Status and perspectives of indirect and direct dark matter searches

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Abstract

In this review article the current status of particle dark matter is addressed. We discuss the main theoretical extensions of the standard model which allow to explain dark matter in terms of a (yet undiscovered) elementary particle. We then discuss the theoretical predictions for the searches of particle dark matter: direct detection in low background underground experiments and indirect detection of neutrinos, gamma-rays and antimatter with terrestrial and space-born detectors. Attention will be placed also on the discussion of the uncertainties, mainly of astrophysical origin, which affect the theoretical predictions. The constraints placed by these searches on the extensions of the standard models will be briefly addressed.

Key words: particle dark matter, direct detection, cosmic rays, gamma rays, antimatter, neutrino telescopes

1 Introduction

Large amounts of dark components have been clearly identified in our Universe, on different scales and by different experimental means. The current view of modern Cosmology sees the Universe very close to being flat, with 30% of its content in the form of a cold dark matter (CDM) component, responsible for structure formation, while the remaining 70% made of a very exotic dark energy component which causes its recent accelerated expansion. Baryons can account at most 4–5% of the total content of the Universe, much less than the CDM amount. This fact points toward a non–baryonic origin of dark matter and this is a clear evidence that our understanding of the elementary particle physics component of matter, beautifully described by the Standard Model (SM), is incomplete. We need to extend the particle content in order to accommodate (at least) one non–baryonic dark matter candidate,
since the only DM candidate in the SM is the neutrino which is unsuited to explain the bulk of DM since it acts as hot dark matter and instead CDM is largely required to succesfully produce the observed large scale structure of the Universe.

Supersymmetry offers a wonderful possibility, since the lighest supersymmetric particle is stable, once R–parity is conserved, and it naturally posseses the properties of a succesfull CDM candidate (neutrality and weak interactions) in many realization of supersymmetry. The most successful and studied candidate is the neutralino, and I will concentrate on this particle in the following, where I will give a brief overview of the strategies for neutralino dark matter searches and of some recent results. For a more detailed discussion and a more exhaustive list if references, I cross–refer the reader to the quoted papers.

2 Strategies for dark matter searches

There are two basic ways to detect WIMP (Weakly Interacting Massive Particles) dark matter which is present in the halo of our Galaxy. The first method, direct detection, relies on the possibility to detect the recoil energy of the nuclei of a low–background detector as a consequence of their elastic scattering with a WIMP. The second method, indirect detection, exploits the possibility to detect products of the annihilation of DM particles, either in the galactic halo or in celestial bodies (namely the Earth and the Sun) where WIMPs may have been accumulated by gravitational capture. In this last case, the signal consists of a flux of neutrinos emitted from the central regions of the body, and the typical observable is a flux of upgoing muons produced by the charged–current conversion of the muon neutrino component of the signal. In the case of DM annihilation in the galactic halo, there are more possibilities: the signal can consists of gamma–rays, neutrinos and antimatter (positrons, antiprotons and antideuterons).

From the experimental side, the searches of DM signals involve many different techniques, ranging from low–background underground detectors, to neutrino telescopes, antimatter and gamma–rays detectors in space, to air-Cerenkov detectors.

3 Direct detection

From the particle physics point of view, direct detection relies on the scattering cross section of the WIMP with the nucleon in the nuclei of the detector. Experimental results have reported a positive indication of a signal in terms
Fig. 1. Direct detection scattering cross section on a nucleon vs. the WIMP mass. The solid lines show the allowed region by the DAMA/NaI experiment compatible with the observed annual modulation effect [(Bernabei et al., 2003)] and derived for a wide variation of galactic halo models [(Bernabei et al., 2003)]. The shaded area shows theoretical predictions for neutralino dark matter in a low–energy supersymmetric standard models. Configurations for masses below about 45 GeV refer to gaugino non–universal models, while for higher masses gaugino–mass universality is assumed [(Bottino et al., 2005a)].

