# Microlensing and Halo Cold Dark Matter

Evalyn I. Gates,[1,2] Geza Gyuk,[2,3] and Michael S. Turner[1,2,3]
[1]Department of Astronomy and Astrophysics, Enrico Fermi Institute, The University of Chicago, Chicago, Illinois 60637-1433
[2]NASA/Fermilab Astrophysics Center, Fermi National Accelerator Laboratory, Batavia, Illinois 60510-0500
[3]Department of Physics, Enrico Fermi Institute, The University of Chicago, Chicago, Illinois 60637-1433
(Received 23 November 1994; revised manuscript received 6 December 1994)

We discuss the implications of the more than 50 microlensing events seen for the composition of the dark halo of our galaxy. Though firm conclusions are not yet possible due to small-number statistics and modeling uncertainties, in most viable models of the galaxy the fraction of massive compact objects in the halo (MACHOs) is between 5% and 30%, consistent with expectations for a universe whose primary component is cold dark matter. An all-MACHO halo cannot yet be excluded; we discuss future measurements that could exclude this possibility.

PACS numbers: 95.35.+d, 98.35.Gi

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). (For microlensing the two images are too close to be resolved; instead, the combined light leads to an achromatic, time-symmetric brightening.) In the past year more than 50 microlensing events have been reported: 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].

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 ($\equiv \tau$). The bulge optical depth was expected to be about $1 \times 10^{-6}$, largely due to lower-main-sequence stars in the disk [6]. OGLE has reported an optical depth (to Baade's window) that is about a factor of 3 larger, $\tau_{\rm bulge} = (3.3 \pm 1.2) \times 10^{-6}$ [3], and the rate observed by MACHO is consistent with this [7]. For an all-MACHO halo the LMC optical depth was expected to be about $5 \times 10^{-7}$ [5]. However, our knowledge of the dark halo is poor, and so uncertainties in this estimate are large, almost a factor of 2 either way [8–10]. Based upon $9.5 \times 10^6$ star years of observations and three events, the MACHO Collaboration report $\tau_{\rm LMC} = 0.8 \times 10^{-7}$ with large uncertainties [11]. (The EROS data are consistent with this [2].) Needless to say, because of the small number of LMC events and uncertainties about the extent of the dark halo, one cannot conclude that the halo MACHO fraction is $= 0.8 \times 10^{-7}/5 \times 10^{-7} = 16\%$.

While the parameters of our dark halo are not well determined, there is plenty of evidence that our galaxy and other spiral galaxies are embedded in extended, dark (roughly spherical) halos: 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 [12–14]. Galactic halos are repositories for both nonbaryonic dark matter (mainly slowly moving particles, or cold dark matter, since fast moving particles such as light neutrinos move too fast to be captured) and baryonic dark matter. Experimental efforts to detect nonbaryonic dark matter have focused on our own halo [15]. 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 in this Letter is to draw conclusions about the MACHO fraction of the halo from the data at hand. Mindful of the small number of events toward the LMC and modeling uncertainties, we proceed as follows. We use the rotation curve, local projected mass density, distribution of luminous material in the disk and bulge, and bulge microlensing rate to constrain models of our galaxy. For "acceptable models" we calculate the MACHO fraction of the halo based upon the reported optical depth to the LMC. In most, but not all, viable models the MACHO fraction of the halo is small, between 5% and 30%.

Models of the Milky Way have three major components [16], a central bulge, a disk, and a dark halo, with large uncertainties in the parameters that define all three. Over the past few years the picture of the bulge has evolved from spherical to barlike [17]. We follow Dwek *et al.* [18] who have utilized diffuse infrared background experiment surface brightness observations to construct a triaxial bulge model

$$\rho_{\rm bar} = \frac{M_0}{8\pi abc}\, e^{-s^2/2}, \qquad s^4 = \left[\frac{x^2}{a^2} + \frac{y^2}{b^2}\right]^2 + \frac{z^4}{c^4}, \tag{1}$$

where the bulge mass $M_{\rm bar} = 0.82 M_0$, the scale lengths $a = 1.49$ kpc, $b = 0.58$ kpc, and $c = 0.40$ 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

 0031-9007/95/74(19)/3724(4)$06.00 

mass is not well determined, and we consider $M_{\rm bar} = 1$, 2, 3, and $4 \times 10^{10} M_\odot$ [16,19].

