Lecture 8:
Observational probes to Dark Matter in the Universe.

Q: How do we know dark matter exists in the Universe?

L: There are many independent ways of measuring dark matter in the Universe. They all confirm that there is a lot of unseen mass, that galaxies are surrounded by this dark matter with a distribution that is much more extended than the visible stars. Clusters of galaxies contain a lot of dark matter, which has a similar distribution as the galaxies and the hot X-ray emitting gas.

Q: What was the first evidence of dark matter?

L: Velocity dispersions of galaxies in clusters, and flat rotation curves in galaxies. Later, gravitational lensing and the dynamics of X-ray emitting hot gas in clusters confirmed the estimates of dark matter. This by itself would not indicate that dark matter had to be a new non-baryonic type of matter.

Q: Why do we think today that dark matter must be non-baryonic?

L: We have another two independent observational probes: primordial nucleosynthesis tells us what the mean baryon density should be. It is less than all the observed mass today. Second, CMB fluctuations can only be understood and matched with present large-scale structure if there is non-interacting, or collisionless dark matter. These fluctuations give us a measure of the density of baryonic matter and dark matter that fully agrees with primordial nucleosynthesis and present measurements of the total mass density in the Universe.

Q: How is the velocity dispersion of hot gas in a cluster determined? Assume hydrostatic equilibrium:

$$\frac{dp}{dr} = \frac{k}{\mu}\frac{d(\rho T)}{dr} = -\frac{GM(r)}{r^2}\rho \ . \tag{1}$$

This can be reexpressed as

$$M(r) = -\frac{kT(r)r}{G\mu}\,\frac{d}{d\log r}\left(\log\rho + \log T\right) \ . \tag{2}$$

Q: What is the velocity dispersion of gas particles? $\sigma^2 = kT/\mu$. So

$$\frac{GM(r)}{r} = -\sigma^2(r)\,\frac{d}{d\log r}\left(\log\rho + \log T\right) \ . \tag{3}$$

This equation is also valid for galaxies if we assume they have an isotropic velocity dispersion. The difference is that galaxies are collisionless, so they can have an anisotropic velocity dispersion tensor. So can the dark matter, and therefore dark matter can support triaxial shapes in galactic halos and clusters of galaxies.

Q: Assume velocity dispersion is roughly constant, what is the implied slope of the density profile?

Q: Assume velocity dispersion in the Coma cluster is $900\,\mathrm{km\,s^{-1}}$, what is the corresponding gas temperature if it is in equilibrium in the same cluster? Assume the hot gas is fully ionized hydrogen.

Q: What is the physical process by which X-rays are emitted from the hot gas in clusters?

L: Free-free emission. Also there are some heavy elements that are not fully ionized even at the very high temperatures of the plasma in a cluster of galaxies, for example FeXXVI. Collisional excitation of the lines of these ions is also important.

Q: What is the characteristic wavelength at which you expect X-ray emission corresponding to the temperature derived for the Coma cluster?

Q: For the FeXXVI ion, note that it is hydrogen-like. Can you compute the energy of the equivalent to the Lyman alpha line for this ion? What do you expect to see at this energy in the spectrum of a cluster of galaxies?