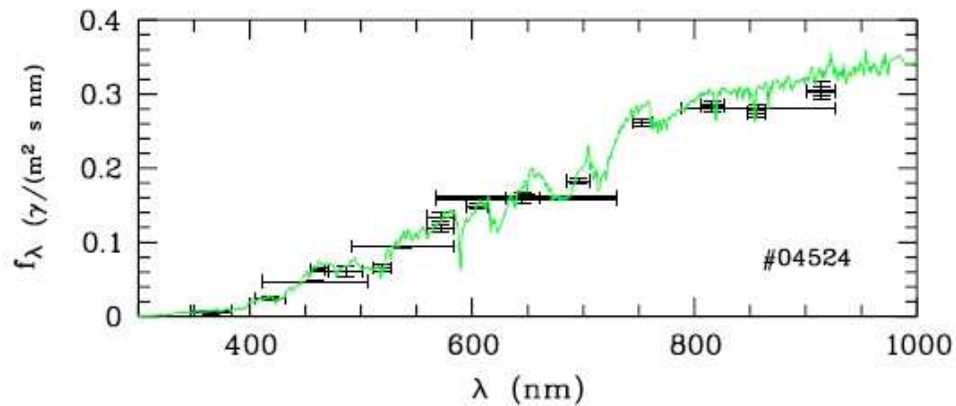
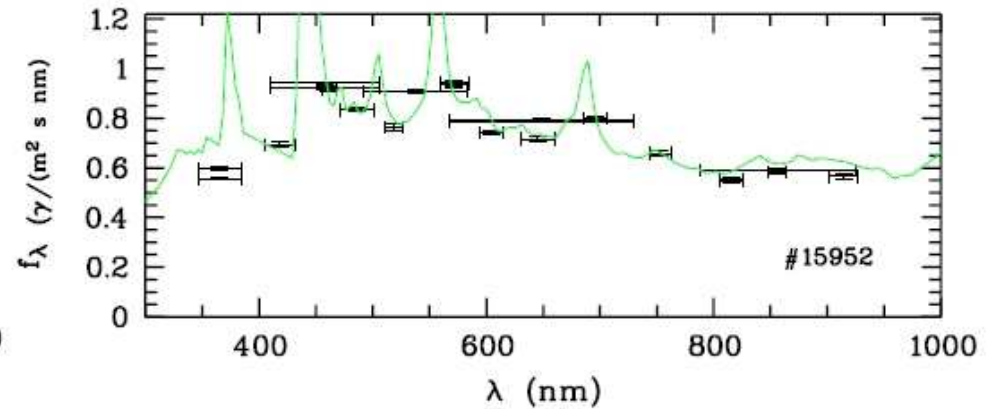
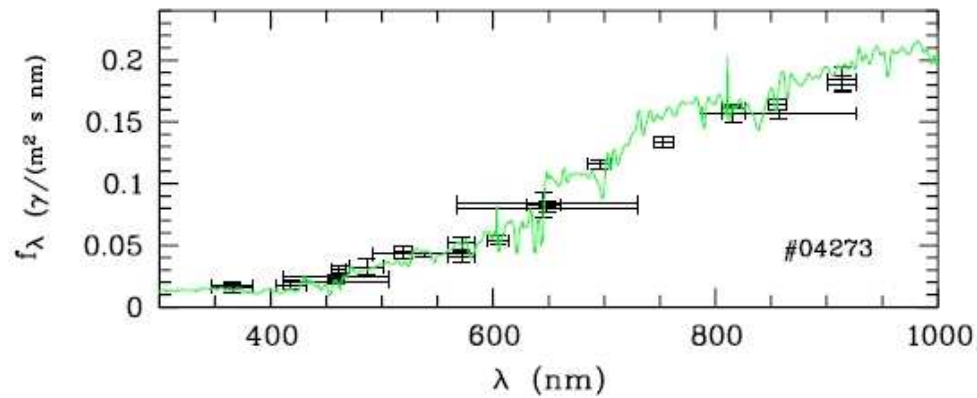
How well can one estimate the redshifts of distant sources from the flux measurements in 17 different passbands?

One Example:

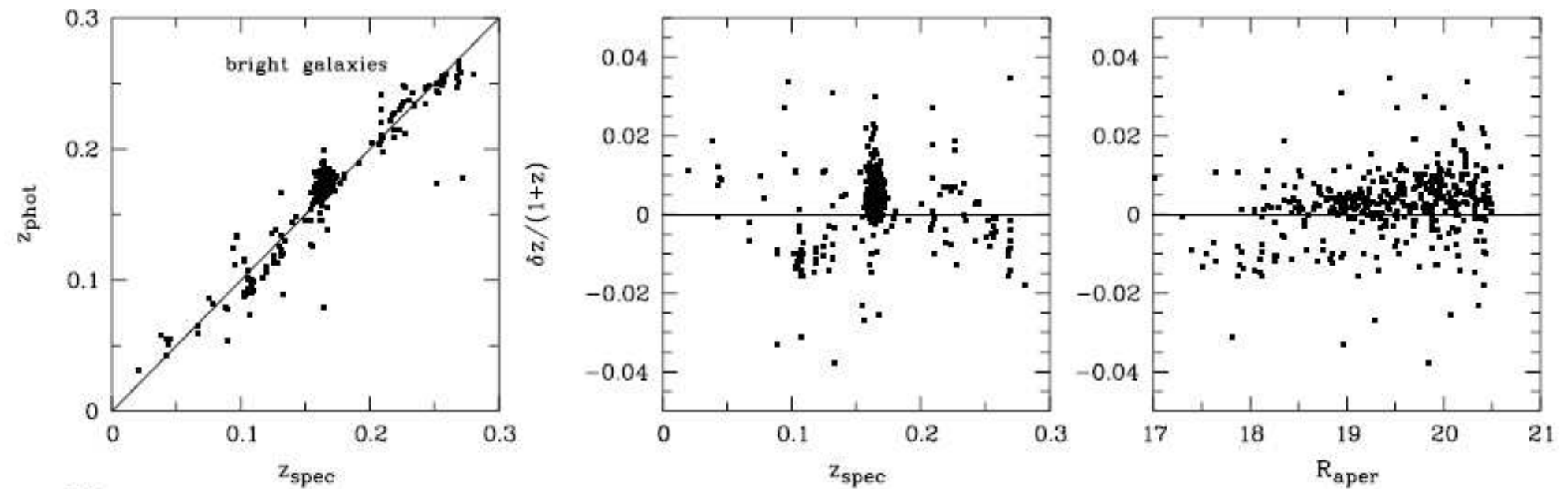


How well can one estimate the redshifts of distant sources from the flux measurements in 17 different passbands?

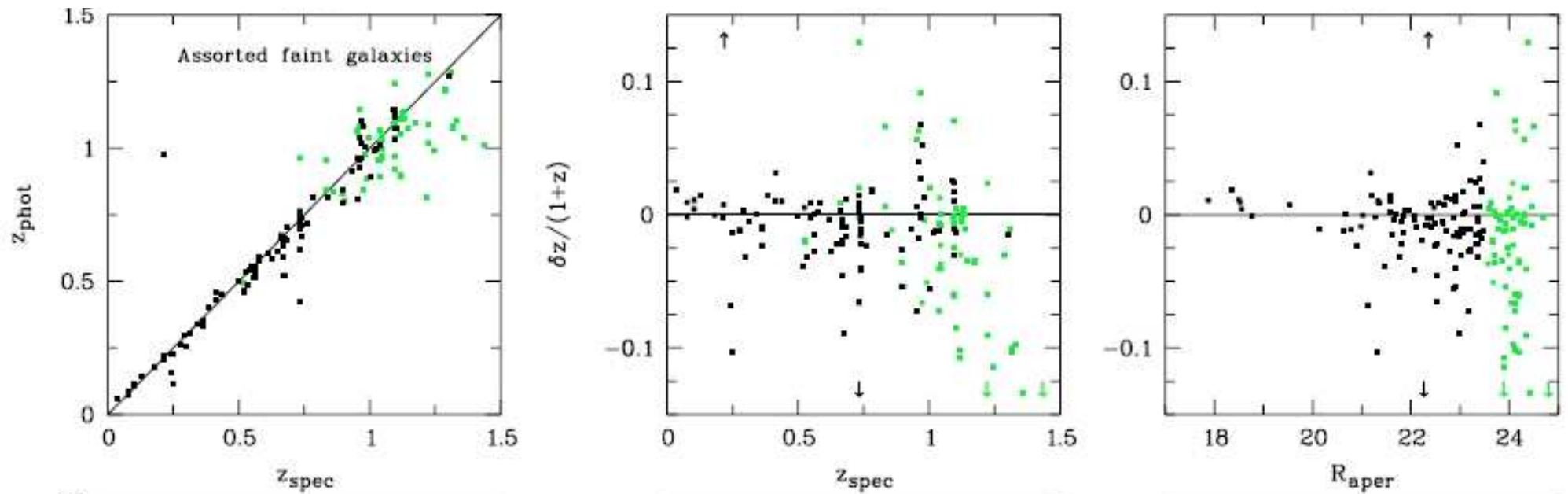
Four Other Examples:



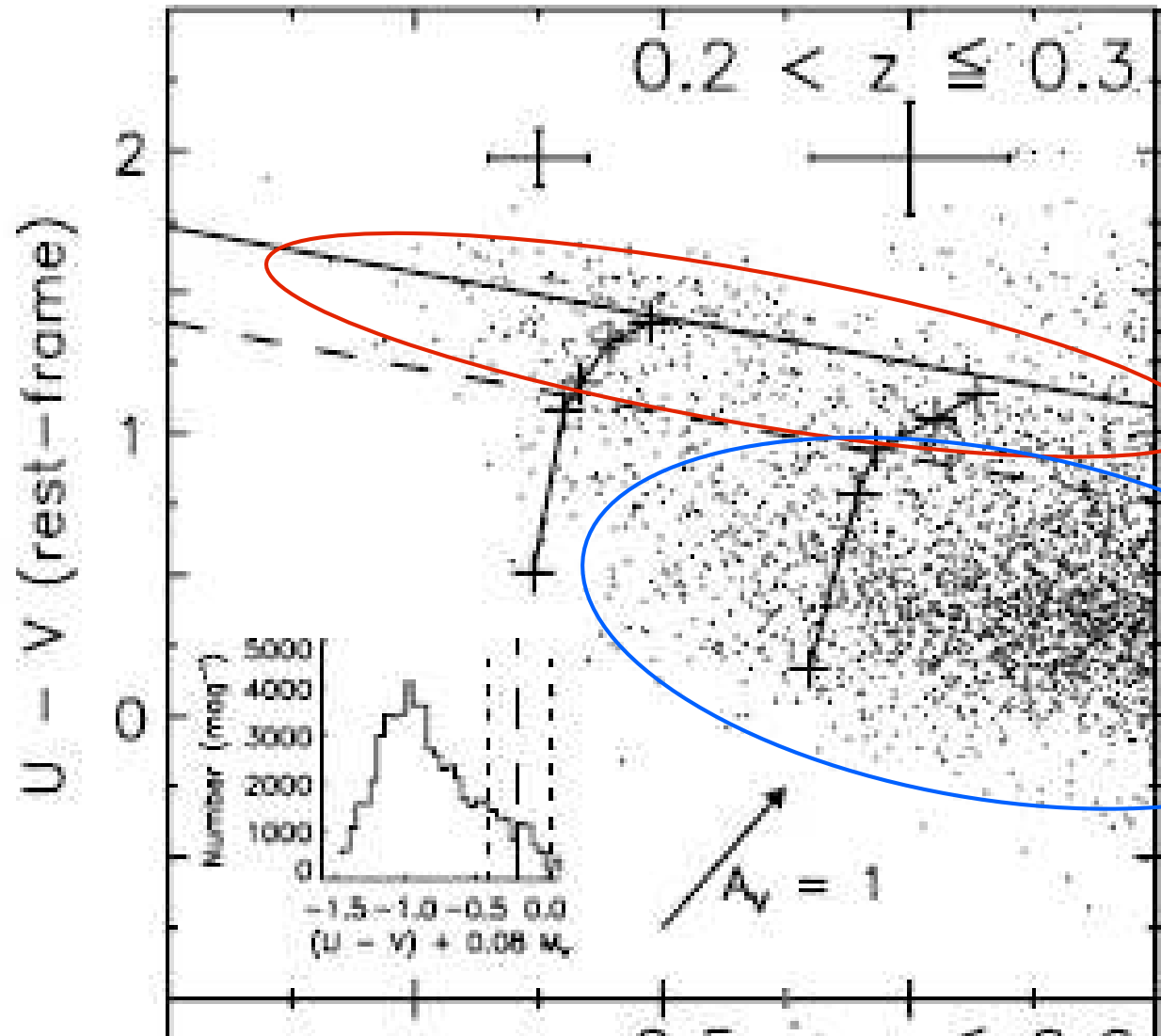
How well do the redshift estimates we derive from the flux measurements in the different passbands compare with spectroscopic redshifts?



