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Dark Matter visible by the EGRET Excess of Diffuse Galactic Gamma Rays?

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The public data from the EGRET space telescope on diffuse galactic gamma rays in the energy range from 0.1 to 10 GeV show an excess for energies above 1 GeV in comparison with the expectations from conventional galactic models. This excess shows all the key features of Dark Matter Annihilation (DMA), like being observable in al sky directions with a shape corresponding to a WIMP mass between 50 and 100 GeV. The intensity of the excess in various directions can be used to reconstruct the DM profile, which - combined with the distribution of visible matter - allows to calculate the rotation curve of our Galaxy. Its peculiar shape, which is not flat, but shows a minimum and maximum, is indeed reconstructed from the gamma rays, thus proving that the EGRET excess traces the DM. Furthermore, the spectral shape of the excess is consistent with mSUGRA and the WMAP relic density for rather heavy squarks and sleptons - $\mathcal{O}(1TeV)$ - and light charginos, neutralinos and gluinos (below 500 GeV).

1. INTRODUCTION

If Dark Matter is a thermal relic from the early Universe, then it is known to annihilate, since the small amount of relic density measured nowadays requires a large reduction in its number density. The annihilation cross section can be obtained directly from its inverse proportionality to the relic density, the latter being well known from precision cosmology experiments [1]. The annihilation into quark pairs will produce π^0 mesons during the fragmentation into hadrons, which in turn will decay into gamma rays. Since DM is cold, i.e. non-relativistic, the fragmenting quarks have an initial energy equal to the WIMP mass. The gamma spectrum from such mono-energetic quarks is well known from electron-positron colliders, which produce exactly such states. For heavy WIMP masses the gamma spectrum is considerably harder than the background spectrum, mainly from π^0 mesons produced in pp-collisions from cosmic rays with gas in the disk. Such an excess of hard gamma rays has indeed been observed by the EGRET satellite and the relative contributions from background and DM annihilation signal can be obtained by fitting their different shapes with a free normalization factor for background and signal. The present analysis on diffuse galactic gamma rays differs from previous ones - see reviews [2–5] and references therein - by considering simultaneously the complete sky map *and* the energy spectrum, which allows us to constrain both the halo distribution *and* the WIMP mass[6, 7].

2. INDIRECT DARK MATTER DETECTION

The neutral particles play a very special role for indirect DM searches, since they point back to the source, thus providing 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 between the gamma rays from DMA and the ones from the background, which is possible because of the different energy spectra: the gamma rays from the mono-energetic quarks from DMA produce a significantly harder spectrum than the gammas from nuclear interaction, which are produced by the interactions between quarks with a steeply falling power law spectrum ($\propto E^{-2.7}$).

The spectral shape of the gamma rays from either the backgrounds or the mono-energetic quarks are well known from accelerator experiments and can be obtained from the well-known PYTHIA code for quark fragmentation[8].

