Extending the DAMA annual-modulation region by inclusion of the uncertainties in astrophysical velocities

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The original annual-modulation region, singled out by the DAMA-Nal experiment for direct detection of WIMPs, is extended by taking into account the uncertainties in the galactic astrophysical velocities. Also the effect due to a possible bulk rotation for the dark matter halo is considered. We find that the range for the WIMP mass becomes 30 GeV ≲ m_χ ≲ 130 GeV at 1σ C.L. with a further extension in the upper bound, when a possible bulk rotation of the dark matter halo is taken into account. We show that the DAMA results, when interpreted in the framework of the minimal supersymmetric extension of the standard model, are consistent with a relic neutralino as a dominant component of cold dark matter (on the average in our universe and in our galactic halo). The discovery potential for the relevant supersymmetric configurations at present generation accelerators is also discussed.

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I. INTRODUCTION

The DAMA-Nal Collaboration has recently reported indication of an annual-modulation effect in a direct search experiment for weakly interacting massive particles (WIMPs) [1–3]. In Ref. [3] it has been shown that a statistical (maximum-likelihood) analysis of the data concerning a total exposure of 19,511 kg×day provides, at a 2σ C.L., a well delimited region in the plane \( \rho_x \sigma^{\text{scalar}}_{(\text{nucleon})} - m_\chi \), where \( m_\chi \) is the WIMP mass, \( \rho_x \) is its local (solar neighborhood) density, and \( \sigma^{\text{scalar}}_{(\text{nucleon})} \) is the WIMP-nucleon scalar elastic cross section. Obviously, the location of the annual-modulation region depends on the functional form adopted for the speed distribution of the dark matter particles, and on the values assigned to the galactic astrophysical velocities. In Refs. [1–3] a standard Maxwellian distribution was taken for the WIMP speed distribution with a root mean square velocity \( v_{\text{rms}} = 270 \text{ km s}^{-1} \) and a WIMP escape velocity in the halo \( v_{\text{esc}} = 650 \text{ km s}^{-1} \).

The DAMA-Nal results on annual modulation were analyzed in Refs. [4–8] in terms of relic neutralinos. It was proved that the DAMA-Nal data are compatible with a neutralino as a major component of dark matter in the universe. In Refs. [4–8] it was also shown that a significant number of the relevant supersymmetric configurations are compatible with supergravity schemes [9] and are explorable at accelerators and/or by indirect searches for relic particles (up-going muons at neutrino telescopes and antiprotons in space).

In the present paper we discuss (i) the extension of the DAMA-Nal annual-modulation region in the plane \( \rho_x \sigma^{\text{scalar}}_{(\text{nucleon})} - m_\chi \), when the uncertainties of the galactic astrophysical velocities are taken into account and (ii) the ensuing consequences of this extension in terms of properties for relic neutralinos and for the related supersymmetric configurations [10].

II. EXTENDED ANNUAL-MODULATION REGION

The differential rate for WIMP direct detection is given by

\[
\frac{dR}{dE_R} = N_T \frac{\rho_x}{m_\chi} \int_{v_{\text{min}}}^{v_{\text{max}}} d\sqrt{v} \sqrt{v} d\sigma \frac{d\sigma}{dE_R}(\sqrt{v},E_R),
\]

where \( N_T \) is the number of the target nuclei per unit of mass, \( \sqrt{v} \) and \( f(\sqrt{v}) \) denote the WIMP velocity and velocity distribution function in the Earth frame (\( \sqrt{v} = |\vec{v}| \)), and \( d\sigma/dE_R \) is the WIMP-nucleus differential cross section. The nuclear recoil energy is given by \( E_R = m_N^2 \sqrt{v} (1 - \cos \theta_0) / m_\chi \), where \( \theta_0 \) is the scattering angle in the WIMP-nucleus center-of-mass frame, \( m_N \) is the nuclear mass and \( m_{\text{reac}} \) is the WIMP-nucleus reduced mass. The velocity \( v_{\text{min}} \) is defined as \( v_{\text{min}} \).
The quantity values are assigned to the relevant astrophysical velocities, transfer nuclear form factor, expressed as a function of the momen-
tational velocity remains almost flat

\[ q^2 = \left[ \frac{m_x}{m_p} \right]^{1/2}, \]

where \( q^2 \) is the thickness parameter for the nucleus surface, \( r_0 = (r^2 - 5s^2)^{1/2} \), \( r = 1.2 A^{1/3} \) fm, and \( j_1(qr_0) \) is the spherical Bessel function of index 1.

