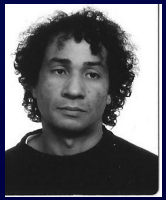
Interstellar radiation over 20 decades of energy

Andy Strong
MPE Garching

with







+ Petra Hüntemeyer,

Igor Moskalenko

Troy Porter

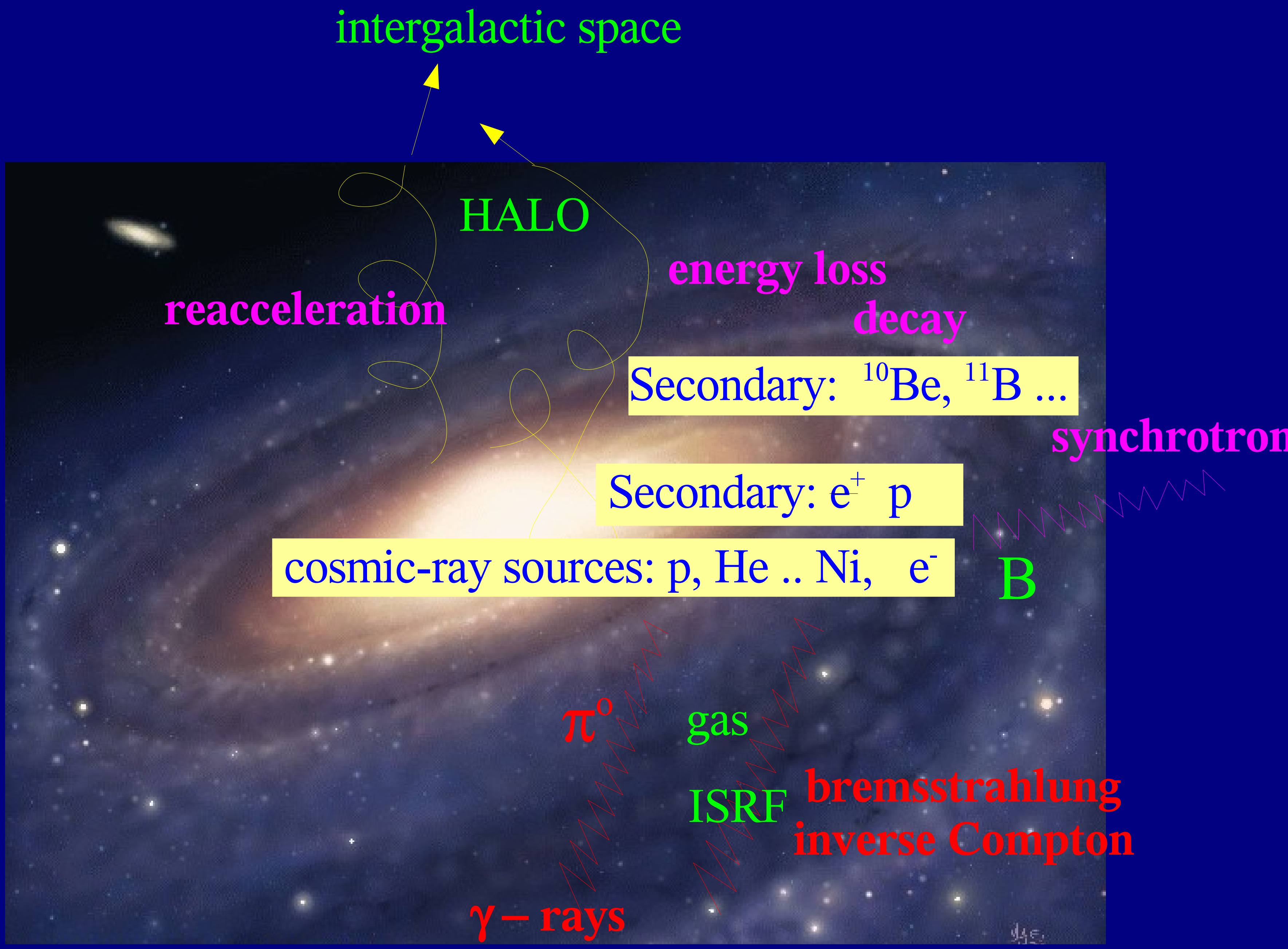
Seth Digel

Elena Orlando

Laurent Bouchet

Brenda Dingus

viewpoint : cosmic-ray production & propagation in the Galaxy

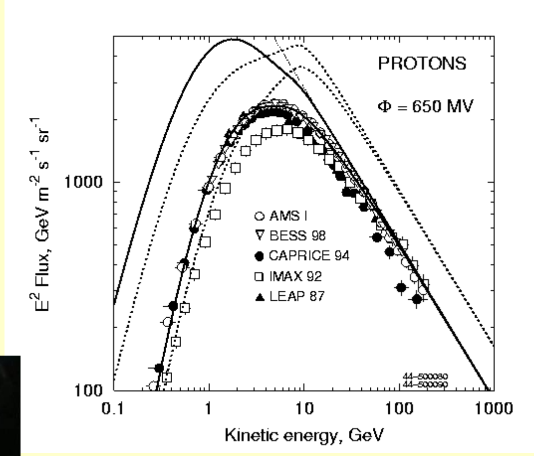


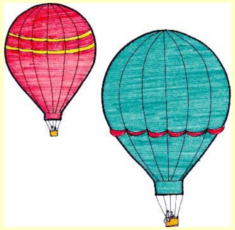
intergalactic space
HALO
reacceleration
energy loss
decay
Secondary: ^{10}Be, ^{11}B ...
synchrotron
Secondary: e^{+} p
cosmic-ray sources: p, He .. Ni, e^{-}
B
π^{o}
gas
ISRF
bremsstrahlung
inverse Compton
γ – rays

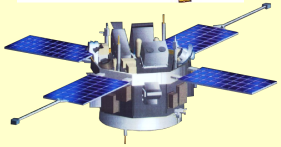
The **goal** : use *all* types of data in self-consistent way to test models of cosmic-ray propagation.

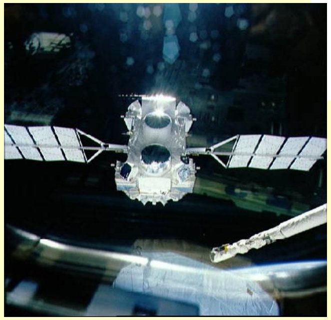
Observed *directly, near Sun:*

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



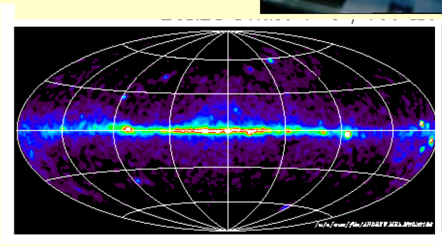


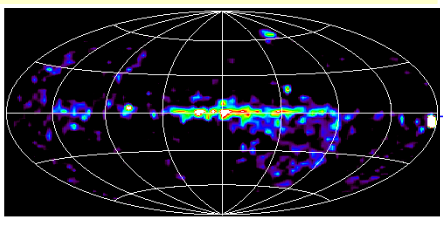


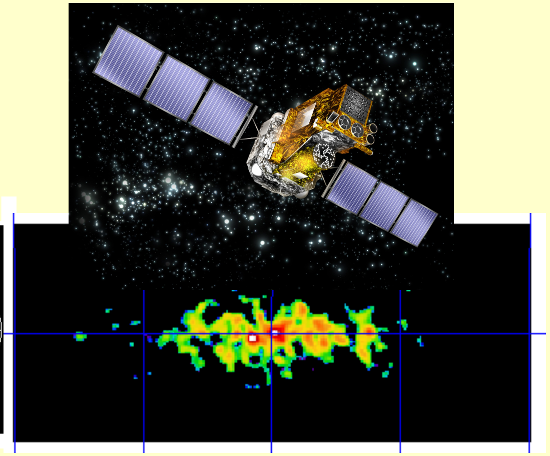


Observed *from whole Galaxy:*

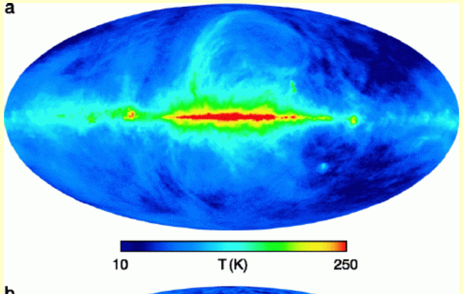
γ - rays







synchrotron



The Basis: 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

Model for cosmic-ray propagation

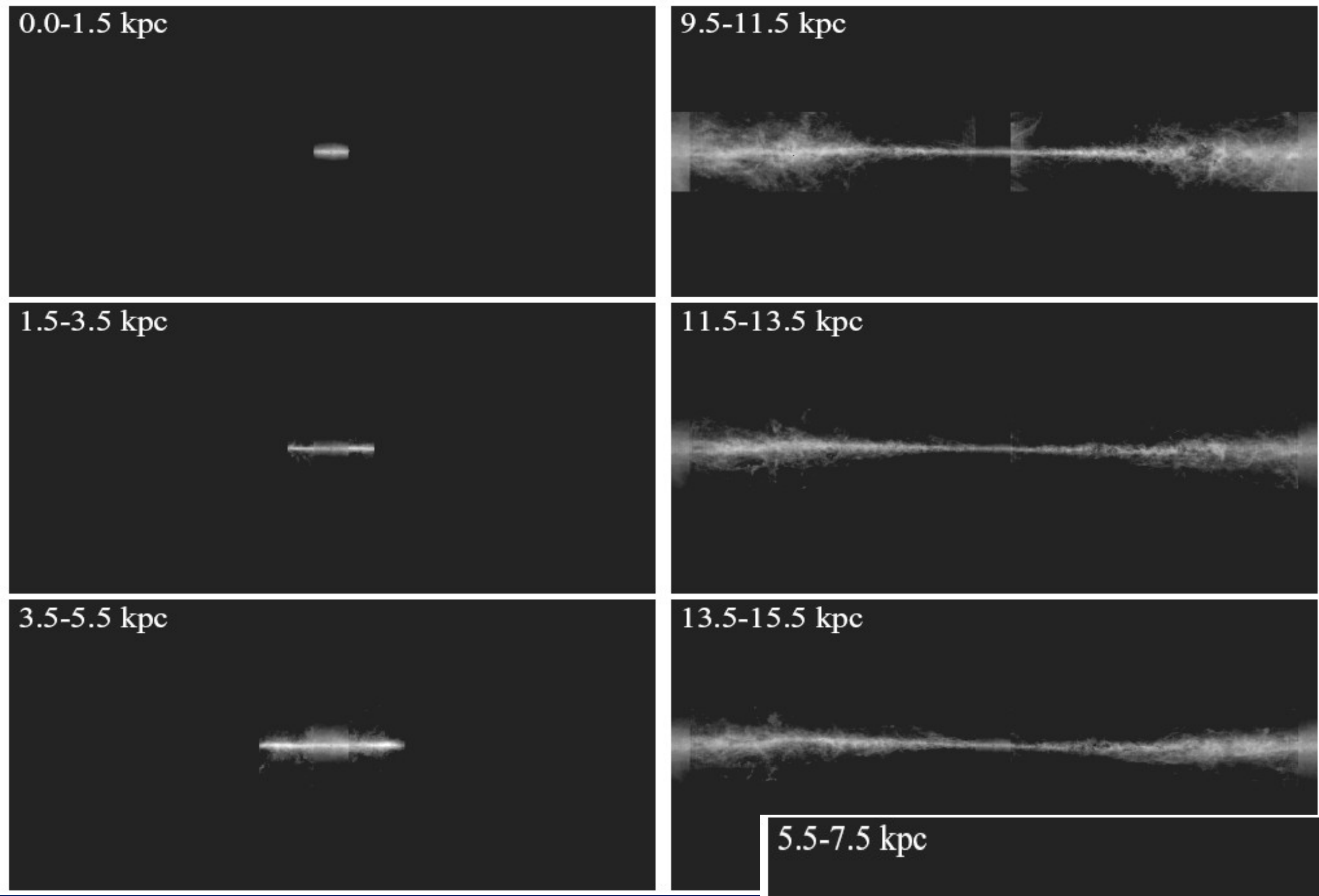
3D gas model based on 21-cm (atomic H), CO (tracer of H_2) surveys
cosmic-ray sources $f\,(\underline{r}, E)$
interstellar radiation field $f\,(\underline{r}, \nu)$
nuclear cross-sections database
energy-loss processes
B-field model
γ – ray, synchrotron

GALPROP code: publicly available
with dedicated Website galprop.stanford.edu

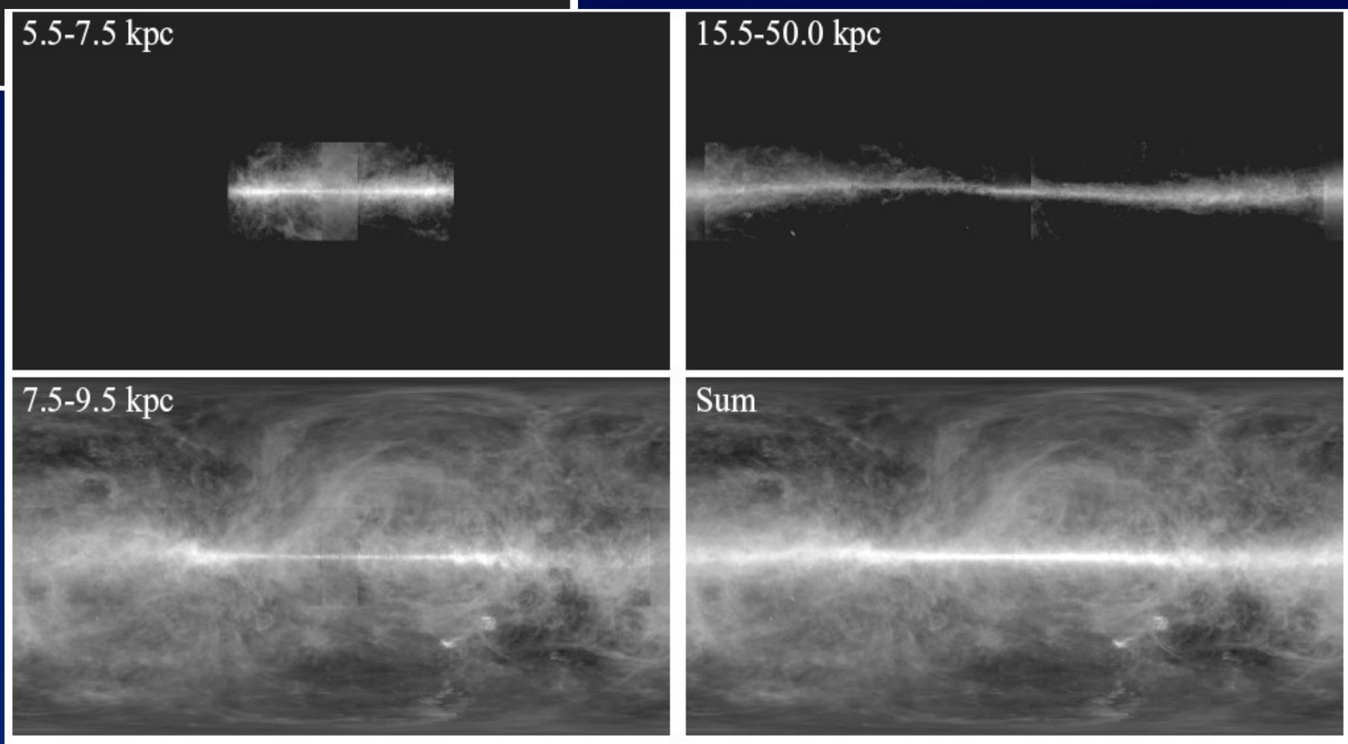
Reference Model for GLAST

Gas Rings: HI
Inner &
Outer Galaxy

Seth Digel'05



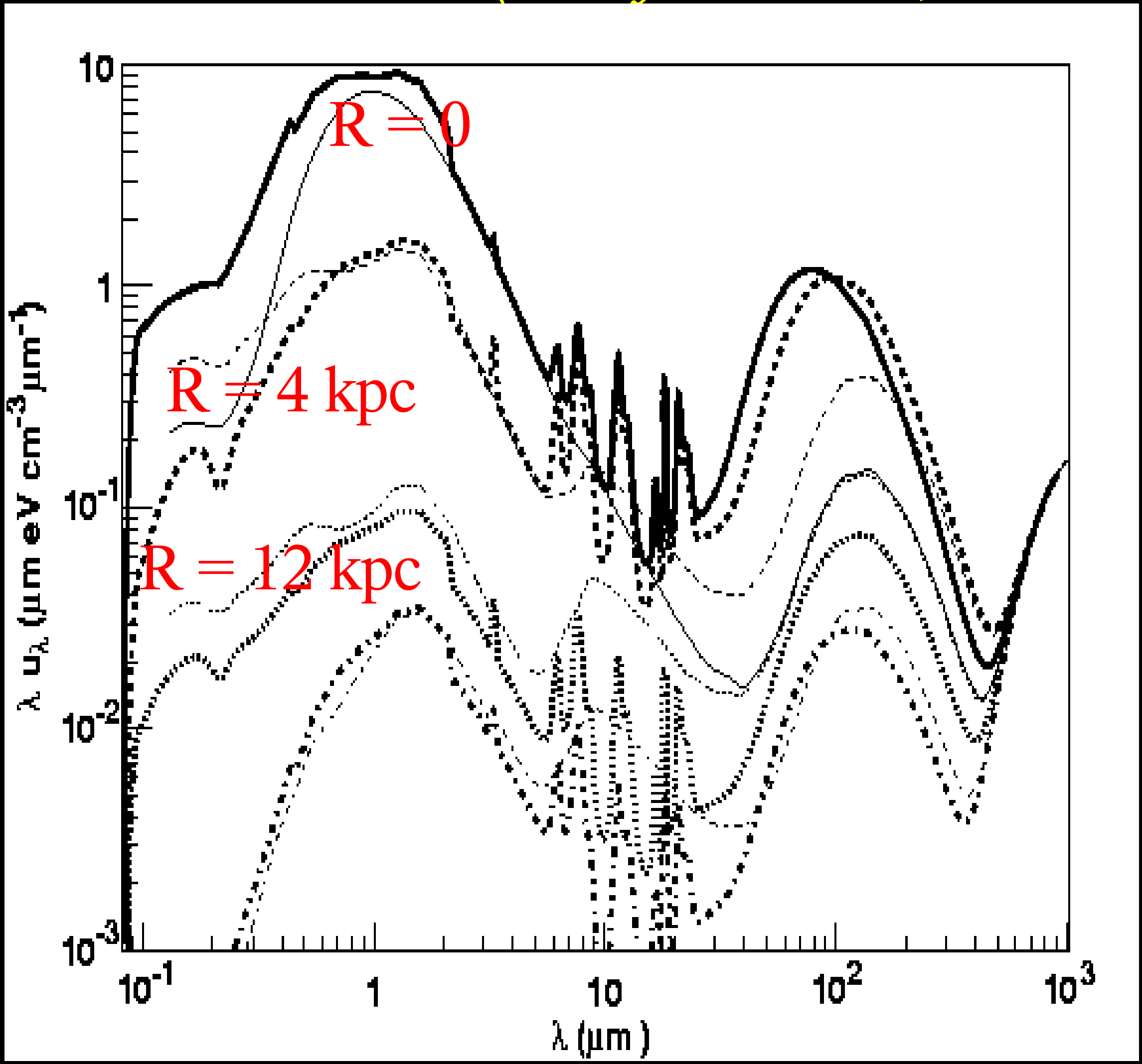
Gas Rings: HI
HI Local Galaxy



Interstellar Radiation Field
(for electron dE/dt, inverse Compton γ-rays):
new model *(Troy Porter, UCSC)*

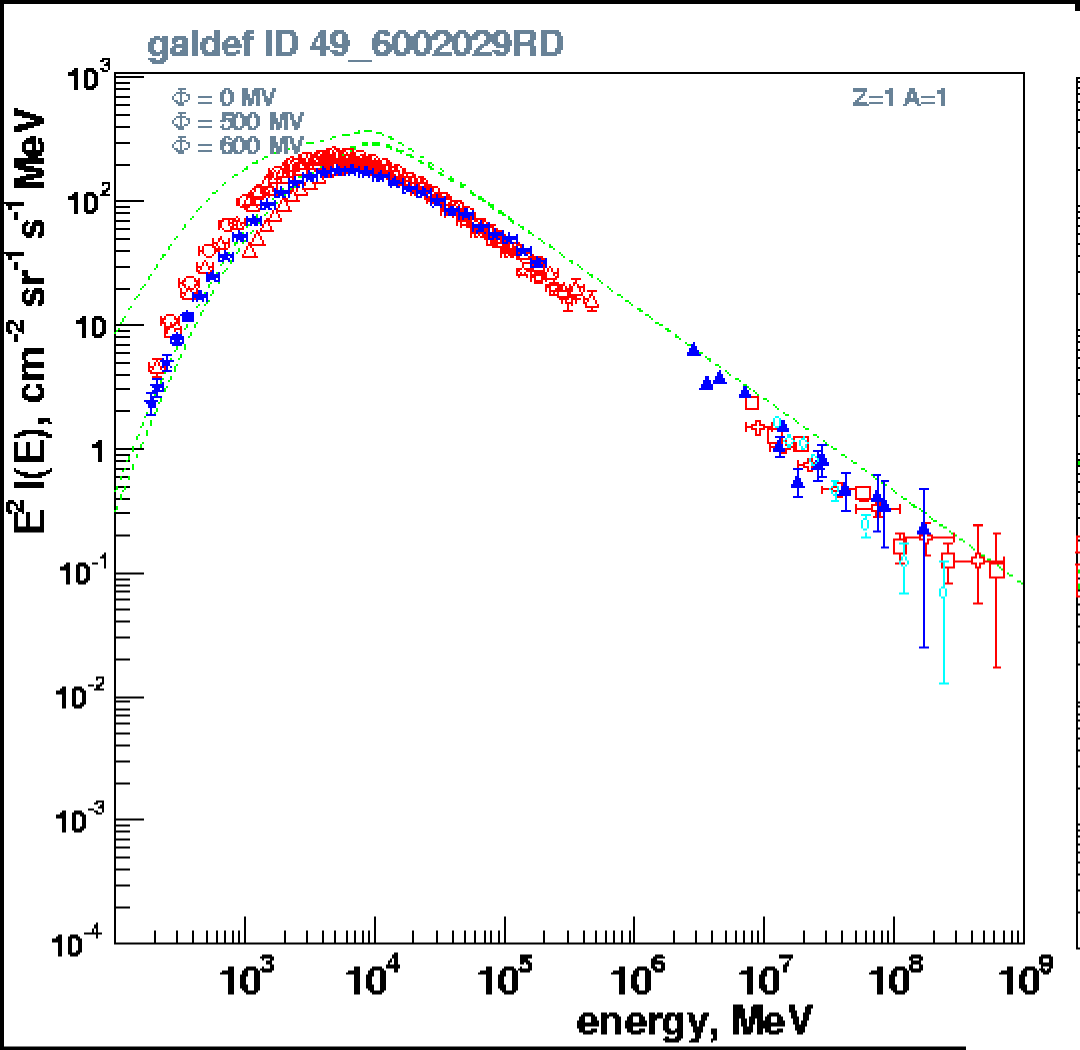
***New** ISRF*
using latest information

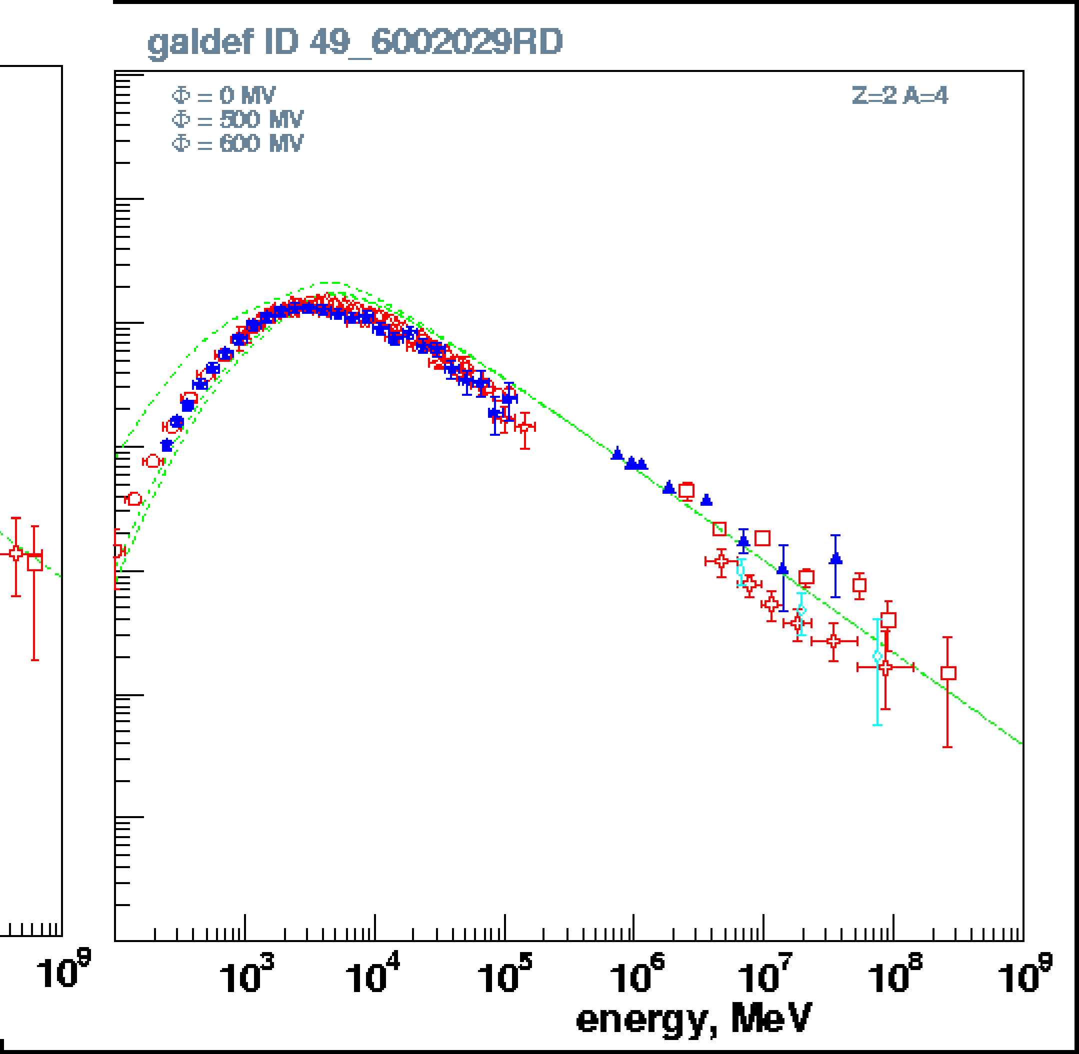
stellar populations,
dust
radiative transfer



