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BELGRADE-MACHO PROJECT: FIRST TWO YEARS' RESULTS

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Abstract. The activities of the Belgrade-MACHO project during its first two years of work are reviewed. The theoretical work on the microlensing optical depths and their connection with the problem of the baryonic dark matter, the shape of the disk and halo of the Milky Way, already yielded significant results. The emphasis is put on the intense use of today's common software and Internet resources. International collaborations and future plans are also briefly considered.

1. MICROLENSING AND GALACTIC DYNAMICS

Microlensing (ML) search has proved to be one of the most important tools for investigating the properties of the halo and disk of our galaxy (e.g. Paczyński 1986; Sackett & Gould 1993; Gould 1996; Alcock *et al.* 1996, 1997a; Ansari *et al.* 1996). Comparison of theoretical models and ML data led to intriguing results (e.g. Gates, Gyuk & Turner 1995). Under the Copernican assumption that the Milky Way is a typical zero-redshift L_* galaxy, one can ask what consequences recently discovered Massive Compact Halo Objects (MACHOs) have for the global picture of baryonic structure evolution in the universe. Exact shape of the Galactic gravitational potential, orbits of celestial bodies in this potential, and the interaction of Galactic subcomponents (thin and thick disk, bulge, bar, halo, etc.) can be discussed with more observational constraints than ever before.

Vigorous astrophysical research addresses these problems. As an illustration, we point out that the bibliography of Samurović, Ćirković & Milošević-Zdjelar (1999, SĆMZ) amounts to 119 refereed research papers and 16 review articles. Entire NASA ADS microlensing bibliography [1], represented in Fig. 1 for the last quarter of the

[1] `http://adswww.harvard.edu`

century, searched by key words, has 794 units. Almost exponential growth with time (with best fit time constant $\tau \sim 5$ years) is faster than in almost any other field of contemporary research, not only within astronomical disciplines.

ML events caused by MACHOs serve various astrophysical purposes: constraining mass distribution in the Galaxy and present-day stellar mass function (see Gould 1996). With this in mind, the investigation of *global* consequences of statistics of ML events along various lines of sight on the Galactic structure and dynamics, other galaxies and universe as a whole, had started at the beginning of 1998, within the framework of the Belgrade-MACHO Project. Hereby we would like to summarize some of the most significant results. Finally, we point out further directions of Belgrade-MACHO project and our collaborations within the world network of gravitational lensing research.