Once a functional form for \( f(v) \) is chosen and specific values are assigned to the relevant astrophysical velocities, the quantity \( \rho \sigma_{\text{scalar}}^{(\text{nucleon})} \) may be extracted from measure-
ments of the differential rate \( dR/dE_R \) as a function of \( m_X \).

Here, for \( f(v) \) we take the standard Maxwell–Boltzmann distribution (as in an isothermal spherical model for the halo) with a finite escape velocity, i.e., in the galactic rest frame we write

\[ f_{\text{gal}}(v^\text{gal}) = N \left( \frac{3}{2\pi v^2_{\text{rms}}} \right)^{3/2} \exp \left( -\frac{3(v^\text{gal})^2}{2v^2_{\text{rms}}} \right), \]

where the normalization factor is

\[ N = \text{erf}(z) - \frac{2}{\sqrt{\pi}} \exp(-z^2)^{-1}, \]

with \( z^2 = 3v^2_{\text{esc}}/(2v^2_{\text{rms}}) \). In the isothermal spherical model, \( v_{\text{rms}} \) is related to the asymptotic value \( v_{\text{esc}} \) of the rotational velocities by the relation \( v_{\text{rms}} = \sqrt{2} v_{\text{esc}} \). The measured rotational velocity remains almost flat (to roughly 15%) between 4 and 18 kpc; here, we identify \( v_{\text{esc}} \) with the rotational velocity of the local system at the position of the Solar System \( v(\odot) = v_0 \), whose physical range will be shortly discussed.

The assumption employed here that \( v_{\odot} = v_0 \) is the one com-
monly used in the literature (see, for instance, Refs. [12,17,18]), although one should be aware that the determi-
nation of \( v_{\odot} \) may be affected by some uncertainties (for ex-
ample, the disk might provide a non-negligible contribution to the rotation speed at distances larger than the solar radius [12]).

To make use of Eqs. (1), (5) has to be transformed to the rest frame of the Earth, which moves through the Galaxy with a velocity

\[ v_\odot = v_0 + 12 \text{ km s}^{-1}. \]

In these expressions the speed of 12 km s\(^{-1}\) stands for the motion of the Solar System with respect to the local system, \( v_{\odot} = 30 \text{ km s}^{-1} \) denotes the Earth orbital speed around the Sun, the angle \( \gamma = 60^\circ \) is the inclination of the Earth orbit, and \( \omega = 2\pi/365 \) days, \( \tau_0 = \text{June 2nd} [17,19] \). Clearly, the velocity \( v \) of the WIMPs, as seen in the Earth’s frame, is related to their velocity in the Galactic frame \( v^\text{gal} \) by the following set of transformation equations:

\[ v_\odot = v^\text{gal} \cos \gamma \cos(\omega(t - \tau_0)), \]

in the azimuthal direction. \( v_\odot \) is given by

\[ v_\odot = v_0 + 12 \text{ km s}^{-1}. \]

In Refs. [1–5] the DAMA-NaI annual-modulation region was extracted from the experimental data, by using a maximum likelihood method and by taking for the velocities \( v_0 \) and \( v_{\text{esc}} \) the following values:

\[ v_0 = 220 \text{ km s}^{-1} \text{ and } v_{\text{esc}} = 650 \text{ km s}^{-1} \] (the relevant region is one of the domains displayed in Fig. 1). The ensuing implications for relic neutralinos, derived in Refs. [4–8], refer to the same set of astrophysical velocities.

In the present paper we extend the analysis of the annual-
modulation region, by considering the physical ranges asso-
ciated to \( v_0 \) and \( v_{\text{esc}} \) [20–22]:

\[ v_0 = (220 \pm 50) \text{ km s}^{-1} \text{ (90% C.L.)}, \]

\[ v_{\text{esc}} = (450 \div 650) \text{ km s}^{-1} \text{ (90% C.L.)}. \]

The statistical method for the extraction of the annual-
modulation region is the same as the one employed in Refs. [1–3], with a lower bound \( m_X \geq 25 \text{ GeV} \).

