Particle Dark Matter Interpretations of Direct Searches

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Abstract. The recent results of direct search experiments for dark matter particles (DMPs) have been discussed by many authors in terms of numerous, quite disparate, theoretical models. Here, after some general considerations related to the possible distributions of DMPs in the galactic halo, the discussion is focussed on a few models: inelastic dark matter, mirror dark matter and relic neutralinos.

1. Introduction
The interpretation of the experimental results derived from direct searches for particle dark matter depends critically on two main aspects: a) one concerns the distribution of the DMPs in the galactic halo, b) the other refers to the nature of the DMP and its related interaction mechanism with the target material employed in the experimental apparatus. Indeed, a detection rate is a convolution of the phase-space distribution function (DF) of the DMP in the halo with the cross-section of the DMP with the particle constituent of the target material, $\sigma_{DMP}^{DMP}$, Thus, the physical information which is derived on properties of a putative DMP from experimental results of direct searches depends on the form of the DF assumed in the analysis. On both aspects (a) and (b) there have recently been considerable developments.

In this brief overview I first underline some of the major novelties in the field of the phase-space distribution functions, then I discuss some of the most interesting particle models which can provide a viable interpretation of the present data from the direct detection experiments.

2. Phase-space distribution functions
In most of the experimental and theoretical analyzes it is customary to employ the isothermal sphere model to describe the galactic phase-space distribution of DMPs, yet this model has more the merit of being structurally simple than the one of being realistic. Actually the DF could present deviations from isotropy either in spatial or in velocity distributions; some specific examples of these categories, and their consequences in the interpretation of direct detection data, are discussed for instance in Ref. [1].

A feature which would modify considerably the standard picture based on thermalized distribution functions is the possible presence of streams in the halo [2]. Also an effect of clumpiness could sizably affect the detection rates.
These aspects have been addressed by recent analyzes carried out with new high-resolution simulations. This is the case of the investigation in Ref. [3], which reports the results obtained with high-resolution simulations of the galaxy halo taken from the Aquarius Project. These authors conclude that the DM local density distribution turns out to be very smooth, implying that bound clumps are very unlikely; the local velocity is also rather smooth with no indication of important effects due to streams. However, this velocity distribution shows some specific features, i.e., it is anisotropic with some deviations from a multivariate Gaussian distribution: mainly some depletion around the maximum and some enhancement over the high-velocity tail (Fig. 1 from Ref. [3] displays these properties).

![Figure 1. Velocity modulus distribution in one of the halo simulations of Ref. [3]. The dashed line denotes a fit obtained with a multivariate Gaussian model. For other details see Ref. [3] from where this picture is taken.](image)

Of particular interest are also the new high-resolution simulations which, together with dark matter, include baryonic matter too. In Ref. [4] it is shown that in these evaluations stellar/gas disk drags the merging satellites toward the disk plane where they are torn apart by tidal forces. This dark disk would be co-rotating with the galactic stellar disk, implying a modification in the velocity distribution usually employed for DMPs (see also Ref. [5]).

Particular attention should be devoted to these last developments in numerical cosmological simulations, which however, for the time being, appear to still suffer from limited statistics and model-dependence.

3. Particle candidates and interaction mechanisms

The most remarkable result in the experimental search for DMPs is represented by the measurement of an annual-modulation effect at 8.2 sigmas, obtained by the DAMA/NaI and DAMA/LIBRA experiments (with a total exposure of 0.82 ton yr) [6]. This effect is just one of the typical signatures expected for DMPs [7].

All other experiments for direct detection, which, on the other hand, do not have the prerequisites for a measurement of the yearly effect, report upper bounds on the DM detection rate [8].

