# DARK MATTER IN THE UNIVERSE *

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The review of the dark matter problem is given from broad astrophysical perspective. The state of the art presentation of different methods of inference about the dark matter is provided together with recent observational suggestions concerning composition of the dark matter.

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## 1. History

The presence of the dark matter in the universe has always been inferred from the gravitational effect exerted on the luminous matter. In the last century John Adams and Urbaine LeVerrier predicted the existence of an unseen object perturbing the motion of Uranus. Eventually a new planet — Neptune has been discovered by Johann Galle in 1846. The same story repeated almost a century later, when the planet Pluto whose existence was analogously foretold from the perturbed motion of Neptune, had been discovered by Lowell about 1930.

The modern story of cosmic dark matter traces back to the 30's and is associated with names of two famous astronomers of these times (the pioneers of extragalactic astronomy) Jan Oort and Fritz Zwicky. In 1932 Oort [1] applied the celebrated virial theorem, which states that in the relaxed systems the potential energy is in average two times greater than the kinetic energy: $2\langle T\rangle = -\langle V\rangle$, to the stars in a Galactic disk. His result was that the total mass of the Galaxy appeared 2 times greater than it could be attributed to the luminous matter $M_{\rm Gal,tot} \sim 2\ M_{\rm Gal,lum}$. A year after that (1933) Zwicky applied the virial theorem to radial velocities of galaxies in the Coma cluster [2] arriving at even much greater discrepancy $M_{\rm Coma,tot} \sim 400\ M_{\rm Coma,lum}$.

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These findings were kept dormant for a number of years, and in the beginning of 70's the whole story revived due to pioneering works of Rubin and Ford [3].

## 2. Astrophysical foundations

### *2.1. Rotation curves*

The primary motivation for Rubin and Ford was the desire to determine the mass of the Milky Way. The most reliable mass measurements in astronomy come from using the Kepler's 3rd law. An adoption of this technique to the galaxies was based on the following idea. Given a star moving in peripheral regions at radial distance $r$ form the center one could have assumed that almost whole mass of the galaxy is concentrated interior to the outlier $M_{gal} \approx M(r)$. Then balancing the gravity with the centrifugal force:

$$\frac{G\,M(r)}{r^2} = \frac{v_{\rm rot}^2}{r} \tag{2.1}$$

implies that if indeed most of the mass was confined inside, the velocity of peripheral stars should go down as $v_{\rm rot}(r) \sim r^{-1/2}$. Contrary to these expectations constant velocities $v_{\rm rot}$ ~const. have been observed creating the so called flat rotation curve problem. Up to now accurate measurements of the velocities of neutral hydrogen HI clouds emitting at 21 cm allowed to confirm flat rotation curves up to radial distances of ca. 50 kpc for thousands of galaxies.

The standard explanation of flat rotation curve phenomenon is that there exists some amount of unseen (nonluminous) matter interacting gravitationally with luminous counterpart. Constant rotation velocity implies that the mass scales like $M(r) \sim r$ hence the density profile behaves (asymptotically) like $\rho(r) \sim r^{-2}$. The right density profile is obtained *e.g.* for the isothermal selfgravitating gas leading to the concept of dark galactic halo.

In order to avoid a singularity at the center the actual form of the potential is softened at some core radius $a$ and usually modeled as:

$$\rho_{\rm dark}(r) = \frac{r_0^2 + a^2}{r^2 + a^2}\,\rho_0\,, \tag{2.2}$$

where $a \approx 5$ kpc is the core radius, $r_0 \approx 8.5$ kpc is the distance of the Solar System from the Galactic center and $\rho_0 \approx 10^{-25}$ g/cm$^3$ [5] is the estimated dark halo density in the vicinity of the Solar System.

Observational support for the existence of dark matter is by no means restricted to the rotation curves alone. There is a subtle interplay of independent pieces of evidence all giving hopefully consistent picture! Some of them will be given in subsequent sections.

