Cosmology

Summer Term 2020, Lecture 08

Rainer Verch

Inst. f. Theoretische Physik
Universität Leipzig
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Dark matter: Rotation curves of galaxies

For galaxies which are sufficiently close, on observing them edge on, one can use the Doppler effect induced blue/redhift from the rotation of the spiral arms (similar to the priciple underlying the Tully-Fisher relation) to actually measure the rotation velocity of the spiral arms at various radii from the galactic center. For many galaxies, it has been found that the rotation velocity does not decrase with growing radius from the center but stays almost constant. Since the luminous matter concentration in a galaxy decreases with increasing radius from the center, by Newtonian gravity the rotation velocity should decrease with increasing radius from the center since otherwise the outer part of the galaxy wouldn't remain gravitationally bound to the galaxy's center (the "bulge").

Simplified argument: Assume a spherically symmetric mass distribution with constant mass density ϱ_0 with radius r (i.e. a ball of radius r with constant mass density ϱ_0. The total mass of this mass distribution is $M_r = (4\pi/3)\varrho_0 r^3$. The (modulus of the) gravitational force on a test mass m_T at some radius $R > r$ from the center of the mass distribution is, by Newton's gravitational law, given by $F_g = Gm_T M_r/R^2$ (where G is Newton's gravitational constant). If the test mass is on a circular orbit of radius R around the center of the mass distribution, the (modulus of the) centripetal force needed for the trajectory is $F_c = m_T v_R^2/R$ where v_R is the tangential velocity (assuming v_R is much smaller than the velocity of light). Equating F_g and F_c yields

$$v_R = \sqrt{GM_r/R}$$

for the test mass to stay on a gravitationally bound orbit of radius R around the spherically symmetric mass distribution.

Dark matter: Rotation curves of galaxies

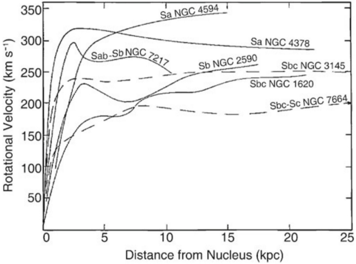


Fig. 3.22 Examples of rotation curves of spiral galaxies. They are all flat in the outer region and do not behave as expected from Kepler's law if the galaxy consisted only of luminous matter. Also striking is the fact that the amplitude of the rotation curve is higher for early-type than for late-type spirals. Source: V. Rubin et al. 1978, *Extended rotation curves of high-luminosity spiral galaxies. IV—Systematic dynamical properties, SA through SC*, ApJ 225, L107, p. L109, Fig. 3. ©AAS. Reproduced with permission

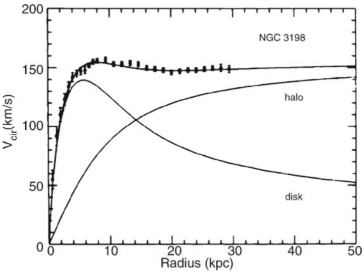


Fig. 3.23 The flat rotation curves of spiral galaxies cannot be explained by visible matter alone. The example of NGC 3198 demonstrates the rotation curve which would be expected from the visible matter alone (curve labeled 'disk'). To explain the observed rotation curve, a dark matter component has to be present (curve labeled 'halo'). However, the decomposition into disk and halo mass is not unambiguous because for it to be so it would be necessary to know the mass-to-light ratio of the disk. In the case considered here, a 'maximum disk' was assumed, i.e., it was assumed that the innermost part of the rotation curve is produced solely by the visible matter in the disk. Source: T.S. van Albada et al. 1985, *Distribution of dark matter in the spiral galaxy NGC 3198*, ApJ 295, 305, p. 309, Fig. 4. ©AAS. Reproduced with permission

Rotation curves of galaxies, showing that the rotation velocity is roughly constant over the luminous galaxy extension. Taken from Peter Schneiders book.

This effect indicates that there may be a large (in fact, dominant) amount of mass within the neighbourhoods of galaxies which is not luminous, or even doesn't participate in the electromagnetic interaction. It is commonly referred to as **dark matter**.

Other indictions for dark matter:

- Observations of the motion of galaxies in the Coma galaxy cluster led Fritz Zwicky ($\sim$ 1933) to conjecture that the mass content in the cluster must exceed the amount of luminous matter. Similar observations have been made on other galaxy clusters.
- The gravitational lens effect observed in galaxy clusters and galaxy mergers also points to a higher mass content in galaxies than is accounted for by the luminous matter observed.
- Large computer simulations of the evolution of the Universe also indicate that there must be a large amount of dark matter in order to explain galaxy formation at the observed time-scales.

The precise nature of the **dark matter** effect is not fully settled and still poses a challenge for gravitational physics, astrophysics, particle physics and cosmology.

The mainstream opinion is that the missing mass is due to a so far not observed type of stable elementary particle. It would need to have features similar to neutrinos in interacting very weakly with other forms of matter and electromagnetism, but much heavier to account for the missing mass. Such a hypothetical type of particle is called WIMP (for *weakly interacting massive particle*).

Other possible, but less favoured explanations are:

- There is more mass of conventional type in galaxies which is just not detected because of low luminosity (brown dwarfs, black holes, gas).
- Additionally, relativistic effects, local rotational energies and gravitational binding energies are underestimated.
- The law of gravity is different at certain length scales (sometimes dubbed MOND for *modified Newtonian dynamics*).

We will not discuss the reasons why these alternative explanations appear less favourable than the WIMP hypothesis. However, the WIMP explanation isn't without problems and the issue of dark matter remains part of present discussion and investigation.

The Universe at large scale: Galaxy counts and redshift surveys

At the largest scales, the Universe shows a homogeneous and isotropic distribution of luminous matter. In the following 3 slides there are illustrations of observations providing evidence for this point of view (all taken from Peter Schneider's book – see for further discussion). The first is a galaxy count survey. The other two are galaxy redshift surveys.

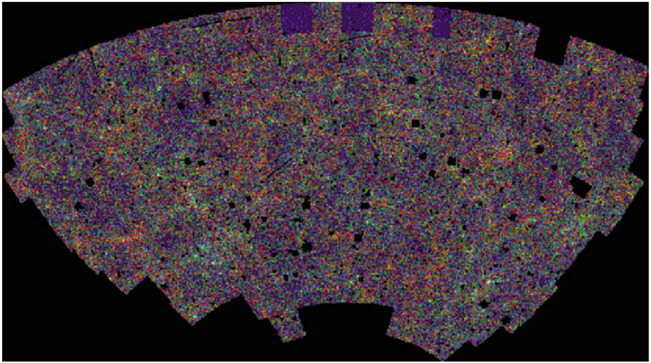
The basic picture that these observations provide is:

- The overall distribution of galaxies is largely homogeneous and isotropic – there are no particular regions in the sky showing very large or systematic deviations from the average galaxy density distribution.
- The scale of the observable Universe so far is $\approx 13 G\ell y$. At a scale of up to $0.8 G\ell y$ (roughly 5% of the largest scale), there are significant density variations: Galaxies tend to arrange in large band-like/web-like structures (also called "walls" or "filaments"), and there are large regions with very low luminous matter density in between ("grand voids"). At larger scale, the web structure becomes homogeneous and isotropic, like a woven piece of cloth viewed from a couple of decimeters.

That picture is also corroborated by computer simulations, as shown in an illustration on a 4th slide taken from Peter Schneider's book.

Large scale matter distribution: Galaxy counts

Fig. 4.1 The APM-survey: galaxy distribution in a $\sim 100 \times 50\,\text{degree}^2$ field around the South Galactic Pole. The intensities of the pixels are scaled with the number of galaxies per pixel, i.e., the projected galaxy number density on the sphere. The 'holes' are regions around bright stars, globular clusters etc., that were not surveyed. Credit: S. Maddox, W. Sutherland, G. Efstathiou & J. Loveday, with follow-up by G. Dalton, and Astrophysics Dept., Oxford University



Large scale matter distribution: Galaxy redshift surveys

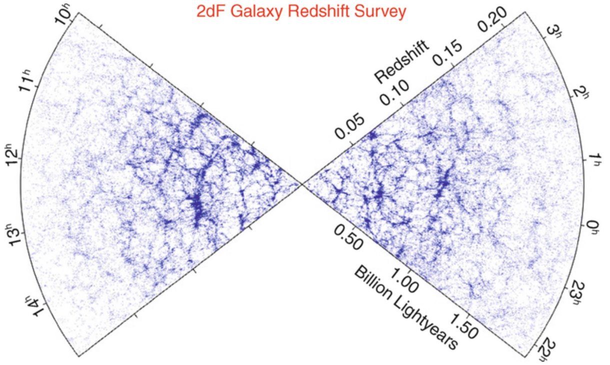
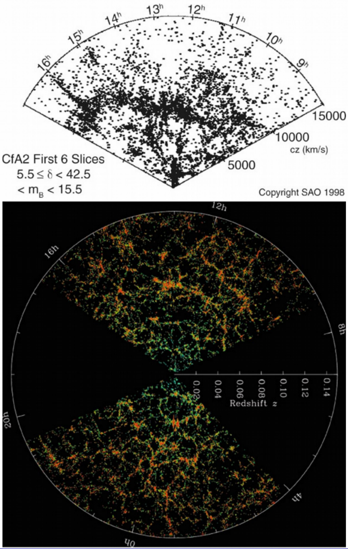


Fig. 7.1 The distribution of galaxies in the complete 2dF Galaxy Redshift Survey. In the radial direction, the escape velocity, or redshift, is plotted, and the polar angle is the right ascension. According the Hubble law, the redshift is directly related to the distance of an object, so that redshift surveys map the three-dimensional distribution of galaxies, with our Galaxy at the center of the figure. In the 2dFGRS, more than 350 000 spectra were taken between 1997 and 2002; plotted here is the distribution of more than 200 000 galaxies with reliable redshift measurements. The data from the complete survey are publicly available. Credit: M. Colless and the 2dF Galaxy Redshift Survey team

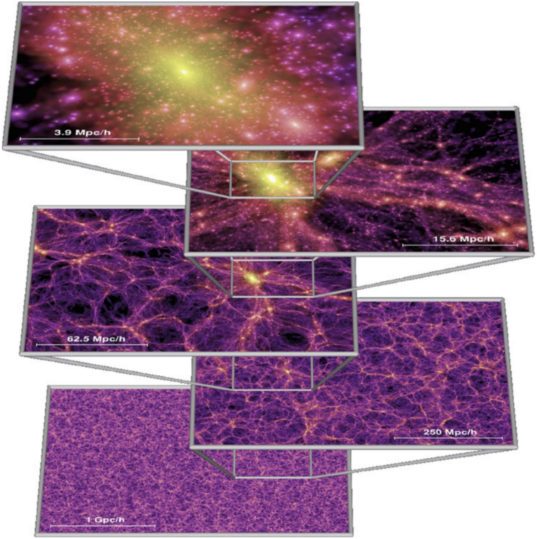
Large scale matter distribution: Galaxy redshift surveys

Fig. 7.2 *Top:* In the CfA galaxy redshift survey, carried out in the 1980s, a large coherent structure of galaxies was found, called the Great Wall. Shown are galaxies with radial velocities of $cz \leq 15\,000\,\mathrm{km/s}$, with declination $8.5° \leq \delta \leq 42°$. The Great Wall is located at a redshift of $cz \sim 6000\,\mathrm{km/s}$, extending in right ascension between $9^{\mathrm{h}} \leq \alpha \leq 16^{\mathrm{h}}$. *Bottom:* The distribution of galaxies as measured from the Sloan Digital Sky Survey. Plotted are galaxies in the narrow declination range $-1.25° \leq \delta \leq 1.25°$. Note that this distribution extends to considerably larger distances than the one in the CfA survey. The *color of the points* indicates the color of the galaxies. The most remarkable feature seen is the long filament of galaxies near the center of the upper part of the figure, called the Sloan Great Wall. Credit: *Top*: J. Huchra, M. Geller, Harvard-Smithsonian Center for Astrophysics. *Bottom*: M. Blanton and the Sloan Digital Sky Survey



Large scale matter distribution: Computer simulations

Fig. 7.13 Distribution of matter in slices of thickness $15h^{-1}$ Mpc each, computed in the Millennium Simulation. This simulation took about a month in 2004, running on 512 CPU processors. The output of the simulation, i.e., the position and velocities of all 10^{10} particles at 64 times steps, has a data volume of ~ 27 TB. The region shown in the two lower slices is larger than the simulated box which has a sidelength of $500h^{-1}$ Mpc; nevertheless, the matter distribution shows no periodicity in the figure as the slice was cut at a skewed angle to the box axes. Source: V. Springel 2005, *Simulating the joint evolution of quasars, galaxies and their large-scale distribution*, Nature 435, 629, Fig. 1. Reprinted by permission of Macmillan Publishers Ltd: Nature, ©2005



CMB – cosmic microwave background

As mentioned, one of the central observations in cosmology is the cosmic microwave background, a microwave radiation with an near-perfect thermal spectrum at equilibrium temperature $T = 2.73\,\mathrm{K}$. The radiation is also very uniform in its intensity and the relative spherical temperature variations, i.e. the degree of temperature anisotropy, is very small, in the range of $10^{-5}...10^{-4}$ and follows roughly a Gaussian (random) distribution.

In the following 2 slides (again taken from Peter Schneider's book), the measurements of the CMB and its temperature anisotropies from the COBE, WMAP and Planck space probe missions are shown.

This points at a very homogeneous and isotropic distribution of radiation at very large distances, and in the hot big bang picture as source of the CMP, at a highly homogenous and isotropic distribution of the plasma prior to the release of the CMB.

Potential alternative origins of the CMB other than from a hot big bang scenario (and expanding Universe) have been discussed but have not been regarded as convincing (like e.g. a cumulative effect from averages of the peculiar motions of galaxies relative to the terrestial observer). There is some good summary of these discussions in Weinberg's book.

CMB and its anisotropies: COBE and WMAP

Illustrations of COBE and WMAP measurements over the celestial sphere. The red bands in the middle originate from the Milky Way foreground.

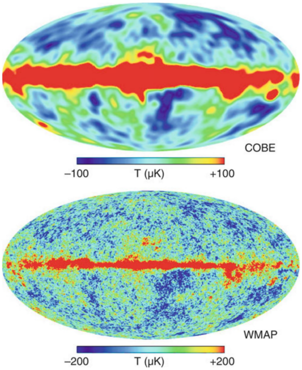


Fig. 8.43 Comparison of the CMB anisotropy measurements by COBE (*top*) and the first-year measurement of WMAP (*bottom*), after subtraction of the dipole originating from the motion of the Sun relative to the CMB rest frame. The enormously improved angular resolution of WMAP is easily seen. Although these maps were recorded at different frequencies, the similarity in the temperature distribution is clearly visible; apart from the different resolution and noise properties, these two maps are essentially indistinguishable. Thus, the COBE results were, for the first time, confirmed independently. Source: C.L. Bennett et al. 2003, *First-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Preliminary Maps and Basic Results*, ApJS 148, 1, p. 15, Fig. 7. ©AAS. Reproduced with permission

CMB and its anisotropies: Planck spectra

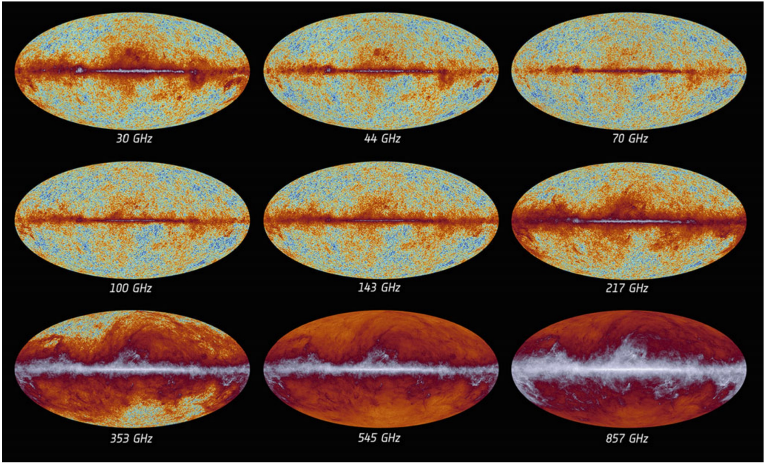


Fig. 8.46 The sky as seen by Planck: All-sky maps in the nine frequency bands of the Planck satellite. Credit: ESA and the Planck Collaboration