On the basis of the analytical properties of the time-
modulated part of the detection rate [17], one expects that a variation in \( v_0 \) induces a sizeable modification in the range of \( m_X \), without affecting \( \rho \sigma_{\text{scalar}}^{(\text{nucleon})} \) significantly. Indeed, an increase (decrease) in \( v_0 \) is expected to extend the original DAMA-NaI region toward lower (larger) WIMP masses for kinematical reasons: \( \rho \sigma_{\text{scalar}}^{(\text{nucleon})} \) cannot appreciably change, since it acts as a normalization factor which is determined by
varying the velocity parameters (anticipated above: 0.3 GeV cm\(^{-1}\) for various values of velocities \(v_0\) and \(v_{\text{esc}}\): \(v_0 = 220\) km s\(^{-1}\), \(v_{\text{esc}} = 650\) km s\(^{-1}\) (solid line); \(v_0 = 220\) km s\(^{-1}\), \(v_{\text{esc}} = 450\) km s\(^{-1}\) (dot–dashed line); \(v_0 = 170\) km s\(^{-1}\), \(v_{\text{esc}} = 550\) km s\(^{-1}\) (dotted line); \(v_0 = 270\) km s\(^{-1}\), \(v_{\text{esc}} = 550\) km s\(^{-1}\) (dashed line). The contour line for \(v_0 = 220\) km s\(^{-1}\), \(v_{\text{esc}} = 550\) km s\(^{-1}\) is indistinguishable on the plot from the solid line. The quantity \(\rho_f^3\) is the local neutralino matter density in units of 0.3 GeV cm\(^{-3}\).

the size of the average detection rate. Also, no sizeable variation of both \(m_\chi\) and \(\rho_\chi\sigma_{\text{scalar}}(\text{nucleon})\) is expected from a variation in \(v_{\text{esc}}\), since the escape velocity provides a cutoff in the integral of Eq. (1) applying only on the flat tail of the velocity distribution \(f(v)\).

We report in Fig. 1 the (2\(^{-}\sigma\) C.L.) annual-modulation regions extracted from the DAMA-NaI data of Ref. [3] (total exposure of 19 511 kg \times day) for sets of values for \(v_0\) and \(v_{\text{esc}}\), which bracket the ranges given in Eqs. (9), (10). The 1\(^{-}\sigma\) ranges for the relevant quantities are given in Table I. Notice that in Fig. 1 the density \(\rho_f\) is given in units of 0.3 GeV cm\(^{-3}\), i.e., \(\rho_f^3 = \rho_\chi/(0.3\text{ GeV cm}^{-3})\).

From the features displayed in Fig. 1 we notice that, as anticipated above: (i) the location of the annual-modulation region is rather sensitive to the velocity \(v_0\), with a sizeable extension in the range of \(m_\chi\), but with small variations in \(\rho_\chi\sigma_{\text{scalar}}(\text{nucleon})\); (ii) the annual-modulation region is essentially independent of \(v_{\text{esc}}\). From the results of Table I we conclude that the uncertainties in \(v_0\) extend the range of \(m_\chi\), as singled out by the DAMA-NaI annual-modulation data, to (at 1\(^{-}\sigma\) C.L.)

\[
30\text{ GeV} \leq m_\chi \leq 130\text{ GeV}. \tag{11}
\]

Taking into account the whole ranges of \(v_0\) and \(v_{\text{esc}}\) [see Eqs. (9), (10)], we find the annual-modulation region which is depicted in Fig. 2. This region, which envelops the domains displayed in Fig. 1, will be hereafter referred to as region \(R_m\).

