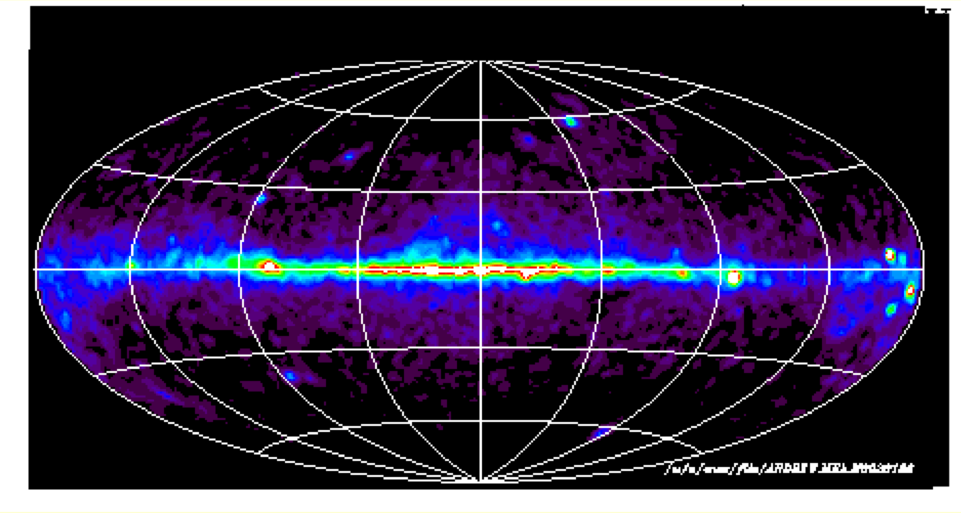
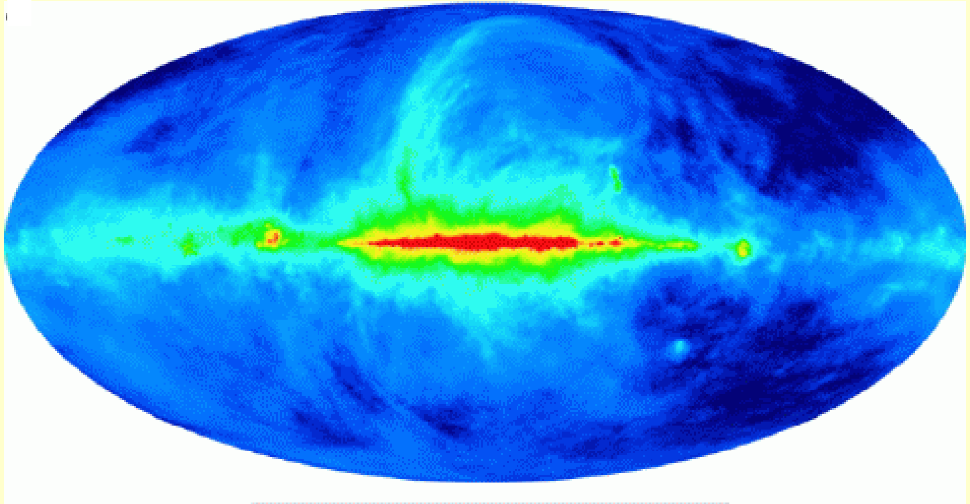
The Galactic magnetic field: the cosmic- ray / gamma-ray / radio connection

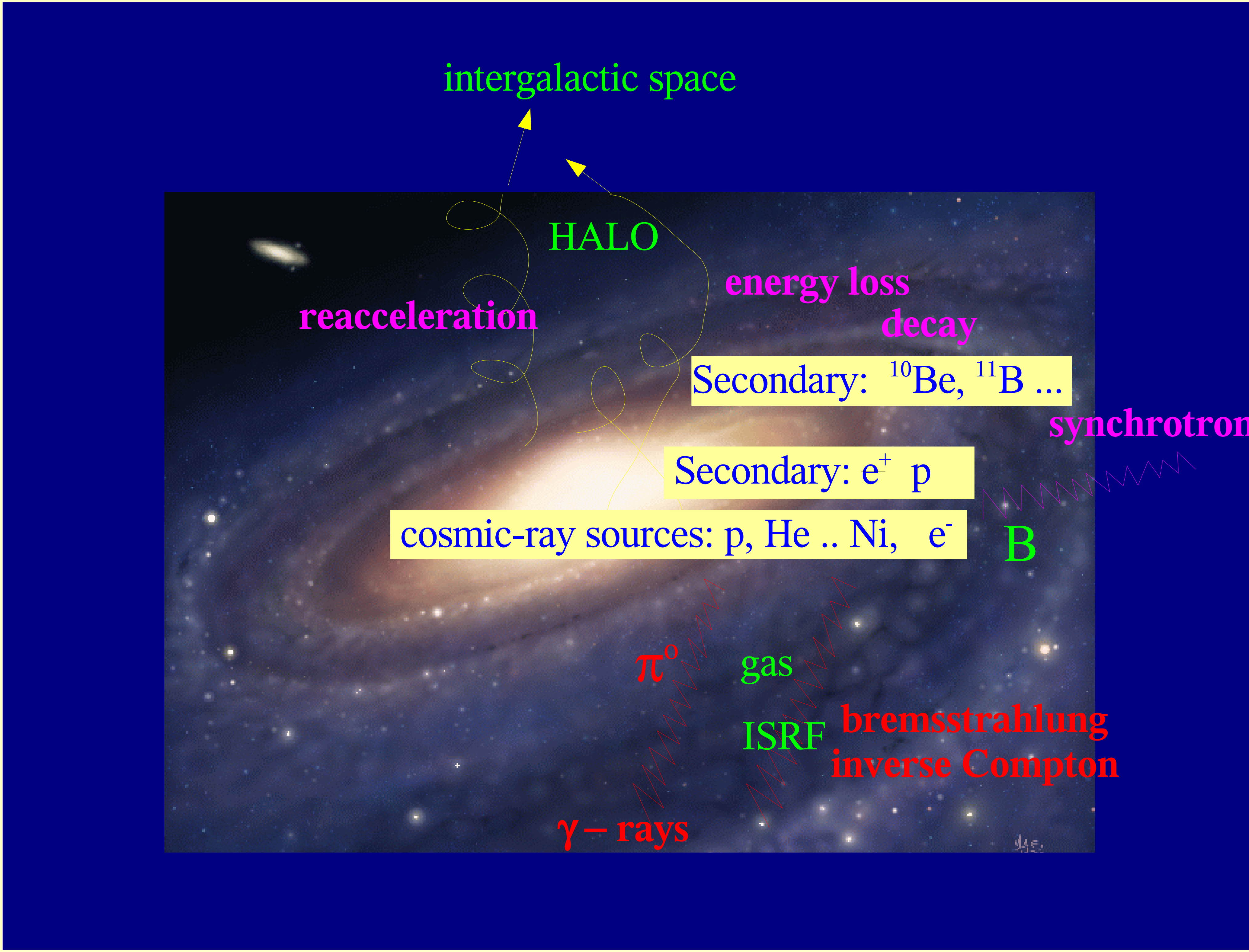


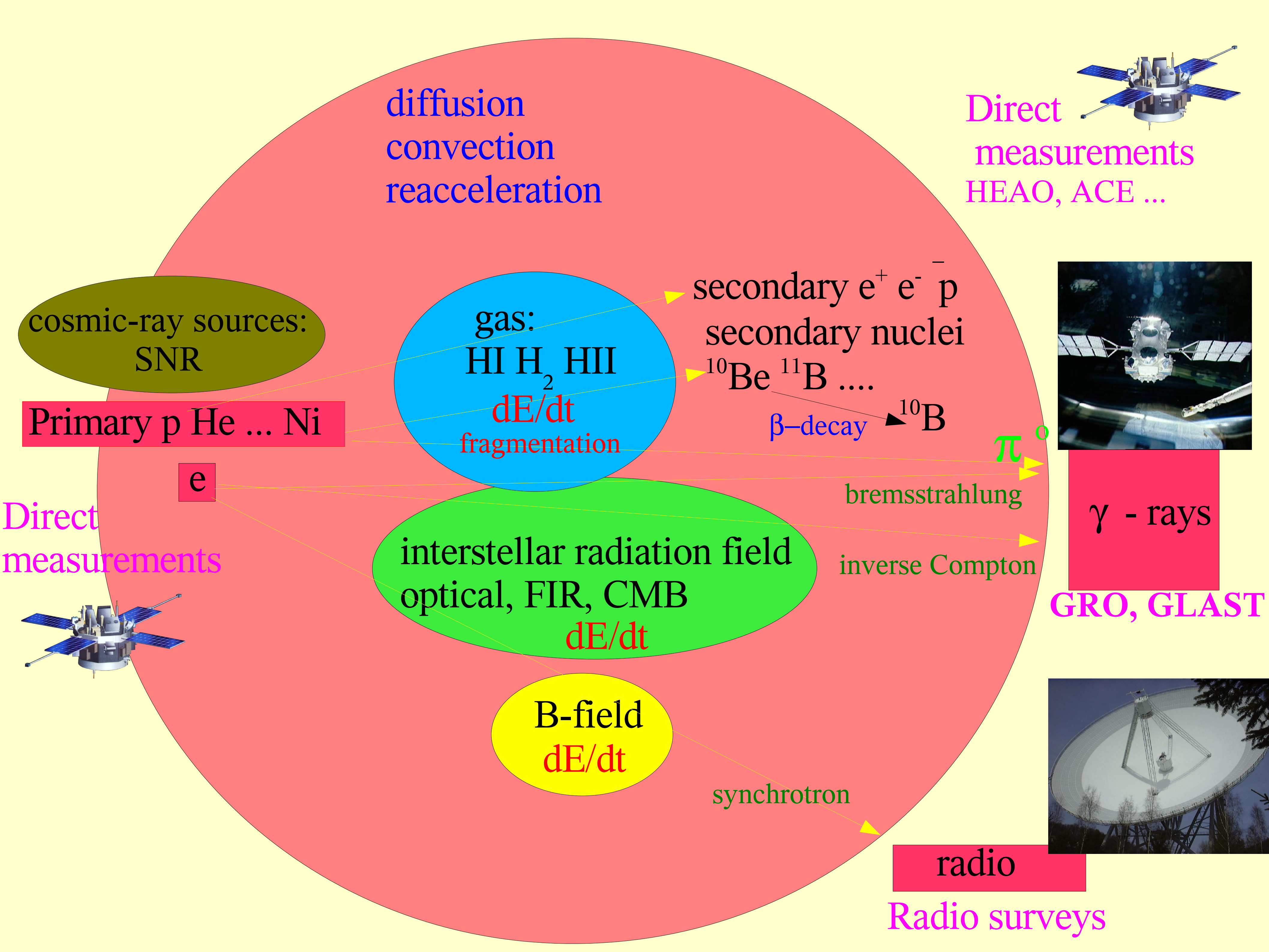


A. Strong, MPE Garching

The Large Scale Magnetic Field of the Galaxy, Princeton, 1 May 2007

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

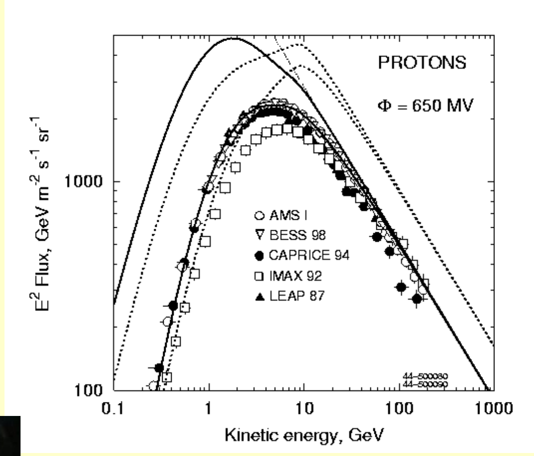

intergalactic space
HALO
reacceleration
energy loss
decay
Secondary: 10Be, 11B ...
synchrotron
Secondary: e+ p
cosmic-ray sources: p, He .. Ni, e-
B
π0
gas
ISRF
bremsstrahlung
inverse Compton
γ – rays

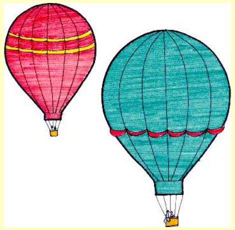

diffusion
convection
reacceleration
Direct
measurements
HEAO, ACE ...
cosmic-ray sources:
SNR
gas:
HI H_2 HII
dE/dt
fragmentation
secondary e^+ e^- $\bar{p}$
secondary nuclei
^{10}Be ^{11}B ....
β–decay
^{10}B
Primary p He ... Ni
e
π^o
bremsstrahlung
γ - rays
inverse Compton
GRO, GLAST
Direct
measurements
interstellar radiation field
optical, FIR, CMB
dE/dt
B-field
dE/dt
synchrotron
radio
Radio surveys

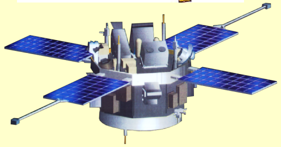
The **goal** : use *all* types of data in self-consistent way to test models of cosmic-ray propagation.

Observed *directly, near Sun:*

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

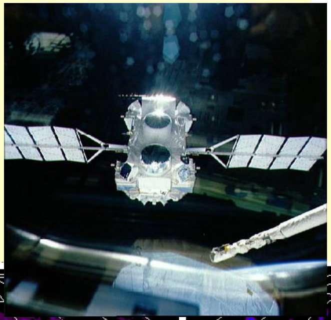


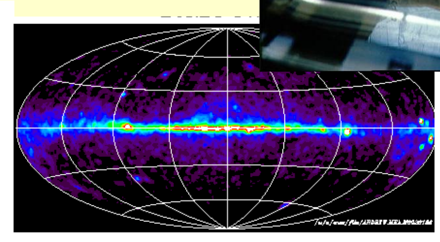


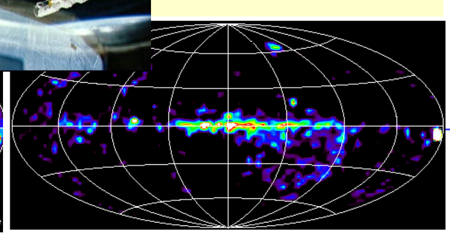


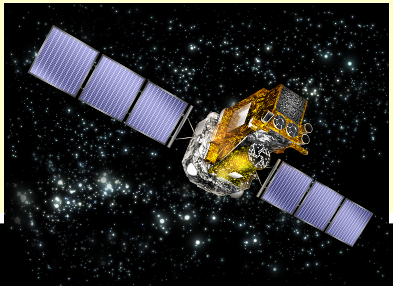
Observed *from whole Galaxy:*

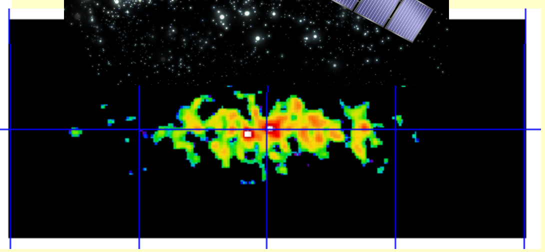
γ - rays



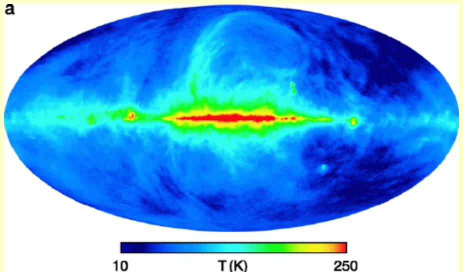








synchrotron



Part 1 : the model: tuning to cosmic-rays and γ-rays OLD

Part 2 : implications for synchrotron & **B** NEW

(in progress, mainly with this conference in view)

galprop

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

project running since 1996 (with Igor Moskalenko, Olaf Reimer, Troy Porter)
c++
galprop code: publicly available many users
continuous development, *with dedicated Website galprop.stanford.edu*
new:
non-linear effects of cosmic rays on propagation
anisotropic inverse Compton scattering

