Signals from Dark Matter Indirect Detection

Indirect Search for Dark Matter

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Outline

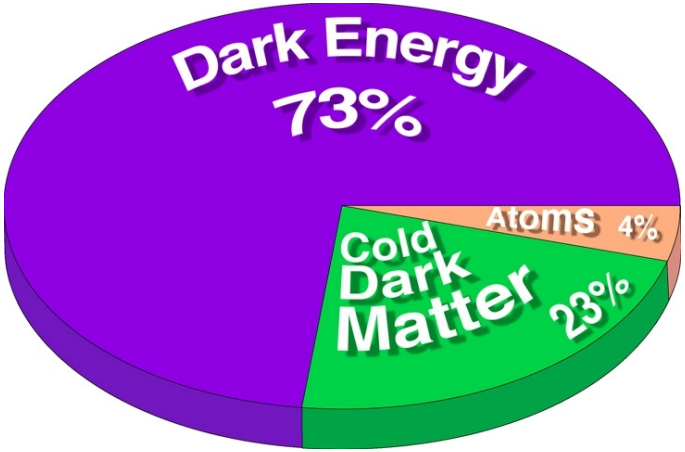
- Introduction
- Indirect detection via charged particles ($e^+, \overline{p} \ldots$)
- via neutrinos (from the sun or the earth)
- via gamma rays (from the halo or the Galactic center)
- A DMA signal?
  The EGRET excess in diffuse γ rays above 1 GeV

Dark Matter

Energy/Matter Content of the Universe

- Combination of CMB data with Hubble expansion data from SNIa
- $\sim$ 27% matter but only $\sim$ 4% baryonic matter
- $\sim$ 1% luminous matter

$\Rightarrow$ existence of baryonic and non baryonic DM

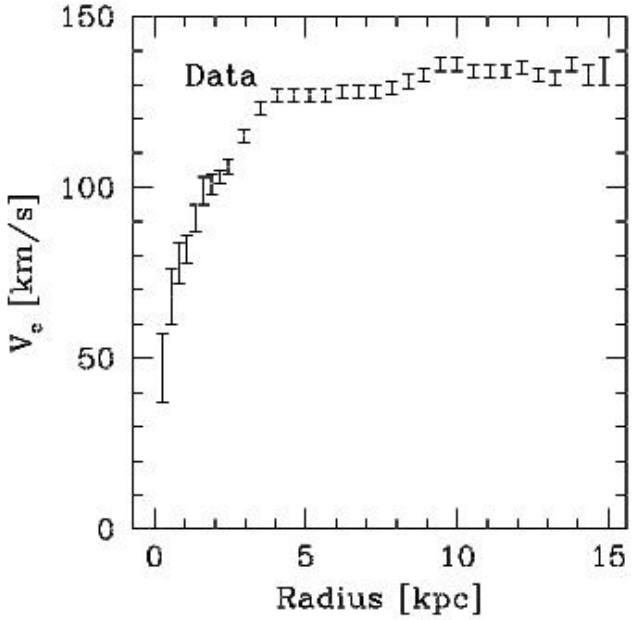


Rotation Curves of Galaxies

Observation vs. Expectation

- Expectation from Kepler's law: $v \propto 1/\sqrt{r}$ for $r \gg r_{disk}$
- Observation: $v \approx const$
- Possible explanation: existence of extended halo of DM

NGC 2403



Dark Matter

Hot Dark Matter Candidates (HDM)

- Neutrinos

$\Rightarrow$ not more than 10% to 15% of Ω_{DM}

Cold Dark Matter Candidates (CDM)

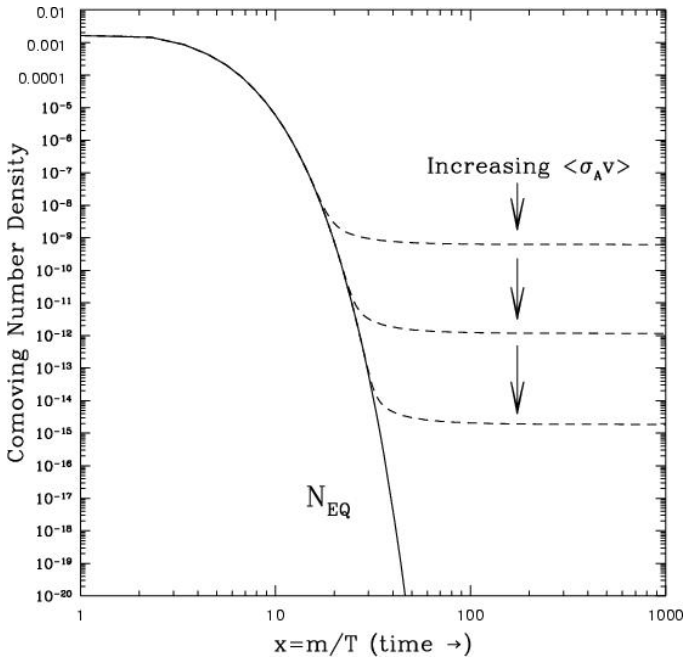
- Massive neutrinos
- Primordial black holes
- Axions
- Weakly Interacting Massive Particles (WIMPs)

Dark Matter

One of the most promising candidates is the **W**eakly **I**nteracting **M**assive **P**article

Why?

- Assumption: DM in thermal equilibrium with early universe
- Approximative solution of the Boltzmann equation:
  $\Omega_\chi h^2 = \frac{m_\chi n_\chi}{\rho_c} \approx \left(\frac{3 \cdot 10^{-27}\ \mathrm{cm}^3\ \mathrm{s}^{-1}}{\langle \sigma v \rangle} \right)$
  $\Rightarrow$ cross sections of weak interaction

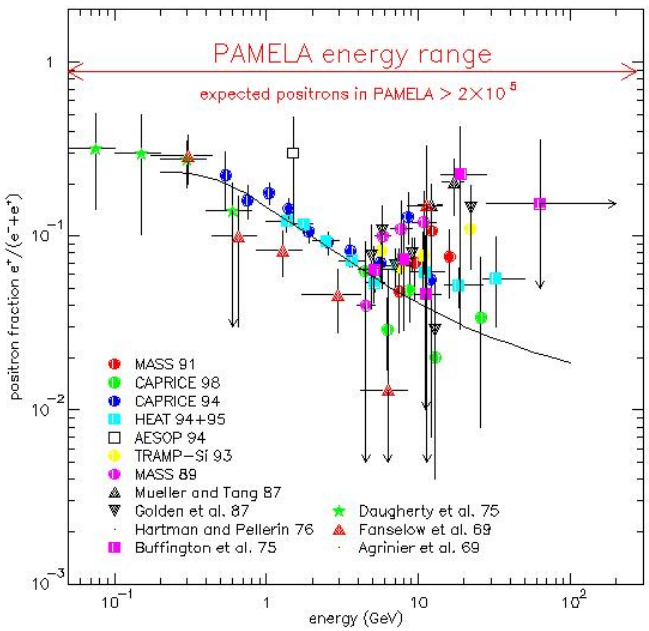


Dark Matter Annihilation

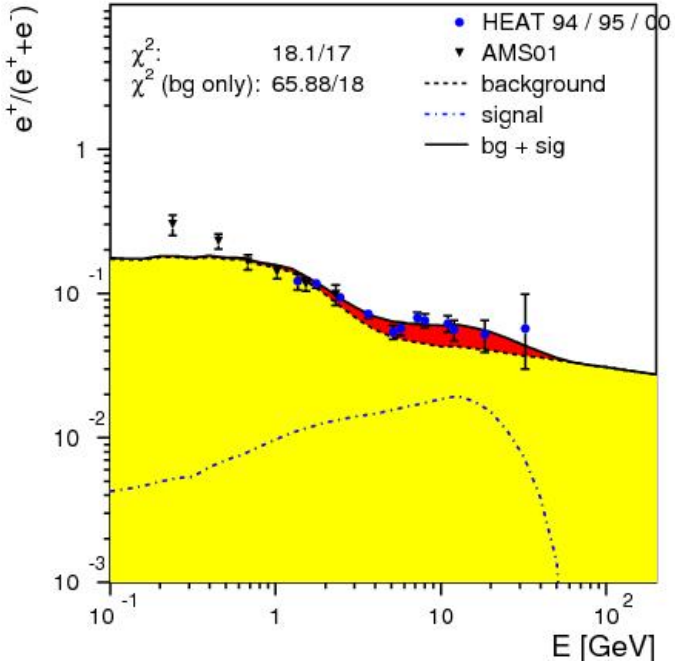
If WIMPs are Majorana particle

- At present WIMPs annihilate almost at rest into pairs of monoenergetic SM particles
- Fragmentation/decay of products
  $\Rightarrow e^+, e^-, p, \overline{p}, \nu, \overline{\nu}, \gamma$
  and maybe light (anti-)nuclei like Deuteron or Helium
- Ordinary matter particles will vanish in the sea of bg
- Antimatter maybe be detectable above bg

