Abstract

Direct and indirect detection rates of relic neutralinos are reviewed in the framework of the Minimal Supersymmetric Standard Model. The theoretical estimates are compared with the most recent experimental limits from low-background detectors and neutrino telescopes. The properties of neutralino under the hypothesis that preliminary experimental results of the DAMA/NaI Collaboration may be indicative of a yearly modulation effect are examined.

Talk presented at “DM97: Dark matter: perspectives and projects”, Osservatorio Astronomico and ICTP, Trieste, 9–11 December 1997

(published in the Proceedings, editor P. Salucci)

*Report on the work done in collaboration with A. Bottino, F. Donato and S. Scopel.
SUPERSYMMETRIC CANDIDATES FOR DARK MATTER †

NICOLAO FORNENGO
Dipartimento di Fisica Teorica, Università di Torino
and INFN - Sezione di Torino
via P. Giuria 1, 10125 Torino, Italy
fornengo@to.infn.it

ABSTRACT

Direct and indirect detection rates of relic neutralinos are reviewed in the framework of the Minimal Supersymmetric Standard Model. The theoretical estimates are compared with the most recent experimental limits from low-background detectors and neutrino telescopes. The properties of neutralino under the hypothesis that preliminary experimental results of the DAMA/NaI Collaboration may be indicative of a yearly modulation effect are examined.

1. Introduction

Supersymmetric theories predict a large number of particles in excess to the Standard Model ones. If the R–parity is conserved, the lightest among all the supersymmetric particles (LSP) must be stable. This feature makes the LSP a dark matter candidate, since this particle can be present today as a relic from the early stages of the evolution of the Universe. Different candidates have been proposed in the framework of supersymmetric theories: the neutralino or the sneutrino1 in gravity mediated models, the gravitino2 or some messenger fields in gauge mediated theories3, the axino4, stable non–topological solitons (Q–balls)5 or others.

In this paper we will focus on the most promising among all the different candidates, the neutralino, which is defined as the lowest mass linear superposition of photino ($\tilde{\gamma}$), zino ($\tilde{Z}$) and the two higgsino fields ($\tilde{H}_1^0$, $\tilde{H}_2^0$), i.e. $\chi \equiv a_1\tilde{\gamma} + a_2\tilde{Z} + a_3\tilde{H}_1^0 + a_4\tilde{H}_2^0$. The aim of this review is at providing the latest results on the calculation of different kinds of detection rates of relic neutralinos, in the framework of the Minimal Supersymmetric extension of the Standard Model (MSSM), constrained by the most recent experimental data coming from accelerator physics. We do not discuss here the details of the model, for which we refer to Refs.6,7 and to the references quoted therein. We only recall the standard assumptions employed here: i) all trilinear parameters are set to zero except those of the third family, which are unified to a common value $A$; ii) all squarks and sleptons soft–mass parameters are taken as degenerate: $m_{\tilde{q}_i} = m_{\tilde{l}_i} = m_0$; iii) the gaugino masses are assumed to unify at $M_{GUT}$, and this implies $M_1 = (5/3)\tan^2\theta_W M_2$ at the electroweak scale. After these conditions are applied, the free parameters are: $M_2, \mu, \tan\beta, m_A, m_0, A$. The parameters are varied in the following ranges: $10 \text{ GeV} \leq M_2 \leq 500 \text{ GeV}$, $10 \text{ GeV} \leq \mu$...
Fig. 1. The scalar neutralino–nucleon cross section $\sigma_{\text{nucleon}}^{\text{scalar}}$, multiplied by the scaling factor $\xi$, is plotted versus the neutralino mass $m_\chi$. The open curve denotes the 90% C.L. upper bound obtained from the total counting rates of Ref. $^6$. The scatter plot represents the theoretical predictions calculated within the MSSM scheme ($\mu > 0$ only). The closed contour delimits the region singled out at 90% C.L. when the data of Ref. $^{12}$ are interpreted in terms of a modulation signal. 

