Title

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Searching for halo dark matter through γ ray lines [*]

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Abstract

We study the possibility of detecting halo cold dark matter through the annihilation process $\chi\bar{\chi} \rightarrow \gamma\gamma$. While such a process produces monoenergetic γ rays, and would be a clear signature of particle dark matter, we show that it will be very difficult to observe if there is a closure density of dark matter.

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1 - Introduction

There is a considerable interest in the possible detection of dark matter [1] through astrophysical observations as well as terrestrial observations [2,3]. If dark matter is made up of massive, weakly interacting particles, one of the best indirect signatures would be the detection of annihilation products of these particles [4,5,6,7]. It has been recently suggested [8,9,10,11,12] that if the halo of our Galaxy is made of particles in the mass range 1 GeV to 100 GeV, and if these particles self-annihilate, as most of the potential candidates do, then monoenergetic γ rays should be observed when they annihilate directly into two photons. The energy of these γ's is very nearly equal to the mass of the (non-relativistic : $v/c \sim 10^{-3}$) parent particles. Very narrow γ lines in the range 1 GeV to 100 GeV would provide a clear signature for dark matter annihilation, if they stand out above the background.

We studied the flux of such γ rays on a space detector, coming from the annihilation of neutral supersymmetric particles such as the photino $\tilde{\gamma}$ or the higgsino $\tilde{h}$, and from a heavy Dirac or Majorana neutrino. We then compared this flux to estimates of the γ background in the range 1 GeV to 100 GeV. Details will be presented in a forthcoming publication, but we essentially conclude that the observation of these γ lines will be very difficult in almost all cases of interest, even with the next generation of gamma ray observatories (GRO and ASTROGAM [13]).

2 - Flux from photino annihilation

The photino $\tilde{\gamma}$ is the supersymmetric partner of the photon, and one of the foremost candidates for dark matter because it naturally implies a near-critical density for the universe. We assume that the dark matter halo of our Galaxy is nearly spherical and nearly isothermal. Then, the dark matter density varies with the distance r to the galactic center as :

$$\rho(r) = \rho_{\odot} \frac{a^2 + r_{\odot}^2}{a^2 + r^2} \tag{1}$$

where $\rho_{\odot}$ is the dark matter density in the solar neighbourhood and a is the core radius. We consider the annihilation process $\tilde{\gamma}\tilde{\gamma} \to \gamma\gamma$, the cross-section for which is $\sigma_{2\gamma}$. The mass of the photino may range from 1 GeV to 100 GeV according to specific models, whereas their mean velocity in the halo is $v \sim 300\, km/s$. The energy E_{γ} of the outgoing γ's is therefore practically equal to the photino mass $m_{\tilde{\gamma}}$. The number of photons received at a detector in the solar system, from photino pair annihilations taking place at a distance R and in the direction defined by galactic latitude b and longitude l is [14] :

$$F = \frac{\sigma_{2\gamma} v}{2\pi} \int_0^\infty \left[\frac{\rho(R,b,l)}{m_{\tilde\gamma}}\right]^2 dR \ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1} \tag{2}$$

when summed over the distance R. This gives :

$$F = \frac{\sigma_{2\gamma} v}{4\pi} \left(\frac{\rho_\odot}{m_{\tilde\gamma}}\right)^2 a \, \frac{(1+A^2)^2}{B^3} \left[\frac{\pi}{2} + \frac{AB}{1+A^2} cosb\,cosl + tan^{-1}\left(\frac{A\,cosb\,cosl}{B}\right)\right] \tag{3}$$

where $A = r_\odot/a$ and $B = \sqrt{1 + A^2(1 - cos^2 b\, cos^2 l)}$. At high galactic latitudes ($b \sim 90^o$), this reduces to :

$$F \sim \frac{\sigma_{2\gamma} v}{8} \left(\frac{\rho_\odot}{m_{\tilde\gamma}}\right)^2 a \sqrt{1 + A^2} \tag{4}$$

