Interpretation of the EGRET Excess in Diffuse Galactic Gamma Rays as a Dark Matter Annihilation Signal

Indirect Search for Dark Matter

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Outline

Problems:

- Rotation curves of galaxies
- Matter content of the universe
- Excess in diffuse γ rays above 1 GeV

Solution:

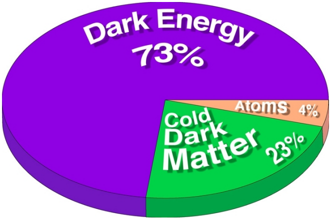
- Dark Matter halo around our galaxy ...
- ... consisting of WIMPs ...
- ... which can annihilate into quarks and give rise to high energetic γ rays from π^0-decays

Dark Matter

Energy/Matter Content of the Universe

- Combination of CMB data with Hubble expansion data from SNIa
- $\sim$ 27% matter but only $\sim$ 4% baryonic matter
- $\sim$ 1% luminous matter

$\Rightarrow$ existence of baryonic and non baryonic DM



Dark Matter

Hot Dark Matter Candidates (HDM)

- Neutrinos

$\Rightarrow$ not more than 10% to 15% of Ω_{DM}

Cold Dark Matter Candidates (CDM)

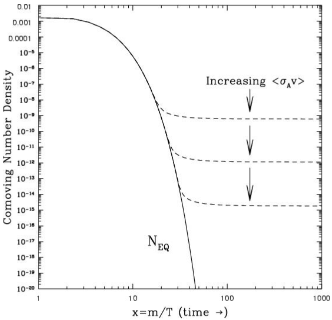
- Massive neutrinos
- Primordial black holes
- Axions
- Weakly Interacting Massive Particles (WIMPs)

$\Rightarrow$ WIMPs are very promising CDM candidates

Dark Matter

Why are WIMPs promising?

- Assumption: DM in thermal equilibrium with early universe
- Approximative solution of the Boltzmann equation:
  $\Omega_\chi h^2 = \frac{m_\chi n_\chi}{\rho_c} \approx \left(\frac{3{\cdot}10^{-27}\ \mathrm{cm}^3\ \mathrm{s}^{-1}}{\langle \sigma v \rangle} \right)$
  $\Rightarrow$ cross sections of weak interaction

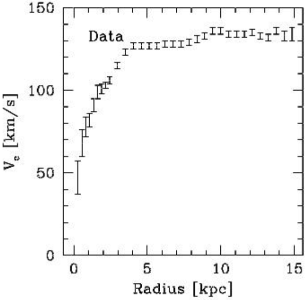


Rotation Curves of Galaxies

Observation vs. Expectation

- Expectation from Kepler's law: $v \propto 1/\sqrt{r}$ for $r \gg r_{disk}$
- Observation: $v \approx const$
- Possible explanation: existence of extended halo of DM

NGC 2403

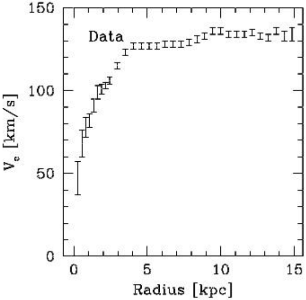


Rotation Curves of Galaxies

Determination of r Dependence

$$
\begin{aligned}
F_Z &= F_G \\
m \cdot v^2/r &= G \cdot m \cdot M(r)/r^2 \\
\Rightarrow v &= G \cdot \sqrt{M(r)/r} \\
v &\stackrel{!}{=} const \\
\Rightarrow M(r) &\propto r \\
\int \rho \, dV &\propto \int \rho(r) r^2 \, dr \\
\Rightarrow \rho(r) &\propto 1/r^2
\end{aligned}
$$

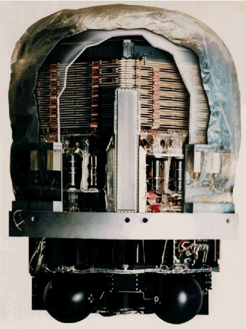
NGC 2403



Diffuse Galactic Gamma Rays

EGRET Experiment

- Installed on CGRO satellite (together with BATSE, OSSE and COMPTEL)
- Measuring from 1991 to 2000
- Energy range from $\sim$ 30 MeV to $\sim$ 100 GeV
- Third EGRET catalog: 271 point sources
- Complete data - point sources = diffuse gamma rays

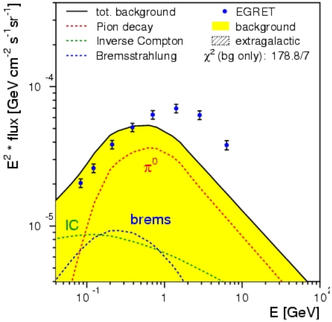


Diffuse Galactic Gamma Rays

Spectrum from the Galactic center:

EGRET Excess

- Comparison with galactic models
  $\Rightarrow$ Excess above 1 GeV
- Excess observed in every sky direction
- Uncertainty of background or new contribution?



