Vol. 29 (1998) *ACTA PHYSICA POLONICA B* No 7

THE NATURE OF DARK MATTER IN OUR GALAXY*

R. Schaeffer

Service de Physique Théorique, CEA/Saclay
F-91191 Gif-sur-Yvette Cedex, France

D. Méra and G. Chabrier

C.R.A.L. (UMR CNRS 5574), Ecole Normale Supérieure
69364 Lyon Cedex 07, France

(Received January 21, 1997)

The existence within galaxies of unidentified matter whose only action is gravity has been known since nearly two decades. Important information on its location has been obtained in the very last few years, thanks to deep stellar surveys, to the microlensing events detected by the EROS, MACHO and OGLE experiments that trace dark stellar-size objects as well as to the quite recent HIPPARCOS data that have determined very accurately the stellar phase-space and whence the gravitational potential in the solar neighborhood. We review these results and discuss what they imply on the nature of Dark Matter within our Galaxy.

PACS numbers: 98.90. +s

1. Introduction

We know for more than half a century that the major part of the world we live in is made of a stuff whose nature is still to be unraveled. Shortly after the discovery in 1929 by Hubble that the Universe was full of galaxies similar to ours, Zwicky, in 1933 realized that their relative motion implies a gravitational potential about 100 times larger that the one generated by the visible matter in these galaxies. Whether this “Dark Matter” was within the galaxies or in-between was unknown. In the late 70’s, it started to be possible [11, 41] to map the velocity field of the hydrogen gas in the plane of the rotating disk (Fig. 1) of some Spiral galaxies, that is seen to extend much

* Presented at the XXXVII Cracow School of Theoretical Physics, Zakopane, Poland, May 30–June 10, 1997.

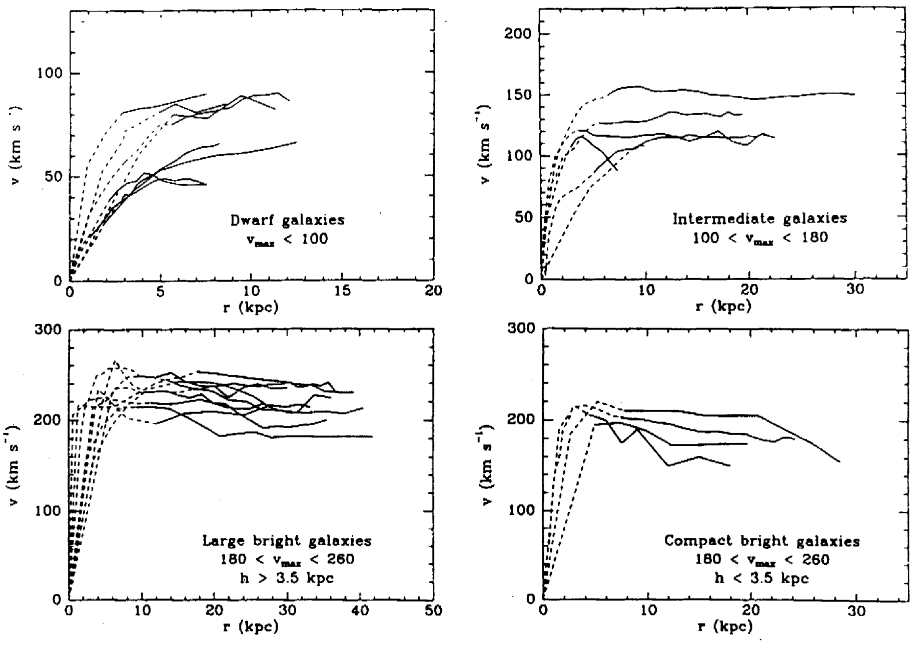

Fig. 1. Rotation curves for Spiral galaxies [13]. Whether the galaxy is small or large, the rotation curves are constant up to the remotest point where the measurement of the rotation velocity can be performed. The dashed part is the one accounted for by the observed luminous component.

further than the luminous stellar population. For all Spiral galaxies where this has been possible, the rotation velocity is found (Fig. 1) to be constant up to at least 3 times the luminous radius. This velocity should decrease as $r^{-1/2}$ beyond the luminous radius should the mass of these galaxies be due to the stars: such rotation curves imply a mass within radius r which increases linearly with the radius. Up to the remotest regions where the measurements can be performed, there is no sign for this velocity to fall off. For our Galaxy also, the rotation velocity stays constant [20], at

$$v_{\mathrm{rot}} = 220\,\mathrm{km\,s^{-1}} \tag{1}$$

up to the remotest point that is accessible to the measurements. There is thus a large fraction of Dark Matter within the galaxies, the amount of which depends on how far the velocity stays constant. The measured velocities are rotation velocities, so the rotating disk may be expected to extend at least up to distances of the order of three times the luminous radius. But this gas represents a totally negligible fraction of the amount of matter necessary to generate the gravitational potential that the gas motion traces. In case the Dark Matter also is located within the rotating disk, the latter is required to have a surface density

$$\Sigma_\odot \; = v_{\rm rot}^2/2\pi G r \tag{2}$$

that behaves as $1/r$ and, at the solar radius $R_\odot = 8.5\,{\rm kpc}\;(1{\rm pc} = 3.06\,10^{18}{\rm cm})$, has to be equal to

$$\Sigma_\odot \; = 208\, M_\odot\, {\rm pc}^{-2}\,, \tag{3}$$

in solar mass $\left(M_\odot = 3\,10^{33}\,g\right)$ units.

The possibility for this Dark Matter to be within a spherical halo around the galaxies (Fig. 2) also is to be considered. In this case, the halo Dark Matter density is

$$\rho_{h\odot} \; = v_{\rm rot}^2/4\pi G r^2, \tag{4}$$

decreasing as $1/r^2$, with a value in the solar neighborhood of

$$\rho_h(R_\odot) = 122\;10^{-4} M_\odot {\rm pc}^{-3}, \tag{5}$$

in units of $10^{-4} M_\odot {\rm pc}^{-3}$ that will turn out to be convenient later on to describe the interior of the Galaxy.

Fig. 2. Sketch of the various components of the Galaxy.

