We discuss the effect induced on the neutralino–nucleon scalar cross-section by the present uncertainties in the values of the quark masses and of the quark scalar densities in the nucleon. We examine the implications of this aspect on the determination of the neutralino cosmological properties, as derived from measurements of WIMP direct detection. We show that, within current theoretical uncertainties, the DAMA annual modulation data are compatible with a neutralino as a major dark matter component, to an extent which is even larger than the one previously derived.

Experiments of direct search for WIMPs have remarkably improved their sensitivity in the last years, allowing the exploration of sizeable regions of the physical parameter space of specific particle candidates for dark matter. This is the case of the neutralino, for which some direct detection experiments are already capable of investigating significant features in domains of the parameter space which are also under current exploration at LEP2.

Currently, the most sensitive direct search experiments are probing, or are starting to probe, a range of \( \rho_0 \sigma^{(\text{nucleon})}_{\text{scalar}} \) from about a few \( 10^{-9} \) to \( 1 \cdot 10^{-8} \) nbarn, where \( \rho_0 \) denotes the local dark matter density normalized to \( 0.3 \) GeV cm\(^{-3} \) and \( \sigma^{(\text{nucleon})}_{\text{scalar}} \) is the neutralino-nucleon scalar cross-section. This goal has already been achieved by the DAMA experiment, which has reported the indication of an annual modulation effect in its counting rate, compatible with

\[
3 \cdot 10^{-9} \text{ nbarn} \lesssim \rho_0 \sigma^{(\text{nucleon})}_{\text{scalar}} \lesssim 1 \cdot 10^{-8} \text{ nbarn},
\]

for values of the WIMP mass which extend over the range \( 30 \text{ GeV} \lesssim m_\chi \lesssim 130 \text{ GeV} \). The region in the \( m_\chi - \rho_0 \sigma^{(\text{nucleon})}_{\text{scalar}} \) plane, singled out by the DAMA experiment at 2–\( \sigma \) C.L., is the one depicted in Fig. 1. We also notice that the uncertainties in the local total dark matter density:

\[
0.1 \text{ GeV cm}^{-3} \leq \rho_t \leq 0.7 \text{ GeV cm}^{-3},
\]

imply for \( \sigma^{(\text{nucleon})}_{\text{scalar}} \) the range:

\[
1 \cdot 10^{-9} \text{ nbarn} \lesssim \sigma^{(\text{nucleon})}_{\text{scalar}} \lesssim 3 \cdot 10^{-8} \text{ nbarn},
\]

Another experiment of WIMP direct detection which is now entering the upper left corner of the region in Fig. 1 is the CDMS experiment.

Once a given range for \( \rho_0 \sigma^{(\text{nucleon})}_{\text{scalar}} \) is singled out by an experiment, the implications for specific particle candidates rely on the theoretical calculation of the \( \sigma^{(\text{nucleon})}_{\text{scalar}} \) cross-section. In the case of neutralino, this quantity usually takes dominant contributions from interaction processes where neutralinos and quarks inside the nucleon interact by exchange of Higgs particles or squarks. The relevant couplings involve the use of quark masses \( m_q \) and quark scalar-densities inside the nucleon \( \langle N|\bar{q}q|N \rangle \), whose values can be related to some physical observables which can be identified with the pion–nucleon sigma term \( \sigma_{\pi N} \), the fractional strange–quark content of the nucleon \( y \) and the strange–to–light-quark mass ratio \( r = 2m_s/(m_u + m_d) \) (see Ref. 5).

Actually, the quantities \( \sigma_{\pi N} \) and \( y \) have recently been the object of various evaluations, based mainly on chiral perturbation theory and on QCD simulations on a lattice; however, the
The points represent $\sigma_{\text{scalar}}$ (nucleon) calculated for a generic scan of the MSSM. Different symbols label different values of the neutralino relic abundance: $\Omega_{\chi}h^2 < 0.01$ (points), $0.01 \leq \Omega_{\chi}h^2 < 0.1$ (crosses) and $\Omega_{\chi}h^2 \geq 0.1$ (circles).

