Signatures of dark matter in underground detectors

Francis Halzen and Tim Stelzer
Department of Physics, University of Wisconsin, Madison, Wisconsin 53706

Marc Kamionkowski
School of Natural Sciences, Institute for Advanced Study, Princeton, New Jersey 08540
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The neutralino, the lightest superpartner in many supersymmetric theories, is arguably the leading dark-matter candidate from both the cosmological and particle-physics points of view. Its mass is bracketed by a minimum value of tens of GeV, determined from unsuccessful accelerator searches, and a maximum value of several TeV, above which neutralinos "overclose" the Universe. If neutralinos exist in our galactic halo, they will be gravitationally captured by scattering off elements in the Sun. Annihilation of neutralinos in the Sun will produce a neutrino flux which can be detected on Earth and thus provide indirect evidence for galactic dark matter. We show that a 1-km^2 area is the natural scale of a neutrino telescope capable of probing the GeV–TeV neutralino mass range by searching for high-energy neutrinos produced by their annihilation in the Sun.

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I. INTRODUCTION

If supersymmetry is nature's extension of the standard model it must produce new phenomena at the scale of several TeV or below [1]. A very attractive feature of supersymmetry is that it provides cosmology with a natural dark-matter candidate [2]. The supersymmetric partners of the photon, Z^0, and two Higgs particles form four neutral states, the lightest of which is the stable neutralino. If this lightest supersymmetric particle has an appreciable cosmological relic abundance it may also be responsible for the dark matter known to exist in the galactic halo. Neutralinos in the halo will scatter off elements in the Sun and become gravitationally trapped [3, 4]. The trapped neutralinos will annihilate producing high-energy neutrinos which may be detected on Earth [5–7]. The Kamiokande [8] and Irvine-Michigan-Brookhaven (IMB) [9] collaborations have already demonstrated that this indirect neutrino signature provides us with a powerful tool for searching for dark matter. They extended limits on neutralinos in the 30–80 GeV window by using this technique.

If neutralinos have masses greater than a few TeV, they "overclose" the Universe. Supersymmetry has therefore been framed inside a well-defined GeV–TeV mass window. Here we ask the question "what size telescope is required to search this range?" We conclude that neutrino detectors of order 1 km^2 are required, although clearly progress is possible with any experiment larger than Kamiokande [5, 10]. There are several projects underway which plan to deploy neutrino telescopes of this scale [11].

The parameter space of supersymmetric models is complicated, even in the so-called minimal supersymmetric standard model (MSSM) [1]. The model is specified by the top-quark mass m_t and five parameters: two unphysical masses M_2 and μ, the ratio of the Higgs vacuum expectation values $\tan\beta = v_2/v_1$, the mass of the lightest Higgs boson M_{H_2}, and the squark masses $M_{\tilde{q}}$. Some of these parameters are constrained by accelerator searches and by cosmological considerations. The ratio of the Higgs vacuum expectation values is bracketed by the values $(1, m_t/m_b)$ where m_b is the bottom-quark mass. Radiative corrections tend to drive the ratio above unity, and the upper bound results from constraints on electroweak symmetry breaking in supergravity models [12]. Unsuccessful accelerator searches have pushed the lightest-Higgs-boson mass above 50 GeV [13]. Finally, naturalness and cosmology favor values of M_2 and μ less than or of the order of 10 TeV; some would argue much less. This still leaves us with a large parameter space to search. In order to perform a manageable analysis of the problem, we choose M_2 and μ as our independent parameters, and fix all other parameters to reasonable values. We set $m_t = 120$ GeV, $\tan\beta = 2$, M_{H_2}=50 GeV, and the squark masses to be either infinite (which minimizes interactions involving quarks and leptons, thereby maximizing the relic abundance but minimizing capture rates), or 2.5 times the neutralino mass which minimizes the relic abundance and maximizes the capture rate.