How well do the redshift estimates we derive from the flux measurements in the different passbands compare with spectroscopic redshifts?

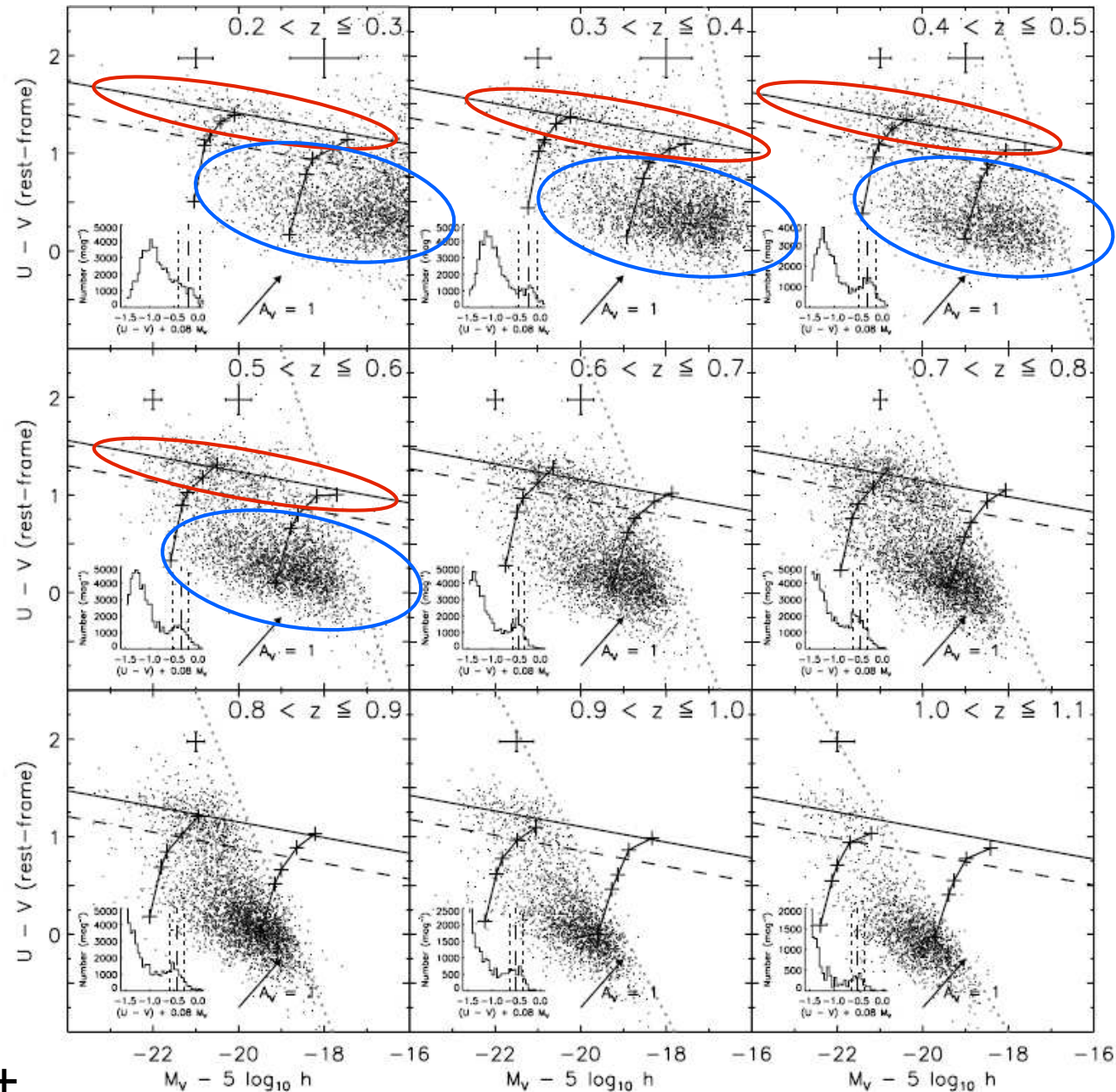


What does the color-luminosity diagram look for galaxies in different redshift slices?



Clear evidence for
“red sequence”
and blue cloud

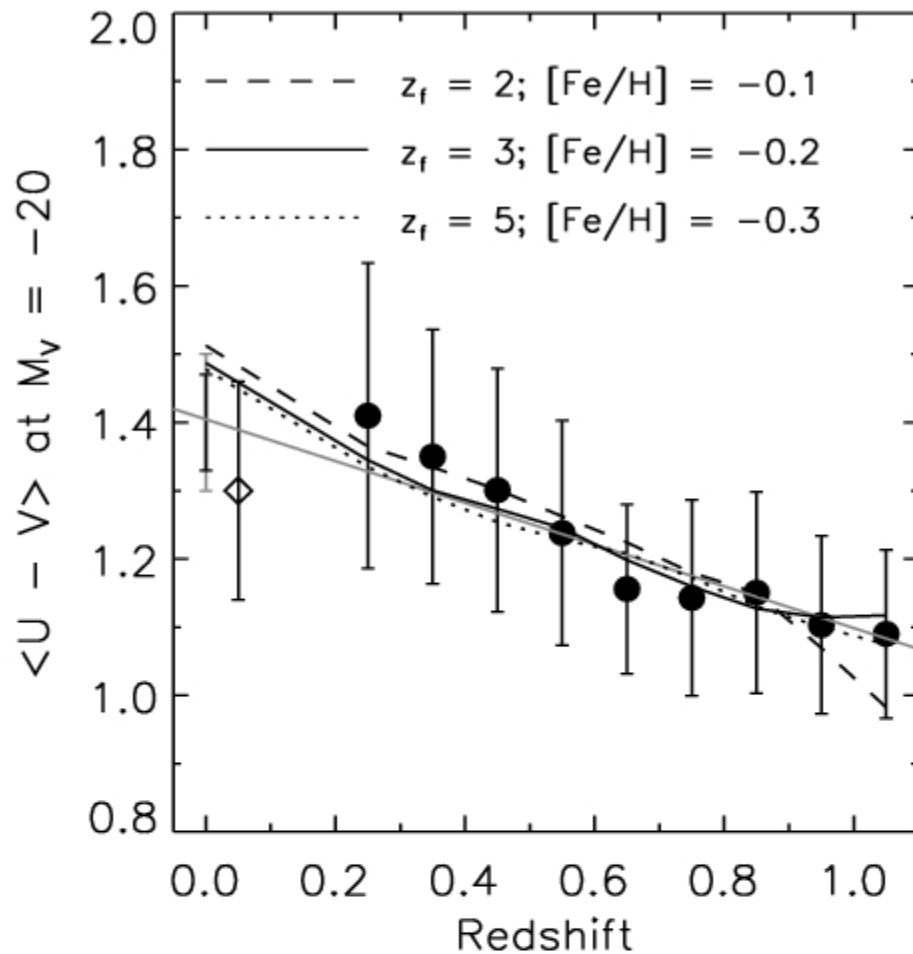
What does the color-luminosity diagram look for galaxies in different redshift slices?



Clear evidence for “red sequence” and blue cloud

Bell+

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

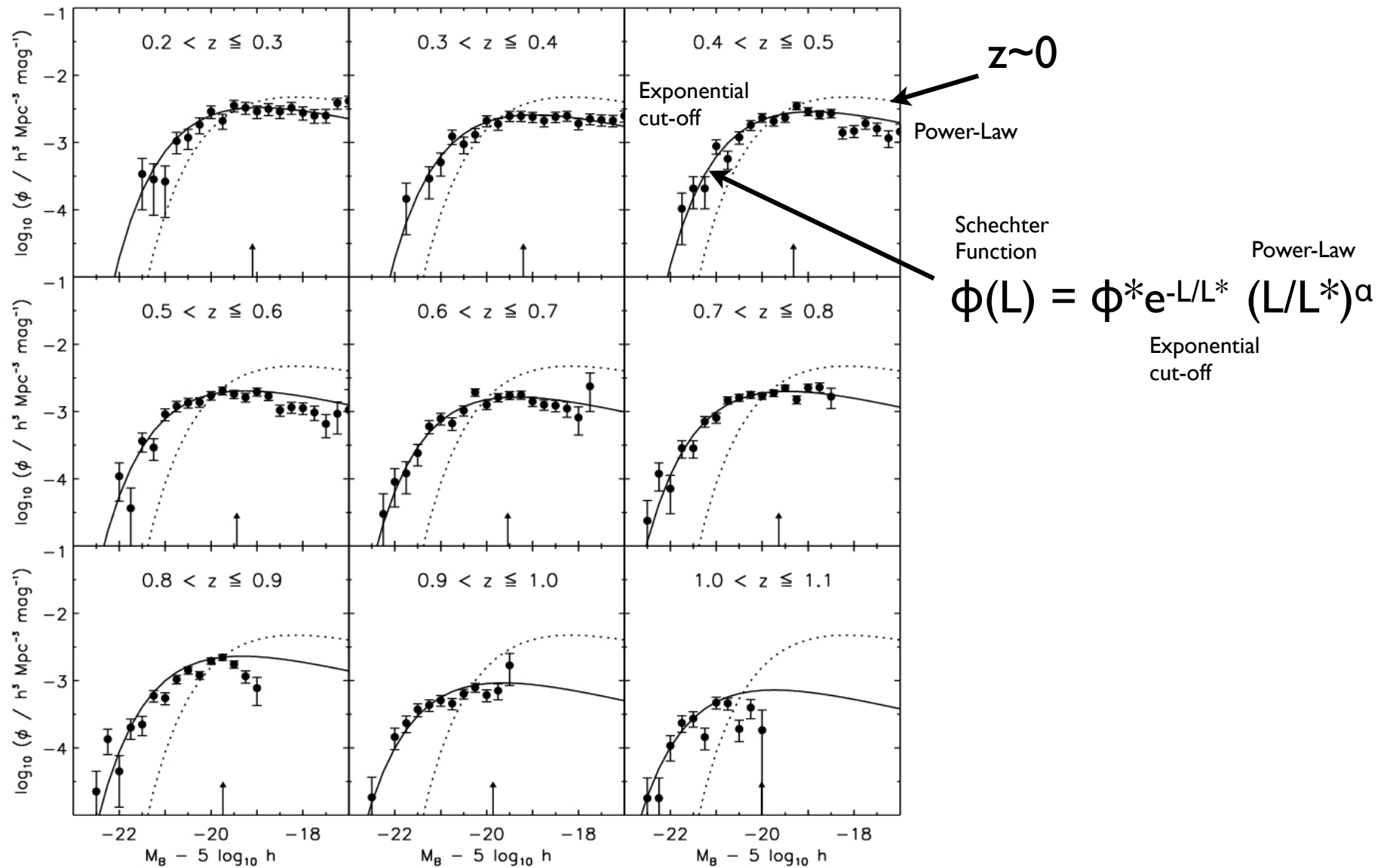


“Red sequence” galaxies are becoming bluer, as one moves to higher redshift.

