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Is dark matter visible by galactic gamma rays?

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Abstract. The EGRET excess in the diffuse galactic gamma ray data above 1 GeV shows all features expected from dark matter WIMP annihilation: (a) It is present and has the same spectrum in all sky directions, not just in the galactic plane. (b) The intensity of the excess shows the $1/r^2$ profile expected for a flat rotation curve outside the galactic disc with an additionally interesting substructure in the disc in the form of a doughnut-shaped ring at 14 kpc from the centre of the galaxy. At this radius a ring of stars indicates the probable infall of a dwarf galaxy, which can explain the increase in DM density. From the spectral shape of the excess the WIMP mass is estimated to be between 50 and 100 GeV, while from the intensity the halo profile is reconstructed. Given the mass and intensity of the WIMPs the mass of the ring can be calculated, which is shown to explain the peculiar change of slope in the rotation curve at about 11 kpc. These results are model-independent in the sense that only the *known shapes* of signal and background were fitted with free normalization factors, thus being independent of model-dependent flux calculations. The statistical significance is more than 10σ in comparison with a fit of the conventional galactic model to the EGRET data. These signals of dark matter annihilation are compatible with supersymmetry including all electroweak constraints. The statistical significance combined with all features mentioned above provide an intriguing hint that the EGRET excess is indeed a signal from dark matter annihilation.

Keywords. Gamma rays; milky way; cosmology; elementary particles.

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1. Introduction

Cold dark matter (CDM) makes up 23% of the energy of the universe, as deduced from the WMAP measurements of 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 dark matter (DM) has to be much more widely distributed than the visible matter, since the rotation speeds do not fall off like $1/\sqrt{r}$, as expected from the visible matter in the centre, but stay more or less constant as a function of distance. For a 'flat' rotation curve the DM has to fall off slowly like $1/r^2$ instead of the exponential drop-off for the visible matter. The fact that the DM is distributed over large distances implies that its properties must be quite different from the visible matter, since the latter clumps in the centre owing to its rapid loss of kinetic energy by the electromagnetic and strong interactions after infall into the centre. Since the DM apparently undergoes little energy loss, it can have at most weak interactions. In addition its mass is probably large, since it cannot be produced with present accelerators. Therefore it is generically called a WIMP, a weakly interacting massive particle.

Weakly interacting particles can annihilate, yielding predominantly quark–antiquark pairs in the final state, which hadronize into mesons and baryons. The stable decay and fragmentation products are neutrinos, photons, protons, antiprotons, electrons and positrons. From these, the protons and electrons disappear in the sea of many matter particles in the universe, but the photons and antimatter particles may be detectable above the background, generated by particle interactions. Such searches for indirect dark matter detection have been actively pursued, see e.g the review by Bergström [2] or more recently by Bertone, Hooper and Silk [3].

The present analysis on diffuse galactic gamma rays differs from previous ones by considering simultaneously the complete sky map *and* the energy spectrum, which allows us to constrain both the halo distribution *and* the WIMP mass. More details have been given elsewhere [4–9]. The constraint on the WIMP annihilation cross-section from WMAP is discussed in §2, while the constraints on the mass and the DM halo profile from the EGRET excess are discussed in §3. The summary is given in §4.

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 WIMPS 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 WIMP's cease to annihilate. They fall out of equilibrium (freeze-out) at a temperature of about $m_\chi/22$ [10] 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 co-annihilation, the present mass density in units of the critical density is given by [11]

$$\Omega_\chi h^2 = \frac{m_\chi n_\chi}{\rho_{\mathrm{c}}} \approx \left(\frac{2\cdot 10^{-27}\,\mathrm{cm}^3\,\mathrm{s}^{-1}}{\langle\sigma v\rangle}\right). \tag{1}$$

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 WIMP mass (except for logarithmic corrections). For the present value of $\Omega_\chi h^2 = 0.113 \pm 0.009$ the thermally averaged total cross-section at the freeze-out temperature of $m_\chi/22$ must have been around $2\cdot 10^{-26}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$. The observed annihilation rate will be compared with this generic cross-section, which basically only depends on the expansion rate of the universe, i.e. on the value of the Hubble constant. However, it should be noted that this cross-section may be energy-dependent and the annihilation cross-section in the present universe may be much smaller than the value deduced from the time of freeze out, when the temperature was $m_\chi/22 \approx$ several GeV. On the other hand, the annihilation rate may be enhanced by the clustering of DM in 'microhaloes', which increases the density locally. This unknown enhancement factor, usually called 'boost factor', may vary from a few to a few thousand [12,13].