Once these parameters have been specified, standard big-bang cosmology can be used to determine the relic abundances of neutralinos in the Universe. Some of the parameter space can be readily eliminated since the corresponding models result in an unacceptably large relic density, i.e., $\Omega_\chi h^2 \gtrsim 1$ where Ω_χ is the fraction of critical density contributed by neutralinos and h is the Hubble parameter in units of 100 km sec^{-1} Mpc^{-1}. On the other hand, since the fraction of critical density contributed by halos is $\Omega_{\rm halo} \sim 0.1$ and h may be ~ 0.5, we say that if $\Omega_\chi h^2 \lesssim 0.02$ the neutralino relic abundance is cosmologically consistent but too small to account for the halo dark matter. On the other hand, in models where $\Omega_\chi \gtrsim \Omega_{\rm halo}$ it is reasonable to assume that the galactic halo dark matter *is* made up of neutralinos and that the local mass density in neutralinos is 0.4 GeV cm^{-3}. The shaded regions in Fig. 1(a) are thus excluded as dark-matter candidates; i.e., these models do not satisfy $0.02 \lesssim \Omega_\chi h^2 \lesssim 1$. The dependence of the relic density on the squark mass is important here and illustrated in Fig. 1(b) which repeats the previous calculation with the squark mass set to 2.5 times the neutralino mass.

Our main conclusions follow from Figs. 2(a)–2(c) which show the detector area required to observe one neutrino event per year. This quantity is shown as a function of M_2 and μ in Figs. 2(a) and 2(b) for the two values of the squark mass taken, as before, to be infinite and 2.5 times the neutralino mass. Various annihilation thresholds are clearly visible. Most noticeable are the thresholds associated with the W and Z masses near 100 GeV. The graphs confirm that a detector of km^2 scale is required to

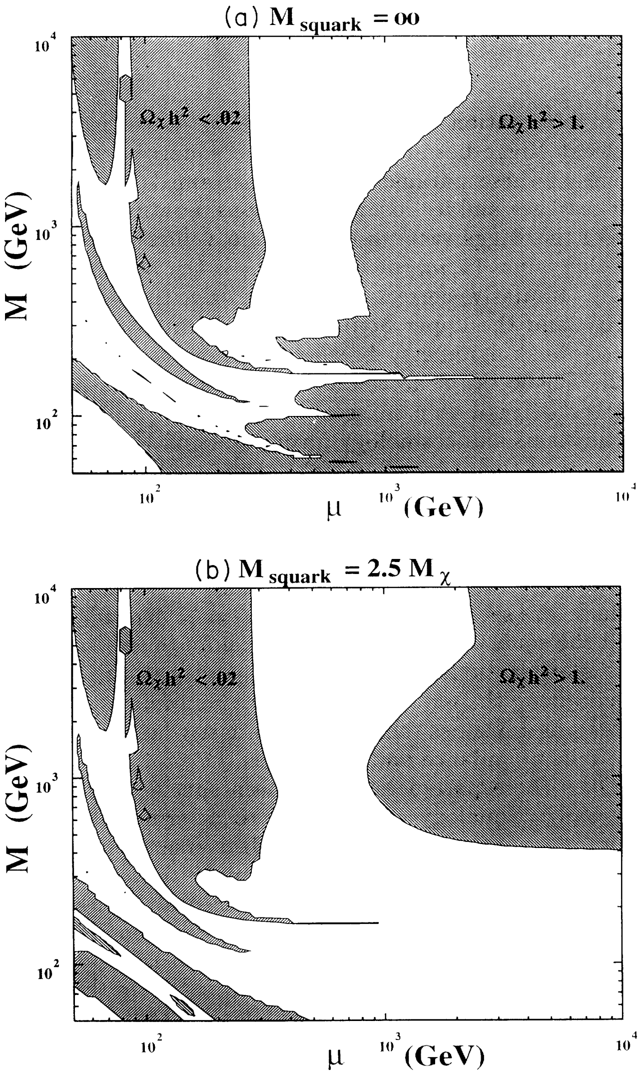

FIG. 1. Regions in the M_2-μ plane in which the neutralino is not a good dark-matter candidate. Upward diagonal regions are areas where $\Omega_\chi h^2 > 1$. Downward diagonal regions are areas where $\Omega_\chi h^2 < 0.02$. (a) shows regions with $M_{\tilde{q}} = \infty$, (b) shows regions with $M_{\tilde{q}} = 2.5\, M_\chi$.