The rate of annihilation of two photinos into two photons has been computed by Bergström and Snellman [8] and by Rudaz [12], whose estimates of $\sigma_{2\gamma}$ differ by nearly 2 orders of magnitude. We have recomputed the cross-section and agree with Rudaz's result :

$$\sigma_{2\gamma} v = \frac{16\alpha^4}{\pi} m_{\tilde\gamma}^2 \left|\sum_f \frac{Q_f^4}{m_{\tilde f}^2} I\left(\frac{m_{\tilde f}^2}{m_{\tilde\gamma^2}}\right)\right|^2 \tag{5}$$

where the sum runs over all the quarks and leptons f . Q_f is the electric charge of fermion f and $m_{\tilde f}$ is the mass of its scalar partners $\tilde f$. α is the fine structure constant. The complex valued function $I(x)$ is defined as :

$$I(x) = \frac{1}{2}\left(1 - x\left[tan^{-1}\left(\frac{1}{\sqrt{x-1}}\right)\right]^2\right) \tag{6}$$

One can assume that all the scalar masses $m_{\tilde f}$ are equal to some common value $\tilde M$. We have relaxed this (unrealistic) assumption without any major change in the results. Previous studies of the monochromatic gamma signature of dark matter annihilation took $\tilde M$ as fixed, leading to the conclusion that $\sigma_{2\gamma} v$ behaved as $m_{\tilde\gamma}^2$ (because $\lim_{x\to 0} I(x) = 0.5$), and that the flux F was therefore independent of the photino mass. As the background decreases at high γ energies (i.e. at high photino mass), the conclusion was that the signal-to-noise ratio would improve for heavier photinos [9,12].

However if one assumes that dark matter is made of photinos, consistency requires that the relic density be fixed, not the mass $\tilde M$. For a given photino relic density $\Omega_{\tilde\gamma}$, and a given photino mass $m_{\tilde\gamma}$, the mass $\tilde M$ is roughly [15] :

$$\tilde M^4 \sim (40\,GeV)^4 \left(\frac{m_{\tilde\gamma}}{1\,GeV}\right)^2 \Omega_{\tilde\gamma} h^2 \tag{7}$$

except when the photino mass is just above one of the thresholds for annihilation into a quark or lepton pair. As usual, here h is the Hubble constant in units of 100 km/s/Mpc. From Equ. 5, the two-photon annihilation cross-section behaves as $1/\Omega_{\tilde{\gamma}}h^2$, and for a fixed value of $\Omega_{\tilde{\gamma}}h^2$, the annihilation rate into two photons is independent both of the photino mass and of the scalar quark and lepton mass $\tilde{M}$. Therefore the γ flux *decreases* with increasing photino mass, and the expected signal decreases. The two-photon annihilation cross-section $\sigma_{2\gamma}v$ is :

$$\sigma_{2\gamma}v \sim 3.1 \times 10^{-31}\mathrm{cm}^3\mathrm{s}^{-1} \left(\Omega_{\tilde{\gamma}}h^2\right)^{-1} \tag{8}$$

At high galactic latitudes ($l = 90^o$), the flux is then :

$$F \sim 2.2 \times 10^{-10}\ \mathrm{photons\,cm^{-2}\,s^{-1}\,sr^{-1}} \left(\frac{1\,GeV}{m_{\tilde{\gamma}}}\right)^2 \left(\Omega_{\tilde{\gamma}}h^2\right)^{-1} \tag{9}$$

taking $\rho_\odot = 0.4\,GeV/cm^3$ and $a \sim r_\odot \sim 8\,kpc$. A detector of $1\,m^2\,sr$ collecting area, such as ASTROGAM [13], will detect N_{line} photons of energy $E_\gamma = m_{\tilde{\gamma}}$ per year, where :

$$N_{line} \sim 70\ \mathrm{photons} \left(\frac{1\,GeV}{E_\gamma}\right)^2 \left(\Omega_{\tilde{\gamma}}h^2\right)^{-1} \tag{10}$$

Note that, if the photino mass is large, the number of photons detected becomes so low that there is no statistically significant signal.