Not only the location of the Dark Matter within our Galaxy, but also its nature are under debate. It could be made of stellar-like objects that were too small to ignite the fusion of hydrogen, thus smaller than the smallest luminous stars, of less than 0.07 $M_\odot$, called *Brown Dwarfs*. It could also be remnants left over by the stars after the end of their evolution, once they have expelled most of their matter: *White Dwarfs* of less than 1.4 $M_\odot$, left over by the lighter stars and sustained by the pressure of their degenerate electrons. It may be *Neutron Stars* of 1.4 $M_\odot$ left over by the heavier stars whose White Dwarf like core reaches the 1.4 $M_\odot$ limit and then collapses to nuclear densities. Another possibility is [38] *molecular Hydrogen* H_2. Finally, it may be neither of those, and result from the existence of a new kind of matter that is *non-baryonic* such as massive neutrinos or another, neutral, massive and stable particle such as the ones appearing in the Supersymmetric Grand Unified theories.

The amount of Dark Matter implied by the observation of these rotation curves can be estimated as follows. Galaxies have a wide distribution in mass and luminosity, but for these estimates, it turns out [42] that one can consider the Universe to be filled by $n_{\rm gal} = 4\ 10^{-2}\ M{\rm pc}^{-3}$ galaxies similar to our own Milky Way Galaxy. (The Hubble constant, which is now known within 20%, is taken to be $H_0 = 60\ {\rm km\,s}^{-1} M{\rm pc}^{-1}$, which in turn implies a critical density of the Universe of $\rho_{\rm crit} = 6.9\ 10^{-30}{\rm g\ cm}^{-3} = 9.9\ 10^{10} M_\odot\ M{\rm pc}^{-3}$.) With a typical mass of the known, luminous, matter (with electromagnetic emissions: stars, gas) per galaxy of $M_{\rm lum} = 10^{11} M_\odot$, we have a density of observed luminous matter in the Universe

$$\Omega_{\rm lum} = \rho_{\rm lum}/\rho_{\rm crit} = 0.004\,. \tag{6}$$

The total of Dark Matter within galaxies depends on their extension. The latter is unknown since the observed rotation velocity stays constant up to the largest observable (three times the luminous radius) galactocentric distances. Assuming galaxies extend up to 100 kpc (ten times the luminous radius), in our typical galaxy, the total mass per galaxy is $M_{\rm tot} = 10^{12} M_\odot$, which leads to an amount of matter within galaxies of

$$\Omega_{\rm gal} = 0.04\,, \tag{7}$$

or more if the galaxies extend further than we have assumed. For the sake of comparison, using the velocity field at scales much larger than the galactic scale, one can determine the total mass density in the Universe to be

$$0.1 < \Omega < 1. \tag{8}$$

So, for galaxy sizes somewhat larger than 100 kpc, all the matter of the Universe may be within galaxies. The question whether it can be entirely baryonic is partially answered by the bounds on the density of baryons in the Universe, ρ_b, obtained [17, 45] from the condition that Primordial Nucleosynthesis forms the light elements (^{2}H,^{3} He,^{4} He,^{7} Li) in the proportions that are observed

$$0.01 < \Omega_b = \rho_b/\rho_{\rm crit} < 0.07. \tag{9}$$

Comparing these numbers with (6), we see that (*i*) we expect more baryons in the Universe than what we see in the form of stars and gas in galaxies. From (7) we conclude also that (*ii*) the Dark Matter within galaxies can be entirely baryonic if the latter do not extend too far, but this is not compulsory. The comparison with (8) on the other hand shows that (*iii*) we do not expect all the Dark Matter to be baryonic. One could naively think that any of the three statements above may be turned around by pushing somewhat the bounds: despite the uncertainties, this nevertheless turns out to be really difficult (and in practice, impossible).

Recent, important, progress has been made in various areas, allowing us to pin down the matter content of the Galaxy with an accuracy that, for the first time, is sufficient to achieve our goal. *Stellar counts* are now sufficiently sensitive to reach all stars down to the smallest ones that are able to start the fusion of Hydrogen into Helium (down to the bottom of what is called the "Main Sequence" of stars), and thus are luminous. This shows [24,32,34] that most of the stellar mass is within the smaller stars, and tells how much. The results [7, 9, 30] of *Kinematic measurements* of stellar motions that deviate slightly from the general rotation have converged [16, 21, 34] in the very last few years. They now provide trustable measurements of the total Disk surface density Σ in the solar neighborhood and of the local matter density. The *microlensing experiments* measure [2,6] the gravitational deviation [36] of the light from background stars by intervening stellar-size objects, whether the latter are luminous or not. The number of such events and the duration of the event provide invaluable information on the total mass density of these intervening objects and on their individual mass distribution.

With all these premises, we are now set to discuss the nature and the location of the Dark Matter in the Galaxy, along the lines of recent work [16, 34, 35] on the matter. As usual, we will separate (Fig. 2) the Galaxy into a Disk, a Bulge, a Stellar Halo and a Dark Halo. The latter contains no known stars, except for extremely dense groups of the oldest stars in the Galaxy, the Globular Clusters.

2. Dark Matter in the Disk

2.1. Mass density in the solar neighborhood

From the statistics of the number of stars of a given luminosity and a well-calibrated mass-luminosity theoretical relation, it is possible to get the number of stars of a given mass, that is to get the mass function. In the solar neighborhood, the latter has been known for years for stars above a fraction of a solar mass, but in the low mass region is new (Fig. 3). Earlier results showed this mass function to drop suddenly near 0.2 $M_\odot$. This was partly due to a systematic error since some pairs of small stars in binary systems were erroneously counted as one larger star. New data exist now that are either [29] free of this systematic error (but with a somewhat larger statistical error), or have more statistics with an approximate correction factor for binaries [24]. The two results [34] (Fig. 3) that we will respectively call mass function (a) and mass function (b), are slightly different. It may, however, be

