



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



## Ingredients to this analysis

From EGRET excess of diffuse Galactic gamma rays

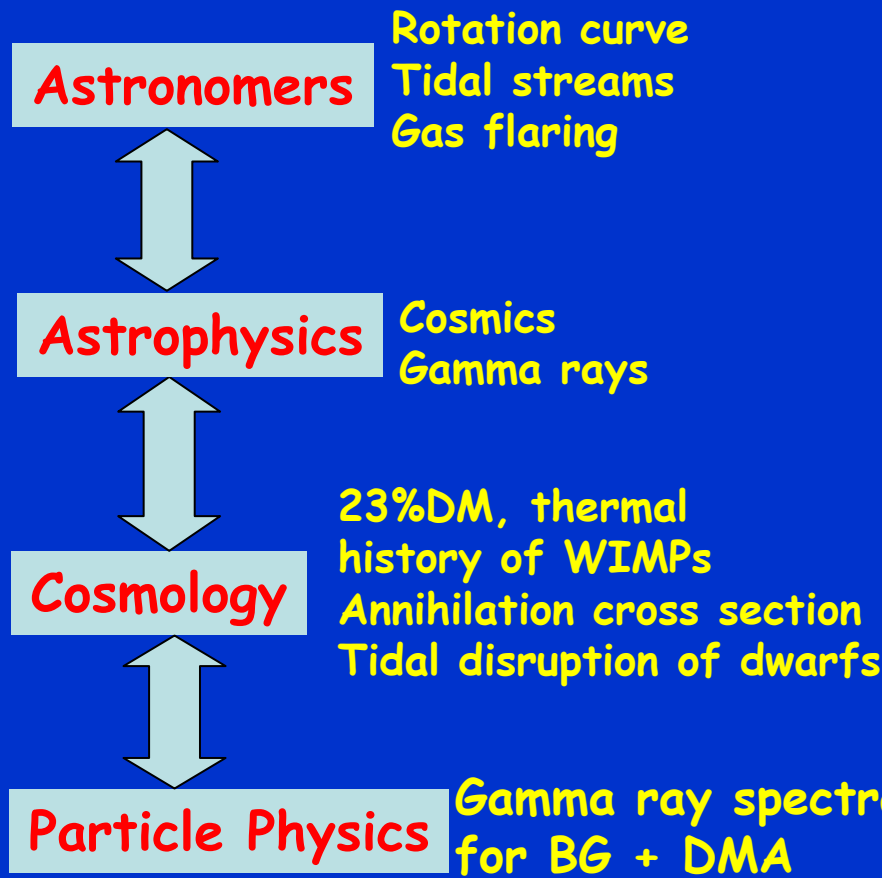
- Determination of WIMP mass
- Determination of WIMP halo (= standard halo + DM ring)

Confirmation:

- Rotation curve
- Canis Major/Monoceros stream
- Sagittarius streams
- Gas flaring

PREDICTIONS

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



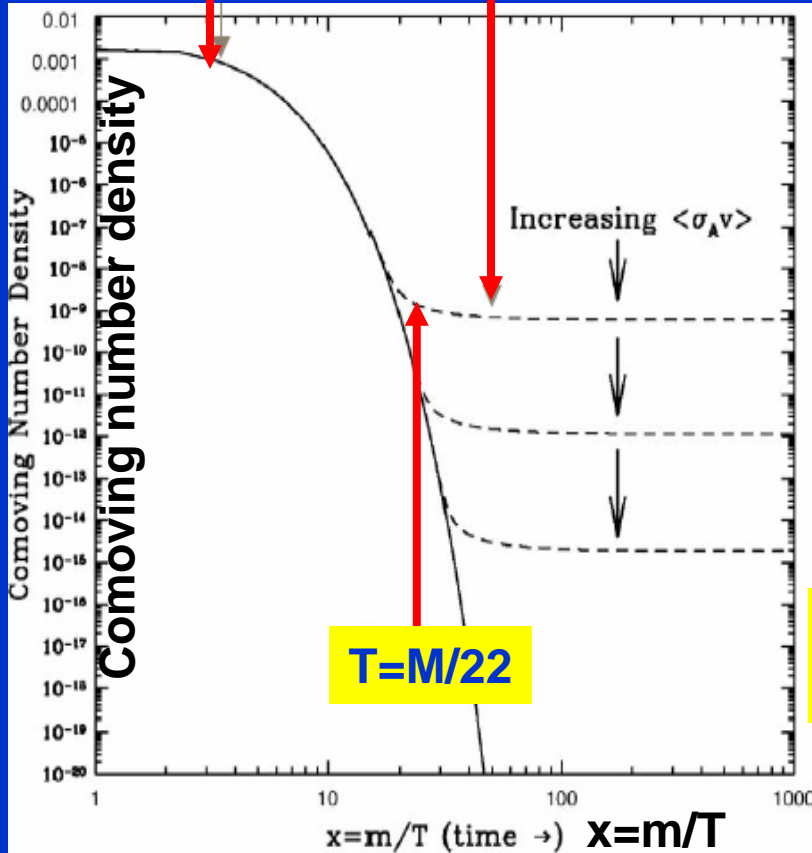


# Thermal History of WIMPs



Thermal equilibrium abundance

Actual abundance



$T \gg M$ :  $f + \bar{f} \rightarrow M + \bar{M}$ ;  $M + \bar{M} \rightarrow f + \bar{f}$   
 $T < M$ :  $M + \bar{M} \rightarrow f + \bar{f}$   
 $T = M/22$ :  $M$  decoupled, stable density  
 (when annihilation rate  $\cong$  expansion-rate, i.e.  $\Gamma = \langle\sigma v\rangle n_\chi(x_{fr}) \cong H(x_{fr})$  !)

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

DM increases in Galaxies:  
 $\approx 1$  WIMP/coffee cup  $\approx 10^5 \langle\rho\rangle$ .  
 DMA ( $\propto \rho^2$ ) restarts again..

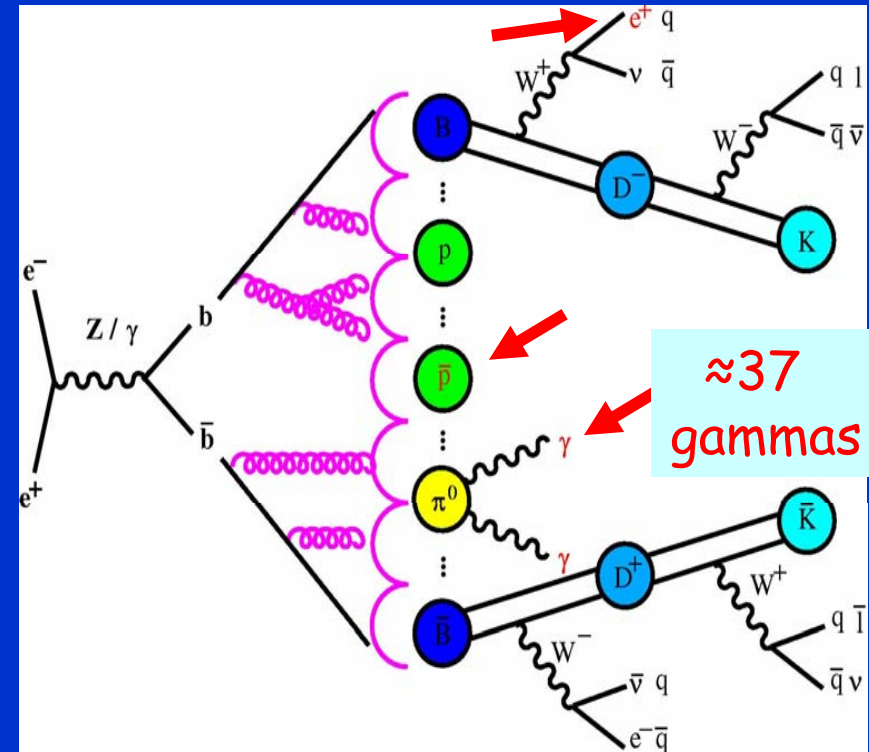
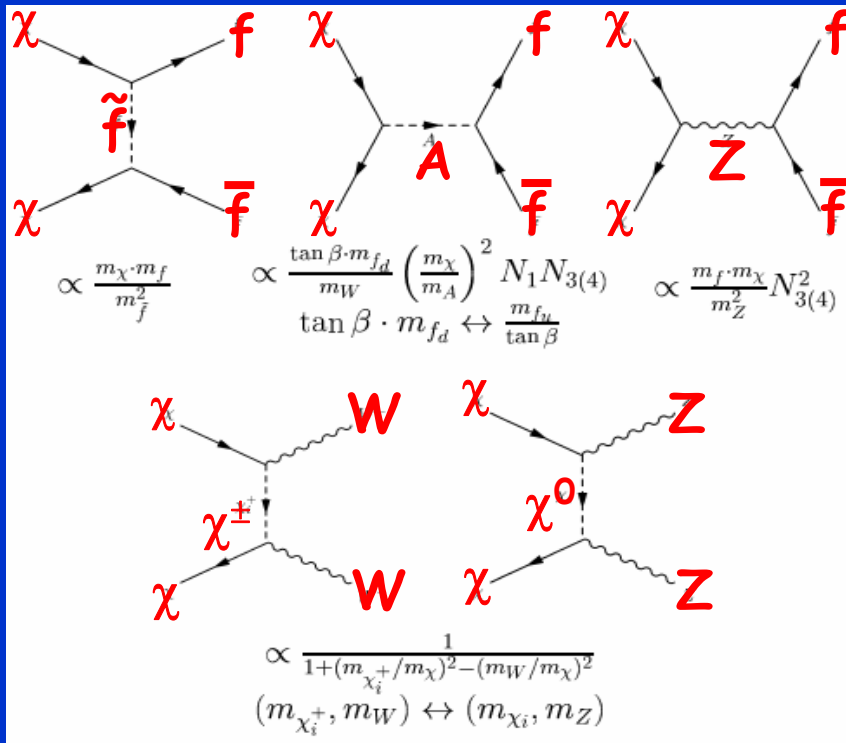
Annihilation into lighter particles, like quarks and leptons  $\rightarrow \pi_0$ 's  $\rightarrow$  Gammas!

Only assumption in this analysis:  
 WIMP = THERMAL RELIC!

Jungmann, Kamionkowski, Griest, PR 1995



# Example of DM annihilation (SUSY)



## Dominant

$\chi + \chi \Rightarrow A \Rightarrow b \text{ bbar quark pair}$   
 Sum of diagrams should yield  
 $\langle \sigma v \rangle = 2 \cdot 10^{-26} \text{ cm}^3/\text{s}$  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.



# Conclusion so far



IF DM particles are thermal relics from early universe they can annihilate with cross section as large as

$$\langle \sigma v \rangle = 2 \cdot 10^{-26} \text{ cm}^3/\text{s}$$

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 sizeable 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)

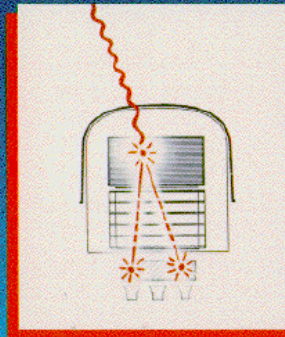
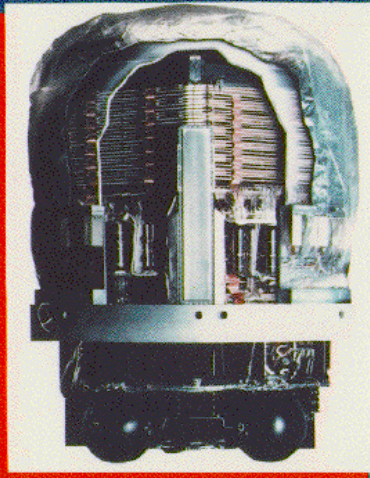
This means: Galactic gamma rays have 2 components with a shape KNOWN from the 2 BEST studied reactions in accelerators: background known from fixed target exp. DMA known from  $e^+e^-$  annihilation (LEP)



# EGRET on CGRO (Compton Gamma Ray Observ.)

## Data publicly available from NASA archive

Energetic Gamma Ray Experiment Telescope (EGRET)



### Instrumental parameters:

Energy range: 0.02-30 GeV

Energy resolution: ~20%

Effective area: 1500 cm<sup>2</sup>

Angular resol.: <0.5°

Data taking: 1991-1994

### Main results:

Catalogue of point sources

Excess in diffuse gamma rays

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

S. D. HUNTER,<sup>1</sup> D. L. BERTSCH,<sup>1</sup> J. R. CATELLI,<sup>1,2</sup> T. M. DAME,<sup>3</sup> S. W. DIGEL,<sup>4</sup> B. L. DINGUS,<sup>1,5</sup>  
 J. A. ESPOSITO,<sup>1,5</sup> C. E. FICHEL,<sup>1</sup> R. C. HARTMAN,<sup>1</sup> G. KANBACH,<sup>6</sup> D. A. KNIFFEN,<sup>7</sup> Y. C. LIN,<sup>8</sup>  
 H. A. MAYER-HASSELWANDER,<sup>6</sup> P. F. MICHELSON,<sup>8</sup> C. VON MONTIGNY,<sup>1,9</sup> R. MUKHERJEE,<sup>1,5</sup>  
 P. L. NOLAN,<sup>8</sup> E. SCHNEID,<sup>10</sup> P. SREEKUMAR,<sup>1,5</sup> P. THADDEUS,<sup>3</sup> AND D. J. THOMPSON<sup>1</sup>

