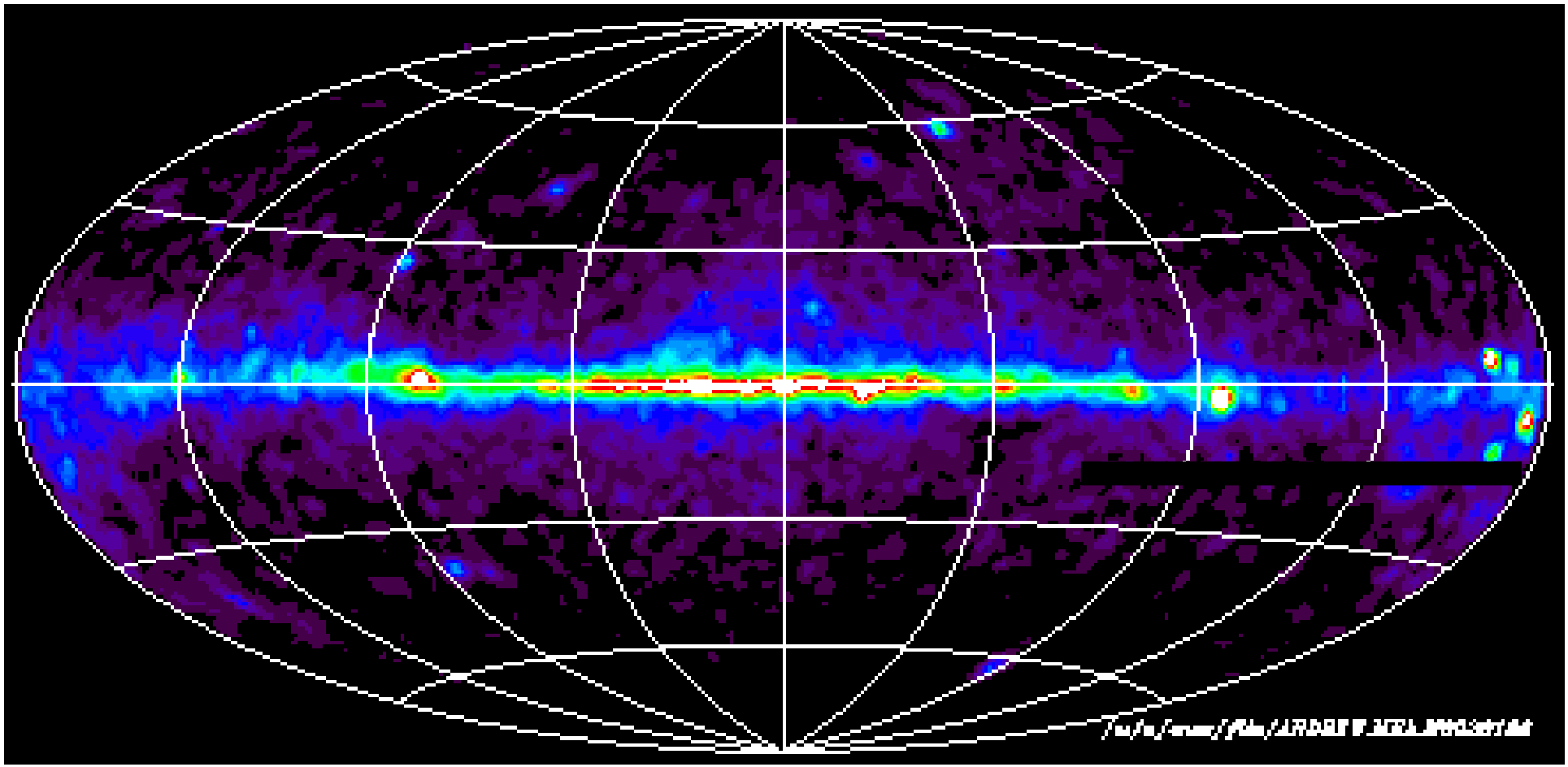
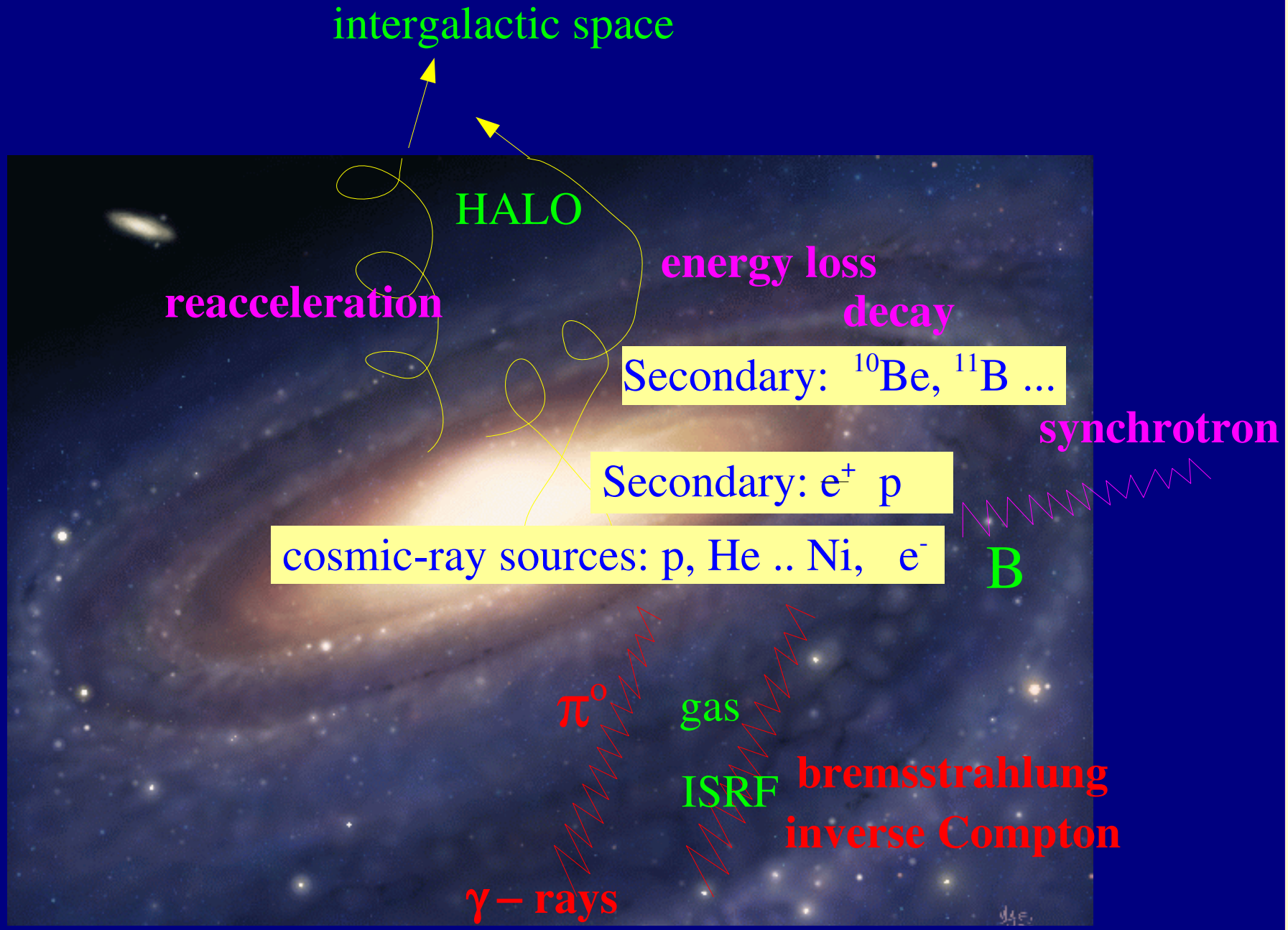
GALPROP:
a cosmic- ray propagation and gamma-ray code

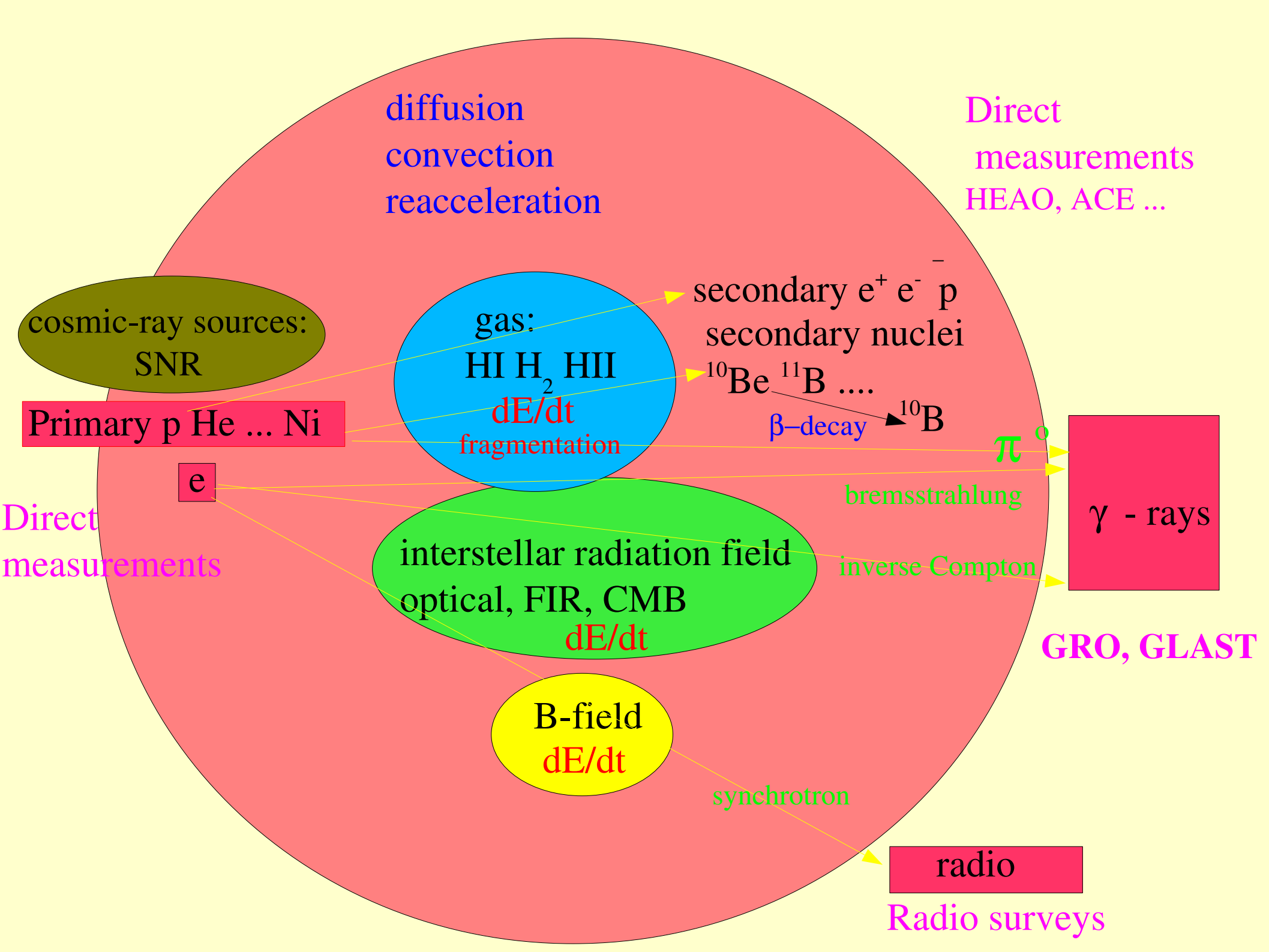


A. Strong, MPE Garching

Tools for SUSY, Annecy, June 28 2006

The basis: cosmic-ray production & propagation in the Galaxy


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


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

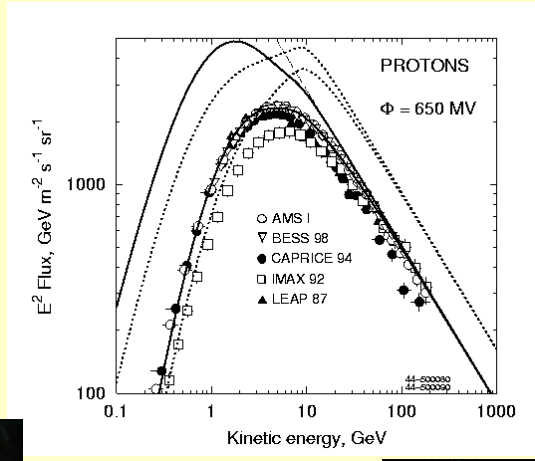
The **goal** : use *all* types of data in self-consistent way to test models of cosmic-ray propagation.

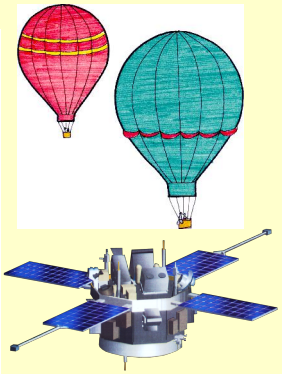
Observed *directly, near Sun:*

primary spectra (p, He ... Fe; e^-)

secondary/primary (B/C etc)

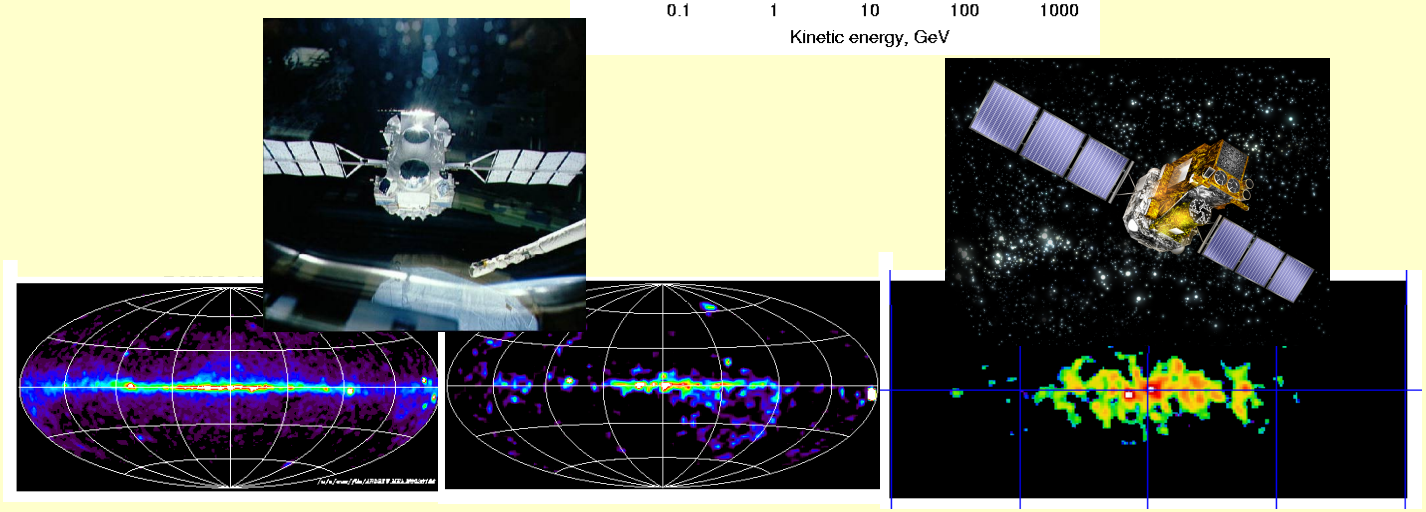
secondary e^+ , pbar



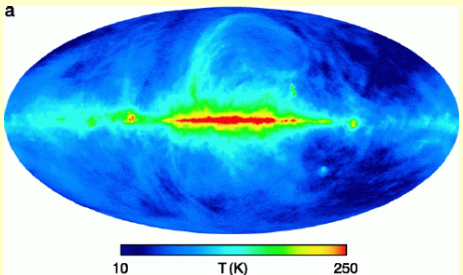


Observed *from whole Galaxy:*

γ - rays



synchrotron



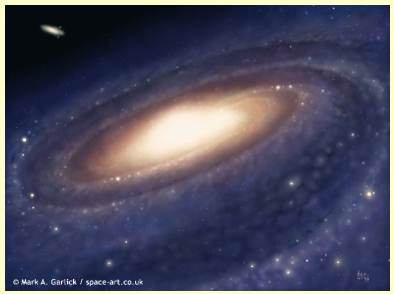
guiding principle:

to fit a wide range of data approximately
is more important than
to fit a small range of data precisely

Compare *galprop* realistic 3D approach to usual 'leaky-box' models which reduce the Galaxy to 0-D and ignore astronomical data.

the original motivation
- to escape from the leaky-box

into the Galaxy



but now...
upcoming *precision* experiments e.g.
GLAST, PAMELA, AMS02, long-duration balloon flights
require correspondingly *detailed* models.

From point of view of DM studies, main application of *galprop* is predicting the astrophysical background from established cosmic-ray processes.

For DM+hybrid codes, see talks by David Maurin, Christian Sander.

galprop

3D gas model based on 21-cm (atomic H), CO (tracer of H_2) 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

γ – ray, synchrotron processes

project running since 1996 (with Igor Moskalenko, Olaf Reimer, Troy Porter)

c++ (with some fortran from historical origins)

galprop code: publicly available since 1998, many users

continuous development, *NEW version shortly with dedicated Website*

new:

non-linear effects of cosmic rays on propagation

anisotropic inverse Compton scattering

Adopted as Standard Model for NASA's GLAST

galprop: 'engineering' approach

compared to analytical/semi-analytical methods:

allows realistic interstellar medium based on observations

not restricted to special cases – easy to add new processes

intuitive – obvious what's going on
(c.f. complex formulae of analytical methods)

uses only observable quantities (cosmic-ray spectrum, secondary/primary ratios)
(avoids e.g. cosmic-ray 'Path Length Distributions')

for *nuclei* it is possible to treat semi-analytically
but for e.g. *electrons*, *positrons* it's **impossible** to do it properly
(rapid energy losses on 3D interstellar radiation field)

for gamma-rays, synchrotron it's **essential**

Cosmic-ray propagation

$$\partial\psi(\underline{r}, p)/\partial t = q(\underline{r}, p)$$

cosmic-ray sources (primary and secondary)

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

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)

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

momentum loss

ionization, bremstrahlung

adiabatic momentum loss

$$- \psi/\tau_f$$

nuclear fragmentation

$$- \psi/\tau_r$$

radioactive decay

Finite Differencing

Each term can be finite-differenced (R, z, p):

$$\frac{\partial \psi_i}{\partial t} = \frac{\psi_i^{t+\Delta t} - \psi_i^t}{\Delta t} = \frac{\alpha_1 \psi_{i-1}^{t+\Delta t} - \alpha_2 \psi_i^{t+\Delta t} + \alpha_3 \psi_{i+1}^{t+\Delta t}}{\Delta t} + q_i$$

The updating scheme (Crank-Nicholson implicit method):

$$\psi_i^{t+\Delta t} = \psi_i^t + \alpha_1 \psi_{i-1}^{t+\Delta t} - \alpha_2 \psi_i^{t+\Delta t} + \alpha_3 \psi_{i+1}^{t+\Delta t} + q_i \Delta t$$

The tridiagonal system of equations:

$$-\alpha_1 \psi_{i-1}^{t+\Delta t} + (1+\alpha_2) \underbrace{\psi_i^{t+\Delta t}} - \alpha_3 \psi_{i+1}^{t+\Delta t} = \psi_i^t + q_i \Delta t$$

Solving for $\psi_i^{t+\Delta t}$.

