

# Indirect evidence for neutralinos as dark matter

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**Abstract.** From the relic density measurement by WMAP the WIMP annihilation cross section can be determined in a model independent way. If the WIMPS are postulated to be the neutralinos of Supersymmetry, then only a limited region of the supersymmetric parameter space matches this annihilation cross section. It is shown that the resulting positrons, antiprotons and gamma rays from the neutralino annihilation (mainly into  $b\bar{b}$  quark pairs) provide the correct shape and order of magnitude for the missing gamma and hard positron fluxes in the Galactic Models and are consistent with antiproton production.

## 1 Introduction

Cold Dark Matter (CDM) makes up 23% of the energy of the universe, as deduced from the temperature anisotropies in the Cosmic Microwave Background in combination with data on the Hubble expansion and the density fluctuations in the universe [1]. The nature of the CDM is unknown, but one of the most popular explanation for it is the neutralino, a stable neutral particle predicted by Supersymmetry [2,3]. The neutralinos are spin 1/2 Majorana particles, which can annihilate into pairs of Standard Model (SM) particles. The stable decay and fragmentation products are neutrinos, photons, protons, antiprotons, electrons and positrons. From these, the protons and electrons are drown in the many matter particles in the universe, but the antimatter may be detectable above the background from nuclear interactions, especially because of the harder positron and gamma spectra expected from neutralino annihilation. This so-called indirect detection of Dark Matter has been discussed much before (see e.g. [4]). Our results differ from these previous results by performing a statistical analysis to gamma rays, antiprotons and gamma rays *simultaneously* and taking into account the best known propagation models and all constraints from WMAP and electroweak data on the SUSY parameter space. More details of this analysis can be found in the contributed paper to this conference[5].

## 2 Annihilation cross section constraints from WMAP

In the early universe all particles were produced abundantly and were in thermal equilibrium through annihilation and production processes. At temperatures below the mass of the neutralinos the number density drops exponentially. The annihilation rate  $\Gamma = \langle \sigma v \rangle n_\chi$  drops exponentially as well, and if it drops below the expansion

rate, the neutralinos cease to annihilate and a relic cosmic abundance remains. For the case that  $\langle \sigma v \rangle$  is energy independent, which is a good approximation in case there is no coannihilation, the present mass density in units of the critical density is given by [3]:

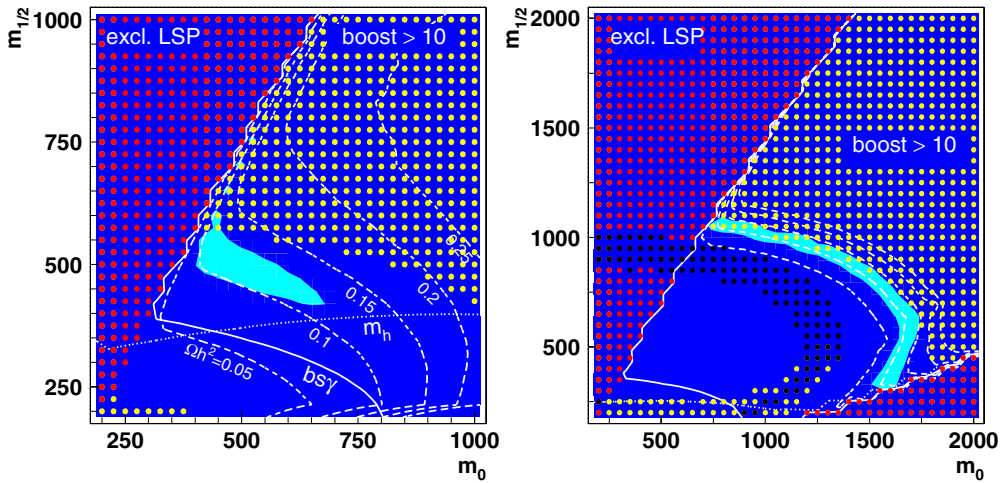
$$\Omega_\chi h^2 = \frac{m_\chi n_\chi}{\rho_c} \approx \left( \frac{3 \cdot 10^{-27} \text{cm}^3 \text{s}^{-1}}{\langle \sigma v \rangle} \right). \quad (1)$$

One observes that the present relic density is inversely proportional to the annihilation cross section at the time of freeze out, a result independent of the neutralino mass (except for logarithmic corrections). For the present value of  $\Omega_\chi h^2 = 0.11$  the thermally averaged total cross section at the freeze-out temperature of  $m_\chi/25$  must have been  $3 \cdot 10^{-27} \text{cm}^3 \text{s}^{-1}$ . This can be achieved only for restricted regions of parameter space in the MSSM, as will be discussed in the next section. Note that the annihilation cross section is given by the Hubble expansion and therefore not dependent on the WIMP model.