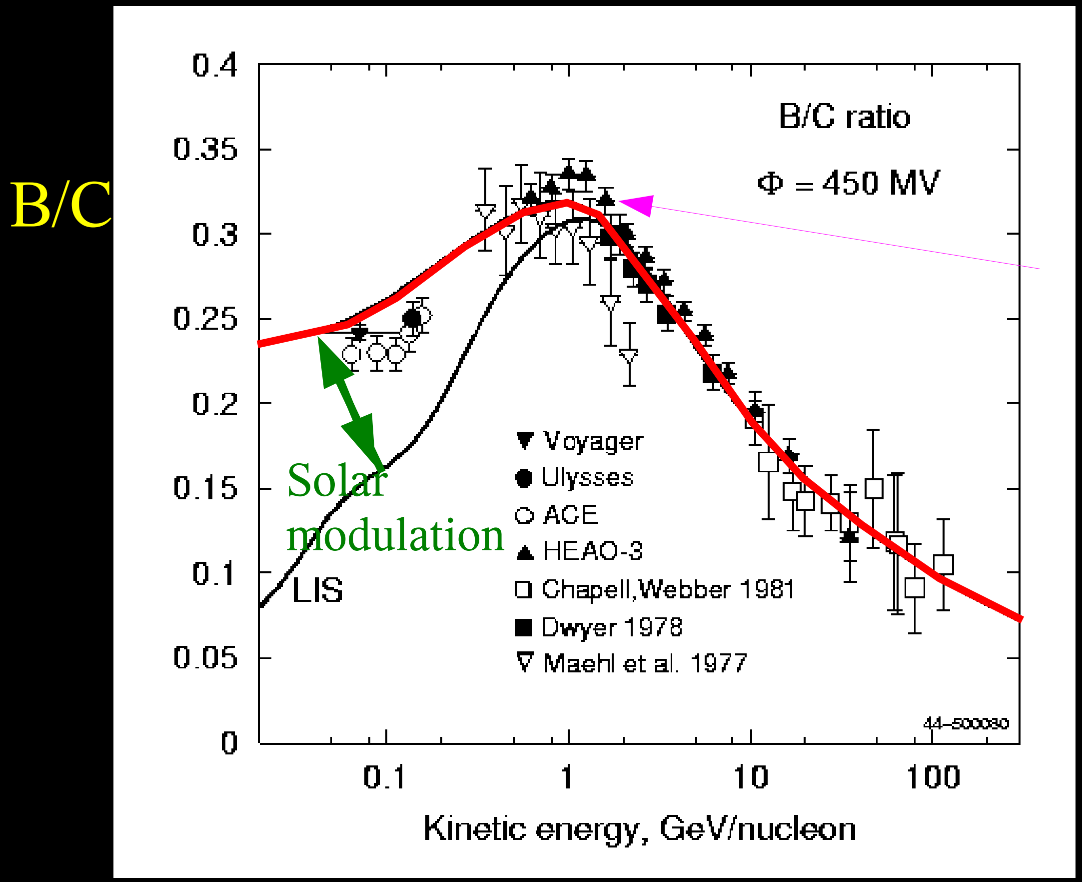
UV optical IR FIR CMB

Key data : primary cosmic-ray nuclei spectra



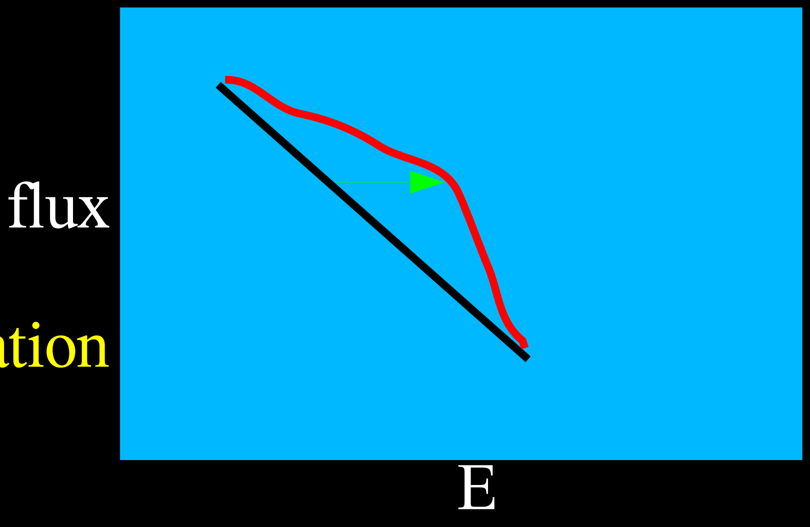


Key data cosmic-ray secondary/primary ratios: e.g. Boron/Carbon probes cosmic-ray propagation parameters

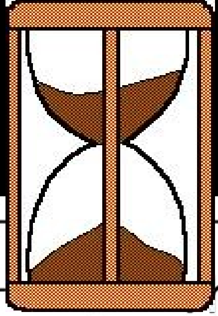


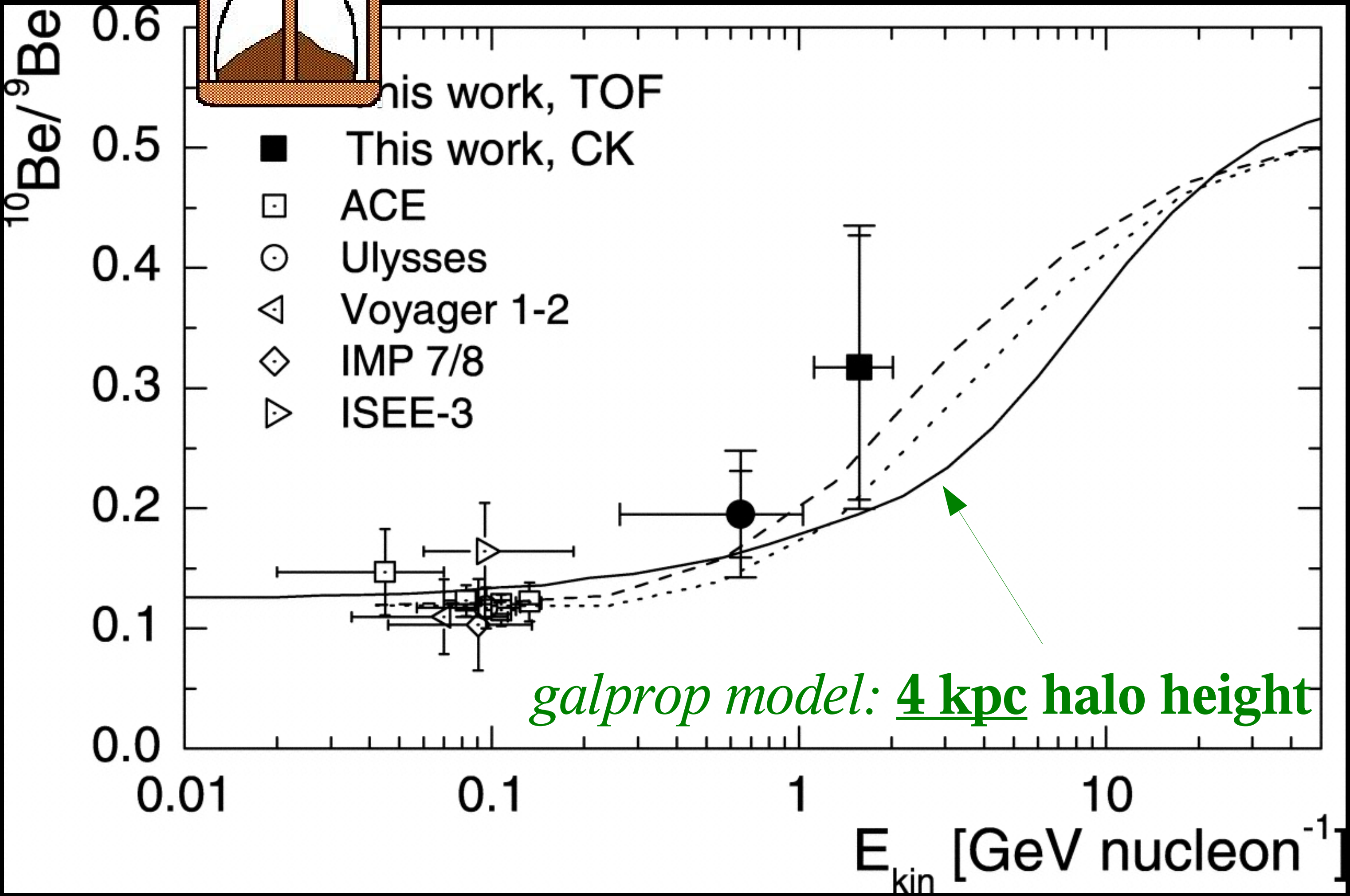
Peak in B/C can be explained by **diffusive reacceleration** with Kolmogorov $D \sim \beta\, p^{1/3}$

Energy-dependent diffusive reacceleration produces <u>bump</u> in particle spectrum



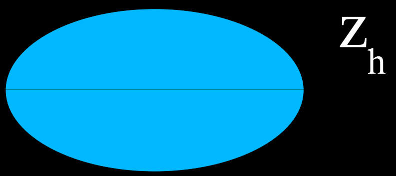
Key data III: Radioactive nuclei: cosmic-ray clocks set limits on size of Galactic halo





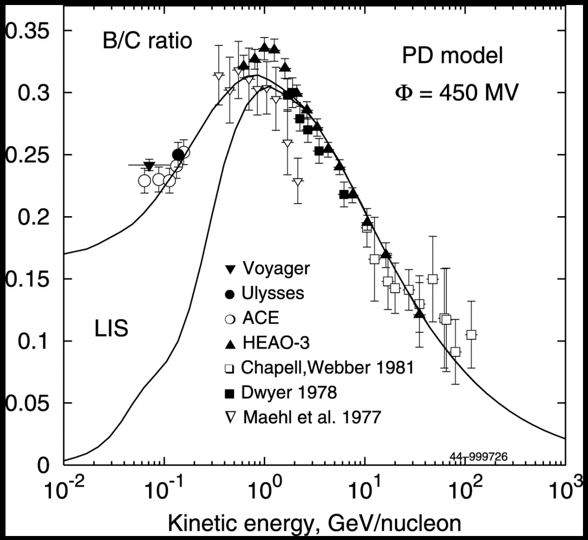
recent data:
ACE, ISOMAX

^{10}**Be** *decays* in 10^6 years, ^{9}**Be** is *stable*
so ratio sensitive to cosmic-ray confinement time, halo size

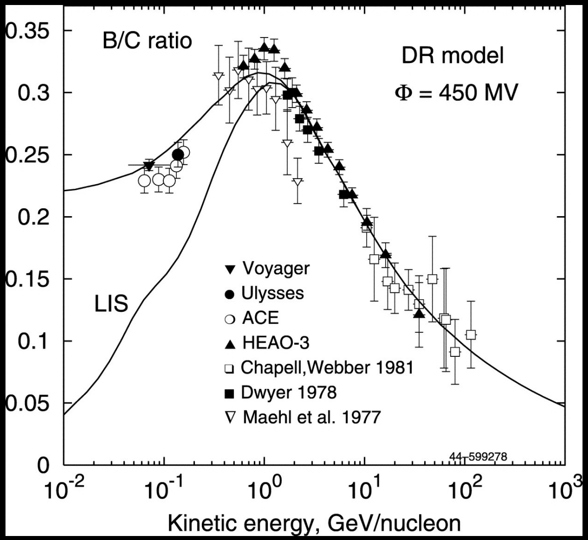


Hams et al. 2004 ApJ 611, 892

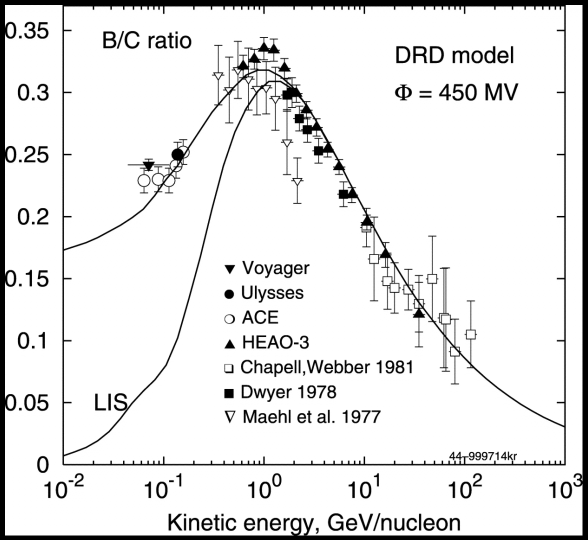
plain diffusion



diffusive reacceleration



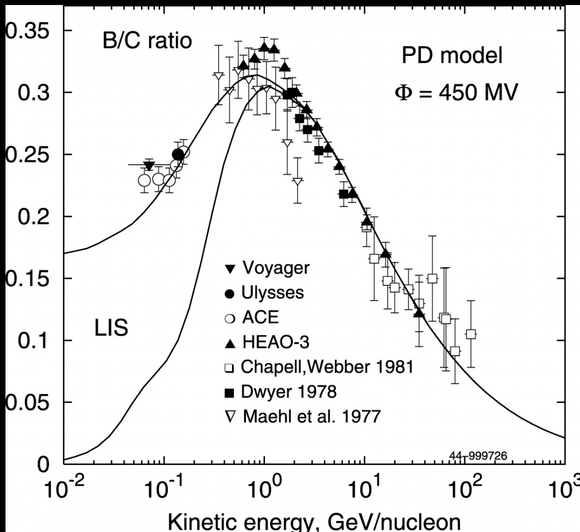
wave damping

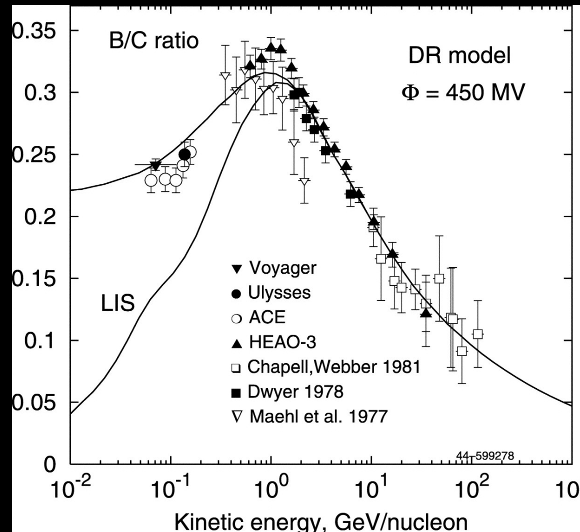


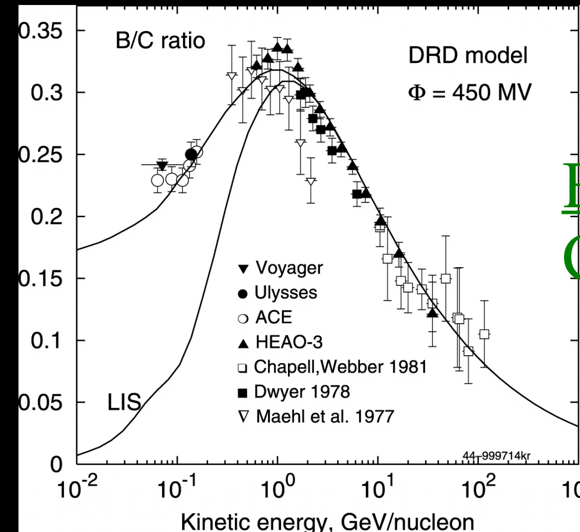
For any model, first adjust parameters to fit Boron/Carbon

Ptuskin et al. 2006 ApJ 642, 902

plain diffusion diffusive reacceleration wave damping



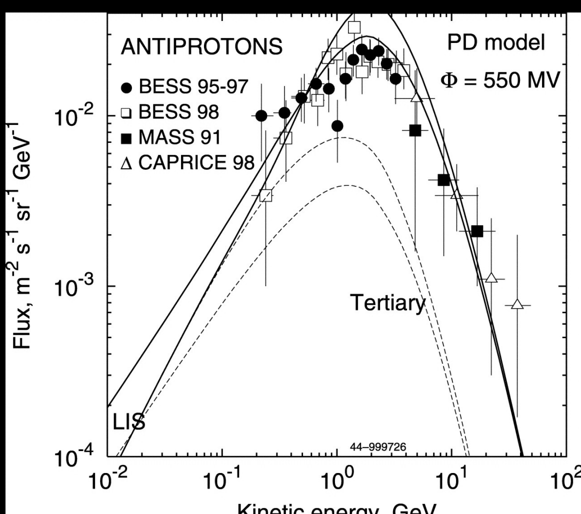


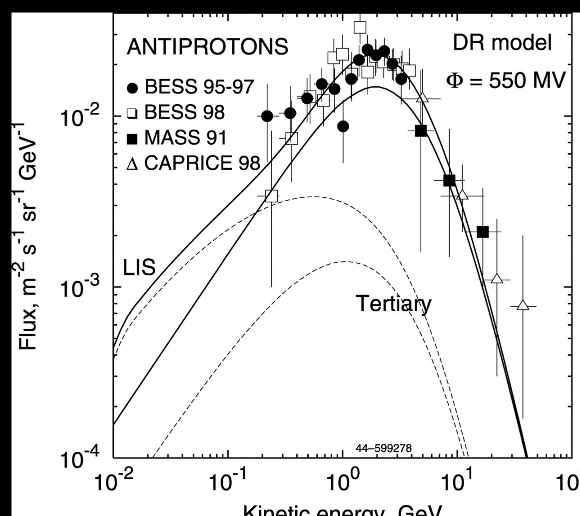


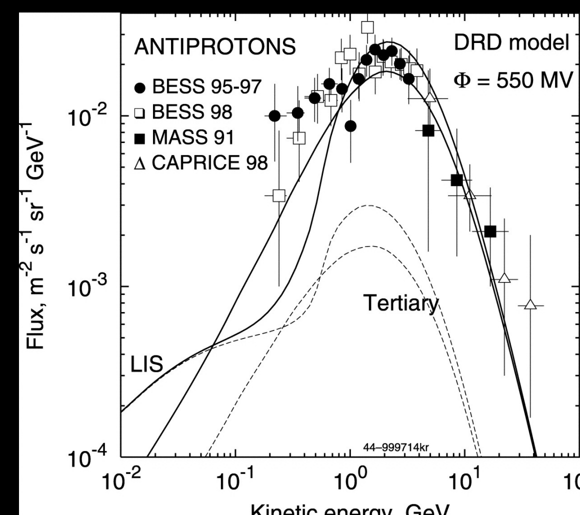
Boron/ Carbon

then predict the other cosmic-ray spectra

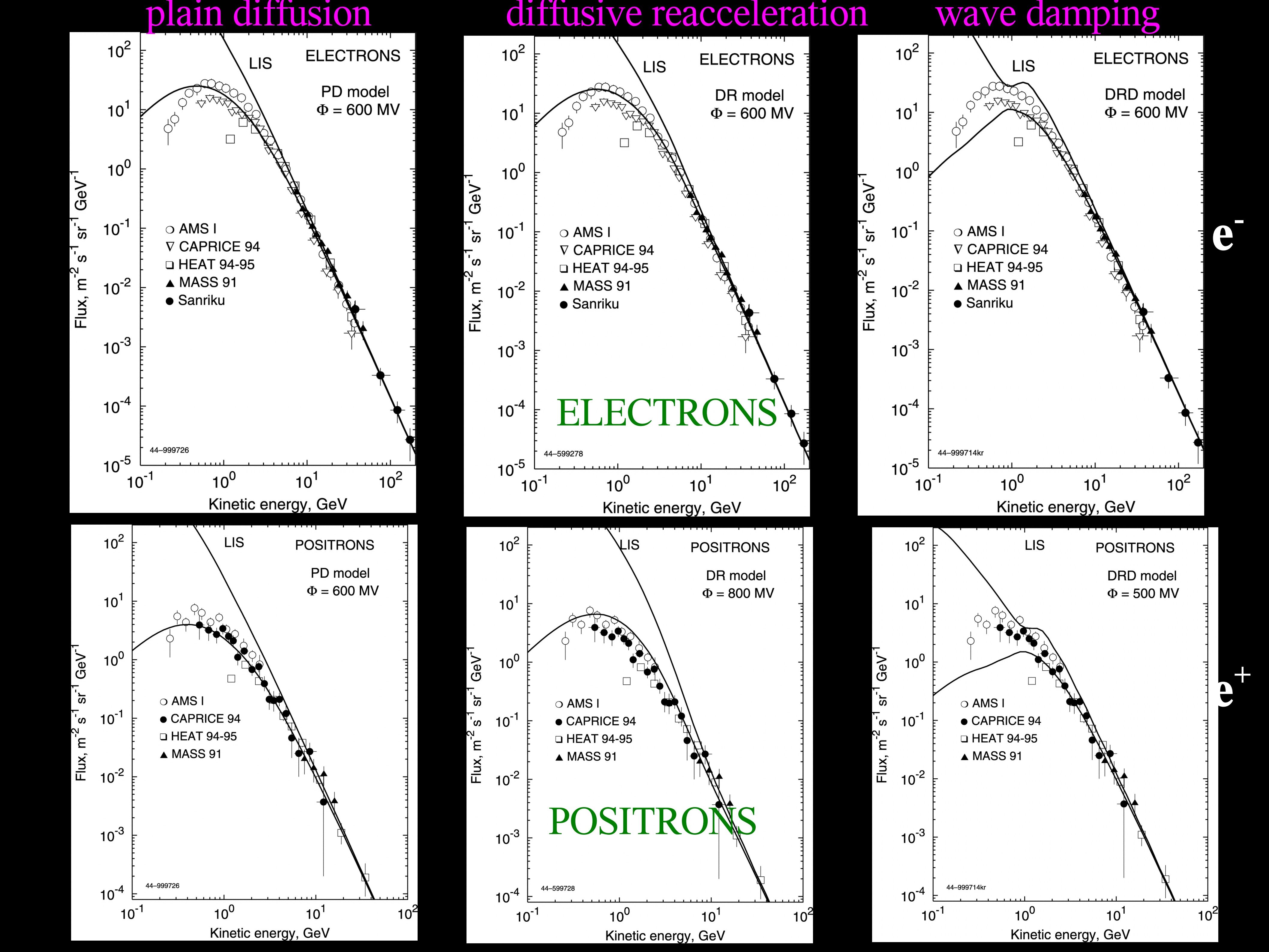
antiprotons







Ptuskin et al. 2006 ApJ 642, 902


plain diffusion
diffusive reacceleration
wave damping
LIS
ELECTRONS
PD model
Φ = 600 MV
DR model
Φ = 600 MV
DRD model
Φ = 600 MV
AMS I
CAPRICE 94
HEAT 94-95
MASS 91
Sanriku
Flux, m^-2 s^-1 sr^-1 GeV^-1
Kinetic energy, GeV
44–999726
44–599278
44–999714kr
ELECTRONS
e-
POSITRONS
PD model
Φ = 600 MV
DR model
Φ = 800 MV
DRD model
Φ = 500 MV
44–999726
44–599728
44–999714kr
POSITRONS
e+

See also ....