$|\mu| \leq 500$ GeV, $65$ GeV $\leq m_A \leq 500$ GeV, $100$ GeV $\leq m_0 \leq 500$ GeV, $-3 \leq A \leq +3$, $1.01 \leq \tan \beta \leq 50$. In our analysis the supersymmetric parameter space is constrained by all the experimental limits on Higgs, neutralino, chargino and sfermion searches at accelerators. Moreover, the constraints due to the $b \to s + \gamma$ process $^8$ are satisfied. In addition to the experimental limits, we require that the neutralino is the lightest supersymmetric particle. Finally, the regions of the parameter space where the neutralino relic abundance exceeds the cosmological bound, i.e. $\Omega_\chi h^2 > 1$, are also excluded.

2. Direct detection

Neutralinos interact with matter both through coherent and spin dependent effects $^6, ^9$. We confine our discussion to the coherent effects, since these are the ones which are currently accessible to direct detection $^9$. The relevant quantity, dependent on the supersymmetric parameters, which enters in the event rate of direct detection as well as in the indirect signals considered in Sect. 3, is $\rho_\chi \times \sigma_{\text{nucleon}}^{\text{scalar}}$, where $\sigma_{\text{nucleon}}^{\text{scalar}}$ is the $\chi$–nucleon scalar cross–section and $\rho_\chi$ is the neutralino local density. The expression of $\sigma_{\text{nucleon}}^{\text{scalar}}$ and its relation to the differential event rate for elastic neutralino–nucleus scattering may be found in Ref. $^9$. The $\chi$ local density can be factorized as $\rho_\chi = \xi \rho_l$, i.e. in terms of the total local dark matter density $\rho_l$. Here $\xi$ is evaluated as $\xi = \min(1, \Omega_\chi h^2/(\Omega h^2)_{\text{min}})$, where $\Omega_\chi h^2$ is calculated as a function of the supersymmetric parameters $^6, ^10$ and $(\Omega h^2)_{\text{min}}$ is a minimal value compatible with observational data.
Fig. 2. Flux of up-going muons $\Phi_\mu^{\text{Earth}}$ as a function of $m_\chi$, calculated within the MSSM scheme ($\mu > 0$). The solid (dashed) line represents the experimental 90% C.L. upper bound of Ref. 9 (10).

and with large–scale structure calculations 7. All the results of this paper refer to the choice $\rho_l = 0.5$ GeV cm$^{-3}$ and $(\Omega h^2)_\text{min} = 0.03^6$.

Fig. 1 shows the present most stringent 90% C.L. upper limit on the quantity $\xi\sigma_{\text{scalar}}^{(\text{nucleon})}$, obtained by the DAMA/NaI Collaboration 11. A possible rotation of the galactic halo can affect the exclusion plot less than a factor of two for $m_\chi \gtrsim 50$ GeV 12. In the same figure our results are provided in the form of a scatter plot, obtained by varying the parameters of the supersymmetric model in the intervals quoted above (only $\mu > 0$ is displayed). We see that the scatter plot of the theoretical predictions reaches abundantly the curve of the 90% C.L. upper bound. This shows that the sensitivity of the direct detection experiment is adequate for a significant exploration of the neutralino parameter space. This result applies to the above mentioned choice of the astrophysical parameters $\rho_l$ and $(\Omega h^2)_\text{min}$. Different choices of these parameters inside their allowed ranges 6,9 can change the theoretical predictions roughly by one order of magnitude.

3. Indirect detection at neutrino telescopes

Pair annihilations of neutralinos may provide other signals for the relic neutralino searches. The annihilation process may occur in the galactic halo or inside celestial bodies, like the Earth or the Sun, where the neutralino may have been accumulated as a consequence of gravitational capture. In the case of annihilation in the halo, the signal consists of photon 13, positron and antiproton 14 fluxes, which can be observed by detectors placed on balloons or satellites. Recent calculations of the $\bar{p}$ fluxes in the MSSM will be presented elsewhere 15. In the case of neutralinos captured in the Earth
and in the Sun, the signal is a flux of $\nu_\mu$'s which can be detected as up–going muons in a neutrino telescope. The values of the calculated fluxes of up–going muons$^{16,17}$ $\Phi_\mu^{\text{Earth}}$ and $\Phi_\mu^{\text{Sun}}$ are displayed in Figs.2,3 together with the experimental 90% C.L. upper bounds of Ref.$^{18}$ (solid line) and Ref.$^{19}$ (dashed line). From Figs.2,3 it turns out that many supersymmetric configurations give muon fluxes exceeding the present experimental upper bounds. Also in this case, the variation of the astrophysical parameters may change the calculated fluxes roughly by one order of magnitude.

Another possible indirect signal, relevant to the neutrino telescope searches, may consist in a $\nu_\mu$ flux produced by neutrino annihilation inside the Large Magellanic Cloud (LMC). Theoretical estimates of the neutrino signal from LMC will be presented elsewhere$^{20}$.

4. Direct detection: yearly modulation of the signal

During the orbital motion of the Earth around the Sun, the direction of the velocity of the relic particles with respect to the detector changes as a function of time, and this induces a time dependence in the differential detection rate, i.e.$^{21,22}$

$$S(E, t) = S_0(E) + S_m(E) \cos[\omega(t - t_0)],$$

where $\omega = 2\pi/365$ days and $t_0 = 153$ days (June 2nd). $S_0(E)$ is the average (unmodulated) differential rate and $S_m(E)$ is the modulation amplitude of the rate. The relative importance of $S_m(E)$ with respect to $S_0(E)$ for a given detector, depends both on the mass of the dark matter particle and on the value of the recoil energy where the effect is looked at. Typical values of $S_m(E)/S_0(E)$ for a NaI detector are from a few percent up to roughly 15%, for neutralino masses of the order of 20–80 GeV and recoil energies below 8–10 KeV.
Fig. 4. The configurations compatible with the closed region of Fig. 1 are plotted in the $m_{\chi}$–tan $\beta$ plane, within the gray area. Configurations which provide muon fluxes from the Earth and from the Sun which exceed the limits of Refs.\textsuperscript{9,10} have been dropped. The dark region on the left side is excluded by current LEP data\textsuperscript{3}. The region on the left of the vertical solid line will be accessible to LEP2\textsuperscript{3}. The region on the left of the vertical dashed line will be explorable at TeV3\textsuperscript{3}. In the region delimited by the closed dashed line, the neutralino relic abundance $\Omega_{\chi}h^2$ may exceed the value 0.1.

The DAMA/NaI Collaboration reported on an analysis of a collection of data over an exposure of 4549 Kg × days, obtained with an experimental set-up consisting of nine 9.70 Kg NaI(Tl) detectors\textsuperscript{22}. The extraction of a possible signal is obtained by employing a maximum likelihood method applied to a binning in the recoil energy of the daily counts per detector. When interpreted in terms of a modulation signal due to a WIMP of mass $m_{\chi}$ and elastic cross section $\sigma^{(\text{nucleon})}_{\text{scalar}}$, the data of Ref.\textsuperscript{22} single out (at 90% C.L.) the region of Fig. 1 which is delimited by a closed contour (hereafter defined as region $R_m$). The occurrence of region $R_m$ as a domain relevant for a possible modulation effect will necessarily require further investigation with much higher statistics. This point has clearly been stressed in Ref.\textsuperscript{22}. Meanwhile, it is very interesting to analyze the possible implications that can be inferred from this preliminary result. Specifically, a number of questions deserve to be answered: a) what would be the features of a neutralino to satisfy the prerequisites of region $R_m$; b) would any other experimental search for relic neutralinos be able to investigate the region $R_m$; c) are neutralino configurations of region $R_m$ accessible to accelerator searches in the near future; d) what are the cosmological and astrophysical implications of relic neutralinos whose scalar elastic cross section is compatible with region $R_m$?

We start our analysis by comparing the result of Ref.\textsuperscript{22} with our calculation within the MSSM scheme. This comparison is shown in Fig.1, where we observe that many supersymmetric configurations provide a value of $\xi\sigma^{(\text{nucleon})}_{\text{scalar}}$ compatible with the re-
Fig. 5. The same configurations of Fig. 4 are displayed in the $m_a$–tan $\beta$ plane, within the gray area. The dark regions are excluded by current LEP searches$^3$ or by theoretical arguments. Configurations which provide $\Omega_\chi h^2 > 0.1$ fall within the region delimited by the closed dashed line. The region on the left of the solid line will be accessible to LEP2$^3$.

region $R_m$ (we will call hereafter set $S$ the supersymmetric configurations compatible with region $R_m$). As it was shown in Ref.$^6$, many of these configurations provide sizeable muon fluxes from the Earth and the Sun, reachable by the foreseeable improvements in neutrino telescopes. This result is interesting since it suggests the possibility to have an independent tool of exploration of the same configurations of set $S$. In the case of the indirect signal from the Earth, it is already possible to exclude part of the configurations of set $S$ since they provide muon fluxes exceeding the Baksan and Macro Collaborations limits$^6$. We therefore include in our following considerations only configurations which are not in conflict with indirect searches at neutrino telescopes (we define this subset as set $T$).

Let us now consider the features of the supersymmetric configurations of set $T$. Fig.4 shows, within the gray area, the neutralino mass ranges compatible with set $T$, for different values of tan $\beta$. The dark area on the left side of the figure is excluded by current LEP data$^8$. The region on the left of the vertical solid line around $m_\chi \simeq 50$ GeV is the region explorable by LEP2$^8$. We notice that, as far as the neutralino sector is concerned, LEP will be able to investigate only marginally the region of parameter space singled out by set $T$. A better chance to explore the neutralino mass range compatible with set $T$ is given by the future upgrades at the Tevatron and by LHC. As an example, the region which extends up to the vertical dashed line is the mass region which will be possibly explored by TeV3$^8$.

Fig.5 shows the properties of the configurations of set $T$ with respect to the lightest
The neutralino local density $\rho_\chi$, calculated for $[\xi \sigma_{\text{scalar}}^{(\text{nucleon})}]_{\text{expt}} = 1 \cdot 10^{-9}$ nbarn and $\rho_l = 0.5$ GeV cm$^{-3}$, is plotted versus the neutralino relic abundance $\Omega h^2$. For the value of $[\xi \sigma_{\text{scalar}}^{(\text{nucleon})}]_{\text{expt}}$ employed here, the neutralino mass is restricted to the range $40 \text{ GeV} \lesssim m_\chi \lesssim 85 \text{ GeV}$, as obtained from the closed contour in Fig. 1. The two horizontal lines denote the physical range for the local density of non–baryonic dark matter. The two solid vertical lines denote the physical band for $\Omega h^2$, and the two dashed lines give the preferred band for the cold dark matter contribution to $\Omega$. The two tilted dot–dashed lines denote the band where linear rescaling procedure for the local density is usually applied.

Higgs mass $m_h$, a parameter which is crucial in establishing the size of both direct and indirect detection signals. The gray area in Fig.5 corresponds to values of $m_h$ and $\tan \beta$ compatible with set $T$. The dark regions are excluded by current LEP searches$^8$ (on the left of the plot) or by theoretical arguments (on the right side). In Fig.5 it is also reported the region which will be accessible to LEP2$^8$. A large portion of the region compatible with the modulation analysis will be covered by the LEP2 searches. In particular, all the region for $\tan \beta \lesssim 3$ will be analyzed.

In Ref.$^6$ it was shown that a large number of configurations belonging to set $T$ provide a large value of the neutralino relic abundance. These configurations are very appealing from the point of view of dark matter, and they are shown in Fig.4,5 where the closed dashed line contains the portion of the parameter space where $\Omega_\chi h^2$ may exceed the value 0.1. In order to investigate the cosmological and astrophysical properties of the configurations of set $T$, we present an analysis which is meant to obtain from the experimental data the relevant cosmological implications for relic neutralinos in the most direct way. We adopt the following procedure$^7$: 1) we evaluate $\sigma_{\text{scalar}}^{(\text{nucleon})}$ and $\Omega_\chi h^2$ by varying the supersymmetric parameters; 2) for any value of $[\rho_\chi \sigma_{\text{scalar}}^{(\text{nucleon})}]_{\text{expt}} = \rho_l [\xi \sigma_{\text{scalar}}^{(\text{nucleon})}]_{\text{expt}}$ compatible with the experimental region $R_m$ we calculate $\rho_\chi = [\rho_\chi \sigma_{\text{scalar}}^{(\text{nucleon})}]_{\text{expt}} / \sigma_{\text{scalar}}^{(\text{nucleon})}$ and restrict the values of $m_\chi$ to stay inside
the region $R_m$. 3) The results are displayed in a scatter plot in the plane $\rho_\chi$ vs. $\Omega_\chi h^2$.

One example of our results is given in Fig.6 for $[\xi\sigma^{(\text{nucleon})}_{\text{scalar}}]_{\text{expt}} = 1 \cdot 10^{-9}$ nbarn ($\rho_l = 0.5$ GeV cm$^{-3}$ is used). The two horizontal lines denote the physical range $0.1$ GeV cm$^{-3} < \rho_l < 0.7$ GeV cm$^{-3}$ for the local density of non–baryonic dark matter$^7$. The solid vertical lines denote the physical band for $\Omega h^2$: $0.03 \lesssim \Omega h^2 \lesssim 1$, and the two dashed lines give the favored band for the cold dark matter contribution to $\Omega$: $0.1 < (\Omega h^2)_{\text{CDM}} < 0.3^7$. The two tilted dot–dashed lines denote the band where linear rescaling procedure for the local density is usually applied. With the aid of this kind of plot we can classify the supersymmetric configurations belonging to region $R_m$ into various categories. Configurations whose representative points fall above the maximum value $\rho_\chi = 0.7$ GeV cm$^{-3}$ have to be excluded (those providing an $\Omega_\chi h^2 > 1$ are already disregarded in the plot). Among the allowed configurations, those falling in the region inside both the horizontal and solid vertical lines are very appealing, since they would represent situations where the neutralino could have the role of a dominant cold dark matter component; even more so, if the representative points fall in the subregion inside the vertical band delimited by dashed lines. Configurations which fall inside the band delimited by the tilted dot–dashed lines denote situations where the neutralino can only provide a fraction of the cold dark matter both at the level of local density and at the level of the average $\Omega$. Configurations above the upper dot–dashed line and below the upper solid horizontal line would imply an unlikely special clustering of neutralinos in our halo as compared to their average distribution in the Universe.

5. Conclusions

In this paper we have reported the most recent calculations of the direct and indirect detection rates of relic neutralinos in the framework of the Minimal Supersymmetric Standard Model. We have shown that the theoretical estimates of the detection rates may be at the level of the present experimental sensitivities of low–background detectors and neutrino telescopes. For many supersymmetric configurations, and for median values of the astrophysical parameters which enter in the calculations of the detection rates, the predicted signals may already exceed the present experimental bounds. This shows that the different experimental efforts to search for relic particles are potentially able to deeply investigate the possibility that neutralino is a component of the dark matter of the Universe. An interesting preliminary analysis of the DAMA/NaI Collaboration has shown that their data are compatible, at 90% C.L., with a modulation signal of the direct detection rate. The features of a neutralino able to satisfy the prerequisites of this signal have been analyzed and it has been shown that many configurations are compatible with a dark matter scenario where the neutralino is the major component, both on galactic and cosmological scales. However, we have to remind here that the occurrence of a possible modulation effect will necessarily require further investigations with much higher statistics. This
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