Diffuse Galactic Gamma Rays

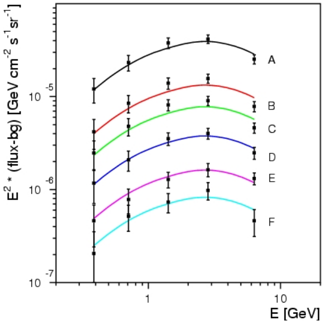
Excess in Different Directions

Spectral shape of excess is independent of sky region
$\Rightarrow$ 2 possibilities

- Uncertainty of background
- New contribution, e.g. DMA

region	l [°]	$\|b\|$ [°]	description
A	330-30	0-5	inner galaxy
B	30-330	0-5	galactic plane avoiding A
C	90-270	0-10	outer galaxy
D	0-360	10-20	intermediate latitudes 1
E	0-360	20-60	intermediate latitudes 2
F	0-360	60-90	galactic poles

Spectrum from different regions:

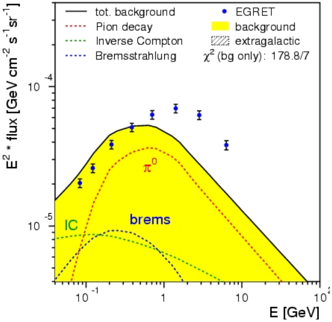


Galactic Background of Diffuse Gamma Rays

Contributions

- Decay of neutral π^0s produced in *pp* reactions of CR with interstellar gas
  $p + p \rightarrow \pi^0 + X \rightarrow \gamma\gamma + X$
- Bremsstrahlung
  $e + p \rightarrow e' + p' + \gamma$
- Inverse Compton
  $e + \gamma \rightarrow e' + \gamma'$

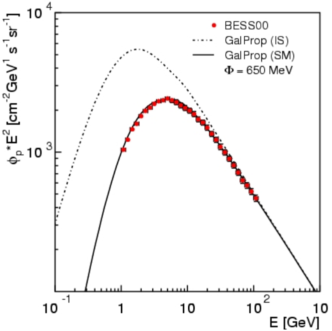
Spectrum from the Galactic center:



Galactic Background of Diffuse Gamma Rays

Dominant Contribution

- π^0 peak
- Shape determined by energy spectrum of CR protons
- CR proton spectrum measured locally by balloon experiments

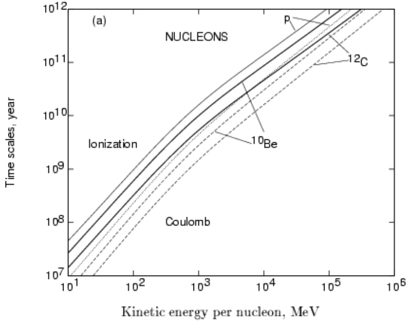


Galactic Background of Diffuse Gamma Rays

Ingredients of Propagation

- Source spectrum
- Source distribution
- Energy losses
- Diffusion
- Convection
- Radioactive decay
- Interaction with interstellar gas
- ...

Energy loss times for nucleons $\approx$ age of universe:



Calculation of bgs with `GalProp`

Moskalenko *et al.* `astro-ph/9906228`

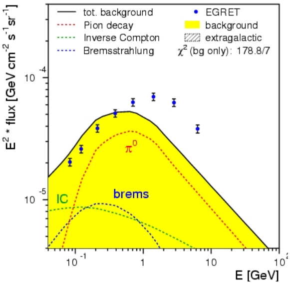
Galactic Background of Diffuse Gamma Rays