Boundary conditions:

$$\psi(R, z_h, p) = \psi(R, -z_h, p) = \psi(R_h, z, p) = 0$$

More about *galprop*:

Solved *numerically* on a grid using Crank-Nicolson scheme

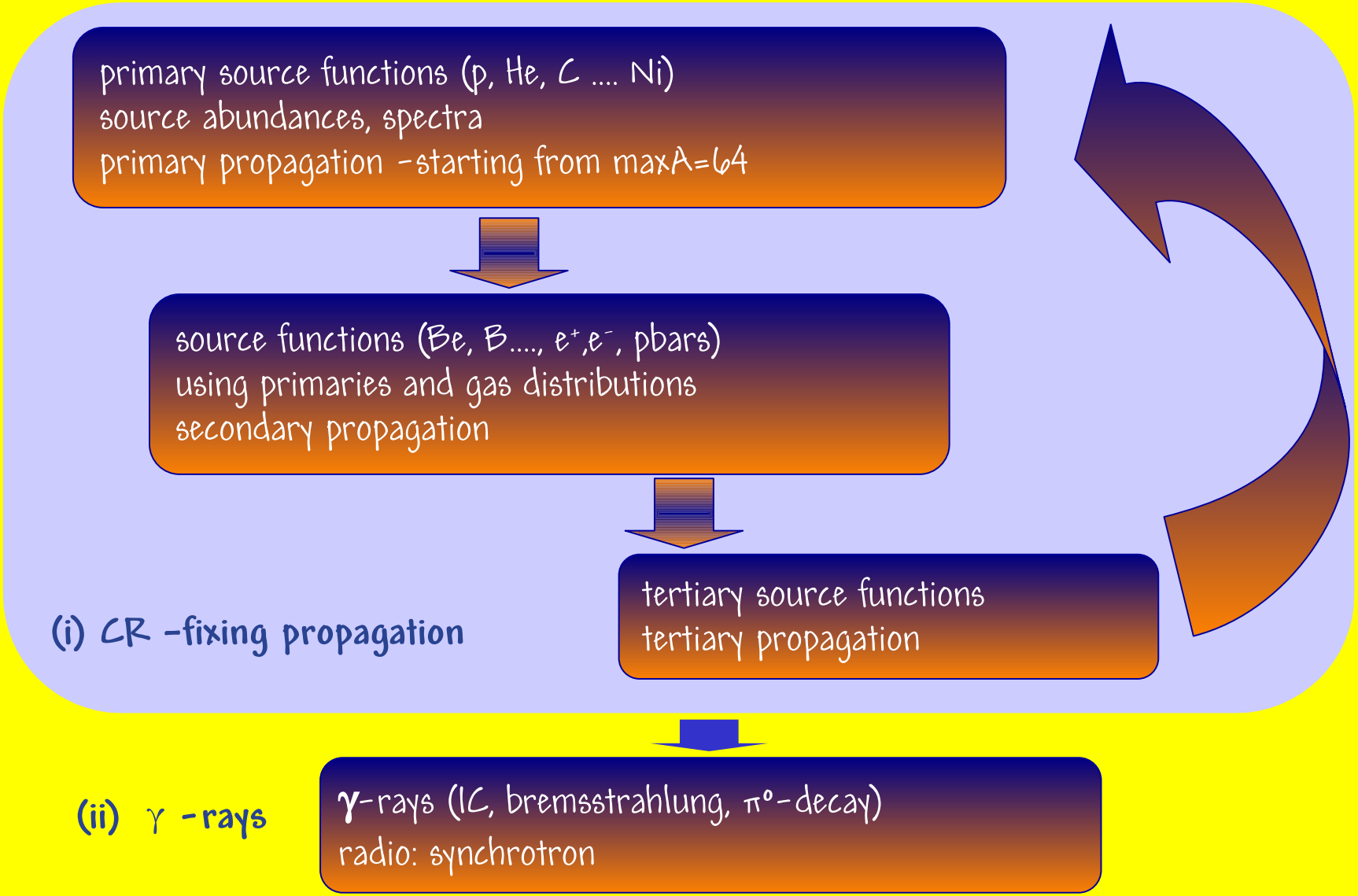
Time-dependent solution, allow to approach steady-state
or can use time-dependent solution (stochastic sources).

Controlled Parameter file with identifier
Output as FITS files (standard in astronomy) tagged with identifier
- # cosmic-ray spectra in 3D
- # gamma-ray skymaps by process
- # synchotron skymaps

Twin program *galplot* used to display and compare with data. Shares classes.

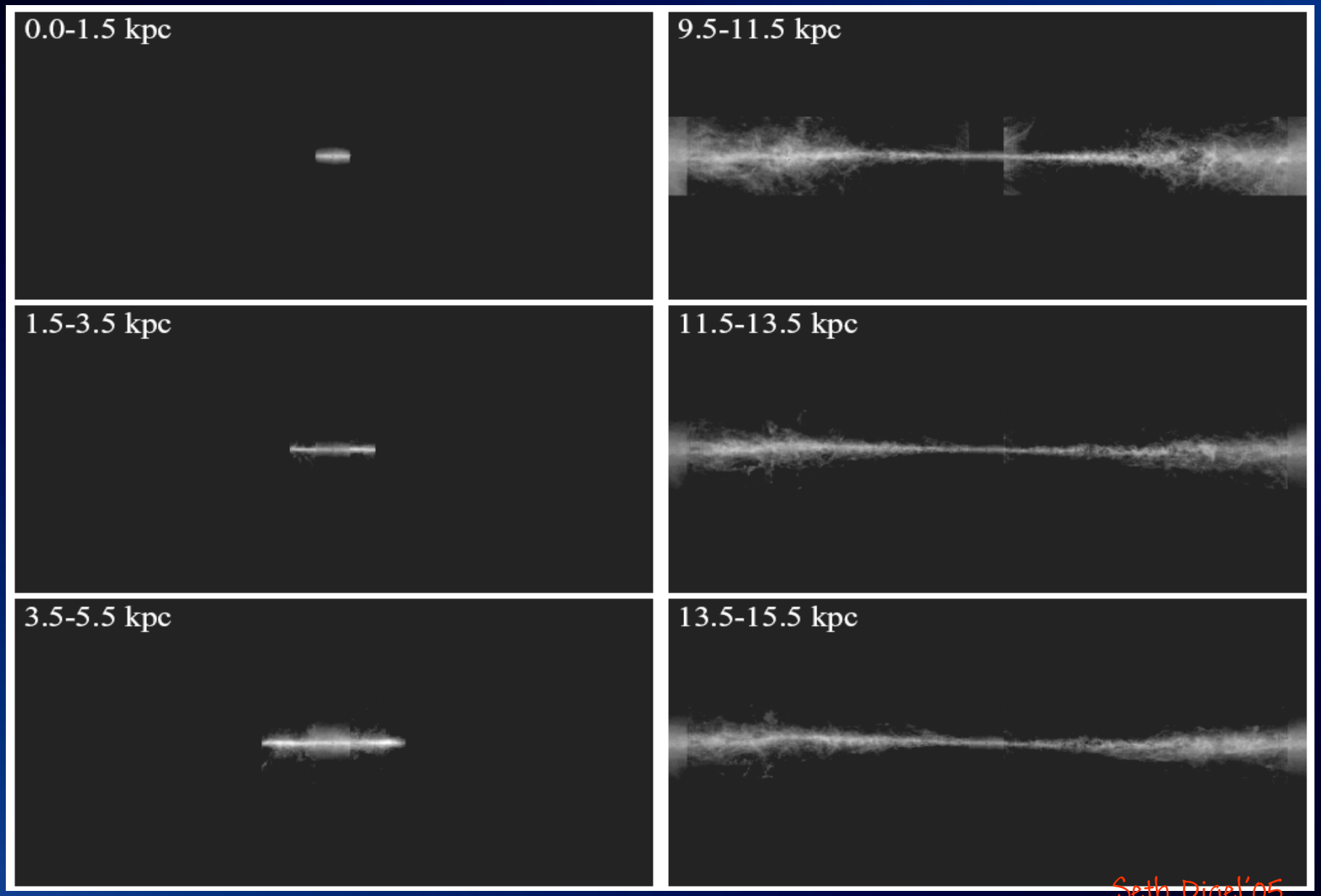
(new) Galprop class encapsulates entire program (useful for hybrids)

algorithm

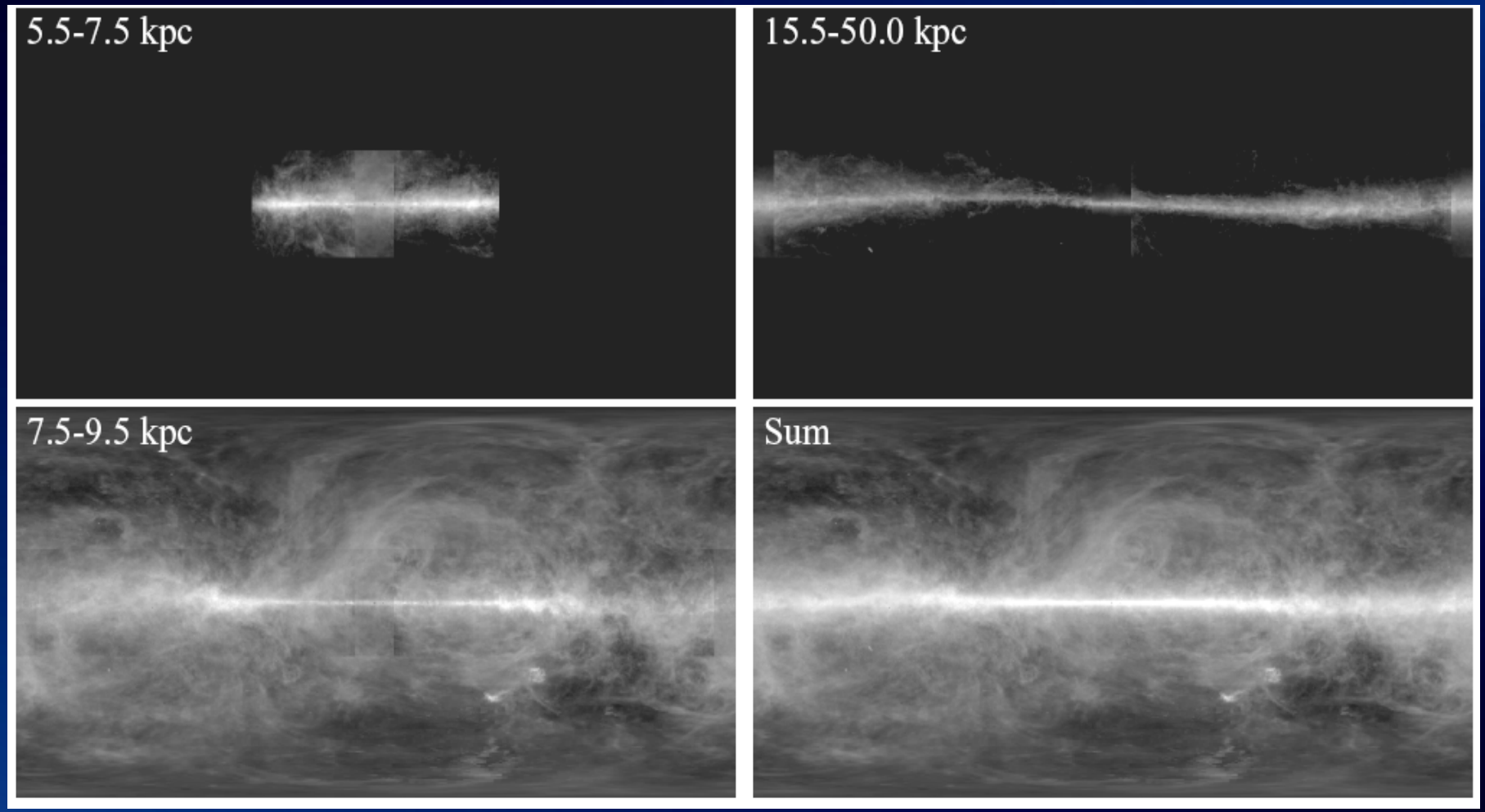

primary source functions (p, He, C .... Ni)
source abundances, spectra
primary propagation -starting from maxA=64
source functions (Be, B...., e+,e-, pbars)
using primaries and gas distributions
secondary propagation
tertiary source functions
tertiary propagation
(i) CR -fixing propagation
(ii) γ -rays
γ-rays (IC, bremsstrahlung, π°-decay)
radio: synchrotron

astronomical input

Gas Rings: HI (Inner & Outer Galaxy)



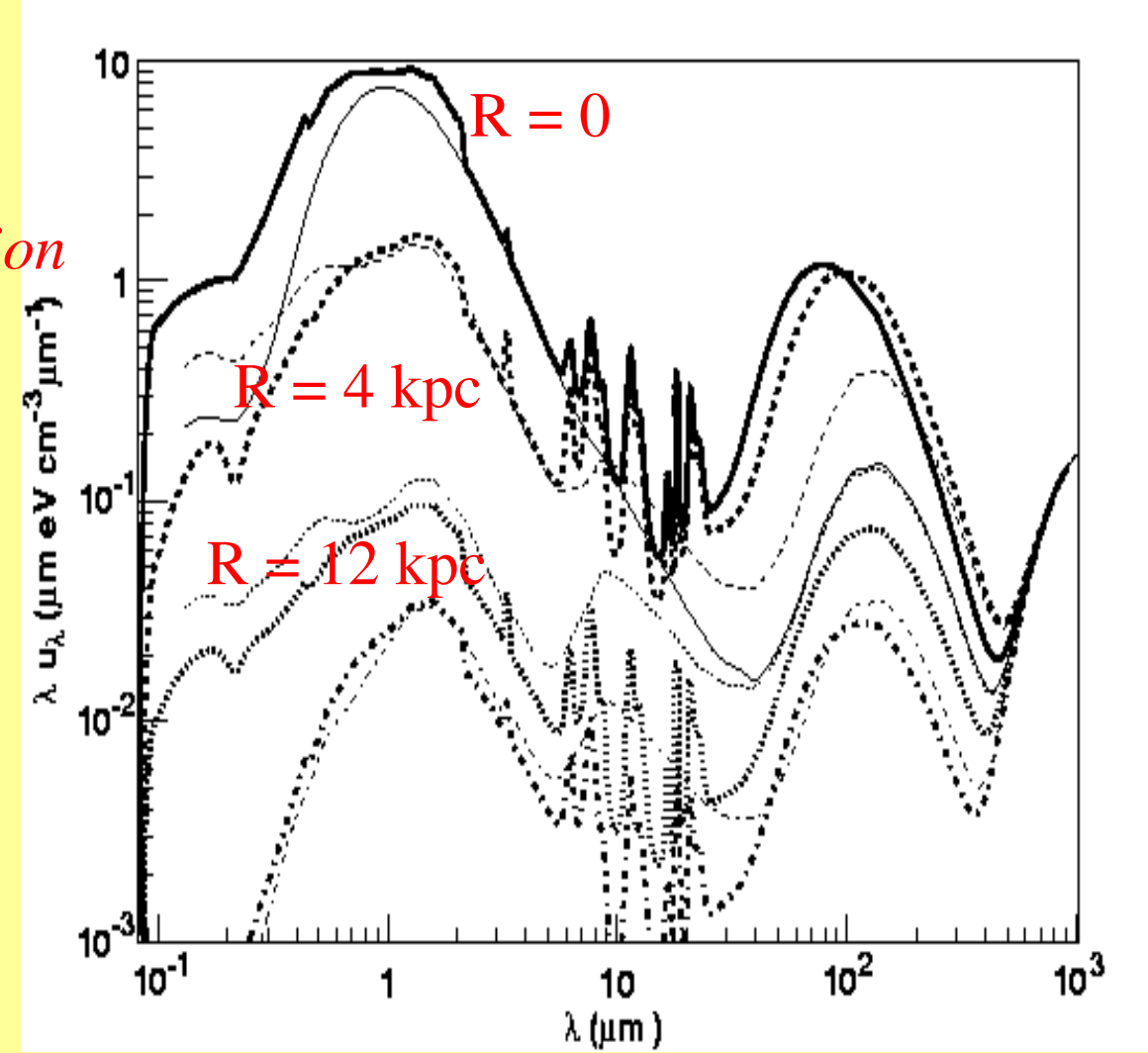
Gas Rings: HI (Our Neighborhood)



Seth Digel'05

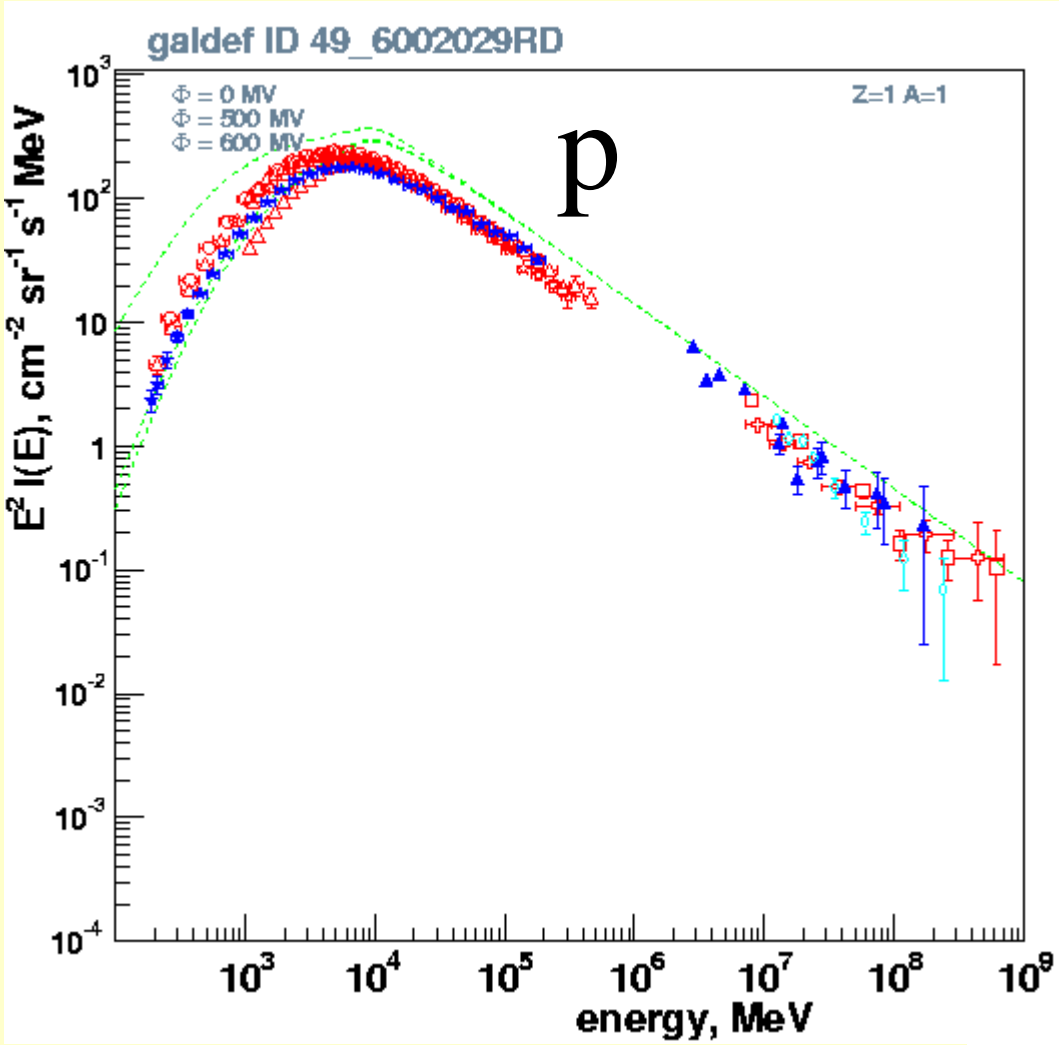
Interstellar Radiation Field (for inverse Compton γ-rays): new model *ApJ 640, L155, 2006 (Troy Porter)*