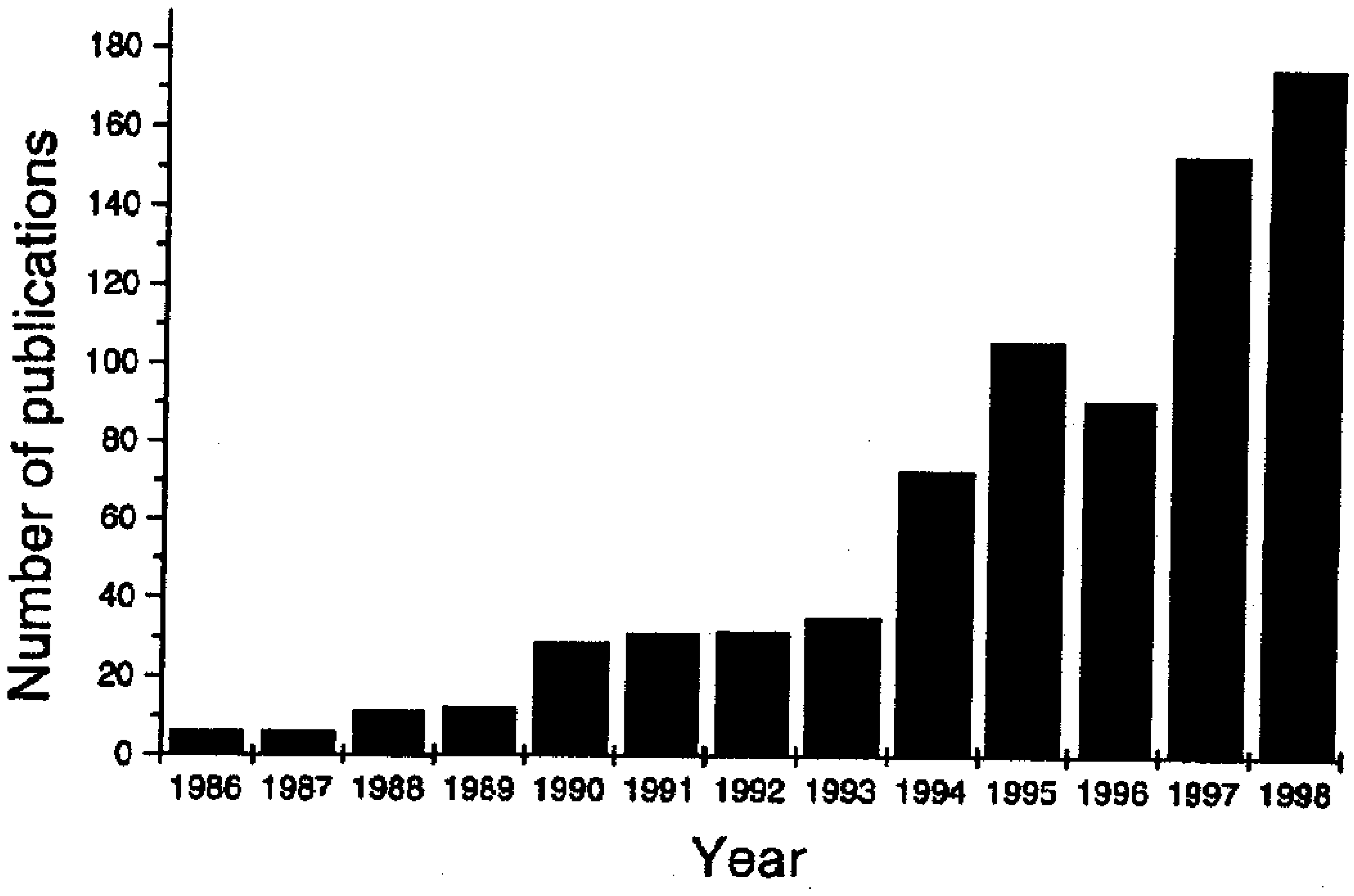

Fig. 1. The temporal distribution of the scientific publications on microlensing and related topics in the last quarter of the century.

2. MACHOS AND BARYONIC DARK MATTER

Baryonic dark matter (BDM) properties are one of the most important problems of today's astrophysics. MACHOs have been included into the total cosmological baryonic budget (Fields, Freese & Graff 1998). Existing ML searches are still insufficient to accurately determine the total MACHO abundance for two basic reasons:

1. All significant ML results are still within $\simeq 50$ kpc: Galactic bulge (surveys by MACHO [2], DUO and OGLE [3] collaborations) or Magellanic Clouds (MACHO and

[2] `http://wwwmacho.mcmaster.ca`, and ML Alerts: `http://darkstar.astro.washington.edu`

[3] `http://www.astro.princeton.edu/~ogle` (Optical Gravitational Lensing Experiment)

EROS [4] collaborations). This is a fundamental constraint, until results towards more distant sources, like M31, are obtained. It may be expected soon, since MEGA and AGAPE[5] coll. already started a survey (Gyuk 1999 private communication).

2. Statistics are still insufficient to determine optical depths in given directions with uncertainties smaller than $\delta\tau/\tau = 0.5$.

Theoretical example for a source at a distance of 50 kpc, like the LMC, assuming moderate halo flattening, is shown in Fig. 2 (SĆMZ).

