Galaxies: Structure, Dynamics, and Evolution

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

Sep 9: Review: Galaxies and Cosmology
Sep 16: No Class — Science Day
Sep 23: Review: Disk Galaxies and Galaxy Formation Basics
Sep 30: Disk Galaxies (II)
Oct 7: Disk Galaxies (III)
Oct 14: No Class
Oct 28: Elliptical Galaxies (I)
Nov 4: Elliptical Galaxies (II)
Nov 11: Elliptical Galaxies (III) / Dark Matter Halos
Nov 18: Dark Matter Halos / Large Scale Structure
Nov 25: Analysis of Galaxy Stellar Populations
Dec 2: Lessons from Large Galaxy Samples at z<0.2
Dec 9: Evolution of Galaxies with Redshift
Dec 16: Galaxy Evolution at z>1.5 / Review for Final Exam
Jan 13: Final Exam
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?
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\(\delta\) line and the magnitude of the 4000 Angstrom break \(D_n(4000)\).

\[ H\delta \text{ line} \]

H\(\delta\) line emission; \(D_n(4000)\) small

H\(\delta\) line absorption; \(D_n(4000)\) large

\[ Dn(4000) \text{ break measured by comparing these two spectral regions} \]

Almost no 4000 Angstrom break

Measurable 4000 Angstrom break

Two features that were used extensively were the H\(\delta\) line and the magnitude of the 4000 Angstrom break \(D_n(4000)\).
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 $3 \times 10^{10} M_{\odot}$

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

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

Figure 1. Conditional density distributions showing trends in the stellar age indicators $D_n(4000)$ and $H\delta_4$ 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.
The structural properties of galaxies also depend on their mass.

\[ \mu^* = \text{surface density of stars} = \frac{M^*}{\text{radius}^2} \]

"concentration of light"

\[ \frac{R90}{R50} = \text{radius containing 90\% of light} / \text{radius containing 50\% of light} \]

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 \( \mu^* \), \( \mu_{1/2} \), 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 \(\text{H}\delta\)) and Structural Properties (\(\mu^*\) 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 \(\text{H}\delta\) as functions of the logarithm of the surface mass density \(\mu_\star\) and of the concentration index \(C\).
Galaxies exist in one of two states: ALIVE and star-forming (fueled by cold gas) or 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 $\mu_*$, and concentration parameters $C = R_{90}/R_{50}$ we looked at before:

![Graphs showing $D_n(4000)$ vs. log $M_*$ and b=SFR/$M_*$ vs. log $M_*$ for different density environments.]

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.

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 $\mu_*$ (left) and $C$ (right).
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
NOW new material for this week
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 $10^4 \times$ longer to reach the same signal to noise as galaxy in local universe.

but current telescopes 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 samples than $10^6$ galaxies

2) Estimate redshifts and other properties from the photometry

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 with Spitzer
- $24, 70, 160$ microns
- $70, 100, 160$ microns with Herschel
- $250, 350, 500$ microns
- plus radio, x-ray, UV from GALEX

Not all bands are necessary of course
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:

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 \( \mathrm{O}[II] \)-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 \( dV/dzd\omega \) (where \( \omega \) is solid angle) strongly depends on the input cosmological parameters, notably \( \Omega_m \) and \( \Omega_\Lambda \). 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\textsuperscript{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 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.

Filters used by COMBO-17:

Fig. 1. COMBO-17 filter set: total system efficiencies in the Wavelengtharmacy 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?

The resulting color magnitude diagram looks like this. Very good!

The interesting thing is that the red sequence looks just as prominent in the COMBO-17 data as in the DEEP 2 data. Notice that COMBO-17 has more galaxies - 25,000.
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
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)?

This figure shows how the colors of the galaxies evolve with redshift. The evolution one expects from the models depends in a simple way on the formation redshift. This is simply due to the fact that the color evolution is a simple power-law with time 
\[ \text{color} = \text{constant} \times \log(t) \]. Hence, if the galaxies formed at higher redshift, they evolve slower. The slow evolution suggests that the galaxies formed early \((z > 2)\).

\[ z \sim 0 \]
Parameterizing the evolution of the luminosity function of “red sequence” galaxies using the Schechter function,

\[ \Phi(L) = \Phi^* e^{-L/L^*} \left( \frac{L}{L^*} \right)^\alpha \]

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 change with redshift?