### *2.2. X-ray emission*

The idea here is to use the X-ray emission from galaxies (ellipticals) for extracting the temperature profiles $T_{\rm gas}(r)$ of the gas. They can be converted into gas density profiles $\rho_{\rm gas}(r)$ by virtue od the equation of state. Then assuming that the gas is in a hydrostatic equilibrium (balance between the pressure and gravity) one can switch from $\rho_{\rm gas}(r)$ to the overall mass of the galaxy necessary to bind the gas. For example [4] the isothermal model of $kT = 3\ keV$ emission from the galaxy M87 (out to 392 kpc away from the center) gives the estimate $M_{\rm tot} \approx 5.7 \times 10^{13}\ \ M_{\odot}$. At the same time the luminous matter of this galaxy is able to account only for $M_{\rm lum} = 2.8 \times 10^{12}\ \ M_{\odot}$. Hence we do have a mass discrepancy verified independently of the rotation curve.

### *2.3. Gravitational lensing*

Gravitational lensing [6] is another powerful tool of investigating the dark matter. Gravitational lensing has its own interesting history tracing back to the early days of General Relativity.

Einstein's theory of General Relativity explains the interaction between massive bodies not by the action of a gravity force but rather as a consequence of spacetime curvature induced by the presence of mass. In particular General Relativity predicts the bending of light in the vicinity of massive bodies at an angle two times bigger than Newtonian estimate. This prediction has first been verified in 1919 during the total solar eclipse giving a strong support to the Einstein's theory. In 1936 Einstein published a paper [7] in which he contemplated ordinary stars acting as gravitational lenses for the stars located behind. He considered the case of a perfect alignment when the source, the lens (having a mass $M$) and the observer are all on one optical axis. The distant source would have been obscured had not been any light bending. However because of the deflection of light by the massive lens the observer will see the source appearing as a luminous ring surrounding the position of the lens. The radius of this ring is

$$R_{\rm E} = \sqrt{\frac{4GM}{c^2 D}} \tag{2.3}$$

— the so called Einstein radius, where $D = \dfrac{D_{\rm OL} D_{\rm OS}}{D_{\rm LS}}$ and $D_{\rm OL}, D_{\rm OS}, D_{\rm LS}$ denote the distances between the observer and the lens, the observer and the source and lens and the source respectively. When the alignment is not perfect the Einstein ring splits into two (or more, depending on lens geometry) images with the sum of their intensities greater than that of an unlensed source. A year after Einstein's paper Fritz Zwicky contemplated the galaxies and their clusters acting as lenses [8]. These papers were treated as mere curiosities until 60's when the subject revived in papers of Sjur Refsdal. Since then gravitational lensing has been gradually gaining interest both theoretically and observationally. In 1979 the first gravitational lens (multiple images of the quasar lensed by a foreground galaxy) has been discovered by Walsh *et al.* and many other discoveries followed — in particular the so called giant arcs and luminous rings *i.e.* the Eistein rings in the optical settings in which clusters of galaxies act as lenses.[1]

Unfortunately there is no enough place here to enter deeper into this fascinating subject. Let us then emphasize the use of gravitational lensing for dark matter problem. As we see from (2.3) the Einstein radius, which sets the scale of the image separation, depends on the lensing mass. Thus from the observed separation of the lensed images one can estimate the total mass of the lens.

A variant of this method which is actually more accurate can be used in the case when the lensing is due to a foreground galaxy. Namely one can model mass distribution in the galaxy as a singular isothermal sphere. This model is parametrized by the velocity dispersion $\sigma$ and the Einstein radius reads:

$$R_{\rm E} = \frac{4\pi\sigma^2}{c^2}\frac{D_{\rm LS}}{D_{\rm OS}}\,, \tag{2.4}$$

so from the observed image separation one can extract the velocity dispersion $\sigma$ which indirectly carries information on the total mass of the system.

The mass inferred from gravitational lensing turns out greater than the contribution of luminous matter constituting the lens. Therefore it provides an independent confirmation that the dark matter is really there.

## 3. Cosmological connection

### *3.1. Matter density in the Universe*

Galaxies are the building blocks of the Universe. Hence there is little surprise that the problem of dark matter (dark galactic halos) acquires cosmological flavor. There are also independent cosmological arguments fitting smoothly into the dark matter story.