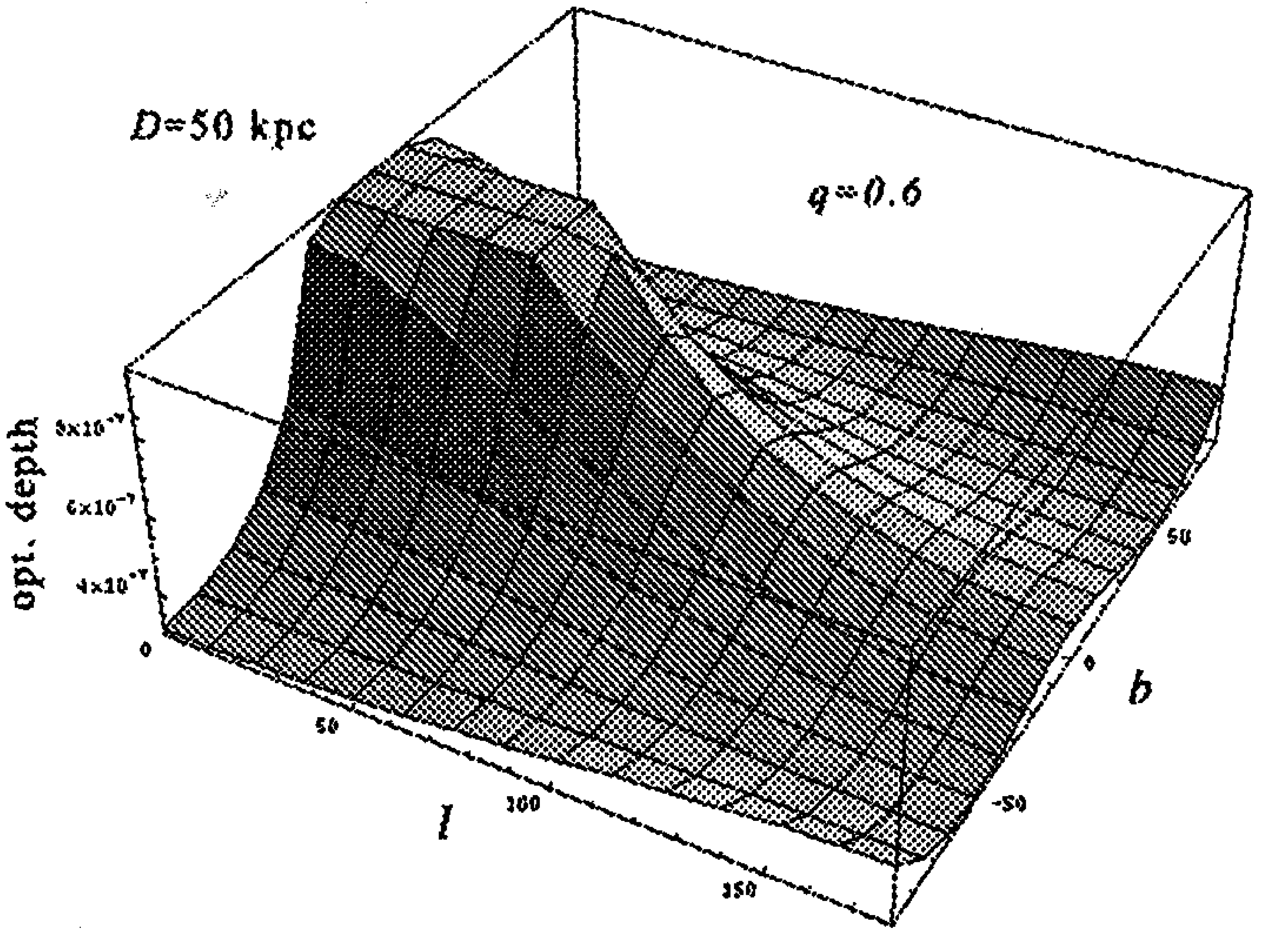

Fig. 2. Predicted ML optical depth towards sources located at $D = 50$ kpc in a model with moderate halo flattening $q = 0.6$

One of the major conclusions of SĆMZ is that nearly spherical haloes contain too much baryonic matter in the form of MACHOs. Although not in direct conflict with the BBNS constraints, it is uncomfortable, since other components of baryonic matter (intergalactic medium manifested through the Lyα forest), also pretend to be dominant in the total budget. This situation, and related value of Hubble constant, are shown in Fig. 3. Proposal of Milošević-Zdjelar, Samurović & Ćirković (1999), removes the inconsistency by taking into account moderate flattening of Milky Way's halo, see Fig. 4, and agrees with recent CMBR studies (Lineweaver et al. 1997), BBNS and light element abundances constraints (Burles et al. 1999), and IGM studies (Burles & Tytler 1998).

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[4] `http://www.lal.in2p3.fr/recherche/eros` (Experience pour la Recherche d'Objets Sombres)

[5] `http://cdfinfo.in2p3.fr/Experiences/AGAPE` (Andromeda Galaxy and Amplified Pixels Exp.)