Actually, Equ. 10 is a crude approximation to the signal that can be expected, since it does not takes into account mass thresholds, nor the (very likely) possibility that different scalar fermions $\tilde{f}$ can have masses $m_{\tilde{f}}$ different from the common assumed value $\tilde{M}$. In addition, this estimate does not take into account the fact that the "freeze-out" temperature, where the photino density drops out of thermal equilibrium and stabilizes [16,15], depends in a complicated way on the photino mass, and thereby affects the resulting relic density. Therefore, we performed an exact computation of the "freeze-out" temperature as a function of the photino mass, taking into account the change in the number of degrees of freedom in the thermal radiation at the time of decoupling. We also computed the annihilation cross-section for the reaction $\tilde{\gamma}\tilde{\gamma} \rightarrow f\bar{f}$, taking into account the energy threshold for the opening of a new $f\bar{f}$ channel. We also took into account the possibility that some scalar partners could be anomalously light. In particular the scalar top quark is very often light in most supersymmetric models, but it must be heavier than the photino (otherwise the photino would be unstable). We studied the case of a scalar top quark almost degenerate in mass with the photino, and saw no noticeable difference. We will detail these calculations and results in a forthcoming publication. Since this is the most extreme situation, we do not think that the assumption of equal masses for the scalar quarks and leptons is a restrictive assumption (in *this* situation of course). We then obtained a more exact relation between the mass of the photino and the masses of the scalar quarks and leptons. This relation was used in the two photon annihilation cross-section (Equ. 5) to compute the expected γ flux and the expected signal. Figure 1 shows the result of this computation, for 3 different values of the relic density ($\Omega_{\tilde{\gamma}} h^2 = 1$, 0.25 and 0.025). The effect of thresholds is seen as small dips in the curves (because the opening of a new $f\bar{f}$ threshold increases the total annihilation rate at the big-bang, which must be corrected by an increase in the scalar mass $\tilde{M}$, and therefore leads to a decrease of the 2 γ annihilation rate).

3 - Background

There is no measurement of γ ray fluxes in the GeV-TeV energy range, so we must extrapolate from lower energy data. There are many different sources of background γ photons. Bremsstrahlung γ's from cosmic ray electrons should be negligible above 1 GeV, but the γ's from the decay of π^o's produced by collisions of cosmic ray protons with the interstellar medium are probably the dominant source of galactic background at energies larger than 1 GeV [17]. From the known distribution of cosmic ray protons, one expects a flux :

$$\frac{dN_{galactic}}{dE_\gamma} \sim 8 \times 10^{-7}\,\mathrm{photons\,cm^{-2}\,s^{-1}\,sr^{-1}\,GeV^{-1}} \left(\frac{1\,GeV}{E_\gamma}\right)^{2.7\pm0.3} \tag{11}$$

at high galactic latitudes, and a correspondingly larger flux in the galactic plane. The extra-galactic background is not well known, and different analyses do not agree on the extrapolation of COS-B and SAS-2 measurements to energies larger than 1 GeV [18]. Since it may drop sharply above 1 GeV, we do not consider it any further, but keep in mind the possibility that it could be of the same order of magnitude as the galactic background. Dark matter provides its own background when it annihilates into fermion-antifermion pairs, which give γ rays among their decay and annihilation end-products, but these γ's have an energy lower than the photino mass (for trivial kinematical reasons), and do not contribute to the line background. To summarize, we take Equ. 11 as representing the background, but we must keep in mind that the background could be an order of magnitude larger. Since the aim is to detect a narrow line, much narrower than the energy resolution of the detector, the interesting quantity is the number of photons received in one energy bin during the time of observation. For a $1\,m^2\,sr$ detector with a 1% energy resolution (bin width $\Delta E_\gamma = 0.01 E_\gamma$), one year of observation will give :

$$N_{background} \sim 2500 \text{ photons} \left(\frac{1\,GeV}{E_\gamma}\right)^{1.7\pm0.3} \tag{12}$$

If one compares the expected signal N_{line} (Equ. 10) to the background $N_{background}$ (Equ. 12), the situation seems hopeless. But this comparison is actually meaningless. We should *not* compare the expected signal to the background but to the *noise*, i.e. the error in measuring the background. This point was overlooked in previous works, but it does make a difference. The statistical uncertainty is the square root of the number of photons received :

$$Noise \sim 50\,\mathrm{photons}\left(\frac{1\,GeV}{E_\gamma}\right)^{0.85\pm0.15} \qquad (13)$$

The situation is then much better, although still not very bright. For $\Omega_{\tilde{\gamma}}h^2 = 0.25$, very light photinos ($m_{\tilde{\gamma}} < 4\,GeV$) could be detected at the two standard deviation level (see Figure 1, and note that the scale is logarithmic).

