Indirect neutralino detection rates in neutrino telescopes

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Neutralinos annihilating in the center of the Sun or the Earth may give rise to a detectable signal of neutrinos. We derive the indirect detection rates for neutrino telescopes in the minimal supersymmetric extension of the standard model. We show that even after imposing all phenomenological and experimental constraints that make the theories viable, regions of parameter space exist which can already be probed by existing neutrino telescopes. We compare with the discovery potential of supersymmetry at CERN LEP 2 as well as direct detections and point out the complementarity of the methods. [S0556-2821(97)01704-9]

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I. INTRODUCTION

Supersymmetric neutralinos with masses in the GeV–TeV range are among the leading nonbaryonic candidates for dark matter in our galactic halo. One of the most promising methods for the discovery of neutralinos in the halo is via observation of energetic neutrinos from their annihilation in the Sun [1] and/or Earth [2]. Through elastic scattering with the atomic nuclei in the Sun or Earth, a neutralino from the halo can lose enough energy to remain gravitationally trapped [3]. Trapped neutralinos sink to the core of the Sun or Earth where they annihilate into ordinary particles: leptons, quarks, gluons, and—depending on the masses—Higgs and gauge bosons. Because of absorption in the solar or terrestrial medium, only neutrinos are capable of escaping to the surface. Neutralinos do not annihilate into neutrinos directly [4], but energetic neutrinos may be produced via hadronization and/or decay of the direct annihilation products. These energetic neutrinos may be discovered by terrestrial neutrino detectors.

In this paper, we consider Čerenkov neutrino telescopes. They consist of large underground arrays of photomultipliers to detect the Čerenkov light emitted by muons generated in charged-current interactions of neutrinos with the medium surrounding the detector. Underground Čerenkov detectors, originally built to search for proton decay, have already started to explore (and constrain) neutralinos as dark matter candidates [5,6]. A new generation of much larger neutrino telescopes, utilizing large volumes of natural water or ice (for a review, see [7]) is currently under construction, which will increase the sensitivity for high-energy neutrino point sources by an order of magnitude or more.

The prediction of muon rates is quite involved: We compute neutralino capture rates in the Sun and Earth, fragmentation functions in basic annihilation processes, propagation through the solar or terrestrial medium, charged-current cross sections, and muon propagation in the rock, ice, or water surrounding the detector. In addition, there may be scattering of the Čerenkov photons generated by the muons, due to impurities in the medium.

II. DEFINITION OF THE SUPERSYMMETRIC MODEL

The minimal $N=1$ supersymmetric extension of the standard model is defined by the following superpotential and soft supersymmetry-breaking potential (for notation and details, see Ref. [8]):

$$W=\epsilon_{ij}(-\hat{\mathbf{e}}_R^*\mathbf{Y}_E\hat{\mathbf{l}}_L^i\hat{H}_1^j-\hat{\mathbf{d}}_R^*\mathbf{Y}_D\hat{\mathbf{q}}_L^i\hat{H}_1^j+\hat{\mathbf{u}}_R^*\mathbf{Y}_U\hat{\mathbf{q}}_L^i\hat{H}_2^j-\mu\hat{H}_1^i\hat{H}_2^j), \tag{1}$$