Adopted as Standard Model for NASA's GLAST to be launched in December

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

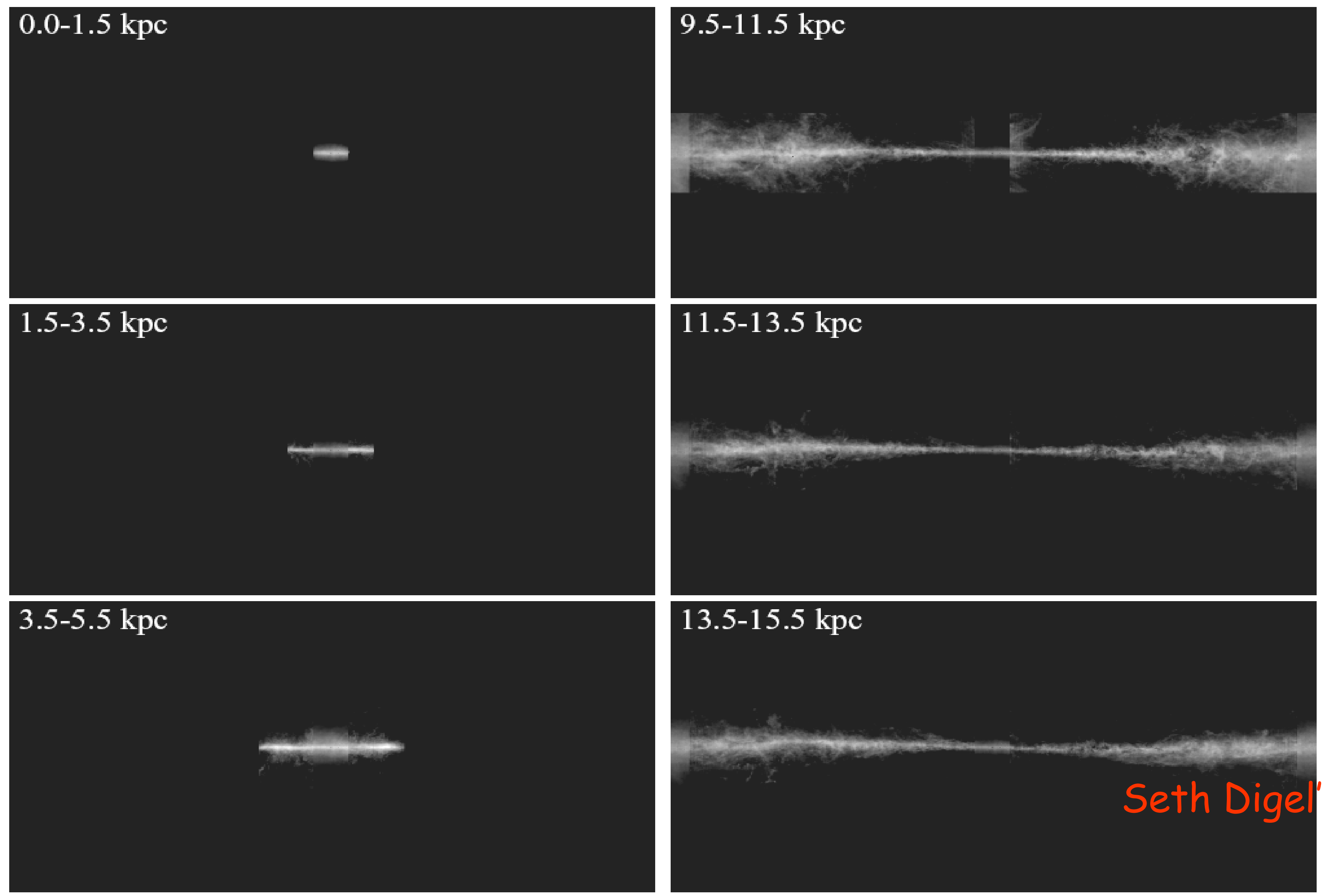
More about *galprop*:

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).

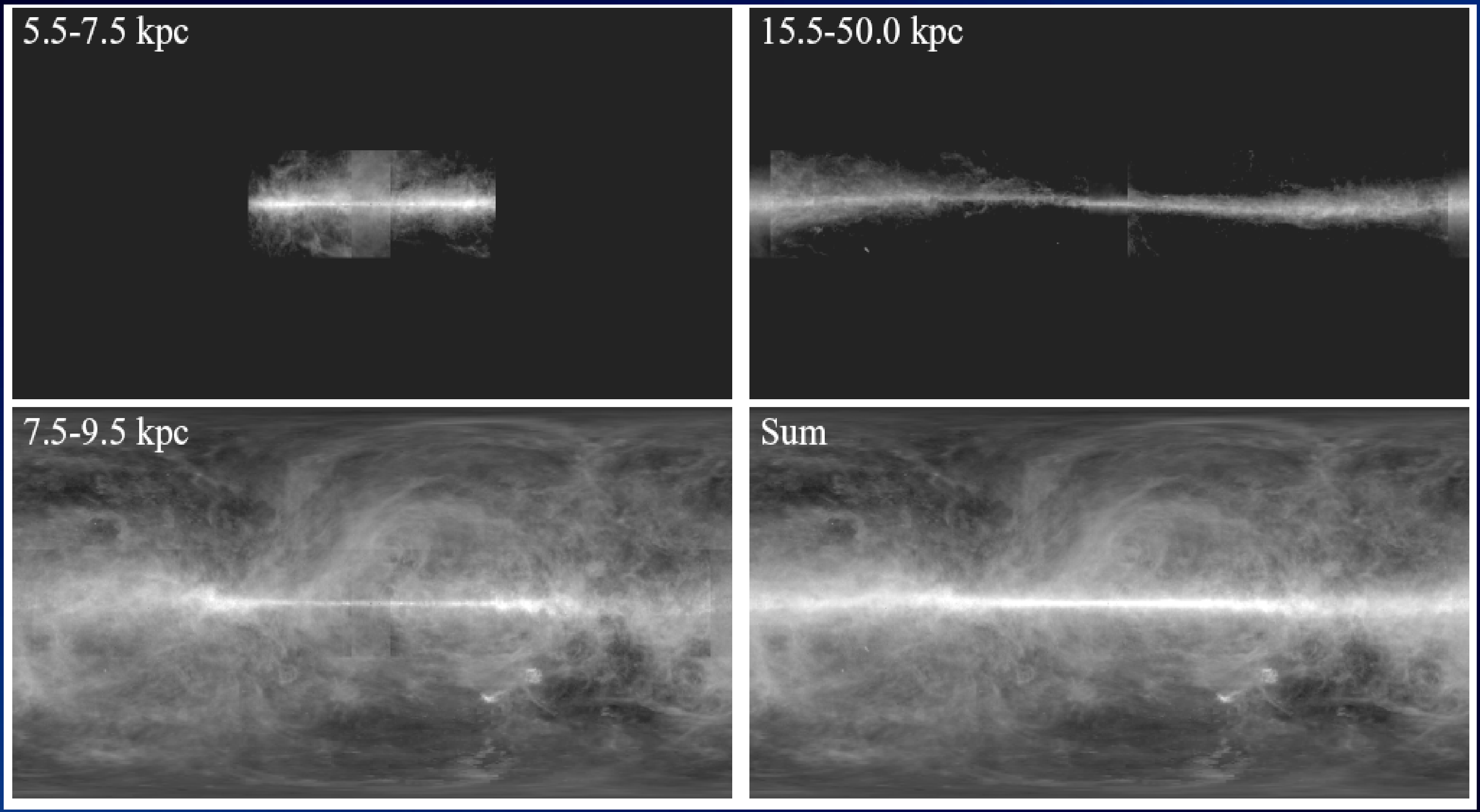
Output (as FITS files)
cosmic-ray spectra in 3D
gamma-ray skymaps by process
synchrotron skymaps

Gas Rings: HI (Inner & Outer Galaxy)



Seth Digel'05

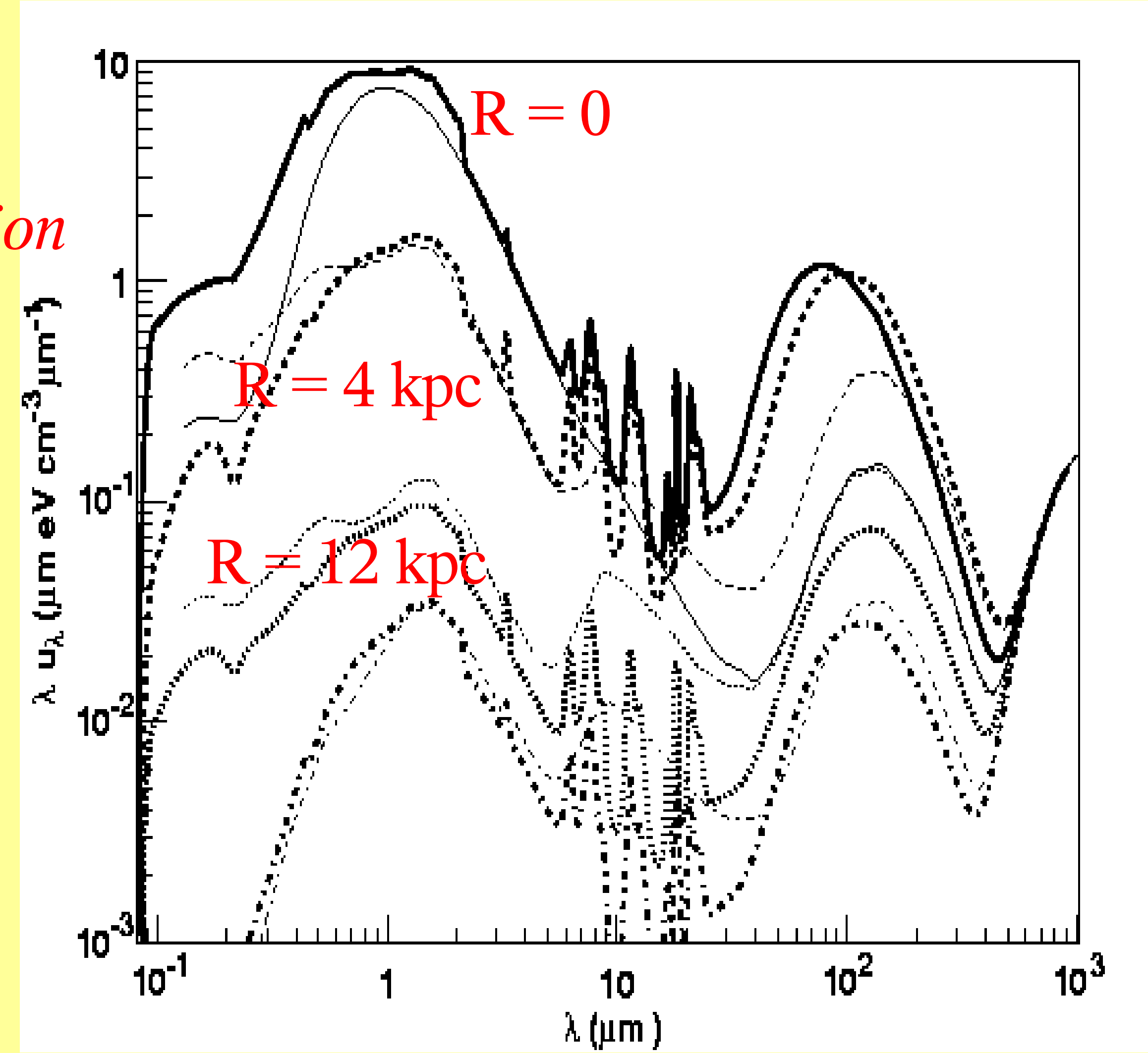
Gas Rings: HI (Our Neighborhood)



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*



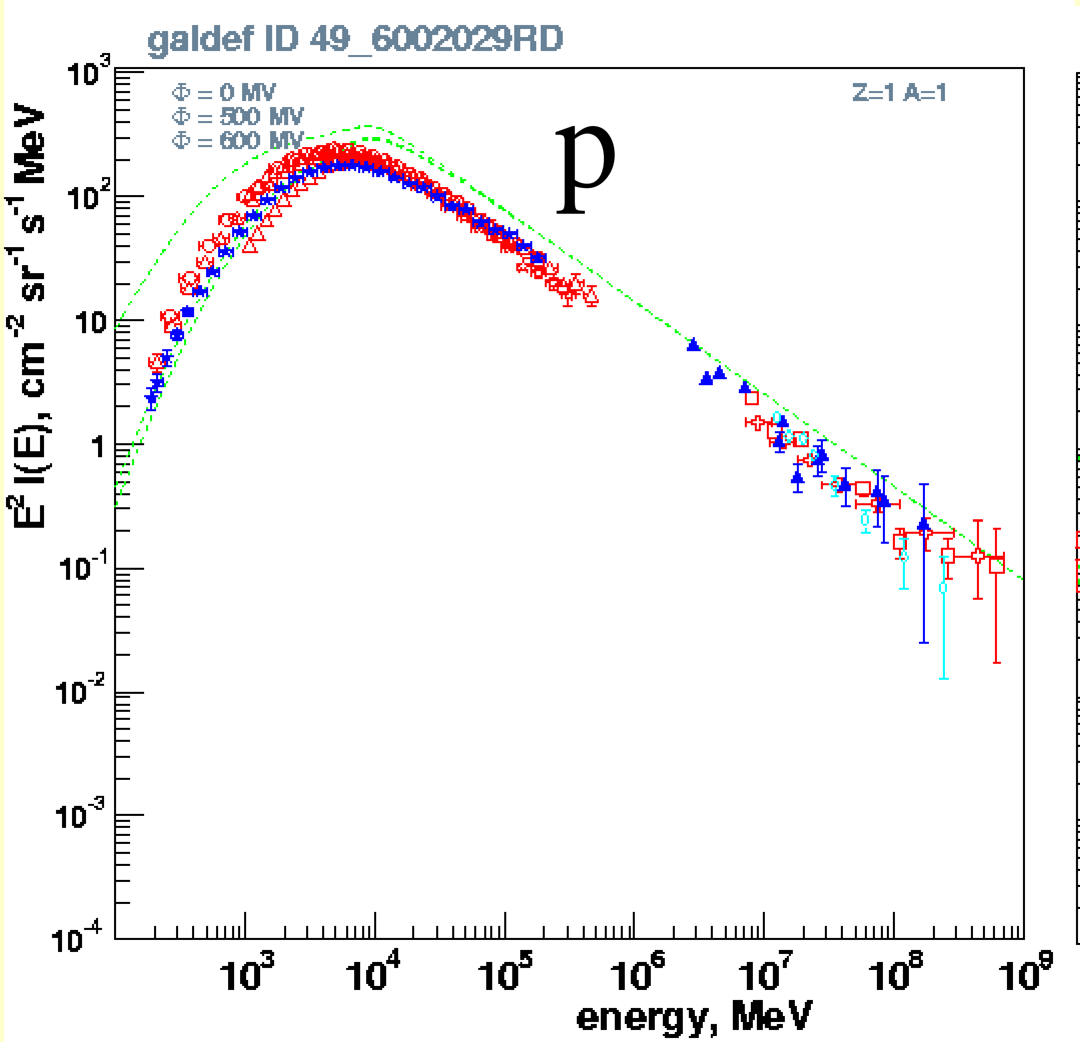
UV optical IR FIR CMB

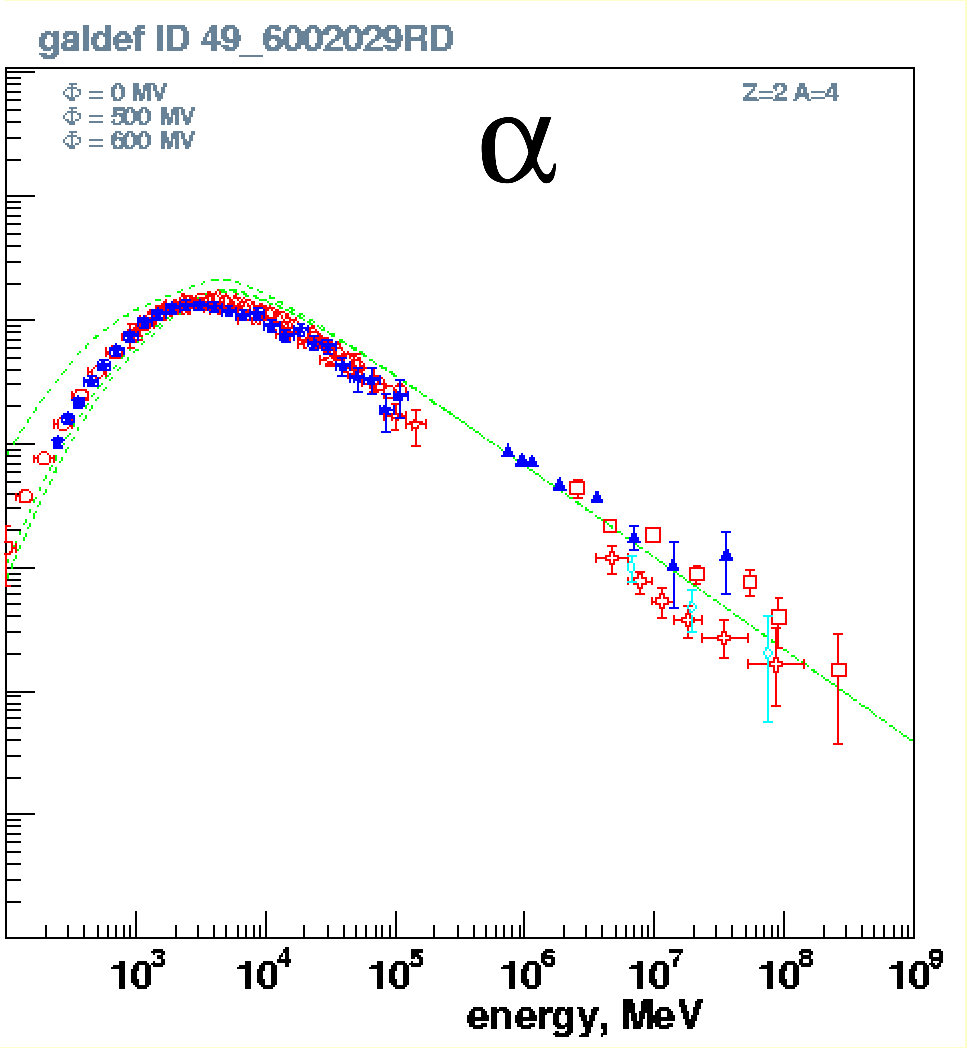
Recent review of cosmic-ray propagation:

