Normal Galaxies (Ch. 24)
+ Galaxies and Dark Matter (Ch. 25)

Here we will cover topics in Ch. 24 up to 24.4, but then skip 24.4, 24.5 and proceed to 25.1, 25.2, 25.3. Then, if there is time remaining, we will go back to 24.4, 24.5, and 25.4. The sections we are postponing are all about processes that occur in the centers of galaxies, so I'd like to keep that separate from the logical progression that leads us from the local galaxies to the large-scale structure of the universe.

In the outline below, figures are referred to by number alone: e.g. 24.12 is Figure 24.12.

Hubble sequence—galaxy classification scheme, originally based on appearance, but correlates with other properties as well.

Symbolically: E0….E7..…S0…..Sa..Sb..Sc..Sd…..Irr

Properties (see diagram discussed in class; also table 24.1)
Ellipticals: featureless—no disk or arms; no gas or dust (a few exceptions); huge range in sizes, from dwarfs to giants; yellow-reddish in color.

S0s: Disks, but no gas or spiral arms. So intermediate between Es and spirals.

Spirals: Flat disk with spiral arms, central bulge. Sequence Sa,…Sd corresponds to increasing size of bulge, increasing tightness of arms, and more gas mass relative to stars. Also parallel sequence of *barred* spirals.

Irregulars: Tend to be smaller than spirals. Many are dwarf irregulars (dIrr). Often found as satellites (e.g. Magellanic Clouds). Blue color, lots of gas.

Masses of galaxies: From 10^6 to 10^7 Mo (dE and dIrr) to 10^{12} Mo (giant Es). The smallest are the most numerous galaxies in the universe. (How do you think we get masses of galaxies?)

How are these different kinds of galaxies distributed in space?

Groups of galaxies— We can use Cepheid variables to make a map of our "local" galactic neighborhood (can get distances out to about 15 Mpc).

Our Local Group—About 50 galaxies within about 1 Mpc (=1000 kpc = (roughly) 10 x size of our Galaxy) of each other. Most of the mass is in the large spirals Milky Way and Andromeda. Most of the galaxies are dE and dIrr galaxies. Many are satellites of larger galaxies (e.g. 3 satellites of Milky Way are LMC, SMC, and Sgr dwarfs, a few others that are more distant; Andromeda has several small satellites) Look at Fig. 24.13.

To get to larger distances, must use brighter standard candles. The next one in the ladder of standard candles is the Tully-Fisher relation ⇒ very tight relation (for disk galaxies) between rotational velocity (from broadening of galaxy's spectral lines—see Fig. 24.11) and luminosity. (Think why this makes sense: the galaxy's rotation is balancing its gravity, which is due to its mass, related to its luminosity…)

So for a galaxy too far away to use any other method, just obtain a spectrum (21 cm neutral hydrogen line is best) and measure width of line; the Tully-Fisher relation then gives you the luminosity, so (knowing the apparent brightness) you get the distance.

This method can be used out to about 200 Mpc ⇒ allows us to make a map of the relatively nearby universe.

Before looking at the results, there is one more rung in the ladder of distance indicators or standard candles, called the Hubble relation or Hubble's law, to consider.

Hubble's Law –this is the basis for our ideas about how the universe formed (the "big bang" theory), so important to understand it.

Using galaxies of known distance (e.g. using Cepheids, Tully-Fisher), find that velocity of recession (redshift) increases linearly with distance (24.16, 24.17). Indicates that universe is expanding.

Recession velocity = constant (H_0) x distance

The constant of proportionality is called the Hubble constant, which is a fundamental measure of age of the universe (next section of course—for now we just want to use it to get distances and map the universe).

See Fig. 24.18 on the "cosmic distance ladder." You should understand what these different distance indicators are, and why each can only be used out to a certain distance.

[Textbook discusses active galactic nuclei, including our own, at this point, sec. 24.4 and 24.5 but we are going to skip to Ch. 25 in our discussion; you should read sec. 24.4 and 24.5 on your own.]

(Skip to sec. 25.5, The Universe on Large Scales.)