Poster 16   Daniele Gaggero : Diffusion of cosmic rays (numerical code)

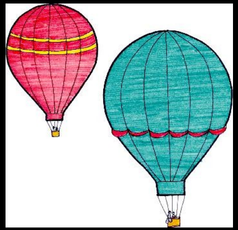
Poster 86   MarkusAckermann : Analysis of diffuse emission with GLAST

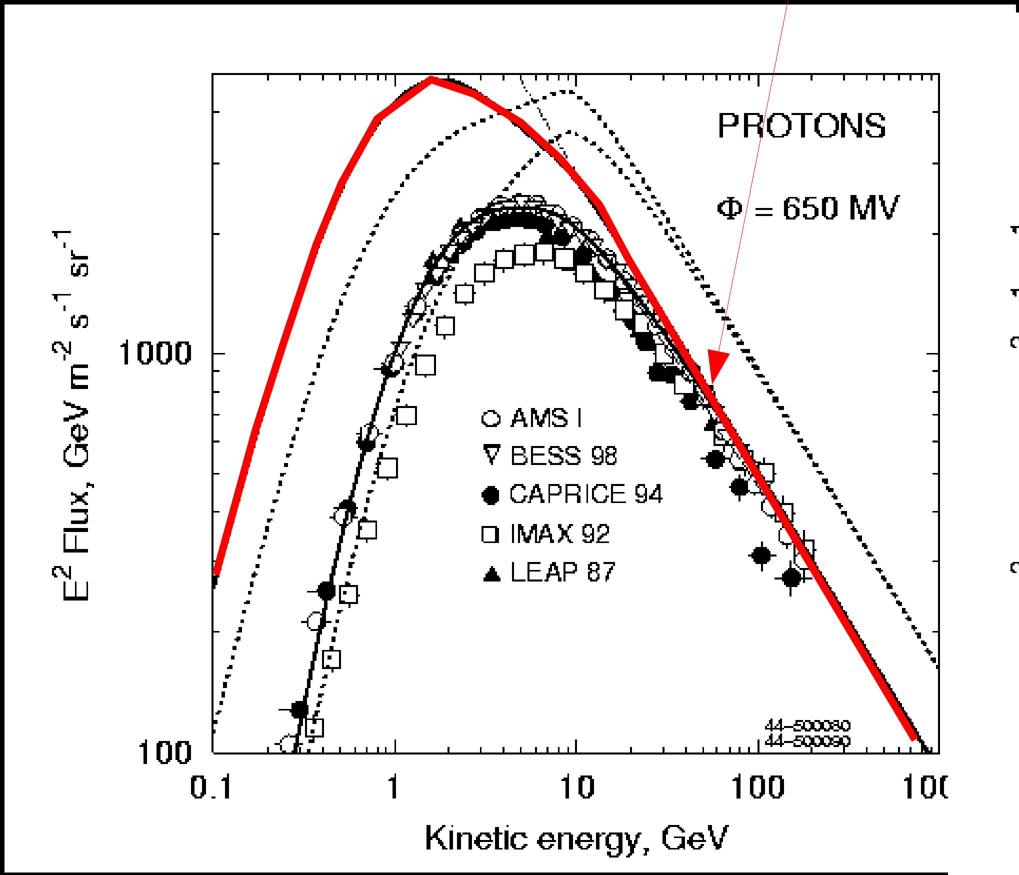
Talk Wednesday Christopher van Eldik : Galactic Centre TeV

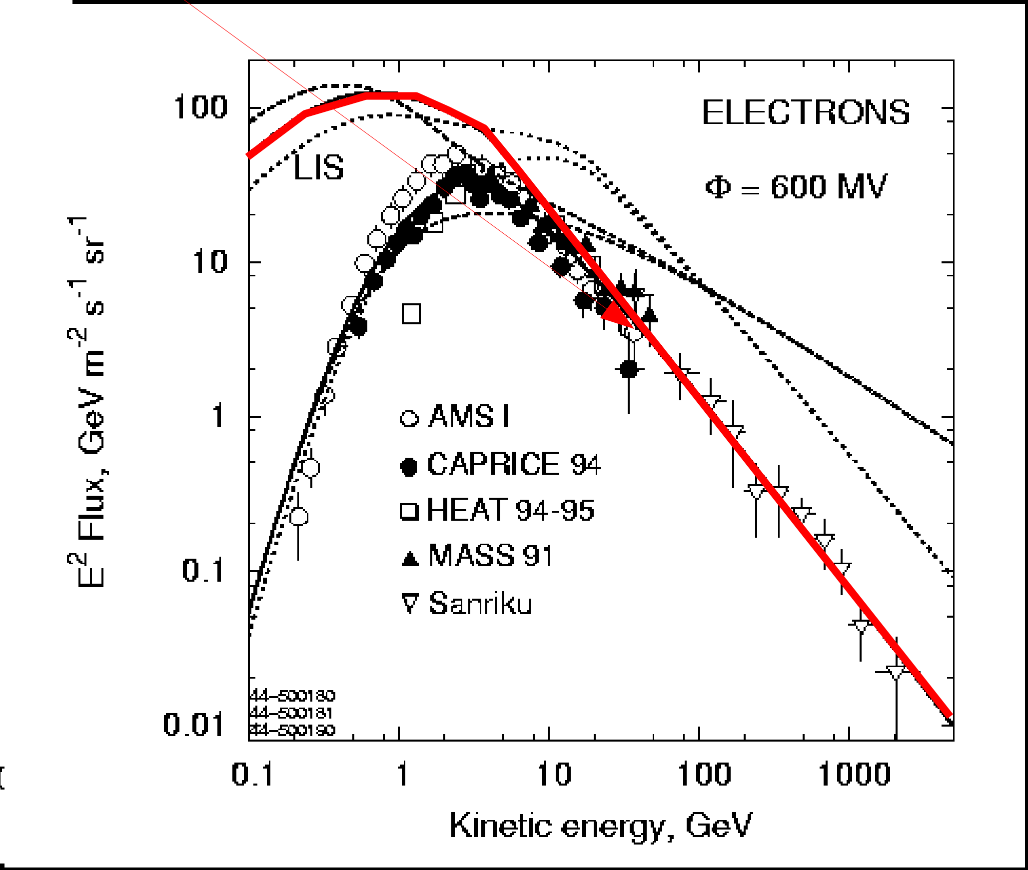
γ - rays

Modelling diffuse Galactic γ - rays:

Conventional model: proton, electron spectra <u>as measured</u>

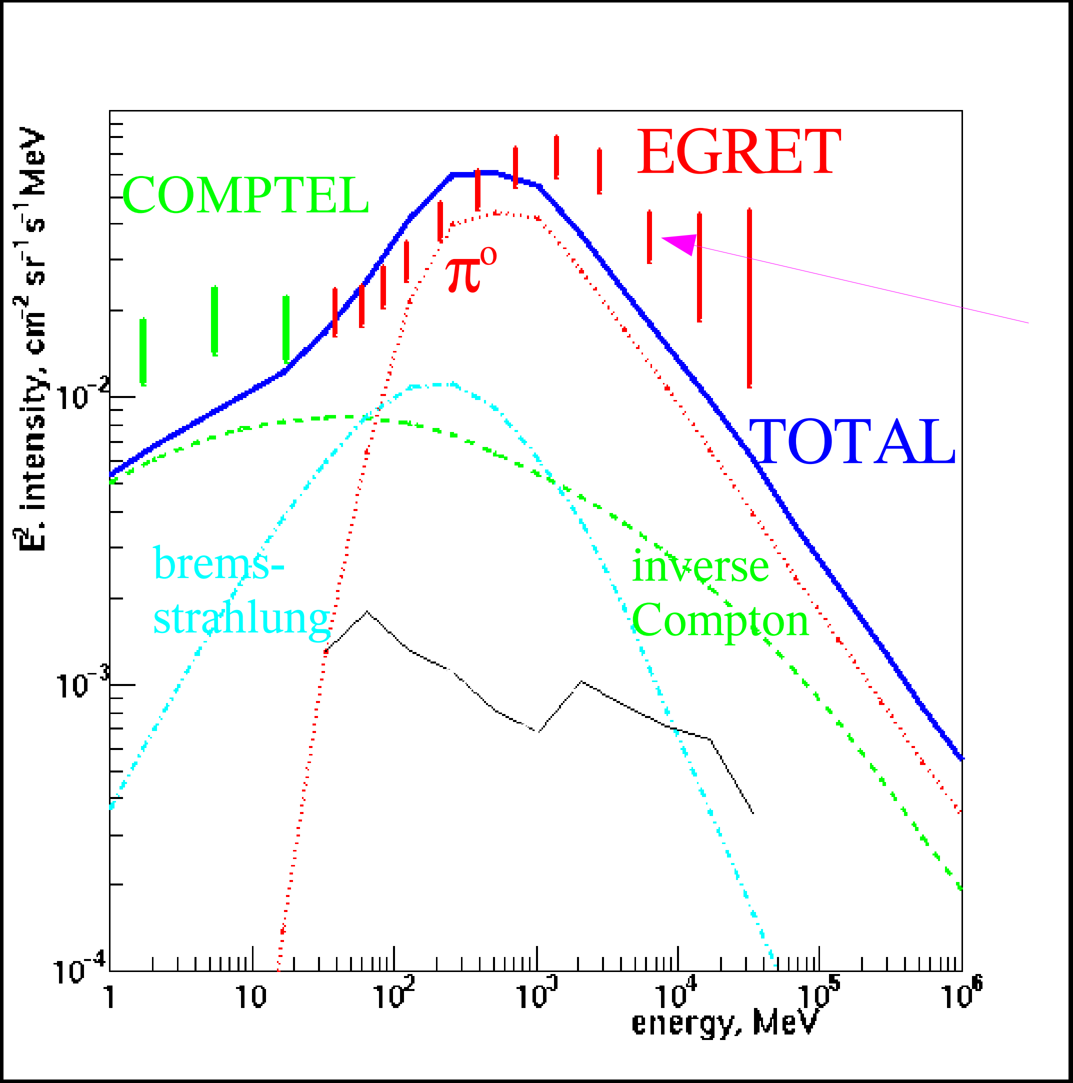






'Conventional' model:
cosmic-ray protons (+He) and electrons as *directly measured*

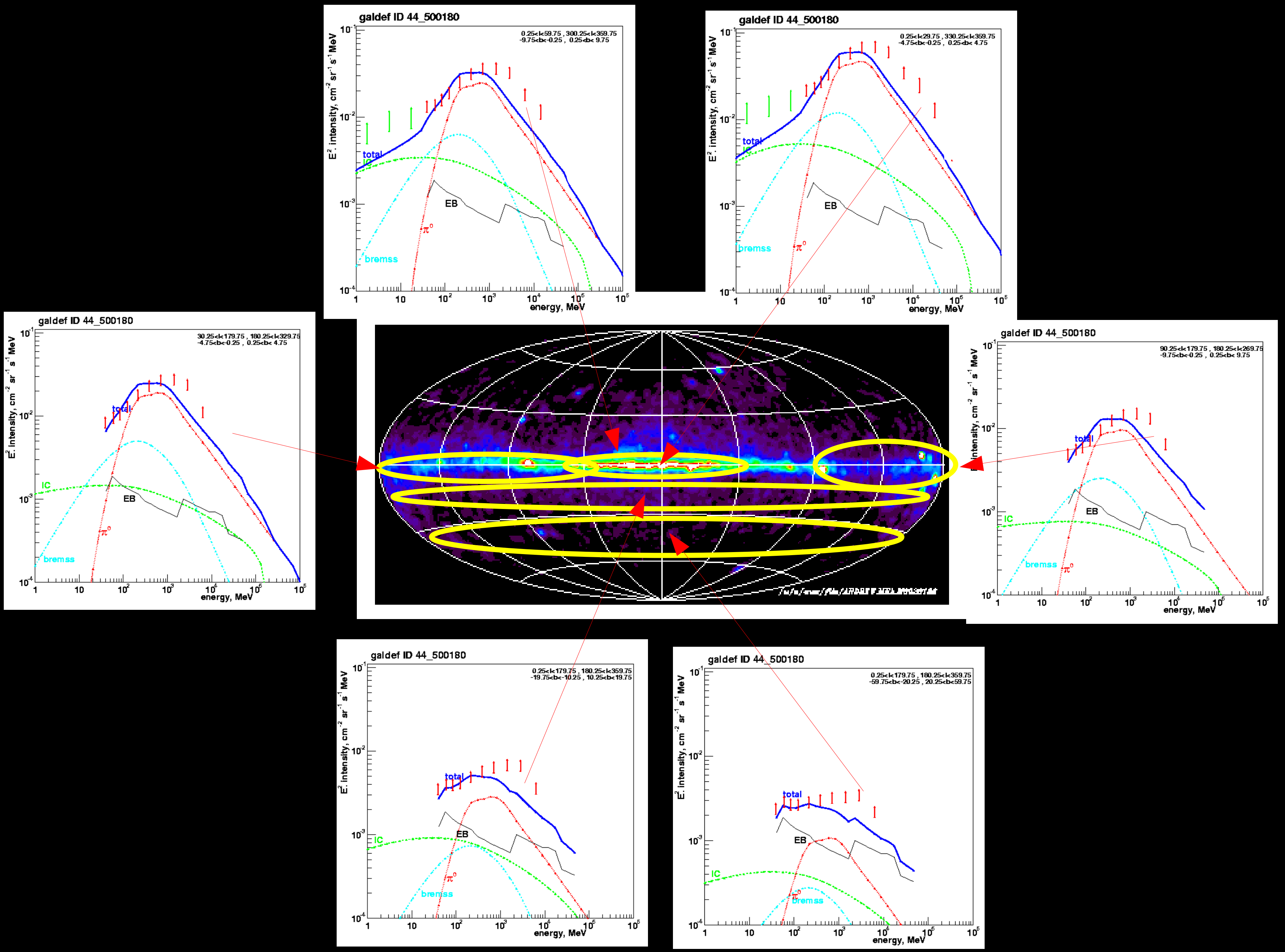
γ - ray spectrum of inner Galaxy



GeV excess

There is a big excess over prediction !

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



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. Unresolved γ - ray sources
7. Exotic: dark matter
8. Instrumental – EGRET response

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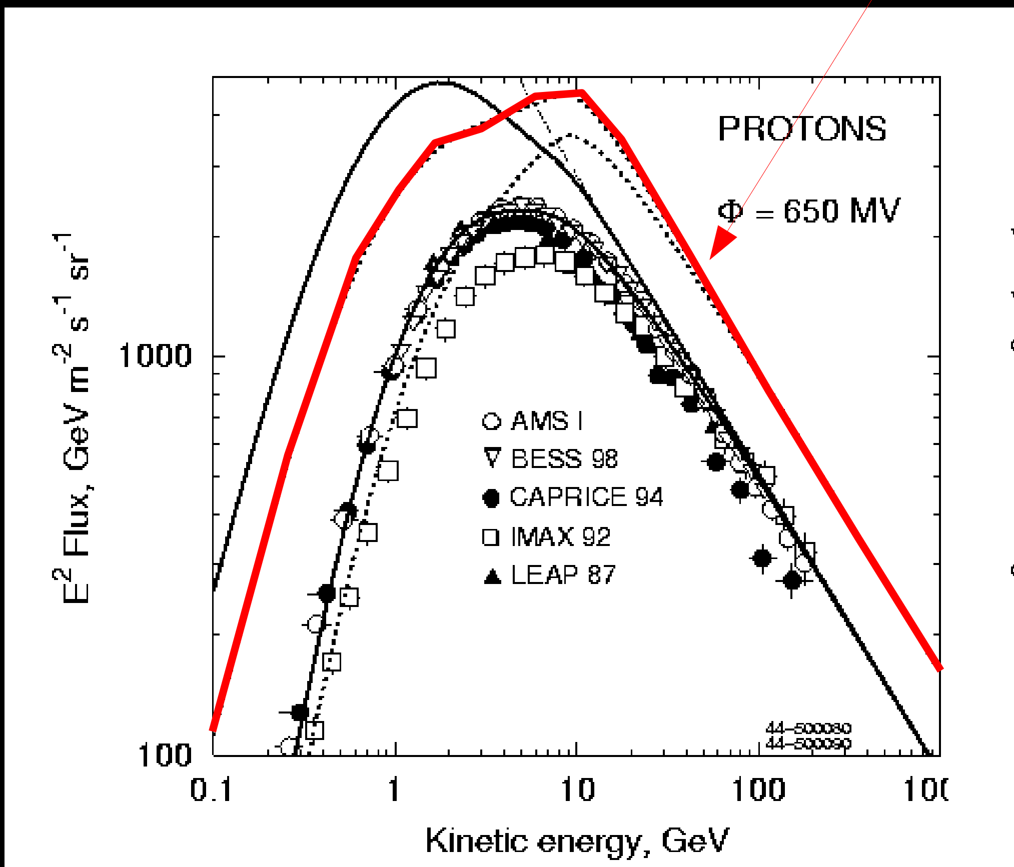
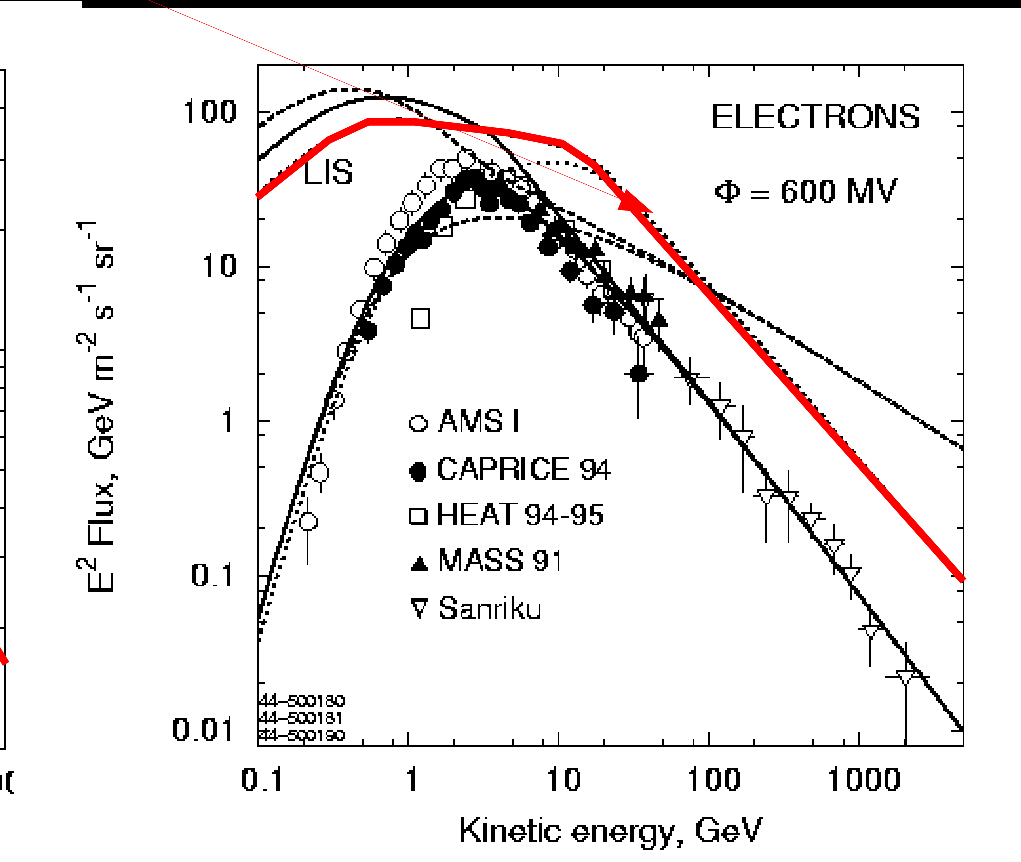
6. Unresolved γ - ray sources
7. Exotic: dark matter
8. Instrumental – EGRET response

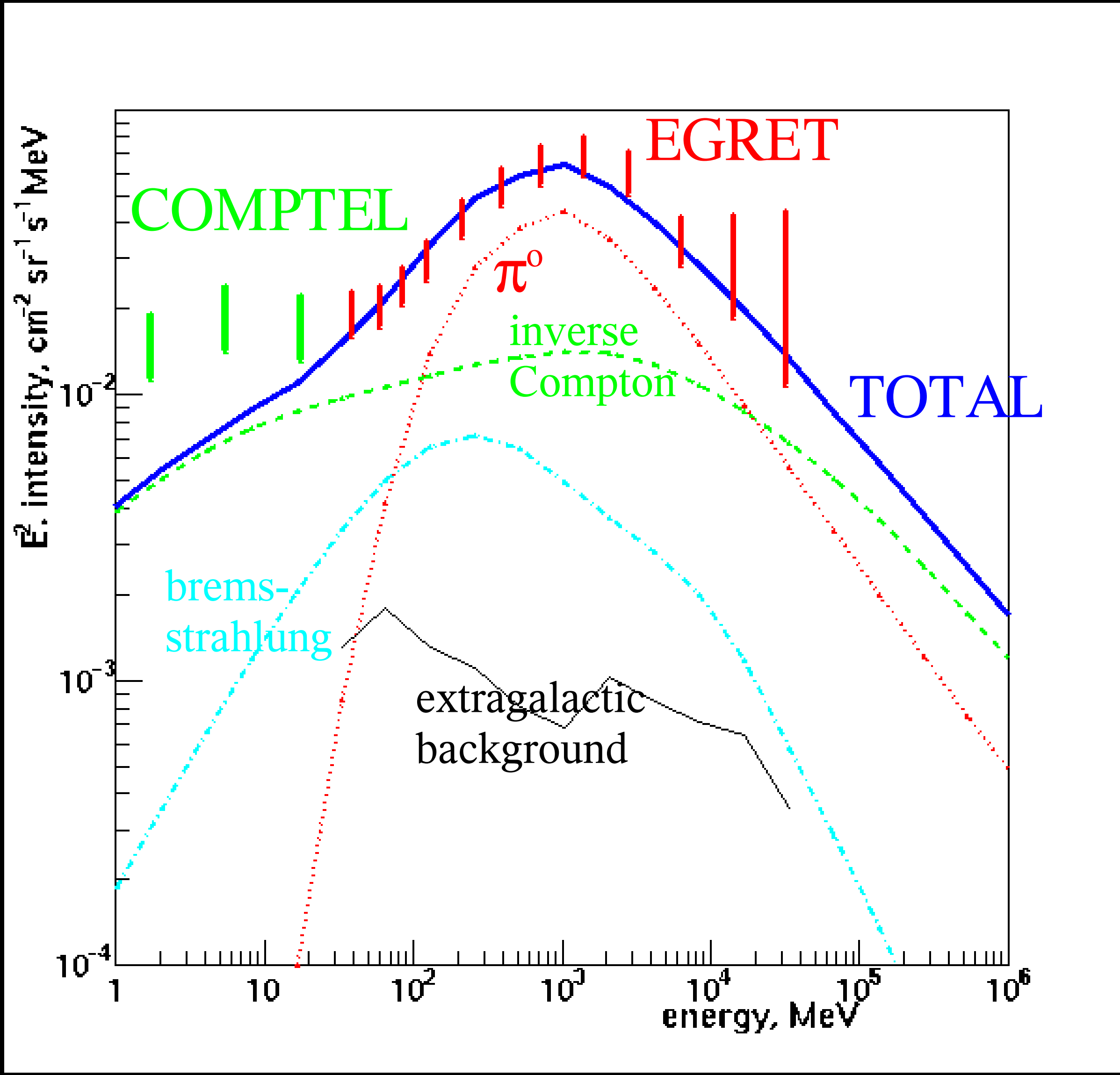
'Optimized' model:

proton, electron spectra factor 2 - 4 higher than measured locally (justification: we are not at a place typical of the Galaxy at large)