It is worth noticing that this annual-modulation region might be further extended, if a possible bulk rotation of the dark matter halo is introduced. Unfortunately, halo models which take realistically into account this phenomenon are not yet available; however, effects of rotation of the dark matter halo on direct detection rates and ensuing upper bounds on cross sections have been addressed in some extreme models [23,24]. To obtain an estimate of the effects of a possible rotation of the isothermal sphere one can consider a class of models [25] which describe the fastest rotating steady state by means of the following recipe:

\[
f_{\text{gal}}(v_{\text{gal}}) = \begin{cases} f_{\text{gal}}(v_{\text{gal}}), & v_{\text{gal}} > 0, \\ 0, & v_{\text{gal}} < 0. \end{cases} \tag{12}
\]
III. SUPERSYMMETRIC MODEL

The WIMP candidate considered in this paper is the neutralino, defined as the lowest-mass linear superposition of photino (\(\tilde{\chi}_1^0\)), zino (\(\tilde{Z}^0\)) and the two Higgsino states (\(\tilde{H}_1^0, \tilde{H}_2^0\)) [27]

\[
\chi = a_1 \tilde{\chi}_1^0 + a_2 \tilde{Z}^0 + a_3 \tilde{H}_1^0 + a_4 \tilde{H}_2^0.
\]

To classify the nature of the neutralino it is useful to define a parameter \(P = a_1^2 + a_2^2\); hereafter the neutralino is called a gaugino, when \(P > 0.9\), is called mixed when \(0.1 < P < 0.9\), and a Higgsino when \(P < 0.1\).

The theoretical framework adopted here is the minimal supersymmetric extension of the standard model (MSSM) [27], which conveniently describes the supersymmetric phenomenology at the electroweak scale, without being constrained by too strong theoretical assumptions. Specific details of the scheme employed in this paper are given in Ref. [6]; here we only recall a few essentials.

The large number of free parameters inherent in the model is reduced to six independent ones, by imposing a few assumptions at the electroweak scale: (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: \(m_{\tilde{g}}^2 = m_{\tilde{q}}^2\); (iii) the gaugino masses are assumed to unify at \(M_{\text{GUT}}\), and this implies that the \(U(1)\) and \(SU(2)\) gaugino masses are related at the electroweak scale by \(M_1 = (5/3) \tan^2 \theta_W M_2\).

The six independent parameters are taken to be \(M_2, \mu, \tan \beta, m_\chi, m_{\tilde{g}}, A\), where \(\mu\) is the Higgs-mixing parameter, \(\tan \beta\) is the ratio of the two Higgs vacuum expectation values, and \(m_\chi\) is the mass of the neutral pseudoscalar Higgs boson. To get the scatter plots shown in this paper, the supersymmetric parameter space has been randomly scanned with the parameters delimited by the following ranges: 10 GeV \(< M_2 \leq 1000\) GeV, 10 GeV \(\leq |\mu| \leq 1000\) GeV, 80 GeV \(< m_\chi \leq 1\) TeV, 100 GeV \(< m_{\tilde{g}} \leq 1\) TeV, \(-3 \leq A + 3\), \(1 \leq \tan \beta \leq 50\). The scan has been performed linearly over \(M_2, \mu, m_{\tilde{g}}, A\), and logarithmically over \(\tan \beta, m_\chi\).

Our supersymmetric parameter space is further constrained by all the experimental limits obtained from accelerators on supersymmetric and Higgs boson searches. The latest data from the CERN \(e^+ e^-\) collider LEP2 on Higgs boson, neutralino, chargino, and sfermion masses are used [28]. Also the constraints due to the \(b \rightarrow s + \gamma\) process [29,30] have been taken into account (see Ref. [6] for the theoretical details). The supersymmetric parameter space has also been constrained by the requirement that the neutralino is the lightest supersymmetric particle (LSP), i.e., regions where the gluino or squarks or sleptons are lighter than the neutralino have been excluded.

One further constraint is due to the requirement that the neutralino relic abundance does not exceed the cosmological bound, derivable from measurements of the age of the Universe [31] and of the Hubble constant [32]. We have adopted here a conservative upper bound, \(\Omega h^2 = 0.7\) \([h\text{ is the usual}\]

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**FIG. 3.** Annual-modulation regions when a possible bulk rotation of the dark matter halo is taken into account. The contour lines refer to the following halo parameters: \(v_0 = 220\text{ km s}^{-1}\), corotating halo (solid line); \(v_0 = 220\text{ km s}^{-1}\), corotating halo with spin parameter \(\lambda = 0.05\) (dotted line); \(v_0 = 170\text{ km s}^{-1}\), counter-rotating halo with \(\lambda = 0.05\) (dashed line); \(v_0 = 270\text{ km s}^{-1}\), counter-rotating halo with \(\lambda = 0.05\) (long-dashed line). The escape velocity is fixed at the value \(v_\text{esc} = 550\text{ km s}^{-1}\) for all the contours.

\[
f_{\text{gal}}(v) = \begin{cases} 0, & v_{\text{gal}} > 0, \\ f_{\text{gal}}(v), & v_{\text{gal}} < 0, \\ \end{cases}
\]

where \(v_{\text{gal}}\) is the azimuthal component of \(v_{\text{gal}}\).

