What galaxies do we expect to detect in surveys?
- Luminosity functions
- Observational biases
- Results for the SDSS

What are the fundamental properties that determine a galaxy’s current state and evolutionary history?
- Calculating stellar masses from observations
- Scaling relations
  - Faber-Jackson relation, fundamental plane
  - Tully-Fisher relation
  - Black-hole mass relation

There is a handout today

HW#6 is due on Wednesday (it will take some time)

(Hopefully) Arecibo remote observing Sat Oct 24 at 7:15 pm.
Galaxies and their environments

Next few classes:
- What is the impact of environment on the evolution of galaxies?

What we need to consider:
- What galaxies do we detect in galaxy surveys?
- What do we mean by the “environment” of a galaxy? How can we measure environment?
- How can we distinguish changes in galaxy properties due to interactions with their environment?
- What interactions do we expect to occur? Where/when/how?

- For Wednesday: review Chapter 6 please.
Explaining the universe

• How did the structures we see today form and evolve from the earliest times (CMB) to the galaxies of today?
• Do our cosmological models predict this behavior?
• Can we observe the development of structure over cosmic time?
Large Scale Structure viewed from redshifts

Galaxies are not randomly distributed in space => Galaxies tend to cluster

If one galaxy has comoving coordinate, x, then the probability of finding another galaxy in the vicinity of x is not random. They are Correlated.

Zone of avoidance

Courtesy of Michael Blanton.
Galaxy surveys

The SDSS has created a catalog of 100 million galaxies.

The Sloan Digital Sky Survey has created the most detailed three-dimensional maps of the Universe ever made, with deep multi-color images of one third of the sky, and spectra for more than three million astronomical objects. Learn and explore all phases and surveys—past, present, and future—of the SDSS.
SDSS

- What galaxies does SDSS detect?
  - What galaxies does SDSS **not** detect?

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The Luminosity Function (LF) gives the number density of galaxies of a specific luminosity. We can write it either as a function of $L$ or $M$. In terms of $M$ (absolute magnitude) the total density of galaxies is:

$$\nu = \int_{-\infty}^{\infty} dM \Phi(M). \quad (3.51)$$
The Luminosity Function (LF) gives the number density of galaxies of a specific luminosity. We can write it either as a function of \( L \) or \( M \). In terms of \( M \) (absolute magnitude) the total density of galaxies is:

\[
\nu = \int_{-\infty}^{\infty} dM \, \Phi(M) .
\] (3.51)

In 1980, Schechter showed that the LF of galaxies is well described by a function that combines a power law and an exponential:

\[
\Phi(L) = \left( \frac{\Phi^*}{L^*} \right) \left( \frac{L}{L^*} \right)^\alpha \exp \left( -\frac{L}{L^*} \right) ,
\] (3.52)

- \( \alpha \) = faint end slope
- \( L^* \) = knee (“characteristic”) luminosity, where slope changes
Virgo cluster

Distance is 16.7 Mpc
The LF of Nearby Galaxies

Binggeli+ 1988 ARAA 26, 509

Fig. 3.51 The luminosity function for different Hubble types of field galaxies (top) and galaxies in the Virgo cluster of galaxies (bottom).
The LF of Nearby Galaxies

Binggeli+ 1988 ARAA 26, 509

• The most common type of galaxies in the Virgo cluster are the dEs

• Different morphological classes have different LFs.

• Although the morphological mix varies dramatically from the field to the cluster, the overall LF is remarkably resilient.
SDSS CMD

Fig. 3.7 The density of galaxies in color-magnitude space. The color of ~ 70,000 galaxies with redshifts 0.01 ≤ z ≤ 0.08 from the Sloan Digital Sky Survey is measured by the rest-frame u − r, i.e., after a (small) correction for their redshift was applied. The density contours, which were corrected for selection effects, are logarithmically spaced, with a factor of $\sqrt{2}$ between consecutive contours. (a) The measured distribution is shown. Obviously, two peaks of the galaxy density are clearly visible, one at a red color of $u − r \sim 2.5$ and an absolute magnitude of $M_r \sim −21$, the other at a bluer color of $u − r \sim 1.3$ and significantly fainter magnitudes. (b) Corresponds to the modeled galaxy density, as is described in the text. Reused with permission from I.K. Baldry, M.L. Balogh, R. Bower, K. Glazebrook & R.C. Nichols 2004, Color bimodality: Implications for galaxy evolution, in: THE NEW COSMOLOGY: Conference on Strings and Cosmology, R. Allen (ed.), Conference Proceeding 743, p. 106, Fig. 1 (2004). ©2004, American Institute of Physics
SDSS redshift “cone diagram”

Credit: SDSS
SDSS redshift distribution

- How were spectroscopic targets selected?
- How “deep” is SDSS?
Spaenhauer diagram

- These are the same galaxies used by Team B in HW #3.

