Excess of EGRET diffuse galactic Gamma Rays interpreted as WIMP (DM) Annihilation

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Outline (see astro-ph/0408272)

• Annihilation cross section determined by Hubble constant and WMAP relic density

• EGRET Data on diffuse Gamma Rays show excess in all sky directions with the SAME energy spectrum

• WIMP mass between 50 and 100 GeV from spectrum of EGRET excess

• Halo parameters from sky map

• Data consistent with Supersymmetry
Dark Matter
annihilation cross section
determined by
Hubble constant!
Hubble const. determines WIMP annihilation $\sigma$-section

WIMP annihilation is a strong source of antiprotons, positrons and gammas by annihilation into quarks.

$\frac{dn_\chi}{dt} + 3H n_\chi = - <\sigma v> (n_\chi^2 - n_{\chi\,eq}^2),$

Boltzmann equation:
$H$-Term takes care of decrease in density by expansion. Right-hand side:
Annihilation and Production.

$T>>M$: $f+\bar{f}\rightarrow M+M; M+M\rightarrow f+\bar{f}$
$T<M$: $M+M\rightarrow f+\bar{f}$
$T=M/25$: $M$ decoupled, stable density
(wenn annihilation rate $\approx$ expansion rate, i.e. $\Gamma=\langle\sigma v\rangle n_\chi \approx H$ !)

Thermal equilibrium abundance
Actual abundance

Present number density ($\Omega h^2=0.113\pm0.009$) requires $<\sigma v>=2.10^{-26} \text{cm}^3/\text{s}$
SUPERSYMMETRY

The hypothesis of supersymmetry holds that every boson should have a fermionic partner, and vice versa.

<table>
<thead>
<tr>
<th>Spin</th>
<th>Standardparticle</th>
<th>Superpartner</th>
<th>Spin</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/2</td>
<td>Leptons (e, (\nu_e), ...)</td>
<td>Sleptons ((e, \nu_e), ...)</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Quarks (u, d, ...)</td>
<td>Squarks ((u, d), ...)</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Gluons</td>
<td>Gluinos</td>
<td>1/2</td>
</tr>
<tr>
<td></td>
<td>(W^\pm)</td>
<td>Wino</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(Z^0)</td>
<td>Zino</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Photon ((\gamma))</td>
<td>Photino ((\gamma))</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>Higgs</td>
<td>Higgsino</td>
<td>1/2</td>
</tr>
<tr>
<td>2</td>
<td>Graviton</td>
<td>Gravitino</td>
<td>3/2</td>
</tr>
</tbody>
</table>

If R-parity is conserved, the lightest supersymmetric particle (LSP) is stable and is a perfect candidate for Dark Matter. Neutralino = \(C_1\) Bino + \(C_2\) \(W_3\) + \(C_3\) Higgsino\(_1\) + \(C_4\) Higgsino\(_2\)
DM annihilation in Supersymmetry

Dominant diagram for WMAP cross section:
\( \chi + \chi \Rightarrow A \Rightarrow b \overline{b} \) quark pair

B-fragmentation well studied at LEP!
Yield and spectra of positrons, gammas and antiprotons well known!
Annihilation cross sections in $m_0 - m_{1/2}$ plane ($\mu > 0$, $A_0 = 0$)

$\tan = 5$

$10^{-27}$  $\bar{b}b$

$10^{-24}$  $\bar{t}t$

For WMAP $\langle \sigma v \rangle \approx 2 \times 10^{-26}$ cm$^3$/s one needs large $\tan \beta$ in bulk region (no coannihilation, no resonances)

