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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Problems:
- Rotation curves of galaxies
- Matter content of the universe
- Excess in diffuse $\gamma$ 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 $\gamma$ rays from $\pi^0$-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

⇒ not more than 10% to 15% of $\Omega_{DM}$

Cold Dark Matter Candidates (CDM)
- Massive neutrinos
- Primordial black holes
- Axions
- Weakly Interacting Massive Particles (WIMPs)

⇒ WIMPs are very promising CDM candidates
Why are WIMPs promising?

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

Observation vs. Expectation
- **Expectation from Kepler’s law:**
  \[ v \propto \frac{1}{\sqrt{r}} \text{ for } r \gg r_{\text{disk}} \]
- **Observation:** \( v \approx \text{const} \)
- **Possible explanation:** existence of extended halo of DM

\[ V_c \text{ [km/s]} \]

\[ R \text{ [kpc]} \]

NGC 2403
Rotation Curves of Galaxies

**Determination of $r$ Dependence**

\[
\begin{align*}
F_Z &= F_G \\
m \cdot \frac{v^2}{r} &= G \cdot m \cdot M(r)/r^2 \\
\Rightarrow v &= G \cdot \sqrt{M(r)/r} \\
v &\equiv \text{const} \\
\Rightarrow M(r) &\propto r \\
\int \rho \, dV &\propto \int \rho(r) r^2 \, dr \\
\Rightarrow \rho(r) &\propto \frac{1}{r^2}
\end{align*}
\]

**NGC 2403**

![Graph showing rotation curve data for NGC 2403 with fit line and data points.](image)
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
EGRET Excess

- Comparison with galactic models
  \[ \rightarrow \text{Excess above 1 GeV} \]
- Excess observed in every sky direction
- Uncertainty of background or new contribution?

Spectrum from the Galactic center:
**Excess in Different Directions**

Spectral shape of excess is independent of sky region

⇒ 2 possibilities

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

<table>
<thead>
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<th>region</th>
<th>l [°]</th>
<th>b [°]</th>
<th>description</th>
</tr>
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<td>0-5</td>
<td>inner galaxy</td>
</tr>
<tr>
<td>B</td>
<td>30-330</td>
<td>0-5</td>
<td>galactic plane avoiding A</td>
</tr>
<tr>
<td>C</td>
<td>90-270</td>
<td>0-10</td>
<td>outer galaxy</td>
</tr>
<tr>
<td>D</td>
<td>0-360</td>
<td>10-20</td>
<td>intermediate latitudes 1</td>
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<td>E</td>
<td>0-360</td>
<td>20-60</td>
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<tr>
<td>F</td>
<td>0-360</td>
<td>60-90</td>
<td>galactic poles</td>
</tr>
</tbody>
</table>

**Spectrum from different regions:**
Introduction
Spectral Fit to EGRET data
Halo Profile

Galactic Background of Diffuse Gamma Rays

Contributions

- Decay of neutral $\pi^0$s 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
  
  $e + \gamma \rightarrow e' + \gamma'$
Galactic Background of Diffuse Gamma Rays

Dominant Contribution

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

- $E^{\Phi}$ vs. $E$ plot with different models and data points.
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

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**Galactic Background**
- Dark Matter Annihilation
- Limits on WIMP Mass
- Extragalactic Background
Galactic Background of Diffuse Gamma Rays

Uncertainty of Solar Modulation

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

- . . . are Majorana particles
  ⇒ WIMPs can annihilate

- . . . were in equilibrium with the early universe
  ⇒ Today WIMPs are almost at rest

- . . . annihilate at rest
  ⇒ a pair of monoenergetic SM particles

Typical Feynman diagram:
**Spectral Shape of DMA Signal**

- Fragmentation and/or decay of Annihilation products
  \[ \Rightarrow \pi^0 s \]
  \[ \Rightarrow \sim 30 \ldots 40 \ \gamma s \text{ per annihilation} \]
- Different \( \gamma \) spectrum than background (continuous CR spectrum)
  \[ \Rightarrow \text{better fit to EGRET spectrum?} \]
- Spectral shape similar for different annihilation 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
  ⇒ bg scaling

- Uncertainties in DM density
  ⇒ signal scaling (boost factor)

- Free bg and signal scaling
  ⇒ use point to point error \( \sim 7\% \) (full error \( \sim 15\% \))
Fit to EGRET Spectrum with CM and DMA signal

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Fit to EGRET Spectrum with OM and DMA signal

- Dark Matter
- Pion decay
- Inverse Compton
- Bremsstrahlung

Galactic Background
Dark Matter Annihilation
Limits on WIMP Mass
Extragalactic Background

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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.)
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.)

\[\chi^2/d.o.f. \text{ and probability:}\]
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

- Add DMA signal to prediction (new)
- Use bg scaling

Sreekumar et al. astro-ph/9709257
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 \( \chi^2 / d.o.f. = 3.7/5 \Rightarrow 59\% \)
- Fit with single power law \( \chi^2 / d.o.f. = 10.9/9 \Rightarrow 21\% \)

Elsaesser et al. astro-ph/0405235

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Introduction
Spectral Fit to EGRET data
Halo Profile

Determination of Halo Parameters
Rotation Curve

Directional Dependence of Excess

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

![Graph showing directional dependence of excess signal in sky region.](image)
Determination of Halo Parameters

Method

- Divide skymap into 180 independent sky directions
  ⇒ 45 intervals for gal. longitude (dlong = 8°)
  ⇒ 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

**Plots**

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

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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)

$|\text{lat}| < 5^\circ$

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

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

$20^\circ < |\text{lat}|$
Determination of Halo Parameters

Experimental Counterpart of Rings

- **Inner ring:**
  \[ M_{\text{inner}} \sim 9 \cdot 10^9 M_\odot \approx 0.3\% \text{ of } M_{\text{tot}} \]
  coincides with maximum of H$_2$ distribution

- **Outer ring:**
  \[ M_{\text{outer}} \sim 8 \cdot 10^{10} M_\odot \approx 3\% \text{ of } M_{\text{tot}} \]
  correlated with ghostly ring of stars at \( \sim 14 \text{ kpc} \) \( (10^8 \ldots 10^9 M_\odot) \)
  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 → no symmetry can be used to calculate \( \Phi \)
- 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
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:
EGRET excess can be explained as Dark Matter annihilation of WIMPs in a mass range between 50 and 100 GeV.

From the directional dependence of the excess a possible halo profile can be determined.

The halo profile needs ringlike structures.

Rings are correlated with observations.

Determined halo profile is compatible with rotation curve of the Milky Way.