Strong, Moskalenko, Ptuskin:
Annual Review Nuclear and Particle Science, vol 57

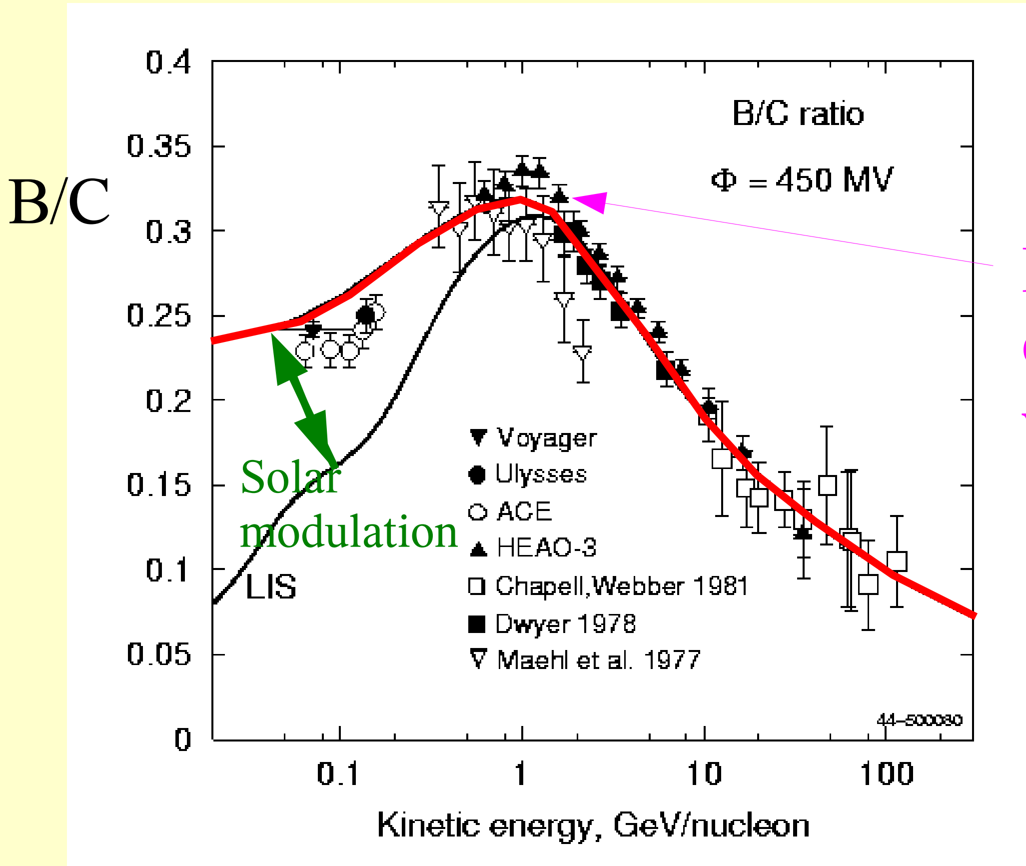
astro-ph/0701517

Key data: primary cosmic-ray spectra

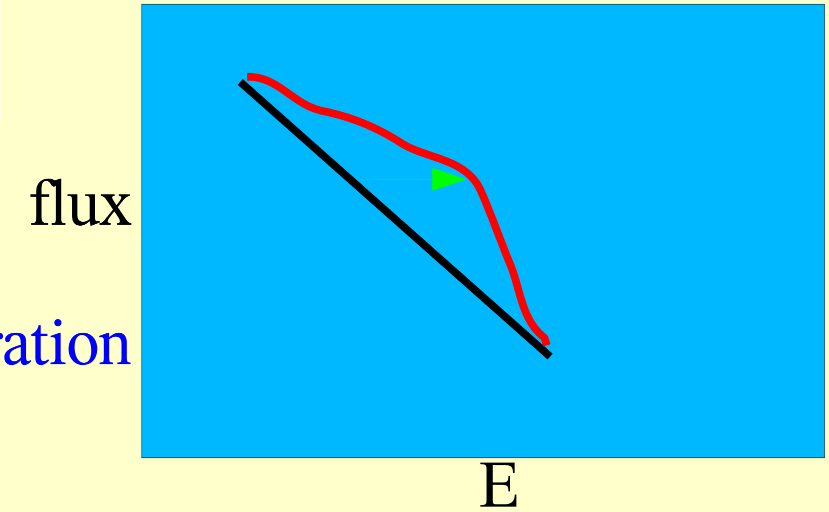




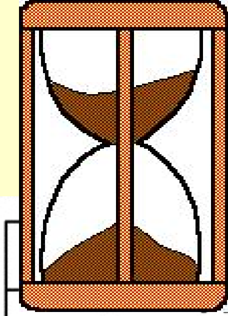
Key data: cosmic-ray secondary/primary ratios: e.g. Boron/Carbon probes cosmic-ray propagation parameters



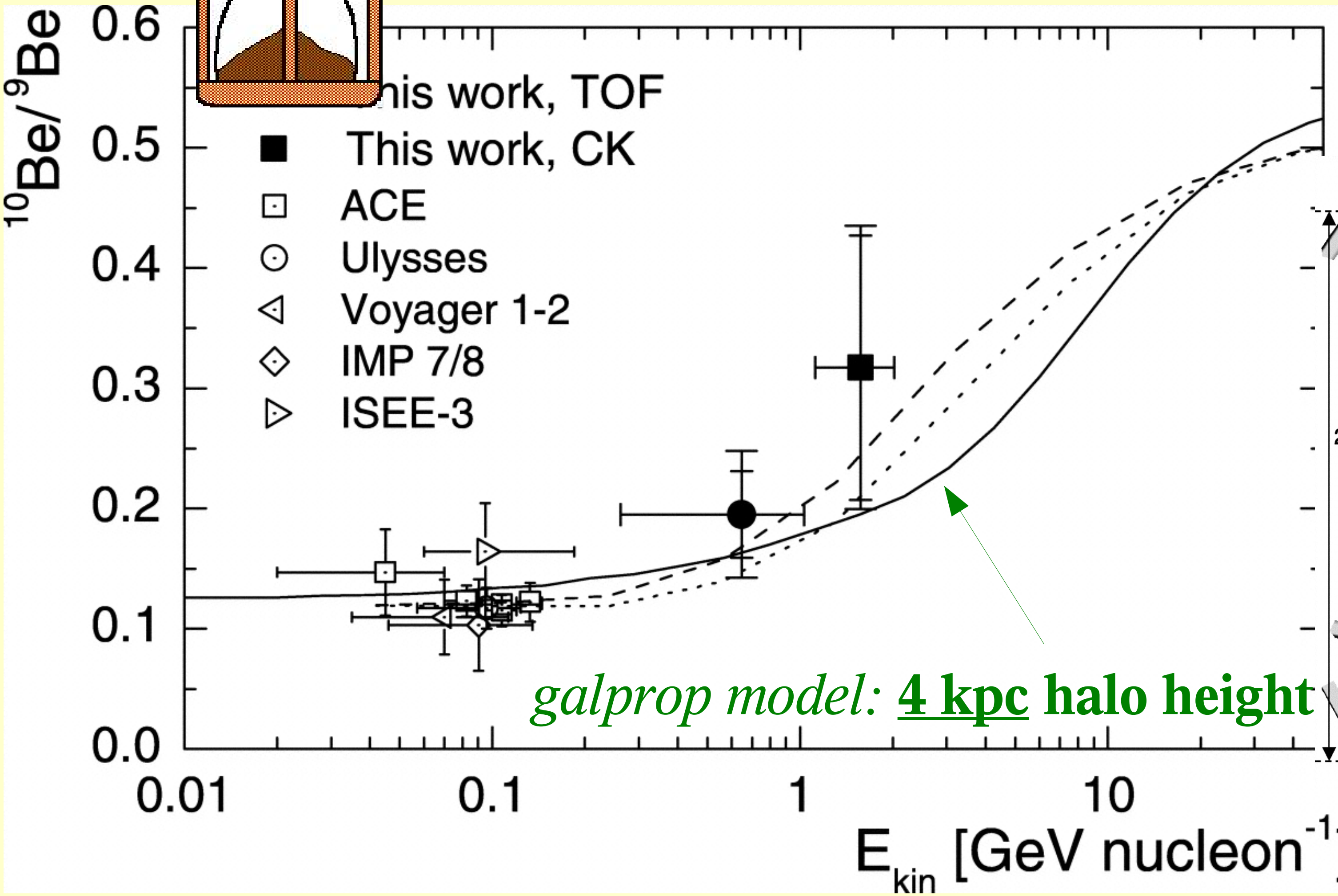
Peak in B/C can be explained by **diffusive reacceleration** with Kolmogorov $D \sim \beta\, p^{1/3}$



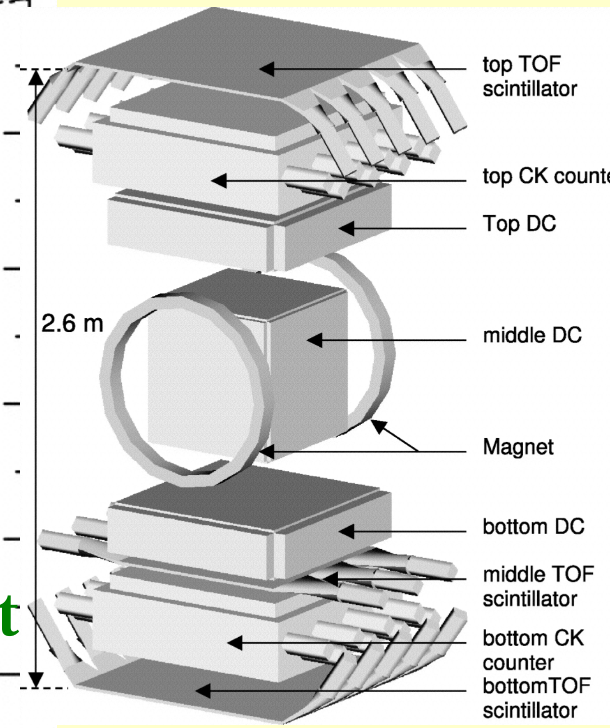
Energy-dependent diffusive reacceleration produces bump in particle spectrum



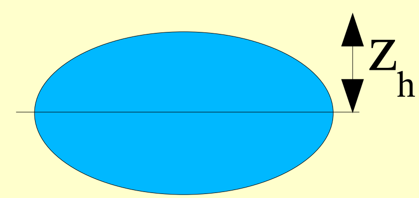
Radioactive nuclei: cosmic-ray clocks set limits on size of Galactic halo



recent data:
ACE, ISOMAX

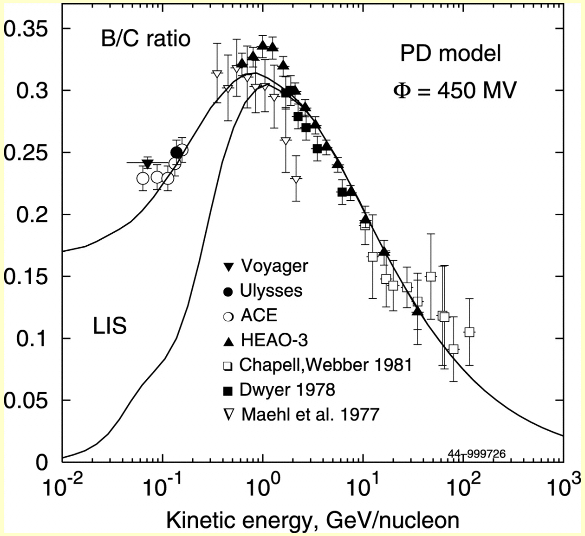


^{10}Be *decays* in 10^6 years, **^{9}Be** is *stable*
so ratio sensitive to cosmic-ray confinement time, halo size