Find that galaxies occur not only in small groups like ours, but in larger galaxy clusters. The nearest is the Virgo Cluster, whose center is about 20 Mpc away. It contains about 2500 galaxies, with a size of about 3 Mpc. We are located in outskirts.

But the Virgo Cluster is only one of many clusters which make up our local "supercluster" (see Fig.25.20, 25.21), which is about 100 Mpc in size.

Using the Hubble relation (sec. 24.3), we can get distances to galaxies even farther away *if* we can obtain their spectra, so we can get their redshift and calculate the distance from the equation above. The collection of redshifts for tens of 1000s of galaxies has taken many years on the largest telescopes, but now we have a good map of the universe out to about 1000 Mpc. The Sloan Digital Sky Survey will very soon provide redshifts for *millions* of galaxies! (See Discovery 25-1).

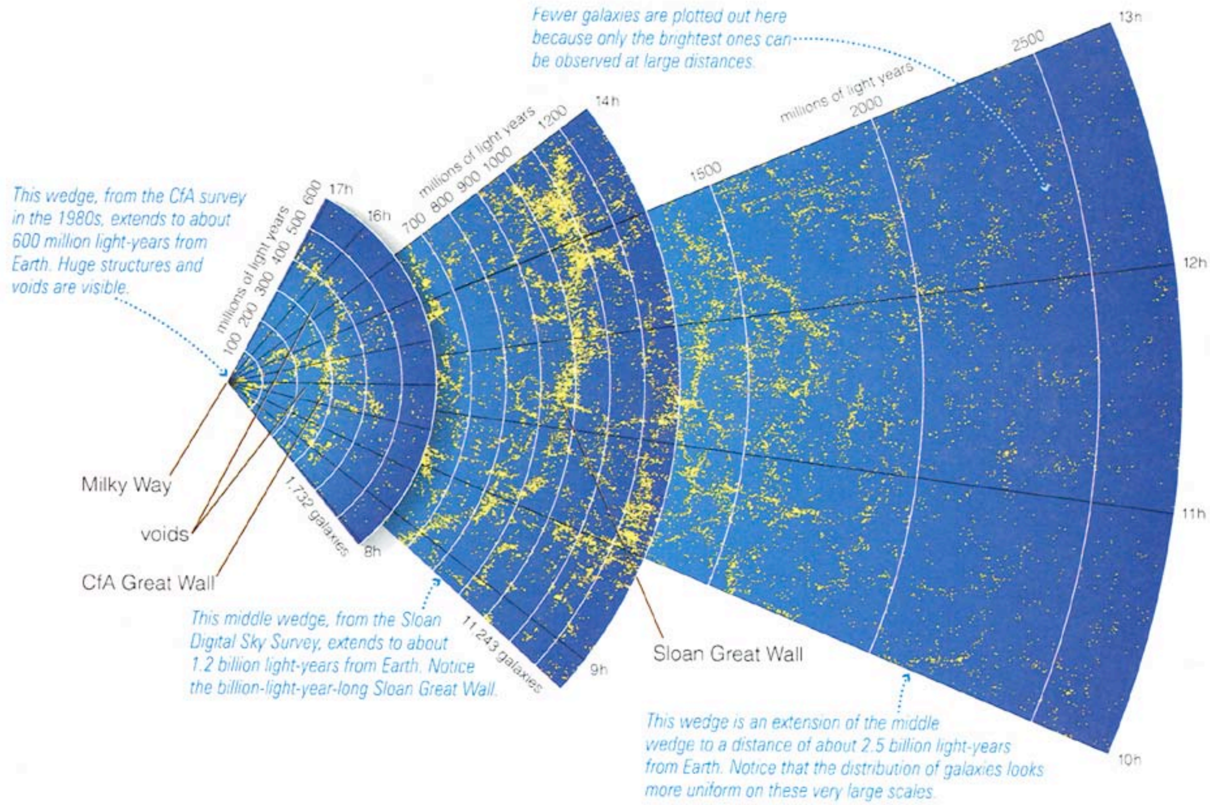
Some results:

<u>Superclusters</u> = clusters of clusters of galaxies. Our Local Supercluster is ~ 100 Mpc across, contains ~ 10,000 galaxies. See Fig. 25.20, 25.21.

