Outline

- Go over AGN growth problem
- Groups and clusters
- How to measure the mass of clusters
- Large scale structure
Homework

- AGN growth problem

A supermassive black hole at the nucleus of a galaxy accretes at the Eddington luminosity with the efficiency of a maximally rotating black hole, $\eta = 0.42$. Find an expression for the mass of the black hole as a function of time – note that the Eddington luminosity changes as the black hole mass changes. How much time is needed to grow a $10^9$ solar mass black hole if one starts with a 10 solar mass black hole?

Why would the black hole be (near) maximally rotating?
Groups and Clusters

- Galaxies are found in collections ranging from an individual, isolated galaxies to massive clusters with many thousands of members.

- Groups are usually defined as containing fewer than about 50 galaxies within a volume about 1 Mpc across, clusters are more than 50 galaxies typically spread across a larger volume.

- Many nearby galaxies that are members of the “Local Group” are very small and dim and would be impossible to detect even at distances of a few Mpc. Thus, strict counting of all the galaxies in a group/cluster is not feasible. Typically a “group” will have several galaxies with stellar luminosities similar to the Milky Way and a larger, but poorly determined number of smaller galaxies.
Nearby Groups and Clusters

- There are a number of other groups of galaxies that are neighbors to the local group, most have 2-4 large galaxies and are named for the largest galaxy.
- The M81 group contains M81, M82 (starburst), NGC 2403, and a number of smaller galaxies, currently 34 known. Several of these galaxies are interacting (notably M82 and M81) and have active star formation.
- Closest cluster is the Virgo cluster at 16 Mpc, with 250 large galaxies that cover a patch about 8 degrees across on the sky. Virgo is an irregular cluster and has 3 “sub clumps”.
- The closest massive cluster is Coma at ~100 Mpc, with ~1000 large galaxies. Coma is a “regular” cluster (smooth galaxy distribution with no sub-clumps) and is classified as a “rich” cluster.
A “Typical” Cluster

- There is a wide range in size and mass of clusters.
- We'll take as “typical” a cluster with 100 L* galaxies, size $r = 1$ Mpc, and velocity dispersion $\sigma = 1000$ km/s.
- “Cluster crossing time scale” = time it takes for a galaxy to cross the cluster
  - $\tau = \frac{r}{\sigma} = 3 \times 10^{24} \text{ cm}/(10^8 \text{ cm/s}) = 3 \times 10^{16} \text{ s} = 10^9$ years.
- This is older than the typical ages of clusters (or galaxies), thus clusters are
  - gravitationally bound
  - relaxed – galaxies are gas are in thermal equilibrium
- Enhanced density of galaxies decreases time between interactions to a few Gyr. Thus, galaxies are likely to have interacted.
Galaxy morphology is correlated with local density of galaxies and location in cluster (virial radius is a measure of the cluster size).

This likely shows effect of interactions on galaxy evolution, but could be due to ram pressure striping removing gas from galaxies in dense regions.
Other cluster components

- Intergalactic or “rogue” stars – stars not associated with a particular galaxy. Thought to be stars ejected in galaxy-galaxy interactions.

- Gas clouds – HI clouds with masses up to $10^8 \, M_\text{Sun}$ and dynamical masses up to $10^9 \, M_\text{Sun}$ with nothing in the visible/UV/IR bands, i.e. no stars. May be primordial gas clouds similar to those from which galaxies formed.

- Hot, $10^7$- $10^8 \, \text{K}$, X-ray emitting plasma – the dominant form of baryonic matter in most rich, regular clusters.

- Dark matter
Cluster Mass

Three ways to determine cluster mass

- Orbits of galaxies
- Gravitational lensing
- X-rays from hot gas

- Do orbits of galaxies on board
Gravitational Lensing

Optical image of Abell 2218
Hot Gas

Mass:
- 1-2% stars
- 13% gas
- 85% dark
Large Scale Structure

2dF Galaxy Redshift Survey

4° slice
82821 galaxies
Large Scale Structure

- 1-2% stars
- 13% gas
- 85% dark
Homework

- For next class: problem 6.6