$$V_{\rm soft}=\epsilon_{ij}(-\tilde{\mathbf{e}}_R^*\mathbf{A}_E\mathbf{Y}_E\tilde{\mathbf{l}}_L^iH_1^j-\tilde{\mathbf{d}}_R^*\mathbf{A}_D\mathbf{Y}_D\tilde{\mathbf{q}}_L^iH_1^j+\tilde{\mathbf{u}}_R^*\mathbf{A}_U\mathbf{Y}_U\tilde{\mathbf{q}}_L^iH_2^j-B\mu H_1^iH_2^j+\text{H.c.})+H_1^{i*}m_1^2H_1^i+H_2^{i*}m_2^2H_2^i+\tilde{\mathbf{q}}_L^{i*}\mathbf{M}_Q^2\tilde{\mathbf{q}}_L^i$$
$$+\tilde{\mathbf{l}}_L^{i*}\mathbf{M}_L^2\tilde{\mathbf{l}}_L^i+\tilde{\mathbf{u}}_R^*\mathbf{M}_U^2\tilde{\mathbf{u}}_R+\tilde{\mathbf{d}}_R^*\mathbf{M}_D^2\tilde{\mathbf{d}}_R+\tilde{\mathbf{e}}_R^*\mathbf{M}_E^2\tilde{\mathbf{e}}_R+\tfrac{1}{2}M_1\tilde{B}\tilde{B}+\tfrac{1}{2}M_2(\tilde{W}^3\tilde{W}^3+2\tilde{W}^+\tilde{W}^-)+\tfrac{1}{2}M_3\tilde{g}\tilde{g}. \tag{2}$$

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Here i and j are SU(2) indices ($\epsilon_{12}=+1$), **Y**'s, **A**'s, and **M**'s are 3×3 matrices in generation space, and the other boldface letters are vectors in generation space.

Electroweak symmetry breaking is caused by both H_1^1 and H_2^2 acquiring vacuum expectation values,

$$\langle H_1^1\rangle = v_1, \quad \langle H_2^2\rangle = v_2, \tag{3}$$

with $g^2(v_1^2+v_2^2)=2m_W^2$, with the further assumption that vacuum expectation values of all other scalar fields (in particular, squarks and sleptons) vanish. This avoids color- and/or charge-breaking vacua.

To reduce the number of free parameters, we make simplifying unification assumptions for the gaugino mass parameters

$$M_1 = \tfrac{5}{3}\tan^2\theta_w M_2, \tag{4}$$

$$M_2 = \frac{\alpha_{\rm em}}{\sin^2\theta_w \alpha_s} M_3, \tag{5}$$

and a simple ansatz for the soft supersymmetry-breaking parameters in the sfermion sector:

$$\mathbf{M}_Q = \mathbf{M}_U = \mathbf{M}_D = \mathbf{M}_E = \mathbf{M}_L = m_0 \mathbf{1}, \tag{6}$$

$$\mathbf{A}_U = {\rm diag}(0,0,A_t), \tag{7}$$

$$\mathbf{A}_D = {\rm diag}(0,0,A_b), \tag{8}$$

$$\mathbf{A}_E = 0. \tag{9}$$

We choose as independent parameters the mass m_A of the CP-odd Higgs boson, the ratio of Higgs vacuum expectation values (VEVs) $\tan\beta = v_2/v_1$, the gaugino mass parameter M_2, the Higgs(ino) mass parameter μ, and the quantities m_0, A_t, and A_b above.

We include one-loop radiative corrections and two-loop leading-logarithmic contributions to the Higgs boson mass matrices using the effective potential approach described in [9].

The neutralinos $\tilde{\chi}_i^0$ are linear combinations of the neutral gauginos $\tilde{B}$, $\tilde{W}_3$ and of the neutral Higgsinos $\tilde{H}_1^0$, $\tilde{H}_2^0$. In this basis, their mass matrix

$$\mathcal{M}_{\tilde{\chi}^0_{1,2,3,4}} = \begin{pmatrix} M_1 & 0 & -\frac{g'v_1}{\sqrt{2}} & +\frac{g'v_2}{\sqrt{2}} \\ 0 & M_2 & +\frac{gv_1}{\sqrt{2}} & -\frac{gv_2}{\sqrt{2}} \\ -\frac{g'v_1}{\sqrt{2}} & +\frac{gv_1}{\sqrt{2}} & 0 & -\mu \\ +\frac{g'v_2}{\sqrt{2}} & -\frac{gv_2}{\sqrt{2}} & -\mu & 0 \end{pmatrix} \tag{10}$$

can be diagonalized analytically to give four neutral Majorana states

$$\tilde{\chi}_i^0 = N_{i1}\tilde{B} + N_{i2}\tilde{W}^3 + N_{i3}\tilde{H}_1^0 + N_{i4}\tilde{H}_2^0, \tag{11}$$

the lightest of which, to be called χ, is then the candidate for the particle making up (at least some of) the dark matter in the universe.

