Astronomy 401/Physics 903
Lecture 13
Galaxy Groups and Clusters

Galaxies are not distributed randomly throughout the universe; they are usually found in associations called **groups** or **clusters**. In both cases, the galaxies are gravitationally bound to each other and orbit the system's center of mass.

1 Classification of clusters

1.1 Galaxy groups

- Usually have less than 50 members
- About 1.4 Mpc across
- Galaxies of the group have velocity dispersion $\sim$ 150 km s^{-1} (this now refers to the velocity of galaxies relative to each other, **not** to the velocity of stars within galaxies)
- Mass of an average group $\sim 2 \times 10^{13}$ M$_\odot$, from the virial theorem
- Typical mass-to-light ratio $\sim$ 260 M$_\odot$/L$_\odot$ $\Rightarrow$ lots of dark matter

1.2 Galaxy clusters

- Contain between $\sim$ 50 to thousands of galaxies
  - Few galaxies $\Rightarrow$ **poor** cluster
  - Lots of galaxies $\Rightarrow$ **rich** cluster
- Higher velocity dispersion than in a group. Characteristic velocity dispersion is 800 km s^{-1}, may exceed 1000 km s^{-1} for very rich clusters
- Typical virial mass $\sim 10^{15}$ M$_\odot$
- Typical mass-to-light ratio $\sim$ 400 M$_\odot$/L$_\odot$ $\Rightarrow$ even more dark matter than in groups
- Further classified as **regular** (spherical and centrally condensed) and **irregular**

2 The Local Group

About 35 galaxies are known to lie within $\sim$ 1 Mpc of the Milky Way — this collection of galaxies is called the Local Group. Most prominent members are the three spiral galaxies, the Milky Way, Andromeda (M31), and M33. The next most luminous are the Large and Small Magellanic Clouds, irregular galaxies near the Milky Way; the LMC is 48 kpc away, and the SMC is about 60 kpc away (can see them from the Southern hemisphere). They are two of the 13 irregular galaxies in the Local Group. The remaining galaxies are dwarf ellipticals or dwarf spheroidals, very small and very faint (which means they're hard to see; there may be some we haven't found yet). Also notable is the Magellanic Stream, a long ribbon of gas tidally stripped from the Magellanic Clouds.

Most of the galaxies in the Local Group are clustered around the Milky Way and Andromeda (see Figure 1), which are on opposite sides of the Local Group about $D = 770$ kpc apart. The center of mass of the group is between them.