3. Indirect dark matter detection

The neutral particles play a very special role for indirect DM searches, since they point back to the source. The charged particles change their direction by the interstellar magnetic fields, energy losses and scattering. Therefore the gamma rays provide a perfect means to reconstruct the intensity (halo) profile of the DM by observing the intensity of the gamma ray emissions in the various sky directions. Of course, this assumes that one can distinguish the gamma rays from DM annihilation from the background, mainly from proton–proton interactions. Both for DMA and *pp* collisions the gamma rays originate mainly from the decay of neutral pions, a light particle produced abundantly in the hadronization process of quarks into hadrons. However, the protons in the galaxies and consequently the quarks inside the protons have a steeply-falling energy spectrum ($N \propto E^{-2.7}$). In contrast, the quarks from DM annihilation are mono-energetic, since the WIMPS annihilate almost at rest, so their mass is converted completely into kinetic energy of the much lighter quarks. Each quark thus obtains an energy corresponding to the mass of the WIMP, which yields a gamma ray spectrum with a sharp cut-off at the mass of the WIMP. So from the shape of the spectrum the WIMP mass can be deduced. The difference in spectral shape between DMA and background allows to obtain their absolute normalizations by fitting their shapes to the EGRET data. These shapes are well-known from accelerator experiments and can be obtained e.g. from the PYTHIA code for quark fragmentation [14]; the parameters in this code have been optimized to fit a wide variety of accelerator data with a single model, the string fragmentation model. The fit of the normalizations can be repeated in many different sky direction to obtain the halo profile of the DM. Given the WIMP *number density* in all directions from the flux of the excess and the WIMP *mass* from the spectrum allows to reconstruct the DM mass distribution in our galaxy, which in turn can be used to reconstruct the rotation curve.

A very detailed gamma ray distribution over the whole sky was obtained by the energetic gamma ray emission telescope (EGRET), one of the four instruments on the Compton Gamma Ray Observatory (CGRO), which collected data from 1991 to 2000. The EGRET was carefully calibrated in the energy range of 0.1 to 30 GeV, but using Monte Carlo simulations the energy range was recently extended up to 120 GeV [15] with a correspondingly larger uncertainty, mainly from the self-vetoing of the detector by the back-scattering from the electromagnetic calorimeter into the veto counters for high energetic showers. However, given these triggering uncertainties at high energies, only data up to 10 GeV is used. It was already noticed in 1997 that the EGRET data showed an excess of gamma ray fluxes for energies above 1 GeV when compared with conventional galactic models [16].

Fitting the three contributions of galactic background, extragalactic background and DMA to the energy spectra of 180 independent sky directions yielded astonishingly good fits with the free normalization of the background agreeing reasonably