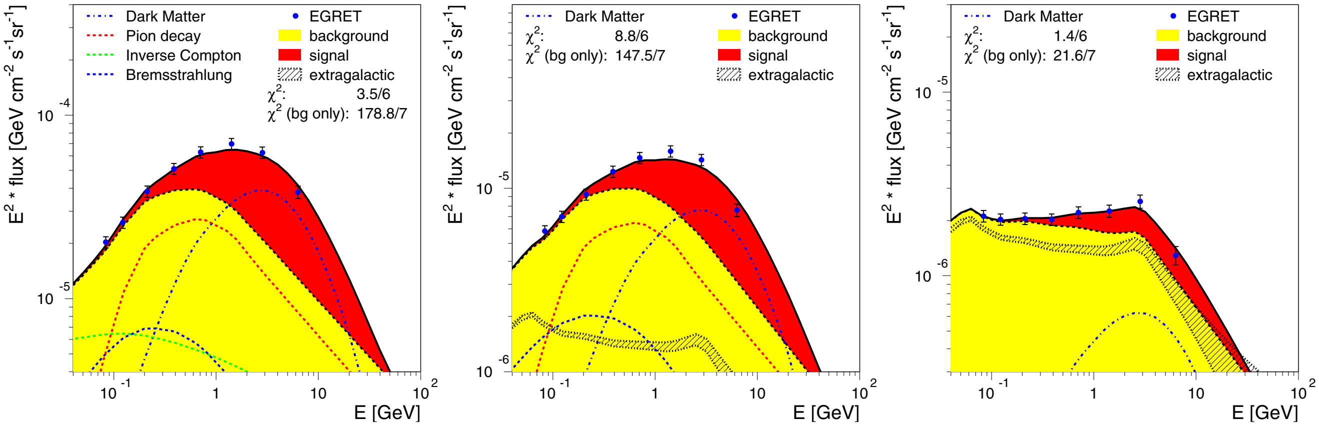

Figure 1: The diffuse gamma-ray energy spectrum of 3 angular regions: from left to right: towards the galactic centre (latitudes $0^\circ < |b| < 5^\circ$; longitudes $0^\circ < |l| < 30^\circ$), the galactic anticentre ($0^\circ < |b| < 10^\circ$; $90^\circ < |l| < 270^\circ$)and the pole regions ($60^\circ < |b| < 90^\circ$; $0^\circ < |l| < 360^\circ$), as measured by the EGRET space telescope. The total background (DMA) is indicated by the light (yellow) (dark (red)) shaded area, respectively. The various contributions to the background and the DMA contribution are indicated as well.

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 during nine years, from 1991 to 2000. The EGRET data is publicly available as high resolution (0.5x0.5 degree) sky maps from the NASA archive[1] with detailed information how to analyse them.

It was already noticed in 1997 that the EGRET data showed an excess in the galactic disk[9] of gamma ray fluxes for energies above 1 GeV if compared with conventional galactic models and repeated later for all sky directions[10]. Fitting the shape of the contributions from Galactic background, extragalactic background and DMA signal to the EGRET data yielded astonishingly good fits with the free normalization of the background agreeing reasonably well with the absolute predictions of the conventional GALPROP model[10] 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 around 60 GeV and a single boost factor, as shown in Fig. 1 for three different sky directions. The high quality of the EGRET data can be appreciated from Fig. 2, where also the sensitivity to the WIMP mass has been plotted.

Alternative explanations for the excess have been plentiful. A summary of these discussions has been given in Ref. [10], where it was noted that by increasing the intensity of the electron and proton spectra at high energies in comparison with the locally measured ones, the description of the data can be improved. The problem with this "optimized solution" is however that the shape of the gamma spectra is still not reproduced well, as shown in Fig. 3. But it is exactly the shape, which was well measured by EGRET, because the relative errors between neighbouring energies are roughly half of the normalization error of 15%. The probability of this optimized solution is below 10^{-7}. Adding DM to the optimized model improves the fit probability to 0.8. Of course, the DM contribution is smaller than in case of the conventional background in Fig. 1, which results in a reduction of the DM normalization factor by roughly a factor three. As with the optimized model, the absolute prediction of the shape proposed by Kamae et al. [11] overshoots the low energy data and undershoots the high energy data, so if only the shape is fitted with a free normalization factor, the excess is always present.

An alternative way of formulating the problems of models without DMA: if the shape of the EGRET excess can

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[1] NASA archive: http://cossc.gsfc.nasa.gov/archive/.

