10 Lecture 10: Cosmic Inventory II: Baryonic and Dark Matter

"The least deviation from the truth is multiplied later."

Aristotle

The Big Picture: Last time we talked about the radiation contents of the Universe: photons and neutrinos and their relative abundances. Today we are going to talk about the dark matter — its historical background, evidence for it and its importance.

Baryonic Matter

When using the term "baryonic matter", both baryons and electrons are implied. Electrons are not baryons, but leptons, but given that the mass of an electron is nearly 2000 times smaller than the mass of a proton or a neutron, electron contribution is negligible.

Unlike the energy density of CMB radiation, which can be described as a gas with a temperature and vanishing chemical potential, the baryonic density must be directly measured. The different methods which measure baryonic density at varying redshifts z largely agree to be about $2 - 5\%$ of the critical density *today*:

$$\Omega_{\rm b}\big|_{\rm today} \equiv \Omega_{\rm b0} \equiv \frac{\rho_{\rm b0}}{\rho_{\rm cr0}} = 0.02 - 0.05. \qquad (227)$$

We also know that the total amount of baryonic matter is constant, so with the expanding Universe, the fractional energy density scales as $\rho_{\rm b} \propto a^{-3}$, so

$$\Omega_{\rm b} = \frac{\rho_{\rm b}}{\rho_{\rm cr0}} = \frac{\rho_{\rm b0}}{\rho_{\rm cr0}} a^{-3} = \Omega_{\rm b0} a^{-3}. \qquad (228)$$

Several methods are used to gauge the baryon content of the Universe:

1. Directly observing visible matter in galaxies. It has been found that the largest contribution comes from the gas in galaxy clusters, while stars in galaxies account for only a comparatively small fraction. This approach estimates $\Omega_{\rm b0} = 0.02$.

2. Looking at spectra of distant galaxies, and measuring the amount of light absorption. The amount of light absorbed quantifies the amount of hydrogen the light encounters along the way. Baryon density is then inferred from the estimate of the amount of hydrogen. This approach roughly estimates $\Omega_{\rm b0} h^{1.5} \approx 0.02$ (Rauch *et al.* 1997, *Astrophysical Journal*, **489**,7).

3. Computing the baryon content of the Universe from the anisotropies of the CMB radiation. This approach puts fairly stringent limits on the baryon content to about $\Omega_{\rm b0} h^2 = 0.024^{+0.004}_{-0.003}$.

4. Inferring the baryon content of the Universe form the light element abundances. These pin down the baryon content to $\Omega_{\rm b0} h^2 = 0.0205 \ \pm 0.0018$.

These estimates are in fairly good agreement. They put a rough baryonic content of the Universe at about $2 - 5\%$ of the critical density. However, as we shall soon see, the total matter density in the Universe is significantly higher than that, so there must be another form of matter other than baryonic.

Dark Matter

The first evidence of what later was named *dark matter* was provided by a Swiss astrophysicist Fritz Zwicky in 1933. He used the virial theorem to show that the observed (luminous) matter was not nearly enough to keep Coma cluster of galaxies together.

For nearly four decades the "missing mass problem" was ignored, until Vera Rubin in the late 1960s and early 1970s measured velocity curves of edge-on spiral galaxies to an theretofore unprecedented accuracy. To the great astonishment of the scientific community, she demonstrated that most stars in spiral galaxies orbit the center at roughly the same speed, which suggested that mass densities of the galaxies were uniform well beyond the location of most of the stars. This was consistent with the spiral galaxies being embedded in a much larger halo of invisible mass ("dark matter halo").

One of the oldest and most straightforward methods for estimating the matter density of the Universe is the mass-to-light ratio technique. The average ratio of the observed mass to light of the largest possible system is used; assuming that the sample is fair, it can be multiplied by the total luminosity density of the Universe to obtain the total mass density $\rho_{\rm m}$. Zwicky was the first to do this with a Coma cluster, but many followed.

Evidence for dark matter: mass-to-light (M/L) ratios. Astronomical observations of individual galaxies provide us with the (line-of-sight) radial luminosity distribution $I(R)$ and the velocities of stars orbiting the center of the galaxy $v(R)$. From the luminosity distribution, the deprojected density of the *luminous matter* $\rho_l(r)$ is computed by Abel integral:

$$\rho_l(r) = -\frac{1}{\pi}\int_r^\infty \frac{dI}{dR}\frac{dR}{\sqrt{R^2-r^2}}, \tag{229}$$

where R denotes the projected radius (as seen in the plane of the sky), and r the spatial (deprojected) radius. From this spherical approximation to the density distribution of the galaxy, the predicted rotation curves due to this luminous matter *alone* can be computed as follows:

$$\frac{m_\star v_l^2}{r} = G\frac{m_\star M(r)}{r^2} \qquad \Rightarrow \qquad v_l = \sqrt{\frac{GM(r)}{r}}, \tag{230}$$

where

$$M(r) = 4\pi\int_0^r \rho_l(r) r^2 dr, \tag{231}$$

the galaxy mass enclosed within the sphere of radius r (recall Newton's law that the force of an isotropic massive sphere at radius r is equivalent to the force due to the point mass with mass $M(r)$). The equation above is simply balancing the gravitational pull of the stars within the sphere traced out by the rotating star and its centripetal force. This $v_l(r)$ is represented by the sum of the contributions of gas and stars in the Fig. 13, which corresponds to the long- and short-dashed lines.