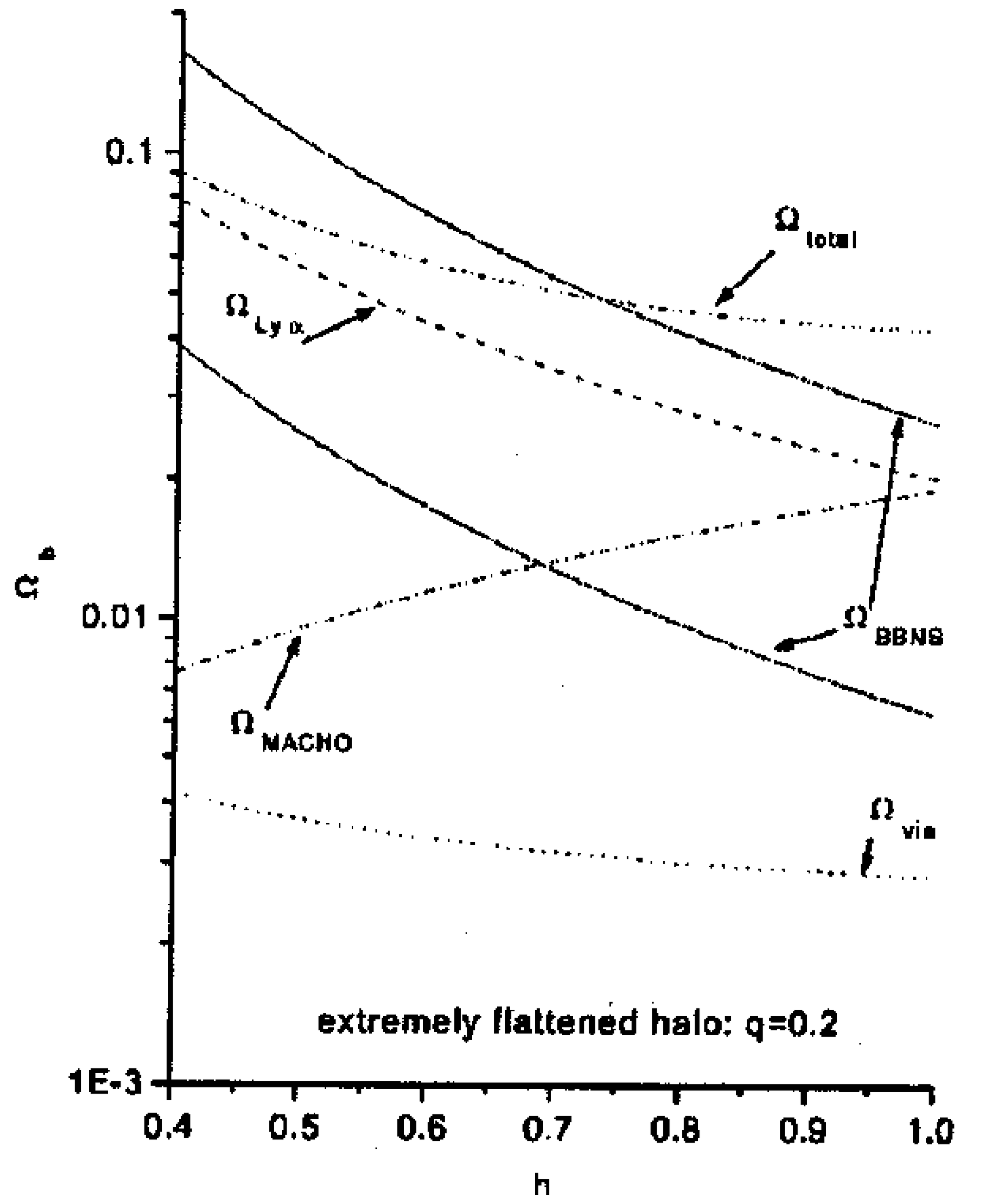

Fig. 3. Various components of the cosmological baryon density as functions of the Hubble parameter h (from SĆMZ) for $q = 0.2$.