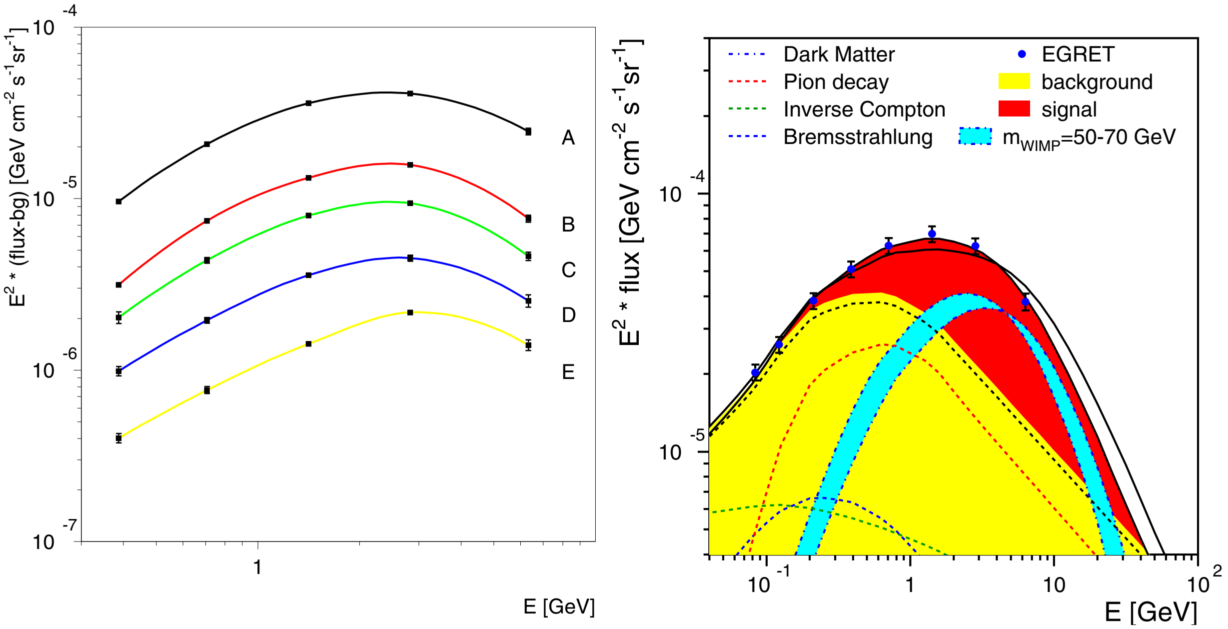

Figure 2: Left: the energy spectrum of the EGRET excess, defined as the difference between the data and the fitted background contribution for 5 of the panels of Fig. 1. Only the small statistical errors have been plotted. Right: the medium shaded (blue) band shows the effect of varying the WIMP mass between 50 and 70 GeV.

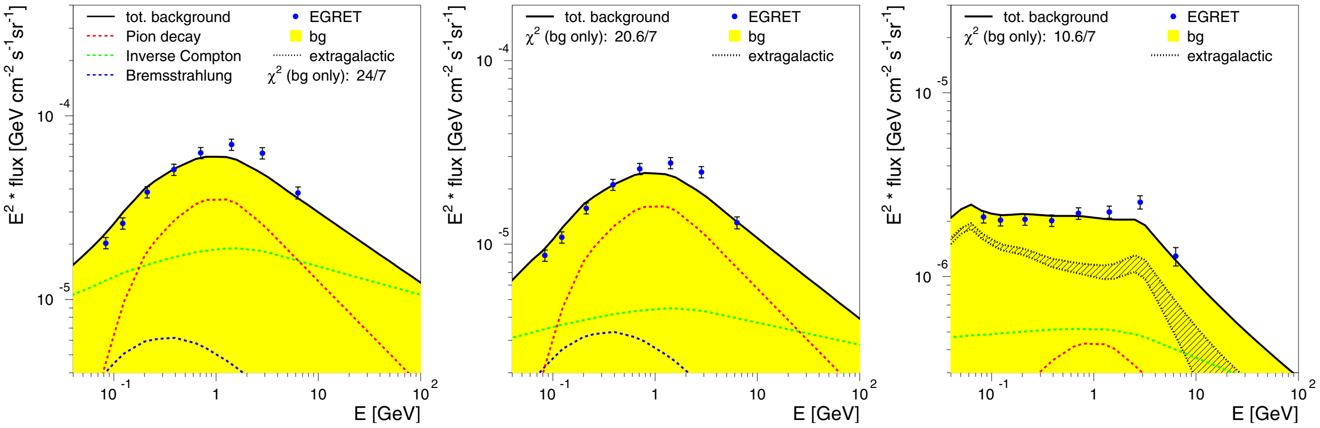

Figure 3: As in Fig. 1, but without DMA and the background shape from Ref. [10], which is "optimized" to explain the EGRET excess without DM. The χ^2 is still poor, as indicated in the figure.

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. In addition, the spatial distribution of gamma rays from DMA is different from the gamma rays from the background.

Although the DM annihilation cross section is known from the relic density, this does not mean we can calculate the flux from DMA, since the flux can be enhanced ("boosted") by the clustering of DM and the cross section can be lowered by the reduced temperature in the present universe (when the p-wave contributions dominate). Therefore we have to keep the absolute normalization of the DMA flux as a free parameter. The different fluxes for the different

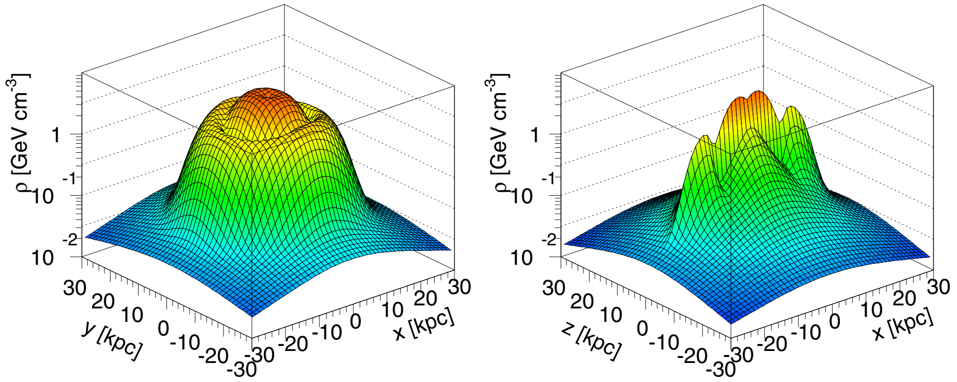

Figure 4: 3D-distributions of the DM halo profile in the galactic xy-plane and xz-plane. In the disk (xy-plane) the vertical axis shows clearly the enhancement in density at a radius of 14 kpc, while the xz-plane, going along the x-axis in the disk (z=0) shows the effect of both rings.