Positron Fraction



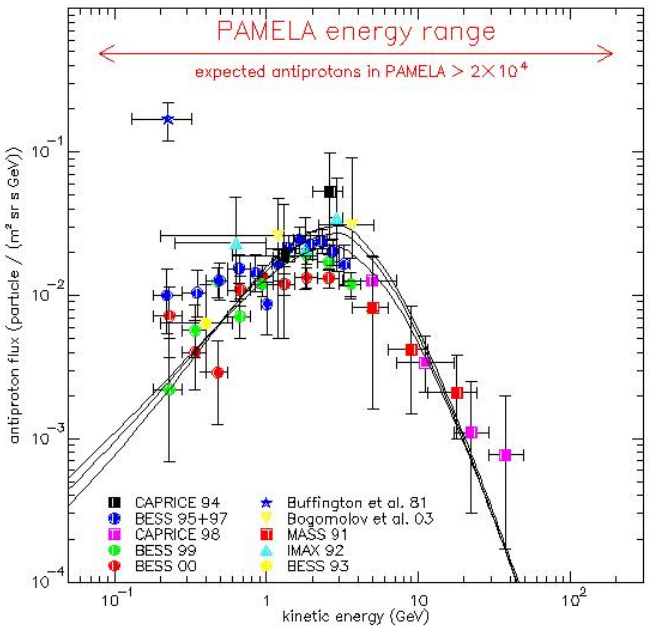
Conventional Model + DMA



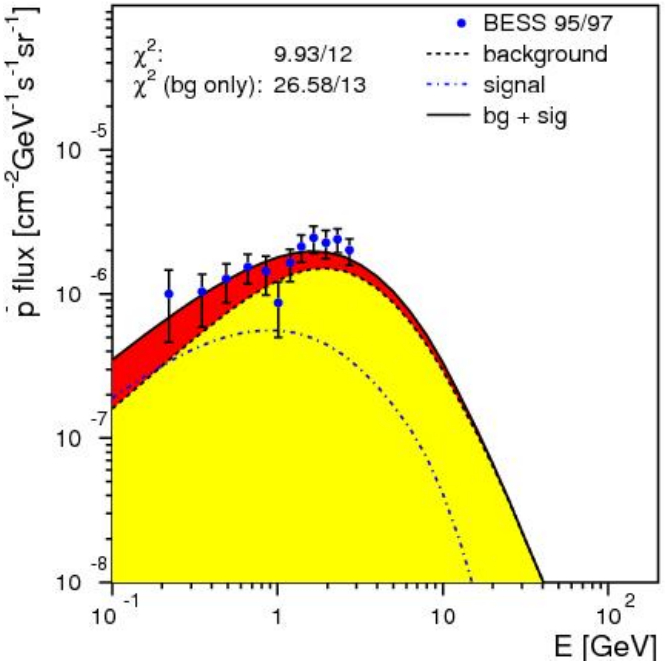
Previous balloon (e.g. HEAT) and satellite (AMS01) experiments show a hint of an excess at high energies

→ possible DMA contribution

Antiprotons



Conventional Model + DMA



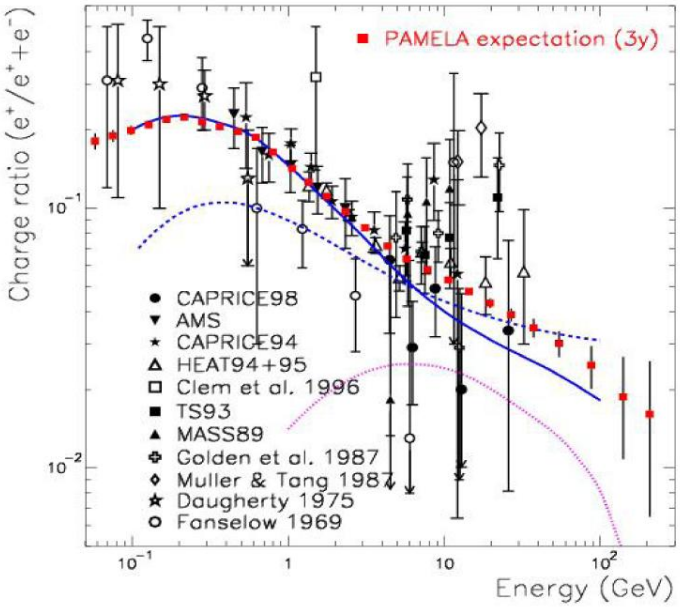
Difficult to compare different experiments because of solar modulation

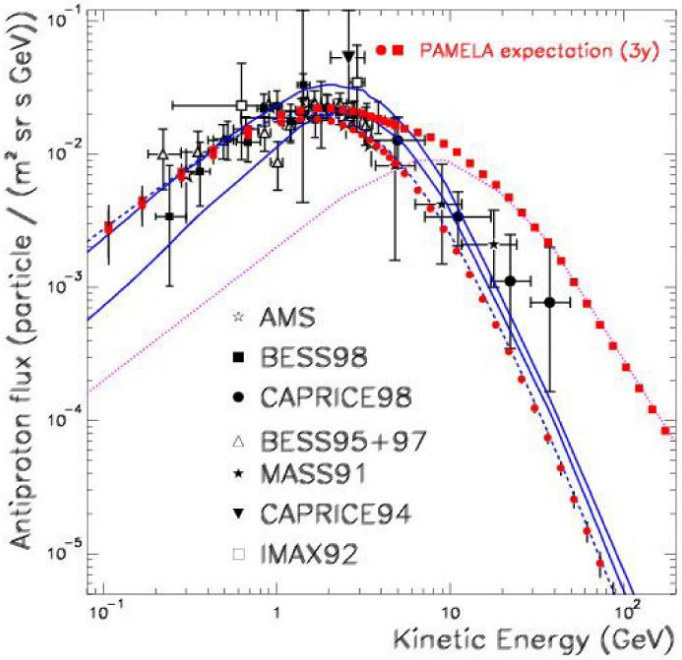
→ still room for a DMA contribution in conventional Galactic models

Pamela, AMS . . .

Pamela (launched at 15th June 06) and **AMS02** (launched in ???) will measure charged particles (Pamela up to O, AMS02 up to Fe)

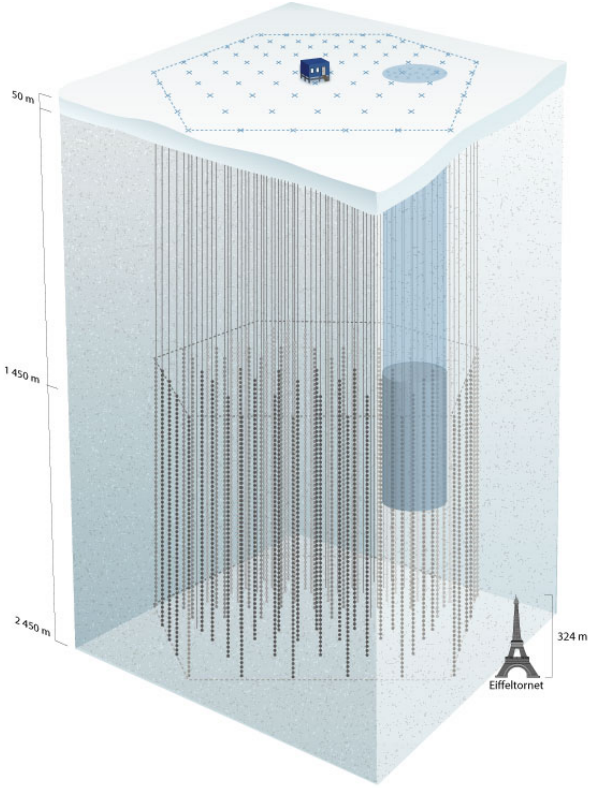
Main scientific goals: antimatter search, Galactic propagation models

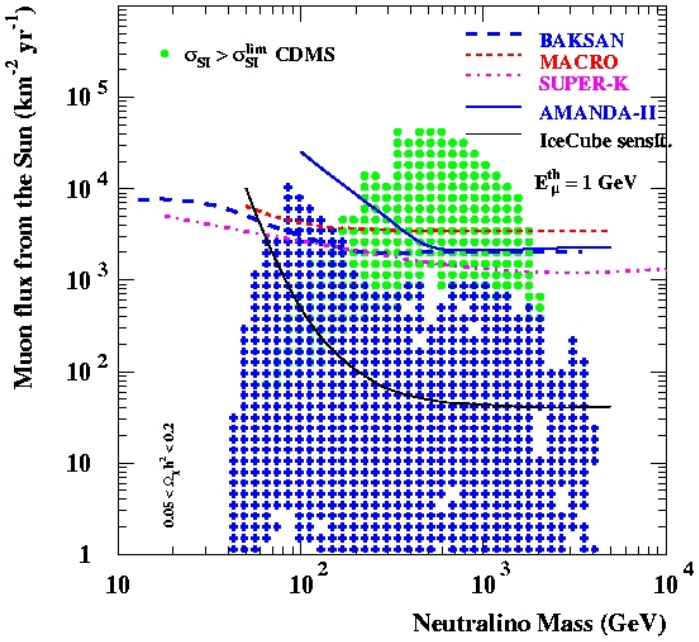




Neutrinos

DM trapped in sun (or earth) $\rightarrow$ annihilation into pairs of SM particles
$\rightarrow$ decay/fragmentation to $X + \nu$
$\rightarrow$ observation by detectors like AMANDA, Baikal, Antares, ICECUBE
...limits comparable to direct detection experiments

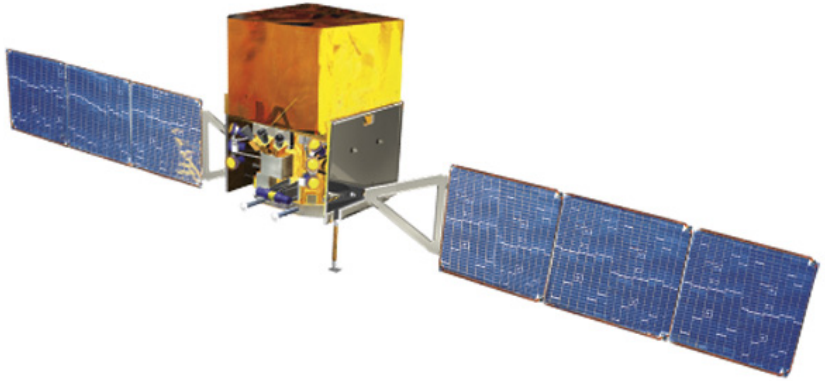




Gamma Rays

- WIMP annihilation in the halo or the Galactic center yields continous spectrum and monoenergetic lines (in many models loop suppressed)
- Propagation of gamma rays is simple . . .
- . . . but bg depends on charged components
- GLAST (up to 300 GeV) will be launched in 2007
- GLAST is successor of EGRET ($<$100 GeV)

