Lecture Note #1: Dark Matter in the Cosmos

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1 Evidence for Dark Matter

Observations of the Universe over astronomical distances suggest there is much more matter than what we can see [1]. From the rotation of single galaxies, to the motion of galaxy clusters, to the distribution of stars across the observable sky, to the pattern of temperature fluctuations in the cosmic microwave background (CMB), much more matter seems to be required than what we can account for using the physics we know. This missing matter is called *dark matter* (DM).

1.1 DM and the CMB

The pattern of temperature fluctions in the $T \simeq 2.725\,K$ cosmic microwave background (CMB) carry a great deal of information about the evolution of the Universe between *recombination* and today [2]. At recombination, which occurred at a redshift of $z \simeq 1100$, free electrons and protons came together to form neutral hydrogen, and the Universe become essentially transparent to photons.[1] The CMB radiation we see today consist of the photons left over at the end of recombination. Therefore, the CMB gives us a snapshot of the Universe at $z \simeq 1100$ reprocessed by expansion history since then.

By examining the pattern of CMB temperature fluctuations, it is possible to deduce the fractions of dark energy, total matter, baryonic matter, and radiation in the Universe today. In Fig. 1, we show the dependence of the CMB temperature power spectrum on different values of the baryon density and the total matter density. In Fig. 2, we show we show the implications of the CMB data on the energy contents of the Universe together with complementary data from supernova surveys and baryon-acoustic oscillations (BAO).

Defining the energy fractions according to $\Omega_i = \rho_i/\rho_c$, where $\rho_c = 3H_0^2/8\pi G \simeq 8.1\,h^2 \times 10^{-47}$ GeV^4 ($h \simeq 0.704 \pm 0.014 = H_0/100\text{kms}^{-1}\text{Mpc}^{-1}$) is the critical density, the combined data gives [3]

$$\begin{aligned} \Omega_{tot} &= 1.0023 \pm 0.0055 \\ \Omega_\Lambda &= 0.728 \pm 0.016 \\ \Omega_m h^2 &= 0.1383 \pm 0.0035 \\ \Omega_b h^2 &= 0.0260 \pm 0.00053 \end{aligned} \tag{1}$$

where Λ refers to dark energy, m to the total (non-relativistic) matter, and b to the baryonic matter (which includes all known particles that aren't relativistic at recombination, including

[1]Recall that we define the redshift z according to $z = \lambda_0/\lambda_1 - 1$, where λ_0 is the wavelength today and λ_1 is the wavelength at emission.

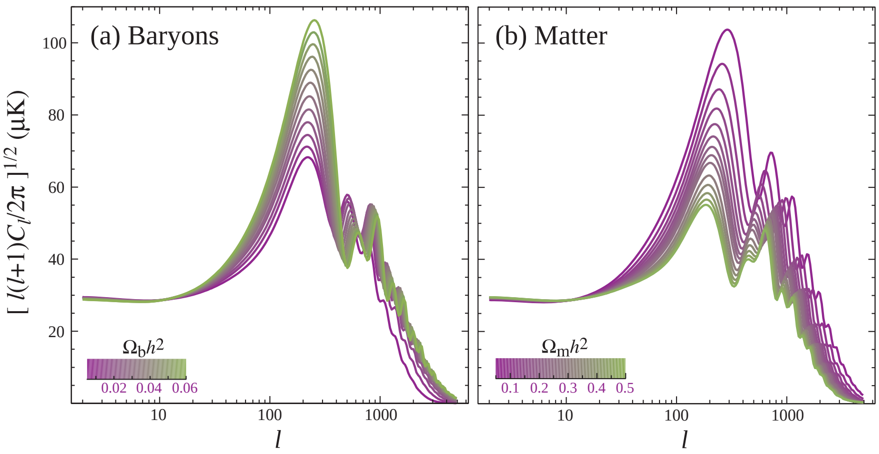

Figure 1: The effect of varying the density of baryons(left) or total matter (right) on the CMB temperature power spectrum, from Ref. [2].

electrons). Not surprisingly, the density of dark matter is defined to be the difference between Ω_m and Ω_b:

$$\Omega_{DM}h^2 = \Omega_m h^2 - \Omega_b h^2 = 0.1123 \pm 0.0035\ . \tag{2}$$

Note that this is quite a precise determination.

