Chin. J. Astron. Astrophys. Vol. 8 (2008), **Supplement**, 54–60
(*http://www.chjaa.org*)

Chinese Journal of
Astronomy and
Astrophysics

Search for Dark Matter in the Gamma-ray Sky

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Abstract The detection of gamma-rays due to pair annihilation of dark matter particles in the Milky Way halo is a viable tecniques to search for supersymmetric dark matter candidates if there is the possibility to separate the signal from the backgroung generated by standard production mechanisms. Here we discuss the status of this indirect search and the prospective for the detection and the complementarity of this search with the similar search in the antiprotons and positrons cosmic rays fluxes.

Key words: gamma rays — dark matter — supersymmetry

1 INTRODUCTION

In the cosmological concordance model that has emerged over the past few years, a considerable fraction of the total energy density today, $\Omega_{\rm CDM} = 0.19$, consists of non-baryonic, collisionless and dissipation-free (i.e. cold) matter (Spergel et al., 2007). To unveil the – so far completely unknown – nature of this dark matter (DM) is one of the most outstanding challenges for cosmology and astroparticle physics today. The list of proposed DM candidates is long, ranging from modified theories of gravity, that would effectively mimic a large non-relativistic component in the total energy content of the universe, to a whole zoo of speculative new particles that the DM may consist of. While the former approach may, in fact, be extremely successful to describe certain isolated phenomena, like the flattening of galactic rotation curves (Bekenstein 2004), it is notoriously difficult to reconcile with the whole range of accessible observations; in the following, we will therefore restrict ourselves to the latter possibility (see Bergström 2000, Bertone et al., 2005a for recent reviews on particle DM).

Search strategies for DM particles (going beyond merely testing their gravitational influence) can be grouped into two categories. In *direct* detection experiments, one tries to trace these particles by looking for the recoil energy they would transfer during scattering events with the atoms of the detector material (see, e.g., Munoz 2004 and references therein). Alternatively, one can use *indirect* detection techniques, making use of the fact that DM particles will generally pair-annihilate in regions of enhanced DM densities; the decay products may then be revealed as exotic contributions to astrophysical fluxes of gamma-ray, neutrino and anti-matter.

A theoretically particularly well-motivated type of DM candidates are weakly interacting massive particles (WIMPs) that appear in various extensions to the standard model of particle physics (SM); with masses and couplings at the electroweak scale, they would be thermally produced in the early universe and automatically acquire the necessary relic density to account for the DM today. Usually, the WIMP appears as the lightest of a whole set of new, heavy particles and its decay into SM degrees of freedom is protected by a new symmetry.

Independent of the particle nature of the WIMP, there are two types of WIMP annihilation signals into gamma-rays: a spectrally continuous flux below m_χ, the mass of the annihilating particle, resulting

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mainly from the decay of π^0 mesons produced in the fragmentation of annihilation final states plus a second contribution tha arises from final state radiation (FSR), where an additional photon is emitted from charged particle final states; this becomes particularly important for a sizable branching ratio into e^+e^- pairs. The second type of signal is monoenergetic gamma-ray lines resulting from WIMP annihilations into two-body final states containing two photons or a Z boson and a photon. Generally, the continuous signal has a much larger rate, but with a signature that is difficult to separate from the other galactic diffuse foreground contributions, while the monoenergetic line signal is a much smaller signal because the DM has to be electrically neutral and the channels ($\chi\chi \rightarrow \gamma\gamma$ or $\chi\chi \rightarrow Z\gamma$) are necessarily loop-suppressed and thus usually negligible in the absence of efficient enhancement mechanisms but, if detected, is easily separated from the other galactic diffuse contributions. Different astrophysical sources can be used to search for a signal from WIMP annihilations. Figure 1 (i.e., Table 1) summarizes the advantages and disadvantages of the different searches. Predicted sensitivities are subject to significant astrophysical uncertainties for most of the studied astrophysical signals. Substructure in Dark Matter Halos is especially uncertain, currently constrained mainly by N-body simulations that can change the predicted flux for given annihilation cross section by several orders of magnitude.

