PHY 475/375
Lecture 13
(May 9, 2012)

The Matter Content of the Universe

The matter density of the universe is an important parameter to know, not only for determining the spatial curvature and expansion rate of the universe, but also to figure out the constituents of the universe.

We can divide matter into two categories:

- *Luminous matter* is detectable by its electromagnetic radiation. Such matter includes stars which radiate primarily at visible, infrared, and ultraviolet wavelengths, and gas which can radiate at a variety of wavelengths depending on their temperatures. Such matter is baryonic, that is, it is made up of protons and neutrons (and their associated electrons). Henceforth, therefore, we will refer to such matter as *baryonic matter*.
- *Dark matter* does not emit any electromagnetic radiation, but is detected via its gravitational influence. While there are many conjectures about the composition of dark matter, the actual composition of dark matter remains unknown.

Baryonic Matter

We can quantify the radiation emitted by a star by measuring the intensity emitted at a particular (range of) wavelengths. For example, you might put a B-band filter on your telescope (note that "filter" in astronomy refers to transmitted radiation, not blocked radiation as in everyday conversation). If you measure the radiation that passes through this B-band filter in the wavelength range 400-490 nm (blue and violet mainly), you will find that the luminosity density of stars within a few Mpc of our Galaxy is

$$j_{\star,B} = 1.2 \times 10^8 \, L_{\odot,B} \, \mathrm{Mpc}^{-3} \tag{8.1}$$

where $L_{\odot,B}$ is the luminosity of the Sun in the B-band, and is equal to 4.7×10^{25} watts.

To convert $j_{\star,B}$ into a mass density $\rho_\star$, we need to know the mass-to-light ratio for stars, i.e., how many kg of star it takes to produce one watt of starlight in the B-band. This isn't easy to get at, since stars have a range of masses. By assuming that the mix of stars in the solar neighborhood is fairly typical, we get a mass-to-light ratio

$$\left\langle \frac{M}{L_B} \right\rangle \approx 4 \, \frac{M_\odot}{L_{\odot,B}} \approx 170,000 \text{ kg watt}^{-1} \tag{8.2}$$

From this, the mass density of stars in the Universe is found to be

$$\rho_{\star,0} = \left\langle \frac{M}{L_B} \right\rangle j_{\star,B} \approx 5 \times 10^8 \ \mathrm{M}_\odot \ \mathrm{Mpc}^{-3} \tag{8.3}$$

Therefore, the current density parameter for stars is

$$\Omega_{\star,0} = \frac{\rho_{\star,0}}{\rho_{c,0}} = \frac{5 \times 10^8 \ \mathrm{M}_\odot \ \mathrm{Mpc}^{-3}}{1.4 \times 10^{11} \ \mathrm{M}_\odot \ \mathrm{Mpc}^{-3}} \approx 0.004 \tag{8.4}$$

where we have taken the value of $\rho_{c,0}$ from equation (4.27) in Lecture 6.

Equation (8.4) tells us that the current density parameter for stars is very small!

- Stars make up less than 0.5% of the density necessary to have a flat Universe.
- The number will increase somewhat if we include brown dwarfs ("wannabe stars" whose mass is too low to ignite nuclear fusion in their cores), and stellar remnants like white dwarfs, neutron stars, and black holes.
- However, it is hard to get a fix on the number density of brown dwarfs and stellar remnants, since they are difficult to detect. Moreover, many would like to consider these objects as (baryonic) dark matter instead.

Galaxies also contain baryonic matter in other forms than stars, stellar remnants, and brown dwarfs.

- For example, the interstellar medium (ISM) between the stars in a galaxy contains significant amounts of gas. In our Galaxy and M31, the mass of this interstellar gas is about 10% of the mass of stars. In irregular galaxies, this may be even greater — about 21% of the mass in the Small Magellanic Cloud (SMC) is in the ISM.
- Moreover, there is a significant amount of gas between galaxies. For example, X-ray images of the Coma cluster of galaxies reveal hot, low density gas with $T \approx 10^8$ K that fills the space between galaxies in this cluster, emitting X-rays with $E \sim kT_{\mathrm{gas}} \sim 9$ keV. The total amount of X-ray emitting gas in the Coma cluster has been estimated to be $M_{\mathrm{Coma,\ gas}} \approx 2 \times 10^{14} \ M_\odot$, about 6-7 times the mass in its stars.