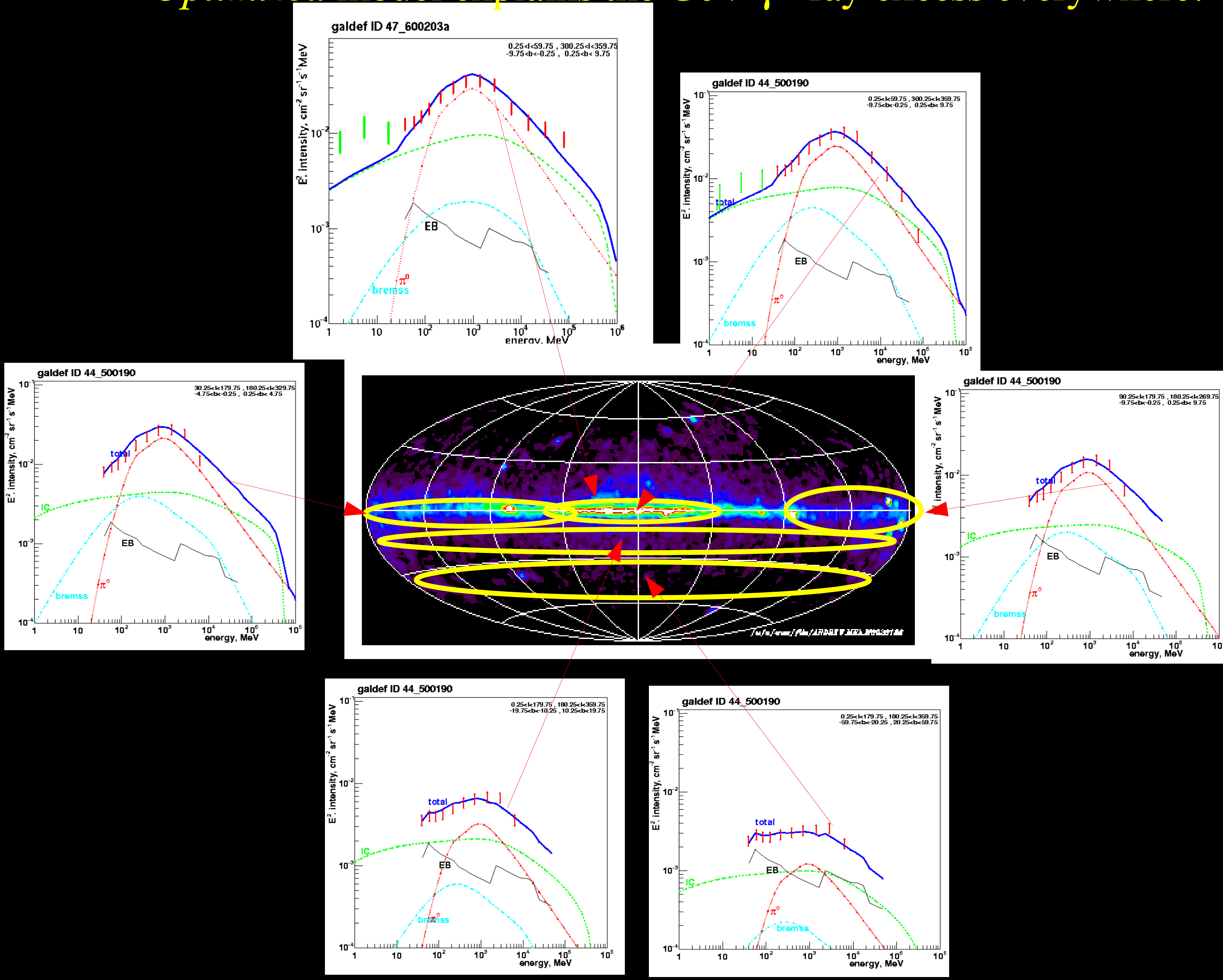


Optimized model: vary cosmic-ray proton, electron spectra but keep compatible with expected spatial variations



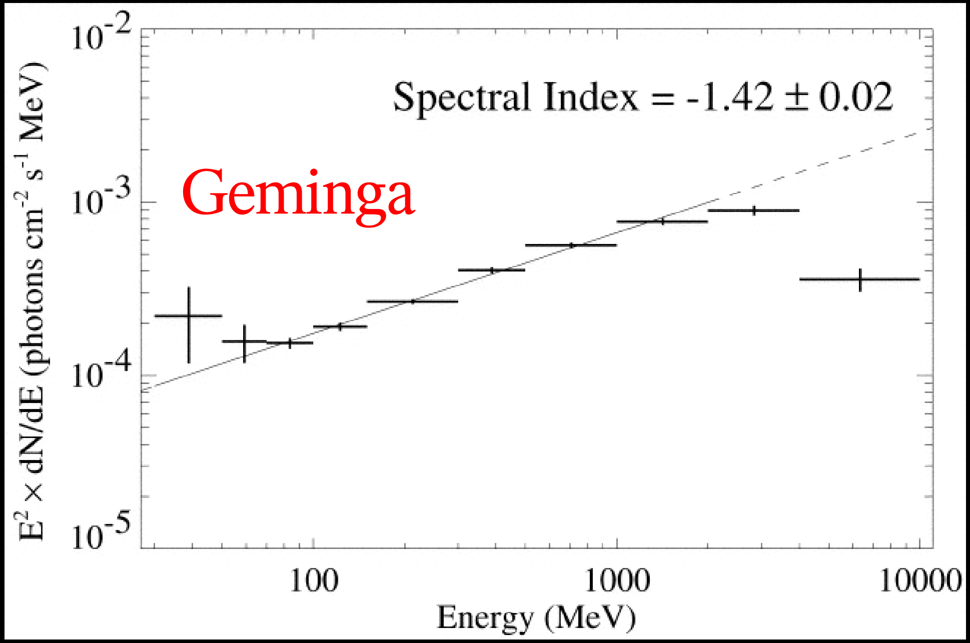
Satisfactory fit above 10 MeV: no more GeV excess

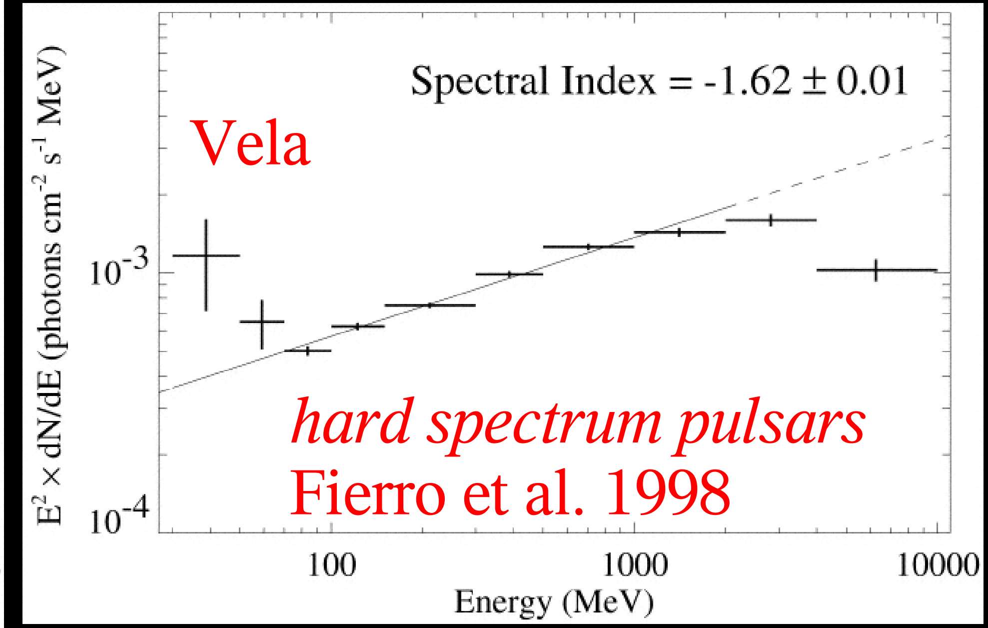
Optimized model explains the GeV γ - ray excess everywhere!



ALTERNATIVE EXPLANATION of GeV excess

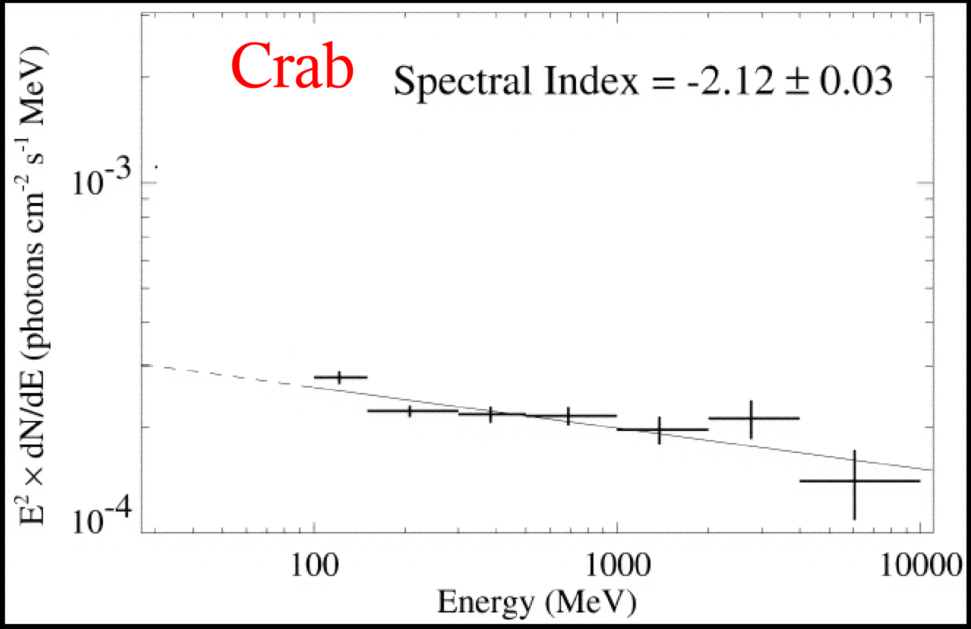
γ-ray pulsars: spectrum very reminiscent of the Galactic emission !



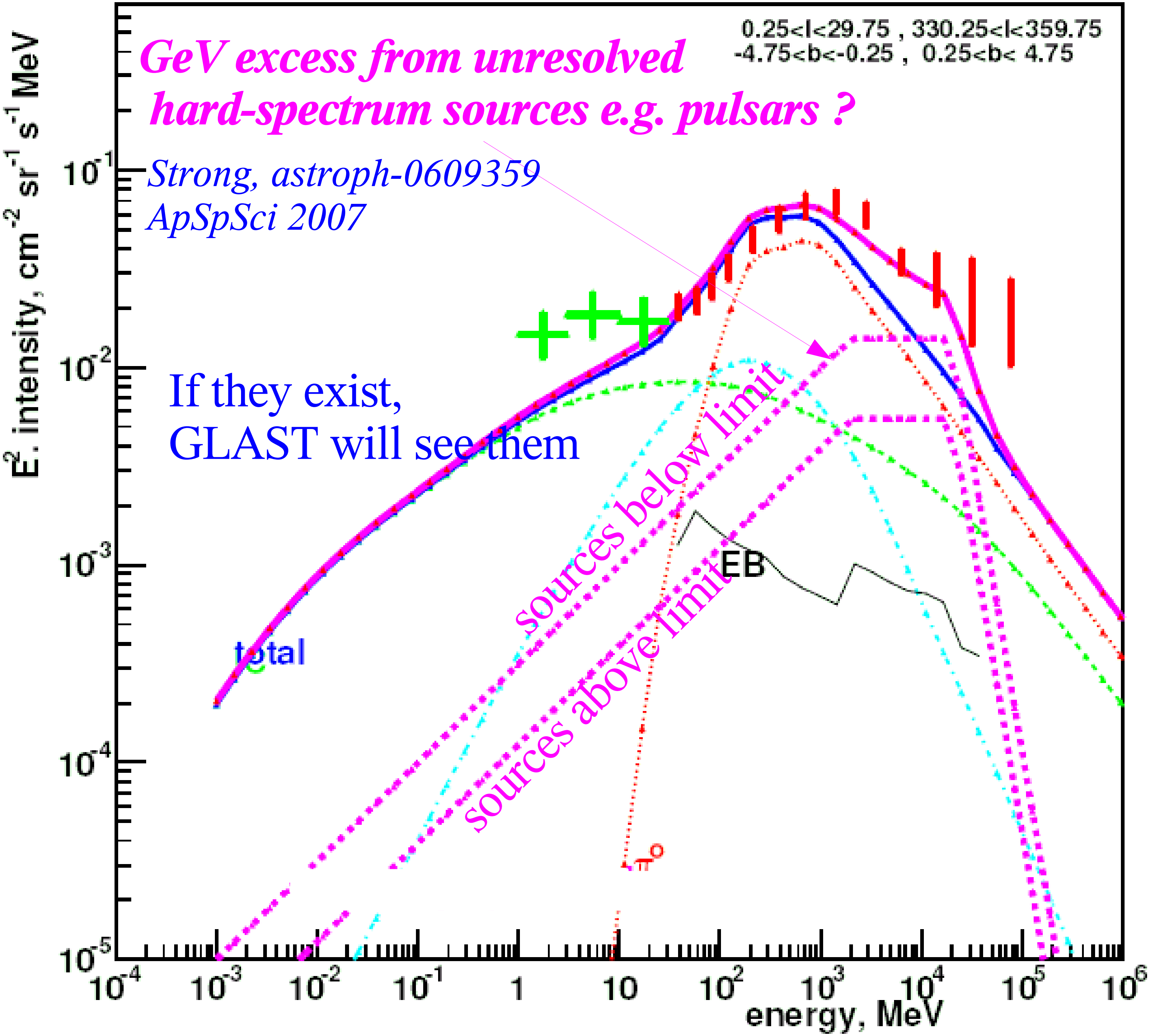


pulsar	index	breaks above
Crab	-2.1	4 GeV
Vela	-1.6	2 GeV
B1706-44	-1.3	1 GeV
B1951+32	-1.9	
Geminga	-1.4	2 GeV
B1055-52	-1.6	1 GeV
B1509-58	-1.7	

for comparison,
Crab is not so hard:



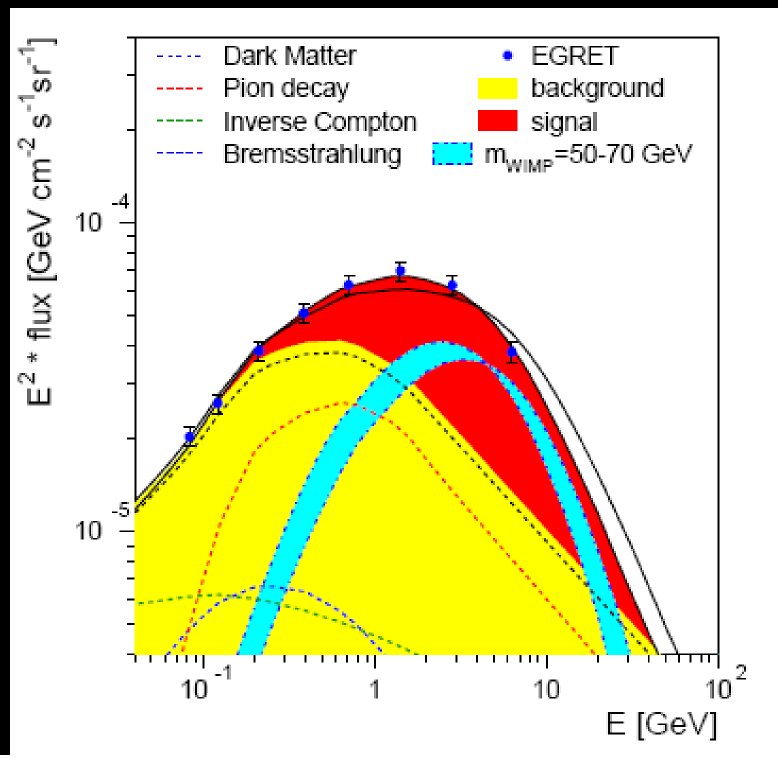
ALTERNATIVE EXPLANATION of GeV excess



OR .....

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]

but produces too many antiprotons ... Bergstrom et al. 2006

Facit: proposed explanations of GeV γ-ray 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 ← current best bet

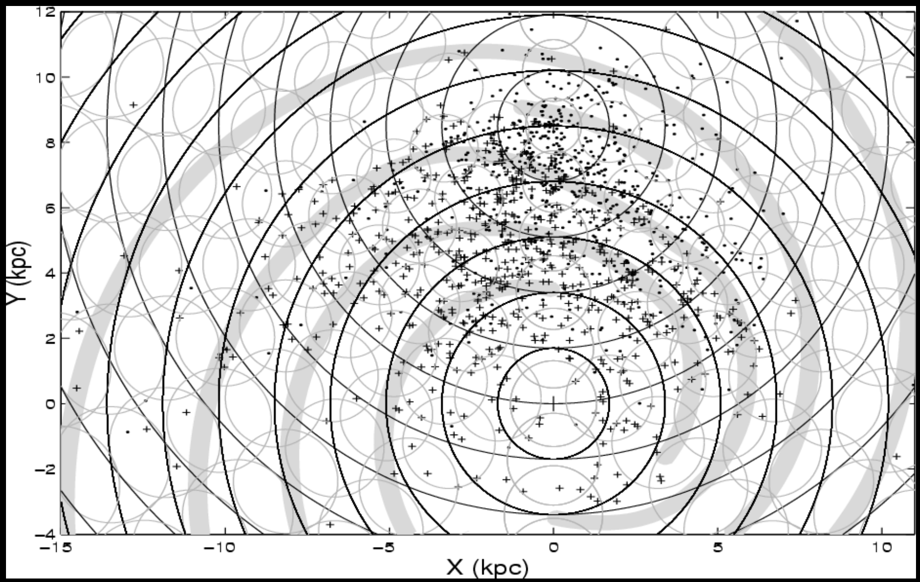
5. Physics of $p + p \rightarrow \pi^o$ NO

6. Hard spectrum SOURCES ← quite plausible

7. 'Exotic' : e.g. dark matter ← who knows

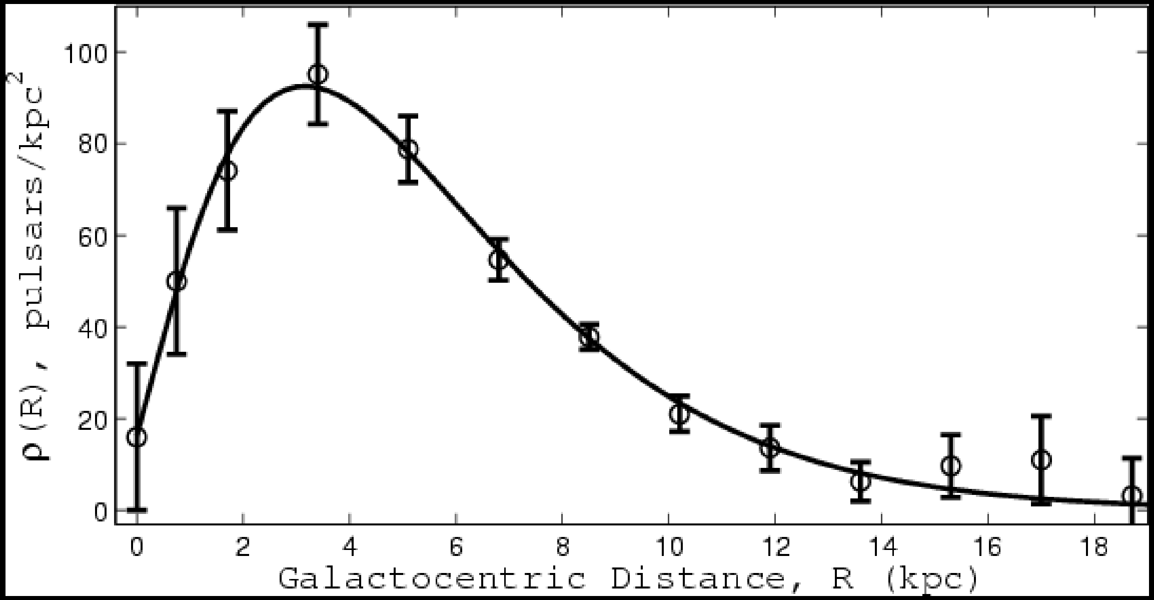
8. Instrumental – EGRET response ← unlikely -await GLAST

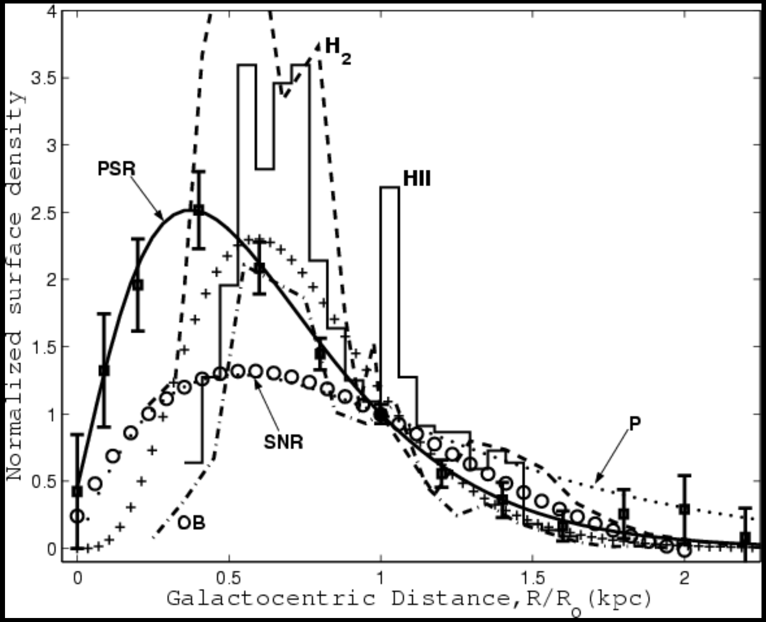
Tracer of SNR cosmic-ray sources: Pulsar distribution



Parkes Deep Survey

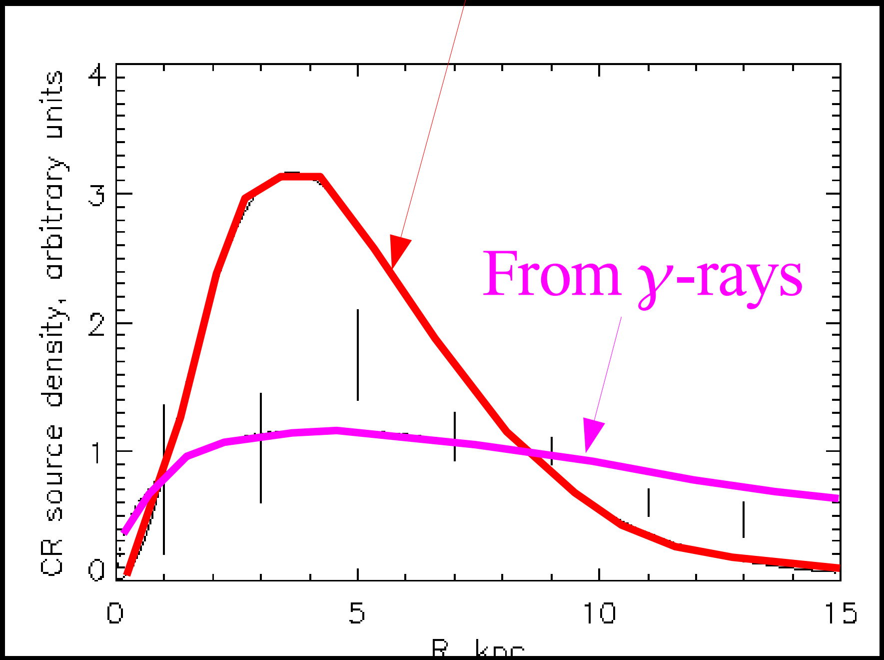
Yusifov & Kücük 2004
Lorimer 2004





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

SNR (traced by latest pulsar surveys: Lorimer 2004)

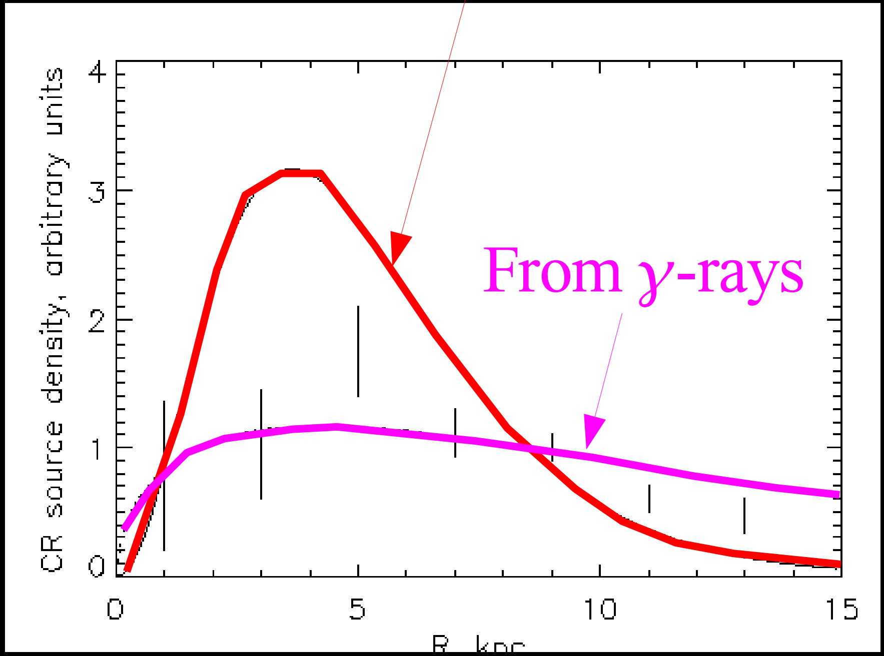


R (kpc)

might be wind gradient (Völk, Breitschwerdt) or...

