Improved constraints on supersymmetric dark matter from muon g-2

E. A. Baltz
ISCAP, Columbia Astrophysics Laboratory, 550 W 120th St., Mail Code 5247, New York, NY 10027

P. Gondolo
Department of Physics, Case Western Reserve University, 10900 Euclid Ave., Cleveland, OH 44106-7077

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The new measurement of the anomalous magnetic moment of the muon by the Brookhaven AGS experiment 821 again shows a discrepancy with the Standard Model value. We investigate the consequences of these new data for neutralino dark matter, updating and extending our previous work [E. A. Baltz and P. Gondolo, Phys. Rev. Lett. 86, 5004 (2001)]. The measurement excludes the Standard Model value at 2.6σ confidence. Taking the discrepancy as a sign of supersymmetry, we find that the lightest superpartner must be relatively light and it must have a relatively high elastic scattering cross section with nucleons, which brings it almost within reach of proposed direct dark matter searches. The SUSY signal from neutrino telescopes correlates fairly well with the elastic scattering cross section. The rate of cosmic ray antideuterons tends to be large in the allowed models, but the constraint has little effect on the rate of gamma ray lines. We stress that being more conservative may eliminate the discrepancy, but it does not eliminate the possibility of high astrophysical detection rates.

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I. INTRODUCTION

In early 2001, the Brookhaven AGS experiment 821 measured the anomalous magnetic moment of the muon \( a_\mu = (g - 2)/2 \) with three times higher accuracy than it was previously known \[1\]. Their result disagreed with the Standard Model prediction at greater than 2.6σ. However, a sign error in the calculation of the hadronic light-by-light contribution to \( a_\mu \) was discovered, reducing the discrepancy to 1.6σ \[2\]. Recently, the same collaboration has released a result with much improved statistics \[3\], and there is again a discrepancy at the 2.6σ level. Supersymmetric particles can give significant corrections to \( a_\mu \) \[4, 5, 6\], thus the Brookhaven measurement is an important constraint on supersymmetric models. There has been a substantial literature on this topic since the announcement of the discrepancy \[4, 5\], discussing various consequences of the older measurement. In this paper, we update the results of \[4\] concerning the implications of the Brookhaven data for supersymmetric cold dark matter, assuming that supersymmetry is the only relevant physics outside of the Standard Model.

There are two significant assumptions in our discussion. The first is that the Standard Model prediction for the muon anomalous magnetic moment is somewhat disputed, primarily in the hadronic contribution. This was clearly demonstrated in the sign error discovered in the last year. The hadronic error is a very significant part of the error budget when comparing the Brookhaven results to the Standard Model. In fact it has been claimed that the Standard Model errors have been significantly underestimated \[5\], but this claim has been refuted \[6\]. Furthermore, there are new evaluations of the hadronic vacuum polarization from firstly \( e^+e^- \rightarrow \text{hadrons} \) indicating a larger discrepancy (3.6σ) and secondly hadronic tau lepton decays indicating a smaller discrepancy (1.3σ) \[5\]. The second caveat is that supersymmetry is only one of many possible scenarios providing corrections to \( a_\mu \) at the weak scale. Theoretical prejudice tends to favor supersymmetry, but other possibilities exist, summarized in Ref. \[3\].

II. SUPERSYMMETRIC MODEL

In the Minimal Supersymmetric Standard Model (MSSM) the lightest of the superpartners (LSP) is often the lightest neutralino. These four states are superpositions of the superpartners of the neutral gauge and Higgs bosons,

\[
\tilde{\chi}^0_1 = N_{11} \tilde{B} + N_{12} \tilde{W}^3 + N_{13} \tilde{H}^0_1 + N_{14} \tilde{H}^0_2. \tag{1}
\]