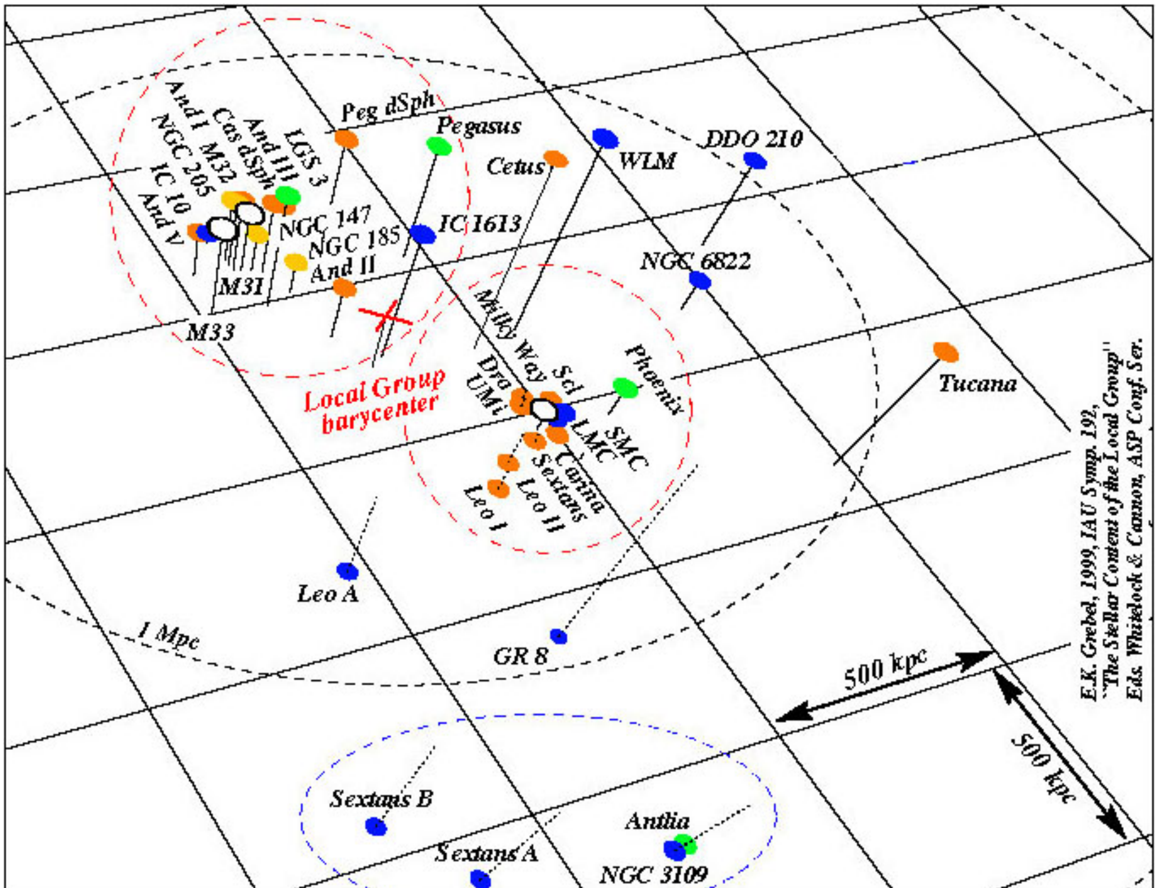

Figure 1: The Local Group

The Milky Way and Andromeda contain about 90% of the luminosity of the Local Group. If the mass follows the luminosity, we expect that they will dominate the mass of the Local Group as well. We can estimate the mass of the two galaxies, and therefore the approximate mass of the Local Group, from their relative motion.

Andromeda and the Milky Way are approaching each other with a velocity of 120 km s^{-1} (the gravitational attraction between them is strong enough to overcome the Hubble flow, i.e. the expansion of the universe). We don't know whether or not they will actually collide because we can't measure the transverse velocity of Andromeda; indirect constraints suggest it's ~ 100 km s^{-1} or less. In the early Universe, the two galaxies were closer together and took part in the expansion of the Universe; at some time $t_{\max}$, their gravitational attraction was strong enough that they reached a maximum separation $r_{\max}$ and then began to move toward each other.

We will use the distance and relative velocity of the two galaxies to estimate their combined mass. From conservation of energy, the relative velocity v and separation r are related by

$$\frac{v^2}{2} = GM\left(\frac{1}{r} - \frac{1}{r_{\max}}\right) \tag{1}$$

where M is the combined mass of the two galaxies and the last term is a constant of integration derived from the fact that $v = 0$ at $r = r_{\rm max}$. Since $v = dr/dt$, this is a differential equation for $r(t)$,

$$\frac{1}{2}\left(\frac{dr}{dt}\right)^2 = GM\left(\frac{1}{r} - \frac{1}{r_{\rm max}}\right), \tag{2}$$

with initial conditions $r = 0$ at $t = 0$. Solving for dt and integrating,

$$\begin{aligned} t_{\rm max} &= \int_0^{t_{\rm max}} dt & (3)\\ &= \int_0^{r_{\rm max}} \frac{dr}{\sqrt{2GM(1/r - 1/r_{\rm max})}} & (4)\\ &= \frac{\pi r_{\rm max}^{3/2}}{2\sqrt{2GM}}. & (5) \end{aligned}$$