Astrophysical source or search technique	Advantages	Disadvantages
Galactic centre	Large number of of photons	Disturbance by many point sources, uncertainty in diffuse background prediction.
Satellites, sub-halos	Low background intensity, good identification of source	Low number of photons.
Milky way halo	Large number of photons	Uncertainty in galactic diffuse background prediction.
Extragalactic	Large number of photons.	Astrophysical,uncertainties, uncertainty galactic diffuse contribution.
Spectral lines	No astrophysical uncertainties, smoking gun signal	Very low number of photons.

Fig. 1 Advantages and disadvantages of the different searches with gamma-rays.

Observations of the gamma-ray signal of WIMPs may not only constrain the particle nature of these particles but also, in the case that the LHC experiments discover a WIMP candidate, establish the connection between those particles and the Dark Matter. If the Dark Matter is identified, GLAST will be able to image the distribution of Dark Matter in the Universe, which will constrain scenarios for structure formation.

The center of our own galaxy is a formidable astrophysical target to search for a Dark Matter signal, the reason being that simulations of Dark Matter halos predict high densities at the center of the galaxy and since the WIMP annihilation rate is proportional to the density squared, significant fluxes can be expected. On the other hand, establishing a signal requires identification of the high energy gamma-ray sources which are close (or near) the center and also an adequate modeling of the galactic diffuse emission due to cosmic rays colliding with the interstellar medium. The latter is even more crucial for establishing a WIMP annihilation signal from the galactic halo.

We focus now on a theoretically particularly well-motivated type of Weakly Interacting Massive Particle (WIMP) dark matter candidate, the neutralino (see Jungman et al., 1996 for a classic review) that appears in most supersymmetric extensions to the Standard Model as the lightest supersymmetric particle (LSP) and is given by a linear combination of the superpartners of the gauge and Higgs fields. The most restrictive supersymmetric extension of the Standard Model is the minimal supergravity (mSUGRA) framework that has five input parameters: $m_{1/2},\ \ m_0,\ \ \mathrm{sign}(\mu),\ \ A_0\ \ \mathrm{and}\ \ \tan\beta$, 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 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 neutralino mass is usually several hundred GeV or less; for very high Higgsino or Wino fractions, however, it can be considerably higher (up to 2.2 TeV in the latter case).

The ISASUGRA output is then used as an input in the DarkSUSY package . The latter is exploited to: a) reject models which violate limits recommended by the Particle Data Group 2002 (PDG) 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 yield by linking to the results of the simulations performed with the Lund Monte Carlo program Pythia as implemented in the DarkSUSY package.

Figure 2 shows our estimates of GLAST sensitivity to a dark matter signal via the observation of WIMP annihilation photons (continuum spectrum) in the $m_{1/2}$ and m_0 mSUGRA parameter plane for $\tan\beta = 10$, 55 and 60. These figures have been obtained performing a detailed scan in the mSUGRA parameter space, computing for each model the neutralino induced γ-ray flux and the relic density (Morselli et al., 2007). The lower right plot shows the comparison for $\tan\beta = 55$ with the exclusion limits from LHC, LC (Baer et al., 2004) and the antimatter experiment PAMELA (Lionetto et al., 2005). The values of the neutralino mass is also shown in both figures on the right. For the region in red, the cosmologically allowed WIMP region, the signal above the blue line (M_{WIMP} ∼200 GeV) is not observable by GLAST due the higher WIMP mass as one moves to higher $m_{1/2}$. The dark matter halo used for the GLAST indirect search sensitivity estimate is a truncated Navarro Frank and White (NFW) halo profile as used in (Cesarini et al., 2004). For steeper halo profiles (like the Moore profile) the GLAST limits move up, covering a wider WMAP (Spergel et al., 2007) allowed region, while for less steep profile (like the isothermal profile) the GLAST limits move down, covering less WMAP allowed region.