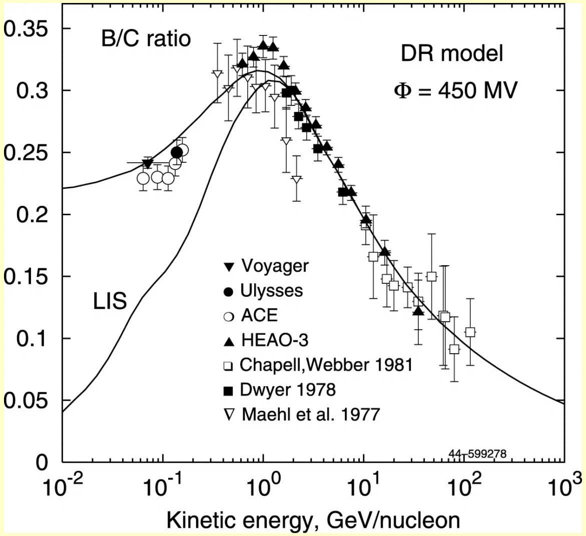


Hams et al. 2004 ApJ 611, 892

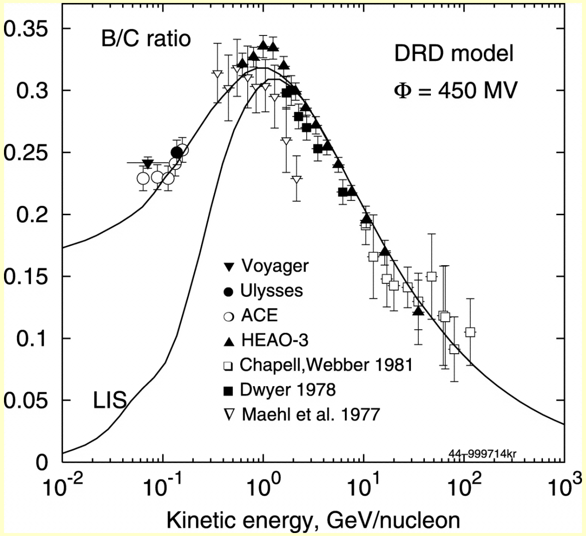
plain diffusion



diffusive reacceleration



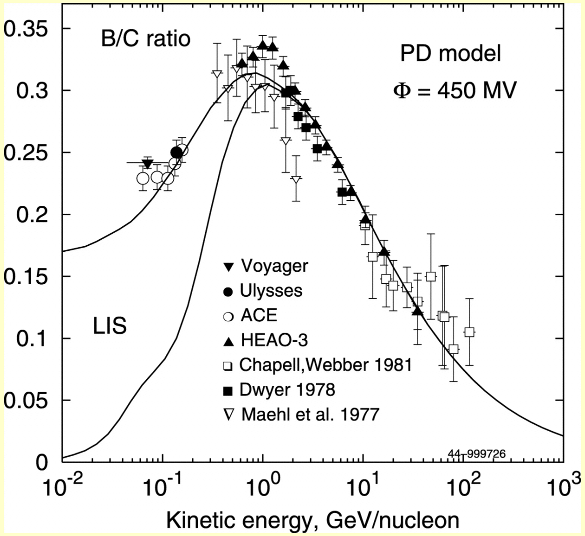
wave damping

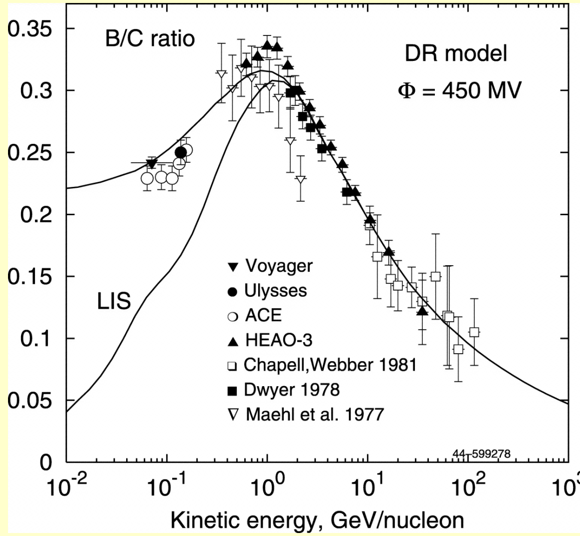


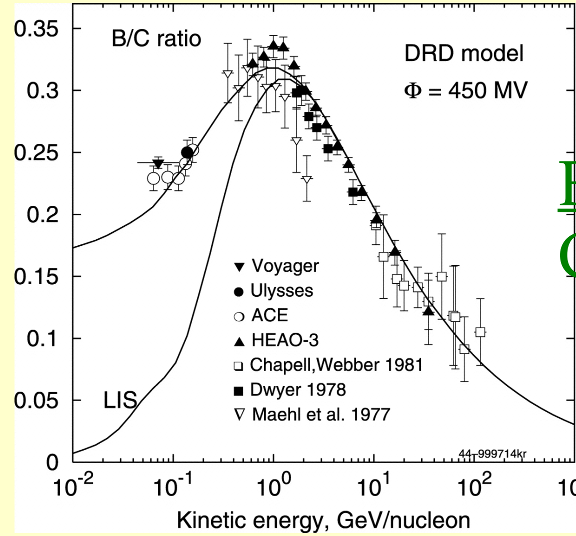
first adjust parameters to fit Boron/Carbon

Ptuskin et al. 2006 ApJ 642, 902

plain diffusion   diffusive reacceleration   wave damping



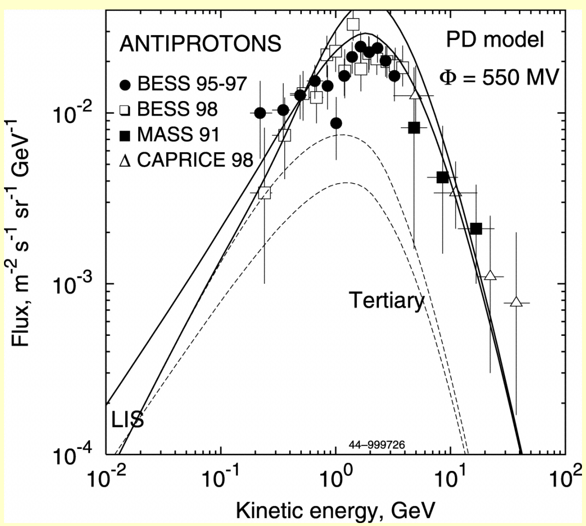


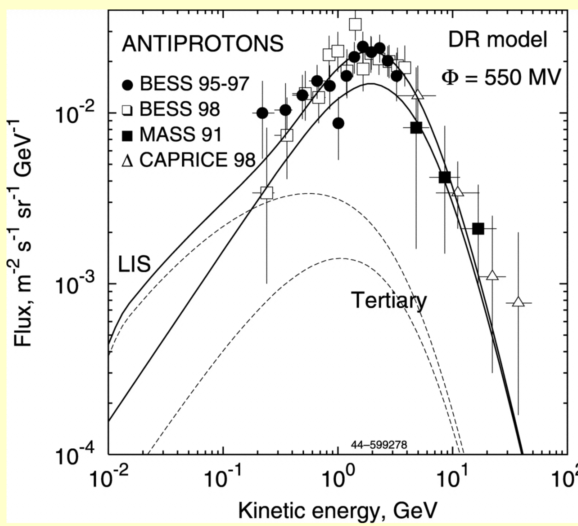


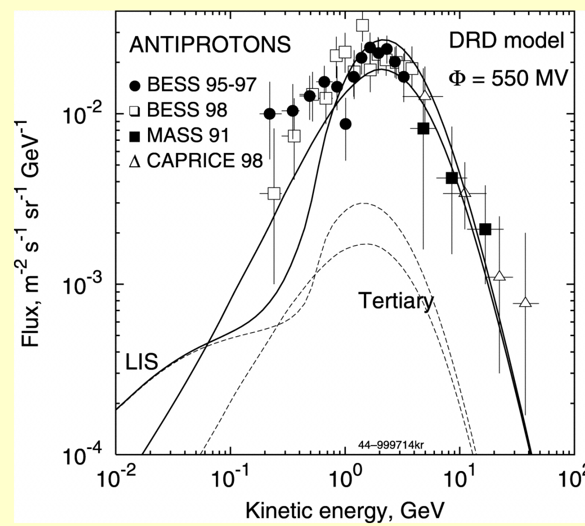
Boron
Carbon

then predict the other cosmic-ray spectra

antiprotons





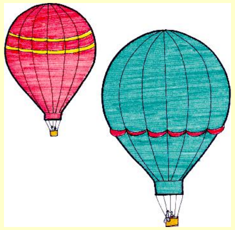


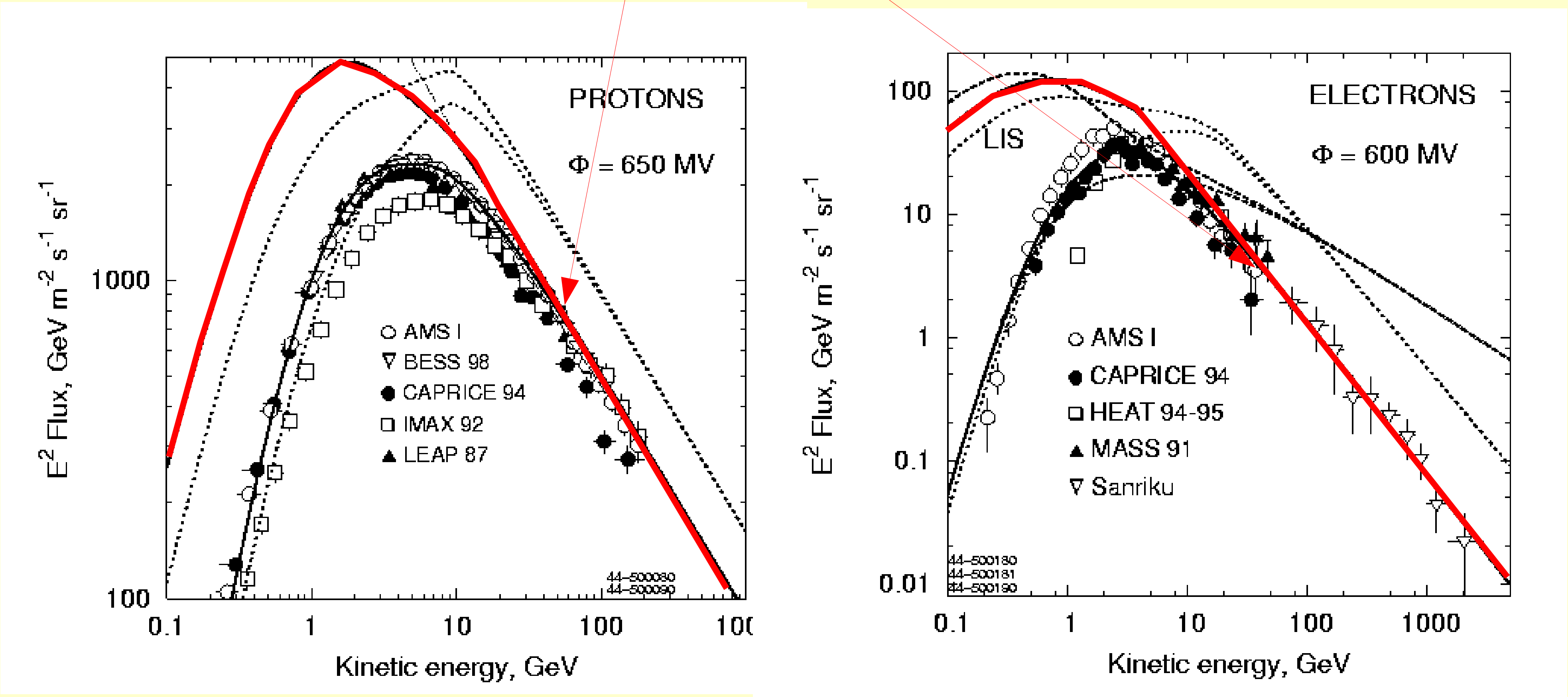
Ptuskin et al. 2006 ApJ 642, 902

γ - rays

Modelling diffuse Galactic gamma-rays:

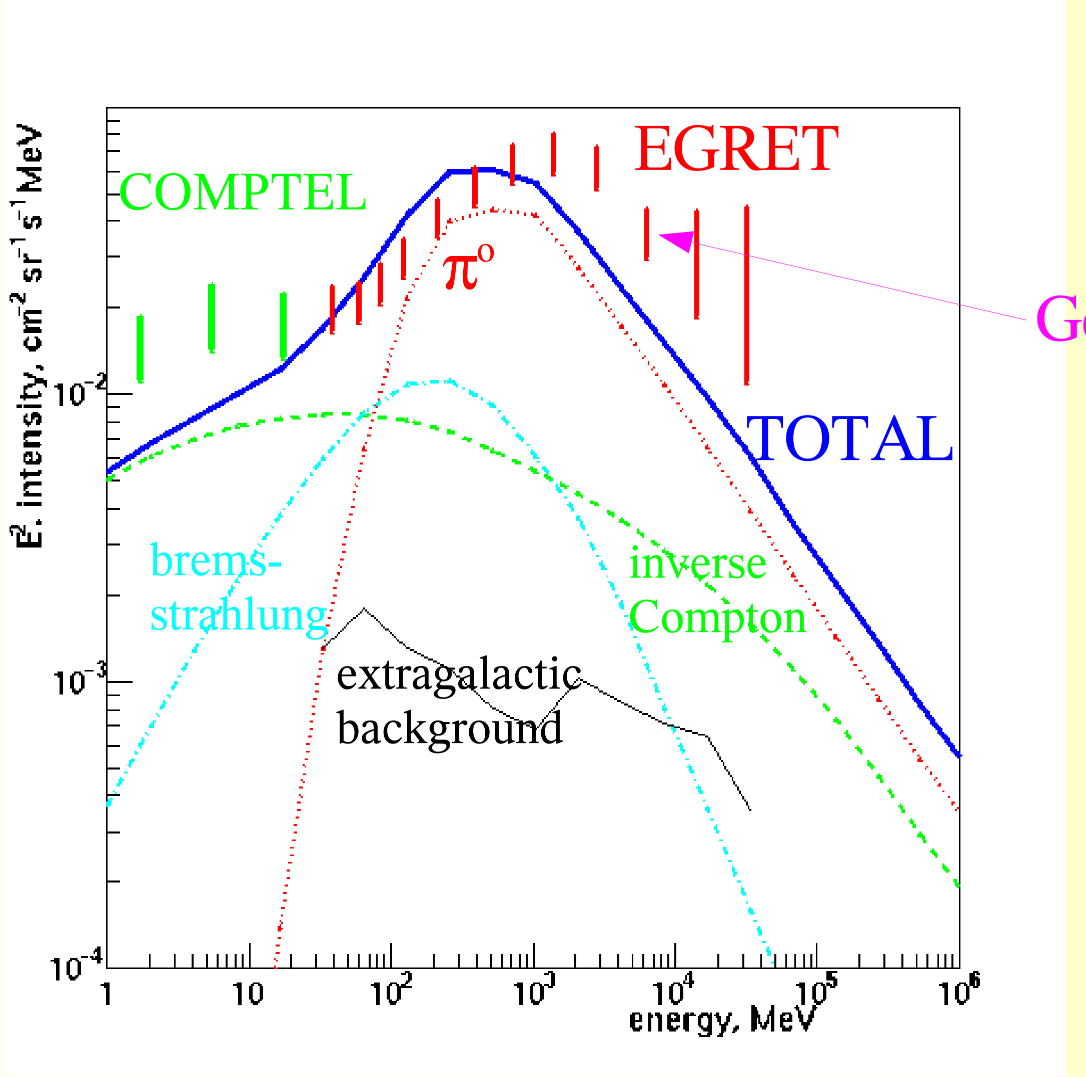
Conventional model: proton, electron spectra as measured





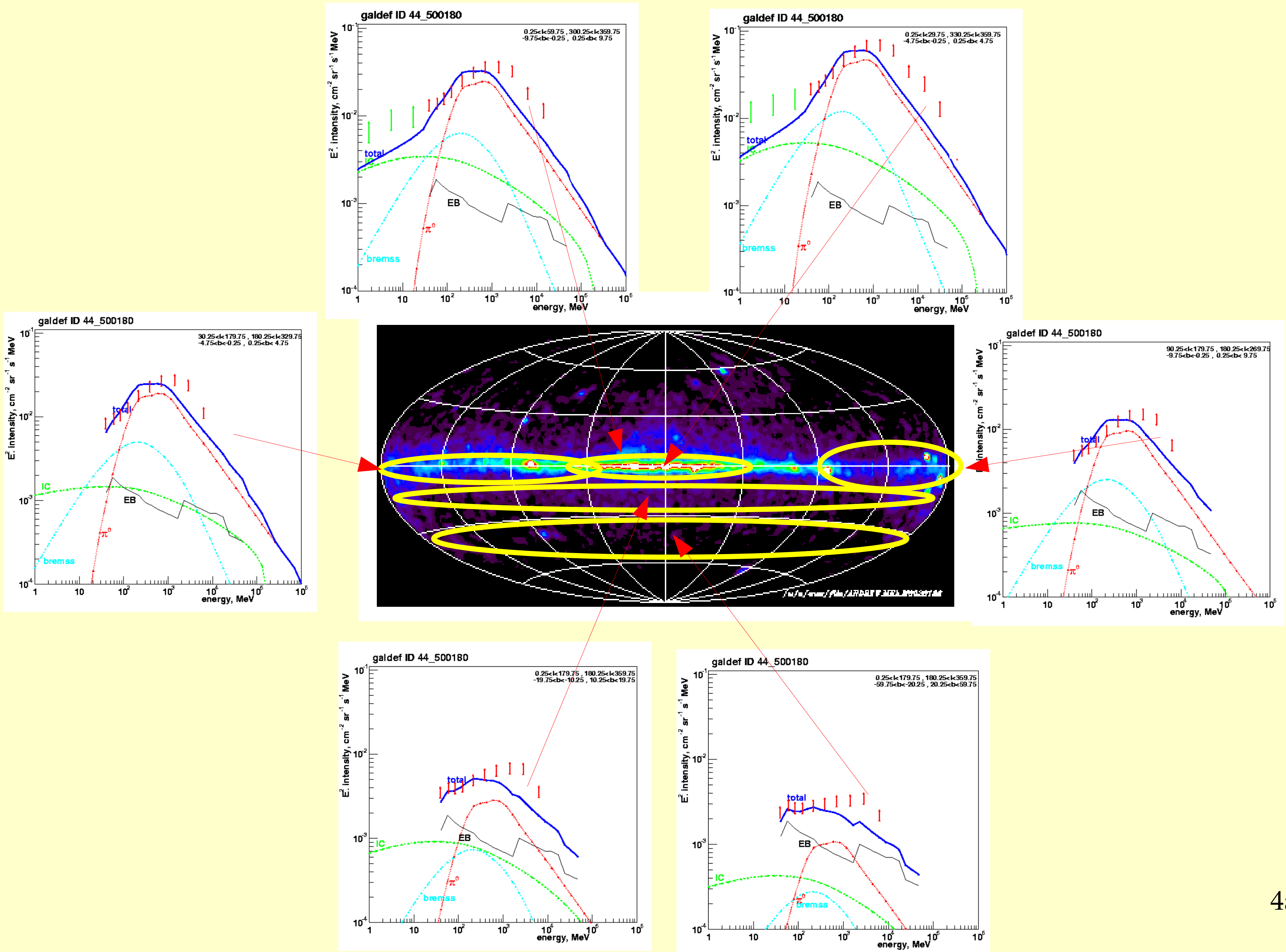
'Conventional' model:
cosmic-ray protons (+He) and electrons as *directly measured*

γ - ray spectrum
of inner Galaxy



There really IS a big excess over prediction !

