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Search for Dark Matter with GLAST

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Abstract The detection of gamma-rays, antiprotons and positrons due to pair annihilation of dark matter particles in the Milky Way halo is a viable techniques to search for supersymmetric dark matter candidates. In particular the EGRET team has seen a convincing signal for a strong excess of emission from the Galactic center that has no simple explanation with standard processes. We will review the limits achievable with the experiment GLAST and we will compare this method with the antiproton and positrons experiments.

Key words: instrumentation: detectors – dark matter – GRB

1 INTRODUCTION

GLAST (Bloom et al. 1998, Morselli 1997) is a next generation high-energy gamma-ray observatory designed for making observations of celestial gamma-ray sources in the energy band extending from 20 MeV to more than 300 GeV. The principal instrument of the GLAST mission is the Large Area Telescope (LAT) that is being developed as a mission involving an international collaboration of particle physics and astrophysics communities from 26 institutions in the United States, Italy, Japan, France and Germany. The main scientific objects are the study of all gamma-ray sources such as blazars, gamma-ray bursts, supernova remnants, pulsars, diffuse radiation, and unidentified high-energy sources. Many years of refinement have led to the configuration of the apparatus shown in Figures 1 and 2, where one can see the 4×4 array of identical towers, each formed by: • Si-strip Tracker Detectors and converters arranged in 18 XY tracking planes for the measurement of the photon direction. • Segmented array of CsI(Tl) crystals for the measurement the photon energy. • Segmented Anticoincidence Detector (ACD).

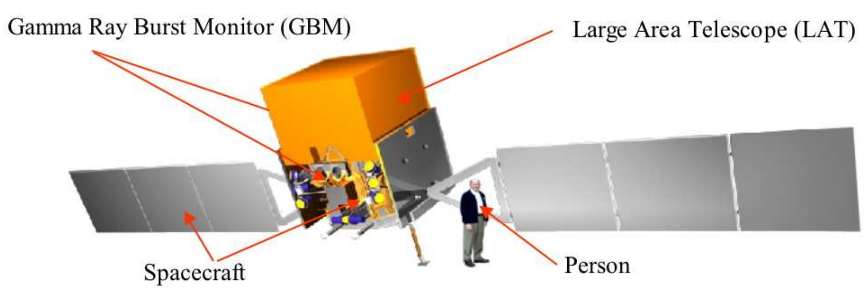

Fig. 1 The GLAST payload.

The main characteristics of the detector, extensively studied with Monte Carlo and beam tests, are an energy range between 20 MeV and 300 GeV, a field of view of ~ 3 sr, an energy resolution of $\sim 5\%$ at 1 GeV, a point source sensitivity of 2×10^{-9} (ph cm^{-2} s^{-1}) at 0.1 GeV, an event deadtime of 20 μs and a

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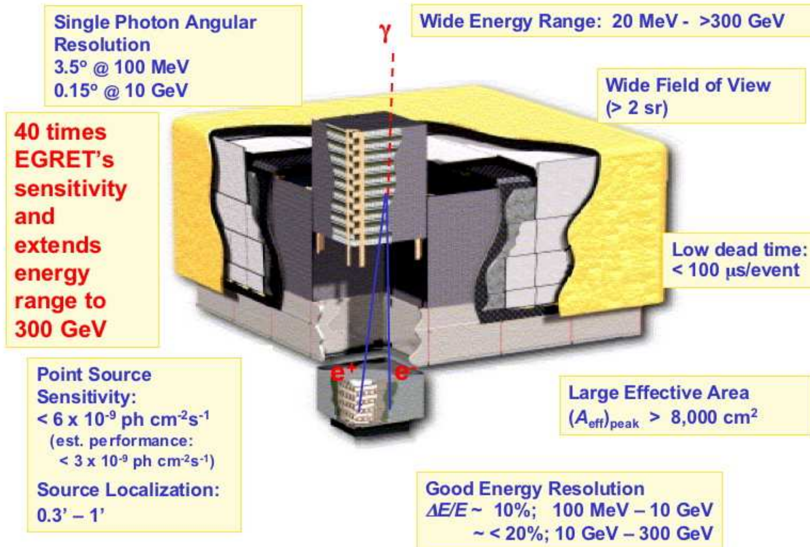

Fig. 2 The GLAST instrument.

peak effective area of 10 000 cm^2, for a required power of 600 W and a payload weight of 3000 kg. A more detailed description of the main GLAST parameters can be found in (Morselli 2002b).

