CHAPTER XII

DARK MATTER

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ABSTRACT. The observational evidence for unseen matter is briefly reviewed for objects ranging from small to very large scales. The existence of large mass discrepancies is clearly recognized in individual spiral galaxies and in rich clusters of galaxies. For other systems - dwarfs, ellipticals, binaries and groups - the results are more uncertain and still rather controversial. The data on spirals indicate values of the cosmological density parameter Ω around 0.02, those on clusters $\Omega \simeq 0.2$. The spatial distribution of this dark matter is still largely unknown: while on the galaxy scale it must be located mainly in the outer parts of the stellar system, in clusters it is unclear whether it follows the distribution of the visible galaxies or not.

1. INTRODUCTION

The main questions concerning dark matter are whether it is really present in the first place and, if so, how much is there, where is it and what does it consist of.

How much. In general one wants to know the amount of dark matter relative to luminous matter. For cosmology the main issue is whether there is enough dark matter to close the universe. Is the density parameter Ω equal to 1?

Where. The problem of the distribution of dark matter with respect to luminous matter is fundamental for understanding its origin and composition. Is it associated with individual galaxies or is it spread out in intergalactic and intracluster space? If associated with galaxies how is it distributed with respect to the stars?

What. What is the nature of dark matter? Is it baryonic or non-baryonic or is it both?

We examine here the observational evidence for dark matter on all scales, from the smallest galaxies to clusters, with the purpose of getting information on these questions. We discuss separately individual galaxies - dwarfs, spirals and ellipticals - and multiple systems - binaries, groups and clusters. The present review is restricted to the more direct evidence based on the kinematics of

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objects in dynamical equilibrium and on X-ray data. Other evidence, e.g. that based on gravitational lensing, is not discussed.

2. OBSERVATIONAL EVIDENCE

2.1. Dwarf Galaxies

The study of the dynamics of these smallest systems offers the possibility of investigating whether dark matter is lumped on very small ($\sim$1 kpc) scales. Recent reviews of this subject are given by Kormendy (1987) and by Freeman (1986). Only dwarf spheroidals and irregulars are discussed here. The more regular and luminous dwarf spirals ($M_B \lesssim -16$), such as those studied by Carignan and Freeman (1985) and discussed by Kormendy (1987), give qualitatively similar results as the higher luminosity spirals and are not considered here.

Dwarf spheroidals. For these systems the evidence for the presence of dark matter comes from optical observations of the stellar radial velocity dispersion. A few nearby objects (Table 1) have been investigated recently by Aaronson (1986) and Aaronson and Olszewski (1987). The two faintest systems have large values of the M/L ratio. These large values do not seem to be explainable as being due to errors in the observations or to uncertainties in the analysis (cf. Tremaine 1986).

Table 1. Dwarf spheroidal galaxies (Aaronson 1986).

Galaxy	M_V	Velocity Dispersion (km/s)	M/L_V
Fornax	-12.6	7 ± 3	2
Sculptor	-11.1	6 ± 2	5
Carina	- 9.4	6 ± 2	8
Draco	- 8.5	11 ± 2	60
Ursa Minor	- 8.5	10 ± 2	80

Dwarf irregulars. Neutral hydrogen is generally used to trace the kinematics of these gas-rich objects. For the larger ones the analysis is based on rotation curves, as for spirals, but it is much more uncertain. For the smaller systems, where random motions dominate or are comparable to rotation, the virial theorem is applied. While for the brighter systems small values of M/L are generally found, in the fainter ones M/L reaches large values (Table 2). Perhaps some of these can be explained as due to large residual gas motions after bursts of star formation. It should be noted that for these fainter irregular systems, as for the spheroidal ones, only the "global" M/L ratios (as given in Tables 1 and 2) are known.

Table 2. Dwarf irregular galaxies (cf. Freeman 1986).

M_B	M/L
-16 to -13	1 - 10
-13 to -10	10 - 30

In conclusion, for both dwarf spheroidals and irregulars there is a clear tendency towards larger M/L values at lower luminosities. This does not necessarily prove, however, the presence of large amounts of dark matter in these objects. An alternative interpretation is that of a varying initial mass function (see Aaronson 1986 and references therein).

At present no clear answer can be given to the question of dark matter in faint dwarf galaxies. The possibility that there may be completely dark systems at the faint end of the luminosity sequence remains a fascinating speculation.