*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

# Basic principle for indirect dark matter searches

From rotation curve:

$$mv^2/r = GmM/r^2 = \text{cons.}$$

and

$$\rho \propto (M/r)/r^2$$

$$\rho \propto 1/r^2$$

for const. rot. curve

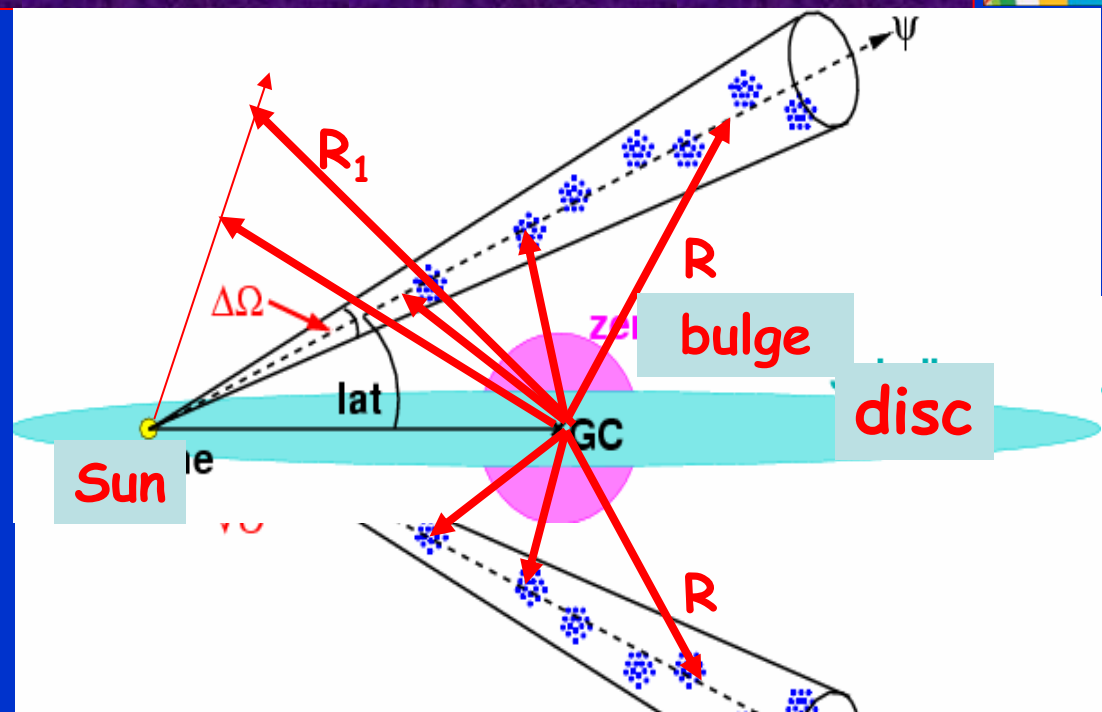
**EXPECT MOST OF DM  
IN CENTRE OF GALAXY**

Divergent for  $r=0$ ?

NFW profile  $\propto 1/r$

Isothermal profile const.

$$\propto 1/(r^2 + a^2)$$



**IF FLUX AND SHAPE MEASURED IN  
ONE DIRECTION, THEN FLUX AND  
SHAPE FIXED IN ALL (=180) SKY  
DIRECTIONS for a given halo profile!**

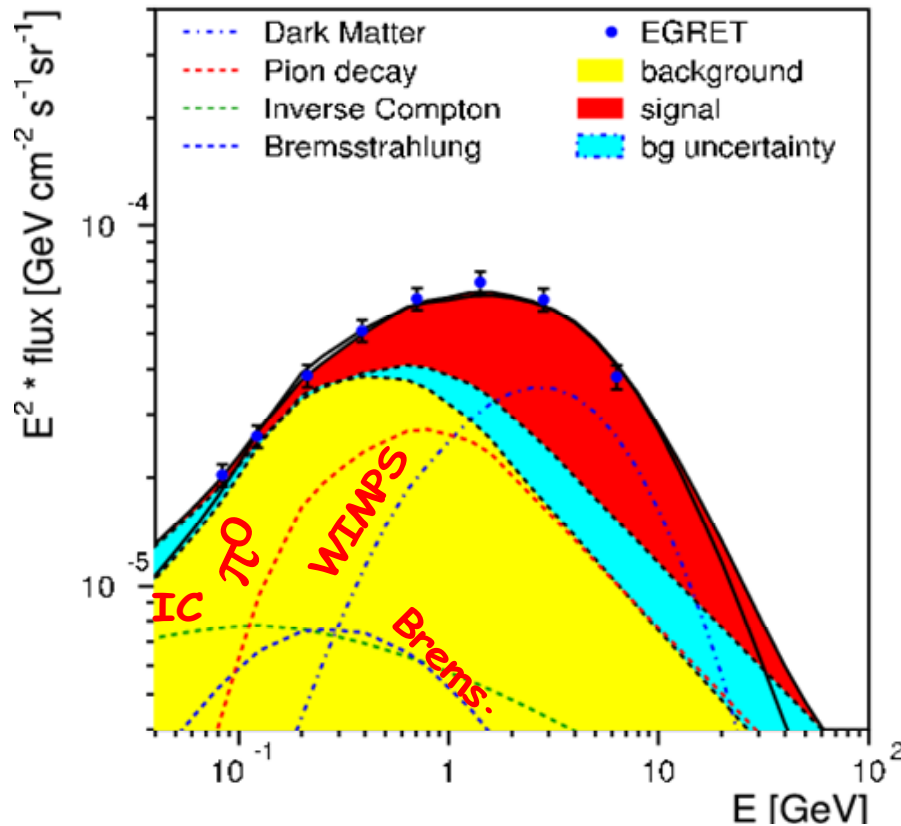
**THIS IS AN INCREDIBLE CONSTRAINT, LIKE SAYING I VERIFY  
THE EXCESS AND WIMP MASS WITH 180 INDEPENDENT MEAS.**



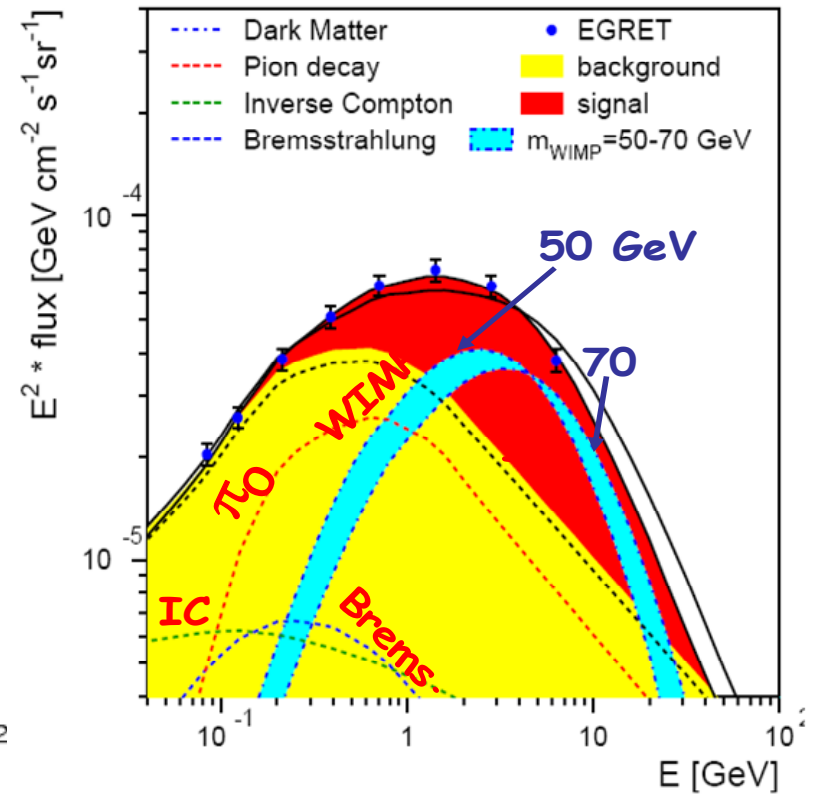
# Background + signal describe EGRET data!



WdB, C. Sander, V. Zhukov, A. Gladyshev, D. Kazakov,  
EGRET excess of diffuse Galactic Gamma Rays as  
Tracer of DM, astro-ph/0508617, A&A, 444 (2005) 51

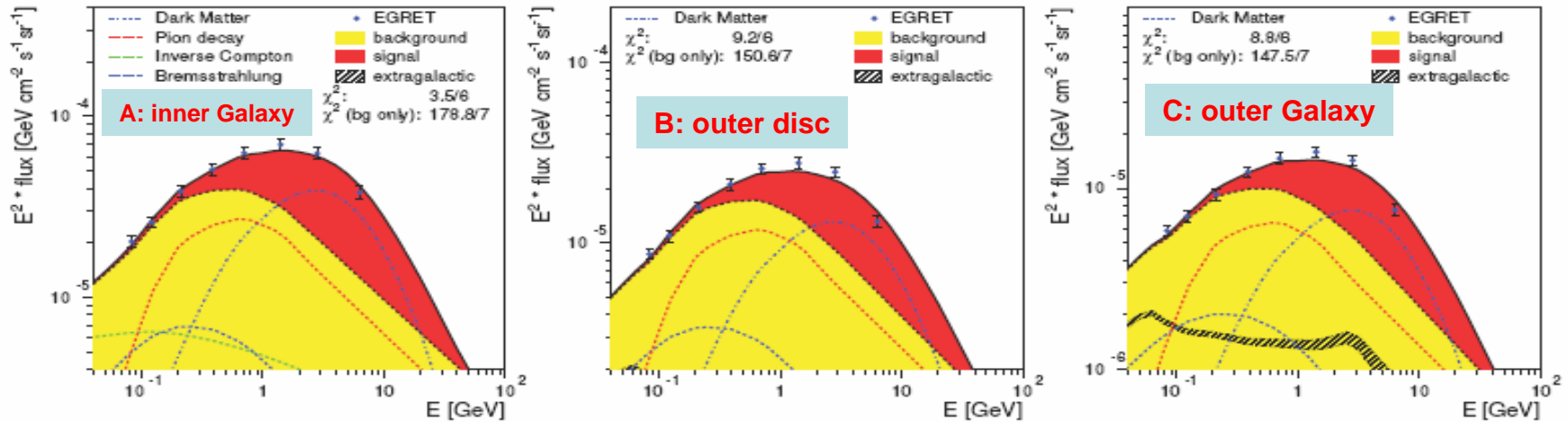


Blue: background uncertainty

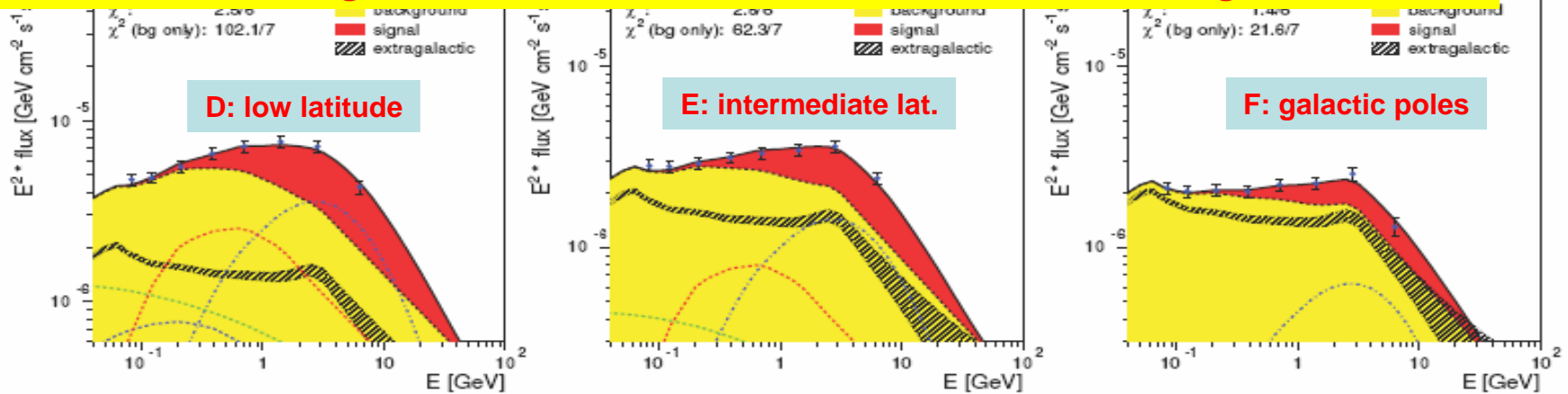


Blue: WIMP mass uncertainty

# Analysis of EGRET data in 6 sky directions

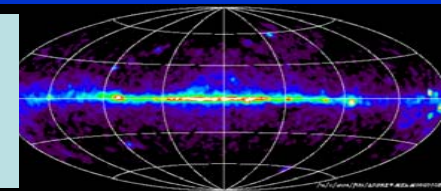


Total  $\chi^2$  for all regions :28/36  $\Rightarrow$  Prob. = 0.8 Excess above background  $> 10\sigma$ .