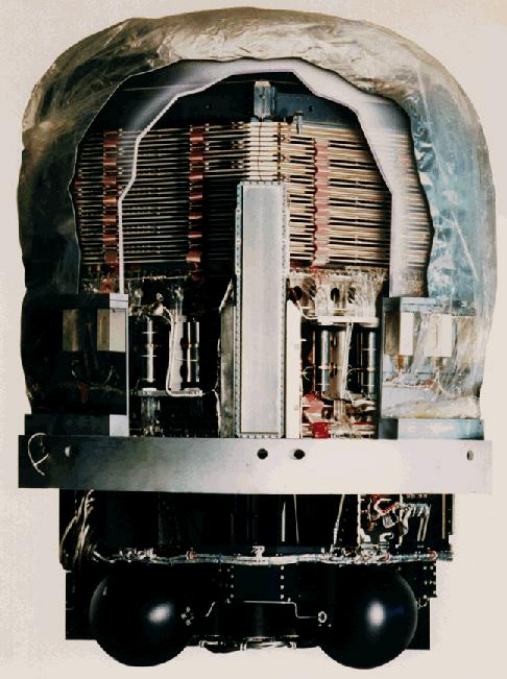
GLAST



Diffuse Galactic Gamma Rays

EGRET Experiment

- Installed on CGRO satellite (together with BATSE, OSSE and COMPTEL)
- Measuring from 1991 to 2000
- Energy range from $\sim$ 30 MeV to $\sim$ 100 GeV
- Third EGRET catalog: 271 point sources
- Complete data - point sources = diffuse gamma rays



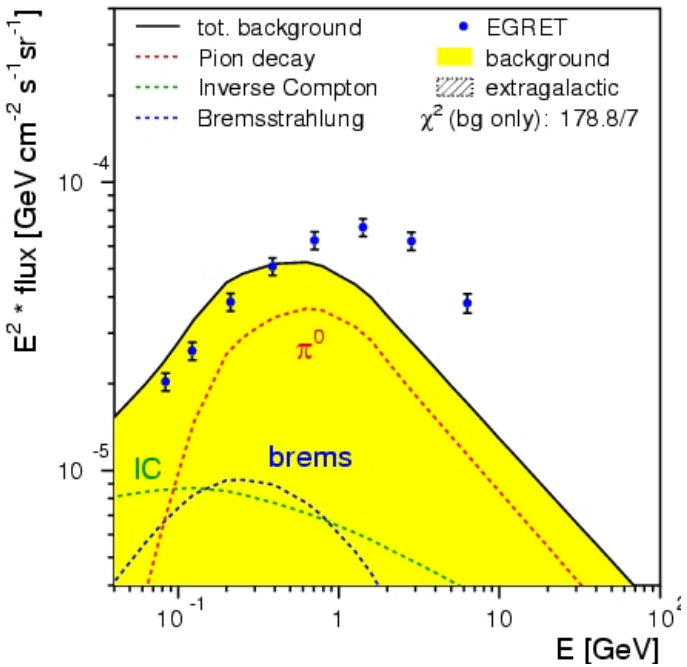
Diffuse Galactic Gamma Rays

EGRET Excess

- Comparison with galactic models ⇒ Excess above 1 GeV
- Spectral shape of excess independent of sky direction
- Uncertainty of bg or a new contribution?

Contributions

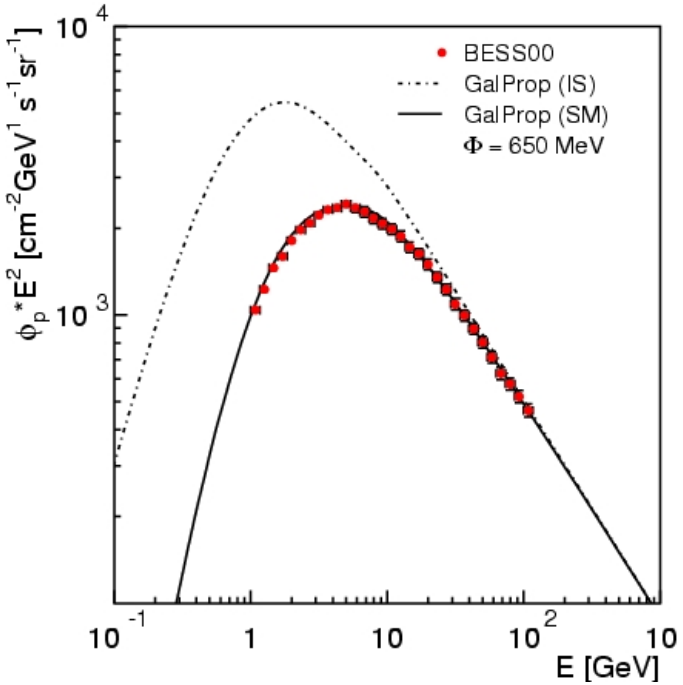
- Decay of π^0s produced in *pp* reactions of CR with IS gas
  $p + p \rightarrow \pi^0 + X \rightarrow \gamma\gamma + X$
- Bremsstrahlung
  $e + p \rightarrow e' + p' + \gamma$
- Inverse Compton
  $e + \gamma \rightarrow e' + \gamma'$



Galactic Background of Diffuse Gamma Rays

Dominant Contribution

- π^0 peak
- Shape determined by energy spectrum of CR protons
- CR proton spectrum measured locally by balloon experiments
- Locally measured spectrum is representative for rest of Galaxy $\rightarrow$ Conventional Model
- Uncertainty by Solar Modulation



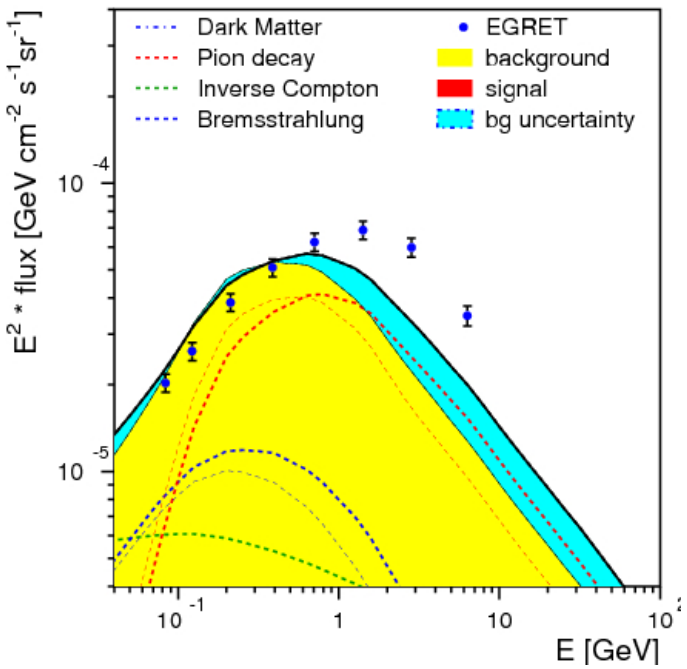
Calculation of bgs with `GalProp`

Moskalenko *et al.* `astro-ph/9906228`

Galactic Background of Diffuse Gamma Rays

Uncertainty of Solar Modulation

- High energies: energy dependence γ_{high} is fixed (≈ 2.7)
- Low energies: uncertainty of γ_{low} can be compensated by solar modulation
- CM: $\gamma_{\text{low}} \approx 2.0 \Rightarrow \Phi_{\text{SM}} \approx 650$ MV
- $\gamma_{\text{low}} \approx 1.8 \Rightarrow \Phi_{\text{SM}} \approx 450$ MV
- $\gamma_{\text{low}} \approx 2.2 \Rightarrow \Phi_{\text{SM}} \approx 900$ MV



Dark Matter Annihilation

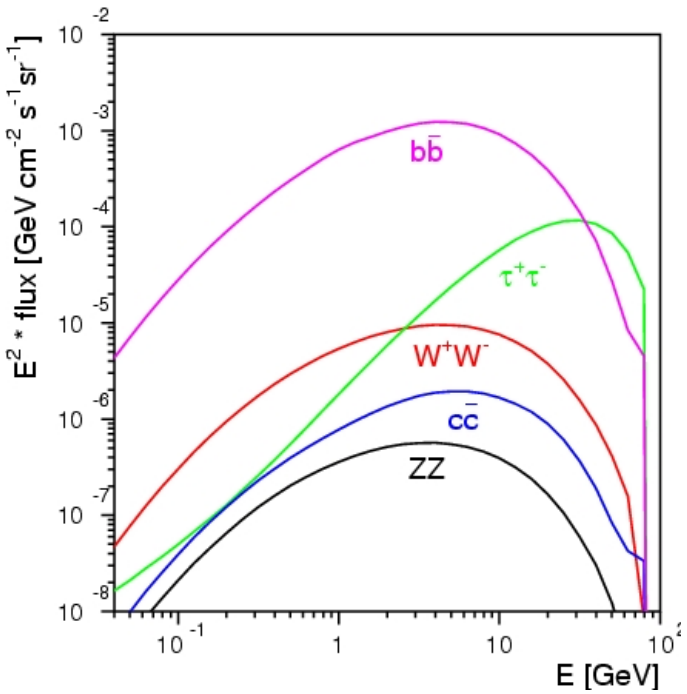
Spectral Shape of DMA Signal . . .