$\tan = 50$

$10^{-24}$  $\bar{b}b$

$10^{-27}$  $\bar{t}t$

EGRET

WMAP

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SUSY Mass spectra in mSUGRA

LSP largely Bino ⇒ DM may be supersymmetric partner of CMB

Charginos, neutralinos and gluinos light
With SUSY spectrum from EGRET data perfect gauge coupling unification possible for $\alpha_s=0.123$ as determined from $R_l = \Gamma_{\text{had}} / \Gamma_{\text{lepton}}$. This value is independent of luminosity. Note $\alpha_s=0.115$ from $\Gamma_{\text{had}}$ alone, but this value is probably low because of systematic uncertainty in LEP lumi. If lumi increased by $3\sigma$, $\alpha_s=0.122$ and $N_v=3.0!$ (dB, Sander, PL B585 (2004))
EGRET excess interpreted as DM consistent with WMAP, Supergravity and electroweak constraints

MSUGRA can fulfill all constraints from WMAP, LEP, $b\rightarrow s\gamma$, $g-2$ and EGRET simultaneously, if DM is neutralino with mass in range 50-100 GeV and squarks and sleptons are $O(1\ TeV)$.
Indirect Dark Matter detection
Indirect detection of DM with gamma rays

- First question: how to tell source of a gamma ray?
- Answer: one cannot, since gammas observed along line of sight, and many sources in a given direction.

- How to distinguish then between sources?
- Point sources from intensity ("hot spots"), if strong enough
- Diffuse gamma ray sources
  \( pp \rightarrow \pi^0 \rightarrow \gamma \gamma + x, \ e\gamma \rightarrow e\gamma, \ eN \rightarrow e\gamma N, \ \text{Extragalactic Background, DMA} \)
  all have quite different ENERGY spectra AND different SKYMAPS

- Strategy: fit SHAPES of various contributions to energy spectrum (FREE NORMALIZATIONS) in 360 SKY DIRECTIONS ->

CHECK if normalizations and intensities in various sky directions are consistent with models, BUT SO WE DO NOT DEPEND ON Galactic models or supersymmetric parameters!!!!!

Beware: errors in EGRET data dominated by systematic uncertainties ->
  strong correlations -> to be taken into account in fits.
Published data not sufficient. Need direct analysis of public EGRET data.
Executive Summary

Expected Profile

Observed Profile

Rotation Curve

Halo profile

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Do other galaxies have bumps in rotation curves?
EGRET DATA on diffuse Gamma rays
EGRET on CGRO (Compton Gamma Ray Observ.)

9 yrs of data taken in space! (1991-2000)

Energetic Gamma Ray Experiment Telescope (EGRET)

- **Instrument Parameters and Capabilities**
  1. **Type**: spark chambers, NaI(Tl) crystals, and plastic scintillators.
  2. **Energy Range**: 20 MeV to about 30 GeV.
  3. **Energy Resolution**: approximately twenty percent over the central part of the energy range.
  4. **Total Detector Area**: approximately 6400 cm²
  5. **Effective Area**: approximately 1500 cm² between 200 MeV and 1000 MeV, falling at higher and lower energies.
  6. **Point Source Sensitivity**: varies with the spectrum and location of the source and the observing time. Under optimum conditions, well off the galactic plane, it should be approximately $6 \times 10^{-8}$ cm² s⁻¹ for $E > 100$ MeV for a full two week exposure.
  7. **Source Position Location**: Varies with the nature of the source intensity, location, and energy spectrum from 5 - 30 arcmin.
  8. **Field of View**: approximately a Gaussian shape with a half width at half maximum of about 20. Note that the full field of view will not generally be used.
  9. **Timing Accuracy**: 0.1 ms absolute
  10. **Weight**: about 1830 kg (4035 lbs)
  11. **Size**: 2.25 m x 1.65 m diameter
  12. **Power**: 190 W (including heater power)
Origins of diffuse gamma rays

Gamma Ray Flux from WIMP annihilation:

$$\phi_\chi(E, \psi) = \frac{\langle \sigma v \rangle}{4\pi} \sum_f \frac{dN_f}{dE} b_f \int_{\text{line of sight}} \frac{1}{2} \frac{\langle \rho^2 \rangle}{M_\chi^2} dl_\psi$$

Similar expressions for:

- $pp \rightarrow \pi_0 + x \rightarrow \gamma\gamma + x$, ($\rho$ given by gas density, highest in disc)
- $e\gamma \rightarrow e\gamma$, $eN \rightarrow e\gamma N$, ($\rho$ given by electron/gamma density, highest in disc)

Extragalactic Background (isotropic)
DM annihilation ($\rho \propto 1/r^2$ for flat rotation curve)

All have very different, but known energy spectra. Cross sections known. Densities not well known, so keep absolute normalization free for each process.