Then one can combine the above functions in order to deal with a more general family of distribution functions \(f_{\text{rot}}(v_{\text{gal}})\), defined as [23]

\[
f_{\text{rot}}(v) = a f_{\text{gal}}(v_{\text{gal}}) + (1 - a) f_{\text{gal}}(v_{\text{gal}}),
\]

where \(a\) is related to the dimensionless galactic angular momentum parameter \(\lambda\) by the relation \(\lambda = 0.36|a - 0.5|\). In order to be consistent with the available extensive numerical work on galaxy formation, \(\lambda\) should not exceed the value 0.05 [26].

Adopting the expression in Eq. (14) for the velocity distribution function, one finds that the annual-modulation region may be extended to the domain depicted in Fig. 3, and the relevant range of \(m_\chi\) would become (at 1σ C.L.)

\[
30\text{ GeV} \leq m_\chi \leq 180\text{ GeV}.
\]

Although the possible occurrence of a bulk rotation of the dark matter halo is a quite interesting possibility deserving further investigation, all subsequent analyses of the present paper will refer to the region \(R_m\), given in Fig. 2.

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Hubble parameter, defined in terms of the present-day value $H_0$ of the Hubble constant as $h = H_0/(100 \text{ km s}^{-1} \text{ Mpc}^{-1})$.

The neutralino relic abundance is calculated here as in Ref. [33]. Inclusion of coannihilation effects [34] in the calculation of $\Omega_\chi h^2$ turns out not to be necessary in the present analysis, since the instances under which these effects might be sizeable [34] are marginal for the supersymmetric configurations concerning the DAMA-Nal data.

Whenever we have to evaluate the neutralino local density without use of the DAMA data, we employ the rescaling procedure. This rescaling consists in assuming that the neutralino local density $\rho_\chi$ may be taken as $\rho_\chi = \xi \rho_1$ ($\rho_1$ is the total local density of non-baryonic dark matter), with $\xi = \min \left[ 1, \Omega_\chi h^2/(\Omega h^2)_{\min} \right]$, i.e., $\rho_\chi$ may be set equal to $\rho_1$ only when $\Omega_\chi h^2$ is larger than a minimal value $(\Omega h^2)_{\min}$, compatible with observational data and with large-scale structure calculations; otherwise, when $\Omega_\chi h^2$ turns out to be less than $(\Omega h^2)_{\min}$, and then the neutralino may only provide a fractional contribution $\Omega_\chi h^2/(\Omega h^2)_{\min}$ to $\Omega h^2$, $\rho_\chi$ is reduced by the same fraction $\xi = \Omega_\chi h^2/(\Omega h^2)_{\min}$ as compared to $\rho_1$. The value to be assigned to $(\Omega h^2)_{\min}$ is somewhat arbitrary, in the range $0.01 \leq (\Omega h^2)_{\min} \leq 0.2$. In the present paper, whenever we have to apply rescaling, we use the value $(\Omega h^2)_{\min} = 0.01$, which is conservatively derived from the estimate $\Omega_{\text{galactic}} \sim 0.03$.

In Fig. 2 we display our results for $\rho_\chi^{0.3} \sigma^{\text{nuclear}}$ in the form of the scatter plot which is derived by scanning the supersymmetric parameter space over the grid defined above. For the evaluation of $\sigma^{\text{nuclear}}$ we use the expressions given in Ref. [6]. The scatter plot shown in Fig. 2 is a consequence of (1) the experimental limits on supersymmetry searches coming from accelerators and from the limits imposed by the $\beta$-$\gamma$ radiative decay and (2) the interval over which the scan of the supersymmetric parameter space is performed. For instance, neutralino searches at LEP constrain the mass of neutralino to be above about 30 GeV, hence a lower limit on the points in Fig. 2 as far as $m_\chi$ is concerned. Accelerator searches on the Higgs bosons constrain the mass and couplings of the supersymmetric Higgs bosons: this has a consequence of determining the maximal values which can be reached by the quantity $\rho_\chi^{0.3} \sigma^{\text{nuclear}}$.

