Dark Matter

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Contents

Summary

A review of the development of the concept of dark matter is given. The dark matter story passed through several stages on its way from a minor observational puzzle to a major challenge for theory of elementary particles.

I begin the review with the description of the discovery of the mass paradox in our Galaxy and in clusters of galaxies. First hints of the problem appeared already in 1930s and later more observational arguments were brought up, but the issue of the mass paradox was mostly ignored by the astronomical community as a whole. In mid 1970s the amount of observational data was sufficient to suggest the presence of a massive and invisible population around galaxies and in clusters of galaxies. The nature of the dark population was not clear at that time, but the hypotheses of stellar as well as of gaseous nature of the new population had serious difficulties. These difficulties disappeared when non-baryonic nature of dark matter was suggested in early 1980s.

The final break through came in recent years. The systematic progress in the studies of the structure of the galaxies, the studies of the large scale structure based on galaxy surveys, the analysis of the structure formation after Big Bang, the chemical evolution of the Universe including the primordial nucleosynthesis, as well as observations of the microwave background showed practically beyond any doubt that the Universe actually contains more dark matter than baryonic matter! In addition to the presence of Dark Matter, recent observations suggest the presence of Dark Energy, which together with Dark Matter and ordinary baryonic matter makes the total matter/energy density of the Universe equal to the critical cosmological density. Both Dark Matter and Dark Energy are the greatest challenges for modern physics since their nature is unknown.

There are various hypothesis as for the nature of the dark matter particles, and generally some form of weakly interactive massive particles (WIMPs) are strongly favored. These particles would form a relatively cold medium thus named Cold Dark Matter (CDM). The realization that we do not know the nature of basic constituents of the Universe is a scientific revolution difficult to comprehend, and the plan to hunt for the dark matter particles is one of the most fascinating challenges for the future.

1 Dark Matter problem as a scientific revolution

Almost all information on celestial bodies comes to us via photons. Most objects are observed because they emit light. In other cases, like for example in some nebulae, we notice dark regions against otherwise luminous background which are due to absorption of light. Thus both light absorption and light emission allow to trace the matter in the Universe, and the study goes nowadays well beyond the optical light. Modern instruments have first detected photon emission from astronomical bodies in the radio and infrared regions of the spectrum, and later also in the X-ray and gamma-ray band, with the use of detectors installed in space.

Presently available data indicate that astronomical bodies of different nature emit (or absorb) photons in very different ways, and with very different efficiency. At the one end there are extremely luminous supernovae, when a single star emits more energy than all other stars of the galaxy it belongs to, taken together. At the other extreme there are planetary bodies with a very low light emission per mass unit. The effectiveness of the emissivity can be conveniently described by the mass-to-light ratio of the object, usually expressed in Solar units in a fixed photometric system, say in blue (B) light. The examples above show that the mass-to-light ratio M/L varies in very broad range. Thus a natural question arises: Do all astronomical bodies emit or absorb light? Observations carried out in the past century have led us to the conclusion that the answer is probably NO.

Astronomers frequently determine the mass by studying the object emission. However, the masses of astronomical bodies can be also determined directly, using motions of other bodies (considered as test particles) around or within the body under study. In many cases such direct total mass estimates exceed the estimated luminous masses of known astronomical bodies by a large fraction. It is customary to call the hypothetical matter, responsible for such mass discrepancy, **Dark Matter**.

The realization that the presence of dark matter is a serious problem which faces both modern astronomy and physics grew slowly but steadily. Early hints did not call much attention.

The first indication for the possible presence of dark matter came from the dynamical study of our Galaxy. Dutch astronomer Jan Henrik Oort (1932) analysed vertical motions of stars near the plane of the Galaxy and calculated from these data the vertical acceleration of matter. He also calculated the vertical acceleration due to all known stars near the Galactic plane. His result was alarming: the density due to known stars is not sufficient to explain vertical motions of stars – there must be some unseen matter near the Galactic plane.

The second observation was made by Fritz Zwicky (1933). He measured radial velocities of galaxies in the Coma cluster of galaxies, and calculated the mean random velocities in respect to the mean velocity of the cluster. Galaxies move in clusters along their orbits; the orbital velocities are balanced by the total gravity of the cluster, similar to the orbital velocities of planets moving around the Sun in its gravitation field. To his surprise Zwicky found that orbital velocities are almost a factor of ten larger than expected from the summed mass of all galaxies belonging to the cluster. Zwicky concluded that, in order to hold galaxies together in the cluster, the cluster must contain huge amounts of some Dark (invisible) matter.

The next hint of the dark matter existence came from cosmology.

One of the cornerstones of the modern cosmology is the concept of an expanding Universe. From the expansion speed it is possible to calculate the critical density of the Universe. If the mean density is less than the critical one, then the expansion continues forever; if the mean density is larger than the critical, then after some time the expansion stops and thereafter the Universe starts to collapse. The mean density of the Universe can be estimated using masses of galaxies and of the gas between galaxies. These estimates show that the mean density of luminous matter (mostly stars in galaxies and interstellar or intergalactic gas) is a few per cent of the critical density. This estimate is consistent with the constraints from the primordial nucleosynthesis of the light elements.

Another cornerstone of the classical cosmological model is the smooth distribution of galaxies in space. There exist clusters of galaxies, but they contain only about one tenth of all galaxies. The majority of galaxies are more or less randomly distributed and are called field galaxies. This conclusion is based on counts of galaxies at various magnitudes and on the distribution of galaxies in the sky.

Almost all astronomical data fitted well to these classical cosmological paradigms until 1970s. Then two important analyses were made which did not match the classical picture. In mid 1970s first redshift data covering all bright galaxies were available. These data demonstrated that galaxies are not distributed randomly as suggested by earlier data, but form chains or filaments, and that the space between filaments is practically devoid of galaxies. Voids have diameters up to several tens of megaparsecs.

At this time it was already clear that structures in the Universe form by gravitational clustering, started from initially small fluctuations of the density of matter. Matter "falls" to places where the density is above the average, and "flows away" from regions where the density is below the average. This gravitational clustering is a very slow process. In order to form presently observed structures, the amplitude of density fluctuations must be at least one thousandth of the density itself at the time of recombination, when the Universe started to be transparent. The emission coming from this epoch was first detected in 1965 as a uniform cosmic microwave background. When finally the fluctuations of this background were measured by COBE satellite they appeared to be two orders of magnitude lower than expected from the density evolution of the luminous mass.

The solution of the problem was suggested independently by several theorists. In early 1980s the presence of dark matter was confirmed by many independent sources: the dynamics of the galaxies and stars in the galaxies, the mass determinations based on gravitational lensing, and X-ray studies of clusters of galaxies. If we suppose that the dominating population of the Universe – Dark Matter – is not made of ordinary matter but of some sort of non-baryonic matter, then density fluctuations can start to grow much earlier, and have at the time of recombination the amplitudes needed to form structures. The interaction of non-baryonic matter with radiation is much weaker than that of ordinary matter, and radiation pressure does not slow the early growth of fluctuations.

The first suggestion for the non-baryonic matter were particles well known at that time to physicists – neutrinos. However, this scenario soon lead to major problems. Neutrinos move with very high velocities which prevents the formation of small structures as galaxies. Thus some other hypothetical non-baryonic particles were suggested, such as axions. The essential property of these particles is that they have much lower velocities. Because of this the new version of Dark Matter was called Cold, in contrast to neutrino-dominated Hot Dark Matter. Numerical simulations of the evolution of the structure of the Universe confirmed the formation of filamentary superclusters and voids in the Cold Dark Matter dominated Universe.

The suggestion of the Cold Dark Matter has solved most problems of the new cosmological paradigm. The actual nature of the CDM particles is still unknown. Physicists have attempted to discover particles which have properties needed to explain the structure of the Universe, but so far without success.

One unsolved problem remained. Estimates of the matter density (ordinary + dark matter) yield values of about 0.3 of the critical density. This value – not far from unity but definitely smaller than unity – is neither favoured by theorists nor by the data, including the measurements of the microwave background, the galaxy dynamics and the expansion rate of the Universe obtained from the study of supernovae. To fill the matter/energy density gap between unity and the observed matter density it was assumed that some sort of vacuum energy exists. This assumption is not new: already Einstein added to his cosmological equations a term called the Lambda-term. About ten years ago first direct evidence was found for the existence of the vacuum energy, presently called Dark Energy. This discovery has filled the last gap in the modern cosmological paradigm.

In the International Astronomical Union (IAU) symposium on Dark Matter in 1985 in Princeton, Tremaine (1987) characterised the discovery of the dark matter as a typical scientific revolution, connected with changes of paradigms. Kuhn (1970) in his book *The Structure of Scientific Revolutions* discussed in detail the character of scientific revolutions and paradigm changes. There are not so many areas in modern astronomy where the development of ideas can be described in these terms, thus we shall discuss the Dark Matter problem also from this point of view. Excellent reviews on the dark matter and related problems are given by Faber & Gallagher (1979), Trimble (1987), Srednicki (1990), Turner (1991), Silk (1992), van den Bergh (2001), Ostriker & Steinhardt (2003), Rees (2003), Turner (2003), Tegmark et al. (2006), Frieman et al. (2008), see also proceedings by Longair & Einasto (1978), and Kormendy & Knapp (1987).

2 Early evidence of the existence of dark matter

2.1 Local Dark Matter

The dynamical density of matter in the Solar vicinity can be estimated using vertical oscillations of stars around the galactic plane. The orbital motions of stars around the galactic center play a much smaller role in determining the local density. Ernst Öpik (1915) found that the summed contribution of all known stellar populations (and interstellar gas) is sufficient to explain the vertical oscillations of stars – in other words, there is no need to assume the existence of a dark population. A similar analysis was made by Kapteyn (1922), who first used the term "Dark Matter" to denote invisible matter which existence is suggested by its gravity only. Both Öpik and Kapteyn found that the amount of invisible matter in the Solar neighbourhood is small.

Another conclusion was obtained by Jan Oort (1932). His analysis indicated that the total density, found from dynamical data, exceeds the density of visible stellar populations by a factor of up to 2. This limit is often called the Oort limit. This result means that the amount of invisible matter in the Solar vicinity should be approximately equal to the amount of visible matter.

The local density of matter has been redetermined by various authors many times. Kuzmin (1952b, 1955) and his students Heino Eelsalu (1959) and Mihkel Jõeveer (1972, 1974) confirmed the earlier result by Öpik. A number of other astronomers, including more recently Oort (1960), Bahcall & Soneira (1980); Bahcall (1984), found results in agreement with Oorts original result. This discussion was open until recently; we will describe the present conclusions below.

For long time no distinction between local and global dark matter was made. The realisation, that these two types of dark matter have very different properties and nature came from the detailed study of galactic models, as we shall discuss below.

2.2 Global Dark Matter – clusters, groups and galaxies

A different mass discrepancy was found by Fritz Zwicky (1933). He measured redshifts of galaxies in the Coma cluster and found that the velocities of individual galaxies with respect to the cluster mean velocity are much larger than those expected from the estimated total mass of the cluster, calculated from masses of individual galaxies. The only way to hold the cluster from rapid expansion is to assume that the cluster contains huge quantities of some invisible dark matter. According to his estimate the amount of dark matter in this cluster exceeds the total mass of cluster galaxies at least tenfolds, probably even more. As characteristic in scientific revolutions, early indications of problems in current paradigms are ignored by the community, this happened also with the Zwicky's discovery.

The next step in the study of masses of systems of galaxies was made by Kahn & Woltjer (1959). They paid attention to the fact that most galaxies have positive redshifts as a result of the expansion of the Universe; only the Andromeda galaxy (M31) has a negative redshift of about 120 km/s, directed toward our Galaxy. This fact can be explained, if both galaxies, M31 and our Galaxy, form a physical system. A negative radial velocity indicates that these galaxies have already passed the apogalacticon of their relative orbit and are presently approaching each other. From the approaching velocity, the mutual distance, and the time since passing the perigalacticon (taken equal to the present age of the Universe), the authors calculated the total mass of the double system. They found that $M_{tot} \geq 1.8 \times 10^{12}~M_\odot$. The conventional masses of the Galaxy and M31 are of the order of $2 \times 10^{11}~M_\odot$. In other words, the authors found evidence for the presence of additional mass in the Local Group of galaxies. The authors suggested that the extra mass is probably in the form of hot gas of temperature about $5{\times}10^5$ K. Using more modern data Einasto & Lynden-Bell (1982) made a new estimate of the total mass of the Local Group, using the same approach, and found the total mass of $4.5 \pm 0.5 \times 10^{12} M_\odot$. This estimate is in good agreement with new determinations of the sum of masses of M31 and the Galaxy including their dark halos (see below).

A certain discrepancy was also detected between masses of individual galaxies and masses of pairs and groups of galaxies. The conventional approach for the mass determination of pairs and groups of galaxies is statistical. The method is based on the virial theorem and is almost identical to the procedure used to calculate masses of clusters of galaxies. Instead of a single pair or group often a synthetic group is used consisting of a number of individual pairs or groups. These determinations yield for the mass-to-light ratio (in blue light) the values $M/L_B = 1\ldots20$ for spiral galaxy dominated pairs, and $M/L_B = 5\ldots90$ for elliptical galaxy dominated pairs (for a review see Faber & Gallagher (1979)). These ratios are larger than found from local mass indicators of galaxies (velocity dispersions at the center and rotation curves of spiral galaxies). However, it was not clear how serious is the discrepancy between the masses found using global or local mass indicators.

