Confinement of CR in Dark Matter relic clumps

V.Zhukov
University Karlsruhe and SINP Moscow State University
W.de Boer
University Karlsruhe

Dark Matter in Universe and the Galaxy

Strong evidences for DM existence:

- galactic rotation curves
- large scale structures
- nucleosynthesis and element abundances

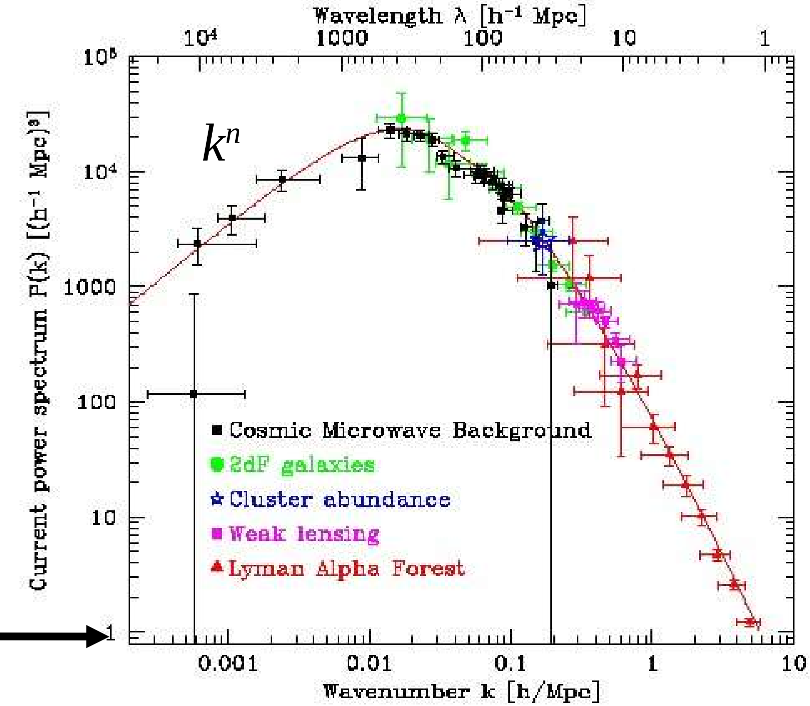
Modern cosmology:

- inflation scenario $\Omega\sim1$, $\Omega_\lambda\sim0.73$, $\Omega_\chi\sim0.23$
- bottom-top scenario $P(k)\sim k^n$, $n>0.95$
  small structures(clumps) are created first
- universal DM profile for different scales

Cuspy ($\gamma>0$) profile from Nbody and analytical simulation (NFW parametrization):

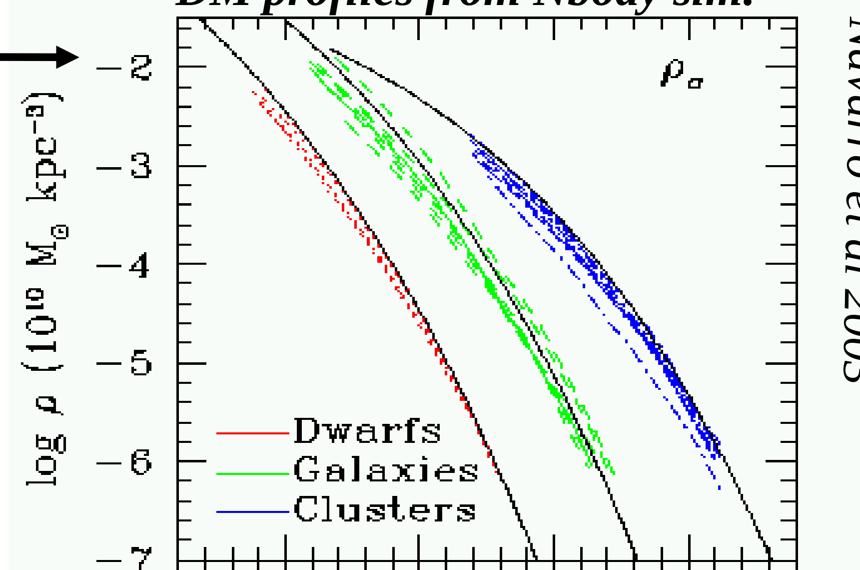
$$\rho(r)=\rho_0\left(\frac{r}{a}\right)^{-\gamma}\left[1+\left(\frac{r}{a}\right)^{\alpha}\right]^{\frac{\gamma-\beta}{\alpha}}$$

Spectrum of structure scales



Tegmark et al 2002

DM profiles from Nbody sim.



Navarro et al 2003

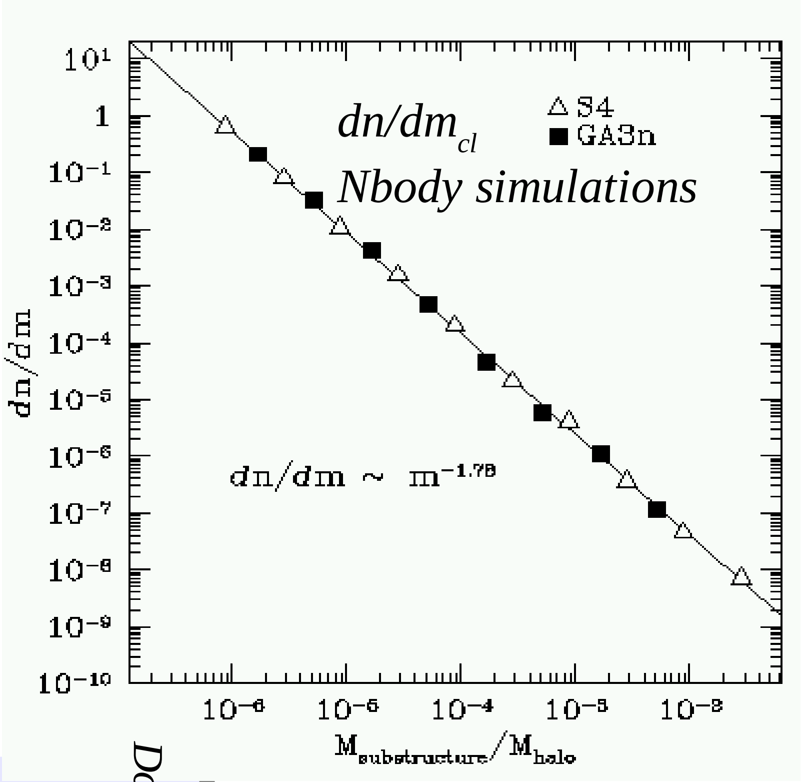
DM clumps

Fraction of DM in relic clumps :

depends upon;

- spectrum of primary fluctuations $\delta \sim k^n$
- clumps density profile : $\rho \sim r^{-\alpha}$, α=1.5-2
  $r<r_c=\delta^3 r_{clump}$, $r_c \sim 10^{-3}$-0.1 r_{cl}, ρ_{max} -?
- mass spectrum dn_{cl} and minimum mass M_{min}
  $M_{min}=10^{-6}$-10^{-8} $M_\odot$ is defined by free streaming of DM after decoupling

Gurevich et al 1997



Stoehr et al 2004

$\zeta \sim$ 0.001-0.1 of DM is in relic clumps
the rest is the 'bulk' DM

Diemand et al 06,
Berezinskii et al 03

Clumps distribution in the Galaxy n_{cl} :

- follows the bulk DM distribution (universal profile)
- tidal disruption by Galactic potential can disturb the distribution (depletion near the center)
- large scale structure appears due to 'recent' infalls (CanisM,Sag.)