GLAST could be of particular interest for the search of dark matter candidates. If dark matter is made by the lightest supersymmetric particles (neutralinos), they would have non-relativistic velocities; hence the neutralino annihilation into two γ's and a γ and a Z as final states can give rise to γ-rays with unique energies $E_\gamma = M_\chi$ and $E'_\gamma = M_\chi\,(1 - m_z^2/4M_\chi^2)$. All the other annihilation processes will give also π^0 that will decay in a continuum gamma-ray flux.

The potential of GLAST has been explored both in the context of a generic simplified toy-model for WIMP dark matter, and in a more specific setup, the case of dark matter neutralinos in the minimal supergravity framework. In the latter, we find that even in the case of moderate dark matter densities in the Galactic center region, there are portions of the parameter space which will be probed by GLAST.

Figure 3 (top) shows the EGRET data located within 2° from the Galactic center together with the diffuse gamma-ray background flux expected from the standard interactions and propagation models of cosmic-ray protons and electrons and an example of the flux due to neutralino annihilation in the dark matter halo (Morselli et al. 2002) In this case the signal is for a $\sim$80 GeV neutralino and for the W^-W^+ annihilation channel (the spectral shape of the other channels is very similar).

Figure 3 (bottom) shows the same fluxes of Figure 3 (top) with the kind of statistical errors that is expected in two years with GLAST (Cesarini et al. 2004) It can be seen that GLAST will have the necessary statistical and energetic accuracy to distinguish the two kinds of spectral shape.

In Figure 4 it is shown a 2×2 degrees galactic center region as seen by INTEGRAL. Each pixel is large 2 arcmin. GLAST will have the same angular resolution as INTEGRAL toward the galactic center and so it will discover if the gamma flux seen by EGRET is due to a diffuse signal or it is generated by one of the sources seen by INTEGRAL.

We focus now on the most widely studied WIMP dark matter candidate, the lightest neutralino, in the most restrictive supersymmetric extension of the Standard Model, the minimal supergravity (mSUGRA) framework (Hall et al. 1983) We fix the five mSUGRA input parameters:

$$m_{1/2},\ \ m_0,\ \ \mathrm{sign}(\mu),\ \ A_0\ \ \text{and}\ \ \tan\beta\,,$$

where m_0 is the common scalar mass, $m_{1/2}$ is the common gaugino mass and A_0 is the proportionality factor between the supersymmetry breaking trilinear couplings and the Yukawa couplings. $\tan\beta$ denotes

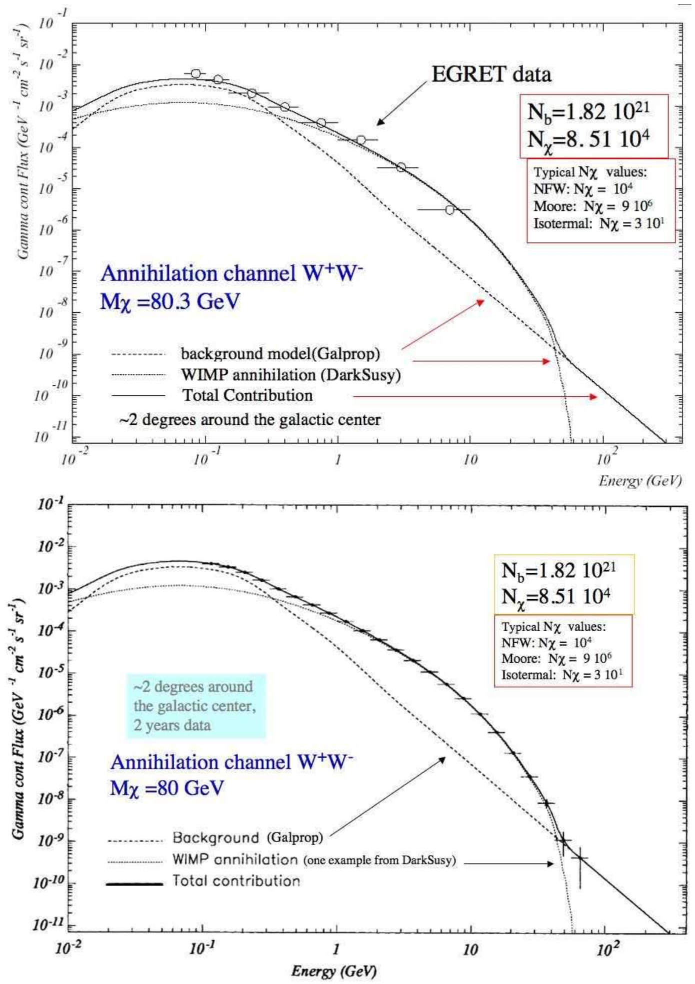

Fig. 3 Top: Fit of the EGRET Galactic Center γ-ray data for a sample WIMP models with $M_\chi = 80.3$ GeV and W^-W^+ annihilation channel. On the bottom the same fluxes with the kind of statistical errors that it is expected in three years with GLAST.

the ratio of the vacuum expectation values of the two neutral components of the SU(2) Higgs doublet, while the Higgs mixing μ is determined (up to a sign) by imposing the Electro-Weak Symmetry Breaking (EWSB) conditions at the weak scale. The parameters at the weak energy scale are determined by the evolution of those at the unification scale, according to the renormalization group equations (RGEs). For this purpose, we have made use of the ISASUGRA RGE package in the ISAJET 7.64 software (Baer et al. 2000). After fixing the five mSUGRA parameters at the unification scale, we extract from the ISASUGRA output the weak-scale supersymmetric mass spectrum and the relative mixings. Cases in which the lightest neutralino is not the lightest supersymmetric particle or there is no radiative EWSB are disregarded. The ISASUGRA output is then used as an input in the DarkSUSY package (Gondolo et al. 2002). The latter is exploited to: a) reject models which violate limits recommended by the Particle Data Group 2002 (PDG) (Hagiwara et al. 2002); b) compute the neutralino relic abundance, with full numerical solution of the density evolution equation including resonances, threshold effects and all possible coannihilation processes (Edsjo et. al. 2003); c) compute the neutralino annihilation rate at zero temperature in all kinematically allowed tree-level final states (including fermions, gauge bosons and Higgs bosons); d) estimate the induced gamma-ray

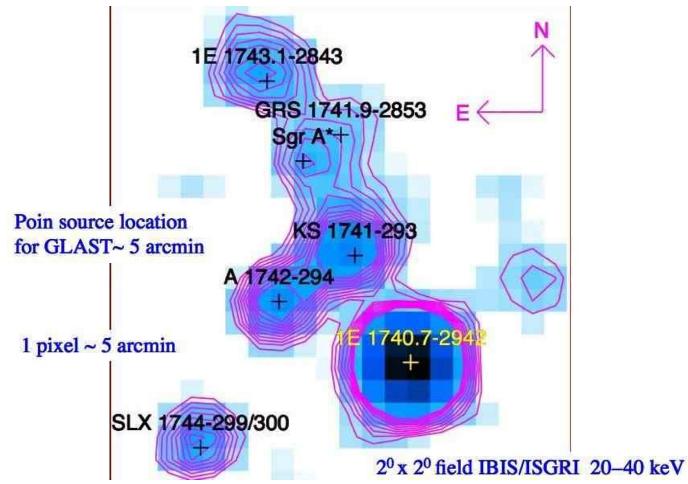

Fig. 4 2×2 degrees galactic center region as seen by INTEGRAL. Each pixel is large 2 arcmin.

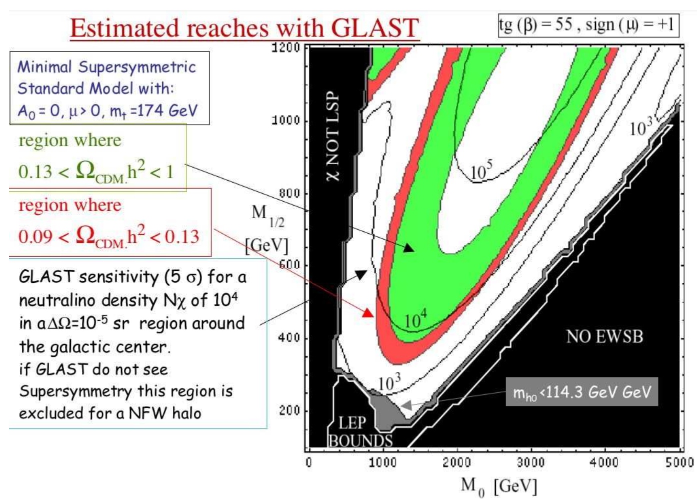

Fig. 5 Contour plot in the mSUGRA $(m_0, m_{1/2})$ plane, for the value of the normalization factor N_χ, that allows the detection of the neutralino γ-ray signal with GLAST. In the green region $0.13 \le \Omega_\chi h^2 \le 1$, while the red region corresponds to the WMAP range $0.09 \le \Omega_\chi h^2 \le 0.13$. The black region corresponds to models that are excluded either by incorrect EWSB, LEP bounds violations or because the neutralino is not the LSP. In the dark shaded region $m_{h_0} < 114.3$ GeV and h_0 is the lightest Higgs.

yield by linking to the results of the simulations performed with the Lund Monte Carlo program Pythia as implemented in the DarkSUSY package.