Extending out to 200 Mpc (Fig. 25.22) and 1000 Mpc (Fig. 25.23) we see larger and larger structures, often huge filaments (e.g. the "Great Wall) and huge voids; the galaxies in the universe are apparently hierarchically clustered up to sizes of around 200 Mpc. (Remember the distance between our galaxy and our nearest neighbors is less than about 1 Mpc.)

So the universe as a whole is a frothy structure of filaments and bubbles surrounding low-density voids. We trace this structure with galaxy positions, but we know that most of it is actually the mysterious dark matter, whose gravity has apparently dragged the visible matter along with it into this structure.

See "map" on next page.



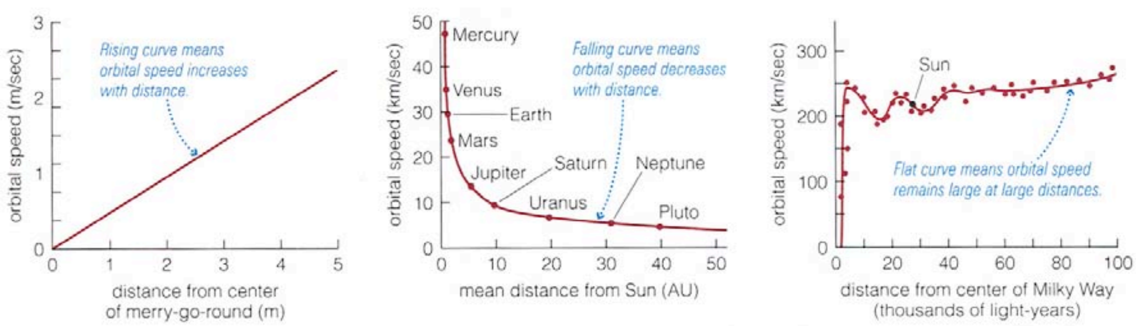
Each of these three wedges shows a "slice" of the universe extending outward from our own Milky Way Galaxy. The dots represent galaxies, shown at their measured distances from Earth. We see that galaxies are not scattered randomly but instead trace out long chains and sheets surrounded by huge voids containing very few galaxies. (The wedges are shown flat but actually are a few angular degrees in thickness; the CfA wedge at left does not actually line up with the two Sloan wedges.)

Evidence that most of the matter is "**dark matter**."

So far we have concentrated on the distribution of galaxies in the universe, but let's return to individual galaxies and clusters of galaxies to see what their masses are—we will find that we are only seeing the "tip of the iceberg."

Masses of galaxies—rotation curves (Fig. 25.1; reread ch. 23.6 if you've forgotten this for our Galaxy) indicate ~ 30 to 90% of mass is invisible "dark matter" (i.e. masses come out about 3 to10 times larger than what we can see in any form). This is similar to what we found from the rotation curve for our Galaxy.

Illustration below is to review what a rotation curve tells us about the mass distribution in any system:

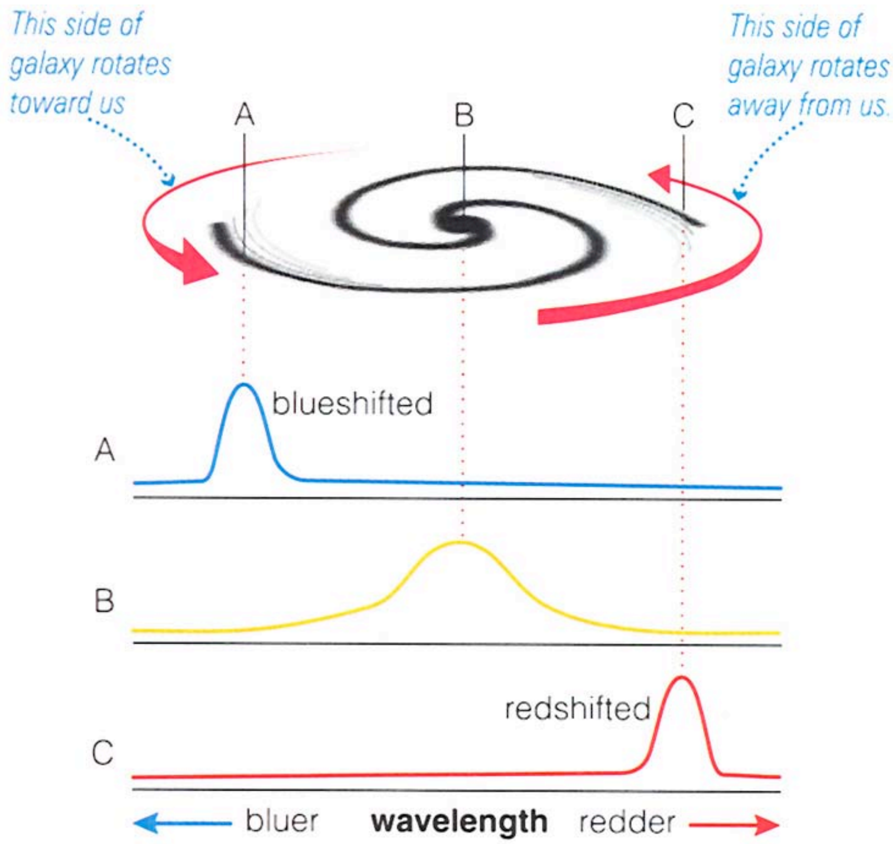


a A rotation curve for a merry-go-round.

b The rotation curve for the planets in our solar system.

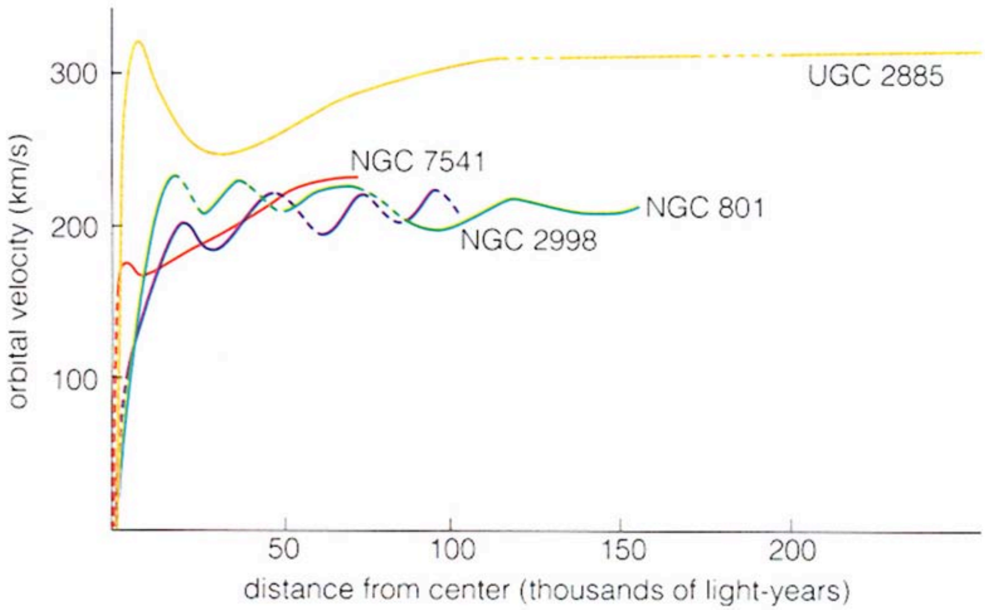
c The rotation curve for the Milky Way Galaxy. Dots represent stars or gas clouds whose rotational speeds have been measured.

How do we get rotation curves for most (disk) galaxies? Neutral hydrogen 21 cm line and the Doppler effect:



Measuring the rotation of a spiral galaxy with the 21-centimeter line of atomic hydrogen. Blueshifted lines on the left side of the disk show how fast that side is rotating toward us. Redshifted lines on the right side show how fast that side is rotating away from us.

Result: Most disk galaxies have rotation curves like the Milky Way
→ dark matter dominates *all* galaxies that have been studied.



