EGRET excess of diffuse galactic gamma rays as a signal of supersymmetric dark matter annihilation and related particle phenomenology

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Astronomy & Astrophysics (2005)
Phys. Rev. Lett. (2005)
Phys. Lett. B (2006)
Int. J. Mod. Phys. A (2006)
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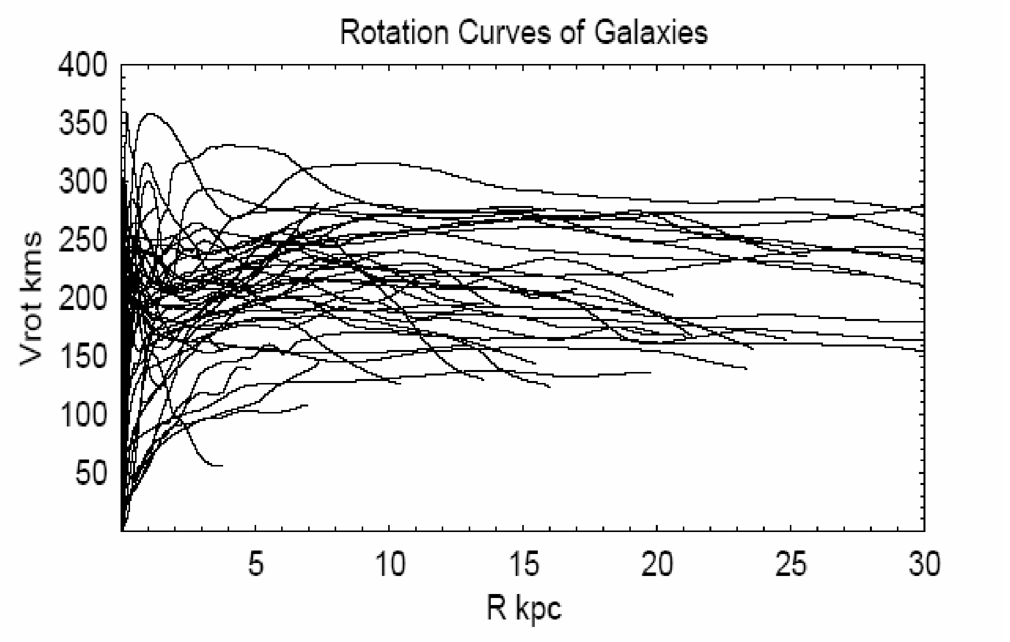
Outlook

- Introduction. Evidence for Dark Matter.
- EGRET data: an excess of the diffuse gamma ray flux
- Dark matter distribution in the Milky Way. Halo density profile. Halo substructure. The Milky Way rotation curve.
- WMAP and EGRET constraints in Constrained Minimal Supersymmetric Standard Model. Phenomenology.
- Conclusions

Evidence for the Dark Matter

- First evidence for the dark matter – motion of galaxies within clusters (F.Zwicky, 1933)

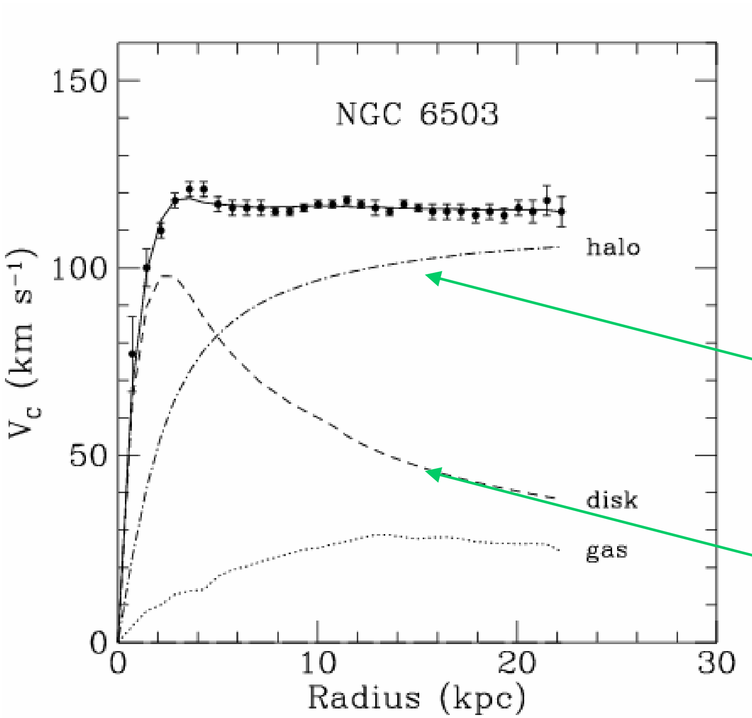
- The most direct evidence for the existence of large amount of the dark matter are the flat rotation curves of spiral galaxies



Evidence for the Dark Matter

- Observation tell us that for large radii *r* $v(r) \propto const$

  which means linear distribution of mass $M_r \propto r$



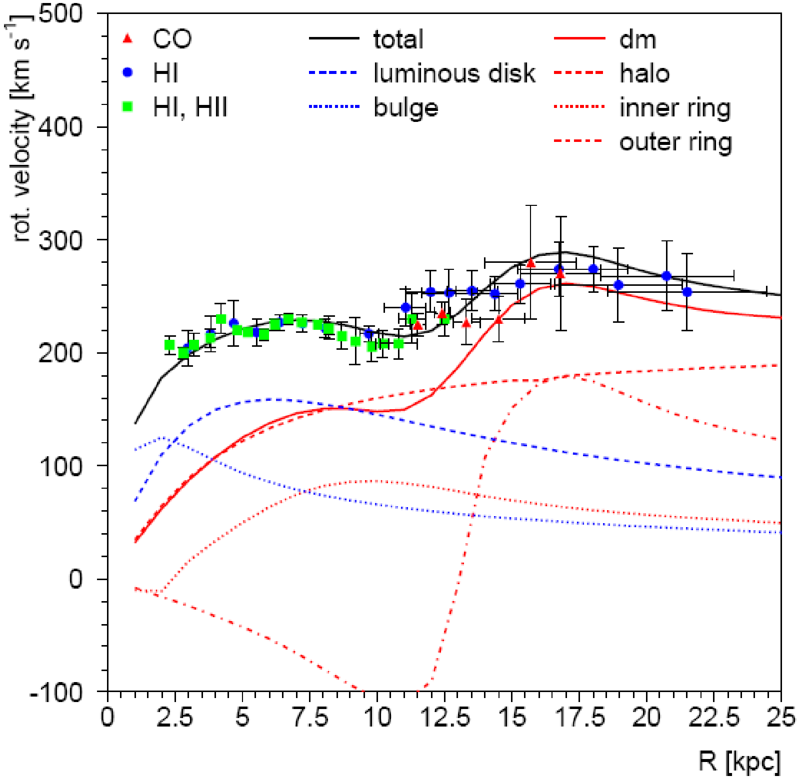
This points to the existence of the huge amount of dark matter surrounding the visible part of the galaxy

Contribution of the dark matter halo alone

Contribution of the disc (visible stars) alone

Evidence for the Dark Matter

- The Milky Way rotation curve has been measured and confirms the usual picture
- Measurements of velocities of Magellanic Clouds tells that the Milky Way has very large and massive halo



WMAP

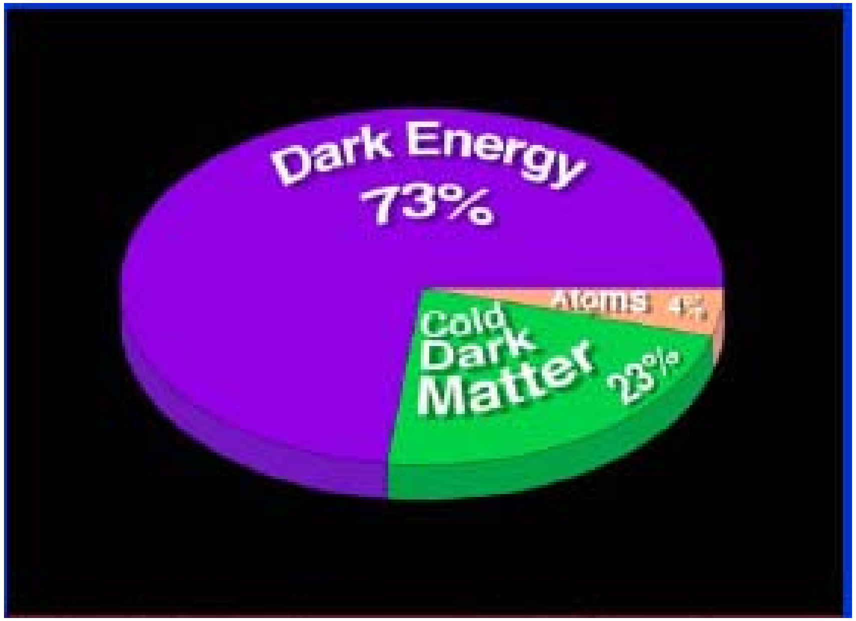
- Results of WMAP

$\rho/\rho_c \simeq 1;\quad \Omega_b = 0.044 \pm 0.004;\quad \Omega_m = 0.27 \pm 0.04;\quad \Omega_\Lambda = 0.73 \pm 0.04;\quad h = 0.71^{+0.04}_{-0.03}$

$0.094 < \Omega_{CDM} h^2 < 0.129\,(95\%CL)$ *C. L. Bennett et al. ApJS.148:97,'03, D. N. Spergel et al. ApJS.148:175,'03*

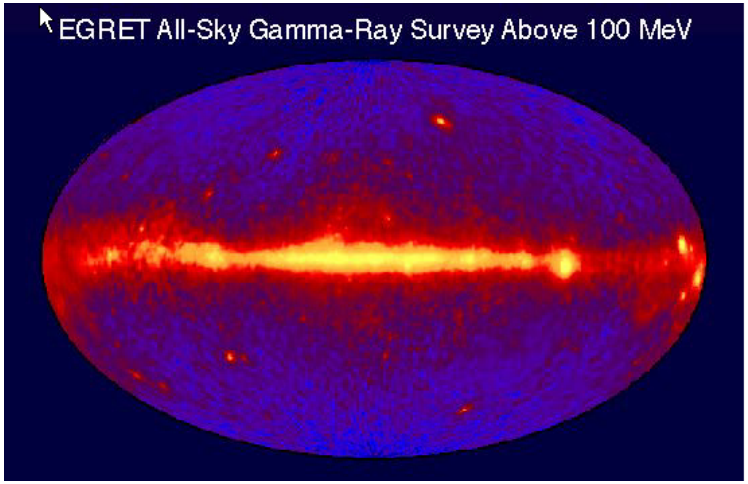
Combination with other cosmic experiments gives

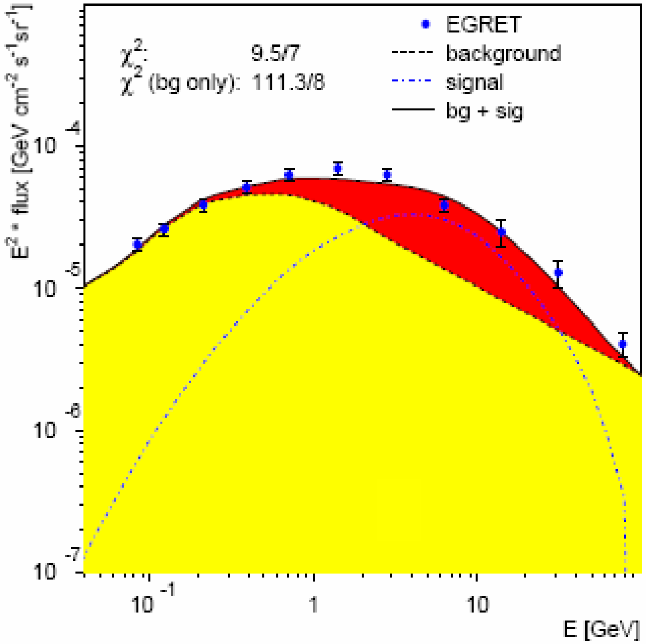
$$\Omega_{DM} h^2 = 0.113 \pm 0.009$$



EGRET Excess

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





- 9 yrs of data taken (1991-2000)

- Main purpose: sky map of point sources above diffuse background.