sky directions in Fig. 1 in principle yield information on the halo profile. To obtain it more precisely from a fit requires first of all a much finer sampling of the sky, which is no problem with the high statistics from EGRET (see Fig. 2) and secondly that one has a functional form for the profile. A survey of the optical rotation curves of 400 galaxies shows that the halo distributions of most of them can be fitted either with the cuspy Navarro-Frenk-White (NFW) or the cored pseudo-isothermal profile or both [12]. These halo profiles can be parametrized as follows:

$$\rho(r) = \rho_0 \cdot (\frac{r}{a})^{-\gamma} \left[1 + (\frac{r}{a})^{\alpha}\right]^{\frac{\gamma-\beta}{\alpha}} , \quad (1)$$

where a is a scale radius and the slopes α, β and γ can be roughly thought of as the radial dependence at $r \approx a$, $r >> a$ and $r << a$, respectively. The cuspy NFW profile [13] is defined by (α, β, γ) =(1,3,1) for a scale $a = 10$ kpc. The isothermal profile with (α, β, γ) =(2,2,0) has no cusp ($\gamma = 0$), but a core which is taken to be the size of the inner Galaxy, i.e. $a = 5$ kpc and $\beta = 2$ implies a flat rotation curve. The EGRET data towards the Galactic center do not show a strong cusp, so we use a cored isothermal halo.

Keeping the boost factor the same for all sky directions and fitting the DM profile in 180 independent sky directions one finds the following surprising result: in addition to the pseudo-isothermal profile defined above the EGRET excess shows a substructure in the form of toroidal rings at 4 and 14 kpc, as displayed in Fig. 4. 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 Fig. 5 the pole regions are described reasonably well without rings, but for the galactic plane the excess is dominated by the inner ring for the inner Galaxy (longitudes $|l| < 50°$) and by the outer ring for the outer galaxy (longitudes $|l| > 70°$). Note that for each bin only the flux integrated for data above 0.5 GeV has been plotted.

The position and shape of the inner ring coincides with the ring of molecular hydrogen. Molecules form from atomic hydrogen in the presence of dust or heavy nuclei. So a ring of neutral hydrogen suggests an attractive gravitational potential. The position and shape of the outer ring coincides with the ring of stars, discovered in 2002 by several independent groups[14–17]. This ring is thought to originate from the infall of a galaxy, so additional DMA is expected there.

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 around 60 GeV, one can determine the mass in the ring and consequently predict the rotation curve[2]. The two ring model describes the peculiar change of

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[2] For the outer ring a total DM mass of about $9 \cdot 10^{10}$ solar masses was found in comparison with about 10^9 solar masses in the form