We notice that a host of configurations fall inside the region $R_m$; thus, the annual-modulation region is compatible with supersymmetric configurations currently allowed by accelerator constraints.

IV. INTERPRETATION OF THE ANNUAL-MODULATION DATA IN TERMS OF RELIC NEUTRALINOS

Let us turn now to the implications of the DAMA-Nal experimental data, once these are interpreted in terms of relic neutralinos. The cosmological properties are examined first; other prominent features of the relevant supersymmetric configurations will be examined afterwards.

A. Neutralino cosmological properties

For the derivation of the relic neutralino properties as regards its local density $\rho_\chi$ as well as its contribution to the average relic abundance $\Omega_\chi h^2$ compatible with region $R_m$, we adopt the straightforward procedure, outlined in Ref. [5], which does not require any use of rescaling in the local neutralino density. The method is the following: (1) We evaluate $\sigma^{\text{nuclear}}$ and $\Omega_\chi h^2$ by varying the supersymmetric parameters over the grid and with the constraints defined in the previous section; (2) for any value of $[\rho_\chi^{0.3} \sigma^{\text{nuclear}}]_{\text{expt}}$ compatible with the region $R_m$ we calculate $\rho_\chi$ as given by $\rho_\chi = [\rho_\chi^{0.3} \sigma^{\text{nuclear}}]_{\text{expt}} / \sigma^{\text{nuclear}}$ and restrict the values of $m_\chi$ to stay inside the region $R_m$ displayed in Fig. 2; (3) the results are then displayed in a scatter plot in the plane $\rho_\chi$ vs $\Omega_\chi h^2$.

Examples of our results are given in Figs. 4(a)–4(c) for a few experimentally allowed values of $\rho_\chi^{0.3} \sigma^{\text{nuclear}}$, which bracket the range implied by the region $R_m$ of Fig. 2. Parts (a)–(c) of Fig. 4 refer to the values $[\rho_\chi^{0.3} \sigma^{\text{nuclear}}]_{\text{expt}} = 4 \times 10^{-9}$ nbarn, $6 \times 10^{-9}$ nbarn and $8 \times 10^{-9}$ nbarn, respectively.

The two horizontal lines delimit the physical range 0.1 GeV cm$^{-3}$ $\leq \rho_1 \leq 0.7$ GeV cm$^{-3}$ for the total local density of nonbaryonic dark matter. This (rather generous) range has been established by taking into account a possible flattening of the dark matter halo [35,36] and a possibly sizeable baryonic contribution to the galactic dark matter [37]. The solid vertical lines delimit the cosmologically interesting range $0.01 \leq \Omega_\chi h^2 \leq 0.7$. The two vertical dashed lines delimit the range: $0.02 \leq \Omega_\chi h^2 \leq 0.2$, which represents the most appealing interval. Indeed, some recent observations and analyses [38] indicate $0.1 \leq \Omega_{\text{matter}} \leq 0.4$ (however, some other analyses, such as the one of Ref. [39] disfavor values on the low side of the quoted range for $\Omega_{\text{matter}}$). Combining this range with the one for $h$ $0.55 \leq h \leq 0.80$ [32], we obtain $0.02 \leq \Omega_{\text{CDM}} h^2 \leq 0.2$. The lower value of the $\Omega_{\text{CDM}} h^2$ range takes into account that cold dark matter might provide only $\sim (80–90)$% of $\Omega_{\text{matter}}$, the remaining fraction of $\sim (10–20)$% being due to hot and baryonic dark matter (as typical of models of cosmological structure formation, see, e.g., Ref. [40]). Our estimates for $\Omega_{\text{CDM}} h^2$ are taken in the spirit of not being too restrictive in establishing the lower value for $\Omega_\chi h^2$ of cosmological interest (in agreement with what usually done also by other authors; for a recent reference see, for instance, Ref. [41]). Values of $\Omega_{\text{CDM}} h^2$ as low as 0.02 may be rather unlikely, although not ruled out.