The collision of the two galaxies will happen at $2t_{\rm max}$ (since it takes the same amount of time for the galaxies to come together from $r_{\rm max}$ as to separate to $r_{\rm max}$), and we can estimate the time from now ($t = t_0$) to the collision as $D/v = 770$ kpc/120 km s^{-1} (this assumes that the relative velocity of the galaxies remains constant). So the time of collision is $2t_{\rm max} = t_0 + D/v$, or

$$t_{\rm max} \approx \frac{t_0}{2} + \frac{D}{2v} \approx 10^{10}\text{yr}. \tag{6}$$

Returning to Equation 1, we can write $r_{\rm max}$ in terms of $t_{\rm max}$ using Equation 5 above. This gives

$$\begin{aligned} \frac{v^2}{2} &= GM\left(\frac{1}{r} - \frac{1}{r_{\rm max}}\right) & (7)\\ &= \frac{GM}{r} - \frac{1}{2}\left(\frac{\pi GM}{t_{\rm max}}\right)^{2/3} & (8) \end{aligned}$$

We know that $t_0 \approx 1.4 \times 10^{10}$ yr, $r(t_0) = D$ (the current separation of the two galaxies), and $v(t_0) = 120$ km s^{-1} , and we determined the value of $t_{\rm max}$ above. Our only unknown is the mass, so we can put in these values, solve for M, and find the total mass

$$M \approx 3 \times 10^{12}\ \mathrm{M}_\odot. \tag{9}$$

This is much larger than the mass of stars and gas contained in the two galaxies; we can see only about 5% of this mass. We conclude that the local group contains a great deal of dark matter. The mass-to-light ratio from this estimate is $M/L \sim 70$ M$_\odot$/L$_\odot$.

3 The Virgo Cluster and the Coma Cluster

There are other groups of galaxies within 10 Mpc of the Local Group—about 20 small groups of galaxies closer to us than the Virgo cluster. Most galaxies live in small groups and poor clusters; probably at most 20% of galaxies live in rich clusters like the Virgo cluster.

The nearest rich clusters are the Virgo cluster and the Coma cluster.

3.1 The Virgo cluster

- Covers $10^\circ \times 10^\circ$ region of the sky. Huge!
- Center about 16 Mpc away.
- Contains about 250 large galaxies and > 2000 smaller ones, within a region about 3 Mpc in diameter.
- Mix of galaxy types: 4 brightest are giant ellipticals, spirals dominate overall, but ellipticals become increasingly common near the center of the cluster. Why?
- M87, giant E1 elliptical, brightest galaxy in the Virgo cluster. Mass $\sim 3 \times 10^{13}$ $\mathrm{M}_\odot$, $M/L \simeq 750$ $\mathrm{M}_\odot/\mathrm{L}_\odot$. Over 99% dark matter! Not a normal elliptical galaxy.

3.2 The Coma Cluster

Another rich cluster, about five times farther away than Virgo. Provided first evidence of dark matter—in 1933 Fritz Zwicky measured the radial velocities of galaxies in the Coma cluster, calculated the velocity dispersion, which we now know is $\sigma = 977$ km s^{-1} , and used the virial theorem to estimate the cluster's mass. The radius of the cluster is about 3 Mpc, so the virial mass is

$$M \approx \frac{5\sigma^2 R}{G} = 3.3 \times 10^{15}\ \mathrm{M}_\odot \tag{10}$$

Zwicky compared this with the luminosity he measured from the combined visible light of all the stars, about 5×10^{12} $\mathrm{L}_\odot$, to find $M/L \approx 660$ $\mathrm{M}_\odot/\mathrm{L}_\odot$. He understood that this was strange, and wrote that the mass of the cluster considerably exceeds the sum of the masses of the individual galaxies. This was the first recognition of dark matter.