The quantity $\sigma_{\text{scalar}}$ in the scatter plot is calculated with the parameters of set 1. The two horizontal lines delimit the physical range for the local density of non-baryonic dark matter. The two solid vertical lines delimit an interval of $\Omega_{\chi}h^2$ of cosmological interest. The two vertical dashed lines delimit a preferred band for cold dark matter. The two slant dot–dashed lines delimit the band where linear rescaling procedure is usually applied. The shaded region is cosmologically excluded on the basis of present limits on the age of the Universe. Different symbols identify different neutralino compositions: circles stand for a higgsino, crosses for a gaugino and dots for a mixed neutralino. The solid (red) lines show to which extent the scatter plot would enlarge if the nuclear parameters of set 2 and of set 3, quoted in Table 1, are used.

These three sets are reported in Table 1: set 1 is our reference set, while set 2 and set 3 are representative of choices which can provide enhanced values for $\sigma_{\text{scalar}}$. We wish to remark that all these choices are well inside their allowed intervals coming from the determination of the quantities $\sigma_{\pi N}$, $y$ and $r$.

Fig. 1 shows the scatter plot of the quantity $\rho_{\chi} \sigma_{\text{scalar}}^{(nucleon)}$ calculated in the minimal supersymmetric standard model (MSSM), for a general scan of its parameter space (for details, see Refs. [3,5]) and for set 1. We see that the annual modulation region is fully compatible with the hypothesis of a relic neutralino as a dark matter component.

In order to discuss the astrophysical and cosmological properties of a relic neutralino in order for it to be compatible with the indica-
tion coming from the DAMA experiment, in Fig. 2 we show a scatter plot of ρχ versus $\Omega h^2$, obtained as follows: i) $\rho_\chi$ is evaluated as $\rho_\chi = \frac{[\rho_\chi \sigma^{(\text{nucleon})}]_{m_\chi}}{\sigma^{(\text{nucleon})}}$, where $[\rho_\chi \sigma^{(\text{nucleon})}]_{m_\chi}$ denotes the set of experimental values of $\rho_\chi \sigma^{(\text{nucleon})}$ inside the DAMA annual modulation region and $\sigma^{(\text{nucleon})}$ is calculated in the MSSM; ii) To each value of $\rho_\chi h^2$, which then pertains to a specific susy configuration, one associates the corresponding value of $\Omega_\chi h^2$, calculated as indicated, for example, in Ref. [6] or references therein. With this procedure, we determine the values of $\rho_\chi$ which, for each calculated $\sigma^{(\text{nucleon})}$ satisfy the DAMA annual modulation data.

The effect induced by the choice of different sets for the parameters $\sigma_{\pi N}$, $y$ and $r$ is shown in Fig. 2 by the solid lines. The three lines delimit the region covered by the scatter plots in the different cases, and show to which extent the region moves downward when these parameters are varied.

The most interesting feature of Fig. 2 is that it shows that the set of susy configurations selected by the DAMA data has a significant overlap with the region of main cosmological interest: $0.02 < \Omega h^2 < 0.1$ GeV cm$^{-3}$ and $0.3 < \rho_\chi < 0.7$ GeV cm$^{-3}$. The extent of this overlap is increasing larger for set 2 and set 3. By way of example, for set 3 one has that, at $\rho_\chi = 0.3$ GeV cm$^{-3}$, $\Omega h^2$ may reach the value 0.3. Therefore, these results reinforce our conclusions of Ref. [6], i.e. that the DAMA annual modulation data are compatible with a neutralino as a major component of dark matter, on the average in the Universe and in our Galaxy.

The same figure shows that different situations may also occur. For instance, for configurations which fall inside the band delimited by the slant dot–dashed lines, the neutralino would provide only a fraction of the cold dark matter both at the level of local density and at the level of the average $\Omega$, a situation which would be possible if the neutralino is not the unique cold dark matter particle component. Clearly, configurations above the upper horizontal line are incompatible with the upper limit on the local density of dark matter in our Galaxy and must be disregarded.

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| $\sigma_{\pi N}$ MeV | $y$ | $r$ | $m_{\chi} < \bar{q}q_{\chi}$ MeV | $m_\chi < \bar{s}s$ MeV | $m_\chi < hh$ MeV | set |
|---------------------|-----|-----|-----------------|-----------------|-----------------|-----|
| 45                  | 0.33| 29  | 23              | 215             | 50              | 1   |
| 60                  | 0.50| 29  | 30              | 435             | 33              | 2   |
| 65                  | 0.50| 36  | 33              | 585             | 21              | 3   |