2.2. Spirals

There now exists indisputable evidence for discrepancies between the dynamically computed mass and the luminous mass of spiral galaxies (cf. review by van Albada and Sancisi 1986). The total masses and mass distributions of these systems are derived from optical and HI rotation curves, which are now available for a large number of objects (Rubin et al. 1985, Bosma 1981, Sancisi and van Albada 1987). The most secure evidence to date, however, comes from the study of the systems in Table 3. These systems have exponential luminosity profiles and HI layers extending far beyond the optical images - out to 10-12 disk scalelengths. Their velocity fields are regular and do not show signs of large deviations from axial symmetry or flows in the radial direction: in other words, there are no indications that the assumption of gas moving in circular orbits is not valid. The estimated total masses, i.e. the mass inside the last measured point on the rotation curve, lead to values of M/L_B in the range of 10 to 30. The corresponding values of Ω, 0.01 to 0.02, are, however, negligible with respect to the closure density of the universe.

The rotation curves for three of the galaxies in Table 3 are shown in Fig. 1. The distance from the centre is given in units of disk scalelength. The curves extend to 10-12 scalelengths and are flat out to the last measured point. The uncertainties in the circular velocities are approximately 2 to 5 km/s. Circular velocities can also be calculated from the luminosity profile (see Fig. 2 top) by assuming

Table 3. Spiral galaxies with large dark halos.

NGC	R_{HI} (kpc)	R_{HI}/h	$V(R_{HI})$ (km/s)	L_B ($10^{10}\ L_{B\odot}$)	M_T/L_B $R < R_{HI}$
2841	36	11.6	280	2.5	26
5055	41	10.0	180	2.8	11
2903	23	12.4	182	1.6	11
3198	30	11.1	149	0.9	16
2403	20	9.5	134	0.8	10
6503	25	12.5	115	0.7	11

Note: The values of R_{HI}, L_B and M_T/L_B are based on H_o = 75 km/s/Mpc.

a constant M/L ratio. If the value of M/L is chosen such as to maximize the contribution by the luminous disk, one obtains an estimate of the minimum amount of dark matter required to explain the observed rotation curve (see Fig. 2 bottom). Clearly there is a large discrepancy between the observed and predicted curves, starting around 2-3 scalelengths and increasing in the outer parts. The local M/L ratio increases from about

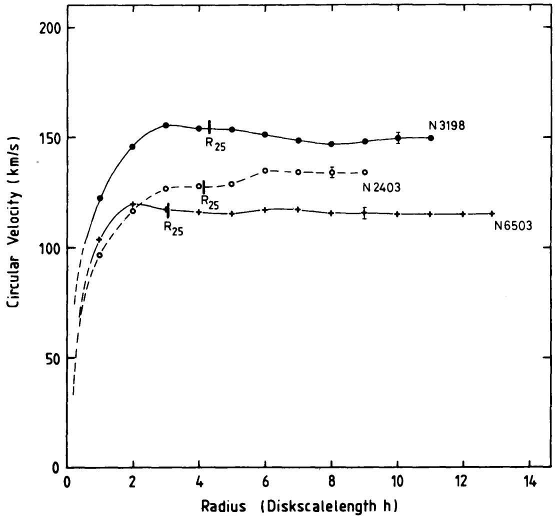

Figure 1. HI rotation curves for three spiral galaxies (Table 3) with extended, symmetrical HI disks and exponential luminosity profiles (from Begeman 1986).