1.1 Model Independent GLAST Reach

The expression of the γ-ray continuum flux for a generic WIMP at a given photon energy E is given by

$$\phi_{\mathrm{wimp}}(E) = \frac{\sigma v}{4\pi} \sum_f \frac{dN_f}{dE} B_f \int_{\mathrm{l.o.s}} dl \frac{1}{2} \frac{\rho(l)^2}{m_{\mathrm{wimp}}^2} \,. \tag{1}$$

This flux depends from the WIMP mass m_{wimp}, the total annihilation cross section times WIMP velocity σv and through the sum of all the photon yield dN_f/dE per each annihilation channel weighted by the corresponding branching ratio B_f. The flux (1) also depends from the WIMP density in the galactic halo $\rho(l)$. The integral has to be performed along the line of sight (l.o.s.). As pointed out in (Cesarini et al., 2004), apart from the $\tau\bar{\tau}$ channel, the photon yields are quite similar. So fixing the halo density profile (for example a NFW profile), a dominant annihilation channel (that is $b\bar{b}$, $t\bar{t}$, W^+W^-, ...) and the corresponding yield, it is possible to perform a scan in the plane (m_{wimp}, σv) in order to determine the GLAST reach and the regions that are already excluded by the EGRET data in the 2 degrees region around the galactic center

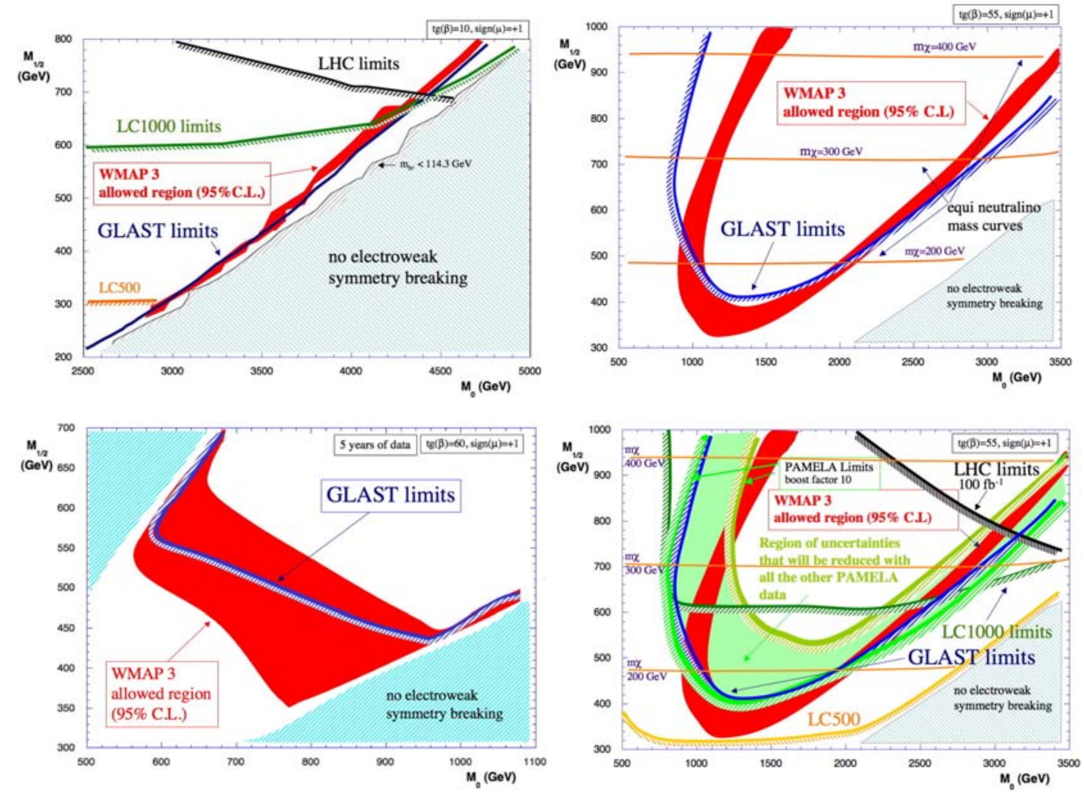

Fig. 2 GLAST sensitivity to a dark matter signal via the observation of WIMP annihilation photons (continuum spectrum) in the $m_{1/2}$ and m_0 mSUGRA parameter plane for $\tan\beta = 10$, 55 and 60. GLAST 3σ sensitivity is shown at the blue line and below. The lower right plot shows the comparison for $\tan\beta = 55$ with LHC, LC and the antimatter experiment PAMELA. The stripped regions correspond to models that are excluded either by incorrect ElectroWeak Symmetry Breaking (EWSB), LEP bounds violations or because the neutralino is not the Lightest Supersymmetric Particle (LSP).