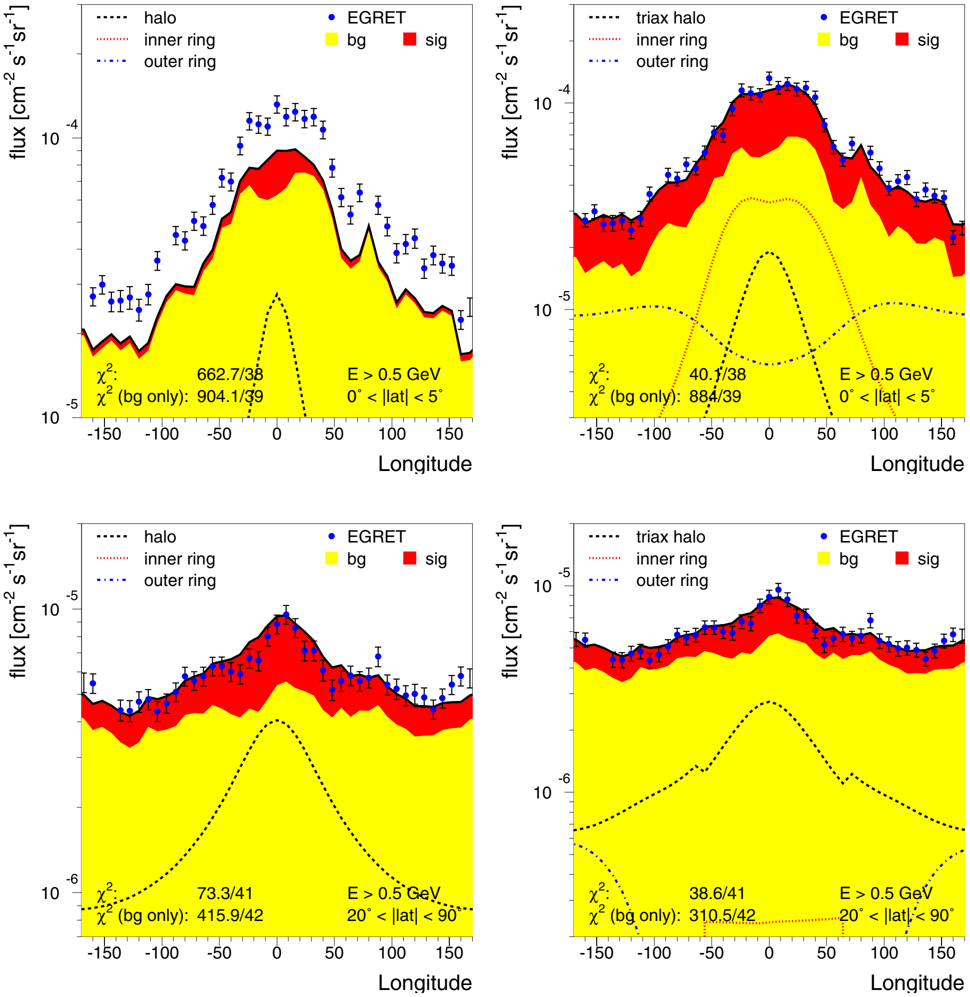

Figure 5: Top row: the longitude distribution of diffuse gamma-rays in the disk of the Galaxy (latitudes $0^\circ < |b| < 5^\circ$) for the pseudo-isothermal profile without (left) and with rings (right). The points represent the EGRET data. Bottow row: as above for the polar regions of our Galaxy (latitudes $20^\circ < |b| < 90^\circ$) .

slope at 11 kpc well, as shown in Fig. 6. The data was obtained as average of the data in Ref. [7]. The contributions from each of the mass terms have been shown separately. The basic explanation for the negative contribution from the outer ring is that a tracer star inside the ring at 14 kpc feels an outward force from the ring, thus a negative contribution to the rotation velocity. The fact that the shape of the rotation curve can be reconstructed from the EGRET excess of gamma rays clearly shows that this excess traces the DM!

3. COMPARISON WITH SUPERSYMMETRY

Supersymmetry [18] presupposes a symmetry between fermions and bosons, which can be realized in nature only if one assumes each particle with spin j has a supersymmetric partner with spin $|j - 1/2|$ ($|j + 1/2|$ for the Higgs

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of stars.

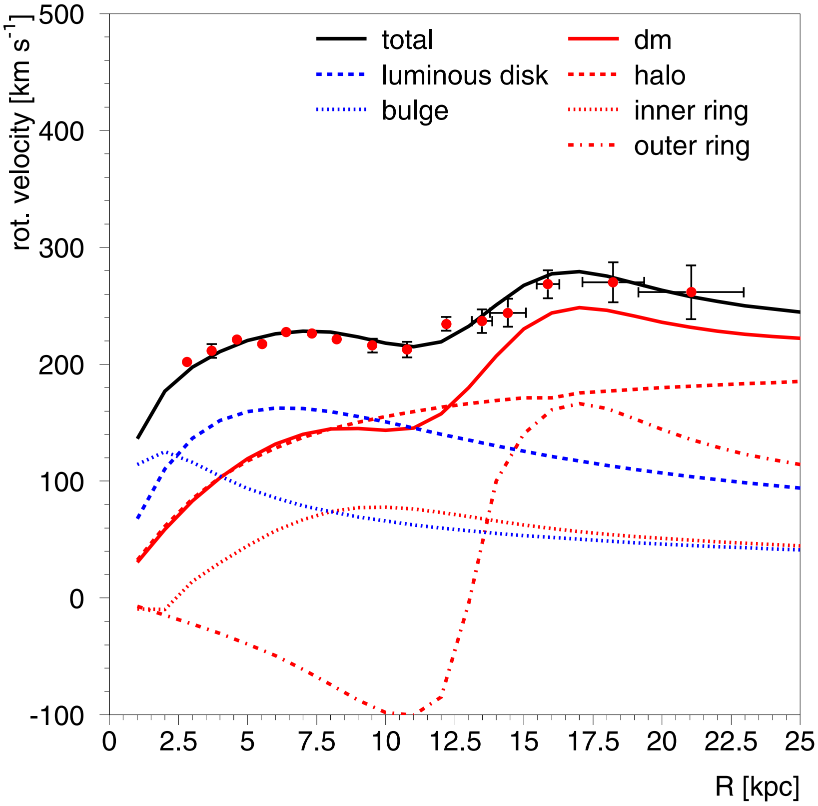

Figure 6: The rotation curve from our Galaxy with the DM contribution determined from the EGRET excess of diffuse gamma rays. The data are averaged from Ref. [6].