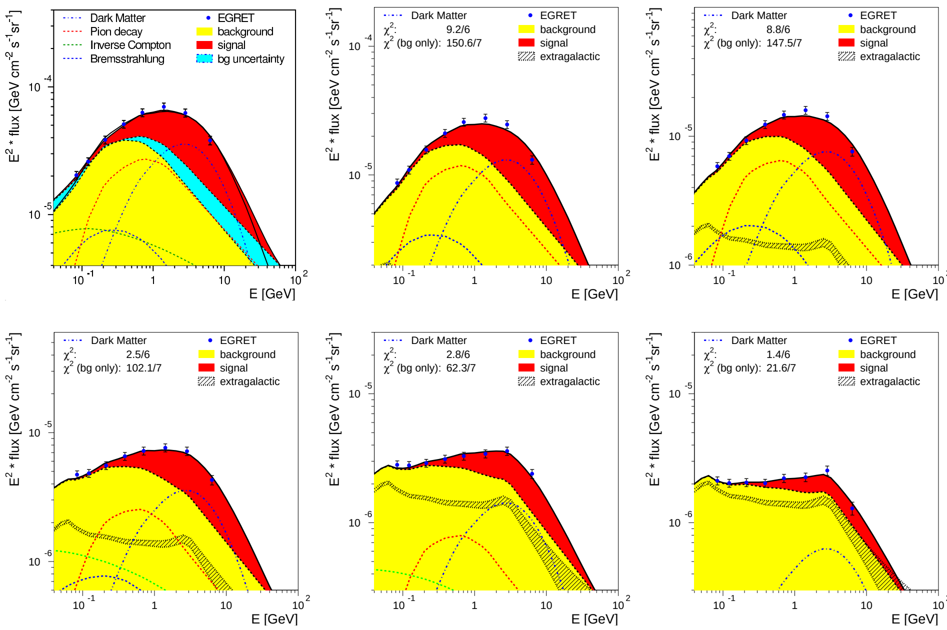

Figure 1. The diffuse gamma-ray energy spectrum of six angular regions. Top: from left to right: towards the galactic centre (latitudes $0° < |b| < 5°$; longitudes $0° < |l| < 30°$), the galactic disk without centre ($0° < |b| < 5°$, $30° < |l| < 330°$); the galactic anticentre ($0° < |b| < 10°$; $90° < |l| < 270°$); bottom: the pole regions (from left to right: all $0° < |l| < 360°$): ($10° < |b| < 20°$); ($20° < |b| < 60°$), ($60° < |b| < 90°$). The dotted line indicates the contribution from the annihilation from 60 GeV WIMPs. The total background (DMA) is indicated by the yellow and red areas, respectively. The background contributions from pion decay, inverse Compton and Bremsstrahlung are indicated as well. The dominant background from pion decay has an uncertainty from solar modulation, which reduces the observed flux of cosmic rays at low energies (below 10 GV). Therefore the cosmic ray spectrum outside the solar system will be different, which affects the gamma ray flux at low energy. This is the dominant uncertainty and its size has been indicated by the blue area in the top left plot. Note that since the background normalization is left free, the low energy data (where only the background contributes) are always well-fitted and different shapes only show up at larger energies.

well with the absolute predictions of the galactic models [17,18] for the energies between 0.1 and 0.5 GeV. Above these energies a clear contribution from dark matter annihilation is needed, but the excess in different sky directions can be explained by a single WIMP mass. The fits for six different sky directions are shown in figure 1.

Alternative explanations for the excess have been plentiful. Among them are the weak point sources, which could not be resolved from the background by the

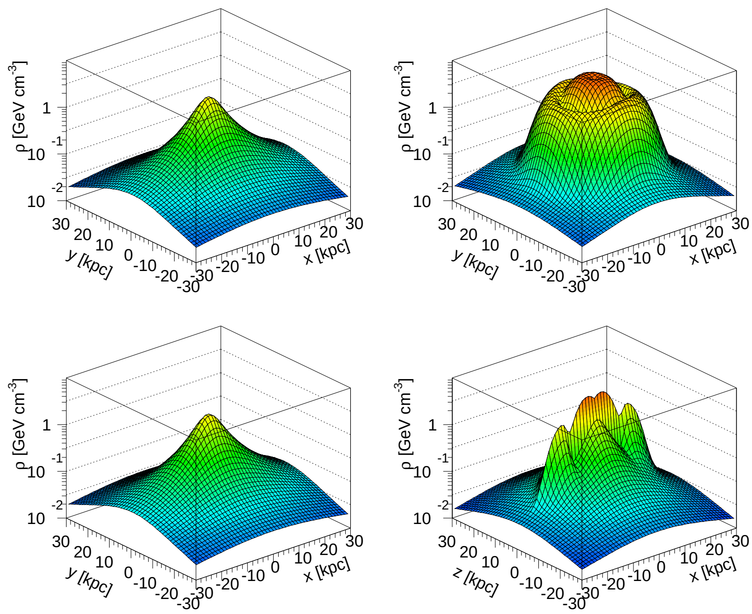

Figure 2. 3D-distributions of the $1/r^2$ haloprofile in the galactic xy-plane (top row) and xz-plane (bottom row) without (left) and with (right) rings.