Fit shape of various contributions with free normalization, but normalization limited by experimental overall normalization error, which is 15% for EGRET data. Point-to-point errors 5-10% (yield good $\chi^2$).
Excess of Diffuse Gamma Rays above 1 GeV
(first publications by Hunter et al, Sreekumar et al. (1997))

A: inner Galaxy (l=±30°, |b|<5°)
B: Galactic plane avoiding A
C: Outer Galaxy
D: low latitude (10-20°)
E: intermediate lat. (20-60°)
F: Galactic poles (60-90°)
Excess of Diffuse Gamma Rays has same spectrum in all directions compatible with WIMP mass of 50-100 GeV

Egret Excess above extrapolated background from data below 0.5 GeV

Excess same shape in all regions implying same source everywhere

Important: if experiment measures gamma rays down to 0.1 GeV, then normalizations of DM annihilation and background can both be left free, so one is not sensitive to absolute background estimates, BUT ONLY TO THE SHAPE, which is much better known.
Diffuse Gamma Rays for different sky regions
Good Fits for WIMP masses between 50 and 100 GeV

3 components: galactic background + extragalactic bg + DM annihilation fitted simultaneously with same WIMP mass and DM normalization in all directions. Boost factor around 70 in all directions and statistical significance > 10σ!
Local electron and proton spectra determine shape of gamma background

Why fit only shapes? BG: gas column density in given direction not better known than 20-30%, so BG not better known. DMA cross section well known, but signal $\propto \rho^2$ and galaxies formed from DM clusters, so clustering may enhance signal ("boost" factor). Extragal. fitted with power law.

CHECK AFTERWARDS IF NORMALIZATION FACTORS AGREE WITH EXP.
Background uncertainties

T. Kamae et al., 2004, astro-ph/0410617

Main results on halo profile, substructure, and WIMP mass not affected after renormalization to data between 0.1 and 0.5 GeV.

Note: point-to-point errors only half of plotted errors of 15%. Statistical errors negligible.
Primary cosmic ray flux

$\propto E^{-n}$

Equivalent c.m. energy $\sqrt{s_{pp}}$ (GeV)

Scaled flux $E^{2.5} J(E)$ ($m^2 \cdot sec^{-1} \cdot sr^{-1} \cdot eV^{-1.5}$)

Energy (eV/particle)

Fixed target (p-A)

HERA ($\gamma$-p)

RHIC (p-p)

Tevatron (p-p)

LHC (p-p)

LHC (C-C)

$n=2.5$

$n=2.7$

$n=3.0$
Energy loss times of electrons and nuclei

$$\tau^{-1} = \frac{1}{E} \frac{dE}{dt}$$

Protons diffuse for long times without losing energy!

If centre would have harder spectrum, then hard to explain why excess in outer galaxy has SAME shape (can be fitted with same WIMP mass!)
Uncertainties in background and signal shapes

- RED = flux from DM Annihilation
- Yellow = background
- Blue = BG uncertainty

Blue: uncertainty from background shape
Blue: uncertainty from WIMP mass

WIMP MASS
50 - 100 GeV

Nov. 23 2004 Seminar Saclay, W. de Boer, Univ. Karlsruhe
Optimized Model from Strong et al. astro-ph/0406254
Change spectral shape of electrons AND protons

Conclusion: data above 0.5 GeV still much better with DM after fitting norm. (Prob. without DM < 10^{-14} ⇒ instead of >10σ one obtains 8σ improvement)
Background scaling factor = Data between 0.1 and 0.5 GeV/GALPROP