The two slant dot-dashed lines delimit the band where linear rescaling procedure for the local density is usually applied. In Figs. 4(a)–4(c) the upper dot-dashed line would refer to a rescaling with $(\Omega h^2)_{\min} = 0.01$, the lower one to the value $(\Omega h^2)_{\min} = 0.2$. However, notice that in deriving the scatter plot of Figs. 4(a)–4(c), no use of rescaling for $\rho_\chi$ is made.

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 (we remind that those providing an $\Omega_\chi h^2 > 0.7$ are already disregarded from the very beginning). Among the allowed configurations, those falling in the region inside both the horizontal and solid vertical lines (called $A$ hereafter) 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 called $B$ hereafter inside the vertical band delimited by dashed lines. Configurations which fall inside the band delimited by the slant 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 $\Omega h^2$. Configurations above the upper dot-dashed line and below the upper horizontal solid line delimit the physical range for the local density of nonbaryonic dark matter. The two solid vertical lines delimit the interval of $\Omega h^2$ of cosmological interest. The two vertical dashed lines delimit the preferred band for cold dark matter. The two slant dot-dashed lines delimit the band where linear rescaling procedure is usually applied. Different symbols identify different neutralino compositions: circles stand for a Higgsino, crosses for a gaugino and dots for a mixed neutralino.

It is worth noticing a few important properties of the scatter plots shown in Figs. 4(a)–4(c).

(1) The scatter plots display a correlation between $\rho_\chi$ and $\Omega h^2$. This feature is expected on the basis of the following properties: (i) $\Omega h^2$ is roughly inversely proportional to the neutralino pair annihilation cross section, (ii) at fixed $[\rho_\chi \sigma_{[\text{nucleon}]}^{\text{expt}}]$, $\rho_\chi$ is inversely proportional to $\sigma_{[\text{nucleon}]}^{\text{expt}}$, (iii) the annihilation cross section and $\sigma_{[\text{nucleon}]}^{\text{expt}}$ are usually correlated functions (i.e., they are both increasing or decreasing functions of the supersymmetric parameters, e.g., $\tan \beta$ or $m_A$).

(2) The domains covered by the supersymmetric configurations in regions $A$ and $B$ are slightly larger for smaller values of $[\rho_\chi \sigma_{[\text{nucleon}]}^{\text{expt}}]$. This feature follows from the fact that $\sigma_{[\text{nucleon}]}^{\text{expt}}$ is bounded from above by accelerator limits (mainly because of lower bounds on Higgs masses); this
implies for \( r_s \) a lower bound, which, however, is less stringent at lower values of \( r_s \).

We can conclude that the DAMA-NaI data are compatible with a relic neutralino as a major component of dark matter in the universe.

B. Other properties of the supersymmetric configurations of set \( S_m \)

Apart from the cosmological properties previously discussed, one of the most interesting questions is whether the supersymmetric configurations, whose representative points fall inside the region \( R_m \) of Fig. 2 (hereafter denoted as configurations of set \( S_m \)), are explorable at accelerators of the present generation. This point was investigated in Ref. [6] in the case of the original DAMA-NaI annual-modulation region. Here we extend our considerations to the larger set \( S_m \) derived from region \( R_m \).

The supersymmetric configurations of set \( S_m \) are constrained by the inequalities

\[
\frac{[\rho_x r^{(\text{nucleon})}]_{\text{expt} \leq \sigma r^{(\text{nucleon})}]}_{\text{expt}}}{\rho_{x_{\text{min}}}} \leq r^{(\text{scalar})} \leq \frac{[\rho_x r^{(\text{nucleon})}]_{\text{expt} \leq \sigma r^{(\text{nucleon})}]}_{\text{expt}}}{\rho_{x_{\text{max}}}}.
\]

where \( \rho_{x_{\text{min}}} = \xi \rho_{t_{\text{min}}} = \xi \times 0.1 \text{ GeV cm}^{-3} \) and \( \rho_{x_{\text{max}}} = \xi \rho_{t_{\text{max}}} = \xi \times 0.7 \text{ GeV cm}^{-3} \), and \( [\rho_x r^{(\text{nucleon})}]_{\text{expt}} \) is any value inside region \( R_m \) as a function of \( m_h \).