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

SNR (traced by latest pulsar surveys: Lorimer 2004)

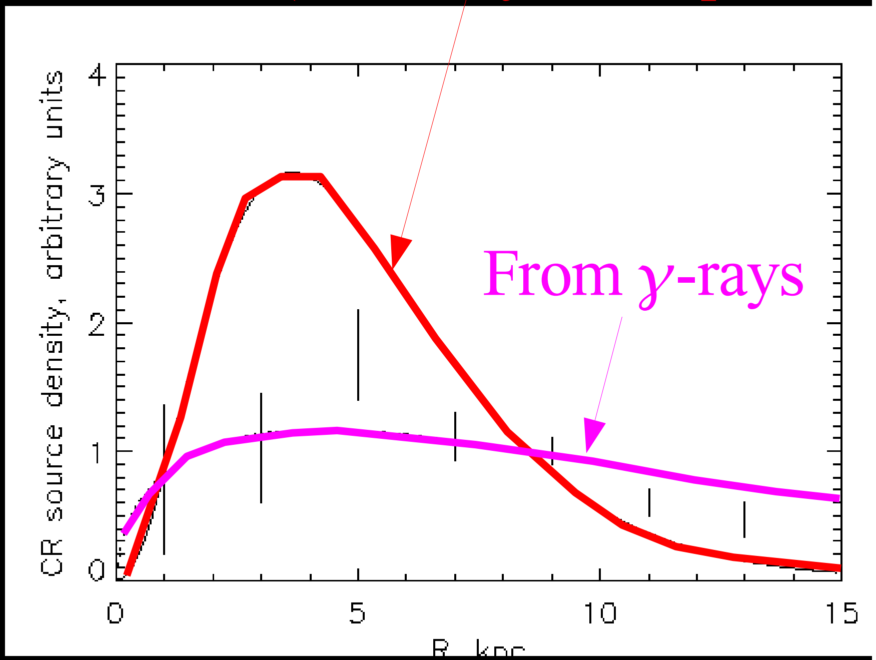


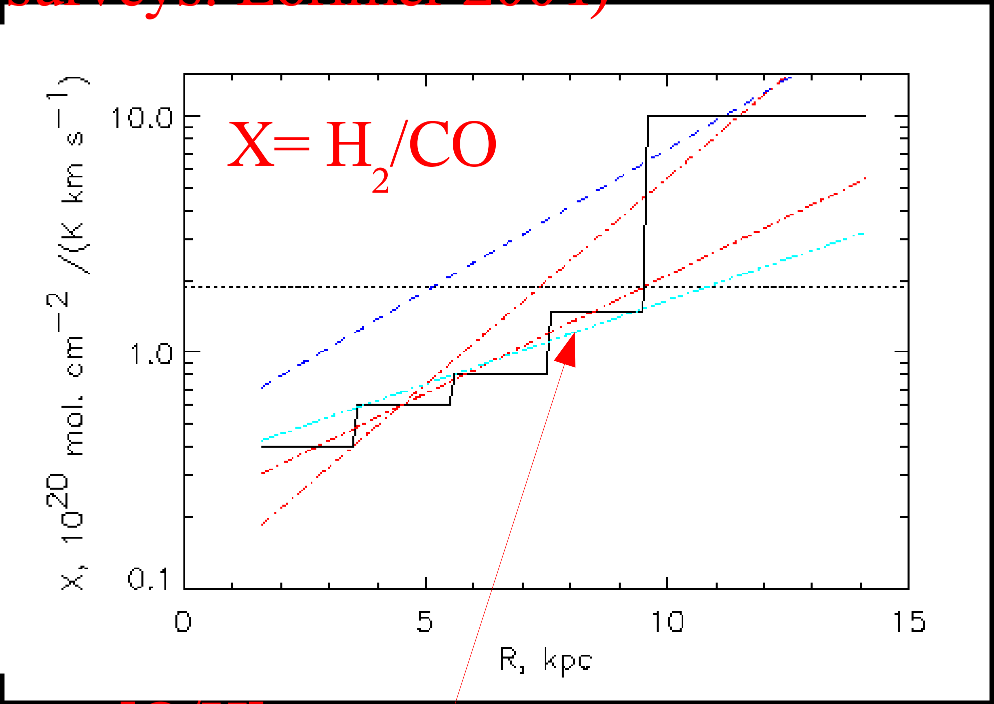
Clue: Galactic metallicity gradient e.g. [O/H]

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

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

SNR (traced by latest pulsar surveys: Lorimer 2004)





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

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

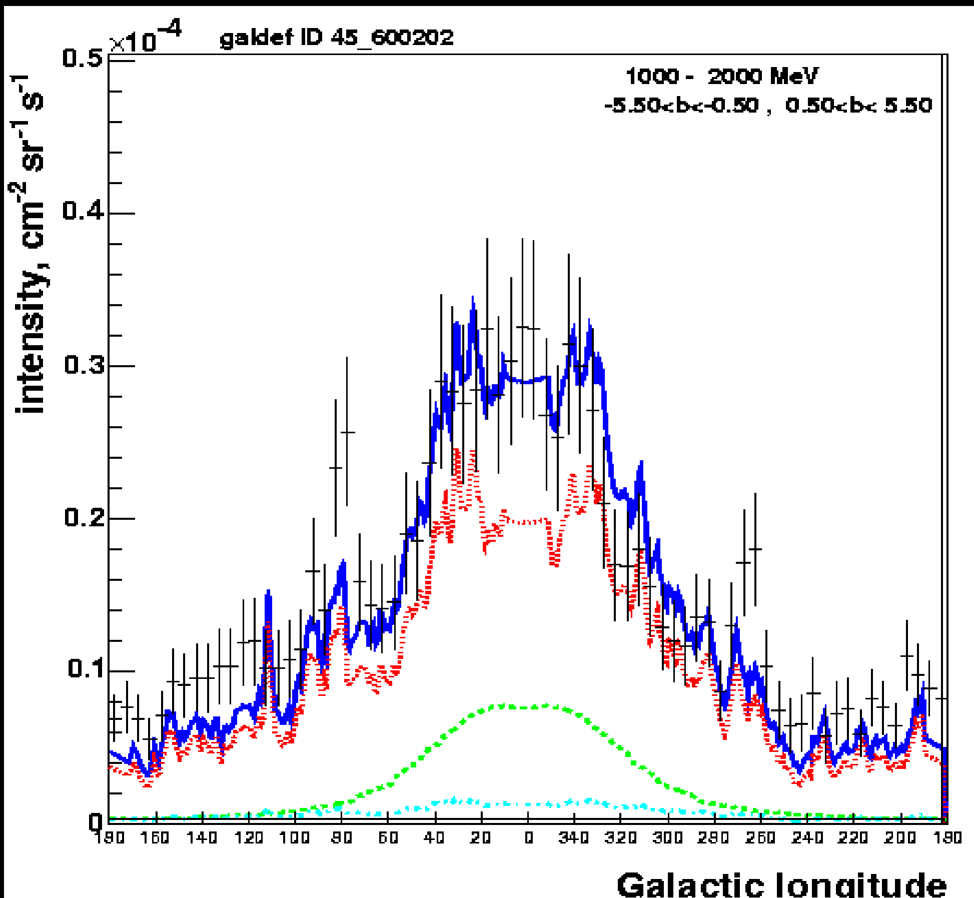
>>>>>>> $\boxed{\textbf{\textit{X = H}}_2 \textbf{\textit{ / CO increases with radius}}}$

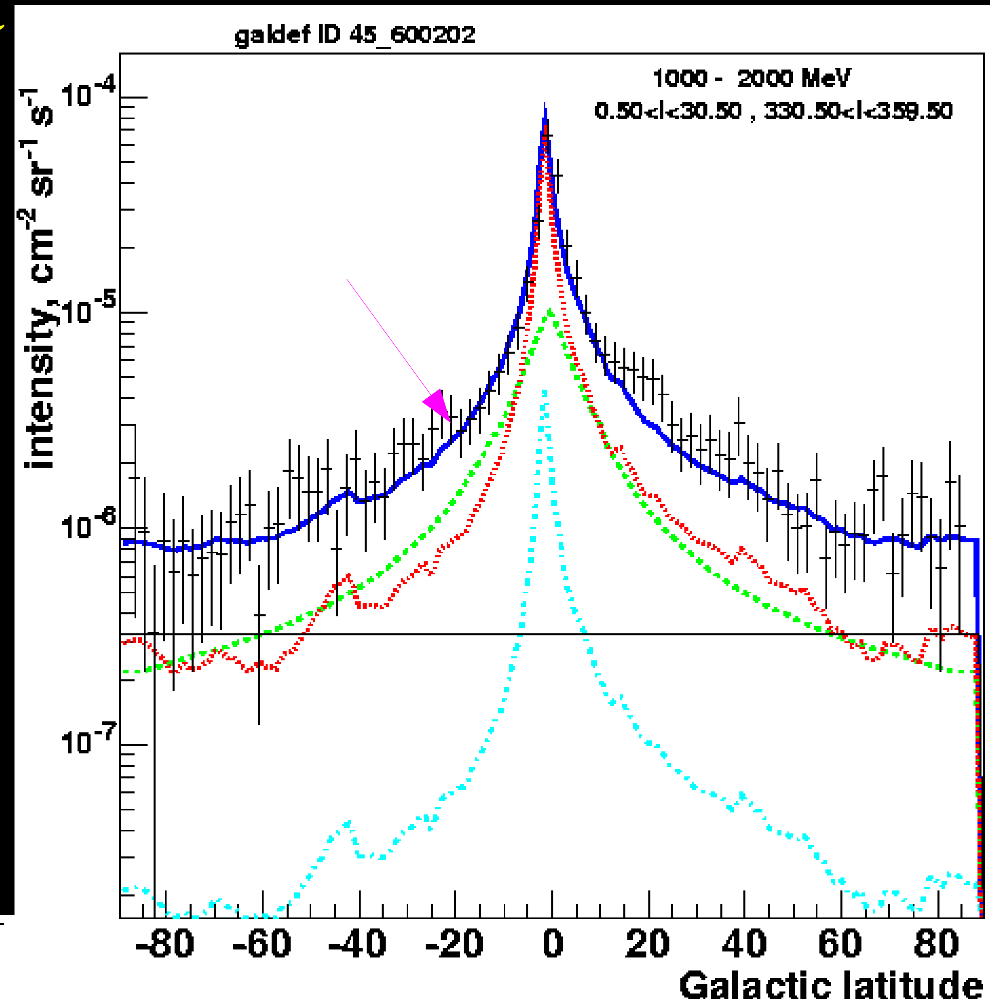
γ-rays = sources(R) * X(R) *CO(R) (+ HI, inverse Compton terms)

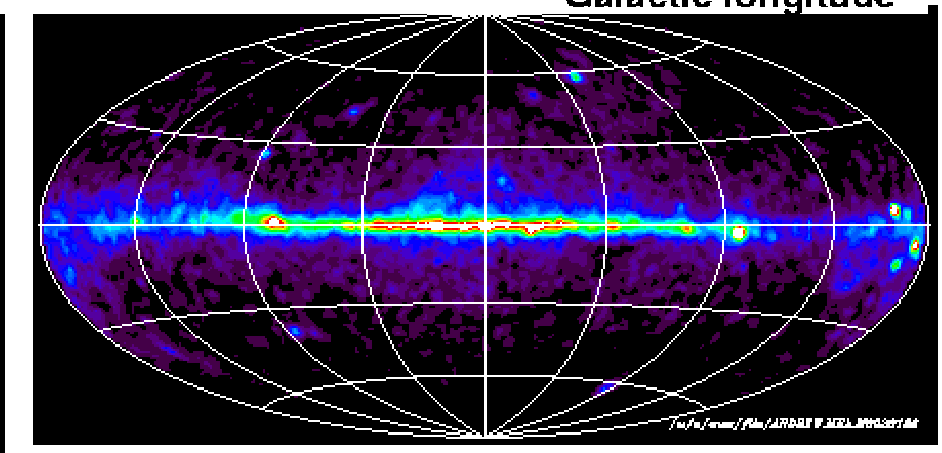
Steeper sources * flatter X = observed gamma-rays

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

EGRET γ -ray data







broadening the energy coverage:

INTEGRAL : down to 20 keV

MILAGRO : up to 15 TeV

it's mainly about cosmic-ray electrons !

radio, hard X, soft gamma sensitive to GeV electrons

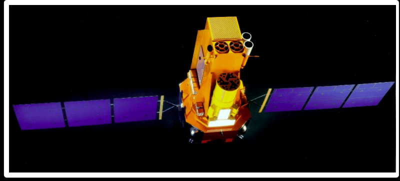
inverse Compton $E = \gamma^2\ e$

synchrotron $= \gamma^2\ B$

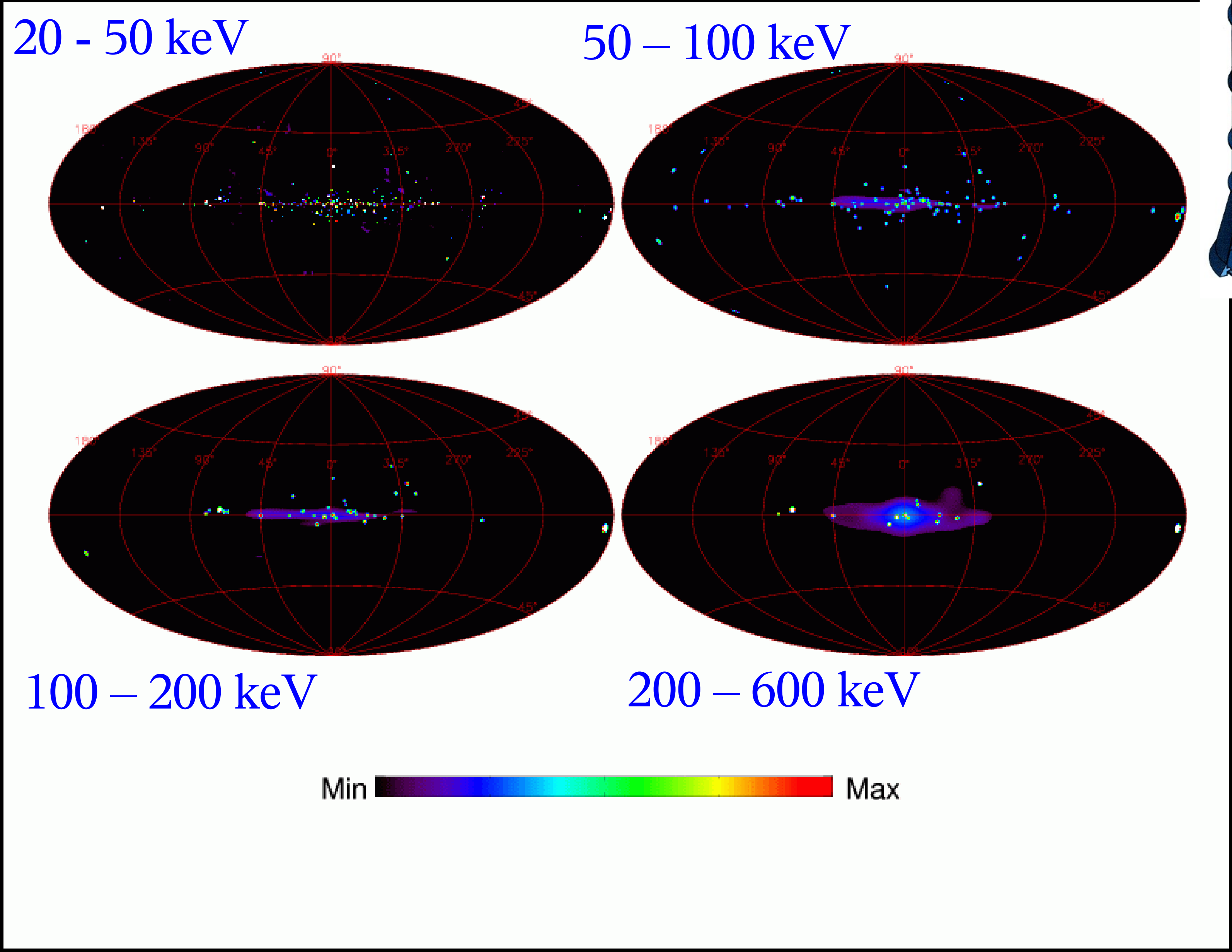
1 GeV electrons + CMB, FIR => keV

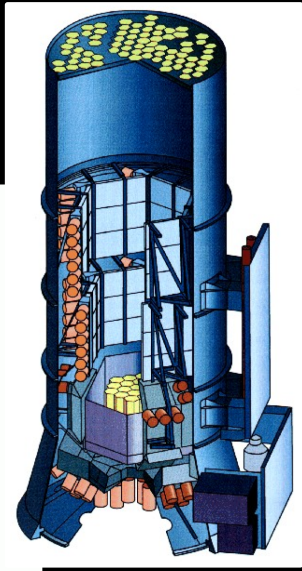
+ starlight => MeV

3μG => GHz radio



INTEGRAL / SPI Galactic emission



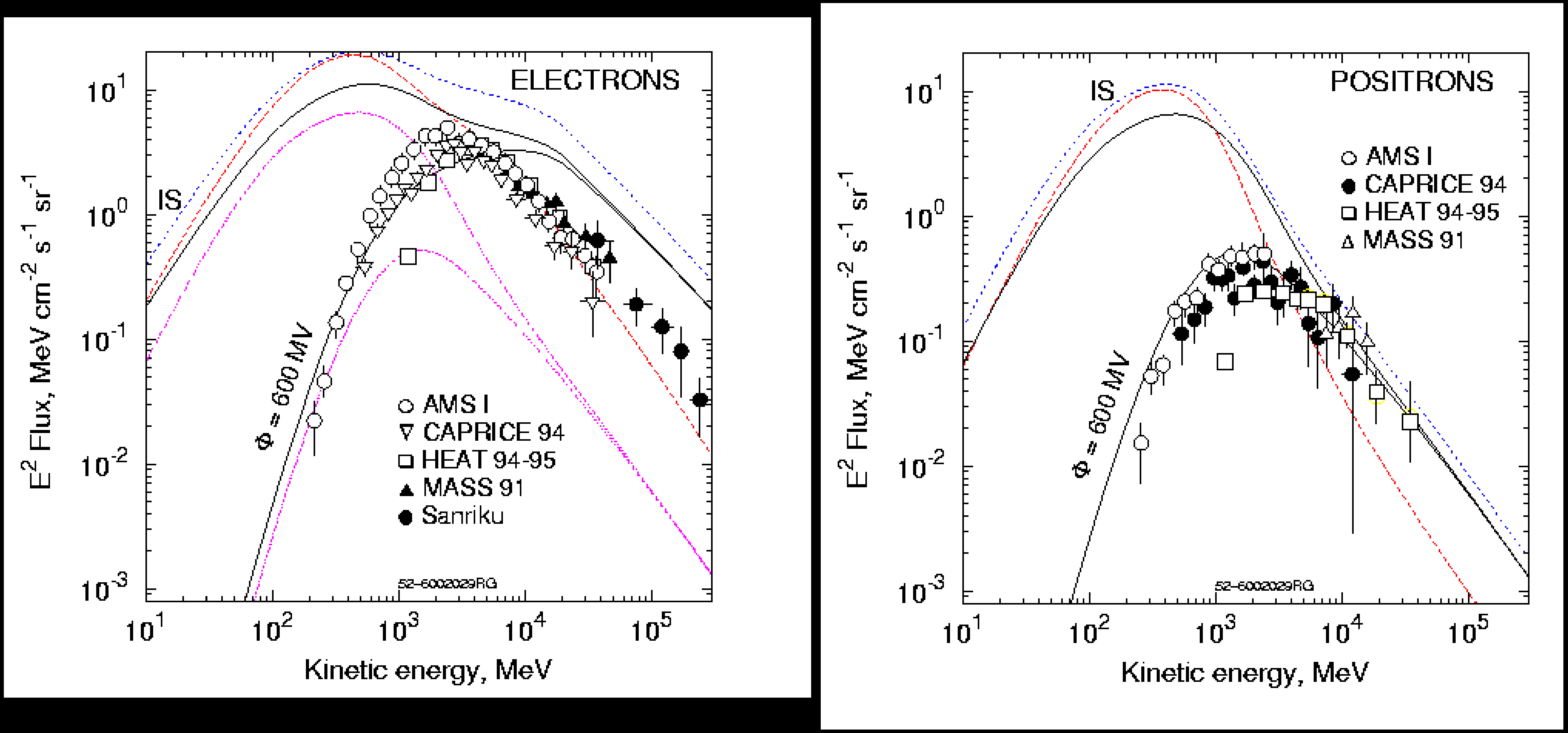


Bouchet et al 2008 ApJ 679,1315

primary cosmic-ray electrons

secondary cosmic-ray positrons

$pp \Rightarrow pn\pi^{+} \Rightarrow e^{+}$



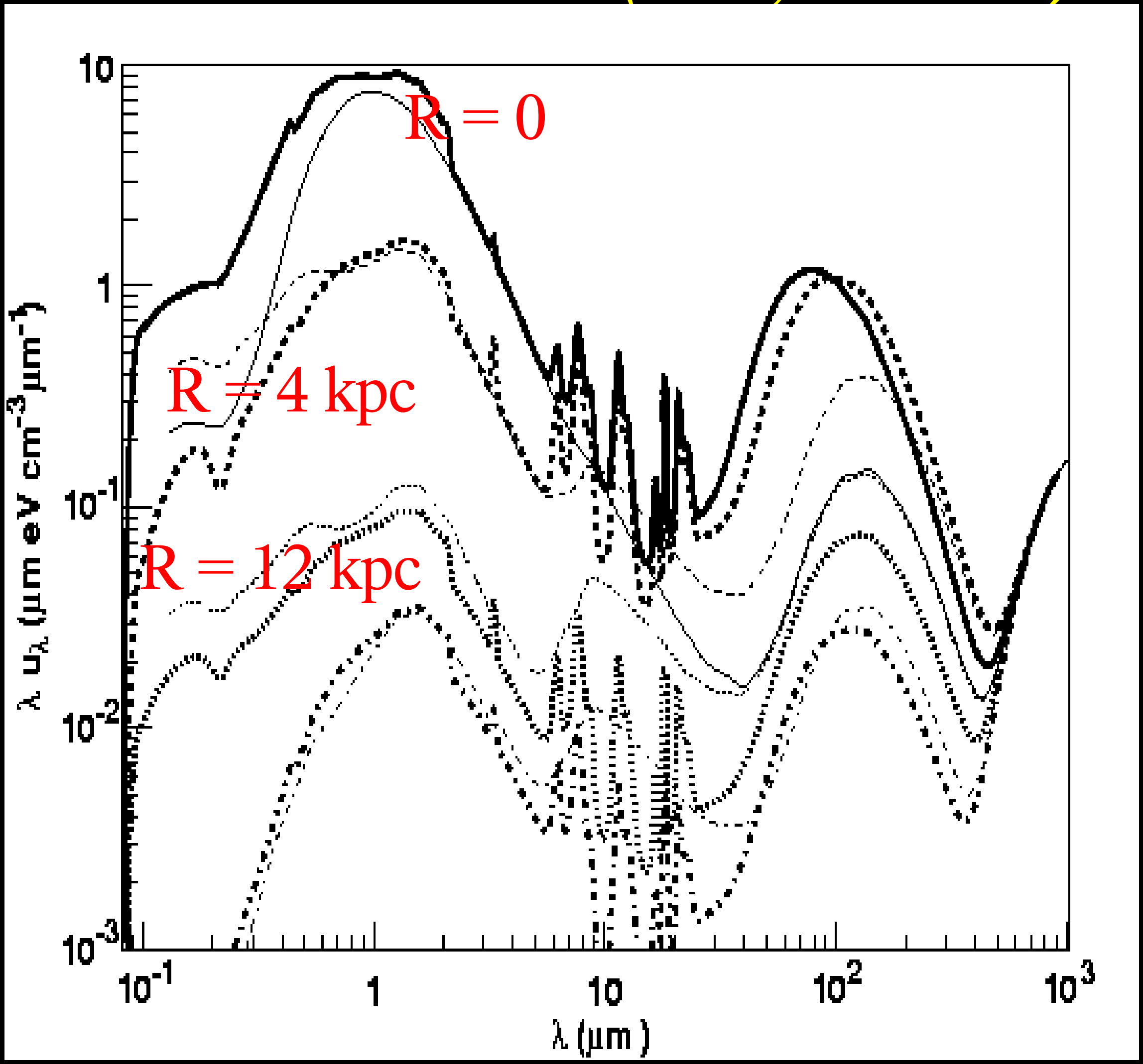
those electrons & positrons can explain a lot !