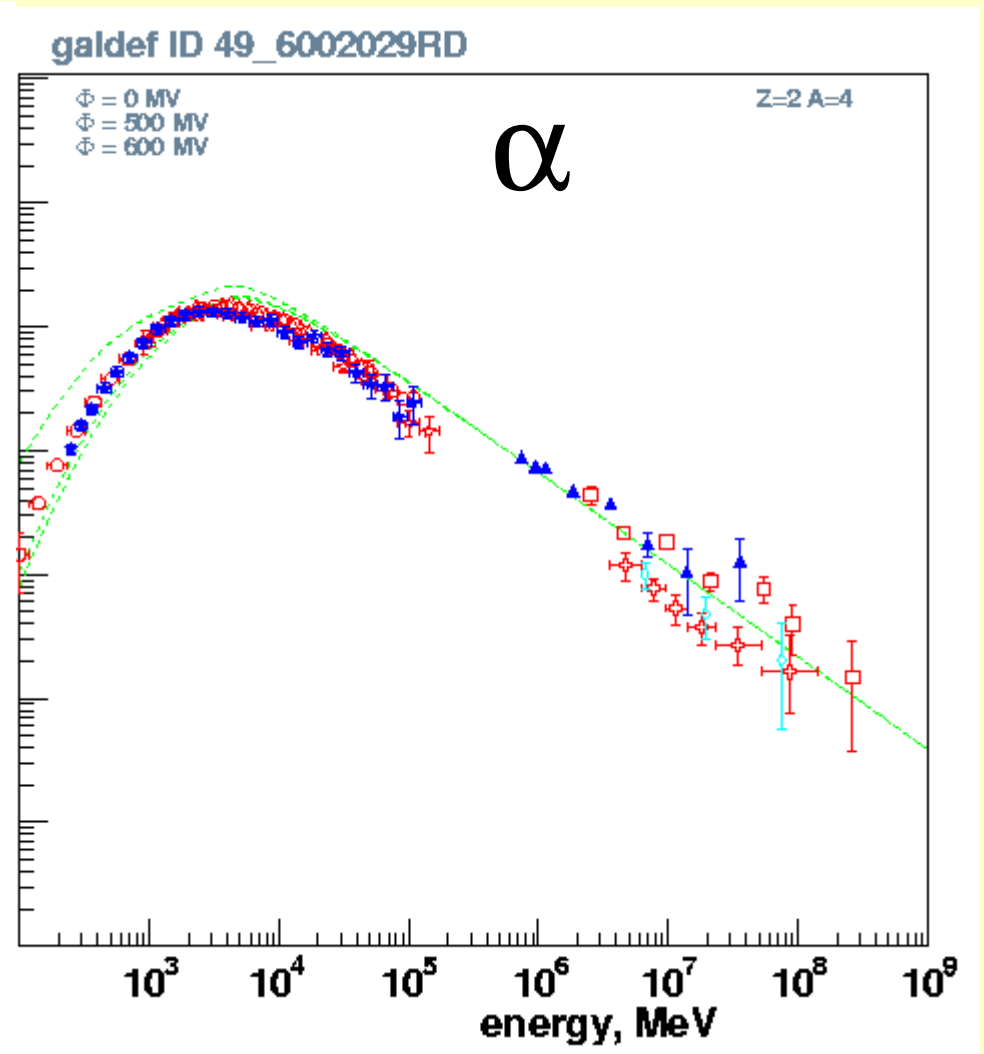
***New** ISRF*
using much
new information
e.g.
COBE



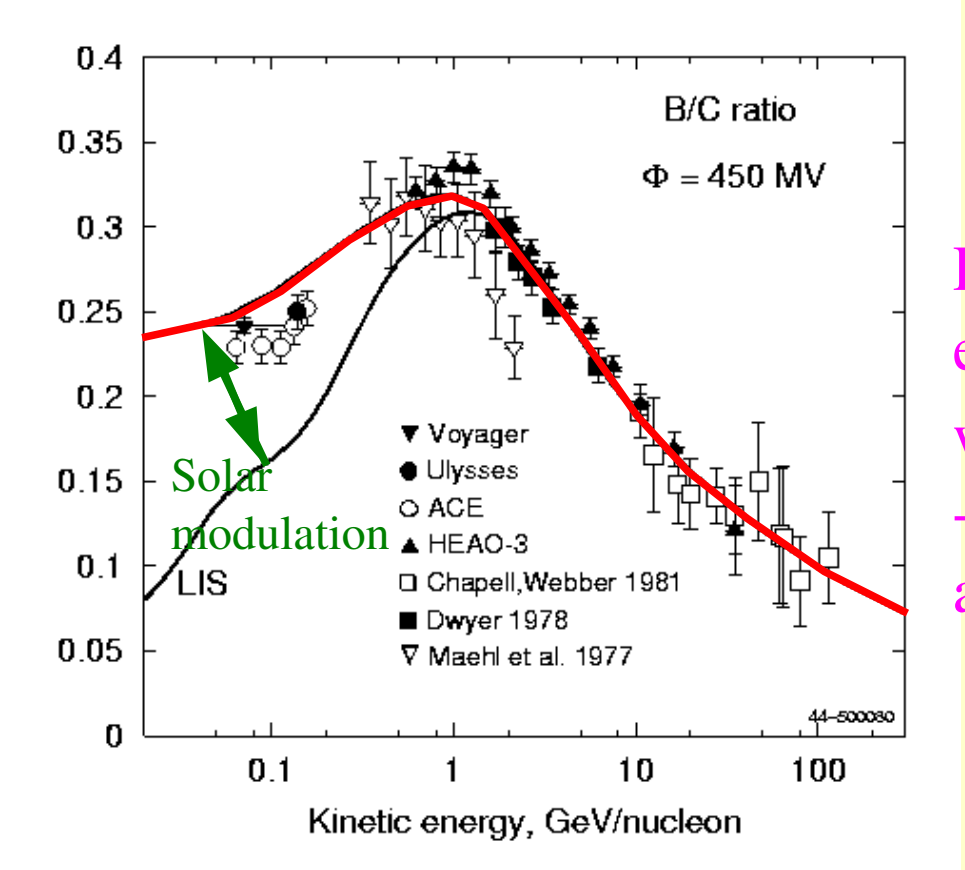
UV optical IR FIR CMB

primary cosmic-ray spectra

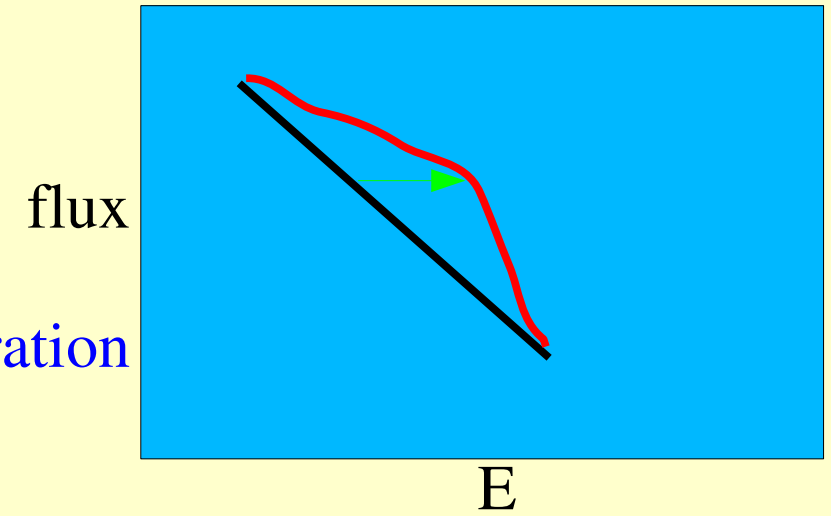




secondary/primary ratio: B/C



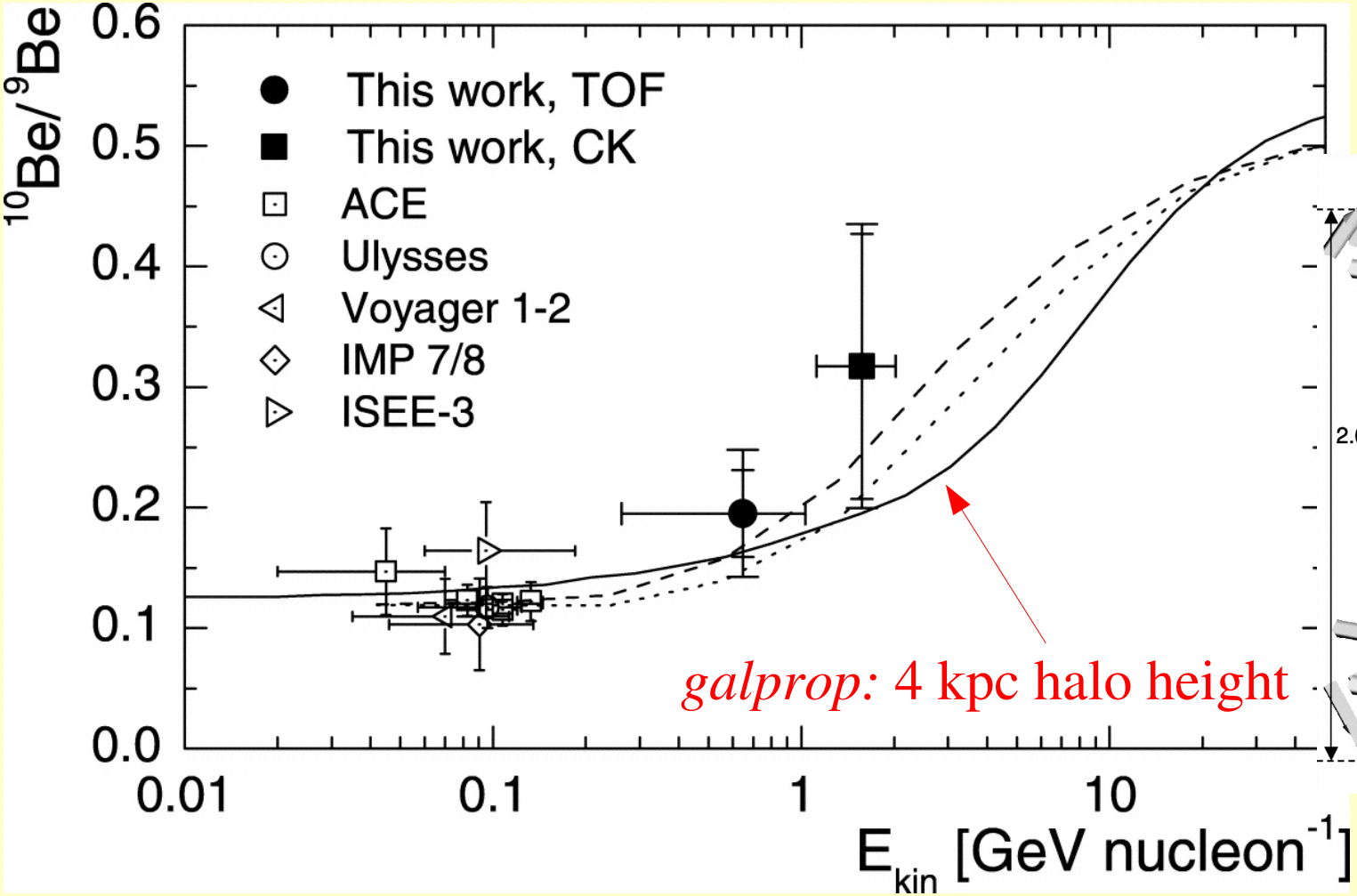
Peak in B/C can be
explained by **diffusive reacceleration**
with Kolmogorov $D \sim \beta p^{1/3}$
+ avoids large cosmic-ray anisotropy
at high energies.

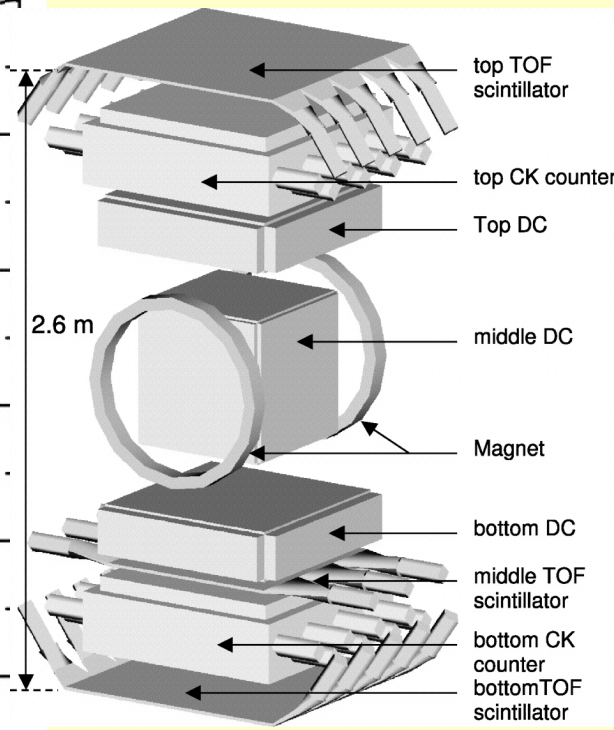


Energy-dependent diffusive reacceleration
produces bump in particle spectrum

Radioactive nuclei set limits on size of halo

New data: ACE, ISOMAX





Hams et al. 2004 ApJ 611, 892

an example of a *galprop* application:

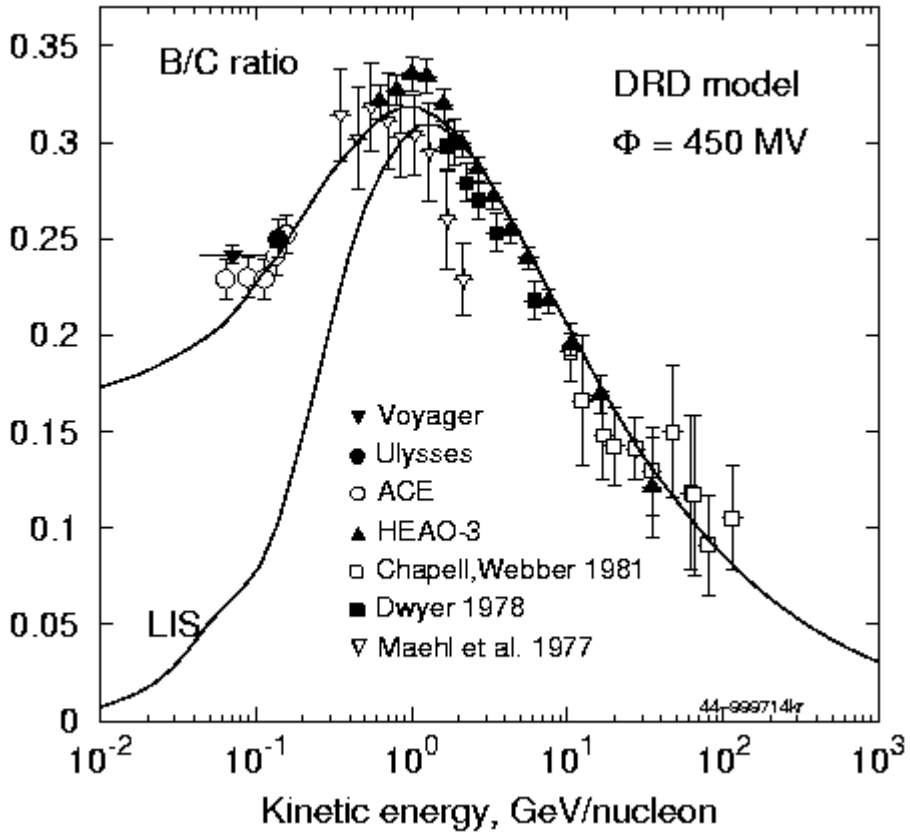
study of diffusion theories:
wave-damping by cosmic rays

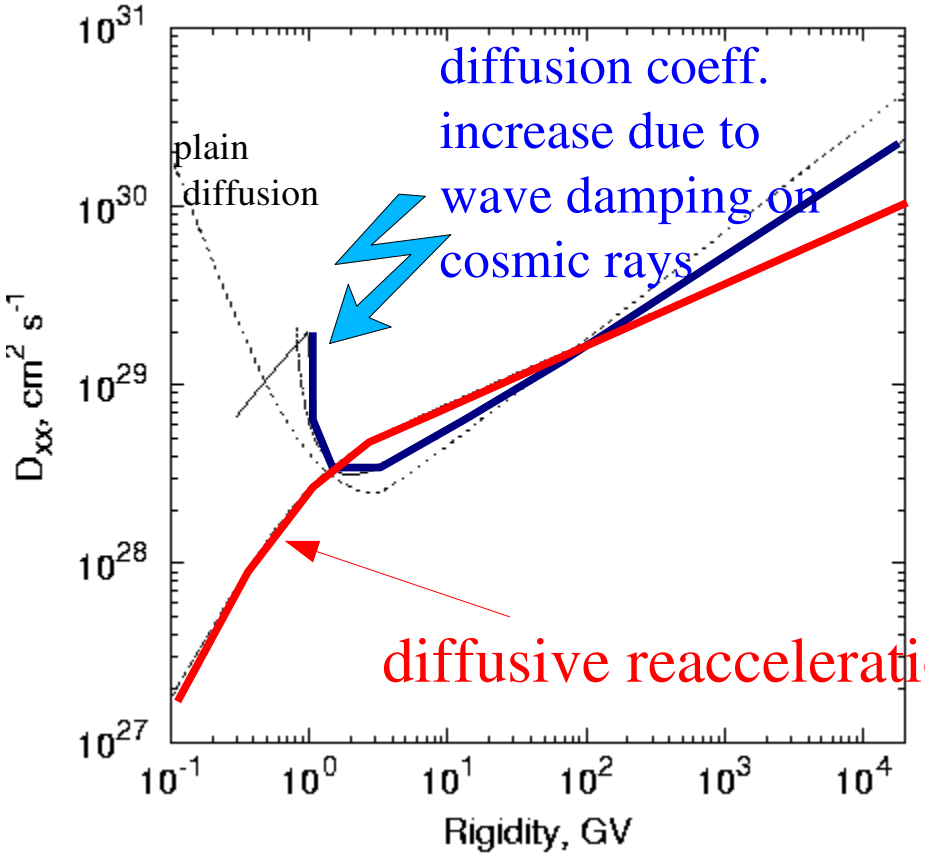
Ptuskin et al. 2006 ApJ 642, 902

secondary/primary ratio: B/C

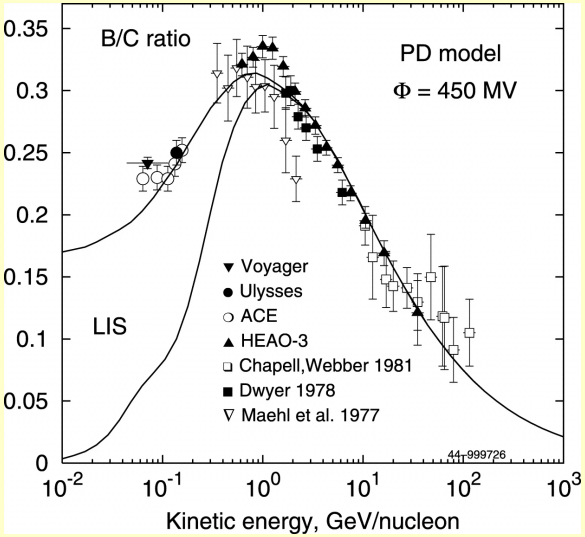
.....yet another explanation of peak in B/C :
dissipation of MHD waves by cosmic rays
Ptuskin et al. 2006, ApJ 642, 902
Effect now included in galprop code.

