We analyse the effect of the compression of the dark matter due to the infall of baryons to the galactic center on the gamma-ray flux. In addition, we also consider the effect of non-universal supersymmetric soft terms. This analysis shows that neutralino dark matter annihilation can give rise to signals largely reachable by future experiments like GLAST. This is a remarkable result if we realise that direct detection experiments will only be able to cover a small region of the parameter space. Actually, in this SUGRA framework we have also been able to fit present excess from EGRET and CANGAROO using different non-universal scenarios, and even fit the data from both experiments with only one scenario. We have also studied the recent HESS data implying a neutralino heavier than 12 TeV. Because of such a heavy neutralino, it is not natural to find solutions in the SUGRA framework. Nevertheless we have carried out a quite model-independent analysis, and found the conditions required on the particle physics side to fit the HESS data thanks to dark matter annihilation.

1 Introduction

It is now well established that luminous matter makes up only a small fraction of the mass observed in Universe. A weakly interacting massive particle (WIMP) is one of the leading candidates for the “dark” component of the Universe. One of the most promising methods for the indirect detection of WIMPs consists of detecting the gamma rays produced by their annihilations in the galactic halo. Concerning the nature of WIMPs, the best motivated candidate is the lightest neutralino, a particle predicted by the supersymmetric (SUSY) extension of the standard model\textsuperscript{1}. We implement in our analysis\textsuperscript{2} the lower bounds on the masses of SUSY particles and Higgs boson, as well as the experimental bounds on the branching ratio of the $b ightarrow s \gamma$ process and on $a^\text{SUSY}_\mu$, for which the more stringent constraint from $e^+e^-$ disfavors important regions of the SUGRA parameter space (see e.g. Ref.\textsuperscript{3,4}). In addition, we have also taken into account the last data concerning the $B_s \rightarrow \mu^+\mu^-$ branching ratio.
2 The gamma-ray flux

For the continuum of gamma rays, the observed differential flux at the Earth coming from a direction forming an angle $\psi$ with respect to the galactic center is

$$\Phi_\gamma(E_\gamma, \psi) = \sum_i \frac{dN_i}{dE_\gamma}(\sigma_i v) \frac{1}{8\pi m_\chi^2} \int_{\text{line of sight}} \rho^2 \, dl,$$

(1)

where the discrete sum is over all dark matter annihilation channels, $dN_i/dE_\gamma$ is the differential gamma-ray yield, $\langle \sigma_i v \rangle$ is the annihilation cross section averaged over its velocity distribution, $m_\chi$ is the mass of the dark matter particle, and $\rho$ is the dark matter density. Actually, when comparing to experimental data one must consider the integral of $\Phi_\gamma$ over the spherical region of solid angle $\Delta \Omega$ given by the angular acceptance of the detector which is pointing towards the galactic center. For example, for EGRET $\Delta \Omega$ is about $10^{-3}$ sr whereas for GLAST, CANGAROO, and HESS it is $10^{-5}$ sr. Note that neutralinos move at galactic velocity and therefore their annihilation occurs at rest.

3 The adiabatic compression model

Recently, SUSY dark matter candidates have been studied in the context of realistic halo models including baryonic matter. Indeed, since the total mass of the inner galaxy is dominated by baryons, the dark matter distribution is likely to have been influenced by the baryonic potential. In particular, its density is increased, and as a consequence typical halo profiles such as Navarro, Frenk and White (NFW) and Moore et al. have a more singular behaviour near the galactic center. The conclusion of the work in Ref. is that the gamma-ray flux produced by the annihilation of neutralinos in the galactic center is increased significantly, and is within the sensitivity of incoming experiments, when density profiles with baryonic compression are taken into account. Indeed, highly cusped profiles are deduced from N-body simulations. In particular, NFW obtained a profile with a behaviour $\rho(r) \propto r^{-1}$ at small distances. A more singular behaviour, $\rho(r) \propto r^{-1.5-1.6}$, was obtained by Moore et al. However, these predictions are valid only for halos without baryons. One can improve simulations in a more realistic way by taking into account the effect of the normal gas (baryons). This loses its energy through radiative processes falling to the central region of forming galaxy. As a consequence of this redistribution of mass, the resulting gravitational potential is deeper, and the dark matter must move closer to the center increasing its density.