We consider only models that satisfy all accelerator constraints on supersymmetric particles and couplings, in particular, the measurement of the $b\to s\gamma$ process at the Cornell accelerator [10], which provides important bounds. However, to show the impact of present dark matter searches, we plot also models which are excluded by these nonaccelerator searches.

III. RELIC DENSITY AND CAPTURE RATES

For each model allowed by the accelerator constraints we calculate the relic density of neutralinos $\Omega_\chi h^2$. We use the formalism in Ref. [11] to carefully treat resonant annihilations and threshold effects, keeping finite widths of unstable particles, including all two-body annihilation channels of neutralinos. The annihilation cross sections were derived using a novel helicity projection technique [12], and were checked against published results for several of the subprocesses.

In this paper, we keep only models in which the neutralino density does not overclose the Universe and in which neutralinos can make up the totality of the galactic dark matter. Namely, we require $\Omega_{\rm gal\,DM}h^2 < \Omega_\chi h^2 < 1$, where (somewhat arbitrarily) we choose $\Omega_{\rm gal\,DM}h^2 = 0.025$. We have adopted a local dark matter density of 0.3 GeV/cm^3.

The capture rate in the Earth is dominated by scalar interactions, and presents kinematic enhancements whenever the mass of the neutralino almost matches one of the heavy elements in the Earth. For the Sun, both axial interactions with hydrogen and scalar interactions with heavier elements are important. For both the Sun and Earth we use the convenient approximations available in [13].

IV. MUON FLUXES FROM NEUTRALINO ANNIHILATIONS

Neutralinos in the core of the Sun and/or Earth can annihilate to a fermion-antifermion pair, to gauge bosons, Higgs bosons, and gluons ($\chi\chi\to\ell^+\ell^-$, $q\bar{q}$, gg, $q\bar{q}g$, W^+W^-, Z^0Z^0, Z^0H^0, $W^\pm H^\mp$, H^0H^0). These annihilation products will hadronize and/or decay, eventually producing high-energy muon neutrinos. Since the rate of muons in a neutrino telescope is approximately proportional to the neutrino energy squared (since both the cross section and the muon range are approximately proportional to the energy), the annihilation channels with the hardest neutrino spectra will be the most important, i.e., W^+W^-, Z^0Z^0, $t\bar{t}$, etc. In our calculation of the neutrino fluxes we have, however, included all annihilation channels (except gluons since they give very soft neutrino spectra).

With Monte Carlo simulations we have considered the whole chain of processes from the annihilation products in the core of the Sun or Earth to detectable muons at the surface of the Earth [14]. We have performed a full Monte Carlo simulation of the hadronization and decay of the annihilation products using JETSET 7.4 [15], of the neutrino inter-

