Dark matter more mysterious than expected

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Based on the lecture *Dark matter — more mysterious than expected*, given by me at the Cosmology School in Kielce on 18 July 2015, I will briefly discuss in this essay the history of dark matter and why this notion is so essential for the contemporary physics. Next, I will present the point of view of the research team I work with, on the presence of nonbaryonic dark matter in the Universe and in spiral galaxies.

1 Historical background

Nonbaryonic dark matter is currently one of the basic and indispensable notions in many branches of physical sciences, including astrophysics. This form of matter constitutes a predominating part of galactic clusters and of separate spiral galaxies (dwarf elliptical galaxies are particularly abundant in it). Nonbaryonic dark matter enabled the formation of structures in the early Universe and currently is the main factor stabilizing spiral galaxies.

The beginnings of the dark matter notion should be linked with the investigations of galaxies and with the person of Fritz Zwicky (Zwicky, 1937). The proper motions of galaxies in galactic clusters suggested higher masses of the clusters than estimated based on their brightness. Obviously, nobody had been using the nonbaryonic dark matter notion at that time, and any kind of matter difficult to detect or invisible in the spectrum band-width available to observations was simply referred to as dark matter.

The other astrophysical objects important in the nonbaryonic dark matter context are spiral galaxies. In 1970, Vera Rubin and W. Kent Ford discovered that the M31 spiral galaxy had a flat optical rotation curve (Rubin & Ford, 1970). Einasto, Kaasik, & Saar (1974), as well as other authors (Kinman et al., 1974), concluded that the evidence had shown that the mass-to-light ratio (M/L) of spiral galaxies increased with the radial distance. If a galactic rotation curve is flat, the mass function of a roughly spherically-symmetric mass distribution should increase for large radii almost linearly with the galactocentric distance. This indicated that a massive spherically symmetric halo may have dominated the contribution to the total galactic mass. By measuring the rotation curves of spiral galaxies, and then by attempting to reconstruct these curves based on the observed galactic brightness profiles, an excess of the dynamical mass over the luminous mass had been ascertained.

The problem with the rotation curves of spiral galaxies arises due to the following observational facts: i) rotation curves are flat, not Keplerian, unlike one could expect for outer galactic parts, ii) dynamical masses differ from the masses of luminous matter, iii) the infra-red band mass-to-light ratios are too high. This ratio should not be greater than 2, otherwise dark matter is required ($M/L = 1$ for the Sun).

The standard modelling of rotation curves arbitrarily assumes a spherically symmetric or spheroidal halo of dark matter in which luminous baryonic matter with a constant mass-to-light ratio is immersed. A spherically symmetric halo of dark matter encircling a spiral galaxy turned out efficient in stabilizing these galaxies. Ostriker & Peebles (1973) came to the conclusion that spherical halos could stabilize galactic disks. Mathews (1978) inferred that there are large amounts of dark matter present in the giant elliptical galaxy M87. His analyses of the X-ray data from the Virgo cluster indicated that the mass of this galaxy was greater than expected based on its brightness. Following these discoveries, most astronomers in the eighties were convinced that dark matter indeed existed around galaxies and clusters. Today, cosmology is the branch of knowledge which requires the dark matter most. The presence of dark matter enables the formation of structures in the Universe.

Zeldovich's research team developed in the eighties a Hot Dark Matter (HDM) theory with the Universe dominated by light neutrinos contributing most to the dark matter content (Zeldovich et al., 1982). But in 1983 White, Frenk and Davis showed that the nonlinear growth simulations of structures in the Universe dominated by massive neutrinos ruled out HDM (White et al., 1983).

In 1984 a Cold Dark Matter (CDM) theory was proposed (Blumenthal et al., 1984) describing the formation and evolution of galaxies and also large-scale structures. In 1992 COBE discovered CMB fluctuations as predicted by CDM, and between 2003 and 2008 WMAP data confirmed the CDM theory predictions.

CDM was finally incorporated to the Standard Cosmological Model. In this model luminous matter makes only 0.5% of the total mass-energy content of the Universe while as much as 99.5% is invisible (of which 4% is ascribed to baryonic matter, 26% to non baryonic dark matter and 70% to dark energy). Galaxies within this model are formed from small initial fluctuations in the density distribution that then grow as the universe expands. The measurements made by COBE and WMAP suggested that the fluctuations had been at the level of 0.001% at the time of recombination ($z = 1000$) and the fluctuations had increased at later stages to the level of 1% (!!), such as we observe them today (z = 0). Therefore CDM is needed. Lack of interactions with plasma allows for much greater fluctuations of CDM density at the time of recombination.