Kinematic observations of individual stars at different radii give us what the true rotation curves are, *i.e.*, what the actual velocity of stars $v(r)$ as the function of radius is. This is shown by points in Fig. 13.

Through the measurements of mass-to-light ratios (which in the absence of dark matter is unity), it has been demonstrated that galaxies, clusters of galaxies and super-clusters have a significant non-luminous massive component – the dark matter.

Figure 14 shows the inferred mass-to-light ratios of many systems, ranging from galaxies to super-clusters. The ratio was first measured on small scales, implying that the density in the

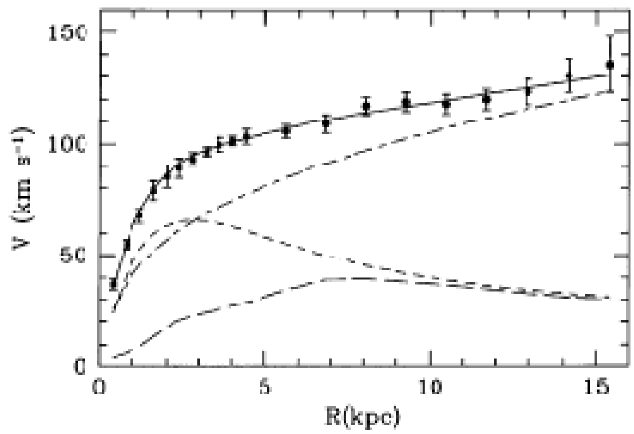

Figure 13: Spiral galaxy M33 (2.5 million light-years away; member of the Local Group of galaxies): image (left) and the observed rotation curves (points) approximated by the best-fitting model (solid lines). Luminous light contribution is from the stellar disc (short-dashed lines), and from the gas (long-dashed lines). The contribution from the dark-matter halo dominates, especially at large radii (dot-dashed line).

Universe is far below critical. As more large-scale measurements came in, the initially linear increase in mass-to-light ratio led some to think that eventually the trend would continue until the critical density is reached, *i.e.*, $\Omega_{\rm m} = \Omega_{\rm T} = 1$. However, it has been shown (see Fig. 14) that mass-to-light ratios do not increase beyond $R \approx 1$ Mpc. The leveling off in the mass-to-light ratio occurs consistent with matter density $\Omega_{\rm m0} \approx 0.3$. Because the total amount of matter is constant, the fractional energy density scales as $\rho_{\rm m} \propto a^{-3}$, so

$$\Omega_{\rm m} = \frac{\rho_{\rm m}}{\rho_{\rm cr0}} = \frac{\rho_{\rm m0}}{\rho_{\rm cr0}} a^{-3} = \Omega_{\rm m0} a^{-3}. \tag{232}$$

More evidence for dark matter. There are other methods which independently prove and quantify the dark matter in the Universe. They include:

- *Gravitational lensing*. Direct consequence of GR: trajectory of a photon is affected by the curvature of spacetime induced by the presence of a massive object (lens).
  - *Weak*: small distortions in the shapes of background galaxies can be created via weak lensing by foreground galaxy clusters. Statistical averaging of these small distortions yields mass estimates of the cluster.
  - *Strong*: light rays leaving a source in different directions are focused on the same spot (the observer here on Earth) by the intervening galaxy or cluster of galaxies. It produces multiple distorted images of the source from which the mass and shape of the lens can be inferred. See Fig. 15.

  The first application of gravitational lensing provided the first and the most notable confirmation of GR: solar eclipse in 1919 confirmed that the Sun bends light which passes near it.

- The baryons-to-matter (baryons and dark matter) ratio in clusters of galaxies, which are the largest known virialized objects, are likely representative of the Universe as a whole. If a good estimate of the baryonic matter $\Omega_{\rm b}$ is adopted from the previously described methods,