With R-parity conserved, this lightest superpartner is stable. For significant regions of the MSSM parameter space, the relic density of the stable neutralino is of the order \( \Omega_\chi h^2 \sim 0.1 \), thus constituting an important (and perhaps exclusive) part of the cold dark matter (for a review see Ref. \[12\]). Note that \( \Omega_\chi \) is the neutralino density in units of the critical density and \( h \) is the present Hubble constant in units of 100 km s\(^{-1}\) Mpc\(^{-1}\). Large scale structure observations favor \( h = 0.7 \pm 0.1 \) and a matter density \( \Omega_M = 0.3 \pm 0.1 \), of which baryons contribute a small amount \( \Omega_b h^2 = 0.02 \pm 0.001 \) \[12\]. CMB anisotropy measurements are consistent with this (summarized in e.g. \[13\]), favoring \( \Omega_M h^2 = 0.15 \pm 0.05 \). We take the
The CP corrections to special scans emphasizing large positive supersymmetric
16, 18, 19, 20]. Furthermore, for this work we have made
are described in more detail in Refs. [15, 16, 17].)
(These models
laxation of this constraint would not significantly alter
constraint on gaugino mass unification, though the re-
massive. For simplicity, we do apply the supergravity
namely a SUSY spectrum that can be significantly more
and trilinear couplings. In contrast to supergravity, this
is more general than the supergravity framework, in that
we do not impose GUT unification of the scalar masses and trilinear couplings. In contrast to supergravity, this allows a purely high higgsino LSP and its consequences, namely a SUSY spectrum that can be significantly more massive. For simplicity, we do apply the supergravity constraint on gaugino mass unification, though the relaxation of this constraint would not significantly alter our results. As is typical, we assume R-parity conservation, stabilizing the lightest superpartner. (These models are described in more detail in Refs. [15, 16, 17].)
To investigate the MSSM parameter space, we have used the database of MSSM models built in Refs. [15, 16, 19, 20]. Furthermore, for this work we have made special scans emphasizing large positive supersymmetric corrections to \( a_\mu \), \( \Delta a_\mu(SUSY) \). The overall ranges of the seven MSSM parameters are given in Table I. The database includes one-loop corrections to the neutralino and chargino masses as given in Ref. [22], and leading log two-loop radiative corrections for the Higgs boson masses as given in Ref. [22]. Supersymmetric contributions to the precision quantities \( a_\mu \) and the \( b \to s\gamma \) branching ratio are also included. The database contains the neutralino–nucleon cross sections and expected detection rates for a variety of neutralino dark matter searches.
Crucial for studies of dark matter, the database includes the cosmological relic density of neutralinos \( \Omega_\chi h^2 \), based on calculations in Refs. [14, 23] considering resonant annihilations, threshold effects, finite widths of unstable particles, all two–body tree–level annihilation channels of neutralinos, and coannihilation processes between all neutralinos and charginos. We are in the process of including a complete treatment of sfermion coannihilations [24].
Recent accelerator constraints are applied to each model in the database. Most important are the LEP bounds [25] on the lightest chargino mass (chargino and neutralino masses are tightly linked)
\[
m_{\chi_i^+} > \begin{cases} 
88.4 \text{ GeV} & , \quad |m_{\chi^0_1} - m_{\chi^+_1}| > 3 \text{ GeV} \\
67.7 \text{ GeV} & , \quad \text{otherwise},
\end{cases}
\]
and on the lightest Higgs boson mass \( m_h \) (which ranges from 91.5–112 GeV depending on \( \tan \beta \)) and the \( b \to s\gamma \) branching ratio [26] (DarkSUSY currently only implements the leading-order calculation [27]).

### III. MUON ANOMALOUS MAGNETIC MOMENT

Supersymmetric corrections to \( a_\mu \) are surprisingly large, enhanced relative to typical weak–scale contributions by the parameter \( \tan \beta \) [4, 5, 6]. This fact makes these precision measurements enticing approaches for searching for supersymmetry. Typically, the supersymmetric corrections are given by

\[
\Delta a_\mu(SUSY) \sim 14 \times 10^{-10} \left( \frac{M_{SUSY}}{100 \text{ GeV}} \right)^{-2} \tan \beta,
\]
where \( M_{SUSY} \) is the typical mass of superpartners.

