The dark connection between Canis Major, Monoceros Stream, gas flaring, the rotation curve and the EGRET excess

From EGRET excess of diffuse Galactic gamma rays
- Determination of WIMP mass
- Determination of WIMP halo (= standard halo + DM ring)

Confirmation:
- Rotation curve
- Canis Major/Monoceros stream
- Gas flaring

PREDICTIONS
- for LHC (if SUSY)
- for direct searches
- for solar neutrinos

Ingredients to this analysis

Rotation curve
Gas flaring
Tidal streams

Astronomers

Cosmics
Gamma rays

Astrophysics

23%DM, thermal history of WIMPs
Annihilation cross section
Tidal disruption of dwarfs

Cosmology

Particle Physics

Gamma ray spectra for BG + DMA

Gamma ray spectra for BG + DMA

Particle Physics
What is known about Dark Matter?

- 95% of the energy of the Universe is non-baryonic
  23% in the form of Cold Dark Matter

- Dark Matter enhanced in Galaxies and Clusters of Galaxies but DM widely distributed in halo -> DM must consist of weakly interacting and massive particles -> WIMP's

- Annihilation with $\langle \sigma v \rangle = 2 \times 10^{-26} \text{ cm}^3/\text{s}$, if thermal relic
Expansion rate of universe determines WIMP annihilation cross section

Thermal equilibrium abundance

Actual abundance

Expansion rate of universe determines WIMP annihilation cross section

\[ T >> M: \quad f + \bar{f} \rightarrow M + \bar{M}; \quad M + \bar{M} \rightarrow f + \bar{f} \]

\[ T < M: \quad M + \bar{M} \rightarrow f + \bar{f} \]

\[ T = M/22: \quad M \text{ decoupled, stable density} \]

(\text{wenn Annihilationrate} \cong \text{Expansions-rate}, \ i.e. \ \Gamma = \langle \sigma v \rangle n_\chi(x_{fr}) \cong H(x_{fr}) !)

\[ \Omega h^2 = 0.113 \pm 0.009 \rightarrow \langle \sigma v \rangle = 2.10^{-26} \text{ cm}^3/\text{s} \]

DM increases in Galaxies:

\[ \approx 1 \text{ WIMP/coffee cup} \approx 10^5 \langle \rho \rangle. \]

DMA (\propto \rho^2) restarts again.

Annihilation into lighter particles, like quarks and leptons -> \( \pi_0 \)'s -> Gammas!

Only assumption in this analysis:

WIMP = THERMAL RELIC!
Example of DM annihilation (SUSY)

**Dominant**
\[ \chi + \chi \Rightarrow A \Rightarrow b \ b \bar{b} \text{ quark pair} \]

Sum of diagrams should yield
\[ \langle \sigma v \rangle = 2.10^{-26} \text{ cm}^3/\text{s} \] to get correct relic density

Quark fragmentation known!
Hence spectra of positrons, gammas and antiprotons known!
Relative amount of \( \gamma, p, e^+ \) known as well.

\[ \approx 37 \text{ gammas} \]
Conclusion so far

IF DM particles are thermal relics from early universe they can annihilate with cross section as large as 
\[ \langle \sigma v \rangle = 2 \times 10^{-26} \text{ cm}^3/\text{s} \]
which implies an enormous rate of gamma rays from \( \pi_0 \) decays (produced in quark fragmentation) 
(Galaxy=10^{40} higher rate than any accelerator)

Expect significant fraction of energetic Galactic gamma rays to come from DMA in this case.
Remaining ones from \( p_{CR} + p_{GAS} \rightarrow \pi_0 + X, \pi_0 \rightarrow 2\gamma \) 
(+some IC+brems)
This means: Galactic gamma rays have 2 components with a shape KNOWN from the 2 BEST studied reactions in accelerators: background known from fixed target exp. DMA known from e+e- annihilation (LEP)
Basic principle for indirect dark matter searches

From rotation curve:

Forces: \( mv^2/r = GmM/r^2 \)
or \( M/r = \text{const. for } v=\text{cons.} \)
and
\( \rho \propto (M/r)/r^2 \)
\( \rho \propto 1/r^2 \)
for flat rotation curve

Expect highest DM density
IN CENTRE OF GALAXY

Divergent for \( r=0? \)
NFW profile \( \propto 1/r \)
Isotherm profile const.

IF FLUX AND SHAPE MEASURED IN ONE DIRECTION, THEN FLUX AND SHAPE FIXED IN ALL (=180) SKY DIRECTIONS!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

THIS IS AN INCREDIBLE CONSTRAINT, LIKE SAYING I VERIFY THE EXCESS AND WIMP MASS WITH 180 INDEPENDENT MEAS.
Instrumental parameters:

- Energy range: 0.02–30 GeV
- Energy resolution: ~20%
- Effective area: 1500 cm$^2$
- Angular resol.: <0.5°


Main results:
- Catalogue of point sources
- Excess in diffuse gamma rays

EGRET OBSERVATIONS OF THE DIFFUSE GAMMA-RAY EMISSION FROM THE GALACTIC PLANE


Received 1995 June 13; accepted 1996 December 5

However, above about 1 GeV the integral intensity predicted by the model is about 60% less than the observed intensity. Although the explanation of this excess is unclear, uncertainties in the neutral pion production function or variations in the cosmic-ray spectrum with Galactic radius may partially account...
Two results from EGRET paper

Enhancement in ringlike structure at 13-16 kpc

Called “Cosmic enhancement Factor”

Excess

Enhancement in ringlike structure at 13-16 kpc
Background + signal describe EGRET data!

Blue: background uncertainty

Blue: WIMP mass uncertainty

50 GeV

70
Analysis of EGRET Data in 6 sky directions

Total $\chi^2$ for all regions : $28/36 \Rightarrow$ Prob. = 0.8 Excess above background > 10$\sigma$.
Fits for 180 instead of 6 regions

180 regions:
8° in longitude ⇒ 45 bins
4 bins in latitude ⇒ 0° < |b| < 5°
5° < |b| < 10°
10° < |b| < 20°
20° < |b| < 90° ⇒

4 × 45 = 180 bins ⇒
> 1400 data points.
Reduced $\chi^2 \approx 1$ with 7% errors
BUT NEEDED IN ADDITION to
1/r² profile, substructure
in the form of 2 doughnut-like rings in the Galactic disc!

ONE RING COINCIDES WITH
ORBIT FROM CANIS MAJOR DWARF GALAXY which loses
mass along orbit by tidal forces

OTHER RING coincides with H₂ ring
Expected Profile

Observed Profile

Halo profile

Dark Matter distribution

\[ v^2 \propto \frac{M}{r} = \text{cons.} \]
\[ \rho \propto \frac{1}{r^2} \text{ for constant rotation curve} \]

Normalize to solar velocity of 220 km/s
How does DM substructure form from tidal disruption of dwarf galaxies?
The Milky Way and its satellite galaxies

Tidal force $\propto \Delta F_G \propto 1/r^3$
Tidal streams of dark matter from CM and Sgt

From David Law, Caltech
N-body simulation from Canis-Major dwarf galaxy

A comprehensive model for the Monoceros tidal stream

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Gas flaring in the Milky Way


Gas flaring needs EGRET ring with mass of $2.10^{10}M_{\odot}$!
Inner Ring coincides with ring of dust and $H_2 \rightarrow$ gravitational potential well!

Enhancement of inner (outer) ring over $1/r^2$ profile 6 (8).
Mass in rings 0.3 (3)% of total DM

4 kpc coincides with ring of neutral hydrogen molecules!
$H+H\rightarrow H_2$ in presence of dust $\rightarrow$ grav. potential well at 4–5 kpc.
Bergstrom et al. astro-ph/0603632, Abstract:

we investigate the viability of the model using the DarkSUSY package to compute the gamma-ray and antiproton fluxes. We are able to show that their (=WdB et al) model is excluded by a wide margin from the measured flux of antiprotons.