EGRET Excess

A: Inner Galaxy ($l=\pm30^0$, $|b|<5^0$)

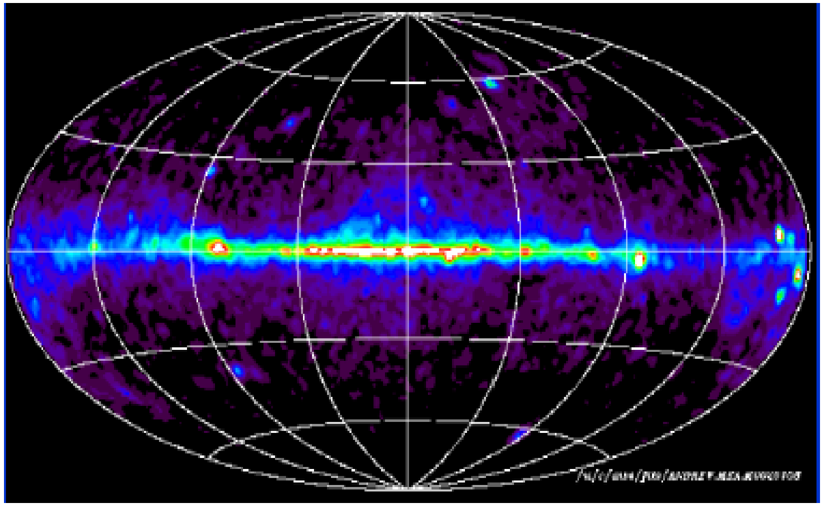
B: Galactic plane avoiding A ($30\text{-}330^0$)

C: Outer Galaxy ($90\text{-}270^0$)

D: Low latitude ($10\text{-}20^0$)

E: Intermediate lat. ($20\text{-}60^0$)

F: Galactic poles ($60\text{-}90^0$)



Region	l, degrees	$\|b\|$, degrees
A	330–30	0–5
B	30–330	0–5
C	90–270	0–10
D	0–360	10–20
E	0–360	20–60
F	0–360	60–90

Excess has the same shape implying the same source everywhere in the galaxy

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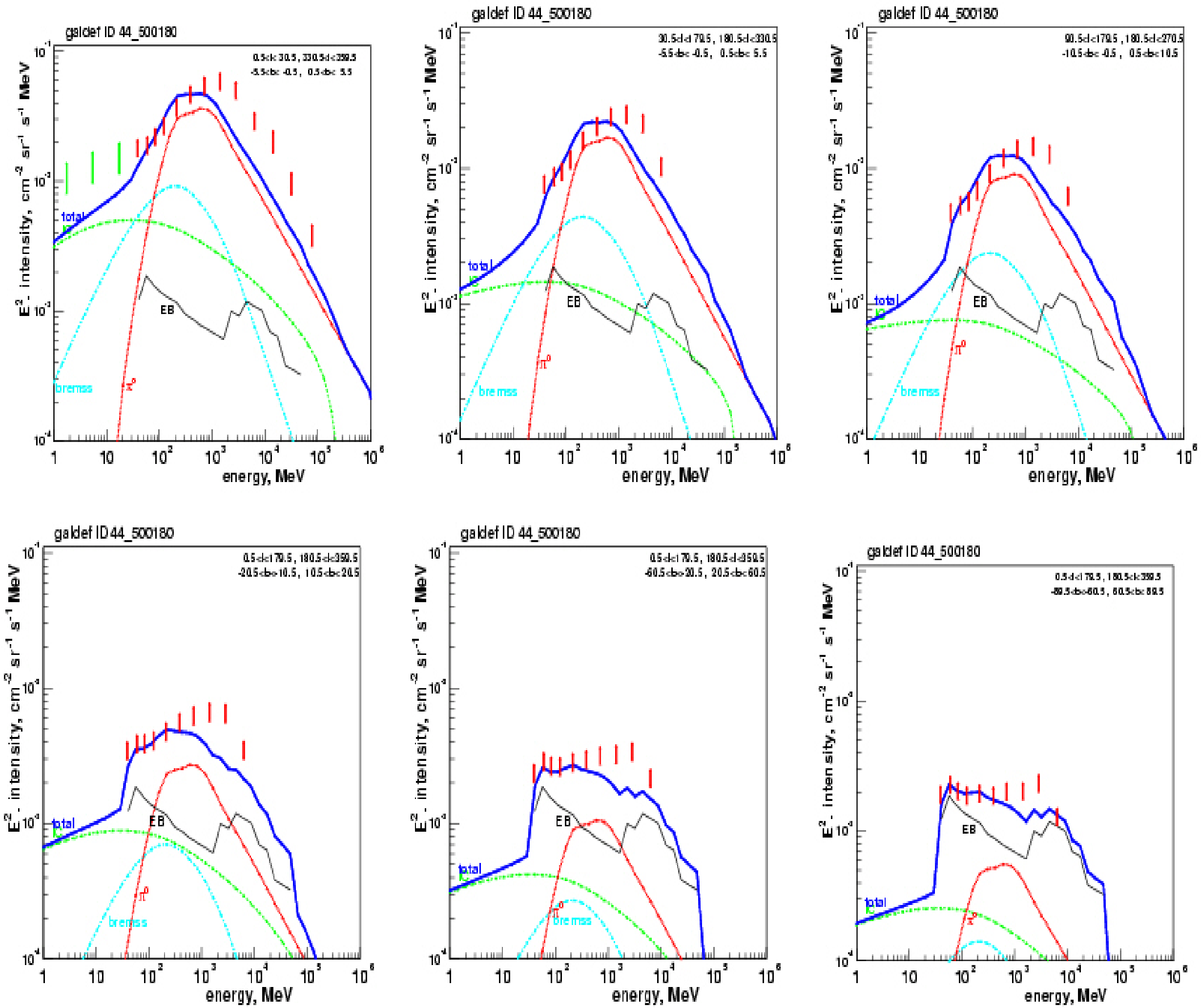

EGRET Excess

A: Inner Galaxy (l=±30^0, |b|<5^0)

B: Galactic plane avoiding A (30-330^0)

C: Outer Galaxy (90-270^0)

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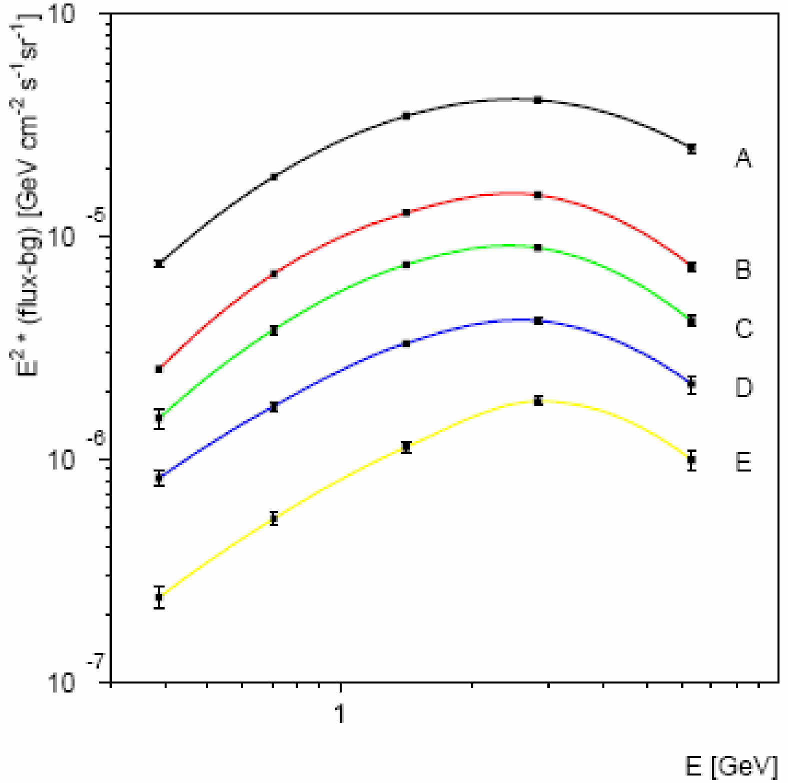


Excess has the same shape implying the same source everywhere in the galaxy

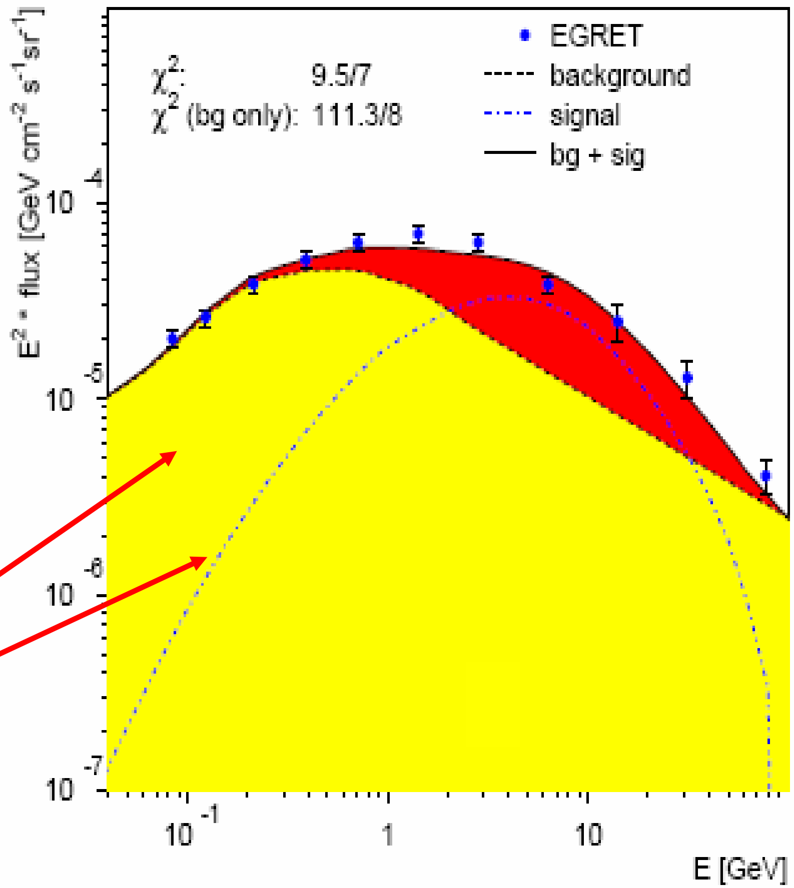
EGRET gamma excess above extrapolated background from data below 0.5 GeV

EGRET Excess vs WIMP annihilation

- The excess of diffuse gamma rays is compatible with WIMP mass of 50 -100 GeV
- Region A: inner Galaxy ($l=\pm30^0$, $|b|<5^0$)

Background

WIMP contribution



EGRET Excess vs WIMP annihilation

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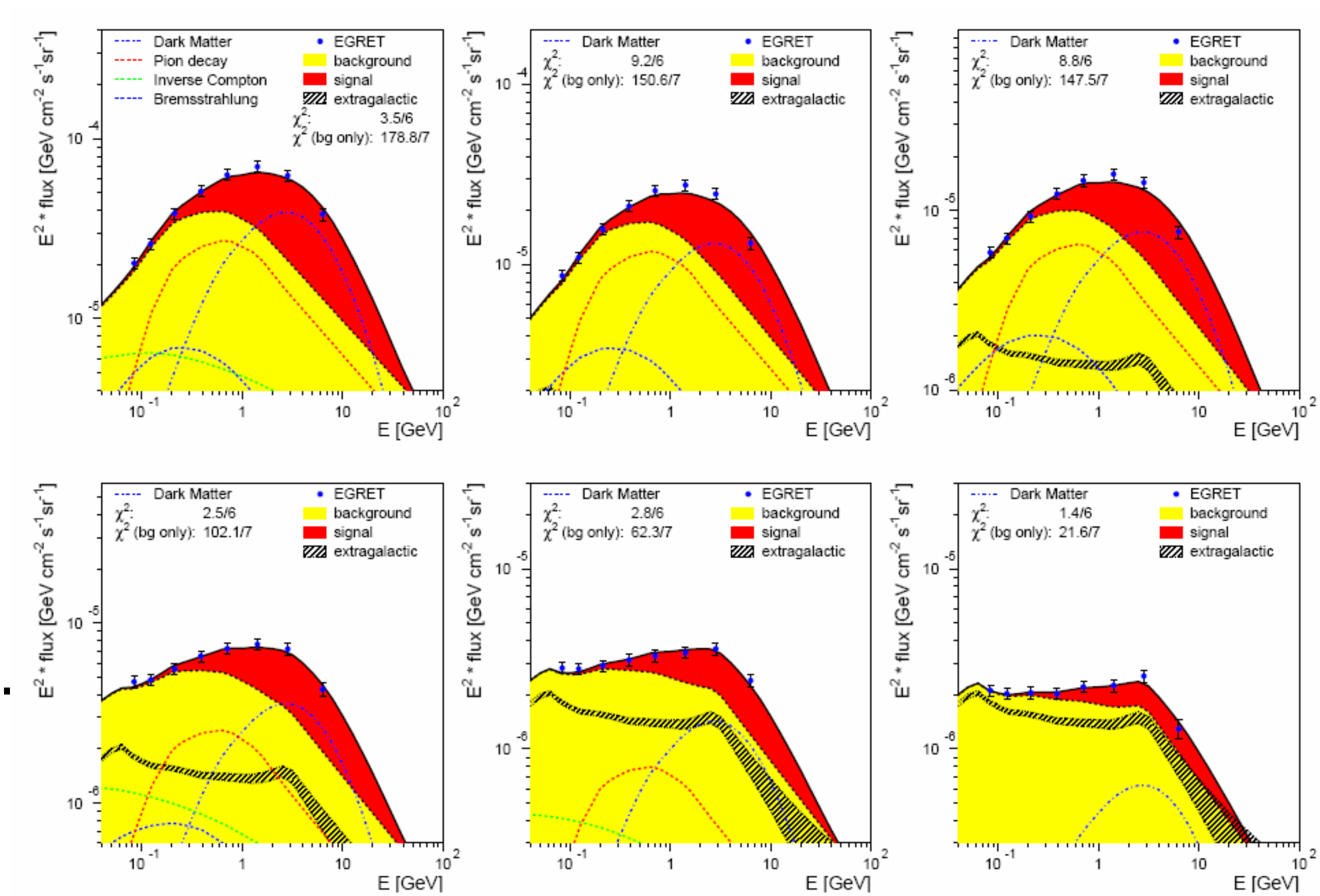