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



4a-f

Proposed explanations of GeV γ - ray excess:

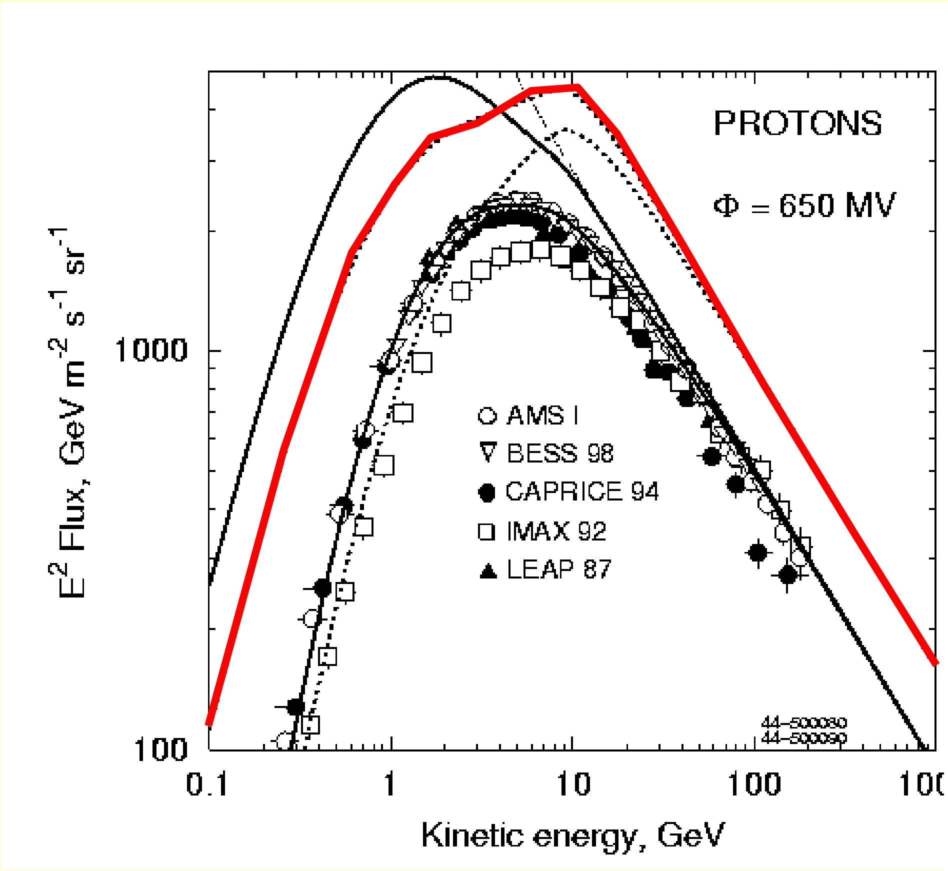
1. SNR with 'injection' CR spectra
2. Hard *nucleon* injection spectrum.
3. Hard *electron* injection spectrum
4. Moderate changes of nucleon and electron spectra
5. Physics of π^o production
6. Unresolved γ - ray sources
7. Exotic: dark matter

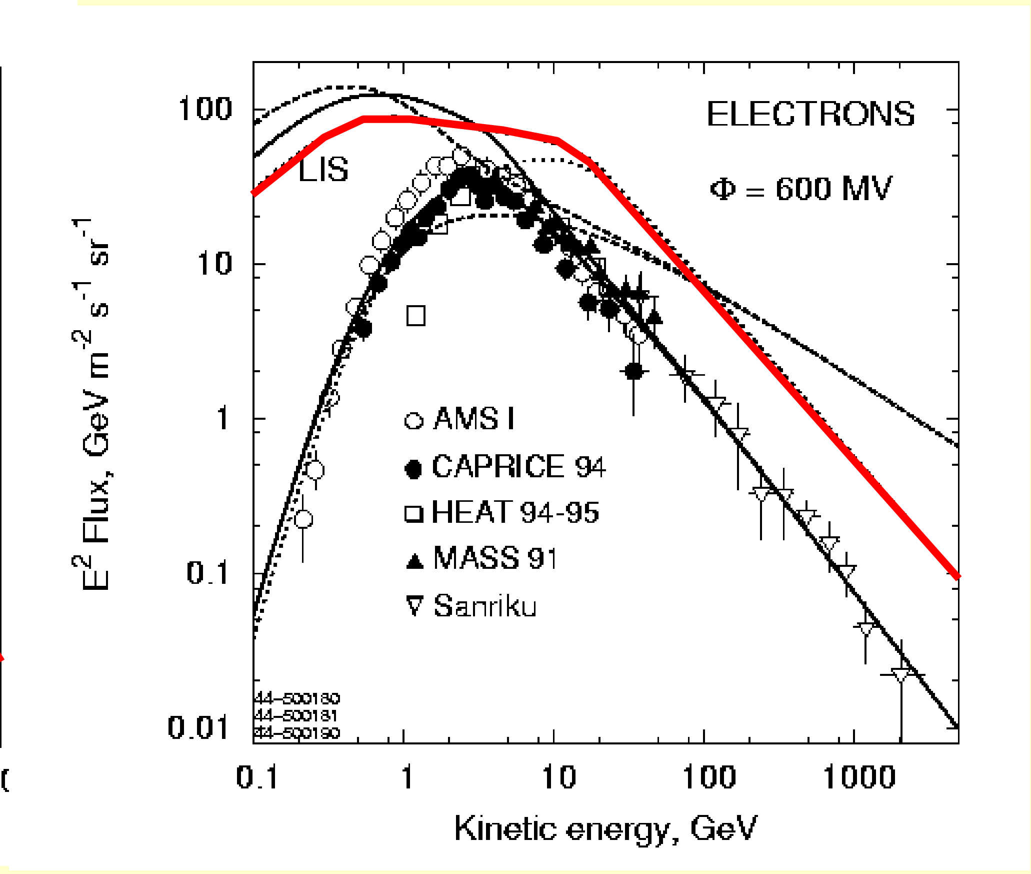
Proposed explanations of GeV γ - ray excess:

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

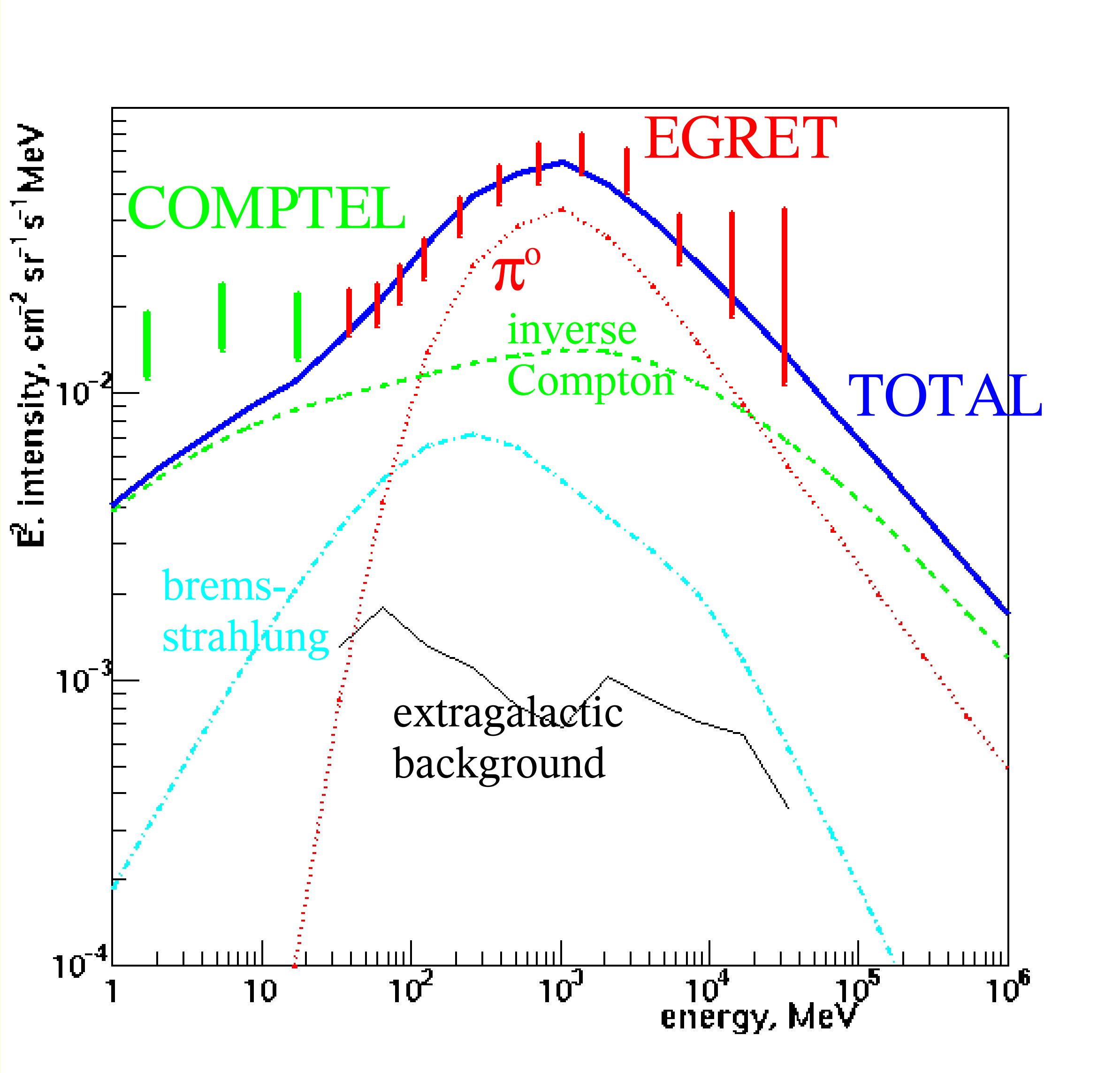
'Optimized' model:

p, e spectra factor 2 - 4 higher than measured
(justification: spatial variations due to stochastic nature of sources)



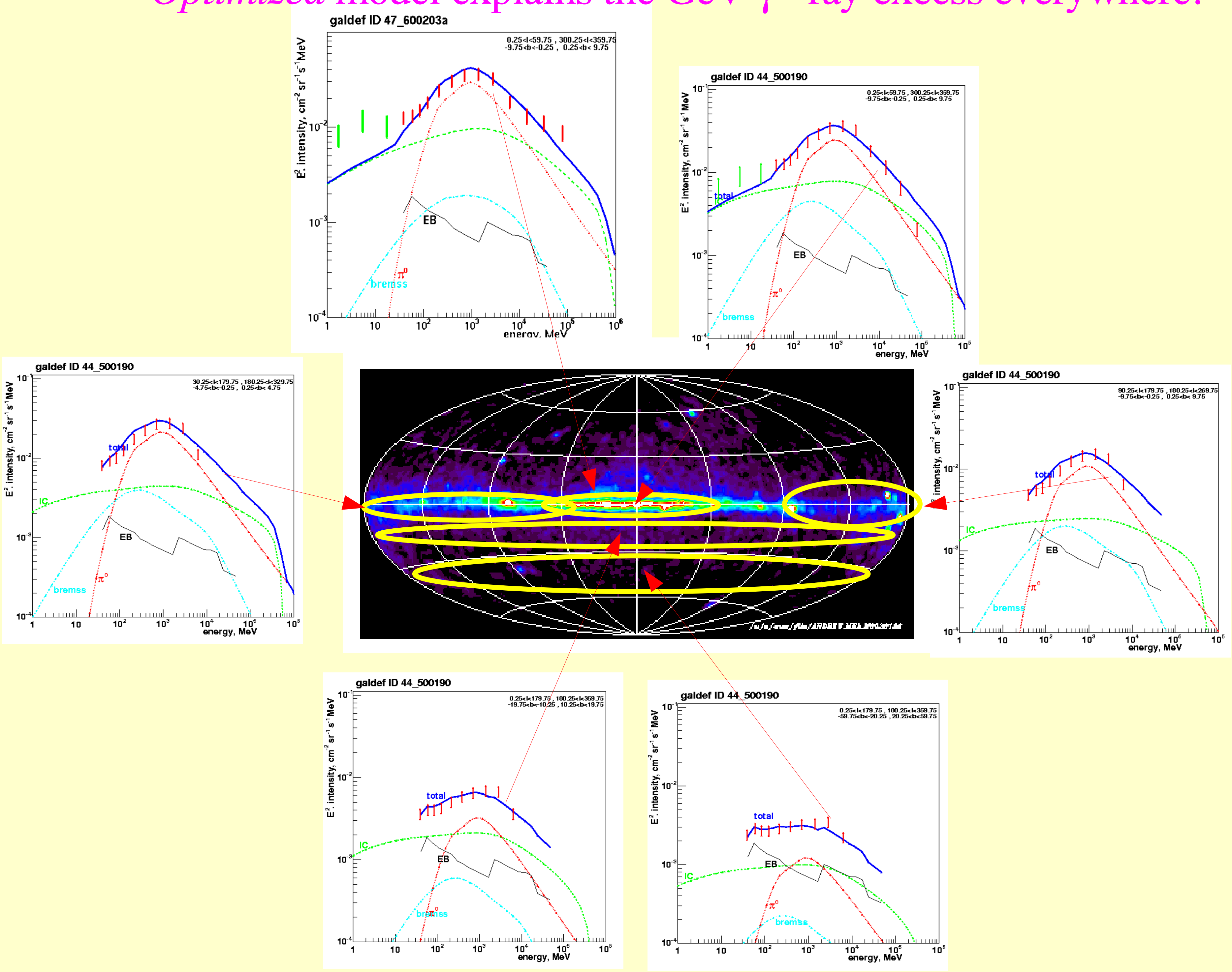


Optimized model: vary cosmic-ray proton, electron spectra but keep compatible with expected spatial variations