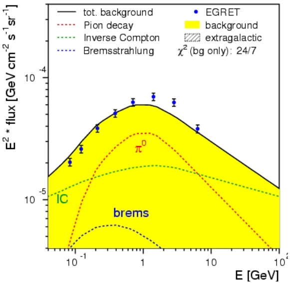
Conventional model

Local *p* and *e* spectrum representative

Optimized model

Local *p* and *e* spectrum not representative

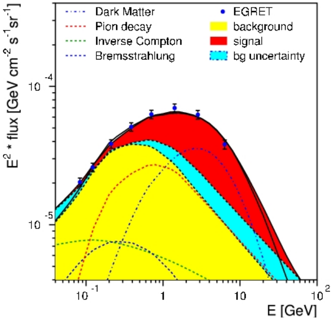




Galactic Background of Diffuse Gamma Rays

Uncertainty of Solar Modulation

- High energies: energy dependence γ_{high} is fixed (≈ 2.7)
- Low energies: uncertainty of γ_{low} can be compensated by solar modulation
- CM: $\gamma_{\mathrm{low}} \approx 2.0 \Rightarrow \Phi_{\mathrm{SM}} \approx 650$ MV
- $\gamma_{\mathrm{low}} \approx 1.8 \Rightarrow \Phi_{\mathrm{SM}} \approx 450$ MV
- $\gamma_{\mathrm{low}} \approx 2.2 \Rightarrow \Phi_{\mathrm{SM}} \approx 900$ MV

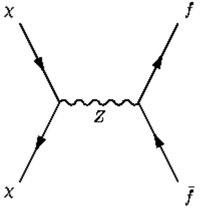


Dark Matter Annihilation

If WIMPs . . .

- . . . are Majorana particles
  $\Rightarrow$ WIMPs can annihilate
- . . . were in equilibrium with the early universe
  $\Rightarrow$ Today WIMPs are almost at rest
- . . . annihilate at rest
  $\Rightarrow$ a pair of monoenergetic SM particles

Typical Feynman diagram:

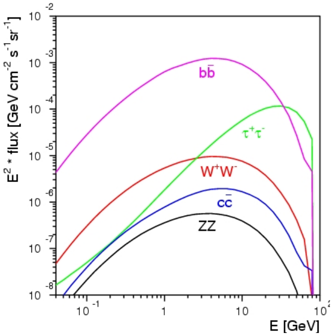


Dark Matter Annihilation

Spectral Shape of DMA Signal ...

- Fragmentation and/or decay of Annihilation products
  $\Rightarrow \pi^0$s
  $\Rightarrow \sim 30 \ldots 40\ \gamma$s per annihilation
- Different γ spectrum than background (continuous CR spectrum)
  $\Rightarrow$ better fit to EGRET spectrum?
- Spectral shape similar for different annihilation processes

Gamma spectra for different processes:



Calculation of signal with `DarkSusy`

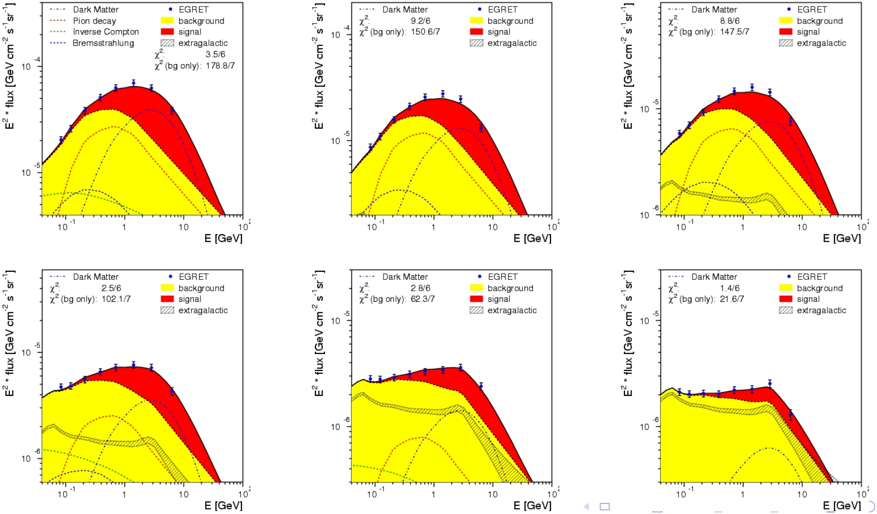
Gondolo *et al.* `astro-ph/0406204`

Fit to EGRET Spectrum with DMA signal

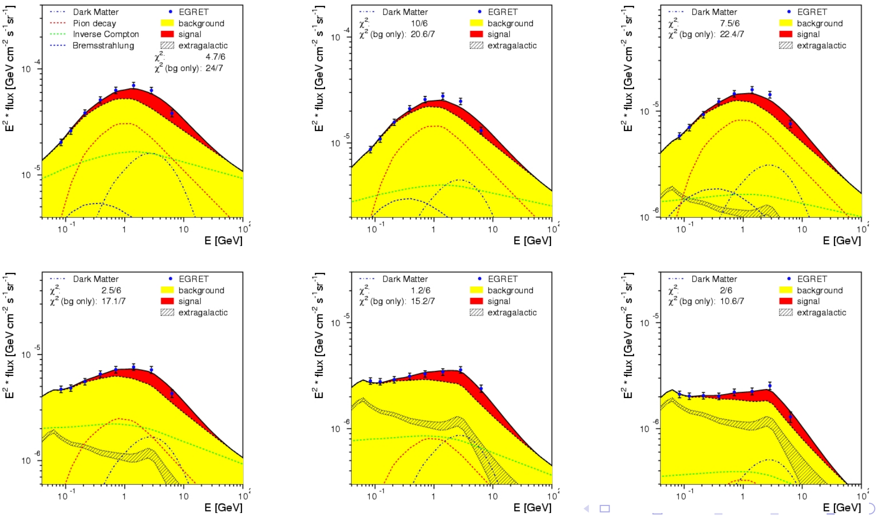
Fit Spectral Shape Only

- Uncertainties in interstellar gas density
  $\Rightarrow$ bg scaling
- Uncertainties in DM density
  $\Rightarrow$ signal scaling (boost factor)
- Free bg and signal scaling
  $\Rightarrow$ use point to point error $\sim$ 7% (full error $\sim$ 15%)

Fit to EGRET Spectrum with CM and DMA signal



Fit to EGRET Spectrum with OM and DMA signal

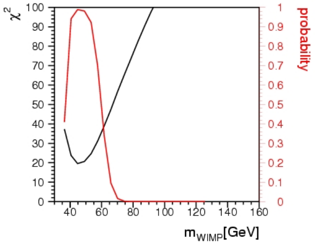


Limits on WIMP Mass

Conventional Model

- $\Sigma\chi^2$ of 6 Regions of the Sky
- Scan over WIMP mass
  $\Rightarrow m_{WIMP} \lesssim 70$ GeV (95% C.L.)

$\chi^2/d.o.f.$ and probability:

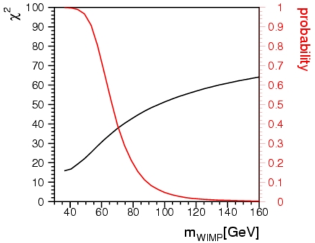


Limits on WIMP Mass

Optimized Model

- $\Sigma\chi^2$ of 6 Regions of the Sky
- Scan over WIMP mass
  $\Rightarrow m_{WIMP} \lesssim 100$ GeV (95% C.L.)

$\chi^2/d.o.f.$ and probability:

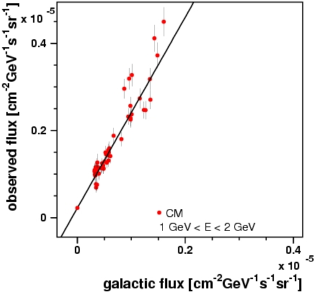


Extragalactic Background

Important bg at large Galactic latitudes (low Galactic bg)

Method of EGB Determination

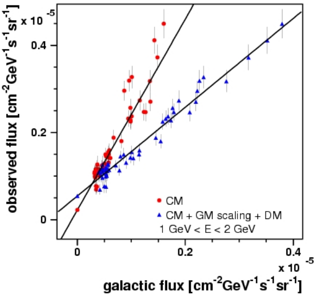
- Choose one energy
- Divide skymap in regions of high and low flux
- Draw observed vs. expected flux
- y-axis intercept is EGB of chosen energy



Extragalactic Background

Modified Method of EGB Determination

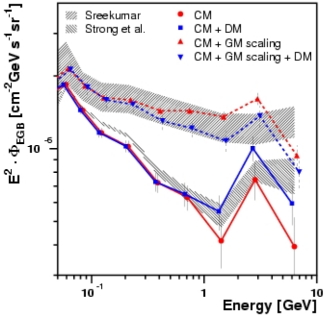
- Use region dependent bg scaling
  Sreekumar *et al.* `astro-ph/9709257`
- Add DMA signal to prediction (new)