Determination of halo profile

- Rotation curves of many galaxies shows that the halo distributions can be fitted with the profile which can be parametrized as follows:

$$\rho_\chi(\tilde{r}) = \rho_0 \left(\frac{R_0}{\tilde{r}}\right)^\gamma \left[\frac{1+\left(\frac{\tilde{r}}{a}\right)^\alpha}{1+\left(\frac{R_0}{a}\right)^\alpha}\right]^{\frac{\gamma-\beta}{\alpha}} \quad \tilde{r} = \sqrt{\frac{x^2}{a^2}+\frac{y^2}{b^2}+\frac{z^2}{c^2}},$$

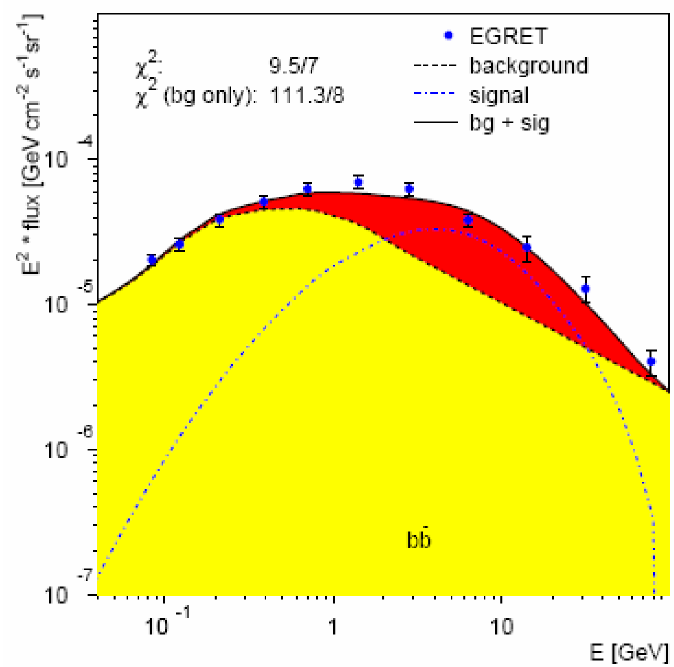
a is a scale radius, α, β, γ define behaviour at $r \approx a$, $r >> a$ and $r << a$

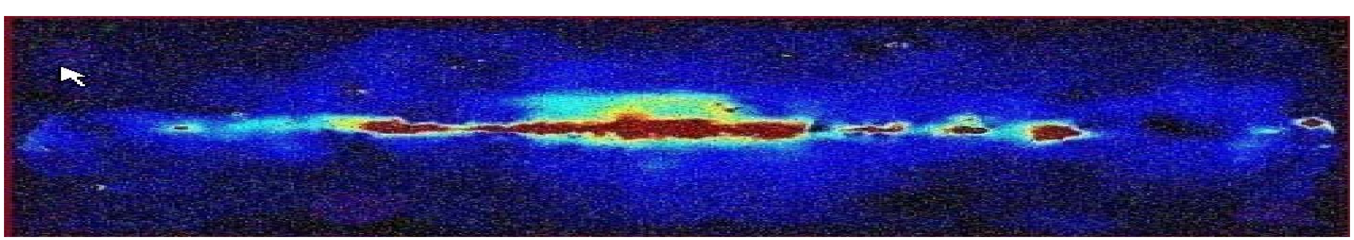
- Parameters in halo profile fitted by requiring minimal difference between boostfactors of various regions.

- ρ_0 can be estimated from the rotation curve to be 0.3 GeV/cm^3 for a spherical profile and R_0 = 8.5 kpc. Otherwise the density has to be rescaled.

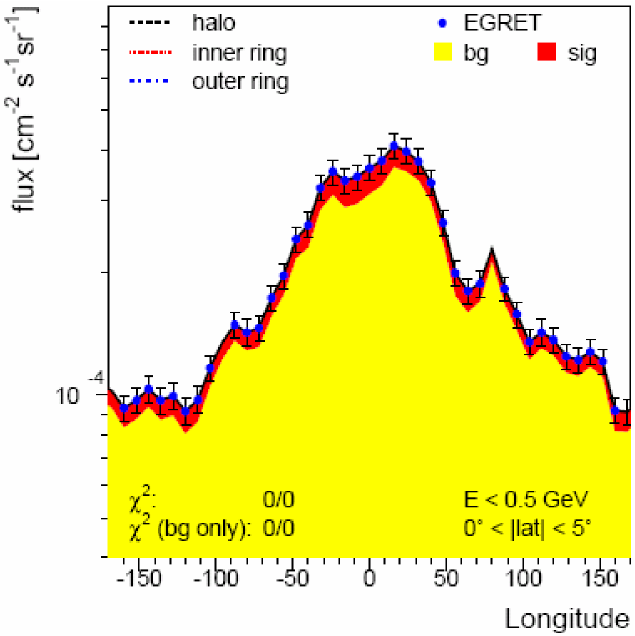
Determination of halo profile

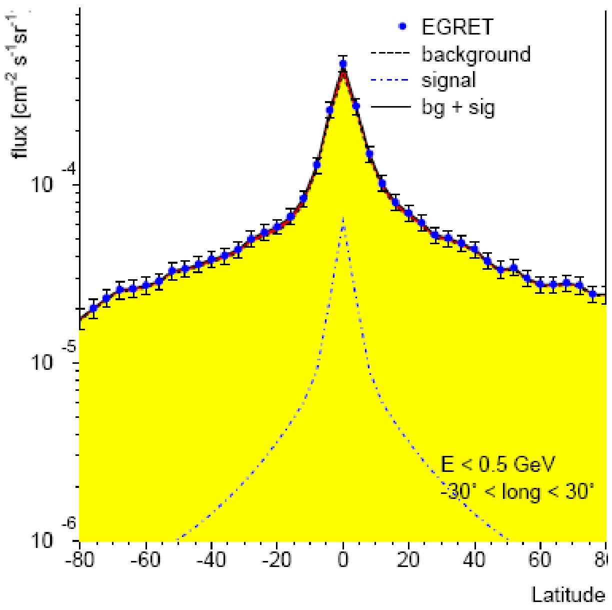
- Energy spectrum of diffuse gamma rays is well described by background + WIMP annihilation
- Longitude and lattitude distributions (different sky directions!) of gammas are used for determination of halo and substructure (rings) parameters





Gammas below 0.5 GeV (EGRET)





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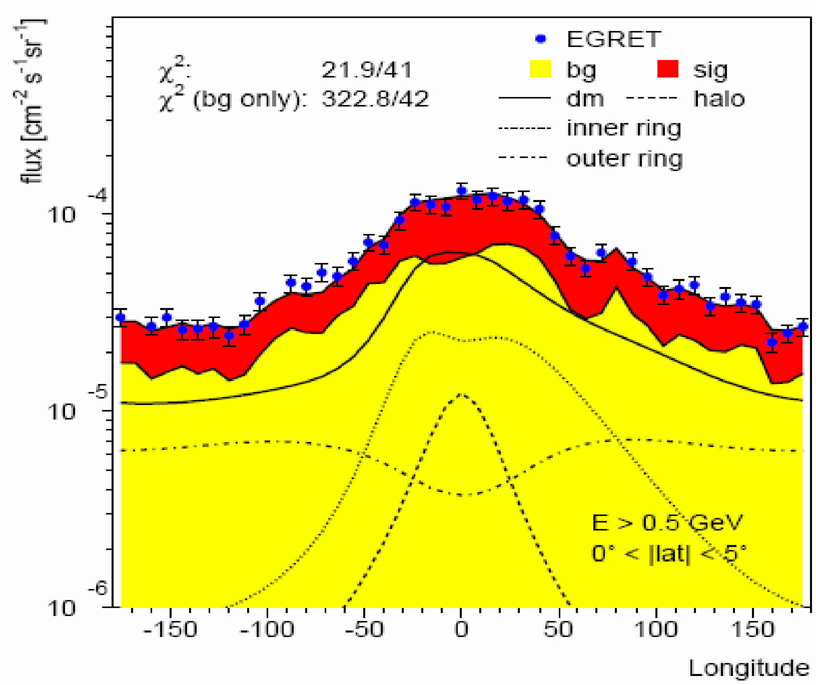
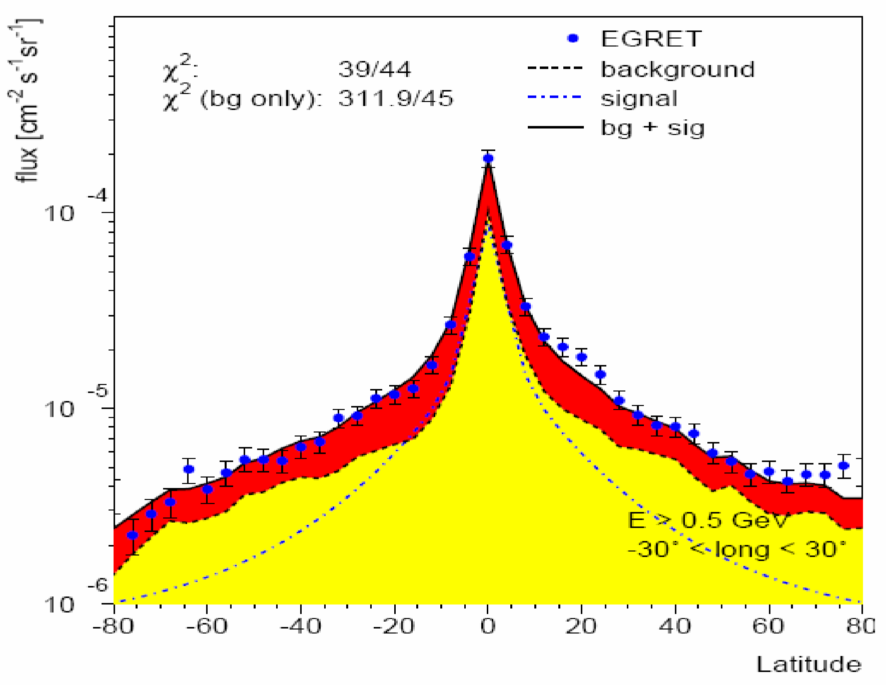




Determination of halo profile

- The possible enhancement of DM density in the disc was parametrized by a set of Gaussian rings in the galactic plane in addition to the expected triaxial profile for the DM halo. At least two rings should be envisaged: one “outer” ring and one “inner” ring. Parameters of the rings can be determined from a fit to the data.