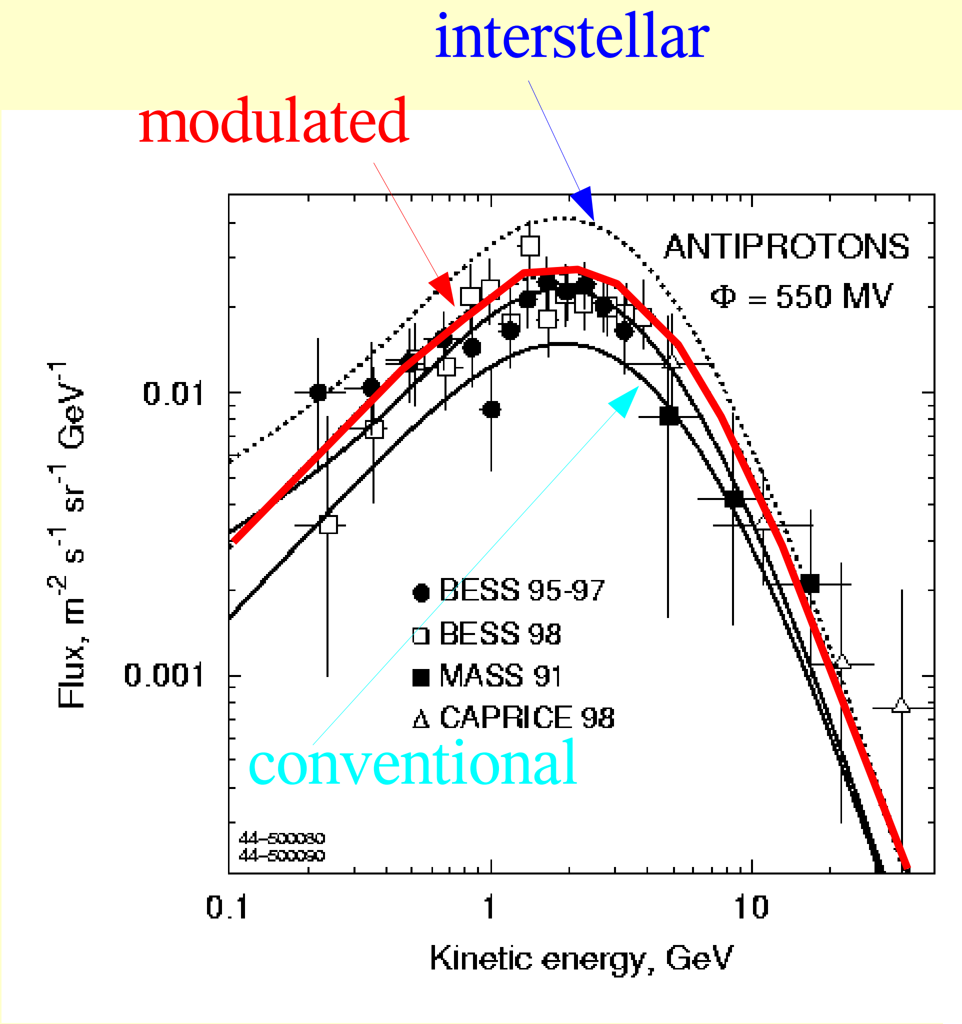


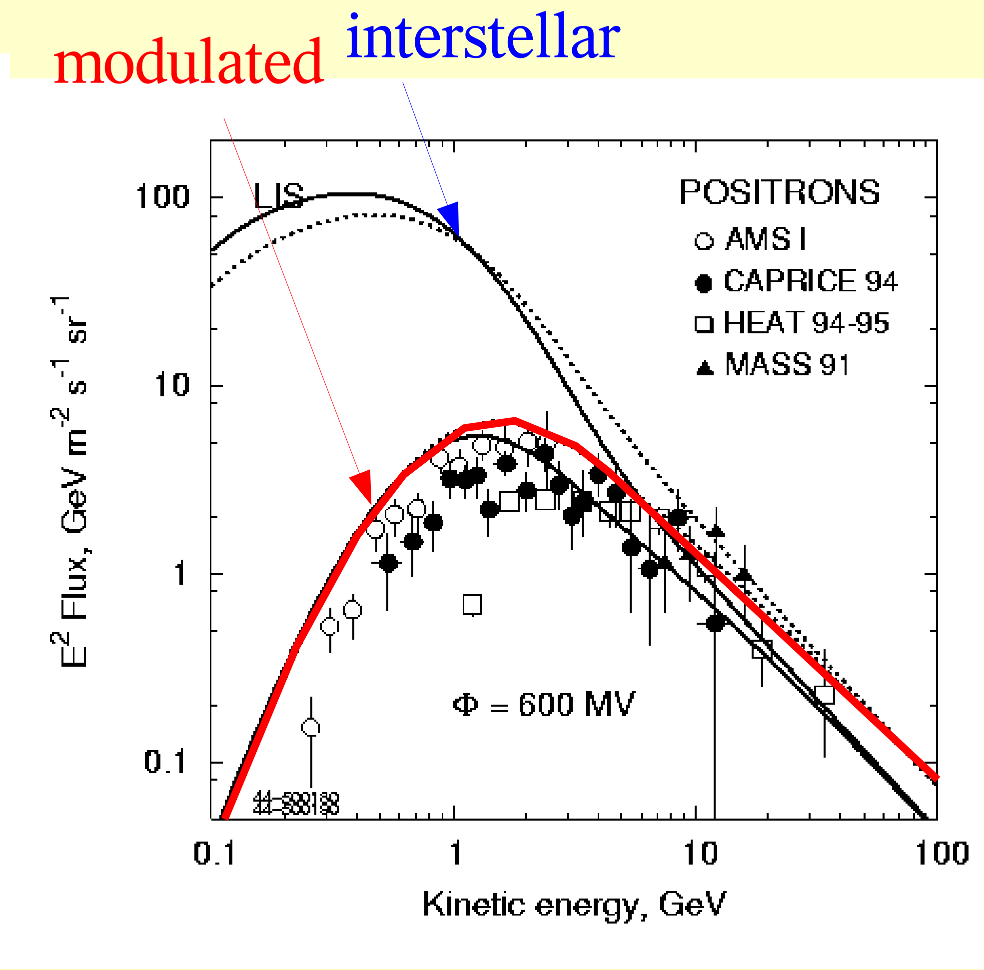
Satisfactory fit above 10 MeV: no more GeV excess

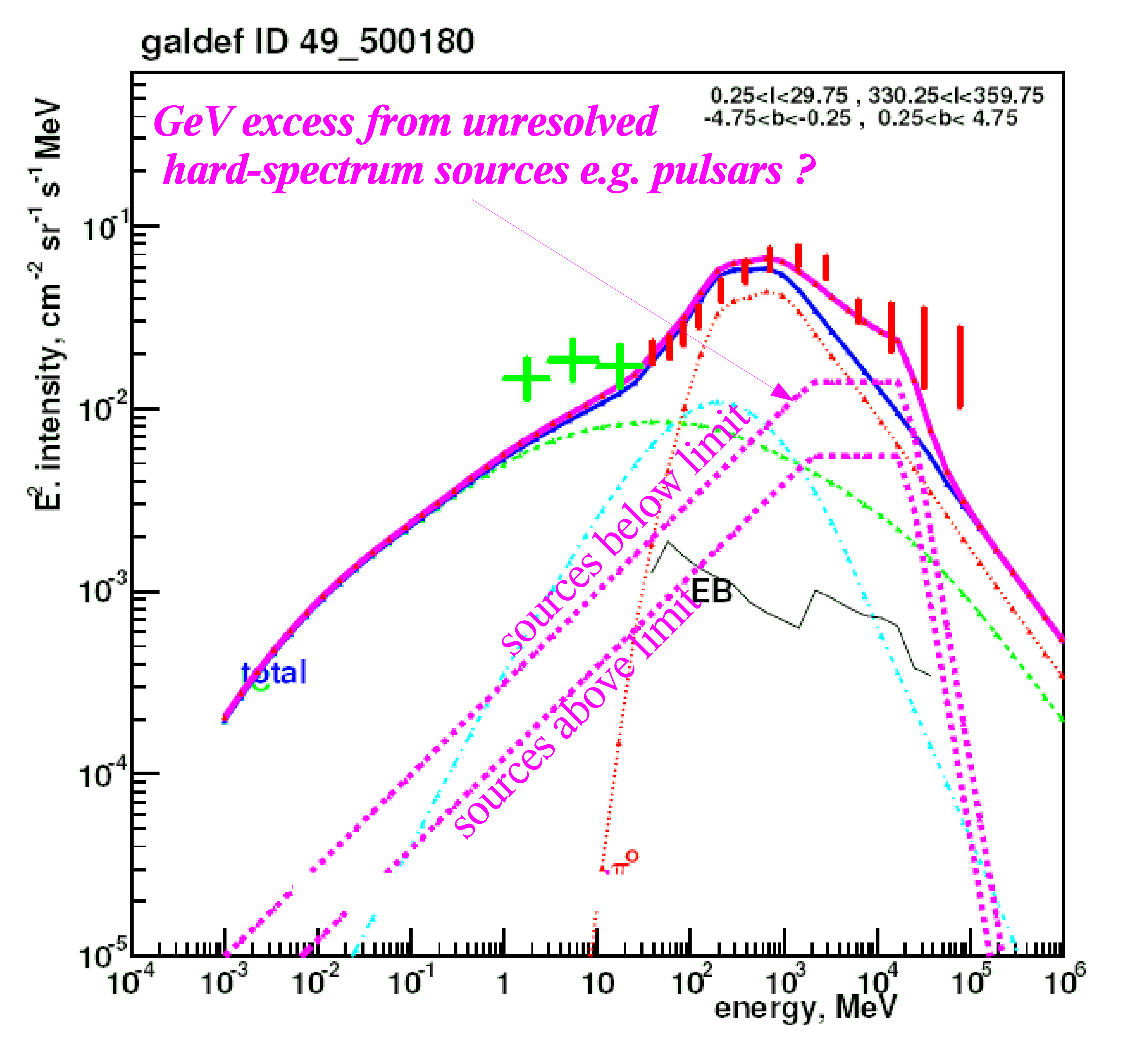
Optimized model explains the GeV γ - ray excess everywhere!



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







galdef ID 49_500180
0.25<l<29.75 , 330.25<l<359.75
-4.75<b<-0.25 , 0.25<b< 4.75
GeV excess from unresolved
hard-spectrum sources e.g. pulsars ?
sources below limit
sources above limit
EB
total
E². intensity, cm⁻² sr⁻¹ s⁻¹ MeV
energy, MeV

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

synchrotron could help sort all this out (if GLAST doesn't)

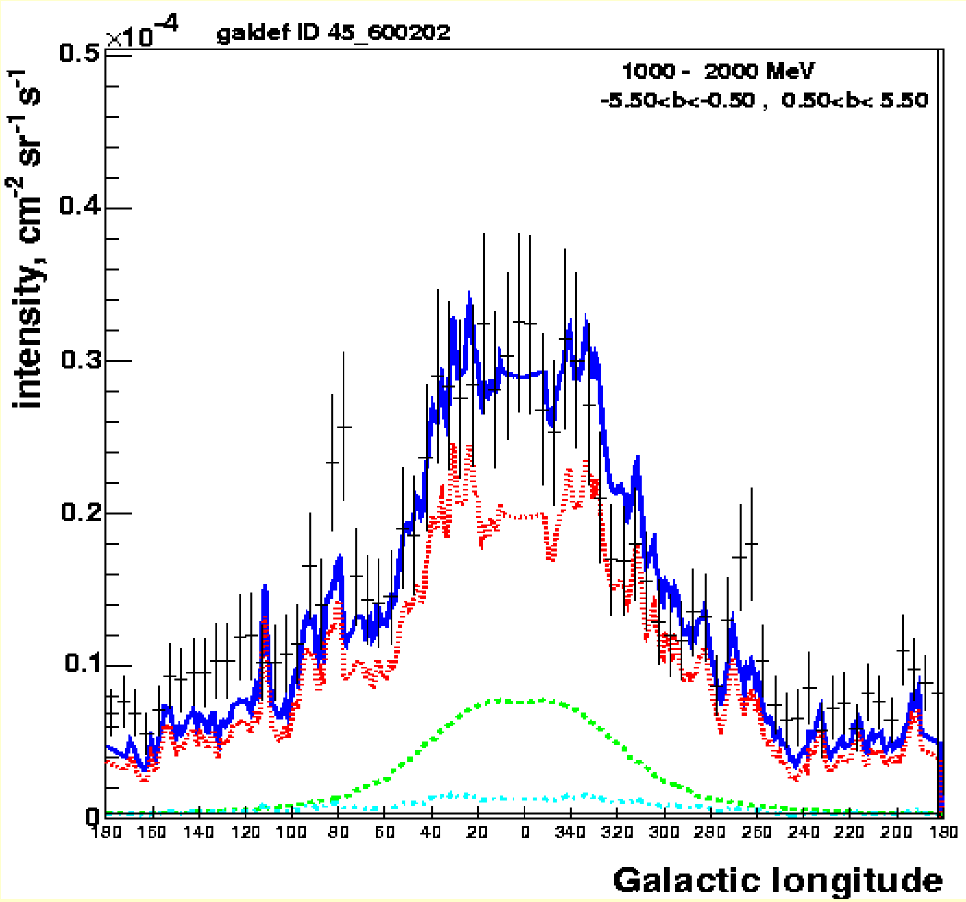
4. Moderate changes in nucleon and electron spectra ← current best bet