A thorough analysis of fluctuations in the background radiation, observation of distant type-Ia supernovae and other arguments (Hubble constant measurement) give a coherent cosmological model. There are fluctuations in the background radiation—coming from fluctuations that gave rise to the cosmic structures. Because these fluctuations were very small, their evolution could be described by simple functions—a plane wave. You get the spectrum—that is, the dependence of the intensity of the wave versus its length. Such a procedure was applied to the observed fluctuations in the background radiation, and to describe the evolution of the primordial fluctuations in the cosmological model. Comparison between what we observe and the properties of the model allowed to determine the values of the parameters in the cosmological model. Finally, Λ-CDM has been accepted as the Standard Cosmological Model.

2 The point of view of my research team

Only a few years ago, both me and my collaborators, belonged to a group of persons convinced about the ubiquity of nonbaryonic dark matter and its indispensability in solving the problem of rotation of spiral galaxies. But our viewpoint has changed during the period of the last few years, mainly due to our investigations.

The first galaxy which appears to contain only little amounts of CDM is the NGC 4736 galaxy (or M94) (Jałocha et al., 2008) and there seems to be a general consensus about this fact. The rotation curves of several galaxies we have investigated so far, break a very simple sphericity test which I suggested in Jałocha et al. (2008) (applied for the first time to galaxy M94, see Fig.1):,

$$v^2(\rho_1)\rho_1 \leq v^2(\rho_2)\rho_2, \qquad \text{if} \qquad \rho_1 \leq \rho_2.$$

Here $v(\rho_i)$ is the observed circular velocity at a radial distance ρ_i from the galactic center. Breaking this test means as much as that, for a spherically symmetric distributed matter, to explain the rotation of a galaxy, fairly peculiar properties of this galaxy would have to be assumed, namely, regions with negatively-definite mass.

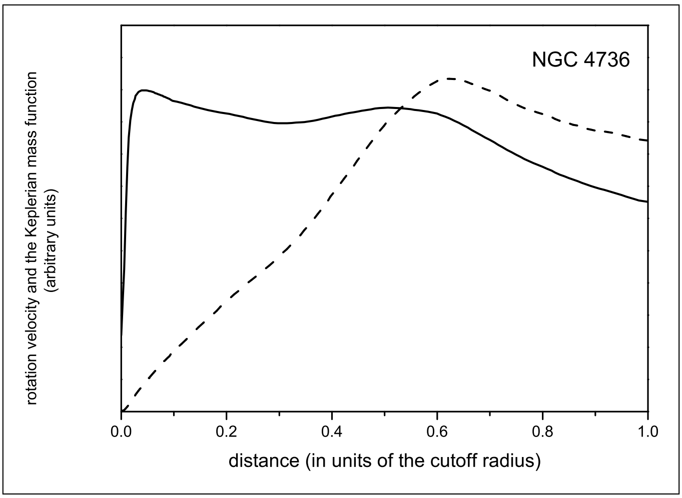

Fig. 1 – This figure shows an observationally determined rotation curve (continuous line) and corresponding to it Keplerian mass function defined as $M_K(\rho) = G^{-1}\rho\, v^2(\rho)$ (dashed line). The Keplerian mass function in this figure is not everywhere increasing. This excludes a purely spherical component and points to a disk-like distribution of matter for which the global disk model is more suitable than the spherical model. (Reconstructed from Jałocha et al., 2008).

In the common approach to the mass distribution modelling in spiral galaxies, it is most often assumed that the mass distribution is proportional to the measured brightness profile, with a mass-to-light ratio being a constant conversion factor throughout the galaxy (although, usually different for various mass components). If such a mass distribution does not lead to predictions that agree with the galactic rotation, the missing dynamical mass is introduced in the form of a dark matter halo. Unlike in this approach, we start with a rotation curve and then obtain a mass-to-light ratio profile as the result, and when the ratio is low we may conclude that the disk model (which we use to model spiral galaxies) well accounts for the galaxy properties. In practice the mass distribution is obtained from the rotation curve by means of an iteration method (it takes into account measurements of the distribution of neutral hydrogen in the region outside the last point on the rotation curve) as described by Jałocha et al. (2008). Fig.2 shows how this method works on the example of galaxy M94. Based on this it can be said that rotation curves of some of galaxies cannot be