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

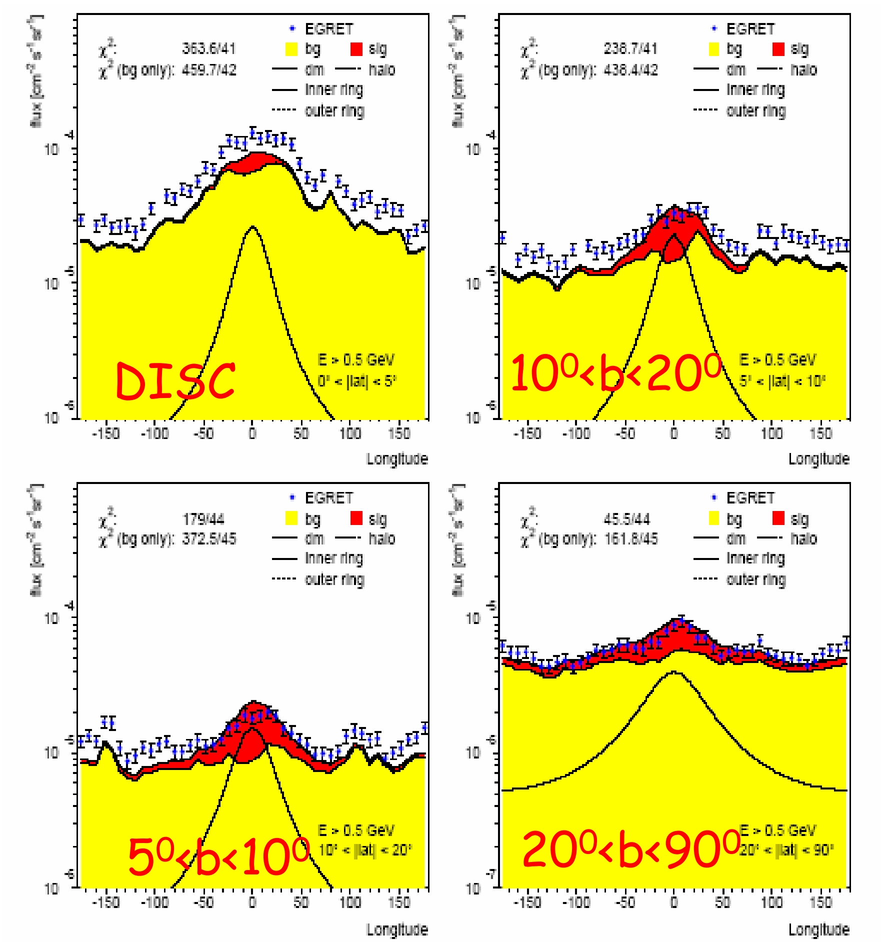
$\propto$ **1/r²**

2 Gaussian ovals

$$\tilde{r} = \sqrt{\frac{x^2}{a^2}+\frac{y^2}{b^2}+\frac{z^2}{c^2}}, \qquad \tilde{r}_{gc} = \sqrt{\frac{x^2}{\tilde{a}^2}+\frac{y^2}{\tilde{b}^2}},$$

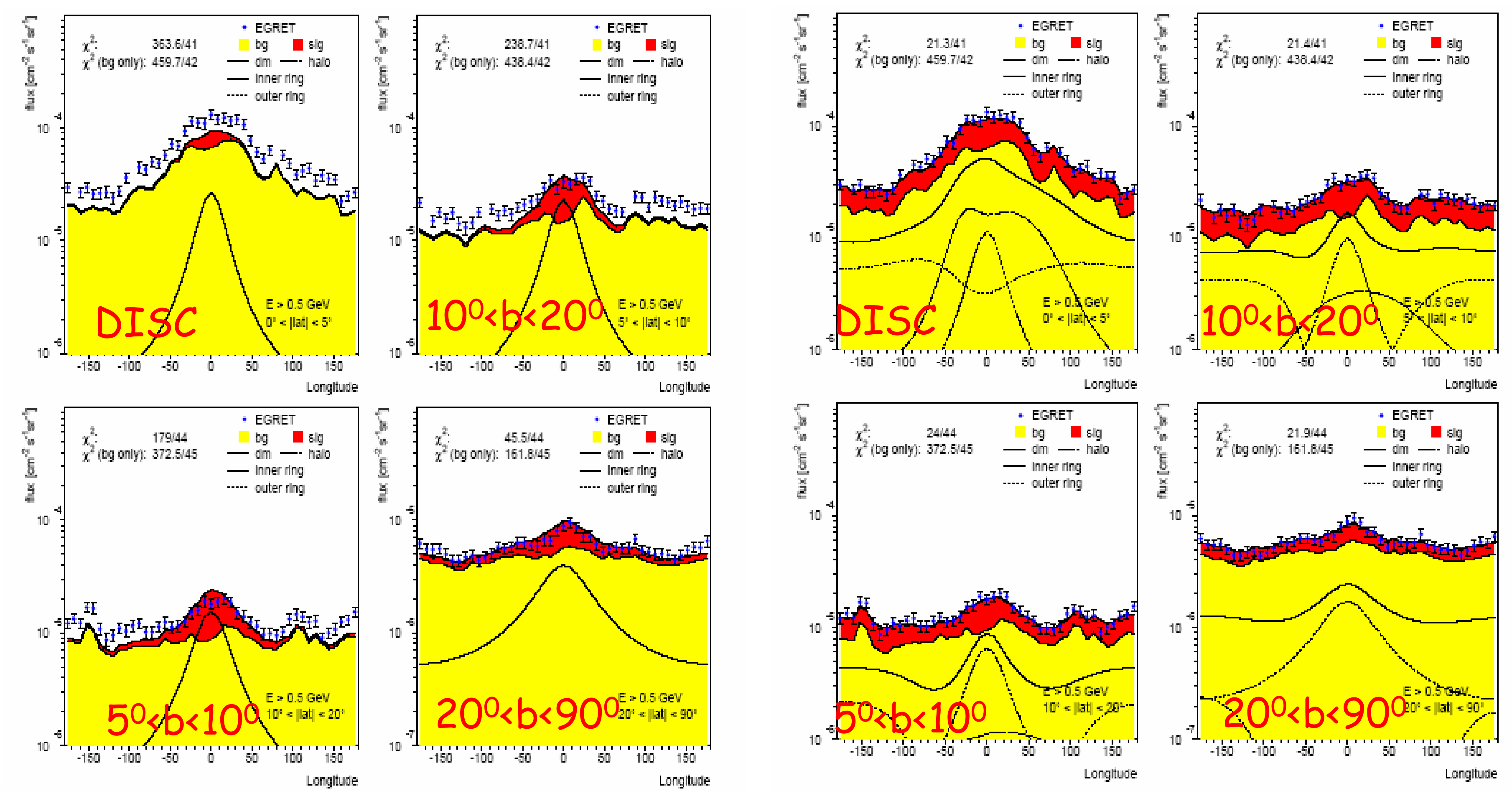
Fits for 1/r² profile with/without rings

WITHOUT rings



Fits for 1/r² profile with/without rings

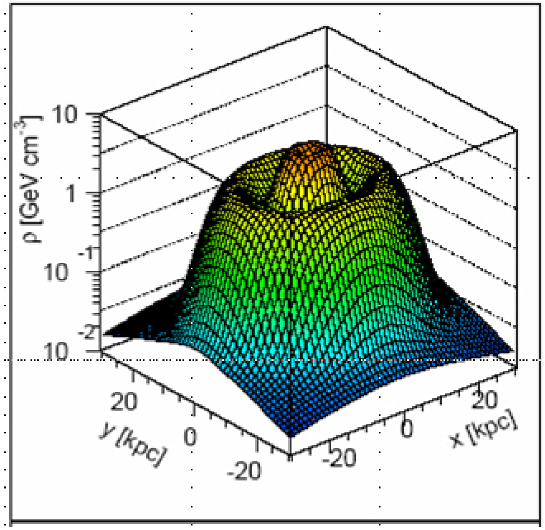
WITHOUT rings WITH 2 rings



Fit results for halo profile

Fit results of halo parameters

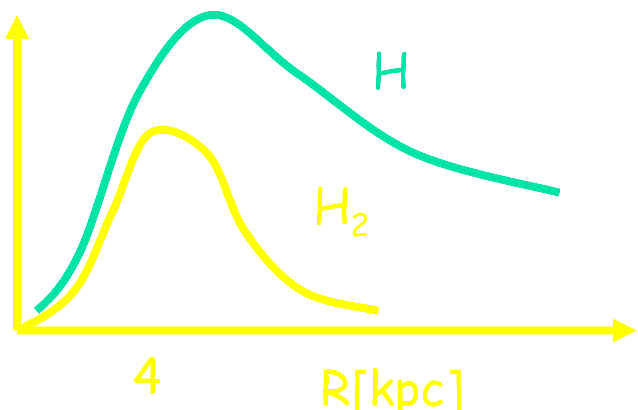
Parameter	Value	Parameter	Value
α	2	R_a	$4.3\ kpc$
β	2	$\sigma_{R,a}$	$3.4\ kpc$
γ	0	$\sigma_{z,a}$	$0.3\ kpc$
R_0	8.5 kpc	ρ_b	1.2-2.1 GeV cm^{-3}
a	4 kpc	R_b	$14\ kpc$
ρ_0	0.42 GeV cm^{-3}	$\sigma_{R,b}$	$2.1\ kpc$
ρ_a	1.8-3.3 GeV cm^{-3}	$\sigma_{z,b}$	$1.3\ kpc$
b/a	0.9	c/a	0.8

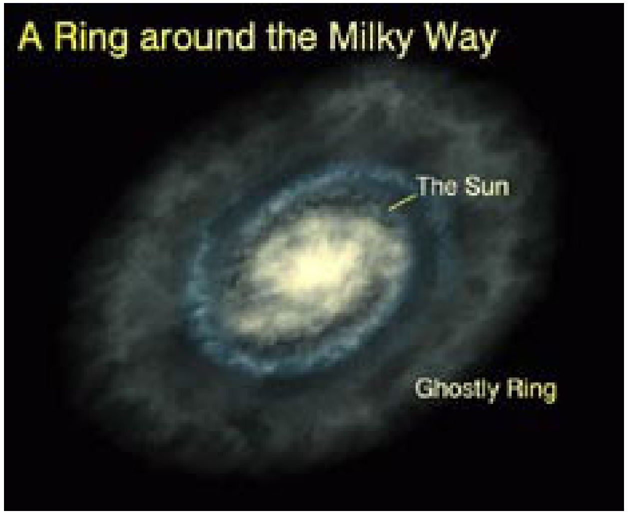


Enhancement of rings over $1/r^2$ profile 2 and 7, respectively.
Mass in rings 1.6% and 0.3% of total Dark Matter

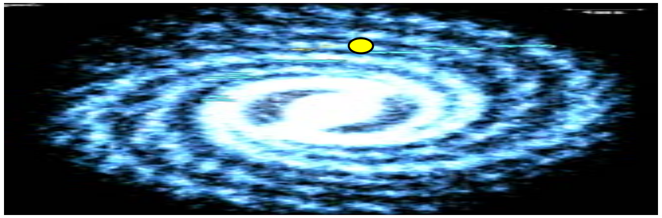
Determination of halo profile

- 14 kpc coincides with ring of stars at 14-18 kpc due to infall of dwarf galaxy (Yanny, Ibata, ….., 2003)
- 4 kpc coincides with ring of neutral hydrogen molecules!

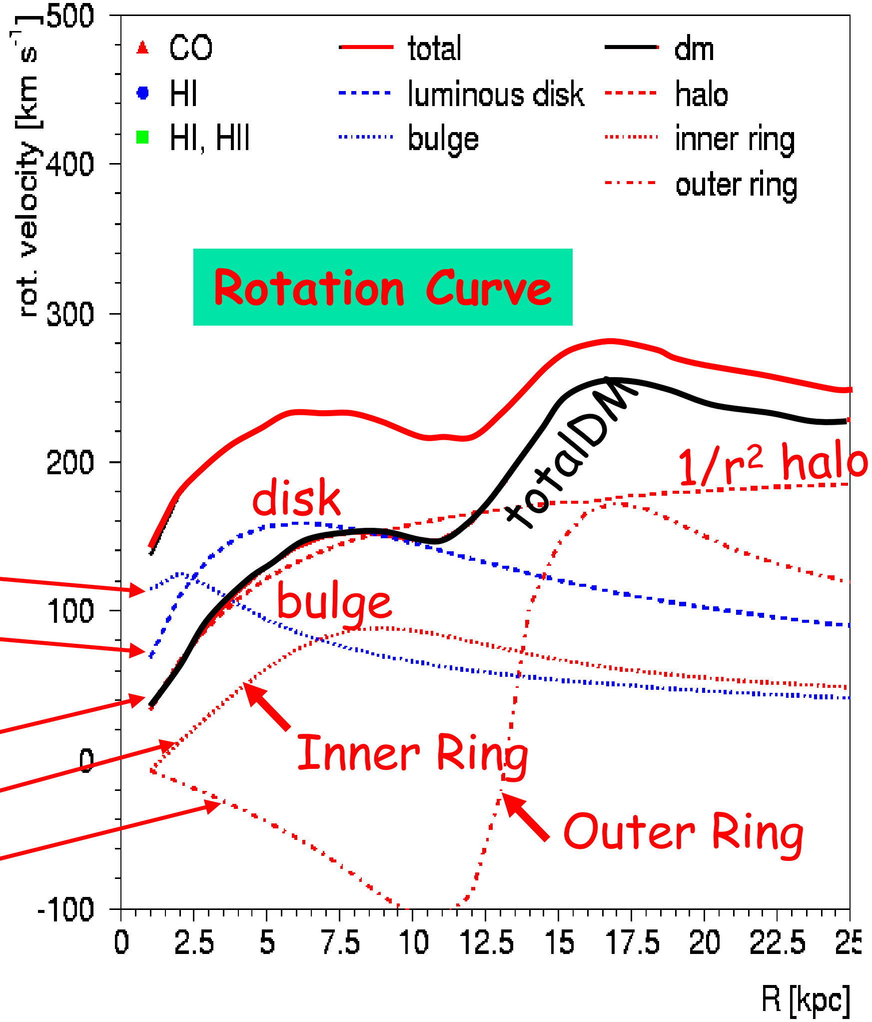




The Milky Way rotation curve



- Contributions to the rotation curve of the Milky Way from
  - Visible bulge
  - Visible disk
  - Dark halo
  - Inner dark ring
  - Outer dark ring