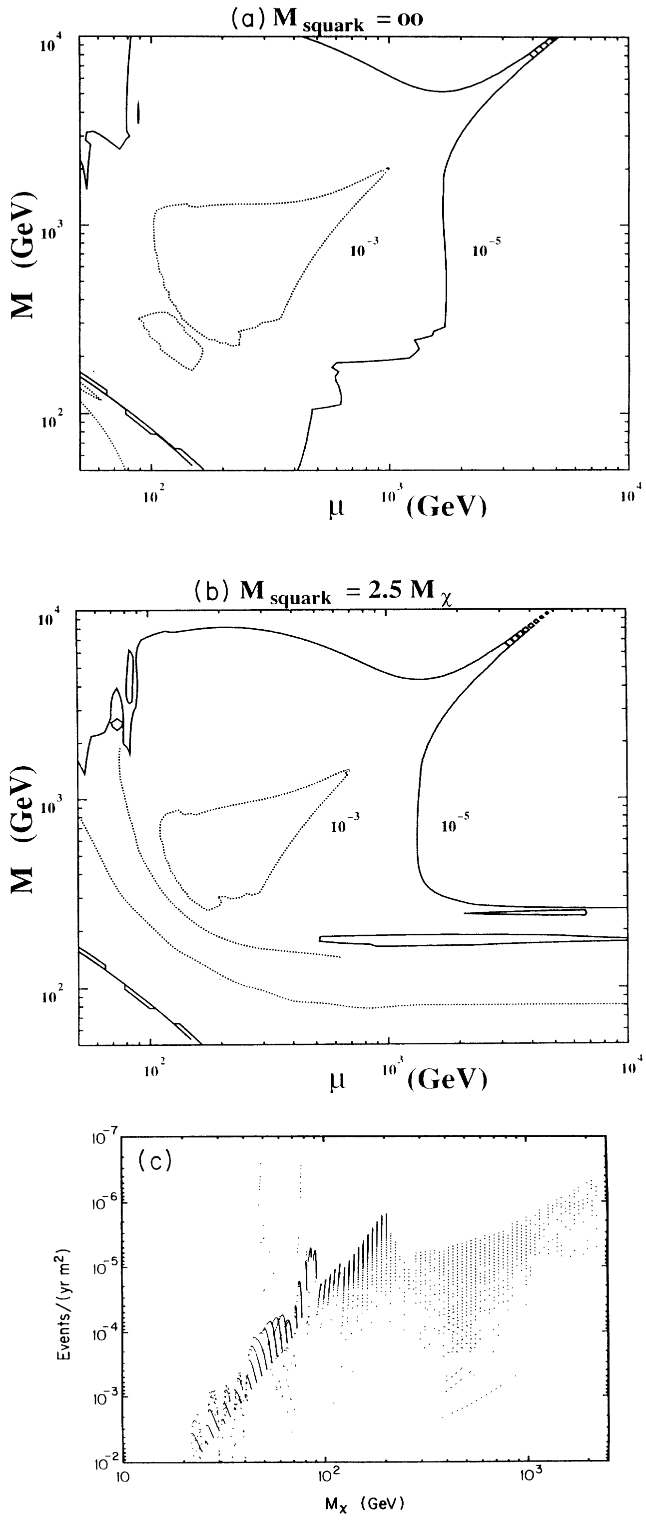

FIG. 2. Events m^{-2} yr^{-1}. (a) and (b) show contours of constant detection rate in the M_2-μ plane for $M_{\tilde{q}} = \infty$ and $M_{\tilde{q}} = 2.5\, M_\chi$. (c) shows the same information as (b) but in a slightly different way. Each dot gives the event rate for a point in the M_2-μ plane in which the neutralino is a good dark-matter candidate ($0.02 \lesssim \Omega_\chi h^2 \lesssim 1$). Note that the density of points is proportional to the area in the M_2-μ plane. We fix $m_t = 120$ GeV, $\tan\beta = 2$, $M_{H_2} = 50$ GeV, and $M_{\tilde{q}} = \infty$.