GALPROP = computer code simulating our galaxy (Moskalenko, Strong)
Fit results of halo parameters

**DM Gamma Ray Flux: ($\langle \sigma v \rangle$ from WMAP)**

$$\phi_x(E, \psi) = \frac{1}{4\pi} \sum_f \frac{dN_f}{dE} b_f \int_{\text{line of sight}} \frac{B_1}{2} \frac{1}{M_x^2} \frac{\rho^2}{\beta} \, dl_q$$

$$\rho_x(r) = \rho_0 \left( \frac{R_0}{r} \right)^\gamma \left[ \frac{1 + \left( \frac{r}{a} \right) \alpha}{1 + \left( \frac{R_0}{a} \right) \alpha} \right]^{\gamma - \frac{2}{\alpha}} + \sum_{n=1}^{N=2} \rho_n \exp \left( -\frac{(r_{gc} - Rn)^2}{2\sigma_{Rn}^2} - \frac{(z_n)^2}{2\sigma_{zn}^2} \right)$$

Enhancement of rings over $1/r^2$ profile 2 and 7, respectively. Mass in rings 1.3 and 0.3% of total DM.

- **Boost factor** $\approx 50-70$ Dokuchaev et al:
  - $10 < B < 100$, IDM2004

14 kpc coincides with ring of stars at 14-18 kpc due to infall of dwarf galaxy (Yanny, Ibata, ...).

4 kpc coincides with ring of neutral hydrogen molecules!

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>2</td>
<td>$R_0$</td>
<td>4.3 kpc</td>
</tr>
<tr>
<td>$\beta$</td>
<td>2</td>
<td>$\sigma_R, a$</td>
<td>3.4 kpc</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>0</td>
<td>$\sigma_{z,a}$</td>
<td>0.3 kpc</td>
</tr>
<tr>
<td>$R_0$</td>
<td>8.5 kpc</td>
<td>$\rho_b$</td>
<td>1.2-2.1 GeV cm$^{-3}$</td>
</tr>
<tr>
<td>$a$</td>
<td>4 kpc</td>
<td>$R_b$</td>
<td>14 kpc</td>
</tr>
<tr>
<td>$\rho_0$</td>
<td>0.42 GeV cm$^{-3}$</td>
<td>$\sigma_{R,b}$</td>
<td>2.1 kpc</td>
</tr>
<tr>
<td>$\rho_a$</td>
<td>1.8-3.3 GeV cm$^{-3}$</td>
<td>$\sigma_{z,b}$</td>
<td>1.3 kpc</td>
</tr>
<tr>
<td>$b/a$</td>
<td>0.9</td>
<td>$c/a$</td>
<td>0.8</td>
</tr>
</tbody>
</table>
Longitude and Latitude for Gammas BELOW 0.5 GeV

In the plane (± 5° in lat.)

Out of the plane (± 30° in long.)
Longitude and Latitude for Gammas ABOVE 0.5 GeV

Longitude: azimuthal angle
Latitude: angle out of the plane
Longitude fits for $1/r^2$ profile with/w.o. rings

**WITH 2 rings**

DISC

10°<b<20°

5°<b<10°

20°<b<90°

**WITHOUT rings**

DISC

E = 0.5 GeV
17° < Lat < 5°

10°<b<20°

5°<b<10°

20°<b<90°

Halo parameters from fit to 180 sky directions: 4 long. profiles for latitudes <5°, 5°<b<10°, 10°<b<20°, 20°<b<90° (=4x45=180 directions)

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Rotation curve shows there is a ring of CDM with a mass of $(4-8) \times 10^{10} \, M_\odot$. Not enough baryons in outer ring to explain mass (only $10^9 \, M_\odot$ in stars)!
Normalization of DMA -> “Boost factor” (= enhancement of DMA by clustering of DM)
**Clustering of DM -> boosts annih. rate**

Annihilation $\propto$ DM density squared!