Problem with DarkSUSY (DS):

1) Flux of antiprotons/gamma in DarkSUSY: \( O(1) \) from DMA. However, \( O(10^{-2}) \) from LEP data

   Reason: DS has diffusion box with isotropic diffusion -> DMA fills up box with high density of antiprotons

2) Priors of DARKSUSY.(and other propagation models as well):

   a) static galactic magnetic fields are negligible
   b) gas is smoothly distributed
   c) propagation in halo and disk are the same

ALL priors likely wrong and can change predictions for DM searches by ORDER OF MAGNITUDE (and still ok with all observations!)
CONFINEMENT AND ISOTROPIZATION OF GALACTIC COSMIC RAYS BY MOLECULAR-CLOUD MAGNETIC MIRRORS WHEN TURBULENT SCATTERING IS WEAK

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it is shown that Galactic cosmic rays can be effectively confined through magnetic reflection by molecular clouds,

Integral excess of positrons in bulge because positrons are trapped in magnetic mirrors between gas clouds?
The van Allen belts are trapped cosmic rays in magnetic mirrors of earth

Radiation in inner belt: 25 Sv/yr inside space ship
Lethal dose for human: 3 Sv/h
Satellites switch of electronics, when entering dense radiation areas.
Escape time of cosmic rays and grammage (distance x density)

**B/C determines grammage**

- B/C = secondary/prim. determines grammage (smaller than disc!)
- In GALPROP: by large halo
- In CHANDRAN: by reflecting molecular clouds

**10Be/9Be determines escape time**

- 10Be ($t_{1/2} = 1.51 \text{ Myr}$) is cosmic clock: lifetime of cosmics $10^7 \text{ yrs.}$
- In GALPROP: by large halo
- In CHANDRAN: by long trapping.
Preliminary results from GALPROP with isotropic and anisotropic propagation

**CHANDRAN model**

**GALPROP model**

**Summary:** with fast propagation perp. to disc (e.g. by convection, fast diffusion or static magnetic fields) one reduces contribution of charged particles from DMA by large factor and can be consistent with B/C and $^{10}$Be/$^9$Be
EGRET excess interpreted as DM consistent with WMAP, Supergravity and electroweak constraints

STMH < 114.1 GeV
m_A = 2 m_χ
boost > 100
excl. LSP
no EWSB

Stau coannihilation
m_A resonance

Charginos, neutralinos and gluinos light

LSP largely Bino ⇒ DM may be supersymmetric partner of CMB
Celestial bodies collect DM in their cores by their high density. Annihilation can result in flux of HIGH energy neutrinos from sun (from b-decays or from Z-decays).

Neutrinos can be detected by large detectors, like Super-Kamiokande, Amanda, Ice-Cube, Baksan by the charged current interactions with nuclei, which yields muons in the detectors.
WIMPs elastically scatter off nuclei => nuclear recoils
Measure recoil energy spectrum in target

If SUSY particle spectrum known, elastic scattering X-section can be calculated
8 physics questions answered SIMULTANEOUSLY if WIMP = thermal relic

- **Astrophysicists:** What is the origin of “GeV excess” of diffuse Galactic Gamma Rays? A: DM annihilation
- **Astronomers:** Why a change of slope in the galactic rotation curve at $R_0 \approx 11$ kpc? A: DM substructure
  - Why ring of stars at 13 kpc?
  - Why ring of molecular hydrogen at 4 kpc?
  - Why S-shape in gas flaring?
- **Cosmologists:** How is DM annihilating? A: into quark pairs
- **How is Cold Dark Matter distributed?** A: standard profile + substructure
- **Particle physicists:** Is DM annihilating as expected in Supersymmetry? A: Cross sections perfectly consistent with mSUGRA for light gauginos, heavy squarks/sleptons
Summary

>>10σ EGRET excess shows intriguing hint that:

- **WIMP is thermal relic with expected annihilation into quark pairs**
- **DM becomes visible by gamma rays from fragmentation** (30–40 gamma rays of few GeV pro annihilation from $\pi_0$ decays)
- Results rather model independent, since only KNOWN spectral shapes of signal and background used, NO model dependent calculations of abs. fluxes. Different shapes or unknown experimental problems may change the gamma ray flux and/or WIMP mass, BUT NOT the distribution in the sky.
- SPATIAL DISTRIBUTION of annihilation signal is signature for DMA which clearly shows that EGRET excess is tracer of DM by fact that one can construct rotation curve and tidal streams from gamma rays.
- **DM interpretation strongly supported independently by gas flaring**
- **DM interpretation perfectly consistent with Supersymmetry**