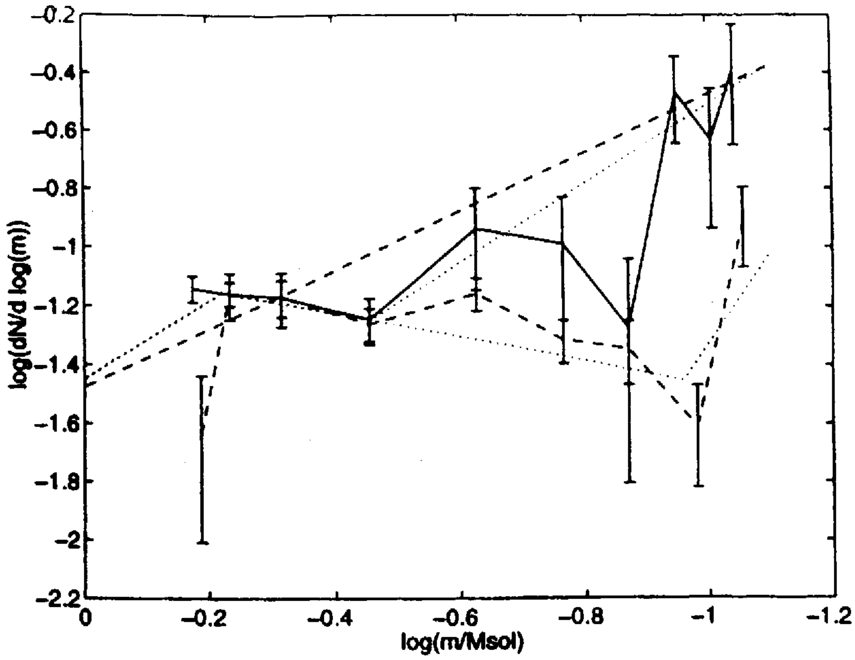

Fig. 3. Stellar mass function at the bottom of the Main Sequence [34]. The solid line (case (a)) is derived from the data of Ref. 29 whereas the dashed line (case (b)) is obtained using the data of Ref. 24. The dotted lines are fits to these two luminosity function. These fits can be taken to be the same for $m > 0.35M_\odot$. The straight dashed line is an overall a m^{-2} fit to the mass function (a).

safer to believe the first one, free of statistical errors, which turns out to yield [32] *a steadily increasing mass function down to the smaller visible stars.* The behaviour of the mass function (b) is somewhat more complex. A specific study [26] in the Bulge shows that, within the observational uncertainties, there is no sign for the mass function to be different from the one in the solar neighborhood (except, of course, for its normalization that reflects the local density).

Despite all the uncertainties, it is now very clear that *the observations extend down to the bottom of the Main Sequence*, that ends at $0.07M_{\odot}$, the limit beyond which these stellar objects are Brown Dwarfs. Very obviously, also, this mass function, which results from collapsing cold hydrogen clouds, has no reason to end at the bottom of the Main Sequence: at the onset of the collapse, the clouds do not know whether they are going to reach the Hydrogen fusion limit and become luminous stars, or not reach it and become Brown Dwarfs. For the mass within these stellar-like objects to be finite, however, there must be an end to the above power-law behaviour. The mass $m_{\rm inf}$ down to which these stellar-like objects exist turns out to be provided by the microlensing experiments. Assuming the mass function is the same in the Galactic Bulge than in the Disk, the MACHO [3] and OGLE [44] results (Sect. 2 below) lead to $m_{\rm inf} = 0.056\ M_{\odot}$ in case (a) and $m_{\rm inf} = 0.047\ M_{\odot}$ in case (b). This implies the estimate given in Table I for the mass density in the form of Brown Dwarfs, which despite all the uncertainties inherent to such a procedure, is seen to be less than 10% the total mass in the form of baryons what is already observed.

This total, directly observed matter density in the Disk can be compared to the total density $\rho_{\rm dyn}$ measured by its gravitational effects, through the motion of stars in the direction z perpendicular to the disk (for $z \ll 300$pc, the vertical acceleration is given by $K_z = 4\pi G\ \rho_{\rm dyn} z$). A very recent study [16] within ≈ 100pc around us using the HIPPARCOS data yield for the first time the quite accurate value

$$\rho_{\rm dyn} = 760 \pm 150\ 10^{-4} M_{\odot}{\rm pc}^{-3}. \tag{10}$$

Adding (Table I) to the observed mass in Main Sequence stars the estimate of the mass in Brown Dwarfs, White Dwarfs, Neutron Stars, and in form of hydrogen gas [12,31], it is seen that *in the Disk, the total of already observed baryonic mass is sufficient to explain the observed gravitational mass.*

TABLE I

Mass density in the solar neighborhood

mass density $(10^{-4} M_\odot \mathrm{pc}^{-3})$	mass function (a)	mass function (b)
$\rho_{\mathrm{MS\,stars}}$	434	311
ρ_{BD}	35	26
$\rho_{\mathrm{WD+NS+RG}}$	33	33
ρ_{gas}	300	300
$\rho_{\mathrm{Disk\ baryonic}}$	810±60	680±60
$\rho_{\mathrm{dyn}} - \rho_{\mathrm{Halo}}$	660±150	630±150
ρ_{Halo}	102	127
ρ_{dyn}	760±150	760±150

For two models of the mass function, (a), that we think is the more realistic and (b) — see Sect. 1.1 for the definition — we give the mass density in the form of Main Sequence stars $(\rho_{\mathrm{MS\,stars}})$, Brown Dwarfs (ρ_{BD}), White Dwarfs, Neutron Stars, Red Giants $(\rho_{\mathrm{WD+NS+RG}})$ and gas (ρ_{gas}) that is actually observed, the total of which giving the mass density $(\rho_{\mathrm{Disk\ baryonic}})$ due to baryonic objects in the Disk. Although somewhat high, the latter is already seen to be consistent with the (rounded off) dynamically determined mass density $(\rho_{\mathrm{dyn}} - \rho_{\mathrm{Halo}})$ where the contribution (ρ_{Halo}) of the mass density Dark Halo, estimated in Table III, has been used to correct the total dynamically measured [16] density (ρ_{dyn}), the difference representing the dynamical density in the solar neighborhood due to the Disk matter only. There is no room for additional Dark Matter in the solar neighborhood. The errors are estimated from Ref. 34).

2.2. Surface density and rotation curve

From the observed matter distribution in the vertical z direction, it is possible to deduce the surface density of the Disk for the various components (Table II), taking into account that there is [22] an observed "thick disk" (with [23] a contribution of 20% to the solar density, and an exponential scale height of 650 pc, note however that older values [22] are 2% of the solar density in the thick disk with a height of 1.3 kpc) extending somewhat above what is usually called Disk. The molecular H_2 gas is seen [12] to be more concentrated towards the plane of the Disk than the stars and [31] than the atomic HI gas. This value of the known existing matter can then be compared to dynamical measurements of the same surface density. A long controversy between the defenders of a low value of the dynamical surface density [9, 21, 30] and those promoting a much higher one [7], has been recently settled (see discussion in Ref. [34]). This dynamical surface density is presently known to a good accuracy (Table II). Wee see that, over the disk thickness (Table II), there is more room than in the immediate solar vicinity (Table I) left for Dark Matter in addition to the small Brown Dwarf component (and there would be even 10% more room would we use the older values for the thick disk).