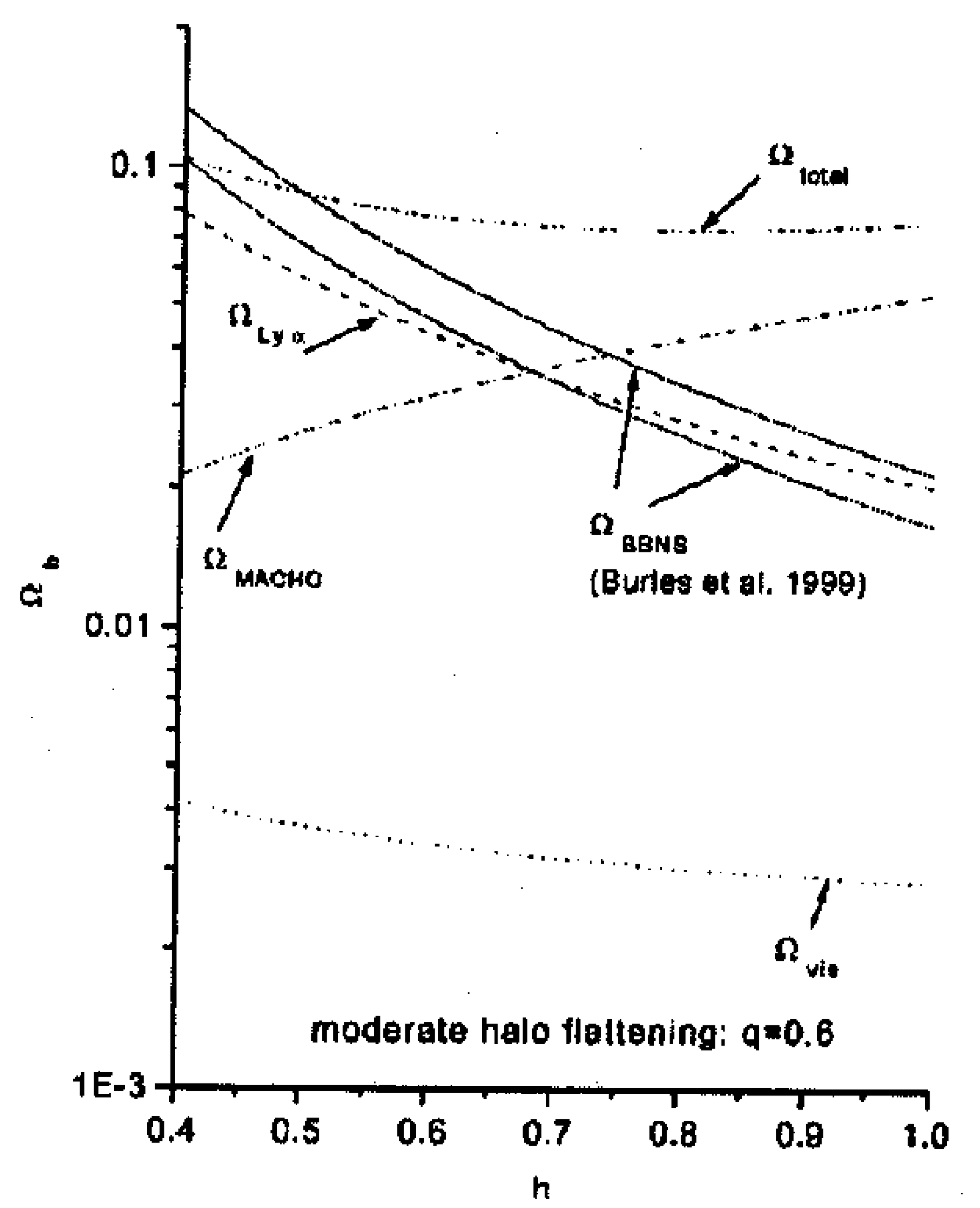

Fig. 4. Dependence of Ω_B on h for moderate halo flattening $q = 0.6$ (from Milošević-Zdjelar, Samurović & Ćirković 1999).

Further investigations are necessary, especially of MACHO formation epoch, probed by early damped Lyα and similar gas-rich systems. This, coupled with ML advances, should be able to solve the problem of baryonic component of DM and unify several branches of astrophysical research into a coherent picture of the evolution of baryonic matter in the universe (Ćirković, Samurović & Milošević-Zdjelar 1999).