Equation (17) implies interesting correlations among the supersymmetric parameters, as displayed in Figs. 5–7. The first of these figures shows the scatter plot of \( \tan \beta \) versus the mass \( m_h \) of the lightest neutral \( CP \)-even Higgs boson (we recall that \( m_h \) may be derived from the supersymmetric parameters listed in Sec. III). The correlation displayed in Fig. 5 between \( \tan \beta \) and \( m_h \) is implied by the fact that \( r^{(\text{scalar})} \) is usually dominated by Higgs-exchange amplitudes, and these are in turn large for large values of \( \tan \beta \) and small values of \( m_h \). As is apparent in Fig. 5 a number of supersymmetric configurations of set \( S_m \) could still be explorable at LEP2, but the others require investigation at a high luminosity Fermilab Tevatron [42,43] or at the CERN Large

![FIG. 5. Scatter plot for set \( S_m \) in the plane \( m_h - \tan \beta \). The hatched region on the right is excluded by theory. The hatched region on the left is excluded by present LEP data at \( \sqrt{s} = 189 \text{ GeV} \). The dotted and the dashed curves denote the reach of LEP2 at energies \( \sqrt{s} = 192 \text{ GeV} \) and \( \sqrt{s} = 200 \text{ GeV} \), respectively. The solid line represents the 95% C.L. bound reachable at LEP2, in case of nondiscovery of a neutral Higgs boson.](image1)

![FIG. 6. Scatter plot for set \( S_m \) in the plane \( m_{\tilde{t}_1} - \tan \beta \). The hatched region is excluded by LEP data.](image2)

![FIG. 7. Scatter plot for set \( S_m \) in the plane \( m_{\tilde{t}_1} - \tan \beta \). The hatched region on the left is excluded by present LEP data. The dashed and the solid vertical lines denote the reach of LEP2 and TeV33, respectively.](image3)
Hadron Collider LHC. Figure 6 shows a correlation between tan $\beta$ and the mass of the lightest top-squark $m_{\tilde{t}}$. The reasons for this feature are more involved, and are discussed in Ref. [6].

A last plot, providing tan $\beta$ versus $m_\chi$, is given in Fig. 7. Again, a correlation shows up here for not too large values of tan $\beta$. LEP2 can only provide an investigation up to $m_\chi \approx 50$ GeV. The exploration up to $\sim 125$ GeV can be performed with Tevatron upgrades (under favorable conditions), while for higher values of $m_\chi$ LHC is needed.

V. CONCLUSIONS

We have investigated how the original DAMA-NaI annual-modulation region in the plane $\rho_X^{\nu(\text{scalar})} - m_\chi$ is extended when the uncertainties in the galactic astrophysical velocities are taken into account. One of the most noticeable consequences is that the range for the neutralino mass becomes $30$ GeV $\leq m_\chi \leq 130$ GeV at $1-\sigma$ C.L., with a further extension in the upper bound, when a possible bulk rotation of the dark matter halo is taken into account. However, the extension of the modulation region implies only slight modifications in the correlations among the supersymmetric parameters in the MSSM scheme.

We have found that a number of supersymmetric configurations singled out by the DAMA-NaI results have cosmological properties compatible with a relic neutralino as a dominant component of cold dark matter (on the average in our universe and in our galactic halo). It has also been discussed the discovery potential for the relevant supersymmetric configurations at accelerators of present generation.

Note added. During the completion of this work there appeared two preprints: hep-ph/9903467 (by L. Roszkowski) and hep-ph/9903468 (by M. Brhlik and L. Roszkowski), where considerations on the effect of the uncertainty in the velocity parameter $v_0$ on WIMP direct searches are presented. The extension of the original DAMA annual modulation region, due to this effect, qualitatively agrees with the ones shown here in Fig. 1. In the preprints hep-ph/9903467 and hep-ph/9903468, at variance with the present paper, no dependence on $v_{\text{esc}}$ and on a possible bulk dark matter rotation has been considered, neither the investigation on supersymmetric candidates has been carried out.

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