TABLE II

Disk surface density in the solar neighborhood

surface density ($M_\odot \mathrm{pc}^{-2}$)	mass function (a)	mass function (b)
$\Sigma_{\mathrm{MS\ stars}}$	29.2	19.2
Σ_{BD}	2.7	2.0
$\Sigma_{\mathrm{WD+NS+RG}}$	2.6	2.6
Σ_{gas}	12.4	12.4
$\Sigma_{\mathrm{Disk\ baryonic}}$	47±4	36±4
$\Sigma_{\mathrm{Disk\ dyn}}$	51±6	51±6

For two models of the mass function, (a), that we think is the more realistic and (b) — see Sect. 1.1 for the definition —- we give the surface density of the Disk in the form of Main Sequence stars $(\Sigma_{\mathrm{MS\ stars}})$, Brown Dwarfs (Σ_{BD}), White Dwarfs, Neutron Stars, Red Giants $(\Sigma_{\mathrm{WD+NS+RG}})$ and gas (Σ_{gas}) that is already observed, the total of which giving the mass density $(\Sigma_{\mathrm{Disk\ baryonic}})$ due to baryonic objects in the Disk. Although somewhat low, the latter is already seen to be quite close to the dynamically measured surface density (Σ_{dyn}). The errors are estimated from Ref. 34).

It is quite clear that the disk surface density alone is ways too small to explain the rotation curve (see Eq. (3)). In the presence of a Dark Halo in addition to the Disk, the rotation velocities and the vertical acceleration are related to the Halo density ρ_{Halo} and to the Disk surface density by [35]

$$v_\odot^2/4\pi G R_\odot^2 \;=\; p\rho_{\mathrm{Halo}} + q\Sigma_\odot/R_\odot \;+ M_{\mathrm{B}}/4\pi R_\odot^3\,, \tag{11}$$

$$K_z/2\pi G \;=\; \Sigma_\odot \;+ 2\rho_{\mathrm{Halo}} z\,, \tag{12}$$

where M_{B} is the mass of the Galactic Bulge. The expression of the coefficients p, q can be found in Appendix B. They are close to unity. Assuming the Disk surface density is known, from the measurement of the rotation velocity [20] $v_\odot \;= 220 \pm 10\ \mathrm{km\,s^{-1}}$ at the solar radius, it is possible to deduce the needed Halo mass density through (11). Similarly, there is a determination [30] of the vertical acceleration at the height $z = 1.1$ kpc,

$$K_z/2\pi G = 71 \pm 6 M_\odot \mathrm{pc}^{-2} \tag{13}$$

that allows a second, independent determination of the same Halo mass density. Applying this procedure to the two cases (a) and (b) considered previously yields the estimates for the Halo density given in Table III. Clearly, the consistent values obtained from both methods (with minor systematic differences depending on the mass function used) show indeed there is a massive Halo. In case some Dark Matter in the disk has still been left out, a possibility that the comparison between the sum of the known components of the disk and the dynamically determined surface density (Table II) leaves open, the Halo mass density would be slightly lower than the values given in Table III.

TABLE III

Estimates of the Halo mass density

$\rho_{\rm Halo}$ $\left(10^{-4}\ M_\odot \mathrm{pc}^{-3}\right)$	(a)	(b)
from rotation velocity	100±17	109±24
from vertical acceleration	109±32	159±32
mean	102±15	127±19

With the surface density of the Disk implied by the mass function (a) or (b) of Table II, the Halo density in the solar neighborhood can be estimated (Eq. (11)) from the knowledge of the rotation velocity. An independent estimate is obtained (Eq. (12)) by comparing the vertical acceleration induced by the same Disk surface density to the one measured [30] at 1.1 kpc above the plane of the Disk. The last line gives the weighted mean of these two independent determinations, according to the mass function which is considered.

One could be tempted to use the measured (Table II) dynamical surface density of the Disk, $\Sigma_{\rm dyn} = 51 \pm 6 M_\odot \mathrm{pc}^{-2}$, to deduce from (13) the value of the Halo density. This, however, is not the right move. The latter has been obtained from a measurement of the vertical acceleration at some average height z, that ranges from 350 pc up to 1 kpc depending on the survey, from which a guessed "Halo correction" is subtracted. The information that there is a Halo thus has already been used to obtain $\Sigma_{\rm dyn}$ and cannot be deduced from the latter. In this sense, the dynamical value of Σ of Table II is not consistent with our estimate of the Halo density of Table III since another value for the latter density has been used to determine it. The associated correction would lower the measured value of $\Sigma_{\rm dyn}$ by 1 (case (a)) or 3 (case (b)) units, down to 50 $M_\odot \mathrm{pc}^{-2}$ or 48 $M_\odot \mathrm{pc}^{-2}$, respectively, well within the error bars.

3. Dark Matter in the Galactic Bulge

The information we have about the Galactic Bulge is:

- Its mass, rather well known: the observed rotation curve allows barely more than $10^{10} M_{\odot}$, a typical value being $M_{\rm B} = 1.2\ 10^{10} M_{\odot}$.
- The mass function of the stars, known with much less accuracy than the one in the solar neighborhood. There is no indication that this mass function is different from the one in the Disk.

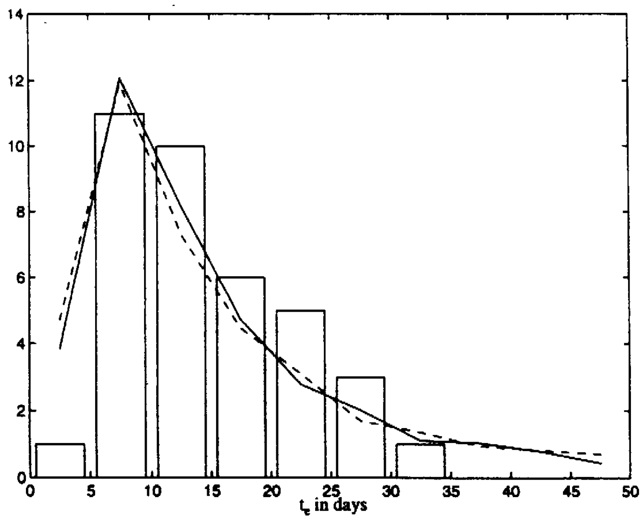

Fig. 4. Fits [34] to the MACHO microlensing data towards the Galactic Bulge. The histogram of the observed effective time (t_e) distribution for the MACHO events is fitted using the mass function (a) with $m_{\rm inf} = 0.056$ (solid line) and the mass function (b) with $m_{\rm inf} = 0.047$ (dashed line). Three events that are clearly intruders in the data, corresponding to times of the order of 80-100 days have been excluded.