A: inner Galaxy ( $l = \pm 30^\circ$ ,  $|b| < 5^\circ$ )  
 B: Galactic plane avoiding A  
 C: Outer Galaxy

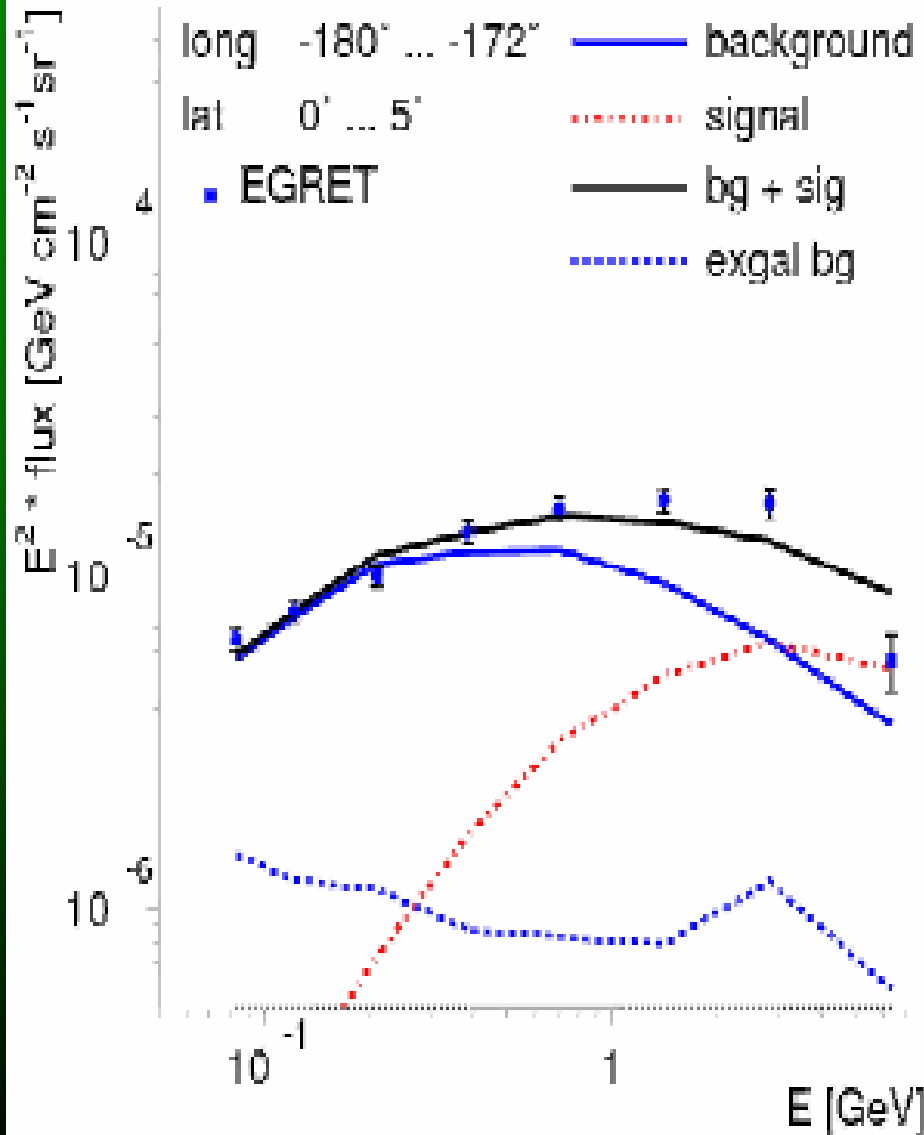
D: low latitude ( $10-20^\circ$ )  
 E: intermediate lat. ( $20-60^\circ$ )  
 F: Galactic poles ( $60-90^\circ$ )







# Fits for 180 instead of 6 regions



180 regions:

$8^\circ$  in longitude  $\Rightarrow$  45 bins

4 bins in latitude  $\Rightarrow 0^\circ < |b| < 5^\circ$

$5^\circ < |b| < 10^\circ$

$10^\circ < |b| < 20^\circ$

$20^\circ < |b| < 90^\circ \Rightarrow$

$4 \times 45 = 180$  bins  $\Rightarrow$

**>1400 data points.**

**Reduced  $\chi^2 \approx 1$  with 7% errors**

**BUT NEEDED IN ADDITION to**

**$1/r^2$  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  $H_2$  ring**

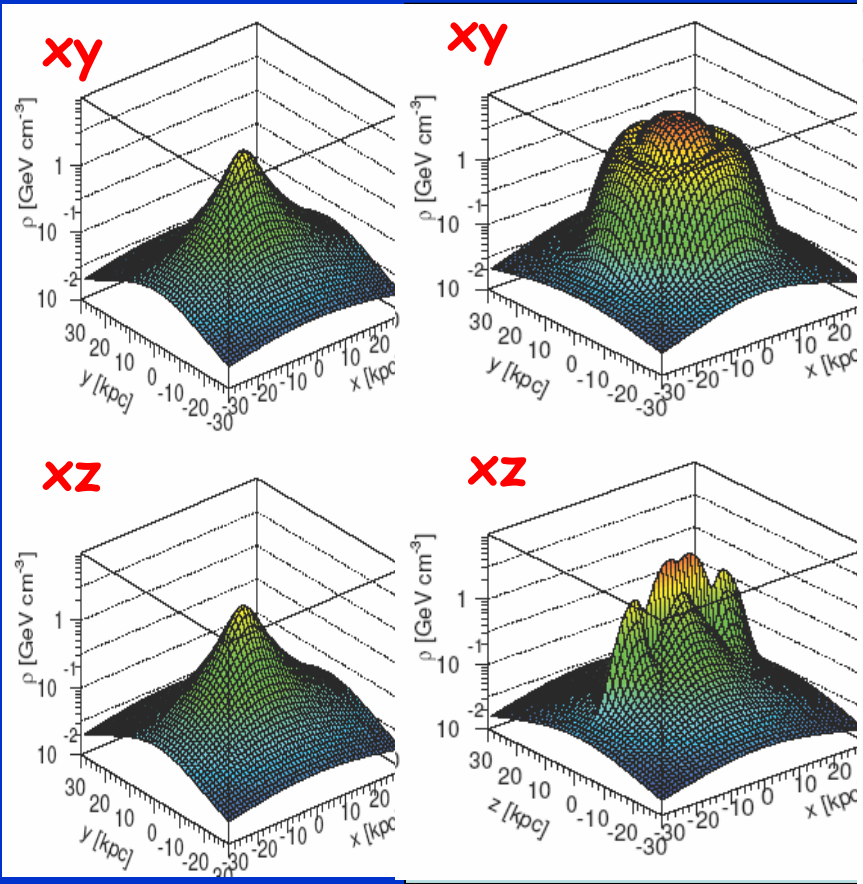


# Dark Matter distribution

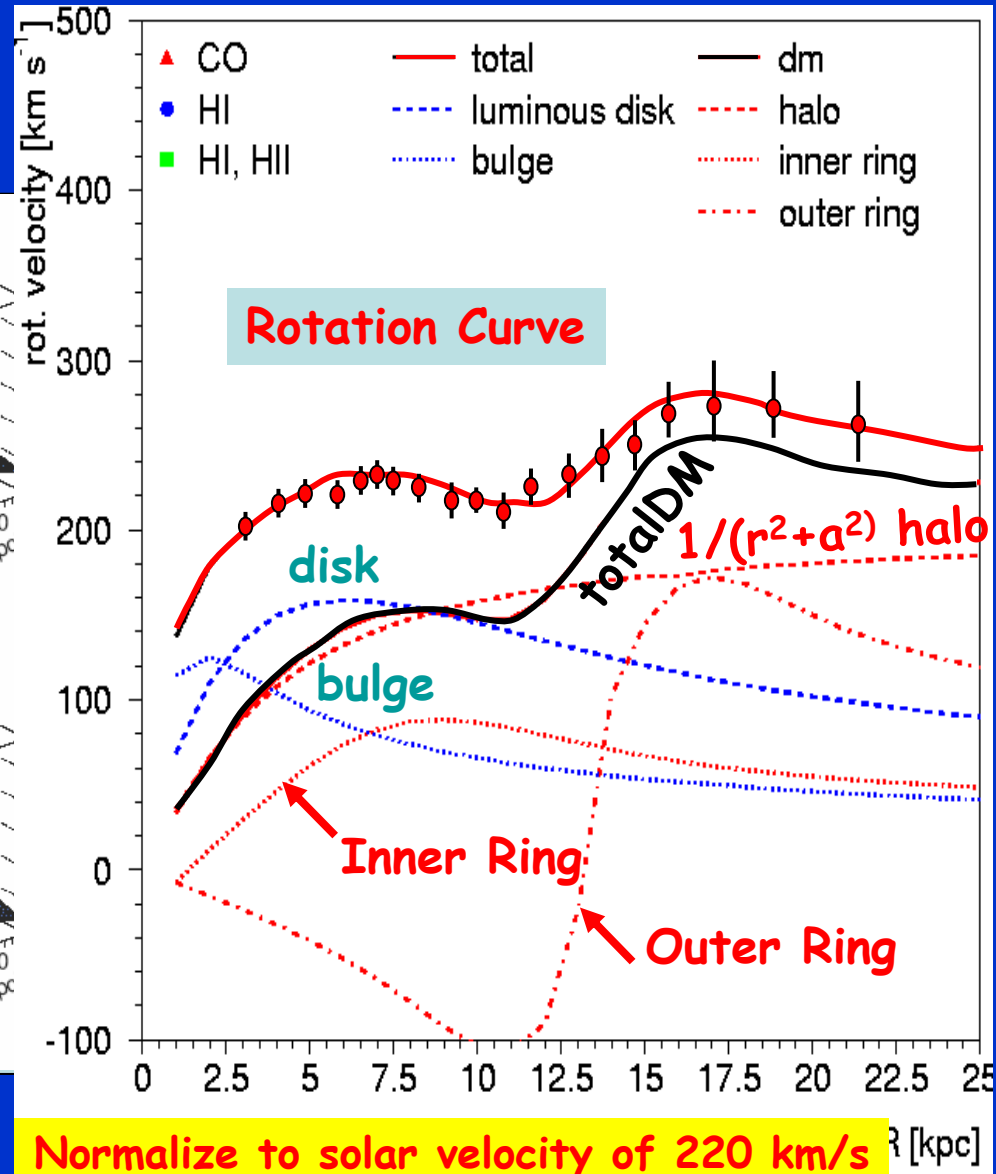


Expected Profile

Observed Profile



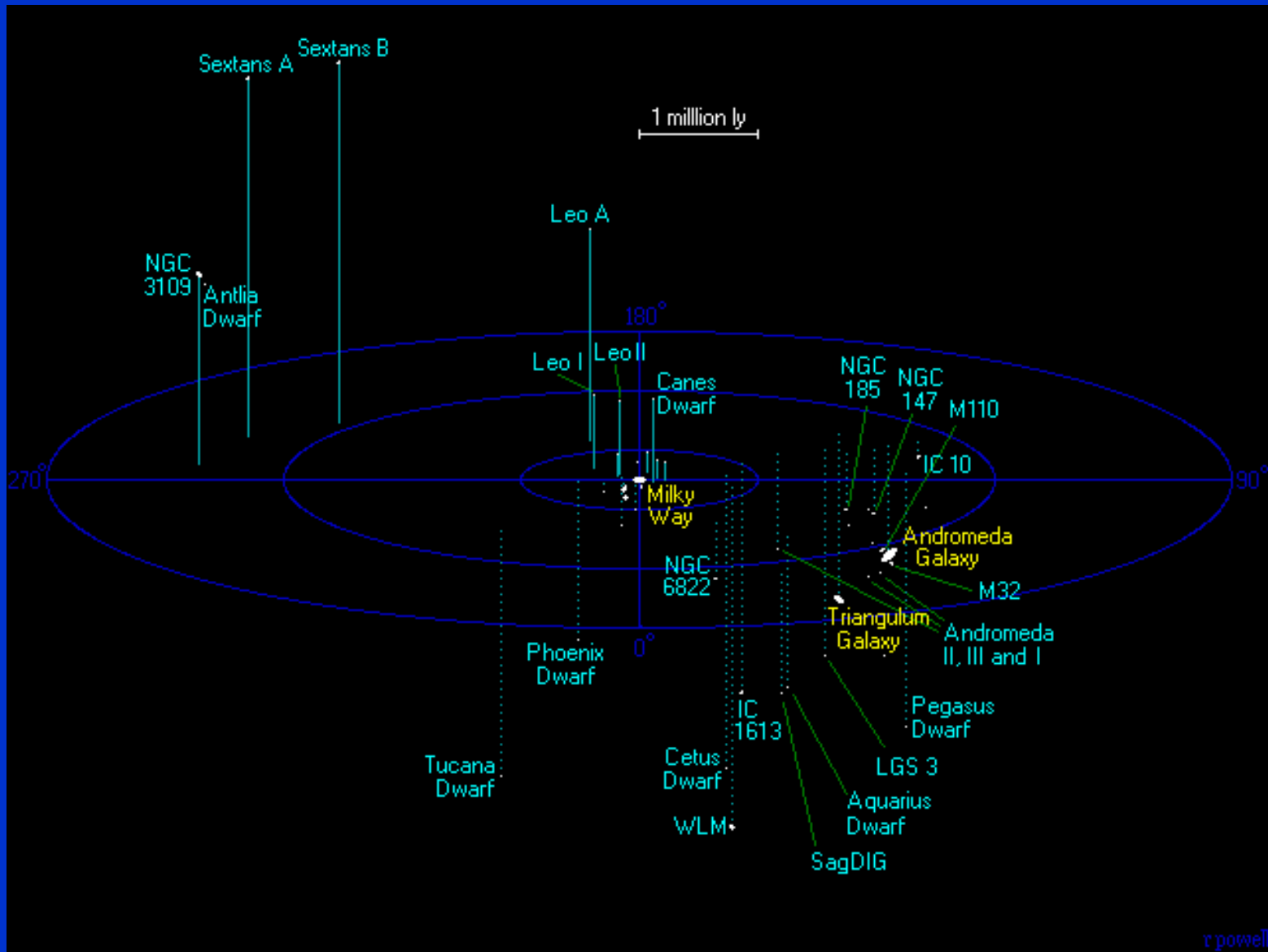
Halo profile



Normalize to solar velocity of 220 km/s

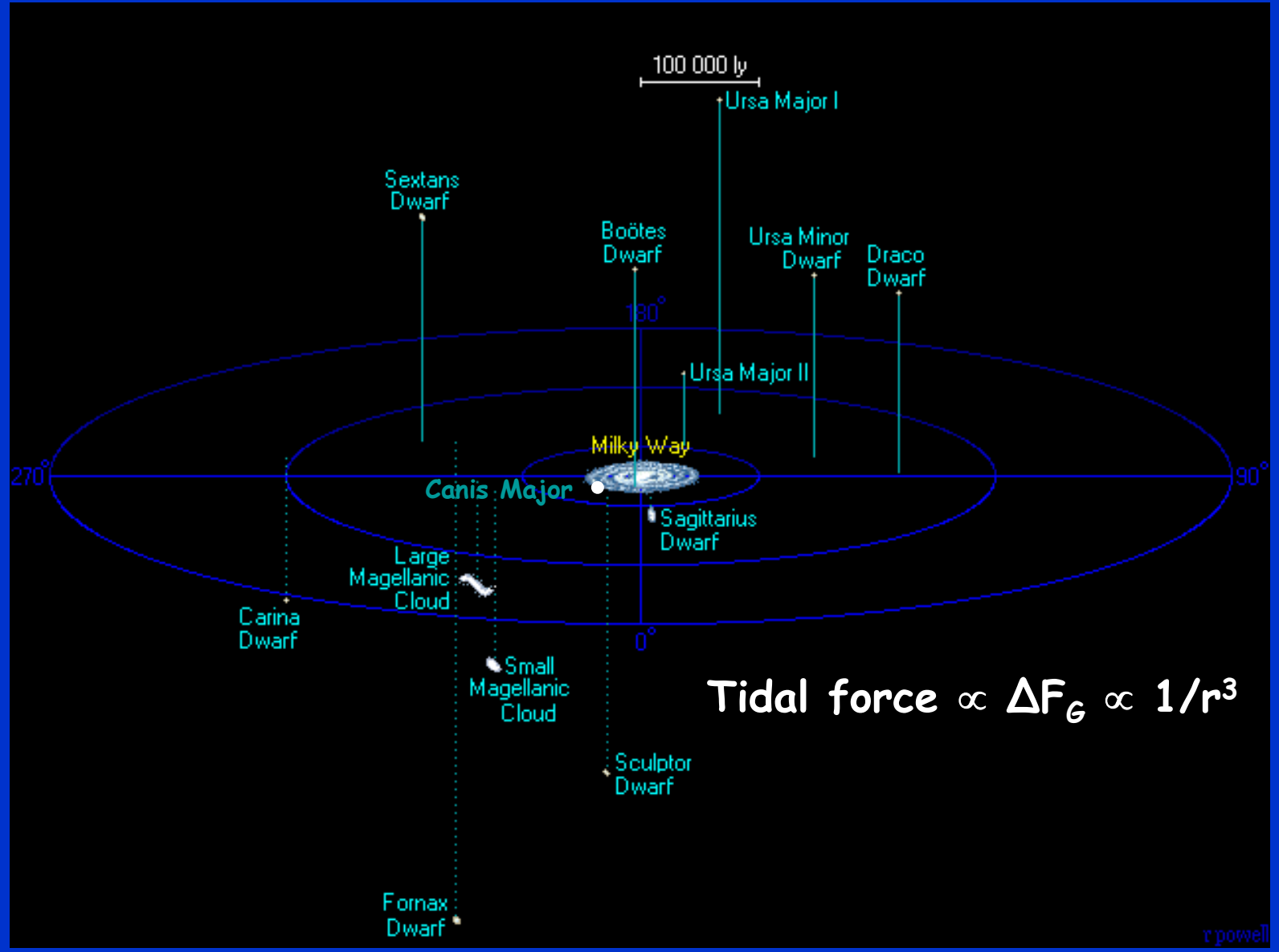


# The local group of galaxies



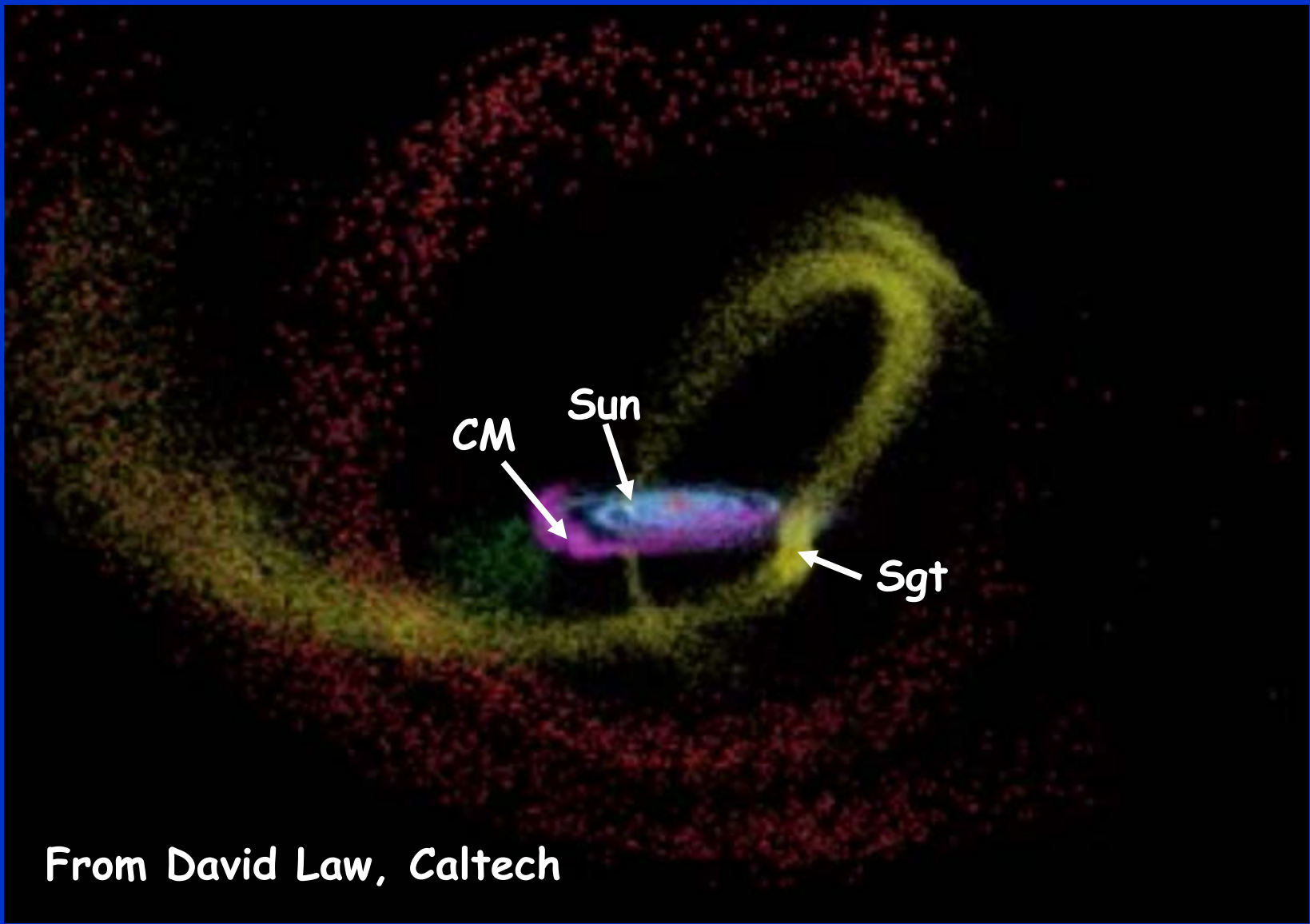


# The Milky Way and its 13 satellite galaxies





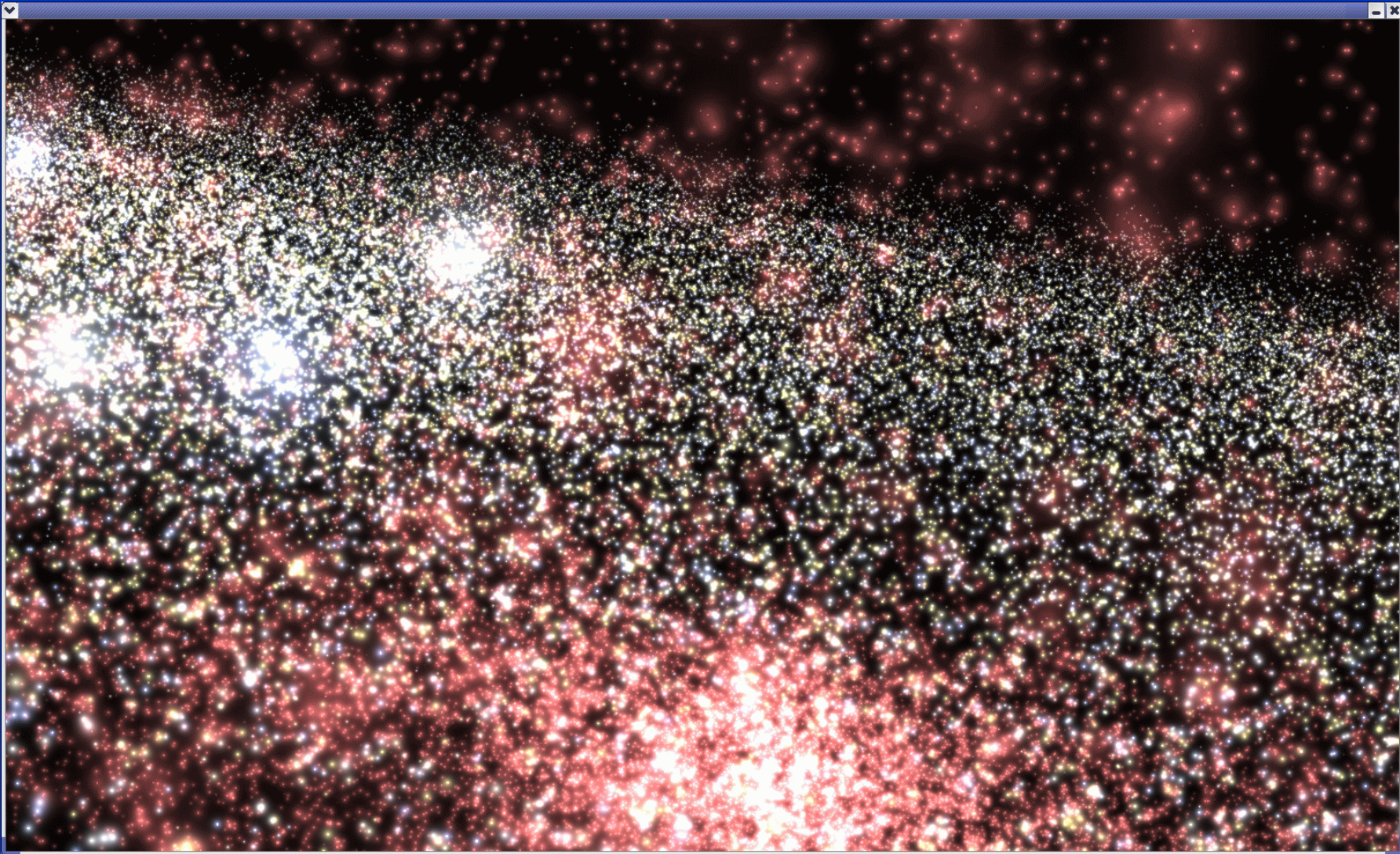
# Tidal streams of dark matter from CM and Sgt