The observed galactic plane γ ray emissivity is found to correlate well with the total gas column density, confirming the interpretation of the observed diffuse flux as primarily being due to cosmic ray interactions (mainly π^0 production in the highest COS-B energy range) with interstellar atoms [19]. Analysis of the COS-B data yields an empirical diffuse galactic γ ray emissivity of $4 \times 10^{-27}\mathrm{s}^{-1}\mathrm{sr}^{-1}(\mathrm{H}_{\mathrm{atom}})^{-1}$ in the 300-800 MeV range, and $2 \times 10^{-27}\mathrm{s}^{-1}\mathrm{sr}^{-1}(\mathrm{H}_{\mathrm{atom}})^{-1}$ in the 800 MeV-6 GeV range. The inferred spectral dependence is proportional to $E^{-2.7}$ [20]. It has been suggested [21] that one may examine high latitude holes in the galactic HI distribution for regions of expected low γ ray background. Specifically, we note that sensitive 21 cm surveys of high latitude HI regions [22] find that the HI consists of cold clouds ($T \sim 100\,K$) with probability (at $|b| = 90^o$) :

$$P(N > N_{cloud}) = 0.5\left(\frac{N_{cloud}}{10^{20}cm^{-2}}\right)^{-0.8} \qquad (14)$$

for $3\times10^{19} < N_{cloud} < 2\times10^{20}\,cm^{-2}$, together with an additional 50 % of the HI in diffuse, warm ($T \sim 5000\,K$) gas. In addition there is an ionized gas contribution that we take from the distribution of diffusion Hα emission and pulsar dispersion measures to be modelled by a layer of HII with scale height 1000 pc and electron density 0.03 cm^{-3} [23,24]. We infer a minimum column gas density towards HI "holes" (defined by $N_{cloud} < 3 \times 10^{19}cm^{-2}$) of about $6\times10^{19}cm^{-2}$ in HI and $9\times10^{19}cm^{-2}$ in HII, totalling $1.5\times10^{20}cm^{-2}$. For comparison, the lowest HI column density in the northern sky over a square degree or so amounts to $4.5\times10^{19}cm^{-2}$ [25]. The inferred galactic γ ray background towards the holes is $6\times10^{-7}cm^{-2}sr^{-1}$ in the 300-800 MeV range, and $3 \times 10^{-7}cm^{-2}sr^{-1}$ in the 800 MeV- 6 GeV range.

4 Higgsinos and neutrinos

If the dark matter is made of Dirac or Majorana neutrinos, or of higgsinos, the situation is a little bit less satisfactory. The main change comes from the different dependences of the annihilation cross-sections. The exchange of scalar quarks and leptons contribute very little to the self-annihilation of the higgsinos, and not at all to the neutrino self- annihilations. The main contribution comes from the exchange of the Z^0 and gives [12,26] :

$$\sigma(\chi\chi \to \gamma\gamma)\, v \sim \frac{2\alpha^2 G_F^2 cos^2 2\beta}{\pi^3} m_\chi^2 \left| \sum_f Q_f^2 T_f\, I\left(\frac{m_f^2}{m_\chi^2}\right)\right|^2 \tag{15}$$

where χ is either a higgsino or a Majorana neutrino. G_F is the Fermi coupling constant, T_f is the third component of the weak isospin of fermion f, and β is an arbitrary parameter in the higgsino case (related to the difference of the vacuum expectation values of the two Higgs fields), and has value zero in the Majorana neutrino case. The annihilation cross-section is 4 times smaller for a Dirac neutrino than for a Majorana neutrino.
The maximal effect obtains for $\beta = 0$, and when the χ mass is much smaller than the top quark mass. Then :

$$\sigma_{2\gamma}\, v \sim 6.2 \times 10^{-34}\, \mathrm{cm}^3\mathrm{s}^{-1} \left(\frac{m_\chi}{1\, GeV}\right)^2 \tag{16}$$