- WIMPs can annihilate at rest into a pair of monoenergetic SM particles
- Fragmentation/decay of products
  $\Rightarrow \pi^0$s
  $\Rightarrow \sim 30 \ldots 40\ \gamma$s per annihilation
- Different γ spectrum than bg (continuous CR spectrum)
  $\Rightarrow$ better fit to EGRET spectrum?
- Spectral shape similar for different annihilation processes

Calculation of signal with `DarkSusy`

Gondolo *et al.* `astro-ph/0406204`

Gamma spectra for different processes ($m_{WIMP} \sim 100$ GeV)

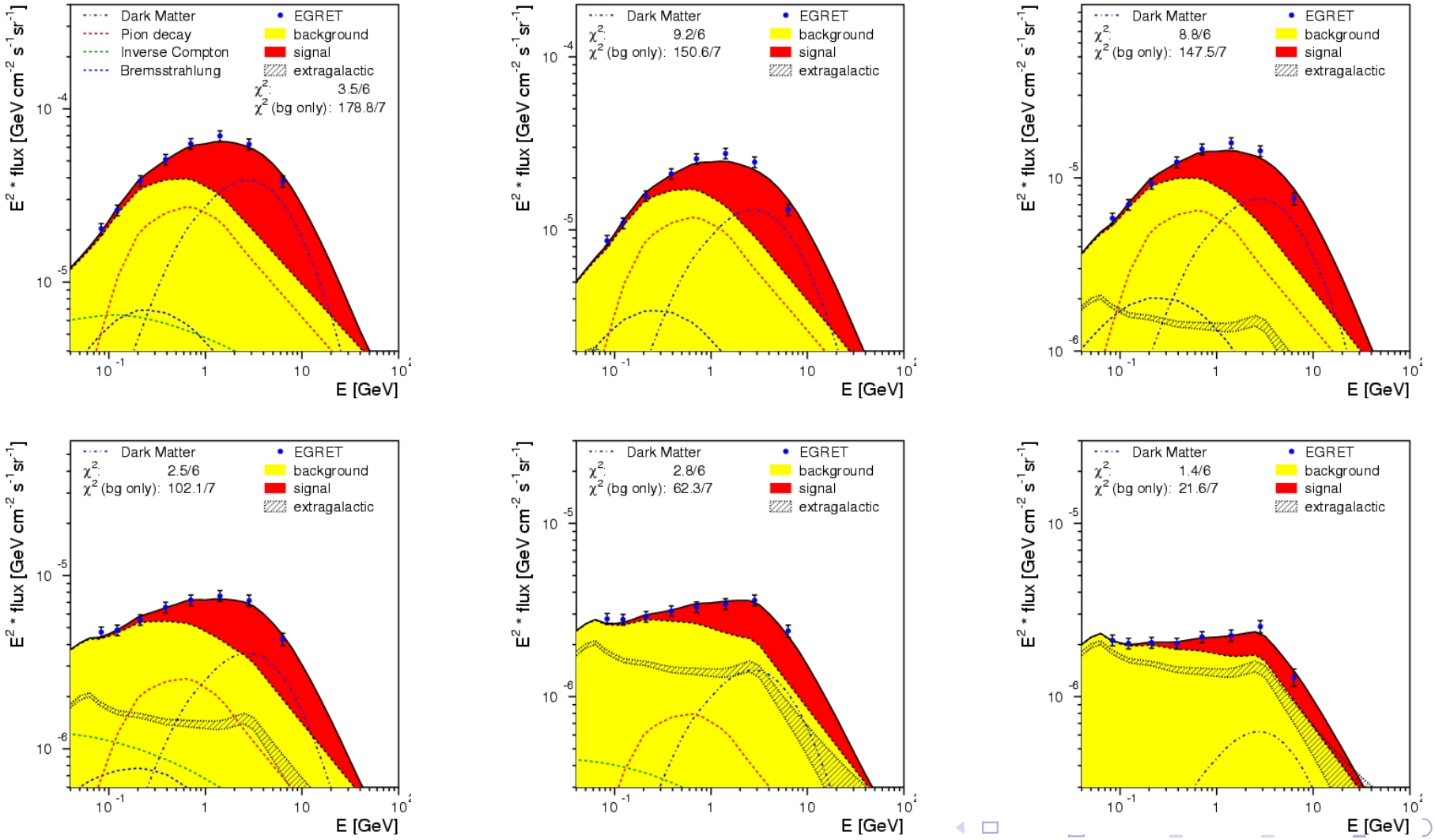


Fit to EGRET Spectrum with DMA signal

Fit Spectral Shape Only

- Uncertainties in interstellar gas density
  $\Rightarrow$ bg scaling
- Uncertainties in DM density
  $\Rightarrow$ signal scaling (boost factor)
- Free bg and signal scaling
  $\Rightarrow$ use point to point error $\sim$ 7% (full error $\sim$ 15%)

Fit to EGRET Spectrum with CM and DMA signal

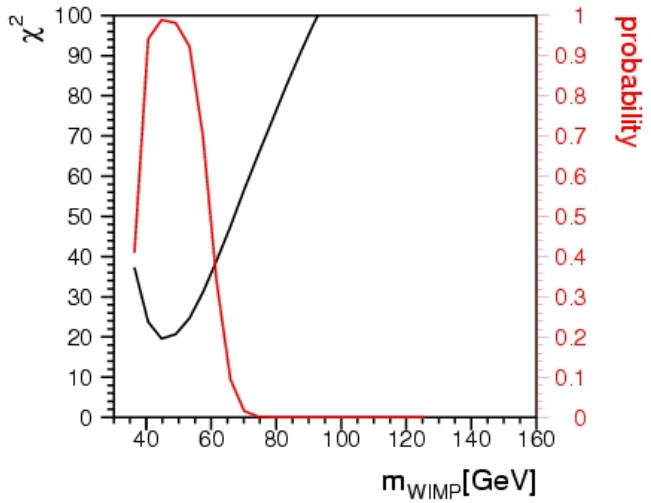


Limits on WIMP Mass

Procedure

- $\Sigma\chi^2$ of 6 Regions of the Sky
- Scan over WIMP mass
  $\Rightarrow m_{WIMP} \lesssim 70$ GeV (95% C.L.)

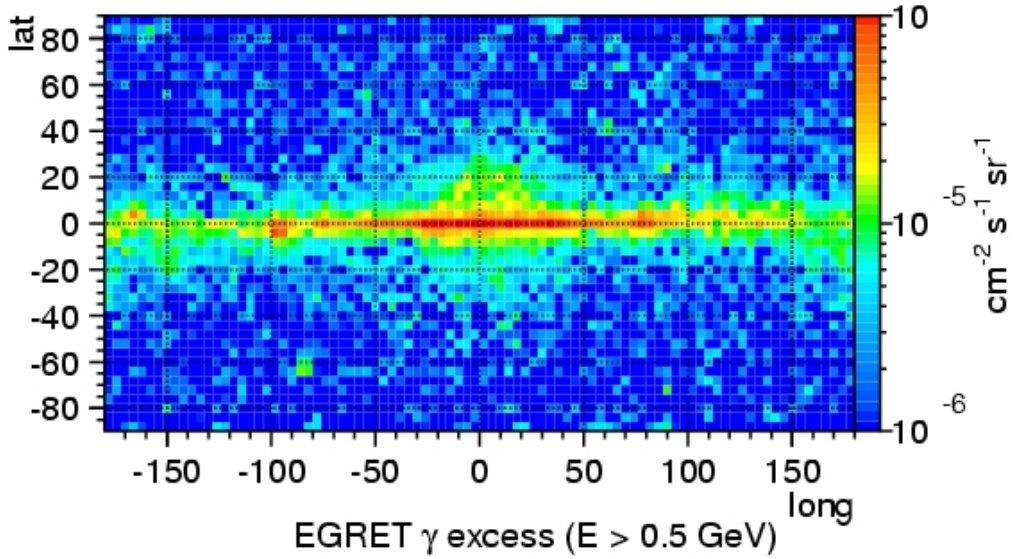
$\chi^2/d.o.f.$ and probability:



Determination of Halo Parameters

Directional Dependence of Excess

- Signal in sky region Ψ: $\Phi_{\mathrm{DM}} \propto \langle \sigma v \rangle \cdot \frac{1}{\Delta\Omega} \int d\Omega \int dl_\psi \left(\frac{\rho(l_\psi)}{m_\chi} \right)^2$
- Smooth $1/r^2$ profile yields not enough signal $\Rightarrow$ clumps
- Assume same enhancement by clumps in all directions

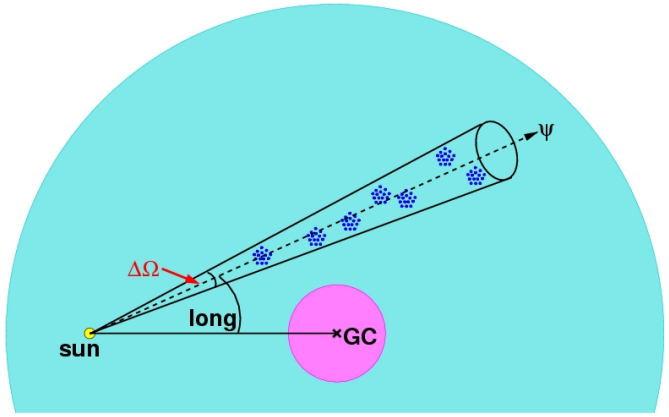


Determination of Halo Parameters

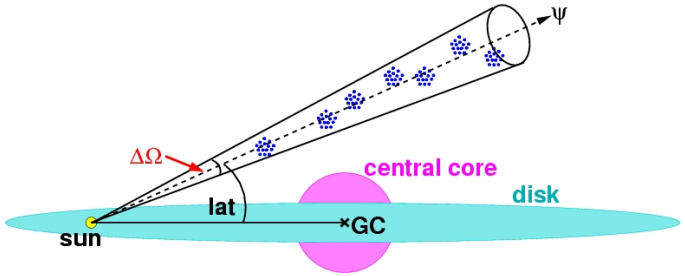
Method

- Divide skymap into 180 independent sky directions
  $\Rightarrow$ 45 intervals for gal. longitude (dlong = 8°)
  $\Rightarrow$ 4 intervals for gal. latitude ($|\text{lat}| < 5°$, $5° < |\text{lat}| < 10°$, $10° < |\text{lat}| < 20°$ and $20° < |\text{lat}|$)
- Divide gamma spectrum in low and high (<>0.5 GeV) energy region
- Use low energy region for bg normalization
- Use high energy region for determination of halo parameters

top view:



side view:



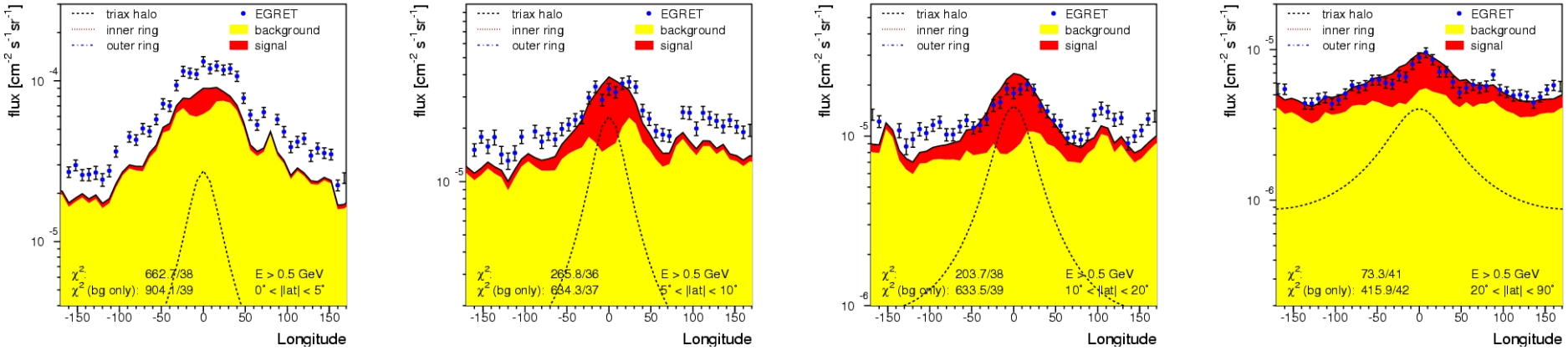
Determination of Halo Parameters

Isothermal Profile Without Rings

Triaxial profile with $1/r^2$ dependence at large r and core at center

- Good agreement at large latitudes
- Too little flux in galactic plane

$|\text{lat}| < 5°$ | $5° < |\text{lat}| < 10°$ | $10° < |\text{lat}| < 20°$ | $20° < |\text{lat}|$



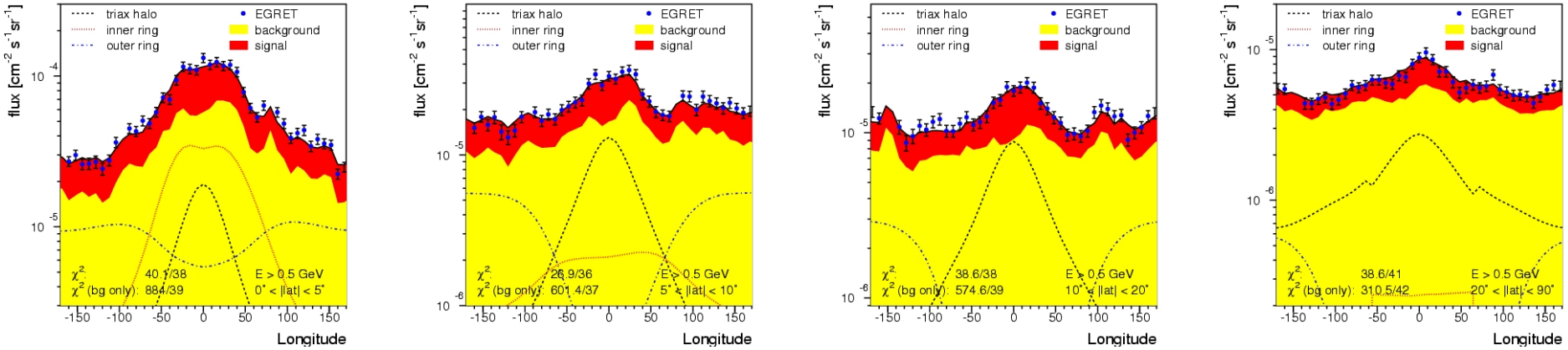
Determination of Halo Parameters

Isothermal Profile With Rings

Additional DM in galactic plane parametrized by two toroidal ringlike structures

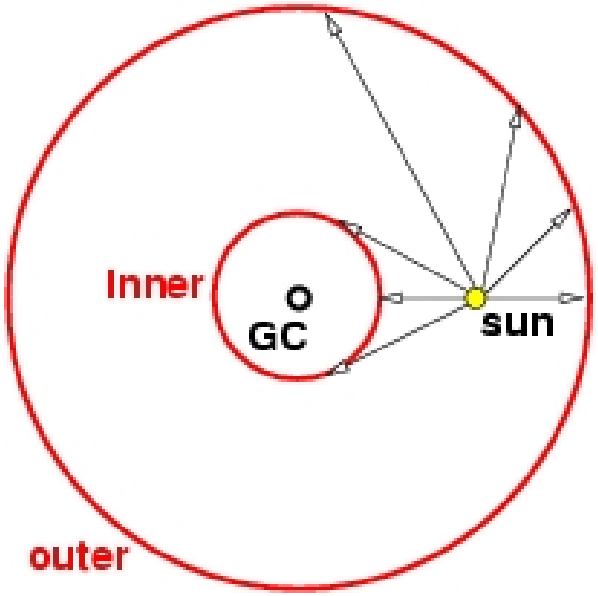
- Inner ring at $\sim$ 4 kpc; $\sim$ thickness of lum. disk (e.g. adiabatic compression)
- Outer ring at $\sim$ 14 kpc; much thicker than disk (e.g. infall of dwarf galaxy)

$|\text{lat}| < 5°$ | $5° < |\text{lat}| < 10°$ | $10° < |\text{lat}| < 20°$ | $20° < |\text{lat}|$

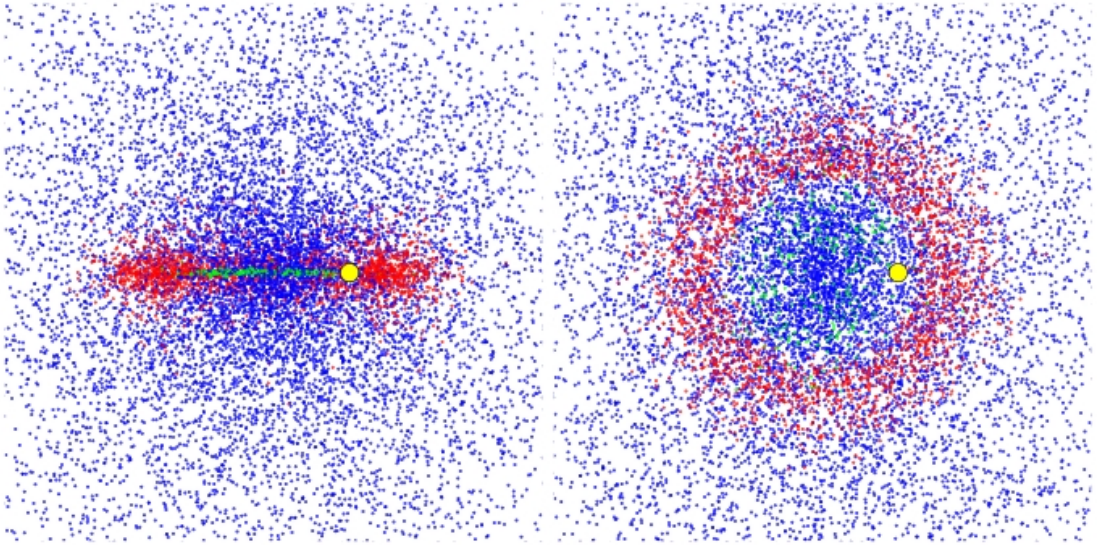


Visualization of Halo Profile

Sensitivity on ring parameters:



Dark Matter:



baryonic matter:

Determination of Halo Parameters

Experimental Counterpart of Rings

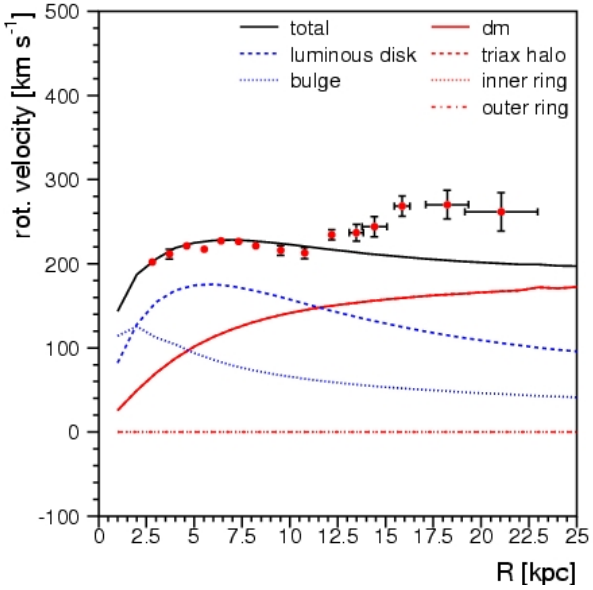
- Inner ring:
  $M_{inner} \sim 9 \cdot 10^9 M_\odot \approx 0.3\%$ of M_{tot}
  coincides with maximum of H_2 distribution
  Hunter *et al.* Astrophys. J. **481** (1997) 205
- Outer ring:
  $M_{outer} \sim 8 \cdot 10^{10} M_\odot \approx 3\%$ of M_{tot}
  correlated with ghostly ring of stars at ~ 14 kpc ($10^8 \ldots 10^9$ $M_\odot$)
  Ibata *et al.* (`astro-ph/0301067`)
- Massive substructures influence rotation curve of milky way