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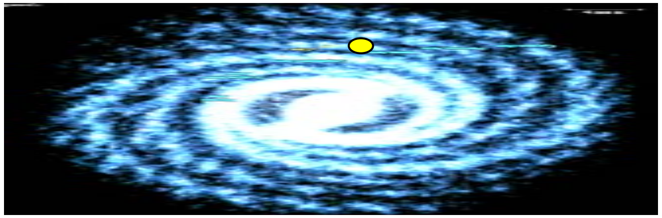

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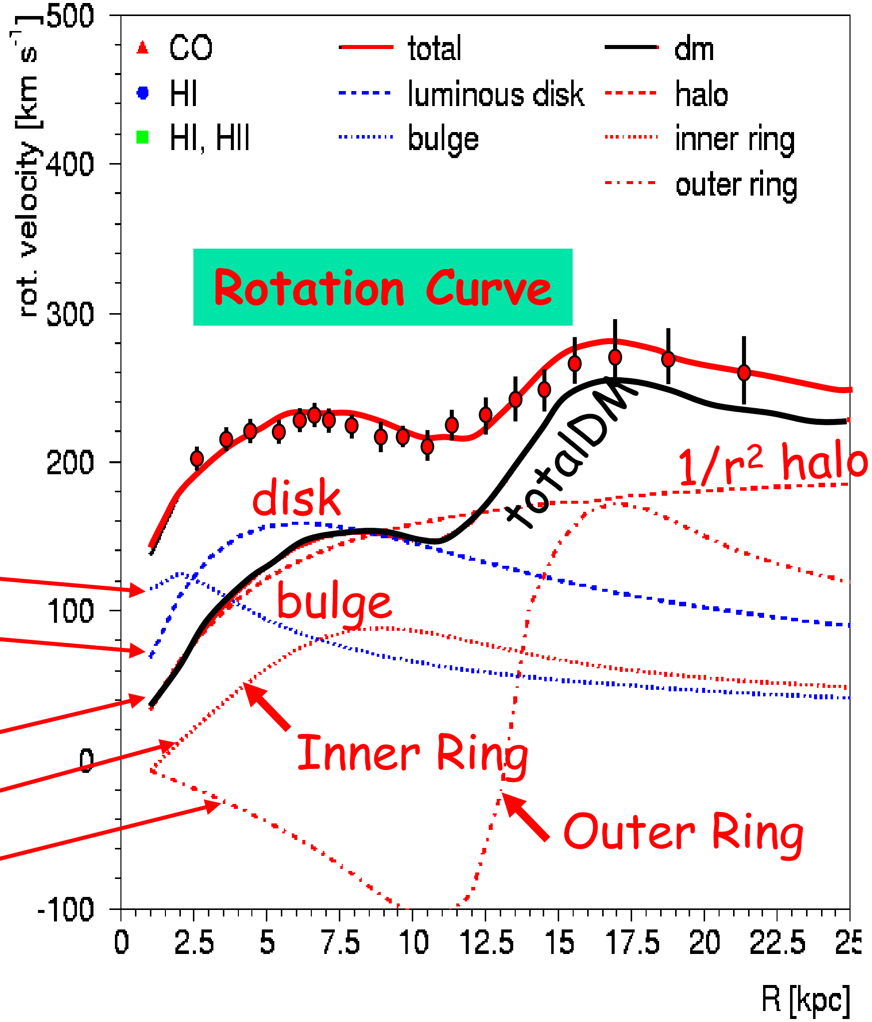
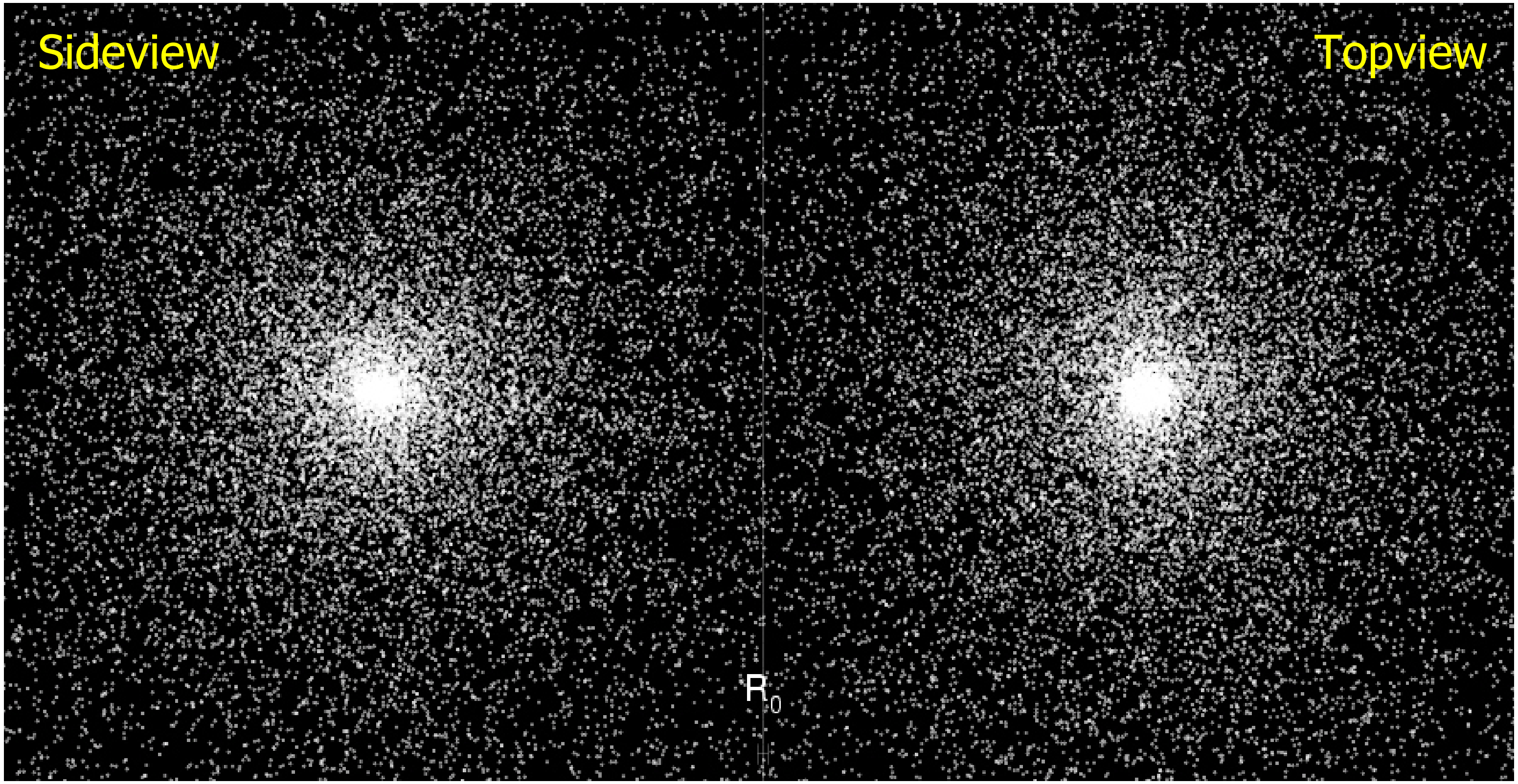
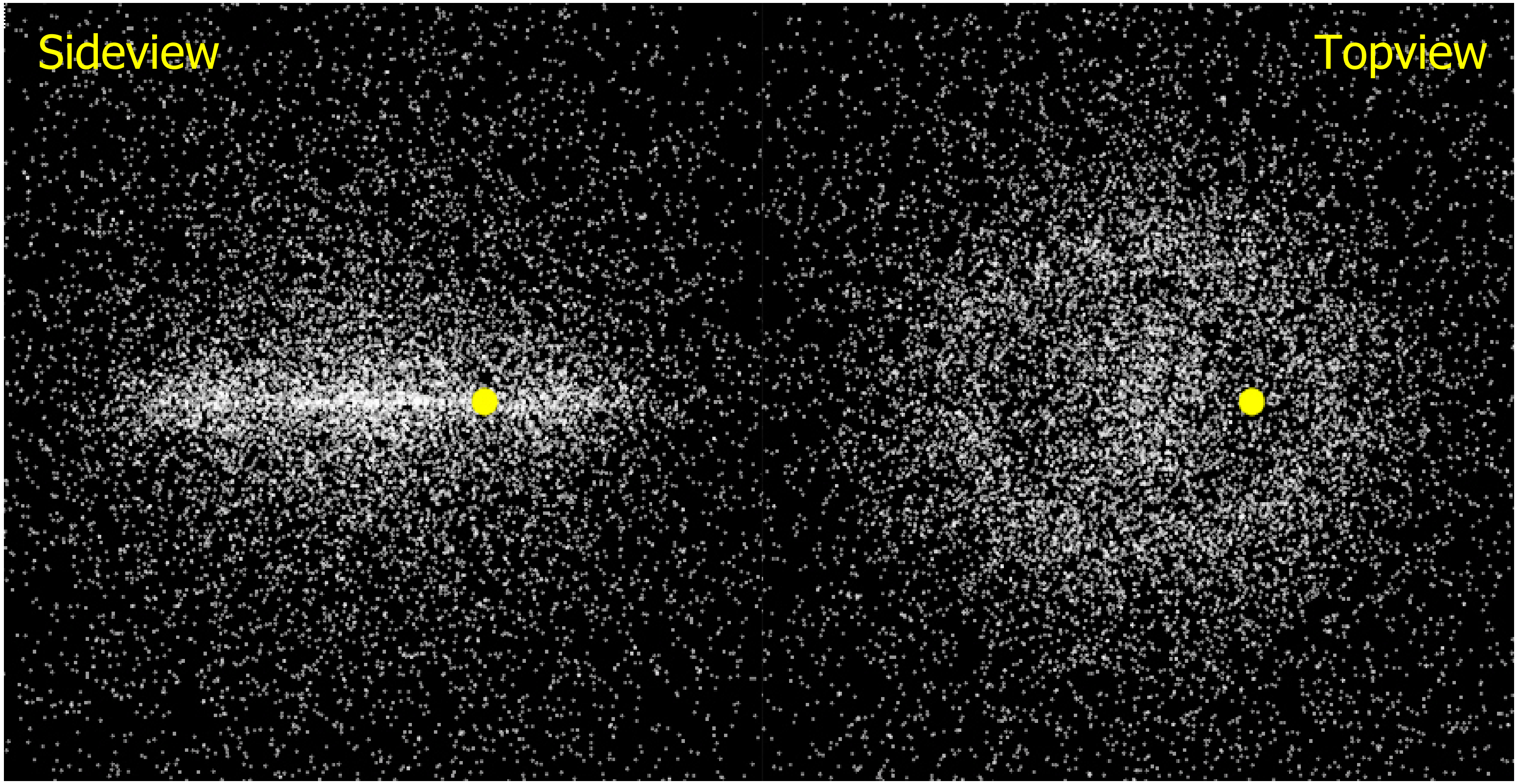


Halo density at 300 kpc



Cored isothermal halo profile. Total mass: 3×10^{12} solar masses

Halo density at 30 kpc



Ring halo substructure. R ~ 4 and 14 kpc.

