EGRET Excess of diffuse Galactic Gamma Rays as a Trace of the Dark Matter Halo
Indirect Search for Dark Matter

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Introduction
Spectral Fit to EGRET data
Halo Profile

Outline

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
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
One of the most promising candidates is the Weakly Interacting Massive Particle

Why?

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

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**NGC 2403**

![Graph showing rotation curve data for NGC 2403](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
Diffuse Galactic Gamma Rays

EGRET Excess
- Comparison with galactic models ⇒ Excess above 1 GeV
- Spectral shape of excess independent of sky direction
- Uncertainty of bg or a new contribution?

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

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Dominant Contribution

- $\pi^0$ peak
- Shape determined by energy spectrum of CR protons
- CR proton spectrum measured locally by balloon experiments
- Locally measured spectrum is representative for rest of Galaxy
  $\rightarrow$ Conventional Model
- Uncertainty by Solar Modulation

Calculation of bgs with GalProp

Moskalenko et al. astro-ph/9906228
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: \( \gamma_{\text{low}} \approx 2.0 \Rightarrow \Phi_{\text{SM}} \approx 650 \text{ MV} \)
- \( \gamma_{\text{low}} \approx 1.8 \Rightarrow \Phi_{\text{SM}} \approx 450 \text{ MV} \)
- \( \gamma_{\text{low}} \approx 2.2 \Rightarrow \Phi_{\text{SM}} \approx 900 \text{ MV} \)
Spectral Shape of DMA Signal...

- WIMPs can annihilate at rest into a pair of monoenergetic SM particles
- Fragmentation/decay of products
  \[ \Rightarrow \pi^0 s \]
  \[ \Rightarrow \sim 30 \ldots 40 \gamma s \text{ per annihilation} \]
- Different $\gamma$ spectrum than bg (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 ∼ 7% (full error ∼ 15%)
Fit to EGRET Spectrum with CM and DMA signal

- Dark Matter
- Pion decay
- Inverse Compton
- Bremsstrahlung
- EGRET background
- Signal
- Extragalactic

χ²: 2.5/6 (bg only): 102.1/7
χ²: 8.8/6 (bg only): 147.5/7
χ²: 1.4/6 (bg only): 21.6/7

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Halo Profile
Galactic Background
Dark Matter Annihilation
Limits on WIMP Mass

Limits on WIMP Mass

Procedure
- $\Sigma \chi^2$ 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:

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**Determination of Halo Parameters**

**Directional Dependence of Excess**

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

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**Figure:**

A color-coded 2D plot illustrating the directional dependence of excess $\Delta \Psi$ for the EGRET $\gamma$-excess. The plot shows variations in signal intensity across different longitudes and latitudes, with color intensity indicating the magnitude of the excess signal. The intensity range is labeled on the right axis in units of $\text{cm}^{-2} \cdot \text{s}^{-1}$. The x-axis represents longitude in degrees, while the y-axis represents latitude in degrees. The data for $E > 0.5 \text{ GeV}$ is highlighted, suggesting a notable concentration of excess near specific regions.
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

| lat | <5° | 5° < |lat| <10° | 10° < |lat| <20° | 20° < |lat|

| Flux (cm$^{-2}$ s$^{-1}$ sr$^{-1}$) |

- Triaxial halo
- Inner ring
- Outer ring
- Background
- Signal

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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)

\[ |\text{lat}| < 5^\circ \]
\[ 5^\circ < |\text{lat}| < 10^\circ \]
\[ 10^\circ < |\text{lat}| < 20^\circ \]
\[ 20^\circ < |\text{lat}| \]
Visualization of Halo Profile

Sensitivity on ring parameters:

Dark Matter:

baryonic matter:
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
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:

![Graph without rings]

with rings:

![Graph with rings]
EGRET excess in the conventional Galactic model can be explained as Dark Matter annihilation of WIMPs in a mass range between 50 and 70 GeV.

From the directional dependence of the excess a possible halo profile can be determined ⇒ halo profile needs ringlike structures, which are correlated with observations.

Determined halo profile is compatible with rotation curve of the Milky Way (de Boer et al., Astronomy & Astrophysics 444 (2005) 51.).

not shown: EGRET data are compatible with DM consisting of supersymmetric neutralinos ⇒ together with constraints from EWSB, Higgs mass, \( Br(b \rightarrow Xs\gamma) \) and \( a_\mu \) only a small region of SUSY parameter space is left over, particle masses are in the discovery range of the LHC (de Boer et al., Phys. Lett. B 636 (2006) 13.).