The luminous matter in the disk follows a double exponential distribution [20]. There is some evidence that the disk has both a "thick" and a "thin" component [20]. We take the sum of a "fixed," thin luminous disk,

$$\rho_{\rm lum}(r,z) = \frac{\Sigma_{\rm lum}}{2h} \exp[-(r - r_0)/r_d] e^{-|z|/h}, \quad (2)$$

with scale length $r_d = 3.5$ kpc, scale height $h = 0.3$ kpc, and local projected mass density $\Sigma_{\rm lum} = 25 M_\odot$ pc$^{-2}$ [21], and a "variable" disk component. For the variable component we consider scale lengths $r_d = 3.5 \pm 1$ kpc, thicknesses $h = 0.15$, 0.3, and 1.5 kpc, and local projected mass densities $\Sigma_{\rm var} \le 75 M_\odot$ pc$^{-2}$. (We also consider a model where the density scales as $1/r$ [22].) Studies of stellar motions have been used to measure the *total* local projected mass density within a distance of 0.3–1.1 kpc of the galactic plane [23], obtaining values between $40 M_\odot$ and $85 M_\odot$ pc$^{-2}$. As a conservative bound we require that $\Sigma_{\rm tot}(1\ {\rm kpc}) = \int_{-1\ {\rm kpc}}^{1\ {\rm kpc}} \rho(r_0, z)\, dz = 25 - 100 M_\odot$ pc$^{-2}$, which explains our chosen range $\Sigma_{\rm var}(1\ {\rm kpc}) \le 75 M_\odot$ pc$^{-2}$.

The third component is the dark halo. We assume independent isothermal distributions for MACHOs and cold dark matter with core radii $a_i = 2, 4, 6, \ldots, 18$, 20 kpc,

$$\rho_{{\rm halo},i} = \frac{a_i^2 + r_0^2}{a_i^2 + r^2} \rho_{0,i}, \quad (3)$$

where $i$ denotes MACHOs and cold dark matter and $\rho_{0,i}$ is the local mass density of component $i$. For the results discussed here we have assumed spherical symmetry. While there is little evidence that halos are spherical and some that they are flattened [24], flattening does not significantly affect the optical depth for microlensing [9,10]. Indeed, we have examined flattened halo models and our results changed very little [25].

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

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

where $\rho$ is the mass density in stars, $s$ is the distance to the star being lensed, and $x$ is the distance to the lens [26]. In estimating the optical depth toward the bulge, we consider lensing of bulge stars by both disk and bulge objects; for the LMC we consider lensing of LMC stars by halo and disk objects.

We require acceptable models of the galaxy to satisfy "kinematic" constraints as well as microlensing constraints. 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 5 and 18 kpc. We adopt the International Astronomical Union value of 220 km s$^{-1}$ for $v_c$ with an uncertainty of $\pm 20$ km s$^{-1}$, and consider galactocentric distances $r_0 = 7.5$, 8.0, 8.5, 9.0, and 9.5 kpc. As a flatness constraint we follow previous work [8] and require that the total variation in $v(r)$ be less than 14% over the aforementioned range and the asymptotic rotation velocity to be greater than 150 km s$^{-1}$. We use the following microlensing constraints: (a) $\tau_{\rm bulge} \ge 2.0 \times 10^{-6}$ and (b) $0.2 \times 10^{-7} \le \tau_{\rm LMC} \le 2 \times 10^{-7}$ [27].

