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
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
### 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: \( v \propto 1/\sqrt{r} \) for \( r \gg r_{disk} \)
- Observation: \( v \approx const \)
- Possible explanation: existence of extended halo of DM
Rotation Curves of Galaxies

Determination of $r$ Dependence

\[ F_Z = F_G \]
\[ \frac{m \cdot v^2}{r} = G \cdot m \cdot \frac{M(r)}{r^2} \]
\[ \Rightarrow v = G \cdot \sqrt{\frac{M(r)}{r}} \]
\[ v = \text{const} \]
\[ \Rightarrow M(r) \propto r \]
\[ \int \rho \, dV \propto \int \rho(r) r^2 \, dr \]
\[ \Rightarrow \rho(r) \propto \frac{1}{r^2} \]
Introduction
Spectral Fit to EGRET data
Halo Profile

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

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EGRET Excess

- Comparison with galactic models
  ⇒ Excess above 1 GeV
- Excess observed in every sky direction
- Uncertainty of background or new contribution?
Excess in Different Directions

Spectral shape of excess is independent of sky region
⇒ 2 possibilities
- Uncertainty of background
- New contribution, e.g. DMA

| region | $l$ [$^\circ$] | $|b|$ [$^\circ$] | 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 $\pi^0$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
  \[ e + \gamma \rightarrow e' + \gamma' \]
Dominant Contribution

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

![Graph showing $\phi_p E^2$ vs E [GeV] with data points and curves for different models.]
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
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: $\gamma_{\text{low}} \approx 2.0 \Rightarrow \Phi_{\text{SM}} \approx 650 \text{ MV}$
- $\gamma_{\text{low}} \approx 1.8 \Rightarrow \Phi_{\text{SM}} \approx 450 \text{ MV}$
- $\gamma_{\text{low}} \approx 2.2 \Rightarrow \Phi_{\text{SM}} \approx 900 \text{ MV}$
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

Gamma spectra for different processes:
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 $\sim 15\%$)
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Galactic Background
Dark Matter Annihilation
Limits on WIMP Mass
Extragalactic Background

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

E^2 flux [GeV cm^-2 s^-1 sr^-1]

Chi^2 for Full Model:
- EGRET
- Background
- Signal
- Extragalactic

Chi^2 (bg only):
- 4.7/6
- 24/7

Chi^2 (bg only):
- 10/6
- 20.6/7

Chi^2 (bg only):
- 7.5/6
- 22.4/7

Chi^2 (bg only):
- 2.5/6
- 17.7/7

Chi^2 (bg only):
- 1.2/6
- 15.2/7

Chi^2 (bg only):
- 2/6
- 10.6/7
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.)

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

\[
\chi^2 \quad \text{probability}
\]

$m_{WIMP} \quad \text{probability}$
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
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

![Graph showing comparison of different methods for extragalactic background.](image)
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
Directional Dependence of Excess

Signal in sky region $\Psi$: $\Phi_{\text{DM}} \propto \langle \sigma v \rangle \cdot \frac{1}{\Delta \Omega} \int d\Omega \int dl_{\psi} \left( \frac{\rho(l_{\psi})}{m_\chi} \right)^2$

- Smooth $1/r^2$ profile yields not enough signal $\Rightarrow$ clumps
- Assume same enhancement by clumps in all directions
Method

- Divide skymap into 180 independent sky directions
  ⇒ 45 intervals for gal. longitude ($d_{\text{long}} = 8^\circ$)
  ⇒ 4 intervals for gal. latitude ($|\text{lat}| < 5^\circ$, $5^\circ < |\text{lat}| < 10^\circ$, $10^\circ < |\text{lat}| < 20^\circ$ and $20^\circ < |\text{lat}|$)

- 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

$\left|\text{lat}\right| < 5^\circ$
$5^\circ < \left|\text{lat}\right| < 10^\circ$
$10^\circ < \left|\text{lat}\right| < 20^\circ$
$20^\circ < \left|\text{lat}\right|$
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)
Visualization of Halo Profile

Dark Matter:

baryonic matter:
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Determination of Halo Parameters
Rotation Curve

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 \( \Rightarrow \) no symmetry can be used to calculate \( \Phi \)
- Solution of Poisson equation \( \Delta \Phi = -4\pi G \cdot \rho \) by Green's 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:**
EGRET excess can be explained as Dark Matter annihilation of WIMPs in a mass range between 50 and 100 GeV

Extragalactic Background has been determined including bg scaling and a possible DM contribution of the galactic flux

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

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

*not shown*: EGRET data are compatible with DM consisting of supersymmetric neutralinos $\Rightarrow$ together with constraints from EWSB, Higgs mass, $Br(b \rightarrow X_S\gamma)$ and $a_\mu$ only a small region of SUSY parameter space is left over (*hep-ph/0511154*)