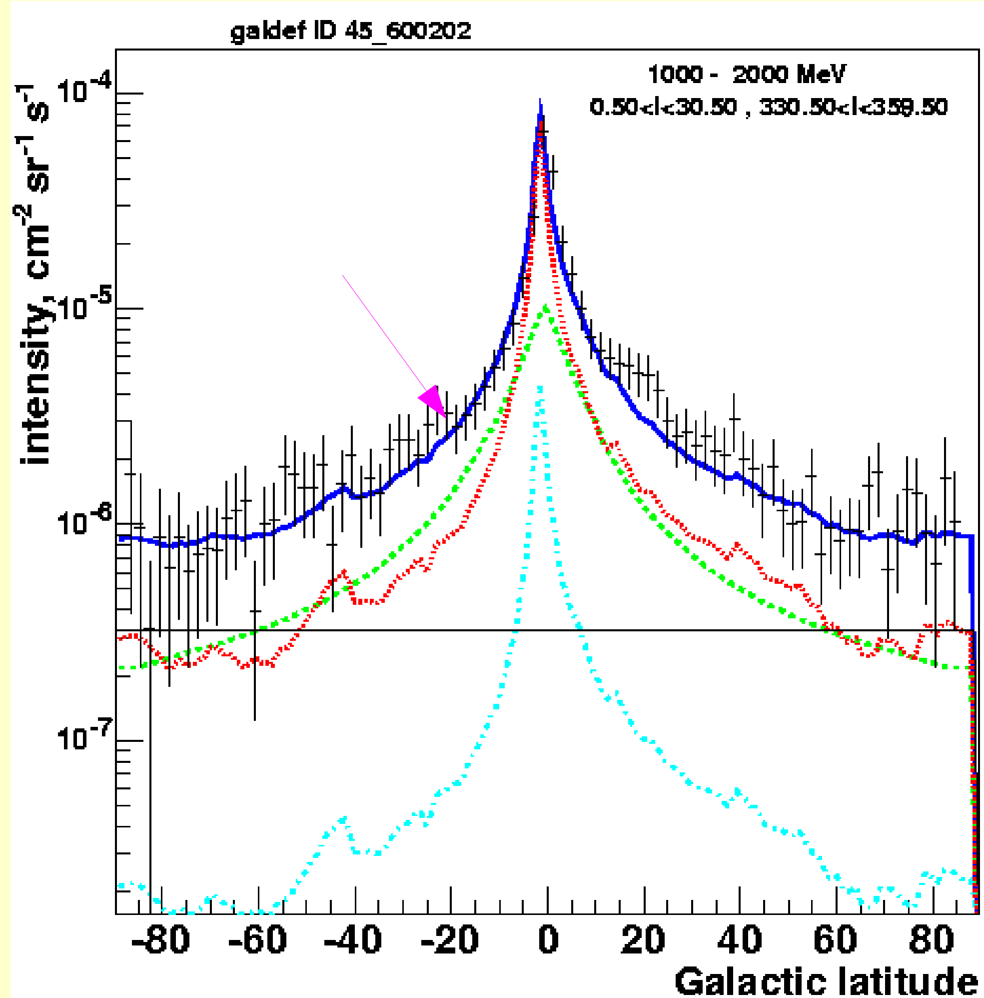
5. Physics of p+p -> π^o NO

6. Hard spectrum SOURCES ← quite likely

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

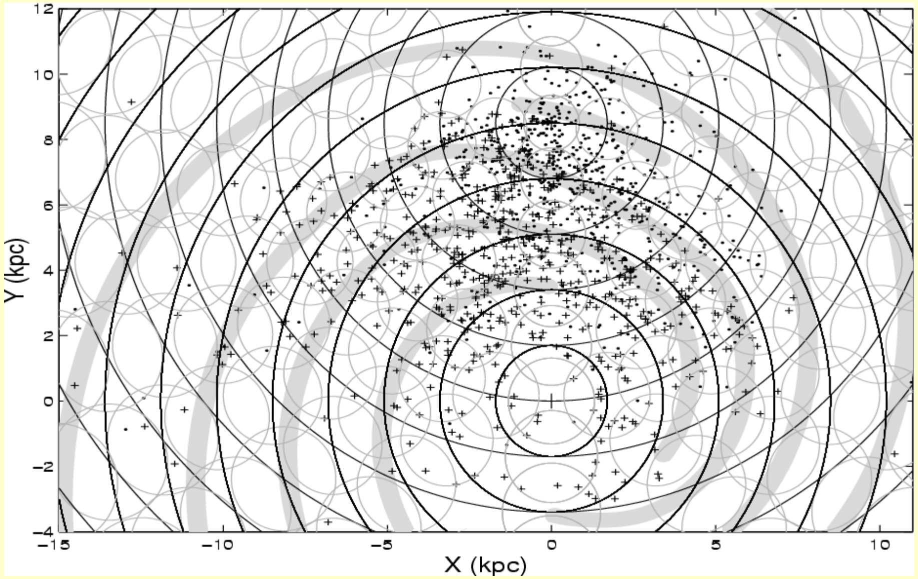
not just spectra .... also skymaps





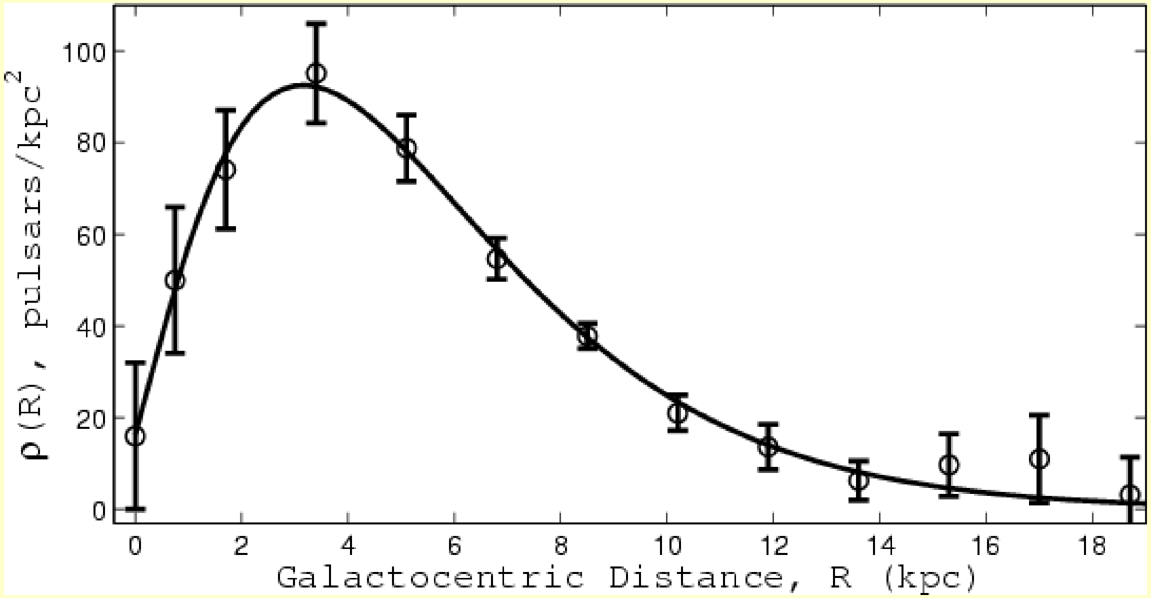
EGRET γ -ray data

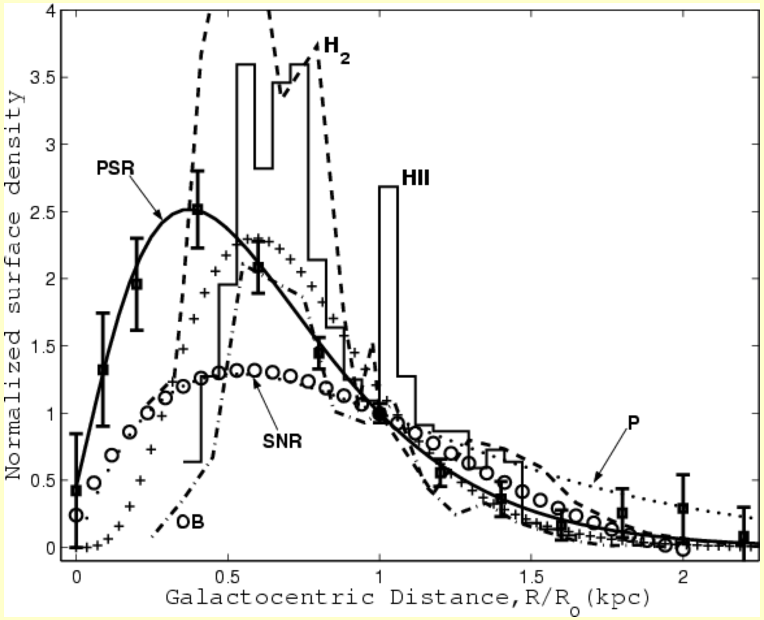
Tracer of SNR cosmic-ray sources: Pulsar distribution



Parkes Deep Survey

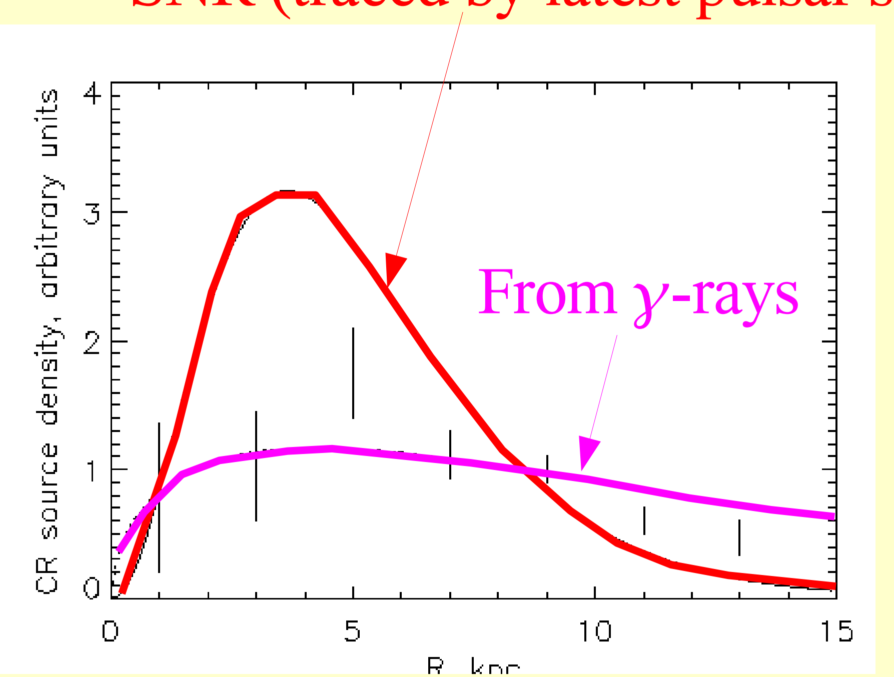
Yusifov & Kücük 2004
(Lorimer 2004: almost same result)





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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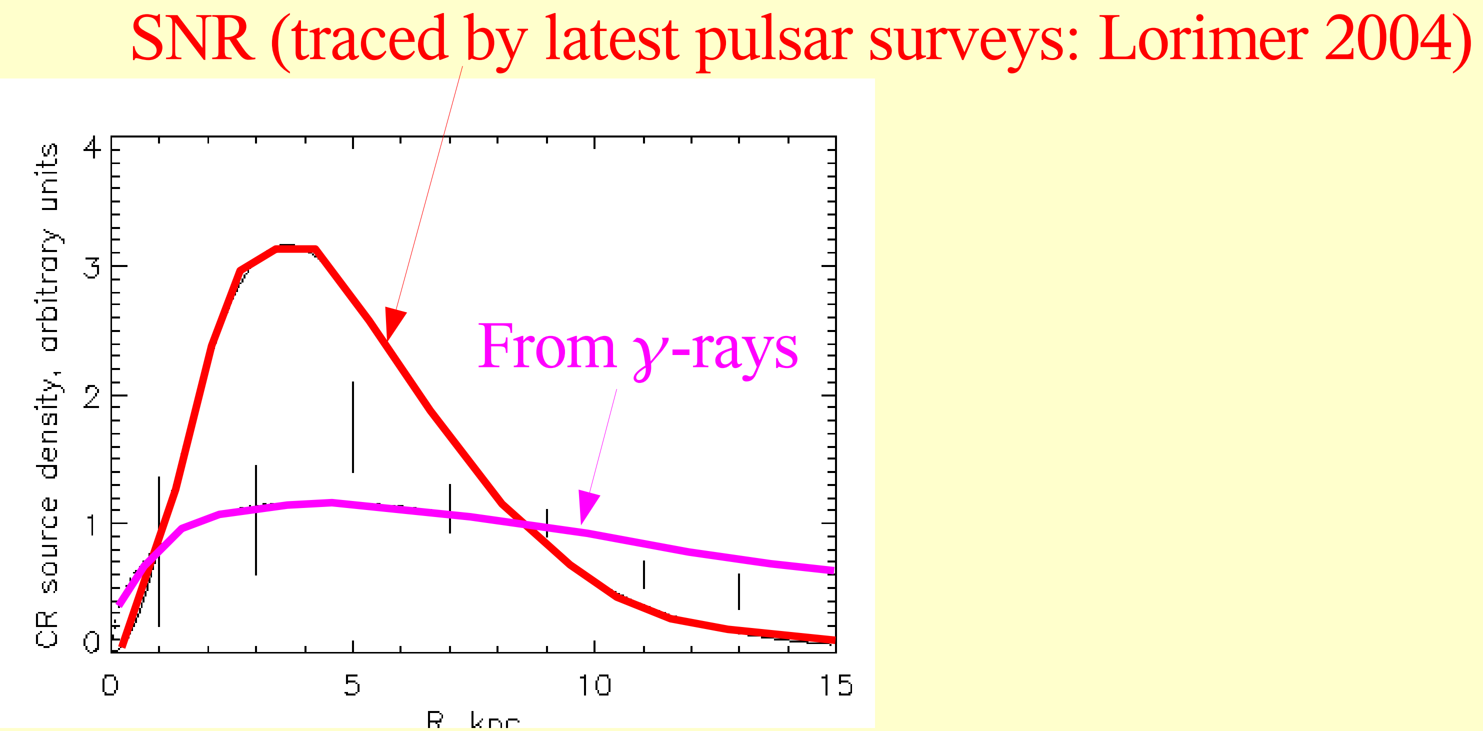
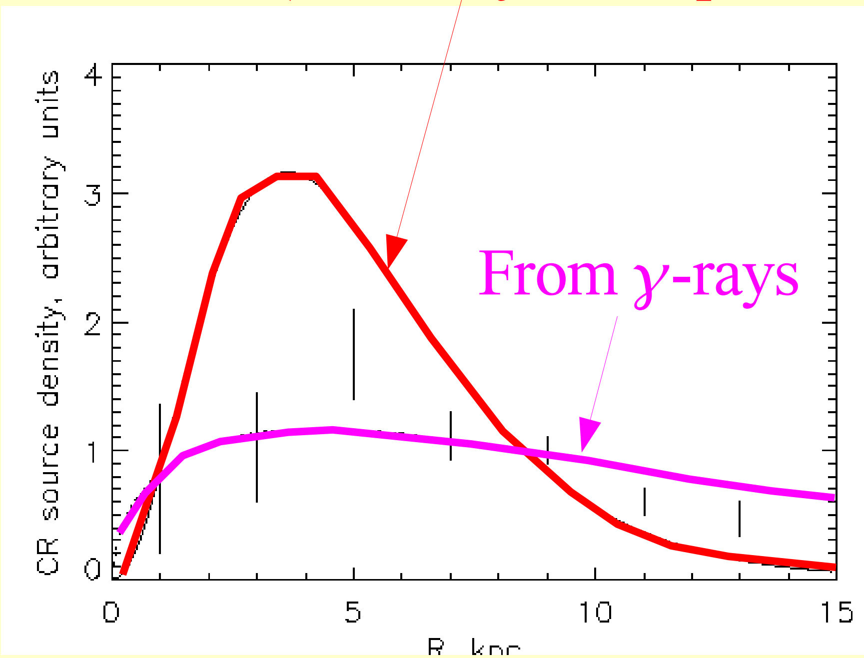


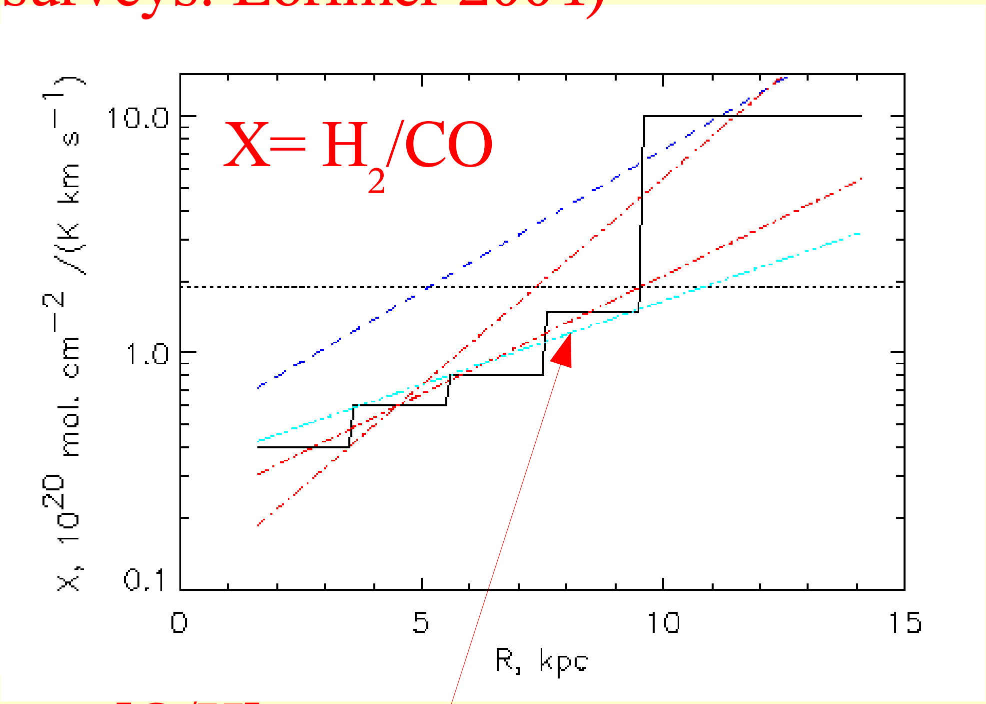
Clue: Galactic metallicity gradient e.g. [O/H]

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

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*

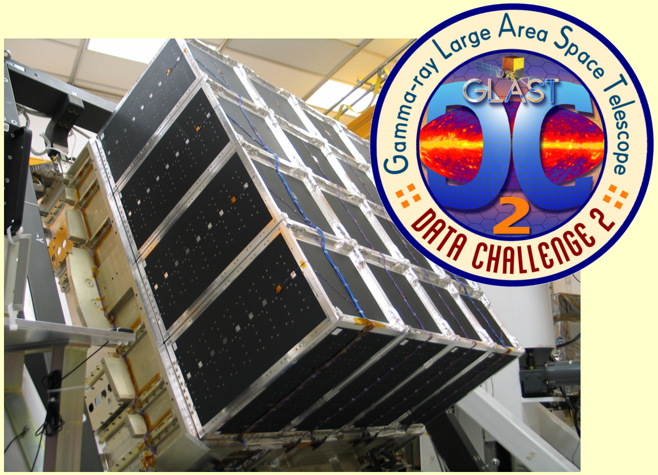
>>>>>>> ***X = H_2 / CO increases with radius***

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*

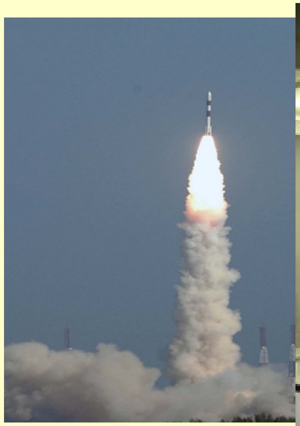
the (near) **γ - ray** future
GLAST..... 30 MeV – 100 GeV
full sky, arcminute resolution