- The extend of the mass function beyond the low-mass end of the Main Sequence stars, into the Brown Dwarf range. It is a well-known property of gravitational systems that the velocity distribution of the moving objects is independent of their mass. But the efficiency of the gravitational deflection of light rays by intervening objects increases with the mass of the latter, the duration of the event going as $m^{1/2}$. From the statistics of deflection times of the microlensing events towards the Bulge seen by the MACHO and OGLE experiments and from the knowledge of the mass function extended down to masses smaller than $0.07 M_{\odot}$ (and assumed to be the same in the Disk and in the Bulge), it is thus possible to deduce [34] a value for $m_{\rm inf}$. Extending to the smaller masses the fits (dotted lines) of the mass functions of Fig. 3 leads (Fig. 4) to [34] $m_{\rm inf} = 0.056 M_\odot$ in case (a) and $m_{\rm inf} = 0.047 M_\odot$ in case (b).

- The number of microlensing events observed towards the Bulge. The 9 OGLE and the 40 MACHO events would call for a mass significantly larger than the above limit, would the Bulge be spherical. It is however now commonly admitted [46] that the Bulge is elongated, as is the case in many other Spiral galaxies similar to the Milky Way Galaxy. An elongated Bulge is consistent with the above results within the mass limit provided by the rotation curve. This information is a genuine contribution of the microlensing surveys: there is no possibility for the traditional astronomical surveys to get a hint to the shape of the Bulge.

4. Dark Matter in the Galactic Halo

The dynamical measurements call for a galactic Halo that decreases approximately as r^{-2} with a density in the solar neighborhood $\approx 1{\cdot}10^{-2} M_\odot \mathrm{pc}^{-3}$, slightly lower than (5) due to the presence of the galactic Disk, that is $\approx 1/7$ of the Disk density. This r^{-2} Halo extends at least up to 60 kpc [28]. The stellar component of the Halo is called *Stellar Halo* or sometimes also *Spheroid* and decreases much faster [40], typically as r^{-3}, with a stellar mass function [14, 33] that, again, is close to the one seen in the disk within the uncertainties. This mass function is seen [14] to be in excellent agreement with the HUBBLE observations of very faint stars. The mass density of visible stars is extremely low [34], of the order of $1.0\, 10^{-4} M_\odot \mathrm{pc}^{-3}$, that is *two orders of magnitude below the total Halo mass density,* a difference that increases with galactocentric distance due to the difference in the radial slopes. The Dark Halo, indeed is dark!

There is no hope for Brown Dwarfs to provide the missing Dark Matter. With the similarity of the mass functions, a similarity of the low mass cut-off $m_{\rm inf} \approx 0.05 M_\odot$ can be expected. This provides an additional $\approx 10\%$ of the visible stellar component in the form of Brown Dwarfs. With the observed slope of the mass function, an extremely low average mass $\langle m \rangle \approx 10^{-7} M_\odot$ (!) would be necessary to provide the missing two orders of magnitude. Even with unrealistically steep slopes beyond the mass of visible stars such as m^{-5} for the mass function (the observed slopes are typically $m^{-2\pm 0.5}$), an average value $\langle m \rangle < 10^{-2} M_\odot$, incompatible — see below — with the microlensing experiments, is needed.

The microlensing events detected by EROS and MACHO in the direction of the Large Magellanic Cloud, a satellite galaxy of ours situated at a distance of 50 kpc, indeed sample the Dark Halo. The results yield 1 (or 2 if one retains the event whose background star is a variable star) events observed by EROS [5,6,39] and 6 (or 8 if one includes the event #10 which originates from a variable star and event #9 which probably is due to a deflecting star in the LMC) observed during the two first years by MACHO [2]. This is a large number, the associated optical depth $\tau_{\rm obs} = 2.2 \pm 1\ 10^{-7}$ corresponding to a sizable fraction (40%) of the dark Halo. The average duration $\langle t_{\rm e} \rangle \approx 28$ days and $\langle t_{\rm e} \rangle \approx 40$ days, respectively, are consistent, taking the uncertainties into account, and lead to an average mass of the intervening Halo objects of $\langle m \rangle \approx 0.5 M_{\odot}$, much larger than the masses which would be needed in case the Dark Matter would be in the form of Brown Dwarfs. A detailed examination of this hypothesis, indeed shows that the time distribution of the events obtained in the Brown Dwarf case has only 0.02% chance to lead to the observed distribution. This is definitely excluded. (And more recent data tend to increase the observed optical depth as well as the average mass!)

The mass of the intervening objects being close to a solar mass, it is tempting to consider [15], [1] the solution of having a population of White Dwarfs as the explanation of the observed microlensing events. This hypothesis, allowed within the uncertainties of the observations, however, is not free of difficulties.

* This large amount of White Dwarfs must originate from a galactic event during which the according number of stars was made. These stars, however must be born all with the nearly the same mass, between [15] 1 and $2M_{\odot}$, whereas in all visible parts, the stellar mass distribution is a scale-free power-law ranging from somewhat below $0.01 M_{\odot}$ to above $50 M_{\odot}$. Indeed stars of mass below $1 M_{\odot}$ would not yet be White Dwarfs, but be Main Sequence stars, whose luminosity would overwhelmingly dominate in the Halo and is obviously not observed. Stars with mass above $2 M_{\odot}$ would have ejected most of their matter (remnants are always of masses between a fraction of a solar mass and $1.4 M_{\odot}$) and produced Halo matter that is very rich in the elements (C, O, Fe) synthesized within these stars: this also is seen not to be possible.

Why is the mass function so different?