(Fritz Zwicky also proposed, with Walter Baade, the existence of neutron stars in 1934, only a year after the discovery of the neutron, and proposed that supernovae were transitions of normal stars into neutron stars. He also proposed that galaxy clusters could be gravitational lenses. And other, crazier stuff.)

4 Hot, intracluster gas

Some of the missing mass in galaxy clusters was discovered when the first X-ray satellites were launched (1977). It was observed that many clusters emit X-rays, from much of their volume. This revealed the **intracluster medium**: a diffuse, irregular collection of stars, and **hot intracluster gas**.

The X-rays are produced by **thermal bremsstrahlung emission** (braking radiation, also called free-free emission). This is emission which occurs when a free electron passes near an ion, emits a photon, and slows down (the ion is necessary for conservation of energy and momentum). Bremsstrahlung radiation has a characteristic, easily identifiable spectrum, and the luminosity density (luminosity per unit volume) depends on the electron density and the temperature:

$$\mathcal{L}_{\mathrm{vol}} = 1.42 \times 10^{-40}\ n_e^2 T^{1/2}\ \mathrm{W\ m^{-3}}. \tag{11}$$

(Important parts: $\mathcal{L}_{\mathrm{vol}} \propto n_e^2 T^{1/2}$) The temperature can be measured from the X-ray spectrum of the gas; for the Coma cluster it is 8.8×10^7 K. The total X-ray luminosity of the cluster is

$$L_x = \frac{4}{3}\pi R^3 \mathcal{L}_{\mathrm{vol}}. \tag{12}$$

We can measure R, L_x and T, so these two equations can be combined to solve for n_e. For the Coma cluster, $n_e = 300\ \mathrm{m}^{-3}$. Very diffuse!

We can then compute the total mass of the gas:

$$M_{\rm gas} = \frac{4}{3}\pi R^3 n_e m_H \tag{13}$$

since there is one proton for every electron. For the Coma cluster, $M_{\rm gas} \approx 3 \times 10^{14}\ \mathrm{M}_\odot$. This is a lot of gas, but much less than the total cluster mass $3.3 \times 10^{15}\ \mathrm{M}_\odot$ we estimated earlier (note that more precise estimates of the mass of the Coma cluster find a total mass in the range 2–$2.6 \times 10^{15}\ \mathrm{M}_\odot$).

4.1 Baryon fraction in clusters

Figure 2 shows that the intracluster gas makes up most of the baryons in clusters, and that the gas fraction increases and the stellar fraction decreases with increasing mass. This is consistent with the increase in mass-to-light ratio with increasing mass. The figure also shows that the total baryon fraction approaches the cosmological value for the most massive clusters. This is probably because "feedback" processes such as gaseous outflows driven by supernovae and accretion onto massive black holes can expel baryons from lower mass halos, but on the largest size and mass scales, halos retain their original baryon fraction.