The observed universe is incredibly well described by one of the homogeneous and isotropic models (Friedman-Robertson-Walker models) with the

[1] Excellent presentation of the theory and observational aspects of gravitational lensing can be found in [9].

metric

$$ds^2 = dt^2 - a(t)^2 \left[ \frac{dr^2}{1 + kr^2} + r^2(d\theta^2 + \sin\theta^2 d\varphi^2) \right] ,$$

where the constant $k = 0, \pm 1$ denotes the curvature of constant time hypersurfaces. Depending on the sign of $k$ one has flat ($k = 0$), open ($k = -1$) or closed ($k = +1$) universe respectively. To which of these types does our Universe really belong is still unsettled (although the closed one is almost excluded observationally). Because the Einstein equations announce that spacetime geometry is related to matter (and energy) distribution, one is able to write down a criterion distinguishing between distinct FRW models in terms of the mass density $\rho$. For this purpose it is convenient to introduce the quantity

$$\Omega = \frac{\rho}{\rho_{\rm crit}}$$

which describes $\rho$ as a fraction of the critical density

$$\rho_{\rm crit} = \frac{3H^2}{8\pi G} = 1.88\, h^2\, 10^{-29} \quad {\rm g/cm}^3 ,$$

where $H = 100\, h$ km/s/Mpc, is the Hubble constant and $0.4 < h < 1$. In terms of the critical density $\Omega = 1$ corresponds to flat FRW model, $\Omega < 1$ and $\Omega > 1$ correspond to open and closed models respectively.

It is thus natural that driven by the desire to learn more about actual geometry of the Universe cosmologists tried to determine the value of $\Omega$ (and in fact still keep trying). The most straightforward approach was to 'count stars' (or rather galaxies) in the Universe. In order to do this in a smart way let us recall how the notion of the luminosity $\mathcal{L}$ is introduced in astronomy:

$$\mathcal{L} = 4\pi \mathcal{F} d^2 , \tag{3.1}$$

where $\mathcal{F}$ is the flux — a directly observable quantity, $d$ is the distance to the source (estimated somehow). The conclusion is that the luminosity is in principle measurable quantity. Then one takes some suitable volume $V$ and writes:

$$\rho_{\rm lum} = \sum_i \frac{1}{V} \mathcal{L}_i \left( \frac{M_i}{\mathcal{L}_i} \right) .$$

This is how the concept of mass to luminosity ($M/\mathcal{L}$) ratio was born. One knows $V$ and luminosities $\mathcal{L}_i$ of the galaxies in the given region and one takes some 'typical' (estimated independently) value of mass to luminosity e.g. $M/L = 5\ M_\odot/\mathcal{L}_\odot$ as typical for galaxies; $M_\odot = 2. \times 10^{33}\ g$ and $\mathcal{L}_\odot = 4. \times 10^3$ erg are the mass and the luminosity of the Sun. Estimates of the matter density in the Universe performed in this way reveal

$$\rho_{\rm lum} = (0.7 \pm 0.1) \times 10^{31}\, h \quad {\rm g/cm}^3$$

so that

$$\Omega_{\rm lum} = \frac{\rho_{\rm lum}}{\rho_{\rm crit}} = (0.0035 \pm 0.001)h^{-1}$$

which is far too small to comparing to $\Omega = 1$. The inclusion of the dark matter as we know it from its dynamical effects leads to the following estimate

$$\Omega = 0.1 - 0.3\,.$$

### *3.2. Distortion of the Hubble flow*

As we recall from the preceding sections the existence of the dark matter has been recognized from dynamical considerations. It would be thus tempting to extend this type of study on the scales much larger than typical intercluster scale. It is generally accepted that the density perturbations [2] $\delta\rho$ on such large scales are still in the linear regime of its gravitational growth. The overdensity region will distort the Hubble flow by exerting excess gravitational attraction on the neighboring galaxies. One can thus write:

$$\boldsymbol{v} = H\boldsymbol{r} + \boldsymbol{v}_p\,,$$

where $H$ is the Hubble constant, $\boldsymbol{r}$ is the position relative to the center of overdensity and $\boldsymbol{v}_p$ is the peculiar velocity. In the linear regime [10]

$$\boldsymbol{v}_p = -\frac{1}{3}H\boldsymbol{r}\Omega^{0.6}\frac{\delta\rho}{\rho}\,.$$

