Excess of EGRET Diffuse Galactic Gamma Rays interpreted as a Signal of Dark Matter 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 distribution from sky map

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

Thermal equilibrium abundance

Actual abundance

Boltzmann equation:

\[ \frac{dn_\chi}{dt} + 3Hn_\chi = - <\sigma v> (n_\chi^2 - n_{\chi eq}^2) \]

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 \( \cong \) expansion rate, i.e. \( \Gamma = <\sigma v> n_\chi \cong H \))

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

Present number density (\( \Omega h^2 = 0.113 \pm 0.009 \)) requires \( <\sigma v> = 2.10^{-26} \text{ cm}^3/\text{s} \)
DM annihilation in Supersymmetry

Dominant diagram for WMAP cross section:
\( \chi + \chi \Rightarrow A \Rightarrow b \bar{b} \) 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 ($\mu > 0, A_0 = 0$)

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

LSP largely Bino \(\Rightarrow\) DM may be supersymmetric partner of CMB

Charginos, neutralinos and gluinos light

<table>
<thead>
<tr>
<th>(\tilde{\chi}_i^0)</th>
<th>(\tilde{\nu}_L^0)</th>
<th>(\tilde{\nu}_R^0)</th>
<th>(\tilde{\chi}_2^0)</th>
<th>(\tilde{\chi}_3^0)</th>
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<tr>
<td>(\tilde{\chi}_1^0)</td>
<td>0.833</td>
<td>0.026</td>
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<td>(\tilde{\chi}_2^0)</td>
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<td>0.621</td>
<td>0.187</td>
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<td>(\tilde{\chi}_3^0)</td>
<td>0.014</td>
<td>0.030</td>
<td>0.442</td>
<td>0.515</td>
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<tr>
<td>(\tilde{\chi}_4^0)</td>
<td>0.033</td>
<td>0.323</td>
<td>0.249</td>
<td>0.395</td>
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</table>
Unification of gauge couplings

Update from Amaldi, dB, Fürstenau, PLB 260 1991

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 $N_\nu = 3.0$! (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 $O(1 \text{ TeV})$.
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→π⁰+x→γγ+x, eγ→eγ, eN→eγN, 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 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.
EGRET DATA on diffuse Gamma Rays
EGRET on CGRO (Compton Gamma Ray Observ.)

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

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 $6 \times 10^{-8} \text{ cm}^2 \text{s}^{-1}$ for $E > 100 \text{ MeV}$ 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:

\[ \phi_x(E, \psi) = \frac{\langle \sigma v \rangle}{4\pi} \sum_f \int dE \frac{dN_f}{dE} b_f \int \text{line of sight} B_l \frac{1}{2} \frac{\langle \rho_x^2 \rangle}{M^2_x} dl \]

Similar expressions for:

- \( pp \rightarrow \pi^0 + x \rightarrow \gamma + x \), (\( \rho \) 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 \( \cong 7\% \) (yields 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!
Uncertainties in background and signal shapes

Blue: uncertainty from background shape

Blue: uncertainty from WIMP mass

RED = flux from DM Annihilation
Yellow = backgr.
Blue = BG uncert.

WIMP MASS
50 - 100 GeV

December 7, 2004 Seminar CERN, W. de Boer, Univ. Karlsruhe
Local electron and proton spectra determine shape of gamma background

No SM

Electrons

Quarks in protons

Quarks from WIMPS

- HEAT94
- CAPRICE94
- Kobayashi99
- AMS01
- GalProp (IS)
- GalProp (SM)

Φ_e * E^2 [cm^{-2} GeV^{-1} s^{-1}sr^{-1}]

Φ_e * E^2 [cm^{-2} GeV^{-1} s^{-1}sr^{-1}]

BESS00

GalProp (IS)

GalProp (SM)

Φ = 550 MeV

Φ = 600 MeV
Background uncertainties


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

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

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

$E \propto E^{-n}$

$n = 2.5$

$2.7$

$n = 3.0$

Energy loss times of electrons and nuclei

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

Protons diffuse for long times without losing energy!

If the center would have a harder spectrum, then it would be hard to explain why the excess in the outer galaxy has the same shape (can be fitted with the same WIMP mass!)

