Abstract  I review the development of the concept of dark matter. The dark matter story passed through several stages, from a minor observational puzzle to a major challenge for theory of elementary particles. Modern data suggest that dark matter is the dominant matter component in the Universe and that it consists of some unknown non-baryonic particles. Dark matter is the dominant matter component in the Universe; therefore, properties of dark matter particles determine the structure of the cosmic web.

Keywords  Dark matter · Large-scale structure of the universe · CMB radiation

1 Dark Matter Story

The masses of astronomical bodies are usually determined directly, using motions of other bodies around or within the body under study. In some cases, total mass estimates found by different methods differ by a large fraction. It is customary to call the hypothetical matter, responsible for such mass discrepancy, dark matter (DM).

The timeline of the study of dark matter is shown in Table 1. 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. However, this difference was understood only later. Thus, we show in the table the whole story.

2 Local Dark Matter

The first indication for the possible presence of dark matter came from the dynamical study of our Galaxy. Öpik [38] was probably the first to estimate the dynamical density of matter in the Galaxy in the vicinity of the Sun. He analysed the vertical motions of stars near the plane of the Galaxy and calculated the dynamical density. He also estimated the density due to all stars near the Galactic plane using the luminosity function of stars. The Dutch astronomer Jacobus Kapteyn [26] made a similar analysis. Öpik and Kapteyn found that the spatial density of known stars is sufficient to explain the vertical motions. The British astronomer James Jeans [24] reanalysed vertical motions of stars near the plane of the Galaxy and found that some dark matter probably exists near the Sun.

A new model of the Galaxy was calculated by Oort [35], who also determined the dynamical density of matter near the Sun. Oort accepted 0.092 solar masses per cubic parsec as the most probable value. He found that the density due to visible stars is 0.038 solar masses per cubic parsec. This difference is often considered as an indication for the presence of dark matter. Oort estimated the total expected mass of faint stars, which is very near to the value found from vertical motions of stars.

Kuzmin [28, 30] and his students in Tartu Observatory showed that the amount of DM in the Galactic disc is small; in contrast, Hill [21], Oort [37], Bahcall [2] and some other astronomers found evidence that up to a half of matter in the solar vicinity may be dark. More accurate recent data showed that the amount of local dark matter is small [18]. If there is some local dark matter, it must be dissipative to release extra kinetic energy during the contraction of matter to a flat disc. This population probably consists of very faint stars or Jupiter-like objects.
Table 1  Dark matter timeline

| Year | Description |
|------|-------------|
| 1915 | First estimates of local DM: Ópik [38], Kapteyn [26], Jeans [24] |
| 1932 | Galactic model and local DM: Oort [35] |
| 1933 | DM in Coma Cluster: Zwicky [57] |
| 1952 | Galactic models and local DM: Kuzmin [28–30] |
| 1957 | Large $M/L$ on the periphery of M31: van de Hulst et al. [54], Roberts [48] |
| 1959 | Mass of the local group: Kahn and Woltjer [25] |
| 1961 | Cluster stability conference: Neyman et al. [34] |
| 1965 | Discovery of CMB: Penzias and Wilson [45] |
| 1972 | Cluster X-ray data on mass of hot gas: Forman et al. [17], Gursky et al. [19] |
| 1972 | Local and global DM different, global DM non-stellar: Einasto [11, 13] |
| 1974 | Parameters of DM coronas/halos: Einasto et al. [14], Ostriker et al. [39] |
| 1975 | DM contradicts classical cosmological paradigm: Materne and Tammann [31] |
| 1977 | $M/L$ of galactic bulges low: Faber et al. [15] |
| 1978 | Extended flat rotation curves: Bosma [6], Rubin et al. [51] |
| 1984 | Cold DM accepted: Blumenthal et al. [3] |
| 1989 | Absence of large amounts of local DM accepted: Gilmore et al. [18] |
| 2012 | CDM particle annihilation detected?: Weniger [55], Tempel et al. [52] |

3 Global Dark Matter

Zwicky [57, 58] measured the 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, which is calculated from the 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 tenfold, probably even more. At this time, astronomers were interested in the structure and evolution of stars, and Zwicky’s work seemed to be remote and uninteresting.

Slowly, more dynamical data on clusters of galaxies were collected, and the discrepancy between the cluster galaxy measured velocities and expected velocities for a stable cluster could not be ignored. In 1961, during the International Astronomical Union General Assembly, a special meeting to discuss the stability of clusters of galaxies was organised by Neyman et al. [34]. However, opinions of astronomers were different, and no definite conclusions were achieved.

Kahn and Woltjer [25] 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 can be explained if both galaxies form a physical system. 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, which is about five times the sum of the conventional masses of the Galaxy and M31. The authors suggested that the extra mass is probably in the form of hot gas of temperature which is about $5 \times 10^5$ K.

A similar problem exists in double elliptical galaxies. The mean mass-to-luminosity ratio of double elliptical galaxies is $M/L \approx 66$ [40, 41], much higher than the estimated masses of individual elliptical galaxies. A certain discrepancy was detected also between masses of individual galaxies and masses of groups of galaxies [22, 42].