Fixing $\tan\beta$, A_0 and sgn(μ), we have performed a scan in the $(m_0, m_{1/2})$ plane searching for the minimum dark matter density, in the GC region, needed to be able to single out the neutralino annihilation signal with GLAST. First we estimate the statistical error (1σ) on GLAST data to be the square root of the number of events. To compute the latter we multiply the flux by the effective area of the detector, by the total observational time and the angular resolution $\Delta\Omega = 10^{-5}$ sr. Then for each value of the pair $(m_0, m_{1/2})$

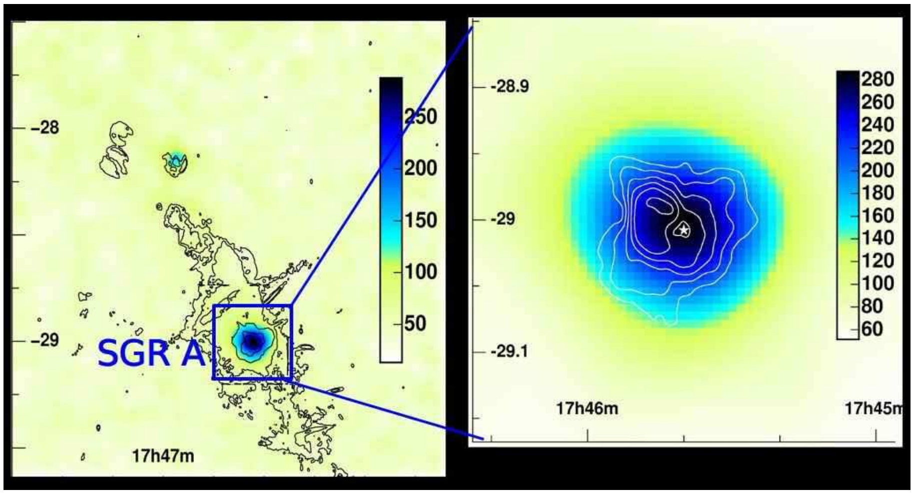

Fig. 6 The galactic center as seen by the H.E.S.S. experiment (Aharonian et al. 2004). The source position is consistent with SGR A* within 6 arcsec and slightly extended.

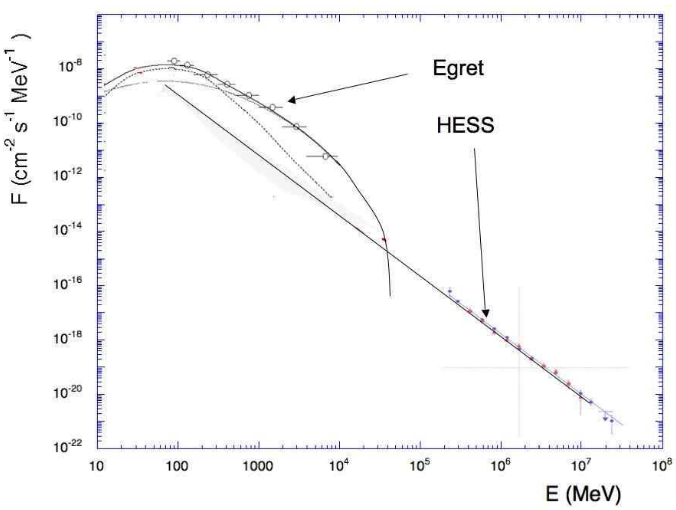

Fig. 7 Extrapolation of the H.E.S.S flux to the EGRET energies if one use the same spectral index measured by H.E.S.S.

we compute the difference between the fluxes $\phi_\gamma = \phi_{\rm b} + \phi_\chi = N_{\rm b} S_{\rm b} + N_\chi S_\chi$ and $\phi'_\gamma = \phi_{\rm b} = N_{\rm b} S_{\rm b}$. If $\phi_\gamma - \phi'_\gamma > 3\sigma$ we consider the SUSY model with those values of $(m_0, m_{1/2})$ to be detectable by GLAST.