The new results of Brookhaven AGS experiment E821 [8] for the anomalous magnetic moment of the muon, \( a_\mu = (g - 2)/2 \), compared with the predicted Standard Model value are

\[
a_\mu(\text{exp}) = 11 659 204(8) \times 10^{-10}, \quad (4) \\
a_\mu(\text{SM}) = 11 659 175(7) \times 10^{-10}, \quad (5) \\
\Delta a_\mu = 29(11) \times 10^{-10}. \quad (6)
\]

This indicates a disagreement with the Standard Model at a 2.6\( \sigma \) confidence level. However, as mentioned in the introduction, there exist newer and conflicting evaluations of the Standard Model contribution which increase or decrease the discrepancy significantly. We will focus on the slightly older evaluation, but we will qualitatively discuss the effects of applying either of the new evaluations. To investigate the implications for the supersymmetric parameter space, we will assume that supersymmetry is the only source of corrections to \( a_\mu \) outside of the Standard Model. Considering a 95\% \( (2\sigma) \) confidence region for the supersymmetric contribution, we accept the following range of \( \Delta a_\mu(SUSY) \)

\[
7 \times 10^{-10} \leq \Delta a_\mu(SUSY) \leq 51 \times 10^{-10}. \quad (7)
\]
We have used the full calculation in Ref. [3] to compute \( \Delta \alpha_\mu \) (SUSY) for the models in the database.

The astrophysical phenomenology of neutralinos depends strongly on the ratio of gaugino and higgsino fractions, defined as

\[
\frac{Z_g}{1 - Z_g} = \frac{|N_{11}|^2 + |N_{12}|^2}{|N_{13}|^2 + |N_{14}|^2}.
\] (8)

We plot this ratio against the neutralino mass for each model in the database in Fig. 1. For clarity, the models have been binned along both axes. In the left panel, we only require that \( \Omega \chi h^2 < 0.25 \), and on the right we apply the more stringent constraint that the neutralino could make up all of the dark matter, \( \Omega \chi h^2 = 0.15 \pm 0.1 \). Models allowed before the new \( \Delta \alpha_\mu \) (SUSY) constraint are plotted as crosses, and models respecting the new \( \Delta \alpha_\mu \) (SUSY) constraint are plotted as crossed circles.

As has been discussed at length previously [7, 8], a \( \Delta \alpha_\mu \) (SUSY) bound that excludes zero from the positive side gives an upper limit on the mass of the neutralino, in this case 650 GeV. This is a large improvement over the cosmological bound based on the neutralino relic density not being too large, an upper limit of 7 TeV [10]. However, if the Standard Model value is included in the allowed region by e.g. considering a 3\( \sigma \) confidence interval or a revised Standard Model calculation, there is no bound on neutralino mass. If the more favorable evaluation is considered, the mass bound becomes 450 GeV.

If the neutralino has a large enough relic density to make up all of the cold dark matter, another effect appears, namely that the neutralino can not be very purely higgsino-like in composition, requiring at least a 5% mixture (in quadrature) of gaugino states. Even without requiring neutralino dark matter, higgsino-like neutralinos are disfavored, with a maximum purity of 99.9% \((Z_g = 0.001)\).

Orthogonal to the neutralino mass and composition but equally important to the value of \( \Delta \alpha_\mu \) (SUSY) are the parameters \( \tan \beta \) (the ratio of vacuum expectation values) and \( m_0 \) (the scalar mass parameter). In Fig. 2 we plot these parameters for the database of models, again indicating the effects of the constraint on \( \Delta \alpha_\mu \) (SUSY). The constraint forces the scalar mass parameter to be small, but the upper bound increases with increasing \( \tan \beta \).