Neutralino – SUSY dark matter

- Still we know nothing about WIMP
- Supersymmetry helps again

	Superfield	Bosons		Fermions		$SU_c(3)$	$SU_L(2)$	$U_Y(1)$
Gauge	$\mathbf{G^a}$	gluon	g^a	gluino	$\tilde{g}^a$	8	1	0
	$\mathbf{V^k}$	Weak	W^k $(W^\pm, Z)$	wino, zino	$\tilde{w}^k$ $(\tilde{w}^\pm, \tilde{z})$	1	3	0
	$\mathbf{V'}$	Hypercharge	B (γ)	bino	$\tilde{b}(\tilde{\gamma})$	1	1	0
Matter	$\mathbf{L_i}$	sleptons	$\tilde{L}_i = (\tilde{\nu}, \tilde{e})_L$	leptons	$L_i = (\nu, e)_L$	1	2	-1
	$\mathbf{E_i}$		$\tilde{E}_i = \tilde{e}_R$		$E_i = e_R$	1	1	2
	$\mathbf{Q_i}$	squarks	$\tilde{Q}_i = (\tilde{u}, \tilde{d})_L$	quarks	$Q_i = (u, d)_L$	3	2	1/3
	$\mathbf{U_i}$		$\tilde{U}_i = \tilde{u}_R$		$U_i = u^c_R$	3^*	1	$-4/3$
	$\mathbf{D_i}$		$\tilde{D}_i = \tilde{d}_R$		$D_i = d^c_R$	3^*	1	2/3
Higgs	$\mathbf{H_1}$	Higgses	H_1 $(h, H, A, H^\pm)$	higgsinos	$\tilde{H}_1$ $(\tilde{h}_1, \tilde{h}_2, \tilde{h}^\pm)$	1	2	-1
	$\mathbf{H_2}$		H_2		$\tilde{H}_2$	1	2	1

Neutralino – SUSY dark matter

- Neutralino – a mixture of superpartners of photon, Z-boson and neutral Higgs bosons

$$\tilde{\chi}^0 = N_1 \tilde{\gamma} + N_2 \tilde{z} + N_3 \tilde{H}_1^0 + N_4 \tilde{H}_2^0$$

photino zino higgsino higgsino

  - Neutral (no electric charge, no colour)
  - Weakly interacting (due to supersymmetry)
  - Stable (!) if R-parity is conserved
  - Heavy enough to account for cold non-baryonic dark matter
  - Annihilation cross sections are known (at least we know how to calculate them)

$$R = (-1)^{3(B-L)+2S}$$

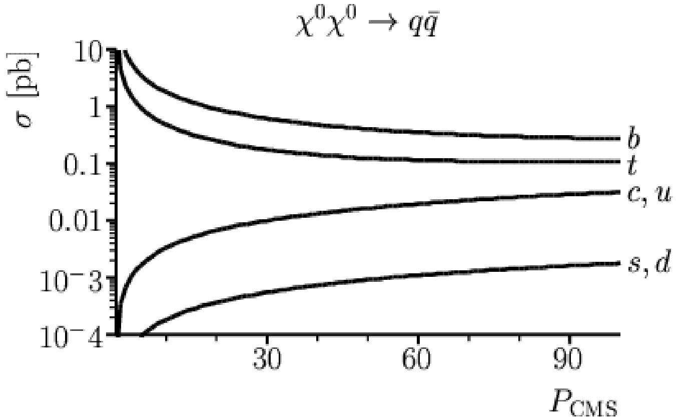
$$R_p = +1, \; R_{\tilde{p}} = -1$$

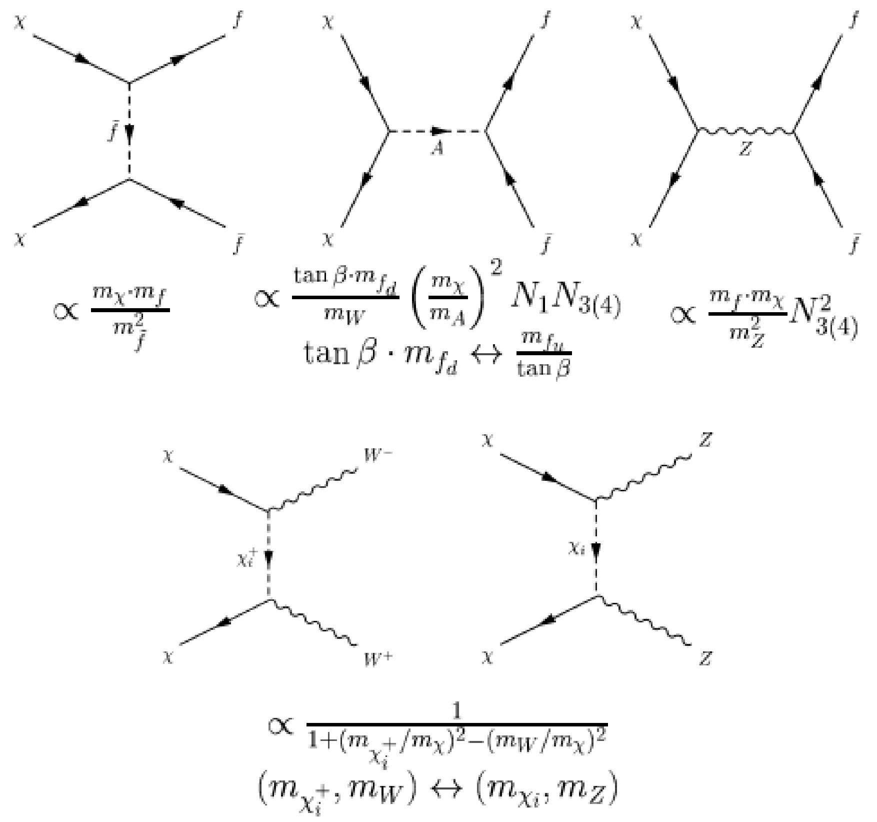
- Perfect candidate for dark matter particle (WIMP)

Neutralino – SUSY dark matter

- Main diagrams for neutralino annihilation
- Dominant diagram for WMAP cross section:

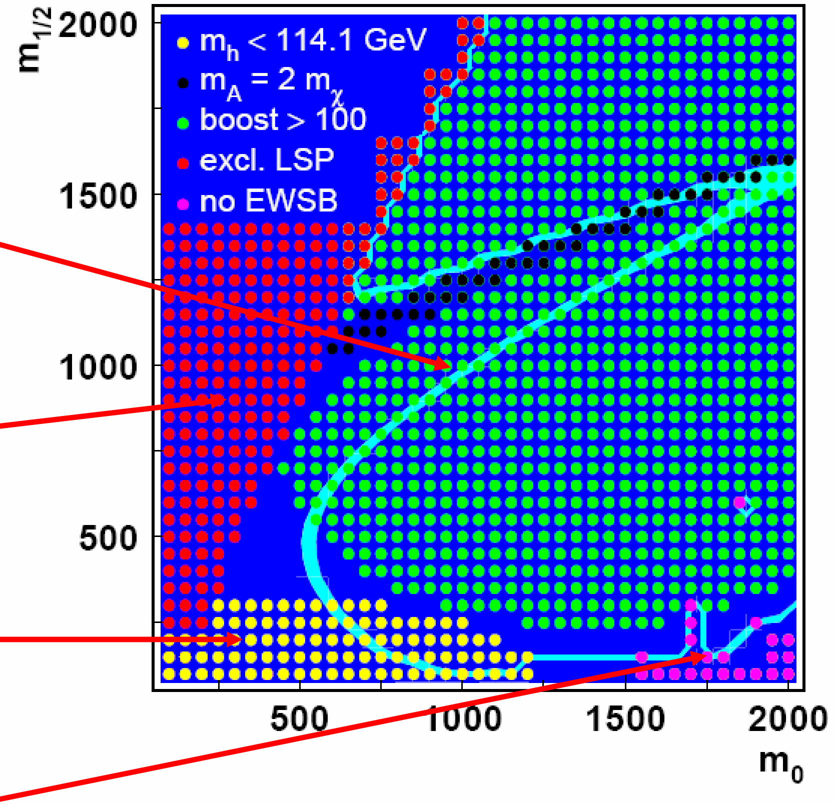
$$\chi\chi \to A \to b\bar{b}$$





Favoured regions of parameter space

- WMAP data leave only very small allowed region as shown by the thin blue line which give acceptable neutralino relic density
- Excluded by LSP
- Excluded by Higgs searches at LEP2
- Excluded by REWSB



m_0 – common scalar mass
$m_{1/2}$ – common gaugino mass

Favoured regions of parameter space

- The region compatible with all electroweak constraints as well as with WMAP and EGRET constraints are rather small

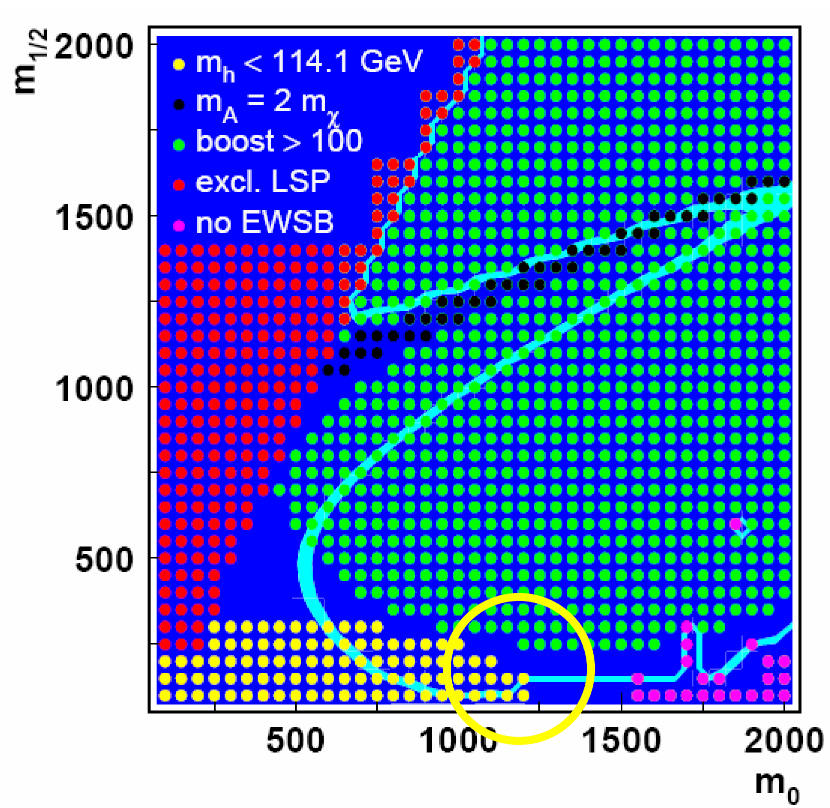
- It corresponds to the best fit values of parameters