Ultimately, some of the best limits on the density of baryonic matter of the universe come from the predictions of primordial nucleosynthesis, and more recently, from the Cosmic Microwave Background (CMB) work by the Wilkinson Microwave Anisotropy Probe (WMAP) satellite observations. As we will learn in a later lecture, the efficiency with which fusion takes place in the early universe, converting hydrogen into deuterium, helium, lithium, and other elements, depends on the density of protons and neutrons present. Detailed studies indicate that the density parameter of baryonic matter must be

$$\Omega_{\mathrm{bary,\ 0}} = 0.04 \pm 0.01 \tag{8.5}$$

Notice that this is larger than the density parameter for stars by a factor of about 10. While stars present an impressive sight in the sky, they constitute a minority of the baryonic matter present in the Universe. Most of the baryonic matter is either too cold (e.g., in stellar remnants and brown dwarfs) or too diffuse (e.g., in low-density gas in clusters) to be at visible (optical) wavelengths.

Dark Matter

We know now that the majority of the matter in the Universe is *nonbaryonic dark matter*, which doesn't absorb, emit, or scatter light of any wavelength.

So, how do we go about detecting such matter? It is usually done by searching for its gravitational influence on visible matter.

The classic method of detecting dark matter is by looking at the orbital speeds of stars in spiral galaxies. Within the flattened disk of such a galaxy, stars are on nearly circular orbits around the center of the galaxy; for example, our Sun is on an approximately circular orbit at $R_s = 8.5$ kpc from the Galactic Center, with an orbital speed of $v_s = 220$ km s^{-1} (which means it takes the Sun about 230 million years to complete one orbit around the center of our Galaxy).

Suppose, therefore, that a star is in orbit of radius R around the center of a galaxy with an orbital speed v. We can then set the centripetal acceleration experienced by this star equal to the acceleration due to the gravitational attraction of the galaxy:

$$\frac{v^2}{R} = \frac{GM(R)}{R^2} \tag{8.8}$$

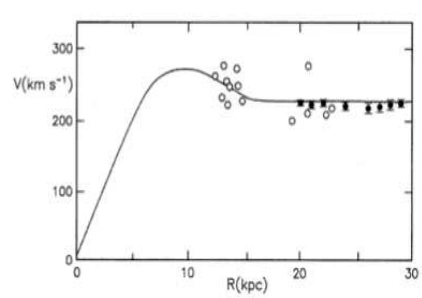
where $M(R)$ is the mass contained in a sphere of radius R with its center at the center of the galaxy. This gives

$$v = \sqrt{\frac{GM(R)}{R}} \tag{8.9}$$

Therefore, if stars contributed all or most of the mass in a galaxy, their velocity would fall as $v \propto 1/\sqrt{R}$ at large radii. This relation between orbital speed and orbital radius is called "Keplerian rotation" in the astronomical literature.

Now, we can check whether this is indeed the case by determining the orbital speed of a galaxy from observations. We won't discuss the details of how orbital speed of a galaxy is measured, but see equations (8.11) to (8.13) in your text if you're interested.

In 1970, Vera Rubin measured the rotation curve of M31. Rubin & Ford (1970) discovered that rather than falling off at large radii, the velocity remained constant instead, as shown in the graph below (taken from Figure 8.4 in your text). Of course, optical observations only go out to about 10-20 kpc from the center of a galaxy, but later observations with radio showed the same trend of a flattened rotation curve at large radii (out to 30 kpc or larger). The open circles in the figure show the optical data from Rubin & Ford (1970), and the closed circles show the radio data from Roberts & Whitehurst (1975); full references are in your text in the caption to Figure 8.4.