As a cross-check, we can also compare the density of baryons determined from the CMB (and SN+BAO) with value that is consistent with Big-Bang Nucleosynthesis (BBN) [5]. In BBN, free protons and neutrons bind to form the light elements. The underlying nuclear physics is understood very well, and starting from the total density of baryons, the relative densities of hydrogen, helium, deuterium, and lithium can be predicted. The value of $\Omega_b h^2$ found this way is consistent with the CMB value (although some of the lithium isotope densities seem to be a bit off).

1.2 DM from Astrophysics

Evidence for dark matter can also be found in many astrophysical systems. This includes the rotation curves of galaxies, the motions of galaxies within galaxy clusters, surveys of galaxy clusters by gravitational lensing, and even the overall distribution of visible matter over very large distances in a *filaments and voids* pattern [6, 7, 8]. Relative to the evidence from the CMB described above, the apparent signals of DM in these cases correspond to effects over much smaller distance scales. It is the multitude of hints pointing towards the existence of DM that make this story so compelling.

In many of the galaxies we can see, the material within them is rotating. The net rate of rotation $v(r)$ can be deduced by measuring the redshift of light coming from them, while the total visible luminosity (and surveys in other frequencies that are more sensitive to dust) is expected to trace the mass of the system. Applying what we know about gravity to such

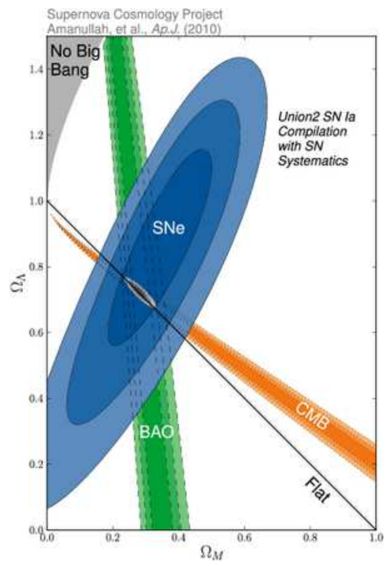

Figure 2: Combined fits to the CMB spectrum, supernova surveys, and BAO. From Ref. [4].

systems, we can compare the observed rotation velocity to what we would predict based on the visible mass distribution. A typical result is shown in Fig. 3, from which it is evident that the visible matter is unable to account for the observed rotation.

Let us suppose instead that the galaxy is embedded within a spherical *halo* of dark matter. Applying Newtonian gravity, one finds

$$v(r) = \sqrt{\frac{GM_<(r)}{r}}\ , \tag{3}$$

where $M_<(r)$ is the total mass within the radius r. For a mass distribution $\rho(r) \propto r^n$, we find $v(r) \propto r^{n/2-1}$. Observationally, the rotation curves typically approach a constant value, implying $n = 2$ and $\rho(r) \propto 1/r^2$ at large radii.

Individual galaxies are frequently found within self-gravitating galaxy clusters, in which the galaxies making them move around under their mutual gravitational influence. While this motion is very complicated, we can described its mean properties using the virial theorem. Applied here, it gives

$$v^2 \sim \frac{GM}{R}\ , \tag{4}$$

where v^2 and R represent typical values, and M is the total mass. Using only the visible mass in this estimate, the predicted value of v^2 is much less than what is observed. In fact, it was precisely this observation that led Fritz Zwicky to first propose DM in 1933.

The amount of matter within galaxy clusters can also be probed through gravitational lensing. By surveying the distortion of light from sources behind a cluster, its total mass distribution can be mapped out. These surveys also find much more matter than what can be accounted for by ordinary matter.