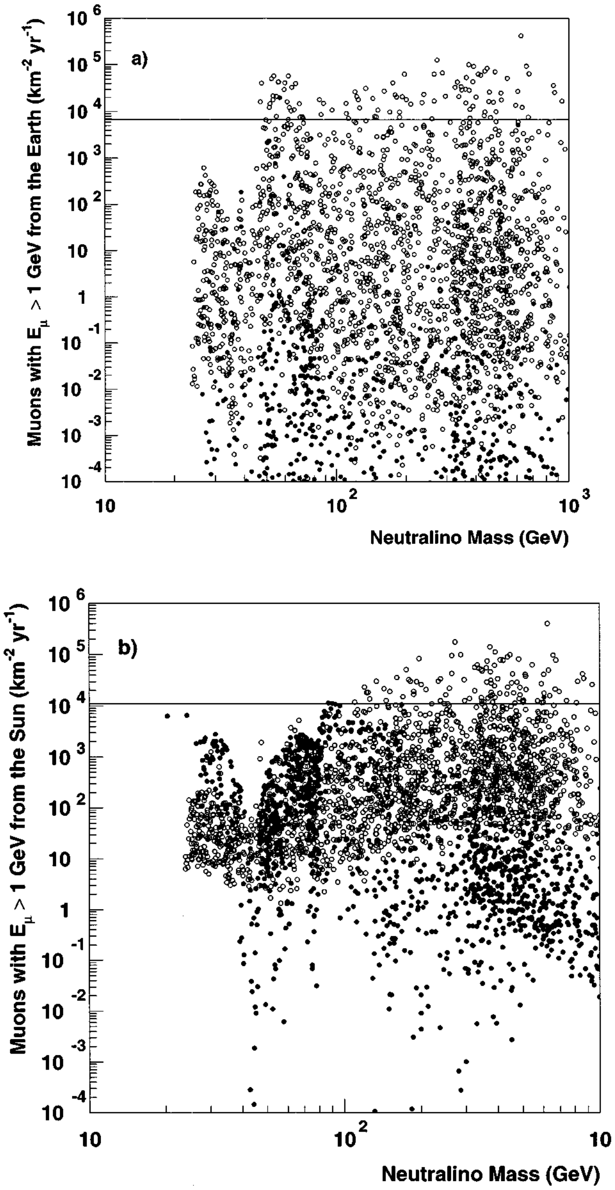

FIG. 1. The indirect detection rates from neutralino annihilations in (a) the Earth and (b) the Sun versus the neutralino mass. The horizontal line is the Baksan limit [6]. Solid circles are from a ''normal'' scan and open circles are from a ''special'' scan with $m_A < 150$ GeV.

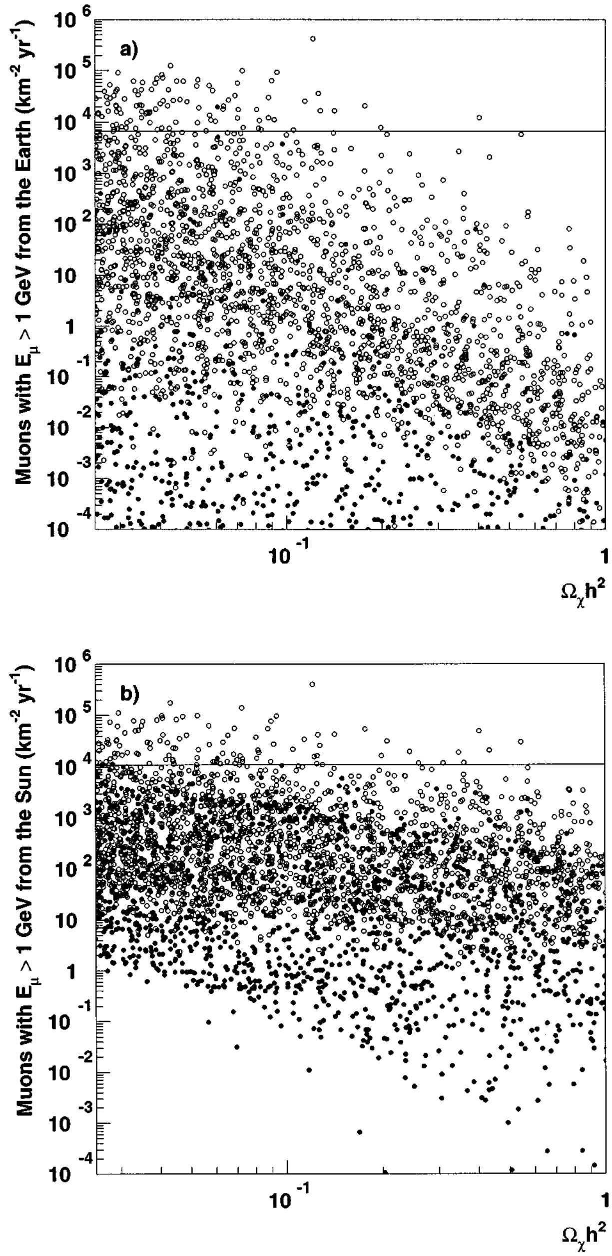

FIG. 2. The indirect detection rates from neutralino annihilations in (a) the Earth and (b) the Sun versus $\Omega_\chi h^2$. The horizontal line is the Baksan limit [6]. Solid circles are from a ''normal'' scan and open circles are from a ''special'' scan with $m_A < 150$ GeV.