bosons). This leads to a doubling of the particle spectrum. Obviously SUSY cannot be an exact symmetry of nature; or else the supersymmetric partners would have the same mass as the normal particles. The mSUGRA model, i.e. the Minimal Supersymmetric Standard Model (MSSM) with supergravity inspired breaking terms, is characterized by only 5 parameters: $m_0,\ m_{1/2},\ \tan\beta,\ \mathrm{sign}(\mu),\ A_0$. 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. Gauge unification is still possible with the precisely measured couplings at LEP [19]. The ratio of the vacuum expectation values of the two Higgs doublets is called $\tan\beta$ and A_0 is the trilinear coupling at the GUT scale. We only consider the dominant trilinear couplings of the third generation of quarks and leptons and assume also A_0 to be unified at the GUT scale. The absolute value of the Higgs mixing parameter μ is determined by electroweak symmetry breaking, while its sign is taken to be positive, as preferred by the anomalous magnetic moment of the muon [19]. The lightest supersymmetric particle (LSP) is stable, if the multiplicative quantum number R-parity, which is +1 for SM particles and -1 for SUSY particles, is conserved. Non-conservation of R-parity would lead to rapid proton decay[18]. The LSP is a perfect candidate for Dark Matter and it can self annihilate into fermion-antifermion pairs by Higgs or Z-exchange in the s-channel or sfermion, chargino and neutralino exchange in the t-channel. The dominant first three possibilities have amplitudes proportional to the fermion mass, so heavy final states are preferred. For values of $\tan\beta \approx 50$ the annihilation cross sections into $b\bar{b}$ quarks are indeed of the order of magnitude required by WMAP. For $m_{1/2}$ below 200 GeV, as required by the EGRET data, the scalar masses have to be in the TeV range for a Higgs mass above 114 GeV, as shown in Fig. 7. This region happens to correspond to a thermally averaged annihilation cross section $\sigma v \approx 2.10^{-26}\ cm^3/s$, as required by the relic density from WMAP. A typical mSUGRA spectrum is shown on the right hand side of Fig. 7. If m_0 is small compared with $m_{1/2}$ the lightest lepton (usually the stau) can be lighter than the neutralino, which happens in the left top corner on the left hand side of Fig. 7. In this case the LSP is

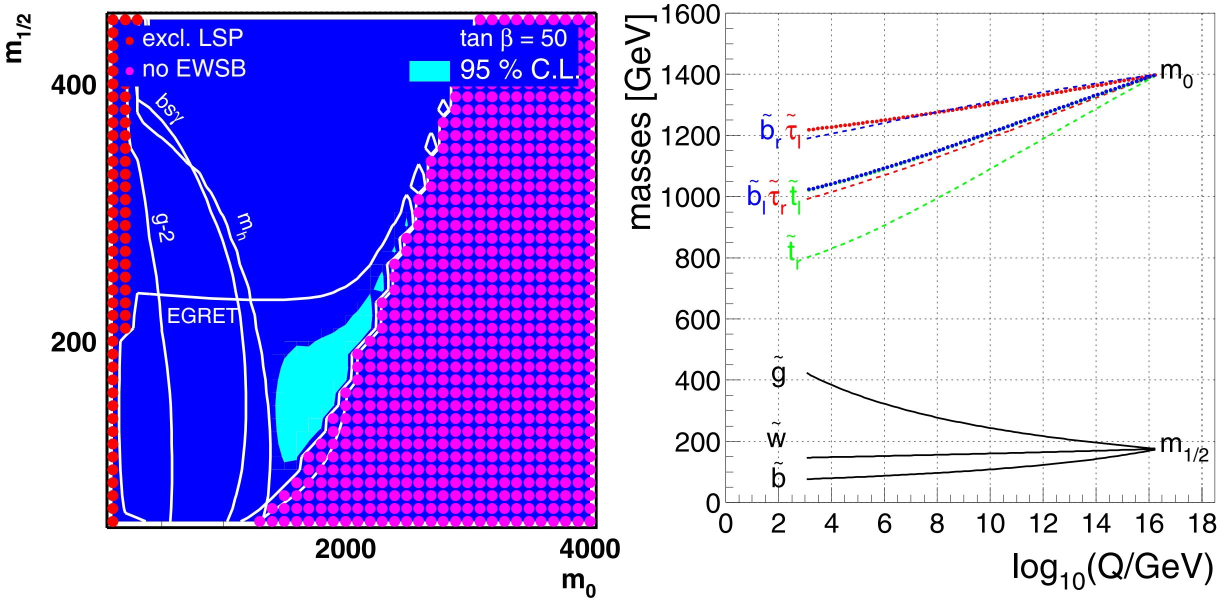

Figure 7: The light shaded (blue) region in the $\mathrm{m}_0, \mathrm{m}_{1/2}$ plane allowed by the combination of WMAP, EGRET, $b \to s\gamma$ and the Higgs limit for $\tan\beta = 51$, $\mu > 0$ and $A_0 = 0$. The excluded regions, where the stau would be the LSP or EWSB fails or are indicated by the dots.

charged and cannot be DM. In the right bottom corner electroweak symmetry breaking does not work.