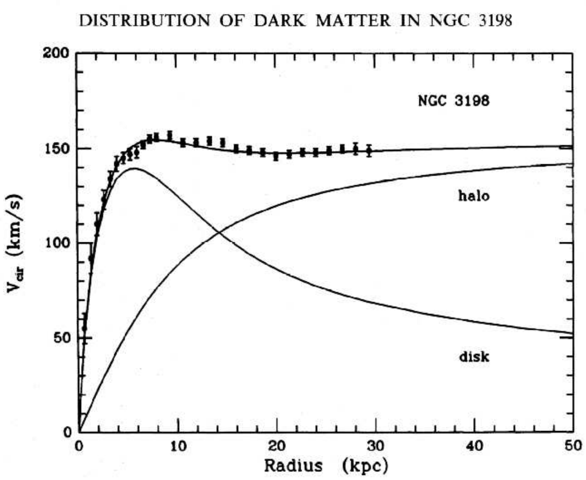

Figure 3: Observed and predicted rotation curves for the spiral galaxy ....

A particularly spectacular example of a lensing survey is the bullet cluster [9], which we show in Fig. 4. This is thought to be the aftermath of a collision between a pair of galaxy clusters. Here, the blue areas trace out the total matter distribution, while the red areas show the map of ordinary matter based on x-ray emission. The interpretation is that the dark matter components of the clusters passed right through each other, while the baryonic components collided in the middle to create shock waves.

1.3 DM and Structure

The distribution of matter in the Universe is found to be very uniform over large distances, above about 100 Mpc. We illustrate this using a map by the 2dF galaxy survey in Fig. 5. Even so, the local fluctuations in the density of matter carry a lot of information, much like the CMB. This fluctuation spectrum can be measured from galaxy surveys, lensing surveys, and from dust maps made by observing the absorption of light by the Lyman alpha line in the hydrogen spectrum. It is found that DM is needed to account for the observed spectrum.

1.4 DM and Other Possibilities

All the evidence we have for DM is based on its gravitational influence on visible matter. A very good description of the data is obtained if we assume the existence of new source of matter with the properties:

1. non-luminous
2. non-relativistic
3. very weakly interacting with itself and with visible matter

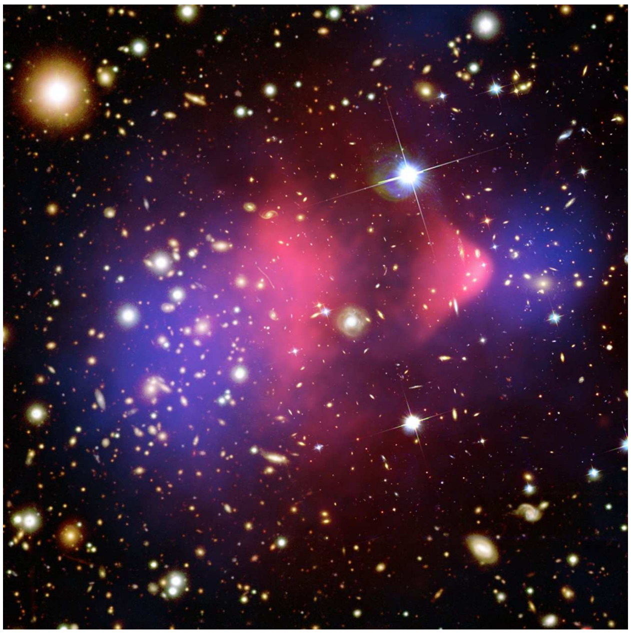

Figure 4: Matter (blue) and baryon (red) distributions within the bullet cluster.

No known elementary particle has these properties, and therefore the existence of DM points towards new and interesting particle physics.

Unfortunately, all our evidence for DM comes from its gravitational influence on visible matter. A logical alternative to DM is that gravity does not work the way we think it does (which is General Relativity). Many attempts have been made to formulate theories of modified gravity, but it has proven difficult to explain all the evidence for DM within these theories. For this reason, DM has been investigated much more thoroughly by cosmologists.

In this course we will focus on the DM hypothesis and its implications for elementary particle physics. One of the main themes will be searches for DM using interactions other than gravity. A discovery in DM in this way would both confirm the DM hypothesis and tell us about the microscopic properties of the DM particle.