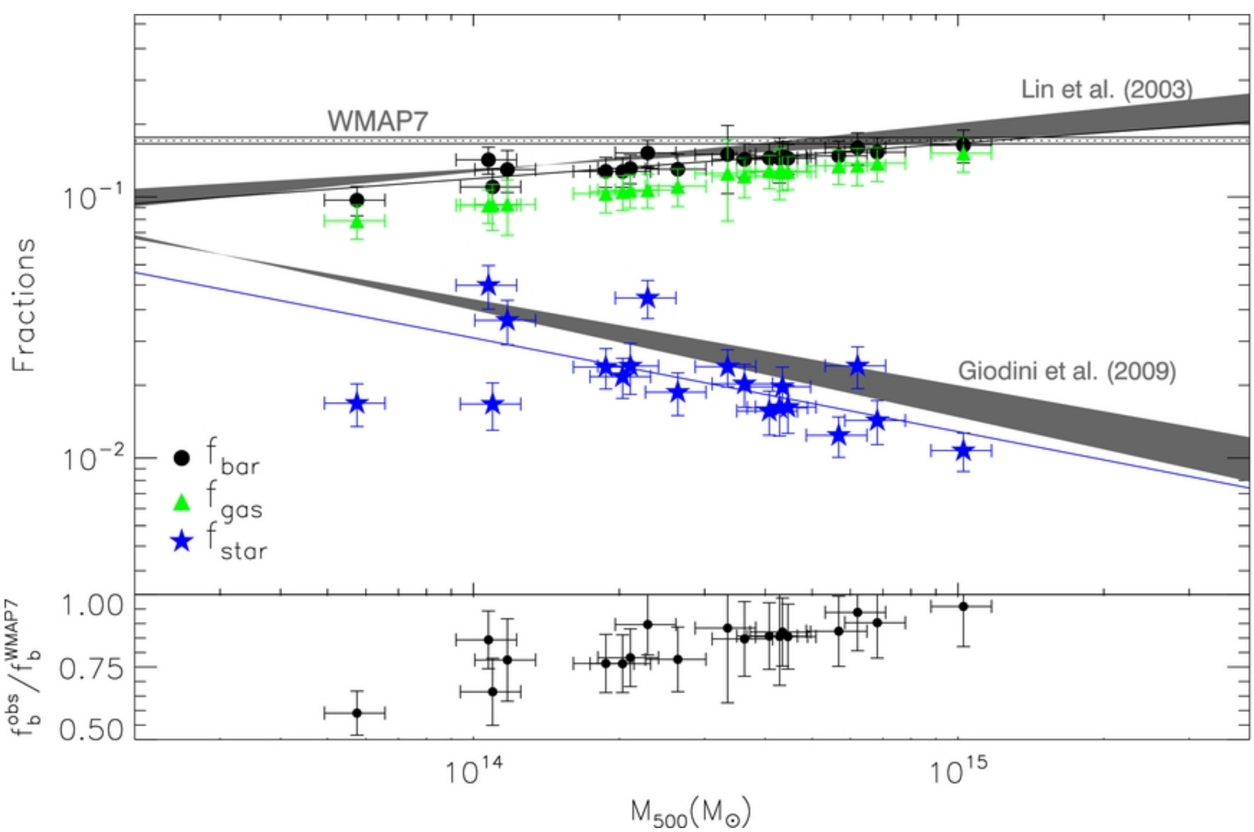

Figure 2: The fraction of total mass in stars, gas and all baryons as a function of mass for galaxy clusters. The total baryon fraction approaches the cosmological value (horizontal line labeled WMAP7) for the most massive clusters. The fraction of mass in stars also decreases with increasing cluster mass (Lagana et al 2011, *ApJ*, 743, 13).

5 Galaxy Interactions in Clusters

Things we observe about galaxy clusters:

- In large clusters like the Virgo cluster, elliptical galaxies become increasingly common toward the center of the cluster
- Rich, regular centrally condensed clusters also have a higher fraction of elliptical galaxies than irregular clusters
- Clusters contain large amounts of hot gas between galaxies, the intracluster medium

These things are evidence for galaxy interactions, which are more likely in the densely populated centers of clusters.

Other observations are also evidence for interactions between galaxies:

- At least 50% of disk galaxies have warped disks (seen with radio observations of HI disks)
- Elliptical galaxies often have discrete shells of stars, or populations of stars with orbits different from those of the rest of the stars in the galaxy

5.1 What happens when galaxies collide?

- The stars don't physically collide, but may interact gravitationally
- Gas clouds collide, triggering star formation
- Entropy increases: disk galaxies with stars on ordered, nearly circular orbits will likely become elliptical galaxies, with stars on random orbits
- Galaxy collisions are inelastic: some of the orbital kinetic energy is converted to internal energy, in the form of random motions of stars. So even galaxies that start out on orbits with velocities greater than the escape velocities of the galaxies can end up gravitationally bound
- Extended tidal structures are produced