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.

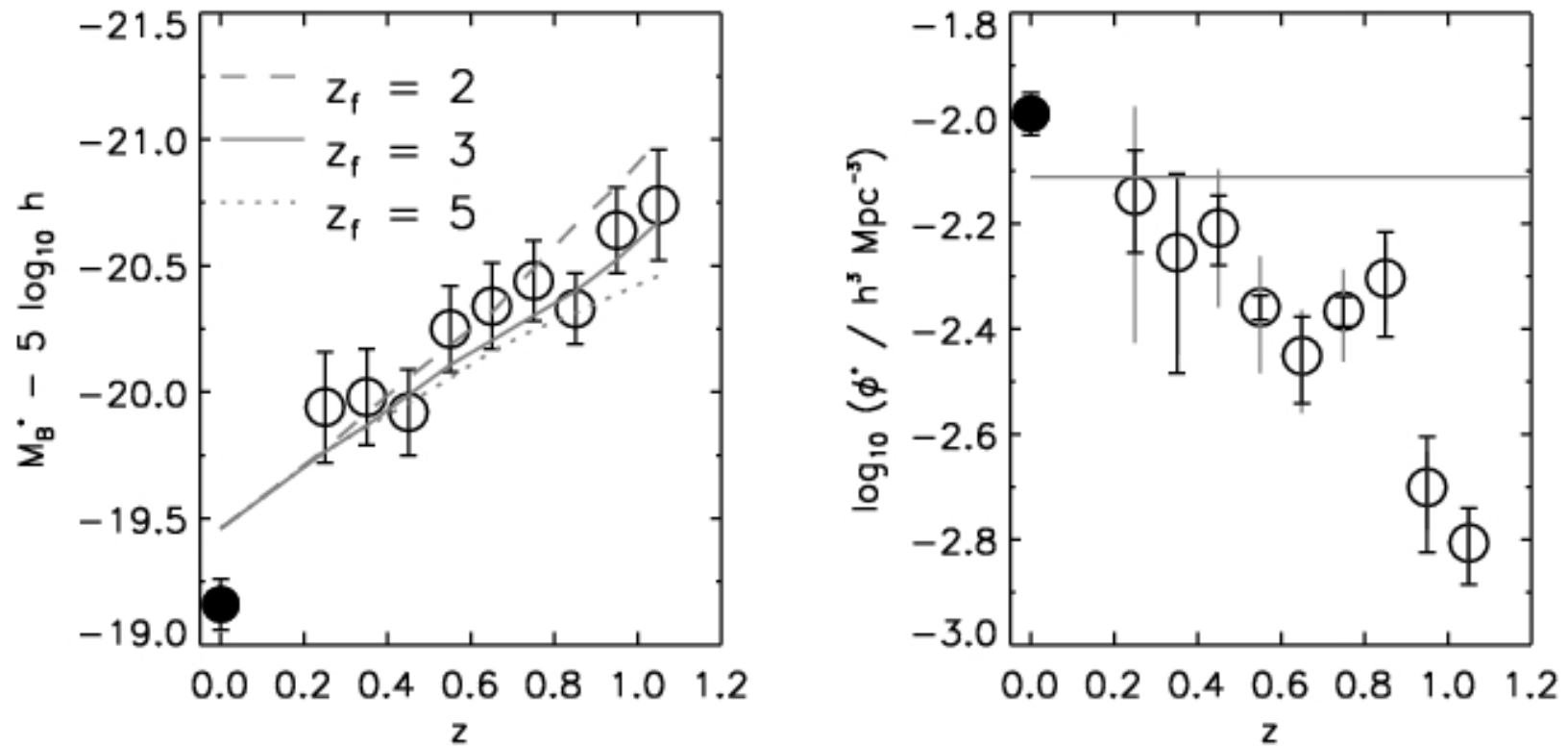
How does the abundance and luminosity of red sequence galaxies change with redshift (as seen from their luminosity function)?



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?



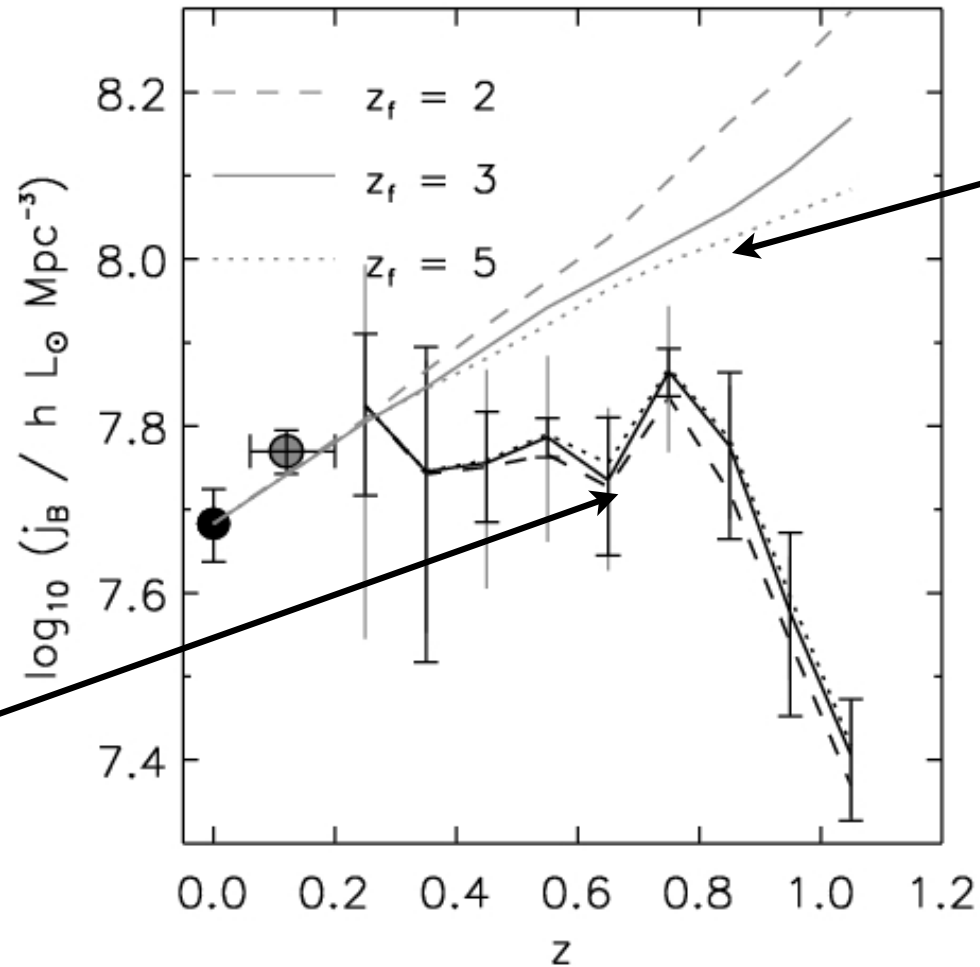
How would you interpret these trends?

How does the total luminosity in “red sequence” galaxies per unit volume change with redshift?

Luminosity in red galaxies per unit volume

(derived by integrating luminosity function)

Observations



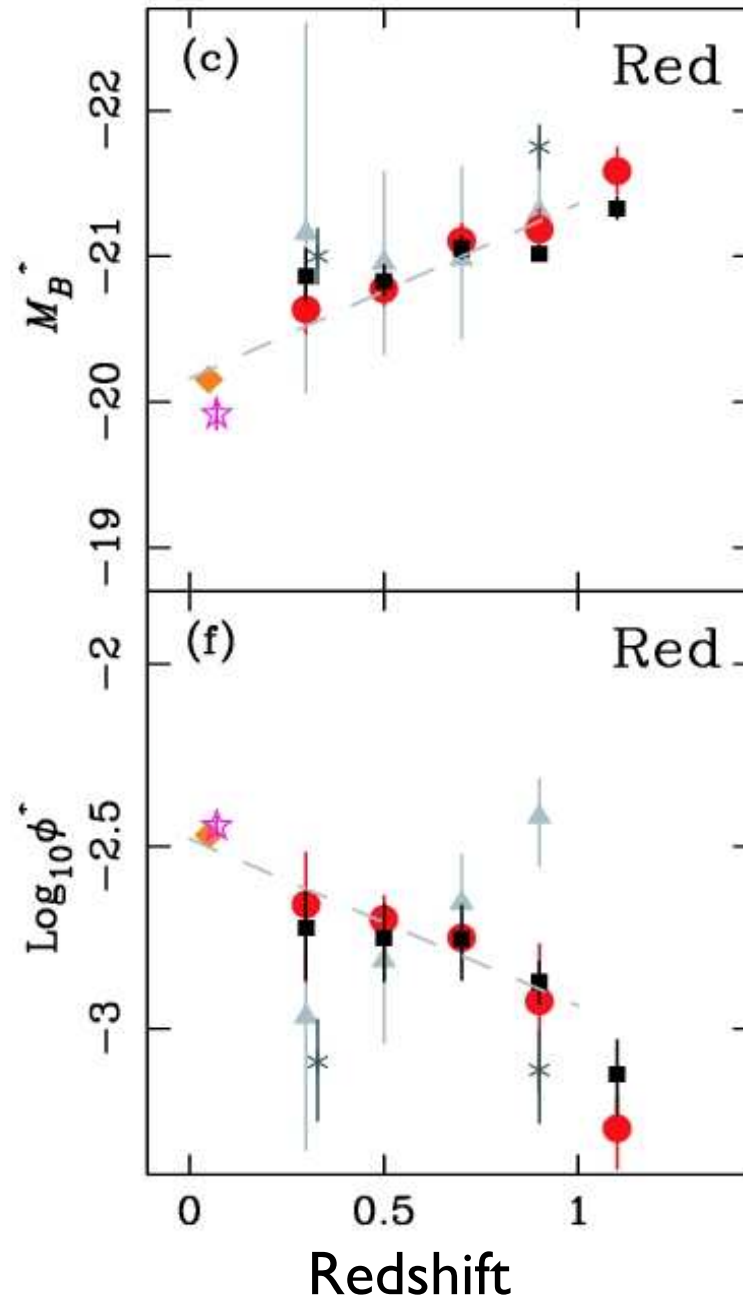
Predictions of instantaneous burst models where all the stars in red sequence galaxies form at some time (redshift) in the past

(from COMBO-17 analysis: Bell et al.)