From David Law, Caltech

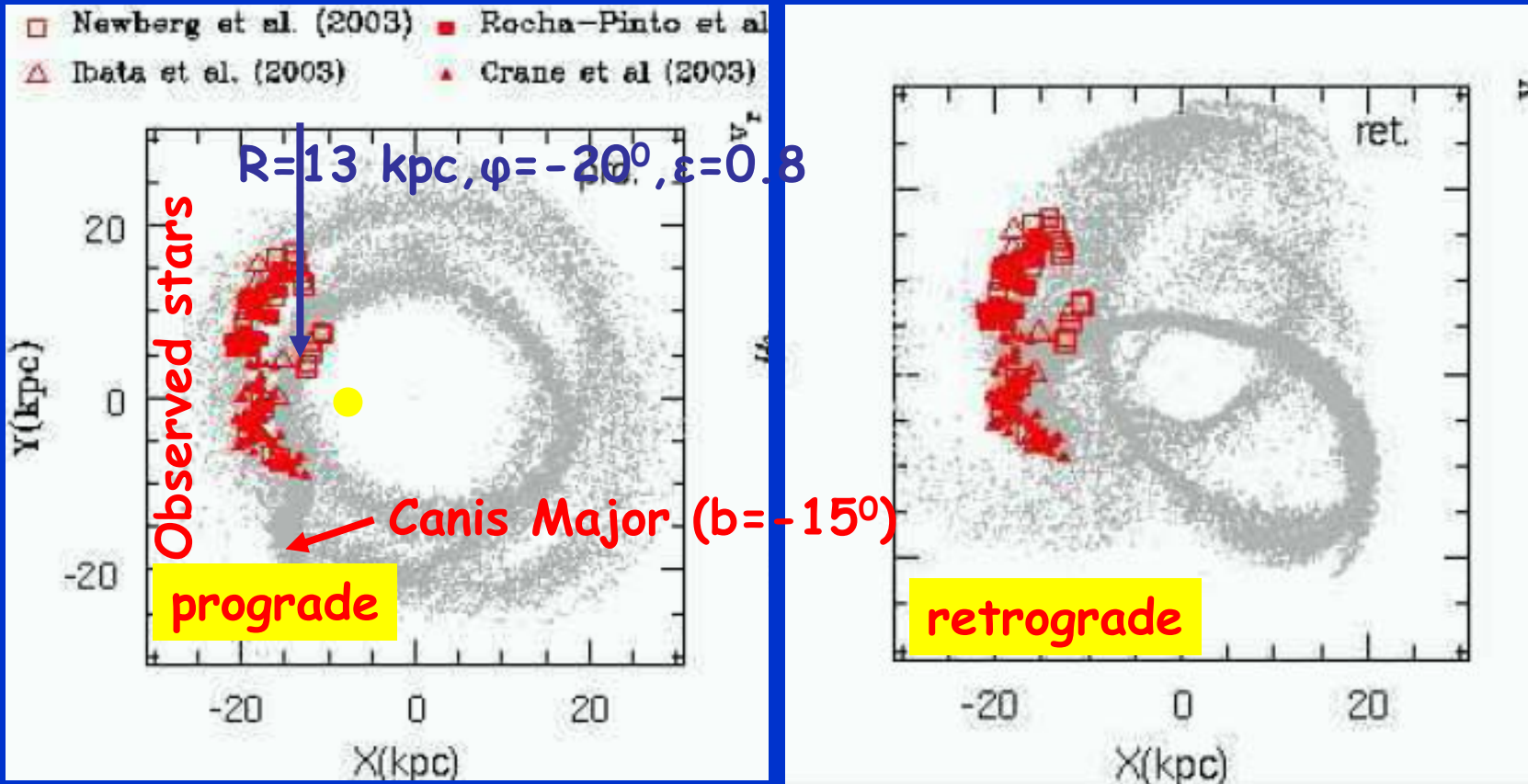


# Artistic view of Canis Major Dwarf just below Galactic disc





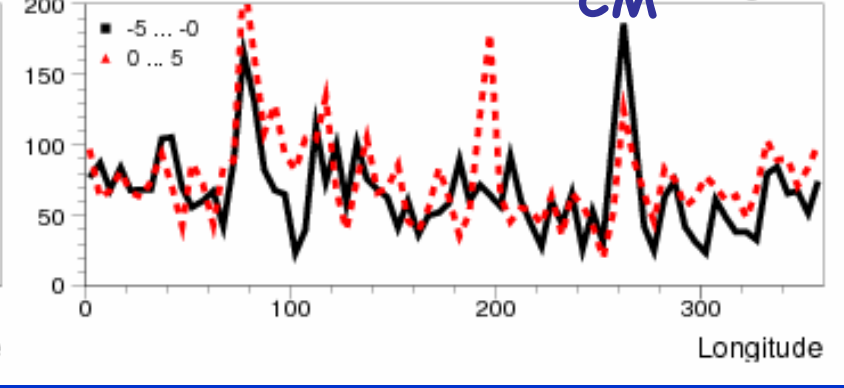
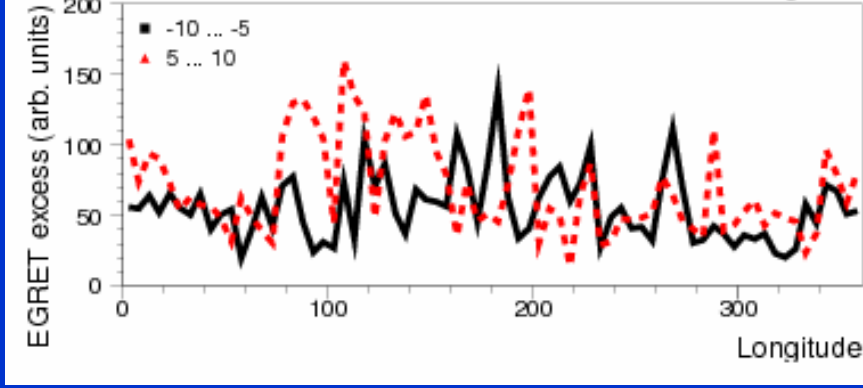
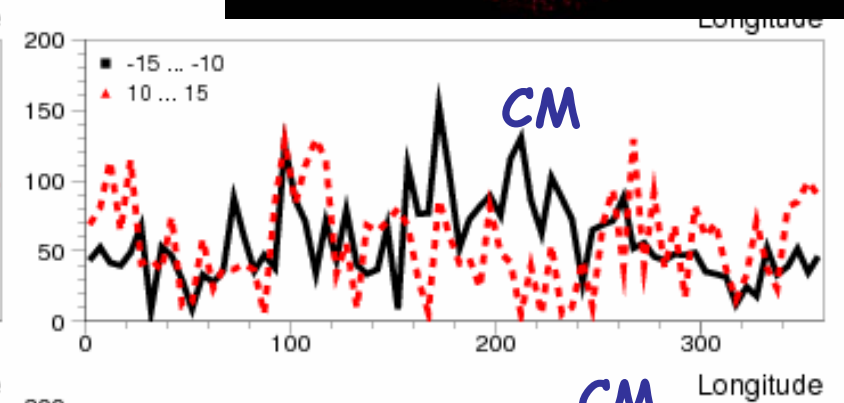
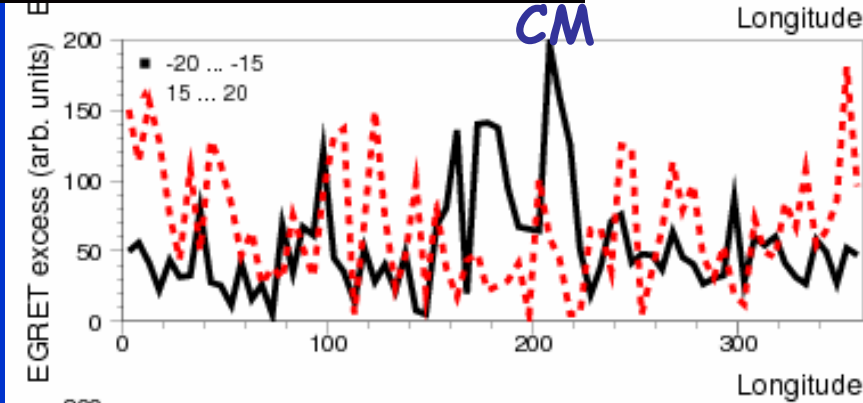
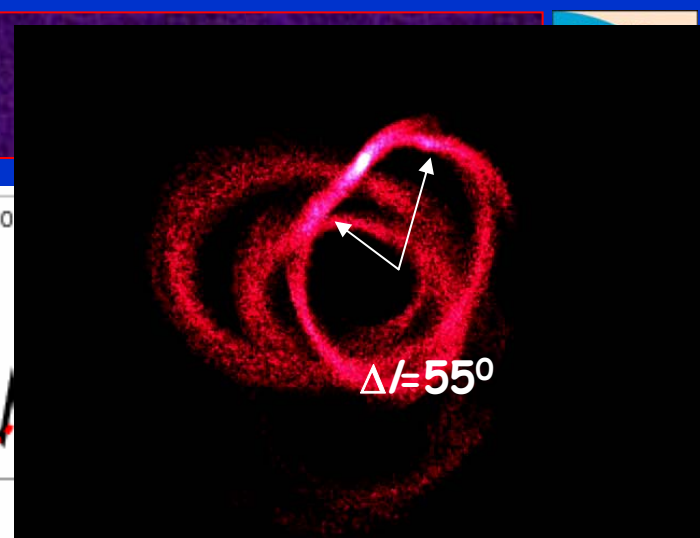
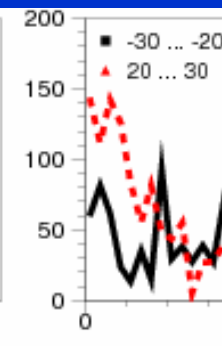
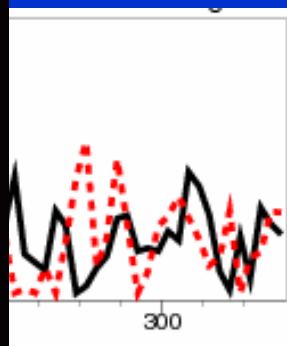
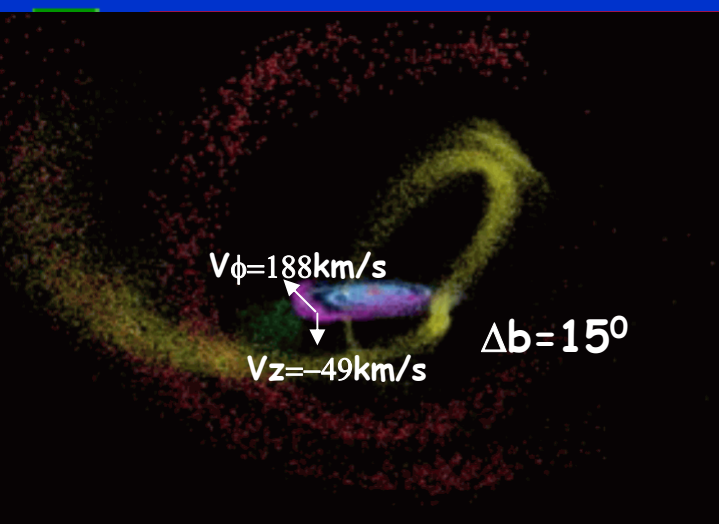
# N-body simulation from Canis-Major dwarf galaxy



## A comprehensive model for the Monoceros tidal stream

J. Peñarrubia<sup>1</sup>, D. Martínez-Delgado<sup>1</sup>, H.W. Rix<sup>1</sup>, M.A Gómez-Flechoso<sup>2</sup>, J. Munn<sup>3</sup>, H. Newberg<sup>4</sup>, E.F. Bell<sup>1</sup>, B. Yanny<sup>5</sup>, D. Zucker<sup>1</sup>, E. K. Grebel<sup>6</sup>