The idea is to use this formula for determining the $\Omega$. However, the density contrast cannot be measured directly. Instead it is easy to measure the contrast of counts $\frac{\delta n}{n}$ and the relation between these two is provided by introducing the bias parameter $b$. The bias parameter informs "how good light traces mass"

$$\frac{\delta n}{n} = b\,\frac{\rho}{\rho}\,,$$

so because we do not know $b$ the $\Omega$ cannot be determined exactly by this method. Quite recent analysis of peculiar motions of about 3000 galaxies revealed [11]:

$$\frac{\Omega^{0.6}}{b} = 0.74 \pm 0.13\,.$$

[2] Understood as $\delta\rho = \rho - \rho_0$ where $\rho_0$ is an average density of the Universe. If the matter distribution in the Universe turn out to be fractal on very large scales as suggested by some data then one will have to abandon this way of thinking (the average density will become meaningless).

What does it mean? If $\Omega = 1$ as many would like to believe, then $b = 1.35$ meaning that the luminous matter is not the whole mass (dark matter!). On the other hand assuming $b = 1$ *i.e.* that light is a perfect mass tracer at very large scales, one has $\Omega = 0.61$ which is too large a value to be accounted for by luminous and dark galactic matter (see Section 3.1). Finally, if $\Omega \sim 0.3$ as suggested by direct methods of inference (including dark halos) then inevitably $b < 1$. Such 'antibiasing' seems illogical.

Summarizing, the distortion of the Hubble flow supports our conviction that the dark matter exists although the uncertainties inherent to this method suggest cautionary attitude towards the results.

### *3.3. Big Bang nucleosynthesis*

The Big-Bang model is often referred to as a standard cosmological model. The justification of this term derives not from the FRW geometry assumed but rather from the fact that standard physics is invoked there and successfully applied to address a variety of fundamental questions [10]. One of a series of events occurring in the early uinverse was the nucleosynthesis — the production of light nuclei from the primeval protons and neutrons. The staring point for nucleosynthesis was the freeze-out (due to expansion of the universe) of beta equilibrium processes $e^- + p \to n + \nu_e$, and $p + \bar{\nu}_e \to n + e^+$. It happened at approximately $T = 0.64$ MeV and $(n/p)$ ratio freezed at about 1/6. The large density of photons relative to baryons kept the nuclei in a dissociated phase long after $\beta$ freeze-out allowing the neutrons to decay freely during this epoch. Hence the abundances of light isotopes are sensitive to the baryon to photon ratio $\eta$:

$$\eta = \frac{N_{\rm bar}}{N_\gamma}\,, \tag{3.2}$$

where $N_{\rm bar}$ denotes the number density of baroyns and $N_\gamma$ the number density of photons respectively.

The idea now is to use the formula (3.2) to estimate the matter density in the Universe contained in baryonic matter $\Omega_{\rm bar}$. It could be derived from the numerator of (3.2). The denominator can be determined from the observed cosmic microwave background radiation, the $\eta$ parameter from the observed abundances of light elements and finally one can write:

$$\Omega_{\rm bar} h^2 = 0.0037\, \eta_{10}\,, \tag{3.3}$$

where $\eta_{10} = \eta/10^{-10}$. Hence the crucial point here is to determine the $\eta_{10}$.

This problem could be approached by tracing the abundance of D, $^3$He, $^4$He and $^7$Li the latter being not decisive because of very large theoretical

and observational uncertainties. The primeval $^4$He abundance is inferred from metal-poor HII regions [12] with the result $Y_p = 0.232 \pm 0.003$ and the inferred 95 % CI range for $\eta$: $\eta_{10} = 1. - 3.$ [13]. The primordial deuterium abundance can be extracted from either of the following three sources:
1) local interstellar matter (ISM)
2) solar system information
3) quasar absorption lines
Besides the measurements of deuterium the ISM method involves also the measurements of $^3$He and a chemical evolution model for these elements with the main idea that the deuterium destroyed in stars shows up in the form of $^3$He. Hata *et al.* [13] for example obtained the D/H ratio:

$$\frac{\mathrm{D}}{\mathrm{H}} = 1.5 - 5.5 \times 10^{-5}$$

and inferred the 95 % confidence interval for $\eta$ was $\eta_{10} = 4.5 - 9$.