Extragalactic Background

Comparison of different Methods

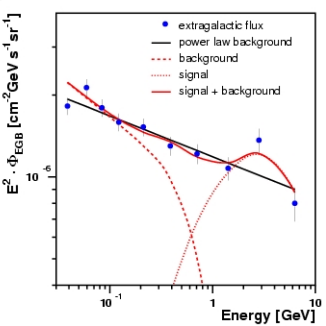
- Bg scaling leads to significantly larger EGB
- All methods show a bump in the GeV range



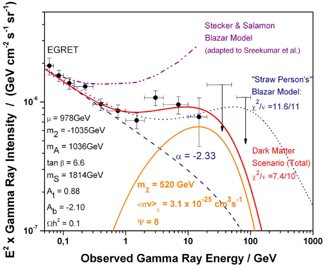
Extragalactic Background

Extragalactic DMA contribution

- Fit of new EGB with double power law and DMA signal ($\chi^2/d.o.f.$=2.45/5 $\Rightarrow$ 78%)
- Fit with single power law ($\chi^2/d.o.f.$=8.2/8 $\Rightarrow$ 42%)



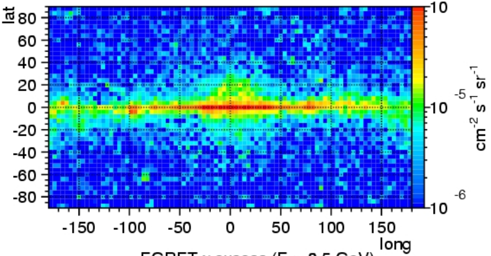
Elsaesser *et al.* `astro-ph/0405235`



Determination of Halo Parameters

Directional Dependence of Excess

- Signal in sky region Ψ: $\Phi_{DM} \propto \langle \sigma v \rangle \cdot \frac{1}{\Delta\Omega} \int d\Omega \int dl_\psi \left(\frac{\rho(l_\psi)}{m_\chi} \right)^2$
- Smooth $1/r^2$ profile yields not enough signal $\Rightarrow$ clumps
- Assume same enhancement by clumps in all directions

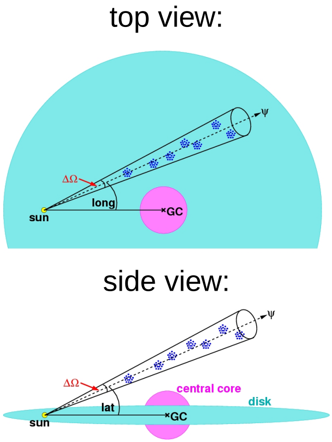


EGRET γ excess (E > 0.5 GeV)

Determination of Halo Parameters

Method

- Divide skymap into 180 independent sky directions
  $\Rightarrow$ 45 intervals for gal. longitude (dlong = 8°)
  $\Rightarrow$ 4 intervals for gal. latitude ($|lat| < 5°$, $5° < |lat| < 10°$, $10° < |lat| < 20°$ and $20° < |lat|$)
- Divide gamma spectrum in low and high (<>0.5 GeV) energy region
- Use low energy region for bg normalization
- Use high energy region for determination of halo parameters



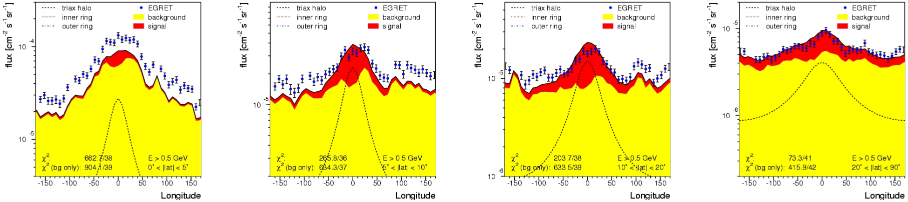
Determination of Halo Parameters

Isothermal Profile Without Rings

Triaxial profile with $1/r^2$ dependence at large r and core at center

- Good agreement at large latitudes
- Too little flux in galactic plane

$|\text{lat}| < 5^\circ$ $\quad$ $5^\circ < |\text{lat}| < 10^\circ$ $\quad$ $10^\circ < |\text{lat}| < 20^\circ$ $\quad$ $20^\circ < |\text{lat}|$