of the annual modulation of the rate due to the Earth motion relative to the WIMP wind: the DAMA/NaI Collaboration has a clear detection of a temporal modulation with the expected amplitude, phase and period [(Bernabei et al., 2003)]. When interpreted as due to dark matter scattering, the allowed region shown in Fig. 1 is obtained for the scattering cross section vs. the WIMP mass. Figure 1 refers to the case of coherent WIMP–nucleus scattering. The same figure shows the comparison of the DAMA/NaI annual modulation region with predictions for neutralinos obtained in two different supersymmetric models [(Bottino et al., 2005a)]. The part of the shaded area which refers to neutralino masses larger than about 50 GeV refers to a low–energy (electroweak scale) realization of the minimal supersymmetric standard model (MSSM). In this models a lower mass bound of about 50 GeV is obtained from LEP searches. Once the gaugino–universality condition, usually assumed in these models, is relaxed, the LEP bound loosens and a lower limit of about 6 GeV on the neutralino mass is obtained instead by Cosmology, requiring that neutralinos do not contribute to the CDM content of the Universe in excess of the experimental upper bound [(Bottino et al., 2003)]. In Fig. 1, the configurations relative to these gaugino non–universal models are those relative to masses below 50 GeV. It is clearly seen that the direct detection cross section predictions are sizeable and able to expain the DAMA/NaI result easily [(Bottino et al., 2005a)].
Fig. 2. The same as in Fig. 1, except that the solid lines denote upper limits from the CDMS detector (Akerib et al., 2005) for some specific galactic halo models, as calculated in Bottino et al. (2005a).

Fig. 3. Direct detection scattering cross section on a nucleon vs. the WIMP mass. The theoretical predictions are here obtained in non–minimal SUGRA, where non–minimality refers to the Higgs sector. Darker points refer to configurations which match the cosmological abundance for CDM. Solid lines refer to current experimental results and future prospects (figure from Baek et al., 2005)).

Figure 2 show the same theoretical predictions confronted against upper limits obtained by the CDMS detector (Akerib et al., 2005). The upper limits are here re–calculated in order to show the sizeable dependence of direct detection on the phase space properties of WIMPs in the galactic halo (Bottino et al., 2005a).

Figure 3 is an example of theoretical prediction in a different supersymmetric models, namely a minimal Supergravity (SUGRA) scheme with non–
universality in the Higgs sector (Baek et al., 2005). In these type of models, especially in strict universal SUGRA, typically the predictions are lower than in the case of low–energy MSSM. Non–universalities are instrumental in obtaining larger detection rates.

4 Antiproton signal

Antiprotons may be produced by WIMP annihilation in the galactic halo. Once they are produced, they suffer a complicated mechanism of propagations inside the galactic diffusive halo, process which involves both diffusion and energy losses. Once they reach the boundary of the heliosphere, antiprotons further suffer propagation against the solar wind, which changes the low–energy part of the antiproton spectrum and leads to the phenomenon of solar modulation, related to the 11 year solar cycle. All these diffusive and energy redistribution processes are properly taken into account by solving the diffusion equations in the specific medium. In the case of galactic propagation, a detailed study of the propagation processes for the DM antiproton signal has shown that the theoretical predictions suffer of large uncertainties in the low energy tail, uncertainties which are related to the poor knowledge of the
Fig. 5. Comparison of the theoretical predictions for the antiproton flux and experimental data (Donato et al., 2004). The full circles/open squares/dots/open circles show the data from BESS95–97 (Orito et al., 2000)/BESS-98 (Maeno et al., 2001)/AMS (Aguilar et al., 2002)/Caprice (Boezio et al., 2001) experiments, respectively. The upper dashed line shows the background prediction. The other lines show predictions from dark matter annihilation, for different WIMP masses (Donato et al., 2004).

A standard component of cosmic antiprotons is also produced by standard cosmic ray processes: this component is the background for this type of dark matter studies. Contrary to the case of the signal, the standard antiproton component suffers from much smaller uncertainties (see Donato et al. (2004) and references therein), of the order of 20–30%. The problem of antiproton searches is therefore to disentangle a signal in the low energy tail, signal which suffers at the moment from large uncertainties, from a much more under control background. The current experimental data on the antiproton flux vs. the antiproton kinetic energy are plotted in Fig. 5 together with the theoretical prediction for the background and some examples of predicted signals from neutralino annihilation. Fig. 5 shows two key features: the first is that the theoretical estimate of the background agrees well with the experimental data, which means that we cannot accommodate a large exotic component; the second is that the low energy tail of the spectrum, which is where the signal could mostly reveal itself, has very similar shape as compared to the background, a feature which prevents antiprotons from having a clear signature. A flux of antiprotons from dark matter annihilation coming out from the background
Fig. 6. Antiproton flux at kinetic energy $T = 0.23$ GeV as a function of the neutralino mass, calculated in the low–energy minimal supersymmetric standard model. For masses lighter than 50 GeV, the model allows for non–universality in the gaugino sector; for higher masses, standard GUT universality holds. The shaded area denotes the amount of exotic antiprotons which can be accommodated at this energy without conflicting with the existing data and background calculations. The astrophysical propagation parameters are set at their best–fit values (Bottino et al., 2004).

could show up at energies larger than a few tens of GeV (a region where no data are currently available and which will be covered in the future by Pamela and AMS): nevertheless this possibility requires somehow large dark matter overdensities, since in this case the WIMP must have a large mass and the WIMP number density scales rapidly with increasing DM mass (the signal scales even faster, with the number density squared).