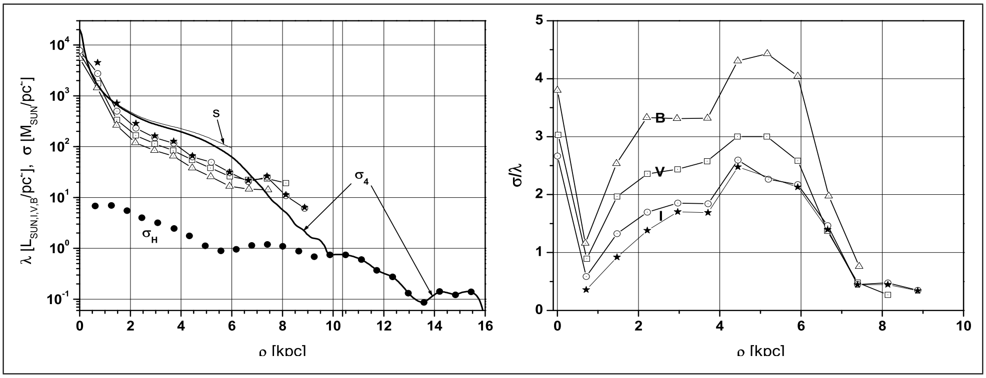

Fig. 2 – **Left panel:** Global distribution of surface density for NGC 4736 found in the iteration method used by Jałocha et al. (2008) (thick solid line σ_4). The matter distribution perfectly accounts for the rotation curve. **Right panel:** The mass-to-light ratio for the galaxy NGC 4736 predicted based on the calculated surface density. A correction for the extinction has been taken into account. B-filter (triangles), V-filter (squares), I-filter (circles) and, additionally, an I-filter with a correction for the extinction taken into account (stars). (Both figures reproduced from Jałocha et al., 2008).

explained under spherical symmetry and the Global Disk Model is thus more suitable. In the disk model the mass-to-light ratios, and consequently, the amount of dark matter can be reduced significantly for a class of galaxies.

2.1 *Microlensing as a means to detect baryonic matter in the Galaxy*

Together with my co-authors I included microlensing measurements in our study of the Milky Way galaxy in the thin disk model Sikora et al. (2012). A crucial notion we have to do with while considering microlensing, is the notion of an optical depth. The optical depth describes the probability of finding a gravitational lens between an observer and the observed object. The image of this object is subject to a distortion arising in consequence of light passing through a neighborhood of the considered lens. What is very important, only a compact object (star, planet) can be a lens, and so, the microlensing is sensitive only to baryonic matter. Nonbaryonic dark matter is not detectable through this phenomenon because it is dispersed and does not form compact clumps of matter. The optical depth is determined based on the microlensing observations in the Milky Way (observed are the changes in the brightness of objects due to lenses passing between us and those objects), but it can also be calculated theoretically if we assume that we know the density of matter in the Galaxy at least inside the Solar circle of about 8 kpc in radius. We compared the optical depth obtained as the result of observations with the optical depth predicted in a theoretical way from the surface density obtained under the assumption that our Galaxy has a disk-like geometry (and so can be modelled as a thin disk), and we obtained an agreement between the measurement and the prediction, see Fig.3. Putting this differently, we demonstrated that the whole matter needed to account

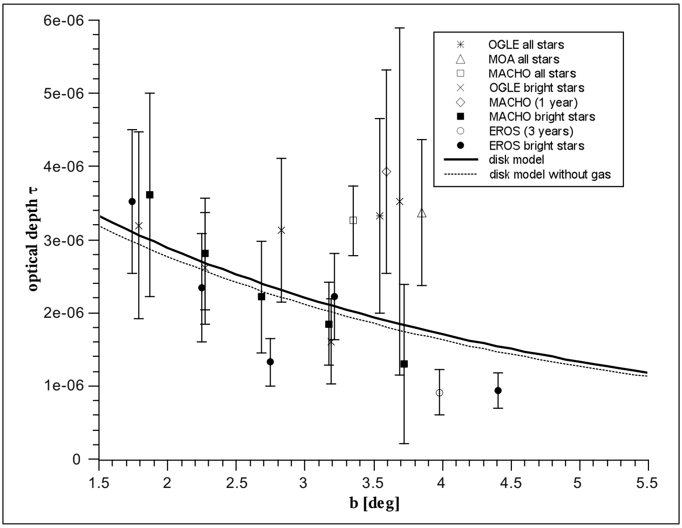

Fig. 3 – Optical depths in disk model with the disk scale height $h = 325$ pc. Points represent the observational data averaged over longitude within the range out to $l = \pm 5^\circ$. (Reproduced from Sikora et al., 2012).

for the Milky Way rotation within the Solar circle is seen through the gravitational microlensing, thus it is certainly a baryonic matter.

2.2 Motion of Galactic halo objects as a means to estimate total Galaxy mass

As one of the most important results concerning the problem of dark matter in galaxies I consider the paper in which my research team deals with the motion of the baryonic halo objects around the Milky Way (Bratek et al., 2014). Objects which contribute to such a halo are, among other things, dwarf galaxies, globular clusters and isolated stars.