- **Malmquist bias**: In a flux-limited sample, luminous galaxies will always be over-represented. The faint galaxies can ONLY be detected in the (small) nearby volume.
SDSS and the “aperture bias”

Spectroscopy as well as photometry!

3” fibers => Beware the aperture bias!

The Luminosity Function (LF) gives the number density of galaxies of a specific luminosity. We can write it either as a function of $L$ or $M$. In terms of $M$ (absolute magnitude), the total density of galaxies is:

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$$

(3.52)

- $\alpha$ = faint end slope
- $L^*$ = knee (“characteristic”) luminosity, where slope changes

• Are there more faint galaxies or luminous ones?
Why do we care about the faint end slope?
Double Schechter fit:

\[ \Phi(L) = \left[ \left( \frac{\Phi^*_1}{L^*_1} \right) \left( \frac{L}{L^*_1} \right)^{\alpha_1} + \left( \frac{\Phi^*_2}{L^*_2} \right) \left( \frac{L}{L^*_2} \right)^{\alpha_2} \right] \times \exp\left(-\frac{L}{L^*}\right) \]  

(3.59)

- In the diagram, “n” is the Sersic index - what does that mean?
- What does the diagram tell you?
From fluxes to stellar masses

- We observe luminosities, especially in optical-NIR bands but what we actually want to know are masses (stellar or stellar+gaseous = baryonic).

- So: what can the luminosities and colors of galaxies tell us about the total mass in stars in the galaxy?
  - Again, we need to understand the
    - (Initial) mass function
    - Star formation history = SFR(t)
  - Then we need to compare the observed spectral energy distribution with models which take into account stellar evolution as well as the star formation history.

- This is best done using spectra, but also (more “cheaply”) from colors.
Deriving stellar masses

O/IR flux (multiple bands) => Convert to stellar mass?

Ingredients/assumptions
• SF law and history
• Stellar population synthesis models
• SED fitting of photometry
  • Need to account for dust/geometry
• M/L - optical color relation
  => Mass estimates

Popular recipes include:
• Bell et al. (2003) ApJS 149, 289
• Kauffmann et al. (2003) MNRAS 341, 33
• Brinchmann et al. (2004)
• Salim et al. (2007) ApJS 173, 267
• Zibetti et al. (2009) MNRAS 400, 1181
• Taylor et al. (2011) MNRAS 418, 1587

“Fitting the SED of Galaxies”: http://www.sedfitting.org
Stellar population synthesis models
Bruzual & Charlot (2003) MNRAS 344, 1000

- **Stellar evolution tracks** from the ZAMS to late stages
  - Need both high mass and low/intermediate mass AGB
  - Treatment of metallicity, stellar mass range, opacity etc not always the same
    e.g. “Padova” group, “Geneva” group

- **Stellar spectral libraries** provide the spectra of individual stars of given T,LC across the HR diagram
  - Need to keep track of wavelength range, resolution etc.
    e.g. BaSeL (91A - 160 μm), STELIB (3200-9500A), Pickles 1150A-2.5μm

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<td>Observational</td>
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<td>BC03</td>
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*The STELIB and Pickles libraries can be extended at shorter and longer wavelengths using the BaSeL library, as described in the text.*
Stellar population synthesis
Bruzual & Charlot 2003, 2011
http://www2.iap.fr/users/charlot/bc2003/galaxev_download.html

Absorption lines:
FUV rise until 13 Gyr caused by low mass post-AGB stars

- 0.1-1 Gyr: strengthening of all Balmer lines (Hα at 656.3 nm to Balmer break at 364.6 nm)
- 0.1-1 Gyr: Balmer break evolved into “4000 Angstrom break” arising from collection of metal lines bluewards of 400 nm in cool stars, sensitive to bursts during past 1-2 Gyr.