The information from the solar system is conceptually very similar. Solar D/H abundance is derived from two distinct sources — solar wind measurements of $^3$He and low temperature heating measurements of meteoritic $^3$He gives the ratio (D + $^3$He)/H as all deuterium has been burned to $^3$He in a pre-main sequence phase of solar evolution, then the high temperature measurements of $^3$He in meteorites are believed to give true solar $^3$He/H ratio. The inferred presolar D/H ratio is

$$\left(\frac{\mathrm{D}}{\mathrm{H}}\right)_{\odot} = 0.6 - 4.6 \times 10^{-5} .$$

For detailed discussion see [14] and references therein.

There have been some measurements of D/H in high redshift quasar absorption systems. One of them indicated high D/H values: D/H $\approx 1.9 - 2.5 \times 10^{-4}$ [15] whereas the other reports significantly lower values D/H $\approx 2.5 \times 10^{-5}$ [16]

The high D/H values are consistent with $^4$He derived $\eta_{10}$ whereas the low values are consistent with the ISM range. These two intervals do not overlap. So the main problem with the big-bang nucleosynthesis one has to resolve now is whether the observed abundances are consistent with a single (range for) $\eta$. Some four years ago the answer was definitely yes and is being reproduced in the textbooks. Now this question has become a subject of a renewed debate.

This way or another the conclusion of this section is that the big-bang nucleosynthesis could be used to assess the baryonic content in the Universe and recent estimates of $\Omega_{\mathrm{bar}}$ are: $\Omega_{\mathrm{bar}} h^2 = 0.005 - 0.014$ (95 % confidence interval from light elements abundances) and with $h = 0.4 - 1.0$ this translates into $\Omega_{\mathrm{bar}} = 0.005 - 0.014$. As we recall from Sec.3.1 the lower bound from nucleosynthesis is bigger than the amount of luminous matter in the Universe. Therefore some fraction of the baryonic matter is non-lumionous — no surprise since some fraction of baryonic matter does not have chance to shine (dust, meteorites, planetary bodies, brown dwarfs, cold neutron stars, black holes etc.). On the other hand the upper bound on the baryonic content of the Universe suggests that the most galactic dark matter is non-baryonic.

## 4. Nonbaryonic dark matter

The candidate particles for the non-baryonic dark matter have to fulfill some conditions. They need to carry non-zero mass — otherwise they would not be able to have gravitational effect on the luminous matter. They ought to be stable over cosmological times — otherwise they would have decayed and wouldn't be there. Finally they have to be left over the early universe with the right relic abundance.

There are over a hundred of exotic particles proposed in the literature for the dark matter. The most serious candidates in this class are: massive neutrinos, neutralinos and an axion.

### *4.1. Massive neutrinos*

The neutrinos of all three flavors $\nu_e, \nu_\mu, \nu_\tau$ must obey a cosmological mass limit $m_\nu \leq 30$ eV. There is no direct method available to measure cosmic neutrinos. Strong indications that the neutrinos indeed have mass come from solar neutrino observations. These experiments can be reconciled with each other as well as with theoretical neutrino flux predictions by assuming $m^2_{\nu_\mu} - m^2_{\nu_e} \approx 10^{-5}$ eV$^2$ in MSW solution [17] or $10^{-10}$ eV$^2$ in vacuum solution [18]. The main problem with the neutrinos is that they are particles relativistic at the decoupling so they constitute the so called hot dark matter. Therefore they are unlikely to be the ultimate explanation for flat galactic curves. It is not even known whether they can be anchored by galaxies significantly. So the only utility of background massive neutrinos would be to make $\Omega$ approaching the unity.

### *4.2. Neutralinos*

Unlike massive neutrinos, the neutralino is supposed to be a constituent of cold dark matter. Its origin is supersymmetric. Supersymmetry is a beautiful theory announcing the fundamental symmetry between fermions and bosons. Unfortunately this symmetry is not realized among observed particles. Hence it predicts new ones — the so called supersymmetric partners.

The favored particle of this kind is neutralino — a 'linear combination' of Zino, photino and Higgsino (the partners of the $Z$-boson, photon and Higgs particle). The experiments aimed at detection of the neutralino fall into two categories: direct and indirect. The direct search consists in measuring the recoils of target nuclei hit by Galactic neutralino. There are two huge experiments of this kind: CRESST (Cryogenic Rare Event Search with Supeconducting Thermometers) performed in Gran Sasso laboratory as a joint effort of Max-Planck Institute für Physik, Technische Universität München and Oxford University and CDMS (Cryogenic Dark Matter Search) located in Stanford and coordinated by Berkeley Center for Particle Astropysics.