Dokuchaev et al 03

Ex. smallest clumps:
$M=10^{-8} M_\odot$, r~100 AU, $<\rho>\sim 100$ GeV/cm^3, $\rho_{max}\sim 10^{3-5}$ GeV/cm^3
~1-100 clumps/pc^3 at $R_\odot$=8.5 kpc , $\rho_{bulk}\sim$ 0.3-0.7 GeV/cm^3

DM annihilation

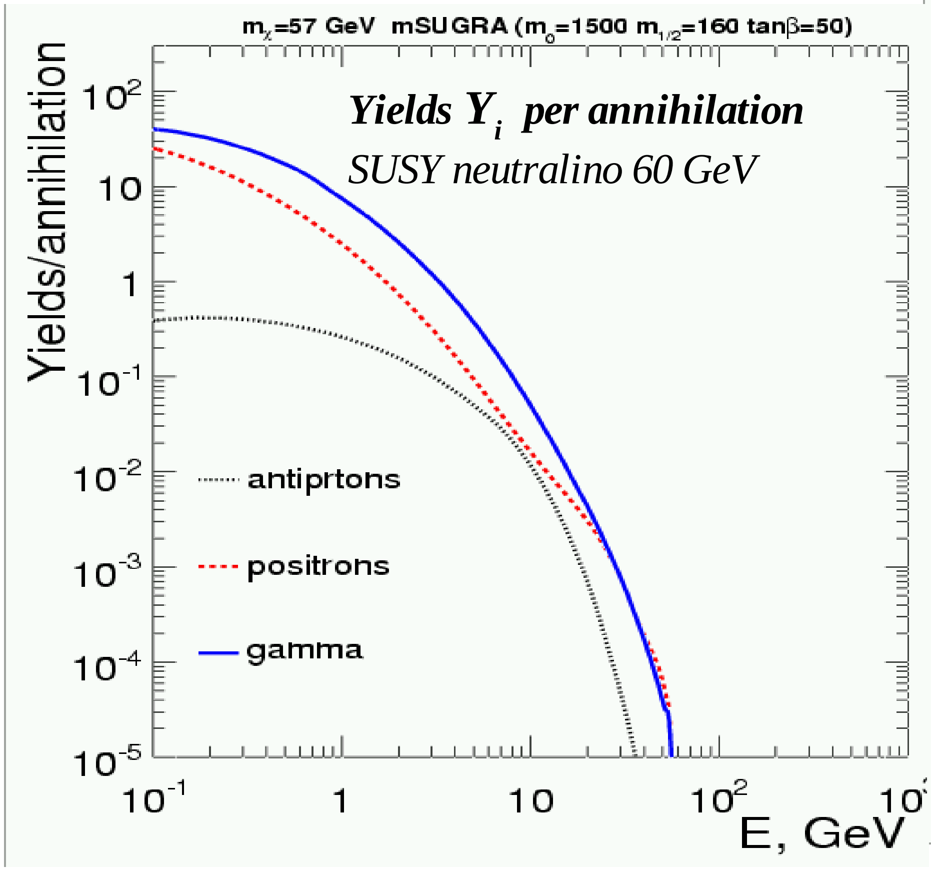
DM can annihilate (or coannihilate) with the averaged cross section $\langle\sigma v\rangle$ constrained by relic density in time of decoupling $T_{dec} \sim m_\chi/20 \sim 3\text{-}50$ GeV

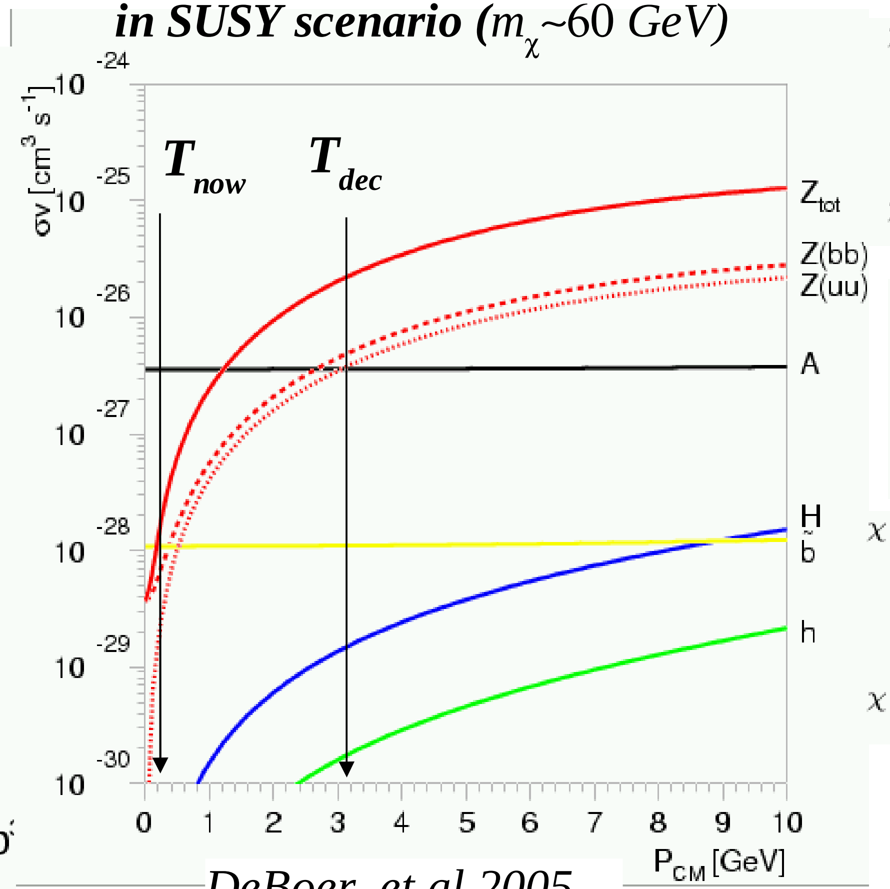
$\langle\sigma v\rangle = 2\ 10^{-27}\ cm^3 s^{-1} / \Omega_\chi h^2 [0.092 - 0.112]$, $\langle\sigma v\rangle \sim 2\ 10^{-26}\ cm^3 s^{-1}$

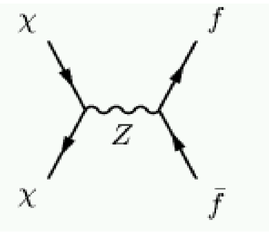
Nowadays (T~1.8 K) $\langle\sigma v\rangle$ can be only smaller

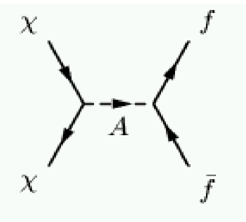
The dominant end state are fermions
After hadronization and fragmentation
stable particles: p, pb, e+, e-, γ

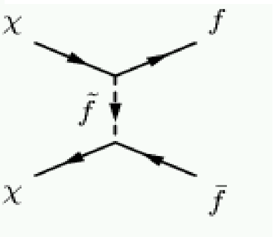
Momentum dependency of $\langle\sigma v\rangle$
for different annihilation channels
in SUSY scenario (m_χ~60 GeV)