=> Bursts produce obvious features

Emission lines: Massive SFR within last few Myrs:

Figure 9. Spectral evolution of the standard SSP model of Section 3 for the solar metallicity. The STELIB/BaSeL 3.1 spectra have been extended blueward of 3200 Å and redward of 9500 Å using the Pickles medium-resolution library. Ages are indicated next to the spectra (in Gyr).
Fig. 2: Optical spectra from both theoretical and empirical stellar libraries (as labelled) demonstrating the improvement of spectral resolution over time with the associated improvement in library size [Courtesy S. Charlot].
Deriving stellar masses

• Assuming stellar mass-to-light ratio based on sampling SED
  • Construct grid from one of PS codes, adopting some IMF
  • Allow SFHs to vary exponentially with time; possibly include random bursts (critical for SF galaxies)
  • Adopt model for internal extinction
  • Adopt model for variation in Z
  • Fit to multiple wavelength bands (e.g. SDSS or SDSS+2MASS or +GALEX etc.)

• Need to have consistency between adopted SFH and stellar mass
  • The history of star formation leads to the buildup of stellar mass
  • Some tension between current estimates of stellar mass and SFH using a standard IMF

• Dust attenuation, metallicity, IMF, bursty SFH are all important complications

• Stellar masses derived for star-forming galaxies are uncertain to about a factor of ~2
• Importance of dust at high redshift
SED fitting: real galaxies

- Need to adopt a molecular cloud-disk-bulge geometry

Fig. 6: Sketch of the geometry assumed within the GRASIL model (Figure 1 from Granato et al. 2000).
Use colors to get stellar mass-to-luminosity ratio

=> Then convert luminosity to stellar mass

Uncertainties of order 0.1 dex
Luminosity and mass functions from SDSS

**Fig. 3.52** *Left panel:* The luminosity function of galaxies, i.e., the number density of galaxies as a function of absolute r-band magnitude. The total luminosity function is shown as the grey histogram, with the smooth curve being a fit with a double-Schechter function (3.59). Also shown are the luminosity function of early-type galaxies, split according to the Sérsic index $n$ into concentrated and less concentrated ones (red and orange histograms, respectively), and late-type galaxies shown in blue. The early-types with $n \leq 2$ are totally subdominant for all $L$, and contribute substantially to the early-type population only for very low luminosities, in agreement with what is seen in Fig. 3.39. *Right panel:* The stellar mass function of galaxies, with the same galaxy populations as in the left-hand panel. The total mass function is again fit with a double-Schechter function. Source: M.R. Blanton & J. Moustakas 2009, Physical Properties and Environments of Nearby Galaxies, ARA&A 47, 159, p. 166, Fig. 3. Reprinted, with permission, from the Annual Review of Astronomy & Astrophysics, Volume 47 ©2009 by Annual Reviews www.annualreviews.org
Galaxy scaling relations

• In the mean, most galaxies follow relations which scale with luminosity, size, surface brightness, dynamical mass, stellar mass, rotational velocity, metallicity etc.

• Understanding the physical basis for the relations is a critical part of our understanding of galaxy formation and evolution.
Scaling relations

• Relations between structure and luminosity have been noticed for a long time

Fig. 3.10 Left panel: effective radius $R_e$ versus absolute magnitude $M_B$; the correlation for normal ellipticals is different from that of dwarfs. Right panel: average surface brightness $\mu_{avg}$ versus $M_B$; with increasing luminosity, the surface brightness of normal ellipticals decreases, while for dwarf ellipticals and spheroidals it increases. Source: R. Bender et al. 1992, *Dynamically hot galaxies. I - Structural properties*, ApJ 399, 462. ©AAS. Reproduced with permission
Galaxy properties from SDSS

- The advent of SDSS allowed studies of huge photometric & spectroscopic datasets
- Find relations between structure (central concentration of light, surface brightness as a function of stellar mass

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 \( \log \mu_s \) or \( C \) and a given value of \( \log M_\odot \). The dotted lines indicate the 10th and 90th percentiles of the distributions.

Kauffmann et al. 2004  MNRAS 353, 713
Measurements of velocity $\Rightarrow$ mass

- $\sigma_0$ is the central velocity dispersion

- Remember the "aperture bias"

- Brighter galaxies are more massive.