## 3 Predictions from supersymmetry

The mSUGRA model, i.e. the Minimal Supersymmetric Standard Model (MSSM) with supergravity inspired breaking terms, is characterized by only 5 parameters:  $m_0$ ,  $m_{1/2}$ ,  $\tan \beta$ ,  $\text{sign}(\mu)$ ,  $A_0$ [6]. Here  $m_0$  and  $m_{1/2}$  are the common masses for the gauginos and scalars at the GUT scale, which is determined by the unification of the gauge couplings. Exact gauge unification is still possible with the precisely measured couplings at LEP [7].

The neutralinos, which are assumed to be the stable, lightest supersymmetric particles, can annihilate through higgs- and Z-exchange in the s-channel and SUSY particles (neutralinos, charginos, sfermions) in the t-channel. At large values of  $\tan \beta$  the dominant channel is the pseudoscalar Higgs exchange with  $b\bar{b}$  quarks in the final state,



**Fig. 1.** The light shaded (blue) area is the region allowed by WMAP and the contours of larger  $\Omega h^2$  are indicated by the dashed lines in steps of 0.05. The upper plot is for  $\tan\beta=51$  and  $A_0 = m_0$ , while the lower plot is for  $\tan\beta=53$  and  $A_0 = 0$ . For the last parameters the neutralino annihilation hits the pseudoscalar Higgs resonance, which allows heavier neutralinos with still a small enough relic density. The black dots indicate the resonance region, where  $|m_A - 2m_{\chi_0}| \leq 10$  GeV. The excluded regions, where the stau would be the LSP or EWSB fails or the boost factors are above 10 are indicated by the dots

which lead to a well defined shape of the final state gammas, positrons and electrons, since the annihilation is practically at rest. The regions of parameter space allowed by the WMAP data are plotted in Fig. 1 for two values of  $\tan\beta$ . It is clear that for  $\tan\beta \approx 50$  only a small region is allowed. Scanning over all possible values of  $\tan\beta$  the neutralino masses allowed by the WMAP data and electroweak constraints are in the range of 150-400 GeV[5], if we exclude the coannihilation regions, which would lead to anomalously large boost factors, as discussed in the next section. For the fits discussed below we use a typical mass of 200 GeV, which corresponds to  $m_{1/2} \approx 500$  GeV. The data are not yet sensitive enough to distinguish between masses in the range given above.

#### 4 Global fits to positrons, antiprotons, and gamma rays

Trying to disentangle the contributions from nuclear interactions and neutralino annihilation to the antimatter fluxes and gamma rays is in practice not easy. We use the following strategy: the shape of the background is taken from the GALPROP program, which represents a detailed simulation of our galaxy[8]. The main background of hard gammas comes from  $\pi_0$  decays, which are produced in nuclear interactions and inverse Compton scattering of electrons on photons. The shape of the neutralino annihilation signal is taken from DarkSusy[9]. These shapes are then multiplied by an arbitrary normalization factor, which is left as a free parameter in the  $\chi^2$  fit to the data.

The following data were used in the fit:

- Gamma ray data from the galactic center in the angular range  $330^\circ < \ell < 30^\circ$  and  $-5^\circ < b < 5^\circ$  from the EGRET space telescope, which has been taking data for about 9 years on the NASA Compton Gamma Ray