# CM dwarf







# Conclusion



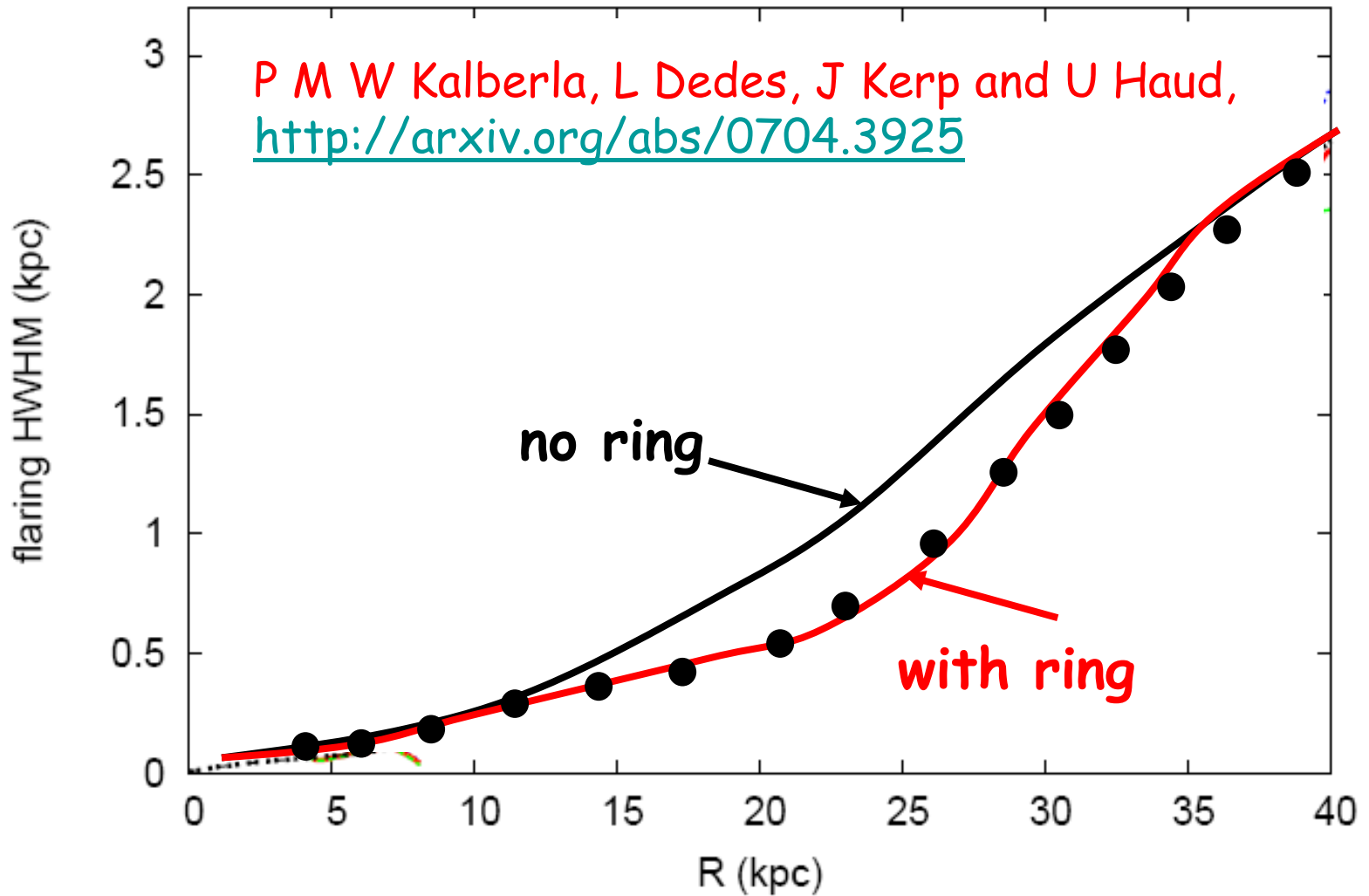
Comparing gamma rays above and below Galactic disk is excellent way to search for tidal streams, since systematic errors cancel and foreground from diffuse part of halo should be the same

Result: one finds a clear correlation between excess of diffuse gamma rays and KNOWN positions of tidal streams of two nearest satellite galaxies

Summary: all proposed indirect searches see signal:  
galactic centre  
galactic poles  
galactic anticentre  
nearest satellite galactic streams



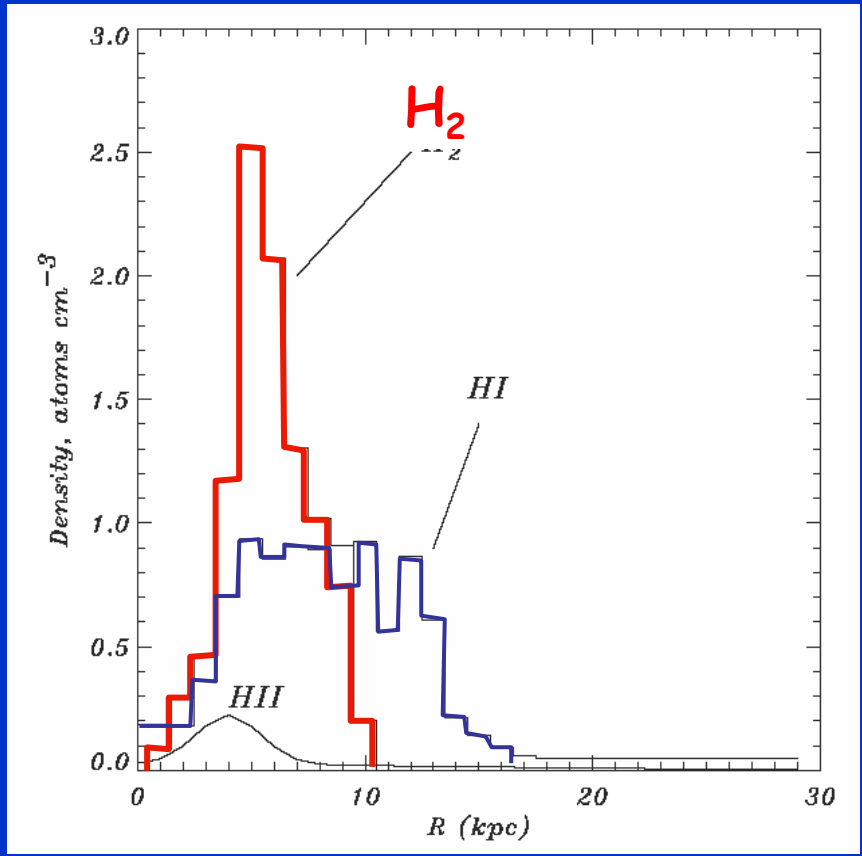
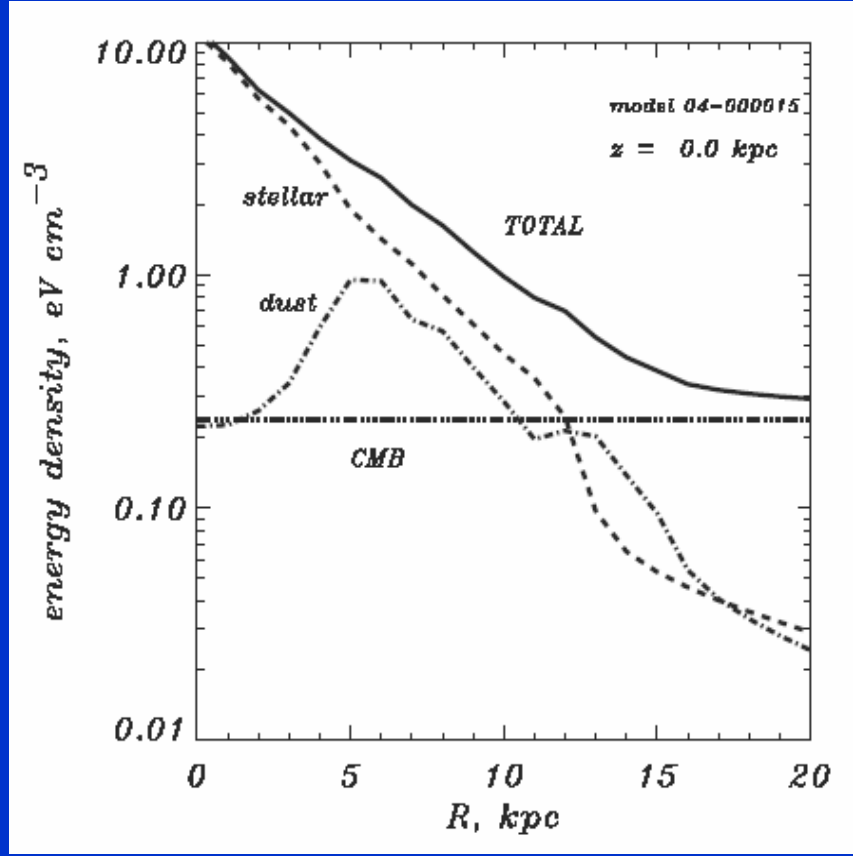
# Gas flaring in the Milky Way



**Gas flaring needs EGRET ring with mass of  $2 \cdot 10^{10} M_{\odot}$ !**



# Inner Ring coincides with ring of dust and H<sub>2</sub> -> 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 -> 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):

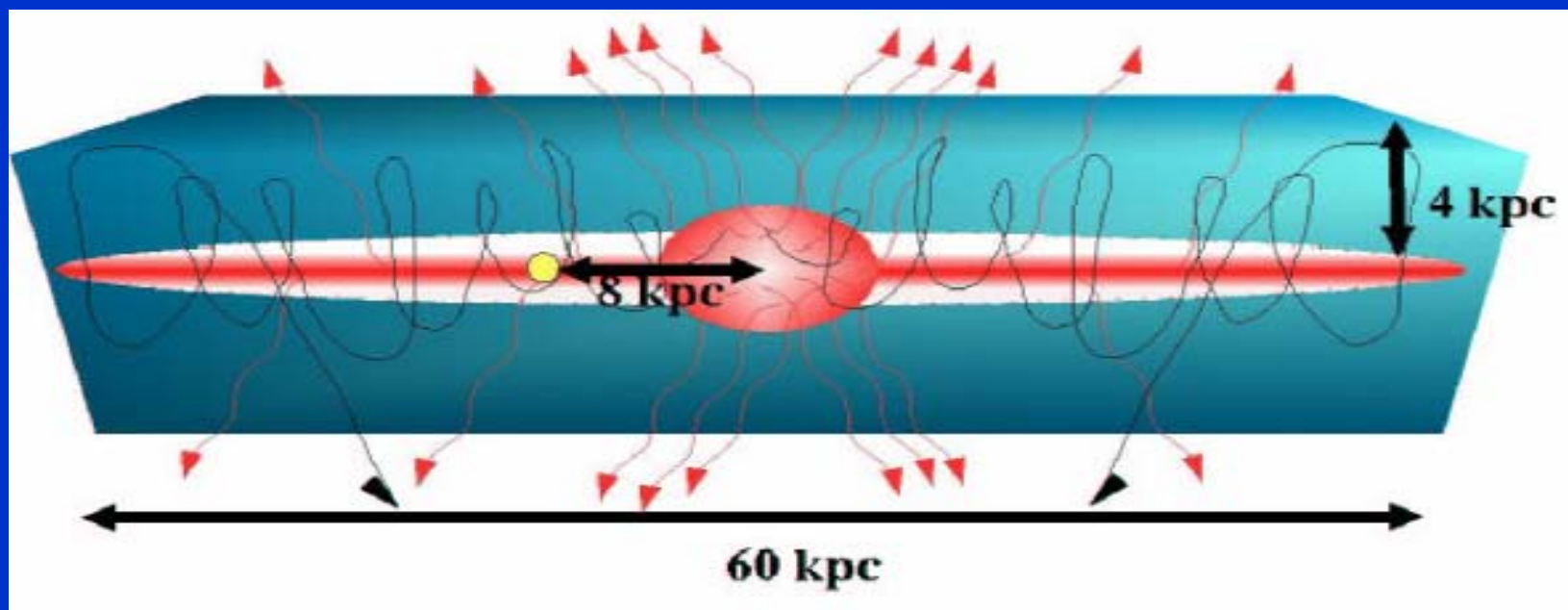
a) static galactic magnetic fields are negligible

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!)

