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Microlensing and Halo Cold Dark Matter

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ABSTRACT

We discuss the implications of the more than 50 microlensing events seen by the EROS, MACHO, and OGLE collaborations for the composition of the halo of our galaxy. The event rates indicate that the halo mass fraction in MACHO's is less than 30%, consistent with expectations for a universe whose primary component is cold dark matter. We caution that the uncertainties are such that a much bigger MACHO fraction cannot yet be excluded.

In 1986 Paczynski suggested microlensing as a probe of dark (or very faint) stars in our galaxy [1] (referred to generically as MAssive Compact Halo Objects, or MACHOs). In the past year more than 50 microlensing events have been reported. (For microlensing the two images are too close to be resolved; instead, the combined light leads to an achromatic, time-symmetric brightening.) The EROS collaboration has seen two events in the direction of the Large Magellanic Cloud (LMC) [2]; the OGLE collaboration has seen 12 events in the direction of the galactic bulge [3]; and the MACHO collaboration has seen three events in the direction of the LMC and more than 40 in the direction of the galactic bulge [4].

The study of microlensing toward the galactic bulge mainly probes the structure of the inner galaxy, while microlensing toward the LMC mainly probes the dark halo [1, 5]. The probability that a given star is being microlensed by a foreground object is referred to as the optical depth for microlensing ($\equiv \tau$). Expectations for the bulge were $\tau_{\rm BULGE} \simeq 1 \times 10^{-6}$, largely due to lower-main-sequence stars in the disk [6]; OGLE reports an optical depth that is about a factor of three larger, $\tau_{\rm OGLE} = 3.3 \pm 1.2 \times 10^{-6}$ [3], and the rate observed by MACHO may be even higher [7]. Expectations for an all-MACHO halo were $\tau_{\rm LMC} \simeq 5 \times 10^{-7}$ [5] (because data poorly constrain the halo, uncertainties in this estimate are large, almost a factor two either way [8, 9, 10]). Based upon 9 million-star years of observations, the three events observed, and estimates of their efficiencies (between 20% and 40%) [11], the MACHO data indicate that $\tau_{\rm MACHO} \simeq 1 \times 10^{-7}$. The EROS data indicate a similar optical depth [2].

Evidence that spiral galaxies, including our own, are embedded in extended, massive (roughly spherical) halos come from galactic rotation curves, the study of satellite galaxies and binary galaxies, the kinematics of the globular clusters in our galaxy, the warping of galactic disks, and the flaring of neutral hydrogen gas associated with disks [12, 13, 14]. Galactic halos are repositories for nonbaryonic dark matter (mainly slowly moving particles, or cold dark matter, since fast moving particles such as light neutrinos move too fast to accumulate), as well as dark baryonic matter. Experimental efforts to detect nonbaryonic dark matter have focussed on our own halo. Determining the mass fraction of the halo in baryons is crucial for estimating the amount of nonbaryonic matter that may exist in our galaxy.

Our purpose here is to use the microlensing data to draw conclusions about the MACHO fraction of the halo—and from it the fraction of the halo that could be particle dark matter. Since the expected microlensing rate in the direction of the LMC depends upon galactic modelling [8, 9, 10] and the LMC microlensing statistics are small, we adopt the following strategy. We use the rotation curve, local projected mass density, distribution of luminous material in the disk and bulge, and bulge microlensing rate to constrain the halo model. From this we estimate $\tau_{\rm LMC}$ for galactic models that are consistent with all this data. Then, based upon the observed LMC rate, we make inferences about the MACHO fraction of the halo—and conclude that it must be small, less than about 30%.