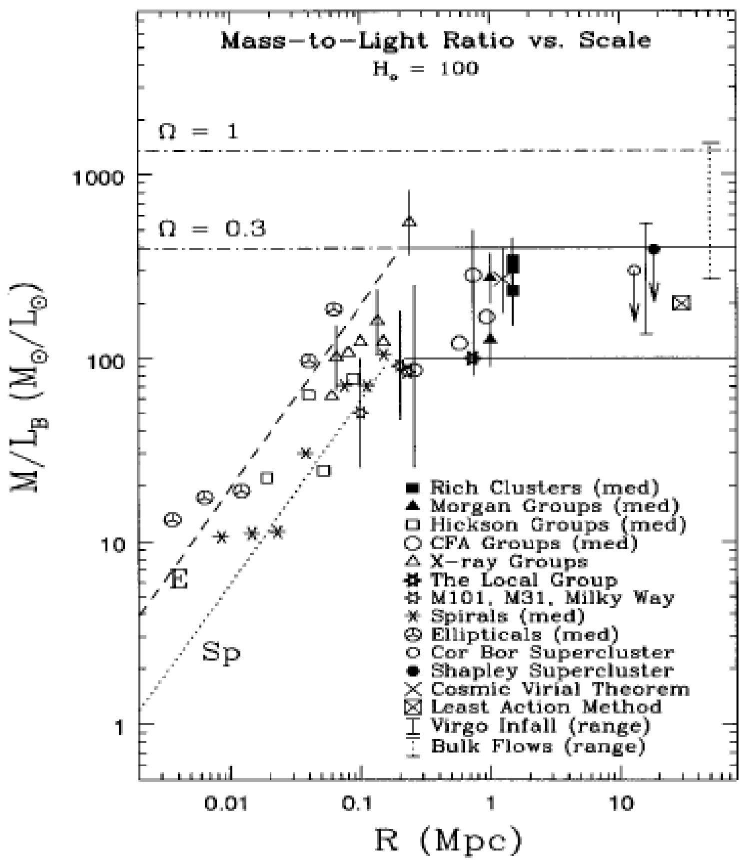

Figure 14: Mass-to-light ratio as a function of scale (Bahcall, Lubin & Dorman 1995, *Astrophysical Journal*, 447, L81). The ratio flattens out to $\Omega_{\rm m} \approx 0.3$ on largest scales.

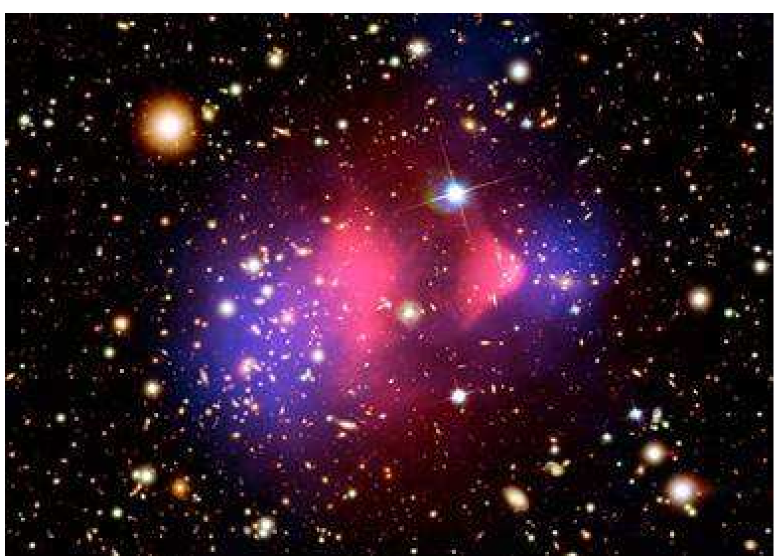

Figure 15: Composite image of the Bullet cluster shows distribution of ordinary matter, inferred from X-ray emissions, in red and total mass, inferred from gravitational lensing, in blue.

measuring the the baryons-to-matter ratio $f_b \equiv \Omega_{\rm b}/\Omega_{\rm m}$ in these clusters will yield the estimate of the fractional density of matter $\Omega_{\rm m}$. The visible (baryonic) matter in clusters of galaxies is largely in hot ionized intracluster gas, with only a small, negligible fraction in stars (about an order of magnitude smaller). This means that the ratio f_b is well-approximated by the ratio of gas-to-matter f_g, which can be measured via:

  - *X-ray spectrum*: measure the mean gas temperature from the overall shape of the X-ray spectrum, and the absolute value of the gas density from the X-ray luminosity.
  - *Sunyaev-Zeldovich effect*: as the CMB radiation passes through the super-cluster whose baryonic mass is dominated by gaseous ionized intracluster medium (ICM), a fraction of photons inverse-Compton scatter off the hot electrons of the ICM. The intensity of the CMB radiation is therefore diminished as compared to the unscattered CMB. This decrease is in magnitude proportional to the number of scatterers, weighted by their temperature.

- Anisotropies in the CMB radiation.

These independent methods, along with others not mentioned here, provide a compelling body of evidence that the baryon density is of order of 5% of the critical density, while the total matter density is about five times larger. This clearly states that most of the matter in the Universe must not be baryons. It must be in some other form — dark matter.

From the standpoint of cosmology, the curvature of the Universe and the cosmic inventory, dark matter is treated on equal footing with baryonic matter — it scales with the expanding Universe as $\rho_{\rm dm} \propto a^{-3}$ and contributes to the total energy density budget of the Universe.