* Even such a narrow initial mass function is probably not sufficient to prevent the formation of a prohibitively large number of luminous stars. As currently seen for already formed stars in our neighborhood, a major (typically $\sim 50\%$) fraction of the collapsing objects form binary or multiple systems with a splitting of the initial mass among the objects. So one may expect an initial mass function peaked around 1–$2 M_{\odot}$ to produce, say, numerous pairs of 0.5–$1 M_{\odot}$ stars that would still be luminous Main Sequence stars. Whence 50% of the halo mass would be in the form of luminous stars, whereas bound from the Hubber Deep Field star counts imply [14]

less than 0.1% of the halo mass to be in the form of a Main Sequence stellar population. This difference is so large that pushing the mass function to higher masses (at the price of producing many heavy elements) does not help sufficiently. The only way out is to assume binaries do not form in the Halo. Why are there no binaries made in the star formation process from which this White Dwarf population originates?

* These White Dwarfs have about solar masses. In Globular Clusters, younger stars of similar mass are observed. The observed White Dwarfs in globular glusters have similar masses, but their number as well as their mass distribution is consistent with the standard, power-law, initial mass distribution of the stars, that is they represent a negligible contribution to the mass budget. The dynamics of these Globular Clusters shows no sign whatsoever of a hidden Dark Matter component [43]. Why are there no such Halo-type White Dwarfs in these Clusters, that formed in the same location?

Other possibilities may be considered to explain the observations:

* New (unknown) variable stars.

* Hypothetical novae eruptions [18]. A particular class of such eruptions have just the right magnitude and time scale, but it is not known whether these are achromatic as is required for a microlensing event to be retained in the observations.

* Primordial Black Holes. The latter hypothesis gets a quite amazing support, in the sense that the size of the horizon (*i.e.* the typical length scale appearing in the problem) at the time of the Quark–Hadron transition is just (Appendix C) of the needed order of magnitude! Hypothetically large energy-density fluctuations just before the transition could be responsible for the formation of such objects.

* The disk is folded: when looking towards the LMC we erroneously think that we sample the Halo. The observed microlensing events would then be due to disk stars [19] that happen to be in a rather unusual place. It however seems that this solution requires a prohibitively large amount of matter in the surroundings of the disk. Searching for microlensing events towards the Small Magellanic cloud, as is currently doing EROS2, and thus sampling the Halo in a different direction, will provide an independent information and settle this question.

* An interesting suggestion [8, 37] is that the LMC might have much larger a depth than usually assumed. The microlensing events observed towards the LMC can then be due to lensing by stars belonging to the Magellanic Cloud rather than to the Halo.

5. Conclusions

There is no longer any mysterious Dark Matter in the galactic Disk. The density obtained by direct counts of the various baryonic components (luminous stars, gas) and the dynamically determined density by measuring the gravitational potential agree within the observational uncertainties. There is a little room for the expected contribution of Brown Dwarfs, small-mass stellar-like objects that failed to ignite the Hydrogen fusion reaction, but barely any more room for anything else. Typical proportions in the Disk could be 67% stars, 27% gas, 6% Brown Dwarfs.

There is likely not to be any Dark Matter problem in the Bulge of the Galaxy. Its mass determined from the rotation curve is sufficient to explain the unexpectedly large number of microlensing events seen there, provided the Bulge is in the form of a Central Bar, as is the case for many other galaxies. Since there is not any problem of explaining the gravitational potential of the Disk by the known baryonic components, one does not expect the Bulge to raise a problem.

There is now definite evidence for a galactic Dark Halo where the mass density of visible stars is barely 1% of the total Halo density. To explain the rotation curves, this Halo is required to have an r^{-2} density profile, normalized to $\approx 1\ 10^{-2} M_{\odot}\mathrm{pc}^{-2}$ in the solar neighborhood. This Halo extends at least up to 60kpc. Its composition is still under debate. The (very few) microlensing events seen towards the Large Magellanic Cloud call for 30% to 50% of the mass to be in the form of $\approx 0.5 M_{\odot}$ objects. This property has not received any convincing explanation, the less unlikely one being White Dwarfs that need to bear rather unusual properties as compared to those which are observed. Microlensing surveys are still under way (MACHO, EROS2) ... and keep steadily to report seeing such events!

And clearly, there is still at least half (and possibly all) of the Dark Matter in the Halo unaccounted for.

Appendix A

Microlensing events

The principle of the microlensing effect is simple [36], and extended discussions of the way to perform the calculations exist [25, 27].

A massive, compact, object of mass m passing at a distance r of the observer of a background star at distance R, deflects the light rays coming from this star. The net result is an amplification of the collected light, by a factor A that depends on the distance d of the object to the line-of-sight

$$A = (u^2+2)/u(u^2+4) \quad , \quad u = d/R_E \,, \tag{A.1}$$

where

$$R_E = [4Gmr(R-r)]^{1/2}/c \tag{A.2}$$

is the Einstein radius. The maximum amplification depends on the distance of closest approach $d_{\rm min}$ to the line-of-sight, called the impact parameter

$$A_{\rm max} = (u_{\rm min}^2+2)/u_{\rm min}(u_{\rm min}^2+4) \quad , \quad u_{\rm min} = d_{\rm min}/R_{\rm E} \,. \tag{A.3}$$

The time between the two instants where $d = R_{\rm E}$, that is $A = 1.34$, is

$$t = 2(1-u_{\rm min}^2)^{1/2} R_{\rm E}/v_T \,, \tag{A.4}$$

v_T being the velocity of the intervening object perpendicular to the line-of-sight. From the measurement of A and t, it is possible to deduce an *effective time* (the MACHO collaboration uses twice this value)

$$t_{\rm e} = R_{\rm E}/v_T \,. \tag{A.5}$$

Another quantity of interest is the *optical depth* τ. Events occurring at distance r with an impact parameter $d_{\rm min}$, corresponding to an object of mass m and velocity v_T contribute to the optical depth by an amount

$$d\tau = p_u(u_{\rm min})\; du_{\rm min}\; p_v(v_T) dv_T\; p_m(m) dm \;\; \pi R_{\rm E}^2 \rho(r)/m\; dr \tag{A.6}$$