Models of the Milky Way have three major components [15], a central bulge, a disk, and a spherical halo, with large uncertainties in the parameters that define all three. The basic picture of our bulge has evolved from a spherical model to recent indications that the bulge may be closer to a bar [16]. We follow Dwek et al. [17] who have utilized DIRBE surface brightness observations to construct a triaxial bulge model:

$$\rho_{\rm BAR} = \frac{M_0}{8\pi abc} e^{-s^2/2}, \tag{1}$$

$$s^4 = \left[\frac{x^2}{a^2} + \frac{y^2}{b^2}\right]^2 + \frac{z^4}{c^4}, \tag{2}$$

where the bulge mass $M_{\rm BAR} = 0.82 M_0$, the scale lengths $a = 1.49\,{\rm kpc}$, $b = 0.58\,{\rm kpc}$ and $c = 0.40\,{\rm kpc}$, and the long axis is oriented at an angle of about $10°$ with respect to the line of sight toward the galactic center. The bulge mass is not well determined, and we consider the range, $M_{\rm BAR} = 1 - 4 \times 10^{10} M_\odot$ [15, 18].

The general form of the disk is also not well known, although the luminous matter follows a double exponential distribution [19]. There is some evidence that the disk may have two components (thick and thin) [19]. For the disk density we use

$$\rho_{\rm DISK}(r, z) = \frac{\Sigma_0}{2h} \exp[-(r - r_0)/r_d] e^{-|z|/h}. \tag{3}$$

The scale length $r_d \sim 3.5\,{\rm kpc}$; estimates of the scale height range from $h = 0.3\,{\rm kpc}$ (thin disk) to $h = 1.5\,{\rm kpc}$ (thick disk). Rather than considering the combination of thin and thick disks, we consider the extremes of a thin disk and a thick disk, as well as a very thin ($h \simeq 0.1 - 0.2\,{\rm kpc}$) disk. We normalize our disk models to the surface density at our position, $\Sigma_0 = \int_{-\infty}^{\infty} \rho_{\rm DISK}(r_0, z) dz$; kinematic studies of stars constrain Σ_0 to $40 - 100 M_\odot\,{\rm pc}^{-2}$ [20]. We also explore a disk whose surface density scales as $1/r$ (Mestel disk; see e.g., Ref. [13]). Such a model has been considered in Ref. [21] because it produces a flat rotation curve in the plane of the galaxy without a halo; however, in order to account for a rotation velocity of $220\,{\rm km\,s^{-1}}$, Σ_0 must be $220 M_\odot\,{\rm pc}^{-2}$.

The third component of our galactic model is the halo. We assume independent isothermal distributions for the MACHOs and cold dark matter with core radii $a_i = 2\,{\rm kpc} - 16\,{\rm kpc}$,

$$\rho_{\rm HALO,i} = \frac{a_i^2 + r_0^2}{a_i^2 + r^2} \rho_{0,i}\ , \tag{4}$$

where i = MACHO, cold dark matter and $\rho_{0,i}$ is the local mass density of component i. More complex halo models are possible: e.g., flattened halos [9, 10]. We do not expect such refinements to significantly affect our basic conclusions; they only serve to increase slightly the theoretical uncertainties.

The average optical depth for microlensing a distant star by a foreground star is [5]

$$\tau = \frac{4\pi G}{c^2} \frac{\int_0^\infty ds \rho(s) \int_0^s dx \rho(x) x(s-x)/s}{\int_0^\infty ds \rho(s)}, \tag{5}$$

where ρ is the mass density in stars, s is the distance to the star being lensed, and x is the distance to the lens [22]. In estimating the optical depth toward the bulge, we consider lensing of bulge stars by both disk and bulge objects; for the LMC we only consider lensing of LMC stars by halo objects. We have assumed that the threshold for the detection of microlensing is a brightening of 1.34 (which roughly corresponds to the experimental thresholds). Further, while the microlensing rate more closely describes what is measured, it depends upon detailed knowledge of the velocity distribution of the lenses, and previous analyses [8, 9] have found that the optical depth correlates reasonably well with the lensing rate.

Kinematic constraints to the galactic model come from the circular rotation speed at our position ($\equiv v_c$) and the requirement that the rotation curve be approximately flat between about 4 kpc and 18 kpc. We adopt the IAU value of $220\,\mathrm{km\,s^{-1}}$ for v_c with an uncertainty of $\pm 20\,\mathrm{km\,s^{-1}}$, and we take our distance from the galactic center to be $r_0 = 8.5 \pm 0.5\,\mathrm{kpc}$. For the flatness constraint we follow our previous work [8] in requiring that the total variation in $v(r)$ be less than 14% over the aforementioned range.

We construct our suite of viable models as follows. Starting with a disk (thick, thin or $1/r$) with local surface density Σ_0 and a bar of mass M_{BAR} we compute τ_{BULGE}, the optical depth to Baade's window, galactic coordinates $(1^\circ, -4^\circ)$, and the contributions of the disk and bulge to the rotation curve at $r = r_0$. For a choice of halo parameters this then determines the local halo density, the full rotation curve, and the optical depth to the LMC. We deem a model viable if: (a) $\tau_{\mathrm{BULGE}} \geq 2.0 \times 10^{-6}$, ($b$) the rotation curve is sufficiently flat, and (c) τ_{LMC} is in the range $0.5 - 2.0 \times 10^{-7}$. The last condition primarily constrains the baryonic mass fraction and does not eliminate many models.

Our results are summarized in Figs. 1-4. We find that in general the disk alone does not provide sufficient lensing to explain the event rate seen toward the bulge by OGLE and MACHO. While τ_{BULGE} increases with Σ_0, Σ_0 reaches its upper bound of $100 M_\odot\,\mathrm{pc}^{-2}$ before τ_{BULGE} reaches 2×10^{-6}. Because the disk material is more concentrated, a thin disk provides more lensing for a given Σ_0 than a thick disk ($\tau \propto 1/h$); however, squeezing the disk to a scale height of 0.1 kpc − 0.2 kpc does not further increase τ for geometric reasons: the line of sight to Baade's window passes above most of the disk material. A disk with a $1/r$ density distribution provides an smaller contribution to the optical depth than an exponential disk. In particular, a $1/r$ disk with $\Sigma_0 = 100 M_\odot\,\mathrm{pc}^{-2}$ provides neither the necessary lensing rate to the bulge nor sufficient support to the rotation curve to preclude the need for a halo [23].

The bar, on the other hand, is a much more efficient source of lensing [24]. In all viable models a bar mass of greater than $2 \times 10^{10} M_\odot$ is required; if τ_{BULGE} is determined to be greater than 3×10^{-6}, as may well be the case, a bar mass of at least $3 \times 10^{10} M_\odot$ seems unavoidable. Should the optical depth be 4×10^{-6}, a bar mass of $4 \times 10^{10} M_\odot$ may be indicated. We note that even higher bar masses ($M_{\mathrm{BAR}} \geq 5 \times 10^{10} M_\odot$) make it difficult to achieve a flat rotation curve interior to the solar radius and thus are not viable.

Turning now to the optical depth to the LMC (Fig. 2), we find as expected that a thin disk makes a negligible contribution to τ_{LMC}, while a thick disk can provide a significant contribution (toward the LMC $\tau \propto h$). In fact, a model with a heavy bar and a thick disk can account for both the bulge and LMC rates without recourse to MACHOs in the halo. We also mention that the LMC microlensing rate is small enough that a significant part of it ($\sim 0.5 \times 10^{-7}$) could be due to microlensing by objects in the LMC itself [25].

Our most striking result is that all viable models have a significant halo component.

This can be traced to the flat-rotation curve constraint (even though it is very conservative) and is essentially independent of the bulge optical depth. That is, while τ_{BULGE} provides us with information about the disk and bulge components of our galaxy, the halo parameters are relatively insensitive to it. This can be seen in Fig. 3, where the local halo density in acceptable models is around $5 \times 10^{-25}\,\mathrm{g\,cm^{-3}}$ with more or less the same uncertainty as previous estimates (see e.g., Refs. [26]).

Even more than the uncertainty in the observed LMC microlensing rate, imprecise knowledge of the galactic model dominates the uncertainties in determining the MACHO fraction of the halo. However, in most viable models, an all-MACHO halo results in an optical depth to the LMC that is many times that observed (Fig. 2), and a significant nonbaryonic halo component seems indicated (Figs. 3 and 4).

To summarize our conclusions: (1) A single component of the galaxy cannot account for both the bulge and LMC events. For example, a spherical halo predicts an LMC rate that is slightly higher than the bulge rate; a thin disk cannot account for either the bulge rate or the LMC rate. A thick disk can explain the LMC events, but not the bulge events. (2) The most promising model for explaining the high bulge rate is an asymmetric bulge (bar) that lenses itself [24] with a lesser contribution from a thin disk. (3) Viable models of the galaxy have a significant halo component and the LMC rate expected for an all-MACHO halo is many times that observed. (4) While the present data cannot preclude an all-MACHO halo, it appears that the fraction of the halo in MACHOs is less than 30%.

If the bulk of the halo is not in the form of MACHOs, what is it? While it is not impossible that it could be baryonic, in a more diffuse form, e.g., clouds of neutral gas [27], cold dark matter is a more compelling possibility. In an $\Omega = 1$ cold dark matter model, the naive expectation for the baryonic mass fraction in our galactic halo is $f_B = \Omega_B$. Based upon primordial nucleosynthesis $0.01h^{-2} \leq \Omega_B \leq 0.02h^{-2}$ [28], which implies $f_B \simeq 0.04 - 0.2$. The expected baryon mass fraction for models with an admixture of massive neutrinos ($\Omega_\nu \sim 0.2 - 0.3$) is only slightly higher. For cold dark matter models with a cosmological constant, $\Omega_\Lambda \simeq 0.8$, $f_B \simeq 0.1 - 0.2$. If the baryonic halo has undergone moderate dissipation, the baryonic mass the baryon fraction in the inner part of the galaxy can be increased, though it is still expected to compose less than half of the local dark matter density [8]. From Fig. 4, it is clear that the baryonic mass fraction in our halo implied from microlensing is consistent with any of these scenarios which provides further motivation for the ongoing experimental efforts to directly detect neutralinos and axions in our own halo.

Acknowledgments

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[22] Our expression for τ when applied to the bulge implicitly assumes that all the mass density in the disk and bulge is available for lensing. However, the lenses are certainly not bright stars. Zhao et al. [24] find that this is a small effect.

[23] Gould [21] has advocated a thin ($h \sim 300\,\mathrm{pc}$), Mestel disk whose local surface density is about $220 M_\odot\,\mathrm{pc}^{-2}$, because: (i) it can marginally account for the bulge rate; (ii) it can marginally account for the LMC rate; and (iii) it produces a flat rotation curve ($v = 220\,\mathrm{km\,s^{-1}}$) in the galactic plane without a halo. However, such a model would not produce a flat rotation curve outside the galactic plane nor would it explain the warping of the disk and the flaring of neutral gas; and of course, it flies in the face of kinematic studies that indicate Σ_0 is at most $100 M_\odot\,\mathrm{pc}^{-2}$.

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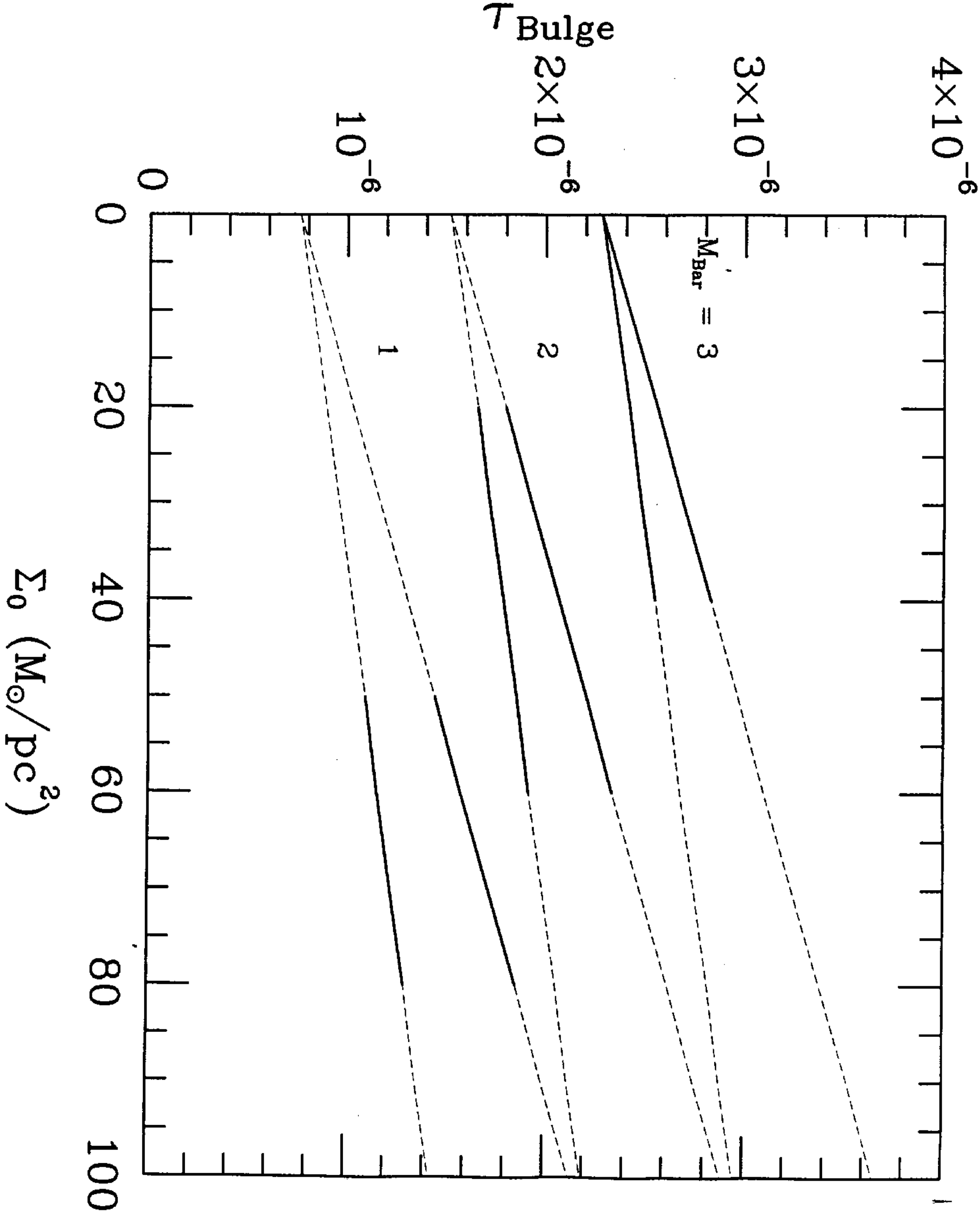
Figure Captions

Figure 1: Optical depth to the bulge for bar masses of 1, 2, and $3\times10^{10}M_{\odot}$ (bottom to top) and thick (lower) and thin (upper) disks as a function of the local surface mass density Σ_0. Solid parts of the lines indicate models that satisfy the kinematic constraints; $r_0 = 8.5\,\mathrm{kpc}$ and $v_c = 220\,\mathrm{km\,s^{-1}}$.

Figure 2: Optical depth to the LMC from an all-MACHO halo (upper lines) and thick and thin disks (lower lines) for bar masses of 1, 2, and $3\times10^{10}M_{\odot}$ (right to left) as a function of the local surface mass density Σ_0. Solid parts of the lines indicate models that satisfy the kinematic constraints; $r_0 = 8.5\,\mathrm{kpc}$ and $v_c = 220\,\mathrm{km\,s^{-1}}$.

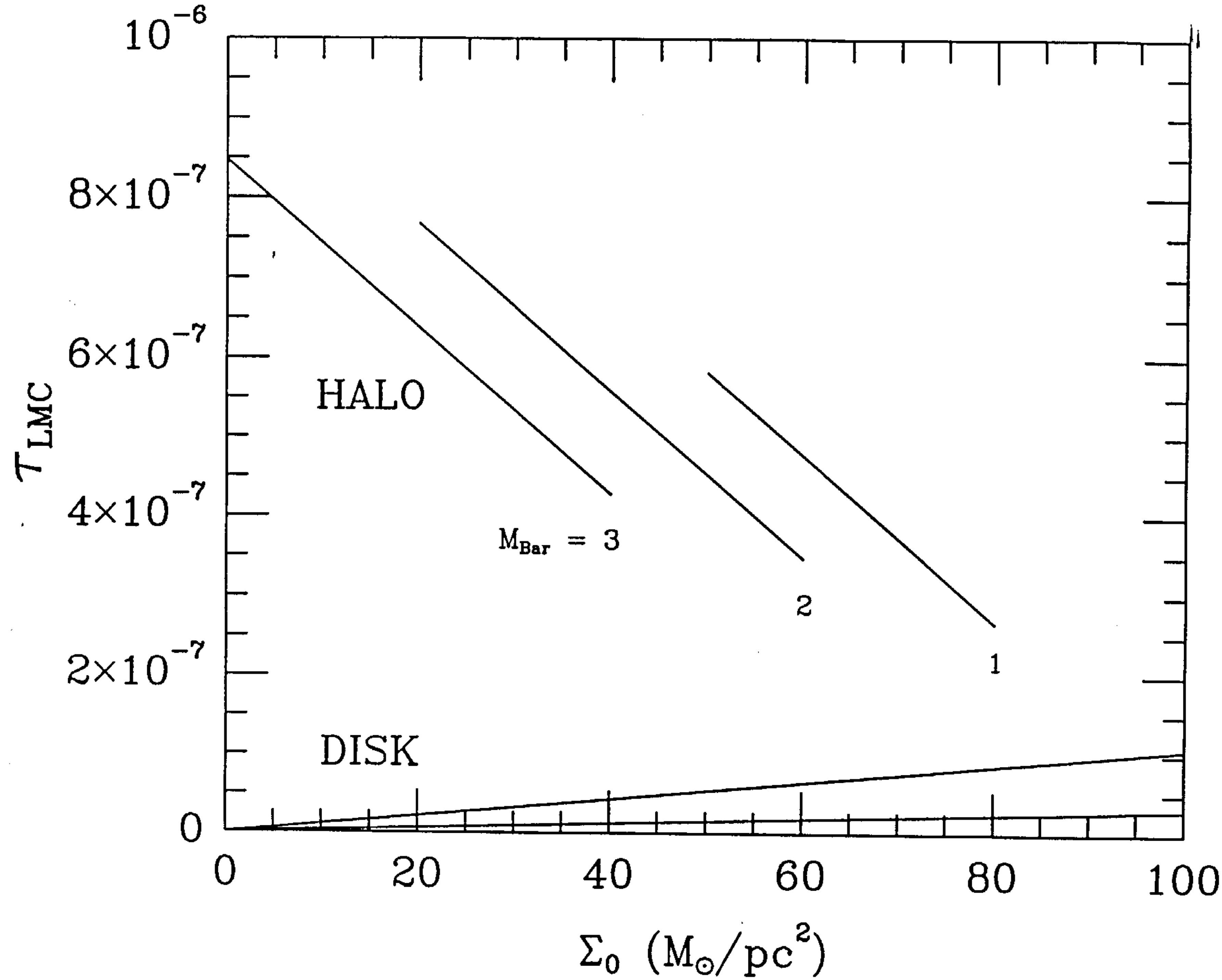
Figure 3: Distribution of local cold dark matter density in viable models for $\Sigma_0 = 40, 60, 80,$ and $100M_{\odot}\,\mathrm{pc}^{-2}$. Since the halo MACHO fraction in most viable models is small, the local cold dark matter density is approximately equal to the total local halo density.

Figure 4: Distribution of halo MACHO mass fraction in viable models for $\Sigma_0 = 40, 60, 80,$ and $100M_{\odot}\,\mathrm{pc}^{-2}$.

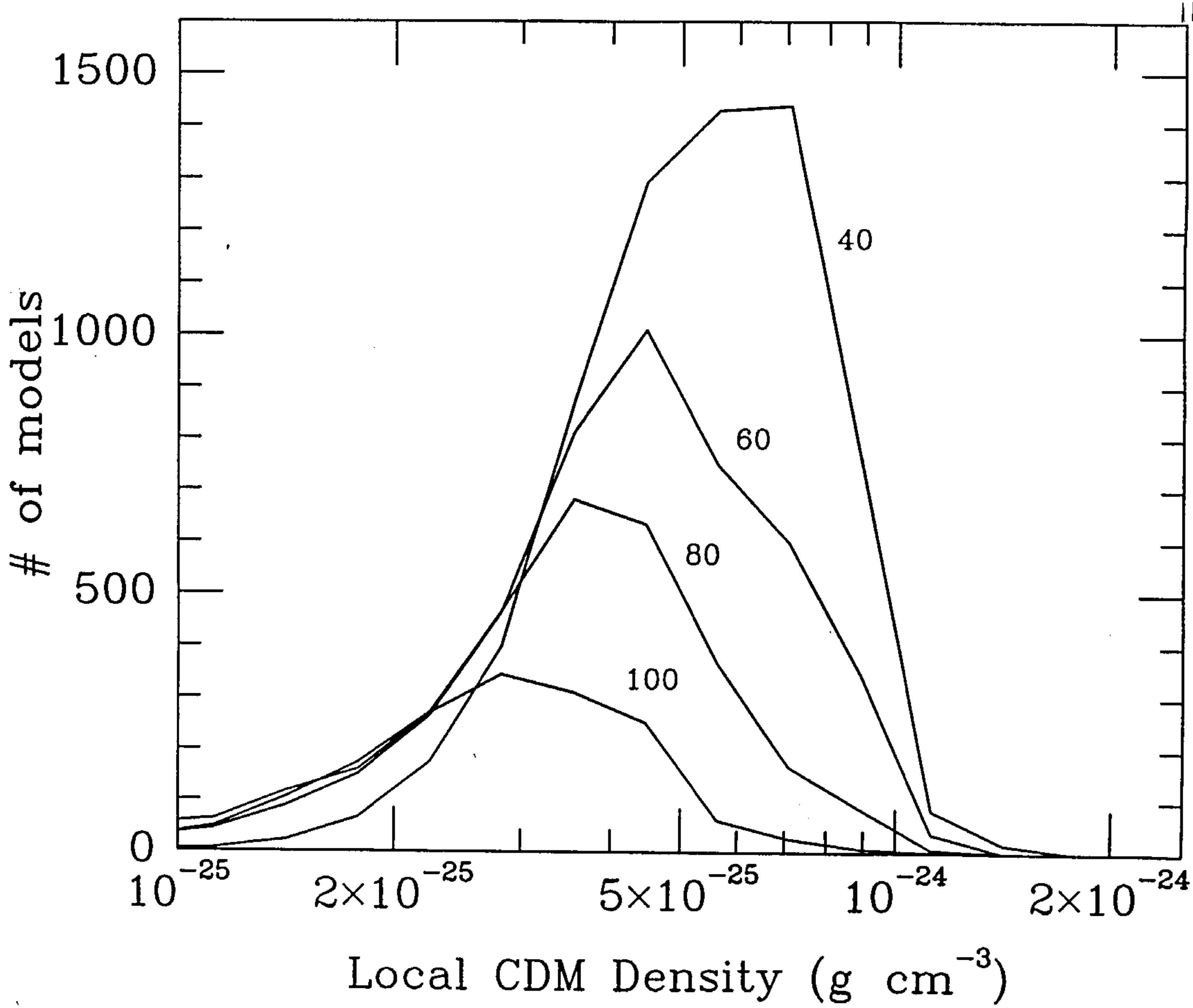


τ_{Bulge}
4×10^{-6}
3×10^{-6}
2×10^{-6}
10^{-6}
0
M_{Bar} = 3
2
1
0
20
40
60
80
100
Σ_0 ($M_\odot$/pc^2)

- FIG 1 -

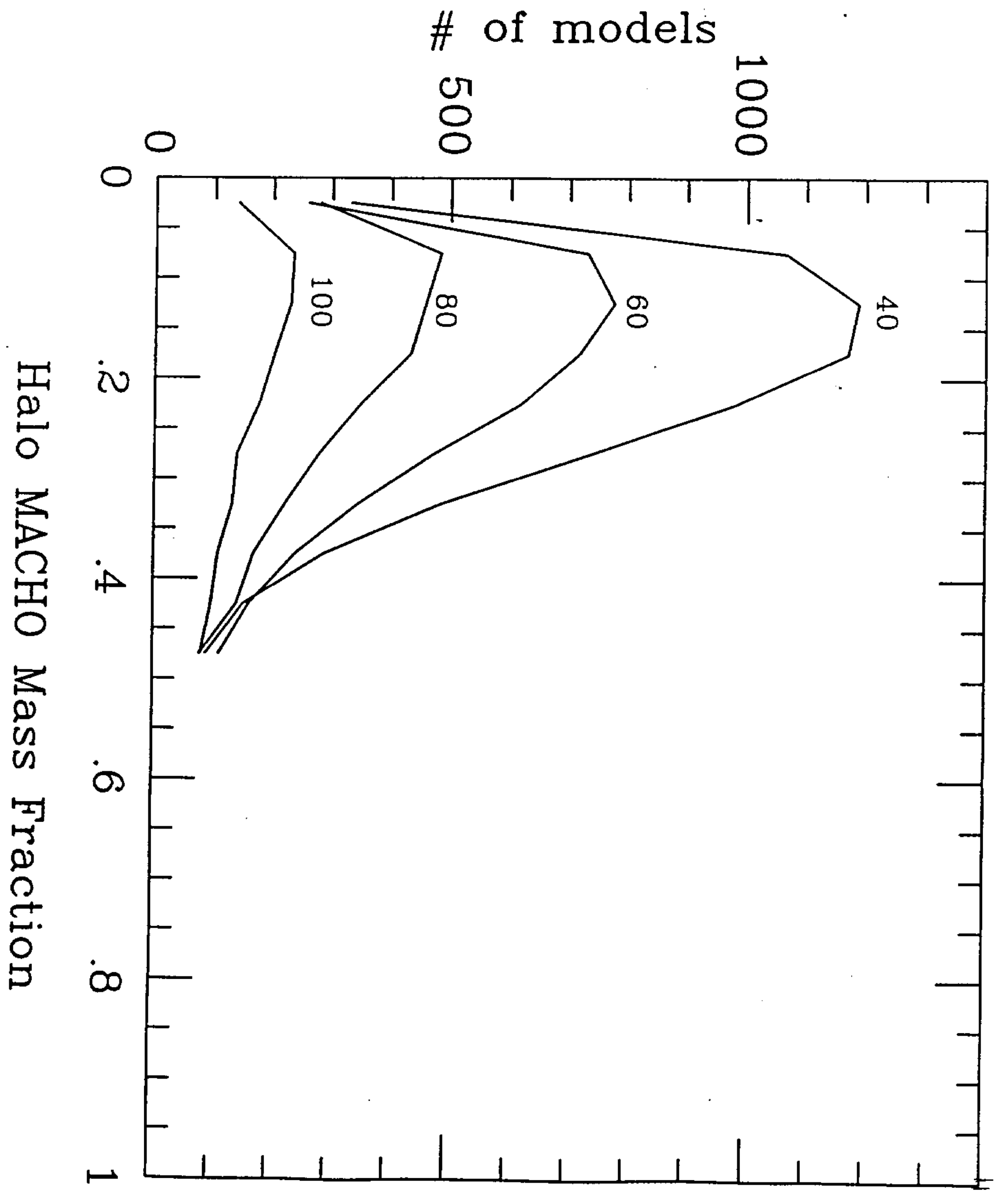

10^{-6}
8×10^{-7}
6×10^{-7}
4×10^{-7}
2×10^{-7}
0
τ_{LMC}
HALO
DISK
M_{Bar} = 3
2
1
0
20
40
60
80
100
Σ_0 ($M_\odot/pc^2$)

- FIG 2 -



# of models
1500
1000
500
0
40
60
80
100
10^{-25}
2×10^{-25}
5×10^{-25}
10^{-24}
2×10^{-24}
Local CDM Density (g cm^{-3})

-FIG 3-



# of models
1000
500
0
Halo MACHO Mass Fraction
0
.2
.4
.6
.8
1
40
60
80
100

-FIG 4-