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. While $\tau_{\rm bulge}$ increases with $\Sigma_{\rm var}$, $\Sigma_{\rm var}$ reaches its upper bound of $75 M_\odot$ pc$^{-2}$, or the rotation-curve constraint is violated, before $\tau_{\rm bulge} = 2 \times 10^{-6}$. For fixed $\Sigma_{\rm var}$ the disk density along the line of sight is about the same, and the difference between a thick ($h = 1.5$ kpc) and thin ($h = 0.3$ kpc) disk is negligible. However, there is less mass in a thin disk and a larger $\Sigma_{\rm var}$ is permitted without violating the rotation-curve constraint. A very thin disk ($h = 0.15$ kpc) does not help further: The line of sight to Baade's window passes above most of the disk material. The results for disks with a $1/r$ density distribution are not significantly different from those of exponential disks.

As others have pointed out, the bar is much more efficient at lensing [29]. In almost all viable models the bar mass is at least $2 \times 10^{10} M_\odot$; if $\tau_{\rm bulge}$ is determined to be greater than $3 \times 10^{-6}$, a bar mass of greater than $2 \times 10^{10} M_\odot$ is needed.

Turning now to the optical depth to the LMC (Fig. 2), we find, as expected, that a thin disk makes a negligible contribution to $\tau_{\rm LMC}$, 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. Moreover, the LMC microlensing

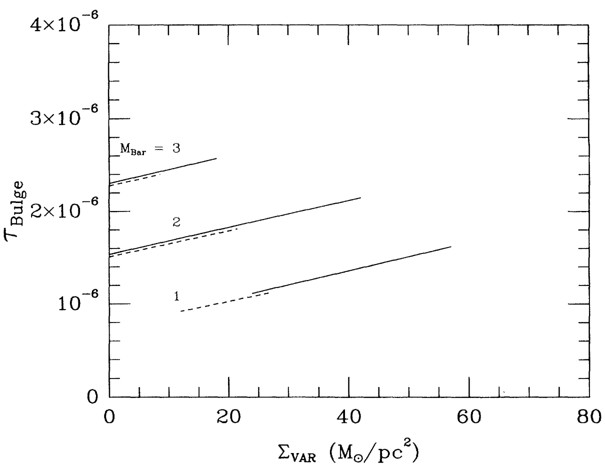


FIG. 1. Optical depth to the bulge for bar masses of 1, 2, and $3 \times 10^{10} M_\odot$ (bottom to top) and thick (broken) and thin (solid) disks as a function of the local projected mass density $\Sigma_{\rm var}$ for models that satisfy the kinematic constraints (here $r_0 = 8.5$ kpc and $v_c = 220$ km s$^{-1}$).

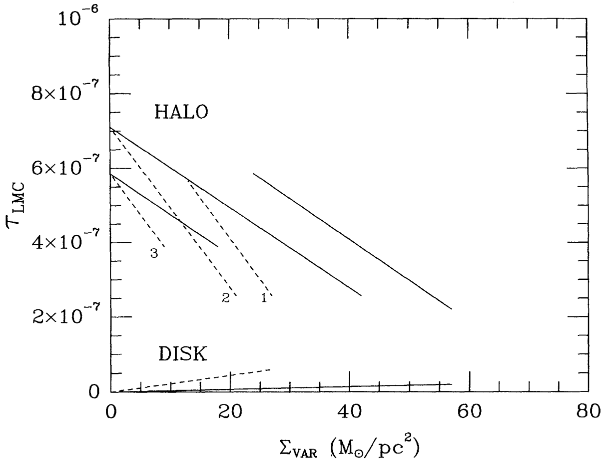


FIG. 2. Optical depth to the LMC from an all-MACHO halo (upper lines) and thick (broken) and thin disks (solid) for bar masses of 1, 2, and $3 \times 10^{10} M_\odot$ (right to left) as a function of $\Sigma_{var}$ for models that satisfy the kinematic constraints (here $r_0 = 8.5$ kpc and $v_c = 220$ km s$^{-1}$).