The current interpretation is that the additional mass required to flatten out the rotation curve is provided by a dark matter halo in the galaxy.

Dark Matter in Clusters of Galaxies

Long before Rubin's discovery of dark matter in Andromeda, though, the first astronomer whose observations suggested the presence of dark matter was Fritz Zwicky, in the 1930's. Zwicky found that the dispersion in the radial velocity of galaxies in the Coma cluster was very large. The stars and gas could not provide enough gravitational attraction to keep the galaxies together in the cluster. Zwicky concluded that in order to keep the galaxies in the Coma cluster from flying off into space, the cluster must contain a large amount of "dark matter."

Another independent line of evidence for dark matter comes from the gravitationally confined, hot, low density, X-ray emitting gas in clusters of galaxies; recall the image we viewed in class for the Coma cluster. In fact, the baryonic matter content of galaxy clusters is dominated by this X-ray emitting intra-cluster gas; its mass exceeds the mass of optically luminous material by a factor of ~ 6; other mass components in clusters are expected to make only very small contributions to the total baryon budget (e.g., Allen et al. 2004, *Monthly Notices of the Royal Astronomical Society*, 353, 457, and references therein). This hot gas would have expanded beyond the cluster if there were no dark matter to keep it confined. In fact, we can use the ratio of the mass of the X-ray emitting gas in the galaxy cluster to the total mass (including the dark matter) of the cluster to constrain various cosmologies.

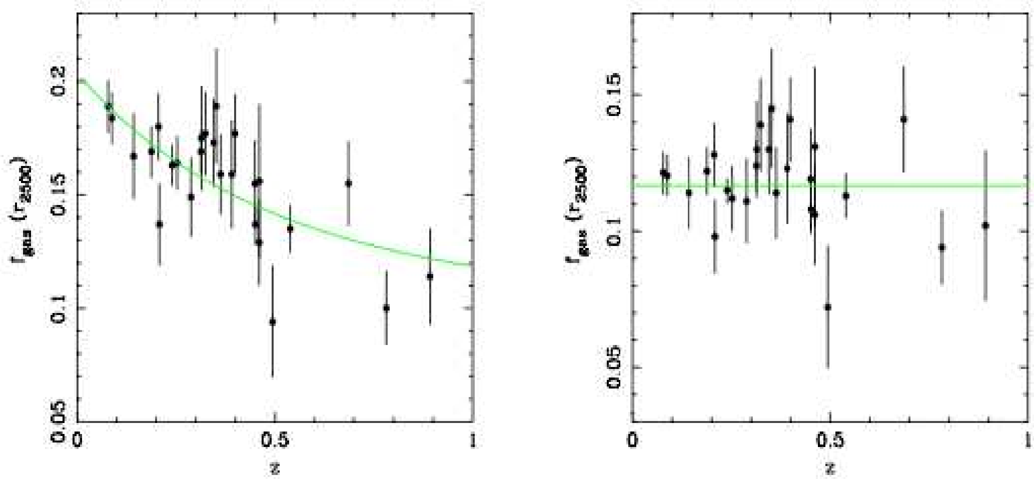
- We can calculate the total mass ($M_{\rm tot}$) in the cluster using the equation of hydrostatic equilibrium, i.e., by balancing the inward gravitational pull against the outward thermal pressure of the gas. This includes the mass of the dark matter, since it is based on the gravitational influence of the mass in the cluster. Hydrostatic equilibrium dictates that $M_{\rm tot} \propto r_C$, where r_C is the radius of the cluster.

- Meanwhile, if n_e is the electron density in the cluster, the mass ($M_{\rm gas}$) of the X-ray emitting gas in the cluster is given by
$$M_{\rm gas} \propto n_e\, r_c^3$$
To connect this to observable quantities, consider that the X-ray luminosity $L_{\rm X}$ is given by $L_X \propto n_e^2\, r_c^3$, so that we get
$$M_{\rm gas} \propto r_c^{3/2}\, L_X^{1/2}$$

- Next, from the definition of angular diameter distance d_A, if the cluster subtends an angle θ_C when observed from the Earth, we have $r_c = \theta_c\, d_A$. Also, if the observed X-ray flux of the cluster is f_X, then
$$L_X = 4\pi f_X\, d_L^2 = 4\pi f_X\,(1+z)^4\, d_A^2$$
where d_L is the luminosity distance, and we have used $d_L = (1+z)^2\, d_A$ from equation (7.37) in the previous lecture.