actions on their way out of the Sun and of the charged-current neutrino interactions near the detector using PYTHIA 5.7 [15], and finally of the multiple Coulomb scattering of the muon on its way to the detector using distributions from Ref. [16].

With respect to calculations using Ref. [17] (e.g., Ref. [18]), this Monte Carlo treatment of the neutrino propagation through the Sun bypasses simplifying assumptions previously made; namely, neutral currents are no longer assumed to be much weaker than charged currents and energy loss is no longer considered continuous. For details on this treatment, see Refs. [14,19].

The muon flux at a detector has been simulated for a set of neutralino masses ($m_{\tilde{\chi}} = 10$, 25, 50, 80.3, 91.2, 100, 150, 176, 200, 250, 350, 500, 750, 1000, 1500, 2000, 3000, and 5000 GeV) and annihilation channels ($c\bar{c}$, $b\bar{b}$, $t\bar{t}$, $\tau^+\tau^-$, W^+W^-, and Z^0Z^0). For each mass and channel, 2.5×10^5 annihilations have been simulated. For masses other than those simulated, an interpolation is performed and the muon flux from channels other than those listed above are easily calculated since all other annihilation products decay to these particles (lighter quarks, electrons, and muons do not contribute significantly to the neutrino flux). For the Higgs bosons, which decay in flight, an integration over the angle of the decay products with respect to the direction of the Higgs boson is performed. Given the branching ratios for different annihilation channels it is then straightforward to obtain the muon flux above any given energy threshold and within any angular region around the Sun or the center of the Earth.

V. INDIRECT DETECTION RATES

To illustrate the potential of neutrino telescopes for discovery of dark matter through neutrinos from the Earth or Sun, we present the results of our full calculation. We show together results obtained with one ''normal'' scan in the parameter space, letting μ, M_2, $\tan\beta$, m_A, m_0, A_b, and A_t vary at random between generous bounds, and one ''special'' scan where we have been more restrictive on the A mass:

$$\begin{aligned}&\mu\in[-5000,5000]\ \text{GeV}\\&M_2\in[-5000,5000]\ \text{GeV}\\&\tan\beta\in[1.2,50]\\&m_A\in[0,1000]\ \text{GeV}\qquad \text{``normal''}\\&m_0\in[100,3000]\ \text{GeV}\\&A_b\in[-3,3]m_0\\&A_t\in[-3,3]m_0\end{aligned}\qquad\begin{aligned}&\mu\in[-5000,5000]\ \text{GeV}\\&M_2\in[-5000,5000]\ \text{GeV}\\&\tan\beta\in[1,2,50]\\&m_A\in[0,150]\ \text{GeV}\qquad \text{``special''}\\&m_0\in[100,3000]\ \text{GeV}\\&A_b\in[-3,3]m_0\\&A_t\in[-3,3]m_0\end{aligned}$$

We recall that the density of points in the figures reflects our choices for scanning the parameter space, and is therefore subjective (for a discussion on this, see Ref. [8]).