with the probability distribution of the impact parameter

$$p_u(u_{\rm min}) = u_{\rm min}/2 \tag{A.7}$$

of the velocity

$$p_v(v_T) = v_T/\sigma^2 \exp[-1/2(v_T/\sigma)^2] \tag{A.8}$$

and of the mass

$$p_m(m) = m\mu(m) / \int m\mu(m) dm \,, \tag{A.9}$$

ρ being the mass density of the intervening objects and $\mu(m)$ their mass function. One can also define the frequency at which events with the above properties occur

$$d\Gamma = 1/t \; d\tau \,, \tag{A.10}$$

where

$$\Gamma = \int d\Gamma = \sum_{\text{all events}} \tag{A.11}$$

is the total number of events per unit time. The optical depth can be obtained as

$$\tau = \int t \, d\Gamma = \sum_{\text{all events}} t \,. \tag{A.12}$$

Such a definition, however, lead an estimate of the optical depth that is very sensitive to statistical fluctuations. It is readily seen that $t_{\rm e}$ is also the true duration t of the event averaged over the distribution of impact parameters

$$t_{\rm e} = \int t \; p_u(u_{\rm min}) d \; u_{\rm min} \,, \tag{A.13}$$

and thus one has also the exact relation

$$\tau = \int t_{\rm e} d\Gamma = \sum_{\text{all events}} t_{\rm e} \tag{A.14}$$

which fluctuates much less than the estimate obtained by using t.

To an event of true duration t corresponds thus a "mean event" of duration $t_{\rm e}$ whose frequency is by definition

$$d\Gamma_{\rm e} \;=\; \frac{1}{t_{\rm e} d\tau_{\rm e}} \,, \tag{A.15}$$

$$d\tau_{\rm e} \;=\; p_v(v_T) dv_T \; p_m(m) dm \; \pi R_{\rm E}^2 \rho(r)/m dr \tag{A.16}$$

with an optical depth that is the same as previously

$$\tau = \int t_{\rm e} d\Gamma_{\rm e} = \sum_{\text{all events}} t_{\rm e} \,. \tag{A.17}$$

The average duration of an event is then

$$\langle t \rangle = \langle t_{\rm e} \rangle = \tau/\Gamma = \frac{\sum_{\text{all events}} t_{\rm e}}{\sum_{\text{all events}}} \,. \tag{A.18}$$

The factors m in $R_{\rm E}^2$ and $1/m$ in ρ/m of (A.16) cancel out, and the optical depth τ is independent of the mass distribution of the objects. The optical depth measures directly the mass density ρ integrated along the line-of-sight.

The average $\langle t_{\rm e} \rangle$, on the other hand, depends on the mass distribution, and especially on its low mass end and can be used to obtain an information on the mass function $\mu(m)$ in the substellar range, where the stellar count can no longer help. This average depends also on the velocity distribution of the lensing objects

$$\langle t_{\rm e} \rangle = 22 \; (220 \text{km } s^{-1}/v_{\rm rot})(\langle m \rangle/0.1 M_\odot)^{1/2} \text{ days} \tag{A.19}$$

towards the LMC, and

$$\langle t_{\rm e}\rangle = 18\ (100{\rm km}\ s^{-1}/\sigma)(\langle m\rangle/0.1M_\odot)^{1/2}\ {\rm days} \qquad ({\rm A.20})$$

towards the galactic Bulge.

More generally, the higher moments of the distribution of te are given by

$$\int t_{\rm e}^n P(t_{\rm e})dt_{\rm e} = \int t_{\rm e}^{n-1} P_v(v_T)dv_T \quad p_m(m)dm \quad \pi R_{\rm E}^2\rho(r)/m\ dr \qquad ({\rm A.21})$$

with $t_{\rm e} = R_{\rm E}/v_T$, but are seen to diverge for $n > 2$ because of the factor $1/v_T$ in $t_{\rm e}$. This is the sign of an undesired sensitivity to the large values of $t_{\rm e}$ already for the moments of order 1 or 2. For this reason, the moments are not the right tool to study the distribution $P(t_{\rm e})$, that samples the distribution of masses m (assuming the velocity distribution is known). This divergence is in practice healed by the observational efficiency that decreases at large times. Whence, the higher moments solely sample this efficiency, not the mass distribution! It is much better [34] to construct directly $P(t_{\rm e})$ from the data and to use some statistical test to decide whether the theoretical prediction for $P(t_{\rm e})$ is consistent with the observed distribution. (An alternate way would be [34] to use the moments of $1/t_{\rm e}$ that are well-behaved and automatically eliminate the undesired sensitivity to the large-time events).

Appendix B

Galactic Halo density

The simplest model for the Galactic Dark Halo density

$$\rho_{h\odot} \ = v^2{}_{\rm rot}/4\pi G r^2 \qquad ({\rm B.1})$$

to describe the observed rotation curve is to be modified to take into account the Disk and the central Bulge. To keep the rotation curve constant, the above density has to be reduced at the galactocentric distances where the other components are important

$$\rho_{h\odot} = v^2{}_{\rm rot}/4\pi G(a^2 + r^2)\,, \qquad ({\rm B.2})$$

where the parameter a is to be suitable chosen.

The Disk is traditionally modeled with an exponentially decreasing surface density

$$\Sigma_\odot = \Sigma_\odot\ \exp[-(r - R_\odot)/R_d]\,, \qquad ({\rm B.3})$$

whereas the central Bulge can, to our purpose, be taken as a point-like mass M_B.

For the rotation velocity at solar distance, we then get [10, 35] at the solar radius

$$v_\odot^2/4\pi G R_\odot^2 = p\rho_{\rm Halo} + q\Sigma_\odot/R_\odot + M_B/4\pi R_\odot^3 \tag{B.4}$$

$$p = [1 - x{\rm Arctg}(1/x)][1+x^2],\ x = a/R_\odot \tag{B.5}$$

$$q = y/2\exp(2y)[I_0(y)K_0(y) - I_1(y)K_1(y)],\ y = R_\odot/2R_d\,, \tag{B.6}$$

where

$$\rho_{\rm Halo} = v_\odot^2/4\pi G R_\odot^2/(1+x^2) \tag{B.7}$$

is the Halo density at the solar radius.

The values of $R_\odot = 8.5$ kpc and $M_B = 1.2\ 10^{10} M_\odot$ are standard parameters. For given $v_\odot$ and $\Sigma_\odot$, the value of the screening length a can then be adjusted to fulfill Eq. (B.4), which in turn yields the value of the Halo density through (B.7).