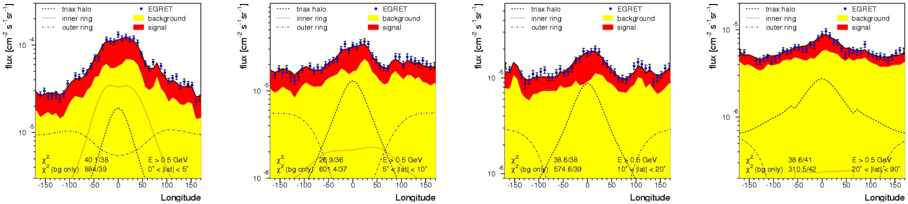
Determination of Halo Parameters

Isothermal Profile With Rings

Additional DM in galactic plane parametrized by two toroidal ringlike structures

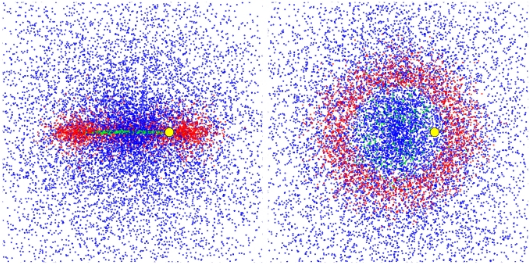
- Inner ring at $\sim$ 4 kpc; $\sim$ thickness of lum. disk (e.g. adiabatic compression)
- Outer ring at $\sim$ 14 kpc; much thicker than disk (e.g. infall of dwarf galaxy)

$|\text{lat}| < 5°$ | $5° < |\text{lat}| < 10°$ | $10° < |\text{lat}| < 20°$ | $20° < |\text{lat}|$



Visualization of Halo Profile

Dark Matter:



baryonic matter:

Determination of Halo Parameters

Experimental Counterpart of Rings

- Inner ring:
  $M_{inner} \sim 9 \cdot 10^9 M_\odot \approx 0.3\%$ of M_{tot}
  coincides with maximum of H_2 distribution
  Hunter *et al.* Astrophys. J. **481** (1997) 205
- Outer ring:
  $M_{outer} \sim 8 \cdot 10^{10} M_\odot \approx 3\%$ of M_{tot}
  correlated with ghostly ring of stars at ~ 14 kpc ($10^8 \ldots 10^9$ $M_\odot$)
  Ibata *et al.* (`astro-ph/0301067`)
- Massive substructures influence rotation curve of milky way

Rotation Curve of the Milky Way

Calculation

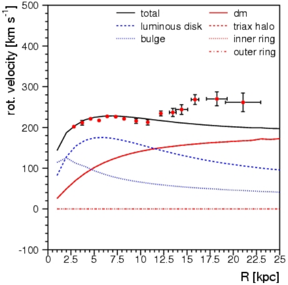
- $\frac{m \cdot v^2}{r} = m \cdot \frac{d\Phi}{dr}$
- Excentricity of halo and rings $\Rightarrow$ no symmetry can be used to calculate Φ
- Solution of Poisson equation $\Delta\Phi = -4\pi G \cdot \rho$ by Greens function
- Ringlike structures will contribute to v^2 with negative sign inside the ring
- Calculated rotation curve has to be compatible with Milky Way

Rotation Curve of the Milky Way

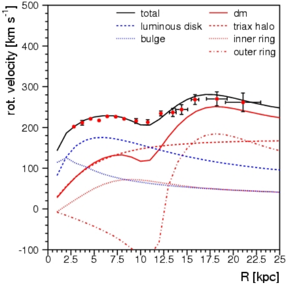
Comparison with Measured Rotation Curve

- Data are averaged from three surveys with different tracers
- Rings of DM can explain change of slope at $\sim$ 10 kpc

without rings:



with rings:



Summary

1. EGRET excess can be explained as Dark Matter annihilation of WIMPs in a mass range between 50 and 100 GeV
2. Extragalactic Background has been determined including bg scaling and a possible DM contribution of the galactic flux
3. From the directional dependence of the excess a *possible* halo profile can be determined $\Rightarrow$ halo profile needs ringlike structures, which are correlated with observations
4. Determined halo profile is compatible with rotation curve of the Milky Way
5. *not shown:* EGRET data are compatible with DM consisting of supersymmetric neutralinos $\Rightarrow$ together with constraints from EWSB, Higgs mass, $Br(b \to X_s \gamma)$ and a_μ only a small region of SUSY parameter space is left over (`hep-ph/0511154`)