It is a standard approach to analyze the motion of these objects in a dark matter potential. This approach was used many times for estimating the Galaxy mass. But we applied a method different from that commonly used: its novelty was in releasing the constraints imposed on the phase space and in considering a gravitational potential of a compact mass, thus corresponding to a Galaxy without dominating dark matter. Constraints arise due to the conditions imposed on the assumed profiles of the secondary quantities derived from the phase-space distribution function, such as the flattening of the velocity dispersion ellipsoid. It is standard to assume it in the form of an anisotropy parameter independent of the distance, which makes the models of the motion of halo objects more stiff.

In the case of a central mass potential (which we use because it should well approximate a compact mass potential for large distances, under the hypothesis of absence of an extended dark halo), we may adopt a model of the phase space equivalent to a system of confocal elliptic orbits, with an arbitrary number density defined over the space of energies and ellipticities. With this idea, we were able to model the dispersion anisotropy as almost arbitrary function of the distance without any restricting conditions. In the result of this, the expected value for the ellipticity of orbits crossing a sphere of a given radius may depend in a complicated way on the distance. Despite the numerical formidability of this problem, we succeeded in developing a general procedure reconstructing the distribution function in the phase space, consistent with the observed profile of the radial velocity dispersion, see Fig.4. Finally, we showed

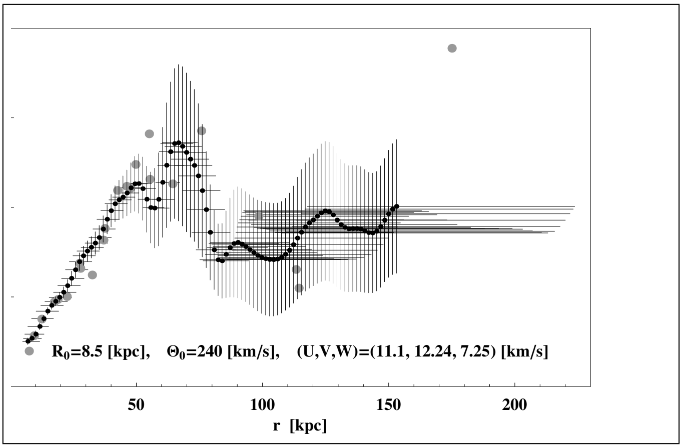

Fig. 4 – Radial velocity dispersion profile (Reproduced from Bratek et al., 2014, see that work for a detailed description.)

that the observed motion of the halo objects is fully consistent with the assumption that our Galaxy mass is low (of the order of 2.4×10^{11} Solar masses), that is, such as one should expect based on the rotation curve of the Galactic disk, if the Galaxy mass is not dominated by nonbaryonic dark matter. It is worth of pointing out that then only a few of the observed halo objects would not be gravitationally linked to the Galaxy (but rather to the Local Group of galaxies). The radial dispersion profile of the baryonic halo objects alone does not give the upper bound on the Galaxy mass. However, this approach allows us to estimate a more important lower bound for the Galaxy mass, consistent with the observed motion of halo objects.

3 Concluding remarks

The arguments for CDM presence in spiral galaxies (and in the Universe in general) are very strong, of course, and the most important comes from the cosmological model. However, we should remember that the cosmological model is the effect of mutual agreement of the model assumptions and of the observational facts, which are not independent. The observational facts have to be interpreted based on a model which they are to confirm. It is possible that there is another cosmological model which would also lead to such an agreement.

Other important arguments come from the observations of galaxy clusters; most importantly, from the fact that the clusters' mass estimates based on the observations of motions of galaxies that are members of the clusters, is higher than the mass estimated based on the brightness. But we have to remember that the first method of estimating the mass is possible only when a cluster is virialized which might not be satisfied.

Another weighty argument is the issue of the stability of spiral galaxies—the massive CDM halo role is to stabilize a galaxy. Here, I can recall the example of the NGC 4736 galaxy. If we have a spiral galaxy, as to which there is presently a consensus that it is CDM poor (the controversy concerns only whether the word 'poor' should be replaced with 'free') and, at the same time, it is stable (it does not even exhibit any instability which the presence of a bar would be a signature of) then this points to stabilizing mechanisms being in action other than a heavy dark halo. Of course, even proving that spiral galaxies are in general devoid of nonbaryonic dark matter would not automatically mean that there is no such matter present in large amounts in space. Since the beginning of our research we have been bringing to attention the fact that a higher clusterization scale of dark matter is another possibility—the scale might be of the size of galaxy clusters, not of the size of single galaxies.

Thus, as it seems, although the arguments for the ubiquitous presence of nonbaryonic dark matter are strong enough, they are not incontestable. In my opinion the most important experimental fact for seriously considering arguments against dark matter is that in spite of the intense efforts, no single particle of dark matter has been detected so far.

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