How does the luminosity function of red galaxies evolve with redshift?

Exponential cut-off
luminosity at bright
end of luminosity
function

Volume density of
galaxies at bright
end of luminosity
function

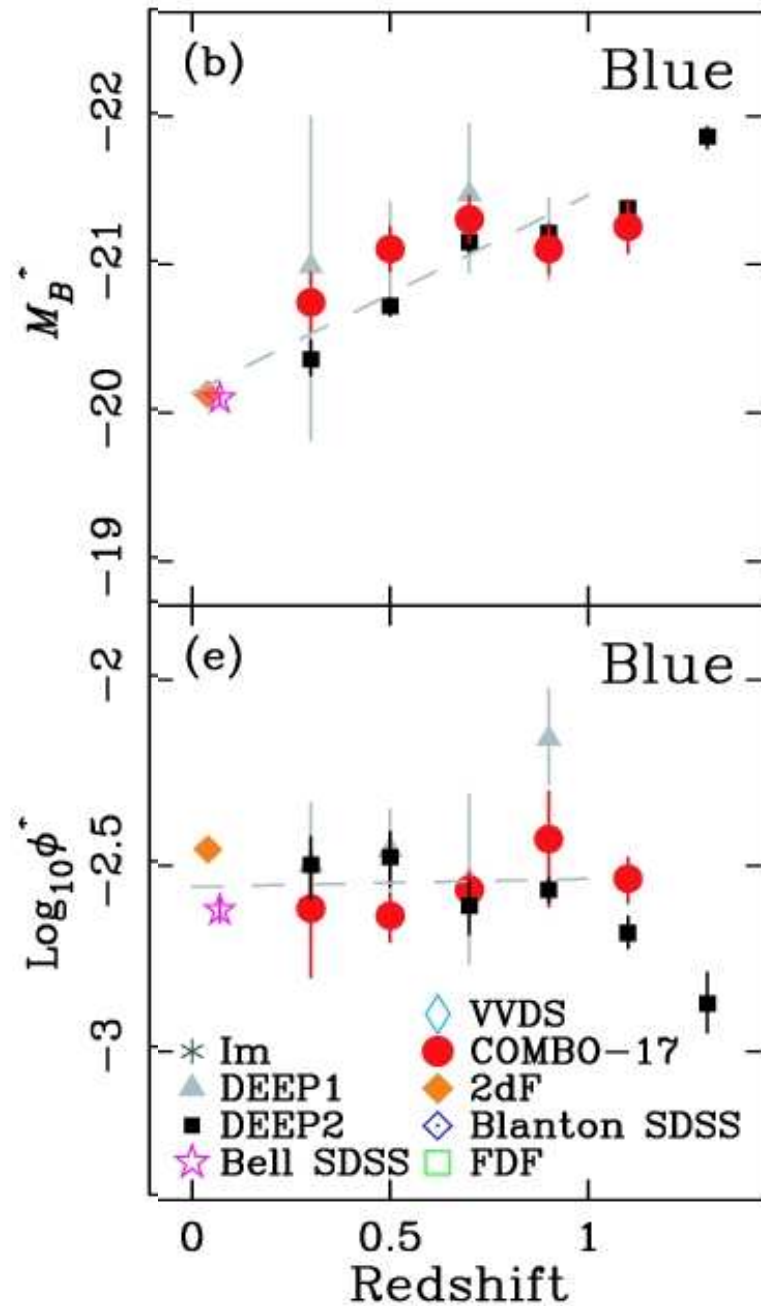


(DEEP 2 Results: Faber+)

How does the luminosity function of blue galaxies evolve with redshift?

Exponential cut-off luminosity at bright end of luminosity function

Volume density of galaxies at bright end of luminosity function

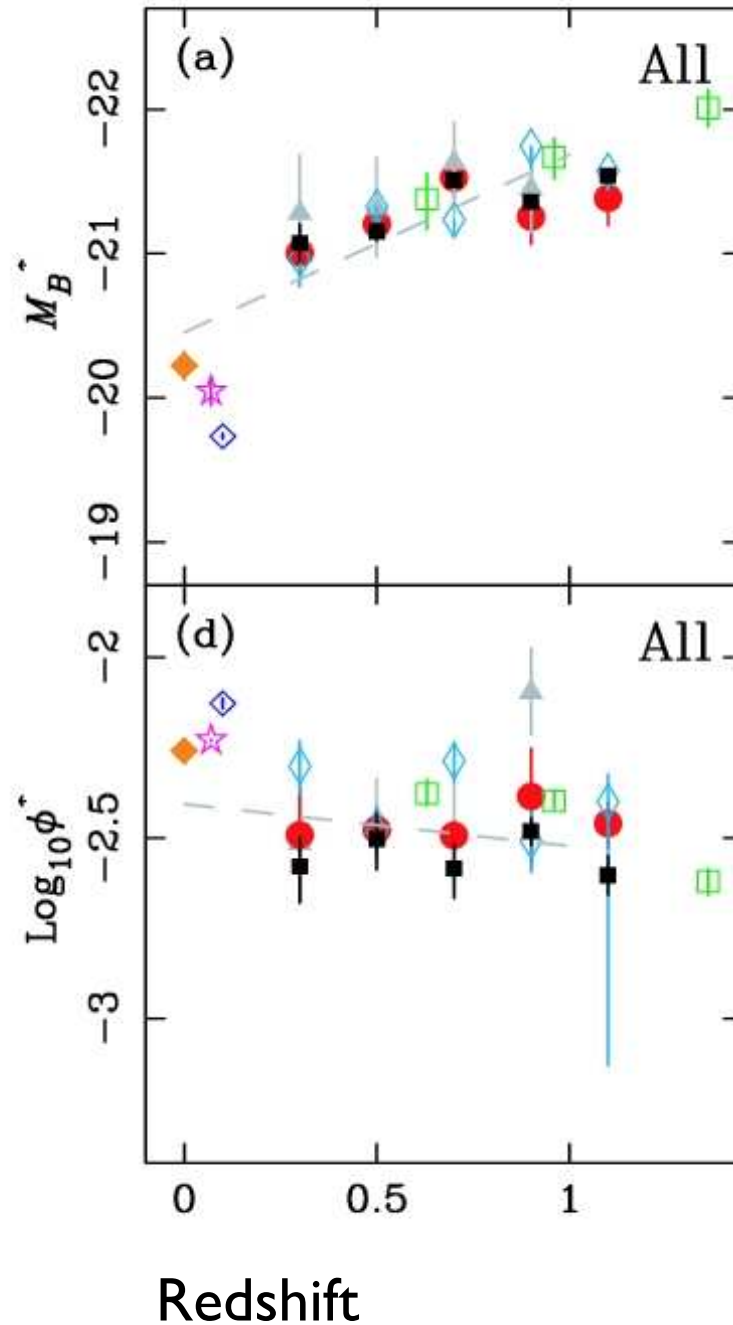


(DEEP 2 Results: Faber+)

How does the luminosity function of all galaxies evolve with redshift?

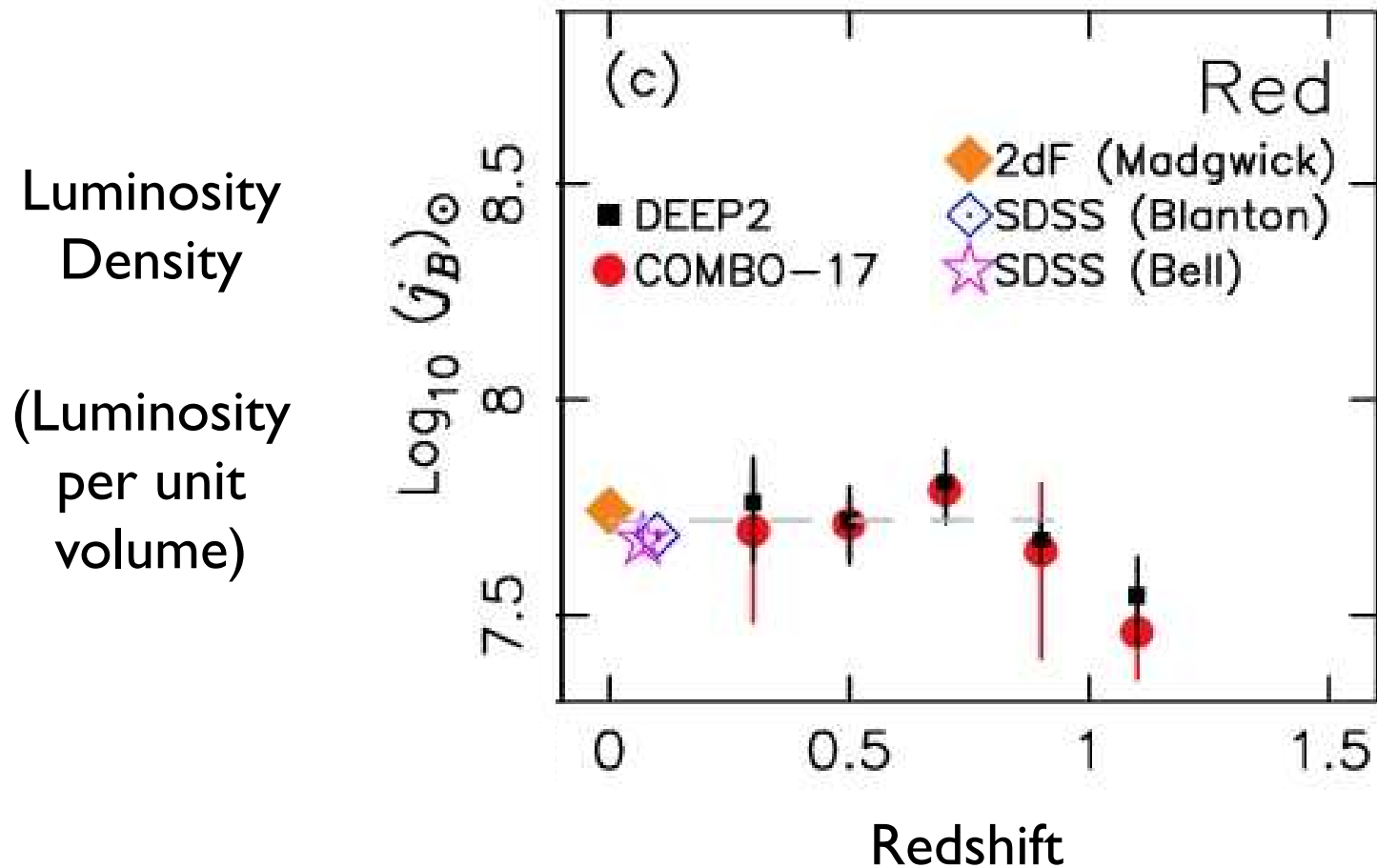
Exponential cut-off
luminosity at bright
end of luminosity
function

Volume density of
galaxies at bright
end of luminosity
function



(DEEP 2 Results: Faber+)