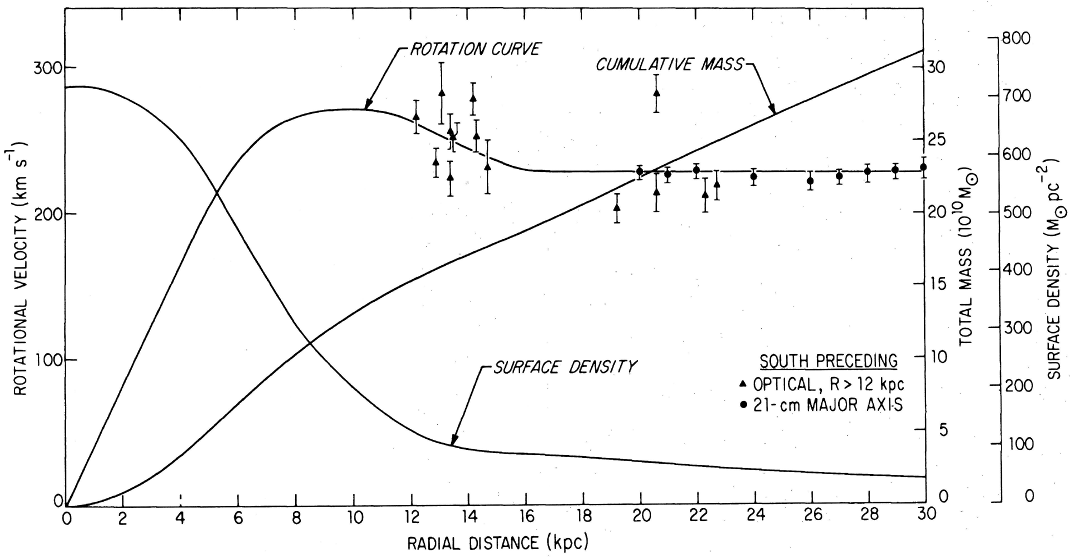

Figure 1: The rotation curve of M31 by Roberts & Whitehurst (1975). The filled triangles show the optical data from Rubin & Ford (1970), the filled circles show the 21-cm measurements made with the 300-ft radio telescope (reproduced by permission of the AAS and the author).

2.3 Rotation curves of galaxies

Another problem with the distribution of mass and mass-to-light ratio was detected in spiral galaxies. Babcock (1939) obtained spectra of the Andromeda galaxy M31, and found that in the outer regions the galaxy is rotating with an unexpectedly high velocity, far above the expected Keplerian velocity. He interpreted this result either as a high mass-to-light ratio in the periphery or as a strong dust absorption. Oort (1940) studied the rotation and surface brightness of the edge-on S0 galaxy NGC 3115, and found in the outer regions a mass-to-light ratio ~ 250. Subsequently, Rubin & Ford (1970) and Roberts & Rots (1973) extended the rotation curve of M31 up to a distance ~ 30 kpc, using optical and radio data, respectively. The rotation speed rises slowly with increasing distance from the center of the galaxy and remains almost constant over radial distances of 16–30 kpc, see Fig. 1.

The rotation data allow to determine the distribution of mass, and the photometric data – the distribution of light. Comparing both distributions one can calculate the local value of the mass-to-light ratio. In the periphery of M31 and other galaxies studied the local value of M/L, calculated from the rotation and photometric data, increases very rapidly outwards, if the mass distribution is calculated directly from the rotation velocity. In the periphery old metal-poor halo-type stellar populations dominate. These metal-poor populations have a low $M/L \approx 1$ (this value can be checked directly in globular clusters which contain similar old metal-poor stars as the halo). In the peripheral region the luminosity of a galaxy drops rather rapidly, thus the expected circular velocity should decrease according to the Keplerian law. In contrast, in the periphery the rotation speeds of galaxies are almost constant, which leads to very high local values of $M/L > 200$ near the last points with a measured rotational velocity.

Two possibilities were suggested to solve this controversy. One possibility is to identify the observed rotation velocity with the circular velocity, but this leads to the presence in galaxies of an extended population with a very high M/L. The other possibility is to assume that in the periphery of galaxies there exist non-circular motions which distort the rotation velocity.

To make a choice between the two possibilities for solving the mass discrepancy in galaxies more detailed models of galaxies were needed. In particular, it was necessary to take into account the presence in galaxies stellar populations with different physical properties (age, metal content, colour, M/L value).

2.4 Mass paradox in galaxies from Galactic models

Classical models of elliptical galaxies were found from luminosity profiles and calibrated using either central velocity dispersions, or motions of companion galaxies. The luminosity profiles of disks were often approximated by an exponential law, and bulge and halo dominated ellipticals by the de Vaucouleurs (1953b) law.

Models of spiral galaxies were constructed using rotation velocities. As a rule, the rotation velocity was approximated by some simple formula, such as the Bottlinger (1933) law, or a polynomial. The other possibility was to approximate the spatial density (calculated from the rotation data) by a sum of ellipsoids of constant density (the Schmidt (1956) model). In the first case there exists a danger that, if the velocity law is not chosen well, then the density in the periphery of the galaxy may have unrealistic values (negative density or too high density, leading to an infinite total mass). If the model is built by superposition of ellipsoids of constant density, then the density is not a smooth function of the distance from the center of the galaxy. To avoid these difficulties Kuzmin (1952a, 1956) developed models with a continuous change of the spatial density, and applied the new technique to M31 and our Galaxy. His method allows to apply this approach also for galaxies consisting of several populations.

A natural generalisation of classical galactic models is the use of all available observational data for spiral and elliptical galaxies, both photometric data on the distribution of colour and light, and kinematical data on the rotation and/or velocity dispersion. Further, it is natural to apply identical methods for modeling of galaxies of different morphological type (including our own Galaxy), and to describe explicitly all major stellar populations, such as the bulge, the disk, the halo, as well as the flat population in spiral galaxies, consisting of young stars and interstellar gas (Einasto, 1965).

Multi-component models for spiral and elliptical galaxies using photometric data were constructed by Freeman (1970). To combine photometric and kinematic data, mass-to-light ratios of galactic populations are needed. Luminosities and colours of galaxies in various photometric systems result from the physical evolution of stellar populations that can be modeled. The chemical evolution of galaxies was investigated by Tinsley (1968) and Cameron & Truran (1971). Combined population and physical evolution models were calculated for a representative sample of galaxies by Einasto (1972, 1974). The last calculations showed that it was impossible to reproduce the rotation data by known stellar populations only. The only way to eliminate this conflict was *to assume the presence of an unknown population – corona – with a very high value of the mass-to-light ratio, and a large radius and mass*. Thus, the detailed modeling confirmed earlier results obtained by simpler models. But here we have one serious difficulty – no known stellar population has so large a M/L value.

Additional arguments for the presence of a spherical massive population in spiral galaxies came from the stability criteria against bar formation, suggested by Ostriker & Peebles (1973). Their numerical calculations demonstrated that initially very flat systems become rapidly thicker (during one revolution of the system) and evolve to a bar-like body. In real spiral galaxies a thin population exists, and it has no bar-like form. In their concluding remarks the authors write: "*Presumably even Sc and other relatively 'pure' spirals must have some means of remaining stable, and the possibility exists that those systems also have very large, low-luminosity halos. The picture developed here agrees very well with the fact, noted by several authors (see, for example, Rogstad & Shostak (1972)), that the mass-to-light ratio increases rapidly with distance from the center in these systems; the increase may be due to the growing dominance of the high mass-to-light halo over the low mass-to-light ratio disk. It also suggests that the total mass of such systems has been severely underestimated. In particular, the finding of Roberts & Rots (1973) that the rotation curves of several nearby spirals become flat at large distances from the nucleus may indicate the presence of very extended halos having masses that diverge rapidly [M(r) prop to r] with distance.*"

3 Dark Matter in astronomical data

Modern astronomical methods yield a variety of independent information on the presence and distribution of dark matter. For our Galaxy, the basic data are the stellar motions perpendicular to the plane of the Galaxy (for the local dark matter), the motions of star and gas streams and the rotation (for the global dark matter). Important additional data come from gravitational microlensing by invisible stars or planets. In nearby dwarf galaxies the basic information comes from stellar motions. In more distant and giant galaxies the basic information comes from the rotation curves and the X-ray emission of the hot gas surrounding galaxies. In clusters and groups of galaxies the gravitation field can be determined from relative motions of galaxies, the X-ray emission of hot gas and gravitational lensing. Finally, measurements of fluctuations of the Cosmic Microwave Background (CMB) radiation in combination with data from type Ia supernovae in nearby and very distant galaxies yield information on the curvature of the Universe that depends on the amount of Dark Matter and Dark Energy.

Now we shall discuss these data in more detail.

3.1 Stellar motions

The local mass density near the Sun can be derived from vertical oscillations of stars near the galactic plane, as was discussed before. Modern data by Kuijken & Gilmore (1989); Gilmore et al. (1989) have confirmed the results by Kuzmin and his collaborators. Thus we come to the conclusion that *there is no evidence for the presence of large amounts of dark matter in the disk of the Galaxy*. If there is some invisible matter near the galactic plane, then its amount is small, of the order of 15 percent of the total mass density. The local dark matter is probably baryonic (low–mass stars or jupiters), since non-baryonic matter is dissipationless and cannot form a highly flattened population. Spherical distribution of the local dark matter (in quantities suggested by Oort and Bahcall) is excluded since in this case the total mass of the dark population would be very large and would influence also the rotational velocity of the Galaxy at the location of the Solar System.

Another information of the distribution of mass in the outer part of the Galaxy comes from streams of stars and gas. One of the streams discovered near the Galaxy is the Magellanic Stream of gas which forms a huge strip and connects the Large Magellanic Cloud (LMC) with the Galaxy (Mathewson et al., 1974). Model calculations emphasize that this stream is due to an encounter of the LMC with the Galaxy. Kinematical data for the stream are available and support the hypothesis on the presence of a massive halo surrounding the Galaxy (Einasto et al., 1976a). Recently, streams of stars have been discovered within the Galaxy as well as around our giant neighbour M31. Presently there are still few data on the kinematics of these streams.

Several measurements of the dark mass halo were also performed using the motion of the satellite galaxies or the globular clusters. Measurements indicate the mass of the dark halo of about $2 \times 10^{12} M_{\odot}$.

However, significant progress is expected in the near future. The astronomical satellite GAIA (to fly in 2011) is expected to measure distances and photometric data for millions of stars in the Galaxy. When these data are available, more information on the gravitation field of the Galaxy can be found.

The motion of individual stars or gaseous clouds can be also studied in nearby dwarf galaxies. Determination of the dark halo was performed for over a dozen of them. Some of the newly discovered dwarfs, coming from the Sloan Digital Sky Survey, are very under-luminous but equally massive as the previously known dwarf galaxies in the Milky Way vicinity, which makes them good candidates for extreme examples of dark matter dominated objects. Also the studies of the disruption rate of these galaxies due to the interaction with the Milky Way imposes limits to the amount of dark mass in these objects. The results indicate that the dark matter in these systems exceeds by a factor a few the mass of stars.

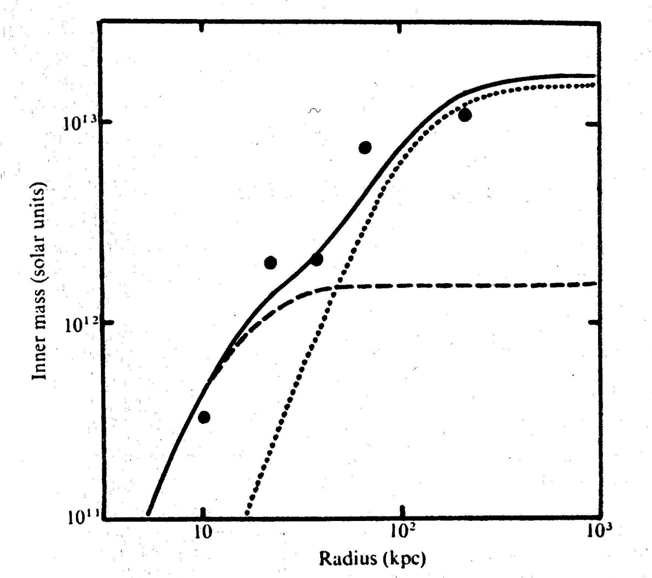

Figure 2: The mean internal mass $M(R)$ as a function of the radius R from the main galaxy in 105 pairs of galaxies (dots). Dashed line shows the contribution of visible populations, dotted line the contribution of the dark corona, solid line the total distribution (Einasto et al., 1974a).

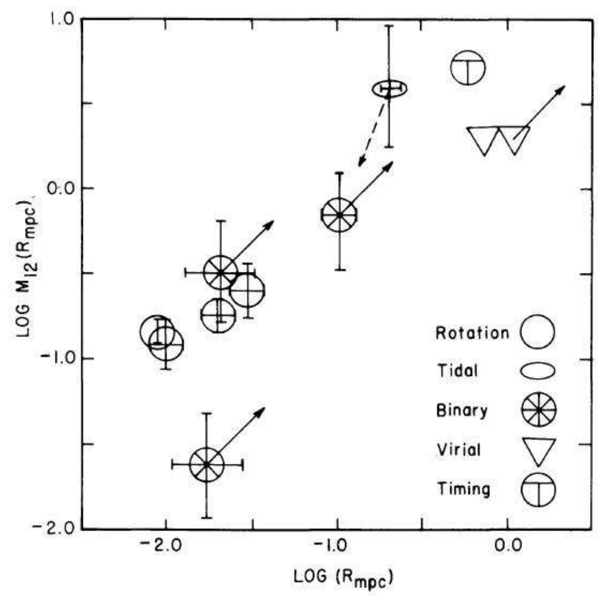

Figure 3: Masses (in units 10^{12} $M_{\odot}$) of local giant galaxies (Ostriker et al., 1974) (reproduced by permission of the AAS and authors).