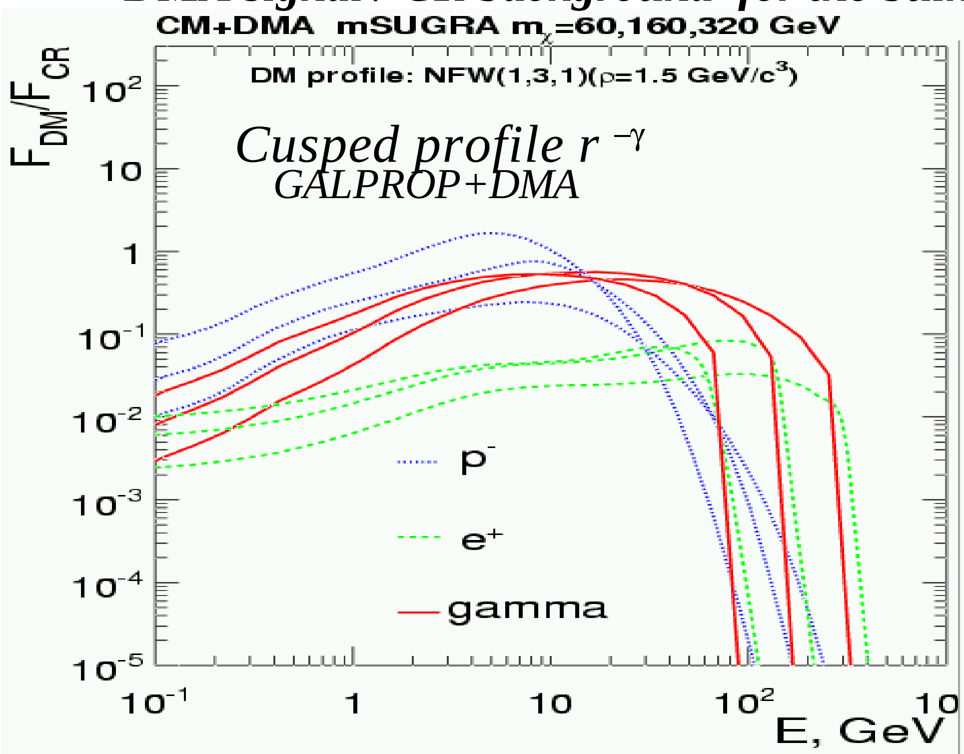


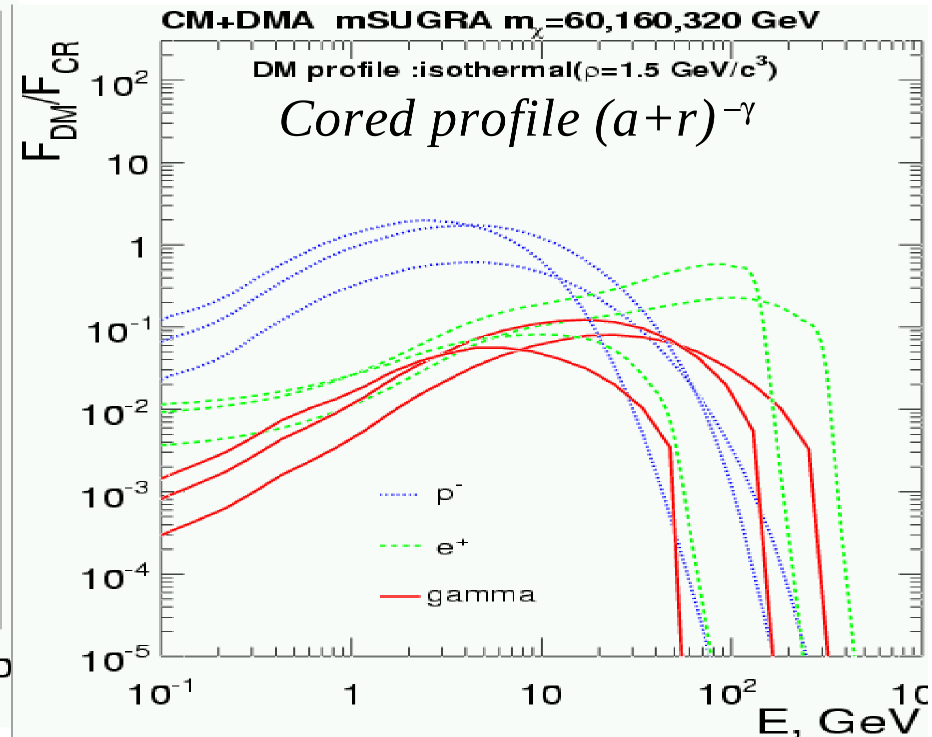
DeBoer et al 2005

DM annihilation(DMA) in the Galaxy

Annihilation signal : $$q_i(r,p) = \langle \sigma v \rangle Y_i(p) \int^r \frac{\rho^2_{DM}(l)}{m^2_\chi} dl$$ ***$q \sim 1/m_\chi^{2-4}$***

DMA signal / CR background for the bulk galactic DM (different profiles and m_χ)





Zhukov et al

Experimental resolution (EGRET, Bess, Caprice, etc) ~10% ***Model uncert. can be much larger..***

Boost factor: *if relic clumps exist*

DM annihilation signal $Q_{DMA} \sim \rho^2$ is dominated by cusp of smallest DM clumps

$\rho_{tot} = \rho_{bulk} + \rho_{cl}$, $\rho_{cl}^{max} >> \rho_{bulk}^{max}$, ***$B = Q_{tot}/Q_{bulk}$, $B = 1\text{-}10^4$ depending on ζ and ρ_{cl}^{max}***

if $n_{cl} \sim \rho_{bulk}$, $B \sim 1/\rho_{bulk}$, $Q_{tot} \sim \rho_{bulk}$ -> effective DMA profile instead of DM bulk profile

CR propagation

CR propagation: as a resonant scattering of CR *f(r)* on MHD turbulences with spectral density *W(k,r)*: $1/k_r \sim r_g = pc/ZeB$

$k \sim 10^{-12}\ cm^{-1}$ for GeV particles in $B \sim 10^{-6}$ G

Source term for a DM clump
$q_i(r,p) \sim \langle \sigma v \rangle\, Y_i(p)\, \rho_o^2/m_\chi^2$

Berezynskii et al 1990

$$\frac{1}{r^2}\frac{\partial}{\partial r}D\frac{\partial}{\partial r}r^2 f - V_c\frac{\partial f}{\partial r} - \frac{1}{r^2}\frac{\partial}{\partial r}r^2 V_c\frac{p}{3}\frac{\partial f}{\partial p} - \frac{\partial}{\partial p}(\dot{p} f) - \frac{f}{\tau} = -q(p,r)$$

diffusion — *Vc-convection* — *P losses* — *Decays and fragmentation*

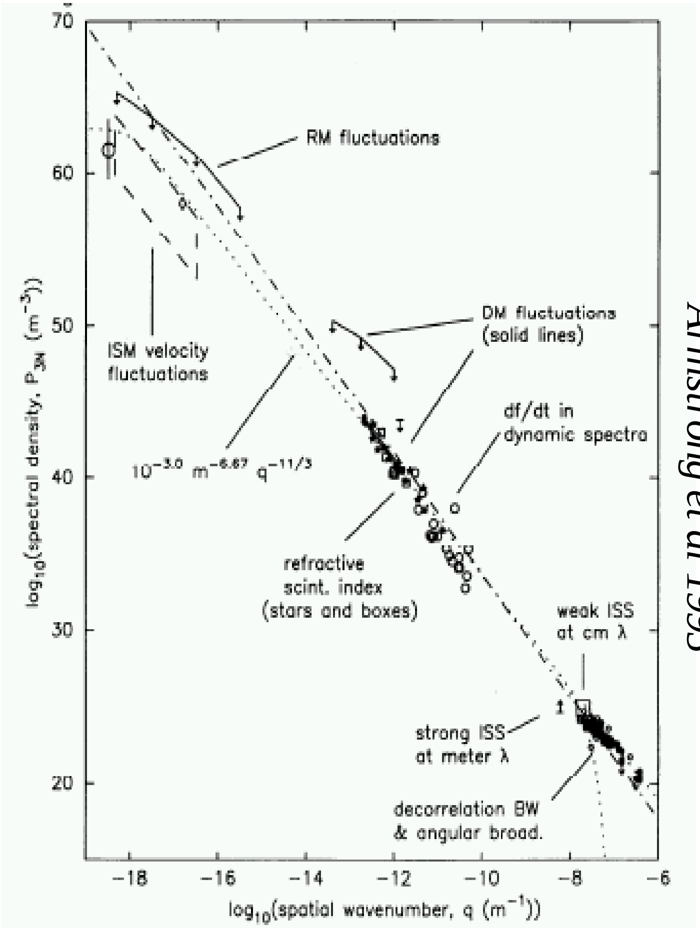
$$D(r) \approx v r_g^2 B^2 / 12\pi W(k_r, r)$$

MHD waves interact with CR

$$\frac{\partial W}{\partial t} + \frac{1}{r^2}\frac{\partial}{\partial r}v_a r^2 W - \frac{\partial v_a}{\partial r}\frac{\partial}{\partial k}kW = (G-S)W$$

Alfven speed $v_a \sim B/\sqrt{4\pi\rho_H}$

growth by CR if $V_{str} > v_a$ — *damping*



Armstrong et al 1995

Scales spectrum in electron density

W(k) is related to the scale of interstellar irregularities, follows $W \sim k^{a-2}$, a=1/3 for Kalamogorov spectrum small scales $1/k < 10^{14}$ cm are created by CR streaming(?)

Growth and damping of MHD turbulences

Enhancement of the MHD waves by CR streaming:

pitch angle scattering $\mu = \cos\theta$

At resonance $v\mu = \Omega/k$

small at E<1 GeV for DMA products

Kulsrud 69
Wentzel 1974

$$G(k,r) \approx \frac{\pi^2 e^2 v_a}{kc^2} \int\int dp d\mu v p^2 (1-\mu^2)\delta(p|\mu| - \frac{eB}{kc}) \times (\frac{\partial f}{\partial \mu} + \frac{v_a p}{v}\frac{\partial f}{\partial p})$$

$$\frac{\partial f}{\partial \mu} \sim \frac{vp^2 c|\mu|}{2\pi^2 e^2 W}\frac{\partial f}{\partial r}$$

Anisotropic term from diffusion equation:
(if Vc~0, Ploss~0, no reacc.)

$$\frac{1}{r^2}\frac{\partial}{\partial r} D \frac{\partial}{\partial r} r^2 f = -q_o \delta(r)$$

Damping:

1. ions -neutral gas friction

$$S_H \sim \frac{1}{2}\langle \sigma_{col} v_a \rangle n_H$$

$\langle n_H \rangle$ ~1 cm^{-3} , $\langle n_{HI} \rangle$ ~0.01 cm^{-3}
molecular clouds n_H~ 10-1000 cm^{-3}
$\langle \sigma_{col} v \rangle$ ~10^{-9} cm^3 s^{-1}

MHD are damped in the dense gas clouds (galactic disk, clouds)

2. nonlinear damping by MHD waves collisions

$$S_{nl} \approx \frac{4\pi v_a W}{B^2 r_g^2} = S_{nl}^0 W$$ << S_H

important in the underdense regions (halo, Local Bubble)

damping by CR significant for the Kraichan spectrum, at $1/k < 10^{13}$ cm

Ptuskin et al 2006

MHD waves from DM clumps

DM clump is a constant , point like source of CR(p,e) can enhance MHD waves.

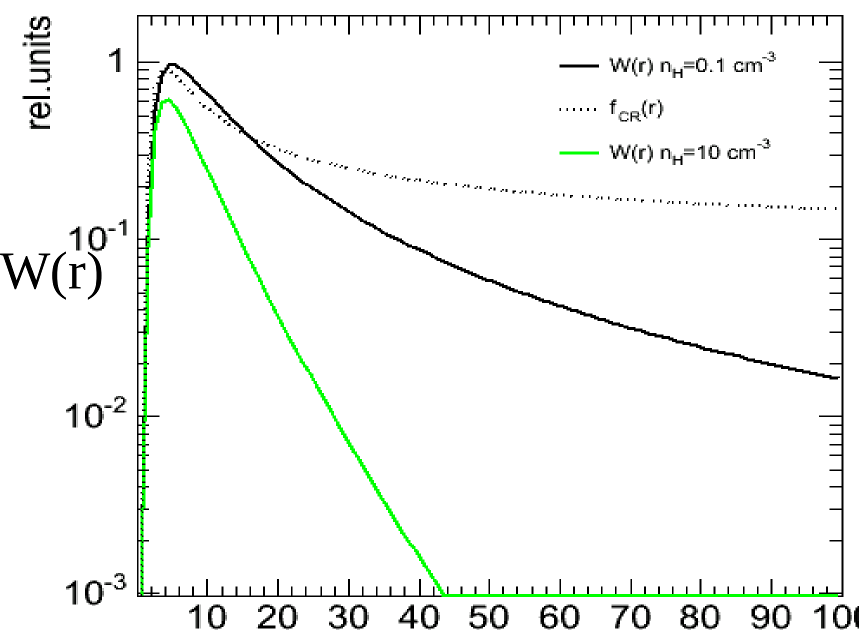
Steady state solution for *W(r)* *(simplified):*

$$W(r) \sim \frac{exp(-g/r - s_H r)}{r^2 (C_0 + s_{nl} exp(-g/r - s_H r)/g)}$$

$s_{nl}=S_{nl}/v_a \quad s_H=S_H/v_a$

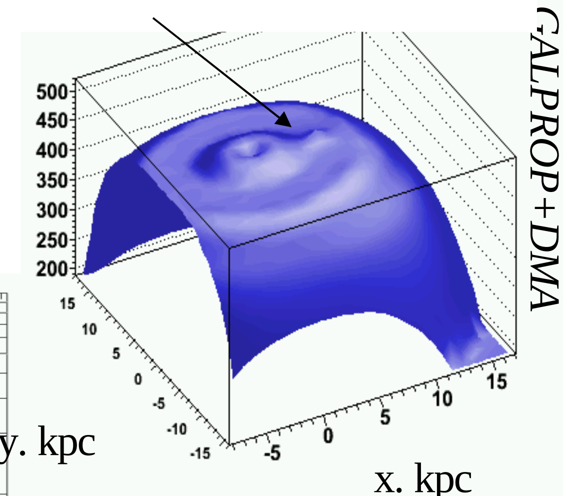
$g \sim \langle\sigma v\rangle Y_{tot}\, \rho_{max}^2\, r_c^3 / m_\chi^2$

W(r) dependency for a DM clump



Maximum at $r_{max} \sim sqrt(g/s_H)$

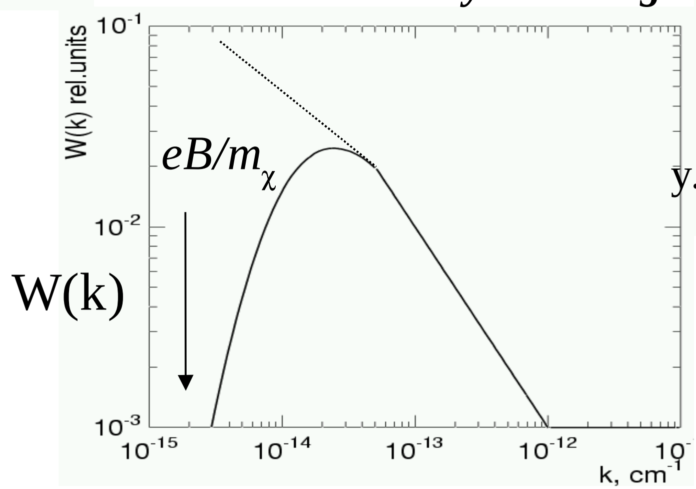
CR p (1GeV) + DMA p from a clump at 8kpc



CR proton density distribution in Galaxy GALPROP Conventional model

W(k) is cutoff at $\sim m_\chi$

can be extended by cascading



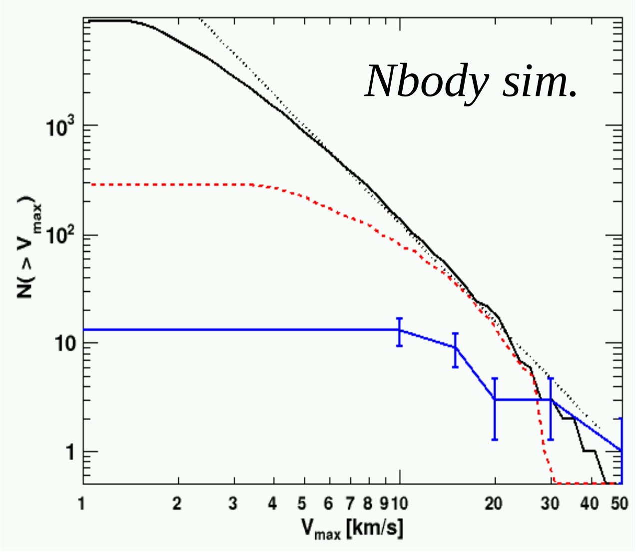
Assumptions:

- **spherical symmetry (growth is along B field)**
- **DM clump is point like source (cusped profile)**
- **f(p)~ const**
- **no losses**
- **Vc~0 , small local convection**
- **Va~const, δB/B is small**
- **no interference between electrons and protons...**

CR confinement in DM clumps

Stability conditions of the confinement zone:

- **slow proper motion of clumps** $V_{cl} < v_a$
- **large external diffusion** $D_{ext} > D_c$ $(W_{int} > W_{ext})$
- **slow external convection** $V_c < v_a$



Moore et al 2002

Distribution of clumps by proper motion in the Galaxy

DM clump can create a trapping region with low D_c

Different environments:

- **molecular gas clouds**

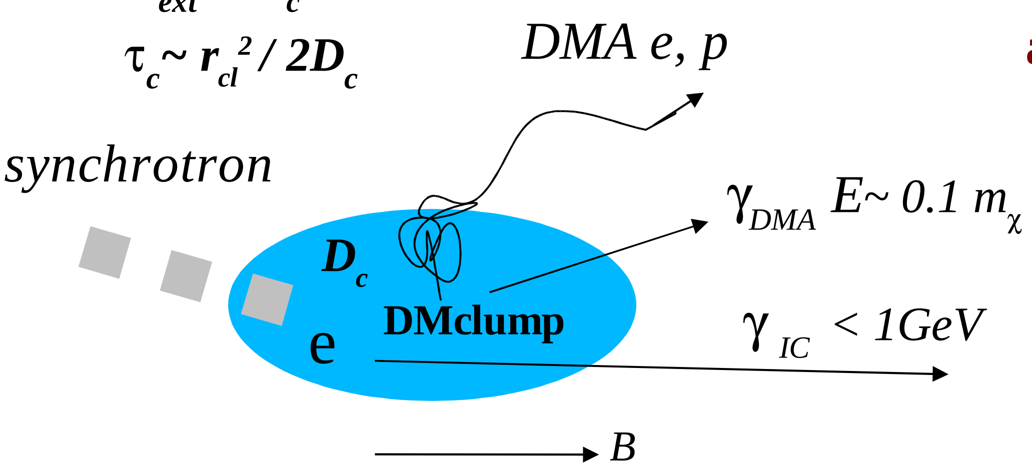
$\rho_{H2} = 10\text{-}1000\ cm^{-3}$ -strong damping

- **underdense regions**

(Local Bubble, galactic halo) $\rho_H < 0.1 cm^{-3}$, low *W* density

$D_{ext} >> D_c$

$\tau_c \sim r_{cl}^2 / 2D_c$



local variations in diffusion coefficient and therefore CR density $f^* v_{str} / B \sim const$

DMA contributions:

- **γ from χχ->ffbar->γ+X**
- **γ from DMA e+,e- via IC ,Bremss.**
- **p+,p-, e+, e- from χχ->ffbar->p,e+X**
- **radio from e+,e- synchrotron losses**

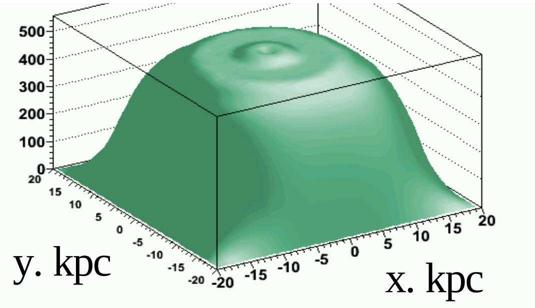
Isotropic galactic model

Isotropic and uniform propagation model:

- *D*- isotropic diffusion and uniform
- averaged gas density <nH> , no gas clouds

Normalize CR primary density to locally observed at R=8.5 kpc

Moscalenko, Strong 2004



CR protons density 1 GeV

Z_h~+-4 kpc	D~6 10^{28} cm^2 s V_{conv}< 10 km/s	Source(r) $n(r,z<100pc)\sim 1cm^{-3}$

δ(100 GeV)<10^{-3}

$T_{esc} \sim Z_h^2/D$

$X = vnT_{esc}$ ~ 7 g/cm²

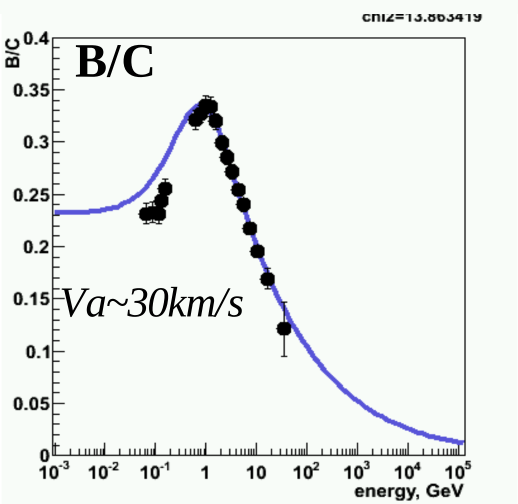
LB:

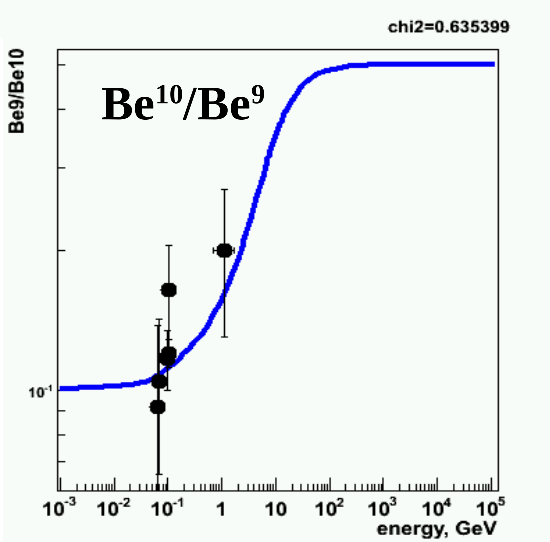
$$\frac{f_{sec}}{f_{prim}} = \frac{vn\sigma_s}{vn\sigma_f + T_{esc}^{-1}}$$

$$\frac{f_{rad}}{f_{stab}} = \frac{\sigma_{rad}}{\sigma_{stab}} \frac{vn\sigma_f + T_{esc}^{-1}}{vn\sigma_f + T_{esc}^{-1} + (\gamma\tau_d)^{-1}}$$

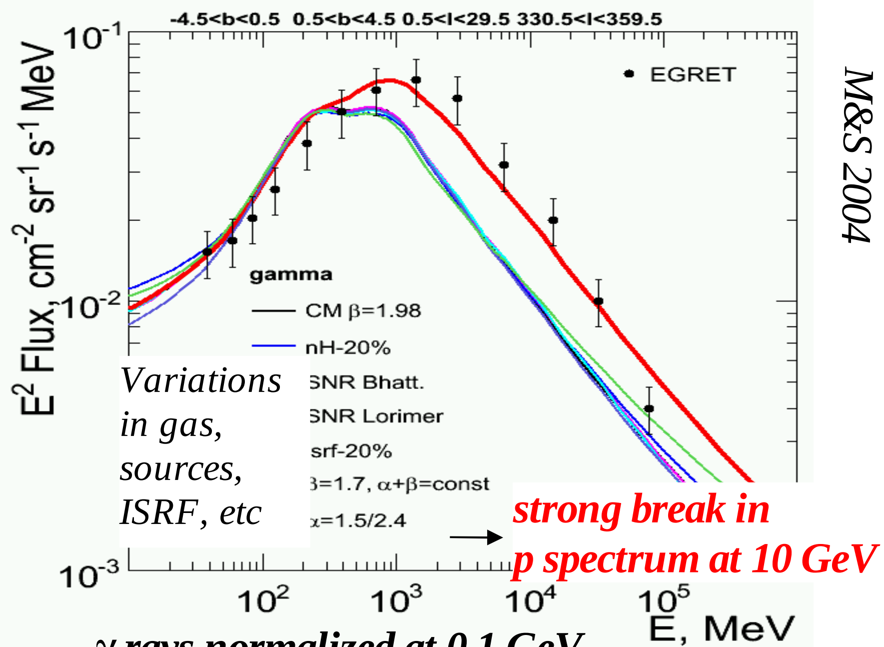
Use locally measured secondaries to constrain the galactic global parameters *(D,Z, Va,Vc)*

Fails to explain gamma rays unless proton (e) interstellar spectrum has a strong break at 1-10 GeV





Conventional Model CM (GALPROP)



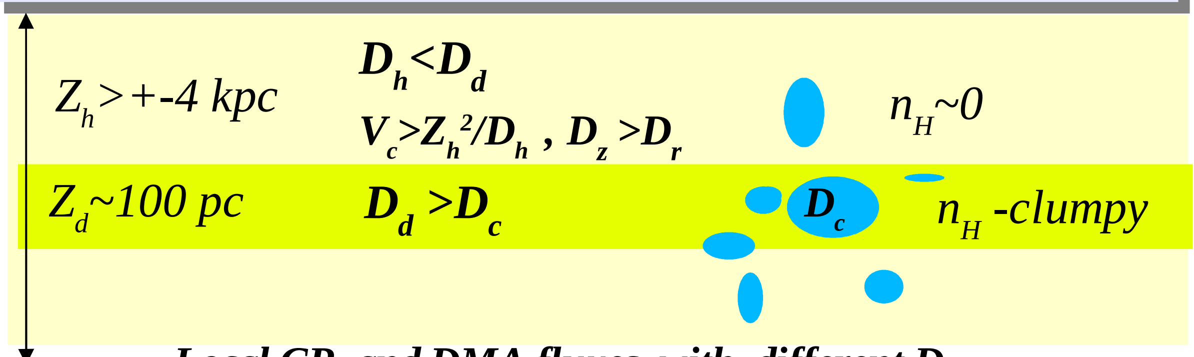
Hunter et al 98
M&S 2004

γ rays normalized at 0.1 GeV

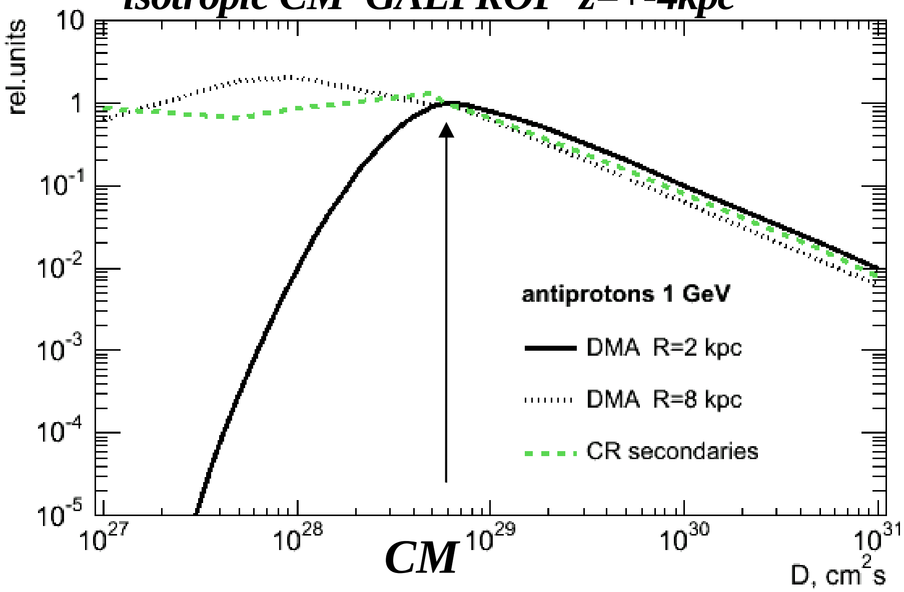
Inhomogeneous model: a possibility

But propagation is not uniform:

- **DM clumps trapping zones with small D_c**
- **gas is clumpy, ~50% in H2 clouds 10-1000 cm^{-3}**
- **Local Bubble, underdense regions, large W is possible**
- **trapping in magnetic mirrors**
- **two zones model, convective halo driven by CR....**



Local CR and DMA fluxes with different D
isotropic CM GALPROP z=+-4kpc



Propagation in non homogeneous medium:
Kulsrud, Pearce 69
Ptuskin, Soutoul, Osborne 90
Zwiebel, Shull 82,
Padoan, Scalo 2006
Chandran 2000 , etc....

Assumptions:

- **Large D_d in the gal. disk z_d~100pc**
- **Small D_h in the halo, large V_{conv}**
- **Clumpy zones with local confinement**
  (DM clumps, trapping in clouds, etc) D_c

Confinement zones with *Dc<Dd:*

- **increase the grammage *X locally***
  (r_{cl}~10pc, n_{cl}=200 cm^{-3})

$$X = v\bar{n}\frac{Z_d^2}{D_d} + \sum^{Ncl} v n_{cl} \frac{r_{cl}^2}{D_c}$$

$$\frac{D_c}{D} \sim \frac{N_{cl} n_{cl} r_{cl}^2}{n z_h^2} \sim N_{cl} * 10^{-2}$$

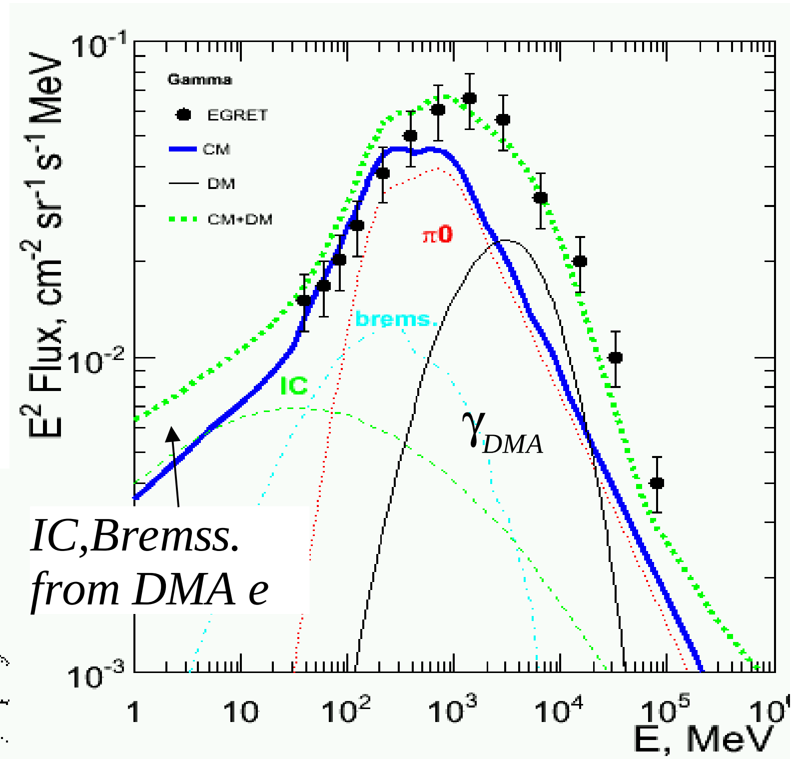
- **isotropize CR** *f=fd+fcl*

$$\delta \sim \frac{D}{v}\frac{1}{f}\frac{\partial f}{\partial x} \approx \frac{D}{v}\frac{1}{f}\left(\frac{\partial f_d}{\partial x} - \sum^{Ncl} \frac{\partial f_{cl}}{\partial x}\right)$$

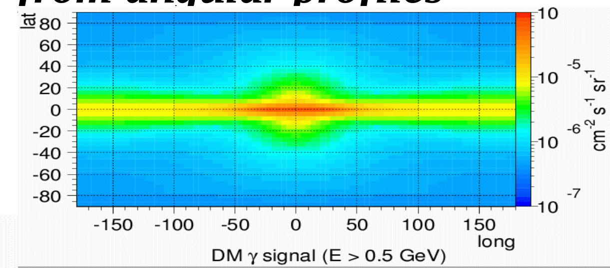
Ex: isotropic propagation model with DMA

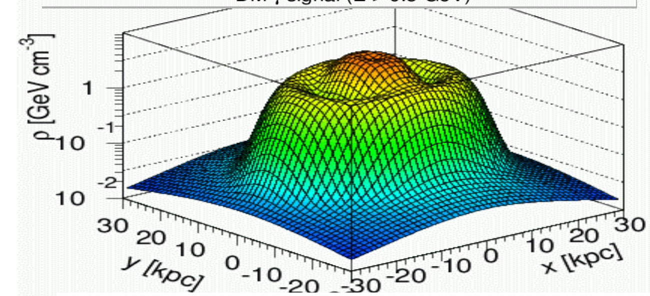
DeBoer et al 2005

EGRET excess interpreted as a DMA signal (SUSY neutralino)
m_χ~ 60 GeV
Boost factor ~50
-> DM clumps