B/C

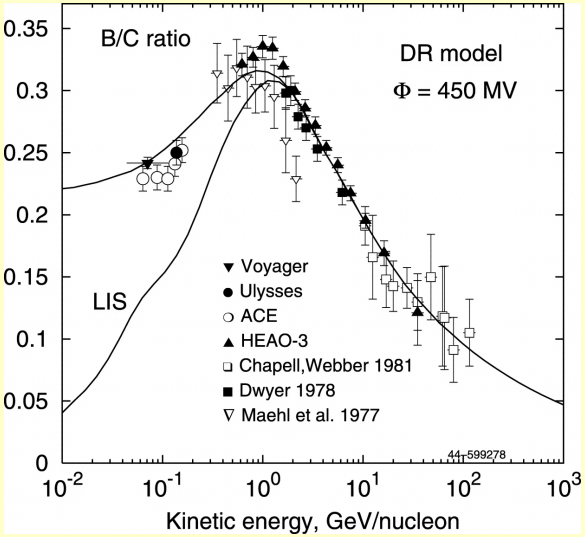




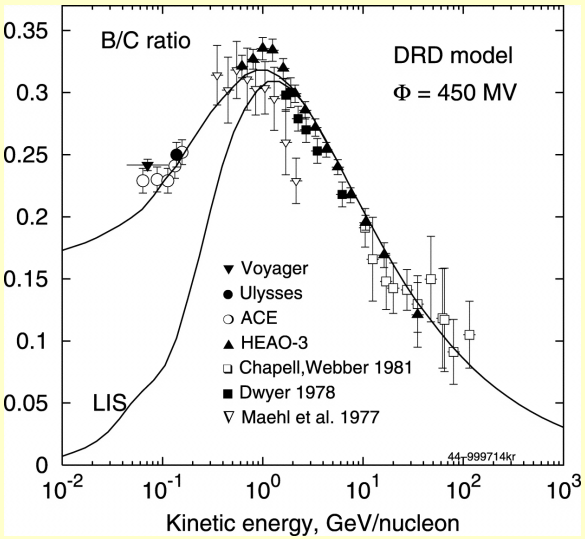
plain diffusion



diffusive reacceleration



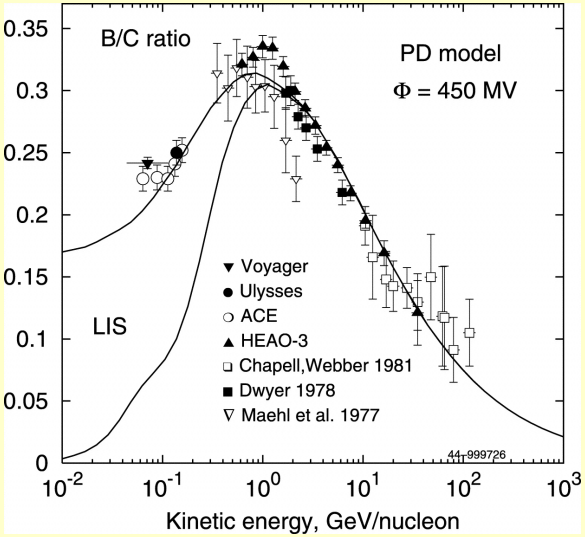
wave damping



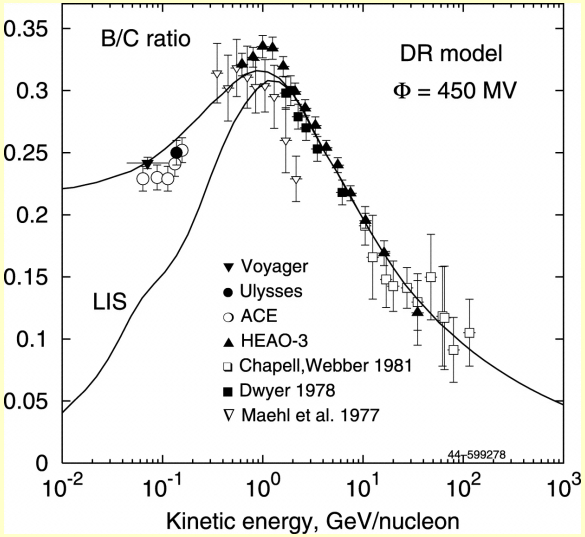
first adjust parameters to fit B/C

Ptuskin et al. 2006 ApJ 642, 902

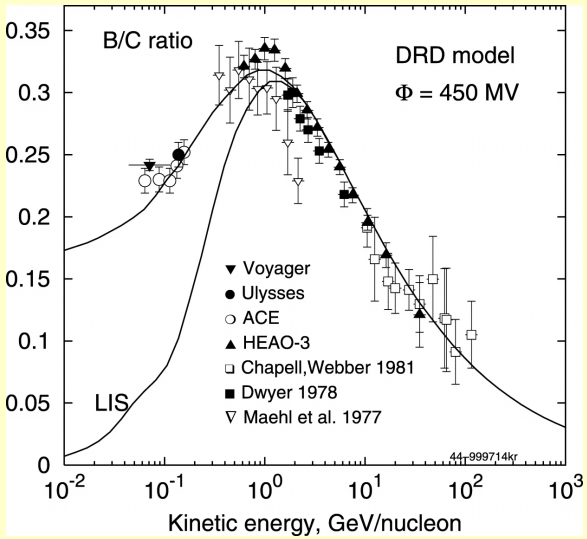
plain diffusion



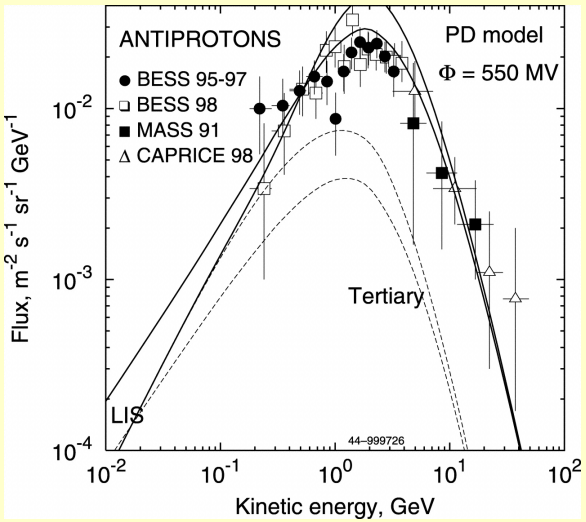
diffusive reacceleration

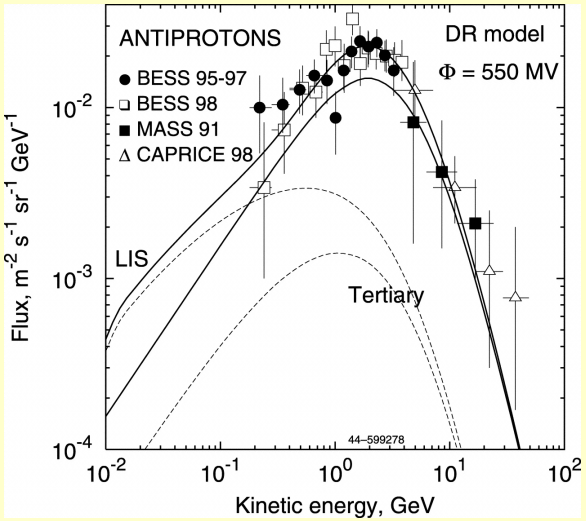


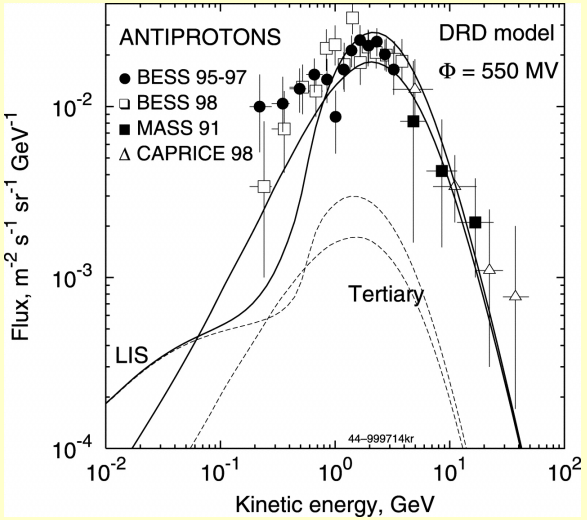
wave damping



then predict other cosmic ray spectra

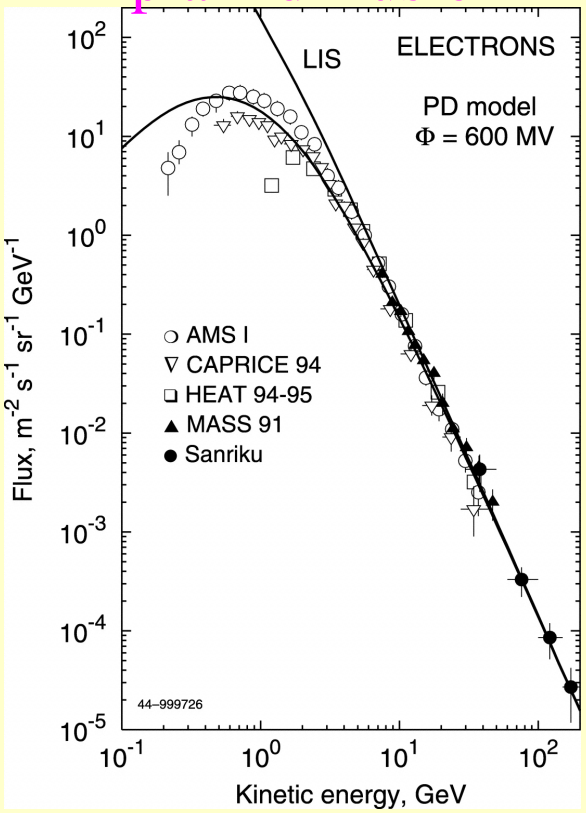


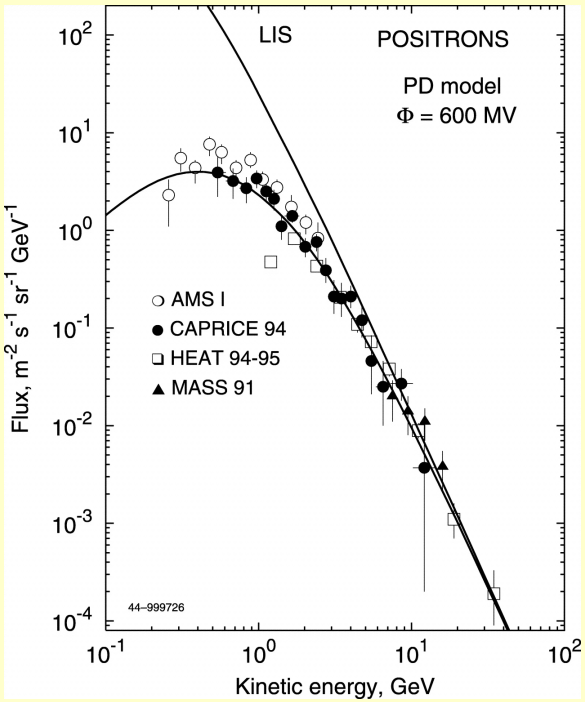




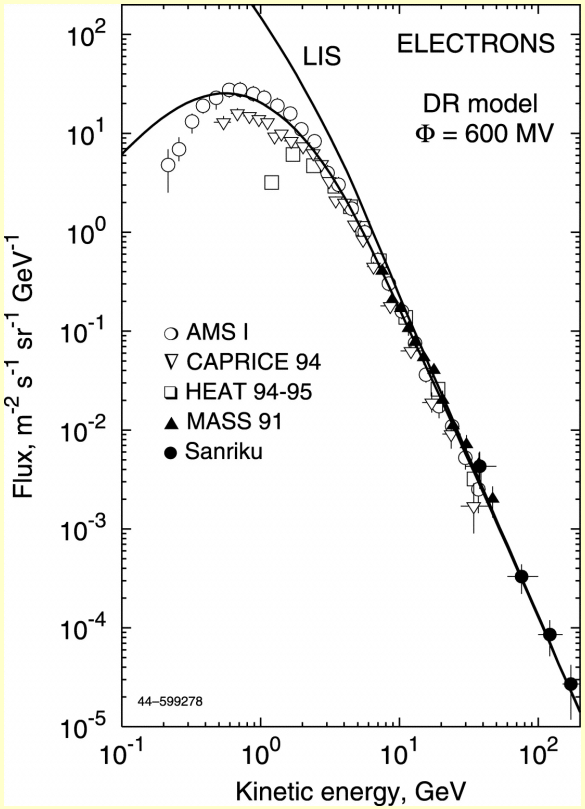
Ptuskin et al. 2006 ApJ 642, 902

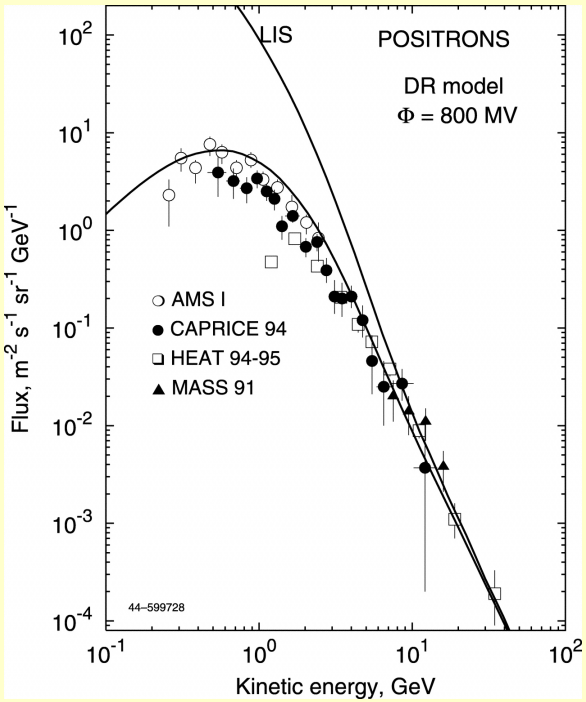
plain diffusion



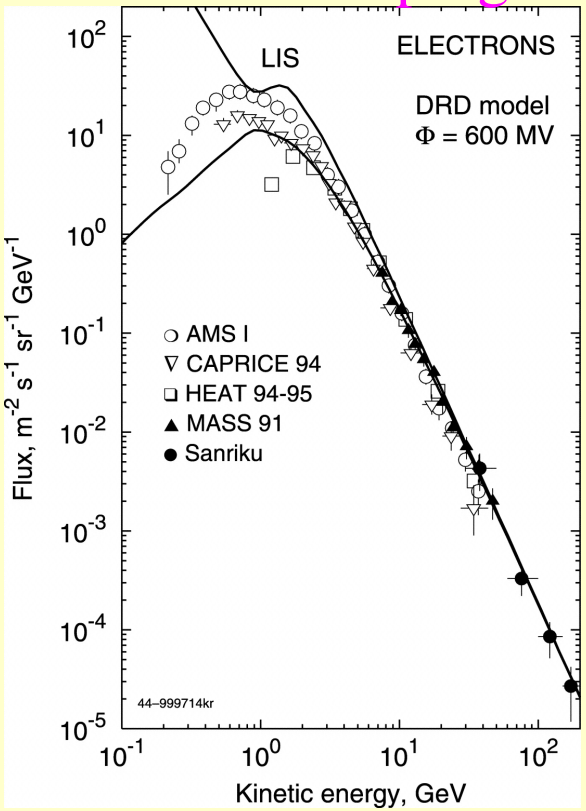


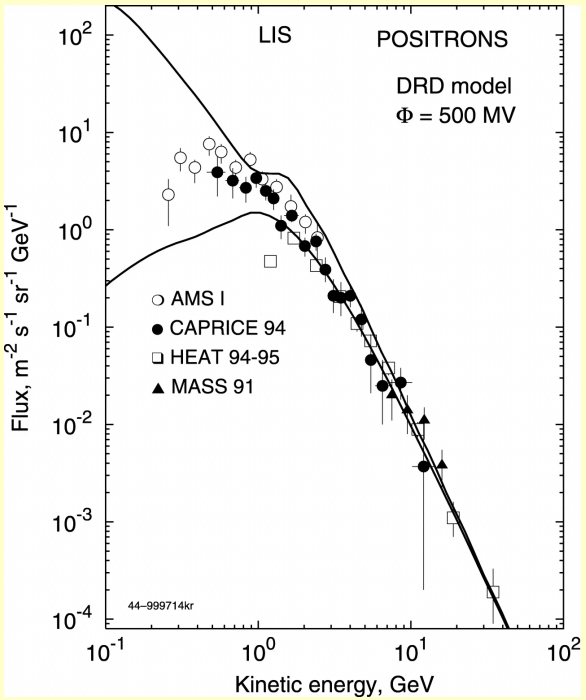
diffusive reacceleration





wave damping

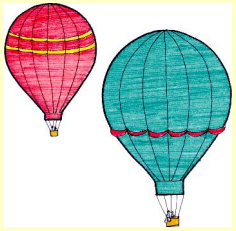


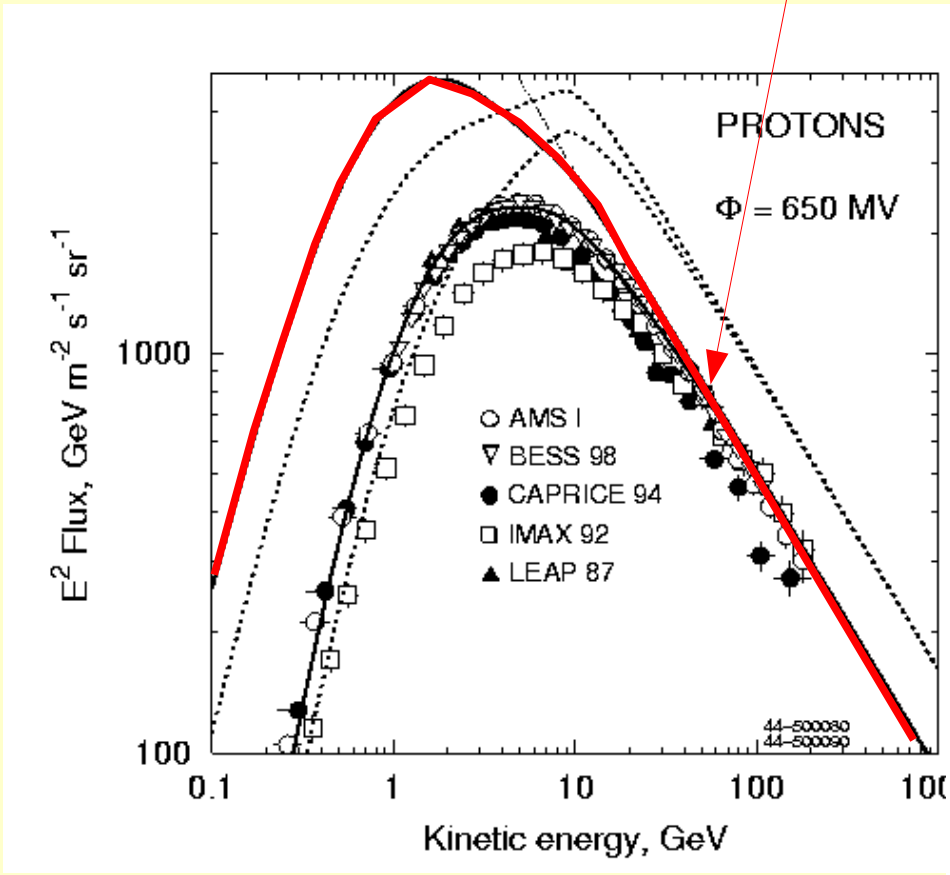


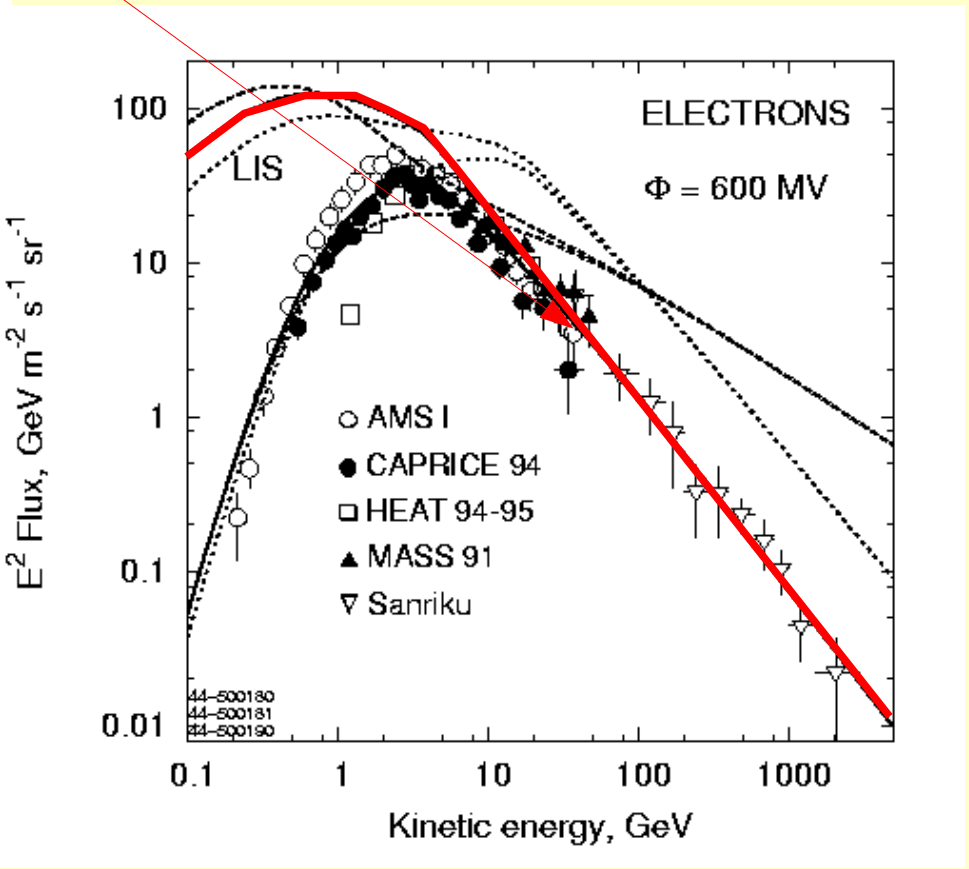
γ - rays

Modelling diffuse Galactic gamma-rays:

Conventional model: p, e spectra as measured

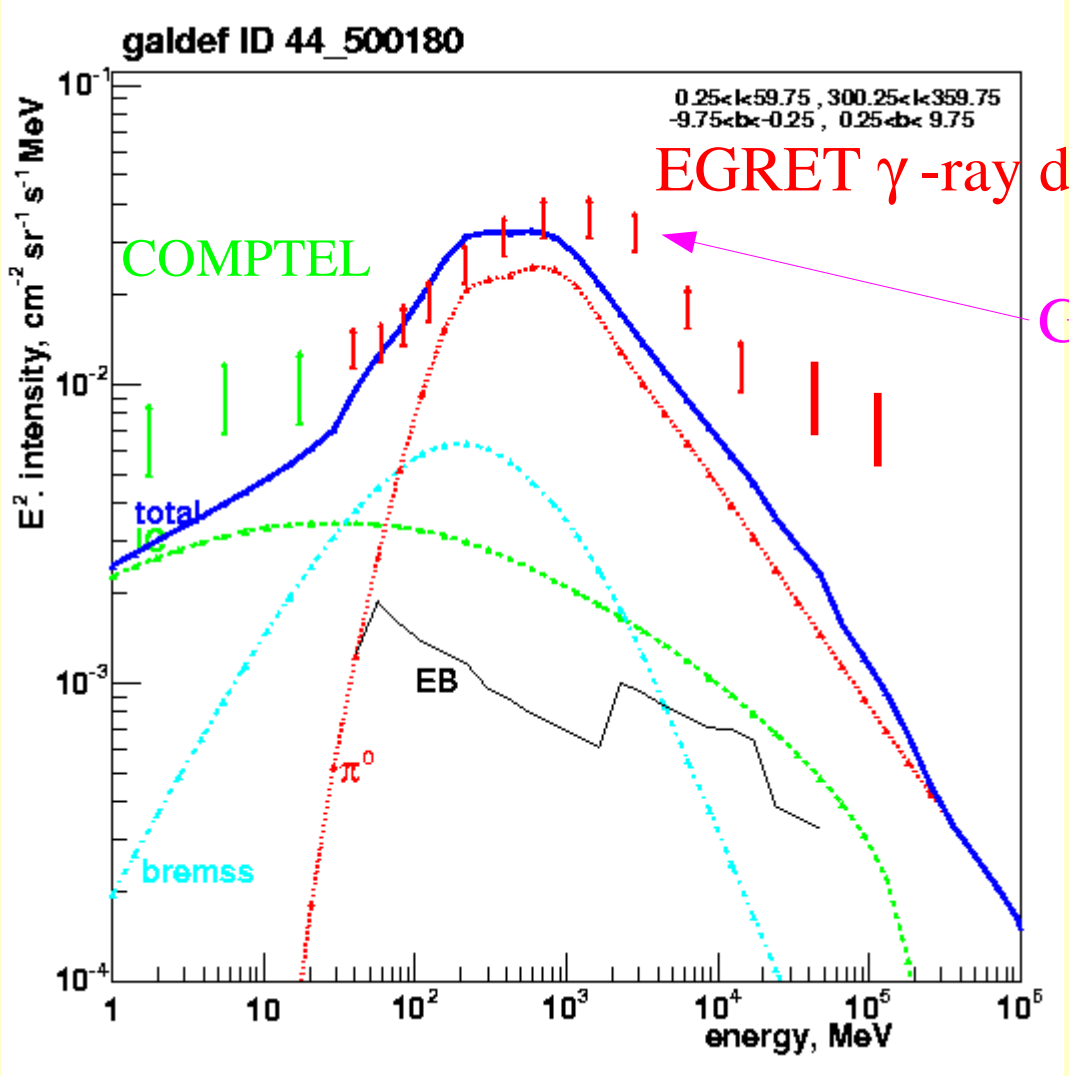






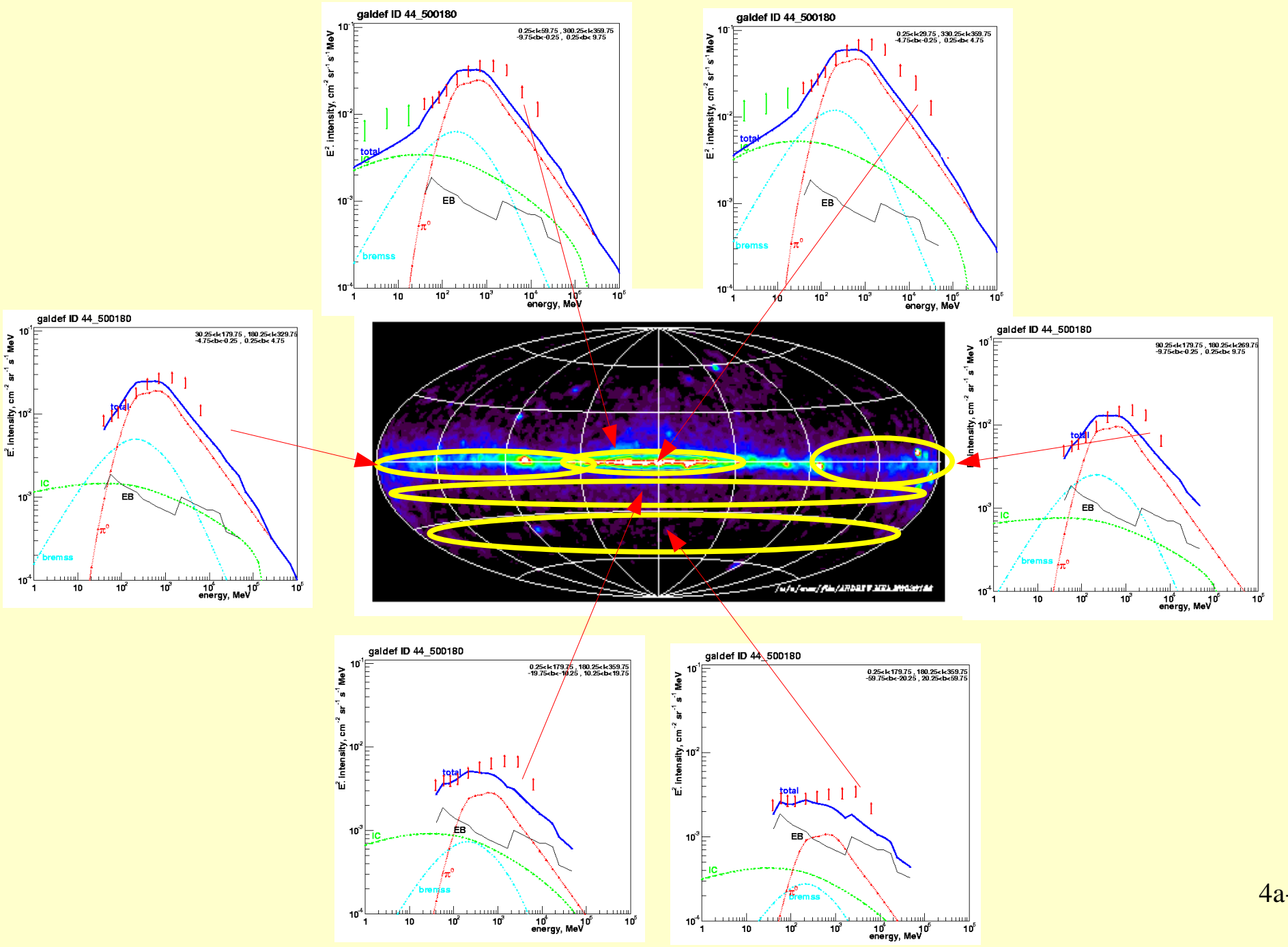
Conventional model:
protons (+He) and electrons as *directly measured*

γ - ray spectrum
of inner Galaxy



There really IS a big excess !

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
2. Hard *nucleon* injection spectrum.
3. Hard *electron* injection spectrum
4. Moderate changes of nucleon and electron spectra
5. Physics of π^o production
6. Sources
7. Exotic: dark matter

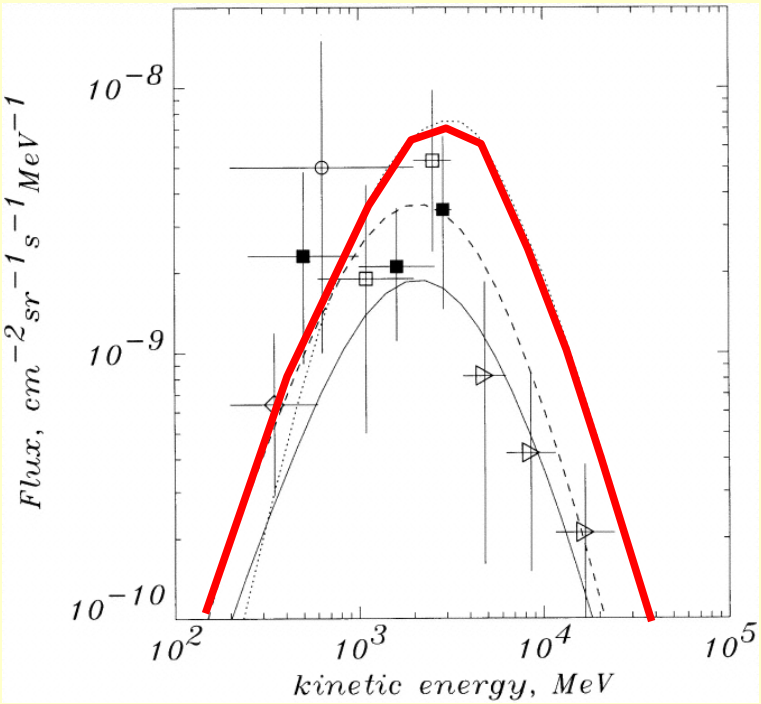
Proposed explanations of GeV γ - ray excess:

Hard proton injection spectrum

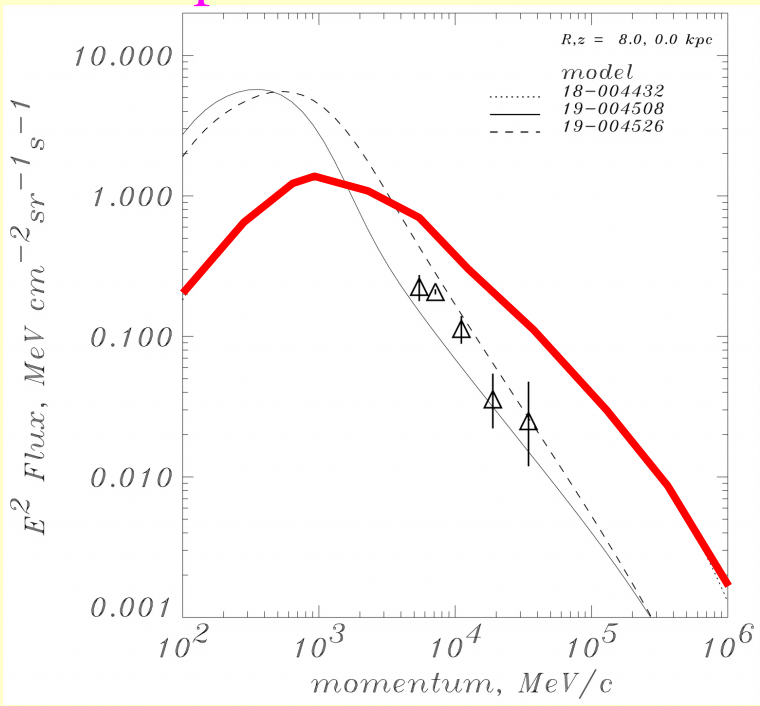
(e.g. if directly measured spectra are different from Galactic)

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

antiprotons



positrons

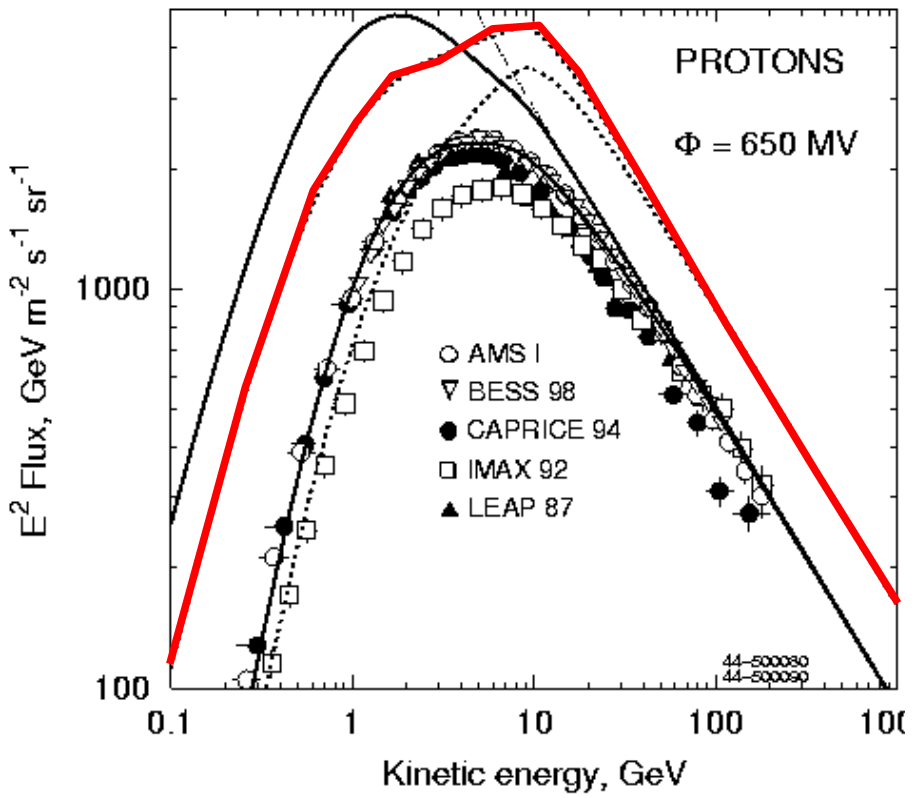


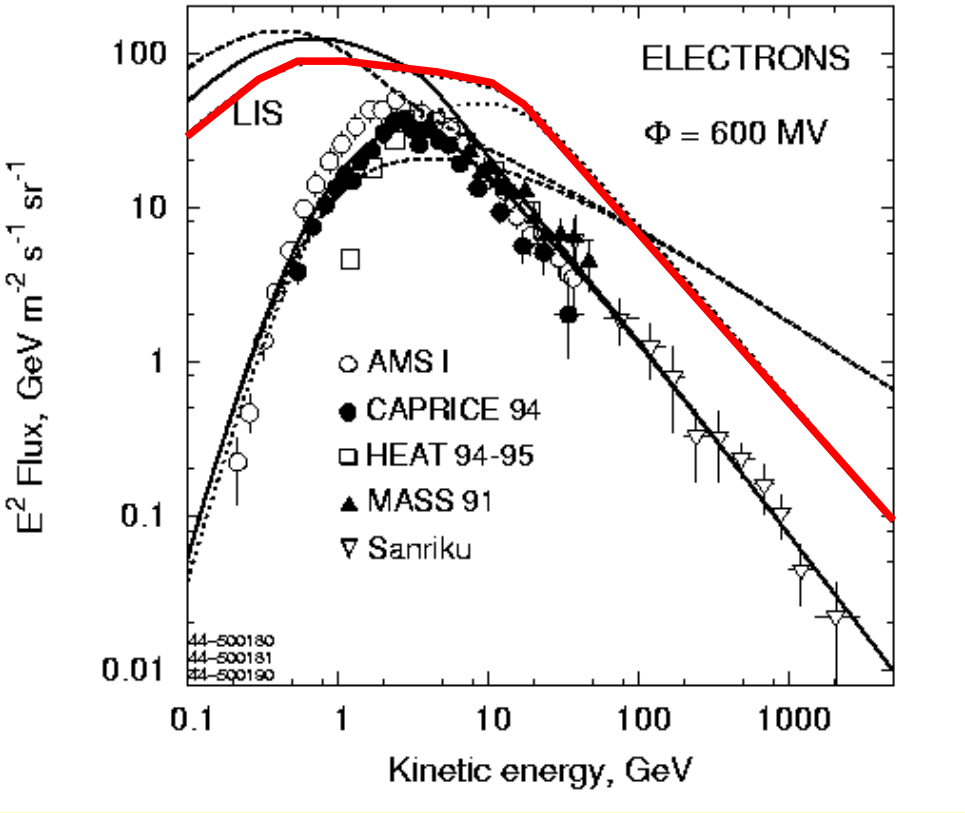
illustrates advantage of combined particles and γ - ray analysis

Optimized model:

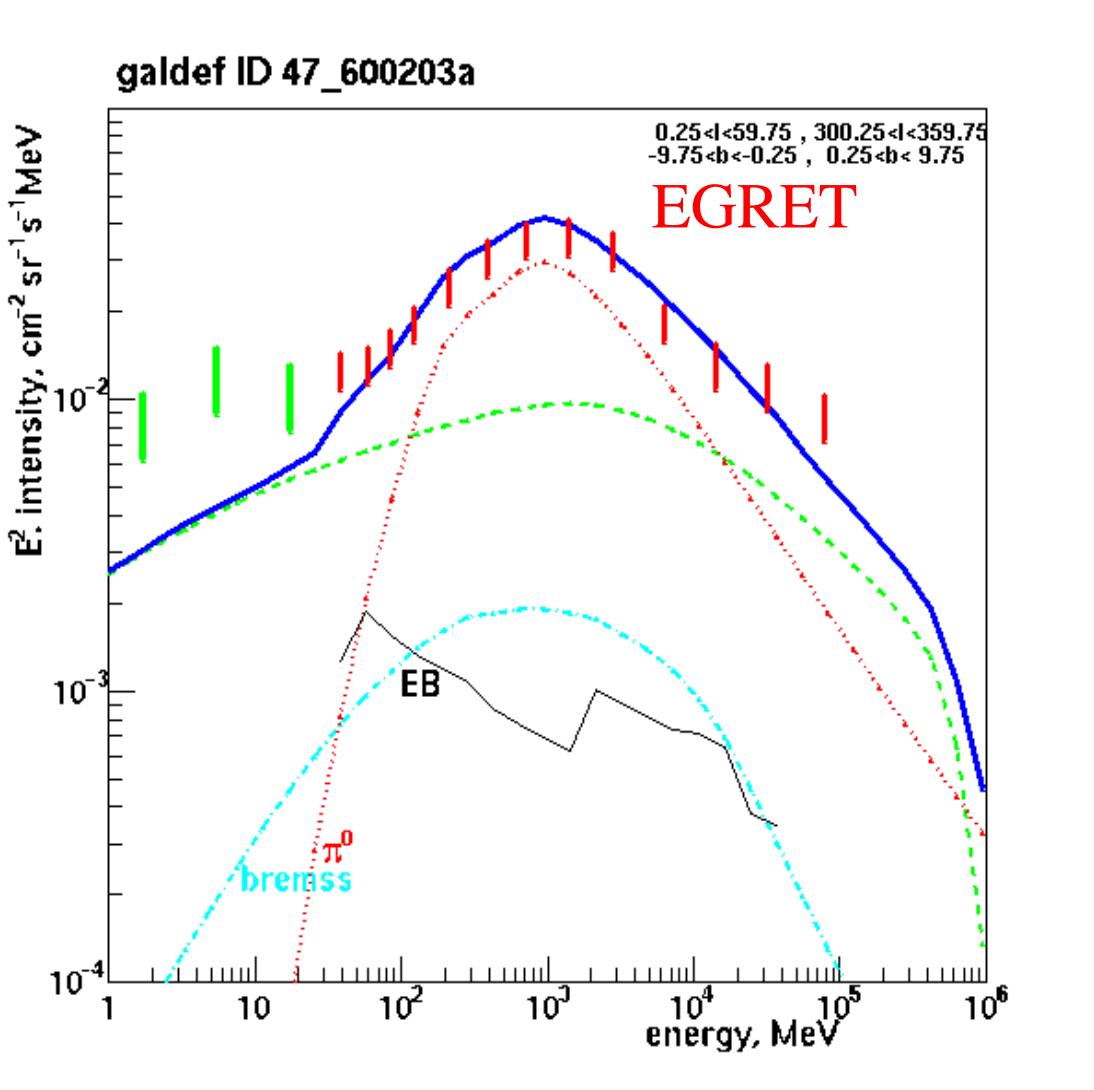
p, e spectra factor 2 - 4 higher than measured

(justification: spatial variations due to stochastic nature of sources)

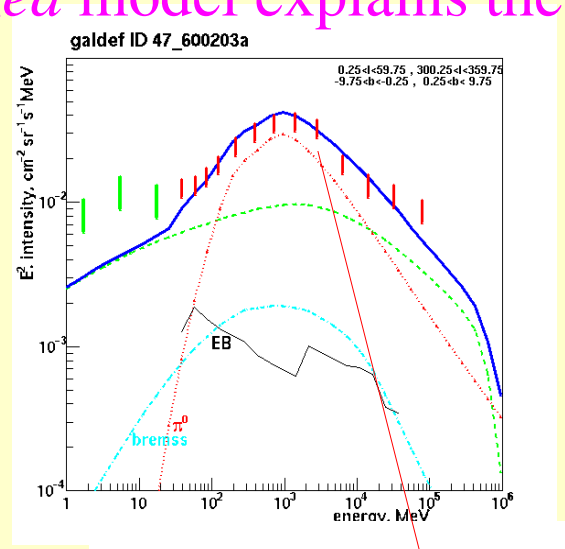


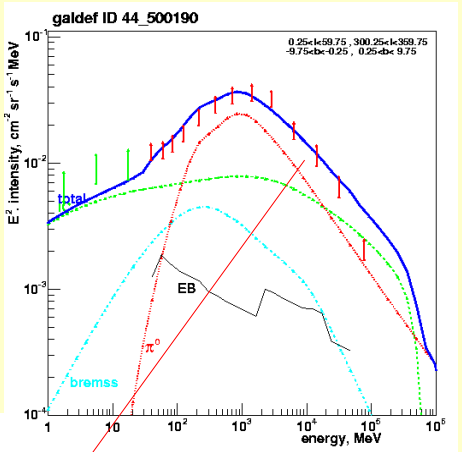


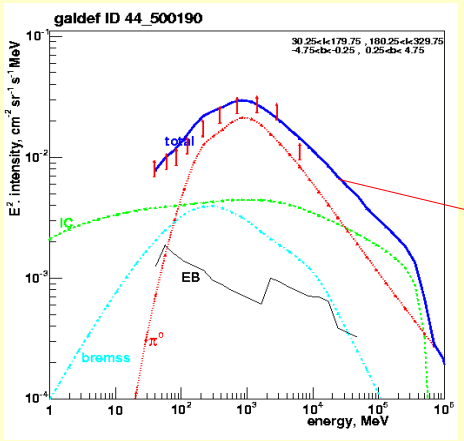
Optimized model: vary proton, electron spectra compatible with expected spatial variations

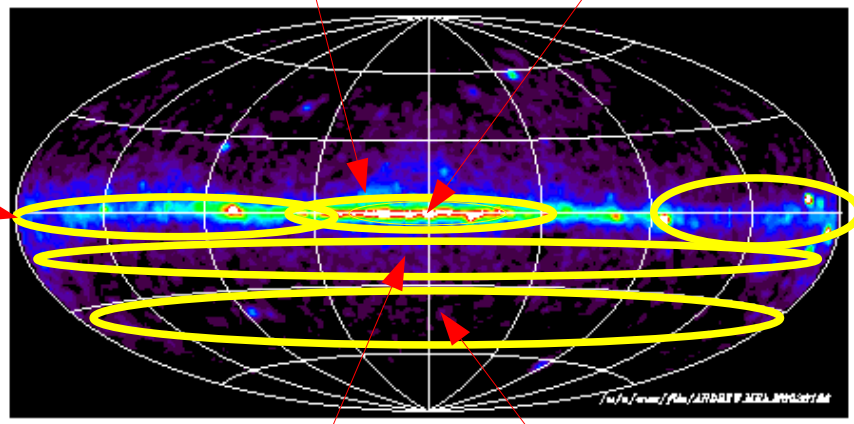


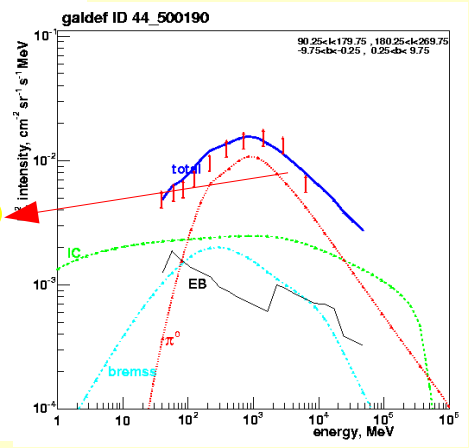
Optimized model explains the GeV γ - ray excess everywhere!

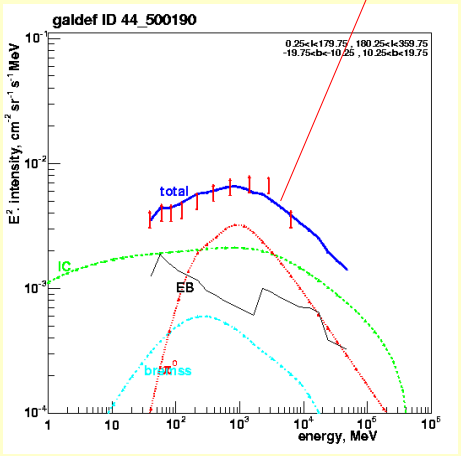


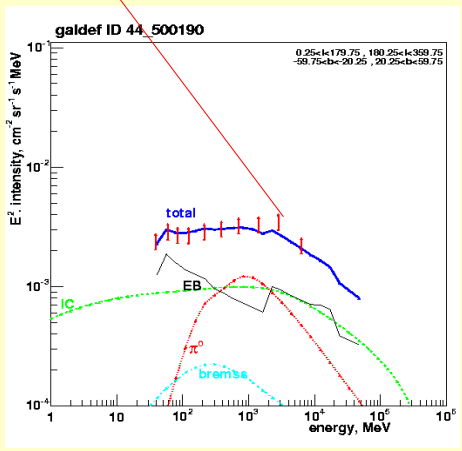












Facit: proposed explanations of GeV excess:

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: GeV peak absent
   and spatial fluctuations not enough to allow locally observed spectrum

4. Moderate changes in nucleon and electron spectra
   Maybe: at least shown it is possible to construct such a model

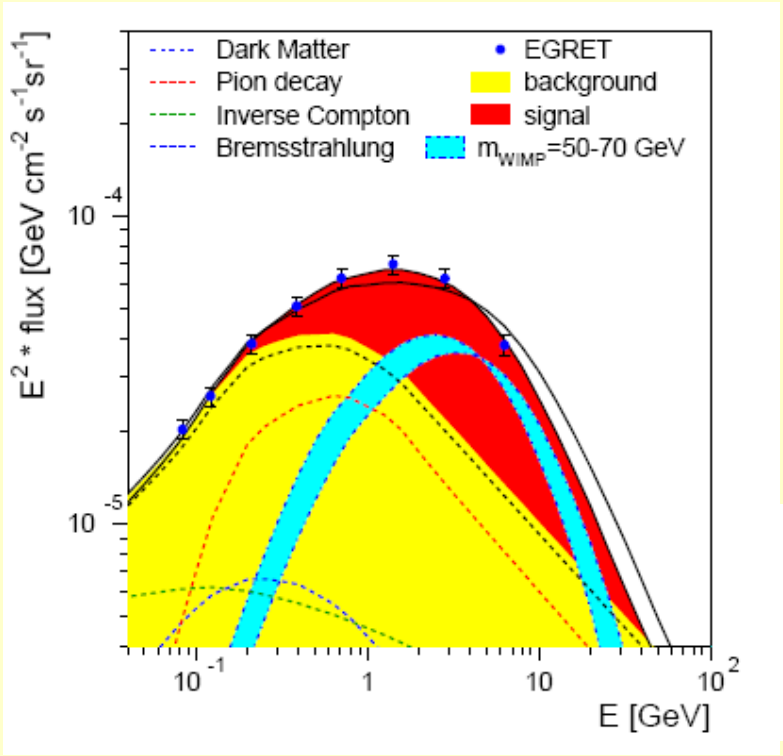
5. Physics of pp -> π^o NO

6. Hard spectrum SOURCES <<<<<<<<<<<<<< likely

7. 'Exotic' : e.g. dark matter
   Maybe, if not #4 or #6

When you have eliminated the impossible
whatever remains, however improbable,
must be the truth.

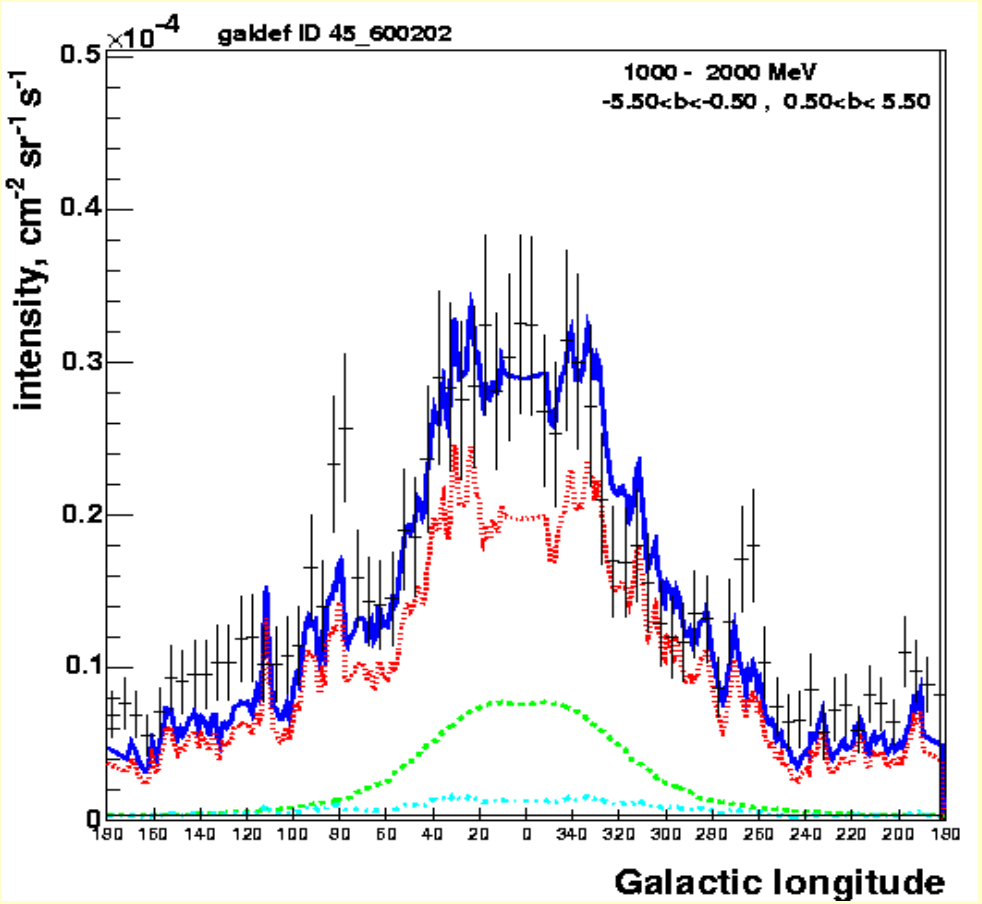
- Sherlock Holmes

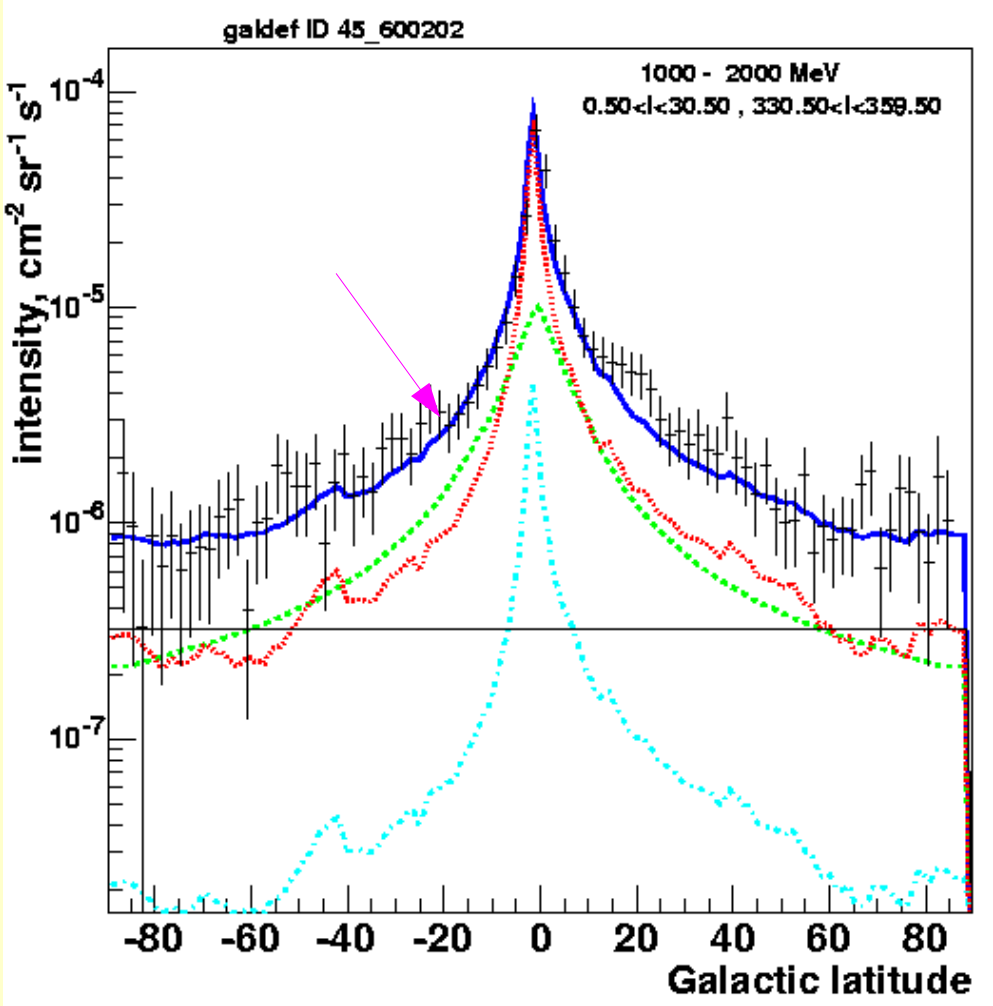


EGRET Excess of Diffuse Galactic Gamma Rays as Tracer of Dark Matter

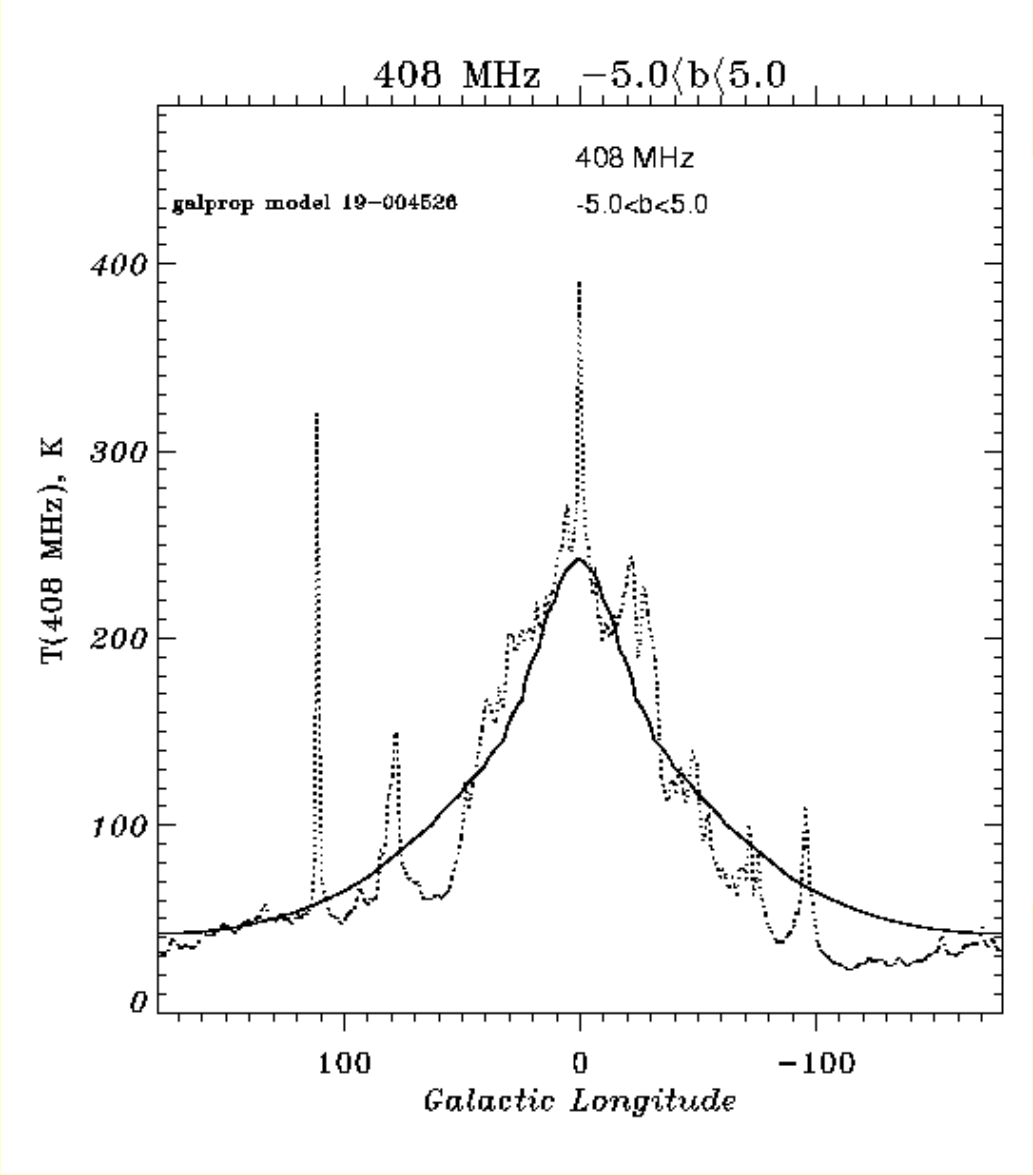
W. de Boer[1], C. Sander[1], V. Zhukov[1], A.V. Gladyshev[2,3], D.I. Kazakov[2,3]

EGRET γ-ray data

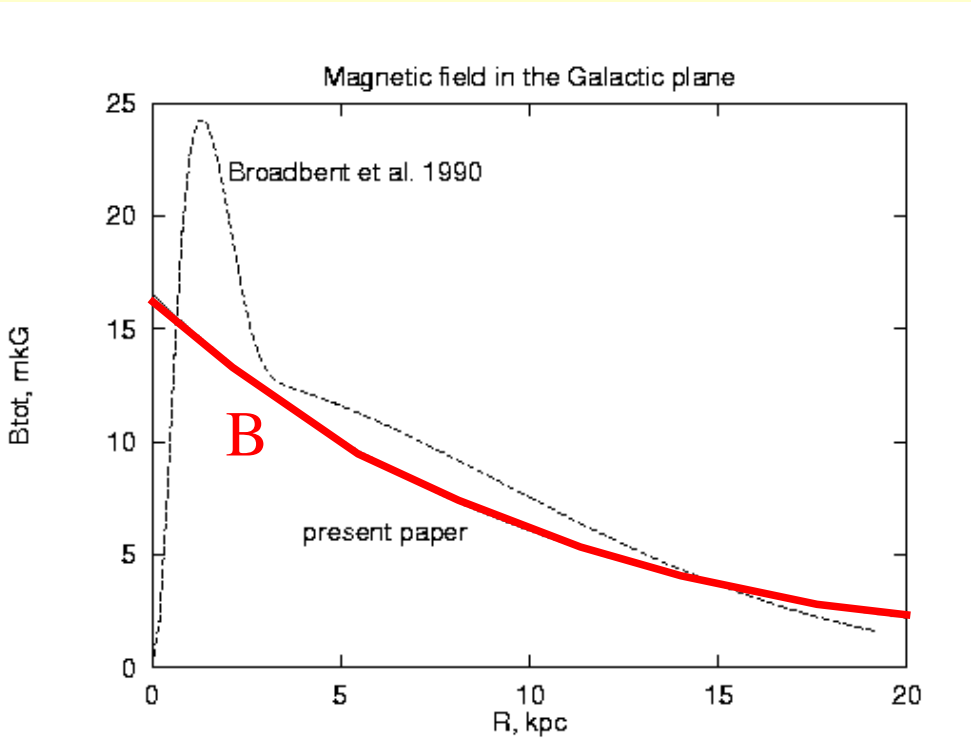




Electrons: Synchrotron and B field



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



B: good agreement with
Zeeman effect, pulsar RM

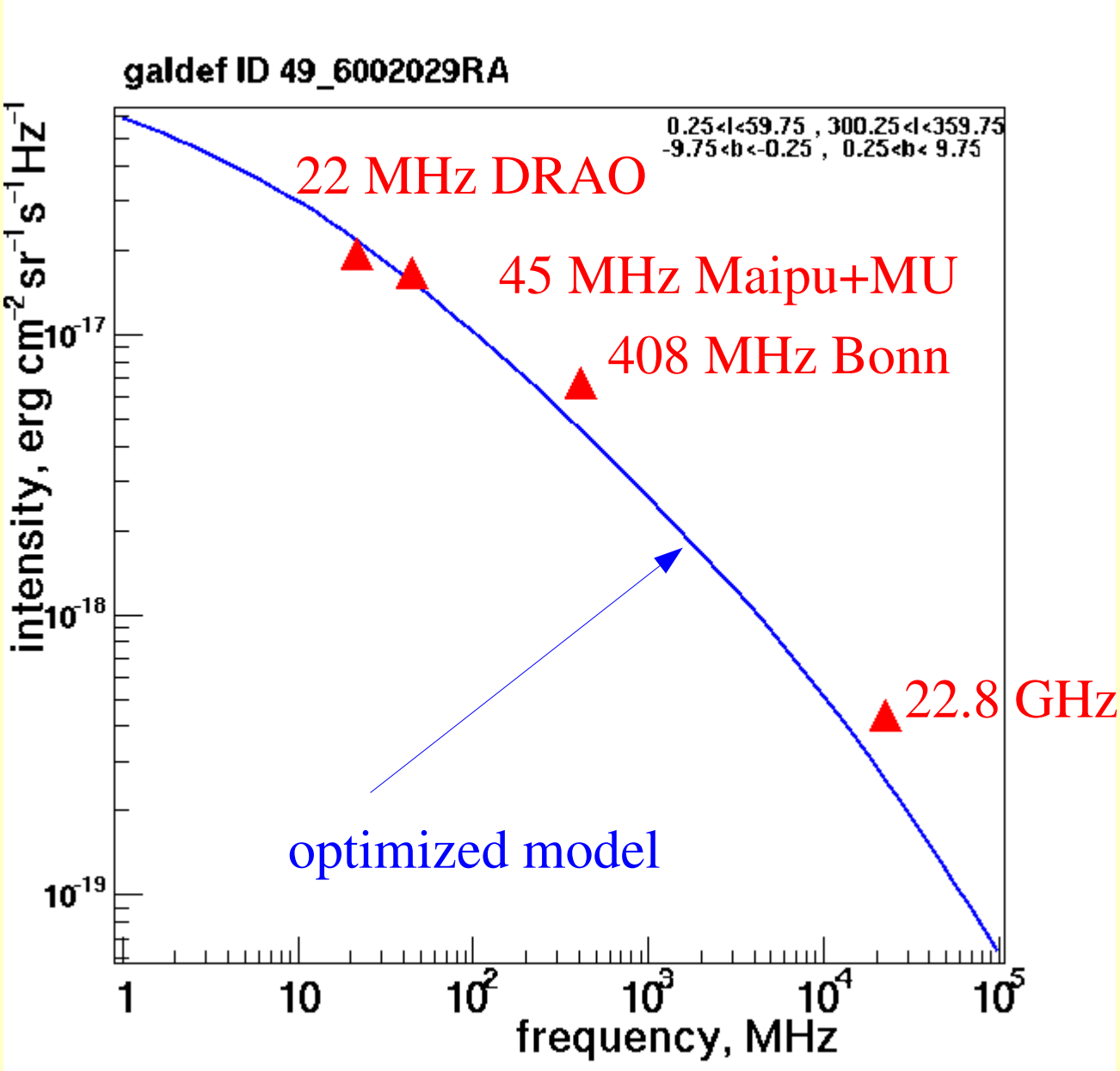
Cosmic-ray electrons from EGRET γ - rays -> B from synchrotron

Strong, Moskalenko & Reimer 2000

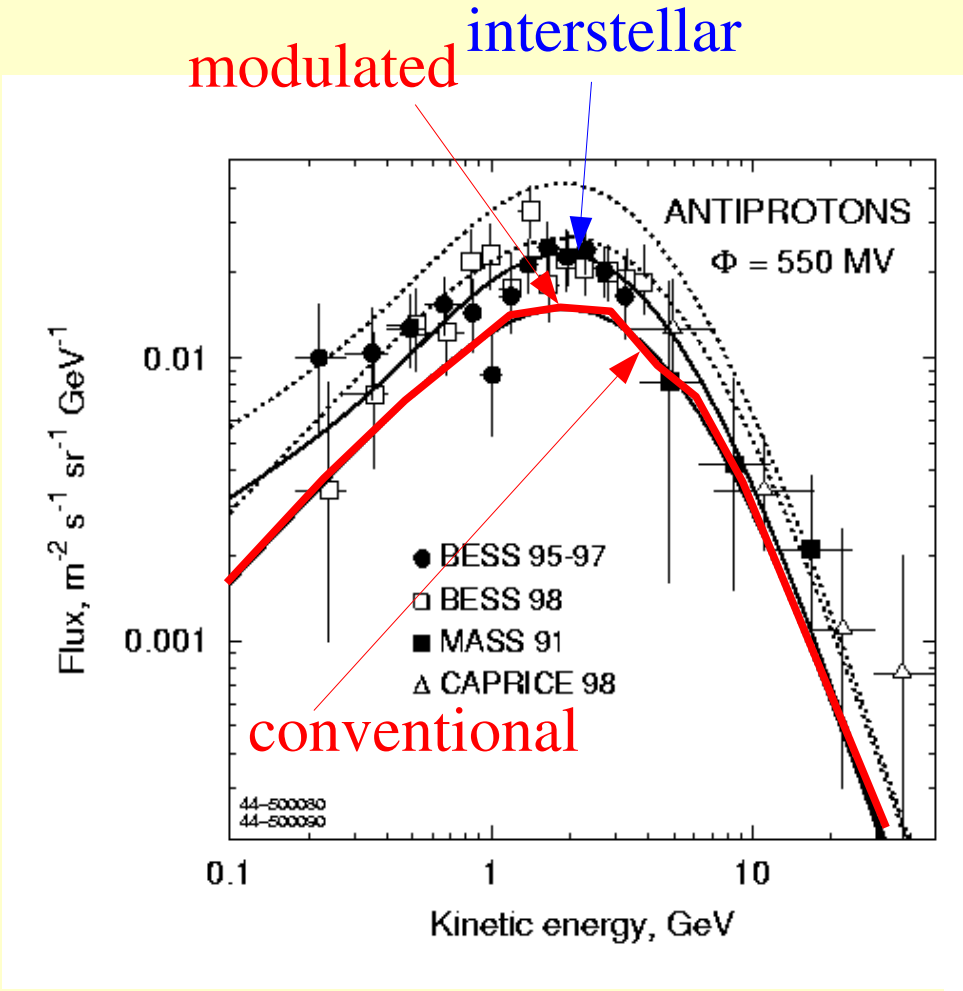
synchrotron spectrum

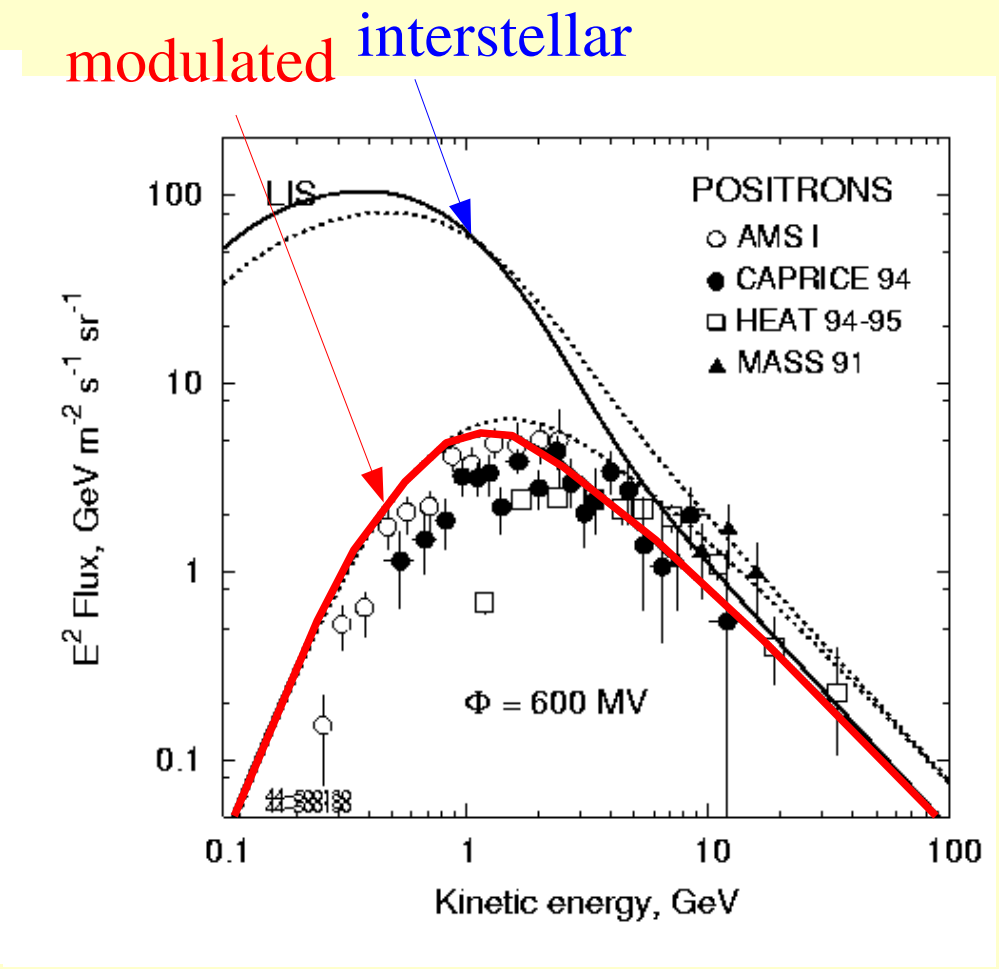
inner Galaxy

from cosmic-ray electrons 1 – 10 GeV

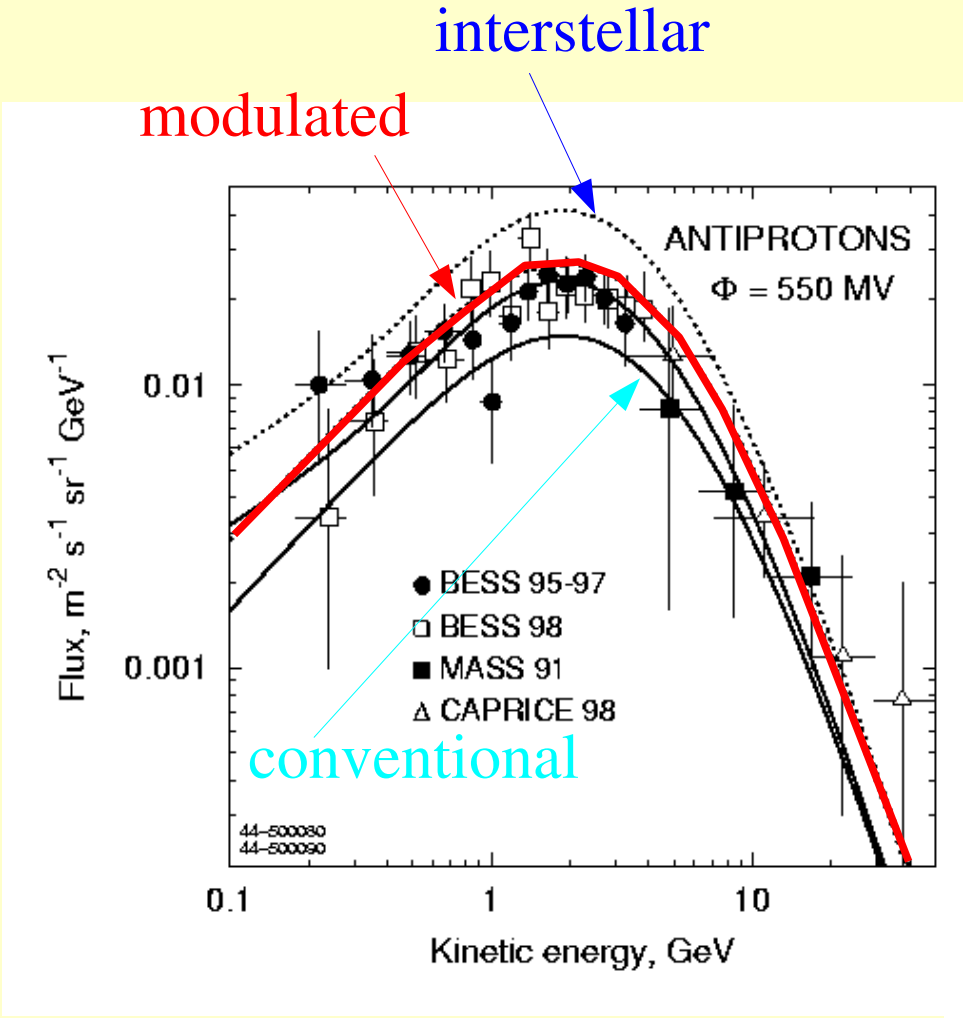


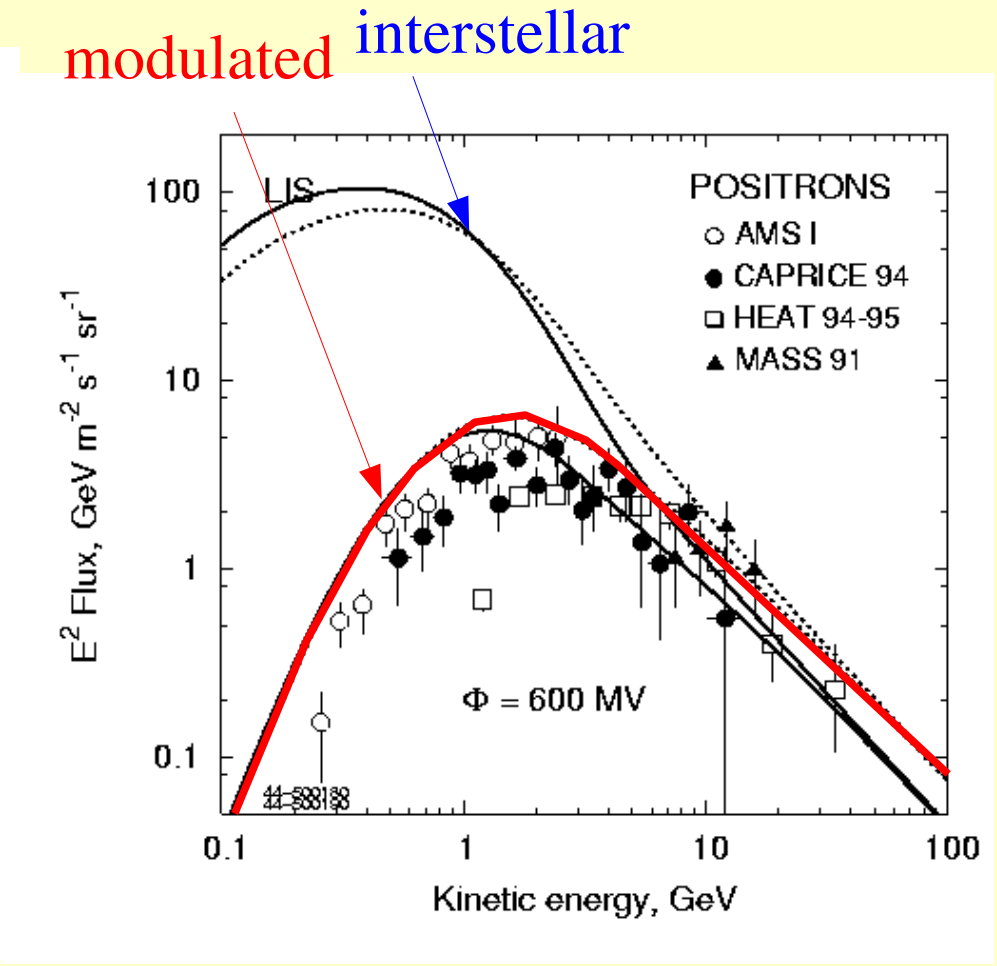
Conventional model underpredicts antiprotons





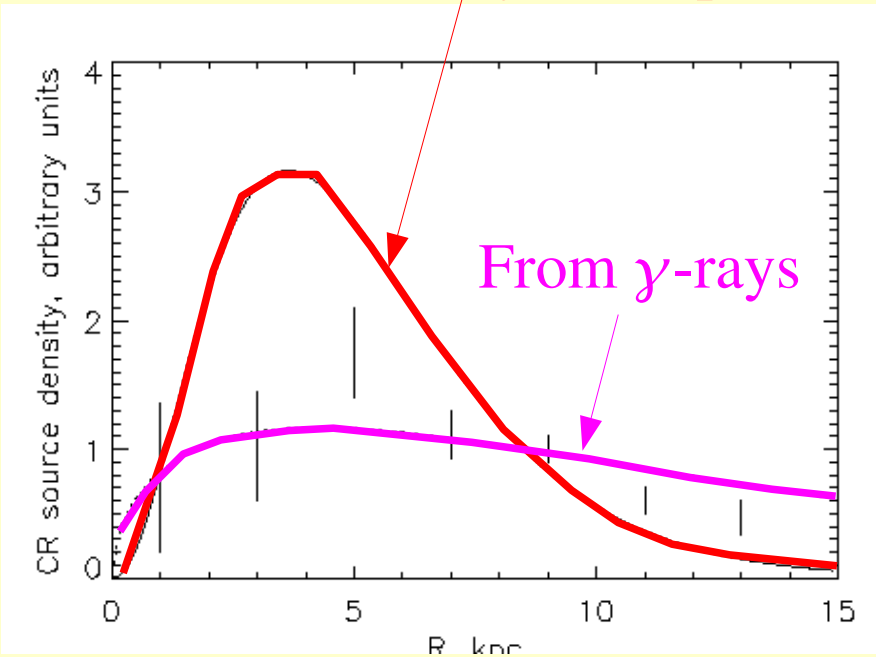
Optimized model for γ - rays also improves antiproton, positron predictions





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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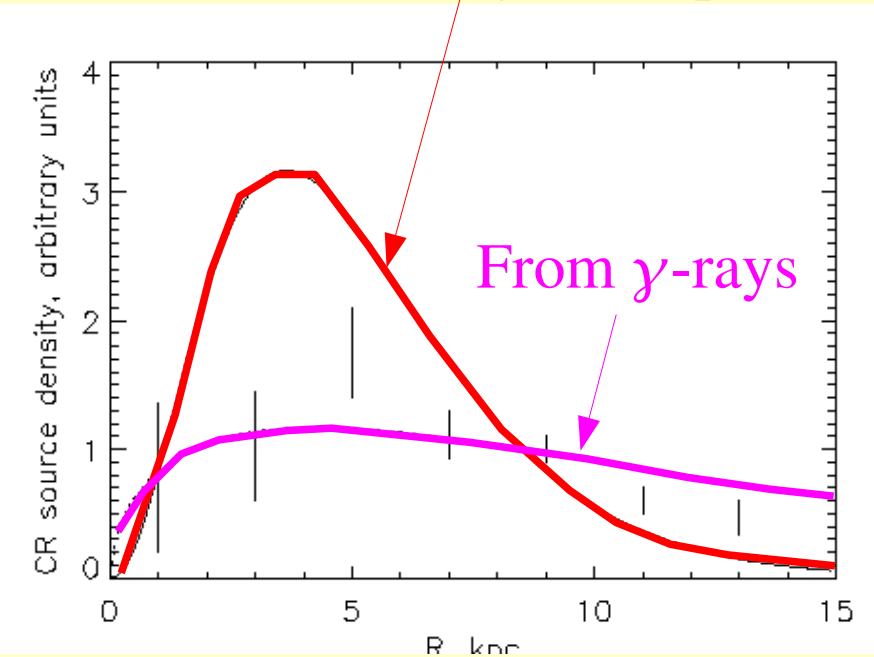

Clue: Galactic metallicity gradient e.g. [O/H]

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

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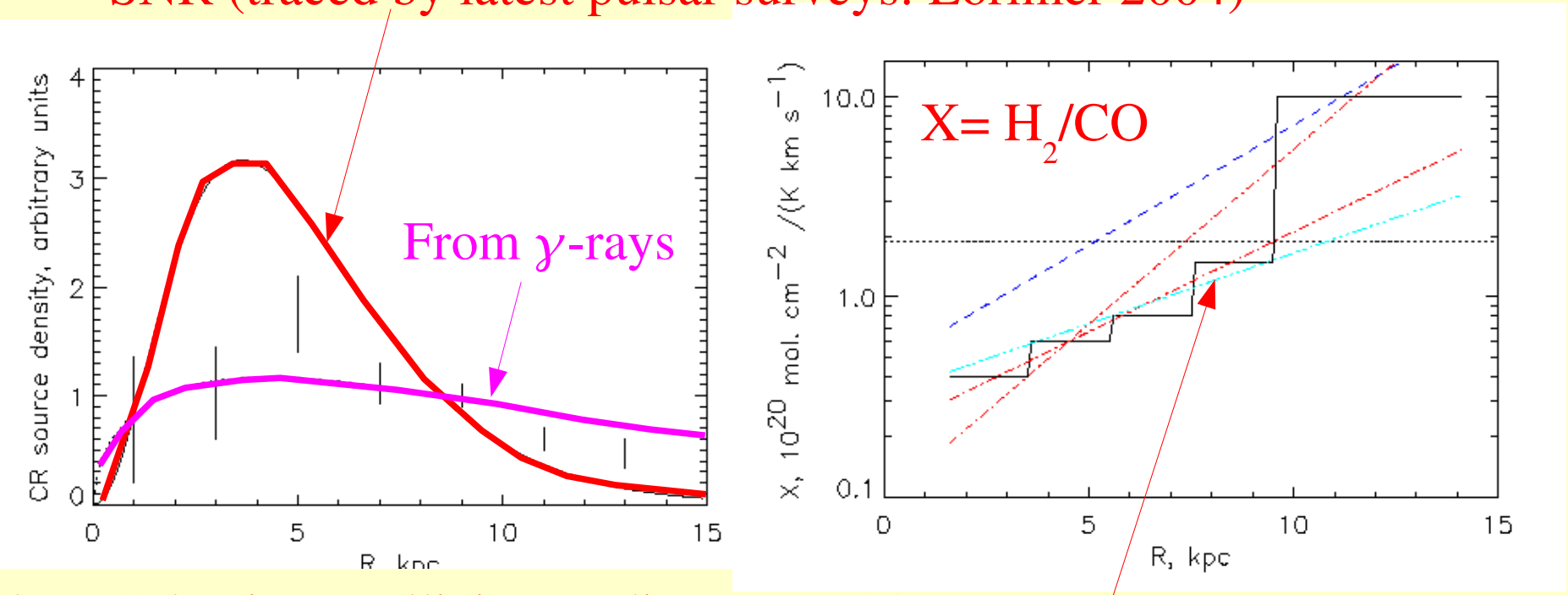


Clue: Galactic metallicity gradient e.g. [O/H]

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

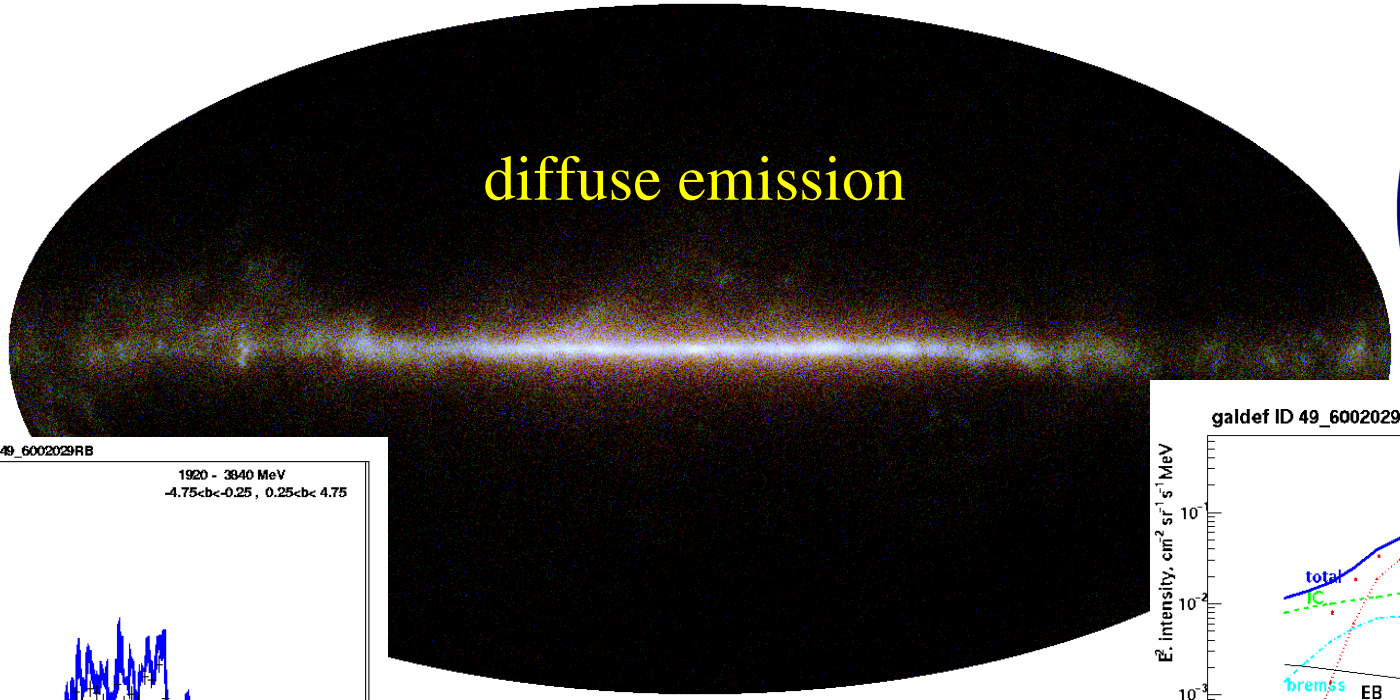
>>>>>>> ***X = H_2 / CO increases with radius***

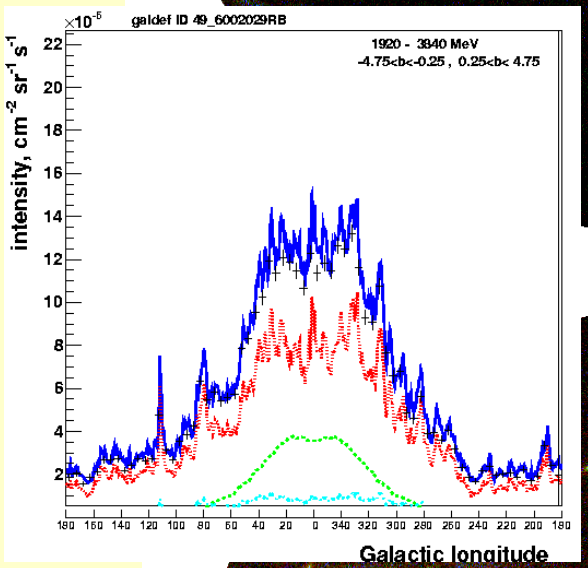
γ-rays = sources(R) * X(R) *CO(R) (+ HI, inverse Compton terms)

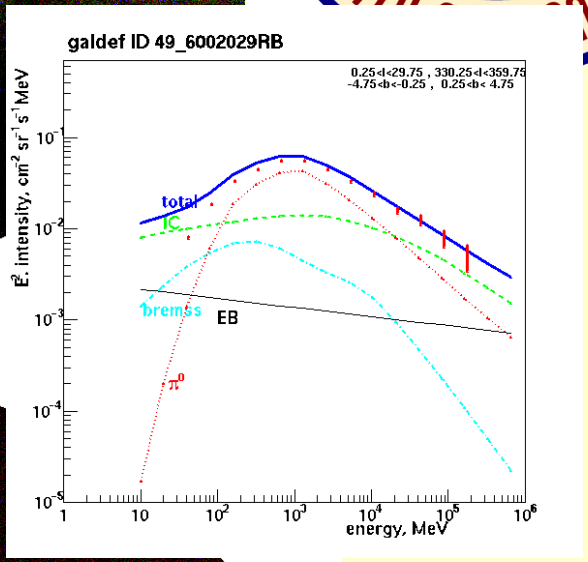
Steeper sources * flatter X = observed gamma-rays

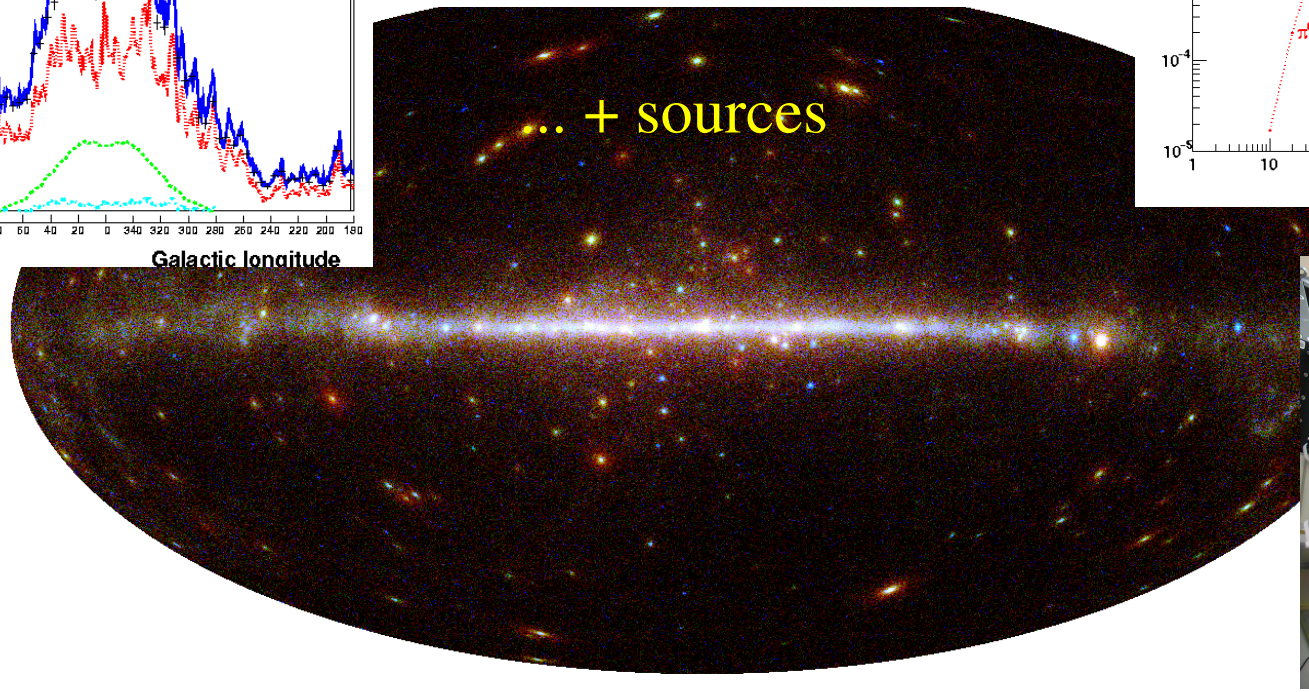
Strong et al. 2004 *A&A 422,L47*

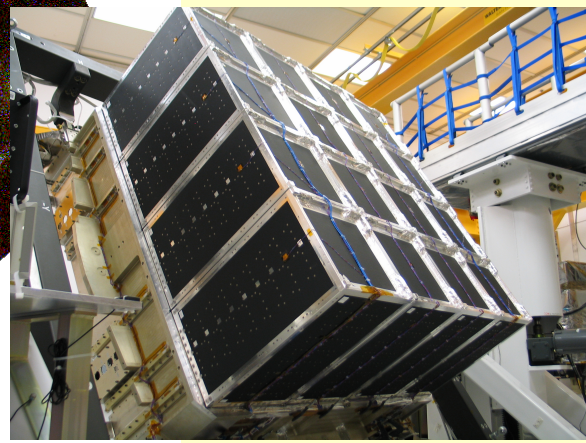
Simulation for GLAST (Data Challenge 2) using *galprop*











END