EGRET excess of diffuse Galactic Gamma Rays interpreted as Dark Matter Annihilation

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Outline (see astro-ph/0408272)

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

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

• Halo distribution from sky map

• Data consistent with Supersymmetry
DM annihilation in Supersymmetry

Dominant diagram for WMAP cross section in MSSM:
\( \chi + \chi \rightarrow A \rightarrow b \bar{b} \) quark pair

Galaxy = SUPER-B-factory with luminosity some 40 orders of magnitude above man-made B-factories

B-fragmentation well studied at LEP!
Yield and spectra of positrons, gammas and antiprotons well known!
Basics from cosmology:
Hubble const. determines WIMP annihilation x-section

- Thermal equilibrium abundance
- Actual abundance

\[ T >> M: \ f + \bar{f} \rightarrow M + \bar{M}; \ M + \bar{M} \rightarrow f + \bar{f} \]
\[ T < M: \ M + \bar{M} \rightarrow f + \bar{f} \]
\[ T = M/22: \ M \text{ decoupled, stable density} \]

(wenn annihilation rate \( \sim \) expansion rate, i.e. \( \Gamma = <\sigma v> n_\chi(x_{fr}) \approx H(x_{fr}) ! \))

More precisely by solving Boltzmann eq:

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

\[ H \text{-Term takes care of decrease in density by expansion. Right-hand side: annihilation and production.} \]

\[ \Omega h^2 = m_\chi n_\chi/\rho_c \approx 2.10^{-27} \text{ [cm}^3/\text{s}]/<\sigma v> \]

(<\sigma v> independent of \( m_\chi \))

Present WMAP \( \Omega h^2 = 0.113 \pm 0.009 \) requires \( <\sigma v> \approx 2.10^{-26} \text{ cm}^3/\text{s} \)

DM density increases locally after galaxy formation.
In this room: \( \approx 1 \) WIMP/coffee cup \( \approx 10^5 \) averaged density.
Basics of background and signal shapes

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

Blue: uncertainty from background shape

Blue: uncertainty from WIMP mass

WIMP MASS
50 - 100 GeV

65
100
Basics of background and signal shapes

**Electrons**

- HEAT94
- CAPRICE94
- Kobayashi99
- AMS01
- Galactic Propagation (IS)
- Galactic Propagation (SM)

**Quarks from WIMPS**

- BESS00
  - Galactic Propagation (IS)
  - Galactic Propagation (SM)
  - $\Phi = 550$ MeV

**Quarks in protons**

- HEAT94
- CAPRICE94
- Kobayashi99
- AMS01
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!)
EGRET on CGRO (Compton Gamma Ray Observ.)

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 $6 \times 10^{-3}$ 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)

9 yrs of data taken (1991-2000)

Main purpose: sky map of point sources above diffuse BG.
Basics of astro-particle physics

Gamma Ray Flux from WIMP annihilation in given direction $\psi$:

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

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 $\approx 7%$ (yields good $\chi^2$).
Executive Summary for fits in 360 sky directions

Expected Profile

Observed Profile

Halo profile

Rotation Curve

- CO
- total
- disk
- 1/r² halo
- luminous disk
- halo
- HI
- HII
- bulge
- inner ring
- outer ring

Observed Profile

Expected Profile

Halo profile

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March. 7, 2005
Moriond Electroweak, 2005, W. de Boer, Univ. Karlsruhe
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°)

March. 7, 2005
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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!
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

Nucleon and electron spectra tuned to fit gamma ray data.

Apart from the difficulty to have inhomogeneous nuclei spectra (SMALL energy losses!) the model does NOT describe the spectrum IN ALL DIRECTIONS!
Optimized Model from Strong et al. astro-ph/0406254
Change spectral shape of electrons AND protons

100 MeV

150 MeV

300 MeV

500 MeV

1000 MeV

2000 MeV
Optimized Model from Strong et al. astro-ph/0406254

Change spectral shape of electrons AND protons

<table>
<thead>
<tr>
<th>Energy range MeV</th>
<th>44_500180 conventional</th>
<th>44_500181 hard electron</th>
<th>44_500190 optimized</th>
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<td>70–100</td>
<td>18</td>
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<td>20000–50000</td>
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<td>35</td>
<td>4</td>
<td>7</td>
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<tr>
<td>30–50000</td>
<td>1528</td>
<td>974</td>
<td>462</td>
<td>796</td>
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</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^{-10}$

$\chi^2 = 306.5/323$ for Optimized Model +DM +correl. errors: Prob = 0.736

Boostfactor=25 for OM vs 70 for CM

tic plane and at energies below 100 MeV. The model reproduces simultaneously the $\gamma$-rays, synchrotron, CR secondary/primary ratios, antiprotons and positrons. In this sense it goes a long way towards realizing our original goal, stated in Strong et al. (2000), to reproduce astrophysical and directly-measured data on cosmic rays in the context of a single model of the high-energy Galaxy.
Determining halo profile

DM Gamma Ray Flux:

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

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

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

2 Gaussian ovals

$$\tilde{r} = \sqrt{\frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2}}, \quad \tilde{r}_{gc} = \sqrt{\frac{x^2}{\tilde{a}^2} + \frac{y^2}{\tilde{b}^2}}$$
### Fit results of halo parameters

#### Parameter values: ($<\sigma v>$ from WMAP)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
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</thead>
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<td>$\alpha$</td>
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</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>

**Boostfactor $\cong 20-200$**

**Dokuchaev et al: 10<B<200, IDM2004**

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- Enhancement of rings over $1/r^2$ profile 2 and 7, respectively.
- Mass in rings 1.6 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!
Halo density on scale of 300 kpc