Actual rotation curves of four spiral galaxies. They are all nearly flat over a wide range of distances from the center, indicating that dark matter is common in spiral galaxies.

Masses of clusters of galaxies—from motions of galaxies in clusters (Fig. 25.2). Inferred masses again come out about 10 times larger than what we can see in galaxies. *Some* of the mass of clusters turns out to be observable in the x-ray part of the spectrum: clusters of galaxies are filled with extremely hot (tens of millions of degrees) gas. However the total mass of this "inctracluster gas" (images shown in 25.4 and 25.6) is only comparable to the mass of galaxies, so it doesn't account for the inferred masses. Again we find that most of the mass is unseen "**dark matter**." (Get about the same thing from estimates of masses of *binary* galaxies—see 25.2.)

⇒ must face fact that most of the mass of the universe is in a form we can't see, i.e. that doesn't emit light at any wavelength. What is it? See discussion earlier (sec. 23.6). Probably unknown exotic fundamental particles, but still uncertain.

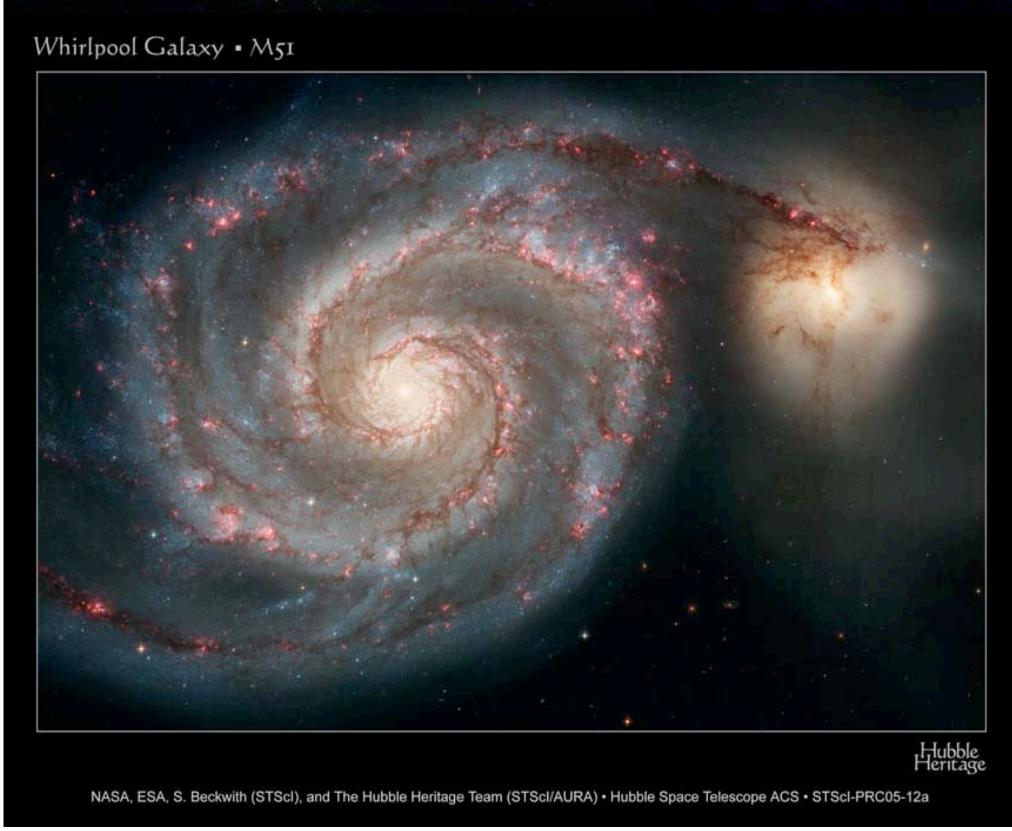
Formation and evolution of galaxies (sec. 25.2 and 25.3 is very good on this subject).

Theoretical simulations and observations of galaxies *very* far away (and so when the universe was much younger) are giving a consistent (and surprising!) picture: That the first galaxies were small irregular objects that repeatedly *merged* in collisions to produce larger and larger galaxies (see Fig. 25.10).