### IV. ASTROPHYSICAL DARK MATTER SEARCHES

There is a large community pursuing the goal of detecting dark matter particles, neutralinos especially, in various astrophysical contexts. The possibilities can be broken up along the lines of “direct” and “indirect” detection. Direct detection means detecting the rare scatterings of neutralinos in our galactic halo with nuclei in a sensitive low background apparatus. Indirect detection means detecting the products of rare annihilations of galactic neutralinos, such as antiprotons, antideuterons, positrons, gamma rays, and neutrinos.

Perhaps the most promising of the astrophysical neutralino searches is the direct detection program. Experiments such as CDMS [28], DAMA [29], and EDELWEISS [30] have pushed exclusion limits down to cross sections as small as \( 10^{-6} \) pb. As has been noted before, the neutralino–nucleon elastic scattering cross section exhibits a significant correlation with \( \Delta \alpha_\mu \) (SUSY) [11], thus a large positive \( \Delta \alpha_\mu \) (SUSY) is exciting for direct searches.

Direct detection is promising even in the case where the neutralinos have a small relic density and thus are only a small component of the dark matter. In this case we perform a conservative rescaling of the galactic neutralino density as

\[
\rho_\chi \rightarrow \rho_\chi \left( \frac{\Omega \chi h^2}{0.25} \right),
\] (9)

where \( \Omega \chi h^2 = 0.25 \) is the current upper limit on the relic density. In the left panel of Fig. 3, we plot the spin-independent neutralino-proton scattering cross section, rescaled according to Eq. 9. The constraint due to \( \Delta \alpha_\mu \) (SUSY) is intriguing, as it bounds the rescaled cross section at around \( 10^{-11} \) pb. In the right panel of Fig. 3, we perform no rescaling, and only consider models with cosmologically interesting relic densities. Here the minimum cross section is around \( 10^{-10} \) pb. The inelastic at 100 GeV and \( 10^{-9} \) pb is due to the lower limit \( \Omega \chi h^2 > 0.05 \). These bounds indicate that there is considerable hope for the next generation of experiments, such as CDMS II and CRESST II [31]. The latter bound is perhaps reachable by future experiments with one ton target masses such as GENIUS [33], CryoArray [34], and XENON [35]. Finally, it is important to note that in the case where the significance of the \( \alpha_\mu \) discrepancy is reduced, the lower bound on the cross section disappears. However, there is not an upper bound on the cross section. Large cross sections are still possible with \( \Delta \alpha_\mu \) (SUSY) consistent with zero.

Neutrino telescopes such as at Lake Baikal [36], SuperKamiokande [37] in the Mediterranean [28], and the south pole [38] are a promising technique for indirect detection. Neutralinos in the galactic halo scatter into orbits around the Earth or Sun, and can then rapidly sink to the cores of these bodies by additional scatterings, resulting in a large density enhancement. This can produce a detectable annihilation signal in neutrinos at high (GeV) energies. It is the capture rate that governs the neutrino flux, and is strongly correlated with the neutralino–nucleon cross section. This places a lower bound on the detection rate, though at small neutralino mass there are threshold effects that remove it [39]. To illustrate, we plot the rate of neutrino-induced through-going muons from the Sun along with the unsubtractable background (from cosmic rays incident on the Sun’s surface) in the top left panel of Fig. 4. It is clear that the \( \Delta \alpha_\mu \) (SUSY) bound cuts away much of the undetectable parameter space, but not all of it. In the top right panel we repeat the calculation for neutrinos from the center of
FIG. 1: Gaugino/higgsino fraction versus mass for the lightest neutralino. In the left panel, we plot all models not excluded by cosmological arguments. In the right panel, only models with an interesting relic density are plotted. Crosses indicate models allowed before applying a constraint on $\Delta a_\mu$ (SUSY), and crossed circles indicate models allowed after imposing the $\Delta a_\mu$ (SUSY) bound.

FIG. 2: Sfermion mass scale versus $\tan \beta$. As in Fig. 1, in the left panel, we plot all models not excluded by cosmological arguments and in the right panel we plot only models with an interesting relic density. Crosses indicate models allowed before applying a constraint on $\Delta a_\mu$ (SUSY), and crossed circles indicate models allowed after imposing the $\Delta a_\mu$ (SUSY) bound. The small “inlet” at $\tan \beta \sim 4$ and $m_0 \sim 400$ GeV is due to the constraint on the Higgs boson mass. It is clear that the relic density cut has little effect on the allowed region.

the Earth, where the prospects are much less promising.