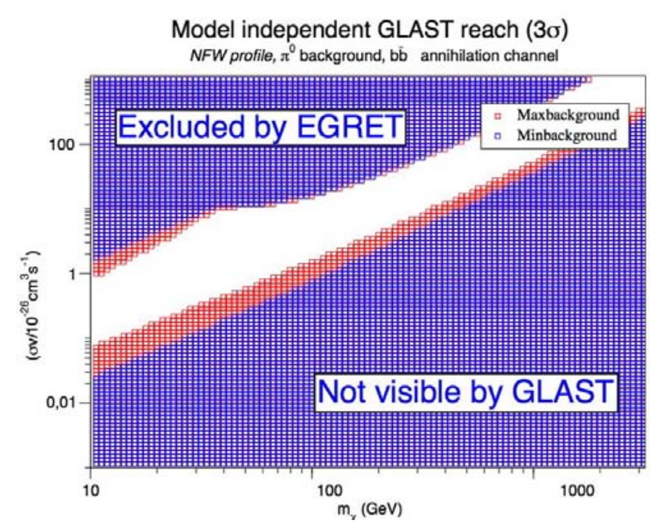

Fig. 3 Cross Section times WIMP velocity versus the WIMP mass. The white region is allowed by EGRET data and detectable by GLAST.