# One propagation model of our Galaxy



**Primary particles** by supernovae explosions, pulsars, ...

**Secondary particles** nuclear interactions.

**Diffusion parameters** determined from sec./prim. ratios, e.g. B/C ratio

**Halo size** determined from radioactive isotopes, e.g.  $^{10}\text{Be}/^9\text{Be}$  ratio  
( $\tau(^{10}\text{Be}) = 1.6 \cdot 10^6 \text{ yr}$ )



# Another propagation model including static magnetic fields and gas clouds and anisotropic diffusion



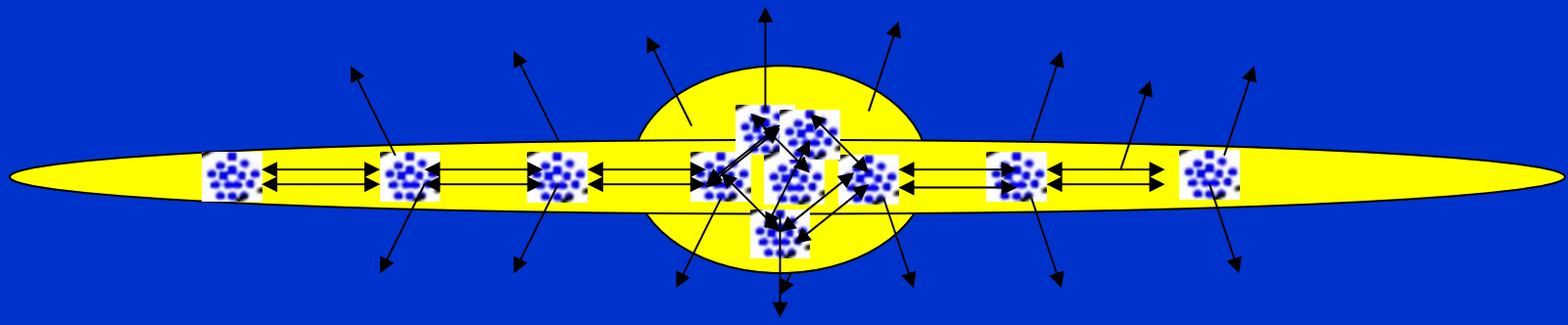
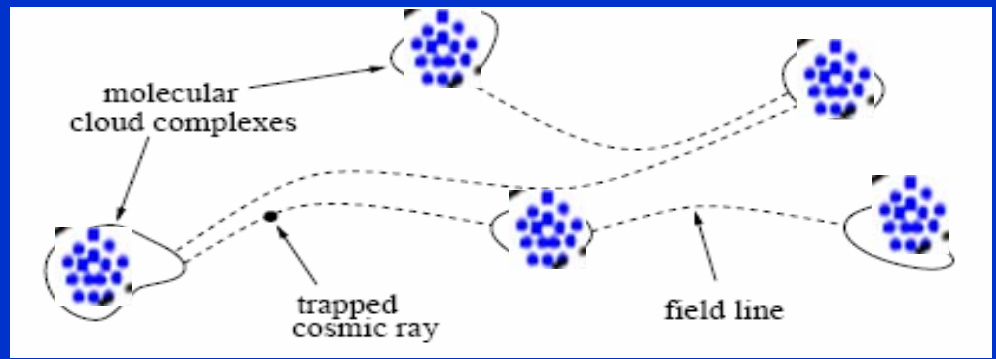
## CONFINEMENT AND ISOTROPIZATION OF GALACTIC COSMIC RAYS BY MOLECULAR-CLOUD MAGNETIC MIRRORS WHEN TURBULENT SCATTERING IS WEAK

BENJAMIN D. G. CHANDRAN

Department of Physics and Astronomy, University of Iowa, 203 Van Allen Hall, Iowa City, IA 52242; benjamin-chandran@uiowa.edu

Received 1998 June 25; accepted 1999 August 6

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



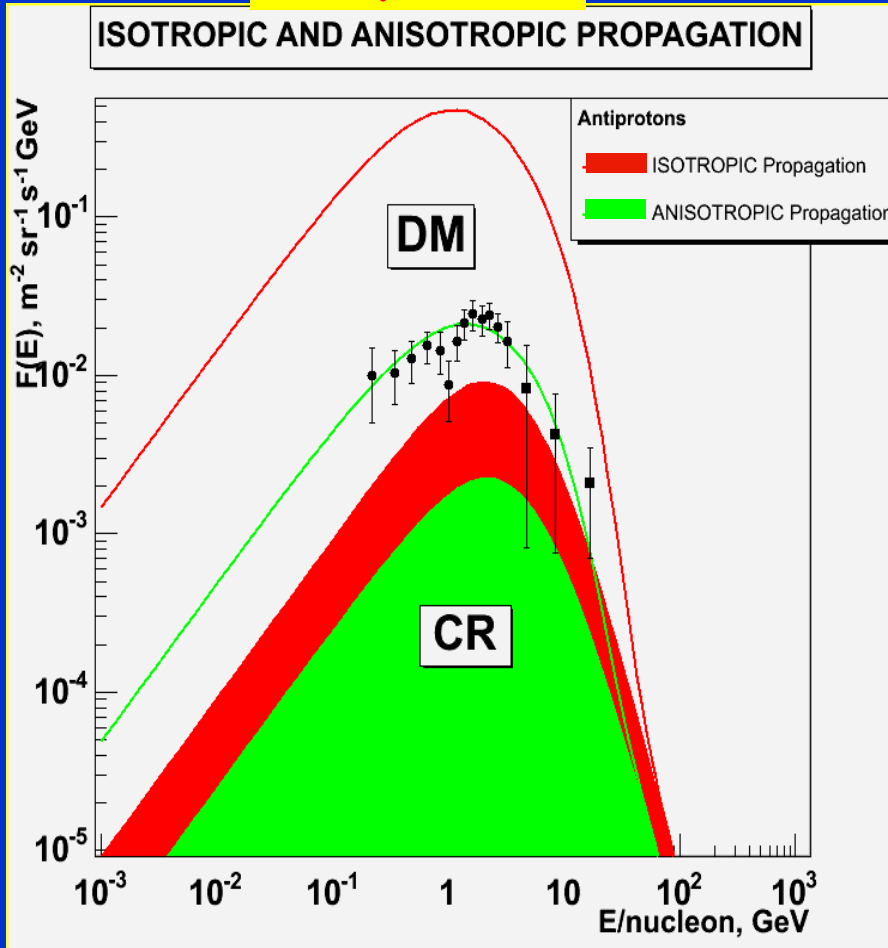
Integral excess of positrons in bulge because positrons are trapped in magnetic mirrors between gas clouds



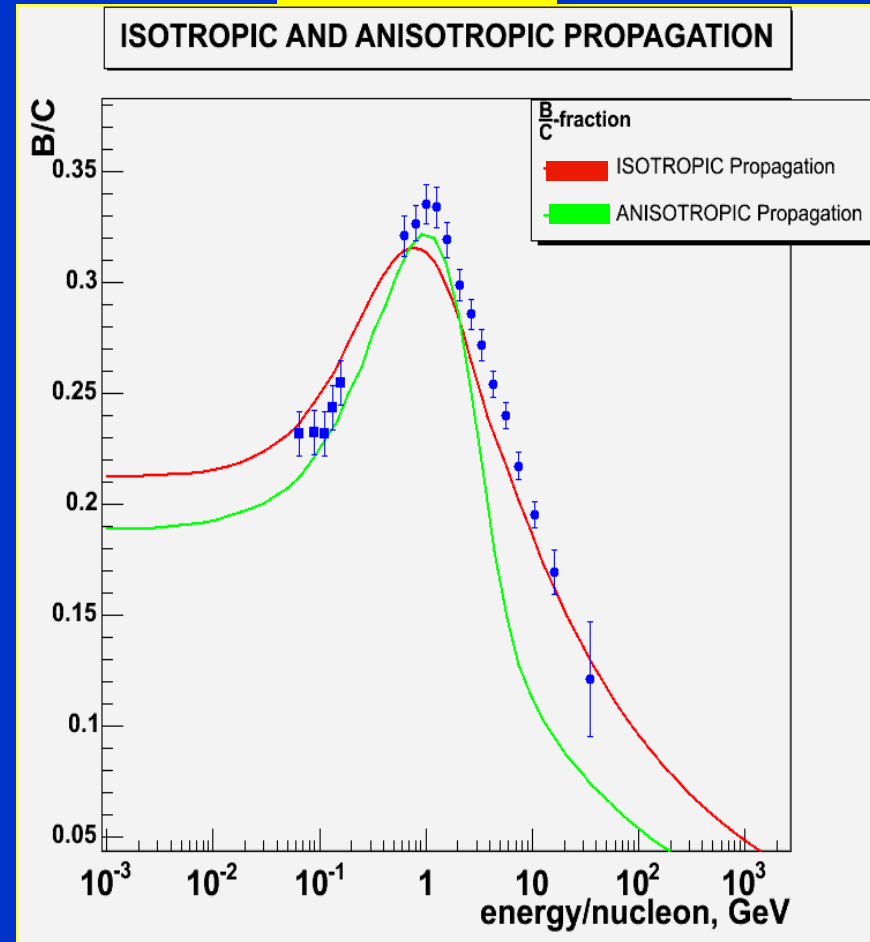
# Preliminary results from GALPROP with isotropic and anisotropic propagation



## Antiprotons



## B/C ratio



**Summary: with anisotropic propagation you can send charged particles wherever you want and still be consistent with B/C and  $^{10}\text{Be}/^9\text{Be}$**



# 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:**

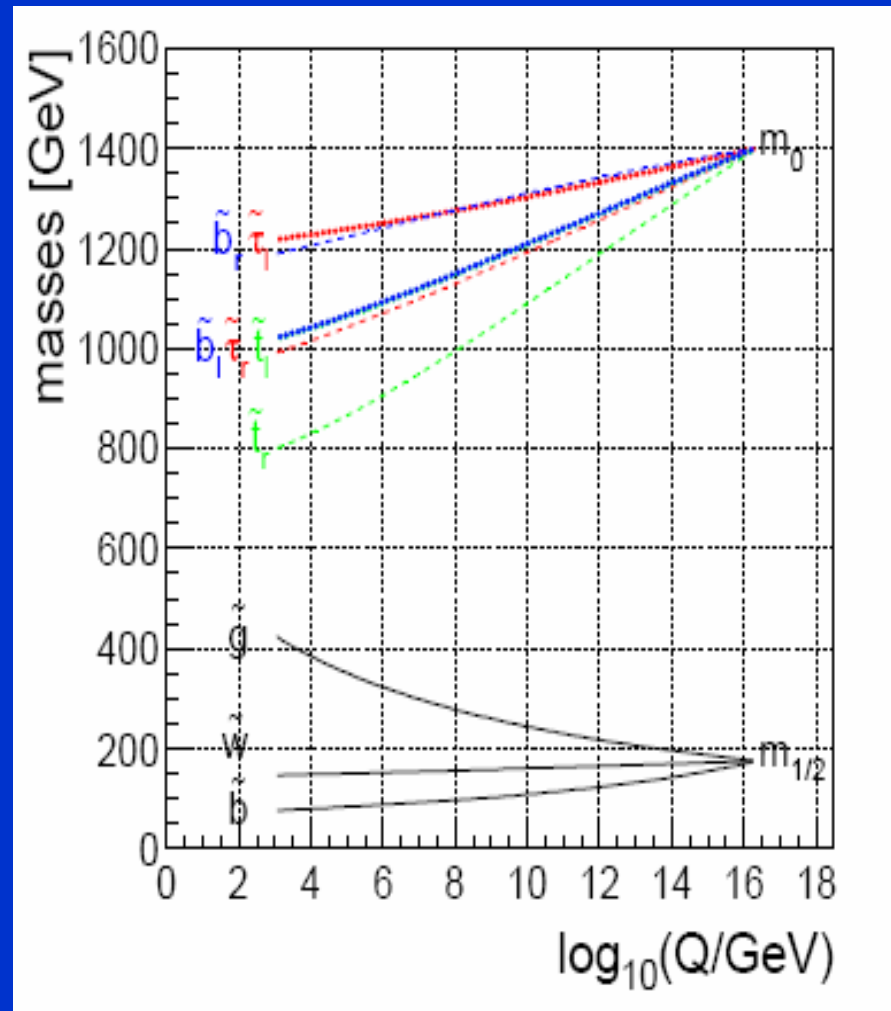
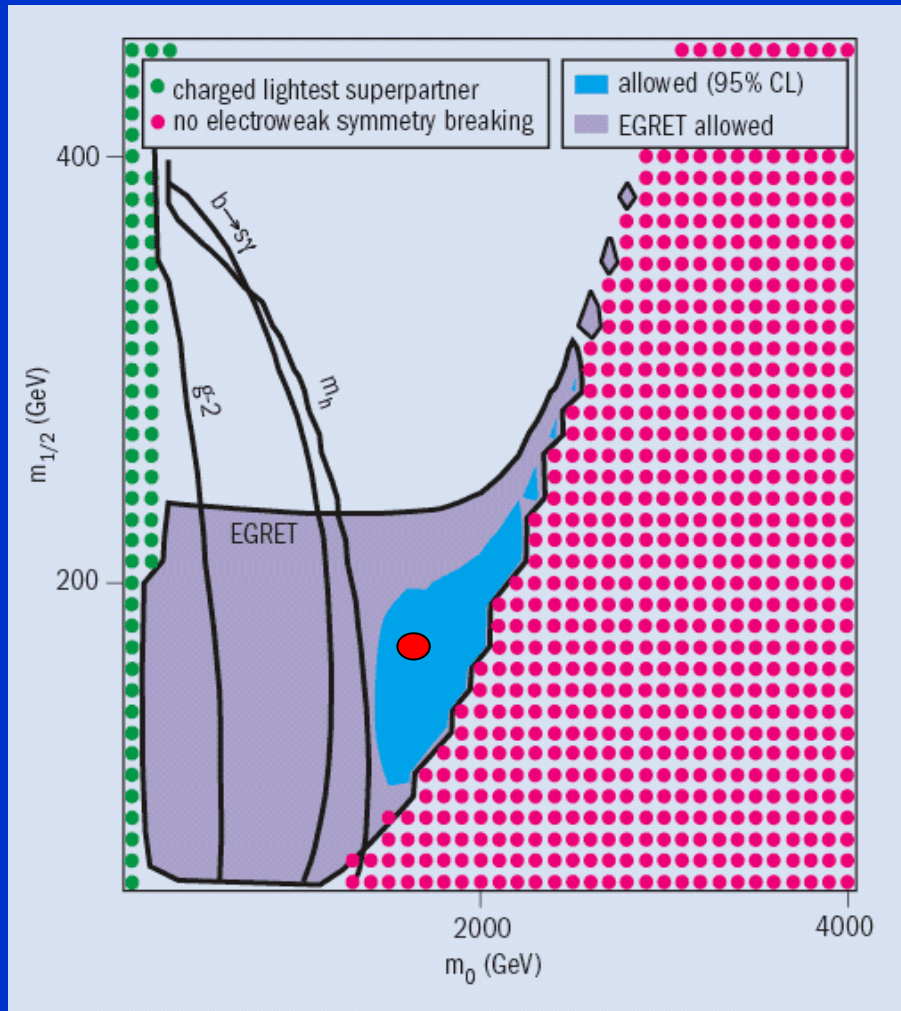
Is DM annihilating as expected in Supersymmetry?