EGRET satellite. This is unlikely, since the point sources usually have a rather soft spectrum. If one assumes that most of the unresolved point sources would have similar spectra, their subtraction would reduce the observed diffuse spectra below 1 GeV, but the data above 1 GeV would be much less affected. With our fitting procedure of the shapes, the background is determined by the data below 1 GeV and would thus become lower with unresolved point sources subtracted. This would lead to an even stronger excess!

Other ways to increase the excess would be to harden the spectra of the primary nuclei and electrons with respect to the locally measured spectra. Inhomogeneities in the spectra could happen e.g. by density fluctuations from the spiral arms or supernovae explosions.

A summary of these discussions has been given by Strong *et al* [15]. They found that by modifying the electron and proton spectra simultaneously, they can improve the description of the data. Since they tried to predict the absolute flux, the overall normalization errors are plotted. However, if one only considers the shape of the spectra, then only the relative systematic errors between the energy points play a role and these are considerably smaller. In this case the probability of the fit is below 10^{-7}, if the shape of the optimized model is fitted to all sky directions [19]. Adding DM to the optimized model improves the fit probability to 0.8 [19], of course with a lower boost factor (about factor three), but still a need for DM is evident. Similar results are obtained for the shape proposed by Kamae *et al* [20]. Here the reduction of the boost factor is considerably less, mainly because these authors try to improve the fit by changing the proton spectra only, while in the optimized model both the electron spectra and proton spectra are modified.