  $\tan\beta = 51$

  $m_0 = 1400$ GeV

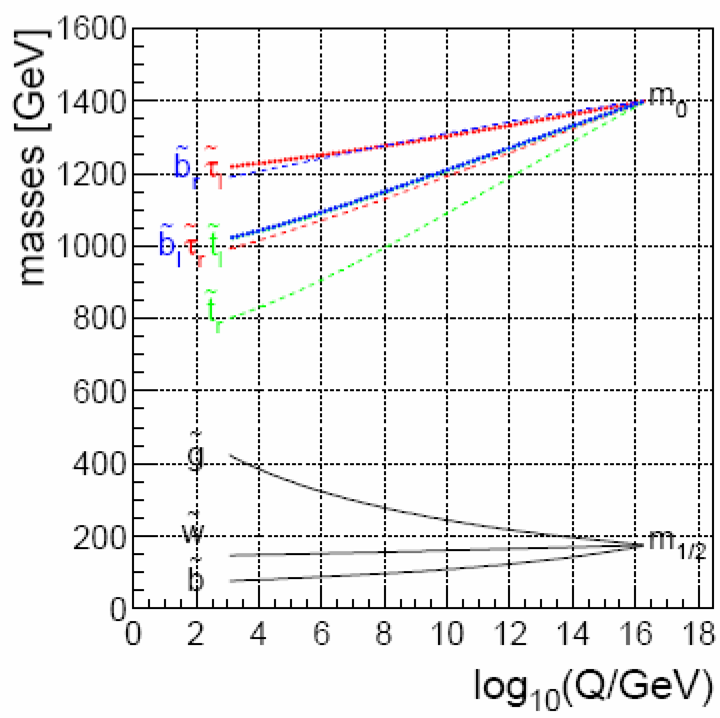
  $m_{1/2} = 180$ GeV

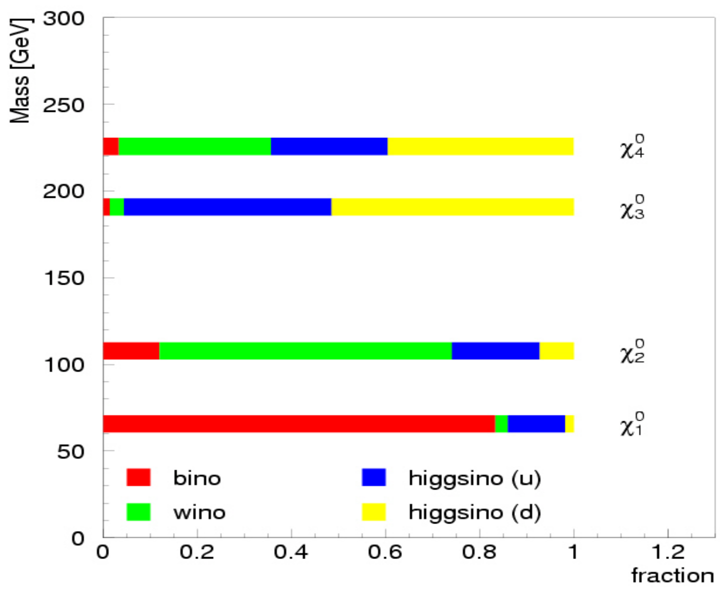
  $A_0 = 0.5\ m_0$



Favoured regions of parameter space

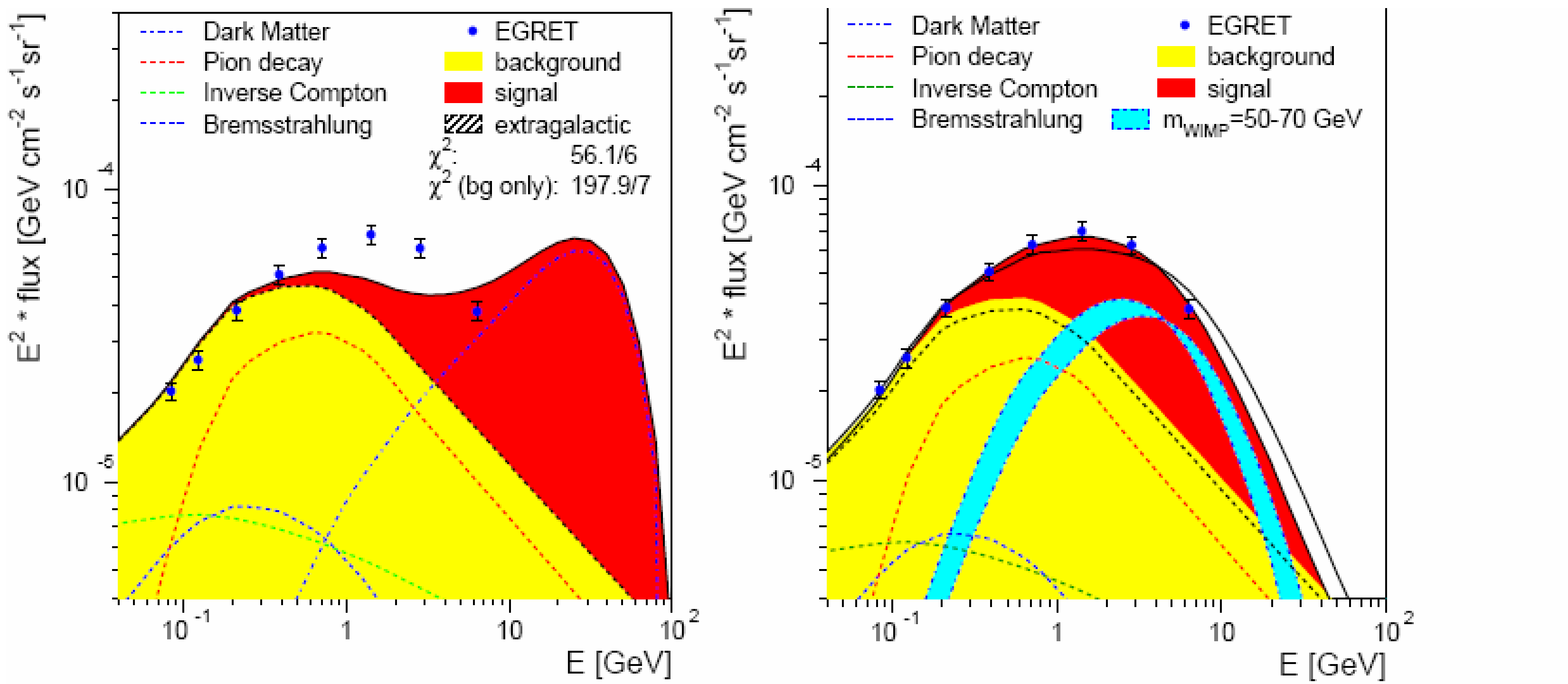
- Superparticle spectrum for m_0=1400 GeV, $m_{1/2}$=180 GeV
- Squarks/sleptons are in TeV range
- Charginos and neutralinos are light





- LSP is largely Bino

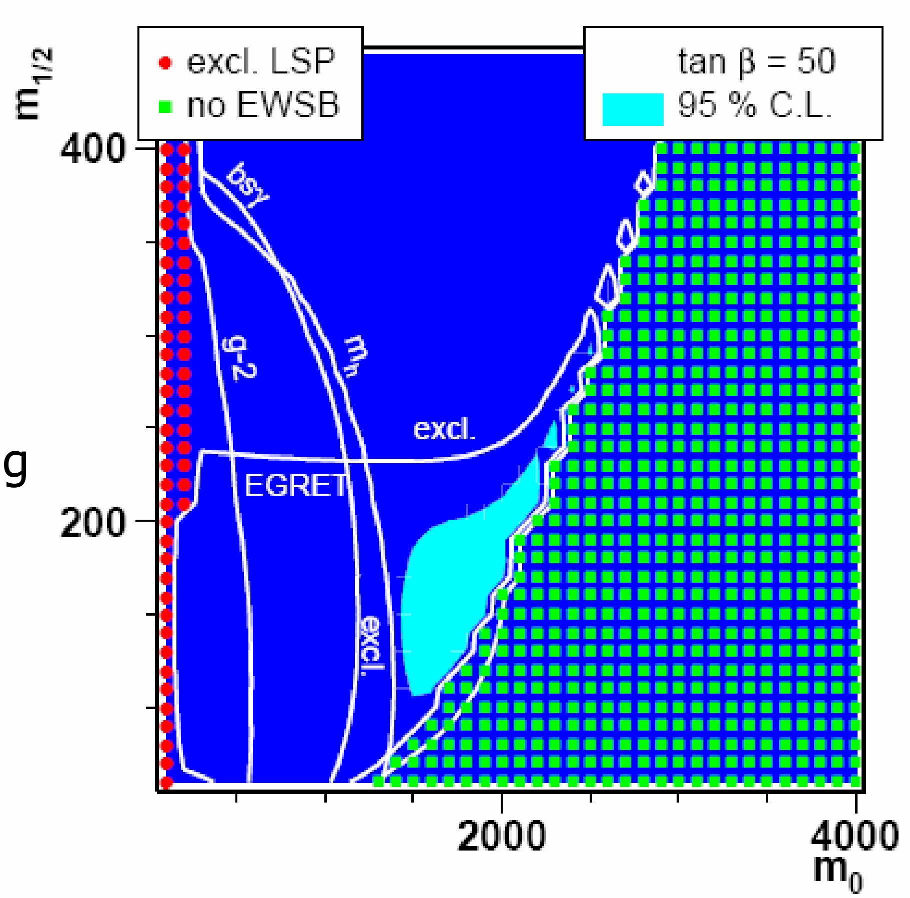
Favoured regions of parameter space



: *The EGRET gamma ray spectrum fitted with DM annihilation for* $(m_0 = 70, m_{1/2} = 250, \tan\beta = 10)$ *(left) and* $(\mathrm{m}_0 = 1400, \mathrm{m}_{1/2} = 175, \tan\beta = 51)$ *(right). In both cases the relic density corresponds to the WMAP value, but in the first case of low* m_0 *the annihilation into stau pairs dominates, while in the latter case the annihilation into b-quarks dominates.*

Favoured regions of parameter space

- SUSY parameter space allowed by the EGRET data and other constraints given by electroweak data, neutrality of the LSP and electroweak symmetry breaking



Favoured regions of parameter space

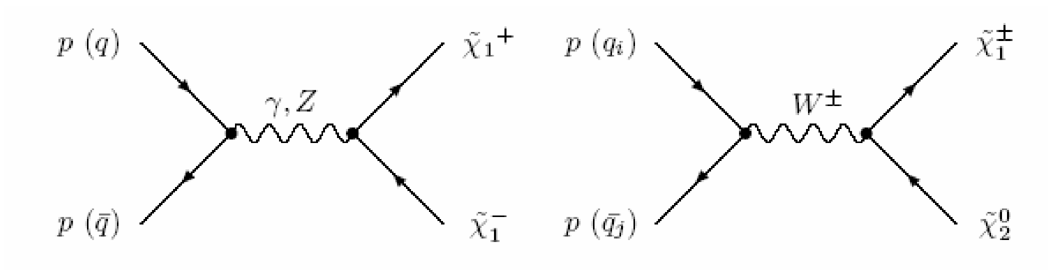
- SUSY parameters and superparticle spectrum

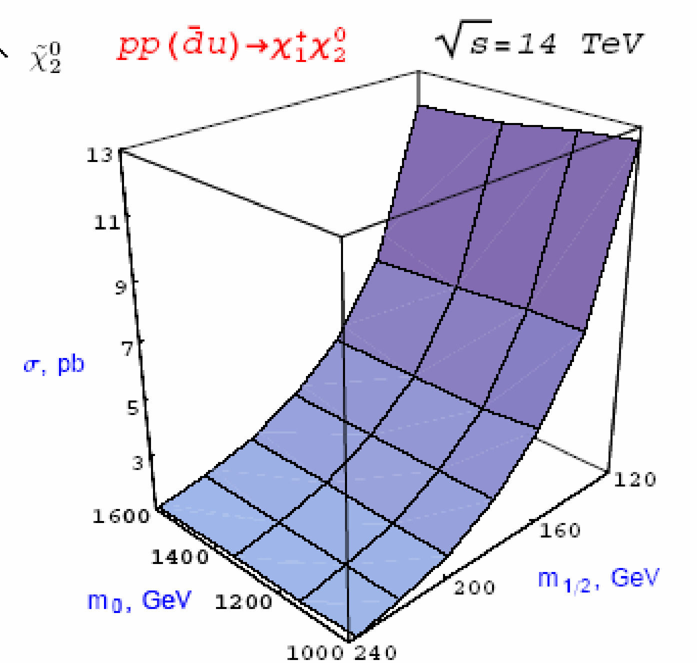
Parameter	Value
m_0	1500 GeV
$m_{1/2}$	170 GeV
A_0	$0 \cdot m_0$
$\tan\beta$	52.2
sign μ	$+$
$\alpha_s(M_Z)$	0.122
$\alpha_{em}(M_Z)$	0.0078153697
$1/\alpha_{em}$	127.953
$\sin^2(\theta_W)_{\overline{MS}}$	0.2314
m_t	175 GeV
m_b	4.214 GeV

Particle	Mass [GeV]
$\tilde{\chi}^0_{1,2,3,4}$	64, 113, 194, 229
$\tilde{\chi}^{\pm}_{1,2}, \tilde{g}$	110, 230, 516
$\tilde{u}_{1,2} = \tilde{c}_{1,2}$	1519, 1523
$\tilde{d}_{1,2} = \tilde{s}_{1,2}$	1522, 1524
$\tilde{t}_{1,2}$	906, 1046
$\tilde{b}_{1,2}$	1039, 1152
$\tilde{e}_{1,2} = \tilde{\mu}_{1,2}$	1497, 1499
$\tilde{\tau}_{1,2}$	1035, 1288
$\tilde{\nu}_e, \tilde{\nu}_\mu, \tilde{\nu}_\tau$	1495, 1495, 1286
$h, H, A, H^{\pm}$	115, 372, 372, 383
Observable	**Value**
$Br(b \to X_s\gamma)$	$3.02 \cdot 10^{-4}$
Δa_μ	$1.07 \cdot 10^{-9}$
Ωh^2	0.117