The annual-modulation effect can be generated by a wide number of possible DM candidates and interaction mechanisms between the DM particle and the target material [6]. The most natural generic candidate is a WIMP, with the neutralino as its most attractive physical realization. Many other possibilities have been examined by various authors; they consists for instance either of candidates which have dominant interactions on atomic electrons, or of inelastic transitions within the DM candidate itself or of a conversion of the impinging particle energy into electromagnetic radiation. These possibilities have been considered in a large number of recent papers. Limits of space allow us only to illustrate the case of the most popular candidate, the neutralino, and a couple of more exotic models: inelastic dark matter and mirror dark matter [9].
3.1. Inelastic dark matter

This model arises from the idea that the DM particle $\chi$ might have a companion exited state $\chi^*$ with a mass splitting $\delta = m_{\chi^*} - m_\chi$ with the property that elastic scattering of $\chi$ off a nucleus is suppressed as compared to the inelastic scattering which would excite $\chi$ into $\chi^*$ [10].

A DM particle with these properties would interact with a target nucleus only if its velocity is larger than $(2m_N E_R)^{-1/2}(m_N E_R/m + \delta)$, where $E_R$ is the deposited energy, $m_N$ is the nuclear mass and $\mu$ is the reduced mass of the DM particle/nucleus system. From these prerequisites some characteristic features follow; in particular, heavier targets are favored over lighter ones and the signal is sizably hindered at low recoil energies as compared to the one expected in the case of elastic scattering of a DMP with the target nucleus.

![Figure 2](image.png)

**Figure 2.** Cross section for a scattering of an inelastic DMP off a nucleon in the model of Ref. [10] as a function of the DMP mass for a representative value of the $\delta$ parameter. The top five lines and the faint short-dashed line on the left denote upper bounds, the other lines enclose the regions at 99 % CL, 90 % CL, for the DAMA/LIBRA results (the two inner curves refer to an analysis including DAMA/LIBRA and DAMA/NaI, the two outer ones contain only the DAMA/LIBRA data). For other details see Ref. [10] from where this picture is taken.

These properties turn out to be of relevance when $\delta \sim v^2 m_\chi \sim 100$ keV ($v$ being the DMP velocity in units of $c$). Indeed, in Ref. [10] it is shown that for masses of the DMP of order 100 GeV, no contradiction exist among the DAMA data and results of other direct experiments. This property is for instance displayed in Fig. 2 taken from [10].

Various possible physical realizations of the inelastic DM particle exist. One of these is represented by sneutrinos in models which contain a lepton-number violation lagrangian: in this case sneutrinos would mix with anti-sneutrinos generating a mass splitting in the mass eigenstates [11]. Another realization could be a fourth generation Dirac neutrino constituted by 2 Majorana states originally degenerate under an U(1) symmetry; the breaking of this U(1) would cause a splitting between the two Majorana fermions [12]. Another viable model could be a fourth generation Dirac neutrino constituted by 2 Majorana states originally degenerate under an U(1) symmetry; a breaking of this U(1) would produce a splitting between the two Majorana fermions, giving rise to a possible inelastic DMP [12]. Finally, it is worth mentioning a model proposed in Ref. [13] and consisting of a Majorana particle with a transition electric/magnetic moment.

3.2. Mirror dark matter

One can entertain the possibility that in nature there is an exact unbroken parity symmetry under the transformation: $\vec{x} \rightarrow -\vec{x}, t \rightarrow t$, with the usual sector of ordinary particles paralleled by a mirror sector constituted by mirror particles in a one-to-one correspondence with ordinary particles. Thus, for example, the electron would have its mirror partner in a mirror electron with the same mass. Couplings of the particles in the mirror sector would be the same as the corresponding couplings in the ordinary sector.

Within this model, which possesses a remarkable pedigree [14], more recently was also developed the idea that stable mirror particles can play the role of dark matter [15, 16, 17], though the relevant cosmology is rather involved. Ordinary particles and mirror particles
Figure 3. The 3σ (dashed-line) and the 5σ (solid-line) DAMA/LIBRA region is represented in the $A' - \nu_{rot}$ (rotational velocity) parameter space together with upper bounds from other experiments. For other details see Ref. [16] from where this picture is taken.

