Outline

- Finish up dark matter
  - Elementary particles
  - Modified gravity
- Galaxies
  - Types
  - Luminosity function
  - Collisions
Dark Matter

- Elementary particles
  - Neutrinos – can calculate number of expected neutrinos from cosmology, analogous to cosmic microwave background. Neutrinos do not contribute sufficient mass unless the individual particles are massive. Recent suggestions of 3.5 keV X-ray line from clusters of galaxies suggesting 7 keV neutrino.
  - Weakly interacting massive particles (WIMPs) – WIMPs of in GeV to TeV mass range solve both dark matter problem and explain mass of Higgs boson. Searching for at LHC and in direct detection experiments (LUX, Xenon1T).
  - Axions – predicted to solve problem in QCD. Convert to photons with sufficient strong magnetic field. Searching for at Axion Dark Matter Experiment.
Modified Gravity

- Modified gravity – maybe Newton's laws are incorrect at large distances or very low accelerations.

- Milgrom suggested “Modified Newtonian Dynamics” (MOND) in which $F = ma$ is replaced by $F = ma^2/a_0$ for $a < a_0 = 10^{-8}$ cm/s$^2$.

- MOND “predicts” flat rotation curves (problem 6-7a) and does remarkably well in explaining the properties of many galaxies.

- Could we modify Newton's gravitational force law instead of Newton's second law ($F = ma$)? Do on board (problem 6-7b).

- Thought to be ruled out by Bullet cluster – a collision between two galaxies in which X-rays show baryons are concentrated at center, while gravitational lensing shows most of the mass is on the outer edges.
Total mass is in blue, X-ray emitting baryonic matter is in red.
Classification of galaxies

- Ellipticals: $E_n$, where $n=0$ for round, $n=7$ for oblong.
- Spirals: $S_x$, where $x$ indicates brightness of bulge relative to arms, how tightly the arms are wrapped, and the definition of the arms: $a$ (bright, tight, fuzzy), $b$, $c$ (dim, loose, sharp). Later “$d$” and $ab$, $bc$, $cd$ were added. If the arms have a central bar, then $SB_x$.
- Elliptical galaxies are “early-type”; spiral galaxies are “late-type”.
- Later additions to classification scheme:
  - Lenticulars: $S0$ and $SB0$, mostly bulge with a little bit of disk typically with poorly defined arms.
  - Use of $SA$, $SAB$, $SB$ for spirals, where $SA = S$, $SAB =$ intermediate.
  - Sub-classification of irregulars: $Irr \ I$ (weak structure), $Irr \ II$ (no structure). Addition of Magellanic cloud types, LMC is an irregular, but is sometimes classified as $SBm$. 
Luminosity functions

- Luminosity function, how does the number of galaxies vary as a function of galaxy luminosity

- $\Phi(L)dL = \text{number of galaxies in luminosity interval } [L, L+dL]$. Can be a density (i.e. divide number by volume) or simply a number (say for all galaxies in the Virgo cluster). Often $\Phi$ is specified in terms of absolute magnitude, $M$, instead of $L$.

- Sometimes, the integral luminosity function is presented – number of galaxies more luminous than $L$.

Measuring $\Phi$ is straightforward for a cluster, all galaxies are at the same distance. Need to be careful about removing foreground/background objects, but these can be identified by redshift. Also, $\Phi$ may be incomplete at low $L$.

- Measuring $\Phi$ in the field is more difficult. Need to either construct a volume limited sample or correct for fact that more luminous galaxies can be detected at larger distances (Malmquist bias).
Different types of galaxies have different luminosity functions. Luminosity function gives quantitative information about distribution of luminosities and relative number of galaxies of different types as a function of luminosity.

Luminosity function is different in different environments. E.g. compared to the field, clusters have fewer spirals and more ellipticals particularly at very high and very low luminosities.
If one looks at a very large number of galaxies, the luminosity function appears to follow the Schechter function:

- Power law (slope $\alpha$) at low luminosity
- Exponential cutoff above $L^*$
- $L^* = 2 \times 10^{10} L_{\text{Sun}}$.

Milky Way and M31 are $\sim L^*$

$$\varphi(L) = \varphi(L^*) \left( \frac{L}{L^*} \right)^{-1} \exp \left( -\frac{L}{L^*} \right)$$
Density of Galaxies

- There is about one $L^*$ galaxy per 100 Mpc$^3$.
- Hence $\phi(L^*) \sim 0.01$ Mpc$^{-3}$.
- Random velocity between nearby galaxies $\sim 500$ km/s.
- Cross-section $\sigma \sim \pi(50 \text{ kpc})^2$.
- Time between collisions $= 1/n\sigma v \sim 3 \times 10^{12}$ years.
  - Compare to age of universe

- Collision rate was higher in early universe because galaxies were closer together.
- Also, galaxies are not uniformly distributed. Clustering greatly increases probability of collision.
Galaxy Collisions

- Collisions cause tidal interactions, can lead to galaxy mergers.
Homework

• For next class:
  – Problem 6-4 (gravitational lensing)