study the full neutralino mass range. The scatter plot of Fig. 2(c) shows the information in Fig. 2(b) in a slightly different way. Each dot gives the event rate for a point in the M_2-μ plane in which the neutralino is a good dark-matter candidate ($0.02 \lesssim \Omega_\chi h^2 \lesssim 1$). Note that the density of points is proportional to the area in the M_2-μ plane. The figure clearly shows that, except for some very special parameters, the discovery of supersymmetric dark matter is within reach of any detector exceeding a 10^5 m^2 area. In order to better illustrate the capabilities of an underground detector we show in Figs. 3(a)–3(c) the detector size required to observe a 4σ signal in one year. The background is from neutrinos produced in cosmic-ray-induced air showers arriving within a 5° cone of the Sun. If the detector can give some crude information on the energy of the neutrino, then the sensitivity of the instrument can be improved because the direction of the neutrinos can be traced to the Sun with an improved accuracy [11]. The calculation still does not include efficiencies and on time of the detector. On the other hand, it is expected that the Earth will produce a signal similar in magnitude to the one calculated from the Sun. For the high end of the GeV–TeV mass range investigated here, the signals from the Sun dominate by a factor of roughly 5 [4]. This result is, however, reversed for the lower neutralino masses. For low-mass neutralinos, signals from the Earth will significantly increase sensitivity. We still conclude that realistically even larger detectors, or better methods of suppressing background, will be required to completely probe MSSM dark matter. However, km-scale detectors will detect dark matter or constrain minimal supersymmetric models to small areas of parameter space.

II. CALCULATION

The details of the capture and annihilation rates entering the neutrino-flux calculation and the computation of the detected neutrino signal can be found in [5] and references therein. The calculation is based on several assumptions in addition to the assumption of the standard MSSM as reviewed in Ref. [1]. We also assume an isotropic Maxwell-Boltzmann distribution of neutralinos with a galactic halo density of 0.4 GeV cm^{-3} and a dispersion velocity 300 km sec^{-1}. We further assume that the Sun moves through the halo with a velocity of 250 km sec^{-1} and use the standard solar model of Bahcall and Ulrich [14] to obtain the distribution of elements in the Sun.

To determine the neutrino energy spectrum at the surface of the Sun given the injection of the annihilation products in the core of the Sun, we use the results of Ritz and Seckel [7]. Since adequate information was not available at high energy, we parametrized the second moment of the neutrino flux: $\int_0^\infty E^2 \frac{dn}{dE} dE$. The actual integral needed for the detection rate is $\int_{E_{\min}}^\infty E^2 \frac{dn}{dE} dE$. Here $E_{\min} \simeq 10$ GeV is the detector threshold energy. The associated error should be small since we are generally looking at neutrinos with energies of order $\frac{1}{3}$ (for an annihilation product, e.g., a τ lepton, undergoing a three-body

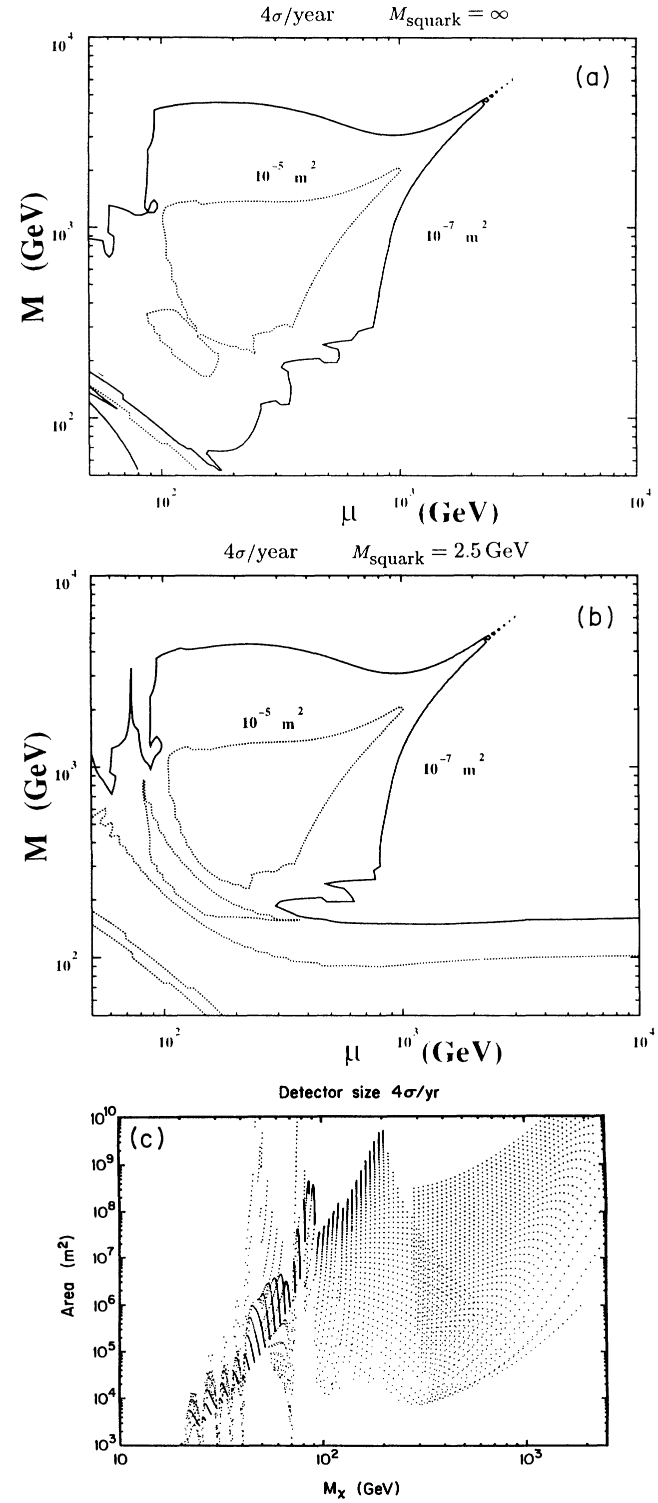

FIG. 3. Detector area required to observe a 4σ effect in one year. (a) and (b) show contours of constant detector area in the M_2-μ plane for $M_{\tilde{q}} = \infty$ and $M_{\tilde{q}} = 2.5\,M_\chi$. (c) shows the same information as (b) but in a slightly different way. Each dot gives the detector size required to observe a 4σ signal in one year for a point in the M_2-μ plane in which the neutralino is a good dark-matter candidate ($0.02 \lesssim \Omega_\chi h^2 \lesssim 1$). Note that the density of points is proportional to the area in the M_2-μ plane. We fix $m_t = 120$ GeV, $\tan\beta = 2$, $M_{H_2} = 50$ GeV, and $M_{\tilde{q}} = \infty$.

decay) to $\frac{1}{2}$ (for those such as a W boson undergoing a two-body decay) times the neutralino mass.

The primary background to the signal is from cosmic-ray-induced air showers. We used the atmospheric neutrino parametrization of Volkova [15], and determined the detection signal following the work of Gaisser and Stanev [16]. We accepted as background any neutrinos which arrived within a 5° cone centered around the Sun, and with energy greater than 10 GeV. Figures 3(a) and 3(b) show the results of this calculation, the area required to detect a 4σ signal in one year.

III. RESULTS AND DISCUSSION

Our central results are displayed in Figs. 2 and 3, which define the detector area required to study supersymmetry in the GeV–TeV range. The graphs confirm that a detector of km^2 scale is required to study the full neutralino mass range. It is clear from Fig. 2, however, that even detectors of more modest size can improve on the current accelerator and underground-detector results. Some neutralinos of 1 TeV mass are observable in a detector just a few times 10^3 m^2. This is just outside the reach of today's largest neutrino detector Gran Sasso, which has an effective area of 10^3 m^2.

We would like to point out that these calculations are only intended to gauge the order-of-magnitude size of detectors required to search the MSSM parameter space for dark-matter candidates. Since extensions of supersymmetry, beyond the minimal model discussed here, can always be invoked to hide the theory beneath experimental limits, we have chosen to make the following simplifications in producing our results: (i) we ignored higher-order radiative corrections to the MSSM; (ii) we show graphs only for an *ad hoc* value $\tan\beta = 2$; this value represents a typical detection rate in the allowed range (1.6,25); and (iii) we fix the neutralino density to the galactic dark-matter density of 0.4 GeV cm^{-3}.

We conclude that a neutrino telescope of 10^5 m^2 or more is clearly a superb instrument to search for supersymmetric dark matter and offers great promise for discovery should the galactic halo be composed of neutralinos. Its failure to observe dark-matter particles would force supersymmetrists to fine-tune their models into small regions of parameter space.

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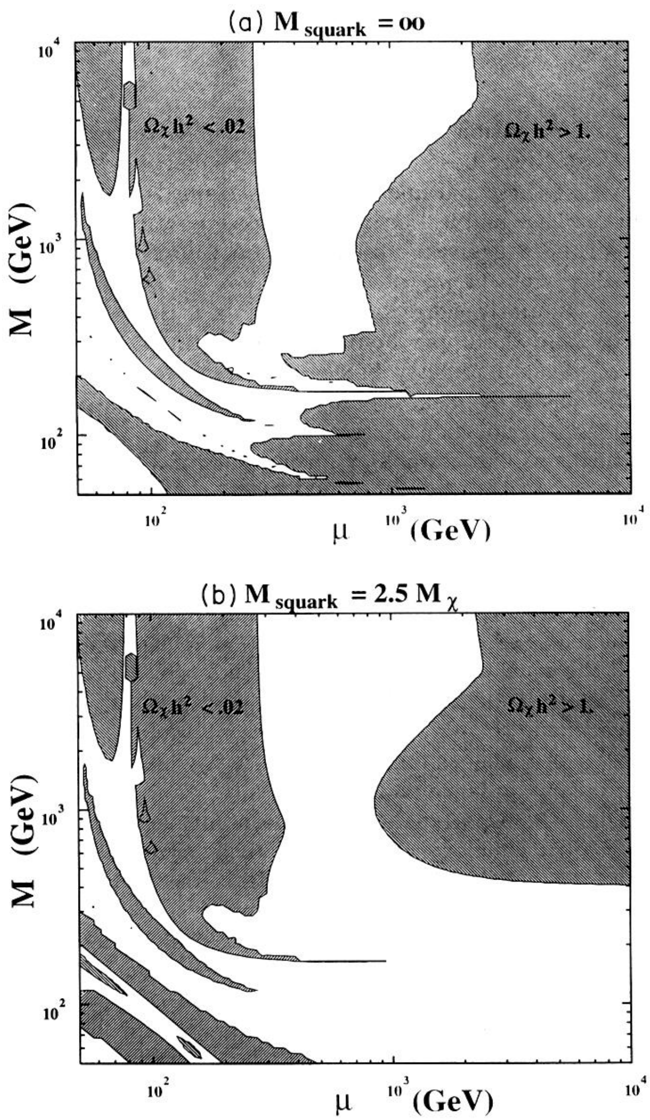

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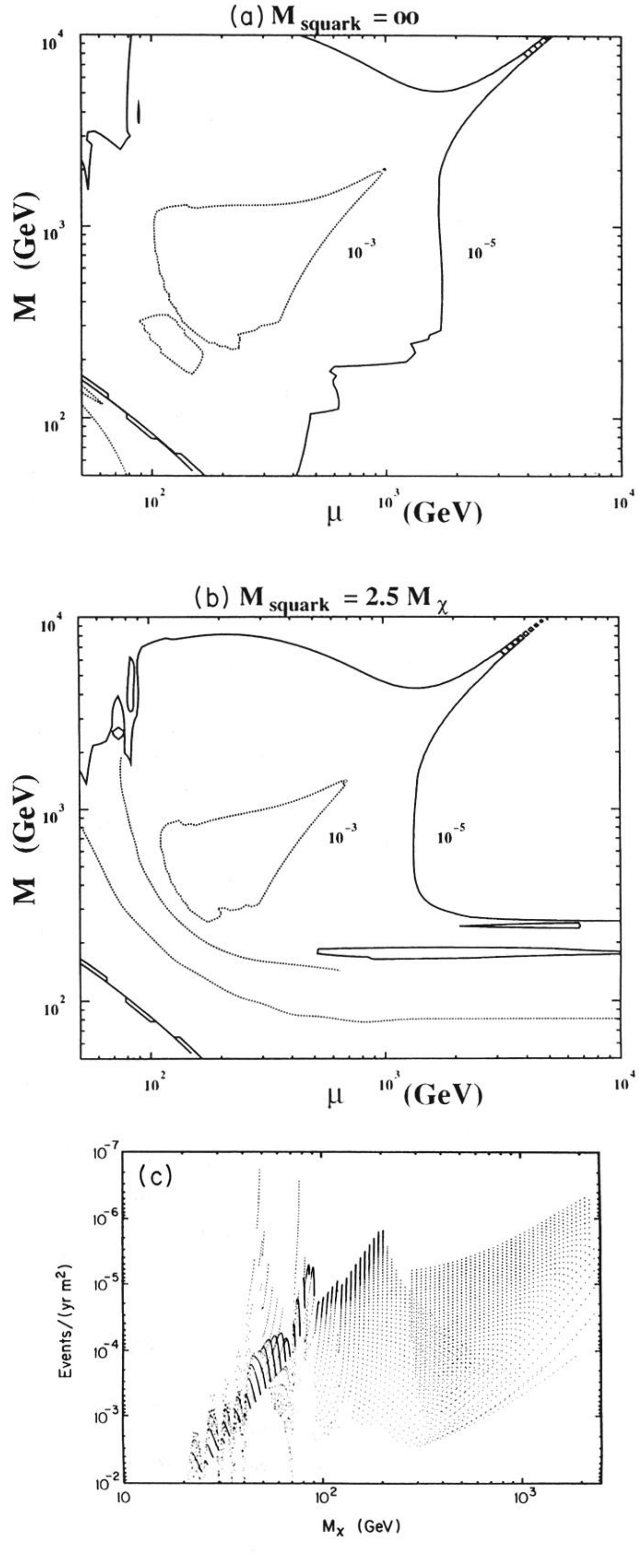