Much of this comes from the observations known as the "Hubble Deep Field"—see Fig. 25.11 in text.

When two similarly sized disk galaxies merge, the product (in simulations) looks very much like an elliptical galaxy. (Not sure what fraction of ellipticals formed this way.) You can see the effects of galaxy collisions in the form of tidal tails (25.9, "The Antennae") and ring galaxies (25.7, the "Cartwheel" galaxy). These images of real galaxies match the simulations of galaxy collisions very well (see right side of Fig. 25.9).

Here is a couple of examples of interacting galaxies. One might resemble our own galaxy's interaction with the Large Magellanic Cloud.

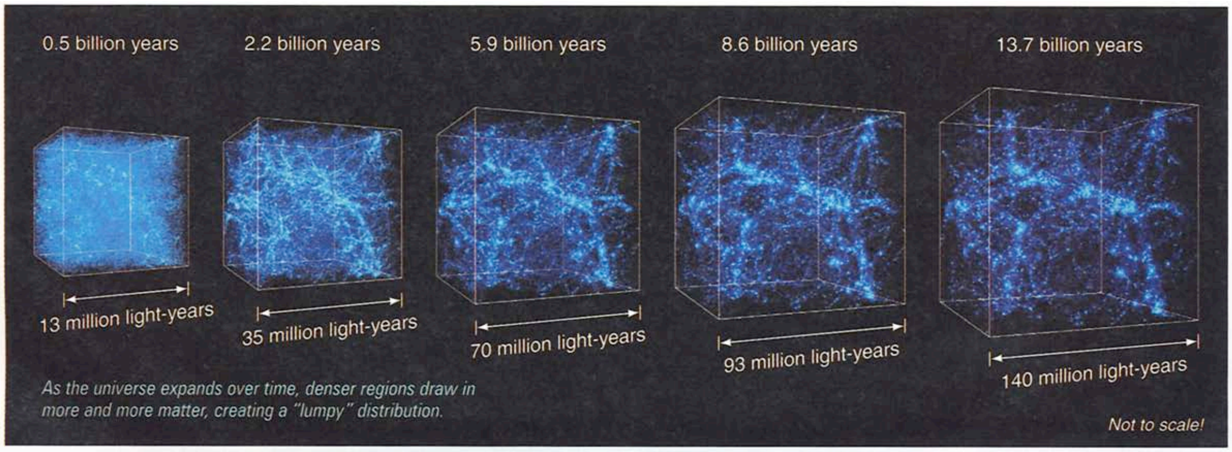


Most large galaxies have probably been pummeled many times by smaller galaxies without affecting their overall type. E.g. the Milky Way has probably "ingested" several small dIrr galaxies.

Many other collisional effects can occur, e.g. excitation of spiral arms (25.14); tidal tails (25.9); starbursts (25.12); galactic cannibalism by giant ellipticals in the centers of rich clusters (25.13). Fifteen years ago astronomers were skeptical whether collision affected any but a tiny fraction of galaxies, but today it is understood that collisions and mergers probably dominated the early evolution of galaxies in our universe.

So now we have seen that the universe of galaxies (and the dark matter that the galaxies trace) is structured from "tiny" loose groupings like our Local Cluster (~1 Mpc in size) to huge superclusters and filaments up to ~ 200 Mpc in size.

How did this structure come to be? Simulations show that if you start with some "seed" galaxies in an expanding universe with dark matter, the galaxies' gravitational attraction on each other does lead to this kind of hierarchical clustering. (Some stills from a simulation are given at the end of these notes.) But the ultimate origin of this structure is in the "seeds," which we will later try to trace back to sound waves before galaxies ever formed, and back further still to "quantum fluctuations" that were the ultimate source of structure in our universe.



Frames from a supercomputer simulation of structure formation. These five boxes depict the development of a cubical region that is now 140 million light-years across. The labels above the boxes give the age of the universe, and the labels below give the size of the box as it expands with time. Notice that the distribution of matter is only slightly lumpy when the universe is young (left frame). Structures grow more pronounced with time as the densest lumps draw in more and more matter.