When the χ is much heavier than the top quark, the cross-section is zero as a consequence of the anomaly cancellation mechanism of the electroweak standard model, as Rudaz remarked [12].
We see immediately that the cross-section is much smaller than in the case of the photino, which can be traced to the higher mass of the exchanged Z^0 compared to the scalar quark and lepton mass $\tilde{M}$. It is not a surprise therefore to find a smaller flux and a smaller number of γ's at a detector :

$$F \sim 4.35 \times 10^{-13}\, \mathrm{photons\, cm^{-2}\, s^{-1}\, sr^{-1}} \tag{17}$$

at high galactic latitudes. Note that the mass of the higgsino or neutrino cancels out in the computation of the flux. A detector of $1\, m^2\, sr$ collecting area will detect :

$$N_{line} \sim 0.14\, \mathrm{photon}\, per\, year \tag{18}$$

which is completely hopeless, *whatever the background.* Since the annihilation cross-section is 4 times smaller for a Dirac neutrino, the signal will be even less detectable.

We performed the same kind of numerical analysis for the neutrino and higgsino cases as for the photino cases, taking thresholds into account and differences in freeze-out temperature. As figure 2 shows, thresholds have an important effect, but in the Ωh^2 range of interest, they decrease the expected signal.

5 Conclusions

We have shown that the observation of the narrow γ ray line due to dark matter annihilation was barely possible if there is a closure density of dark matter ($\Omega h^2 > 0.25$). In the most favourable case, namely if the dark matter is made up of photinos with light masses ($m_{\tilde{\gamma}} <$ 5 GeV), the signal-to-noise ratio is of order one for a detector of 1 $m^2 sr$ acceptance, operating for one year. The detection of the γ ray line from Majorana or Dirac particle annihilations is impossible. The signal is buried orders of magnitude below the noise of the background.

The best candidate for the γ ray line detection is the photino, provided its contribution to the dark matter density in the universe is small : $\Omega h^2 \approx 0.025$. Dark matter seems therefore to be elusive with respect to its γ ray line annihilation for a square meter class detector probing the galactic halo. There are at least two reasons for some degree of optimism, however. Suppose that our galactic nucleus, or some remote AGN, is found to be a source of GeV gamma rays. We propose that further scanning of the spectrum with better than one percent energy resolution is a worthwhile follow-up observation. Should a narrow line be found, this would be a "smoking gun" for a dense cloud of weakly annihilating photinos as an energy source for the galactic nucleus. Such dense clouds with gamma ray luminosities that could approach quasar-like luminosities are not unexpected in certain scenarios for galaxy formation [27,21]. Use of high spatial resolution better than 1 degree will enable future γ ray telescopes to probe holes in the galactic halo gas distribution and thereby reduce the expected galactic gamma ray background and improve the signal to noise ratio by a factor of ~ 3 relative to the predictions given in the figures. Moreover, we should not abandon hope that a feasible design for a gamma ray telescope with many square meters of effective area may eventually be forthcoming.