The second class of experiments watch at high energy neutrinos produced by annihilation of a neutralino in our neighborhood. Such neutrinos could be seen by a new generation of Cherenkov detectors like AMANDA or Superkamiokande.

Having in mind ambiguities in the details of supersymmetric models one should rather wait until first experimental evidence in favor of supersymmetric particles before taking seriously these particles as a candidate for the dark matter. For more detailed discussion of these issues the reader is referred to [19].

### *4.3. Axion*

Axion is a particle associated with the Quantum Chromodynamics (QCD). QCD is the leading theory of strong interactions. In its pure form, however, it has one extremely serious problem: the strong CP problem. Its essence is that QCD predicts the electric dipole moment for the neutron to be the same as a magnetic one. In fact the experiments indicate that the electric dipole moment for the neutron is $10^{-9}$ times smaller than the magnetic moment. The most elegant solution provided by Peccei and Quinn invokes the new chiral U(1) symmetry. At some large energy scale $f_a$ a new phase is spontaneously broken and the associated Nambu-Goldstone boson is called an axion — a pseudoscalar particle related with the pion. Hence the following estimate holds:

$$m_a \approx m_{\pi^0} \frac{f_{\pi^0}}{f_a},$$

where $f_{\pi^0} = 93$ MeV is pion decay constant. Since $f_a$ is large one sees that axion is light and weakly interacting. An axion is supposed to be created in the early universe as a coherent field oscillation but in low momentum modes. Hence it is non-relativistic from the start (cold dark matter).

There are very stringent limits for the mass of an axion coming from stellar evolution. The explanation of stellar longevity lies not in timescales provided by their energy generation processes (nuclear reactions are very fast) but rather in processes of energy transfer. In a standard picture the energy produced in the center of the star can be transported away by either photons or neutrinos. The competition between these two processes is temperature dependent since the photon lunminosity scales like $\mathcal{L}_\gamma \sim T_c^{1/2}$ and neutrino luminosity $\mathcal{L}_\nu \sim T_c^8$. The conclusion is that photon cooling is more efficient for central temperatures $T_c \leq 10^8\ K$ with the characteristic timescale of photon diffusion $\tau \sim 10^5 - 10^{10}$ yrs. In hot environments $\nu\bar{\nu}$ cooling prevails with timescales $\tau \sim 1\ s - 10^5$ yrs depending on the temperature involved. For example protoneutron stars are expected to cool down rapidly via neutrino emission in a few seconds. An axion can intervene this scheme by acting as additional coolant.

Hence the first bound comes from the age of the Sun and solar neutrino flux — very massive axion would accelerate solar evolution so that emerging picture would be inconsistent with observations. Second class of arguments comes from the existence of red giants. In later stages of evolution of massive stars, the hydrogen in central parts is exhaust and converted into helium. Such helium core collapses, heats up and after reaching some threshold temperature helium starts burning in nuclear reactions (so called helium flash). If stellar cores were cooled additionally by axion emission (effectively enough) they wouldn't have chance of helium ignition. Finally the third constraint on axion emission comes from the SN 1987 data where the neutrinos were observed up to 12 s after explosion in perfect agreement with standard picture of neutrino cooling. On the other hand axion cooling would shorten the neutrino burst. Therefore only a narrow window of possible axion masses remains $m_a = 10^{-6} - 10^{-2}$ eV [20].

There are two experiments underway to detect Galactic axions. One in Livermore [21] and one in Kyoto [22]. They make use of axion two - photon coupling named the "haloscope" method. This two-photon coupling allows for axion–photon conversion in the presence of external magnetic field. Hence the idea is to place a microwave resonator in a strong magnetic field and search for the appearance of a narrow line from conversion of Galactic axions.