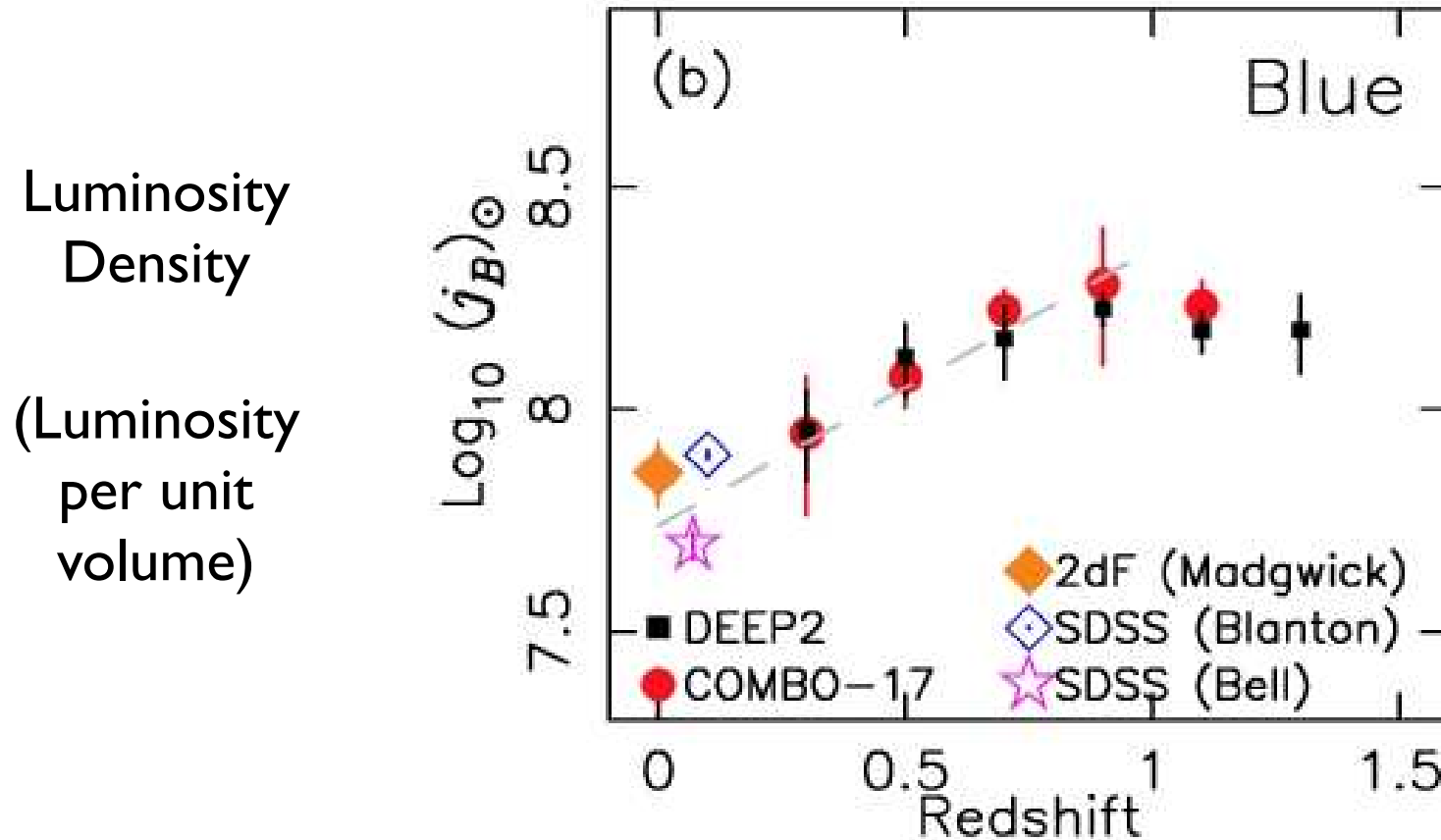
Faber et al. combined the results of Bell et al. with the DEEP2 results. They split galaxies into red and blue galaxies.



The luminosity density of the red galaxies is constant, but may fall at the earliest times. From stellar evolution, one would expect it to rise.

(DEEP 2 Results: Faber+)

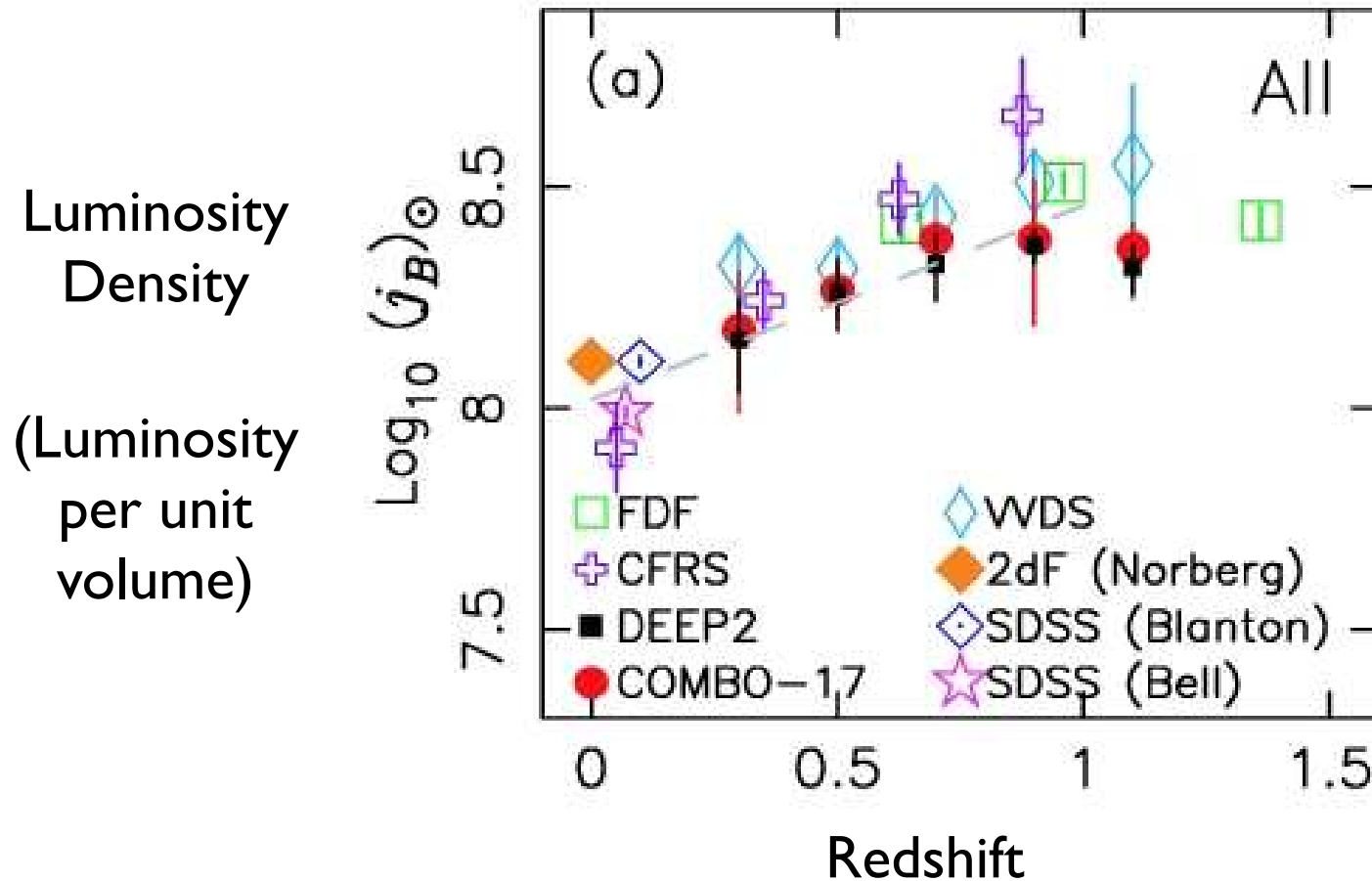
Faber et al. combined the results of Bell et al. with the DEEP2 results. They split galaxies into red and blue galaxies.



The luminosity density of the blue galaxies also increases towards earlier times. Galaxies were forming stars faster in the past.

(DEEP 2 Results: Faber+)

Faber et al. combined the results of Bell et al. with the DEEP2 results. They split galaxies into red and blue galaxies.

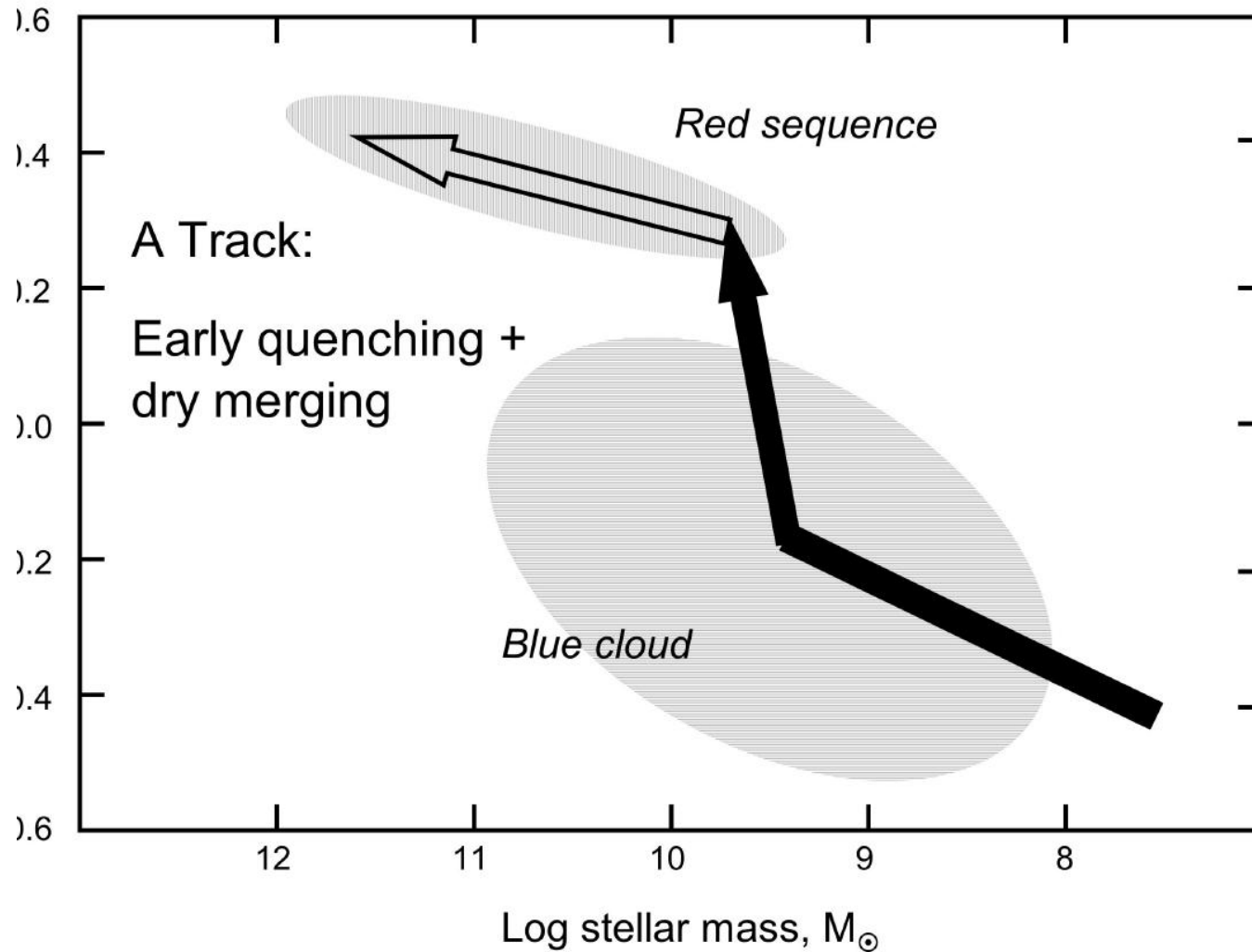


The luminosity density in all galaxies increases, as one goes back in time.