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

Luminosity in red galaxies per unit volume
(derived by integrating luminosity function)

Observations

(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
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
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
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.

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.
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, and that of the blue galaxies is evolving. It is going down from high redshift to low redshift.

This result is consistent with the Bell et al result. So what happens?

Faber et al. (and in a different paper, Bell et al.) suggest various explanations. One is merging, the other is that blue galaxies stop forming stars at some stage, become red (move up), and then merge (move left). Probably all those processes play a role.

All in all, the results are intriguing, if true: we expect that the luminosity density of the red galaxies goes down with time - but instead, it remains constant; and we expect the luminosity density of blue galaxies to remain constant with time (or to increase); and instead it decreases!

The luminosity density of the blue galaxies also increases towards earlier times. Galaxies were forming stars faster in the past.
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, and that of the blue galaxies is evolving. It is going down from high redshift to low redshift.

This result is consistent with the Bell et al result. So what happens?

Faber et al. (and in a different paper, Bell et al.) suggest various explanations. One is merging, the other is that blue galaxies stop forming stars at some stage, become red (move up), and then merge (move left). Probably all those processes play a role.

All in all, the results are intriguing, if true: we expect that the luminosity density of the red galaxies goes down with time - but instead, it remains constant; and we expect the luminosity density of blue galaxies to remain constant with time (or to increase); and instead it decreases!

The luminosity density in all galaxies increases, as one goes back in time.
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) → **CRASH!** ← Galaxy (with gas)

galaxy evolution

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

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

Galaxy (without gas) → **CRASH!** ← Galaxy (without gas)
How might galaxies move from the blue cloud to red sequence?

There are many possibilities!

B Tracks:
Late quenching, no dry merging

Red sequence

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

There are many possibilities!

C Tracks:
- Mixed quenching
- dry merging
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 H$\alpha$ 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$\alpha$ emission. One challenge is that dust extinction can attenuate the H$\alpha$ emission in galaxies and requires correction. Fortunately, one can use H$\beta$ emission from galaxies to estimate this extinction, since the ratio of fluxes in H$\alpha$ to H$\beta$ is almost the same under a variety of conditions. After correction for dust extinction, one can directly estimate the dust extinction from H$\alpha$ 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.
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

Efficient Star Forming Regime

Halo Mass Growth

Cosmic Time
Efficient Star Forming Regime

Halo Mass Growth

Galaxy Halo Mass

Cosmic Time

Quenched?
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 $z = 2.88$. 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]
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?

\[ \sigma = \text{velocity dispersion} \]
\[ I_e = \text{Surface Brightness} \]
\[ r_e = \text{Size} \]

offset
Let's look at another sample, this time for “red sequence” galaxies outside of clusters:

More difficult than for clusters, since many fewer sources per field on which to obtain spectra

- Small dots: galaxies at $z=0$
- Tiny black dots: galaxies at $z=0.7$
Using the masses derived from velocity dispersion, we can derive mass to light ratios!

Not surprisingly, the measured mass-to-light ratio of galaxies from fundamental plane studies correlates with color.

![Graph showing the correlation between mass-to-light ratio and color.](image-url)
How does the mass-to-light ratio of early-type galaxies evolve with redshift?

Points are from the observations.

Lines give model results assuming the stars in red sequence galaxies all form at the same time.

One again can attempt to determine when the stars in red galaxies form!
This is the result. The massive field galaxies evolve as slowly as cluster galaxies. The lower mass field galaxies maybe not - but this can be a selection effect. All in all, the result from the Fundamental Plane show that the mass-to-light ratios of early-type galaxies evolve quickly with redshift. Hence the fact that the luminosity density of early-types is constant translates directly into the conclusion that the mass density must decrease with increasing redshift