Superparticle production at LHC

- Light SUSY particles can be produces in reactions



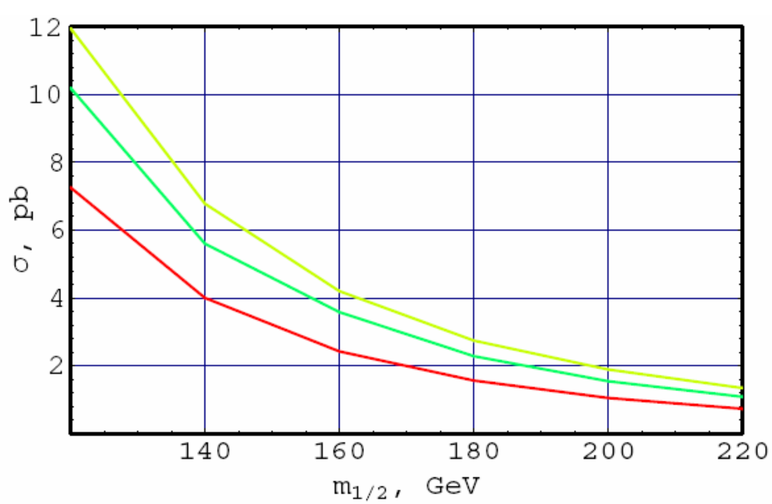


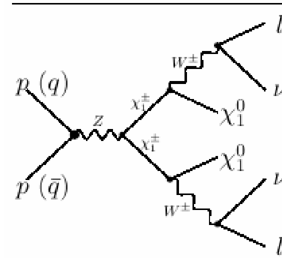
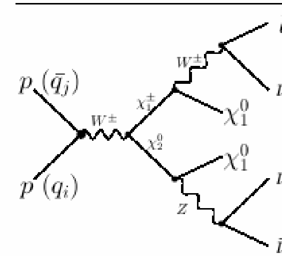
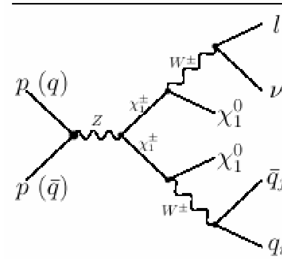
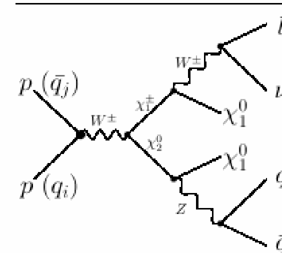
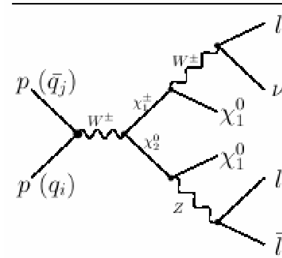
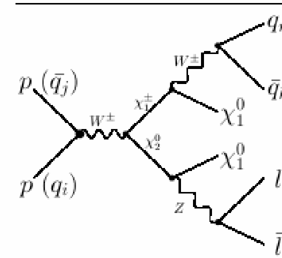
- The first chargino is relatively light due to the gaugino component

- The cross-section is almost independent of m_0

Superparticle production at LHC

- Dependence of the cross-sections on $m_{1/2}$ and cascade decays of chargino and neutralino
- Yellow – $pp(q\bar{q}) \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^+ + X$
- Green – $pp(q\bar{q}) \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^- + X$
- Red – $pp(q\bar{q}) \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^- + X$



Process	Final states	Process	Final states
	2ℓ, 2ν, E_T, $\sigma \approx 0.25$ pb		ℓ, 3ν, E_T, $\sigma \approx 0.28$ pb
	ℓ, ν, $2j$, E_T, $\sigma \approx 0.50$ pb		ℓ, ν, $2j$, E_T, $\sigma \approx 1.0$ pb
	3ℓ, ν, E_T, $\sigma \approx 0.14$ pb		2ℓ, $2j$, E_T, $\sigma \approx 0.29$ pb

Superparticle production at LHC

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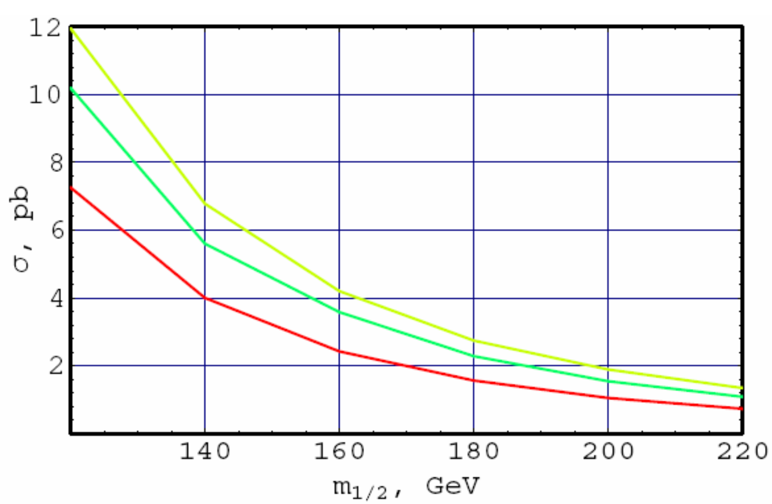
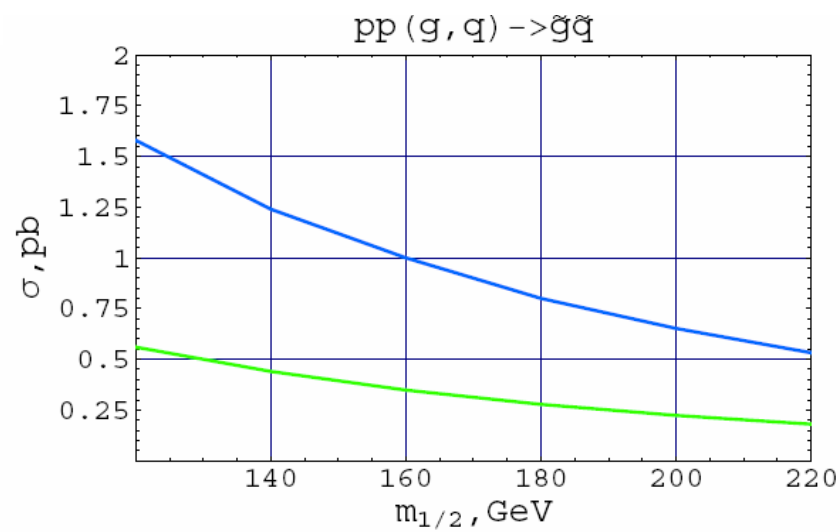
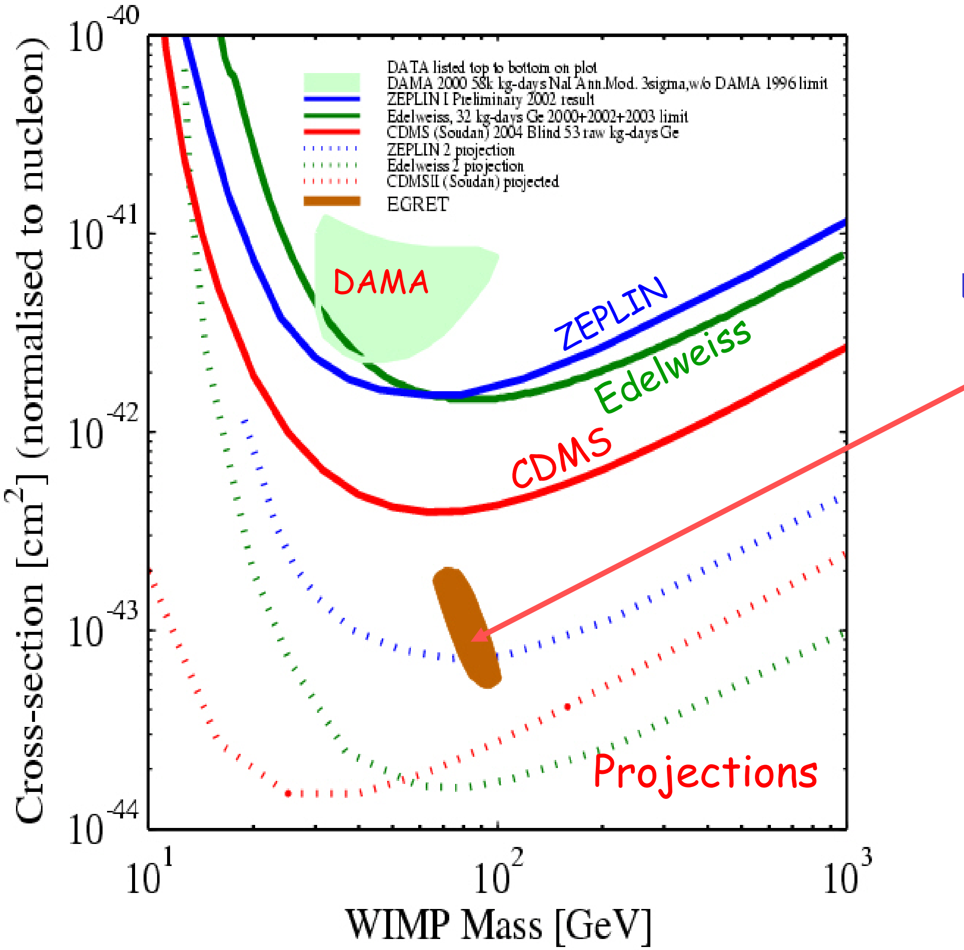
- Production cross-sections are unexpectedly large compared to the production cross-sections for strongly interacting particles





Comparison with direct DM searches

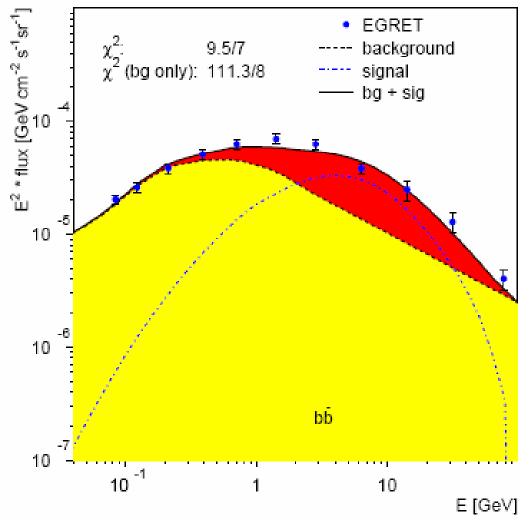


- Prediction from EGRET data assuming supersymmetry

Summary

- Astrophysicists:

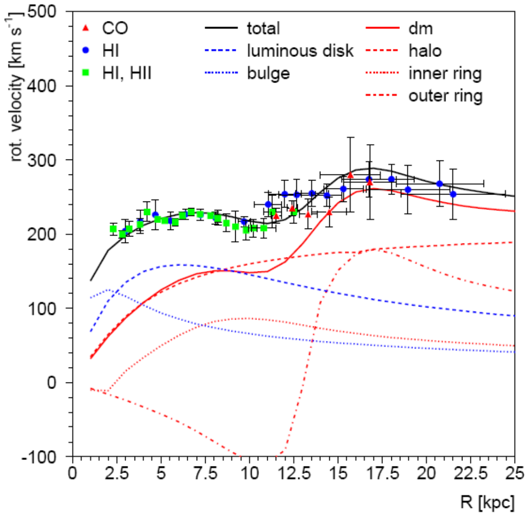
  What is the origin of "GeV excess" of diffuse galactic gamma rays?
- Answer: Dark matter annihilation



- Astronomers:

  Why a change of slope in the Milky Way rotation curve at R_0=8.3 kpc?

  Answer: Dark matter substructure

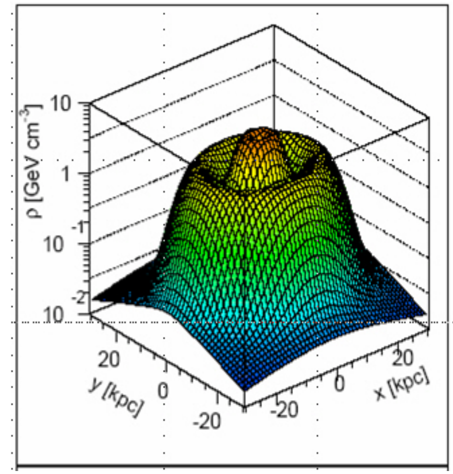


Summary

- Cosmologists:

  How is Cold Dark Matter distributed?

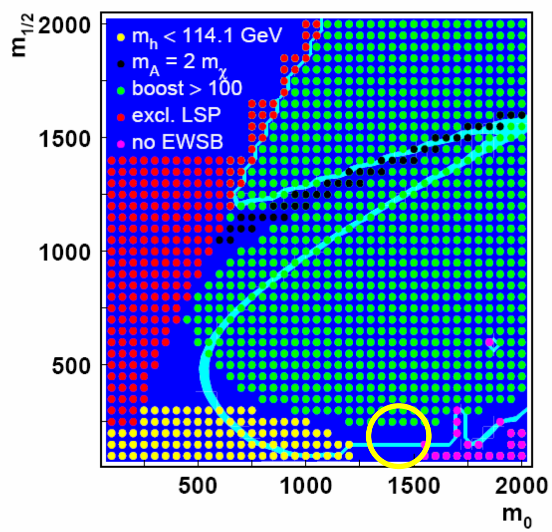
  Answer: $1/r^2$ profile + substructure (two rings)



- Particle physicists:

  Is DM annihilating as expected in Supersymmetry?

  Answer: Cross sections are perfectly consistent with SUSY



Summary

- Particle physicists:

  New interesting phenomenology.

  EGRET constraint is consistent with GUT and direct DM searches