Babcock [1], Oort [36], Roberts [48] and Rubin and Ford [49] discovered that the rotation curves of spiral galaxies are flat on the periphery of galaxies. This is contrary to expectations, since the luminosity of galaxies falls rapidly on the periphery and a Keplerian decrease of the rotation curve is expected. If rotation velocities were identified with circular velocities, these observations suggested very high values of mass-to-luminosity ratios $(M/L)$ on the periphery of galaxies.

Detailed models of galaxies using available data on all basic stellar populations (core, disc, bulge, halo, flat population of young stars and interstellar gas) suggested that it is impossible to reproduce the rotation curves of galaxies using independent data on $M/L$ ratios of galactic populations [9, 10, 12]. In order to bring rotation data into agreement with data on known populations, the presence of a new population with very large $M/L$ value, mass and radius has to be assumed [11, 13]. To find the main parameters of the new population—corona—the motion of satellite galaxies was studied by Einasto et al. [14]. This analysis showed that the mass and effective (harmonic) radius of the corona exceed the mass and radius of known populations almost tenfold. This analysis was confirmed by Ostriker et al. [39]; both independent data suggested that the previously unknown population dominates the mass budget of the Universe: the mean density of matter is about $0.2$ of the critical cosmological density. Ostriker et al. used the term ‘halo’ to denote the massive population.

The dark matter problem was discussed in a regional conference on January 1975 in Tallinn. The main subject of the discussion was the nature of the dark matter. Two basic
models were suggested: faint stars or hot gas. It was found that both models have serious difficulties.

The problem was discussed again at the Third European Astronomical Meeting in Tbilisi on June 1975. This meeting was the first well-documented international discussion between supporters and opponents of the dark matter concept. Materne and Tammann [31] concluded that systems of galaxies are stable with conventional masses. Their most serious argument was that 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.

Soon, new observational data arrived, which supported the presence of massive halos/corona of galaxies. Both optical [50, 51] and radio [6] data confirmed flat rotation curves of galaxies at large galactocentric distances. Faber and Jackson [15, 16] found that velocity dispersions and mass-to-light ratios for elliptical galaxies and bulges of galaxies are considerably lower than expected before. This observation demonstrates clearly that conventional stellar populations cannot be identified with dark halos/corona.

New independent observations confirmed large masses of clusters of galaxies. Already early X-ray observations of clusters of galaxies showed that the mass of the hot X-ray-emitting gas is not sufficient to hold clusters together. These data also allowed one to estimate the total masses of clusters and confirmed earlier measurements on the basis of velocity dispersions of galaxies in clusters [17, 19, 27].

An additional estimate of the masses of clusters of galaxies came from gravitational lensing, also supporting large masses of clusters of galaxies.

### 4 The Nature of Dark Matter

By the end of the 1970s, most objections against the dark matter hypothesis had been rejected. 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—the main argument in favour of the classical cosmological paradigm.
- If the massive halo (corona) is neither stellar nor gaseous, of what stuff is it made?
- And a more general question: What is the role of dark matter in the evolution of the Universe?

Answers to these problems came from completely new areas of research—observations of the cosmic microwave background (CMB) radiation and large-scale distribution of galaxies.

According to the current understanding, the Universe began with a Big Bang and was initially very hot. It expanded rapidly and cooled and, at a certain epoch, was cool enough for atoms to recombine. The effective temperature of the radiation drops as the Universe expands. The cosmic microwave background radiation, a remnant of the initial hot Universe, was detected by the American radio astronomers [45].

As emphasised by Peebles and Yu [44] and Zeldovich [56], structures in the Universe were created by the growth of small inhomogeneities of the density. During the initial hot phase of the evolution of the Universe, the matter and radiation were coupled and density inhomogeneities could not grow. As the Universe expanded, the gas cooled, and at recombination, the gas became neutral. From this time on, density fluctuations in the gas had a chance to grow by gravitational instability. The 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, only lower upper limits for the amplitude of CMB fluctuations were obtained. On the other hand, theoretical calculations show that at the epoch of recombination, the density (and temperature) fluctuations must have an amplitude of the order of \( 10^{-3} \). Otherwise, structure could not be formed, since the gravitational instability works very slowly in an expanding Universe.

This controversy can be solved if non-baryonic elementary particles, such as massive neutrinos, form 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 fits the observational data. Second, the total amount of 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. If dark matter is non-baryonic, then this helps to explain the paradox of small temperature fluctuations of the cosmic microwave background radiation. Density perturbations of non-baryonic dark matter already start growing during the radiation-dominated era, whereas the growth of baryonic matter is damped by radiation.

The only known non-baryonic particle was the neutrino; thus, it is natural that first neutrinos were considered as dark matter particle candidates. The power spectrum of neutrino-dominated dark matter is cut at small scales due to rapid motion of particles. Figure 1 shows results of numerical simulation, based on such a model. In Fig. 2, the actual distribution of galaxies, groups and clusters of galaxies is shown. The comparison shows that the neutrino-dominated model has no fine structure in the distribution of galaxies and systems of galaxies.