In addition, neutralinos can annihilate in the galactic halo. The relevant rates are quite small, but the enormous mass of the halo compensates, and the annihilation products may be detectable. Gamma rays propagate essentially freely, thus the expected rate is largest towards the galactic center where the dark matter density is largest. Charged particles are trapped by the galactic magnetic field and effectively diffuse, so these annihilation products would originate more nearby.

The detection of the gamma ray lines from direct annihilations either to two photons, or to a photon and a $Z$ boson would be a gold-plated signature of neutralinos in the galactic halo [18]. Gamma ray experiments such as the atmospheric Čerenkov telescopes (ACTs) VERITAS [40] and MAGIC [41], and the GLAST [42] satellite
FIG. 3: Neutralino–nucleon elastic scattering cross section versus neutralino mass. In the left panel, we have only applied the upper constraint on relic density, and rescaled the effective cross section to account for a low galactic density of low relic density neutralinos. In the right panel we plot only those models that could account for all of the dark matter, and we do not perform a rescaling. The inlet at 100 GeV and $10^{-19}$ pb is due to the lower limit $\Omega_\chi h^2 > 0.05$. Crosses indicate models allowed before applying a constraint on $\Delta a_\mu$(SUSY), and crossed circles indicate models allowed after imposing the $\Delta a_\mu$(SUSY) bound.

hope to detect these lines. Assuming that the galactic halo is an isothermal sphere with a 1 kpc core, we plot the reach of these experiments in the bottom left panel of Fig. 4. Note that with this assumption the emission enhancement from around the black hole at the galactic center is insignificant [43], so we neglect it. We notice that applying the $\Delta a_\mu$(SUSY) bound has little effect on the prospects for these experiments. It appears that the detection of the gamma ray lines is quite difficult. Other assumptions, including clumping of the dark matter or a lack of a central core lead to significantly higher predictions [43].

The intensity of cosmic ray positrons [44] from neutralino annihilation is not much affected by the constraint on $\Delta a_\mu$(SUSY).

The final possibility we mention is that antideuterons may be an interesting annihilation product to search for [45]. The background from mundane cosmic ray processes should be relatively smaller (a smaller fraction of the annihilation signal) at low energies than for antiprotons. A signal may be detectable in experiments such as AMS [46] and GAPS [47], as seen in the bottom right of Fig. 4. It is interesting that the $\Delta a_\mu$(SUSY) constraint eliminates the models with the lowest rates, and furthermore that the whole parameter space is covered for neutralino masses between 100 GeV and 500 GeV. Separating a signal from the background with antideuterons may be difficult however.

V. CONCLUSIONS

In this paper we have discussed the recent confirmation of a discrepancy with the Standard Model of the anomalous magnetic moment of the muon [3], updating and expanding the results of Ref. [7]. Assuming that supersymmetry is responsible for the discrepancy, we have investigated the consequences for astrophysical dark matter searches. We have confirmed that the constraint significantly improves the prospects for direct detection experiments trying to measure the rare scatterings of galactic neutralinos. Neutrino telescopes are also helped by this result. The prospects for the detection of gamma ray lines from neutralino annihilations at the galactic center are not much affected. The prospects for detecting cosmic ray antideuterons as neutralino annihilation products are also significantly improved. In all cases, if the discrepancy disappears, there remain supersymmetric models with detectable rates for all of these experiments.

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[1] H. N. Brown et al., Phys. Rev. Lett. 86, 2227 (2001).