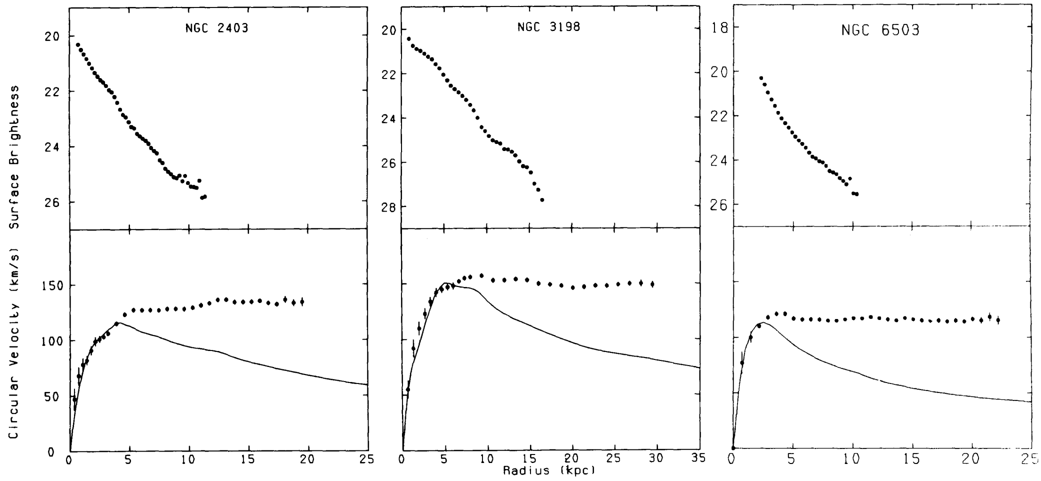

Figure 2. Light profiles and rotation curves for three spiral galaxies with extended, symmetrical HI disks. Upper panels: luminosity profiles from Wevers (1984). Lower panels: HI rotation curves (dots with error bars, Begeman 1986) and curves representing the circular velocity of stars and gas (solid line). The light contribution has been calculated from the luminosity profile by assuming that M/L is constant with radius and has the maximum value allowed by the observed rotation curve.

1-4 in the inner parts to several thousands in the outer parts (assuming that the dark matter lies in a disk; see van Albada and Sancisi 1986). The amount of dark matter inside the last measured point is about 4 times as large as the mass of the disk (assumed to have constant M/L). This should be regarded as the minimum amount of dark matter required as, in principle, the disk contribution could be much less. It is likely, however, that the estimated maximum value of the M/L ratio for the disk is close to the true value. This is based on various results and arguments (cf. Kent 1986, and van Albada and Sancisi 1986). The conclusion then is that dark matter is concentrated in the outer parts of spiral galaxies; in the inner parts, although not entirely ruled out, its presence is not required by the observations.

To sum up, dark matter is present in the outer parts of spiral galaxies. It amounts to at least 4 times the luminous material inside 2 Holmberg radii (about 10 disc scalelengths). The local M/L values are of order 5000 or larger.

Several questions remain unanswered at present:

1. What is the total mass of a galaxy? Where is the boundary of the dark halo? No convincing case has been found as yet of declining

rotation curves. The ones found so far are subject to various criticisms and are in doubt (cf. Sancisi and van Albada 1987). For our galaxy, however, Tremaine (1986) finds from a study of the kinematics of distant globular clusters and companions that a boundary is present at a radius of about 30 kpc.

2. What is the explanation of the well known "conspiracy" of disk and halo to produce a flat rotation curve through the combination of a declining rotation curve of the disk and a rising one of the halo? This seems to form at present the greatest puzzle of all and throws some serious doubts on the very hypothesis of dark halos to explain rotation curves.

3. What is the distribution of dark matter: a spherical halo or a disk which becomes darker (and perhaps thicker) in the outer parts? Although the halo hypothesis is generally favoured there is no compelling observational evidence as yet.

4. Do amount and distribution of dark matter depend on luminosity, morphological type, or environment? Some recent attempts to study these aspects are those of Carignan and Freeman (1985), Bahcall and Casertano (1985), Burstein and Rubin (1985) and Burstein et al. (1986).

5. What is the nature of the dark matter associated with galaxies? Is it all baryonic? What are its constituents?

2.3. Ellipticals

The study of total masses and mass distributions in elliptical galaxies has been vigorously pursued in recent years using optical, radio and X-ray observations.

Optical studies. The analysis of velocity dispersions from stellar absorption measurements leads to values of M/L independent of radius (Tonry 1983) and generally close to 10 out to one effective radius r_e. Such values can be attributed to a stellar population, thus no dark matter is required in the bright inner parts of ellipticals.

HI data. A few hydrogen-rich ellipticals have now been studied in detail. Maps of the HI density and velocity have been obtained and rotation curves, although less accurate than for spirals, have been derived out to several effective radii. The velocity fields indicate sufficient large-scale regularity and symmetry to make the mass determination reliable. For NGC 4278 Raimond et al. (1981) derive M/L_B values larger than 15 (H_o=75) out to $5r_e$ = 13 kpc, assuming that the inclination angle is less than 60°. From the velocity field we tentatively estimate a minimum inclination angle of 30°, which would lead to M/L_B less than 40. For NGC 1052 van Gorkom et al. (1986) estimate M/L_B = 11 (H_o=75) inside $6r_e$ = 21 kpc. This value agrees within the errors with the M/L inside one r_e derived from the stellar velocity dispersion by Davies and Illingworth (1986). This result would indicate that no dark matter is needed inside $6r_e$ = 21 kpc in this elliptical galaxy.