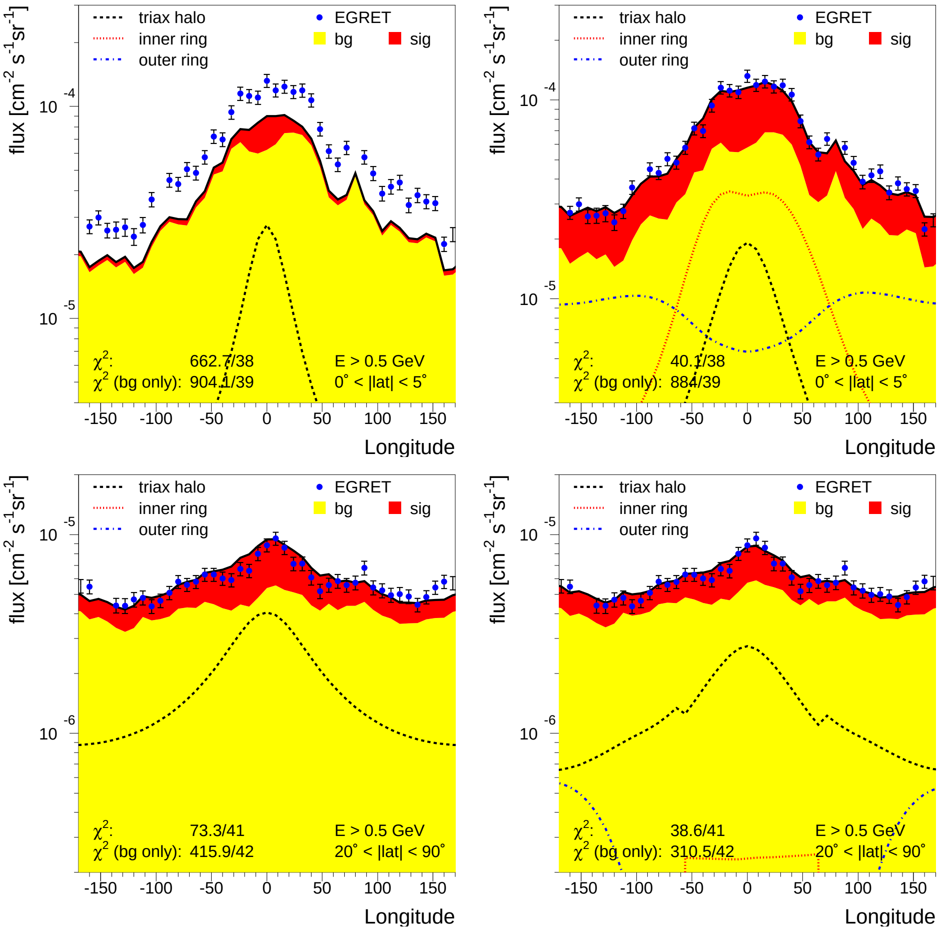

Figure 3. Top row: the longitude distribution of diffuse gamma-rays in the disc of the galaxy (latitudes $0^\circ < |b| < 5^\circ$) for the $1/r^2$ profile without rings (left) and with rings (right). The points represent the EGRET data. The contributions from the background and the neutralino annihilation signal have been indicated by the yellow and red areas, respectively. Bottow row: as above for the polar regions of our galaxy (latitudes $20^\circ < |b| < 90^\circ$). Here the ring-like structures hardly contribute.

An alternative way of formulating the problems of the models without DMA: if the shape of the EGRET excess can be explained perfectly in all sky directions by a gamma contribution originating from the fragmentation of mono-energetic quarks, it is very difficult to replace such a contribution by an excess from nuclei (quarks) or electrons with a steeply falling energy spectrum.

From the excess in the various sky directions one can obtain the halo profile under the assumption that the clustering of the DM is similar in all sky directions. This is not necessarily true, since near the centre of the galaxy clumps may be tidally disrupted by the flyby of stars. The annihilation rate is in general proportional to

$B\rho^n$, where B is the boost factor and n is between 1 and 2, depending on how much of the DM is clustered ($n = 2$ for no clustering and $n = 1$ if all DM is in clusters). Since the EGRET excess measures only the product $B\rho^n$, several choices can be made. For definiteness, we use $n = 2$ and B to be the same for all directions and an isothermal halo, which falls like $1/r^2$ as expected for a flat rotation curve. The result is surprising: in addition to the isothermal profile the EGRET excess show a substructure in the form of toroidal rings at 4 and 14 kpc, as shown in figure 2: on the left-hand side the contribution from the $1/r^2$ profile is shown, while for the right-hand side the ring structure is added. Such enhanced gamma radiation at 4 and 14 kpc was already observed in the original paper on the EGRET excess [16]. The analysis is sensitive to the radii of ring-like structures, since we are not located at the centre. Assuming a constant flux along the ring automatically yields more flux from the nearest parts. The need for these additional rings is most easily seen by comparing the longitudinal profiles in the galactic plane and towards the galactic poles. As shown in figure 3 the pole regions are described reasonably well without rings, but for the galactic plane the $1/r^2$ profile only describes the data towards the centre. For the larger latitudes one needs the rings, as indicated by the right top panel. Note that for each bin only the flux integrated for data above 0.5 GeV has been plotted.

The position and shape of the outer ring coincides with the ring of stars, discovered in 2003 by several groups [21–23]. These stars show a much smaller velocity dispersion (10–30 km/s) and larger z-distribution than the thick disc, so it cannot be considered an extension of the disc. A viable alternative is the infall of a dwarf galaxy [21,24], for which one expects in addition to the visible stars a DM component. From the size of the ring and its peak density one can estimate the amount of DM in the outer ring to be $\approx 10^{10}$–10^{11} solar masses. Since the gamma ray excess requires the full 360° of the sky, one can extrapolate the observed 100° of visible stars to obtain a total mass of $\approx 10^8$–10^9 solar masses [21,22], so the baryonic matter in the outer ring is only a small fraction of its total mass.

The inner ring at 4.2 kpc with a width of 2.1 kpc in radius and 0.2 kpc in z is more difficult to interpret, since the density of the inner region is modified by adiabatic compression and interactions between the bar and the halo. However, it is interesting to note that its coordinates coincide with the ring of cold dense molecular hydrogen gas, which reaches a maximum density at 4 kpc and has a width of 2 kpc as well [16]. Molecules form from atomic hydrogen in the presence of dust or heavy nuclei. So a ring of neutral hydrogen suggests an attractive gravitational potential in this region, in agreement with the EGRET excess.