(DEEP 2 Results: Faber+)

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 importance 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)

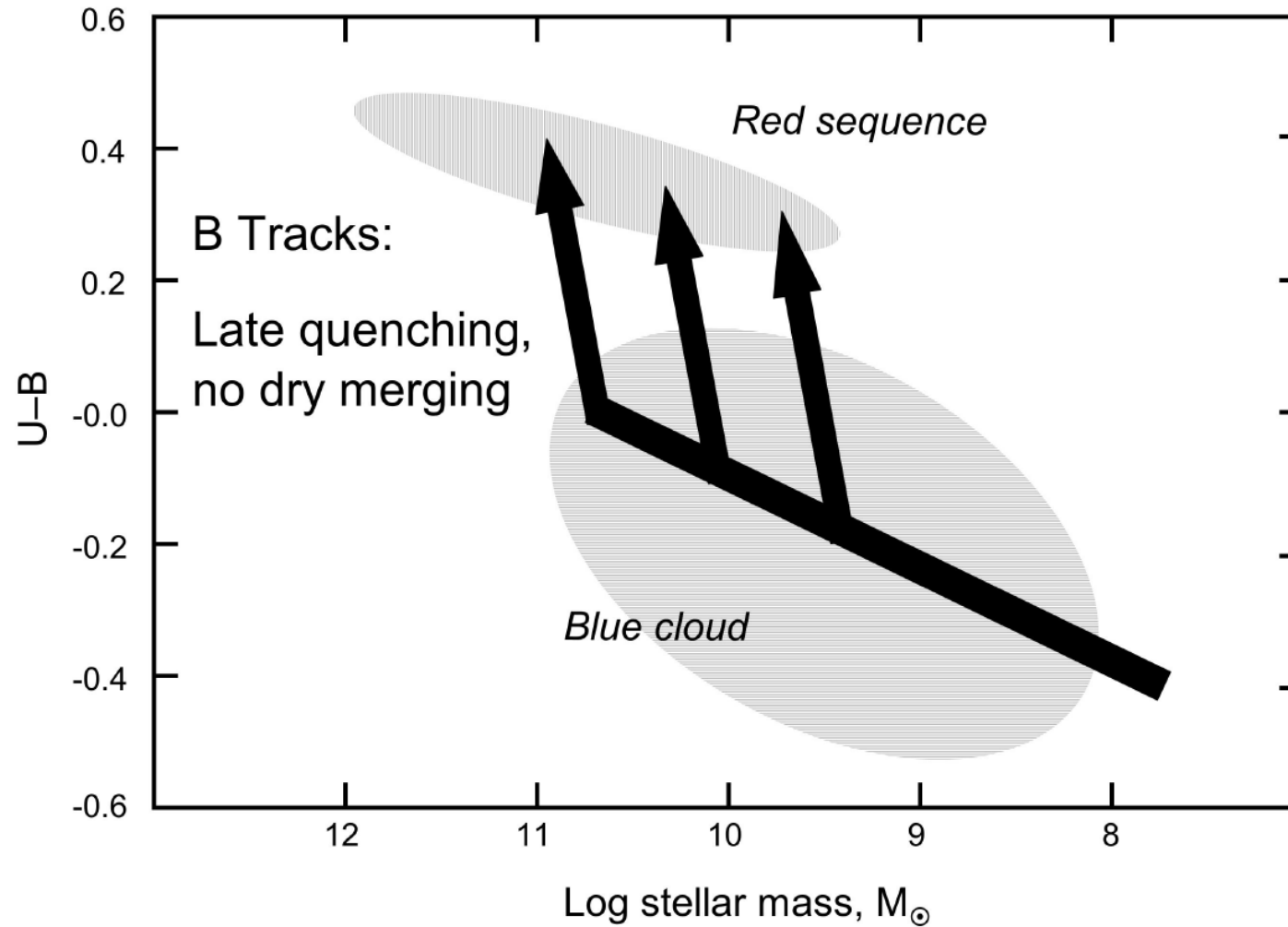
Galaxy
(without gas)



Galaxy
(without gas)

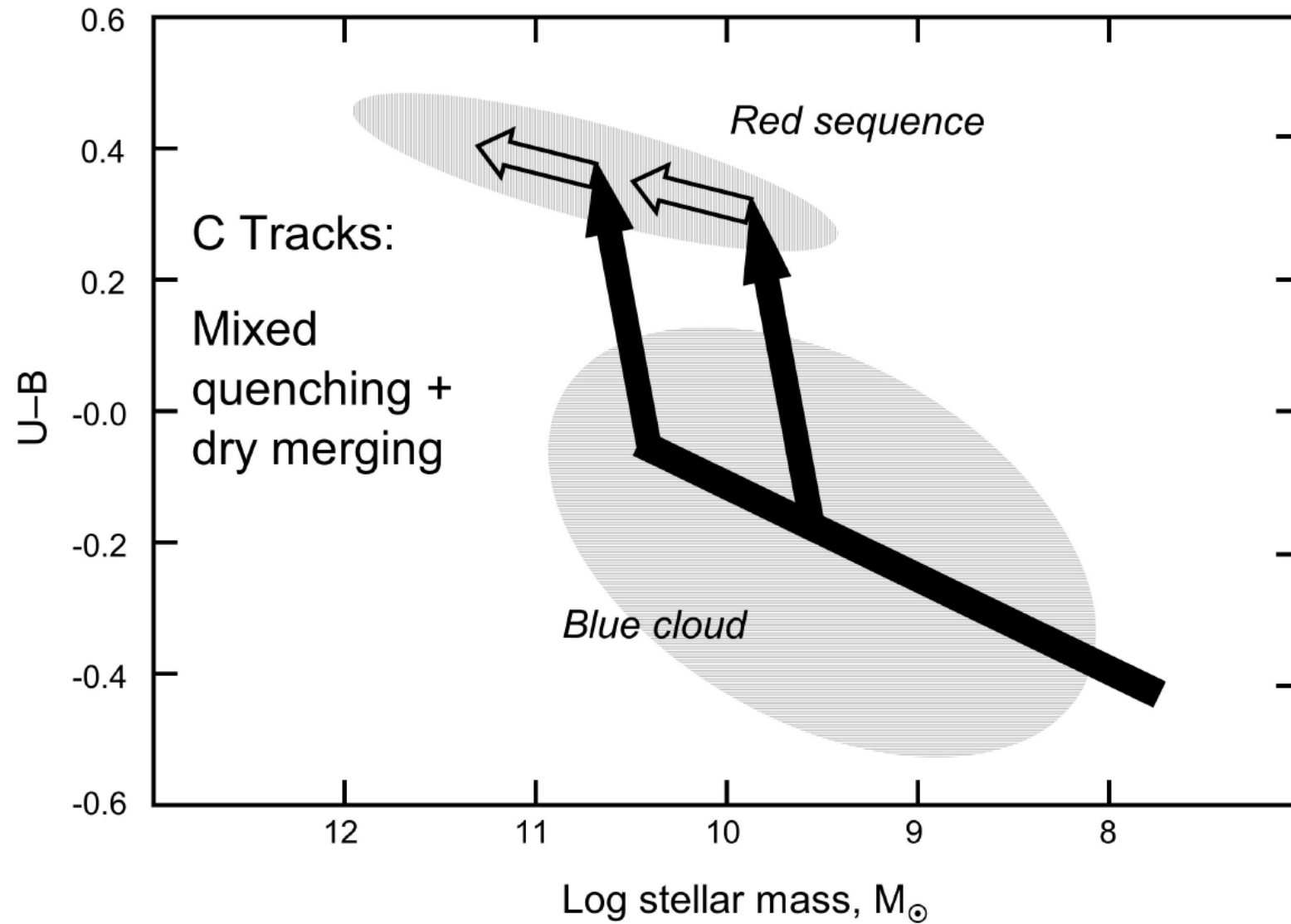
How might galaxies move from the blue cloud to red sequence?

There are many possibilities!



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

There are many possibilities!



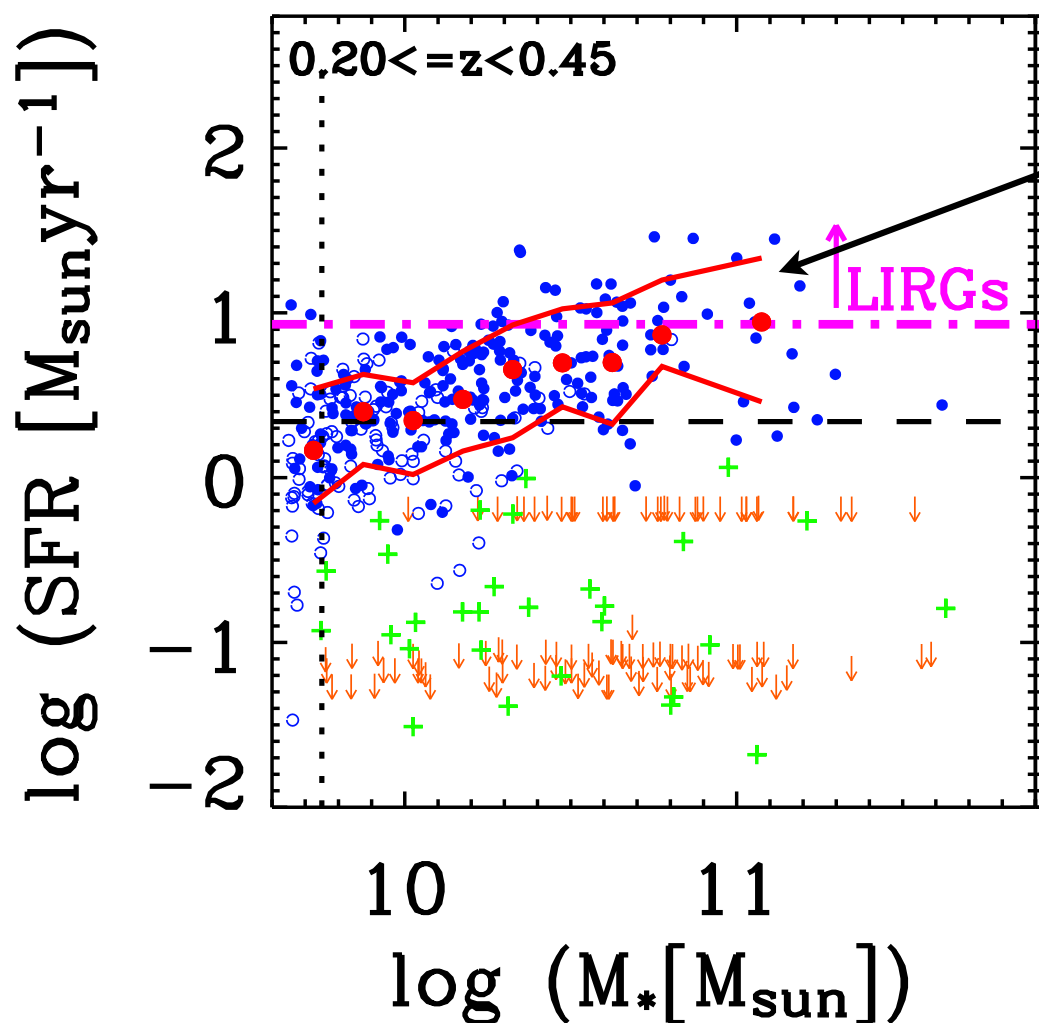
Besides this movement of galaxies from the blue cloud to the red sequence, how does star formation proceed on the blue cloud?