Figure 5 shows the GLAST capability for $\tan\beta$=55 to probe in two years the supersymmetric dark matter hypothesis. The figures show in the $(m_0, m_{\frac{1}{2}})$ plane, the iso-contour regions for the minimum allowed value of the neutralino density in a $\Delta\Omega = 10^{-5}$sr region around the galactic center. The density depends on the halo shape of the neutralino distribution, that is still matter of debate and can vary from a value of $N_\chi = 3 \times 10^1$ for an isotermal profile up to $N_\chi = 10^4$ for a NFW profile (Navarro et al. 1996) and up to $N_\chi = 10^7$ for a Moore profile (Ghigna et al. 2000) GLAST indeed can explore a good portion of the supersymmetric parameter space especially at large values of $\tan\beta$ and if the halo has a NFW (or steeper) profile. This is a very steep ($1/r$) profile but consistent with available dynamical constraints on the Galaxy.

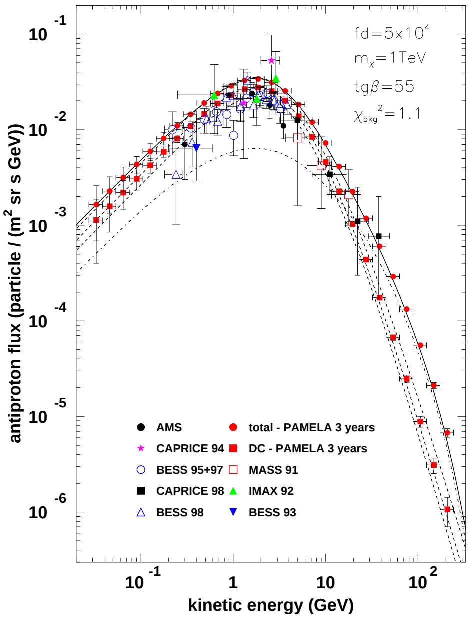

Fig. 8 Antiproton absolute flux: theoretical predictions for total uncertainty and best B/C fit for DC model (dashed lines) . Experimental data are from [9]. The PAMELA expectations points (red squares) for DC background are for three years of data taking. The dash-dotted line is a neutralino induced contribution for a neutralino mass of 1 TeV (see text) and a clumpiness factor fd of 5×10^4 while the solid line is total contribution calculated with the addition of the DC background and the red circles are the corresponding PAMELA points.

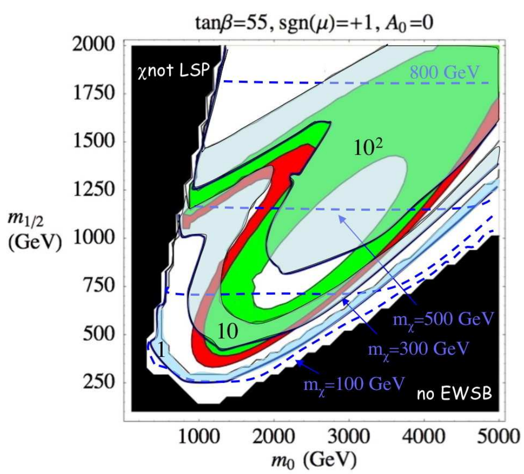

Fig. 9 Contour plots for the minimum fd needed for a PAMELA disentanglement (upper bounds of the translucent bands) and for the maximum fd allowed by current experimental data (lower bounds of the translucent bands). In the upper panel $\tan\beta = 50$ while in the lower panel $\tan\beta = 55$. The other parameters (keep fixed) are $A_0 = 0$ and $\mathrm{sgn}(\mu)$. Black color represents the regions in the parameter space that are excluded either by accelerator bounds or because electroweak symmetry breaking is not achieved or because the neutralino is not the lightest supersymmetric particle. The translucent regions denote the parameter space domains that correspond to models detectable by PAMELA. Red (dark shaded) are domains with Ωh^2 in the WMAP region $0.09 < \Omega h^2 < 0.13$, while green (light shaded) are the parameter space domains with $0.13 < \Omega h^2 < 0.3$. We also show the equi-neutralino mass contours (blue dashed lines).