This increase in the dark matter density is often treated using adiabatic invariants. The present form of the adiabatic compression model was numerically and analytically studied by Blumental et al. This model assumes spherical symmetry, circular orbit for the particles, and conservation of the angular momentum $M(r)r = \text{const.}$, where $M(r)$ is the total mass enclosed within radius $r$. The mass distributions in the initial and final configurations are therefore related by $M_i(r_i) r_i = [M_b(r_f) + M_{DM}(r_f)] r_f$, where $M_i(r)$, $M_b(r)$ and $M_{DM}(r)$ are the mass profile of the galactic halo before the cooling of the baryons (obtained through N-body simulations), the baryonic composition of the Milky Way observed now, and the to be determined dark matter component of the halo today, respectively. This approximation was tested in numerical simulations. Nevertheless, a more precise approximation can be obtained including the possibility of elongated orbits. The models and constraints that we used in this work for the Milky Way can be found in Table I of Ref. As one can see in, at small $r$ the dark matter density profile following the adiabatic cooling of the baryonic fraction is a steep power law $\rho \propto r^{-\gamma_c}$ with $\gamma_c \approx 1.45(1.65)$ for a NFW$_c$(Moore$_c$) compressed model.
4 Supersymmetric Models

As discussed in detail in Ref. 4 in the context of indirect detection, $\sigma_i$ can be increased in different ways when the structure of mSUGRA for the soft terms is abandoned. In particular, it is possible to enhance the annihilation channels involving exchange of the CP-odd Higgs, $A$, by reducing the Higgs mass. In addition, it is also possible to increase the Higgsino components of the lightest neutralino. Thus annihilation channels through Higgs exchange become more important than in mSUGRA. This is also the case for $Z^-, \chi_1^\pm$, and $\tilde{\chi}_1^0$-exchange channels. As a consequence, the gamma-ray flux will be increased.

In particular, the most important effects are produced by the non-universality of Higgs and gaugino masses. These can be parameterised, at $M_{GUT}$, as follows

\[ m_{H_d}^2 = m^2(1 + \delta_1) , \quad m_{H_u}^2 = m^2(1 + \delta_2) , \]  

and

\[ M_1 = M , \quad M_2 = M(1 + \delta_2') , \quad M_3 = M(1 + \delta_3') , \]  

We concentrated in 2 our analysis on the following representative cases:

- **a)** $\delta_1 = 0$, $\delta_2 = 0$, $\delta_{2,3}' = 0$,
- **b)** $\delta_1 = 0$, $\delta_2 = 1$, $\delta_{2,3}' = 0$,
- **c)** $\delta_1 = -1$, $\delta_2 = 0$, $\delta_{2,3}' = 0$,
- **d)** $\delta_1 = -1$, $\delta_2 = 1$, $\delta_{2,3}' = 0$,
- **e)** $\delta_{1,2} = 0$, $\delta_2' = 0$, $\delta_3' = -0.5$,
- **f)** $\delta_{1,2} = 0$, $\delta_2' = -0.5$, $\delta_3' = 0$.

Case **a)** corresponds to mSUGRA with universal soft terms, cases **b)**, **c)** and **d)** correspond to non-universal Higgs masses, and finally cases **e)** and **f)** to non-universal gaugino masses. The cases **b)**, **c)**, **d)**, and **e)** were discussed in Ref. 4, and are known to produce gamma-ray fluxes larger than in mSUGRA, whereas case **f)** will be of interest when discussing heavy WIMP signals predictions in the perspective of atmospheric Cherenkov telescopes like e.g. CANGAROO.

5 Confronting experiments

5.1 EGRET

The EGRET telescope on board of the Compton Gamma-Ray Observatory has carried out the first all-sky survey in high-energy gamma-rays ($\approx 30$ MeV – 30 GeV) over a period of 5 years, from April 1991 until September 1996. As a result of this survey, it has detected a signal above about 1 GeV, with a value for the flux of about $10^{-8}$ cm$^{-2}$ s$^{-1}$, that apparently cannot be explained with the usual gamma-ray background. The source, possibly diffuse rather than pointlike, is located within the 1.5° ($\Delta\Omega \sim 10^{-3}$ sr) of the galactic center. Due to the lack of precision data in the high energy bins, it seems impossible however to distinguish any annihilation channel leading to this photon excess. The results can be seen in Fig. 1, where case **c)** of Eq. (4) have been studied for a scan on $m$ and $M$ from 0 to 2 TeV and $\tan\beta = 35$. Let us remark that it is possible to differentiate each point of the parameter space ($m$, $M$) by its gamma-ray spectrum. The higher fluxes for instance corresponds to the closing of the A-pole, whereas the lower flux spectrum is obtained through the opening of the A-pole (see e.g. point **B** of Fig. 3 in 2).
Figure 1: Gamma–ray spectra $\Phi_\gamma(E_\gamma)$ from the galactic center as functions of the photon energy for the SUGRA case c) discussed in Eq. (4) for $\tan \beta = 35$, $A = 0$ and $\mu > 0$, compared with data from the EGRET experiment. NFW and Moore et al. profiles with adiabatic compression are used with $\Delta \Omega \sim 10^{-3}$ sr. All points shown after a scan on $m$ and $M$ (0 – 2000 GeV) fulfil the accelerator constraints discussed in the text, and WMAP bounds.