To avoid these difficulties, dissipation-less particles heavier than neutrinos were suggested by Blumenthal et al. [4], Bond et al. [5] and Peebles [43]. Here, particles such
as axions, gravitinos or photinos play the role of dark matter. These particles were called cold since free streaming of particles is unimportant and particles behave as a cold non-dissipative gas. Numerical models based on cold dark matter (CDM) represent the fine structure of the Universe well [32]. The properties of the cold dark matter model were analysed in detail by Blumenthal et al. [3].

Searches for elementary particles that could serve as candidates for dark matter particles have been carried out in particle acceleration centres, so far with no definite results. Thus, indirect evidence for the presence of dark matter has been explored. One of the recently analysed datasets of interest to investigate possible effects of dark matter comes from the Fermi Gamma-ray Space Telescope, launched on June 11, 2008. Its Large Area Telescope (LAT) can detect gamma rays in an energy interval from about 20 MeV to 300 GeV. Recently, Weniger [55] claimed that there is strong evidence of a monochromatic gamma ray line from the Galaxy centre with an energy \( E = 130 \text{ GeV} \) present in the Fermi Large Area Telescope data. Soon, it was detected that actually there is a double-line spectrum with peaks at energies at 111 and 129 GeV in the Galactic centre. The double peak-like excess can be interpreted as a signal of dark matter direct two-body annihilations into two channels with monochromatic final state photons.

Tempel et al. [52, 53] and Hektor et al. [20] analysed the gamma ray spectrum of the Galaxy centre, as well as of the nearby clusters of galaxies. These authors found from stacked gamma ray spectra of clusters a similar double-peak signal. Figure 3 shows the observed 110 and 130 GeV excess in Fermi LAT data. The signal from galaxy clusters is boosted due to galaxy cluster subhalos. Since the signal from the Galaxy centre and from nearby galaxy clusters shows exactly the same double-peak structure, the signal must come from the same physics. Authors conclude that “The presence of a double peak is a generic prediction of dark matter annihilation pattern in gauge theories, corresponding to \( \gamma\gamma \) and \( \gamma Z \) final states. Thus, the two seemingly unrelated gamma ray spectra, from the Galactic centre and from the galaxy clusters, favour the particle physics origin of the excess over any astrophysics origin”. If these claims are true, this could be a strong evidence that DM is of particle physics origin, representing a breakthrough both in cosmology and in particle physics.

The presence of large amounts of matter of unknown origin has given rise to speculations on the validity of the Newton’s law of gravity at large distances. One such attempt is modified Newtonian dynamics (MOND), suggested by Milgrom and Bekenstein [33]. MOND and other similar models are able to explain a number of observational data without assuming the presence of dark matter.

However, there exist several arguments that make these models unrealistic. The strongest argument in favour of the presence of non-baryonic dark matter comes from the CMB data. In the absence of large amounts of non-baryonic
matter during the radiation-dominated 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 $10^{-3}$, which is needed to form all observed structures.

The other strong argument in favour of the presence of some matter in addition to ordinary baryonic matter comes also from CMB data. The wavenumber of the first acoustic peak in the CMB spectrum is a very accurate indicator of the total matter/energy density of the Universe. Experiments show that, with great accuracy, the total density is equal to the critical cosmological density. On the other hand, both direct determinations as well as the nucleosynthesis constraints show that the density of baryonic matter is only about 4% of the critical density. In other words, there must exist some other forms of matter/energy than ordinary matter. The other forms are dark matter and dark energy. Dark energy causes the acceleration of the Universe. It was detected by comparison of nearby and distant supernovae by Riess et al. [47] and Perlmutter et al. [46].

There exist 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 [7]. This is a pair of galaxy clusters, where the smaller cluster (bullet) has passed the primary cluster almost tangentially to the line of sight. Weak gravitational lensing observations show that the distribution of matter is identical with the distribution of galaxies. The hot X-ray gas has been separated by ram pressure stripping during the passage. 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.

With the discovery of dark energy, the build-up of the modern cosmological paradigm has reached a mature stage. However, the story of dark matter is not over yet—we still do not know of what non-baryonic particles the dark matter is made and the nature of dark energy is completely unknown.

5 Conclusions

The main conclusions of the study of dark matter can be formulated as follows:

1. The discovery of dark matter was the result of combined study of galaxies, their populations and systems of galaxies.
2. The dark matter story is a typical paradigm shift. Evidence for dark matter has been collected independently in many centres.
3. There are two dark matter problems—dark matter in the Galactic disc and dark matter around galaxies and clusters.
4. The dark matter in the Galactic disc is baryonic (faint stars or jupiters). The amount is small.
5. The dark matter around galaxies is non-baryonic cold dark matter. It constitutes about 0.25 of the critical cosmological density.
6. The dark matter is needed to start early enough gravitational clustering to form structure. This solves the Big Bang nucleosynthesis controversy.
7. Essential information on the nature of dark matter comes from the structure of the cosmic web. The nature of DM particles is still unknown.

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