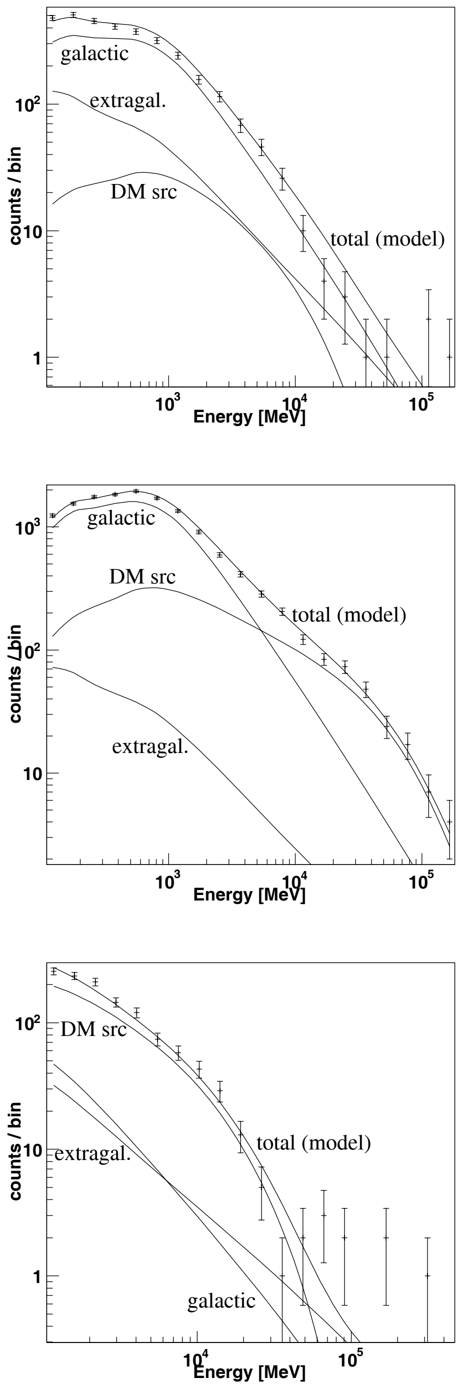

Fig. 4 Examples of spectral fits of simulated DM point sources of intensity Φ, for different values of m_χ and different annihilation channels. On the left for $\Phi = 2 \times 10^{-3}$ ph m^{-2} s^{-1}, $m_\chi = 150$ GeV, $b\bar{b}$, (l, b)=$(0, 25)$; in the middle for $\Phi = 2 \times 10^{-2}$ ph m^{-2} s^{-1}, $m_\chi = 150$ GeV, $b\bar{b}$, (l, b)=$(50, 0)$ and on the right for $\Phi = 2 \times 10^{-2}$ ph m^{-2} s^{-1}, $m_\chi = 150$ GeV, 80% $b\bar{b}$, 20% e^+e^-, (l, b)=$(0, 50)$. Solid lines are fits obtained under the assumption of annihilation to $b\bar{b}$. For each model we also give the significance of the detection. Points with error bars are photon counts from the simulated observation.

(Cesarini et al., 2004, Mayer et al., 1998), i.e. the flux predicted by the susy+background model must not exceed the total flux predicted from EGRET data. The result of the scan is given in figure 3. For every couple of values ($m_{\rm wimp}$, σv) we compute the expected flux (1) and we performed a standard χ^2 statistical analysis to see if GLAST is able to disentangle the WIMP contribution among the standard astrophysical π^0 background as used in (Cesarini et al., 2004) . The result is given at a 3σ confidence level. The background uncertanties are reflected in the red regions. We assumed a total exposure of 3.7×10^{10} $\rm cm^2$ s, for a period of 4 years of data taking and an angular resolution (at 10 GeV) of $\sim 3 \times 10^{-5}$ sr as it can be derived from the GLAST LAT performance in *http://www-glast.slac.stanford.edu/software/ IS/glast_lat_performance.htm*.

1.2 Point Sources of Dark Matter Annihilation

There is the possibility that the annihilation signal originates from large Dark Matter overdensities around Intermediate Mass Black Holes. It was recently shown that a $\rho \propto r^{-3/2}$ DM overdensity can be predicted in any halo at the center of any galaxy old enough to have grown a power-law density cusp *in the stars* via the Bahcall-Wolf mechanism (Merritt et al., 2006). Collisional generation of these DM "crests" (Collisionally REgenerated STtructures) was demonstrated even in the extreme case where the DM density was lowered by slingshot ejection from a binary super-massive black hole. Although it is unlikely that a spike may survive around the Super-massive Black Hole at the Galactic center, they can evolve unperturbed around Intermediate Mass Black Holes (IMBHs), i.e. wandering BHs with mass $10^2 \lesssim M/M_\odot \lesssim 10^6$. Scenarios that seek to explain the properties of the observed super-massive black holes population result, in fact, in the prediction of a large population of IMBHs. In Figure 4 we show some illustrative examples of simulated sources. On the left there is an an example with a moderate diffuse background contribution and a source corresponding to EGRET's faintest detected source. For a more complete description of the figure see Morselli et al., 2007, Bertone et al., 2006. If we apply this analysis to the mini-spikes scenario discussed in (Bertone et al., 2005b), consisting of a population of ~ 100 DM overdensities, dubbed mini-spikes, around Intermediate Mass Black Holes, we found that a large number of these objects can be detected and identified with GLAST, if they exist, while null searches would place extremely stringent constraints on the whole scenario.

2 CONCLUSIONS

In this paper we presented the searches for particle Dark Matter to be performed with the GLAST-LAT instrument. Several complementary astrophysical sources had been examined, each presenting its own advantages and challenges. Here we discussed the WIMP annihilation signal from galactic center and from annihilation signal originates from large Dark Matter overdensities around Intermediate Mass Black Holes. For the galactic center, cosmologically interesting regions of the parameter space ($\sigma v \sim 10^{-26}$) are within the reach. For th signal around Intermediate Mass Black Holes, we found that a large number of these objects can be detected and identified with GLAST or the model will be severly constrained.

GLAST is now integrated on the space-craft and undergoing final testing. The launch is foreseen for early 2008.

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