To prove that the enhanced gamma ray density is indeed connected to non-baryonic mass the rotation curve was reconstructed from the excess of the diffuse gamma rays in the following way: since the flux determines the number density of DM for a given boost factor and since the mass of each WIMP is between 50 and 100 GeV, one can determine the relative masses of the components (rings plus spherical part) and consequently predict the shape of the rotation curve. The absolute value of the mass can be obtained by requiring the rotation speed of the solar system to be 220 km/s at 8.5 kpc. The two ring model describes the peculiar change of slope at 11 kpc well, as shown in figure 4. The contributions from each of the mass terms have been shown separately. The basic explanation for the negative contribution

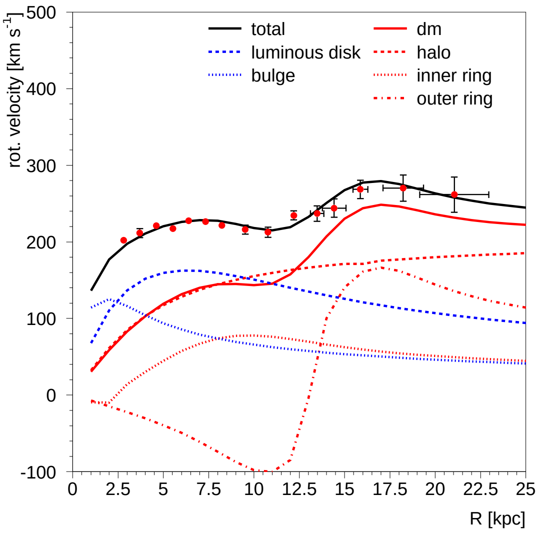

Figure 4. The rotation curve from our galaxy with the DM contribution determined from the EGRET excess of diffuse gamma rays. The data are averaged from ref. [7].

from the outer ring is that a tracer star at the inside of the ring at 14 kpc feels an outward force from the ring, and hence a negative contribution to the rotation velocity. It has often been argued that the outer rotation curve cannot be taken seriously, because the errors are large due to the fact that the absolute values of the rotation velocities strongly depend on the value of R_0, the distance between the solar system and the galactic centre. This is true, as shown by Honma and Sofue [25], but they show that the *change in slope* at about $1.3R_0$ is independent of R_0. In addition, it has been argued that the inner and outer rotation curves are difficult to compare, since the methods are completely different. The methods are indeed different, but the first 3 data points from the outer rotation curve (between 8 and 11 kpc) show the same slope as the ones from the inner rotation curve, so there seems to be no systematic effect related to the different methods.

4. Summary and outlook

In summary, the EGRET data shows an intriguing hint of DM annihilation, since it explains many unrelated facts simultaneously:

(a) An excess of diffuse galactic gamma rays which shows a *spectrum* consistent with the expectation from WIMP annihilation into gamma rays originating from the fragmentation of mono-energetic quarks.

(b) The excess is present in *all* sky directions with the same spectrum, thus excluding that it originates from anomalous contributions in the centre of the galaxy.

(c) The excess shows a strongly increased intensity at positions where extra DM is expected, namely at two doughnut-shaped structures at radii of 14 and 4 kpc from

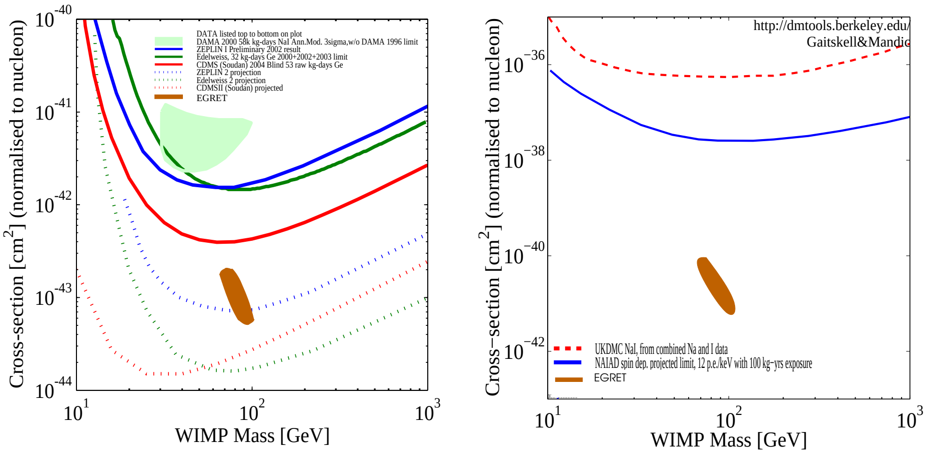

Figure 5. The spin-independent (left) and spin-dependent (right) neutralino–nucleon cross-section as a function of the neutralino mass for the SUSY parameters from this analysis [6] (oval shaped (red-brown) area) in comparison with results from present and future direct DM detection experiments.