Porter, Moskalenko, Strong, Orlando, Bouchet 2008 ApJ 682, 400 (July 20)

Interstellar Radiation Field

new model *(Troy Porter)*

New *ISRF*
using much
new information
on
stellar
populations,
dust
radiative transfer

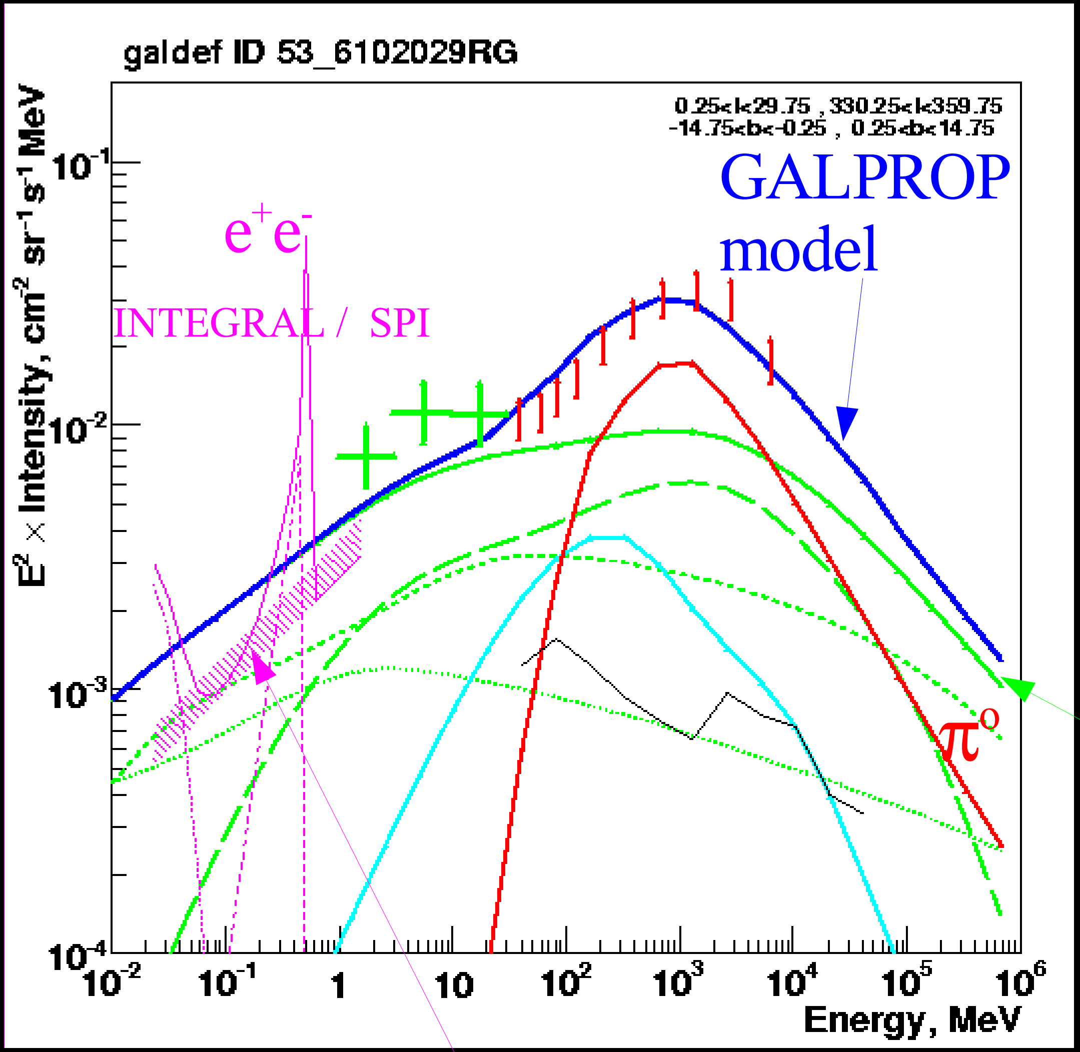


essential for
inverse Compton
gamma rays

UV optical IR FIR CMB

Gamma-rays, inner Galaxy

inverse Compton
from primary electrons, secondary electrons, positrons



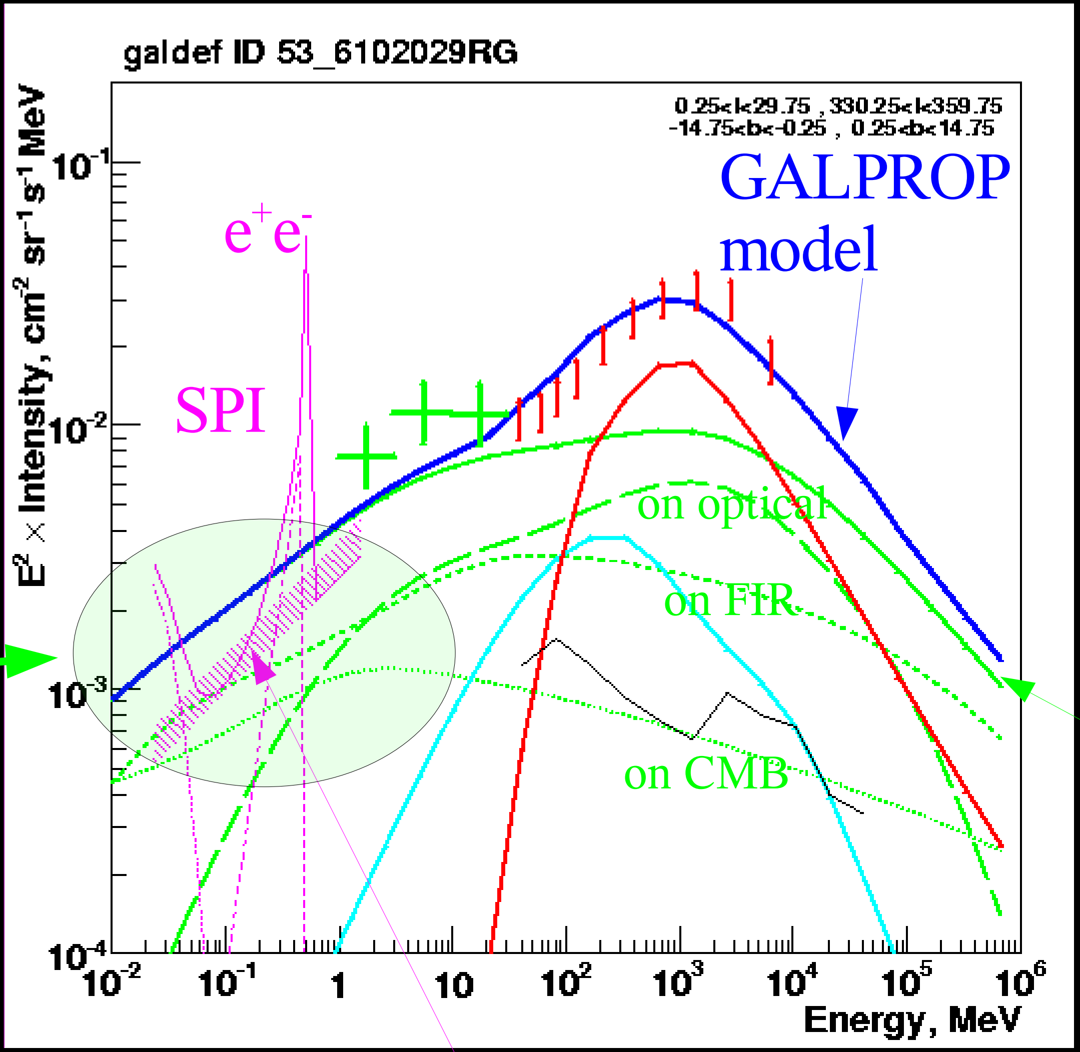
Bouchet et al power-law continuum

Porter, Moskalenko, Strong, Orlando, Bouchet ApJ 682, 400

Gamma-rays, inner Galaxy

inverse Compton
from primary electrons, secondary electrons, positrons

power-law
continuum
emission
explained
by
inverse Compton !



inverse Compton
total

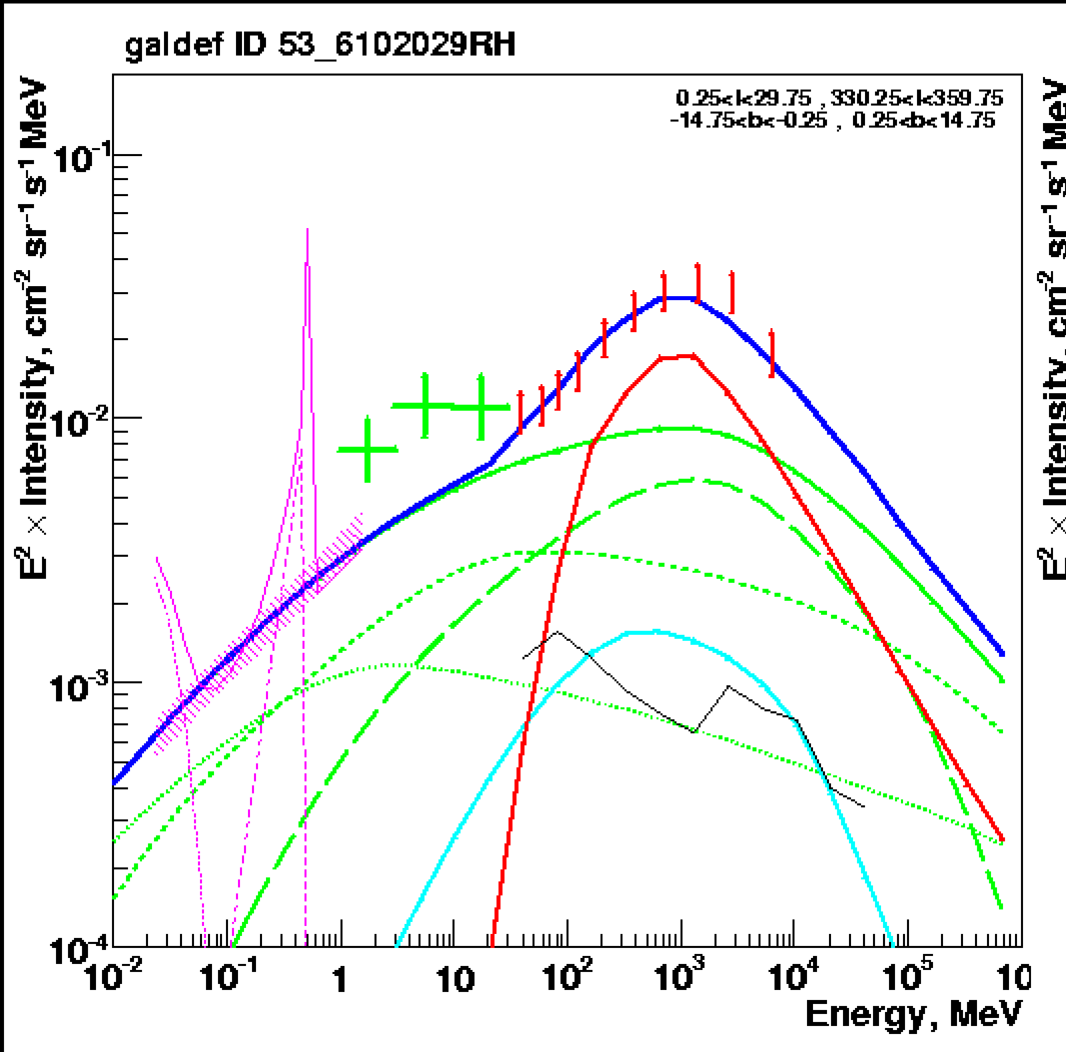
Bouchet et al : power-law continuum

Porter, Moskalenko, Strong, Orlando, Bouchet ApJ 682, 400

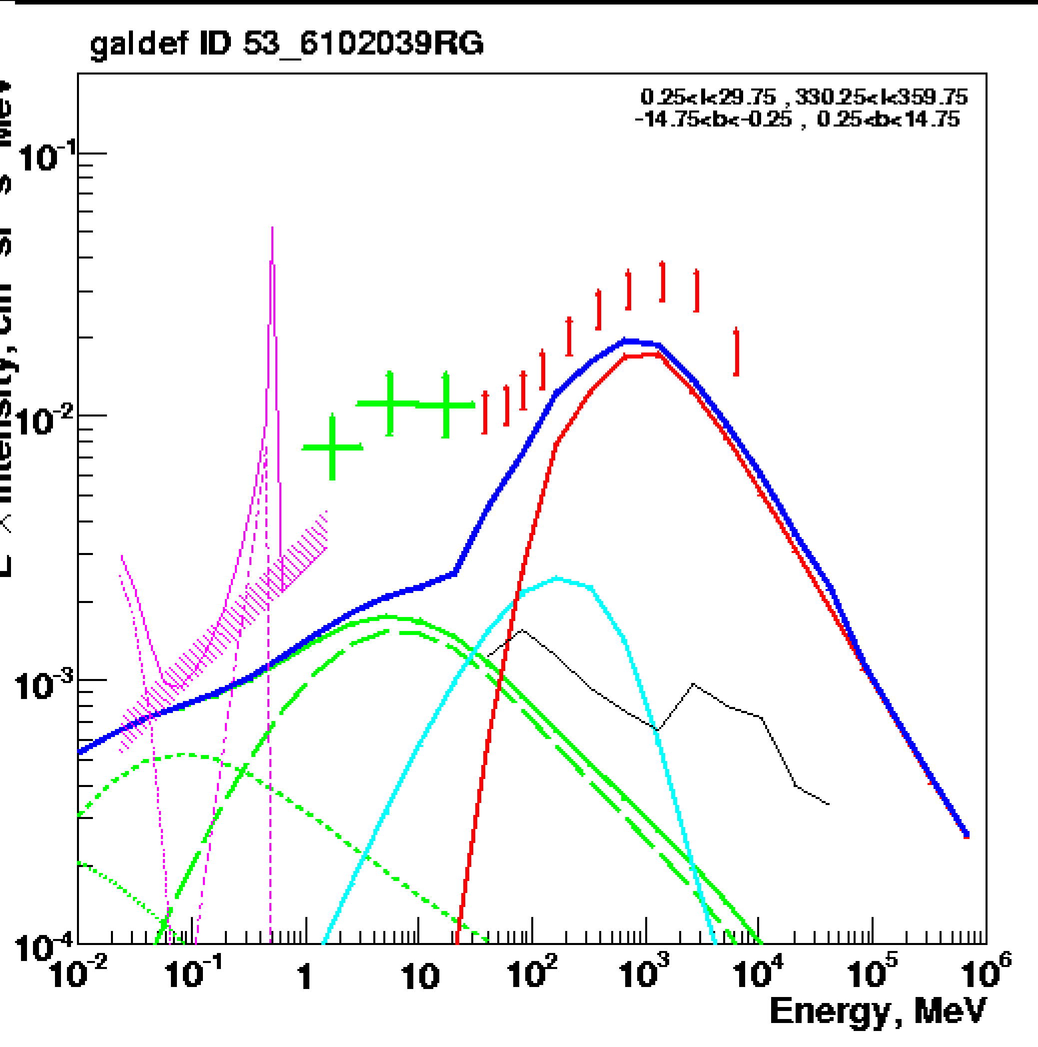
Gamma-rays, inner Galaxy

inverse Compton from

primary electrons only



secondary electrons, positrons only

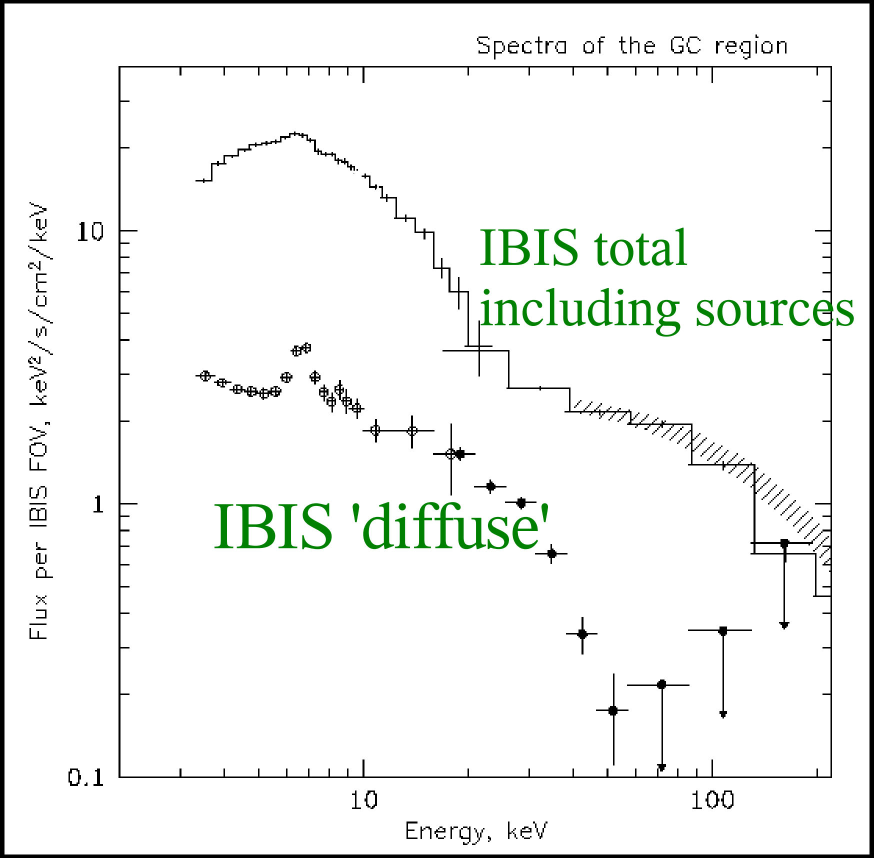


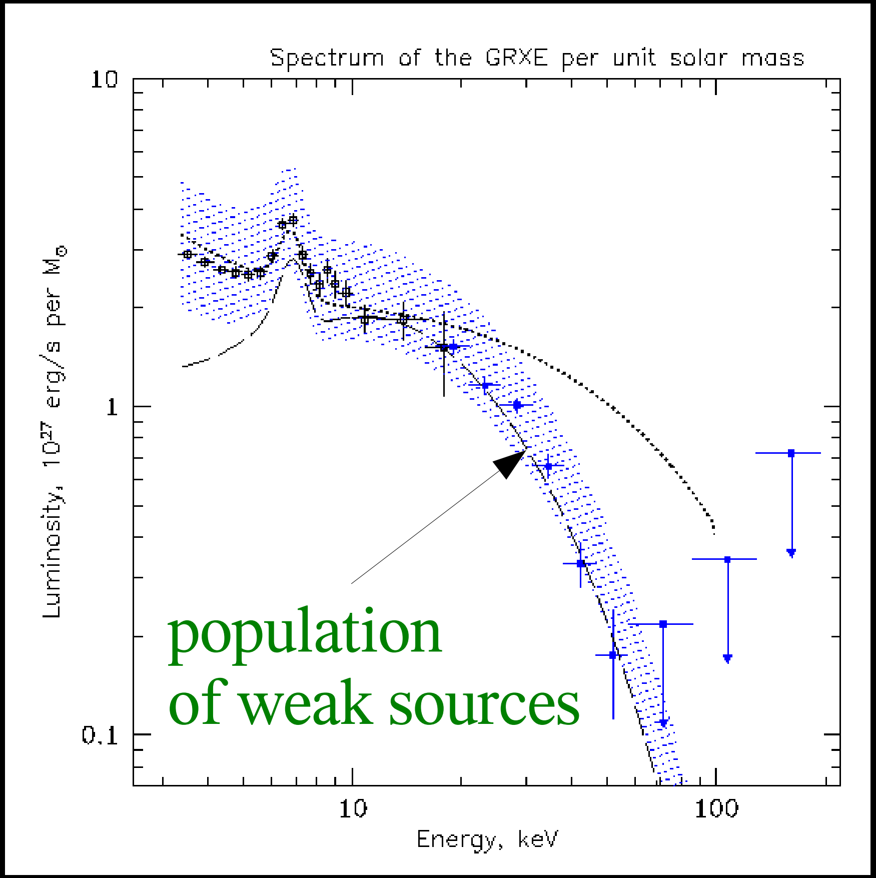
inverse Compton origin of hard X and gamma-rays

secondary positrons, electrons important

even hard X-rays trace cosmic rays !!