## 5. Where does dark matter reside? — In search for MACHOs

As we recall from the preceding sections the most reliable information about dark matter comes from dynamical considerations at the level of galaxies and their clusters. In order to address the question of interrelation between the hierarchy of the large-scale structure in the Universe and the dark matter content, Neta Bahcall, Lori Lubin and Vera Dorman performed a detailed study of the observed $M/\mathcal{L}$ ratio as a function of scale for spiral and elliptical galaxies, their groups, clusters and superclusters

[23]. The result was $M/\mathcal{L}(spirals) \sim 100\ h$, $M/\mathcal{L}(\text{ellipticals}) \sim 400\ h$ and $M/\mathcal{L}(\text{groups and clusters}) \sim 100-400\ h$. The value obtained for groups and clusters is typical for the mixture of spirals and ellipticals. So the conclusion is that $M/\mathcal{L}$ ratio does not grow with scale. It is thus of utmost importance to better understand the galactic halo composition.

There are several possibilities of dark halo components. First is gaseous matter but this is ruled out by X-ray observations, then there could be some faint unresolved stars — ruled out by Hubble Space Telescope. Some dark matter can be baryonic (so called MACHO — Massive Compact Halo Objects): some types of dark compact baryonic structures are known to exist (jupiters, brown dwarf *etc.*) and moreover they must exist by demand of consistency with big-bang nucleosynthesis. Finally there can be nonbaryonic dark matter as briefly described in a preceding section. The case for it being stronger from the cosmic structure formation theories which could be made successful only by including some cold dark matter.

In 1986 Bohdan Paczyński proposed a method of probing the MACHO content of the halo using gravitational lensing of stars from the Large Magellanic Cloud [24]. His idea was to watch a dense stellar field in LMC with hope of seeing the effect of lensing by compact objects in the halo of our Galaxy. Because in such a setting the image separation $\delta\varphi \sim 2 \times 10^{-4}\ (m/M_\odot)^{1/2}$ arc sec is too small one uses the fact that the total brightness of unresolved images is greater than that of unlensed star (by a factor of 1.34 at the Einstein ring). Because the intrinsic brightness of a randomly chosen star in LMC is not known a priori one should watch its time variations due to relative motions in the system (observer–lens–star) across the line of sight. Theoretically predicted light curve is very characteristic: symmetric with respect to the maximum and achromatic. It allows for distinguishing the microlensing events from stellar variability which results in mostly asymmetric and wavelength dependent light curves.

In 1991 these dreams came true and three projects: american MACHO, french EROS and Polish–American OGLE took off. The last project was not arranged according to original Paczyński idea of looking toward LMC. Because of very small optical depth to microlensing $\tau \sim 10^{-6} - 10^{-7}$ the prediction was to see at best a few microlensing events by watching millions of stars in LMC. However no-one knew whether the method worked at all. Therefore Polish–American group decided to look at the central bulge of our Galaxy to have greater chance of seeing the microlensing but at the expense of probing the disk rather than the halo. In early 1992 all three groups announced first microlensing events [25]. Since then there are about 18 events detected by MACHO and EROS teams and about 200 by OGLE. The duration of microlensing event depends on the mass $m$ of the lens $\Delta t = 100(m/M_\odot)^{1/2}$ days. Consequently the duration of microlensing (and the duration of the project) constrain the range of MACHO massess probed by this method — $10^{-7} - 10^{2}\ M_\odot$. This is a very reasonable range since the bodies less massive than $10^{-7}\ M_\odot$ are likely to evaporate on less than a lifetime of the Galaxy, and objects more massive than $10^4\ M_\odot$ would have disrupted the globular clusters.

The results from the microlensing events detection have been used in the study performed by Gates, Gyuk and Turner [26]. They modelled the Galaxy as having 5 components:
*(i)* luminous disk modelled as thin double-exponential disk:

$$\rho_{\rm lum}(r,z) = \frac{\Sigma_{\rm lum}}{2h} \exp\left(-\frac{r-r_0}{r_d}\right) \exp\left(-\frac{|z|}{h}\right),$$

where $\Sigma_{\rm lum} = 25\ M_\odot/{\rm pc}^2$, $r_d = 3.5$ kpc and $h = 0.3$ kpc.
*(ii)* dark disk (containing a few per cent of luminous disk mass) modelled in a similar manner with $h = 1 - 1.5$ kpc.
*(iii)* baryonic and
*(iv)* CDM dark halos modelled as independent isothermal halos:

$$\rho_{{\rm halo},i} = \frac{a_i^2 + r_0^2}{a_i^2 + r^2}\, \rho_{0,i}\,,$$

where subscrpit $i$ denotes independent components.
*(v)* the central bulge modelled as triaxial bar

$$\rho_{\rm bar} = \frac{M_0}{8\pi abc} \exp\left(-\frac{s^2}{2}\right),$$

where:

$$s^4 = \left[\left(\frac{x}{a}\right)^2 + \left(\frac{y}{b}\right)^2\right]^2 + z^4/c^4\,,\ M_{\rm bulge} = 0.82\,,\ M_0 = (1.0{-}4.0)\times 10^{10}\ M_\odot\,,$$

with the remaining parameters $a = 1.49$ kpc, $b = 0.58$ kpc and $c = 0.40$ kpc.