Rotation Curve of the Milky Way

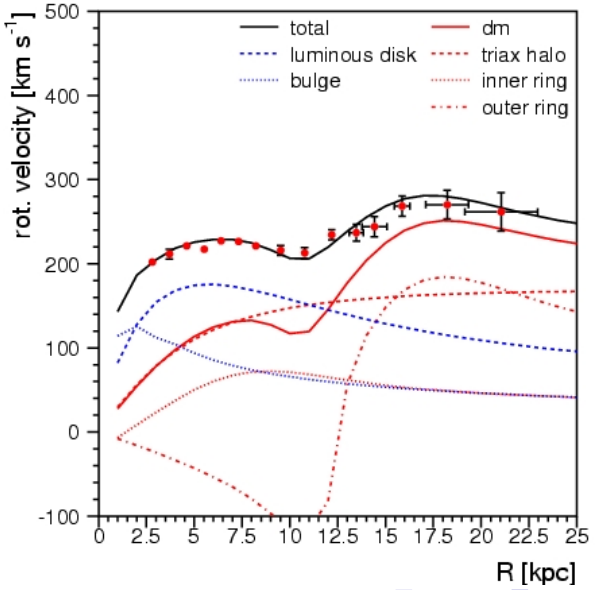
Comparison with Measured Rotation Curve

- Data are averaged from three surveys with different tracers
- Rings of DM can explain change of slope at $\sim$ 10 kpc

without rings:



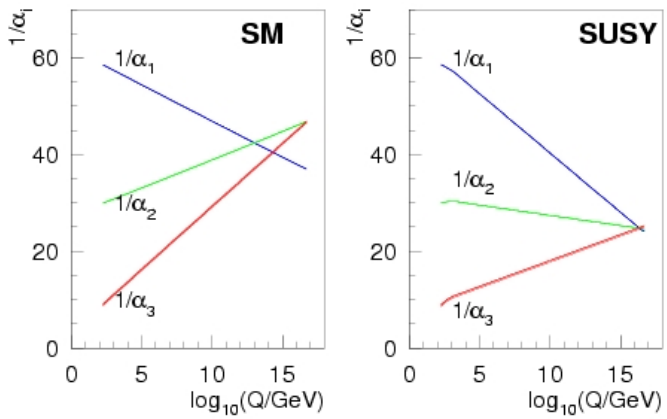
with rings:



Supersymmetry

Problems in the Standard Model (SM)

- No gauge coupling unification
- Hierarchy problem
- Fine tuning problem
- No DM candidat



Simultanous Soulution with Supersymmetry (SUSY)

- SUSY particles change running of couplings
- Hierarchy/fine tuning: SUSY-contributions have opposite sign $\rightarrow$ cancellation $\rightarrow$ logarithmic scale dependence
- DM: lightest Neutralino is (often) perfect candidat (massive, stable, only weak interaction)

Supersymmetry

SUSY is broken, e.g. mSUGRA $\rightarrow$ 5 new parameters

- m_0: unified mass of the fermion partners
- $m_{1/2}$: unified mass of the gauge boson partners
- $\tan\beta$: ratio of the VEVs of the 2 Higgs doublets
- unified trilinear coupling A_0, sign(μ)

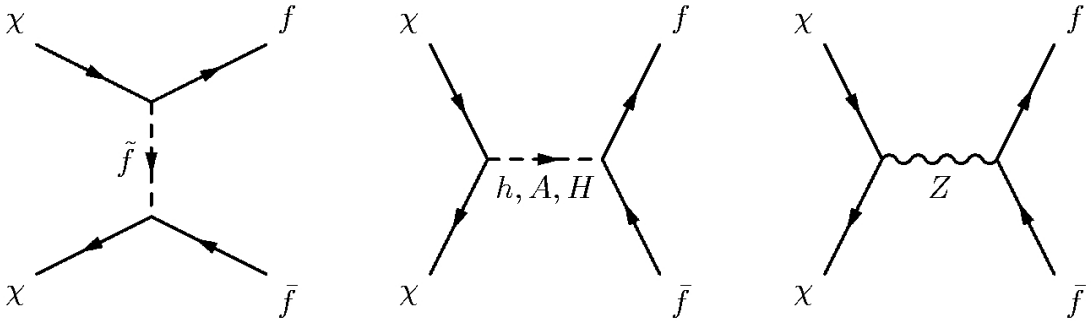
Contraints of the parameter space

- Higgs mass $m_h > 114.4$ GeV (`SuSpect`, `hep-ph/0211331`)
- $Br(b \rightarrow X_s\gamma) = (3.43 \pm 0.36) \times 10^{-4}$ (`micrOMEGAs`, `hep-ph/0112278`)
- $\Delta a_\mu = (27 \pm 10) \times 10^{-10}$ (`micrOMEGAs`)
- $\Omega_{\mathrm{DM}} = 0.113 \pm 0.008$ (`micrOMEGAs` or `DarkSusy`, `astro-ph/0406204`)
- SUSY mass limit, EWSB, LSP neutral ... (`SuSpect`, `hep-ph/0211331`)

Neutralino Annihilation

- Neutralino is mixture:
  $|\chi_0\rangle = N_1|B_0\rangle + N_2|W_0^3\rangle + N_3|H_1\rangle + N_4|H_2\rangle$
- Annihilation cross section depends on SUSY **and** SM parameters

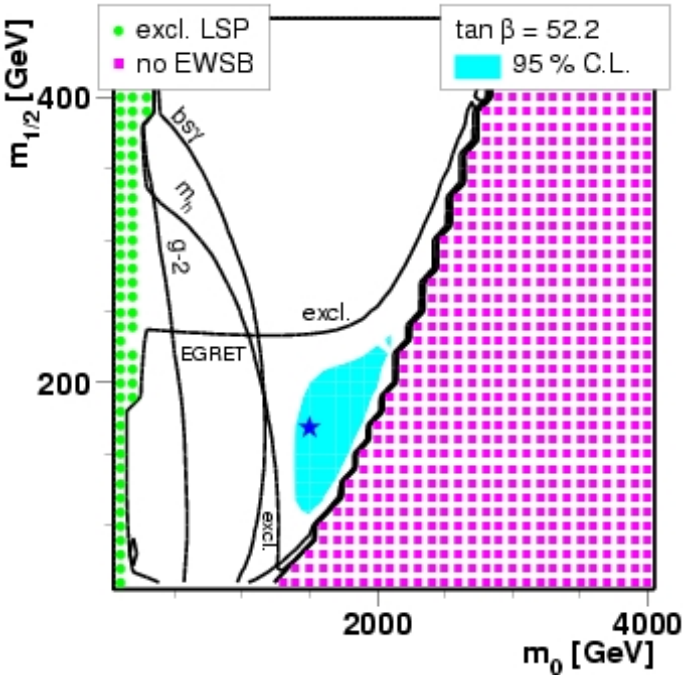
Feynman graphs:



$\propto \frac{\mathbf{m_\chi \cdot m_f}}{\mathbf{m_{\tilde{f}}^2}}$ $\propto \frac{\tan\beta \cdot \mathbf{m_{f_d}}}{\mathbf{m_W}} \mathbf{N_1 N_{3(4)}}$ $\tan\beta \cdot \mathbf{m_{f_d}} \leftrightarrow \frac{\mathbf{m_{f_u}}}{\tan\beta}$ $\propto \frac{\mathbf{m_f \cdot m_\chi}}{\mathbf{m_Z^2}} \mathbf{N_{3(4)}^2}$

Allowed Parameter Space

- Scan over m_0-$m_{1/2}$-plane for fixed values of $\tan\beta = 52.2$ and $A_0 = 0$ GeV
- 2σ-contours for allowed region + consistency of the models (LSP neutral, EWSB ok)
- with EGRET-excess only a small region is left over:
  m_0: $\sim$1500 GeV ... $\sim$2000 GeV
  $m_{1/2}$: $\sim$100 GeV ... $\sim$250 GeV

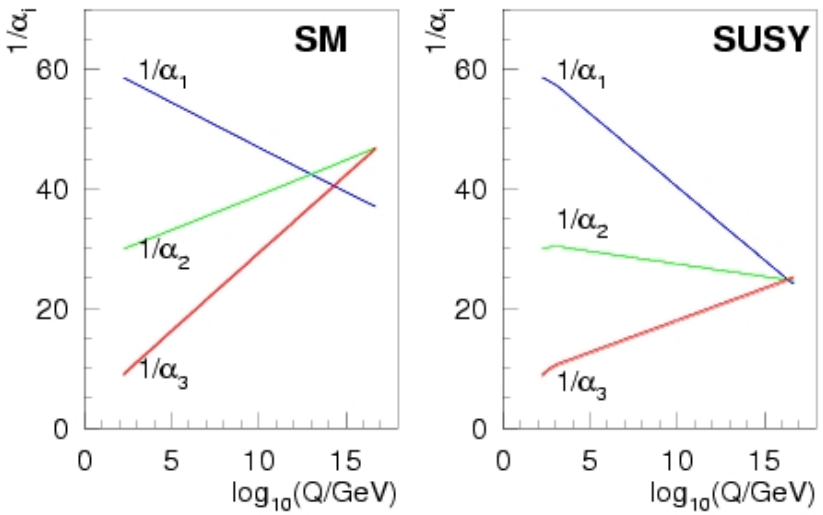


SUSY mass spectrum

Typical parameter set:

Parameter	value
m_0	1500 GeV
$m_{1/2}$	170 GeV
A_0	$0 \cdot m_0$
$\tan\beta$	52.2
$\alpha_s(M_Z)$	0.122
$m_t(pole)$	175 GeV
$m_b(m_b)$	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
$\tilde{t}_{1,2}$	906, 1046
$\tilde{b}_{1,2}$	1039, 1152
$\tilde{\tau}_{1,2}$	1035, 1288
$\tilde{\nu}_e, \tilde{\nu}_\mu, \tilde{\nu}_\tau$	1495, 1495, 1286
$h, H, A, H^\pm$	115, 372, 372, 383

Unification of gauge couplings:



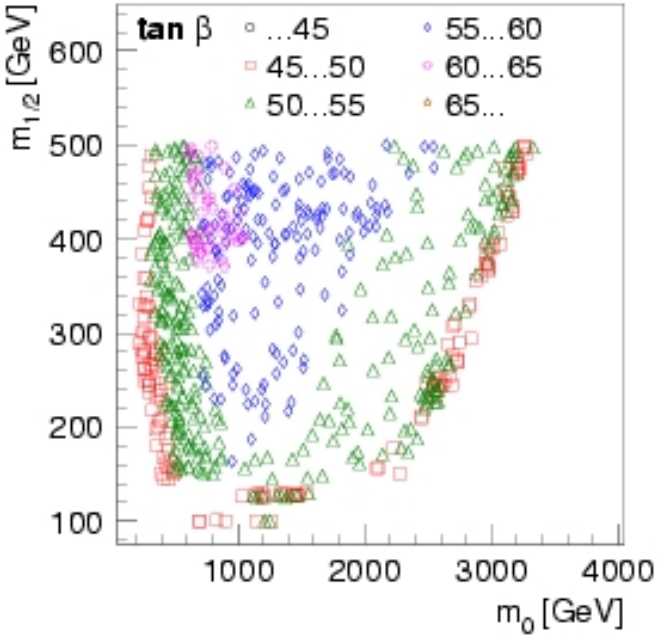
Observable	value
$Br(b \to X_s\gamma)$	$3.02 \cdot 10^{-4}$
Δa_μ	$1.07 \cdot 10^{-9}$
Ωh^2	0.117

Allowed Parameter Space version 2

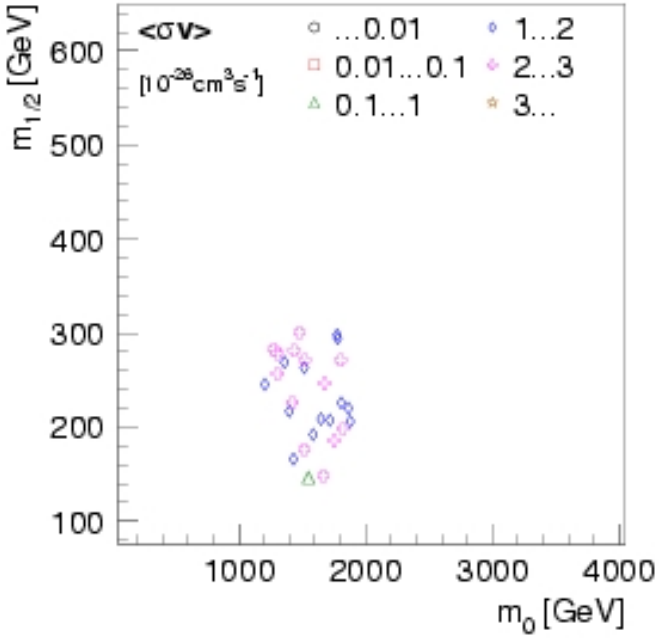
Scatterplot of m_0, $m_{1/2}$ and $\tan\beta$; only parameter sets with correct RD are plotted

Solutions at smallest $m_{1/2}$ yield at low T too small XS (p-wave) $\rightarrow$ large unphysical boost factors

wo. exp. constraints:



w. exp. constraints:



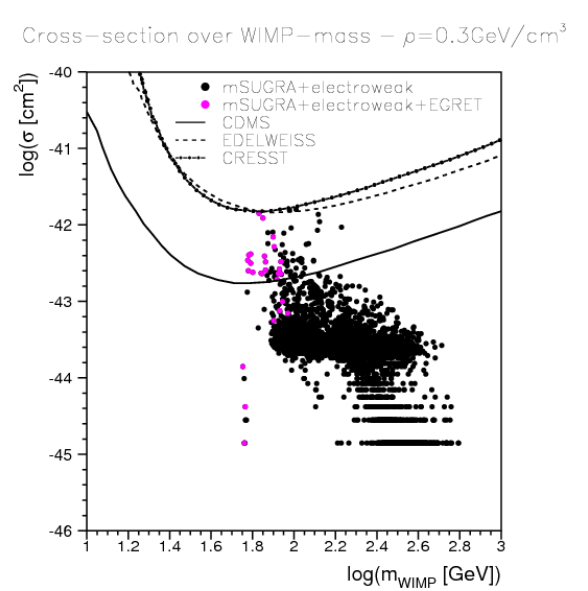
Summary

1. EGRET excess in the conventional Galactic model can be explained as Dark Matter annihilation of WIMPs in a mass range between 50 and 70 GeV
2. From the directional dependence of the excess a *possible* halo profile can be determined $\Rightarrow$ halo profile needs ringlike structures, which are correlated with observations
3. Determined halo profile is compatible with rotation curve of the Milky Way (de Boer *et al.*, Astronomy & Astrophysics 444 (2005) 51.)
4. EGRET data are compatible with DM consisting of supersymmetric neutralinos $\Rightarrow$ together with constraints from EWSB, Higgs mass, $Br(b \to X_s\gamma)$ and a_μ only a small region of SUSY parameter space is left over, particle masses are in the discovery range of the LHC (de Boer *et al.*, Phys. Lett. B 636 (2006) 13.)

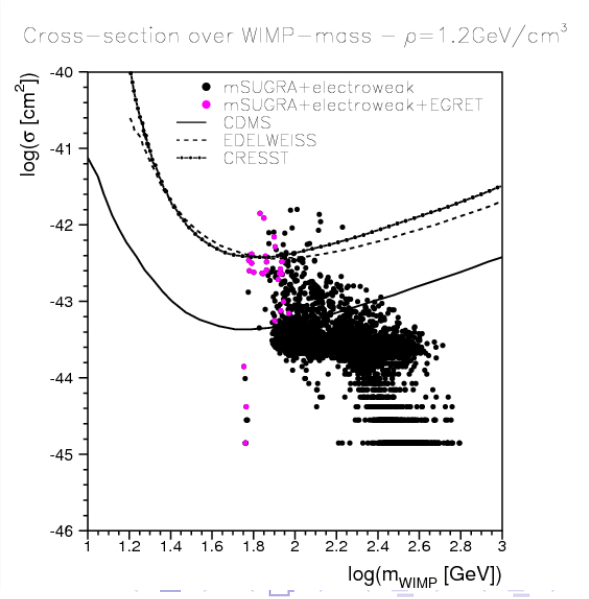
Direct Detection limits

- Best limits from CDMS/EDELWEISS/CRESST
- Cross section limit normalized to local $\rho = 0.3$ GeV cm^{-3}
- Our halo model has a higher $\rho = 1.2$ GeV cm^{-3}
- Even larger uncertainties, if most of DM is in clumps

$\rho = 0.3$ **GeV cm^{-3}:**



$\rho = 1.2$ **GeV cm^{-3}:**



Galactic Bg of Gamma Rays & Charged Particles

Propagation Equation

$$\begin{aligned}\frac{\partial\psi}{\partial t} &= q(\vec{r},p) - \frac{1}{\tau_f}\psi - \frac{1}{\tau_r}\psi + \vec{\nabla}\cdot\left(D_{xx}\vec{\nabla}\psi - \vec{V}\psi\right) \\ &+ \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{1}{p^2}\psi - \frac{\partial}{\partial p}\left[\dot{p}\psi - \frac{p}{3}\left(\vec{\nabla}\cdot\vec{V}\right)\psi\right]\end{aligned}$$

Ingredients of Propagation

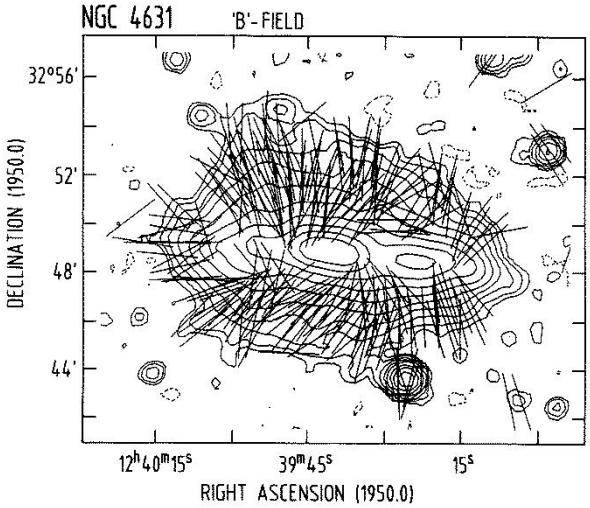
- Source spectrum
- Distribution of sources, gas and galactic fields
- Diffusion, Convection
- Energy losses, radioactive decay, interaction with IS gas ...