3.3. Neutralinos
In Ref. [18] it is proved that the DAMA/LIBRA annual modulation data agree very well with the theoretical expectations within an effective Minimal Supersymmetric extension of the Standard Model (effMSSM) at the electroweak scale without gaugino masses unification at a grand unification scale [19]. This is displayed in Figs. 4-5, where the quantity $\xi \sigma_{\text{scalar}}^{(\text{nucleon})}$ is displayed as a function of the DMP mass ($\xi$ is the DMP fractional local density and $\sigma_{\text{scalar}}^{(\text{nucleon})}$ is the DMP-nucleon cross section). The region covered by a (red) slant hatching denotes the DAMA annual modulation region, under the hypothesis that the effect is due to a DMP with a coherent interaction with nuclei, the channeling effect [20] being disregarded in Fig.4 and included in Fig.5. This region represents the domain where the likelihood-function values differ more than 6.5σ from the null hypothesis (absence of modulation). It has been derived by the DAMA Collaboration by varying the WIMP galactic distribution function over the set considered in Ref.[1] and by taking into account other uncertainties of different origins. The scatter plot represents supersymmetric configurations calculated with the model summarized in [18], at a fixed representative set of values for the couplings of the Higgs bosons or of the squarks with nucleons. The (red) crosses denote configurations with a neutralino relic abundance which matches the WMAP cold dark matter amount (0.098 $\leq \Omega_{\chi}h^2 \leq 0.122$), while the (blue) dots refer to configurations where the neutralino is subdominant ($\Omega_{\chi}h^2 < 0.098$).
Figure 4. $\xi\sigma^{(nucleon)}$ as a function of the DMP mass (see text for explanations). No channeling effect is included here in the analysis of the experimental data.

Figure 5. $\xi\sigma^{(nucleon)}$ as a function of the DMP mass (see text for explanations). The channeling effect is included here in the analysis of the experimental data.

Figure 6. $\xi\sigma^{(nucleon)}$ as a function of the DMP mass. The theoretical features are the same as in Figs. 4-5. The other lines represent the upper bounds derived from the data of Ref. [22] by varying the form of the DF (for full explanation of notations see [18]).

The comparison between the theoretical predictions and the DAMA annual modulation region in case of specific forms of DFs is discussed in [18]. In this paper it is also shown that, although in general light DMP are severely constrained by cosmic antiprotons, a large set of the light neutralino population discussed above is compatible with the cosmic antiproton bounds especially for values of local dark matter density and local rotational velocity in the low side of their physical ranges and for values of the diffusion parameters not too close to the values of
their maximal set.

Obviously, also in the case of direct experiments which only provide upper bounds the dependence of the halo DF has to be taken into account. In Fig. 6 we show for instance what is the effect of changing the DF in the case of the CDMS experiment [22].

As for the comparison among the results of various direct searches, it is worth stressing that, apart from DAMA/NAI and DAMA/LIBRA experiments, other experiments [8] are not sensitive to the annual modulation effect which is the peculiar signature of the DM signal. In the derivation of upper bounds, event discrimination procedures, not based on the peculiar signature of the effect, are applied; this makes the comparison of these upper limits with DAMA results somewhat uncertain. However, these upper bounds, even when taken at their face values, are not in conflict with the annual-modulation data and with the neutralino interpretation for masses in the range \( m_\chi \simeq 7 - 10 \text{ GeV} \) [18]. Comparisons of DAMA/LIBRA data with results of other direct experiments has been largely discussed in recent literature [23].

We finally wish to mention that the whole population of light neutralinos \((6 \text{ GeV} \leq m_\chi \leq 50 \text{ GeV})\) might produce sizable signals at neutrino telescopes [24] and in searches in space for antideuterons [25], and most notably can be searched for at Large Hadron Collider [26].

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