In Fig. 1 we show our predictions for the indirect detection rates as a function of neutralino mass. The horizontal lines are the best present limits for indirect searches and come from the Baksan detector [6]. The limits are $\Phi_\mu^{\text{Earth}}<2.1\times10^{-14}$ cm^{-2} s^{-1} and $\Phi_\mu^{\text{Sun}}<3.5\times10^{-14}$ cm^{-2} s^{-1} at 90% confidence level and integrated over a half-angle aperture of 30° with a muon energy threshold of 1 GeV. Quite a few models with high neutrino rates are already ruled out by the Baksan data. These models have large $\tan\beta\gtrsim30$, low H_2 mass, and large mixing for stop squarks. In Fig. 1 it can also be seen that a neutrino telescope of an area around 1 km^2, which is a size currently being discussed, would have a large discovery potential for supersymmetric dark matter. We recall that, after subtraction of the atmospheric neutrino fluxes (by means of an on-source off-source difference, e.g.), the remaining background is due to high-energy neutrinos produced by cosmic ray collisions in the solar atmosphere, and is at the level of 15 muons (>1 GeV)/km^2/yr [20].

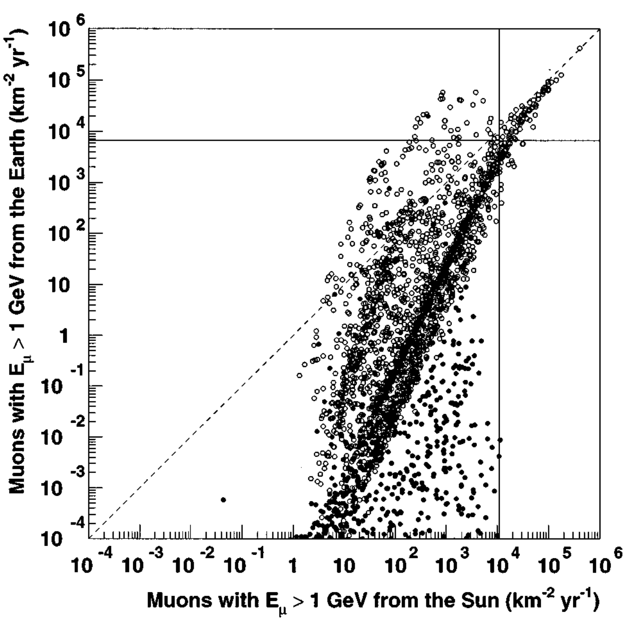

FIG. 3. The indirect detection rates in the Earth versus the indirect detection rates in the Sun. The horizontal and vertical lines are the Baksan limits [6]. The dashed line, indicating equal rates, is shown just for convenience. Solid circles are from a ''normal'' scan and open circles are from a ''special'' scan with $m_A<150$ GeV.

In Fig. 2 we show the muon rates versus $\Omega_\chi h^2$. The general trend is that large $\Omega_\chi h^2$ corresponds to lower rates, as would be expected from crossing symmetry between annihilation and scattering cross sections. Note, however, the large spread of the predicted rates for a given value of $\Omega_\chi h^2$.

In Fig. 3 a comparison is made between the predicted rates from the Earth and from the Sun for the same set of models. In the region yet to explore, the rate from the Sun is generally larger than the rate from the Earth.

In Fig. 4 the indirect detection rate is compared to the direct detection rate in ^{76}Ge. As can be seen, there is a correlation between the two, although for the Sun it is not as strong as for the Earth, where a high capture rate is due to a large scalar cross section, which also means a high rate in germanium.[1] Without forgetting the huge spread, we see that for a given factor of improvement in sensitivity, indirect detection from the Sun generally scores better than direct de-

[1] Recently, a paper appeared (V.A. Bednyakov *et al.*, Report No. hep-ph/9606261), where no high germanium rates were found in a variant of the special scan employed here. This seems to be due to their use of a more restricted model, imposing unification conditions of the scalar mass parameters at the grand unified theory (GUT) scale, which we do not.