Appendix C

Horizon scale in the primordial Universe

At time t, when the Universe is at temperature T with the equation of state

$$\rho = g^*/2\ a\ T^4\,, \tag{C.1}$$

where $g*$ describes the degrees of freedom (2 for the sole photons)

$$g^* = \Sigma_{\rm bosons} + 7/8\Sigma_{\rm fermions}\,, \tag{C.2}$$

the Einstein evolution equation give the expansion parameter R (whence $R\ \alpha\ t^{1/2}$),

$$1/R\ dR/dt = (2t)^{-2} = 8\pi/3G\rho. \tag{C.3}$$

The mass within the horizon (sphere of radius $2ct = R\int_0^t \frac{dt}{R}$) is then

$$M_H = 4\pi/3\rho(2ct)^3. \tag{C.4}$$

and can be expressed as a function of the temperature

$$\begin{aligned} M_H &= c^3/2G(3c^2/8\pi G g^* a)^{1/2}T^{-2} \\ &= 1.5(T/200{\rm MeV})^{-2}(g^*/60)^{-1/2}M_\odot. \end{aligned} \tag{C.5}$$

REFERENCES

[1] F. Adams, G. Laughlin, *Astrophys. J.* **468**, 586 (1996).

[2] C. Alcock *et al.*, *Nature* **365**, 621 (1993).

[3] C. Alcock *et al.*, *Phys. Rev. Lett.* **74**, 2867 (1995); *Astrophys. J.* **461**, 84 (1996), *Astrophys. J.* **471**, 774 (1996), *Astrophys. J.* **479**, 119 (1997).

[4] C. Alcock *et al.*, *Nucl. Phys. Proc. Suppl.* **51B**, 131 (1996).

[5] R. Ansari *et al.*, *Astron. Astrophys.* **314**, 94 (1996).

[6] E. Aubourg *et al.*, *Nature* **365**, 623 (1993).

[7] J. Bahcall, C. Flynn, A. Gould, *Astrophys. J.* **389**, 234 (1992).

[8] F. Bauer, Thèse Université Paris 7, 1997.

[9] O. Bienaymé, A. Robin, M. Crézé, *Astron. Astrophys.* **180**, 94 (1987).

[10] J. Binney, S. Tremaine, *Galactic Dynamics*, Princeton University Press, 1987.

[11] A. Bosma, Ph.D., Rijkuniversiteit Groningen, 1978; *Astron. J.* **86**, 1791 (1981).

[12] L. Bronfman *et al.*, *Astrophys. J.* **324**, 248 (1988).

[13] S. Casertano, van Gorkom, *Astron. J.* **101**, 1231 (1991).

[14] G. Chabrier, D. Méra, *Astron. Astrophys.* (1997), in press.

[15] G. Chabrier, L. Segretain, D. Méra , *Astrophys. J.* **468**, L21 (1996).

[16] M. Crézé *et al.*, *Astron. Astrophys.* (1997), in press.

[17] P. Delbourgo-Salvador *et al.*, *Astron. Astrophys.* **150**, 53 (1985).

[18] M. Della Valle, M. Livio, *Astrophys. J.* **457**, L77 (1996).

[19] N.W. Evans, G. Gyuk, M. Turner, J. Binney, astro-ph./9711224, 1997.

[20] M. Fich, S. Tremaine, *Annu. Rev. Astron. Astrophys.* **29**, 409 (1991).

[21] C. Flynn, B. Fuchs, *Mon. Not. R. Astron. Soc.* **270**, 471 (1994).

[22] G. Gilmore, N. Reid, *Mon. Not. R. Astron. Soc.* **202**, 1025 (1983).

[23] A. Gould, J. Bahcall, C. Flynn, *Astrophys. J.* **465**, 759 (1996).

[24] A. Gould, J. Bahcall, C. Flynn, *Astrophys. J.* **482**, 913 (1997).

[25] K. Griest, *Astrophys. J.* **366**, 412 (1991).

[26] J. Holtzman *et al.*, *Astron. J.* **106**, 1826 (1993).

[27] M. Kiraga, B. Paczynski, *Astrophys. J.* **430**, L101 (1994).

[28] C. Kochanek, *Astrophys. J.* **457**, 228 (1996).

[29] P. Kroupa, *Astrophys. J.* **453**, 358 (1995).

[30] K. Kuijken, G. Gilmore, *Mon. Not. R. Astron. Soc.* **239**, 571 (1989); *Mon. Not. R. Astron. Soc.* **239**, 605 (1989); *Mon. Not. R. Astron. Soc.* **239**, 650 (1989).

[31] F.J. Lockmann, L.M. Hobbs, J.M. Shull, *Astrophys. J.* **301**, 380 (1986).

[32] D. Méra, G. Chabrier, I. Baraffe, *Astrophys. J.* **459**, L87 1996.

[33] D. Méra, G. Chabrier, R. Schaeffer, *Europhys. Lett.* **33**, 327 (1996).

[34] D. Méra, G. Chabrier, R. Schaeffer, *Astron. Astrophys.* (1998), in press.

[35] D. Méra, G. Chabrier, R. Schaeffer, *Astron. Astrophys.* (1998), in press.

[36] B. Paczynski, *Astrophys. J.* **304**, 1 (1986).

[37] N. Palanque *et al.*, submitted to *Astron. Astrophys.* (1998).

[38] D. Pfenniger, F. Combes, L. Martinet, *Astron. Astrophys.* **285** 79 (1994).

[39] C. Renault *et al.*, *Astron. Astrophys.* (1997), in press.

[40] H. Richer, G. Fahlman, *Nature* **358**, 383 (1992).

[41] V.C. Rubin, K. Ford, N. Thonnard, *Astrophys. J.* **225**, L107 (1978); *Astrophys. J.* 238, 471 (1980).

[42] R. Schaeffer, Mais où donc est la matière noire de notre Galaxie?, Course given at Aussois, Ed. A. Baglin, Meudon, France, 1995.

[43] R. Schaeffer, S. Maurogordato, A. Cappi, F. Bernardeau, *Mon. Not. R. Astron. Soc.* **263**, L21 (1993).

[44] A. Udalski *et al.*, *Acta Astron.* **44**, 165 (1993).

[45] J. Yang *et al.*, *Astrophys. J.* **281**, 493 (1984).

[46] H. Zhao, D. Spergel, R. Rich, *Astrophys. J.* **440**, L13 (1995).