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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-borne 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.

Keywords: 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. The neutrino is unsuited to explain the bulk of DM since it acts as hot dark matter, while instead CDM is largely required to successfully produce the observed large scale structure of the Universe.

Supersymmetry offers a wonderful possibility, since the lightest supersymmetric particle is stable, once R-parity is conserved, and it naturally possesses the properties of a successful 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 of 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,

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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 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. Fig. 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 shows the same theoretical predictions compared 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).

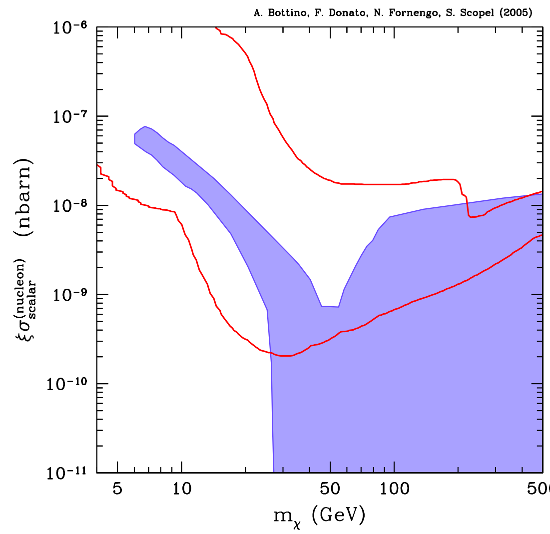

Fig. 1. Direct detection scattering cross section on a nucleon vs. the WIMP mass. The solid lines show the allowed region by the DAMA/NaI experiment compatible with the observed annual modulation effect (Bernabei et al., 2003) and derived for a wide variation of galactic halo models (Bernabei et al., 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).

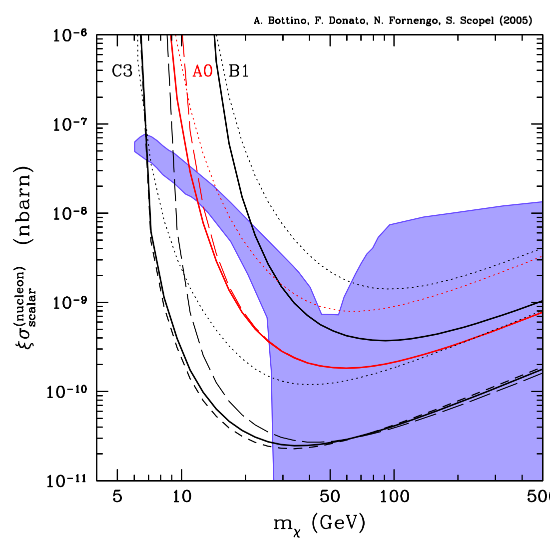

Fig. 2. The same as in Fig. 1, except that the solid lines denote upper limits from the CDMS detector (Akerib et al., 2005) for some specific galactic halo models, as calculated in Bottino et al. (2005a).

As a general comment on the DAMA/NaI and CDMS results, we wish to remind that it is not possible to make a direct comparison among the DAMA allowed region in Fig. 1 and the upper limits shown in Fig. 2 for CDMS, since the DAMA region, as presented by the experimental Collaboration and reproduced here, is a convolution obtained after varying galactic halo models, while the