- Putting all this together, we get $\dfrac{M_{\rm gas}}{M_{\rm tot}} \propto \dfrac{r_c^{3/2}\, L_X^{1/2}}{r_C} \propto \Big[r_c L_X\Big]^{1/2} \propto \Big[d_A\,(1+z)^4\, d_A^2\Big]^{1/2}$
or, finally,
$$\frac{M_{\rm gas}}{M_{\rm tot}} \propto (1+z)^2\, d_A^{3/2}$$
Through d_A, therefore, the calculated value of $M_{\rm gas}/M_{\rm tot}$ depends on the assumed cosmology.

If we assume that the ratio $M_{\rm gas}/M_{\rm tot}$ is independent of redshift, we can fit cosmological models to the values of this ratio obtained from observations.

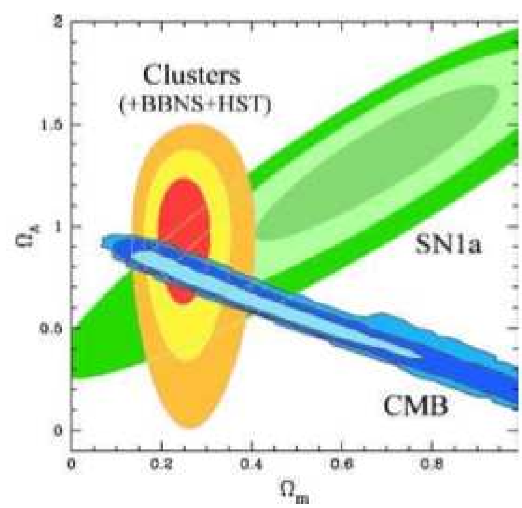


Allen et al. (2004) observed 26 galaxy clusters in the redshift range $0.07 < z < 0.9$ with the Chandra X-ray observatory. Plots of the ratio $M_{\rm gas}/M_{\rm tot}$ (which they call $f_{\rm gas}$) versus the redshift are shown in the figure above for two assumed cosmologies. On the left is the plot for $\Omega_m = 1$ and $\Omega_\Lambda = 0$ with $H_0 = 50$ km s^{-1} Mpc^{-1}, and on the right is the plot for $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$ with $H_0 = 70$ km s^{-1} Mpc^{-1}. Under the assumption that $M_{\rm gas}/M_{\rm tot}$ should be constant with redshift, the data clearly favor the latter cosmology over the former.

Allen et al. (2004) also plotted a grid of cosmological models and their results are shown in the figure on the right. The innermost contour is the one with the highest confidence. The best-fitting parameters are

$$\Omega_m = 0.245 \pm 0.054, \qquad \Omega_\Lambda = 0.96 \pm 0.29$$

(I've combined their systematic and random errors in quadrature). While this is consistent with the Benchmark model within the errors, the method is clearly most sensitive to Ω_m.



By combining their X-ray data on galaxy clusters with Cosmic Microwave Background (CMB) data, Allen et al. (2004) set even tighter constraints close to the Benchmark model. Their best-fitting parameters for the combined fit are

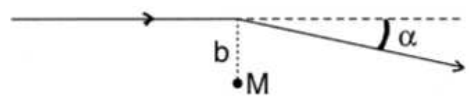
$$\Omega_m = 0.28 \pm 0.06, \qquad \Omega_\Lambda = 0.73 \pm 0.05$$

(Once again, I've combined their systematic and random errors in quadrature).

Gravitational Lensing

So far, we have discussed the gravitational effects of dark matter on baryonic matter. In addition, dark matter also affects the trajectory of photons. That is, dark matter can bend and focus light, acting as a *gravitational lens*.