[2] M. Knecht and A. Nyffeler, Phys. Rev. D, in press.
FIG. 4: Indirect detection of neutralinos. In all plots, small crosses indicate cosmologically interesting models ($0.05 < \Omega_\chi h^2 < 0.25$), and crossed circles indicate such models that pass the $\Delta m_{\nu}$ (SUSY) cut. In the top left we plot the rate of through-going muons in a neutrino telescope for the annihilations in the Sun, with the BAKSAN and SuperKamiokande bounds, and the reach of a km$^2$ telescope. In the top right, we plot a similar rate for neutrinos from the center of the Earth. In the bottom left we plot the flux in the gamma ray lines from the galactic center, assuming a 1 kpc core isothermal sphere halo. The future reach of the GLAST, VERITAS, and MAGIC experiments is included. In the bottom right we plot the flux of antideuterons at a kinetic energy of 500 MeV, together with the future sensitivity of the GAPS detector.

hep-ph/0111058; M. Knecht, A. Nyffeler, M. Perrot-tet and E. de Rafael, Phys. Rev. Lett. 88, 071802 (2002); M. Hayakawa and T. Kinoshita, hep-ph/0112102; I. Blokland, A. Czarnecki and K. Melnikov, Phys. Rev. Lett. 88, 071803 (2002).

[3] BNL Colloquium July 30, 2002, E821 Collaboration, [4] D. A. Kosower, L. M. Krauss and N. Sakai, Phys. Lett. B 133, 305 (1983); T. C. Yuan, R. Arnowitt, A. H. Chamseddine and P. Nath, Z. Phys. C 26, 407, (1984); J. L. Lopez, D. V. Nanopoulos and X. Wang, Phys. Rev. D 49, 366 (1994); U. Chattopadhyay and P. Nath, Phys. Rev. D 53, 1648 (1996).

[5] T. Moroi, Phys. Rev. D 53, 6565 (1996).
[6] A. Czarnecki and W. J. Marciano, Nucl. Phys. B 76, 245 (1999); Phys. Rev. D 64, 013014 (2001).
[7] E. A. Baltz and P. Gondolo, Phys. Rev. Lett. 86, 5004 (2001).
[8] L. L. Everett, G. L. Kane, S. Rigolin and L. Wang, Phys. Rev. Lett. 86, 3484 (2001); J. L. Feng and K. T. Matchev, Phys. Rev. Lett. 86, 3480 (2001), U. Chattopadhyay and P. Nath, Phys. Rev. Lett. 86, 5854 (2001); S. Komine, T. Moroi and M. Yamaguchi, Phys. Lett. B 506, 93 (2001); S. P. Martin and J. D. Wells, Phys. Rev. D 64, 035003 (2001); H. Baer, C. Balazs, J. Ferrandis and X. Tata, Phys. Rev. D 64, 035004 (2001); R. Arnowitt,
B. Dutta, B. Hu and Y. Santoso, Phys. Lett. B 505, 177 (2001); J. Ellis, D. V. Nanopoulos and K. A. Olive, Phys. Lett. B 508, 65 (2001); A. B. Lahanas, D. V. Nanopoulos and V. C. Spanos, Phys. Lett. B 518, 94 (2001).

[9] F. J. Ynduráin, hep-ph/0102312.
[10] W. J. Marciano and B. L. Roberts, hep-ph/0105056.
[11] G. Jungman, M. Kamionkowski and K. Griest, Phys. Rep. 267, 195 (1996).

[12] D. N. Schramm and M. S. Turner, Rev. Mod. Phys. 70, 303 (1998).
[13] X. Wang, M. Tegmark and M. Zaldarriaga, astro-ph/0105056.
[14] G. Jungman, M. Kamionkowski and K. Griest, Phys. Rep. 267, 195 (1996).

[15] L. Bergström and P. Gondolo, Astropart. Phys. 5, 263 (1996).
[16] J. Edsjö and P. Gondolo, Phys. Rev. D 56, 1879 (1997).
[17] J. Edsjö, PhD Thesis, Uppsala University, hep-ph/9704384.