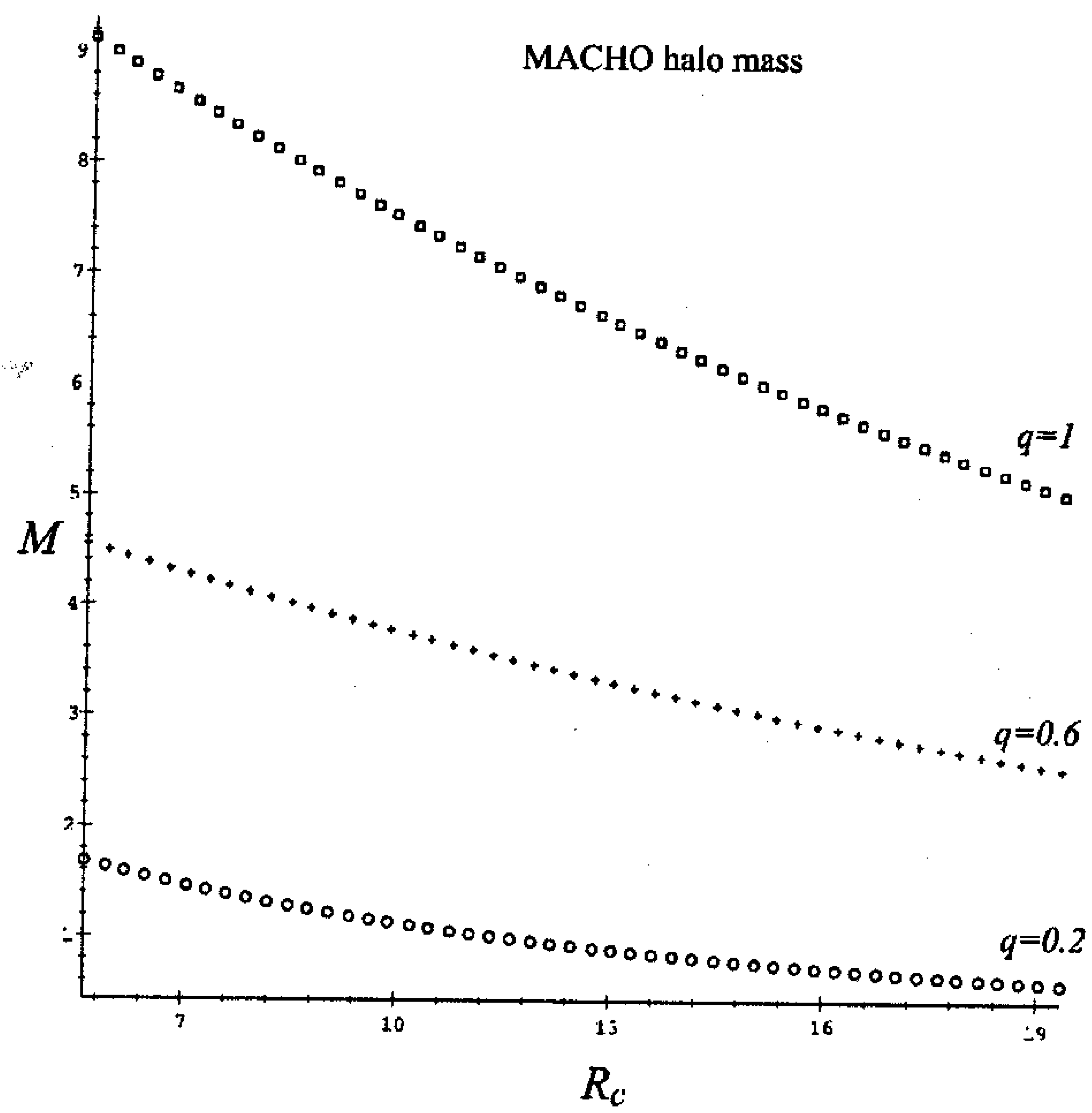

Fig. 5. Dependence of the MACHO halo mass (in units of 10^{11} $M_{\odot}$) for three choices of flattening parameter q as a function of halo core radius (SĆMZ). Square points represent spherical ($q = 1$), circles extremely flattened ($q = 0.2$), and crosses the intermediate case ($q = 0.6$). Moderate halo flattening agrees with the most recent estimate of the total mass of the halo within 50 kpc, by Wilkinson & Evans (1999) on $\sim 5.4^{+0.2}_{-3.6} \times 10^{11} M_{\odot}$.