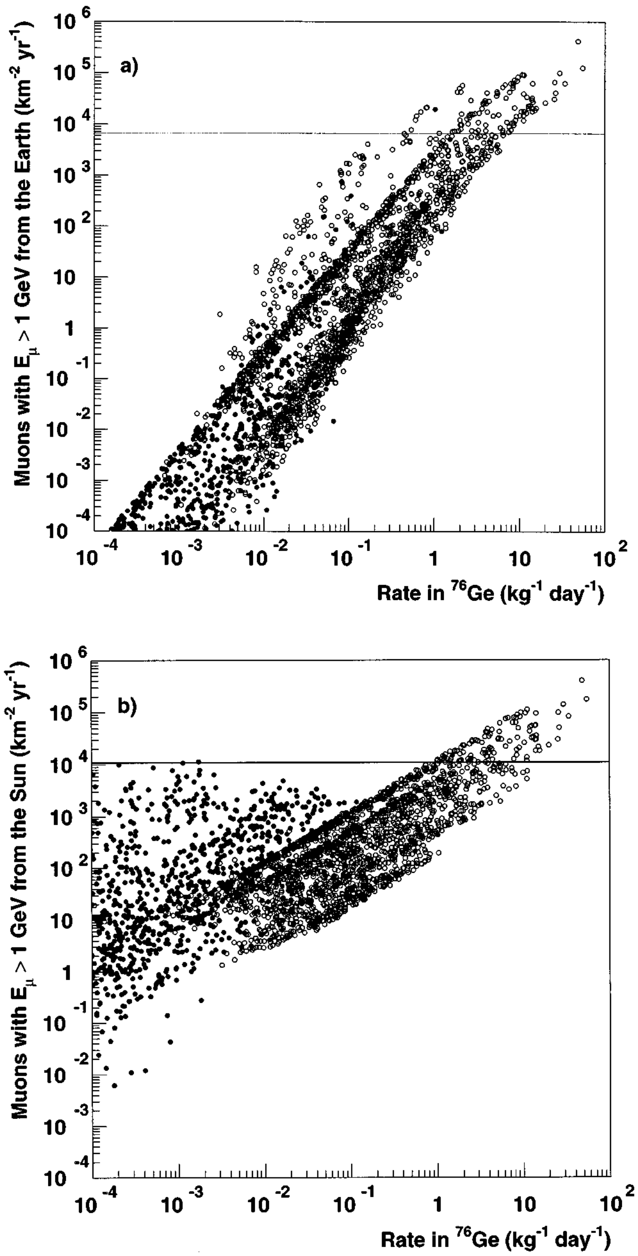

FIG. 4. The indirect detection rates from neutralino annihilations in (a) the Earth and (b) the Sun versus the direct detection rate in ^{76}Ge. The horizontal line is the Baksan limit [6]. Solid circles are from a ''normal'' scan and open circles are from a ''special'' scan with $m_A < 150$ GeV.