X-ray data. The Einstein observations of elliptical galaxies have been used to determine total masses out to several effective radii (Forman, Jones and Tucker, 1985). The analysis is based on the assumption of hydrostatic equilibrium for the hot gaseous halo surrounding the galaxies. For M 87 (Fabricant and Gorenstein 1983) and NGC 4472 (Forman et al. 1985) the density and the temperature profiles are both available, although the latter are quite uncertain. The M/L values are about 200 out to 10 r_e for M 87, and 20 out to 3 r_e for NGC 4472. Recently Fabian et al. (1986) have reanalysed the X-ray data for 14 ellipticals and have derived minimum total binding masses yielding values of M/L between 10 and 100. All these estimates, however, are dependent on the assumption of hydrostatic equilibrium, which may not be justified in the outer parts of the X-ray emitting regions as suggested by the sometimes irregular and asymmetric shape of the outer contours (see for example the X-ray map of NGC 4472 in Forman et al. 1985). A recent discussion of these general uncertainties is given by Trinchieri, Fabbiano and Canizares (1986), who find that the mass within the observed region could be as low as that derived from optical measurements. This is true also for NGC 4472. Moreover, in the case of the Sombrero galaxy (NGC 4594) the M/L values from X-ray studies seem inconsistent with that from the extrapolated, flat HI rotation curve, which indicates a much lower value. For M 87, which has perhaps the best information, the main problem arises from its central location in the Virgo cluster and from the possibility that at least part of the estimated binding mass belongs to the cluster. We conclude that the X-ray results, although certainly consistent with the presence of extended and massive halos around elliptical galaxies, do not seem to form as yet incontrovertible evidence of their existence.

Shells. The presence of ripples in the light distribution around ellipticals, revealed first by Malin and Carter (1980), has been used by Hernquist and Quinn (1986) and by Dupraz and Combes (1986a) to set constraints on the amount of dark matter around the elliptical galaxy NGC 3923. They find values of M/L of order 100. These results are based on the hypothesis of a sudden tidal disruption of a companion and the large M/L value derived is directly related to this assumption. In fact, Dupraz and Combes (1986b) argue that no dark matter is needed if a slowly decaying orbit is adopted.

In conclusion, in the inner parts of elliptical galaxies there is no need for any dark matter, as for spiral galaxies. For the outer parts there is no indisputable evidence yet for the presence of massive dark halos.

2.4. Binary Galaxies

In analogy with stars, double galaxies might be expected to give valuable information on the masses of galaxies. But expectations since early work of Holmberg and Page have not come true, despite considerable effort. The difficulties lie mainly in the interpretation (cf. White et al. 1983). The large range of M/L values found is indicative of the great uncertainties in the mass estimates.

An important requirement is a sample of well-isolated pairs, so that it is reasonable to assume that the galaxies only feel each others gravitational field. Such samples do exist (e.g. Karachentsev 1972), but the linear separation of these pairs is only a few optical diameters. In this case one learns less from the statistical analysis of a sample of pairs than from HI rotation curves of individual galaxies, which also extend over several optical diameters in a number of cases. The mass-to-light ratio of about 10 found for Karachentsev's sample (Karachentsev 1985) is consistent with M/L for galaxies with extended HI rotation curves.

Double galaxies become more interesting when their separations exceed the linear size covered by HI rotation curves (true separation > 50 kpc, or > 3 optical diameters). This restriction leads to severe problems:

1. The sample will be contaminated by non-physical pairs (e.g. sample of Peterson 1979).

2. The pairs are in general no longer isolated with respect to the galaxies surrounding them (e.g. they may belong to a group). Even though they may be physical pairs in the sense that they are isolated in space, their dynamics may be affected by other galaxies. Thus the velocity difference ΔV is perhaps not solely due to the galaxies in the pair. This is a problem for pairs in groups with crossing times less than the Hubble time.

A satisfactory solution of these problems has not yet been found. In addition, there are other problems with the mass determinations of binary galaxies:

3. An assumption must be made regarding the gravitational interaction of two galaxies in a pair. Since galaxies are surrounded by dark matter it seems unlikely that a model consisting of two point masses moving around each other in elliptic orbits is adequate.