Such an idea dates back to Einstein himself. Following his publication of the general theory, Einstein predicted that if a photon passes an object of mass M at an impact parameter b (as shown in Figure 8.5 in your text, reproduced on the right), the local curvature of space-time will cause the photon to be deflected at an angle α given by



$$\alpha = \frac{4GM}{c^2 b} \tag{8.48}$$

Therefore, light from a distant star that just grazes the Sun's surface should be deflected by an angle

$$\alpha = \frac{4GM_\odot}{c^2 R_\odot} = 1.7 \text{ arcsec} \tag{8.49}$$

Note that one could work out this deflection using Newtonian gravity and $E = mc^2$ from special relativity, but one would get only half the value compared to that determined from the full general relativity equation. A very short time after Einstein's prediction of the deflection by the Sun, an eclipse expedition photographed stars in the vicinity of the Sun. Comparison of the eclipse photographs with photographs of the same star field taken six months earlier revealed that the apparent positions of the stars were indeed deflected by exactly the amount which Einstein had predicted.

In a similar way, a galaxy or cluster of galaxies can act as a gravitational lens by bending the light from a galaxy or other object directly behind it. If the lensing galaxy or cluster is exactly along the line of sight between the observer and the lensed object, the image produced is a perfect ring (usually called an *Einstein ring*), with angular radius

$$\theta_E = \left(\frac{4GM}{c^2 d} \frac{1-x}{x} \right)^{1/2} \tag{8.50}$$

where M is the mass of the lensing galaxy or gal, d is the distance from the observer to the lensed object, and xd is the distance from the observer to the lensing galaxy or cluster (so $0 < x < 1$). The angular radius θ_E is called the *Einstein radius*.

In practice, we rarely see the full Einstein ring. Instead, we see arc-shaped images into which the background galaxy or object has been distorted. We looked at some of these in lecture, and one of them (Abell 2218) is given in Figure 8.7 in your text.

By looking at these lensed images, we can reconstruct a model of the mass distribution forming the lens, and construct a map of the dark matter distribution in the cluster (as we saw in one of the images shown in lecture).

What we've described so far is usually called *strong lensing*, and are most commonly seen when the lenses are clusters of galaxies or very large galaxies. In a larger number of cases, though, individual galaxies acting as lenses are not strong enough to form giant arcs or multiple images. Instead, the background objects are stretched and magnified, but by such small amounts that it is hard to measure. This is appropriately called *weak lensing*.

With weak lensing, the dark matter distribution cannot be reproduced by looking at any one lensed galaxy. Instead, astronomers look at the average properties of lensed galaxies. By noting the degree to which a group of lensed galaxies appear unusually flat and unusually similar to their neighbors, astronomers can estimate the dark matter distribution producing these weak gravitational lensing distortions.

Finally, another technique that became popular in the 1990's is called *microlensing*, in which the lensing object is usually a smaller object like a star.

- Astronomers used this technique to try and detect the population of massive compact objects in the halo of our Galaxy (called *MACHO*s, short for Massive Compact Halo Objects), because it was believed that this population might form all or part of the dark matter component in the Galactic halo; *note that, in this case, we are expanding the definition of dark matter to include non-luminous or low luminosity baryonic matter.*

- To detect lensing by *MACHO*s in the halo of our Galaxy, various research groups monitored millions of stars in the Large Magellanic Cloud (LMC), one of the nearest galaxies in our neighborhood. Their objective was to detect instances where the light coming from such stars in the LMC would be bent by a *MACHO* in the halo of our Galaxy. Of course, the Einstein ring in such cases is too small to be resolved. Instead, astronomers were looking for changes in the flux of LMC stars. This was because *MACHO*s in our dark halo and stars in the LMC are in constant relative motion. Therefore, the typical signature of a microlensing event is a star which becomes brighter as the angular distance between the star and a *MACHO* decreases, then becomes dimmer as the angular distance increases again. The typical time scale for a lensing event is the time it takes a *MACHO* to travel through an angular distance equal to the Einstein radius θ_E as seen from Earth. Generally speaking, therefore, more massive *MACHO*s produce larger Einstein rings and thus will amplify the lensed star for a longer time.