the centre of the galaxy. At 14 kpc has observes a ring of stars thought to originate from the infall of a dwarf galaxy, while at 4 kpc one finds an enhanced concentration of molecular hydrogen thought to form from atomic hydrogen in the presence of dust or heavy nuclei, which can be collected in the gravitational potential of a ring of DM.

(d) The enhanced excess of gamma rays cannot be due to additional gas in these rings as proven by the rotation curve calculated from the gamma ray excess: the mass in the rings perfectly describe the hitherto unexplained change of slope in the rotation curve at a distance of about 11 kpc. The amount of visible matter is far too low to have such an impact on the rotation curve.

The results mentioned above make no assumption on the nature of the dark matter, except that its annihilation produces hard gamma rays consistent with the fragmentation of mono-energetic quarks between 50 and 100 GeV. WIMPs produce such mono-energetic quarks with energies equal to the WIMP mass. WIMP masses in this range and the observed WIMP self-annihilation cross-section are consistent with the lightest supersymmetric particle predicted in the minimal supersymmetric model with supergravity-inspired symmetry breaking, called the mSUGRA model [8]. The enhancement of the annihilation by the clustering of DM found to be of the order of 100 is of the right order of magnitude [12,13].

Within this supersymmetric model one finds a spin-independent cross-section for elastic scattering of a WIMP on a proton of about 10^{-43} cm^2, which is within reach [26] of future experiments as shown in figure 5. This elastic scattering cross-section was calculated with dark SUSY [27].

Direct and indirect detection experiments do not prove the supersymmetric nature of the WIMPs. If the WIMPs are indeed the lightest supersymmetric particle, then this will become clear at the future LHC collider under construction at CERN in Geneva, where supersymmetric particles of the mass range deduced from the EGRET data [6] should be observable from 2008 onwards, if they exist.

In our analysis, we only fit the known spectral shapes of the various processes with arbitrary normalizations, so the analysis becomes largely model-independent. Interestingly, the normalization factors come out to be in agreement with expectations, both for the WIMP signal and the background.

Alternative models for the EGRET excess without DM have to assume that the locally measured fluxes of protons and electrons are not representative for our galaxy. These models provide significantly worse fits to the data, if one takes the strong correlations in the errors between the different energy bins into account. Of course such models do not explain the correlation of the gamma rays with the stability of the ring of stars at 14 kpc and the change of slope in the rotation curve at $r = 1.3R_0$. Other objections [28] for the interpretation of DMA for the EGRET excess with the halo profile from [7] have been that the flux of antiprotons from DMA would be much higher than the observed flux. They calculate this antiproton flux with a simple diffusion model with isotropic diffusion. In such models the antiprotons rattle around in the galaxy without hardly escaping to the outer space. This results in a high local density of antiprotons, yielding a gamma ray flux and antiproton flux from DMA of the same order of magnitude, although antiprotons are only rarely produced in DMA: from LEP data on quark fragmentation one knows that the production of antiprotons is about two orders of magnitude below the production of gamma rays. If one chooses anisotropic propagation with fast diffusion and/or convection perpendicular to the galactic disc, a large fraction of the antiprotons will also escape to the outer space just like the gamma rays. Such anisotropic propagation is expected already from the magnetic field lines, which tend to be perpendicular to the disc outside the disc, but tangential to the spiral arms in the plane of the disc. Of course, the propagation is constrained by the ratio of secondary over primary particles, like the B/C ratio. So the question of the antiproton yield in comparison with the EGRET excess needs clearly a much more elaborate study of the propagation models, which are important for charged particles, but of much lesser importance for gamma rays.

Therefore the statistical significance of the EGRET excess of at least 10σ, if fitted to the shape of the diffuse gamma ray background only, combined with all features mentioned above provides an intriguing hint that this excess is indeed indirect evidence for dark matter annihilation.

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