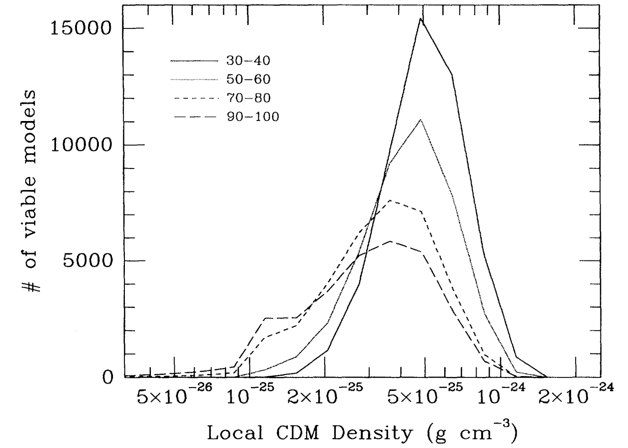


FIG. 3. Distribution of local cold dark matter density in viable models for $\Sigma_{tot} = 30-40$, $50-60$, $70-80$, and $90-100 M_\odot$ pc$^{-2}$. Note that the local cold dark matter density in viable models is consistent with previous estimates [28], and would be slightly larger in flattened halo models [25].

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 [30], which would even further reduce our estimates for the halo MACHO fraction.

To summarize: (i) A single component of the galaxy by itself cannot account for both the bulge and LMC events: A halo predicts a bulge rate that is comparable to the LMC rate; a thin disk cannot account for either the bulge rate or the LMC rate; and a thick disk can explain the LMC events, but not the bulge events. (ii) The most promising model for explaining the high bulge rate is a bar of mass at least $2 \times 10^{10} M_\odot$ [29] with a lesser contribution from a thin disk. (iii) Most viable models of the galaxy have a significant halo component. (iv) While the present data cannot preclude an all-MACHO halo, the fraction of the halo in MACHOs in most viable models is between 5% and 30%. This is consistent with searches for faint halo stars that indicate that their contribution to the halo mass is small (provided that the mass function of halo stars is "smooth"; see, e.g., Ref. [31]).

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 [32], cold dark matter is a more compelling possibility. For cold dark matter (CDM) models the naive expectation for the baryonic mass fraction in the halo is $f_B = \Omega_B/(\Omega_B + \Omega_{CDM})$. (Primordial nucleosynthesis implies $\Omega_B \simeq 0.009h^{-2} - 0.022h^{-2}$ [33]; $H_0 = 100h$ km s$^{-1}$ Mpc$^{-1}$.) For the cold dark matter models under consideration (standard CDM, CDM + a small admixture of massive neutrinos, and CDM with a cosmological constant) this implies $f_B \sim 0.04-0.2$. If the baryonic halo has undergone moderate dissipation, the baryonic mass 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 and provides further motivation for the ongoing experimental efforts to directly detect halo neutralinos and axions.

Finally, what are the prospects for sharpening our conclusions? The viable models with high MACHO fraction (greater than 75%) and little or no necessity for halo cold dark matter have a number of common features: $v_c \lesssim 220$ km s$^{-1}$; $\Sigma_{var} \gtrsim 40 M_\odot$ pc$^{-2}$; $r_d \gtrsim 4$ kpc; $\tau_{bulge} \lesssim 2.5 \times 10^{-6}$; and $\tau_{LMC} \gtrsim 1.5 \times 10^{-7}$ [25]. As the number of microlensing events increase, should, with high confidence, $\tau_{bulge}$ be found to be greater than $2.5 \times 10^{-6}$ and/or $\tau_{LMC}$ be found to be less than $1.5 \times 10^{-7}$, an

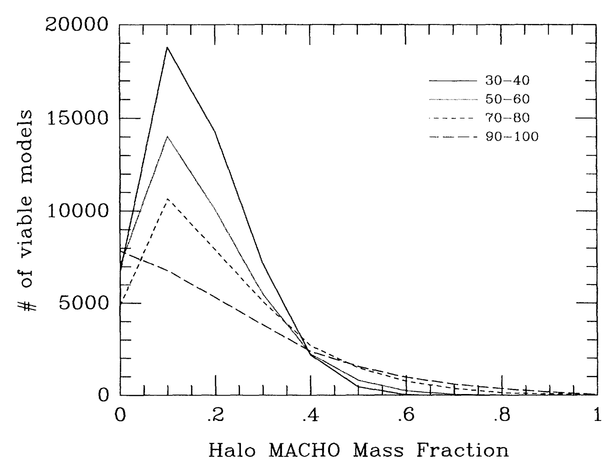


FIG. 4. Distribution of halo MACHO mass fraction in viable models for $\Sigma_{tot} = 30-40$, $50-60$, $70-80$, and $90-100 M_\odot$ pc$^{-2}$.

all-MACHO halo could be excluded. Likewise, improved measurements of the rotation curve of our galaxy or the total projected mass density could be used to exclude an all-MACHO halo. Thus, a variety of data can help settle the issue of whether there is a need or even room for cold dark matter in the halo of our galaxy [25].

We thank John Bahcall and Scott Tremaine for helpful conversations. This work was supported in part by the DOE (at Chicago and Fermilab) and NASA (at Fermilab through Grant No. NAG 5-2788). G. G. was also supported in part by an NSF predoctoral fellowship.

[1] B. Paczynski, Astrophys. J. **304**, 1 (1986).
[2] E. Aubourg *et al.,* Nature (London) **365**, 623 (1993).
[3] A. Udalski *et al.,* Astrophys. J. **L69**, 426 (1994); (to be published); Acta Astron. **43**, 289 (1993); **44**, 165 (1994); **44**, 227 (1994).
[4] C. Alcock *et al.,* Nature (London) **365**, 621 (1993).
[5] K. Griest, Astrophys. J. **366**, 412 (1991).
[6] K. Griest *et al.,* Astrophys. J. **372**, L79 (1991); M. Kiraga and B. Paczynski, *ibid.* **430**, L101 (1994).
[7] C. Alcock *et al.,* Report No. astro-ph/9407009.
[8] E. Gates and M. S. Turner, Phys. Rev. Lett. **72**, 2520 (1994).
[9] C. Alcock *et al.,* Report No. astro-ph/9411019.
[10] J. Frieman and R. Soccimarro, Astrophys. J. **L23**, 431 (1994).
[11] C. Alcock *et al.,* Phys. Rev. Lett. **74**, 2867 (1995).
[12] D. Zaritsky and S. D. M. White, Astrophys. J. (to be published).
[13] J. Binney and S. Tremaine, *Galactic Dynamics* (Princeton University Press, Princeton, 1987).
[14] C. S. Frenk and S. D. M. White, Mon. Not. R. Astron. Soc. **193**, 295 (1980).
[15] See, e.g., J. R. Primack, D. Seckel, and B. Sadoulet, Annu. Rev. Nucl. Part. Sci. **38**, 751 (1988); P. F. Smith and D. Lewin, Phys. Rep. **187**, 203 (1990).
[16] J. N. Bahcall, M. Schmidt, and R. M. Soneira, Astrophys. J. **265**, 730 (1983); J. A. R. Caldwell and J. P. Ostriker, *ibid.* **251**, 61 (1981).
[17] L. Blitz, in *Back to the Galaxy,* edited by S. S. Holt and F. Verter, AIP Conf. Proc. No. 278 (AIP, New York, 1993), p. 98; J. Binney, *ibid.* p. 87.
[18] E. Dwek *et al.,* NASA/GSFC Report, 1994 (unpublished).
[19] S. M. Kent, Astrophys. J. **387**, 181 (1992).
[20] G. Gilmore, R. F. G. Wyse, and K. Kuijken, Annu. Rev. Astron. Astrophys. **27**, 555 (1989).
[21] See, e.g., J. N. Bahcall, Astrophys. J. **276**, 169 (1984); K. Kuijken and G. Gilmore, *ibid.* **376**, L9 (1991). Taking a smaller value for $\Sigma_{\rm lum}$ would allow for larger $\Sigma_{\rm var}$ and hence larger $\tau_{\rm bulge}$; however, taking $\Sigma_{\rm lum} = 0$ only increases $\tau_{\rm bulge}$ by $0.3 \times 10^{-6}$.
[22] Such a model (referred to as a Mestel disk [13]) produces a flat rotation curve in the plane of the galaxy; however, in order to account for a rotation velocity of 220 km s$^{-1}$, a local surface mass density of $220 M_\odot$ pc$^{-2}$ is required. P. Sackett has recently revisited these models, because a thin Mestel disk ($h \sim 0.3$ kpc) whose local surface density is about $220 M_\odot$ pc$^{-2}$ can (i) marginally account for the bulge rate, (ii) marginally account for the LMC rate, and (iii) produce a flat rotation curve ($v = 220$ 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; moreover, it is in severe conflict with kinematic studies that indicate $\Sigma_{\rm tot}(1\ {\rm kpc})$ is at most $100 M_\odot$ pc$^{-2}$ [23].
[23] J. N. Bahcall, C. Flynn, and A. Gould, Astrophys. J. **389**, 234 (1992); K. Kuijken and G. Gilmore, *ibid.* **367**, L9 (1991), and Ref. [16].
[24] See, e.g., H. Rix, Report No. astro-ph/9501068.
[25] E. Gates, G. Gyuk, and M. S. Turner (to be published).
[26] Our expression for $\tau$ when applied to the bulge implicitly assumes that all the mass density in the disk and bulge is available for lensing. However, the bulge lenses are certainly not bright stars. Zhao, Spergel, and Rich [29] find that correcting for this is a small effect. To account for the fact that the lenses are unlikely to be bright stars we simply do not include the contribution of the fixed luminous disk to $\tau_{\rm bulge}$.
[27] The range we adopt for $\tau_{\rm LMC}$ is the 95% confidence range derived from the likelihood function based upon three events assuming Poisson statistics. However, the issue of uncertainties is far more complicated and the true 95% confidence range is probably larger; see A. Gould and C. Han, Report No. astro-ph/9410052. For example, the measured optical depth $\tau_{\rm MEAS} = (\pi/4E)\Sigma_i \hat{t}_i/\varepsilon_i$, where the sum $i$ runs over events, $\hat{t}_i$ is the duration of event $i$, and $\varepsilon_i$ is the "efficiency" of detecting an event of duration $\hat{t}_i$. The MACHO efficiency drops significantly for $\hat{t}_i \ll$ 10 days and $\tau_{\rm LMC}$ could be larger than reported due to short duration events. However, because of the null results of the EROS CCD search for short-duration events and the MACHO spike analysis it seems unlikely that this is the case.
[28] References [8,16]; M. S. Turner, Phys. Rev. D **33**, 886 (1986); R. Flores, Phys. Lett. B **215**, 73 (1988).
[29] B. Paczynski *et al.,* Princeton Observatory Report No. POP-573 (1994); H. Zhao, D. N. Spergel, and R. M. Rich, Report No. astro-ph/9409022.
[30] K. Sahu, Nature (London) **370**, 275 (1994).
[31] J. Bahcall *et al.,* Astrophys. J. **435**, L51 (1994). In fact, A. de Rujula *et al.* (Report No. astro-ph/9408099) have raised the question of where the brown dwarf stars are.
[32] See, e.g., F. De Paolis *et al.,* Reports No. astro-ph/9411016 and No. astro-ph/9411018.
[33] C. Copi, D. N. Schramm, and M. S. Turner, Science **267**, 192 (1995).