Solution of propagation equation with `GalProp`

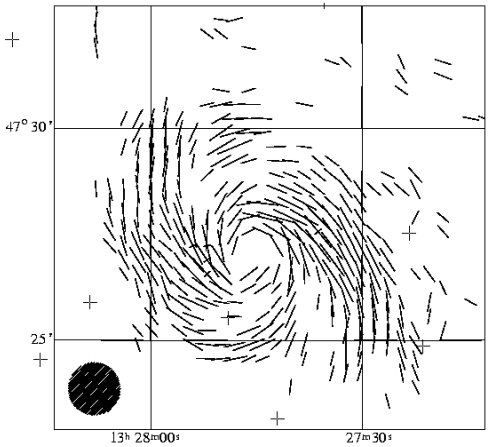
Moskalenko *et al.* `astro-ph/9906228`

Magnetic Field of Galaxies

NGC 4631:



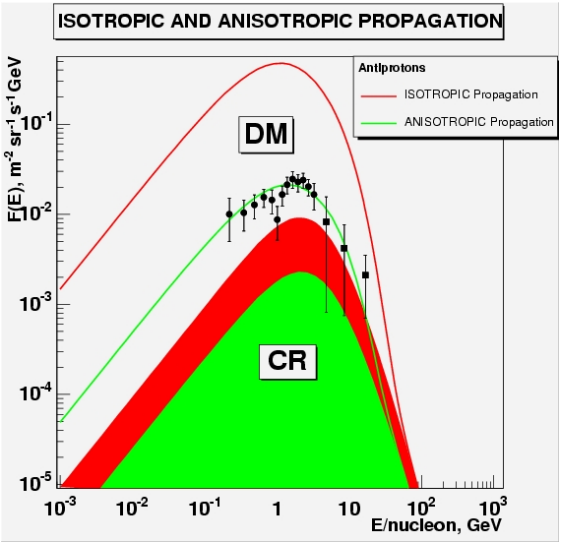
M51:



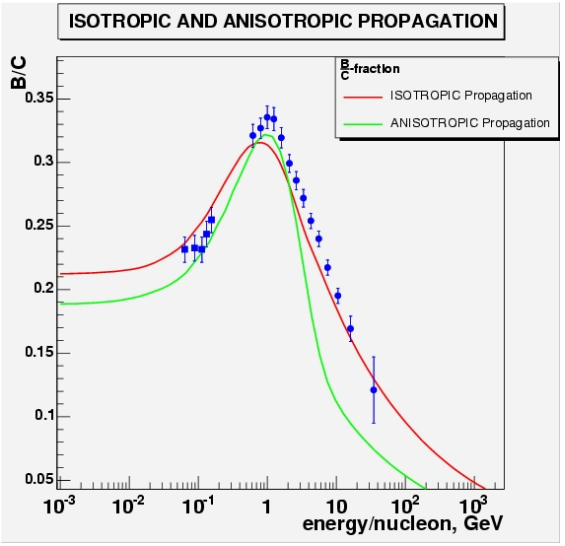
- A few μG perpendicular to galactic disk and along spiral arms
- Diffusion preferentially $\perp$ to disk? Slow radial diffusion?
- Isotropic $\rightarrow$ anisotropic diffusion
- Alternative: strong convection

Preliminary results from GalPROP with isotropic and anisotropic diffusion

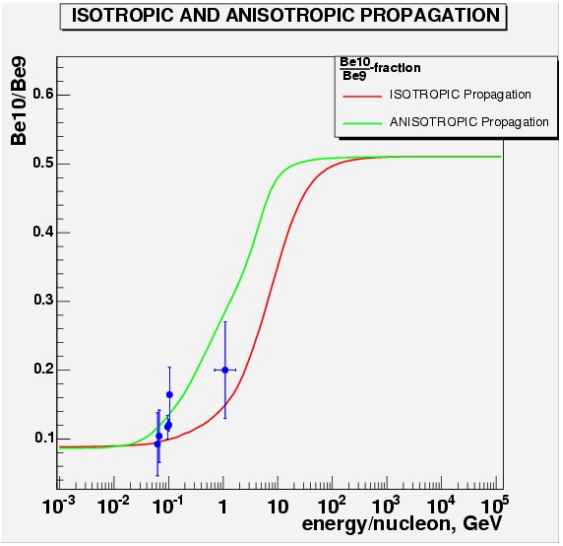
Antiprotons:



B/C:



Be^{10}/Be^{9}:

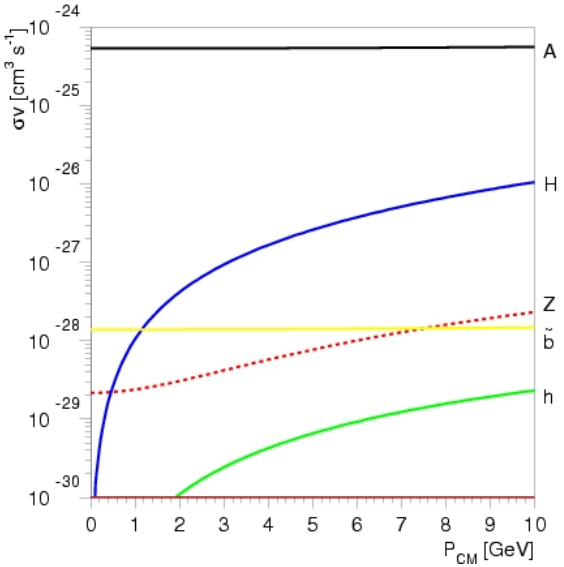


With anisotropic propagation flux of the charge particles can be tuned within a range of 2 orders of magnitudes, while the model is still ok with B/C an Be^{10}/Be^{9}!

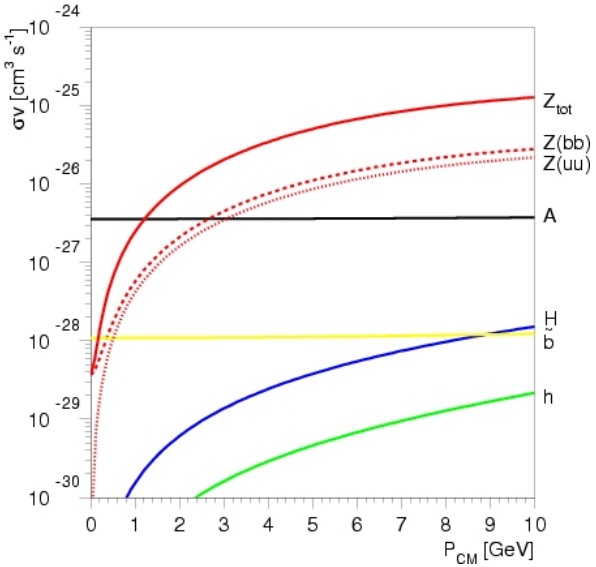
Neutralino Annihilation

- s-wave (z.B. s-channel via A): $\langle \sigma v \rangle = \text{const}$
  with $\Omega_{DM} = 0.113 \pm 0.008$ yields $\langle \sigma v \rangle \approx 2 \times 10^{-26}$ cm^3/s
- p-wave (z.B. s-channel via Z): $\langle \sigma v \rangle \propto v$
  todays DMA cross section is very small $\rightarrow$ large boostfactors

σ via A is dominant:



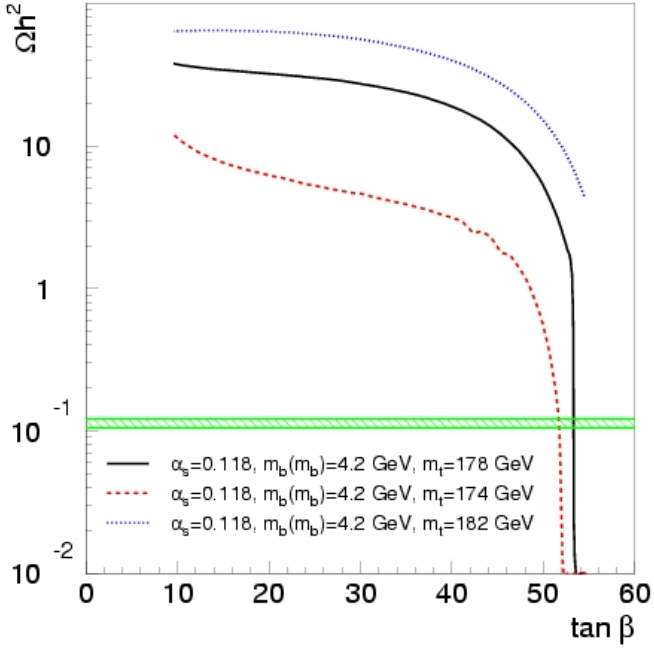
σ via Z is dominant:



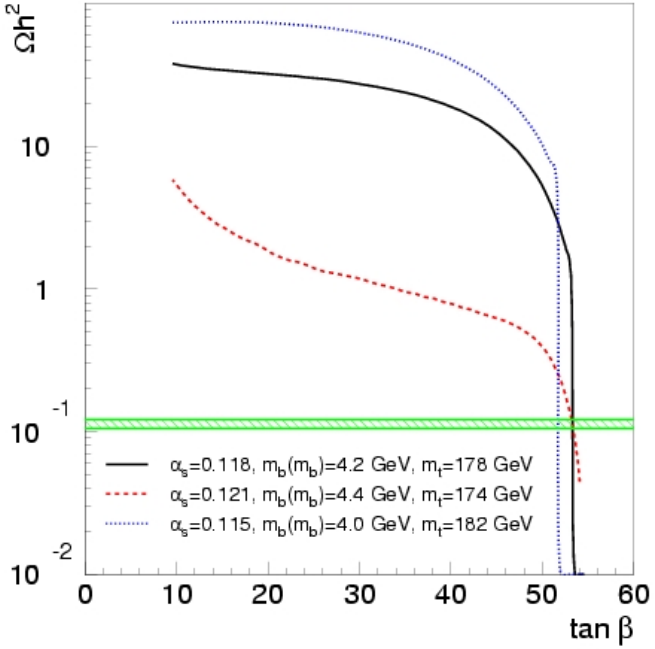
Cross sections calculated with `CalcHEP, hep-ph/0412191`

RD dependence on SM parameters

Top mass m_t:



with m_b und α_s:



Large uncertainty, in particular for large tan β; **Reason:** RGE of breaking parameters and EWSB $\rightarrow$ uncertainties, e.g. in

$$m_A^2 = m_1^2 + m_2^2 = m_{H_1}^2 + m_{H_2}^2 + 2\mu^2 \rightarrow \langle \sigma v \rangle \rightarrow \Omega_{\mathrm{DM}}$$

Electroweak symmetry breaking

- Pseudoscalar Higgs mass:
  $m_A^2 = m_1^2 + m_2^2 = m_{H_1}^2 + m_{H_2}^2 + 2\mu^2$
- Condition: $\frac{M_Z^2}{2} = \frac{m_1^2 - m_2^2 \tan^2\beta}{\tan^2\beta - 1}$
- Dependence on SM parameters by RGE
- For large $\tan\beta \rightarrow$ running of m_1 and m_2 is steep
  $\rightarrow$ large uncertainty in m_A ...
  $\rightarrow$ ... in $\langle\sigma v\rangle$ ...
  $\rightarrow$ ... and in RD

Running of breaking parameters: