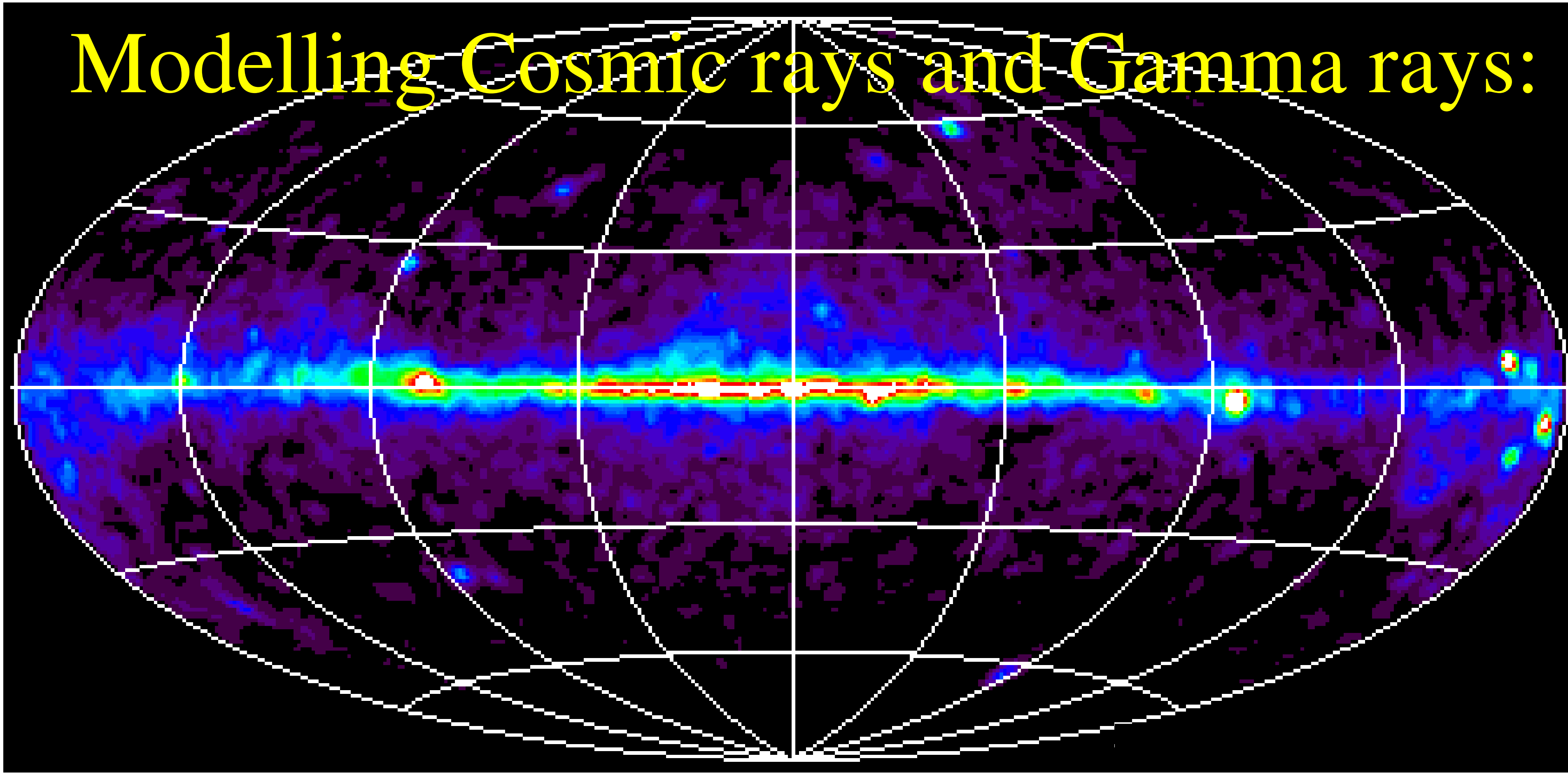
Modelling Cosmic rays and Gamma rays:



A. Strong

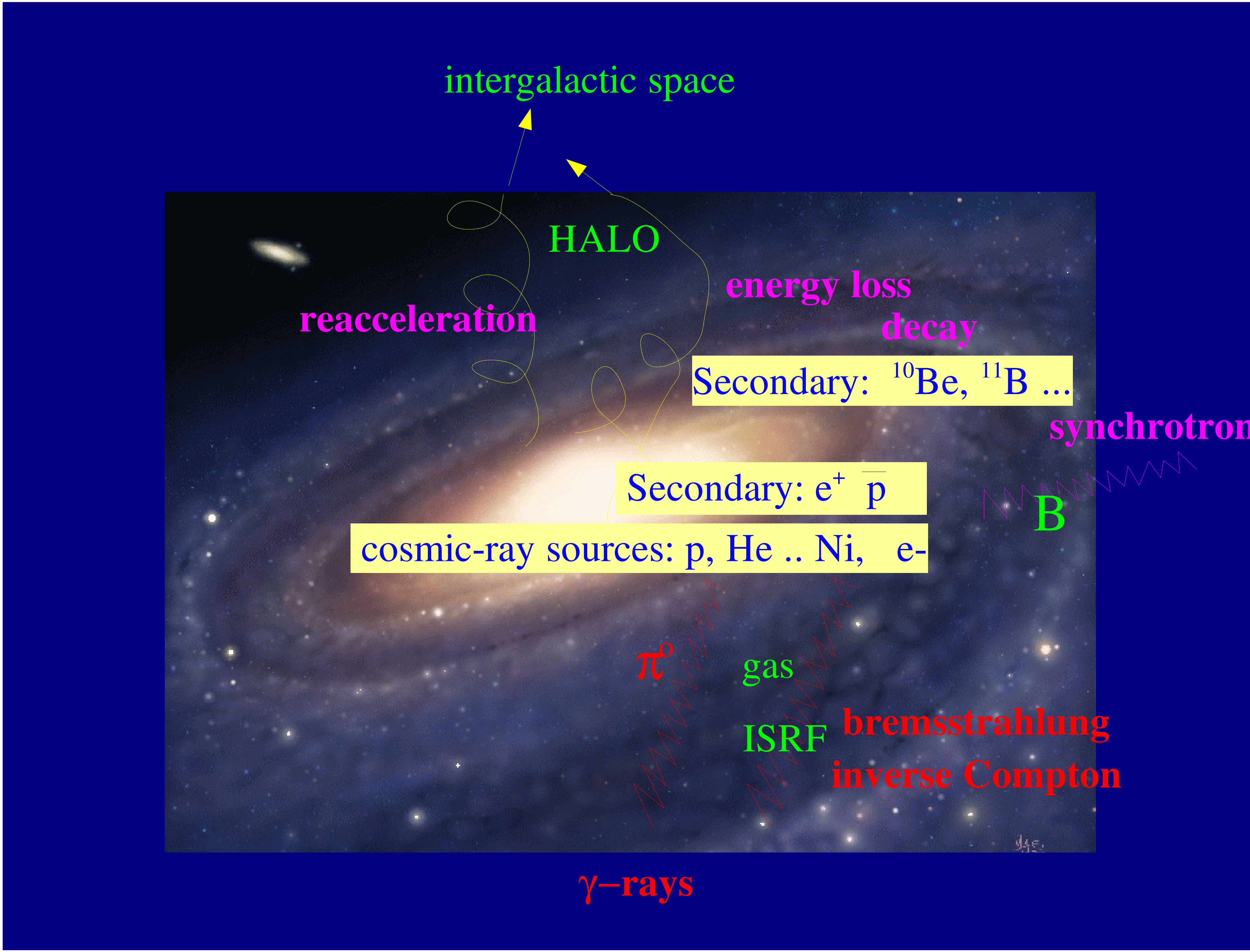
Copenhagen, September 2004

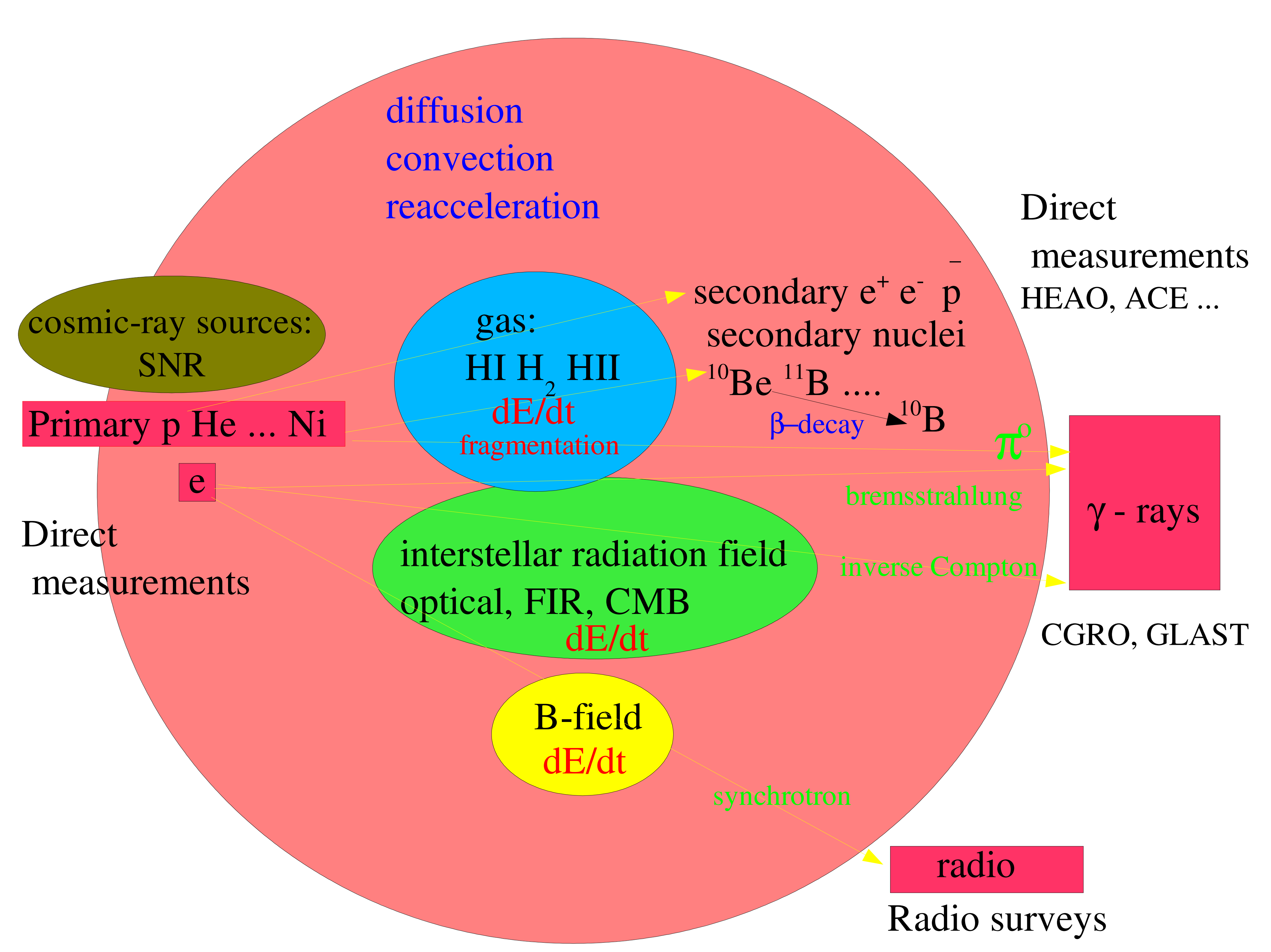
Work done with

Igor Moskalenko (NASA Goddard)

Olaf Reimer (Bochum)

Seth Digel (Stanford)

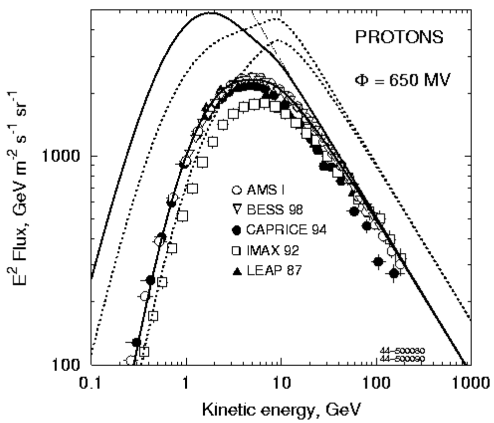

intergalactic space
HALO
reacceleration
energy loss
decay
Secondary: ^{10}Be, ^{11}B ...
synchrotron
Secondary: e^{+} $\bar{p}$
B
cosmic-ray sources: p, He .. Ni, e-
π^{0}
gas
ISRF
bremsstrahlung
inverse Compton
γ–rays


diffusion
convection
reacceleration
Direct
measurements
HEAO, ACE ...
secondary e+ e- p
secondary nuclei
10Be 11B ....
10B
β–decay
cosmic-ray sources:
SNR
gas:
HI H2 HII
dE/dt
fragmentation
Primary p He ... Ni
e
π0
bremsstrahlung
γ - rays
Direct
measurements
interstellar radiation field
optical, FIR, CMB
dE/dt
inverse Compton
CGRO, GLAST
B-field
dE/dt
synchrotron
radio
Radio surveys

The **goal** : use *all* types of data in self-consistent way to test models of cosmic-ray propagation.

Observed *near sun:*

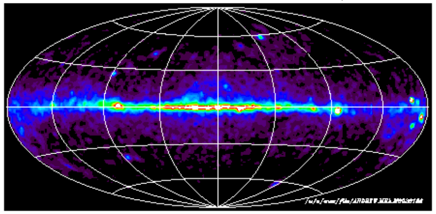
- primary spectra (p, He ... Fe; e^-)
- secondary/primary (B/C etc)
- secondary e^+
- secondary antiprotons

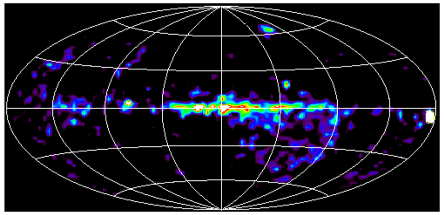


Observed *from whole Galaxy:*

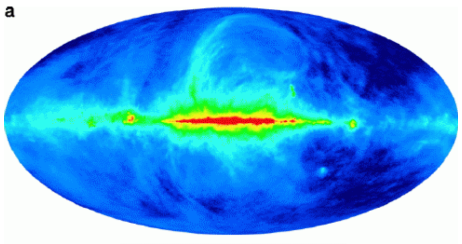
γ - rays

EGRET COMPTEL





synchrotron



Cosmic-ray propagation

$\partial\psi(\underline{r}, p)/\partial t = q(\underline{r}, p)$ cosmic-ray sources (primary and secondary)

$+ \nabla \cdot (D_{xx} \nabla\psi \qquad \psi)$

diffusion convection

$+ \partial/\partial p\, [p^2 D_{pp} \partial/\partial p\, \psi / p^2]$ $D_{pp} D_{xx} \sim p^2 v_A^2$

diffusive reacceleration (diffusion in p)

$- \partial/\partial p\, [\, dp/dt\, \psi \qquad - p/3\, (\nabla \cdot \quad)\, \psi\,]$

momentum loss adiabatic momentum loss

ionization, bremstrahlung

$-\psi/\tau_f$ nuclear fragmentation

$-\psi/\tau_r$ radioactive decay

galprop

numerical solution of cosmic-ray transport
2D or 3D grid
time-independent or time-dependent

primary source functions (p, He, C .... Ni)
source abundances, spectra
primary propagation

secondary source functions (Be, B...., e^+ e^- p)
using primaries and gas distributions
secondary propagation

tertiary source functions
tertiary propagation

γ- rays (inverse Compton, π^o - decay, bremsstrahlung)
radio: synchrotron

galprop

3D gas model based on HI, CO surveys
cosmic-ray sources $f(\underline{r}, p)$
interstellar radiation field $f(\underline{r}, \nu)$
nuclear cross-sections database
energy-loss processes
B-field model
solar modulation

γ- ray processes

galprop code: publicly available since 1998, many users
continuous development
Strong & Moskalenko ApJ 1998, 2000, 2004

Standard propagation model:

halo: sharp boundary, free escape.
diffusion: Kolmogorov $D_{xx}(p) \sim \beta p^{1/3}$
diffusive reacceleration: $v_A \sim 30$ km s^{-1}
no convection

This can give secondary/primary energy-dependence (GeV peak) *without ad-hoc break* in $D_{xx}(p)$.

(cf traditional procedure : $D_{xx}(p)$ = const below 3 GeV, $p^{0.6}$ above 3 GeV

Radioactive ^{10}Be ($\tau = 10^6$ yr) sets limits on halo size and convection

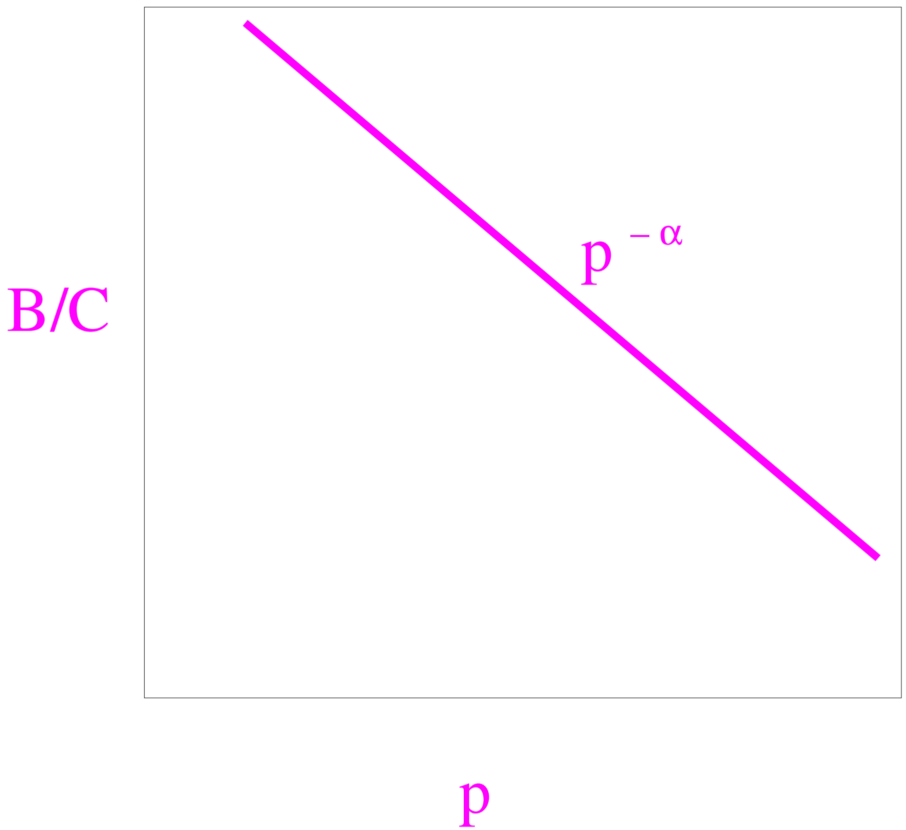
Strong & Moskalenko 1998:

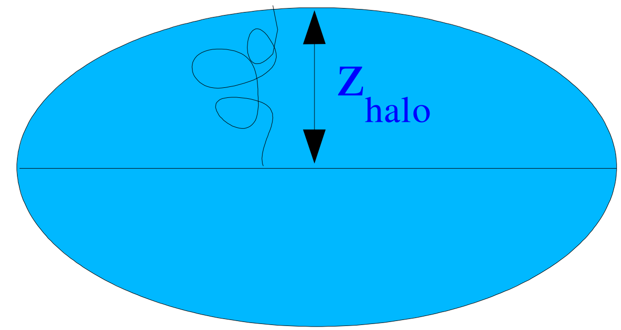
Halo height = 4 kpc

convection velocity < 7 km s^{-1} kpc^{-1}

NB needs more work since convection expected from Galactic wind!

Reference secondary/primary ratio: B/C ($^{10+11}B/^{12+13}C$)





simple diffusion :

$\beta = v/c$

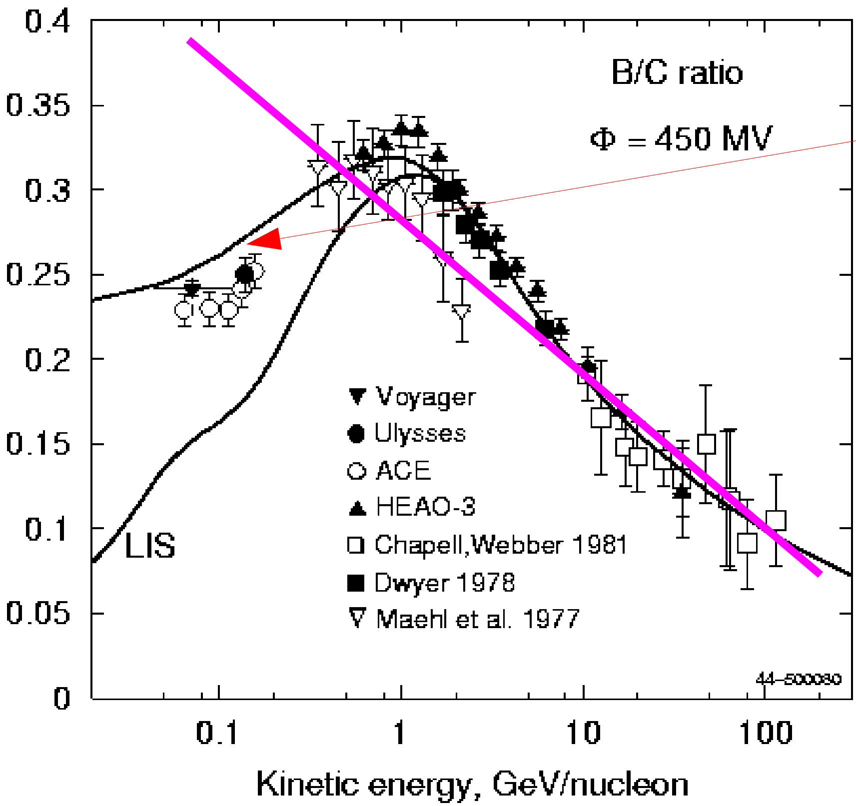
$D_{xx} \sim \beta\, p^{\alpha}$

$z_{halo} \sim (D_{xx}\, t)^{1/2}$

$t \sim z^2_{halo} / D_{xx}$

$B/C \sim \beta \sigma n\, t \sim \beta / D_{xx} \sim p^{-\alpha}$

Reference secondary/primary ratio: B/C



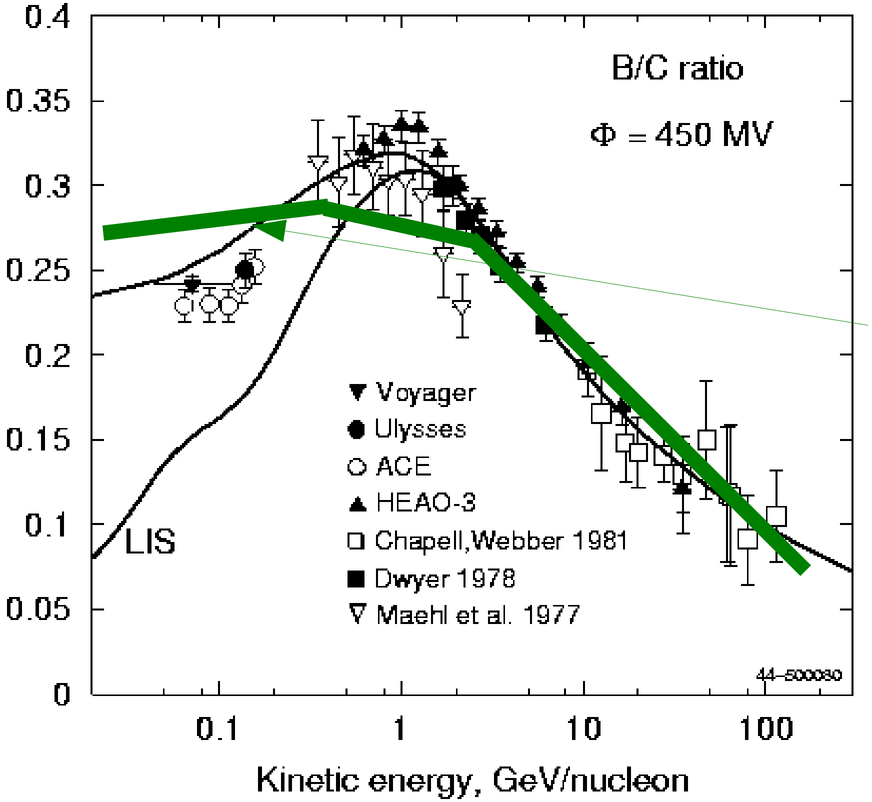
But observe fall-off at low energy peak in B/C

for $D \sim \beta\, p^{\,0.6}$
(required to fit high energies)

$B/C \sim \beta / D \sim p^{\,-0.6}$

E

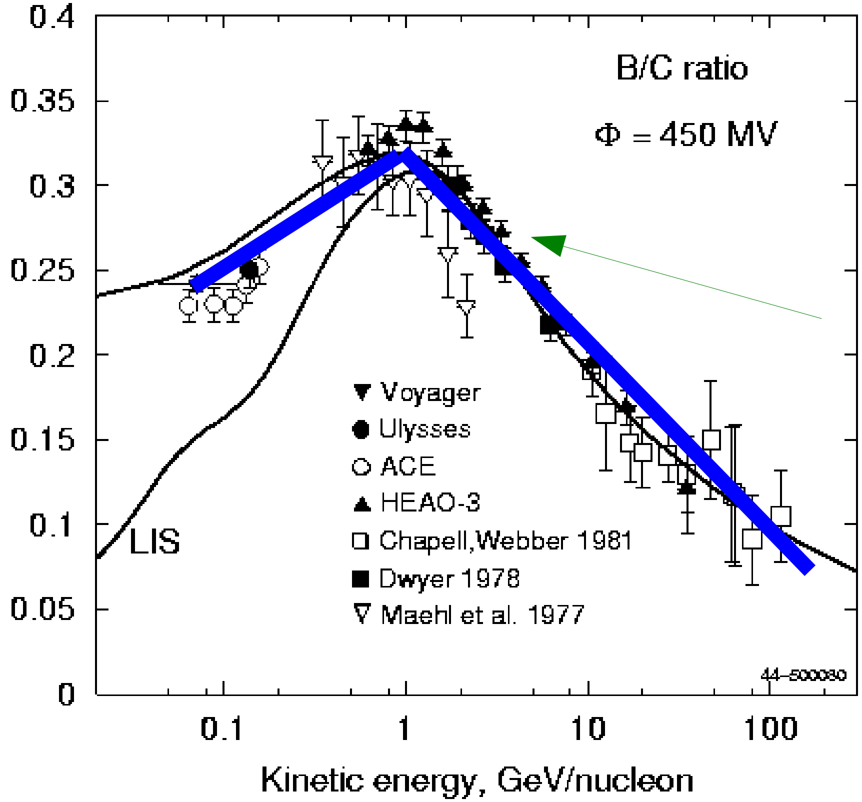
Reference secondary/primary ratio: B/C



Convection : constant time to reach halo and escape: B/C ~ β

Falloff too slow, no peak

Reference secondary/primary ratio: B/C



Conventional approach

ad-hoc break in $D_{xx}(p)$

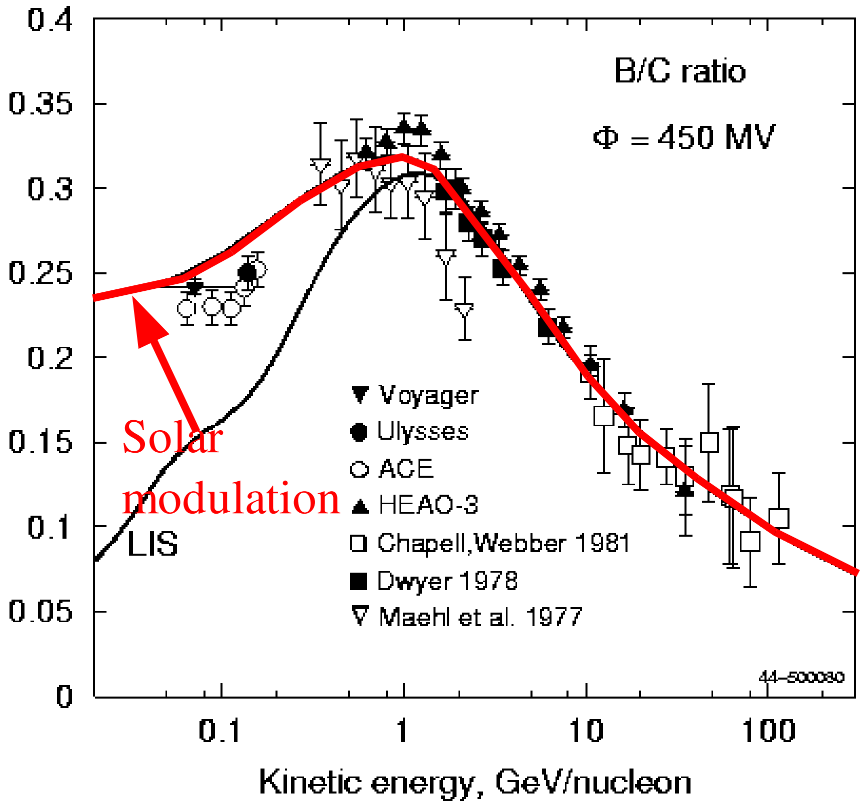
Can reproduce data but

no physical origin

Used in ' elaky-box' models

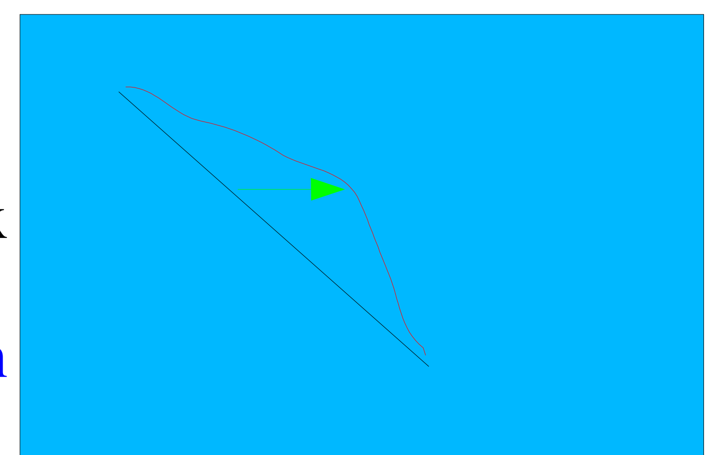
E

Reference secondary/primary ratio: B/C



Peak in B/C
explained by diffusive reacceleration
with Kolmogorov $D \sim \beta p^{1/3}$
+ avoids large cosmic-ray anisotropy
at high energies.

flux

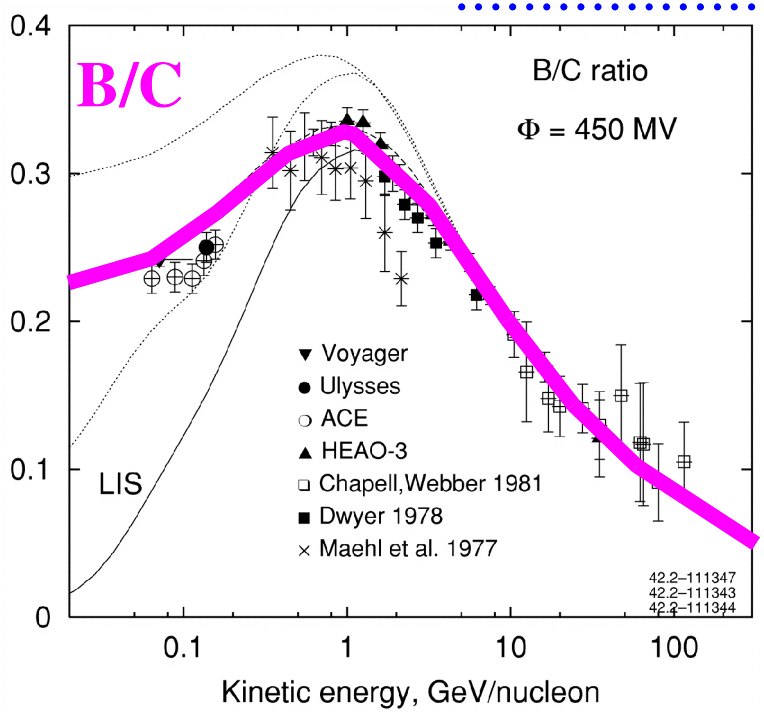


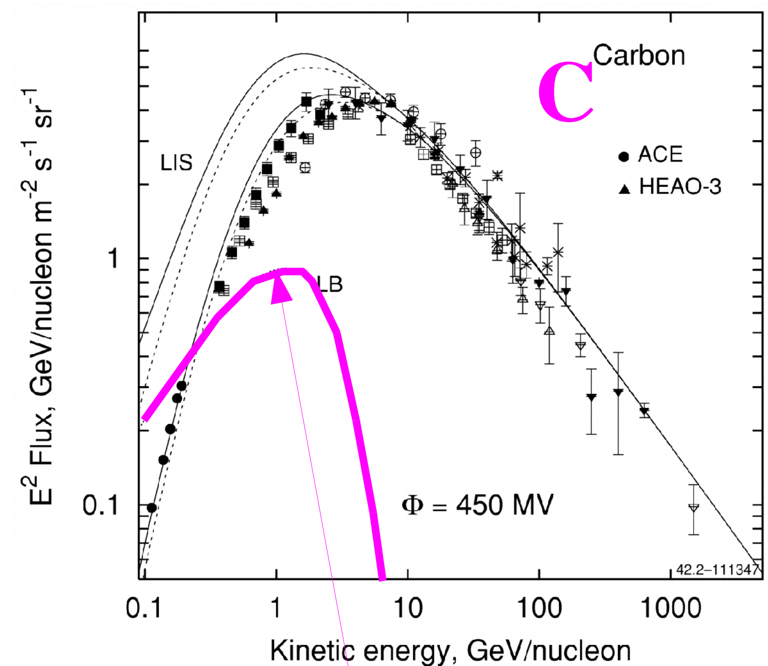
E

Energy-dependent diffusive reacceleration
produces bump in particle spectrum

Reference secondary/primary ratio: B/C

.... *another explanation*

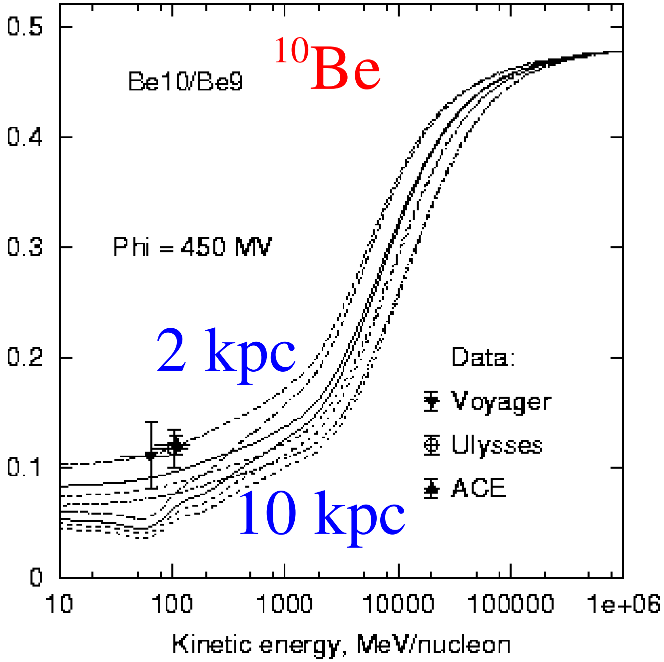


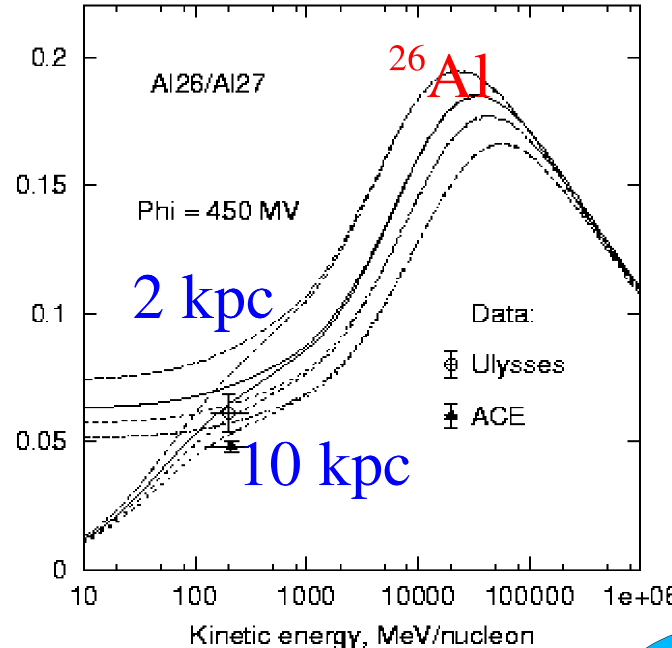


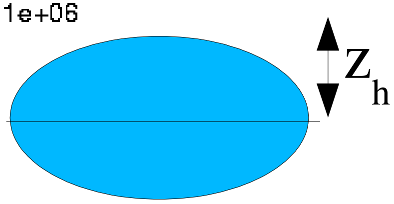
Peak in B/C can also be due to a LOCAL SOURCE of cosmic-ray *primaries* with steep spectrum, good candidate: LOCAL BUBBLE

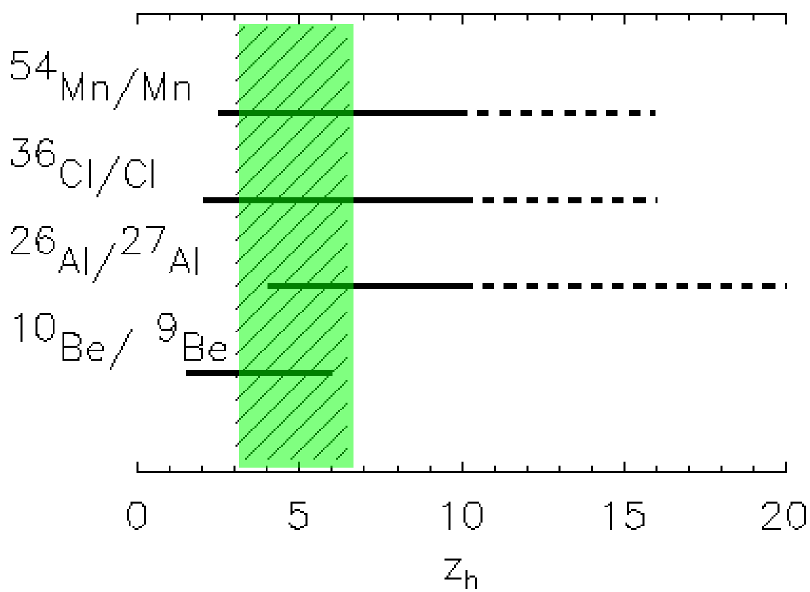
(Moskalenko et al. 2003)

Radioactive nuclei set limits on size of halo







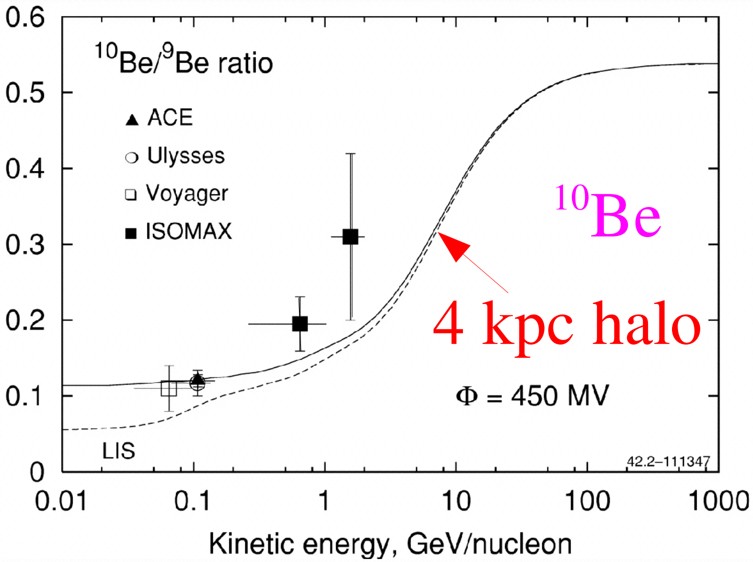


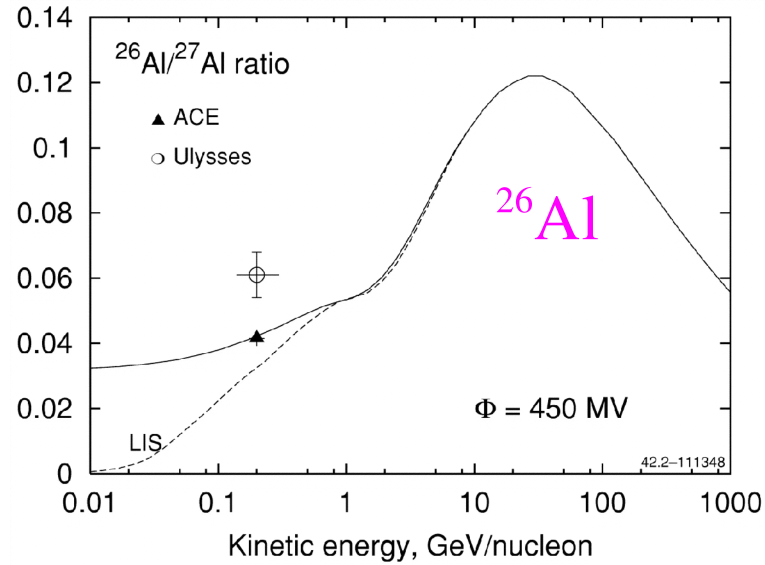
$3 < z < 7$ kpc

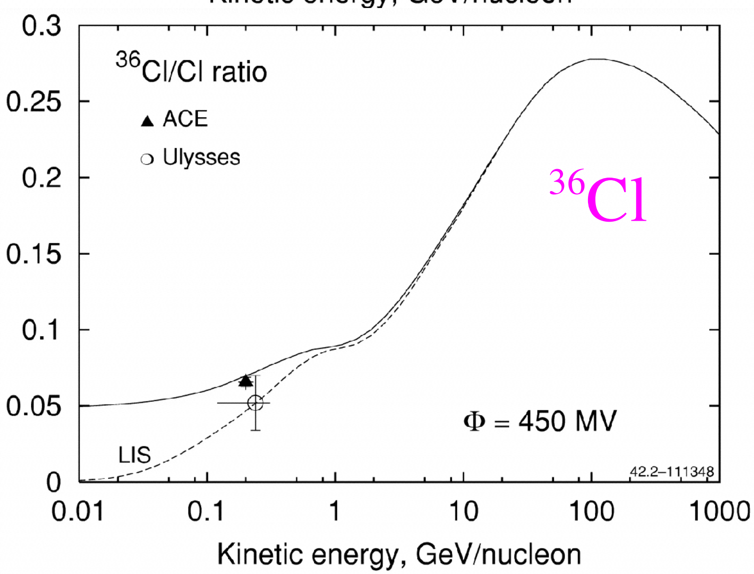
Strong & Moskalenko
COSPAR 2001

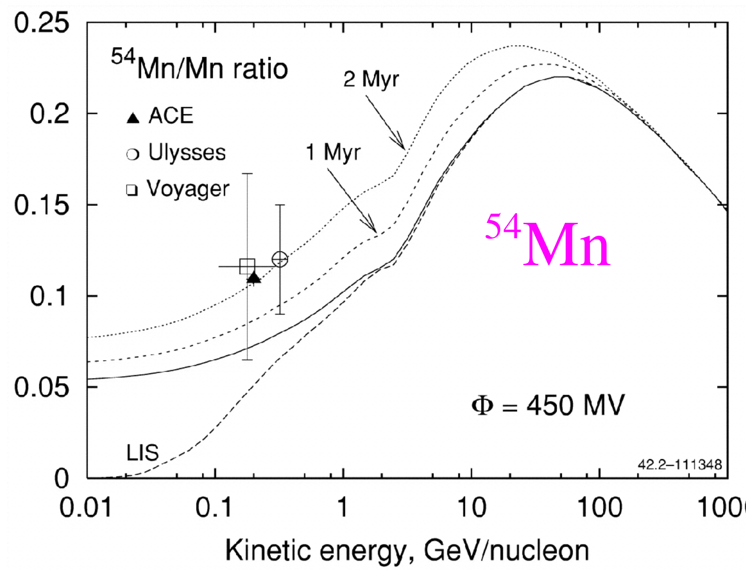
Radioactive nuclei set limits on size of halo

New data: ACE, ISOMAX





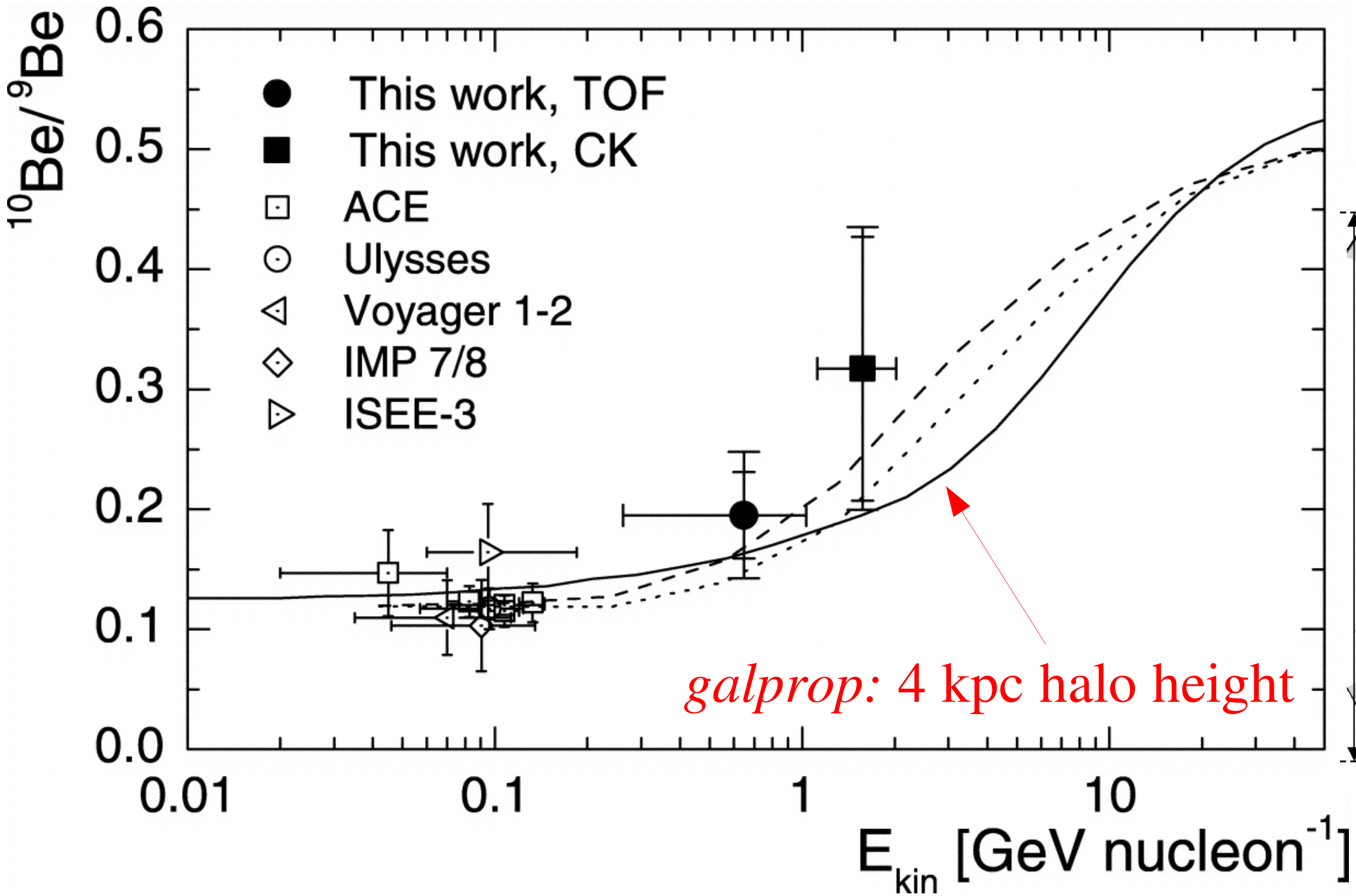


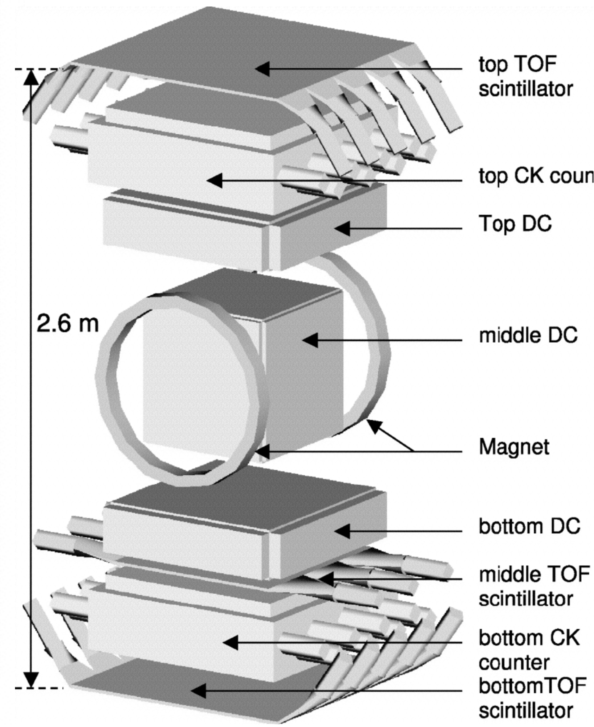


Moskalenko et al. 2003

Radioactive nuclei set limits on size of halo

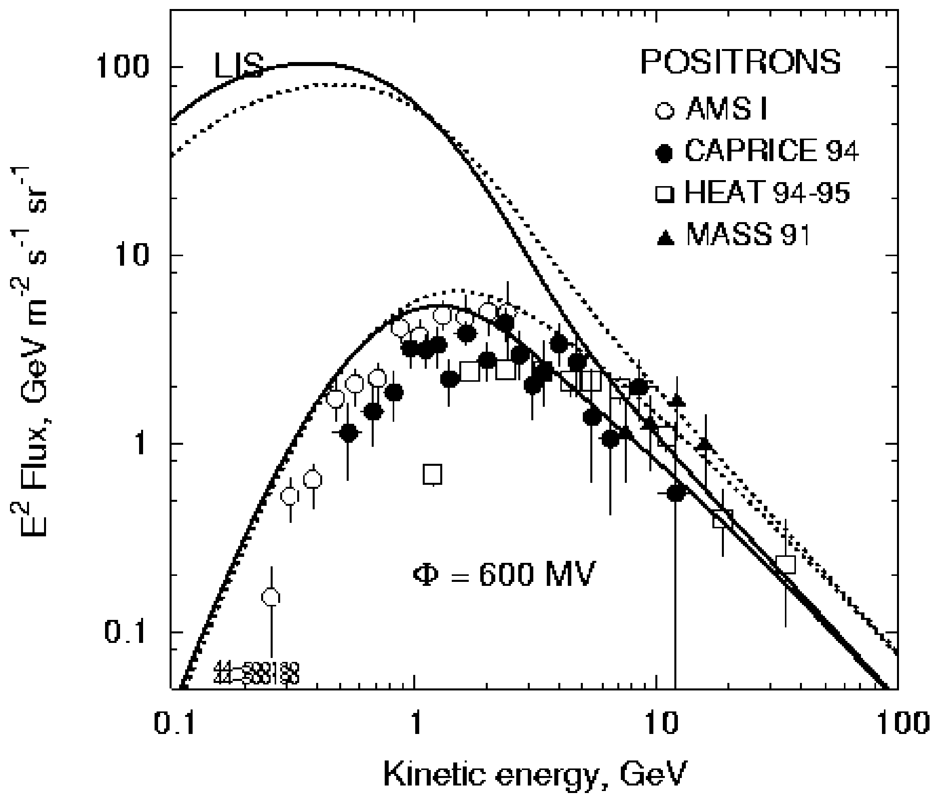
New data: ACE, ISOMAX

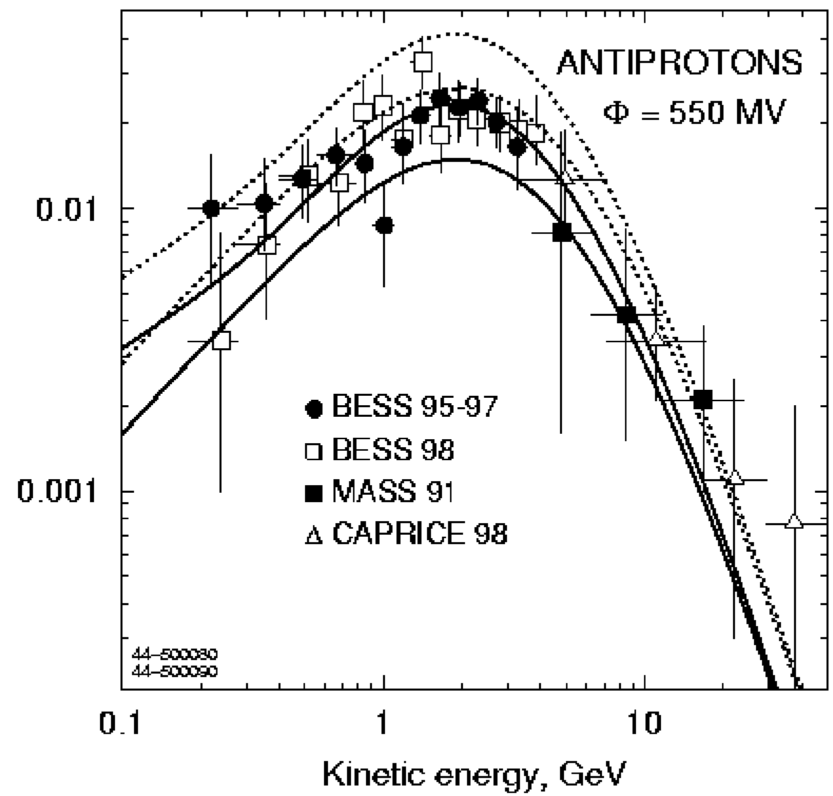




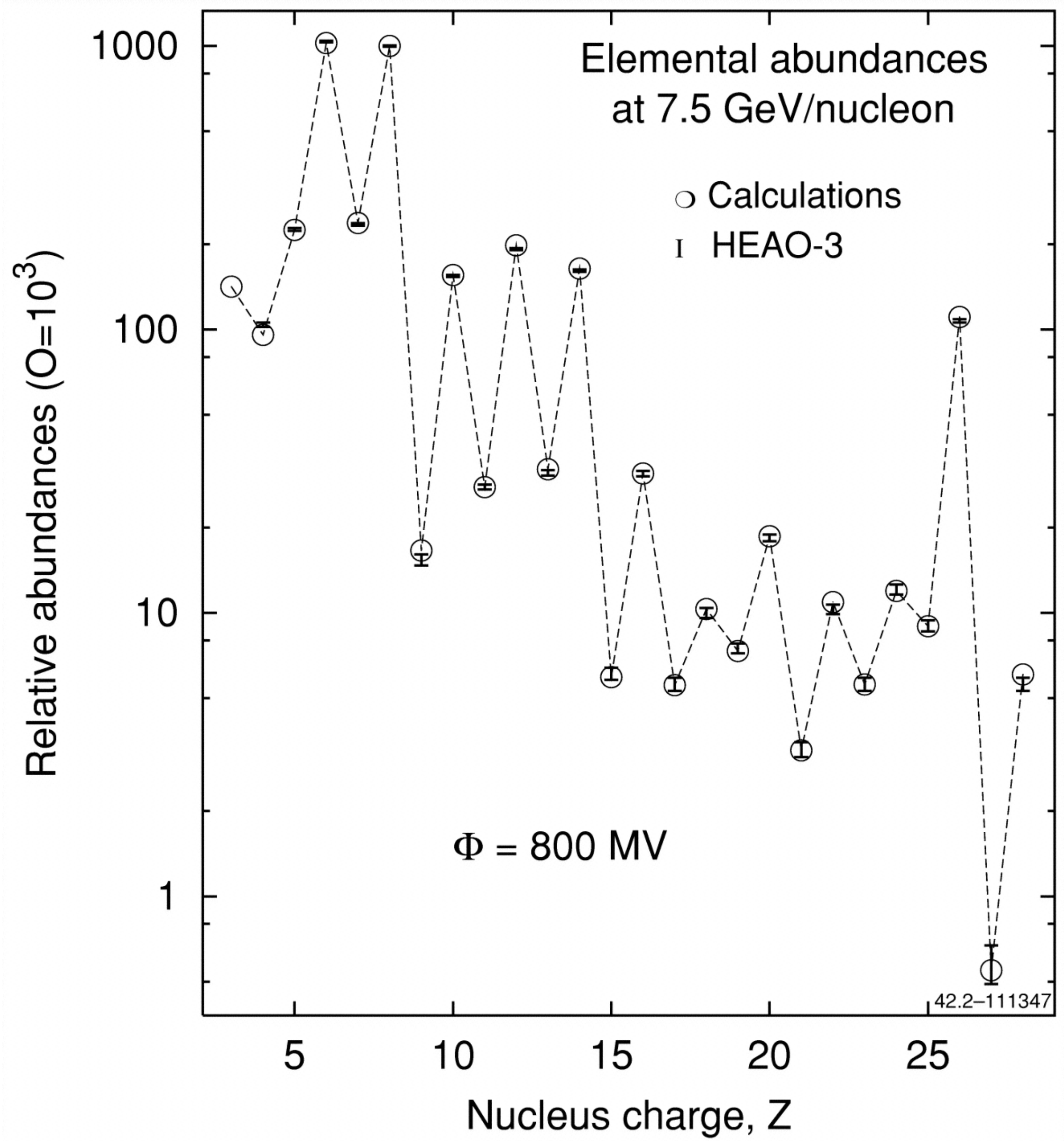
Hams et al. 2004 ApJ Aug 20

Secondary positrons, antiprotons
good test of model (production in p-p collisions like γ-rays !)



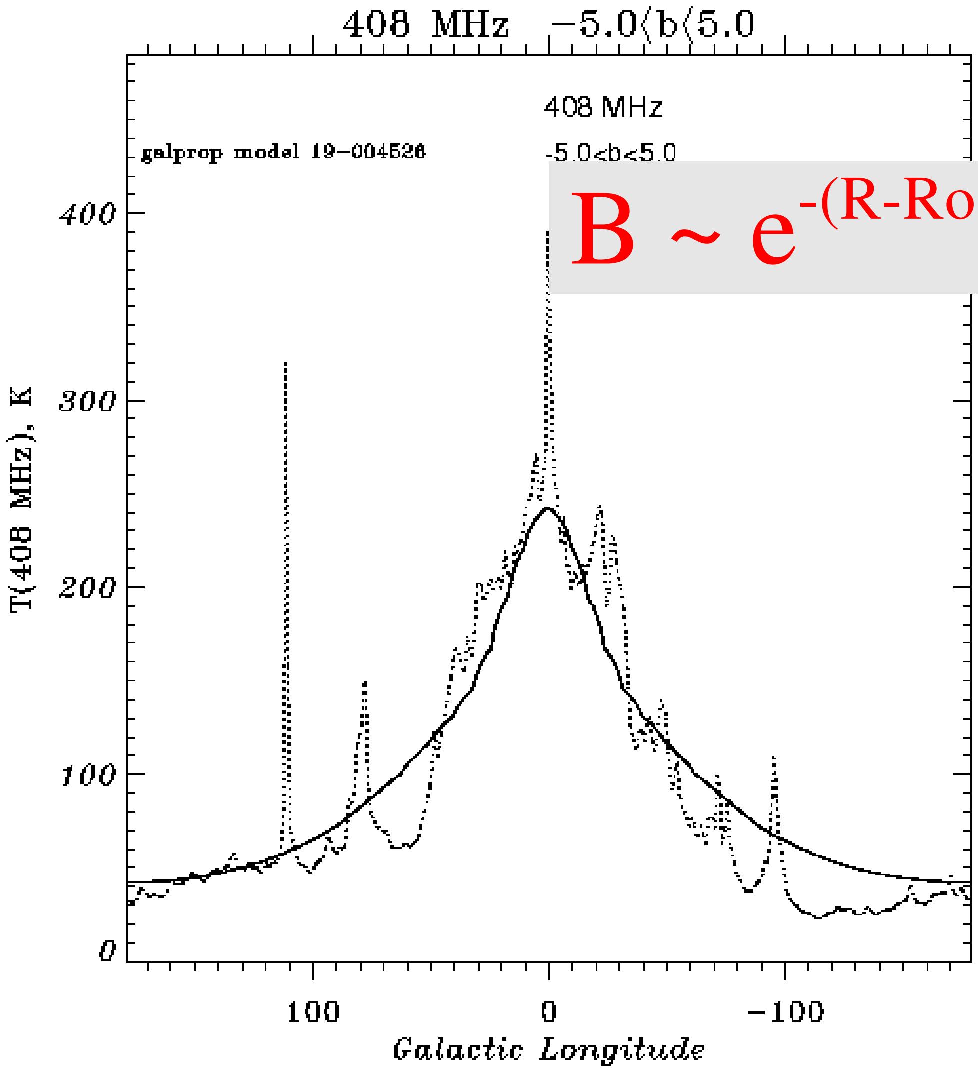


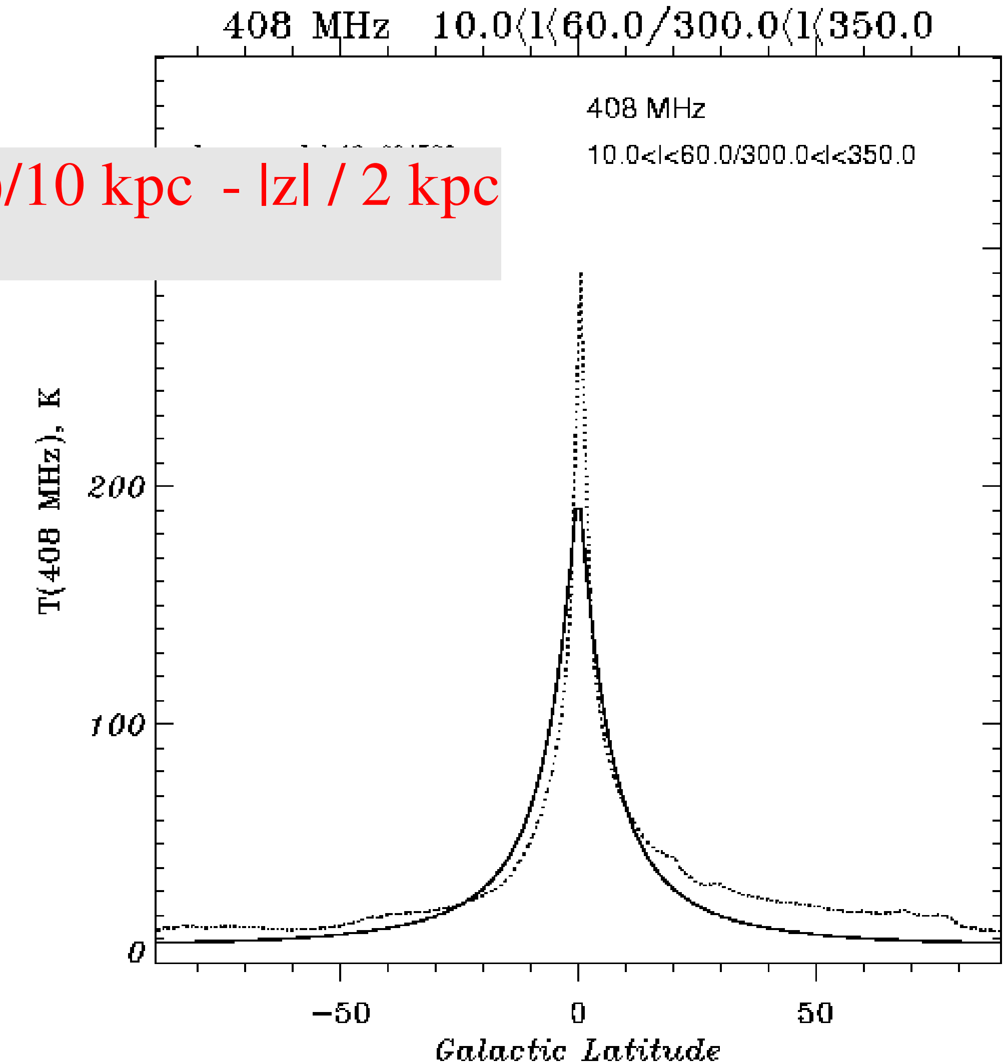
galprop-computed cosmic-ray elemental abundances



Moskalenko et al. 2003

Synchrotron and B field





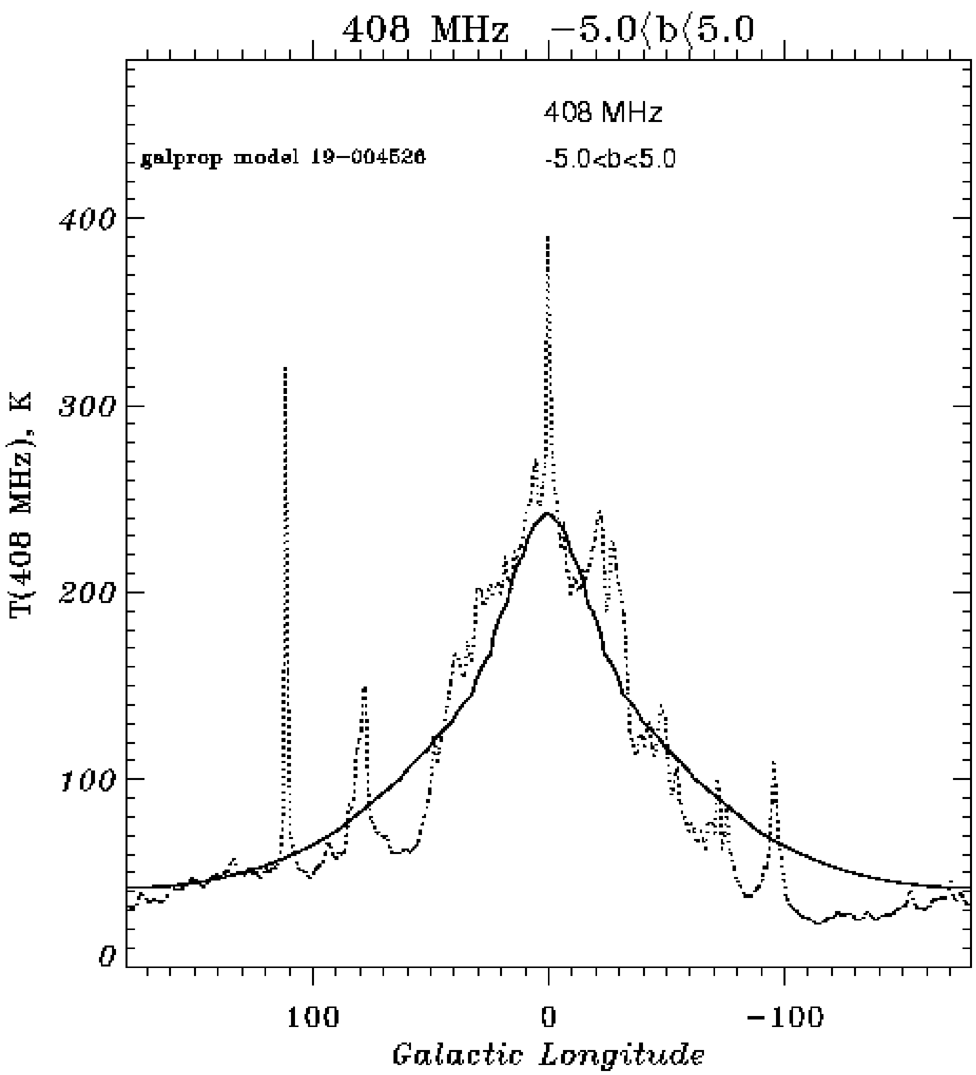
$$B \sim e^{-(R-R_o)/10\,\mathrm{kpc}\ -\ |z|/2\,\mathrm{kpc}}$$

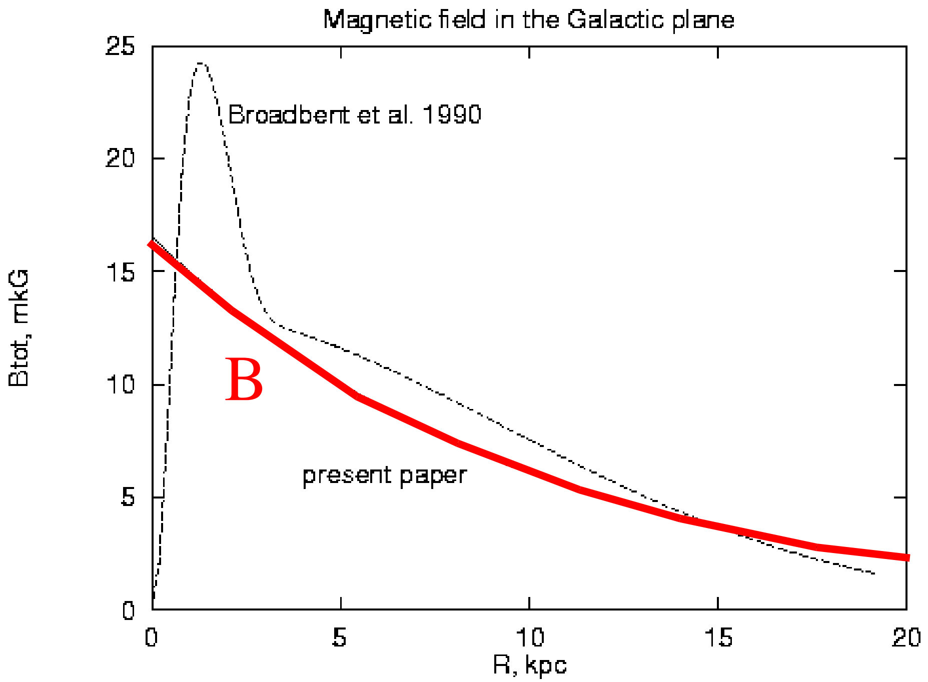
Cosmic-ray electrons from EGRET γ- rays -> B from synchrotron

Strong, Moskalenko & Reimer 2000

Synchrotron and B field

$$B \sim e^{-(R-Ro)/10\ kpc\ -\ |z|\ /\ 2\ kpc}$$

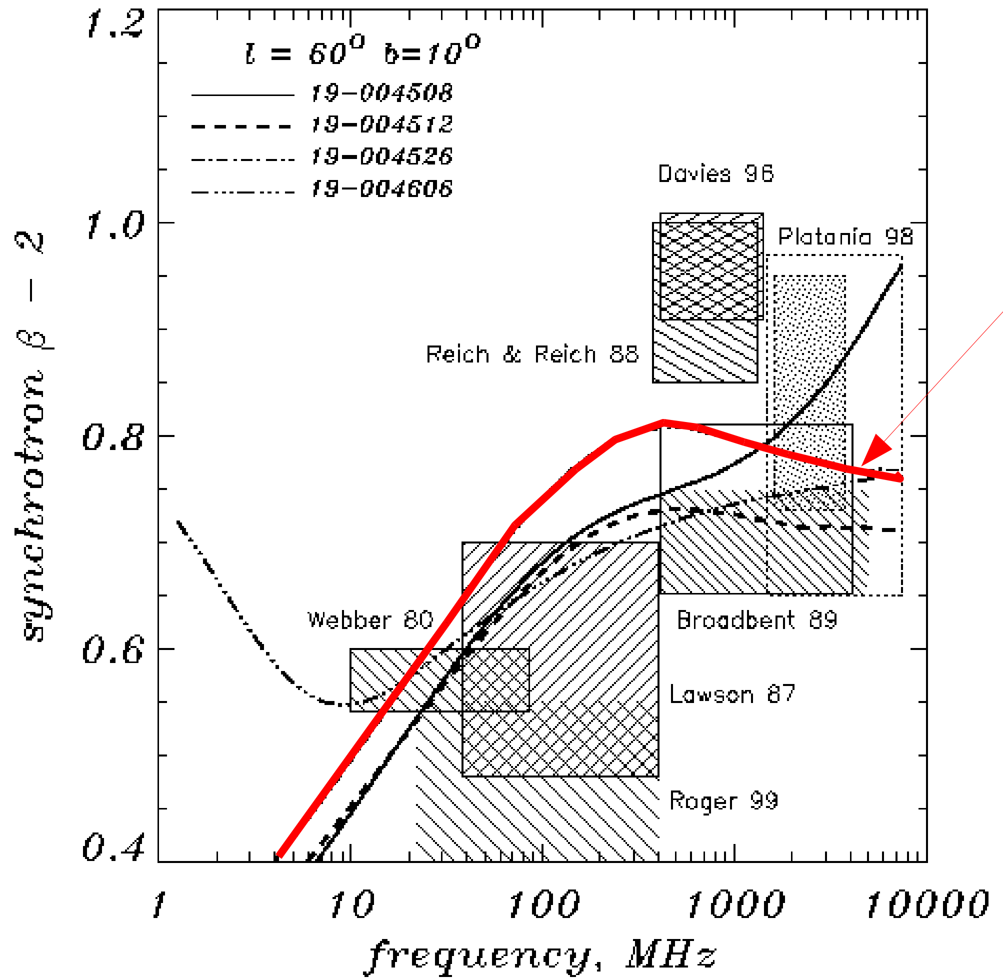




Cosmic-ray electrons from EGRET γ- rays -> B from synchrotron

Strong, Moskalenko & Reimer 2000

Synchrotron spectral index constrains interstellar electron spectral shape



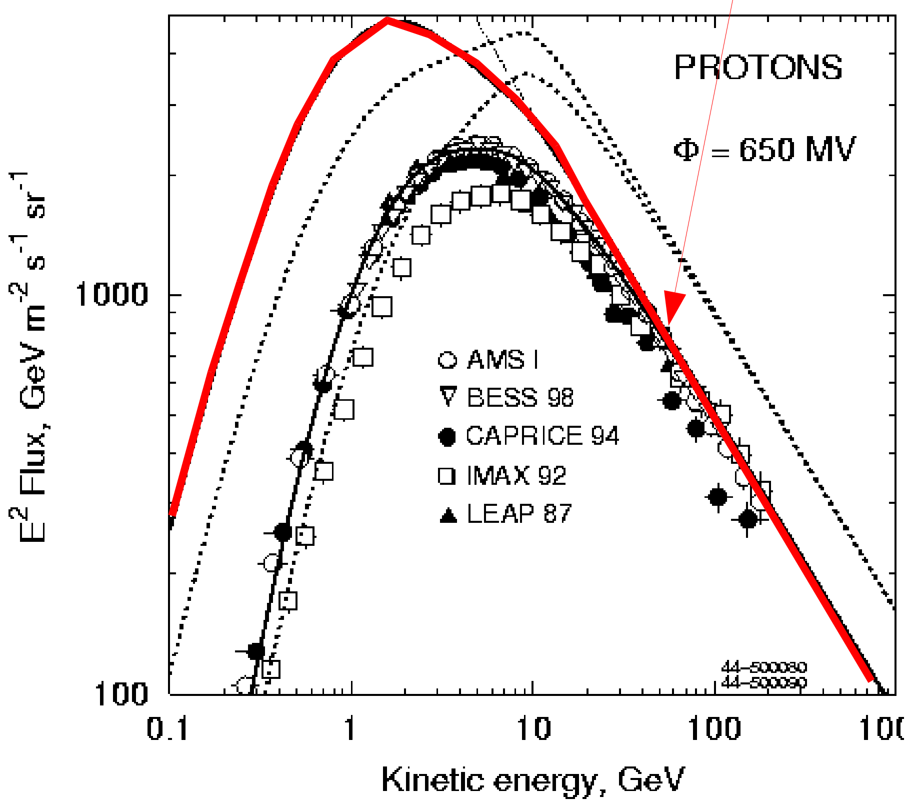
for γ-rays

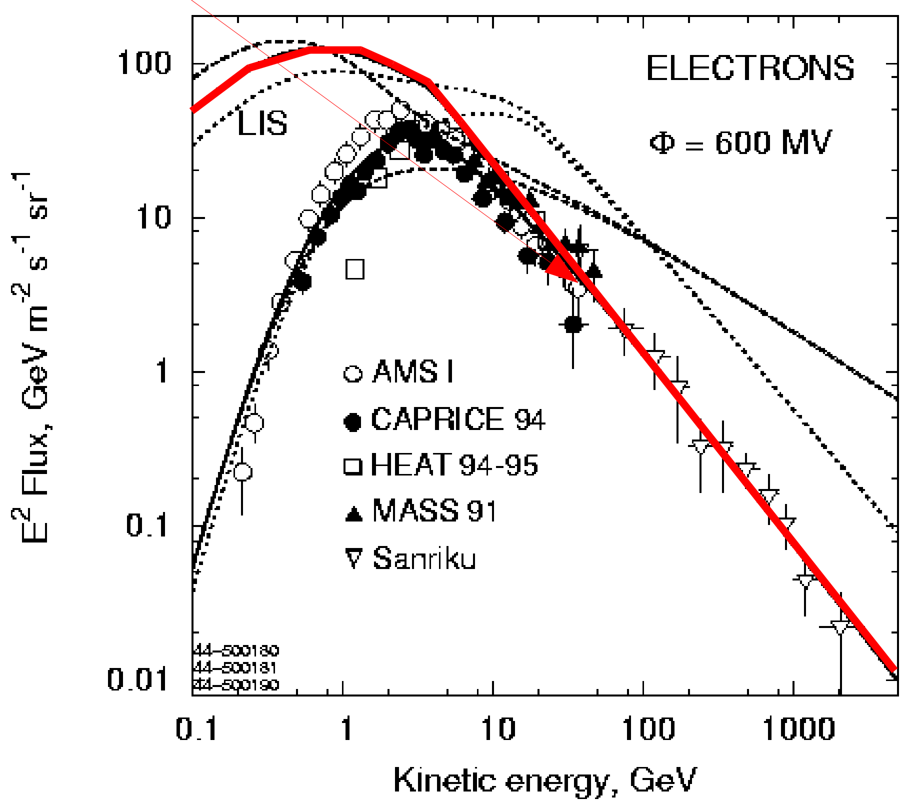
Strong, Moskalenko & Reimer 2000

New WMAP etc. data not yet exploited !

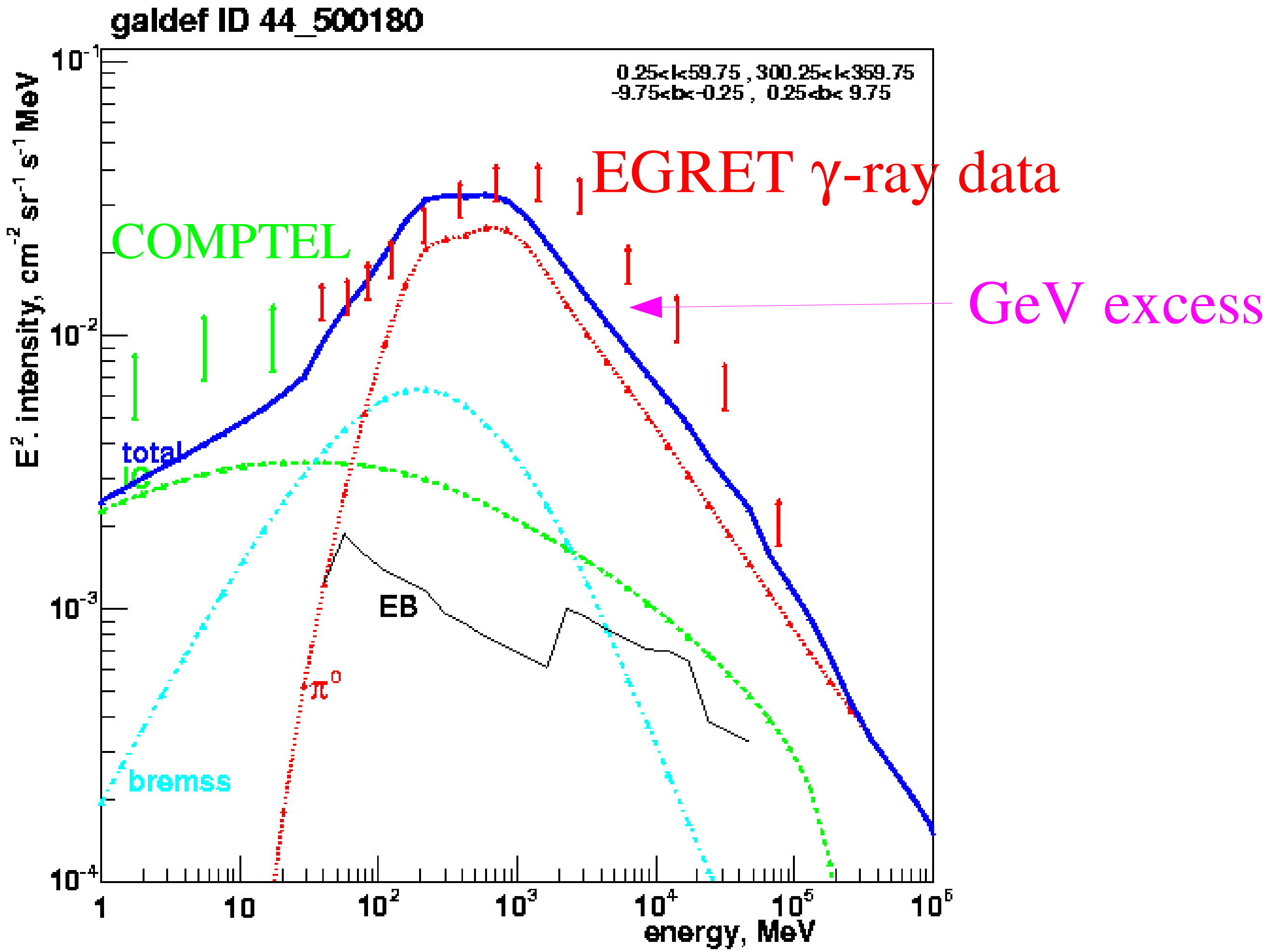
Modelling diffuse Galactic gamma-rays:

Conventional model: p, e spectra <u>as measured</u> (& demodulated)





Conventional model: protons (+He) and electrons as directly measured



There really IS an excess !

Proposed explanations of GeV γ- ray excess:

1. SNR with injection CR spectra

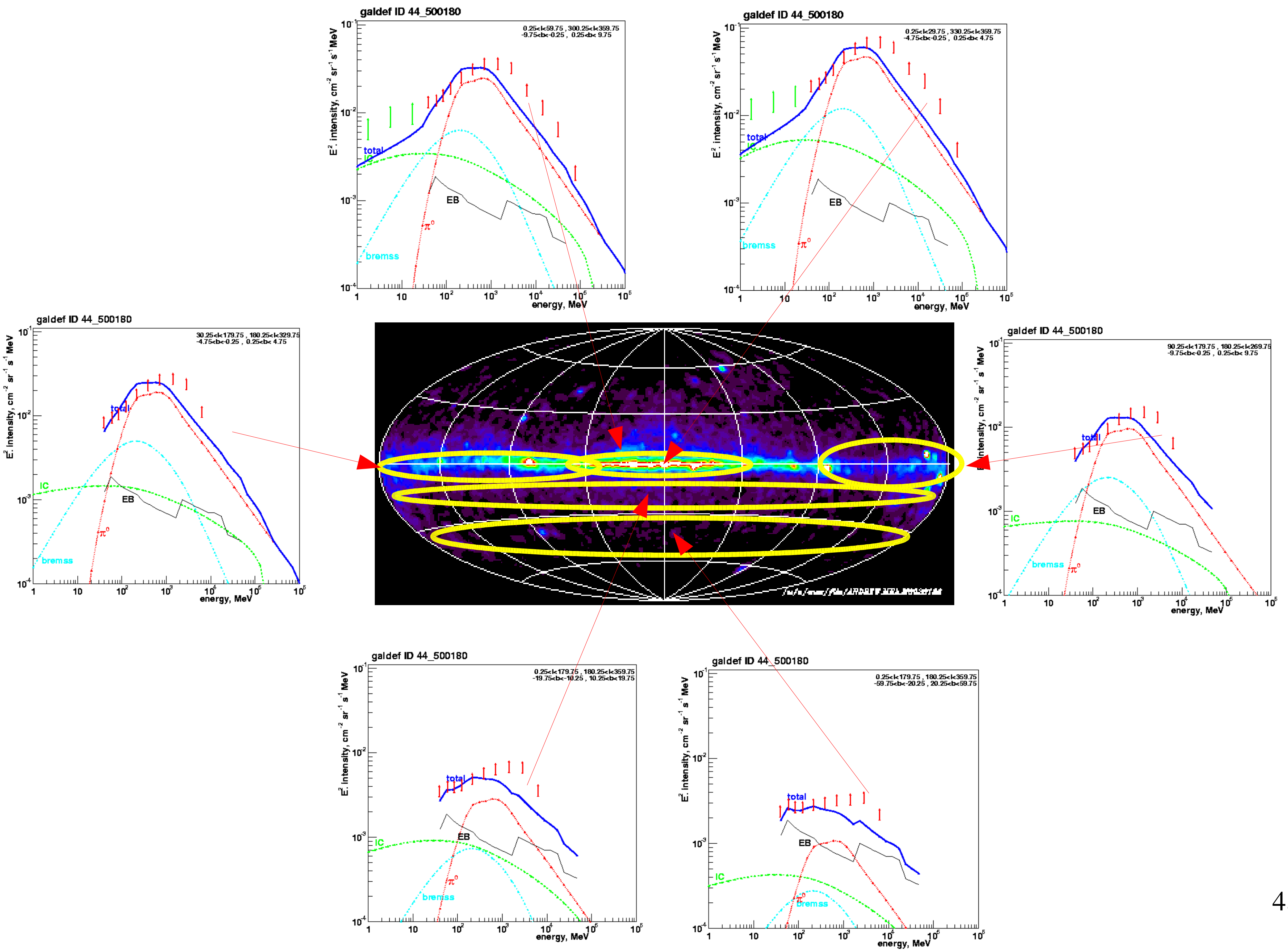
2. Hard nucleon injection spectrum.

3. Hard electron injection spectrum

4. Moderate changes of nucleon and electron spectra

5. Exotic: dark matter

Wherever you look, the GeV γ-ray excess is there !



4a-f

Proposed explanations of GeV γ- ray excess:

1. SNR with injection CR spectra:
   harder than propagated spectra => excess

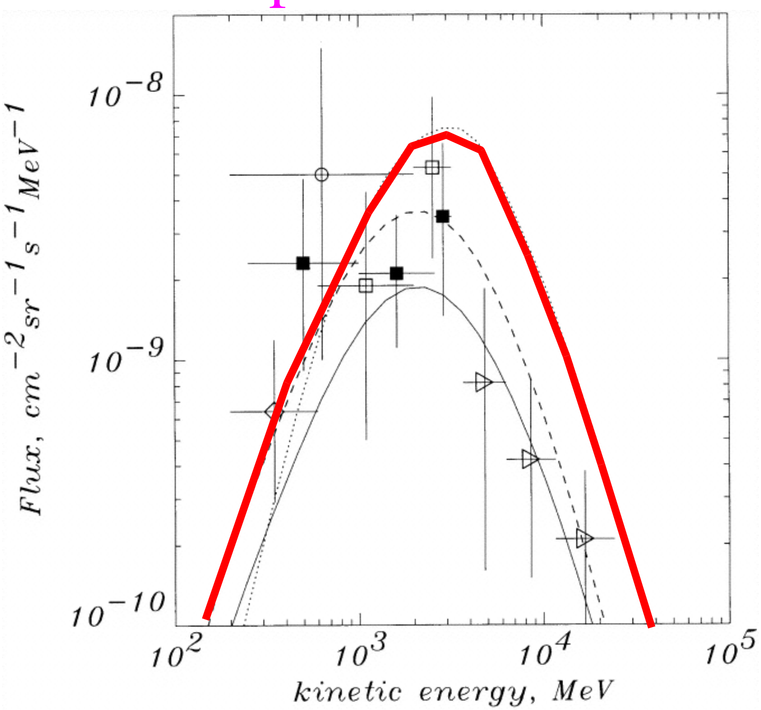
NO: would give only excess at low latitudes, but observed everywhere

Proposed explanations of GeV γ- ray excess:

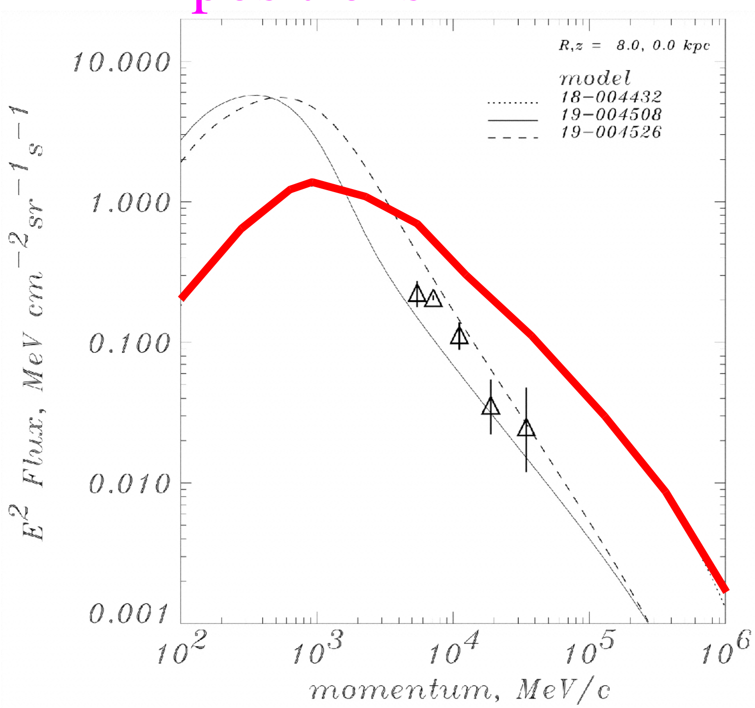
#2. Hard proton injection spectrum
(e.g. if directly measured spectra are different from Galactic)

NO: too many antiprotons, positrons (produced along with γ- rays).

antiprotons

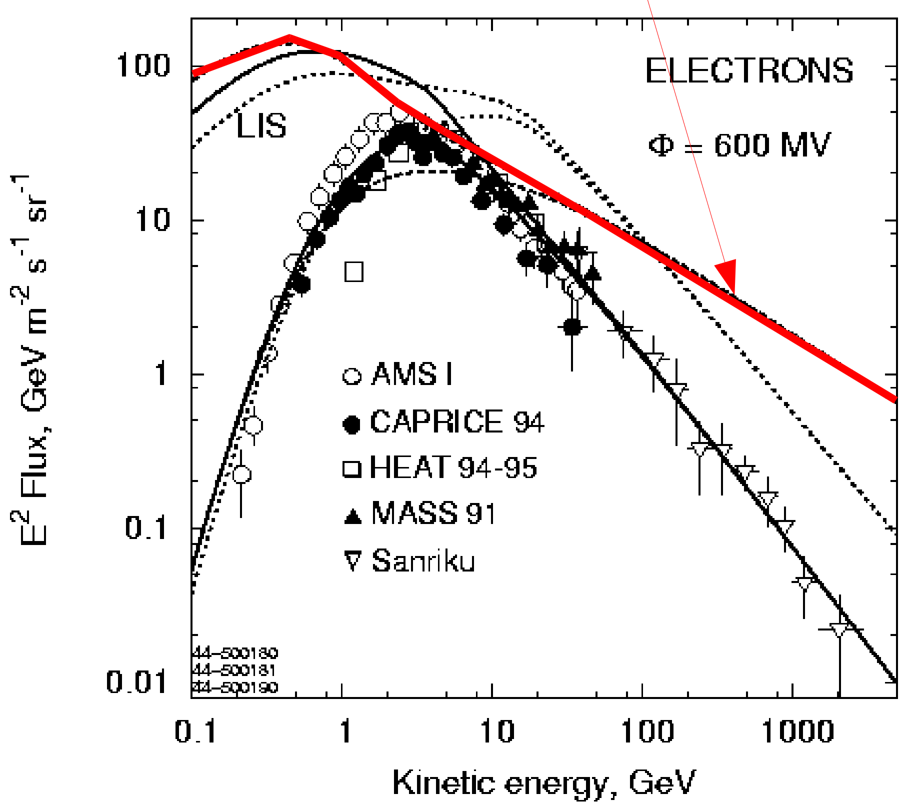


positrons

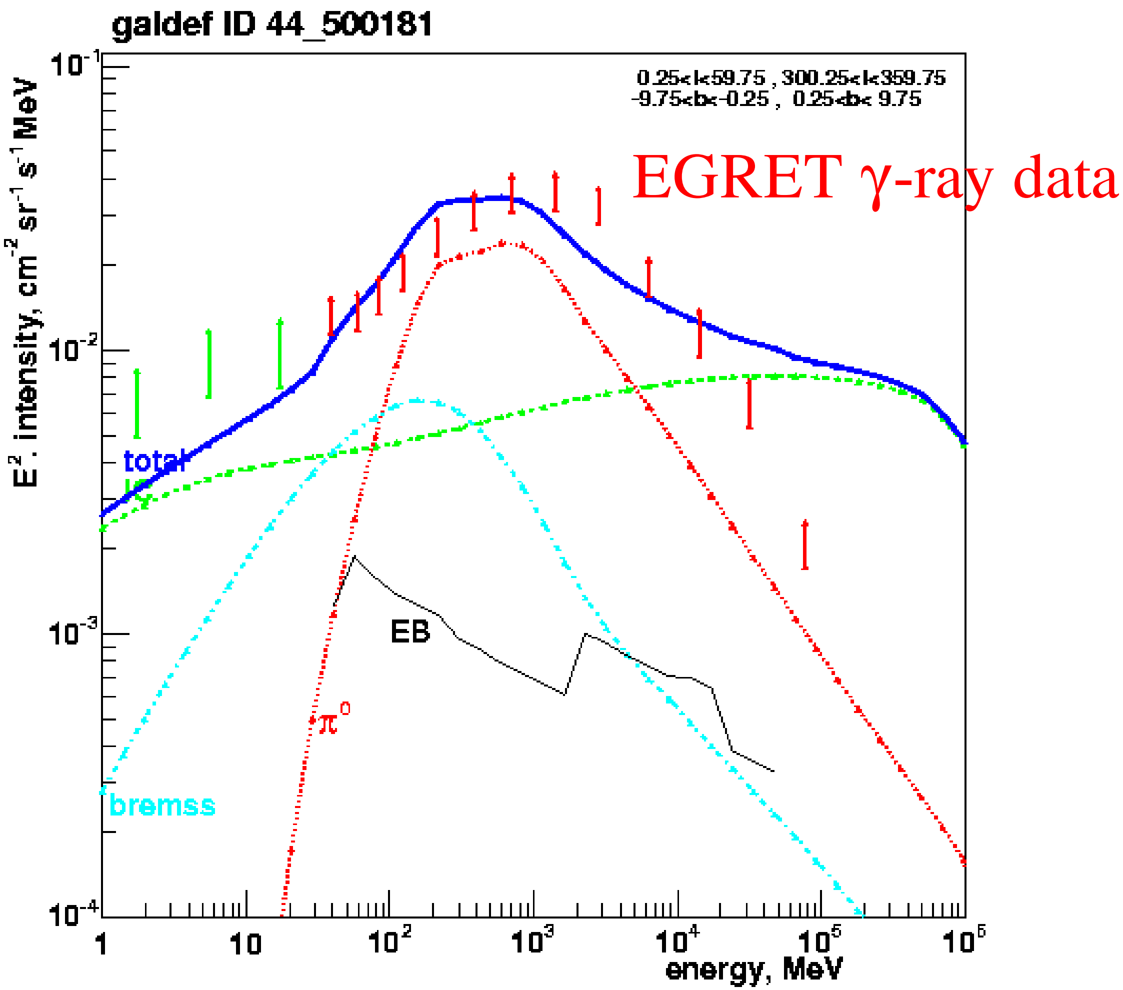


illustrates advantage of combined particles and γ- ray analysis

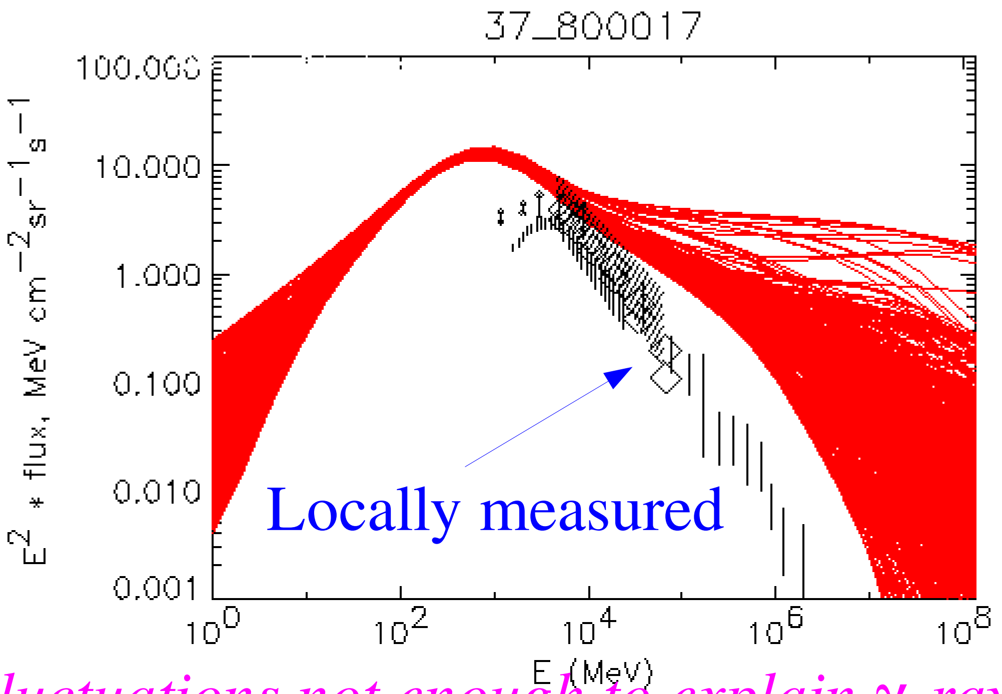
Possible origin of GeV γ- ray excess
Hard electron injection spectrum



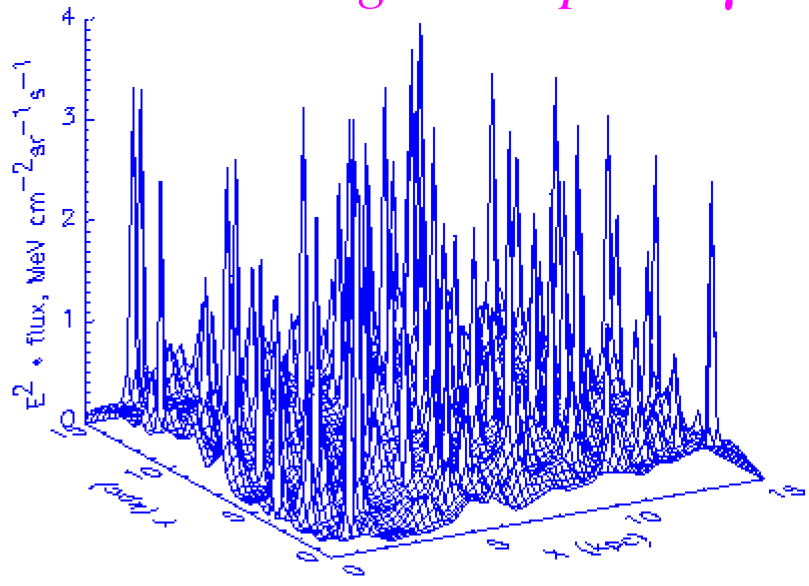
Hard electron injection spectrum: problem E_γ > 10 GeV



Electron spectrum fluctuates with position



Fluctuations not enough to explain γ-ray GeV excess!



rate $1/10^4$ yr/kpc^3

Depends on SN rate

Proposed explanations of GeV γ-ray excess:

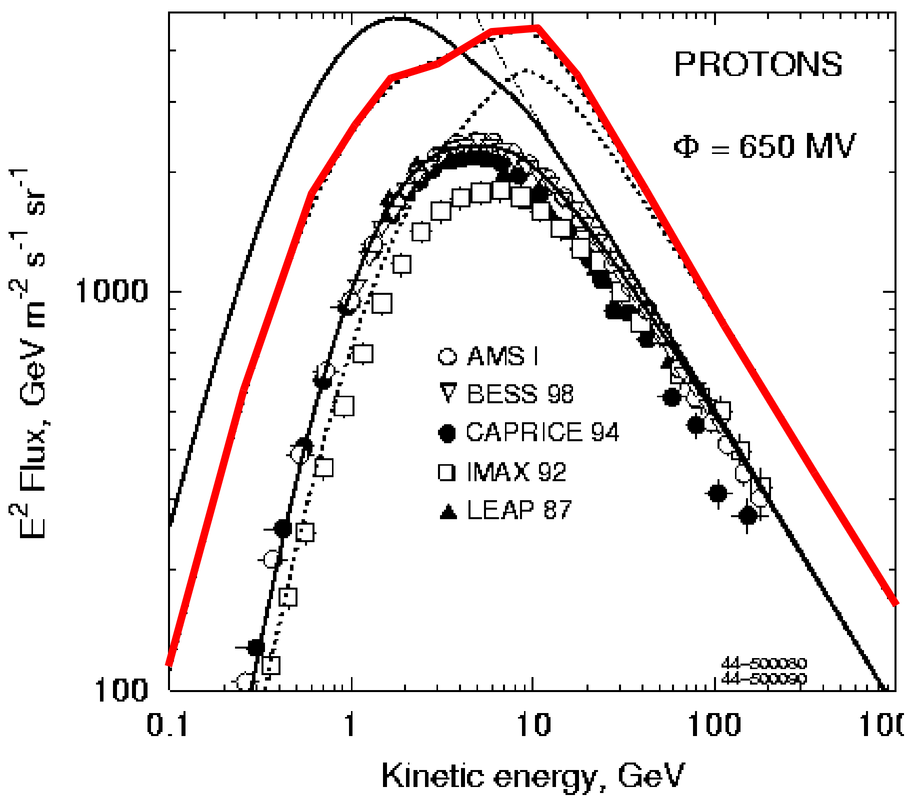
3. Hard electron injection spectrum
(interstellar harder than observed locally due to large energy losses causing big spatial fluctuations)

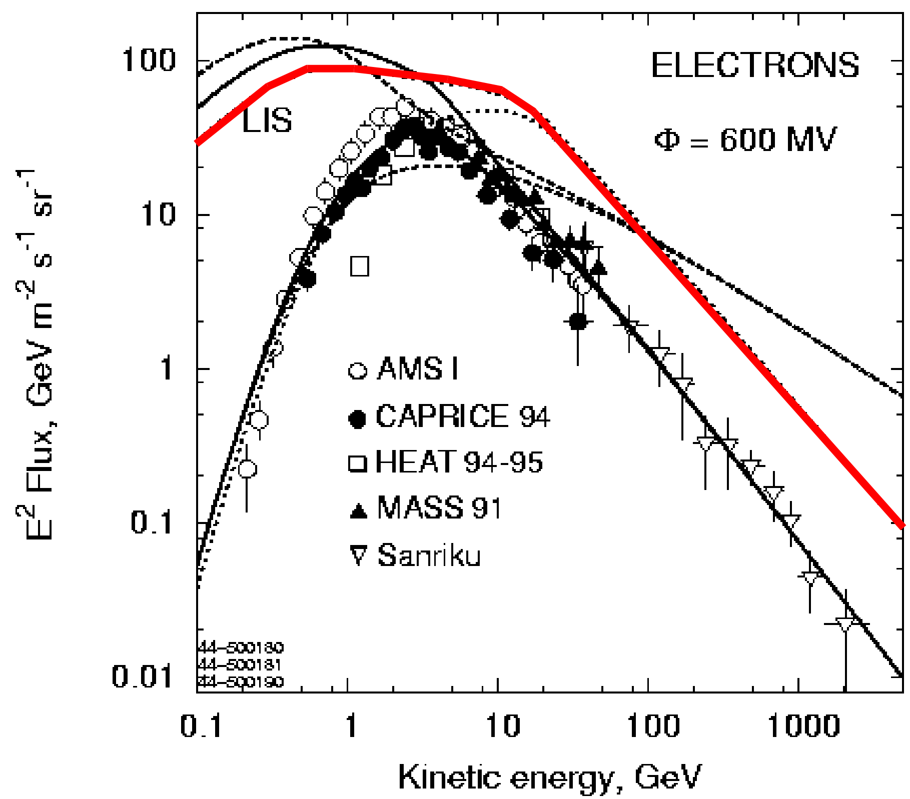
NO: too hard above 10 GeV

and

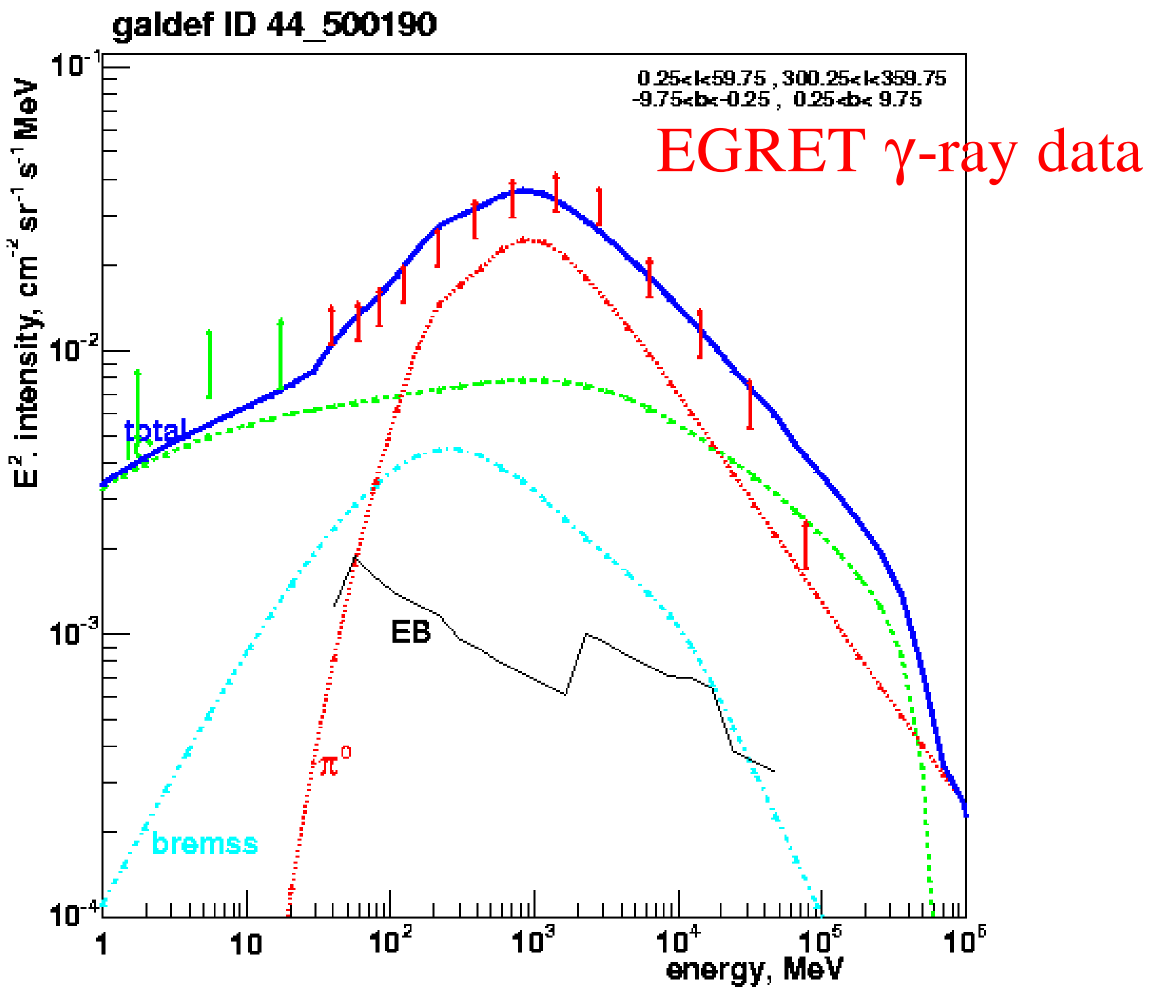
spatial fluctuations not enough to allow locally observed spectrum

Optimized model: *p, e* spectra factor 2-3 higher than measured (justification: spatial variations due to stochastic nature of sources)

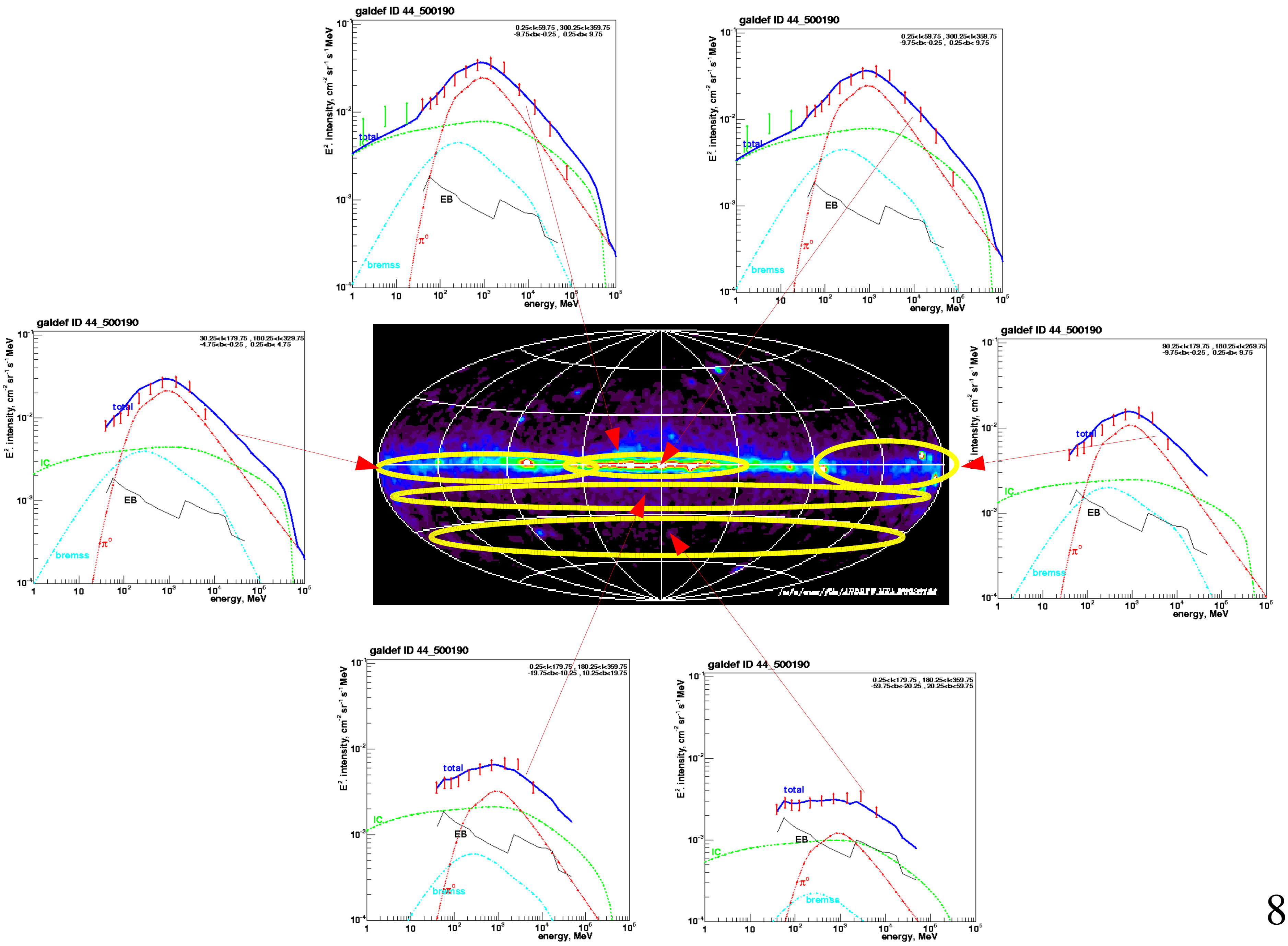




Optimized model: vary proton, electron spectra compatible with expected spatial variations



Optimized model explains the GeV γ- ray excess everywhere!



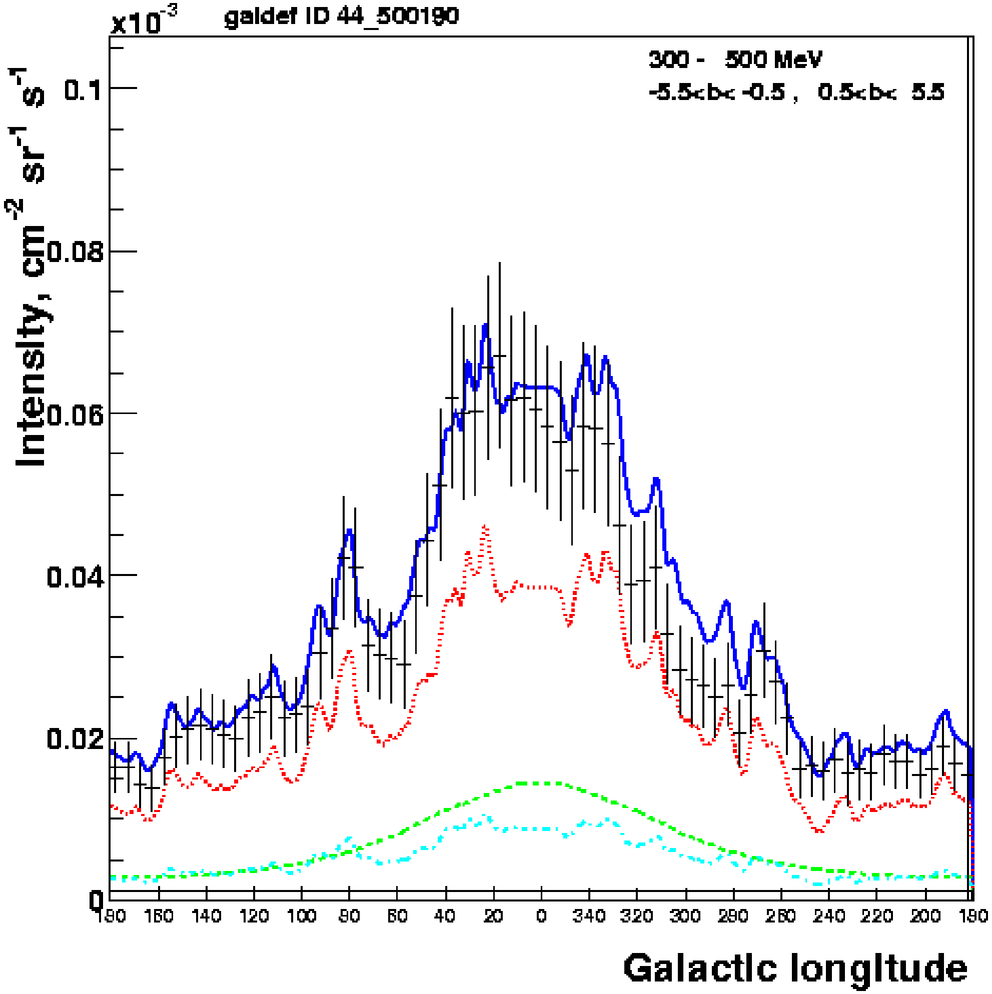
8a-f

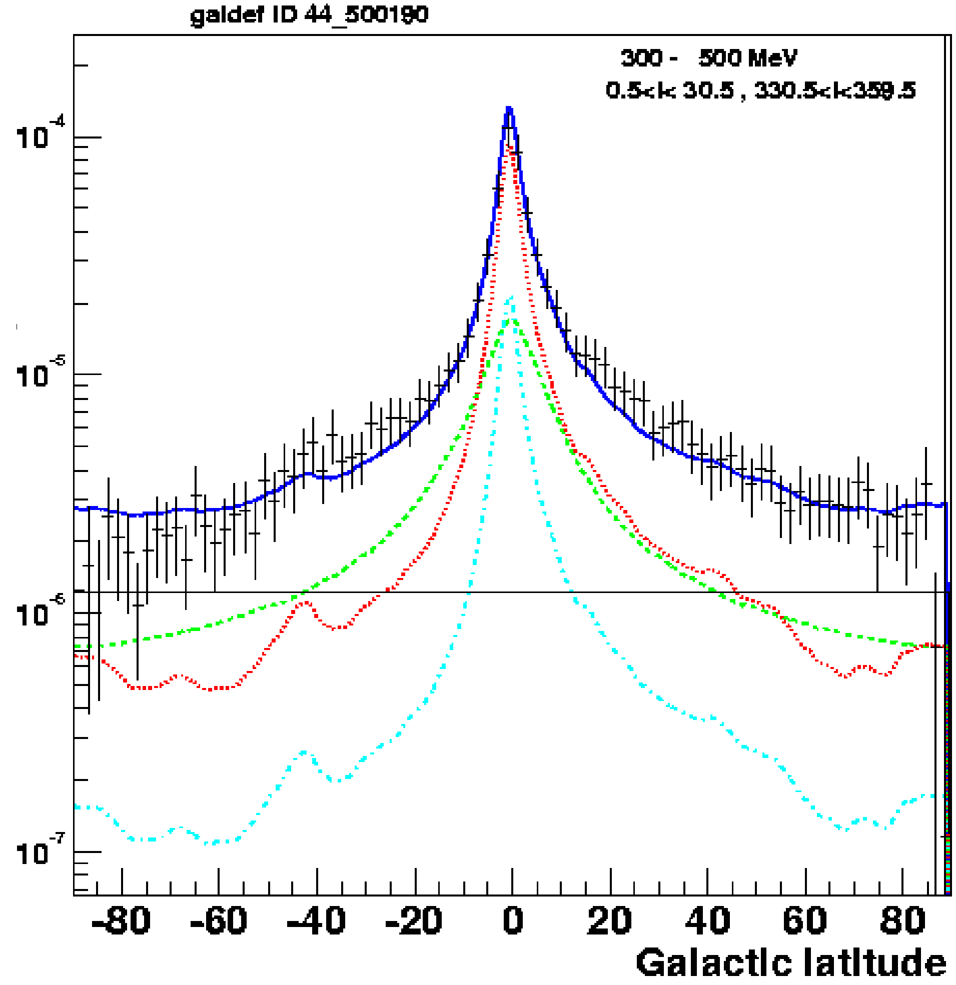
Proposed explanations of GeV $\gamma-$ ray excess:

4. Moderate changes in nucleon and electron spectra:

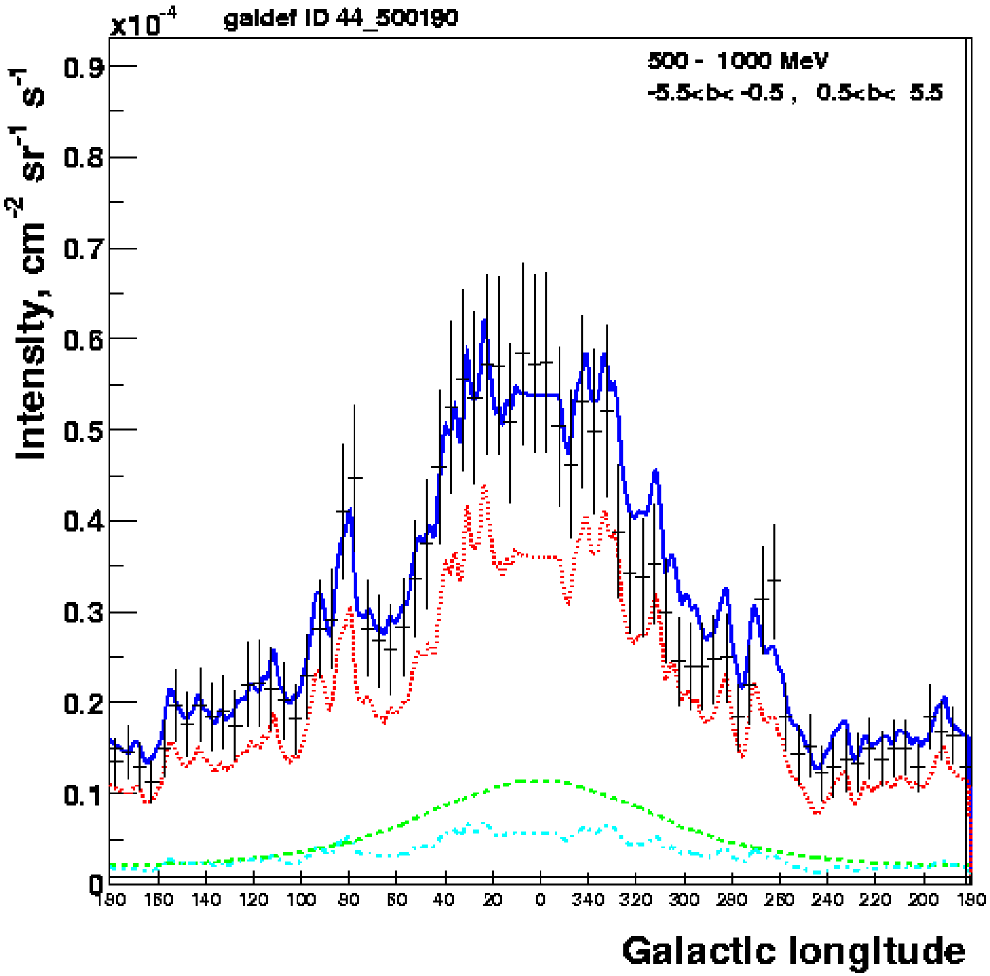
YES !

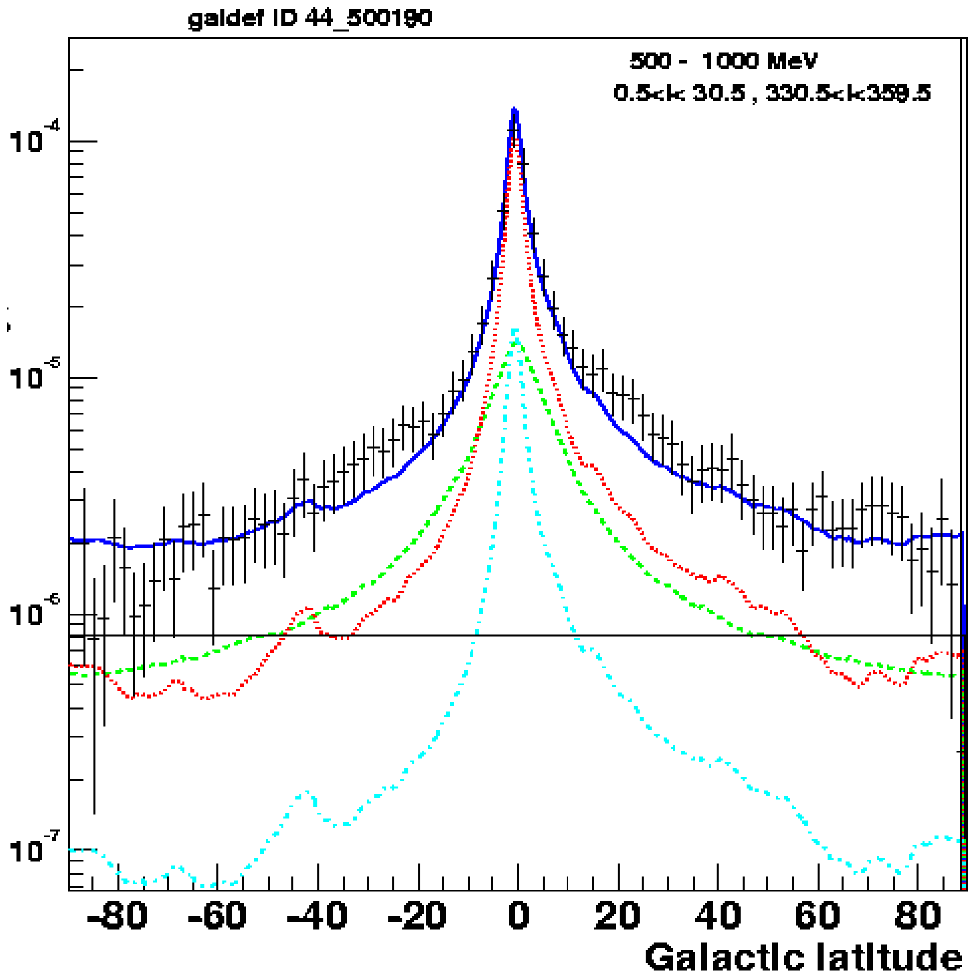
Optimized model Longitude, Latitude profiles
EGRET γ-ray data





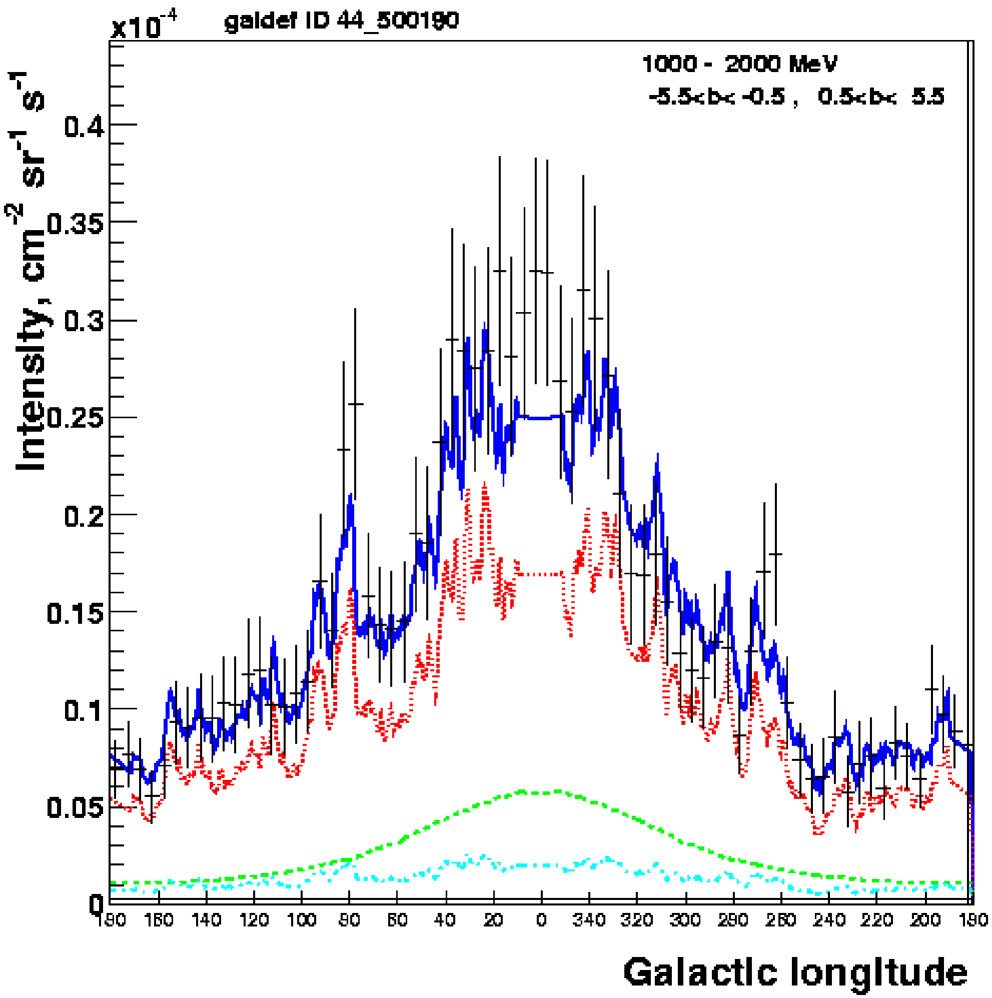
Optimized model Longitude, Latitude profiles
EGRET γ-ray data

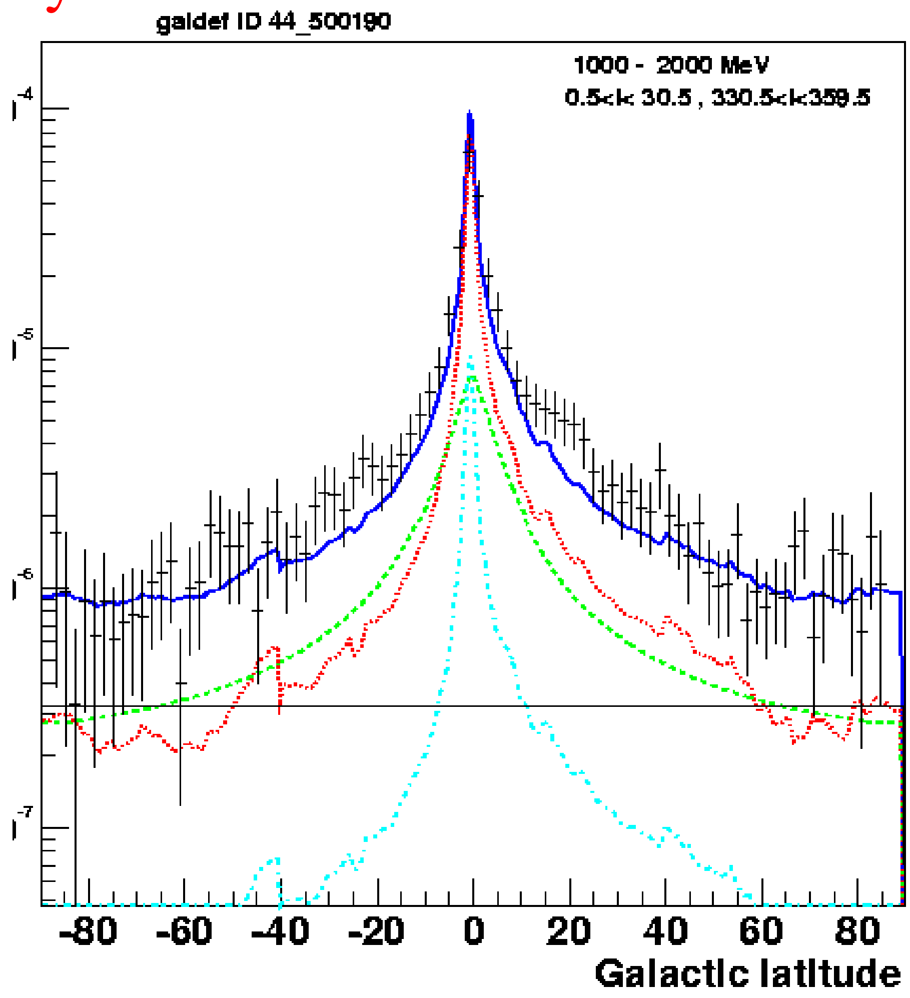




9g 10g

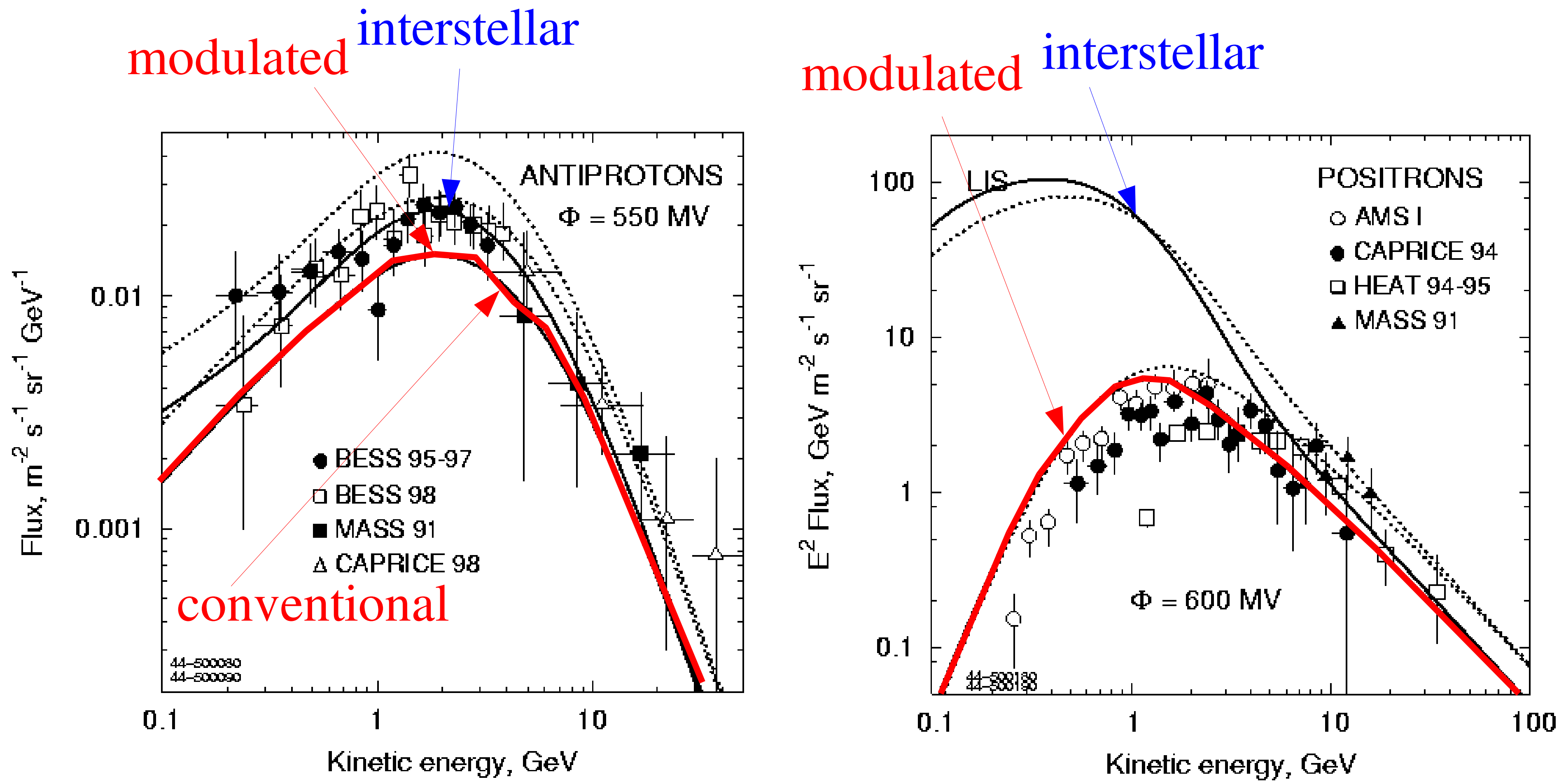
Optimized model Longitude, Latitude profiles
EGRET γ-ray data



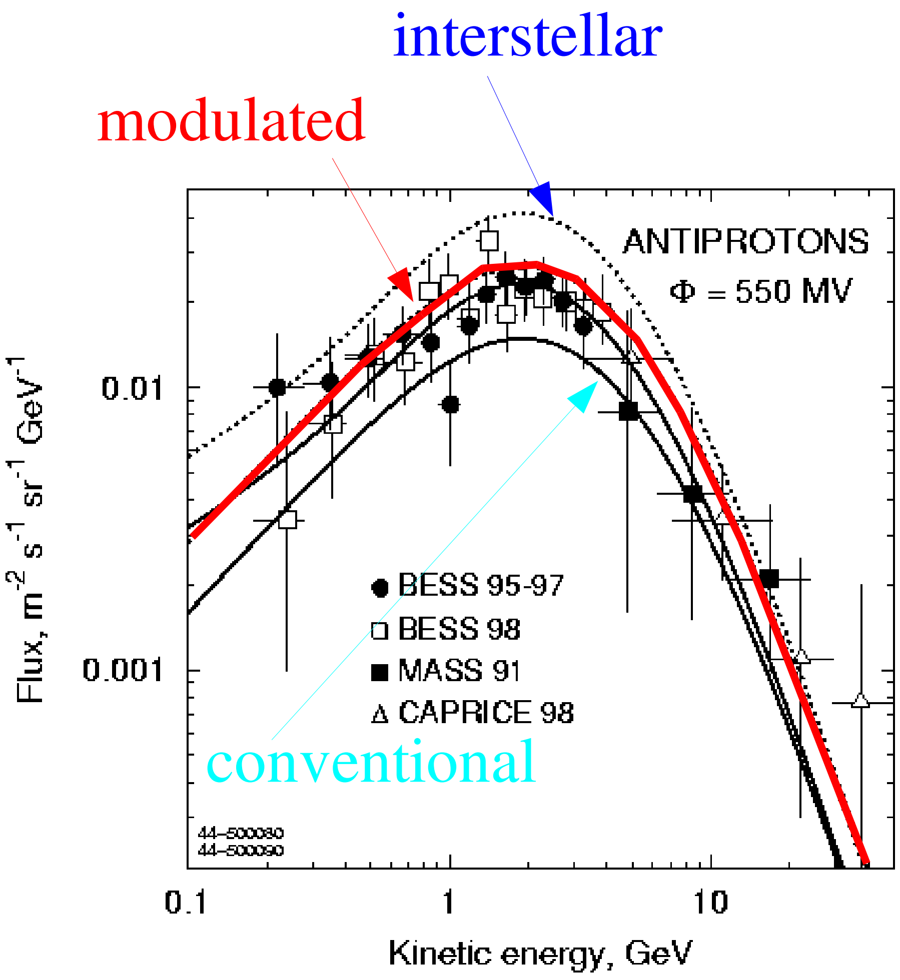


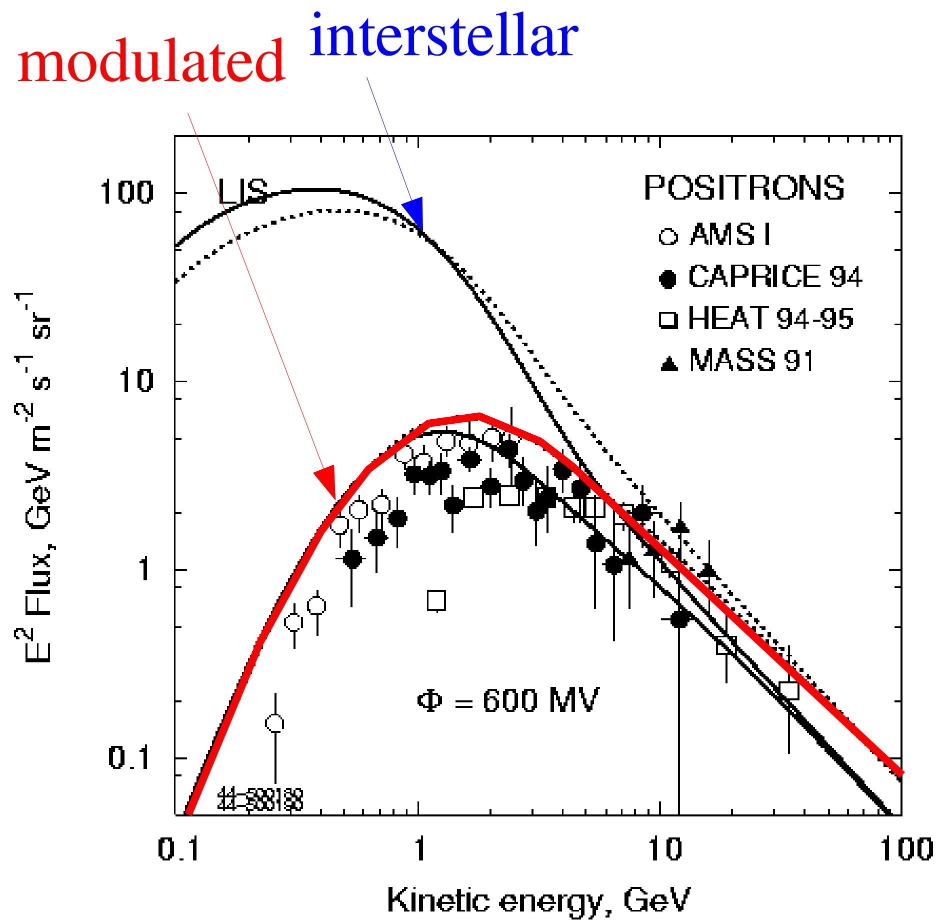
9h 10h

Conventional model underpredicts antiprotons



Optimized model for γ- rays also improves antiproton, positron predictions





Proposed explanations of GeV excess:

1. SNR with injection CR spectra:
   NO: would give only excess at low latitudes, but observed everywhere

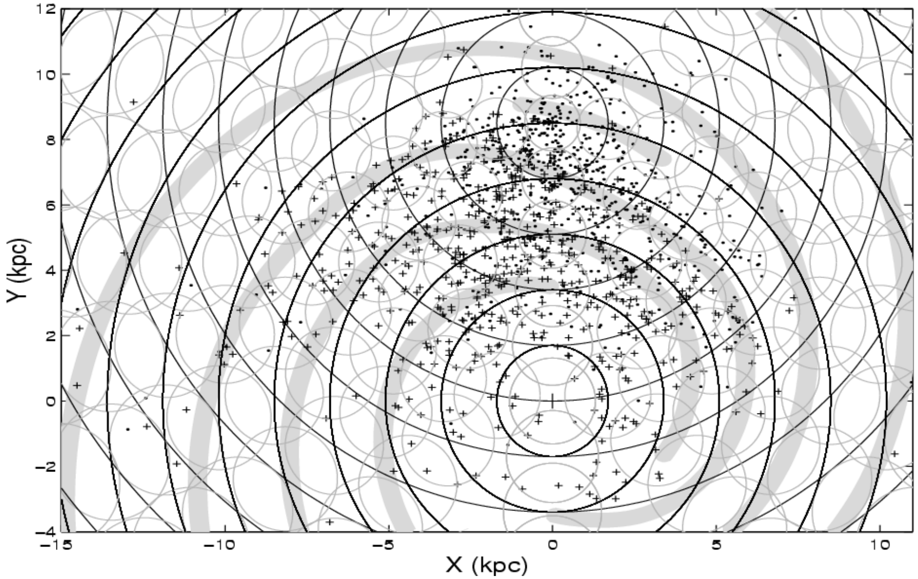
2. Hard nucleon injection spectrum:
   NO: too many antiprotrons, positrons.

3. Hard electron injection spectrum:
   NO: too hard above 10 GeV
   and spatial fluctuations not enough to allow locally observed spectrum

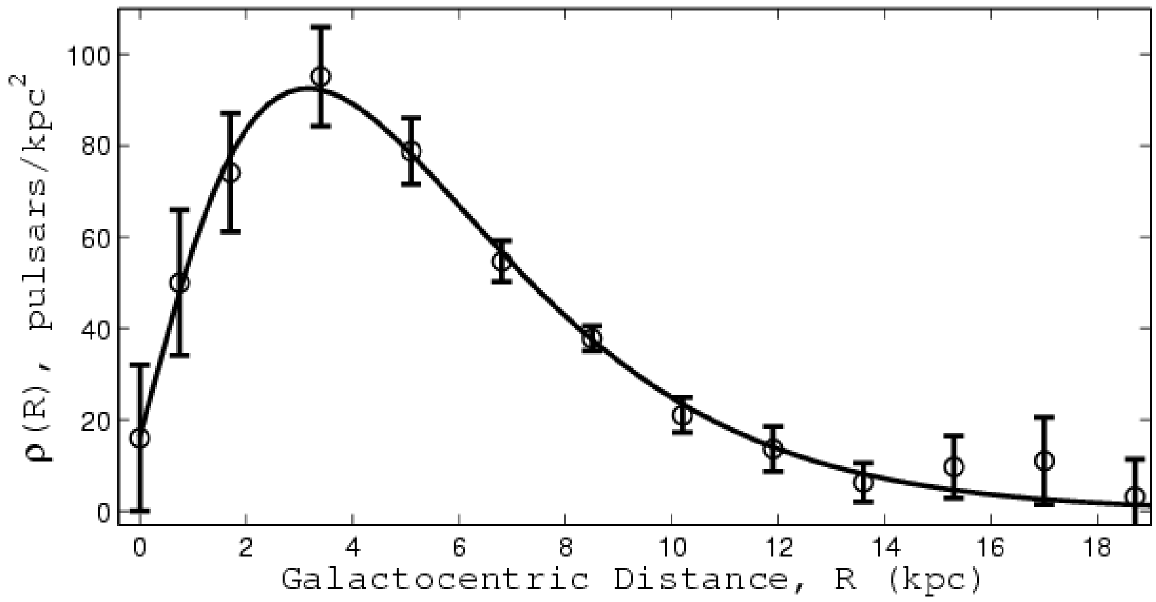
4. Moderate changes in nucleon and electron spectra
   YES !

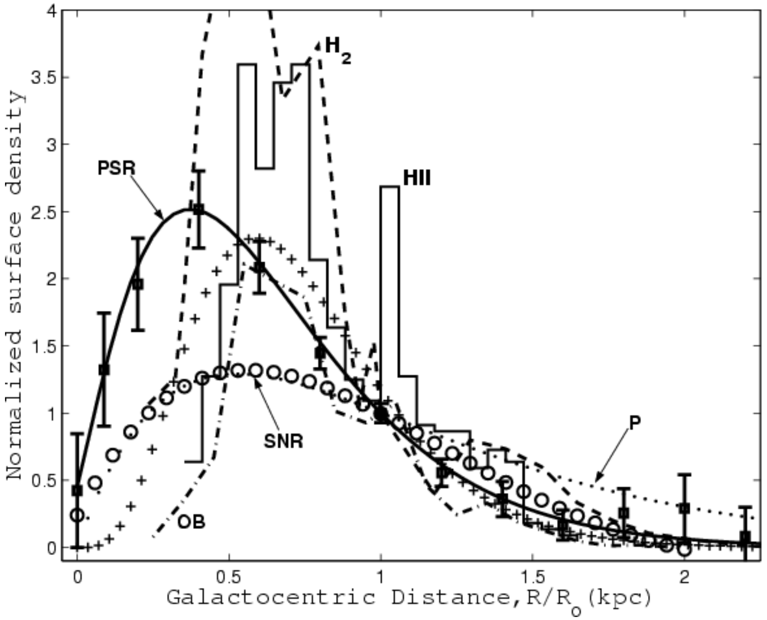
5. Exotic: dark matter (WIMPS: e.g. de Boer et al. astro-ph/0312037)
   Maybe, if not #4

Pulsar distribution



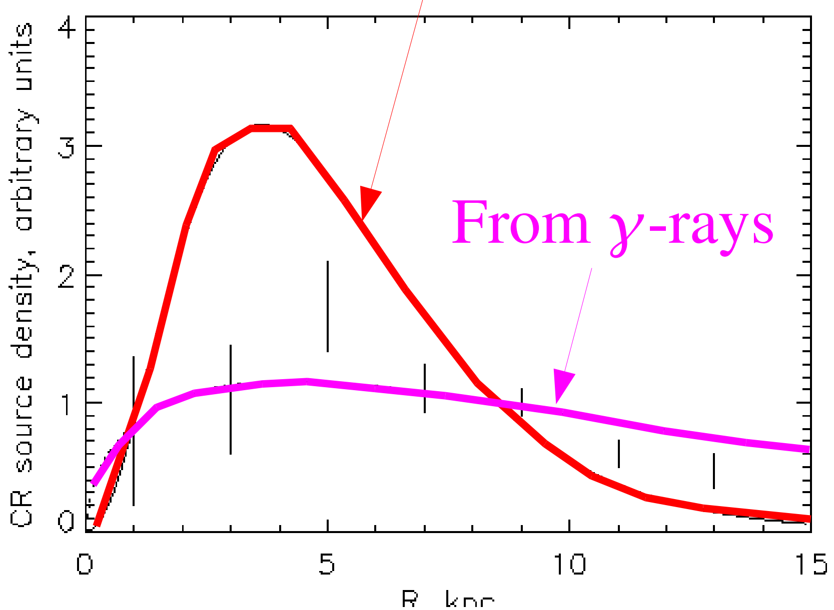
Yusifov & Kücük 2004
(Lorimer 2004: almost same result)





Old mystery of cosmic-ray gradient:
gradient based on γ-rays much smaller than SNR gradient.

SNR (traced by latest pulsar surveys: Lorimer 2004)



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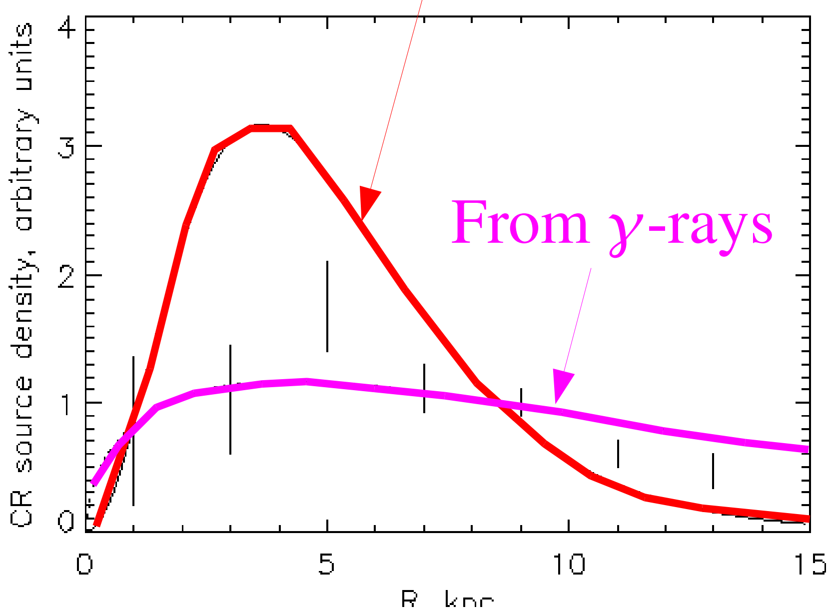

Clue: Galactic metallicity gradient e.g. [O/H]

metallicity decreases with R, X= H_2 / CO *decreases with metallicity*

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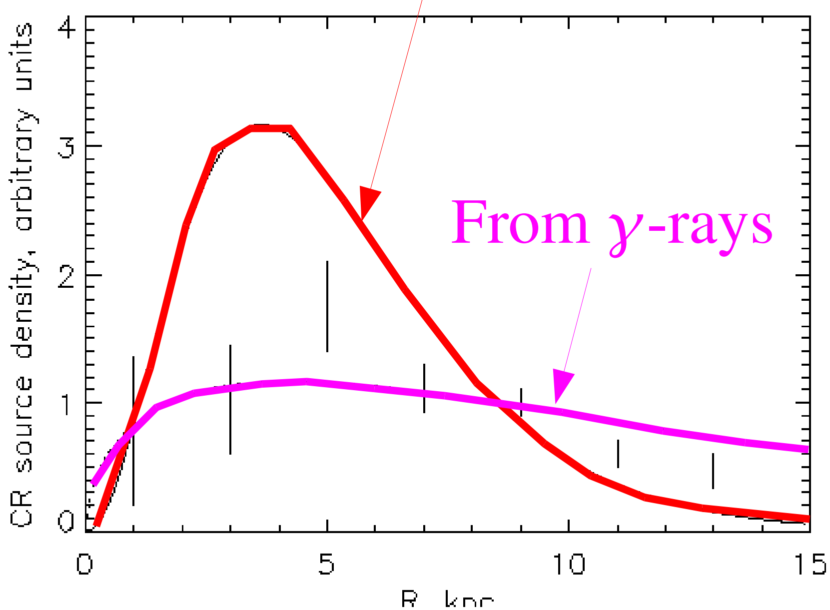
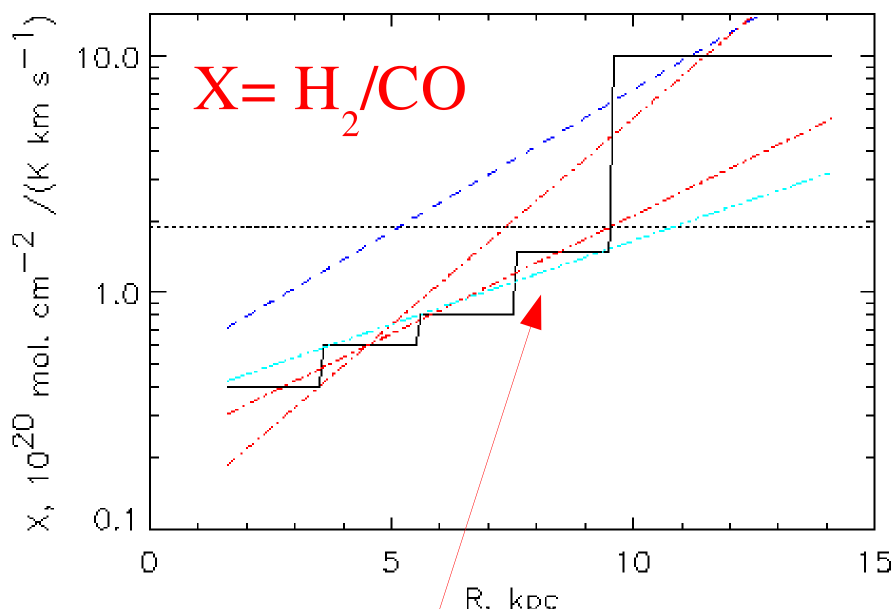




Clue: Galactic metallicity gradient e.g. [O/H]

metallicity decreases with R, X= H_2 / CO *decreases with metallicity*

>>>>>> ***X = H_2 / CO increases with radius***

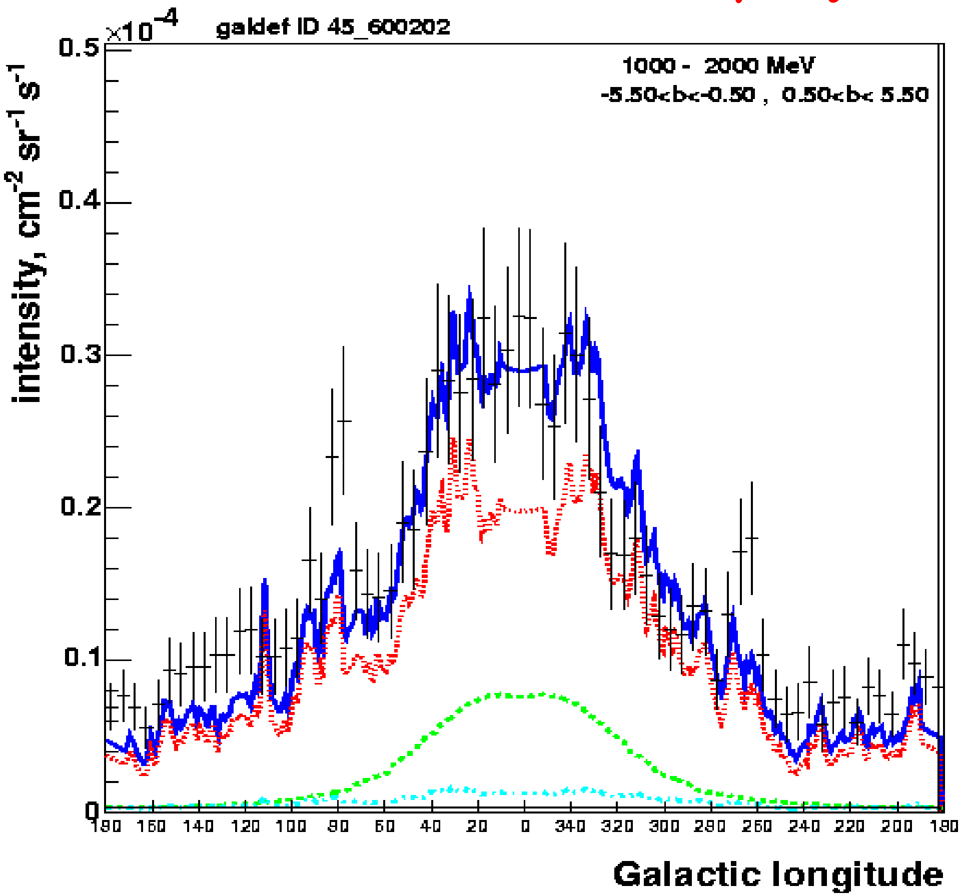
γ-rays = sources(R) * X(R) *CO(R) (+ HI, inverse Compton terms)

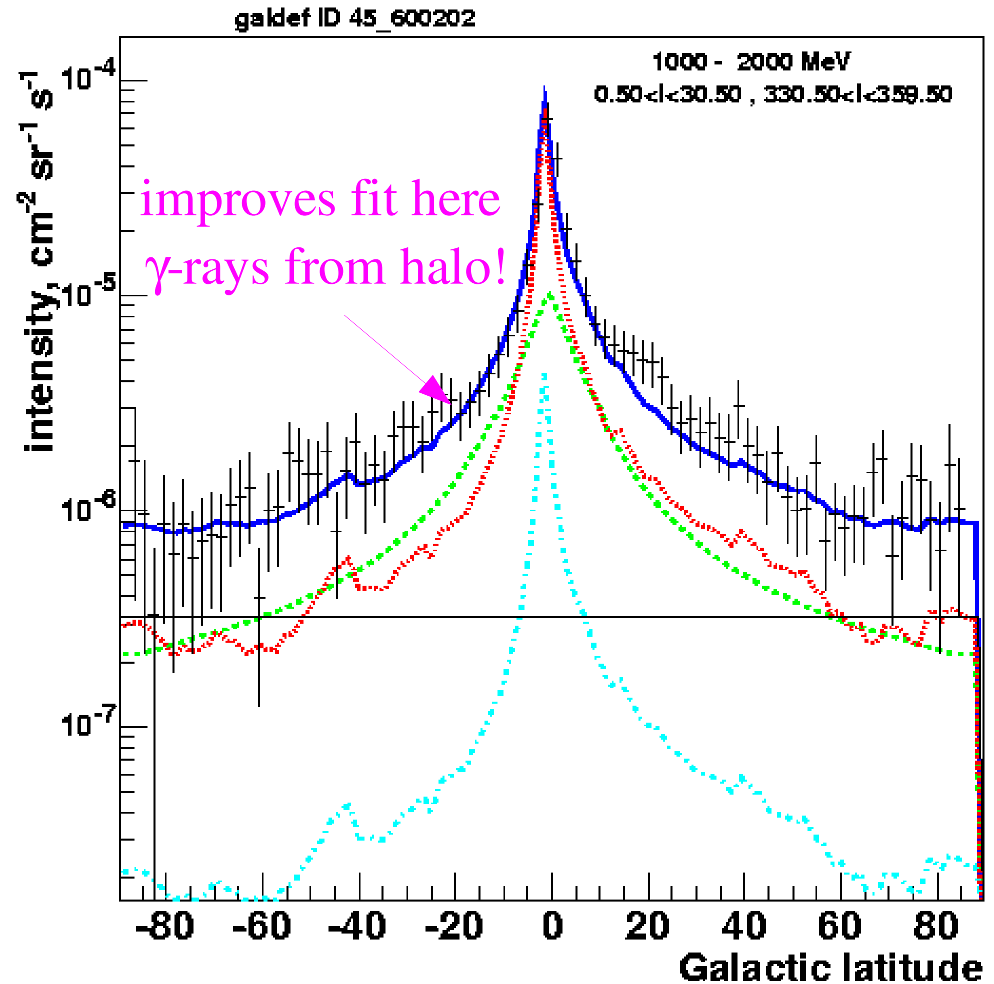
Steeper sources * flatter X = observed gamma-rays

more info: astro-ph/0405275 A&A in press

Pulsar-SNR source distribution , H_2/CO (R)

EGRET γ-ray data





Agrees with SNR distribution: supports SNR origin of cosmic rays

Conclusions

1. diffusive reacceleration model works well – but not proven

2. halo height ~ 4 kpc

3. γ - ray GeV excess caused by interstellar nucleon and electron spectra which are higher than directly measured

4. Bonus: predicts positrons & antiprotons correctly in reacceleration model !

5. SNR origin of CR consistent with EGRET data considering effect of metallicity gradient on H_2 / CO
   ⟶ better understanding of γ - ray / CR relation

Outlook:

more physical input (e.g. this meeting !) for

B-field model
cosmic-ray propagation
truly self-consistent models

Use of *galprop* to test such models against all available data.

Near future: GLAST γ - ray observatory: 2007

Galprop formula

relevance to this conference: B, propagation, galprop code

what could be done together

galprop model

2D / 3D / equilibrium / time dependent, stochastic sources

CR propagation: primary, secondary, e^+, p^- etc.

Injection -- diffusion -- convection-- energy-loss – reacceleration

γ- rays : using HI, CO, interstellar radiation field