Then they constructed ca. 10 mln models by varying parameters and constrained them by actual rotation curve, local projected mass density, observed amount of luminous matter in disk and bulge and optical depths for microlensing towards LMC (from MACHO team) and towards the bulge (from OGLE team). The result was that in most viable models (assessed by maximum likelihood) the MACHO fraction in the halo is 0–30 %. Therefore despite first detections of compact massive dark objects in the halo there is strong theoretical indication that most of the galactic dark halo is composed with the cold dark matter whose identity still remains to be established.

## 6. Alternative avenues and perspectives

It would be unfair to leave the reader with a feeling that the above depicted standard view about the dark matter is the only possible. There have been attempts in the literature to seek the solution of the dark matter problem in modified dynamics or modified gravity at large scales. Although outside the mainstream of research these approaches are worth mentioning in our closing remarks.

First alternative approach was provided by Milgrom [27] who proposed his MOND (MOdified Newtonian Dynamics) model. He proposed that in low acceleration limit[3] $a < a_0 = 10^{-8}$ cm/s$^2$ the Newtonian dynamics should be modified in such a way that

$$\frac{a^2}{a_0} = \frac{GM}{r^2},$$

instead of $a = GM/r^2$. This idea is of course an ad hoc modification of Newton's law and lacks theoretical framework (or relativistic counterpart). However the simple MOND model has proven amazingly resilient in spite of sustained attacks. It is partly due to a successful explanation within MOND of such observable relations like: flat rotation curves, luminosity-velocity correlations (Tully–Fisher and Faber–Jackson relations), the critical maximum surface density in spiral and elliptical galaxies, large mass discrepancy in low-surface brightness systems, the magnitude of mass discrepancy in clusters of galaxies or the magnitude of Virgo infall. Moreover Milgrom was able to predict later observationally confirmed effects. Namely that the rotation curves in luminous high surface brightness galaxies should decline to asymptotically flat value whereas in low-lumnosity low surface brightness galaxies should slowly rise to asymptotically flat value.

Some people trying to justify the MOND model contemplated scalar-tensor gravity theory [28]. However calculation of the light bending in such class of models [29] reveals that gravitational lensing in scalar-tensor theories is too small to account for the observed lensing effects.

Finally the most recent of alternative theories was proposed by Mannheim and Kazanas [30]. They proposed the Weyl conformal gravity program within which they were able to derive a modified Schwarzschild solution which in the weak field limit is able to explain flat rotation curves. Weyl gravity is more aesthetically appealing than General Relativity: it is based on a local invariance principle (conformal metric invariance), encompasses the largest symmetry group which keeps the light cones invariant, its lack of scale probably indicates its renormalizability. However the recent paper of

[3] There is a numerical coincidence $a_0 = cH$ where $H$ is the Hubble constant.

Edery and Paranjape [31] casts doubts on the Weyl conformal program as a solution for the dark matter. The Mannheim and Kazanas model has troubles with right deflection of light beeing thus in conflict with gravitational lensing evidence for mass discrepancy in the Universe.

Which of the sketched in this paper approaches proves correct in the future still remains an open question. However it is indeed a fascinating idea that such macroscopic thing like the shape of galactic rotation curves may become decisive in choice of the correct theory of fundamental interactions (Peccei-Quinn symmetry in QCD, supersymmetry *etc.*). Concerning the ideas of modified gravity it is not widely known that the dark matter vs. modified gravity controversy raged long ago in trying to understand the motion of Uranus. Alternative laws of gravitation were weighted against the unseen matter [32] with the result known for everyone now. However if it turns out that some types of supersymmetric theories are correct it is not excluded that they may lead to a new formulation of gravity after all!

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