2 Distributions of DM

Dark matter plays a key role in determining the distribution of visible matter in the Universe. In this section we will discuss how DM is distributed throughout our Universe.

Before getting into specifics, let us first outline how a smooth initial distribution of DM evolved into the less-than-homogeneous pattern we seem to see today. Within the ΛCDM model and assuming an early period of inflation, quantum fluctuations in the inflaton field gave rise to small fluctuations in the density of matter in the Universe over very small and very large (super-horizon) distances. After inflation, these fluctuations evolved under the

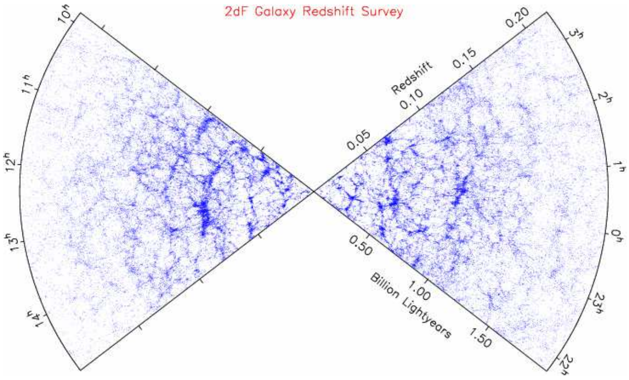

Figure 5: Galaxy survey by the 2dF Collaboration.

influence of the Hubble expansion and particle interactions. Fluctuations in the density of DM began growing in earnest when matter become the dominant source of energy in the Universe at $z = z_{eq} \simeq 3200$. On the other hand, fluctuations in the density of baryons are delayed until recombination at $z \simeq 1100$ because of their strong coupling to photons.

When a fluctuation grows large enough, it begins to self-gravitate and is said to become *non-linear* (because we can no longer describe it reliably using linearized equations). This process happens first for DM. Once it does, the resulting clumps of DM are potential wells for baryons, pulling them in. Thus, DM acts as a scaffolding upon which baryons can attach, cluster, and form stars and galaxies. In particular, we expect that the visible matter in the Universe should trace the distribution of DM.

2.1 Large-Scale (DM) Structure

As mentioned above, the spectrum of fluctuations in the density of visible matter carry a lot of information. This information is similar but complementary to the information carried in the spectrum of temperature fluctuations in the CMB. We can characterize the fluctuations according to ...

2.2 Galactic DM

Popular Fits:

- (α, β, γ)

$$\rho(r) = \rho_\odot \left(\frac{r_\odot}{r}\right)^\gamma \left[\frac{1 + (r_\odot/r_s)^\alpha}{1 + (r/r_s)^\alpha}\right]^{(\beta-\gamma)/\alpha} \tag{5}$$

where $\rho_\odot \simeq 0.3$ GeV/cm^3 and $r_\odot = 8.5\,$kpc, along with:

$$\begin{array}{c|cccc} \text{Profile} & \alpha & \beta & \gamma & r_s(\text{kpc}) \\ \hline \text{NFW} & 1 & 3 & 1 & 20 \\ \text{Moore} & 1 & 3 & 1.16 & 30 \\ \text{Iso-Core} & 2 & 2 & 0 & 5 \end{array} \qquad (6)$$

- Einasto:

$$\rho(r) = \rho_\odot \exp\left(-\frac{2}{\alpha}\left[\left(\frac{r}{r_\odot}\right)^\alpha - 1\right]\right) , \qquad (7)$$

with $1.0 \lesssim \alpha \lesssim 2.0$.

References

[1] Some of the many nice textbooks on cosmology include:
E. W. Kolb and M. S. Turner, "The Early universe," Front. Phys. **69**, 1 (1990);
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[2] For a nice review of CMB physics, see:
W. Hu, "Lecture Notes on CMB Theory: From Nucleosynthesis to Recombination," [arXiv:0802.3688 [astro-ph]].

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[5] A nice review of BBN:
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