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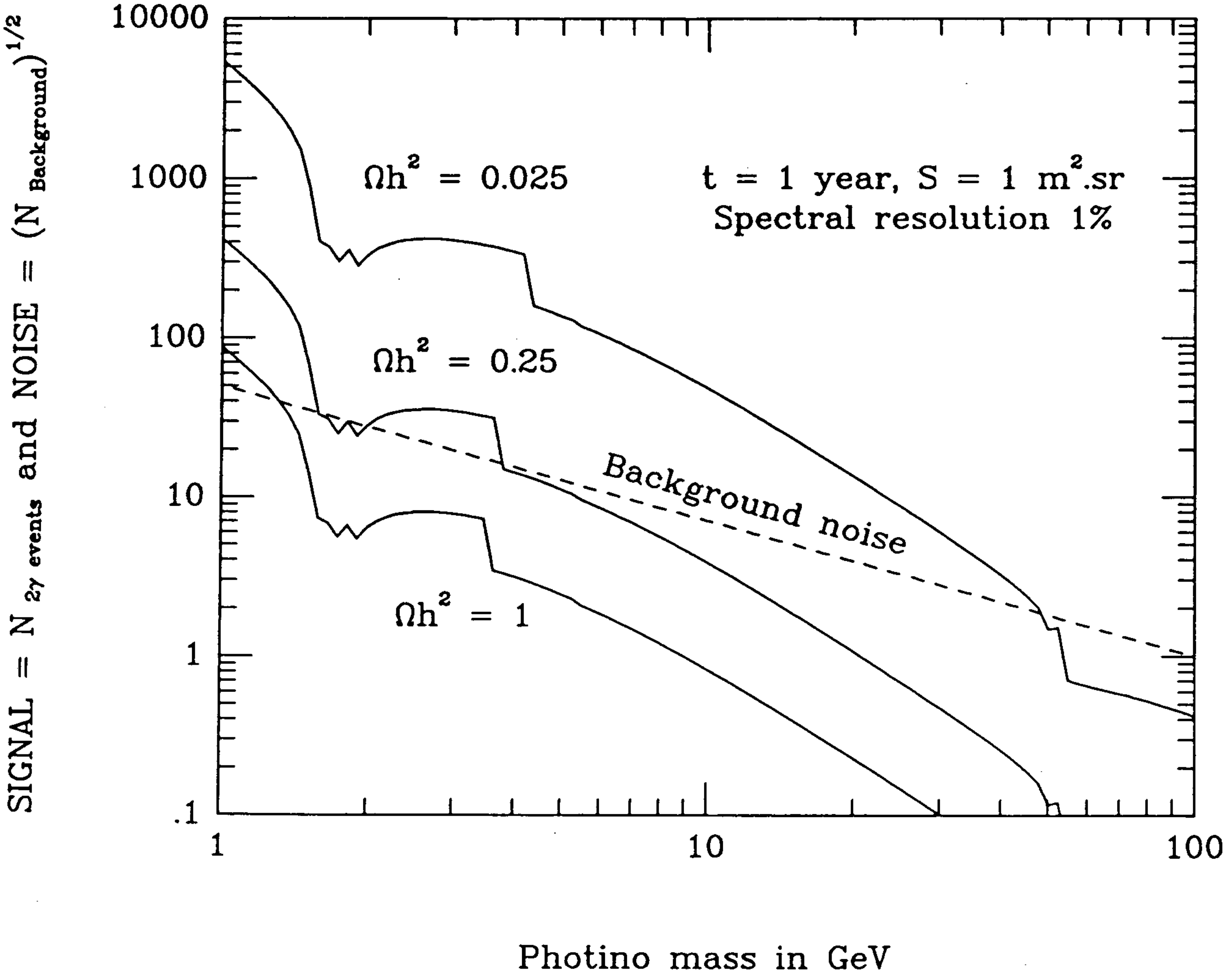
Figure caption

Figure 1 : Expected signal and noise for monoenergetic γ rays due to photino pair annihilation in the halo of our Galaxy. Full lines display the total number of annihilation γ's received on a detector like ASTROGAM (1 $m^2 sr$ detector surface, 1% energy resolution, and one year of exposure), for 3 different relic photino densities $\Omega_{\tilde{\gamma}} h^2 = 1, 0.25 \, \mathrm{and} \, 0.025$. The dotted line corresponds to the noise on the number of background photons received in *the same energy bin* as the annihilation line.

Figure 2 : Same as Figure 1, but in the case of a Majorana ν_M and a Dirac neutrino ν_D. The vertical lines correspond to a relic density $\Omega h^2 = 1$ (left bars) and $\Omega h^2 = 0.025$ (right bars). The higgsino case would correspond to the Majorana line shifted downwards by a factor $cos^2 2\beta$ (see text and Equ. 15).



SIGNAL = $N_{2\gamma\ \mathrm{events}}$ and NOISE = $(N_{\mathrm{Background}})^{1/2}$
10000
1000
100
10
1
.1
1
10
100
Photino mass in GeV
Ωh^2 = 0.025
Ωh^2 = 0.25
Ωh^2 = 1
t = 1 year, S = 1 m^2.sr
Spectral resolution 1%
Background noise

Figure 1

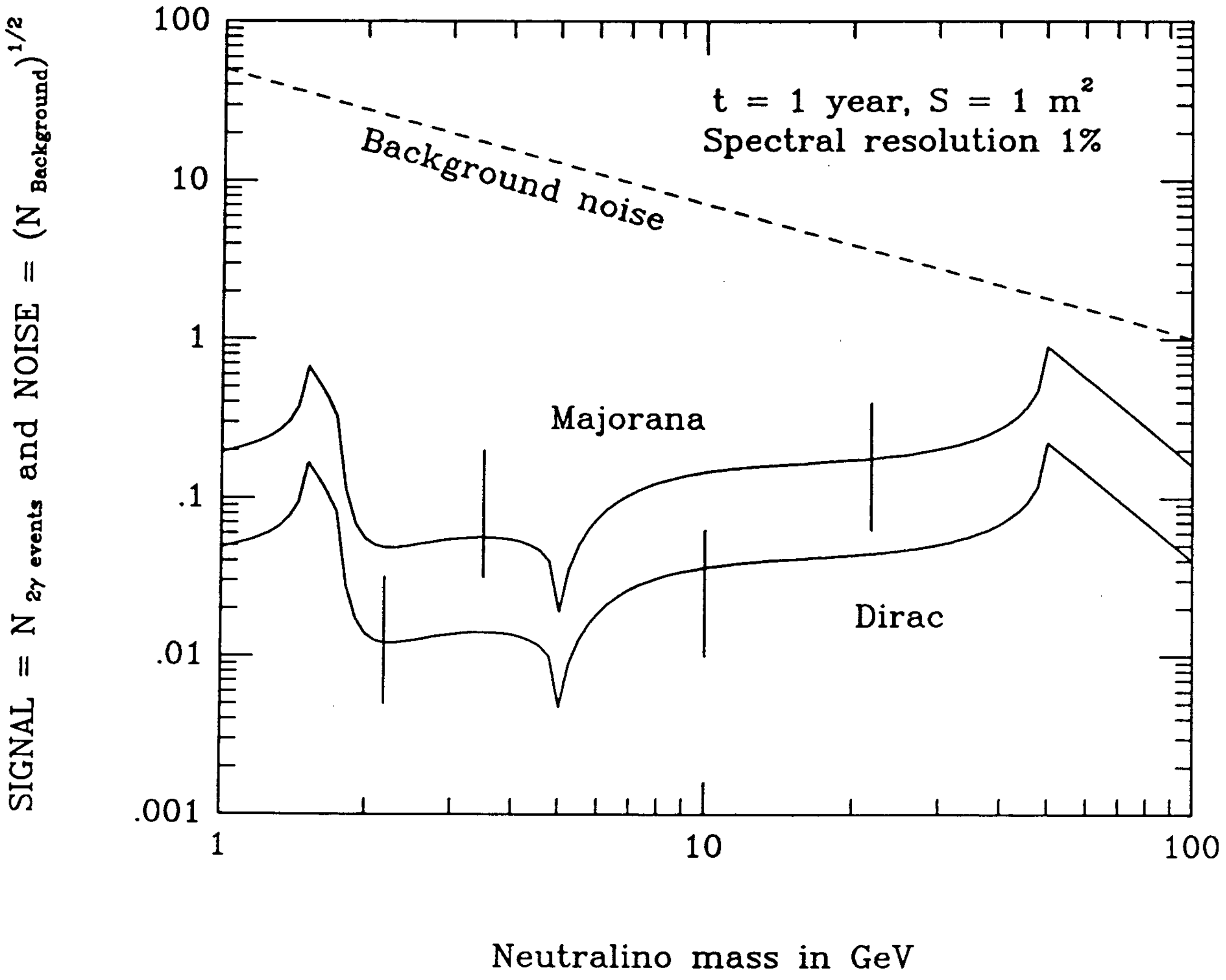

SIGNAL = $N_{2\gamma\ \mathrm{events}}$ and NOISE = $(N_{\mathrm{Background}})^{1/2}$
100
10
1
.1
.01
.001
1
10
100
Neutralino mass in GeV
$t = 1$ year, $S = 1\ \mathrm{m}^2$
Spectral resolution 1%
Background noise
Majorana
Dirac

Figure 2