December 7, 2004
Seminar CERN, W. de Boer, Univ. Karlsruhe
Optimized Model from Strong et al. astro-ph/0406254
Change spectral shape of electrons AND protons
Optimized Model from Strong et al. astro-ph/0406254
Change spectral shape of electrons AND protons
Optimized Model from Strong et al. astro-ph/0406254
Change spectral shape of electrons AND protons

In this sense it WILL go a long way towards realizing a model reproducing astronomical and directly-measured data on cosmic rays in the context of a single model of the high-energy Galaxy WITHOUT DM.
I believe it is impossible!

### Table 3. Comparison of models using $\chi^2$ for full sky.

<table>
<thead>
<tr>
<th>Energy range MeV</th>
<th>44.500180 conventional</th>
<th>44.500181 hard electron</th>
<th>44.500190 optimized</th>
<th>Number of data points</th>
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<td>30–50</td>
<td>90</td>
<td>38</td>
<td>34</td>
<td>78</td>
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<td>50–70</td>
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<tr>
<td>70–100</td>
<td>18</td>
<td>49</td>
<td>30</td>
<td>78</td>
</tr>
<tr>
<td>100–150</td>
<td>38</td>
<td>89</td>
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<td>500–1000</td>
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<td>1000–2000</td>
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<td>20000–50000</td>
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<td>7</td>
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<tr>
<td>30–500000</td>
<td>1528</td>
<td>974</td>
<td>462</td>
<td>796</td>
</tr>
</tbody>
</table>

Probability of optimized model if $\chi^2$ measured in 360 sky directions and integrate data with $E>0.5$ GeV:

- $\chi^2 = 962.3/324$ for Optimized Model without DM +correl. errors: Prob = $< 10^{-14}$
- $\chi^2 = 306.5/324$ for Optimized Model +DM +correl. errors: Prob = 0.736

Boostfactor=25 for OM vs 70 for CM
Expected Profile

Observed Profile

Halo profile

Rot. Velocity [Km/s]

Rotation Curve

- CO
- total
- dm
- HI
- luminous disk
- halo
- HII, HII
- bulge
- inner ring
- outer ring

v_2 \propto \frac{M}{r} = \text{const.}

\rho \propto \frac{1}{r^2}

\rho \propto \frac{1}{r}

Divergent for r=0?

NFW

Isotherm const.

Observed Profile

2003, Ibata et al, Yanny et al.
Longitude fits for 1/r^2 profile with/w.o. rings

WITH 2 rings

DISC

50 < b < 100

E = 0.5 GeV

100 < b < 200

E = 0.5 GeV

200 < b < 900

E = 0.5 GeV

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)
Fit results of halo parameters

\[ \phi_X(E, \psi) = \frac{\langle \sigma v \rangle}{4\pi} \sum_f \frac{dN_f}{dE} b_f \int_{\text{line of sight}} B_t \frac{1}{2} \frac{\rho_X^2}{M_X^2} d\phi \]

\[ \rho_X(\vec{r}) = \rho_0 \left( \frac{R_0}{\vec{r}} \right)^\gamma \left[ 1 + \left( \frac{\vec{r}}{a} \right)^\alpha \right]^{\frac{\gamma-\beta}{\alpha}} + \sum_{n=1}^{N=2} \rho_n \exp \left( -\frac{(\vec{r}_n - R_n)^2}{2\sigma_{R_n}^2} \right) - \frac{(z_n)^2}{2\sigma_{z_n}^2} \]

\[ \propto \frac{1}{r^2} \]

2 Gaussian rings

Enhancement of rings over \( \frac{1}{r^2} \)

profile 2 and 7, respectively.

Mass in rings 1.3 and 0.3% of total DM

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!