[18] L. Bergström, P. Ullio, and J. H. Buckley, Astropart. Phys. 9, 137 (1998).
[19] L. Bergström, J. Edsjö and P. Gondolo, Phys. Rev. D 58, 103519 (1998).
[20] E. A. Baltz and J. Edsjö, Phys. Rev. D 59, 023511 (1999); L. Bergström, J. Edsjö, and P. Ullio, Astrophys. J. 526, 215 (1999).

[21] M. Drees, M. M. Nojiri, D.P. Roy and Y. Yamada, Phys. Rev. D 56, 276 (1997); D. Pierce and A. Papapoulos, Phys. Rev. D 50, 565 (1994), Nucl. Phys. B 430, 278 (1994); A. B. Lahanas, K. Tamvakis, and N. D. Tracas, Phys. Lett. B 324, 387 (1994).
[22] S. Heinemeyer, W. Hollik, and G. Weiglein, Comm. Phys. Comm. 124, 76 (2000).
[23] P. Gondolo and G. Gelmini, Nucl. Phys. B 360, 145 (1991).
[24] J. Edsjö, P. Gondolo, M. Schelke and P. Ullio, in preparation.
[25] D. E. Groom et al. (Particle Data Group), Eur. Phys. J. C 15, 1 (2000).
[26] M. S. Alam et al. (CLEO Collaboration), Phys. Rev. Lett. 71, 674 (1993) and Phys. Rev. Lett. 74, 2885 (1995).

[27] P. Gondolo, J. Edsjö, L. Bergström, P. Ullio, and E.A. Baltz, astro-ph/0012234.
[28] R. Abusaidi et al., Phys. Rev. Lett. 84, 5699 (2000).
[29] R. Bernabei et al., Phys. Lett. B 480, 23 (2000).
[30] A. Benoit et al., astro-ph/0206271 (2002).
[31] M. Drees, Y. G. Kim, T. Kobayashi and M. M. Nojiri, hep-ph/0011359 (2000).
[32] M. Bravin et al., Astropart. Phys. 12, 107 (1999); M. Altman et al., astro-ph/0106142 (2001).
[33] H. V. Klapdor-Kleingrothaus, in “Beyond the desert 1997,” Castle Ringberg, Germany, eds. H. V. Klapdor-Kleingrothaus and H. Paes (IOP, Bristol, 1998), p. 485; H. V. Klapdor-Kleingrothaus et al., in “Beyond the desert 1999,” Castle Ringberg, Germany, eds. H. V. Klapdor-Kleingrothaus and I. Krivosheina (IOP, 2000), p. 915.
[34] R. J. Gaitskell, astro-ph/0106200 (2001).
[35] E. Aprile et al., Proceedings of Xenon ’01 astro-ph/0207671 (2001).
[36] L. A. Belolaptikov et al., Astropart. Phys. 7, 263 (1997).
[37] A. Okada et al. (Super-Kamiokande collaboration), astro-ph/0007003 (2000).
[38] C. Carloganu, in “Cosmology And Particle Physics (CAPP 2000)” Verbier, Switzerland (2000).
[39] E. Andre et al., Astropart. Phys. 13, 1 (2000); F. Halzen et al., Proc. of 26th ICRC (1999).

[40] http://parsn3.physics.purdue.edu/veritas.
[41] http://hegra1.mppmu.mpg.de/MAGICWeb.
[42] http://www-glast.stanford.edu.
[43] P. Gondolo and J. Silk, Phys. Rev. Lett. 83, 1719 (1999).
[44] E. A. Baltz and J. Edsjö, Phys. Rev. D 59, 023511 (1999); E. A. Baltz, J. Edsjö, K. Freese and P. Gondolo, Phys. Rev. D 65, 063511 (2002).
[45] P. Chardonnet, J. Orloff and P. Salati, Phys. Lett. B 409, 313 (1997); F. Donato, N. Fornengo and P. Salati, Phys. Rev. D 62, 043003 (2000).
[46] J. Alcaraz et al., Nucl. Instrum. Meth. A478, 119, (2002).
[47] K. Mori et al., Astrophys. J. 566, 604 (2002).