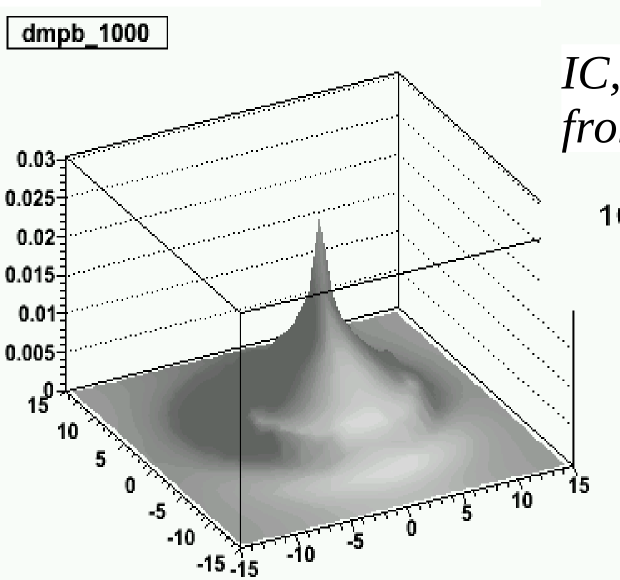


Reconstruct DMA effective profile (clumps distribution) from angular profiles

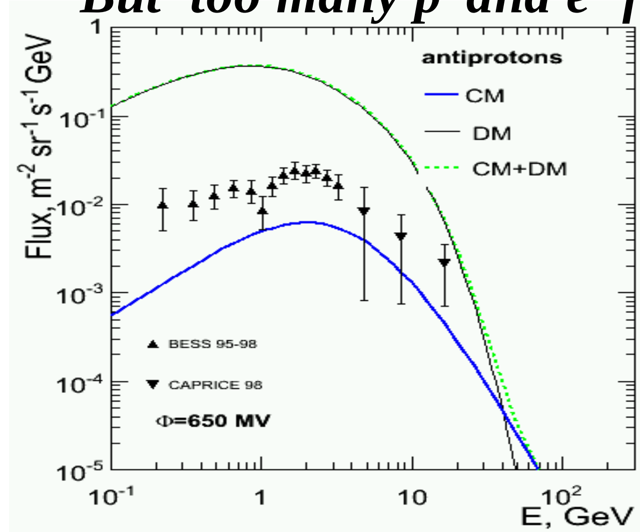


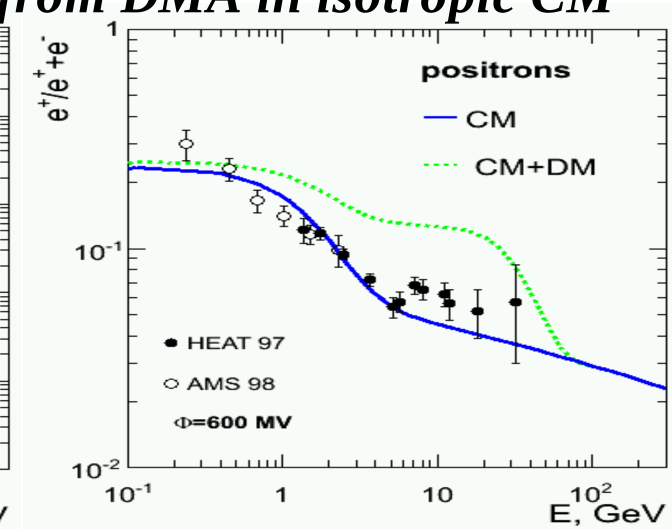


Explains rotation curves



But too many p^- and e^+ from DMA in isotropic CM





DMA antiprotons(1GeV) in CM
DM rings like structure from 'EGRET' profiles (GALPROP+DMA)

Ex: DMA in model with inhomogeneous medium

Decouples locally observed CR secondaries (B,Be, etc) from charged DMA and gamma rays

GALPROP** (Moscalenko, Strong) **modified:

***including DMA using 'EGRET' profile, anisotropic nonuniform propagation** (AD+DMA)*

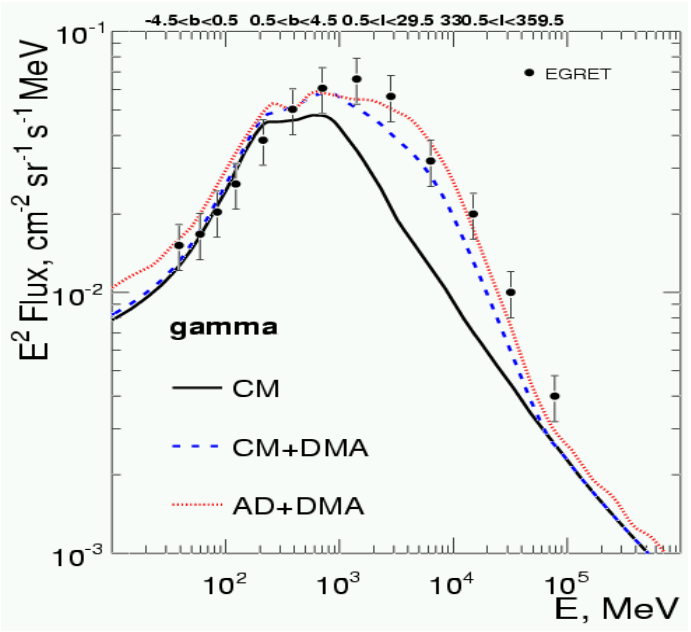
More parameters, more freedom, for.ex:

Zd=200 pc $D_d=10^{30}\ cm^2\ s$ n(r,z), snr(r,z) (Lorimer et al)

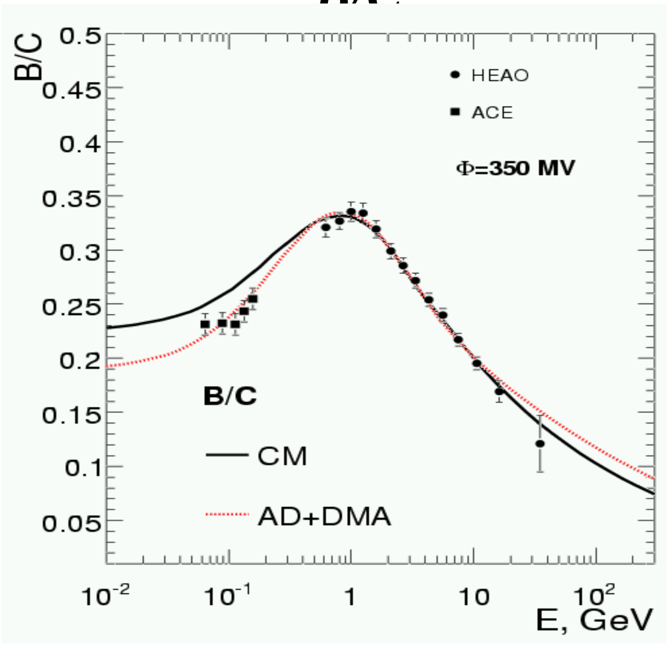
*Zh=4 kpc $D_h=10^{28}\ cm^2\ s$, Vc=z*dV/dz=20 km/s/kpc*

nH2 scaling~40

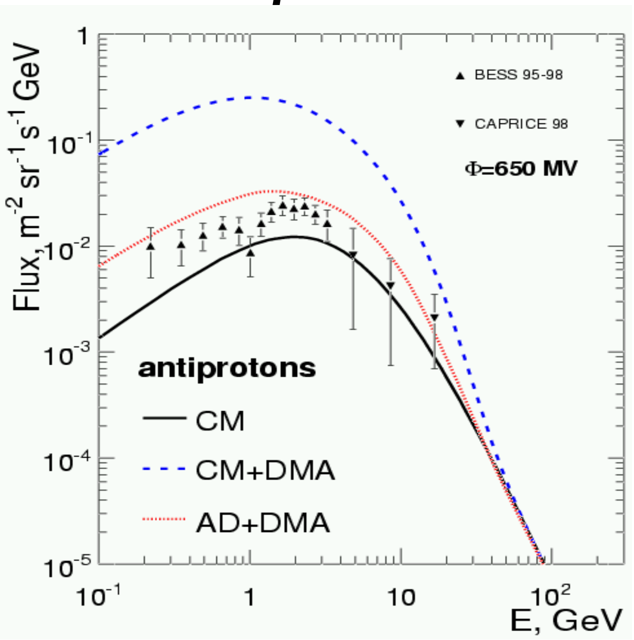
Gamma rays



B/C



antiprotons



Summary

- **Annihilation in cuspy relic DM clumps can produce MHD waves with scales $k > eB/m_\chi$ and confine charged CR**

- **The confinement zones will contribute to small scale variations in propagation parameters. These variations can decouple locally observed fluxes from the galactic averages**

- **The confinement zones can isotropize CR and produce secondaries locally thus allowing larger diffusion coefficient in the galactic disk**

- **The annihilation signal can be attributed to the gamma rays, antiprotons and positrons. In inhomogeneous medium the DMA charged contributions can be not directly related to the gamma rays from DMA**