Concentrating on the low energy tail of the antiproton flux, we may therefore derive constraints on the exotic DM production and use this bound to constrain supersymmetric models. Antiprotons represent the best indirect signals for constraining dark matter searches, even though we must remember the large astrophysical uncertainty which they suffer. Fig. 6 shows an example for neutralinos in the low–energy MSSM with (for masses above 50 GeV) and without (for masses below 50 GeV) gaugino universality. The plot is shown for the best–fit value of the astrophysical propagation parameters: uncertainty of one order of magnitude above and below the plotted points must be taken into account. Even in this unfortunate situation we see that antiprotons searches can offer a quite strong constraint on low mass neutralinos. This is better shown in Fig. 7, where we show the regions in the astrophysical parameter space which are compatible with antiprotons produced by low–mass neutrali-
Fig. 7. Regions in the astrophysical–propagation–parameters space where the fit to the experimental antiproton data of a background+signal–component is statistically acceptable. In this case the plane convective velocity $v_c$ vs. the height $L$ of the diffusive region is shown. Big circles, small circles and dots refer to neutralino masses of 10, 20, 30 GeV, respectively. \textit{Bottino et al.} [2005b].

Fig. 8. The same as in Fig. 6, calculated in a minimal (universal) SUGRA scheme \textit{[Donato et al., 2004]}.

We see that the predicted signals are compatible with observations only is a very limited and correlated sector of the astrophysical parameter space. This situations is expected to improve significantly in the near future: therefore we
5 Antideuteron signal

The WIMP annihilation process in the galactic halo may produce also antideuterons, which then suffer analogous diffusive and energy loss processes as the antiprotons. In Donato et al. (2000) it has first been shown that the low energy tail of the antideuteron flux offers a very good signal–to–background ratio, mostly due to kinematical reasons. The low–energy antideuteron flux could be able to set clear constraints (or detect a signal), especially for light mass neutralinos.
Fig. 10. Antideuteron flux at kinetic energy $T = 0.24$ GeV produced by neutralino annihilation in the galactic halo (Donato et al., 2000). The supersymmetric model is a low–energy minimal supersymmetric standard model. The horizontal line shows the predicted sensitivity of AMS for a 3 years data taking on board of the International Space station.

therefore offer a very good handle to detect a signal, contrary to antiprotons which currently seems better suited to set limits. Fig. 9 shows the antideuteron background and signals vs. kinetic energies: below 1–3 GeV of kinetic energy the background is very much depressed, contrary to the signal.

Fig. 10 then shows the predictions in the MSSM for one low–energy bin, compared to the expected sensitivity for positive detection for the AMS detector on board of the ISS in a 3 years data taking. We see that a large fraction of the configurations are accessible to detection. The proposed experiment GAPS (Baltz et al., 2002) is designed to access an order of magnitude more in sensitivity, which will allow to cover most of the configurations of the MSSM.
Fig. 11. Positron fraction vs. the positron energy. The data points are from HEAT. The solid lines refer to background estimates and neutralino annihilation production in the galactic halo (figure from Baltz et al. (2002)).

6  Positron signal

Dark matter annihilation in the galactic halo may also produce a positron signal. Fig. 11 shows the experimental result of the HEAT detector, which seems to indicate a bump in the spectrum around energies of 10–30 GeV. This feature is hardly compatible with the background estimates and this could point toward the presence of an exotic component. Fig. 11 shows an example of positron production from neutralino annihilation. Even in this case the spectral shape is difficult to reproduce, even though the agreement between theoretical predictions and data improves. One has to notice also that the HEAT data would require a sizeable overdensity of dark matter in order to explain the positron excess. This overdensity should also be quite local in the Galaxy, since positron do not travel long distances in the diffusive halo.

7  Gamma rays signal

Dark matter annihilation into gamma–rays is one of the best possibilities to be looked for. In this case there is no uncertainty coming from propagation of the signal, contrary to the antimatter case. However what are quite uncertain in this case are the properties of the source, especially if one looks toward the galactic center which is the place where the dark matter density is larger (except in the case of the presence of sizeable clumps, which nevertheless represent an additional element of uncertainty).

At energies around 1–10 GeV the EGRET detector observes a possible ex-
Fig. 12. Gamma ray flux vs. energy (Bottino et al., 2004). The data points refer to EGRET. The dashed line is an estimate of the gamma ray diffuse background, while the dotted line refers to gamma rays production from a 30 GeV neutralino annihilating in the galactic halo. The solid line is the total gamma ray flux.

Fig. 13. Gamma ray flux vs. energy. The data points refer to EGRET. The dashed line is the standard background component. The lower solid line refer to a gamma ray contribution from a 520 GeV neutralino annihilation and the upper solid curve is the sum of this contribution and the standard background. The dot–dashed and dotted lines show the prediction of gamma rays produced in blazar models (figure from Elsaesser et al. (2005)).

cess of gamma–rays over the standard background. Fig. 12 shows these data together with a possibile explanation of the effect as due to relatively light neutralinos in the MSSM. In this case, an overdensity factor of the dark matter of the order of 30 above the case of a NFW density shape is needed. This
Fig. 14. Gamma ray flux vs. energy (Fornengo et al., 2004). The right panel shows the comparison among the HESS data and predictions for gamma ray flux produced by annihilation of TeV–scale neutralinos.

Fig. 15. Gamma ray flux vs. energy. The data points refer to EGRET and HESS. The curves are predictions for astrophysical gamma–ray production in different galactic models (figure from Aharonian et al. (2004)).

is a typical situation for the gamma–rays case: typically overdensity factors are required in order to produce sizeable signals. These factors may be due to clumps along the line of sight toward the galactic center, or to steeper density profiles, as predicted in some dynamical models of structure formation.

Fig. 13 shows that the EGRET excess could instead be explained in terms of standard astrophysical processes, with some (relatively minor) modifications of
Fig. 16. Neutralino annihilation cross section into a gamma–ray line relative to the total annihilation cross section vs. the neutralino mass. The dashes lines refer to the future expected sensitivity of GLAST and HESS (figure from Zaharijas et al. (2004)).

Fig. 17. Integral gamma–ray flux from M31 galaxy vs. the neutralino mass for a 1 TeV neutralino in the low–energy minimal supersymmetric standard model (Fornengo et al., 2004). The expected sensitivities of GLAST and VERITAS are shown.

Another possible excess from the galactic center over the background could be present at larger energies, as seen, among others, by the HESS detector. Fig. 14 shows this excess around the TeV energy scale, together with an interpretation in terms of neutralino annihilation. Although it may be possible to explain this gamma ray production in terms of DM contributions, nevertheless this flux is likely to be due to standard sources, as shown for instance in Fig. 15 and explained in Aharonian et al. (2004). The fact that the HESS data are very
Fig. 18. Upgoing muon flux from neutrinos produced by neutralino annihilation in the center of the Earth, in the low-energy minimal supersymmetric standard model (Bottino et al., 2004). The solid/dashed/dotted lines refer to upper limits from SuperKamiokande/MACRO/Amanda experiments.

well reproduced by a power low profile, this points toward the interpretation in terms of a standard source. In this case, interesting limits on the neutralino annihilation component could be set (Zaharijas et al., 2004).

Neutralinos may also produce a gamma–ray line, in addition to a diffuse flux. Since this is a 1–loop process, it is suppressed as compared to the diffuse one. The prospects of detecting such a line are not very good, although GLAST and HESS could access some configurations, as shown in Fig. 16.

A possibility of looking for gamma–rays from dark matter annihilation in external galaxies has also been proposed. Fig. 17 shows some prospects for searching for this contributions from M31 galaxy with next generation detectors.

8 Neutrinos from Earth and Sun

Finally, we have the possibility to look for a neutrino signal produced in the center of the Earth or the Sun where DM may accumulate after gravitational capture. The muon neutrino component of this flux is then detected as upgoing muons in a neutrino telescope. Fig. 18 and Fig. 19 show the theoretical predictions in the MSSM for the upgoing muon flux coming from the Earth and the Sun, compared to the current experimental sensitivities. We see that
Fig. 19. Upgoing muon flux from neutrinos produced by neutralino annihilation in the Sun, in the low–energy minimal supersymmetric standard model (Bottino et al., 2004). The solid/dot–dashed/dashed/dotted lines refer to upper limits from SuperKamiokande/Baksan/MACRO/Amanda experiments.

Fig. 20. Predictions of upgoing muon flux from neutrinos produced by neutralino annihilation in the Sun for a large–area neutrino telescope, in the low–energy minimal supersymmetric standard model. The solid and dashed lines show the expected sensitivities. The dot–dashed lines show the neutrino production from cosmic–rays interactions with the solar corona (figure from Bergstrom et al. (1998)).

the neutrino signal is not suited for light neutralinos, since in this case the flux is too soft. Larger mass neutralinos may easily produce harder neutrinos which then can produce muons above the detector threshold.
Fig. 20 shows prospects for a km–size detector, for which the threshold energy is larger and therefore only large mass neutralinos could be accessed.

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