4. OBJECTIONS TO THE DMA INTERPRETATION

The DMA interpretation of the EGRET excess would mean that DM is not so dark anymore, but DM is visible from the 30-40 flashes of energetic gamma rays for each annihilation. This would be great, but are there more mundane explanations? Attempts to modify the electron and proton spectra from the locally measured spectra do not describe the shape of the EGRET data in all sky directions, as discussed in detail before by comparing the EGRET data with the "optimized model". Here we summarize some other (wrong) objections.

1. Are the EGRET data reliable enough to make such strong conclusions? The EGRET detector was calibrated in a quasi mono-energetic gamma ray beam at the SLAC accelerator, so its response is well known[20]. Also the monitoring during the flight was done carefully [21]. We have only used data in the energy range between 0.1 and 10 GeV, where the efficiency is more or less flat. So the 9 years flight provided accurate and reliable data, especially it would be hard to believe in an undetected calibration problem, which would only effect the data above 0.5 GeV and fake the gamma ray spectrum from the fragmentation of mono-energetic quarks.

2. The gamma ray spectrum above 0.1 GeV is dominated by pp-interactions and therefore strongly dependent on the proton energy spectrum. This cosmic ray spectrum was measured only locally in the solar neighbourhood. Could a harder spectrum near the Galactic center, where protons can be accelerated by the many supernovae there, explain the EGRET excess? No, first of all the energy loss times of protons with energies above a few GeV are longer than the lifetime of the universe, so by diffusion one expects everywhere the same energy spectrum. This is proven by the fact, that gamma ray spectrum for the Galactic center and the Galactic anticenter can be described by the *same* background shape.

3. Is the background well enough known to provide evidence for DMA? The background is dominated by pp-collisions with a known shape and fitting the normalization yields a "self-calibrating" background: changing

the slope of the proton spectra yields too many low energy gamma rays, thus providing a shape different from the data. Fitting this "wrong" shape with a free normalization reduces then the low energy excess again and recovers the high energy excess. Note that this "self-calibration" of the background also takes care of gas clouds, ringlike or asymmetric structures in the background, uncertainties in the absolute value of the total cross sections, etc.

4. Is it possible to explain the excess in diffuse gamma rays with unresolved point sources? This is unlikely, first of all since the known point sources [22] are only a small fraction of the diffuse gamma rays and the majority of the resolved sources has a rather soft spectrum, typically well below 1 GeV, as can be seen from the plots in the Appendix. If this part of the spectrum would be dominated by unresolved sources, then the diffuse component below 1 GeV would be lower than assumed, which in turn would lead to a lower normalization of the background and a correspondingly stronger excess for a fixed background shape. So arguing against DMA by unresolved sources goes in the wrong direction.

5. Is one not over-interpreting the EGRET data by fitting so many parameters for the different components: triaxial halo, inner ring and outer ring? No, first of all the excess and enhancement in a ringlike structure at 14 kpc was already discovered in the original paper by [9]. What we did is just trying to see if the excess fits: a) a single WIMP mass in all directions; b) an isothermal DM profile plus the substructure; c) the Galactic rotation curve. Since each sky direction has 7 independent data points times 180 sky directions, one has more than 1200 independent data points with the different DM halo components being determined by independent sky directions: the outer ring parameters are determined mainly by 30 sky directions towards the Galactic anticenter, the inner ring parameters by ca. 15 sky directions towards the Galactic center and the triaxial halo parameters by ca. 130 sky directions out of the Galactic plane. And the most remarkable thing is that all these independent sky directions all show an excess, which can be explained by a single WIMP mass around 60 GeV. This is like having 180 independent experiments at an accelerator all saying we see a significant excess of gamma rays corresponding to π^0 production from mono-energetic quarks. Then asked what mass they need to describe the excess, they all say 60 GeV!

6. The tracing of DM relies largely on the outer rotation curve of our Galaxy, which has large uncertainties from the distance r_0 between the Sun and the Galactic center and is determined with a different method than the inner rotation curve. Can this fake the results? The outer rotation curve indeed depends strongly on r_0, as shown by [23], who varied r_0 between 7 and 8.5 kpc. At present one knows from the kinematics of the stars near the black hole at the center of our Galaxy that $r_0 = 8 \pm 0.4$ kpc [24], so the distance is already reasonably well known. But whatever the value of r_0, the change in slope around $1.3r_0$ is always present, indicating a ringlike DM structure is always needed. Furthermore the outer rotation curve shows first the same decrease as the inner rotation curve and only then changes the slope, so the different methods agree between r_0 and $1.3r_0$.