Krivonos et al. 2007



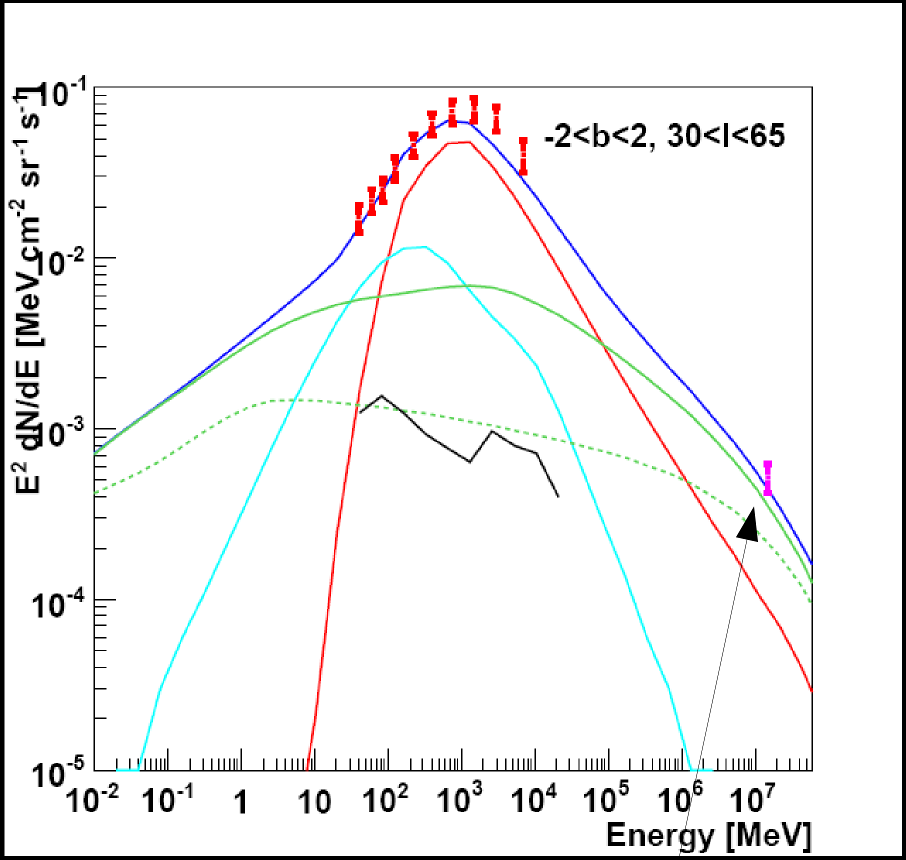


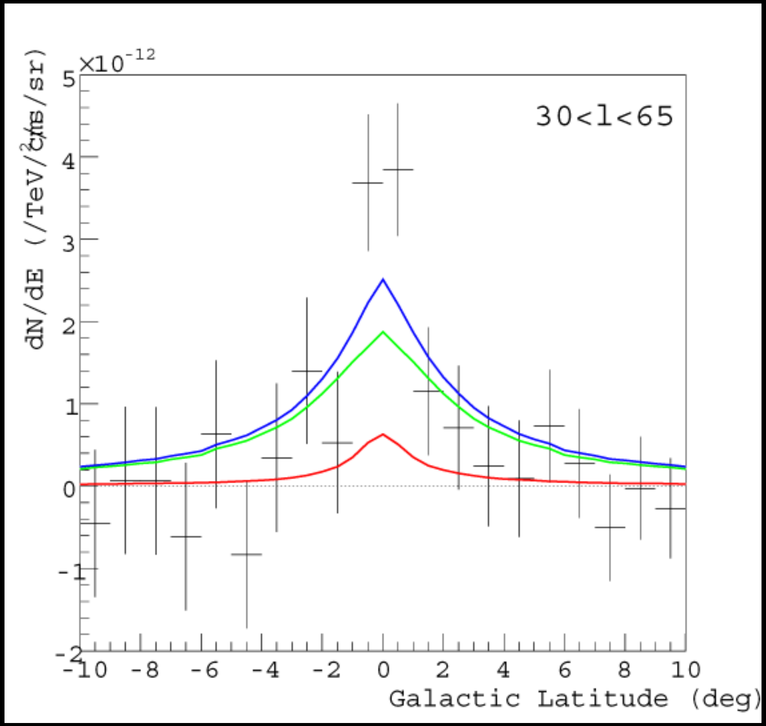
inner Galaxy as seen by an instrument with IBIS FOV, with diffuse traced by 4.9μ DIRBE map

ridge emission < 50 keV is mainly magnetic CV's and coronally active stars

Inner Galaxy

same model, extended to > TeV





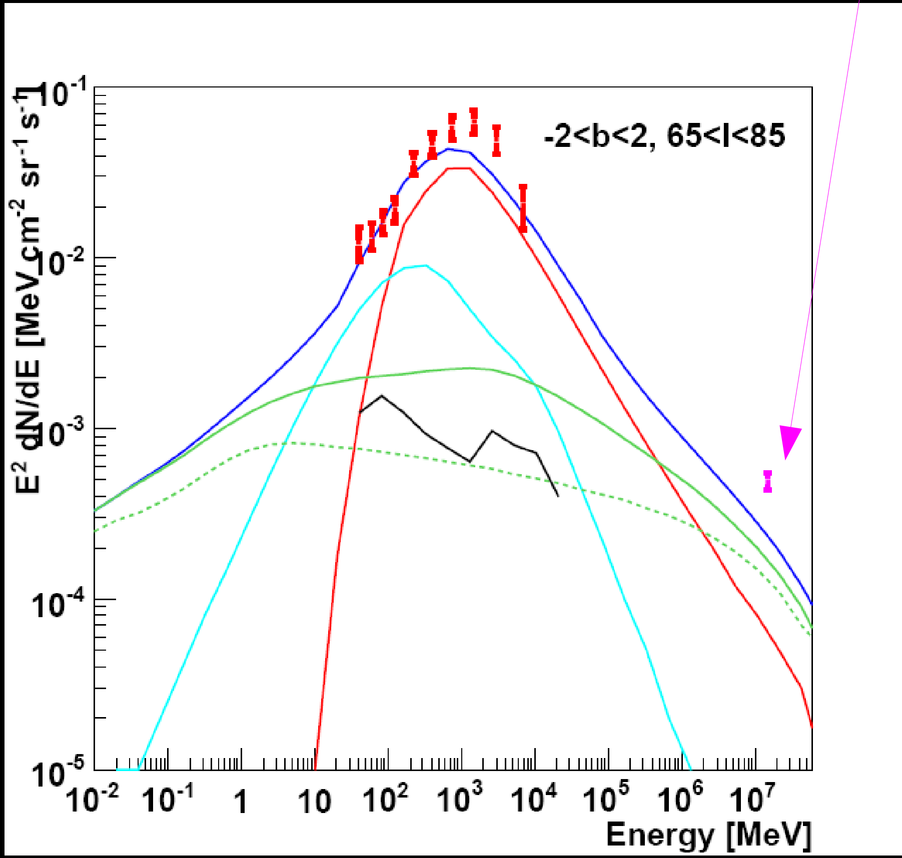
- **arXiv:0805.0417**

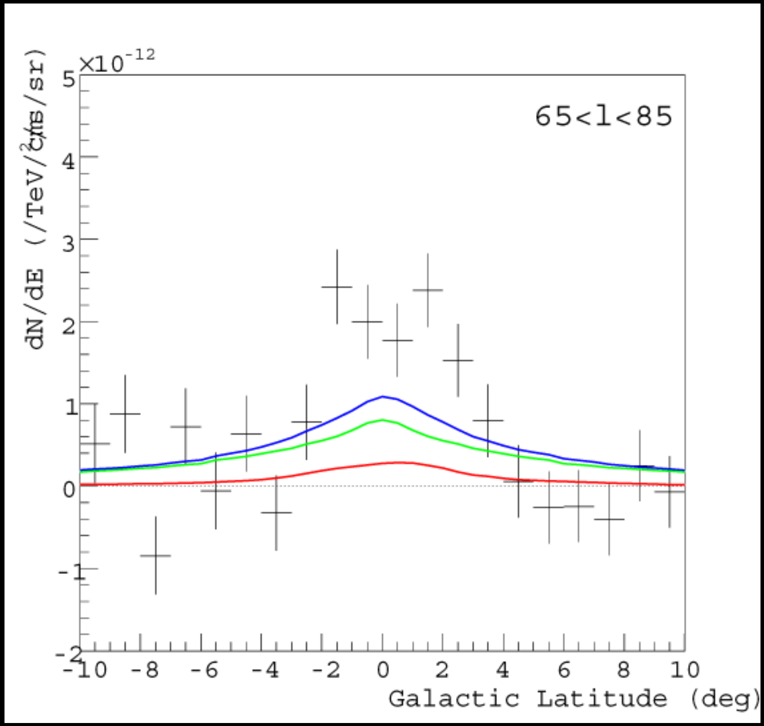
  Milagro, Abdo et al. 2008
  Fig: Petra Hüntemeyer

Cygnus Region

Excess over prediction

more CR in Cygnus ?





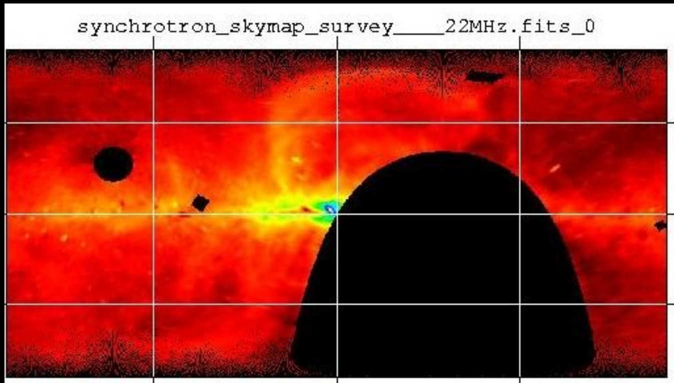
Milagro, Abdo et al. 2008
Fig: Petra Hüntemeyer

- **arXiv:0805.0417**

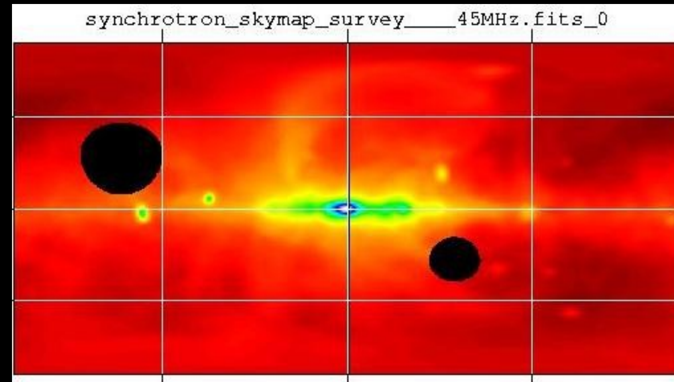
The final link...

radio ....

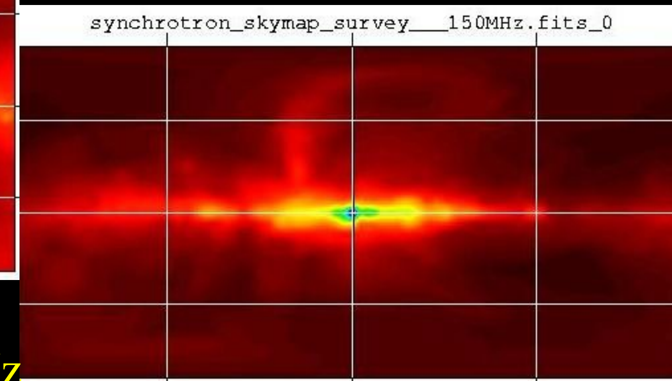
Continuum sky surveys



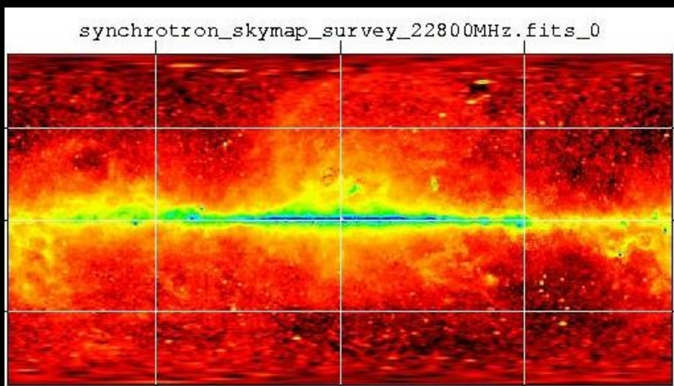
22 MHz



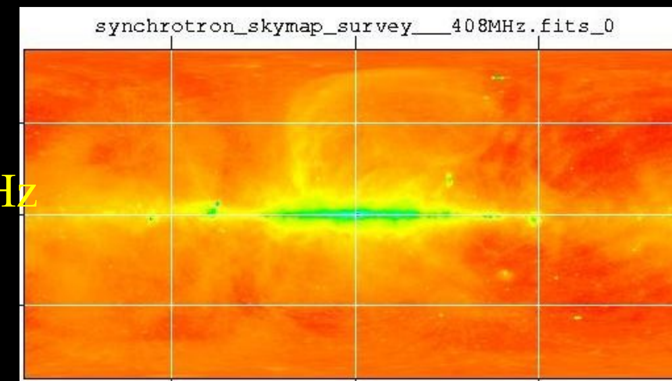
45 MHz



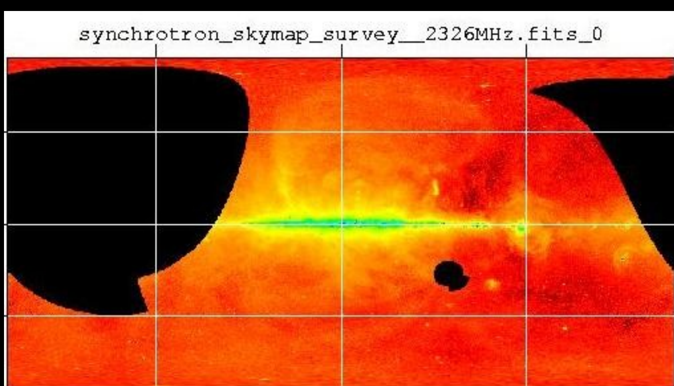
150 MHz



23 GHz

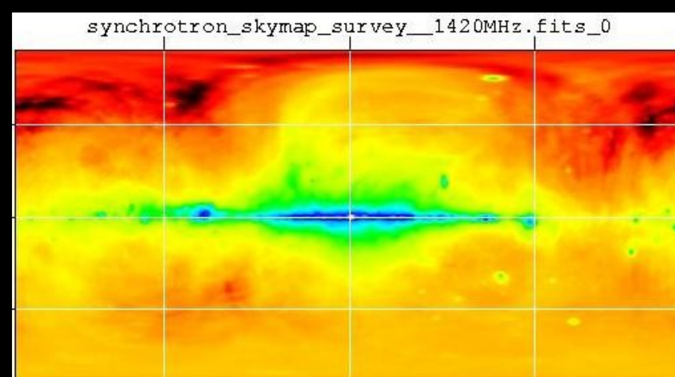


408 MHz

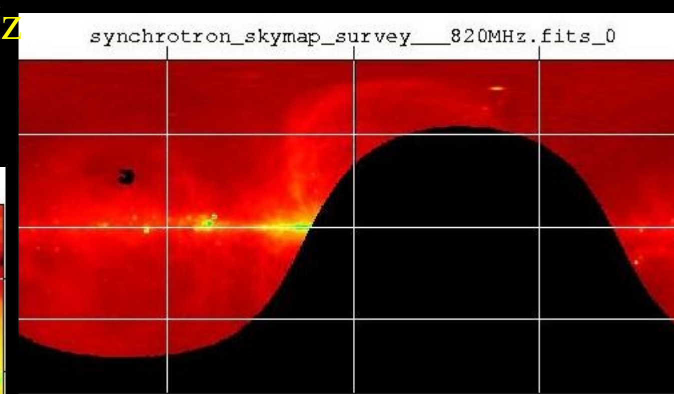


2.3 GHz

1.4 GHz



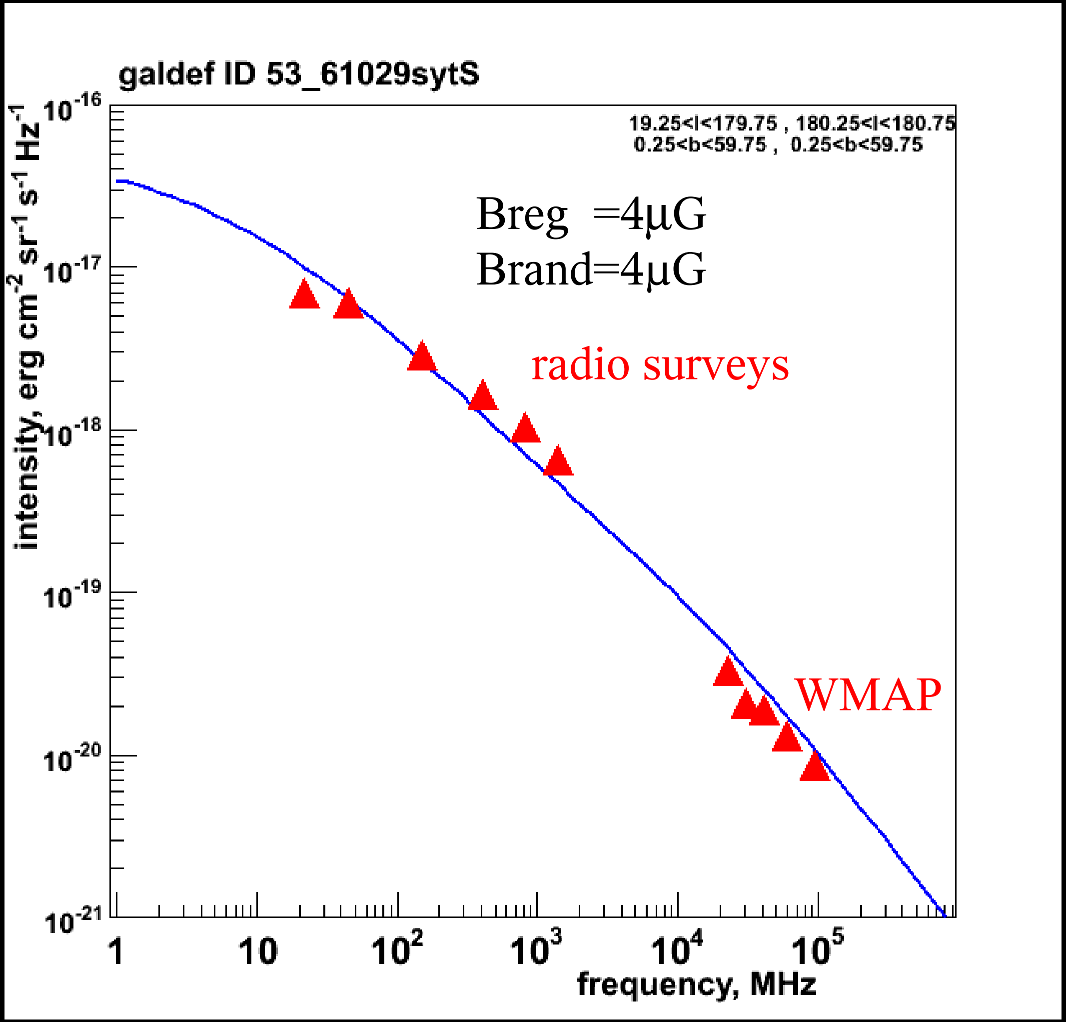
820 MHz



B-field: spiral + random, with cosmic-ray electrons + positrons

optimized model

RADIO SPECTRUM NORTHERN GALAXY

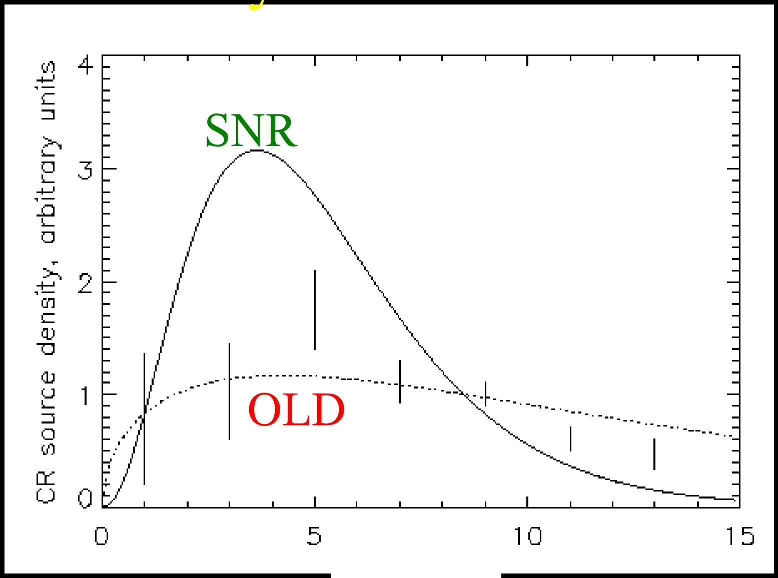


Model based on gamma-rays gives a good fit to the radio data

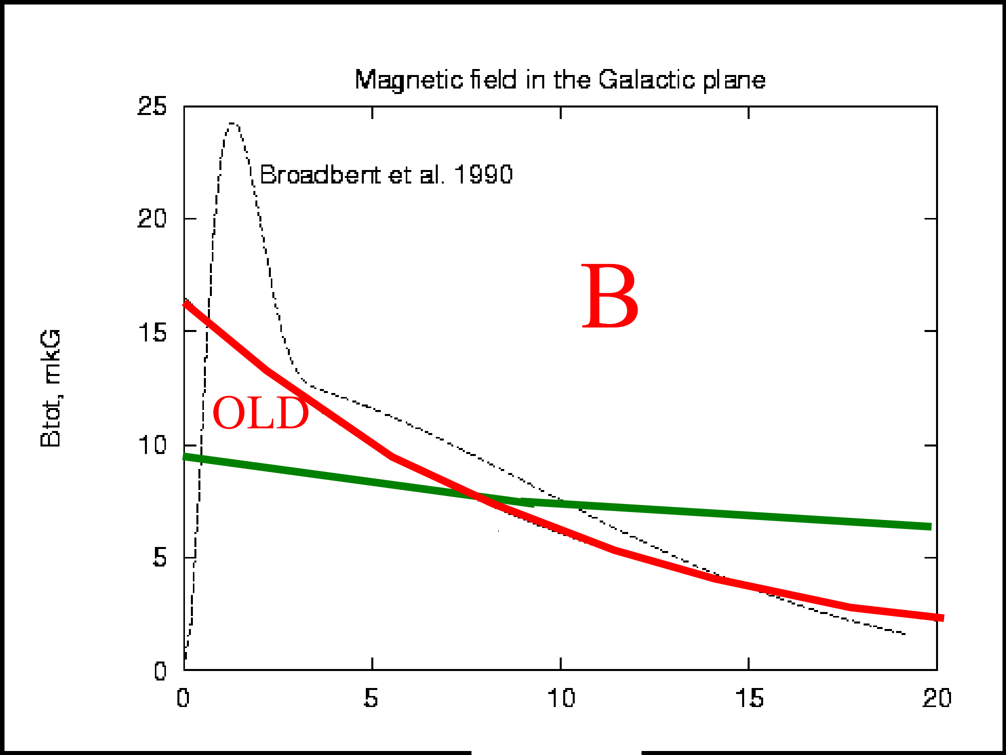
$$B(\mu G) = 8\, e^{-(R - R_o)/50\,\mathrm{kpc}\ -\ |z|/3\,\mathrm{kpc}}$$