Boostfactor \( \approx 50-70 \) Dokuchaev et al: 10\(<B<100, \ \text{IDM2004} \)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
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</thead>
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<tr>
<td>( \alpha )</td>
<td>2</td>
<td>( \sigma_{R,a} )</td>
<td>3.4 kpc</td>
</tr>
<tr>
<td>( \beta )</td>
<td>2</td>
<td>( \sigma_{z,a} )</td>
<td>0.3 kpc</td>
</tr>
<tr>
<td>( \gamma )</td>
<td>0</td>
<td>( \rho_b )</td>
<td>1.2-2.1 GeV cm(^{-3} )</td>
</tr>
<tr>
<td>( R_0 )</td>
<td>8.5 kpc</td>
<td>( R_b )</td>
<td>14 kpc</td>
</tr>
<tr>
<td>( a )</td>
<td>4 kpc</td>
<td>( \sigma_{R,b} )</td>
<td>2.1 kpc</td>
</tr>
<tr>
<td>( \rho_0 )</td>
<td>0.42 GeV cm(^{-3} )</td>
<td>( \sigma_{z,b} )</td>
<td>1.3 kpc</td>
</tr>
<tr>
<td>( \rho_a )</td>
<td>1.8-3.3 GeV cm(^{-3} )</td>
<td>( c/a )</td>
<td>0.8</td>
</tr>
<tr>
<td>( b/a )</td>
<td>0.9</td>
<td></td>
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</tr>
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</table>
Do other galaxies have bumps in rotation curves?

Sofue & Honma
Normalization of background:

Compare with GALPROP, which gives absolute prediction of background from gas distributions etc.
Background scaling factors

Background scaling factor = Data between 0.1 and 0.5 GeV/GALPROP
GALPROP = computer code simulating our galaxy (Moskalenko, Strong)
Normalization of DMA -> "Boost factor" (= enhancement of DMA by clustering of DM)
Clustering of DM -> boosts annihilation rate

Annihilation \propto DM density squared!

Clumps in N-body simulations with kpc resolution

Clumps in analyt. calculations with pc resolution

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$^{-1}$

Fitted boost factor: 20-70 (depending on background)

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
What do we have?

DMA describes all sky directions with single WIMP mass and WIMP annihilation into mono energetic quarks

DM distributed as $1/r^2$ profile with substructure at positions with enhanced gravitational potential

Rotation curve can be reconstructed from GAMMA Rays! (First time real explanation for change of slope in outer RC)

What is the problem?

Many aspects from different fields $\rightarrow$ hard to judge all aspects simultaneously.
Objections from astrophysicists

Astrophysicists: cannot believe collisionless DM, i.e. particles which experience only gravity, is self-annihilating and that particle physicists even believe to know spectral shapes of final states! They prefer their “local bubbles”.

Answer:

too bad, but their “local bubbles” or “optimized models” do not work if they learn what covariance matrices are.
Objections from particle physicists

Particle physicists:
you assume spectrum of protons to be the same everywhere in galaxy. How can you be sure?

Answers:
1) If centre of galaxy would be different because of SN there, no reason to get same shape of excess in outer galaxy (very few SN)

2) Energy loss times > age of universe, very hard to image strong changes in spectral shape if protons diffuse from centre to us in $\approx 10^8$ yr
Objections from astronomers

Astronomers: outer rotation curve determined with different method than inner rotation curve. Hard to compare. Furthermore slope depends on distance to centre ($R_0$).

Sofue & Honma

Inner rotation curve

Outer rotation curve

$R_0=8.3$ kpc

$R_0=7.0$

Answer: First points of outer rot. curve in perfect agreement with inner rot. curve. CHANGE in slope for any $R_0$

Black hole at centre:

$R_0=8.0 \pm 0.4$ kpc
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.
Future Experiments

SPACE Experiments:

Pamela (2005) $\Rightarrow$ antiprotons, positrons
GLAST (2007) $\Rightarrow$ gammas (higher energies)
AMS (2008) $\Rightarrow$ all nuclei, gammas, positrons, antiprotons

Accelerators:

LHC $\Rightarrow$ all SUSY particles?
ILC(500) $\Rightarrow$ Charginos, top, Higgs

Direct DM searches:

CDMS (taking data), Edelweiss, Cresst, ZEPLIN, Genius, ..
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 $R_0=8.3$ 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:
  Is DM annihilating as expected in Supersymmetry?
1. DM made of WIMPS annihilating into quarks, which yield hard gammas from $\pi_0$ decays

2. Annihilation cross section consistent with WMAP and HUBBLE constant!
   
   Gamma excess shows substructure:
3. a ring (doughnut) of DM at 14 kpc coinciding with ring of stars thought to originate from the infall of a dwarf galaxy
4. and ring of DM at 4 kpc correlated with molecular $H_2$

5. From the ENERGY SPECTRUM of the excess of gamma rays DM: WIMP mass 50-100 GeV (same WIMP mass from ALL sky directions!)

6. From INTENSITY: halo distribution ($1/r^2+$substructure) $\Rightarrow$ 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!