7. The outer ring at 14 kpc has a mass around $9 \cdot 10^{10}$ solar masses. This is around 50% of the total mass inside the ring and one may worry about the disk stability of the Milky Way by the infall of such a heavy Galaxy. However, large spiral galaxies show bumps of similar size [25], so it seems not to be uncommon to have masses of this size forming ringlike structures. Note that only ringlike structures can form maxima and minima in the outer rotation curve, since the rotation velocity squared is proportional to the *derivative* of the gravitational potential. Furthermore, the stars in the ring at 14 kpc are all old, so the infall might have happened before the growing of the disk.

8. One observes a ring of molecular hydrogen near the inner ring and a ring of atomic hydrogen near the outer ring. Could this excess of hydrogen not be responsible for the excess of the gamma rays? No, our method of fitting only the shapes with a free normalization implies that this analysis is insensitive to density fluctuations of the background, which change the normalization, not the shape.

9. How can one be sure that the outer ring originated from the tidal disruption of a rather massive satellite galaxy, so one can expect an enhanced DM density in the ring? One finds three independent ringlike structures: stars,

atomic hydrogen gas and excess of gamma radiation. The stars show a scale height of several kpc and a low velocity dispersion, so they cannot be part of the Galactic disk. Therefore the infall of a satellite galaxy is the natural explanation. Since the tidal forces are proportional to $1/r^3$, the satellite will be disrupted most strongly at its pericenter, which can lead to DM density enhancements at the pericenter after a few orbits [26]. Some of the stars and gas may be caught in this potential well. All three are found at 14 kpc with the stars all being old and more than 90% of the mass being DM as deduced from the strong EGRET excess at this radius.

10. Is it not peculiar that if a ringlike structure originates from the infall of satellite galaxy, that it lies in the plane of the Galaxy? No, in principle the infall can happen in all directions with respect to the plane, but the angular momenta of the inner halo and a baryonic disk tend to align after a certain time by tidal torques [27].

5. SUMMARY AND OUTLOOK

As mentioned in the Introduction, if DM is a thermal relic from the early Universe, then it is known to annihilate, since the small amount of relic density measured nowadays requires a large reduction in its number density. The annihilation into quark pairs will produce π^0 mesons during the fragmentation into hadrons, which in turn will decay into gamma rays. For heavy WIMP masses the gamma spectrum is considerably harder than the background spectrum. Such an excess of hard gamma rays has indeed been observed by the EGRET satellite and the relative contributions from background and DM annihilation signal can be obtained by fitting their different shapes with a free normalization factor for background and signal. This method of a "self-calibrating" background yields results practically independent of propagation models of our Galaxy.

This excess of hard diffuse gamma rays shows all the features expected from Dark Matter Annihilation:

- The excess is visible in *all* sky direction with a *same* spectrum corresponding to the annihilation of WIMP pairs with a WIMP mass around 60 GeV.

- The excess follows the distribution of a pseudo-isothermal halo profile - as observed in many galaxies - with an additional increased intensity at two toroidal shaped structures at radii of 14 and 4 kpc from the centre of the Galaxy. At these radii one finds an enhanced density of hydrogen gas. Assuming that the baryons follow the gravitational potential of DM one expects DM there. In addition, at 14 kpc one has observed a ring of stars thought to originate from the infall of a dwarf galaxy, while at 4 kpc one finds an enhanced concentration of dust and molecular hydrogen. The dust shields the latter against dissociation by UV radiation and can be collected in the gravitational potential well of a ring of DM.

- Knowing the halo profile of the DM together with the distribution of visible matter allows to reconstruct the rotation curve of our Galaxy. The gravitational potential wells of the ringlike DM substructure cause minima and maxima in the rotation curve, since the rotation velocity squared is proportional to the derivative of the gravitational potential. These have indeed been observed and are perfectly explained by the EGRET excess of gamma rays, thus proving that this excess traces the DM in our Galaxy!

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. WIMP masses in this range and the observed WIMP self annihilation cross section are consistent with WIMPs being the Lightest Supersymmetric Particle predicted in the Minimal Supersymmetric Model with supergravity inspired symmetry breaking, called the mSUGRA model. The statistical significance of the EGRET excess of at least 10 σ combined with all features mentioned above provides an intriguing hint that DM is not so dark, but visible by its annihilation.

Acknowledgments

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