5.2 CANGAROO-GLAST

Recently, the CANGAROO–II atmospheric Cherenkov telescope has made a significant detection of gamma rays from the Galactic center region 11. In particular, the collaboration has published the spectrum obtained in six energy bins, from 200 GeV to 3 TeV. Observations taken during 2001 and 2002 have detected a statistically significant excess at energies greater than $\sim 250$ GeV, with an integrated flux of $\sim 2 \times 10^{-10}$ photons cm$^{-2}$ s$^{-1}$. These measurements indicate a very soft spectrum $\propto E^{-2.6\pm0.5}$.

It is interesting to see whether it is possible to obtain such a candidate in SUGRA scenarios imposing the accelerator and WMAP constraints, and within the framework of adiabatically compressed halos. The baryonic cooling effect on the fluxes gives us the order of magnitude needed to fit with both data with a 1 TeV neutralino in the non–universal case e) with $M_3 = 0.5M$. It is worth noticing that the CANGAROO-II collaboration in 11 pointed out already that the EGRET and CANGAROO-II data can be relatively smoothly connected with a cutoff energy of 1–3 TeV. Typical points of the parameter space fulfilling all experimental constraints and fitting both set of data lie between $(m = 800 \text{ GeV}, M = 800 \text{ GeV})$ and $(m = 3 \text{ TeV}, M = 3 \text{ TeV})$.

It is also interesting to see the complementarity of GLAST with EGRET and CANGAROO. GLAST will perform an all-sky survey detection of fluxes with energy from 1 GeV to 300 GeV, exactly filling the actual lack of experimental data in this energy range (see Fig. 2), and checking the CANGAROO results. Indeed, we have calculated that the integrated gamma ray flux for such a signal will be around $5 \times 10^{-11}$ cm$^{-2}$ s$^{-1}$. We have shown this sensitivity curve in Fig. 2 for $\Delta \Omega = 10^{-5}$, which is the typical detector acceptance, following the prescriptions given in 13. We clearly see that GLAST will finish to cover the entire spectrum.

5.3 HESS

The HESS Cherenkov telescope experiment has recently published new data on gamma rays, detecting a signal from the Galactic Center 12. The measured flux and spectrum differ substantially from previous results, in particular those reported by the CANGAROO collaboration, exhibiting a much harder power–law energy spectrum with spectral index of about $-2.2$ and extended up to 9 TeV. The authors of 12 already pointed out that if we assume that the observed gamma rays represent a continuum annihilation spectrum, we expect $m_\chi \gtrsim 12$ TeV. Actually such a heavy neutralino-LSP is not natural in the framework of a consistent supergravity model when we impose the renormalisation group equations and radiative electroweak symmetry breaking.
6 Conclusion

We have analysed the effect of the compression of the dark matter due to the infall of baryons to the galactic center on the gamma-ray flux. In addition, we have also consider the effect of
non-universal soft terms, that arises naturally in string motivated framework. This analysis shows that neutralino dark matter annihilation can give rise to signals largely reachable by future experiments like GLAST. This is a remarkable result if we realise that direct detection experiments will only be able to cover a small region of the parameter space. Actually, in this SUGRA framework we have also been able to fit present excess from EGRET and CANGAROO using different non-universal scenarios, and even fit the data from both experiments with only one scenario. We have also carried out a quite model-independent analysis, and found the conditions required on the particle physics side to fit the HESS data thanks to dark matter annihilation. In any case, we must keep in mind that the current data obtained by the different gamma-rays observations from the Galactic Center region do not allow us to conclude about a dark matter annihilation origin rather than other less exotic astrophysics sources. Fortunately, this situation may change with the improvement of angular resolution and energy sensitivity of future detectors like GLAST.

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