3.2 Dynamics and morphology of companion galaxies

The rotation data available in early 1970s allowed to determine the mass distribution in galaxies up to their visible edges. In order to find how large and massive galactic coronas or halos are, more distant test particles are needed. If halos are large enough, then in pairs of galaxies the companion galaxies are located inside the halo, and their relative velocities can be used instead of the galaxy rotation velocities to find the distribution of mass around giant galaxies. This test was made independently by Einasto et al. (1974a) and Ostriker et al. (1974), see Figs. 2 and 3. The paper by Ostriker et al. begins with the statement: *"There are reasons, increasing in number and quality, to believe that the masses of ordinary galaxies may have been underestimated by a factor of 10 or more"*. The closing statement of the Einasto et al. paper is: *"The mass of galactic coronas exceeds the mass of populations of known stars by one order of magnitude. According to new estimates the total mass density of matter in galaxies is 20% of the critical cosmological density.*"

The bottom line in both papers was: since the data suggest that all giant galaxies have massive halos/coronae, dark matter must be the dynamically dominating population in the whole Universe.

Results of these papers were questioned by Burbidge (1975), who noticed that satellites may be optical. To clarify if the companions are true members of the satellite systems, Einasto et al. (1974b) studied the morphology of companions. They found that companion galaxies are segregated morphologically: elliptical (non–gaseous) companions lie close to the primary galaxy whereas spiral and irregular (gaseous) companions of the same luminosity have larger distances from the primary galaxy; the distance of the segregation line from the primary galaxy depends on the luminosity of the satellite galaxy, Fig. 4. This result shows, first of all, that the companions are real members of these systems – random by-fliers cannot have such properties. Second, this result demonstrates that diffuse matter has an important role in the evolution of galaxy systems. Morphological properties of companion galaxies can be explained, if we assume that (at least part of) the corona is gaseous.

Additional arguments in favour of physical connection of companions with their primary galaxies came from the dynamics of small groups. Their mass distribution depends on the morphology: in systems with a bright primary galaxy the density (found from kinematical data) is systematically higher, and in elliptical galaxy dominated systems it is also higher. The mass distribution found from the kinematics of group members smoothly continues the mass distribution of the primary galaxies, found from rotation data (Einasto et al., 1976b).

3.3 Extended rotation curves of galaxies

The dark matter problem was discussed in 1975 at two conferences, in January in Tallinn (Doroshkevich et al., 1975) and in July in Tbilisi. The central problems discussed in Tallinn were: Deuterium abundance and the mean density of the universe (Zeldovich, 1975), What is the physical nature of the dark matter? and: What is its role in the evolution of the Universe? Two basic models were suggested for coronas: faint stars or hot gas. It was found that both models have serious difficulties (Jaaniste & Saar, 1975; Komberg & Novikov, 1975).

In Tbilisi the Third European Astronomical Meeting took place. Here the principal discussion was between the supporters of the classical paradigm with conventional mass estimates of galaxies and of the new one with dark matter. The major arguments supporting the classical paradigm were summarised by Materne & Tammann (1976). Their most serious argument was: *Big Bang nucleosynthesis suggests a low-density Universe with the density parameter* $\Omega \approx 0.05$*; the smoothness of the Hubble flow also favours a low-density Universe.*

It was clear that by sole discussion the presence and nature of dark matter cannot be solved, new data and more detailed studies were needed. The first very strong confirmation of the dark matter hypothesis came from new extended rotation curves

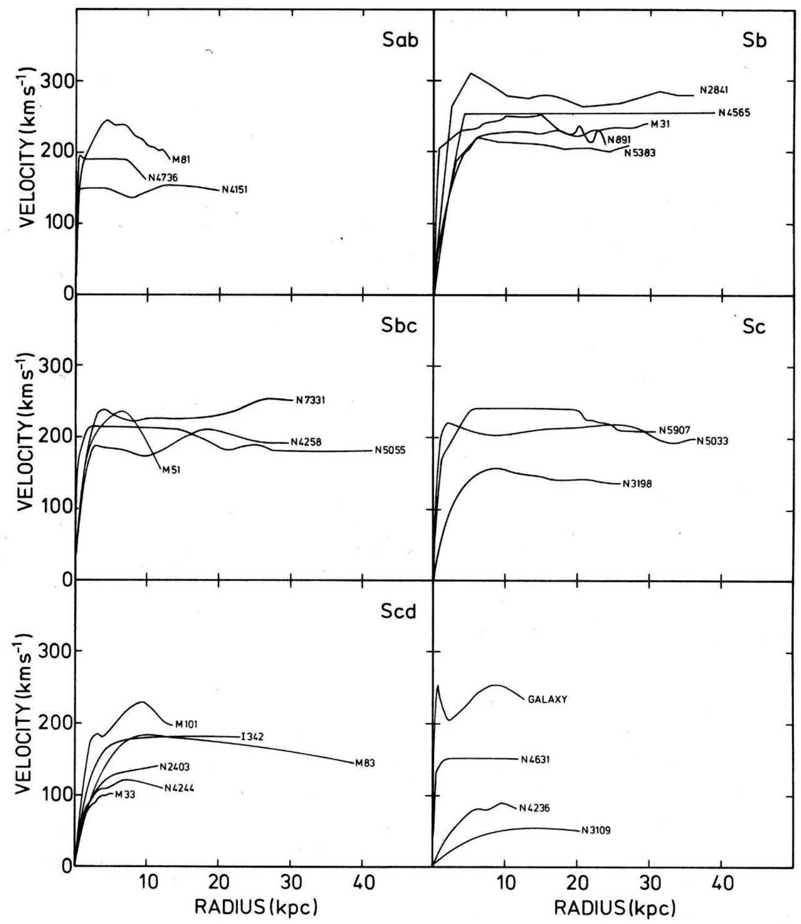

Figure 5: The rotation curves of spiral galaxies of various morphological type according to Westerbork radio observations (Bosma, 1978) (reproduced by permission of the author).

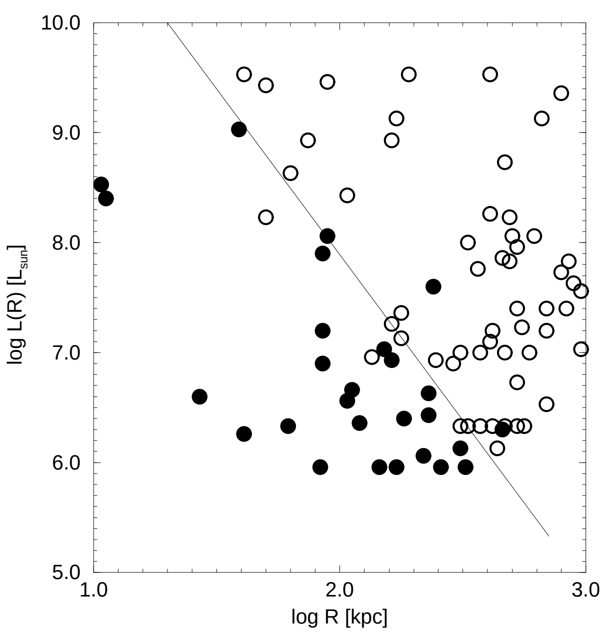

Figure 4: The distribution of luminosities of companion galaxies $L(R)$ at various distances R from the main galaxy. Filled circles are for elliptical companions, open circles for spiral and irregular galaxies (Einasto et al., 1974b).

of galaxies.

In early 1970s optical data on rotation of galaxies were available only for inner bright regions of galaxies. Radio observations of the 21-cm line reached much longer rotation curves well beyond the Holmberg radius of galaxies. All available rotation data were summarised by Roberts (1975) in the IAU Symposium on Dynamics of Stellar Systems held in Besancon (France) in September 1974. Extended rotation curves were available for 14 galaxies; for some galaxies data were available until the galactocentric distance $\sim 40\ h^{-1}$ Mpc (we use in this paper the Hubble constant in the units of $H_0 = 100\ h$ km s^{-1} Mpc^{-1}), see Fig. 1 for M31. About half of galaxies had flat rotation curves, the rest had rotation velocities that decreased slightly with distance. In all galaxies the local mass-to-light ratio in the periphery reached values over 100 in Solar units. To explain such high M/L values Roberts assumed that late-type dwarf stars dominate the peripheral regions.

In mid-1970s measurements of a number of spiral galaxies with the Westerbork Synthesis Radio Telescope were completed, and mass distribution models were built, all-together for 25 spiral galaxies (Bosma, 1978), see Fig. 5. Observations confirmed the general trend that the mean rotation curves remain flat over the whole observed range of distances from the center, up to ~ 40 kpc for several galaxies. The internal mass within the radius R increases over the whole distance interval.

At the same time Vera Rubin and her collaborators developed new sensitive detectors to measure optically the rotation curves of galaxies at very large galactocentric distances. Their

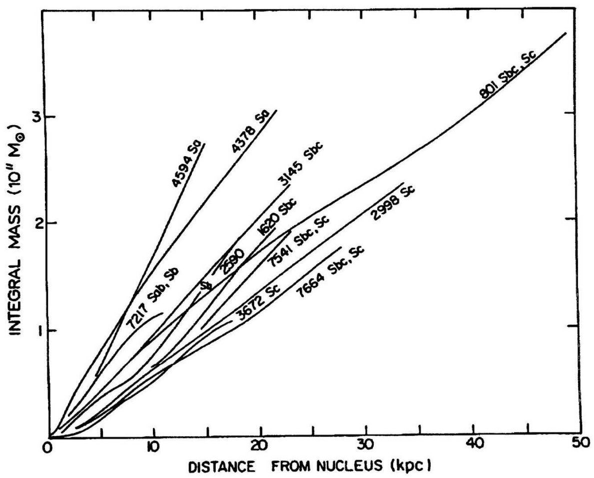

Figure 6: The integral masses as a function of the distance from the nucleus for spiral galaxies of various morphological type (Rubin et al., 1978) (reproduced by permission of the AAS and authors).

results suggested that practically all spiral galaxies have extended flat rotation curves (Rubin et al., 1978, 1980). The internal mass of galaxies rises with distance almost linearly, up to the last measured point, see Fig. 6.

These observational results confirmed the concept of the presence of dark halos of galaxies with a high confidence.

Another very important measurement was made by Faber and collaborators (Faber & Jackson, 1976; Faber et al., 1977; Faber & Gallagher, 1979). They measured the central velocity dispersions for 25 elliptical galaxies and the rotation velocity of the Sombrero galaxy, a S0 galaxy with a massive bulge and a very weak population of young stars and gas clouds just outside the main body of the bulge. Their data yielded for the bulge of the Sombrero galaxy a mass-to-light ratio $M/L = 3$, and for the mean mass-to-light ratios for elliptical galaxies about 7, close to the ratio for early type spiral galaxies. These observational data confirmed estimates based on the calculations of physical evolution of galaxies, made under the assumption that the lower mass limit of the initial mass function (IMF) is for all galactic populations of the order of 0.1 $M_\odot$. These results showed that the mass-to-light ratios of stellar populations in spiral and elliptical galaxies are similar for a given colour, and the ratios are much lower than those accepted in earlier studies based on the dynamics of groups and clusters. In other words, high mass-to-light ratios of groups and clusters of galaxies cannot be explained by visible galactic populations.

Earlier suggestions on the presence of mass discrepancy in galaxies and galaxy systems had been ignored by the astronomical community. This time new results were taken seriously. As noted by Kuhn, a scientific revolution begins when leading scientists in the field start to discuss the problem and arguments in favour of the new and the old paradigm.

More data are slowly accumulating (Sofue & Rubin, 2001). New HI measurements from Westerbork extend the rotation curves up to 80 kpc (galaxy UGC 2487) or even 100 kpc (UGC 9133 and UGC 11852) showing flat rotation curves (Noordermeer et al., 2005). The HI distribution in the Milky Way has been recently studied up to distances of 40 kpc by Kalberla (2003); Kalberla et al. (2007). The Milky Way rotation curve has been determined by Xue et al. (2008) up to ~ 60 kpc from the study of ~ 2500 Blue Horizontal Branch stars from SDSS survey, and the rotation curves seems to be slightly falling from the 220 km s^{-1} value at the Sun location. Earlier determinations did not extend so far and extrapolations were affected by the presence of the ring-like structure in mass distribution at ~ 14 kpc from the center. Implied values of the dark matter halo from different measurements still differ between themselves by a factor 2 - 3, being in the range from $10^{12} - 2.5 \times 10^{12} M_\odot$. The central density of dark matter halos of galaxies is surprisingly constant, about 0.1 $M_\odot$ pc^{-3} (Gilmore et al., 2007). Smallest dwarf galaxies have half-light radius about 120 pc, largest star clusters of similar absolute magnitude have half-light radius up to 35 pc; this gap separates systems with and without dark halos (Gilmore et al., 2008).

3.4 X-ray data on galaxies and clusters of galaxies

Hot intra-cluster gas emitting X-rays was detected in almost all nearby clusters and in many groups of galaxies by the Einstein X-ray orbiting observatory. Observations confirmed that the hot gas is in hydrodynamical equilibrium, i.e. gas particles move in the general gravitation field of the cluster with velocities which correspond to the mass of the cluster (Forman & Jones, 1982; Sarazin, 1988; Rosati et al., 2002).

The distribution of the mass in clusters can be determined if the density and the temperature of the intra-cluster gas are known. This method of determining the mass has a number of advantages over the use of the virial theorem. First, the gas is a collisional fluid, and particle velocities are isotropically distributed, which is not true for galaxies as test particles of the cluster mass (uncertainties in the velocity anisotropy of galaxies affect mass determinations). Second, the hydrostatic method gives the mass as a function of radius, rather than the total mass alone as given by the virial method.

Using Einstein X-ray satellite data the method was applied to determine the mass of Coma, Perseus and Virgo clusters (Bahcall & Sarazin, 1977; Mathews, 1978). The results were not very accurate since the temperature profile was known only approximately. The results confirmed previous estimates of masses made with the virial method using galaxies as test particles. The mass of the hot gas itself is only about 0.1 of the total mass, approximately comparable to the luminous mass in galaxies.

More recently clusters of galaxies have been observed in X-rays using the ROSAT satellite (operated in 1990–1999), and the XMM-Newton and Chandra observatories, launched both in 1999. The ROSAT satellite was used to compile an all-sky catalogue of X-ray clusters and galaxies. More than 1000 clusters up to a redshift ~ 0.5 were catalogued. Dark matter profiles have been determined in a number of cases (Humphrey et al., 2006).

The XMM and Chandra observatories allow to get detailed images of X-ray clusters, and to derive the density and temperature of the hot gas (Jordán et al., 2004; Rasia et al., 2006). Using the XMM observatory, a survey of X-ray clusters was initiated to find a representative sample of clusters at redshifts up to $z = 1$. The comparison of cluster properties at different redshifts allows to get more accurate information on the evolution of clusters which depend critically on the parameters of the cosmological model.

Chandra observations allow to find the hot gas and total masses not only for groups and clusters, but also for nearby galaxies (Humphrey et al. (2006), see also Mathews et al.

(2006), Lehmer et al. (2008)). For early-type (elliptical) galaxies the virial masses found were 0.7–9×10^{13} $M_\odot$. Local mass-to-light ratio profiles are flat within an optical half-light radius (R_{eff}), rising more than an order of magnitude at $\sim 10R_{eff}$, which confirms the presence of dark matter. The baryon fraction (most baryons are in the hot X-ray emitting gas) in these galaxies is $f_b \sim 0.04 - 0.09$. The gas mass profiles are similar to the profiles of dark matter shifted to lower densities. The stellar mass-to-light ratios in these old bulge dominated galaxies are $M_*/L_K \sim 0.5 - 1.9$ using the Salpeter IMF (for the infrared K-band, the ratios for the B-band are approximately 4 times higher). Interesting upper limits for the amount of hot plasma in the halo of the Milky Way were obtained in 2008 from the comparative study of the tiny absorption lines in a few Galactic and extragalactic X-ray sources, giving the total column density of O VII less than 5×10^{15} cm^{-2}. Assuming that the gaseous baryonic corona has the mass of order of $\sim 6\times10^{10} M_\odot$, this measurement implies a very low metalicity of the corona plasma, below 3.7 percent of the solar value (Yao et al., 2008).

3.5 Galactic and extragalactic gravitational lensing

Clusters, galaxies and even stars are so massive that their gravity bends and focuses the light from distant galaxies, quasars and stars that lie far behind. There are three classes of gravitational lensing:

- Strong lensing, where there are easily visible distortions such as the formation of Einstein rings, arcs, and multiple images, see Fig. 7.
- Weak lensing, where the distortions of background objects are much smaller and can only be detected by analyzing the shape distortions of a large number of objects.
- Microlensing, where no shape distortion can be seen, but the amount of light received from a background object changes in time. The background source and the lens may be stars in the Milky Way or in nearby galaxies (M31, Magellanic Clouds).

Figure 7: The Hubble Space Telescope image of the cluster Abell 2218. This cluster is so massive that its gravity bends the light of more distant background galaxies. Images of background galaxies are distorted into stretched arcs (Astr. Pict. of the Day Jan. 11, 1998, Credit: W. Couch, R. Ellis).

The strong lensing effect is observed in rich clusters, and allows to determine the distribution of the gravitating mass in clusters. Massive galaxies can distort images of distant single objects, such as quasars: as a result we observe multiple images of the same quasar. The masses of clusters of galaxies determined using this method confirm the results obtained by the virial theorem and the X-ray data.

Weak lensing allows to determine the distribution of dark matter in clusters as well as in superclusters. For the most luminous X-ray cluster known, RXJ 1347.5-1145 at the redshift $z = 0.45$, the lensing mass estimate is almost twice as high as that determined from the X-ray data. The mass-to-light ratio is $M/L_B = 200 \pm 50$ in Solar units (Fischer & Tyson, 1997; Fischer et al., 1997). For other recent work on weak lensing and X-ray clusters see Bradač et al. (2005); Dietrich et al. (2005); Clowe et al. (2006b); Massey et al. (2007).

A fraction of the invisible baryonic matter can lie in small compact objects – brown dwarf stars or jupiter-like objects. To find the fraction of these objects in the cosmic balance of matter, special studies have been initiated, based on the microlensing effect.

Microlensing effects were used to find Massive Compact Halo Objects (MACHOs). MACHOs are small baryonic objects as planets, dead stars (white dwarfs) or brown dwarfs, which emit so little radiation that they are invisible most of the time. A MACHO may be detected when it passes in front of a star and the MACHOs gravity bends the light, causing the star to appear brighter. Several groups have used this method to search for the baryonic dark matter. Some authors claimed that up to 20 % of dark matter in our Galaxy can be in low-mass stars (white or brown dwarfs). However, observations using the Hubble Space Telescope's NICMOS instrument show that only about 6% of the stellar mass is composed of brown dwarfs. This corresponds to a negligible fraction of the total matter content of the Universe (Graff & Freese, 1996; Najita et al., 2000).

4 The nature of Dark Matter

By the end of 1970s most objections against the dark matter hypothesis were rejected. In particular, luminous populations of galaxies have found to have lower mass-to-light ratios than expected previously, thus the presence of extra dark matter both in galaxies and clusters has been confirmed. However, there remained three problems:

- It was not clear how to explain the Big Bang nucleosynthesis constraint on the low density of matter, and the smoothness of the Hubble flow.
- If the massive halo (corona) is not stellar nor gaseous, of what stuff is it made of?
- And a more general question: in Nature everything has its purpose. If 90 % of matter is dark, then there must be a reason for its presence. What is the role of dark matter in the history of the Universe?

First we shall discuss baryons as dark matter candidates.

4.1 Nucleosynthesis constraints on the amount of baryonic matter

According to the Big Bang model, the Universe began in an extremely hot and dense state. For the first second it was so hot that atomic nuclei could not form – space was filled with a hot

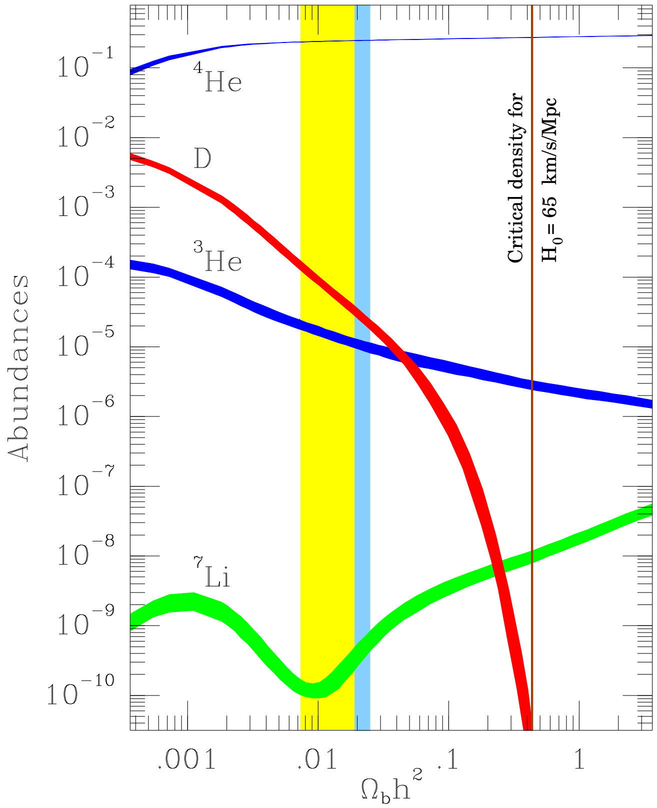

Figure 8: The big-bang production of the light elements. The abundance of chemical elements is given as a function of the density of baryons, expressed in units of $\Omega_b h^2$ (horizontal axis). Predicted abundances are in agreement with measured primeval abundances in a narrow range of baryon density (Schramm & Turner, 1998).

soup of protons, neutrons, electrons, photons and other short-lived particles. Occasionally a proton and a neutron collided and sticked together to form a nucleus of deuterium (a heavy isotope of hydrogen), but at such high temperatures they were broken immediately by high-energy photons (Schramm & Turner, 1998).

When the Universe cooled off, these high-energy photons became rare enough that it became possible for deuterium to survive. These deuterium nuclei could keep sticking to more protons and neutrons, forming nuclei of helium-3, helium-4, lithium, and beryllium. This process of element-formation is called "nucleosynthesis". The denser proton and neutron "gas" is at this time, the more of these light elements will be formed. As the Universe expands, however, the density of protons and neutrons decreases and the process slows down. Neutrons are unstable (with a lifetime of about 15 minutes) unless they are bound up inside a nucleus. After a few minutes, therefore, the free neutrons will be gone and nucleosynthesis will stop. There is only a small window of time in which nucleosynthesis can take place, and the relationship between the expansion rate of the Universe (related to the total matter density) and the density of protons and neutrons (the baryonic matter density) determines how much of each of these light elements are formed in the early Universe.

According to nucleosynthesis data baryonic matter makes up 0.04 of the critical cosmological density (Fig. 8). Only a small fraction, less than 10%, of the baryonic matter is condensed to visible stars, planets and other compact objects. Most of the baryonic matter is in the intergalactic matter, it is concentrated also in hot X-ray coronas of galaxies and clusters.

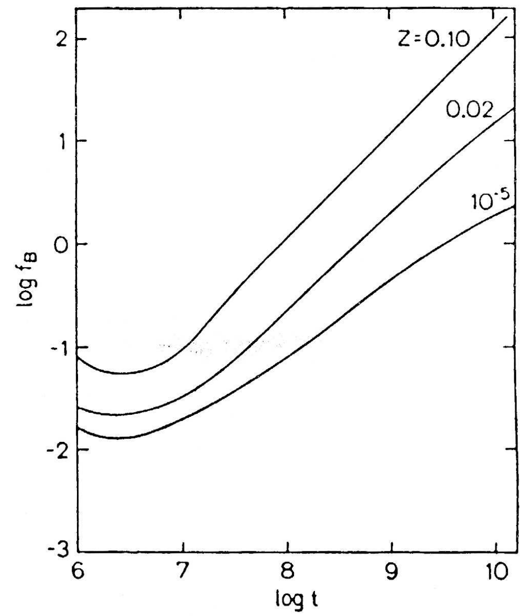

Figure 9: The evolution of mass-to-light ratios f_B of galactic populations of different metal abundance Z (Einasto, 1972). The age of population t is expressed in years. An identical lower limit of IMF 0.1 $M_\odot$ was accepted.

4.2 Baryonic Dark Matter

Models of the galaxy evolution are based on stellar evolution tracks, star formation rates (as a function of time), and the initial mass function (IMF). For IMF the Salpeter (1955) law is usually used:

$$F(m) = am^{-n}, \tag{1}$$

where m is the mass of the forming star, and a and n are parameters. This law cannot be used for stars of arbitrary mass, because in this case the total mass of forming stars may be infinite. Thus we assume that this law is valid in the mass interval m_0 to m_u (the lower and upper limit of the forming stars, respectively).

Early models of physical evolution of galaxies were constructed by Tinsley (1968) and Einasto (1972). These models show that the mass-to-light ratio M_i/L_i of the population i depends critically on the lower limit of the IMF, m_0. It is natural to expect that in similar physical conditions (the metalicity of the gas in star formation regions) the lower mass limit of forming stars has similar values (Fig. 9). An independent check of the correctness of the lower limit is provided by homogeneous stellar populations, such as star clusters. Here we can assume that all stars were formed simultaneously, the age of the cluster can be estimated from the HR diagram, and the mass derived from the kinematics of stars in the cluster. Such data are available for old metal-poor globular clusters, for relatively young medium-metal-rich open clusters as well as for metal-rich cores of galaxies. This check suggests that in the first approximation for all populations similar lower mass limits ($m_0 = 0.05 \ldots 0.1\ M_\odot$) can be used; in contracting gas clouds above this limit the hydrogen starts burning, below not. Using this mass lower limits we get for old metal-poor halo populations $M_i/L_i \approx 1$, and for extremely metal-rich populations in central regions of galaxies

$M_i/L_i = 10\ldots30$, as suggested by the central velocity dispersion in luminous elliptical galaxies. For intermediate populations (bulges and disks) one gets $M_i/L_i = 3\ldots10$, see Fig. 9. Modern data yield slightly lower values, due to more accurate measurements of velocity dispersions in the central regions of galaxies, as suggested in pioneering studies by Faber & Jackson (1976); Faber et al. (1977), and more accurate input data for evolution models.

To get very high values of M/L, as suggested by the dynamics of companion galaxies or rotation data in the periphery of galaxies, one needs to use a very small value of the mass lower limit $m_0 \ll 10^{-3}\ M_\odot$. All known stellar populations have much lover mass-to-light values, and form continuous sequences in color-M/L and velocity dispersion-M/L diagrams.

For this reason it is very difficult to explain the physical and kinematical properties of a stellar dark halo. Dark halo stars form an extended population around galaxies, and must have a much higher velocity dispersion than the stars belonging to the ordinary halo. No fast-moving stars as possible candidates for stellar dark halos were found (Jaaniste & Saar, 1975). If the hypothetical population is of stellar origin, it must be formed much earlier than all known populations, because known stellar populations of different age and metalicity form a continuous sequence of kinematical and physical properties, and there is no place where to include this new population into this sequence. And, finally, it is known that star formation is not an efficient process – usually in a contracting gas cloud only about 1 % of the mass is converted to stars. Thus we have a problem how to convert, in an early stage of the evolution of the Universe, a large fraction of the primordial gas into this population of dark stars. Numerical simulations suggest, that in th early universe only a very small fraction of gas condenses to stars which ionize the remaining gas and stop for a certain period further star formation (Cen, 2003; Gao et al., 2005b).

Stellar origin of dark matter in clusters was discussed by Napier & Guthrie (1975); they find that this is possible if the initial mass function of stars is strongly biased toward very low-mass stars. Thorstensen & Partridge (1975) discussed the suggestion made by Truran & Cameron (1971) that there may have been a pre-galactic generation of stars (called now population III), all of them more massive than the Sun, which are now present as collapsed objects. They conclude that the total mass of this population is negligible, thus collapsed stars cannot make up the dark matter.

Recently weak stellar halos have been detected around several nearby spiral galaxies at very large galactocentric distances. For instance, a very weak stellar halo is found in M31 up to distance of 165 kpc (Gilbert et al., 2006; Kalirai et al., 2006). The stars of this halo have very low metalicity, but have anomalously red colour. The total luminosity and mass of these extended halos is, however, very small, thus these halos cannot be identified with the dark halo.

Gaseous coronas of galaxies and clusters were discussed in 1970s by Field (1972), Silk (1974), Tarter & Silk (1974), Komberg & Novikov (1975) and others. The general conclusion from these studies was that gaseous coronas of galaxies and clusters cannot consist of neutral gas since the intergalactic hot gas would ionise the coronal gas. On the other hand, a corona consisting of hot ionised gas would be observable. Modern data show that part of the coronal matter around galaxies and in groups and clusters of galaxies consists indeed of the X-ray emitting hot gas, but the amount of this gas is not sufficient to explain the flat rotation curves of galaxies (Turner, 2003).

The result of these early discussions of the nature of dark halos were inconclusive – no appropriate candidate was found. For many astronomers this was an argument against the presence of dark halos.

4.3 Non-baryonic Dark Matter and fluctuations of the CMB radiation

Already in 1970s suggestions were made that some sort of non-baryonic elementary particles, such as massive neutrinos, magnetic monopoles, axions, photinos, etc., may serve as candidates for dark matter particles. There were several reasons to search for non-baryonic particles as a dark matter candidate. First of all, no baryonic matter candidate did fit the observational data. Second, the total amount of dark matter is of the order of 0.2–0.3 in units of the critical cosmological density, while the nucleosynthesis constraints suggest that the amount of baryonic matter cannot be higher than about 0.04 of the critical density.

A third very important observation was made which caused doubts to the baryonic matter as the dark matter candidate. In 1964 Cosmic Microwave Background (CMB) radiation was detected. This discovery was a powerful confirmation of the Big Bang theory. Initially the Universe was very hot and all density and temperature fluctuations of the primordial soup were damped by very intense radiation; the gas was ionized. But as the Universe expanded, the gas cooled and at a certain epoch called recombination the gas became neutral. From this time on density fluctuations in the gas had a chance to grow by gravitational instability. Matter is attracted to the regions were the density is higher and it flows away from low-density regions. But gravitational clustering is a very slow process. Model calculations show that in order to have time to build up all observed structures as galaxies, clusters, and superclusters, the amplitude of initial density fluctuations at the epoch of recombination must be of the order of 10^{-3} of the density itself. These calculations also showed that density fluctuations are of the same order as temperature fluctuations. Thus astronomers started to search for temperature fluctuations of the CMB radiation. None were found. As the accuracy of measurement increased, lower and lower upper limits for the amplitude of CMB fluctuations were obtained. In late 1970s it was clear that the upper limits are much lower than the theoretically predicted limit 10^{-3}.

Then astronomers recalled the possible existence of non-baryonic particles, such as heavy neutrinos. This suggestion was made independently by several astronomers (Cowsik & McClelland (1973); Szalay & Marx (1976); Tremaine & Gunn (1979); Doroshkevich et al. (1980b); Chernin (1981); Bond et al. (1983)) and others. They found that, if dark matter consists of heavy neutrinos, then this helps to explain the paradox of small temperature fluctuations of the cosmic microwave background radiation. This problem was discussed in a conference in Tallinn in April 1981. Recent experiments by a Moscow physicist Lyubimov were announced, which suggested that neutrinos have masses. If so, then the growth of perturbations in a neutrino-dominated medium can start much earlier than in a baryonic medium, and at the time of recombination perturbations may have amplitudes large enough for structure formation. The Lyubimov results were never confirmed, but it gave cosmologists an impulse to take non-baryonic dark matter seriously. In the conference banquet Zeldovich gave an enthusiastic speech: *"Observers work hard in sleepless* *nights to collect data; theorists interpret observations, are often in error, correct their errors and try again; and there are only very rare moments of clarification. Today it is one of such rare moments when we have a holy feeling of understanding the secrets of Nature.*" Non-baryonic dark matter is needed to start structure formation early enough. This example illustrates well the attitude of theorists to new observational discoveries – the Eddington's test: *"No experimental result should be believed until confirmed by theory"* (cited by Mike Turner (2000)). Dark matter condenses at early epoch and forms potential wells, the baryonic matter flows into these wells and forms galaxies (White & Rees, 1978).

The search of dark matter can also be illustrated with the words of Sherlock Holmes *"When you have eliminated the impossible, whatever remains, however improbable, must be the truth"* (cited by Binney & Tremaine (1987)). The non-baryonic nature of dark matter explains the role of dark matter in the evolution of the Universe, and the discrepancy between the total cosmological density of matter and the density of baryonic matter, as found from the nucleosynthesis constraint. Later studies have demonstrated that neutrinos are not the best candidates for the non-baryonic dark matter, see below.

4.4 Alternatives to Dark Matter

The presence of large amounts of matter of unknown origin has given rise to speculations on the validity of the Newton law of gravity at very large distances. One of such attempts is the Modified Newton Dynamics (MOND), suggested by Milgrom & Bekenstein (1987), for a discussion see Sanders (1990). Indeed, MOND is able to represent a number of observational data without assuming the presence of some hidden matter. However, there exist several arguments which make this model unrealistic.

First of all, in the absence of large amounts of non-baryonic matter during the radiation domination era of the evolution of the Universe it would be impossible to get for the relative amplitude of density fluctuations a value of the order of 10^{-3}, needed to form all observed structures.

Second, there exist numerous direct observations of the distribution of mass, visible galaxies and the hot X-ray gas, which cannot be explained in the MOND framework. One of such examples is the "bullet" cluster 1E 0657-558 (Clowe et al., 2004; Markevitch et al., 2004; Clowe et al., 2006a), shown in Fig. 10. This is a pair of galaxy clusters, where the smaller cluster (bullet) has passed the primary cluster almost tangentially to the line of sight. The hot X-ray gas has been separated by ram pressure-stripping during the passage. Weak gravitation lensing yields the distribution of mass in the cluster pair. Lensing observations show that the distribution of matter is identical with the distribution of galaxies. The dominant population of the baryonic mass is in X-ray gas which is well separated from the distribution of mass. This separation is only possible if the mass is in the collisionless component, i.e. in the non-baryonic dark matter halo, not in the baryonic X-ray gas.

5 Dark Matter and structure formation

It is clear that if dark matter dominates in the matter budget of the Universe, then the properties of dark matter particles determine the formation and evolution of the structure of the Universe. In this way the dark matter problem is related to the large-scale structure of the Universe.

5.1 The distribution of galaxies and clusters

Already in the New General Catalogue (NGC) of nebulae, composed from observations by William and John Herschel, a rich collection of nearby galaxies in the Virgo constellation was known. de Vaucouleurs (1953a) called this system the Local Super-galaxy, presently it is known as the Virgo or Local Supercluster. Detailed investigation of the distribution of galaxies became possible when Harlow Shapley started in the Harvard Observatory a systematic photographic survey of galaxies in selected areas, up to 18th magnitude (Shapley, 1940). Shapley discovered several other rich superclusters, one of them is presently named the Shapley Supercluster. These studies showed also that the mean spatial density of galaxies is approximately independent of the distance and of the direction in the sky. In other words, the Harvard survey indicated that galaxies are distributed in space more-or-less homogeneously, as expected from the general cosmological principle.

A complete photographic survey of galaxies was made in the Lick Observatory with the 20-inch Carnegie astrograph by Shane & Wirtanen (1967). Galaxy counts were made in cells of size $10' \times 10'$, and the distribution of the number density of galaxies was studied. The general conclusion from this study was that galaxies are mostly located in clusters, the number of galaxies per cluster varying widely from pairs to very rich clusters of the Coma cluster type. The Lick counts were reduced by Jim Peebles and collaborators to exclude count limit irregularities; the resulting distribution of galaxies in the sky is shown in Fig. 11.

A much deeper photographic survey was made using the 48-inch Palomar Schmidt telescope. Fritz Zwicky used this survey to compile for the Northern hemisphere a catalogue of galaxies and clusters of galaxies (Zwicky et al., 1968). The galaxy catalogue is complete up to 15.5 photographic magnitude. George Abell used the same survey to compile a catalogue of rich clusters of galaxies for the Northern sky, later the catalogue was continued to the Southern sky (Abell, 1958; Abell et al., 1989). Using apparent magnitudes of galaxies approximate distances (distance classes) were estimated for clusters in both catalogues. Authors noticed that clusters of galaxies also show a tendency of clustering, similar to galaxies which cluster to form groups and clusters. Abell called these second order clusters superclusters, Zwicky – clouds of galaxies.

The Lick counts as well as galaxy and cluster catalogues by Zwicky and Abell were analysed by Jim Peebles and collaborators (Peebles (1973), Hauser & Peebles (1973), Peebles & Hauser (1974), Peebles (1974)). To describe the distribution of galaxies Peebles introduced the two-point correlation (or covariance) function of galaxies (Peebles & Groth, 1975; Groth & Peebles, 1977; Fry & Peebles, 1978). This function describes the probability to find a neighbour at a given angular separation in the sky from a galaxy. At small separations the spatial galaxy correlation function can be approximated by a power law: $\xi = (r/r_0)^{-\gamma}$, with the index $\gamma = 1.77 \pm 0.04$. The distance r_0, at which the correlation function equals unity, is called the correlation length. For galaxy samples its value is $r_0 \approx 5\,h^{-1}$ Mpc, and for clusters of galaxies $r_0 \approx 30\,h^{-1}$ Mpc. On scales ≥ 5 times the correlation length the correlation function is very close to zero, i.e. the distribution of galaxies (clusters) is

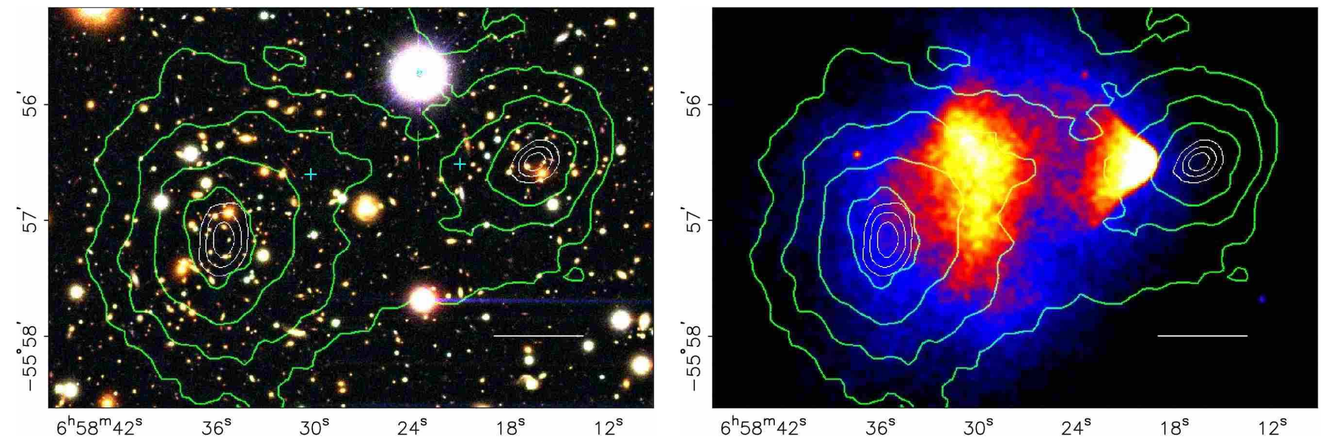

Figure 10: Images of the merging 'bullet' cluster 1E0657-558. The left panel shows a direct image of the cluster obtained with the 6.5-m Magellan telescope in the Las Campanas Observatory, the right panel is a X-ray satellite Chandra image of the cluster. Shock waves of the gas are visible, the gas of the smaller 'bullet' cluster (right) lags behind the cluster galaxies. In both panels green contours are equidensity levels of the gravitational potential of the cluster, found using weak gravitational lensing of distant galaxies. The white bar has 200 kpc/h length at the distance of the cluster. Note that contours of the gravitational potential coincide with the location of visible galaxies, but not with the location of the X-ray gas (the dominant baryonic component of clusters) (Clowe et al., 2006a) (reproduced by permission of the AAS and authors).

essentially random.

The conclusion from these studies, based on the apparent (2-dimensional) distribution of galaxies and clusters in the sky confirmed the picture suggested by Kiang (1967) and de Vaucouleurs (1970), among others, that galaxies are hierarchically clustered. However, this hierarchy does not continue to very large scales as this contradicts observations, which show that on very large scales the distribution is homogeneous. A theoretical explanation of this picture was given by Peebles in his hierarchical clustering scenario of structure formation (Peebles & Yu, 1970; Peebles, 1971).

5.2 Superclusters, filaments and voids

In 1970s new sensitive detectors were developed which allowed to measure redshifts of galaxies up to fainter magnitudes. Taking advance of this development several groups started to investigate the environment of relatively rich clusters of galaxies, such as the Coma cluster and clusters in the Hercules supercluster, with a limiting magnitude about 15.5. During this study Chincarini, Gregory, Rood, Thompson and Tifft noticed that the main clusters of the Coma supercluster, A1656 and A1367, are surrounded by numerous galaxies, forming a cloud around clusters at the redshift ~7000 km/s. The Coma supercluster lies behind the Local supercluster, thus galaxies of the Local supercluster also form a condensation in the same direction at the redshift about 1000 km/s. In between there is a group of galaxies around NGC 4169 at the redshift ~4000 km/s, and the space between these systems is completely devoid of galaxies (Chincarini & Rood, 1976; Gregory & Thompson, 1978). A similar picture was observed in front of the Hercules and Perseus superclusters.

In 1970s there were two main rivaling theories of structure formation: the pancake theory by Zeldovich (1970), and the hierarchical clustering theory by Peebles (1971). According to the Zeldovich scenario the structure forms top-down: first matter collects into pancakes and then fragments to form smaller units. In the hierarchical clustering scenario the order of the formation of systems is the opposite: first small-scale systems (star-cluster sized objects) form, and by clustering systems of larger size (galaxies, clusters of galaxies) form; this is a bottom-up scenario.

Zeldovich asked Tartu astronomers for help in solving the question: Can we find observational evidence which can be used to discriminate between various theories of galaxy formation? In solving the Zeldovich question we started from the observational fact suggesting that random velocities of galaxies are of the order of several hundred km/s. Thus during the whole lifetime of the Universe galaxies have moved from their place of origin only by about 1 h^{-1} Mpc. In other words – if there exist some regularities in the distribution of galaxies, then these regularities must reflect the conditions in the Universe during the formation of galaxies.

In mid-1970s first all-sky complete redshift surveys of galaxies were just available: the de Vaucouleurs et al. (1976) Second Revised Catalogue of Galaxies, the Shapley-Adams revised catalogue by Sandage & Tammann (1981), complete up to the magnitude 13.5 (new redshifts were available earlier (Sandage, 1978)). The common practice to visualise the three-dimensional distribution of galaxies, groups and clusters of galaxies is the use of wedge-diagrams. In these diagrams, where galaxies as well as groups and clusters of galaxies were plotted, a regularity was clearly seen: galaxies and clusters are concentrated to identical essentially one-dimensional systems, and the space between these systems is practically empty (Jõeveer & Einasto, 1978). This distribution was quite similar to the distribution of test particles in a numerical simulation of the evolution of the structure of the Universe prepared by the Zeldovich group (Doroshkevich et al. (1980a), early results of simulation were available already in 1976). In this simulation a network of high- and low-density regions was seen: high-density regions form cells which surround large under-dense regions. Thus the observed high-density regions could be identified with Zeldovich pancakes.

The Large-Scale Structure of the Universe was discussed at the IAU symposium in Tallinn 1977. The amazing prop-

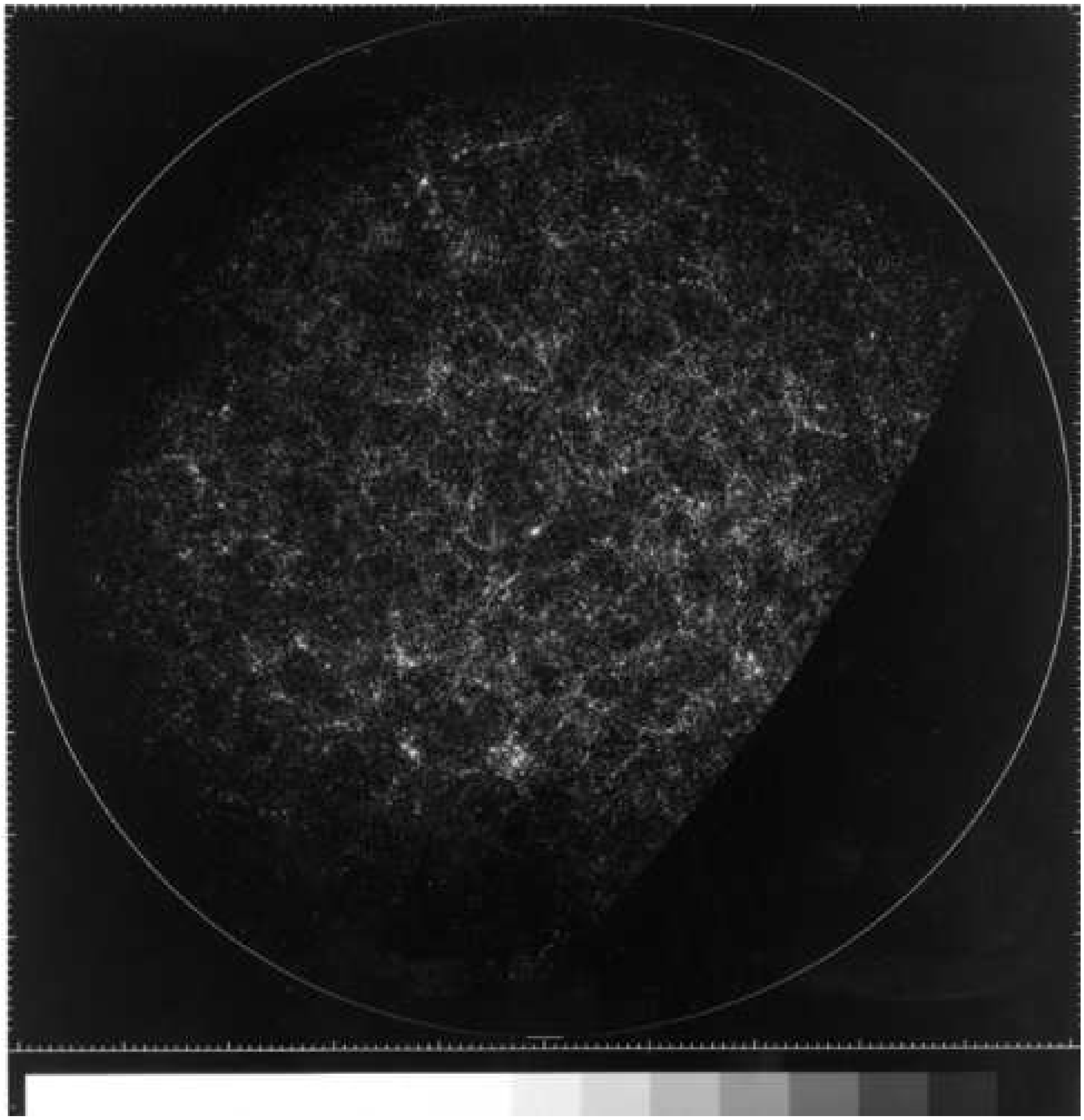

Figure 11: The two-dimensional distribution of galaxies according to the Lick counts (Seldner et al., 1977). The north galactic pole is at the center, the galactic equator is at the edge. Superclusters are well seen, the Coma cluster is located near the center (reproduced by permission of the AAS and authors).

erties of the distribution of galaxies were reported by four different groups: Tully & Fisher (1978) for the Local supercluster, Jõeveer & Einasto (1978) for the Perseus supercluster, Tarenghi et al. (1978) for the Hercules supercluster, and Tifft & Gregory (1978) for the Perseus supercluster; see also Gregory & Thompson (1978) for the Coma supercluster and Jõeveer et al. (1978) for the distribution of galaxies and clusters in the Southern galactic hemisphere. The presence of voids (holes) in galaxy distribution was suggested in all four reports. Tully & Fisher demonstrated a movie showing a filamentary distribution of galaxies in the Local supercluster. Jõeveer and Einasto emphasized the presence of fine structure: groups and clusters of galaxies form chains in superclusters and connect superclusters to an infinite network, as seen from wedge diagrams in Fig. 12. They demonstrated also morphological properties of the structure of superclusters: clusters and groups within the chain are elongated along the chain, and main galaxies of clusters (supergiant galaxies of type cD) are also elongated along the chain. A long chain of clusters, groups and galaxies of the Perseus-Pisces supercluster is located almost perpendicular to the line of sight. The scatters of positions of clusters/groups along the chain in the radial (redshift) and tangential directions are practically identical. This demonstrates that the chain is essentially an one-dimensional structure.

A direct consequence from this observation is that galaxies and groups/clusters of the chain are already formed within the chain. A later inflow from random locations to the chain is excluded, since in this case it would be impossible to stop galaxies and clusters in the chain after the inflow. The main results of the symposium were summarised by Malcolm Longair as follows: *To me, some of the most exiting results presented at this symposium concerned the structure of the Universe on the largest scales. Everyone seemed to agree about the existence of superclusters on scales* $\sim 30-100$ *Mpc. But perhaps even more surprising are the great holes in the Universe. Peebles' picture, Einasto's analysis of the velocity distribution of galaxies which suggests a "cell-structure" and Tiffts's similar analysis argue that galaxies are found in interlocking chains over scales* $\sim 50-100$ *Mpc forming pattern similar to a lace-tablecloth.*

New data gave strong support to the pancake scenario by Zeldovich (1978). However, some important differences between the model and observations were evident. First of all,

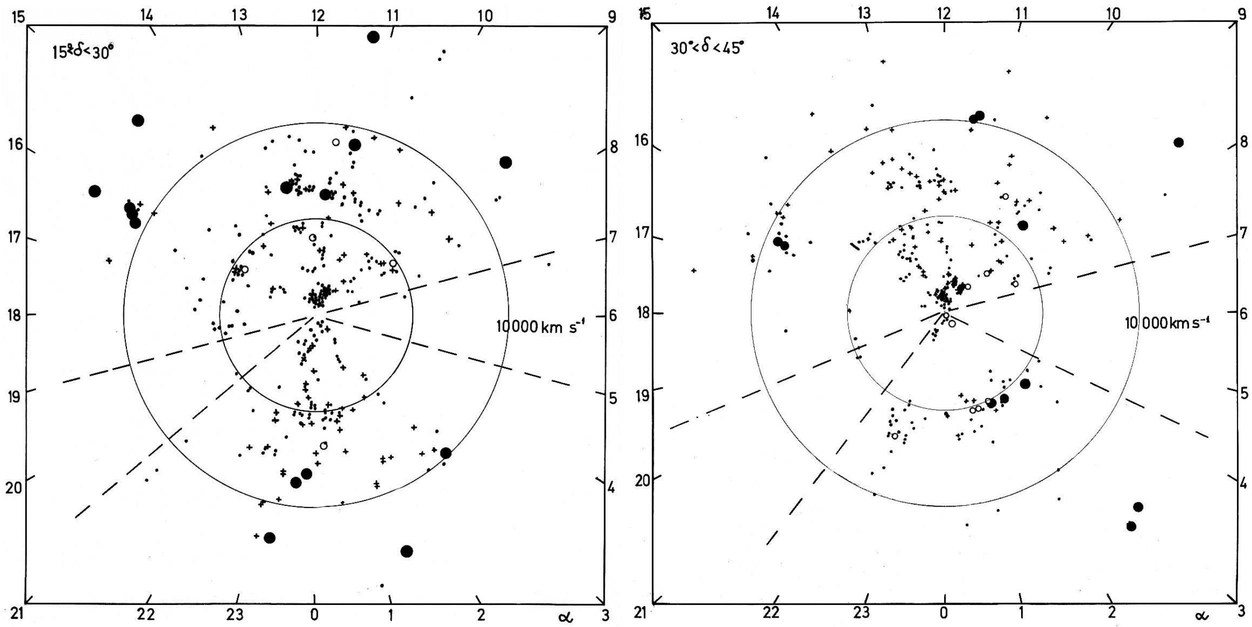

Figure 12: Wedge diagrams for two declination zones. Filled circles show rich clusters of galaxies, open circles – groups, dots – galaxies, crosses – Markarian galaxies. In the 15° – 30° zone two rich clusters at RA about 12 h are the main clusters of the Coma supercluster, in the 30° – 45° zone clusters at RA about 3 h belong to the main chain of clusters and galaxies of the Perseus-Pisces supercluster. Note the complete absence of galaxies in front of the Perseus-Pisces supercluster, and galaxy chains leading from the Local supercluster towards the Coma and Perseus-Pisces superclusters (Jõeveer & Einasto, 1978).

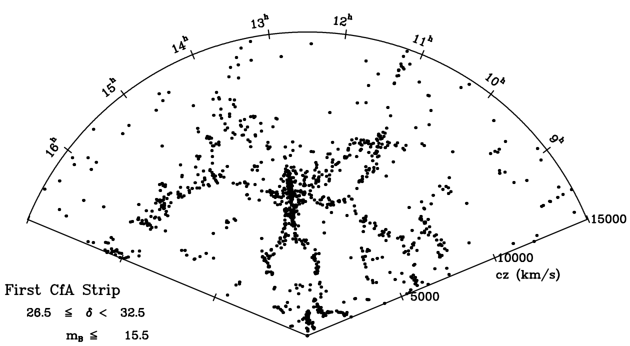

Figure 13: A slice of the Universe according to the CfA Second redshift survey (de Lapparent et al., 1986). Galaxy chains connecting the Local and Coma superclusters are seen more clearly; the connection between the Hercules and Coma superclusters is also visible (reproduced by permission of the AAS and authors).

numerical simulations showed that there exists a rarefied population of test particles in voids absent in real data. This was the first indication for the presence of physical biasing in galaxy formation – there is primordial gas and dark matter in voids, but due to low density no galaxy formation takes place here. Theoretical explanation of the absence of galaxies in voids was given by Enn Saar (Einasto et al., 1980). In over-dense regions the density increases until the matter collapses to form compact objects (Zeldovich pancakes). In under-dense regions the density decreases exponentially but never reaches a zero value – gravity cannot evacuate voids completely.

The second difference lies in the structure of galaxy systems in high-density regions: in the original pancake model large-scale structures (superclusters) have rather diffuse forms, real superclusters consist of multiple intertwined filaments: Jõeveer & Einasto (1978), Zeldovich et al. (1982), Oort (1983). In the original pancake scenario small-scale perturbations were damped. This scenario corresponds to the neutrino-dominated dark matter. Neutrinos move with very high velocities which wash out small-scale fluctuations. Also, in the neutrino-dominated Universe superclusters and galaxies within them form relatively late, but the age of old stellar populations in galaxies suggests an early start of galaxy formation, soon after the recombination epoch. In other words, the original pancake scenario was in trouble (Bond et al., 1982; Peebles, 1982; Zeldovich et al., 1982; Bond & Szalay, 1983; White et al., 1983).

The presence of voids in galaxy distribution was initially met with scepticism, since 3-dimensional data were available only for bright galaxies, and faint galaxies could fill voids. However, independent evidence was soon found. A very large void was discovered in Bootes by Kirshner et al. (1981). The filamentary nature of galaxy distribution is very clearly seen in the 2nd Center for Astrophysics (Harvard) Redshift Survey by Huchra, Geller and collaborators (de Lapparent et al., 1986; Huchra et al., 1988), complete up to 15.5 apparent blue magnitude in the Northern Galactic hemisphere, see Fig. 13.

Huchra initiated a near-infrared survey of nearby galaxies, the Two Micron All-Sky Survey (2MASS) (Huchra, 2000; Skrutskie et al., 2006). Photometry in 3 near-infrared spectral bands is completed, it includes about half a million galaxies up to the limiting K magnitude 13.5. The redshifts are planned to be measured for all galaxies up to $K = 11.25$. The advantage of this survey is the coverage of low galactic latitudes up to 5 degrees from the Galactic equator. For the Southern sky the redshift survey of 2MASS galaxies is almost completed using the 6 degree Field Survey with the Australian large Schmidt telescope. The filamentary character of the distribution of galaxies is very well seen.

A much deeper redshift survey up to the blue magnitude 19.4 was recently completed using the Anglo-Australian 4-m telescope. This Two degree Field Galaxy Redshift Survey

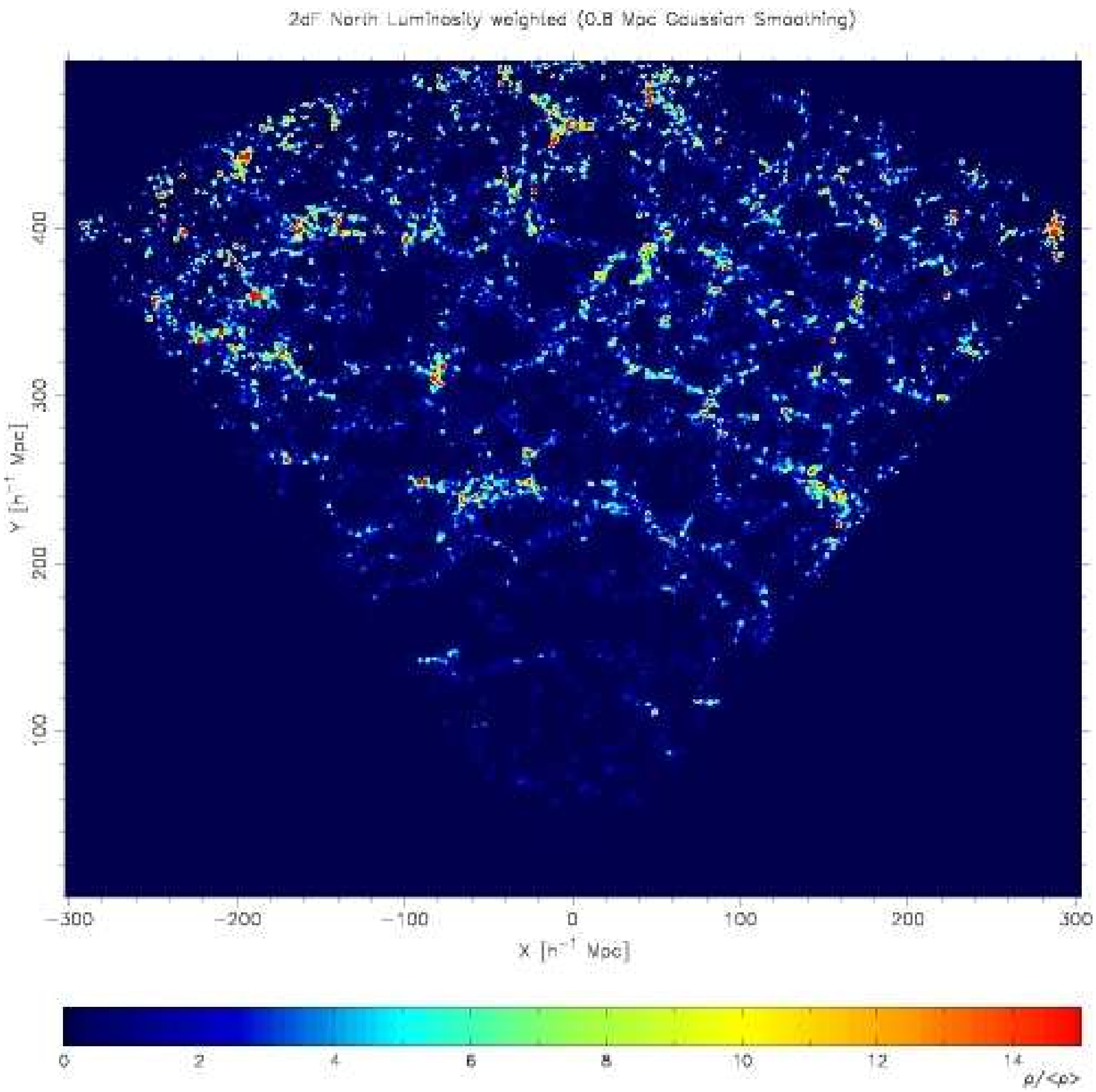

Figure 14: A wedge diagram of the luminosity density field of galaxies of the 2dFGRS Northern equatorial zone, ±1.5 degrees around the equator. The luminosity densities have been corrected for the incompleteness effect; the RA coordinate is shifted so that the plot is symmetrical around the vertical axis. The rich supercluster at the distance $\sim 250\ h^{-1}$ Mpc from the observer is SCL126, according to the supercluster catalogue by Einasto et al. (2001). This figure illustrates the structure of the cosmic web (the supercluster-void network). The density field shows that rich superclusters contain many rich clusters of galaxies, seen in picture as red dots. Filaments consisting of less luminous galaxies and located between superclusters are also clearly seen (Einasto et al., 2007).

(2dFGRS) covers an equatorial strip in the Northern Galactic hemisphere and a contiguous area in the Southern hemisphere (Colless et al., 2001; Cross et al., 2001). Over 250 thousand redshifts have been measured, which allows to see and measure the cosmic web (supercluster-void network) up to the redshift 0.2, corresponding to a co-moving distance about $575\ h^{-1}$ Mpc. The luminosity density field calculated for the Northern equatorial slice of the 2dFGRS is shown in Fig. 14.

Presently the largest project to map the Universe, the Sloan Digital Sky Survey (SDSS) mentioned already before, has been initiated by a number of American, Japanese and European universities and observatories (York et al., 2000; Stoughton et al., 2002; Zehavi et al., 2002). The goal is to map a quarter of the entire sky: to determine positions and photometric data in 5 spectral bands of galaxies and quasars of about 100 million objects down to the red magnitude $r = 23$, and redshifts of all galaxies down to $r = 17.7$ (about 1 million galaxies), as well as the redshifts of Luminous Red Giants (LRG, mostly central galaxies of groups and clusters) down to the absolute magnitude about −20. All 7 data releases have been made public. This has allowed to map the largest volume of the Universe so far. LRGs have a spatial density about 10 times higher than rich Abell clusters of galaxies, which allows to sample the cosmic web with sufficient details up to a redshift ~ 0.5.

5.3 Structure formation in the Cold Dark Matter scenario

A consistent picture of the structure formation in the Universe slowly emerged from the advancement in the observational studies of the large scale structure and the Cosmic Microwave Background, and in the development of theory. The most important steps along the way were the following.

Motivated by the observational problems with neutrino dark matter, a new dark matter scenario was suggested by Blumenthal et al. (1982); Bond et al. (1982);

Pagels & Primack (1982); Peebles (1982); Bond & Szalay (1983); Doroshkevich & Khlopov (1984) with hypothetical particles as axions, gravitinos, photinos or unstable neutrinos playing the role of dark matter. This model was called the Cold Dark Matter (CDM) model, in contrast to the neutrino-based Hot Dark Matter model. Newly suggested dark matter particles move slowly, thus small-scale perturbations are not suppressed, which allows an early start of the structure formation and the formation of fine structure. Advantages of this model were discussed by Blumenthal et al. (1984).

Next, the cosmological constant, Λ, was incorporated into the scheme. Arguments favouring a model with the cosmological constant were suggested already by Gunn & Tinsley (1975); Turner et al. (1984); Kofman & Starobinskii (1985): combined constraints on the density of the Universe, ages of galaxies, and baryon nucleosynthesis.

Finally, there was a change in the understanding of the formation of initial perturbations which later lead to the observed structure. To explain the flatness of the Universe the inflation scenario was suggested by Guth (1981), Kofman et al. (1985) and others. According to the inflation model in the first stage the expansion of the Universe was extremely rapid (this early stage is called the inflation epoch). Such an evolutionary scenario allows for the creation of the visible part of the Universe out of a small causally connected region and explains why in the large scale the Universe seems roughly uniform. Perturbations of the field are generated by small quantum fluctuations. These perturbations form a Gaussian random field, they are scale-invariant and have a purely adiabatic primordial power spectrum.

These ideas were progressively incorporated into the computer simulations of increasing complexity.

Pioneering numerical simulations of the evolution of the structure of the Universe were made in 1970s by Miller (1978), Aarseth et al. (1979) and the Zeldovich group (Doroshkevich et al., 1980a), using direct numerical integration. In early 1980s the Fourier transform was suggested to calculate the force field which allowed to increase the number of test particles.

Numerical simulations of structure evolution for the hot and cold dark matter were compared by Melott et al. (1983), and by White et al. (1983, 1987) (standard CDM model with density parameter $\Omega_m = 1$). In contrast to the HDM model, in the CDM scenario the structure formation starts at an early epoch, and superclusters consist of a network of small galaxy filaments, similar to the observed distribution of galaxies. Thus CDM simulations reproduce quite well the observed structure with clusters, filaments and voids, including quantitative characteristics (percolation or connectivity, the multiplicity distribution of systems of galaxies).

Models with the cosmological $\Lambda-$term were developed by Gramann (1988). Comparison of the SCDM and ΛCDM models shows that the structure of the cosmic web is similar in both models. However, in order to get a correct amplitude of density fluctuations, the evolution of the SCDM model has to be stopped at an earlier epoch.

The largest so far simulation of the evolution of the structure – *the Millennium Simulation* – was made in the Max-Planck Institute for Astrophysics in Garching by Volker Springel and collaborators (Springel et al., 2005; Gao et al., 2005a; Springel et al., 2006). The simulation is assuming the ΛCDM initial power spectrum. A cube of the comoving size of 500 h^{-1} Mpc was simulated using about 10 billion dark matter particles that allowed to follow the evolution of small-scale features in galaxies. Using a semi-analytic model the formation and evolution of galaxies was also simulated (Di Matteo et al., 2005; Gao et al., 2005b; Croton et al., 2006). For simulated galaxies photometric properties, masses, luminosities and sizes of principal components (bulge, disk) were found. The comparison of this simulated galaxy catalogue with observations shows that the simulation was very successful. The results of the Millennium Simulation are frequently used as a starting point for further more detailed simulations of evolution of single galaxies.

One difficulty of the original pancake scenario by Zeldovich is the shape of objects formed during the collapse. It was assumed that forming systems are flat pancake-like objects, whereas dominant features of the cosmic web are filaments. This discrepancy has found an explanation by Bond et al. (1996). They showed that in most cases just essentially one-dimensional structures, i.e. filaments form.

The ΛCDM model of structure formation and evolution combines essential aspects of both original structure formation models, the pancake and the hierarchical clustering scenario. First structures form at very early epochs soon after the recombination in places where the primordial matter has the highest density. This occurs in the central regions of future superclusters. First objects to form are small dwarf galaxies, which grow by infall of primordial matter and other small galaxies. Thus, soon after the formation of the central galaxy other galaxies fall into the gravitational potential well of the supercluster. These clusters have had many merger events and have "eaten" all its nearby companions. During each merger event the cluster suffers a slight shift of its position. As merger galaxies come from all directions, the cluster sets more and more accurately to the center of the gravitational well of the supercluster. This explains the fact that very rich clusters have almost no residual motion in respect to the smooth Hubble flow. Numerous examples of the galaxy mergers are seen in the images of galaxies collected by the Hubble Space Telescope.

6 Matter-energy content of the Universe

6.1 Dark Matter and Dark Energy

In early papers on dark matter the total density due to visible and dark matter was estimated to be about 0.2 of the critical cosmological density. These estimates were based on the dynamics of galaxies in groups and clusters. This density estimate can be interpreted in two different ways: either we live in an open Universe where the total density is less than the critical density, or there exists some additional form of matter/energy which allows the Universe to be closed, i.e. to have the critical total density. The additional term was identified with the Einstein Λ-term, so that the total matter/energy density was taken to be equal to the critical cosmological density (Gunn & Tinsley, 1975; Turner et al., 1984; Kofman & Starobinskii, 1985). Initially there was no direct observational evidence in favour of this solution and it was supported basically on general theoretical grounds. In its early evolution the size of the Universe increases very rapidly and any deviation from the exact critical density would lead to a rapid change of the relative density, either to zero, if the initial density was a bit less than the critical one, or to infinity, if it was greater than critical. In other words, some fine tuning is needed to keep the density at all times equal to the critical one.

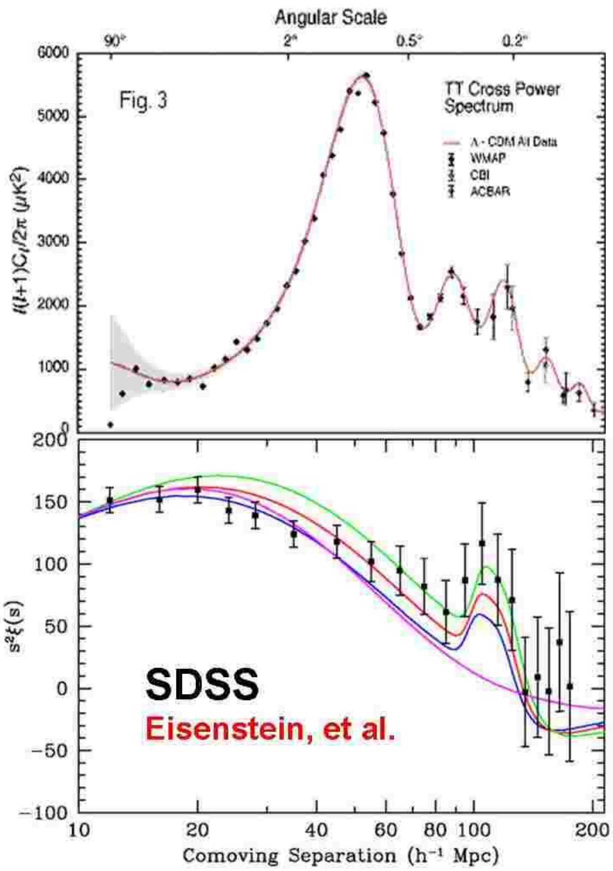

Figure 15: Upper panel shows the acoustic peaks in the angular power spectrum of the CMB radiation according to the WMAP and other recent data, compared with the ΛCDM model using all available data. The lower panel shows the signature of baryonic acoustic oscillations in the matter two-point correlation function (Eisenstein et al., 2005; Kolb, 2007) (reproduced by permission of the author)

In subsequent years several new independent methods were applied to estimate the cosmological parameters. Of these new methods two desire special attention. One of them is based on the measurements of small fluctuations of the Cosmic Microwave Background (CMB) radiation, and the other on the observation of distant supernovae.

According to the present cosmological paradigm the Universe was initially very hot and ionized. The photons provided high pressure and prevented baryons from moving. Perturbations of baryons did not grow, but oscillated as sound waves. The largest possible wavelength of these oscillations is given by the sound horizon size at the decoupling. This wavelength is seen as the first maximum in the angular power spectrum of the CMB radiation. The following maxima correspond to overtones of the first one. The fluctuations of CMB radiation were first detected by the COBE satellite. The first CMB data were not very accurate, since fluctuations are very small, of the order of 10^{-5}. Subsequent experiments carried out using balloons, ground based instruments, and more recently the Wilkinson Microwave Anisotropy Probe (WMAP) satellite, allowed to measure the CMB radiation and its power spectrum with a much higher precision (Spergel et al., 2003). The position of the first maximum of the power spectrum depends on the total matter/energy density. Observations confirm the theoretically favoured value 1 in units of the critical cosmological density, see Fig. 15.

When recombination begins, the small overdensities of baryon gas launch spherical shock waves in the photon-baryon fluid. After some time photons completely decouple from baryons, and the baryons loose photon pressure support. The shock stops after traveling a distance of about 150 Mpc (in comoving coordinates). This leads to an overdensity of the baryonic medium on a distance scale of 150 Mpc. This overdensity has been recently detected in the correlation function of Luminous Red Giant galaxies of the SDSS survey (Eisenstein et al., 2005; Hütsi, 2006), see lower panel of Fig. 15. Baryonic acoustic oscillations depend on both the total matter/energy density and the baryon density, thus allowing to estimate these parameters.

Another independent source of information on cosmological parameters comes from the distant supernova experiments. Two teams, led by Riess et al. (1998, 2007) (High-Z Supernova Search Team) and Perlmutter et al. (1999) (Supernova Cosmology Project), initiated programs to detect distant type Ia supernovae in the early stage of their evolution, and to investigate with large telescopes their properties. These supernovae have an almost constant intrinsic brightness (depending slightly on their evolution). By comparing the luminosities and redshifts of nearby and distant supernovae it is possible to calculate how fast the Universe was expanding at different times. The supernova observations give strong support to the cosmological model with the Λ term, see Fig. 16.

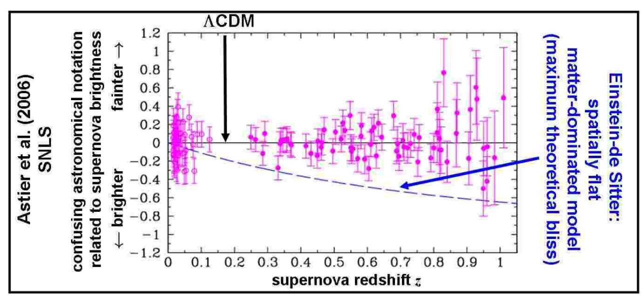

Figure 16: Results of the Supernova Legacy Survey: apparent magnitudes of supernovae are normalised to the standard ΛCDM model, shown as solid line. Dashed line shows the Einstein-de Sitter model with $\Omega_m = 1$ (Kolb, 2007) (reproduced by permission of the author).

Different types of dark energy affect the rate at which the Universe expands, depending on their effective equation of state. The cosmological constant has one equation of state. The other possible candidate of dark energy is quintessence (a scalar field) that has a different equation of state. Each variant of dark energy has its own equation of state that produces a signature in the Hubble diagram of the type Ia supernovae (Turner, 2003).

The combination of the CMB and supernova data allows to estimate independently the matter density and the density due to dark energy, shown in Fig. 17. The results of this combined approach imply that the Universe is expanding at an accelerating rate. The acceleration is due to the existence of some previously unknown dark energy (or cosmological constant) which acts as a repulsive force (for reviews see Bahcall et al. (1999), Frieman et al. (2008)).

Independently, the matter density parameter has been determined from clustering of galaxies in the 2-degree Field Red-

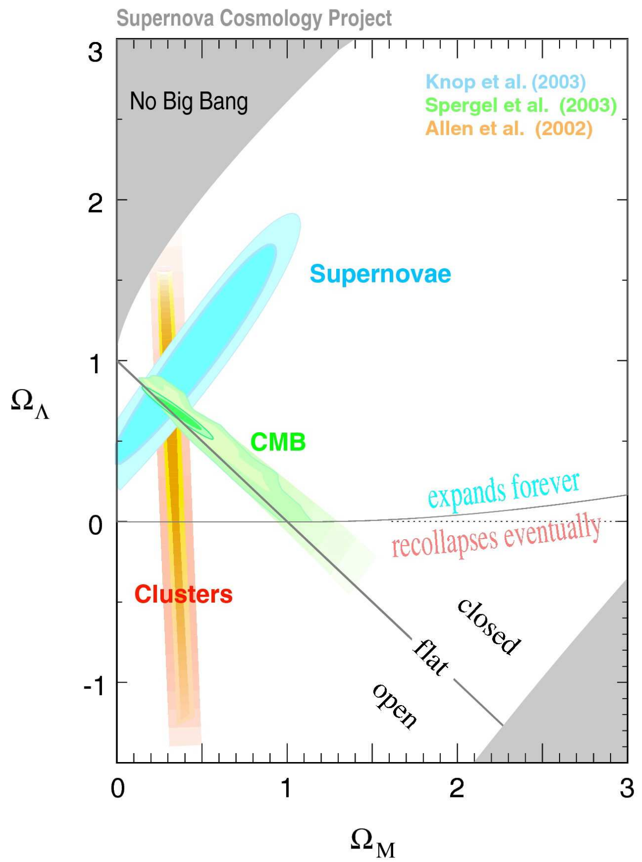

Figure 17: Combined constraints to cosmological densities Ω_Λ and Ω_M, using supernovae, CMB and cluster abundance data. The flat Universe with $\Omega_\Lambda + \Omega_M = 1$ is shown with solid line (Knop et al., 2003).

shift Survey and the Sloan Digital Sky Survey. The most accurate estimates of cosmological parameters are obtained using a combined analysis of the 2dFGRS, SDSS and the WMAP data (Spergel et al., 2003; Tegmark et al., 2004; Sánchez et al., 2006). According to these studies the matter density parameter is $\Omega_m = 0.27 \pm 0.02$, not far from the value $\Omega_m = 0.3$, suggested by Ostriker & Steinhardt (1995) as a concordant model. The combined method yields for the Hubble constant a value $h = 0.71 \pm 0.02$ independent of other direct methods. From the same dataset authors get for the density of baryonic matter, $\Omega_b = 0.041 \pm 0.002$. Comparing both density estimates we get for the dark matter density $\Omega_{DM} = \Omega_m - \Omega_b = 0.23$, and the dark energy density $\Omega_\Lambda = 0.73$. These parameters imply that the age of the Universe is 13.7 ± 0.2 Gigayears.

6.2 The role of dark energy in the evolution of the Universe

Studies of the Hubble flow in nearby space, using observations of type Ia supernovae with the Hubble Space Telescope (HST), were carried out by several groups. The major goal of the study was to determine the value of the Hubble constant. As a by-product also the smoothness of the Hubble flow was investigated. In this project supernovae were found up to the redshift (expansion speed) 20 000 km s^{-1}. This project (Sandage et al., 2006) confirmed earlier results that the Hubble flow is very quiet over a range of scales from our Local Supercluster to the most distant objects observed. This smoothness in spite of the inhomogeneous local mass distribution requires a special agent. Vacuum energy as the solution has been proposed by several authors (Baryshev et al. (2001) and others). Sandage emphasises that no viable alternative to vacuum energy is known at present, thus the quietness of the Hubble flow gives strong support for the existence of vacuum energy.

7 Conclusions

The discoveries of dark matter and the cosmic web are two stages of a typical scientific revolution (Kuhn, 1970; Tremaine, 1987). As often in a paradigm shift, there was no single discovery, new concepts were developed step-by-step.

First of all, actually there are two dark matter problems – the local dark matter close to the plane of our Galaxy, and the global dark matter surrounding galaxies and clusters of galaxies. Dark matter in the Galactic disk is baryonic (faint stars or jupiters), since a collection of matter close to the galactic plane is possible, if it has formed by contraction of pre-stellar matter towards the plane and dissipation of the extra energy, that has conserved the flat shape of the population. The amount of local dark matter is low, it depends on the mass boundary between luminous stars and faint invisible stars.

The global dark matter is the dominating mass component in the Universe; it is concentrated in galaxies, clusters and superclusters, and populates also cosmic voids. Global dark matter must be non-baryonic, its density fluctuations start to grow much earlier than perturbations in the baryonic matter, and have at the recombination epoch the amplitude large enough to form all structures seen in the Universe. Initially neutrinos were suggested as particles of dark matter (hot dark matter), but presently some other weakly interacting massive particles, called cold dark matter, are preferred.

Recently direct observational evidence was found for the presence of Dark (or vacuum) Energy. New data suggest that the total matter/energy density of the Universe is equal to the critical cosmological density, the density of baryonic matter is about 0.04 of the critical density, the density of dark matter is about 0.23 of the critical density, and the rest is dark energy.

A number of current and future astronomical experiments have the aim to get additional data on the structure and evolution of the Universe and the nature and properties of dark matter and dark energy. Two astronomical space observatories are planned to be launched in 2008: the Planck CMB mission and the Herschel 3.5-m infrared telescope. The main goal of the Planck mission is to measure the CMB radiation with a precision and sensitivity about ten times higher than those of the WMAP satellite. This allows to estimate the values of the cosmological parameters with a very high accuracy. The Herschel telescope covers the spectral range from the far-infrared to sub-millimeter wavelengths and allows to study very distant redshifted objects, i.e young galaxies and clusters.

Very distant galaxies are the target of the joint project GOODS – The Great Observatories Origins Deep Survey. Observations are made at different wavelengths with various telescopes: the Hubble Space Telescope, the Chandra X-ray telescope, the Spitzer infrared space telescope, and by great ground-based telescopes (the 10-m Keck telescope in Hawaii, the 8.2-m ESO VLT-telescopes in Chile). Distant cluster survey is in progress in ESO.

NASA-DOE have approved the mission DESTINY – the

Dark Energy Space Telescope. Its goal is to detect and obtain precision photometry, light-curves and redshifts of over 2000 type Ia supernovae over the redshift range $0.5 < z < 1.7$ to constrain the nature of dark energy.

The largest so far planned space telescope is The James Webb Space Telescope (JWSP) – a 6.5-m infrared optimized telescope, scheduled for launch in 2013. The main goal is to observe first galaxies that formed in the early Universe.

To investigate the detailed structure of our own Galaxy the space mission GAIA will be launched in 2011. It will measure positions, proper motions, distances and photometric data for 1 billion stars, repeatedly. Its main goal is to clarify the origin and evolution of our Galaxy and to probe the distribution of dark matter within the Galaxy.

The story of the dark matter and dark energy is not over yet – we still do not know of what non-baryonic particles the dark matter is made of, and the nature of dark energy is also unknown. Both problems are a challenge for physics. So far the direct information of both dark components of the Universe comes solely from astronomical observations.

Acknowledgments

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