- **Clumps in N-body simulations with kpc resolution**
- **Clumps in analyt. calculations with pc resolution**

Veniamin Berezinsky  
Laboratori Nazionali del Gran Sasso INFN, Italy  
Vyacheslav Dokuchaev & Yury Eroshenko  
Institute for Nuclear Research of the Russian Academy of Sciences  
Moscow, Russia

Clustersize: $10^{14}$ cm = 10x solar system  
$M_{\text{min}} \approx 10^{-8} M_\odot$  
Cluster density $\approx 25$ pc$^{-3}$  
Halo mass fraction in clumps: 0.002

Clumps with $M_{\text{min}}$ give the dominant contribution to DM annihilation -> many in a given direction -> similar boost factor in all directions

Boost factor $\sim \langle \rho^2 \rangle / \langle \rho \rangle^2 \sim 10-100$, i.e. effective annihilation cross section is 20-200 $10^{-26}$ cm$^3$ s$^{-1}$
Galactic Parameters

Further parameters:
- $R_{200} = 295$ kpc
- DM: $3 \times 10^{12}$ Mo
- Baryonic: $6 \times 10^{10}$ Mo

Mass of outer (inner) ring
$\approx 1.3 \ (0.3)\%$ of total DM.
Only so important, while nearby!!!!!!!
More on Halo Profiles
Halo profiles

**Isothermal cored profile**

Without rings

With rings

**NFW cuspy profile**

(Universal profile from Navarro, Frenk, White)

Without rings

With rings

\[ \alpha, \beta, \gamma = 2, 2, 0 \]

\[ \alpha, \beta, \gamma = 1, 3, 1 \]
Tidal disruption of DM clumps in centre by flyby of stars

Tidal force:

\[ F_t = 2 \frac{GM M_x}{R^3} R_x, \]

Movement under tidal force:

\[ \Delta x = \frac{F_t}{M_x} \frac{(\Delta t)^2}{2} \]

Tidal heating:

\[ \Delta E = F_t \Delta x = 2 \frac{G^2 M^2 M_x R_x^2}{R^4 V^2}. \]

If tidal heating stronger than binding

Energy: DISRUPTION OF CLUMP

Reduction of boost factor in centre!

NFW profile allowed with B=1!

Dokuchaev et al., to be publ.
EGRET data compatible with prolate isothermal halo profile with $b/a \approx 0.9$, $c/a \approx 0.8$

Angular momentum along short axis c as expected from N-body simulations (Bailin, Steinmetz, astro-ph/0408163)

W. de Boer et al., astro-ph/0408272
Fit with outer ring only in observable star region

0.1 < $E_\gamma$ < 0.5 GeV

$E_\gamma$ > 0.5 GeV

Stars only observed in galactic anticentre

EGRET data requires complete ring of DM, not only in region where stars observed
Future Experiments
SAME Halo and WIMP parameters as for GAMMA RAYS but fluxes dependent on propagation! DMA can be used to tune models: at present no convection, nor anisotropic diffusion in spiral arms.
Dark Matter Searches with AMS-02

AMS: Alpha Magnetic Spectrometer

Large acceptance detector (0.8 m²sr) with excellent particle identification by Silicon Tracker in SC magnet, RICH, TRD, TOF, EM Calorimeter
Expected statistics after one year of AMS-02 operations

**Gamma rays**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boostfaktor</td>
<td>1.1</td>
</tr>
<tr>
<td>$\chi^2$ EGRET</td>
<td>7.3/6</td>
</tr>
<tr>
<td>$\chi^2$ (bg only)</td>
<td>34.5/7</td>
</tr>
</tbody>
</table>

**Antiprotons**

- $\chi^2$ BESS: 6.5/12
- $\chi^2$ (bg only): 27.4/13

**Positrons**

- Boostfaktor: 1.5
- $\chi^2$ HEAT: 20/17
- $\chi^2$ (bg only): 59.4/18
AMS-02 capabilities

Beryllium

- B is secondary produced in nuclear interaction, C is primary produced in stars. B/C is sensitive to the diffusion constant.