Fig. 3.30 The Faber–Jackson relation expresses a relation between the velocity dispersion and the luminosity of elliptical galaxies. It can be derived from the virial theorem. Data from R. Bender et al. 1992, ApJ 399, 462
Elliptical galaxies: The Faber-Jackson Relation

\[ L \propto \sigma_0^4, \text{ or} \]

\[ \log(\sigma_0) = -0.1 M_B + \text{const.} \]

But it is clear that surface brightness/size also plays a role, so taking size into account, yields the fundamental plane:

\[ \log R_e = 0.34 \langle \mu \rangle_e + 1.4 \log \sigma_0 + \text{const.}, \]

\[ (3.30) \]

WHY????
Elliptical galaxies: The Fundamental Plane

\[ \log R_e = 0.34 \langle \mu \rangle_e + 1.4 \log \sigma_0 + \text{const.} \]

**Fig. 3.31** Projections of the fundamental plane onto different two-parameter planes. *Upper left:* the relation between radius and mean surface brightness within the effective radius. *Upper right:* Faber-Jackson relation. *Lower left:* the relation between mean surface brightness and velocity dispersion shows the fundamental plane viewed from above. *Lower right:* the fundamental plane viewed from the side—the linear relation between radius and a combination of surface brightness and velocity dispersion. Source: J. Kormendy & S. Djorgovski 1989, *Surface photometry and the structure of elliptical galaxies*, ARA&A 27, 235, Fig. 2, p. 255. Reprinted, with permission, from the *Annual Review of Astronomy & Astrophysics*, Volume 27 © 1989 by Annual Reviews www.annualreviews.org
Galaxy scaling relations

• In the mean, most galaxies follow relations which scale with luminosity, size, surface brightness, dynamical mass, stellar mass, rotational velocity, metallicity etc.

• Understanding the physical basis for the relations is a critical part of our understanding of galaxy formation and evolution.

Ellipticals:
• **Faber-Jackson relation**: correlation between the masses and luminosities of galaxies, with the sense that more massive galaxies are also the more luminous
• **Kormendy relation**: correlation between the effective radii of galaxies and their surface brightness at that radius.
• The **Fundamental Plane** (FP) is a 3-dimensional plane showing strong correlations between the effective radii, luminosities and velocity dispersions of galaxies. (Also called $D_n - \sigma$ relation)
• **Mass-metallicity Relation**: correlation between the masses (estimated from luminosity) and the average metallicities of stellar populations (which dictate color) in galaxies. The relation implies that larger galaxies are better at retaining the heavy elements produced within them than are low-mass galaxies. (Also called color-magnitude relation)
Tully-Fisher relation

\[ L \propto V^\alpha \]

Similar to scaling reln for Ells

Giovanelli et al. 1997

SCI : cluster Sc sample
24 clusters, 782 galaxies
The Tully-Fisher relation

Circular velocity => \[ V^2 = \frac{GM}{R} \] so that \[ M \sim RV^2 \]

Assume \( M/L \)
\[ M = L \frac{M}{L} \]

Surface brightness \[ \Sigma = \frac{L}{\pi R^2} \] so that \[ R \sim \sqrt{\frac{L}{\Sigma}} \]

\[ RV^2 = L \frac{M}{L} \]

Substituting for \( R \) and then solving for \( R \) gives
\[ L \sim \frac{V^4}{\Sigma (M/L)^2} \]

So, the TF relation with \( \alpha = 4 \) works if:

surface brightness \( \times (M/L)^2 = \text{const.} \)

Why?

- Is it reasonable that either \( \Sigma \sim \text{const}, \) or \( M/L \sim \text{const} \) or \( \Sigma (M/L)^2 \sim \text{const}? \)
The Baryonic Tully-Fisher relation

Since the (observable) baryon content of low mass SF galaxies is dominated by gas not stars, use the baryonic mass in place of $L$ or $M_*$. 

$M_b$ is the total mass in baryons.


line:

$$\log M_b = 4 \log V_f + 1.7$$

(McGaugh 2005)
The Baryonic Tully-Fisher relation

Since the (observable) baryon content of low mass SF galaxies is dominated by gas not stars, use the baryonic mass in place of $L$ or $M_\star$.

McGaugh 2012, reproduced by Bernstein-Cooper et al. 2014

Blue squares: dSphs
Cyan circle: Leo P
Green triangles: gas-rich galaxies
Red circles: star-dominated galaxies
The Black Hole-Host Galaxy relation

- Amazingly, it appears that the mass of a supermassive black hole depends on the mass of the galaxy it resides in.
The Black Hole-Host Galaxy relation

- Amazingly, it appears that the mass of a supermassive black hole depends on the mass of the galaxy it resides in.