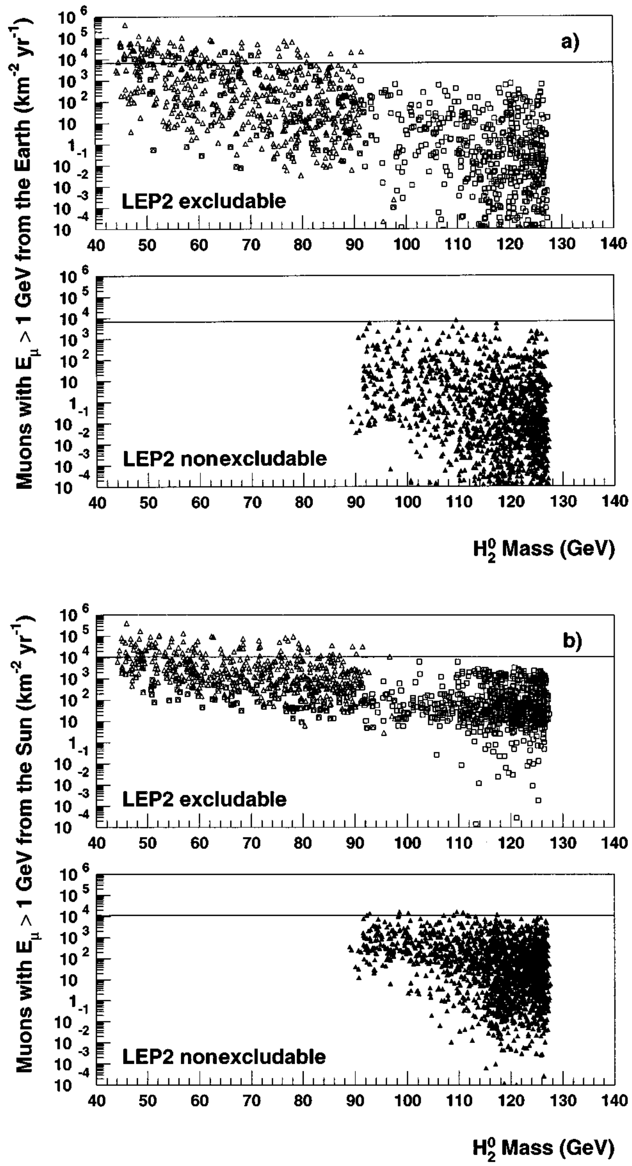

FIG. 5. The indirect detection rates from neutralino annihilations in (a) the Earth and (b) the Sun versus m_{H_2}. The horizontal line is the Baksan limit [6]. The upper part shows models which can be excluded at LEP 2 after 150 pb^{-1} of running at 192 GeV and the lower part shows models which cannot be excluded by LEP 2. The open triangles are models that can be excluded due to no Higgs boson discovery and the open squares are models that can be excluded due to no chargino discovery.

tection, which in turn generally scores better than indirect detection from the Earth.

Note that the muon rates in real experiments may be significantly lower (by as much as an order of magnitude for neutralinos in the lower-mass range) due to the need to impose a higher-energy threshold for the signal than assumed here. We have taken 1 GeV for neutrino telescopes which is true for a small scale detector such as Baksan; for a kilometer-scale array, it is more likely to be tens of GeV. Likewise, the germanium rate given is the integrated rate from zero recoil energy to the kinematical limit. Present-day detectors typically only sample a small range of recoil energies.

Since the special scan employs fairly low values of the A mass, one may wonder whether the A or the lightest Higgs boson H_2 would be light enough to be discovered or excluded at the CERN e^+e^- collider LEP 2. In particular, one could expect this for the models that give high neutrino rates, since a low Higgs boson mass gives a large spin-independent scattering cross section of (mixed) neutralinos and therefore large capture and annihilation rates. Using the expected exclusion limits for LEP 2 given in Ref. [21] we find, indeed, that the models in our sample with the highest rates are within reach of LEP 2, because of the large cross section for $e^+e^- \rightarrow AH_2$. Technically this is due to the fact that these models have a large value of the factor $\cos^2(\beta-\alpha)$ that governs the ZAH_2 coupling (with α being the CP-even Higgs mixing angle). In Fig. 5 we show the indirect detection rates versus m_{H_2}: The models that can be probed by LEP 2 are shown in the upper part of the figure, the others in the lower part. We have used the combination of all four LEP experiments and assumed a total integrated luminosity of 150 pb $^{-1}$ at 192 GeV. We have also included the possible LEP 2 lower limit of 95 GeV on the mass of the chargino and the bounds coming from the $e^+e^-\rightarrow ZH_2\rightarrow Zb\bar{b}$ process. LEP 2 will probe all models in our scan with $m_{H_2}\lesssim 90$ GeV and, in particular, most of the models already ruled out by Baksan. On the other hand, there are many models giving quite large indirect detection rates that cannot be probed by LEP 2, but that would be accessible at a large neutrino telescope.

In conclusion, indirect dark matter searches and LEP 2 probe complementary regions of the supersymmetric parameter space. Moreover, direct detection (see [8]) is reaching a sensitivity that allows some models to be excluded, with somewhat different characteristics than those probed by the other methods. This illustrates a nice complementarity between direct detection, indirect detection, and accelerator methods to bound or confirm the minimal supersymmetric standard model.

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