essentially no R- dependence of B

cosmic-ray source distribution

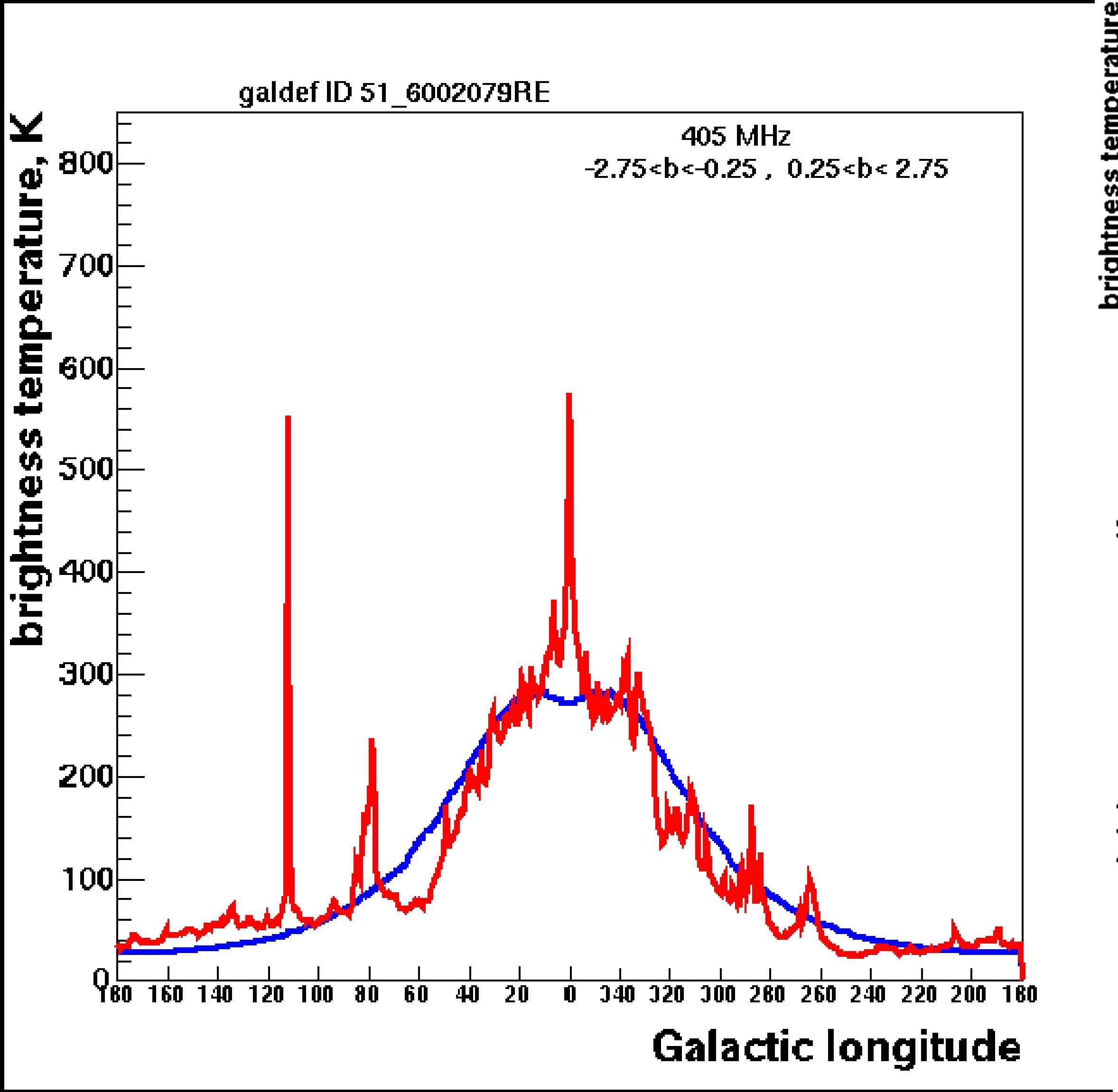


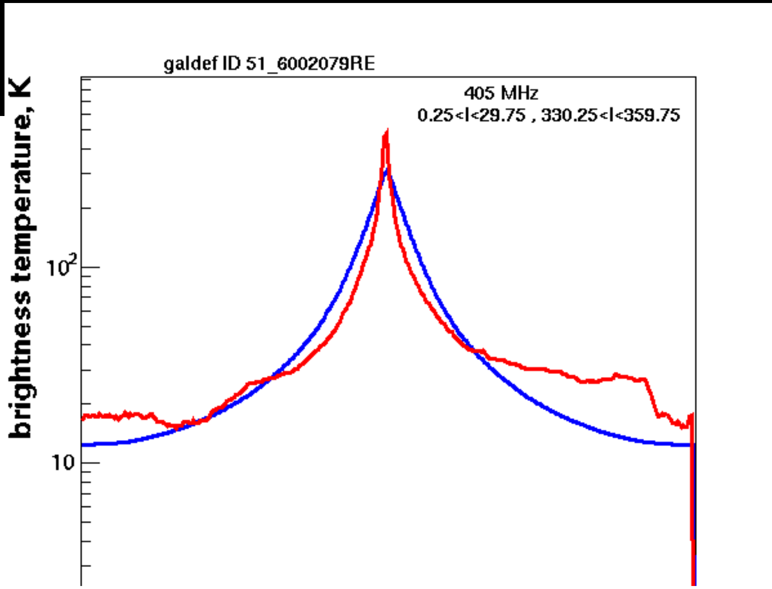
R, kpc

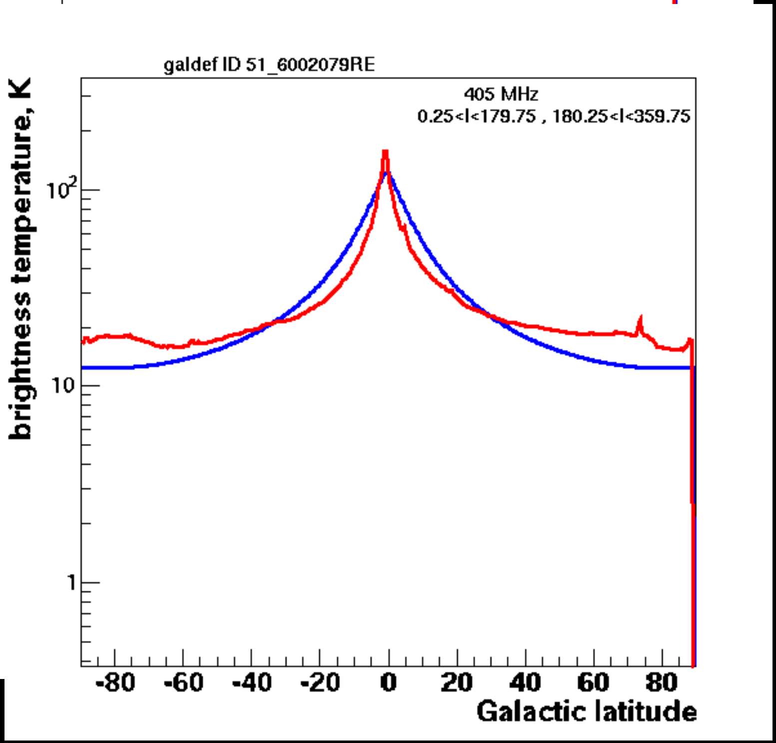


R, kpc

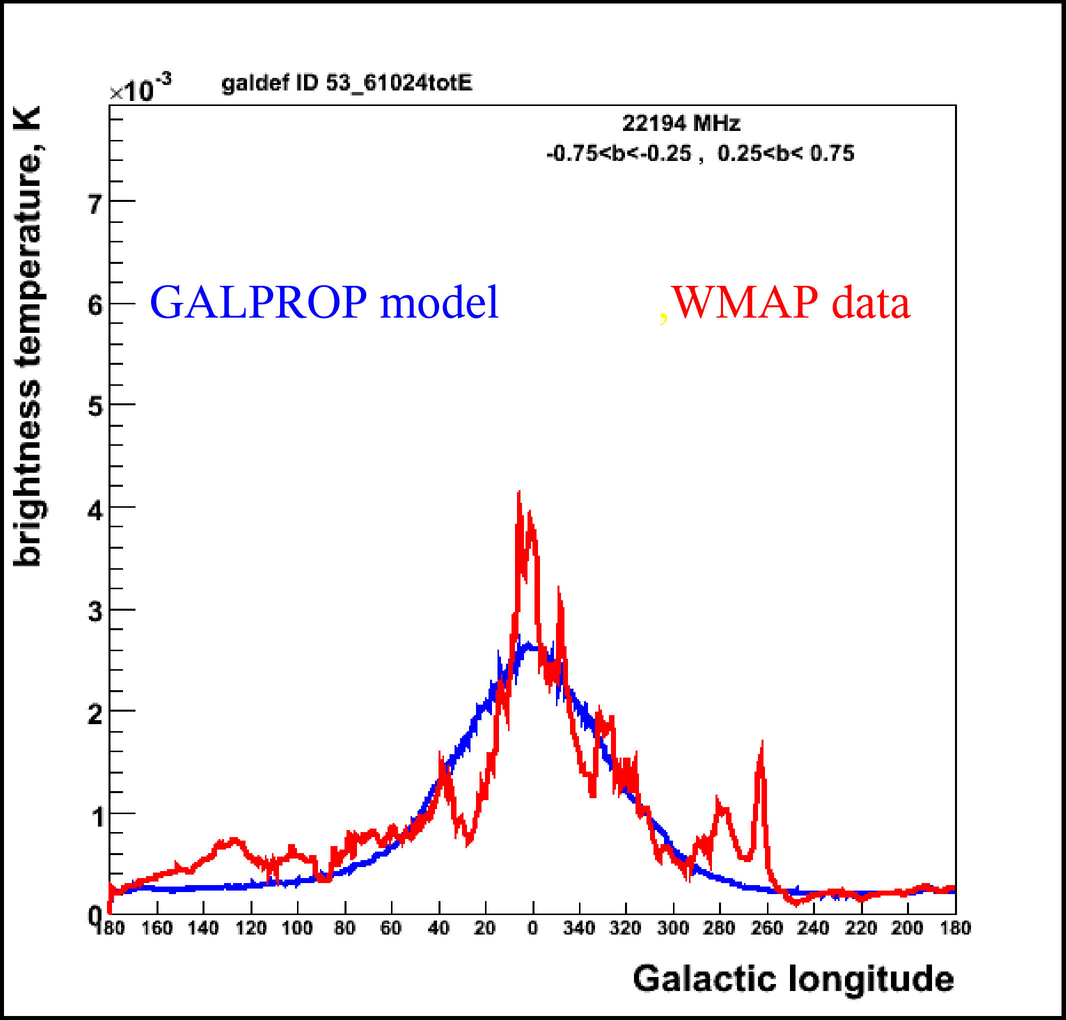
Best-fit **B** model using *galprop* analysis



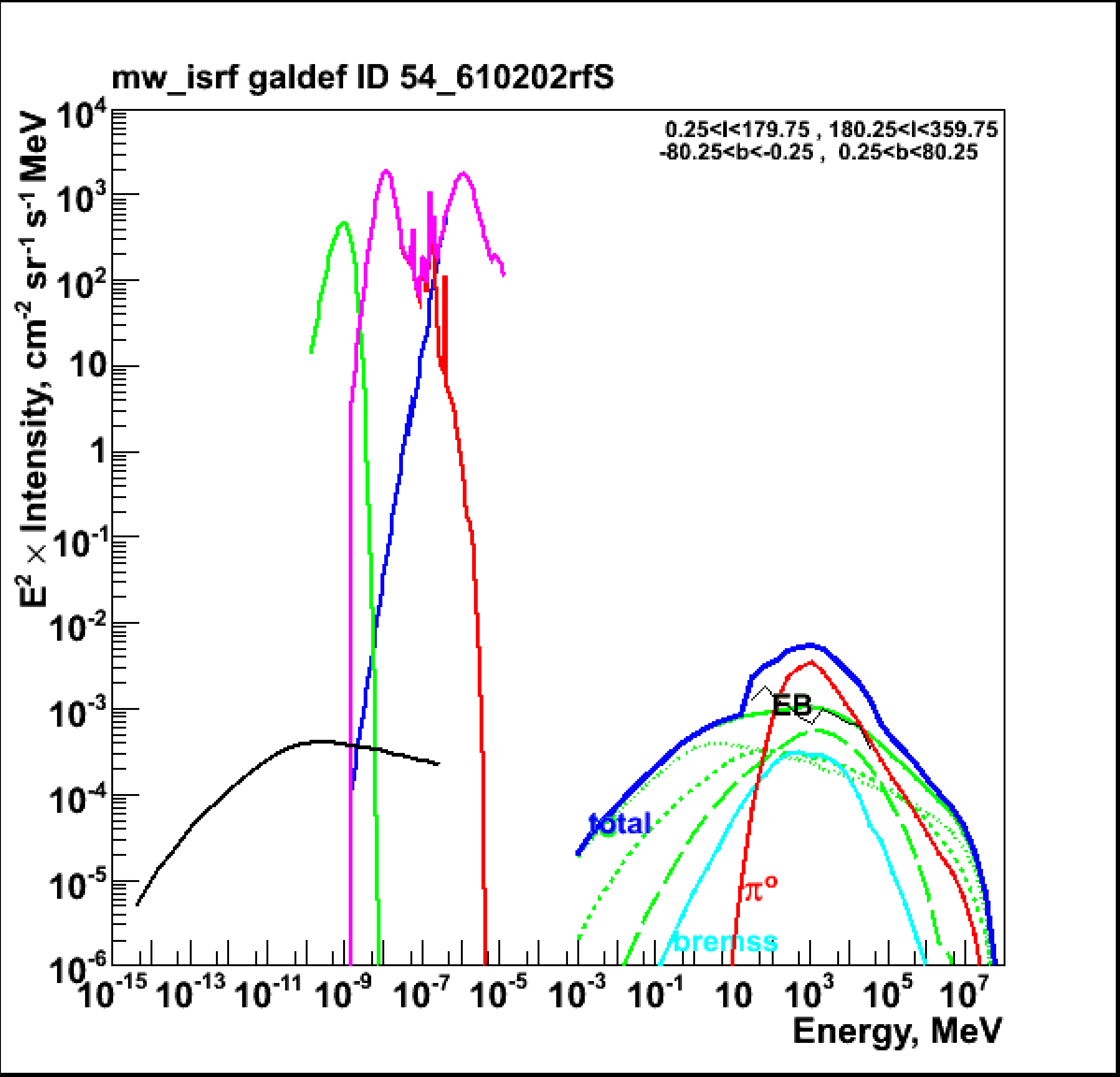




B-field: bisymmetric spiral + random component
23 GHz WMAP



Interstellar radiation over 20 decades of energy

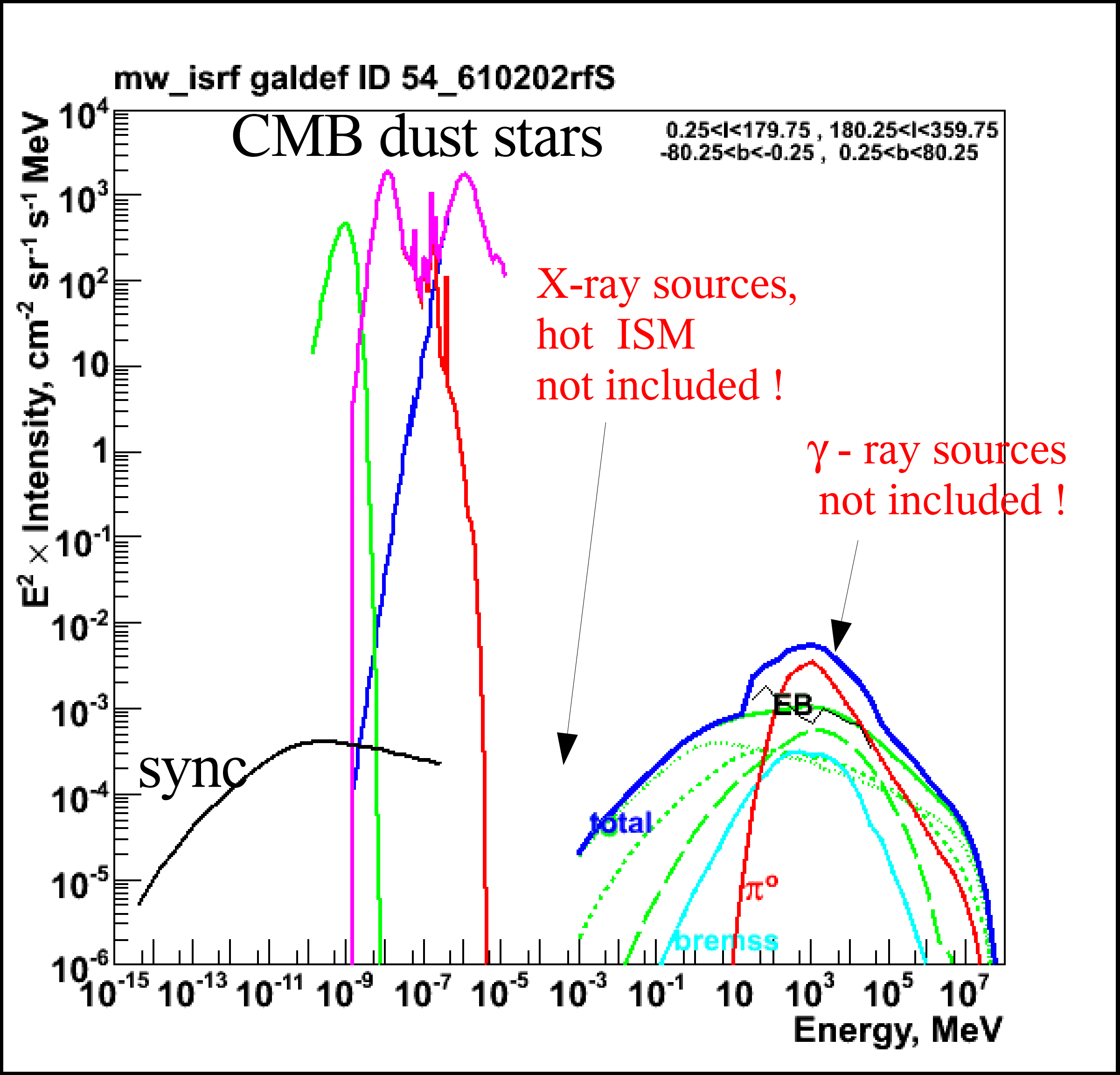


radio IR optical X γ

μwave

based on GALPROP model fitted to MW data

Interstellar radiation over 20 decades of energy



it's incomplete,
obviously
(in progress)

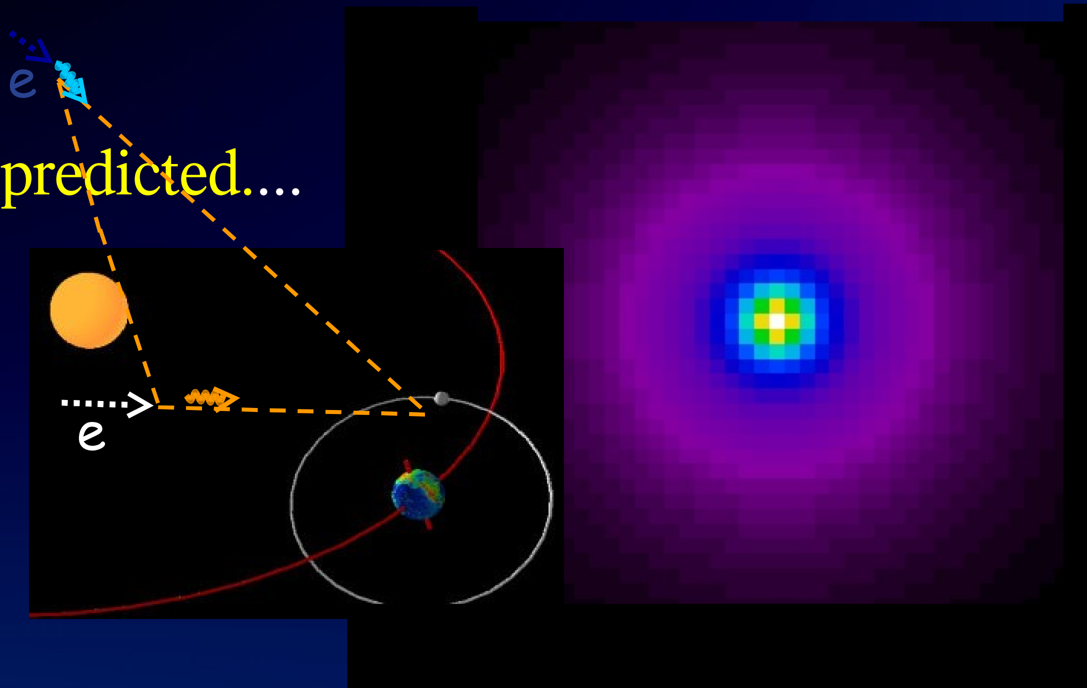
radio IR optical X γ

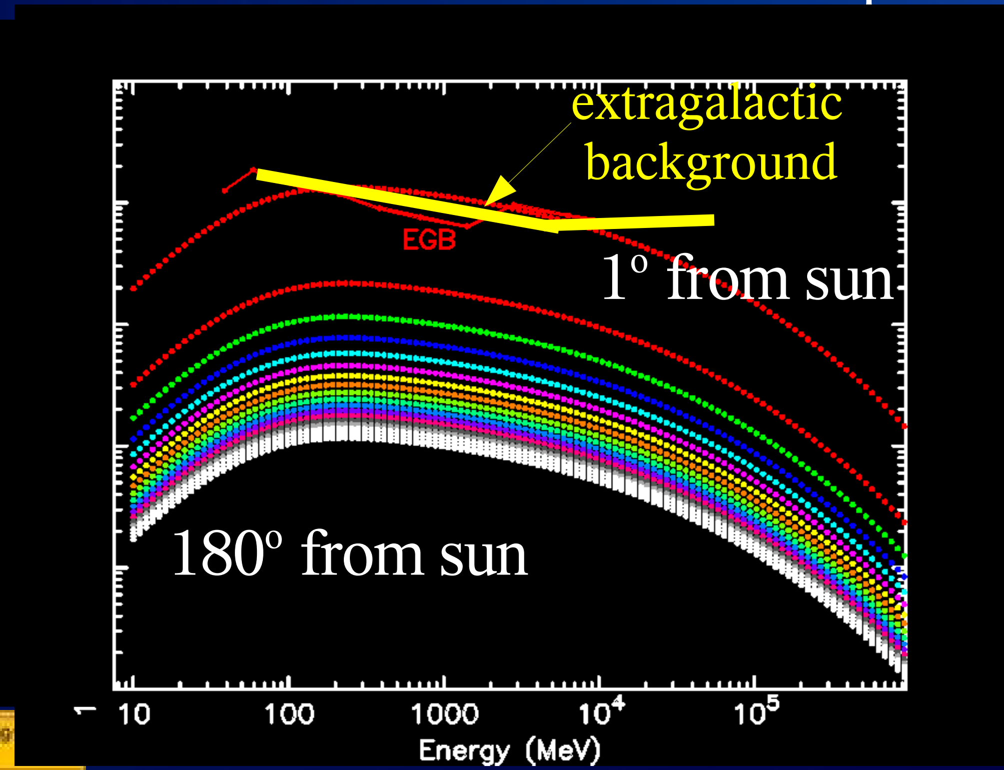
μwave

Nearer home: THE SUN

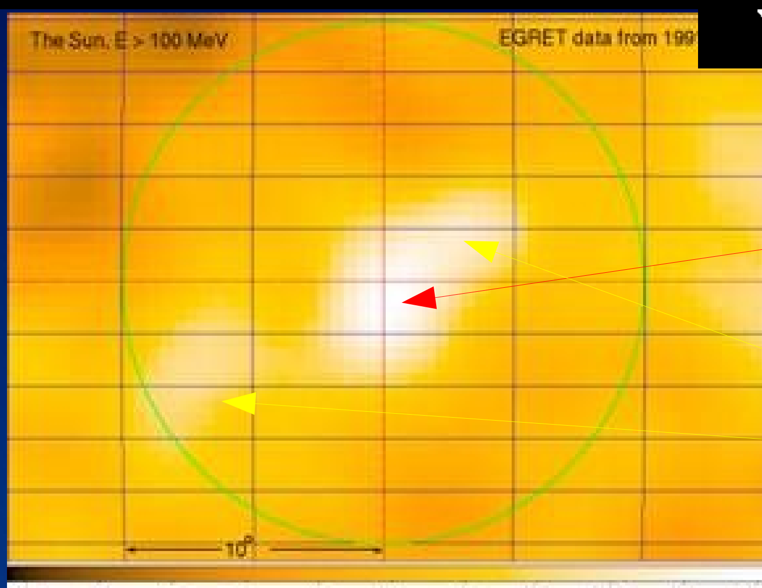
inverse Compton γ-rays by cosmic-ray electrons on solar radiation in heliosphere

predicted....





observed !
EGRET data



sun

paths of known sources

Orlando & Strong 2008

probes cosmic rays in inner heliosphere .... promising for GLAST

Outlook

GLAST operational , first results later this year

continue to exploit synergy

cosmic-rays - gammas – radio - microwave