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

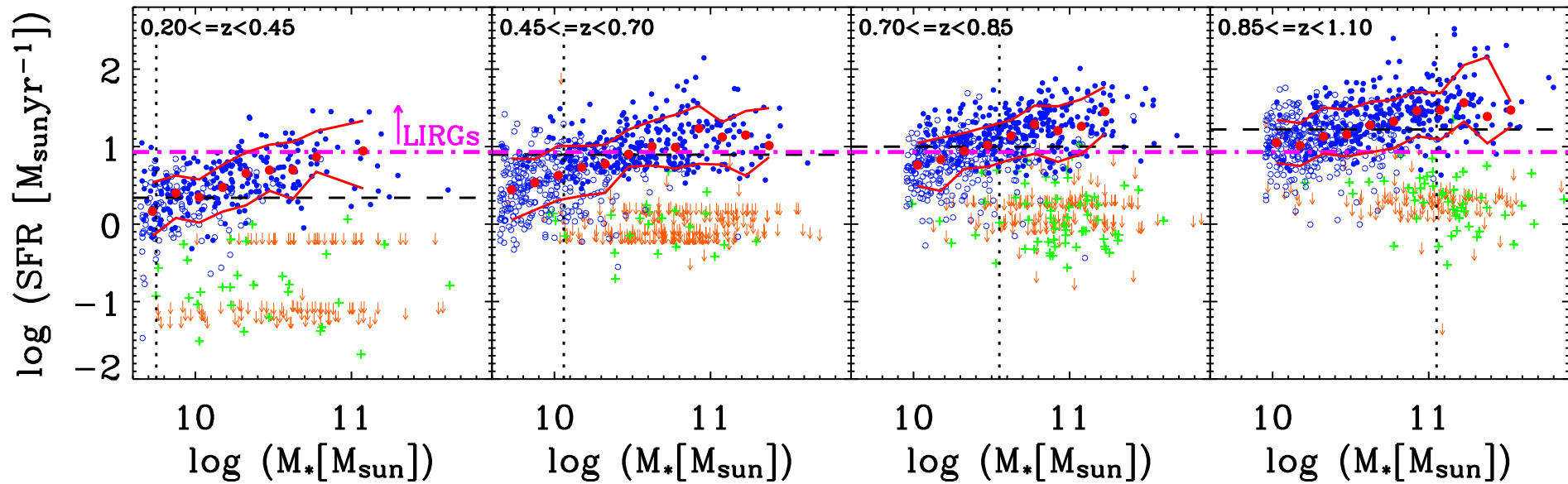
Suggests that SFR is proportion to stellar mass

called "main sequence of star formation" for galaxies

Implies exponential growth of galaxies

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...

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?

I. Using the H α 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 H α emission. One challenge is that dust extinction can attenuate the H α emission in galaxies and requires correction. Fortunately, one can use H β emission from galaxies to estimate this extinction, since the ratio of fluxes in H α to H β is almost the same under a variety of conditions. After correction for dust extinction, one can directly estimate the dust extinction from H α fluxes.

Deriving the Star Formation Rate in Distant Galaxies

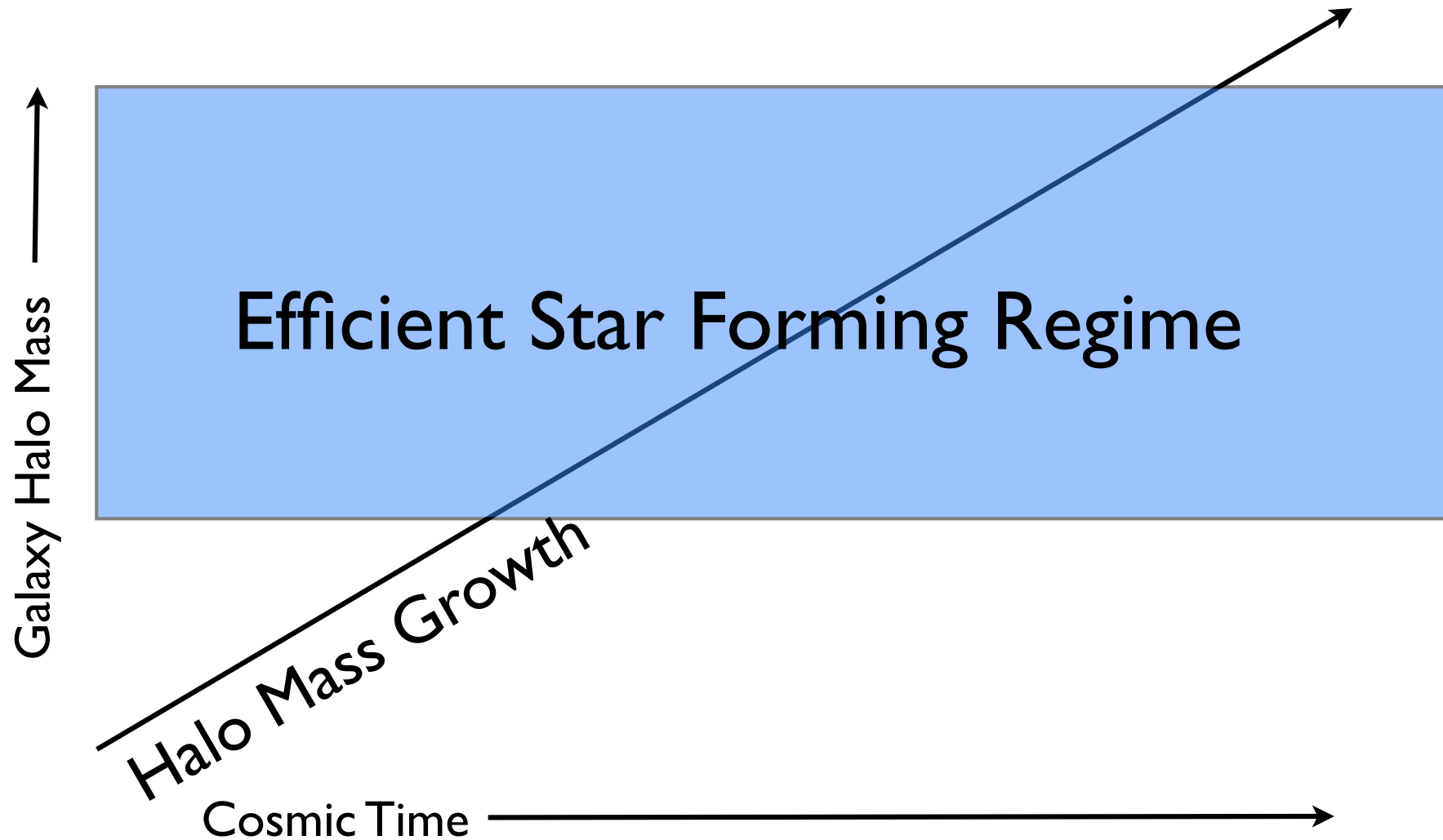
2. Using the UV light Hot O and B stars in galaxies produce a lot of UV light in general. One can use this UV light to estimate the star formation rate in distant galaxies. However, dust extinction can be a key challenge, as even a small amount of dust extinction can attenuate most of the UV light.
3. 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

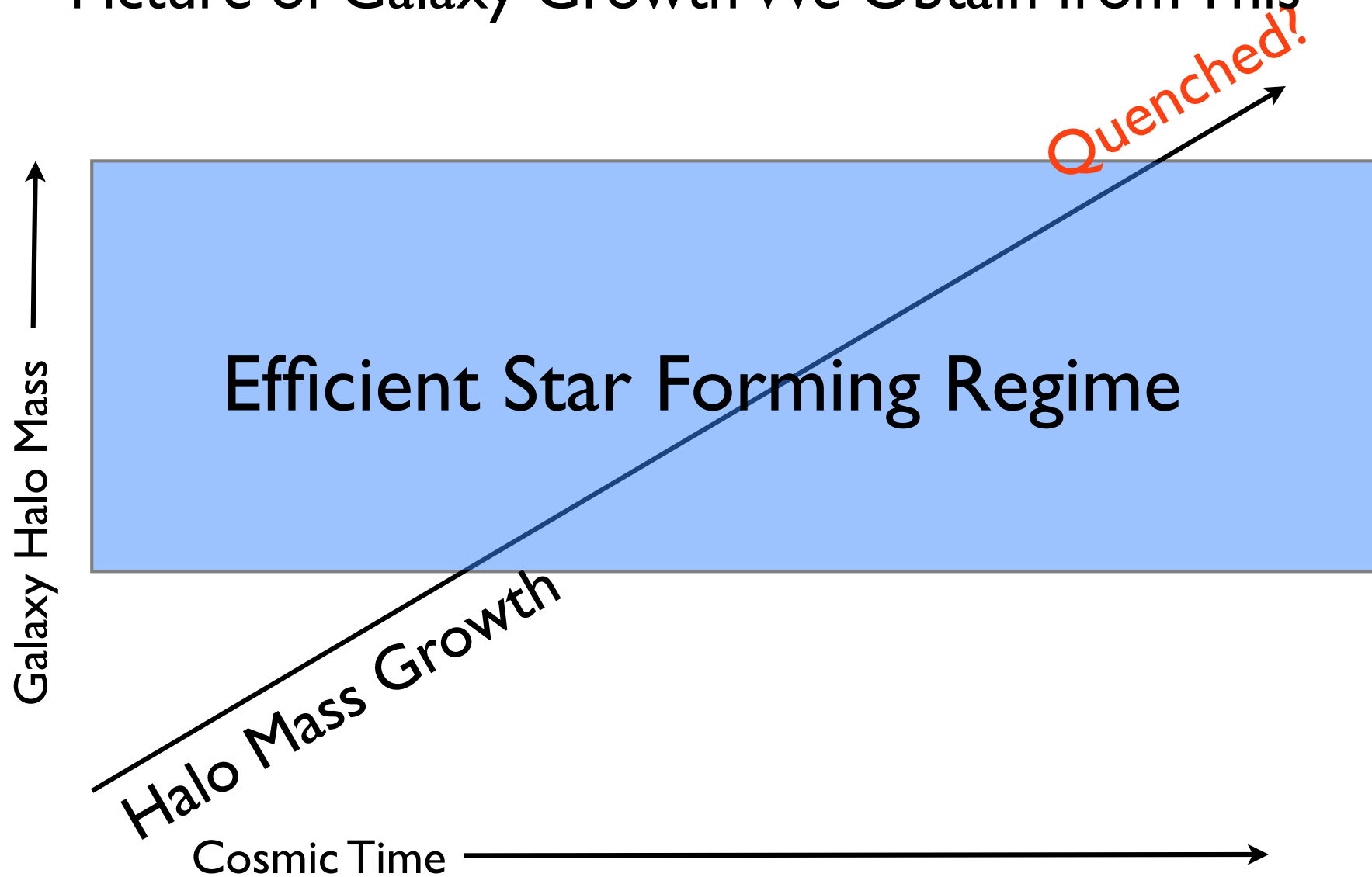
4. Using the radio emission. Synchrotron emission from electrons in supernovae explosions produce significant radio emission in star forming galaxies. Since supernovae explosions are proportional to the star-formation rate, one can use light in the radio as a probe of the star formation rate. The correlation 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 byproduct 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



Picture of Galaxy Growth We Obtain from This



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.