Recently the H.E.S.S. experiment has discovered a powerful TeV gamma-ray source in the galactic center (Aharonian et al. 2004). The source position is consistent with SGR A* within 6 arcsec and slightly extended (see Figure 6) with an unbroken power-law with $\Gamma = 2.2$ and no evidence for variability on a variety of time scales.

There have been studies to connect the H.E.S.S. flux with neutralino annihilation (Profumo 2005, Bergstrom et al. 2005) but as can be noted from Figure 7, the extrapolation of the H.E.S.S flux to the EGRET energies with the same power law gives a flux that is a factor hundred less and then it is very likely that the two sources are different.

The search for a supersymmetric signal with GLAST will be complementary to the search for neutralinos looking at the distortion of the secondary positron fraction and secondary antiproton flux that will be performed with PAMELA and AMS. Figure 8 shows the PAMELA expectations for the antiproton flux for the best standard production and propagation model (Lionetto et al. 2005) obtained with the use of its geometrical factor and detector characteristics (Picozza et al. 2003). The primary contribution to the $\bar{p}$ flux has been computed using the public code DarkSUSY. We have modified the $\bar{p}$ propagation in order to be consistent with the diffusion and convection (DC) model as implemented in Galprop. We assumed diffusion coefficient spectra used in Galprop with our best fit values for the diffusion constants D_0 and δ. In DarkSUSY the convection velocity field is constant in the upper and lower Galactic hemispheres (with opposite signs, and so it suffers unnatural discontinuity in the Galactic plane) while Galprop uses a magnetohydrodynamically induced model in which the component of velocity field along the Galactic latitude (the only one different from zero) increases linearly with the galactic latitude. We have assumed an averaged convection velocity calculated from the Galactic plane up to the Galactic halo height z. The SUSY contribution to the $\bar{p}$ flux is shown in Figure 8 for a neutralino mass of 1 TeV (obtained from a particular choice of mSUGRA parameters) and a clumpiness factor fd of 5×10^4. Higher neutralino masses improve high energy data fit but only with the increase of the clumpiness factor because of the dependence from the inverse neutralino mass squared m_χ in the $\bar{p}$ flux (Lionetto et al. 2005). For different values of the mSUGRA parameters we found the minimal values of the clumpiness factors fd needed to disentangle a neutralino induced component in the antiproton flux with PAMELA. We computed this factor as a function of the mSUGRA parameters, fixing A_0, $\tan\beta$ and $\mathrm{sign}(\mu) = +1$. In this way the clumpiness factor becomes a function of m_0 and $m_{1/2}$ parameters. Similar analysis were already made in the literature (see for example Profumo et al. 2004).

For the discrimination we requested the following conditions:

1. The total antiproton flux $\phi_{\mathrm{tot}} = \phi_{\mathrm{bkg}} + \phi_{\mathrm{susy}}$ gives a good fit of the experimental data.
2. Difference between ϕ_{tot} and the DC model ϕ_{bkg} is detectable by PAMELA.

The first condition is satisfied if:

$$\chi^2_{\mathrm{fit}} = \frac{1}{N-1} \sum_n \frac{(\Phi_n^{\mathrm{exp}} - \Phi_n^{\mathrm{tot}})^2}{(\sigma_n^{\mathrm{exp}})^2} \leq \chi^2_{\mathrm{fit},0} \tag{1}$$

where $\chi^2_{\mathrm{fit},0} = 1.7$, for $N = 40$ experimental points. The second condition is satisfied if

$$\chi^2_{\mathrm{discr}} = \frac{1}{M-1} \sum_m \frac{(\Phi_m^{\mathrm{bkg}} - \Phi_m^{\mathrm{tot}})^2}{(\sigma_m^{P,\mathrm{bkg}})^2} \geq \chi^2_{\mathrm{discr},0} \tag{2}$$

where $\chi^2_{\mathrm{discr},0} = 1.8$, for $M = 29$ points and where $\sigma_m^{\mathrm{P,bkg}}$ are the PAMELA statistical errors associated to the background flux.

For each model we found the minimal value of the clumpiness factor fd needed to satisfy both conditions. As the clumpiness factor is a function of m_0 and $m_{1/2}$ parameters, we made contour plots calculating equi-clumpiness factors lines. We also found the maximally allowed values for fd in order not to violate the condition (1). The results is shown in Figure 8 for $\tan\beta = 55$. Other example are in (Lionetto et al.2005). It can be see that PAMELA will be able to disentangle a neutralino induced component for halo models that has fd as low as ~ 1 and this kind of search is very complementary to the GLAST search.

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