- In essence, microlensing events produce a very typical light curve with a symmetric rise and fall time. Nevertheless, searching for *MACHO*s is a difficult task, since there are many other reasons for variability, and one has to pick out this typical light curve from amongst many others. The *MACHO* collaboration analyzed about 9.5 million light curves from its 2 yr LMC monitoring and found only 6 to 8 microlensing events.

- Even with the small number of positive detections, the results are significant. The research groups found no short duration microlensing events toward the LMC, suggesting that the dark halo of our Galaxy *does not have* a significant population of brown dwarfs with $M < 0.08\,M_\odot$.

- Instead, the long time scales of the observed lensing events ($\Delta t > 35$ days) suggest typical MACHO masses of $M > 0.1 M_{\odot}$. One possibility is that the *MACHO*s are white dwarfs or neutron stars — the dark remnants of an earlier generation of stars, but this is problematic because if there were enough of these around to be a significant component of the dark matter population, we should have detected the other byproducts of such an early stellar population. Or, perhaps *MACHO*s are primordial black holes, or other exotic objects not currently known. This is possible, but would be surprising.

- Most importantly, perhaps the microlensing events are not due to lenses in the halo of our Galaxy, and therefore are not telling us about the dark matter in the Galactic halo — in a typical microlensing event, the distance of the *MACHO* cannot be determined, and so the location of the lens population cannot be found. Efforts continue to find ways to measure distances to these *MACHO*s (e.g., a microlensing parallax satellite).

Finally, as to the question of what dark matter may be, the short answer is that *we don't know yet*. While *MACHO*s like brown dwarfs, neutron stars, and black holes have been considered as possible candidates for baryonic dark matter, events that occurred early in its history set a ceiling on the baryonic content of the Universe, and therefore, the majority of dark matter is likely nonbaryonic.

- Nonbaryonic dark matter candidates are usually divided into two categories: Hot Dark Matter (HDM), and Cold Dark Matter (CDM). The "hot" and "cold" here refer to speeds: HDM candidates move with high speeds close to the speed of light (ultrarelativistic), whereas CDM candidates travel at slow speeds.

- One candidate that has been considered for HDM is the neutrino, since it is after all a nonbaryonic particle that travels with ultrarelativistic velocities, provided it possesses a small mass. Normally, neutrinos are assumed to be practically massless, but a finite mass is not implausible. Calculations show that a mean neutrino mass of $m_{\nu}c^2 \approx 4$ eV would be required to provide all the nonbaryonic dark matter in the universe. Yet, calculations based on oscillations from one form of neutrino into another show a mass closer to 0.05 eV (maximum). This means that neutrinos could make up no more than 0.5% of the nonbaryonic dark matter. HDM candidates have fallen out of favor because such ultrarelativistic particles make it hard to account for the generation of structure on the scale of galaxies in the universe (although they would be good at forming larger scale structures like superclusters).

- Instead, the currently favored model is a CDM model, which requires particles sufficiently massive that they move at slow velocities. The potential candidates are called WIMPS, short for Weakly Interacting Massive Particles. Particle physicists have provided many candidates, and significant efforts are ongoing, but no WIMPS have been detected to date. Some WIMPs may mutually annihilate when pairs of them interact, and produce gamma rays. Recently (Physical Review Letters, Dec 2011), scientists published results from an examination of two years of data from the Fermi-Large Area Telescope (LAT). They looked at LAT-detected gamma rays with energies in the range from 200 MeV to 100 GeV from ten of the roughly two dozen dwarf galaxies known to orbit the Milky Way. No gamma-ray signal consistent with the annihilations expected from four different types of commonly considered WIMP particles was found. These results show for the first time that WIMP candidates within a specific range of masses and interaction rates cannot be dark matter.