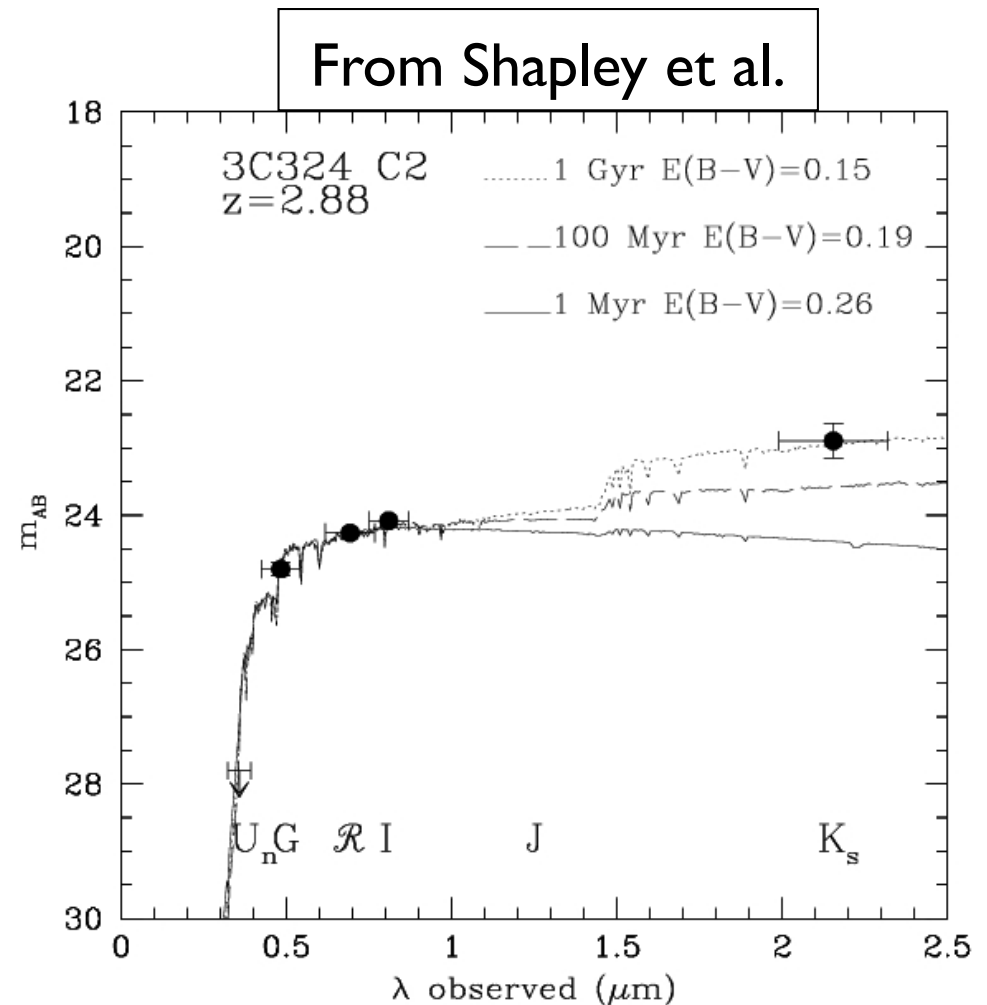
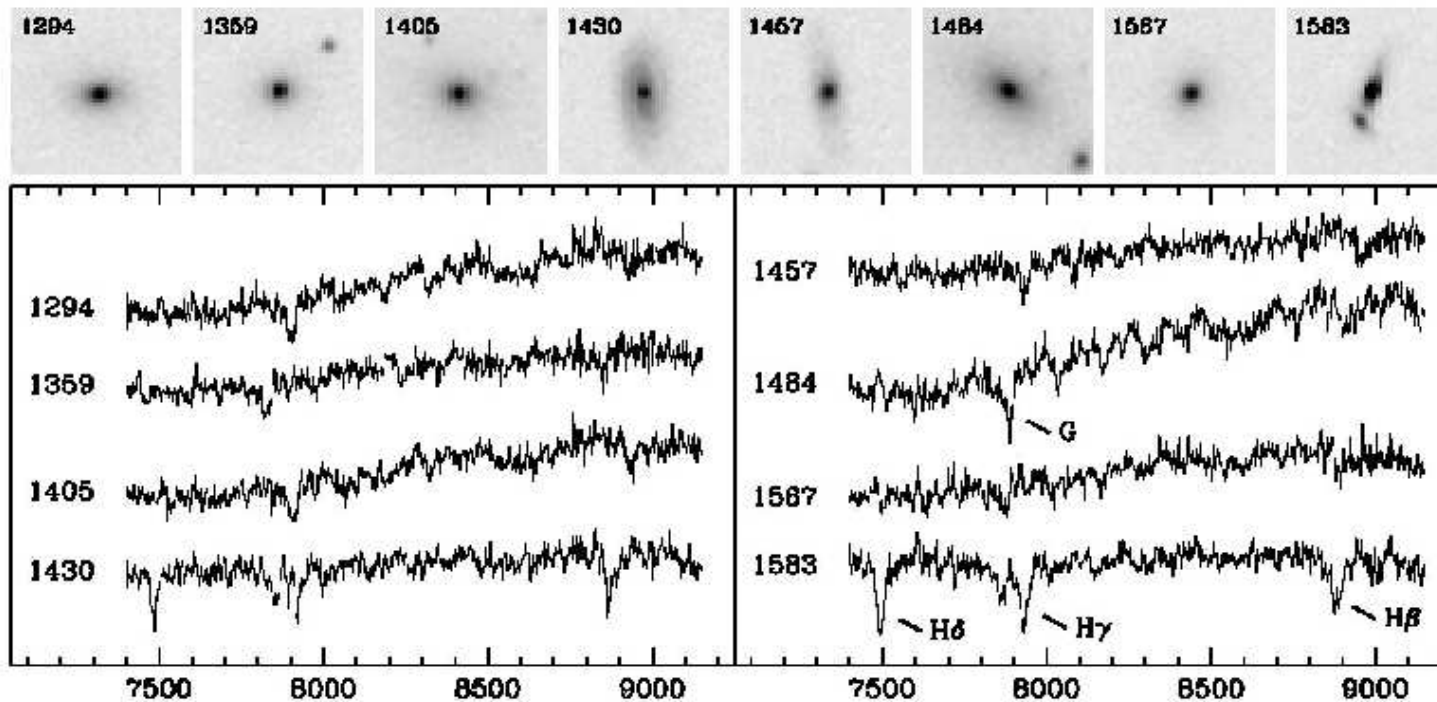


FIG. 6.—Age-dust degeneracy. The points indicate the observed SED of 3C 324-C2, an LBG at $z = 2.880$. Shown with the points are BC96 constant star formation models of different ages, modified by the amount of dust extinction required to reproduce the observed $G-R$ color. The dotted line is a 1 Gyr 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 $R-K_s$ 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.

Fitting 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

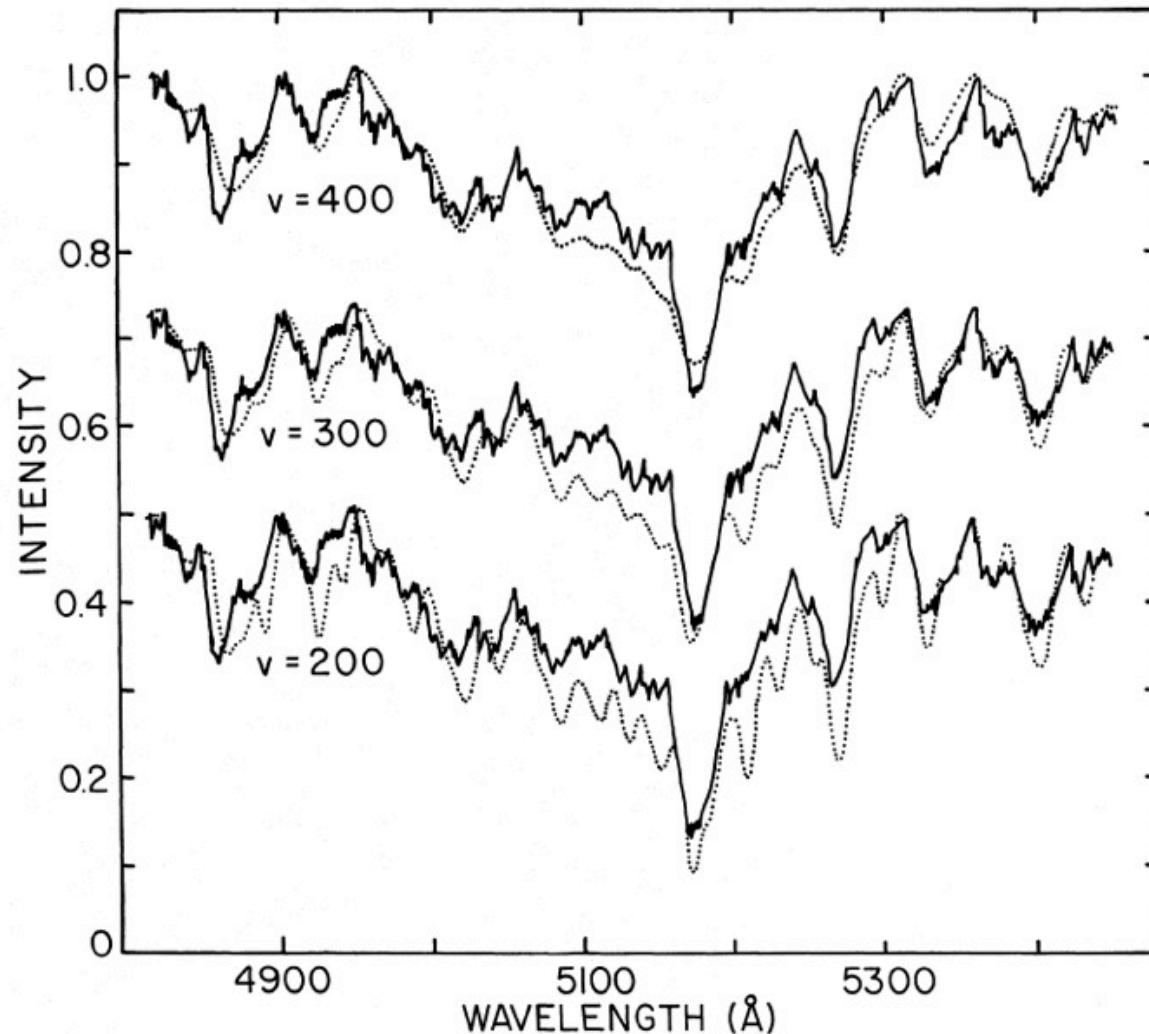


FIG. 3.—NGC 4472 compared with standard star HR 1805 (K3 III), broadened by various line-of-sight velocities (*dotted line*)

We noted that red sequence galaxies appear to evolve by passive evolution...

Can we gain more insight into these galaxies by looking at their dynamics?

Where are these galaxies on the fundamental plane relative to galaxies in the nearby universe?