4. Results will in general depend on the unknown ellipticity of the orbits or, alternatively, on the anisotropy of the velocity distribution. That is, the resulting mass for assumed circular orbits will differ from the resulting mass for assumed radial orbits (about a factor of 3).

White et al. (1983) try to overcome these problems by using the observations not only to solve for M/L, but also for the anisotropy of the velocity distribution and the type of gravitational interaction. To make such an analysis possible one must assume that the model (and reality) is scale-free, that is: anisotropy and type of gravitational potential are independent of radius. It seems unlikely that these assumptions could be valid; for example dynamical friction and merging must have led to a depletion of elongated orbits for small orbital dimensions.

In conclusion, binary galaxies data support the evidence for dark matter in individual spiral galaxies but they do not provide reliable results for larger linear scales.

2.5. Groups of Galaxies

In the case of groups the situation is perhaps slightly better than for binary galaxies. A large number of groups have been studied. Huchra and Geller (1982) find a wide range of M/L values, from 10 to 300. Tully (see paper in this volume) finds a similar large spread. Williams and Rood (1986) derive M/L values between 1 and 3 from their HI study of the Hickson compact groups. In all these studies the main assumption made is that the groups are uncontaminated systems in dynamical equilibrium. This may not be always true (see e.g. Valtonen and Byrd 1986). The question remains, therefore, whether the large spread in the M/L values is spurious or whether it reveals an intrinsic variation in the amount of dark matter present in the various groups.

2.6. Clusters of Galaxies

The presence of dark matter in clusters of galaxies was advocated already fifty years ago by Zwicky (1933). The conclusion is based on the virial analysis of radial velocities of the cluster members and on the assuption that the clusters are bound and in equilibrium. The results for the Coma, Perseus and Virgo Clusters are summarized in Table 4. The M/L value for the Virgo cluster core is based on the assumption that this system is bound but not virialized. The mass-to-light ratios in Table 4 yield values of Ω between 0.2 and 0.3.

Table 4. Mass-to-light ratios for rich clusters of galaxies (H_o = 75 km/s/Mpc).

Cluster	M/L_B	Radius	Reference
COMA	350	3^o = 5.0 Mpc	Kent and Gunn (1982)
PERSEUS	580	3^o = 3.8 "	Kent and Sargent (1983)
VIRGO core	370	6^o = 1.7 "	Huchra (1985)

In these analyses the distribution of dark matter is assumed to follow that of the light. The effect on the total mass determination when this assumption is relaxed has been investigated by The and White (1986). A factor three smaller or larger estimate of the total mass is obtained in the cases of respectively a concentration of dark matter in the inner parts or a more extended distribution in the outer parts. Despite the significantly lower mass in the case of a central concentration, a large amount of dark matter is still needed.

In principle, X-ray observations can also be used to trace the binding mass of clusters. But uncertainties in the temperature distribution of the gas have hampered the analysis of the X-ray data and have made it difficult, as in the case of the elliptical galaxies, to draw firm conclusions about the dark mass in clusters.

3. AMOUNT OF DARK MATTER: SUMMARY OF OBSERVATIONAL EVIDENCE

The general balance of the amount of dark matter associated with the various objects discussed above is summarized in Table 5. The cosmological density parameter Ω is based on the observed mean luminosity density of galaxies (Davis and Huchra 1982). It is clear that the strongest evidence for dark matter comes from the study of rotation curves of spiral galaxies, which require relatively small amounts of dark matter, and from the virial analysis of the velocity dispersions in clusters, which lead to cosmologically important quantities of dark matter. The known baryonic matter consists of stars ($M/L \simeq 10$) and hot intergalactic gas. The total mass of the latter as estimated from the observations of diffuse X-ray emission in clusters, is rather uncertain, but it seems to be at least as large as the stellar component (Henriksen and Mushotzky 1985), and may be represented, therefore, with M/L values ranging from 10 to 30. If we compare the M/L values of clusters with those of stars and gas together we find a factor 10 in the cluster M/L unaccounted for.

Table 5. Summary of observational evidence for dark matter (H_0 = 75 km/s/Mpc).