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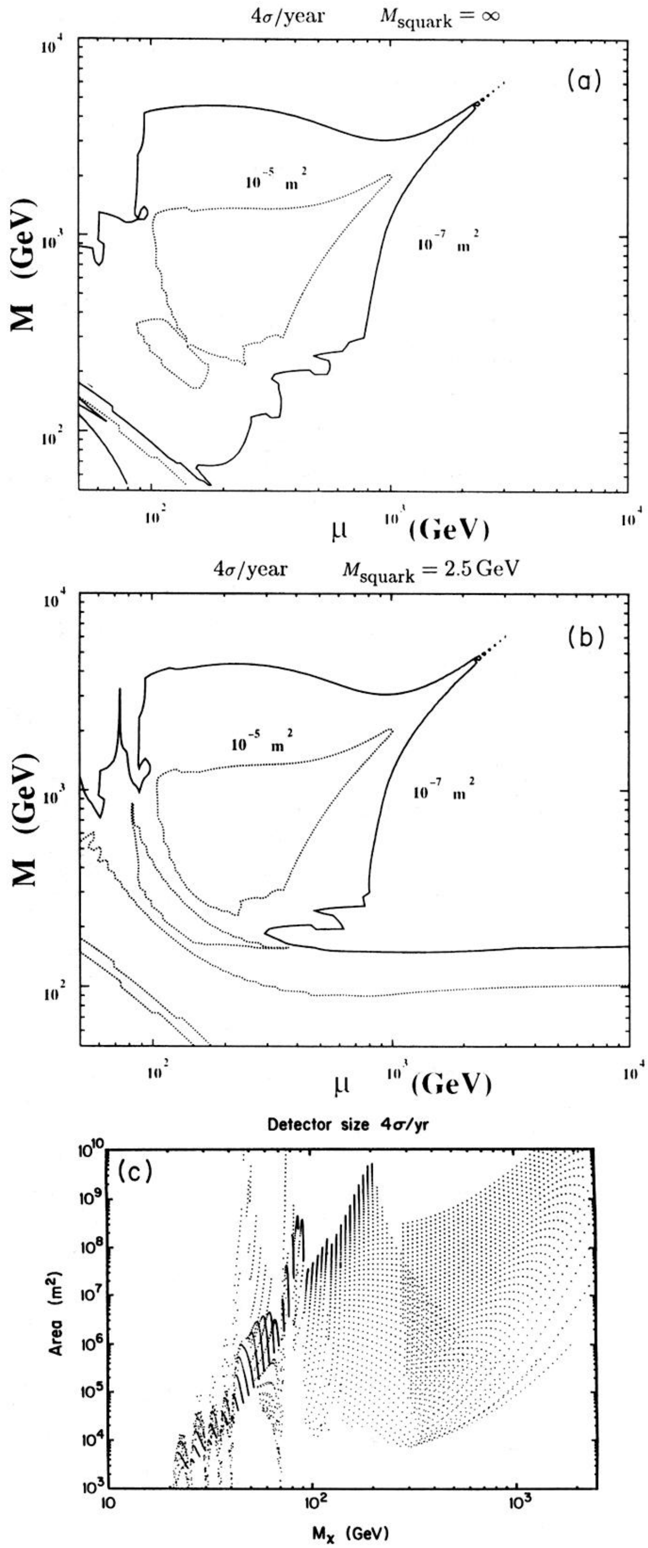

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