- $^{10}\text{Be} \left( t_{1/2} = 1.5\text{Myr} \right) / \text{Be}$ will allow to estimate the propagation time and size of the ISM.

Boron

- $^3\text{He}/^4\text{He}$ ratio is sensitive to the density of the ISM.

Helium

- $^3\text{He}/^4\text{He}$ ratio is sensitive to the density of the ISM.
### LHC Chargino/Neutralino associated production \( \times \)-sections

<table>
<thead>
<tr>
<th>Process</th>
<th>( \chi\chi )</th>
<th>( \chi+\chi- )</th>
<th>( \chi+\chi^0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f + f\bar{f} \to \chi_1 + \chi_1 )</td>
<td>10000</td>
<td>2977</td>
<td>5521</td>
</tr>
<tr>
<td>( f + f\bar{f} \to \chi_{\pm 2} + \chi_{\pm 2} )</td>
<td>136</td>
<td>138</td>
<td>138</td>
</tr>
<tr>
<td>( f + f\bar{f} \to \chi_{1} + \chi_{1} )</td>
<td>70</td>
<td>57</td>
<td>57</td>
</tr>
<tr>
<td>( q + q\bar{q} \to \chi_{1} + \chi_{\pm 1} )</td>
<td>470</td>
<td>141</td>
<td>224</td>
</tr>
<tr>
<td>( q + q\bar{q} \to \chi_{3} + \chi_{1} )</td>
<td>138</td>
<td>753</td>
<td>1381</td>
</tr>
</tbody>
</table>

**Pythia:**

- Total \( \chi\chi \) \( \times \)-section: 11 pb.
- \( \chi+\chi- \): 2l, 3pb
- \( \chi+\chi^0 \): 3l, 6pb

**Calculated with Pythia (Isasugra) (Martin Niegel)**

**Parameters:**
- \( m_{\chi/2} \) = 175.00000
- \( sign(m_\mu) \) = 1.00000
- \( \tan(bet) \) = 51.00000
- \( m_0 \) = 1400.00000
- \( A_0 \) = 0.00000

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Comparison with direct DM Searches

Spin-independent

Spin-dependent

Predictions from EGRET data assuming Supersymmetry
Physics Questions

- **Astrophysicists:**
  What is the origin of “GeV excess” of diffuse Galactic Gamma Rays?

- **Astronomers:**
  Why a change of slope in the galactic rotation curve above $R_0=8.5$ kpc?
  Why ring of stars at 14 kpc so stable?
  Why ring of molecular hydrogen at 4 kpc so stable?

- **Cosmologists:**
  How is Cold Dark Matter distributed?

- **Particle physicists:**
  Where are the Supersymmetric Particles?
Answers

1. DM made of WIMPS annihilating into quarks, which yield hard gammas from $\pi_0$ decays

2. Annihilation cross section is given by the HUBBLE constant!

   Gamma excess shows substructure:

3. a ring of DM at 14-18 kpc coinciding with ring of stars thought to originate from infall of a dwarf galaxy

4. and ring of DM at 4 kpc correlated with molecular $H_2$

5. From ENERGY SPECTRUM of excess of gamma rays DM: WIMP mass 50-100 GeV

6. From INTENSITY: halo distribution and rotation curve

7. WIMP has properties of the lightest supersymmetric particle

Conventional models based on “local bubbles” cannot explain the stability of the ring of stars at 14 kpc nor the shape of the rotation curve nor the good agreement for all the answers SIMULTANEOUSLY!
EGRET galactic gamma ray data provides an intriguing hint that:
- since statistical significance of excess more than 10σ
and since the WIMP has all properties expected from SUSY -

DM may be the Supersymmetric Partner of the CMB

This conclusion only depends on the SHAPE of the diffuse gamma ray background, not its absolute normalization!

LHC experiments will tell in 2008 if this picture is true