A: Cross sections perfectly consistent with mSUGRA for light gauginos, heavy squarks/sleptons





# Expected SUSY mass spectra in mSUGRA



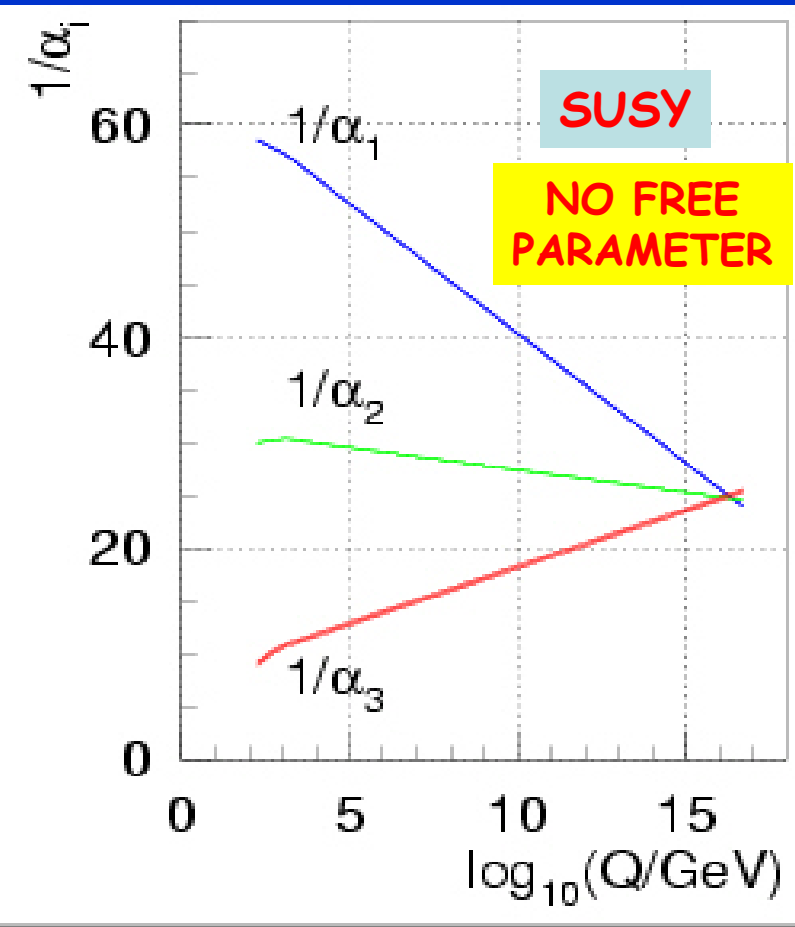
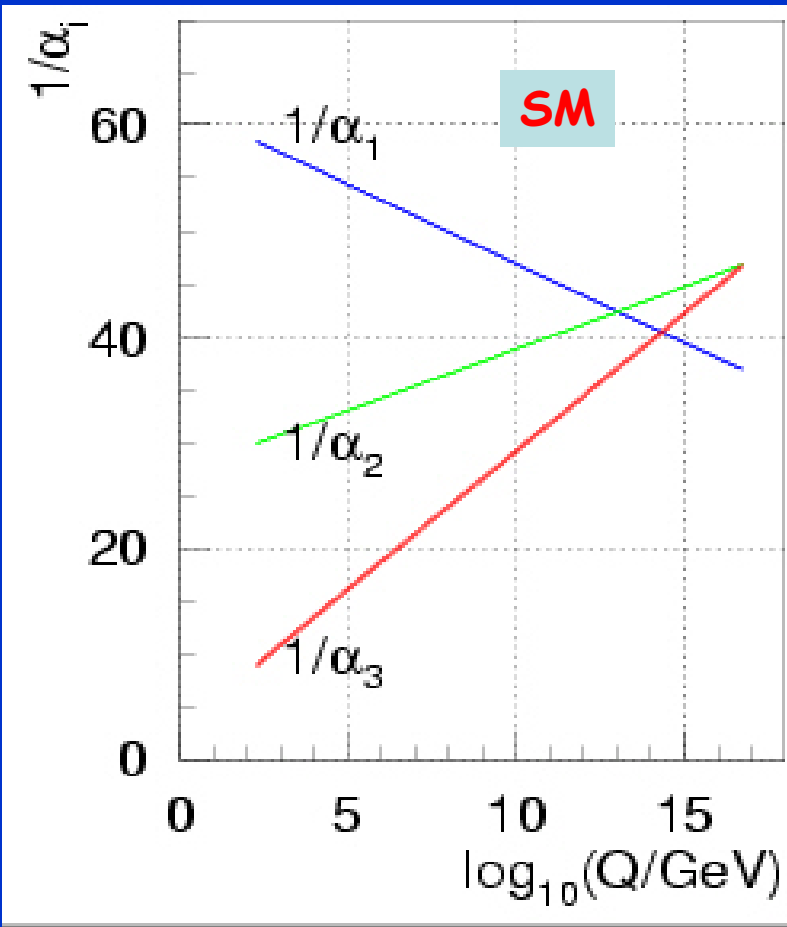
**mSUGRA: common masses  $m_0$  and  $m_{1/2}$  for spin 0 and spin  $\frac{1}{2}$  particles**



# Gauge unification perfect with SUSY spectrum from EGRET



Update from Amaldi, dB, Fürstenau, PLB 260 1991

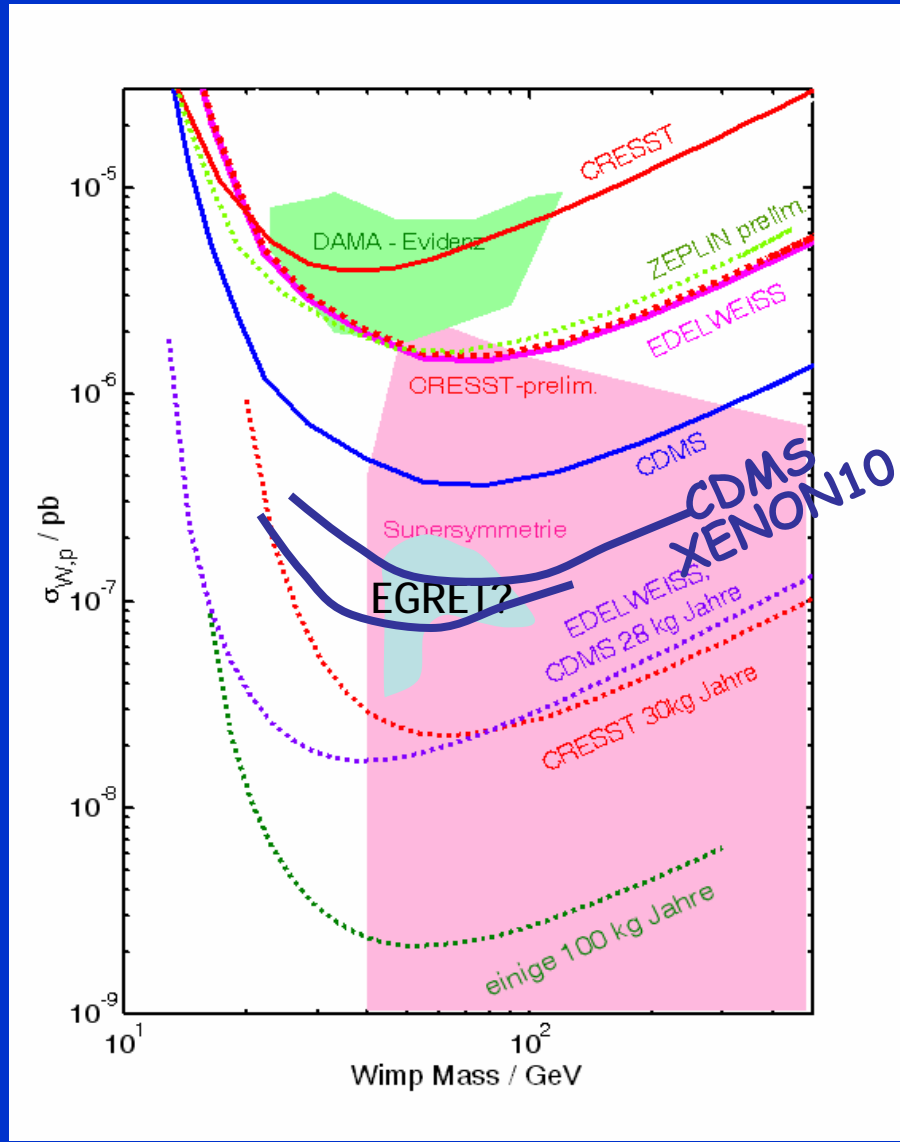
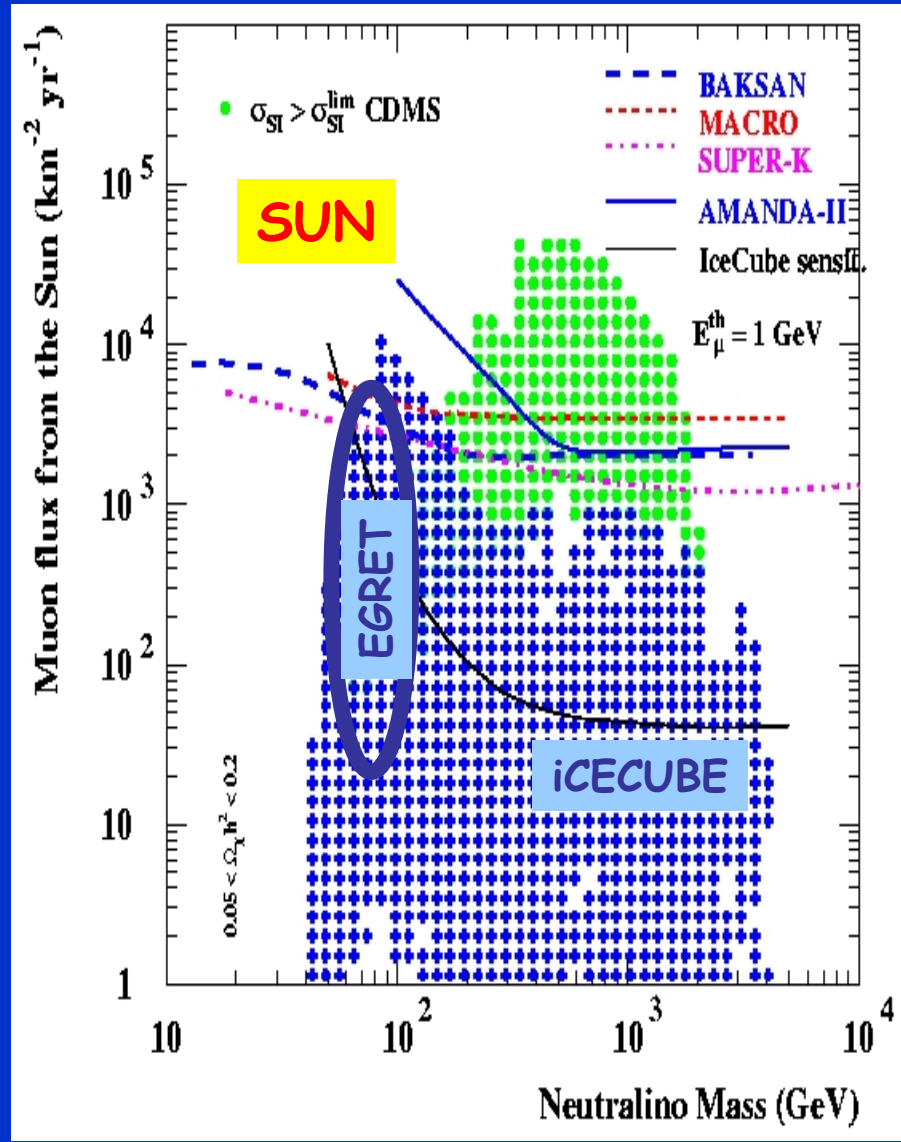


With SUSY spectrum from EGRET + WMAP data and start values of couplings from LEP data perfect gauge coupling unification!

Also  $b \rightarrow s\gamma$  and  $g-2$  agree within  $2\sigma$  with SUSY spectrum from EGRET



# Solar neutrinos and direct DM detection





# Summary



>>  $10\sigma$  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