Cored isothermal profile with scale 4 kpc
Total mass: $3 \times 10^{12}$ solar masses
Halo density on scale of 30 kpc
Longitude fits for $1/r^2$ profile with/w.o. rings

**WITHOUT rings**

$E > 0.5$ GeV

**WITH 2 rings**

Halo parameters from fit to 180 sky directions: 4 long. profiles for latitudes $<5^\circ$, $5^\circ<b<10^\circ$, $10^\circ<b<20^\circ$, $20^\circ<b<90^\circ$ (=4x45=180 directions)
Longitude on linear scale

Below 0.5 GeV

$\chi^2$: 0/0
$\chi^2$ (bg only): 0.9/0
$E < 0.5\,\text{GeV}$
$0' < |\text{lat}| < 2.5'$

Above 0.5 GeV

$\chi^2$: 28.3/38
$\chi^2$ (bg only): 475.9/39
$E > 0.5\,\text{GeV}$
$0' < |\text{lat}| < 2.5'$

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Do other galaxies have bumps in rotation curves?
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 $\rightarrow$ "Boost factor" (= enhancement of DMA by clustering of DM)
Clustering of DM $\rightarrow$ boosts annih. rate

Annihilation $\propto$ DM density squared!

Clustersize: $10^{14}$ cm = 10x solar system

$M_{\text{min}} \approx 10^{-8} - 10^{-6}$ $M_{\odot}$

Cluster density $\approx 25$ pc$^{-3}$

Halo mass fraction in clumps: 0.002

From Berezinsky, Dokuchaev, Eroshenko

Boost factor $\sim \langle \rho^2 \rangle / \langle \rho \rangle^2 \sim 20$-$200$

Clumps with $M_{\text{min}}$ give the dominant contribution to DM annihilation $\rightarrow$

many in a given direction $\rightarrow$

similar boost factor in all directions
What about Supersymmetry?

Assume mSUGRA

5 parameters: $m_0$, $m_{1/2}$, $\tan b$, $A$, sign $\mu$
Annihilation cross sections in $m_0 - m_{1/2}$ plane ($\mu > 0$, $A_0 = 0$)

For WMAP $\sigma v \approx 2 \times 10^{-26}$ cm$^3$/s one needs large $\tan \beta$
Coannihilations vs selfannihilation of DM

If it happens that other SUSY particles are around at the freeze-out time, they may coannihilate with DM. E.g. Stau + Neutralino $\rightarrow$ tau
Chargino + Neutralino $\rightarrow$ W

However, this requires extreme fine tuning of masses, since number density drops exponentially with mass.

But more serious: coannihilation will cause excessive boost factors.
Since $\sigma_{anni} = \sigma_{coanni} + \sigma_{selfanni}$ must yield $\langle \sigma v \rangle = 10^{26}$ cm$^3$/s.
This means if coannihilation dominates, selfannihilation $\approx 0$.
In present universe only selfannihilation can happen, since only lightest neutralino stable, other SUSY particles decayed, so no coannihilation.
If selfannihilation $\times$-section 0, no indirect detection.
CONCLUSION: EGRET data excludes largely coannih.
EGRET excess interpreted as DM consistent with WMAP, Supergravity and electroweak constraints

MSUGRA can fulfill all constraints from WMAP, LEP, $b\to s\gamma$, $g-2$ and EGRET simultaneously, if DM is neutralino with mass in range 50-100 GeV and squarks and sleptons are $O(1 \text{ TeV})$.
SUSY Mass spectra in mSUGRA compatible with WMAP AND EGRET

<table>
<thead>
<tr>
<th>( \tilde{b}^0 )</th>
<th>( \tilde{t}^0 )</th>
<th>( \tilde{h}_1^0 )</th>
<th>( \tilde{h}_2^0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tilde{\chi}_1^0 )</td>
<td>0.833</td>
<td>0.026</td>
<td>0.122</td>
</tr>
<tr>
<td>( \tilde{\chi}_2^0 )</td>
<td>0.119</td>
<td>0.621</td>
<td>0.187</td>
</tr>
<tr>
<td>( \tilde{\chi}_3^0 )</td>
<td>0.014</td>
<td>0.030</td>
<td>0.442</td>
</tr>
<tr>
<td>( \tilde{\chi}_4^0 )</td>
<td>0.033</td>
<td>0.323</td>
<td>0.249</td>
</tr>
</tbody>
</table>

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

Charginos, neutralinos and gluinos light
Unification of gauge couplings

With SUSY spectrum from EGRET data and start values of couplings from final LEP data perfect gauge coupling unification possible.
Comparison with direct DM Searches

Spin-independent

Spin-dependent

Predictions from EGRET data assuming Supersymmetry
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.
Summary

EGRET excess shows all key features from DM annihilation:

Excess has same shape in all sky directions: everywhere it is perfectly (only?) explainable with superposition of background AND mono-energetic quarks of 50-100 GeV

Results and x-sect. in agreement with SUPERSYMMETRY

Excess follows expectations from galaxy formation:
1/r² profile with substructure,
visible matter/DM ≈ 0.02

Excess connected to MASS, since it can explain peculiar shape of rotation curve

These combined features provide FIRST (> 10σ) EVIDENCE that DM is not so dark and follow ALL DMA expectations imagined so far.

Conventional models CANNOT explain above points SIMULTANEOUSLY, especially spectrum of gamma rays in all directions, DM density profile, shape of rotation curve, stability of ring of stars at 14 kpc,..