Object	Radius (kpc)	M/L_B	Ω
Dwarfs	3	----	----
Spirals	30	10–30	0.01–0.02
Ellipticals	10–50	(10–100 ?)	
Binaries	20–50	10– ?	
Groups	50–250	10–300 ?	
Clusters	2000–5000	350	0.2

4. DISTRIBUTION OF DARK MATTER

From the analysis of rotation curves it appears that at least a fraction of the dark matter in clusters is associated with individual galaxies and is located in their outer parts. This is, however, only a small fraction. It is not clear where the remaining part is, whether it is all associated with galaxies or whether it is spread out in intracluster space. The former possibility seems unlikely considering the small separation between galaxies in the dense cluster regions. Dynamical arguments can be used to set a limit of about 15 % on the fraction of dark matter associated with individual galaxies (Merritt and White 1987). It is interesting to note that the dark matter in spirals, although closely coupled to the light, does not follow its distribution, as it is more extended. One may wonder whether such a segregation might also occur on the scale of clusters and whether dark matter might be generally more extended than luminous matter and perhaps not be traced at all by the light.

5. NATURE OF DARK MATTER

The observational evidence obtained so far, and briefly reviewed here, does not seem to provide clear information on the question of the nature and composition of dark matter. The amounts required would not be inconsistent with the possibility of it being exclusively baryonic material. Any hypothesis on the nature and origin of dark matter, at least for dark matter associated with spiral galaxies, should account for the large local M/L values mentioned above and for its close "coupling" with the luminous material (i.e. the disk-halo conspiracy).

6. ALTERNATIVES

Alternative explanations, less conventional than the presence of large quantities of dark matter, have been proposed for the observed mass discrepancies. Finzi (1963), and more recently Milgrom (1983), Milgrom and Bekenstein (1987 and references therein) and Sanders (1984, 1986), have made radical suggestions involving modifications of Newtonian dynamics or gravity and have compared their predictions with the observations. So far these comparisons do not seem to have led to inconsistencies which would rule out such alternatives.

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DISCUSSION

RUBIN: You have discussed with great clarity the deconvolution of the rotation curves by making use of the maximum disk. I would like to mention recent observations which may be relevant. John Graham and I have used the Kitt Peak 4-m Echelle spectrograph + CCD at very high velocity resolution (0.125 A/pix) to obtain spectra of the same galaxies for which we had earlier obtained rotation curves. In a large fraction of the galaxies, the rotation velocities do not go smoothly to zero with decreasing nuclear distances, but instead go to a velocity near 50 km/s. I have not yet made mass models, but the observations suggest a nuclear mass which causes locally a falling density within a few arcsec (hundreds of parsecs).

SANCISI: A very interesting result. I wonder whether it may be related to the presence of central components in the light distribution of several disk galaxies as shown by the photometric profiles published recently by Kent (1986, Astr. J. 91, 1301).

N. BAHCALL: The increase of the dark matter component, or M/L, with the increasing scale of the system - from galaxies through clusters of galaxies- may possibly be further extended to the cores of the rich superclusters. Our data (Bahcall, Soneira and Burgett 1986 Ap.J.) suggest that large velocity dispersions (>1000 km/s) may exist in rich superclusters. If so, the M/L ratios in superclusters, on scales of 20 h^{-1} Mpc, may be still larger than that of clusters by a factor of ~ 2 - 3.

SANCISI: Yes, possibly. But I am not sure about a systematic relative increase of the dark matter component with increasing scale of the system. As to superclusters, are they bound systems in dynamical equilibrium?

FANG: Does the ratio of the luminous matter to dark matter depend on the morphology of galaxies ?

SANCISI: From the small number of good cases studied so far there seems to be no clear evidence of such a dependence.

CANIZARES: Relative to the question whether or not the dark matter in clusters is closely tied to the galaxies, the distribution of X-ray emitting hot gas (which is "virialized" and so traces the potential) does not closely follow the galaxies, in general. Therefore, the dark matter must be more widely distributed between the visible galaxies. The distribution of X-ray gas can also set limits on the degree of concentration of the dark matter.

BURKE: With respect to the distribution of matter in clusters of galaxies,the data on gravitational lenses provide definite conclusions. The original twin quasar 0957+561, an incontrovertible example of lensing, requires the matter to be distributed in a fashion very different from that implied by the distribution of luminous matter. It does not seem to be directly related to the galaxies in the foreground cluster, at least not without giving eccentric M/L values to the indidual galaxies. It is almost certainly distributed in a diffuse manner.

SANCISI: I am glad you mention gravitational lenses, which seem indeed to become an important source of evidence on the presence and distribution of dark matter in the universe. Unfortunately it has not been possible to discuss this evidence in the present review.