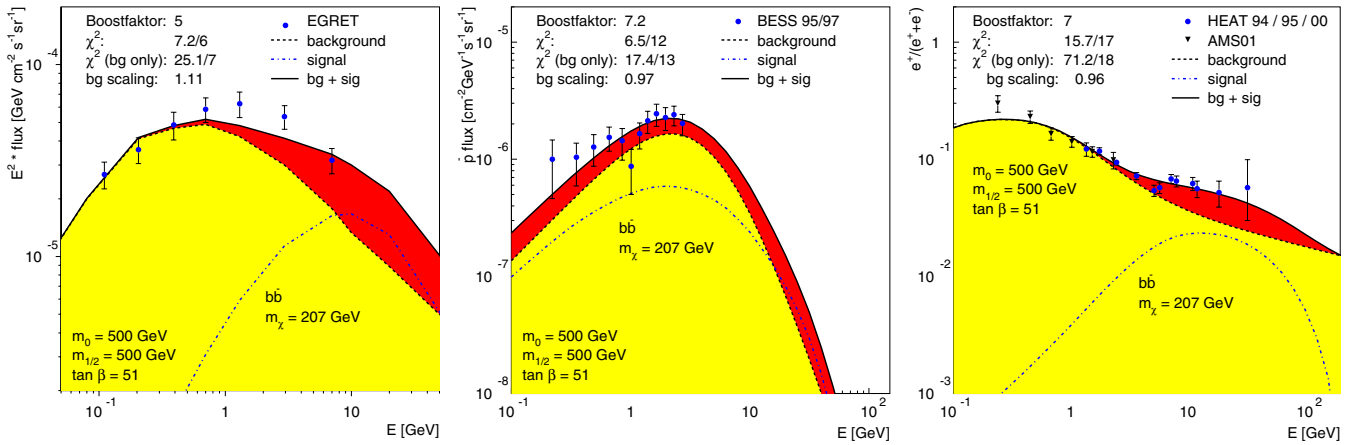
Observatory (CGRO). We use the data as presented in [10].

- Positron data from AMS [11] and HEAT [12].
- Antiproton data from BESS in the years 1997 and 1998 [13]

The fit results are shown in Fig. 2. The free parameters are only the normalization factors for signal and background for each of the particle species and their values have been indicated in the figures. The boost factors, i.e. the free normalization factor after correcting for the different propagations and energy losses, for antiprotons, positrons and gamma rays are all around 5-7 for the NFW halo profile[14] taken<sup>1</sup>. Much larger factors are not expected from theories of galaxy formation. If we select SUSY parameters in the so-called coannihilation region, where e.g. the stau and neutralino are almost degenerate, the boost factors come out to be much larger, since the fast annihilation cross section in the early universe by stau-neutralino coannihilation does not operate in the present universe anymore and the small present annihilation cross section for heavy neutralinos needs a large boost factor to fit the data. The regions for which the boostfactors are above 10 are indicated in Fig. 1.

The  $\chi^2$  improves significantly with the inclusion of Dark Matter in the fits. The  $\chi^2/d.o.f.$  is reduced from 113/35 (110/38) for the background only fit to 29/32 (33/35) for the fit including neutralino annihilation, where the numbers in brackets are valid, if one takes the shape *and* normalization from GALPROP, while the first numbers are obtained if only the shape is taken and the background normalization is left free. This corresponds to about a 4 (6)  $\sigma$  effect, if calculated with Gaussian errors. For the antiprotons the increase in probability is the least

<sup>1</sup> We use the default  $(\alpha, \beta, \gamma) = (1, 3, 1)$  for a scale  $a = 10$  kpc and a local relic density of  $0.8$  GeV/cm<sup>3</sup>.



**Fig. 2.** From top to bottom: Gamma ray , positron and antiproton spectrum with contributions from nuclear interactions (grey/yellow) and neutralino annihilation (dark/red) for a neutralino mass of 207 GeV. The normalization factors for signal, called boostfaktor, and background (bg scaling) and the values of  $\chi^2$  with and without signal have been indicated

significant, as expected, since the shape of background and signal are similar.

It should be noted that the statistical significance is *independent* of the choice of halo or propagation parameters, since different halo or propagation parameters would only lead to different normalization factors in the fit, but the  $\chi^2$  is not affected, since it is only sensitive to the shape of the distribution with free normalization parameters.

## 5 Conclusion

It is shown that the discrepancies between EGRET data and the galactic models can be reduced by taking as an additional source of hard gammas the annihilation of Dark Matter, assuming Dark Matter is made of neutralinos, as predicted by Supersymmetry. In addition, it is shown that adding the positrons from neutralino annihilation in the *same* Dark Matter model to the *same* background model improves also the  $\chi^2$  fit to the positron data significantly, while the increase in antiprotons is compatible with the data. These facts, statistical significant improvement of the global fit for positrons, antiprotons and gamma rays *simultaneously* for a supersymmetric model with an annihilation cross section compatible with the model-independent WMAP value, provide strong experimental evidence for the supersymmetric nature of Dark Matter.

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