3. MACHOS AND THE SHAPE OF THE MILKY WAY

ML studies enable us to determine, in principle, the shape of Milky Way's components:
Spiral arms. First results are obtained by EROS search (Ansari 1999 private comm.)
Disk. Besides other methods that confirmed that Galaxy has a weak bar inclined $10^o - 30^o$ to the Sun-Galactic Centre line (surface photometry, star counts, gas and stellar kinematics), Samurović et al. (1998) proposed that it could be detected by changes in ML optical depth along the bulge (ML events show excess compared to theoretical estimates).
Halo. The most important parameter is q – the degree of flattening. It was shown in SĆMZ that extreme values (like $q \sim 0.2$) for the dynamically dominant halo component, required by some models, like the Pfenniger, Combes & Martinet (1994)

molecular DM model, are incompatible with the ML data, see Fig. 5. Recent analysis of the local stellar velocity distribution based upon HIPPARCOS data agrees with that (Bienaymé 1999). Different arguments point to an oblate gravitating dark halo, which, in turn, causes flattening of stellar and gaseous (Lyα-absorbing) haloes.

Various software packages were used in order to obtain results. Most of the work was done using a free version of Unix operating system, Linux. Software ranges from free GNU codes (compilers, editors, utilities) to commercial large mathematical packages (Mathematica and Maple). Unfortunately, no application can perform all: complete calculation, production of plots and detailed analysis.

4. PLANS FOR THE FUTURE

There are several lines of research we would like to pursue in the near future.

(1) Construction of models incorporating both gaseous and MACHO haloes, strongly constrained by ML observational data. In order to build a total set of constraints in which the realistic model of the composition of the baryonic matter in the universe should be built, we should consider BBNS which entered the epoch of very high precision, Gunn-Peterson optical depths for both HI and HeII (e.g. Jakobsen 1998), vast statistics of the Lyα forest lines, observations of low-redshift absorption in well-defined galactic haloes (e.g. Chen *et al.* 1998) and improved X-ray data on the hot gas distribution in both clusters and small groups of galaxies. Models should also be able to account for known large-scale phenomena, particularly the Magellanic Stream, which shows presence of Galactic gaseous halo up to of ~ 50 kpc (Weiner & Williams 1996) . Within reach of current knowledge, the development of such models is clearly defined task of near future.

(2) Inclusion of MACHO formation in cooling flows would present a powerful theoretical basis for analysis of universality and evolution of the BDM (e.g. Nulsen & Fabian 1997). Detailed understanding of these processes is still lacking.

(3) The detailed probing of the Galactic potential remains the main effort of Belgrade-MACHO project. Apart from lines of sight towards M31 (for which we are insured from AGAPE and MEGA coll. to have data in less than two years) and several globular clusters, lines of sight towards distant pulsars may also be of interest in this respect, due to Shapiro Phase Shift (changes in their stable beat by any object crossing along the line-of-sight), e.g. Fargion & Conversano (1998). Monitoring pulsars could, therefore, present a tool for discovering dark objects, even planets as close as those within Solar System.

(4) Lensing of stars by spherical gas clouds (Henriksen & Widrow 1995, Draine 1998) could explain the extreme scattering effects (ESEs) (Fiedler *et al.* 1985) manifested as a class of variations at GHz frequences. Extragalactic point radio sources can be amplified and deamplified when the lens crosses the line of sight. Walker & Wardle (1998) suggested that this can be due to a halo population of $\sim 10^{14}$ molecular gas clouds that have mass $\approx 10^{-3} M_{\odot}$ and radius $R \approx 3$ AU (Shchekinov 1998).

Belgrade-MACHO project relies on the data of large observational ML network maintaining constant contact with EROS, AGAPE, MEGA and PLANET teams. In order to provide the information concerning the latest research we created the home page: `http://www.geocities.com/CapeCanaveral/7102/Belgrade-MACHO.html`.

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