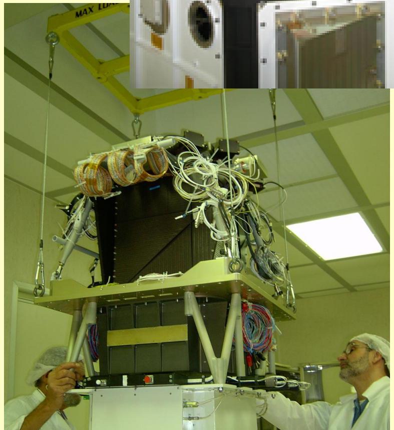
GLAST - Planck synergy

co-operative efforts started

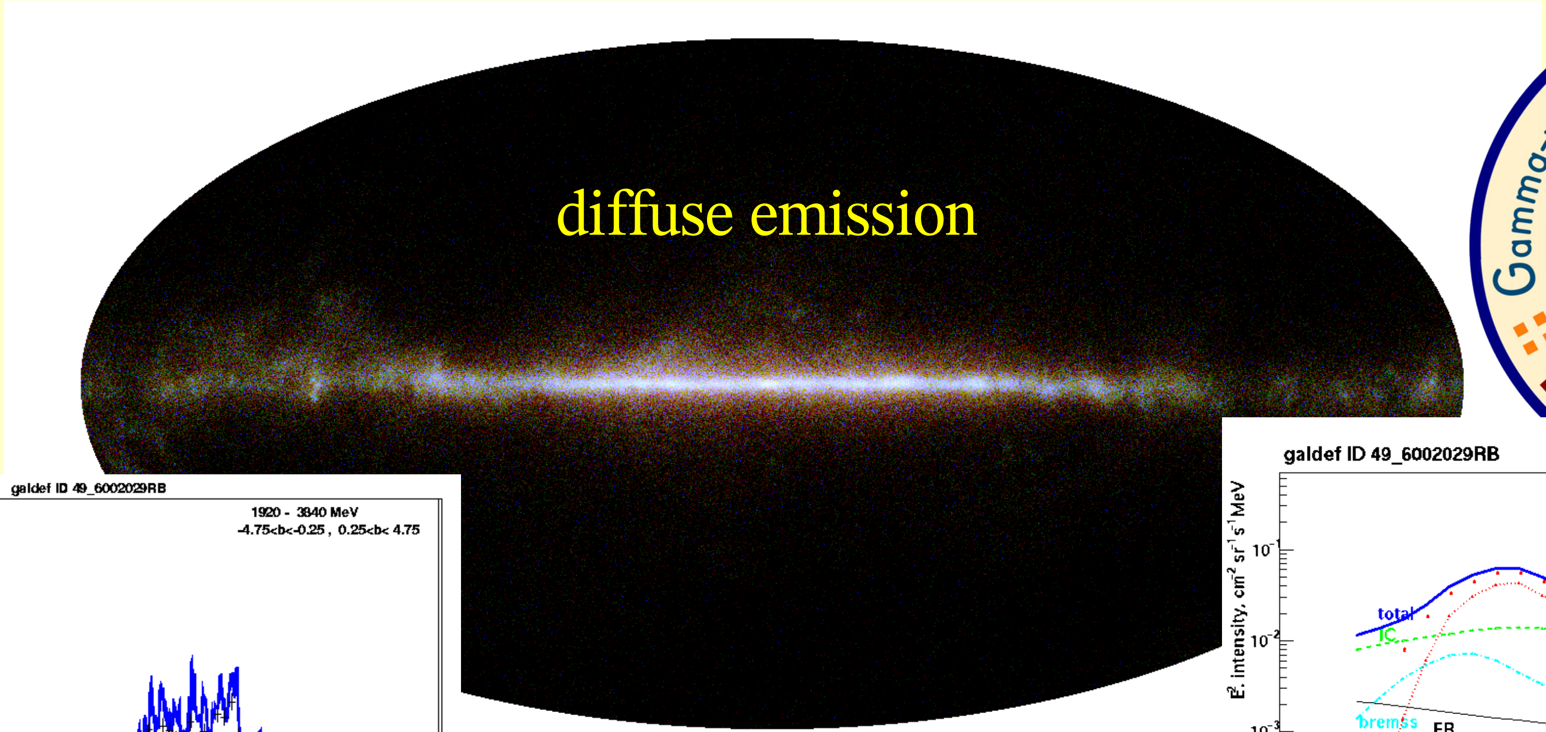
AGILE – γ - ray satellite launched April 23 2007

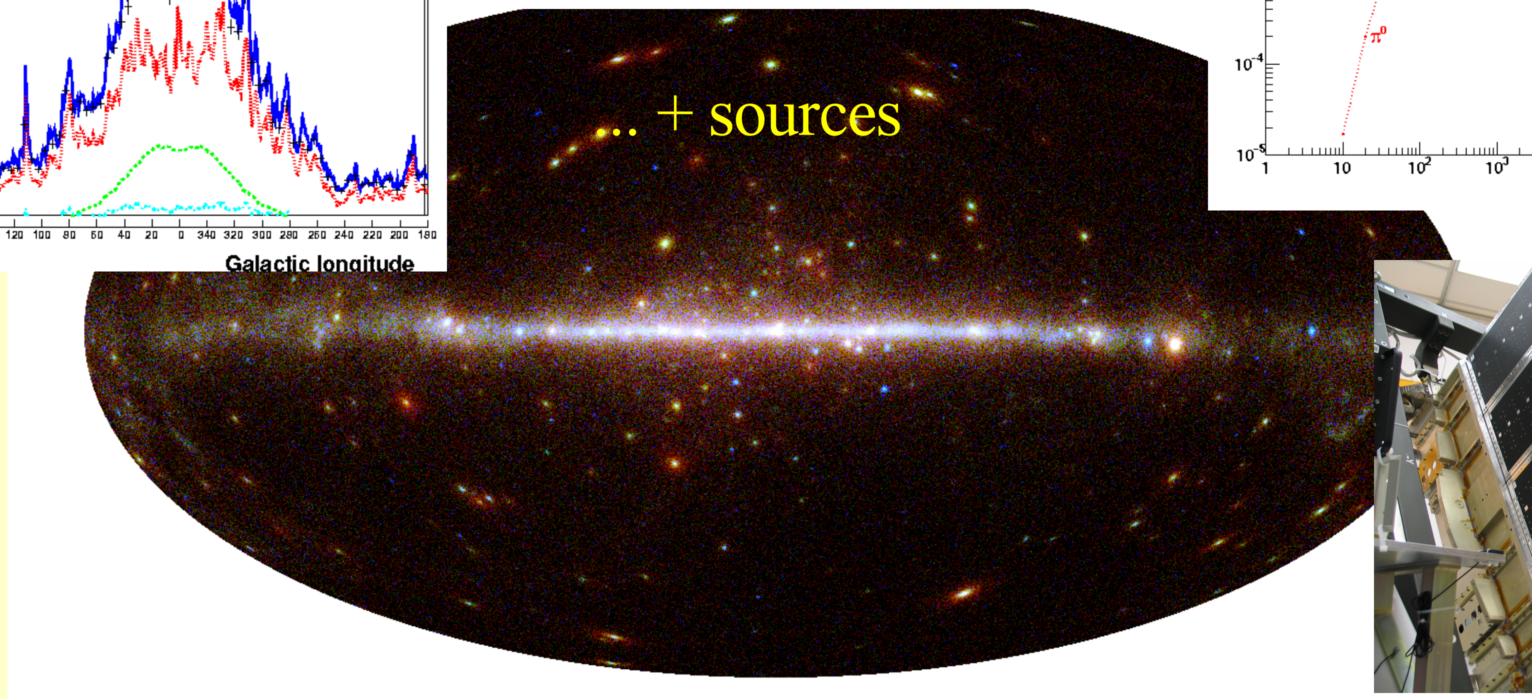


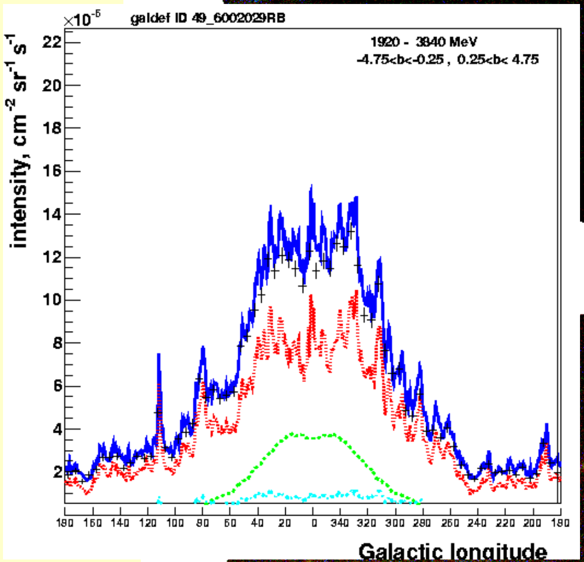
PAMELA – cosmic-ray satellite launched June 2006

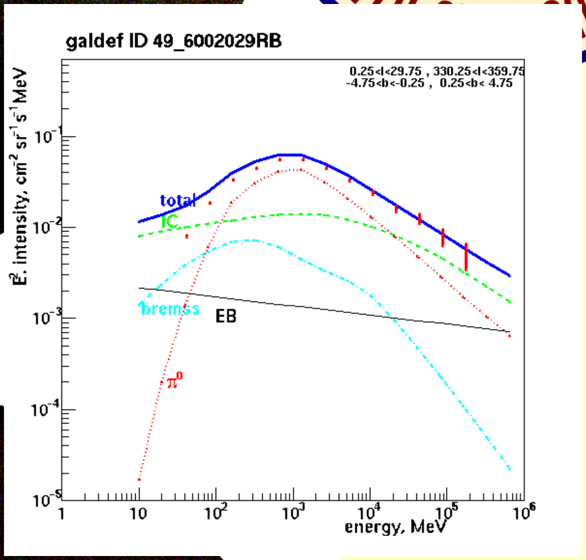


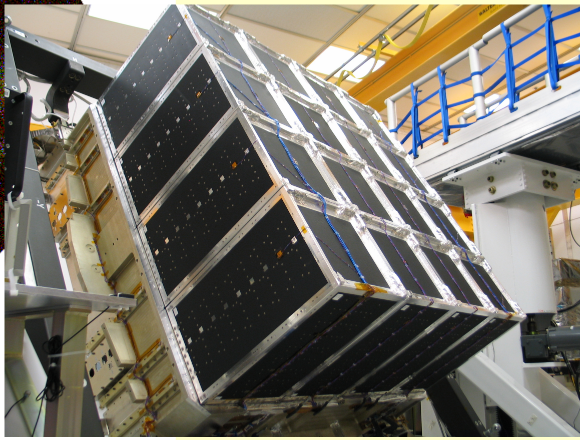
Simulation for GLAST using *galprop*











So we sort of understand cosmic-ray propagation.

What are consequences for synchrotron emission & **B** ?

The procedure:

1 - build model consistent with γ - rays: electron spectrum, spatial distribution
2 - tune **B** to fit 408 MHz skymaps
3 - compare radio spectrum with data

Step 1 is not very sensitive to **B** (it just affects electron energy losses)
so this procedure is robust

Use a very simple **B**-model (we're just starting on this ! - one reason I'm here)
exponential in *R* and *z*
random **B** only (not bad for a start since regular < random)

Large scale random B
No **B** topology (yet !)
No polarization (yet !)
No fine details of Galactic structure
but still a lot of physics – cosmic ray propagation, ISM

current *galprop* synchrotron studies

From CR and gammas we can get the *electrons*
Knowing the *electrons* + *synchrotron* we can get *B*.

→ Synchrotron is the *missing link*

both intensity and spectrum / index are predicted by the model
and provide essential constraints on both **B** and cosmic-ray propagation
not yet much exploited in cosmic-ray context

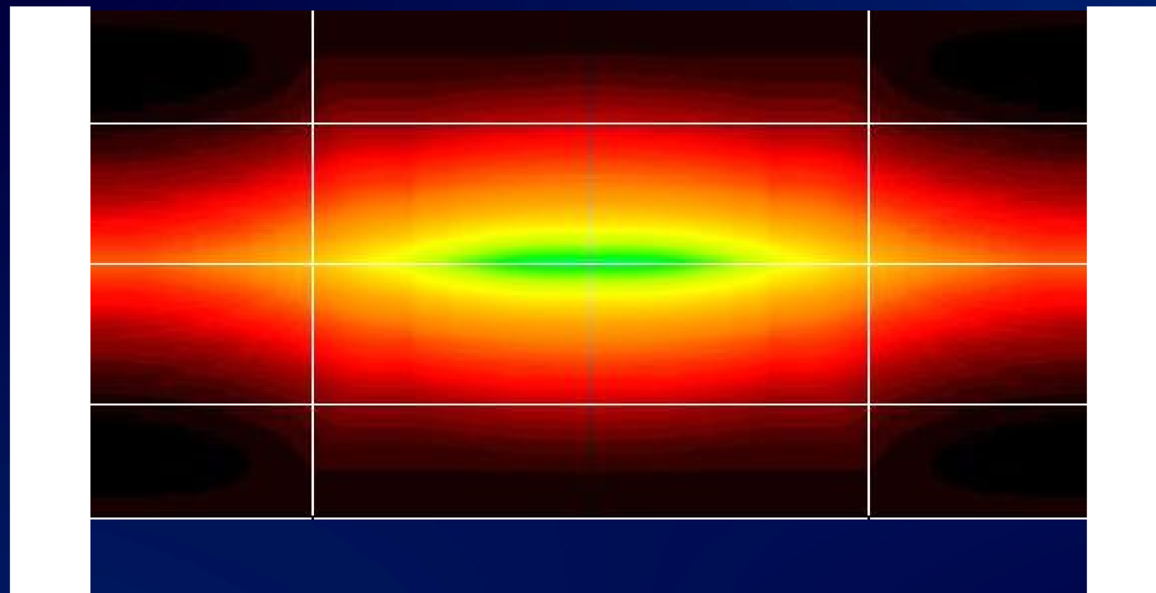
beyond templates: want to understand what's going on
simple ideas e.g. "spectrum steepens with energy due to losses" often misleading

for *electrons* the factors determining the spatial distribution & spectrum are

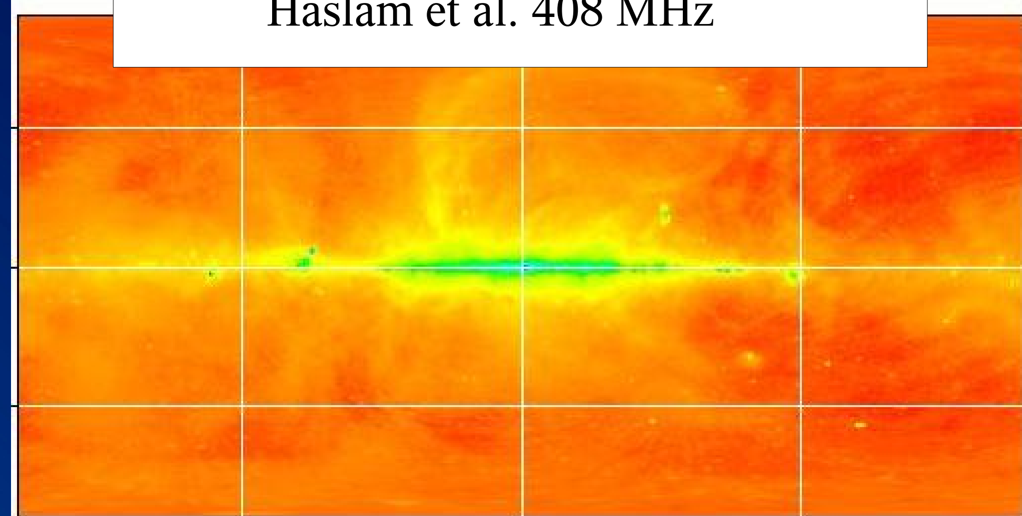
- injection spectrum : from cosmic-rays / γ-rays
- source distribution : from γ-rays / SNR
- energy losses : from ISRF, B
- energy-dependent diffusion : from cosmic-rays / γ-rays
- halo size : from cosmic-rays

The only freedom left in modelling the synchrotron is **B** !

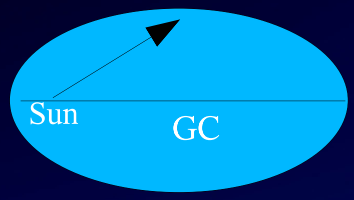
galprop synchrotron skymap @ 408 MHz

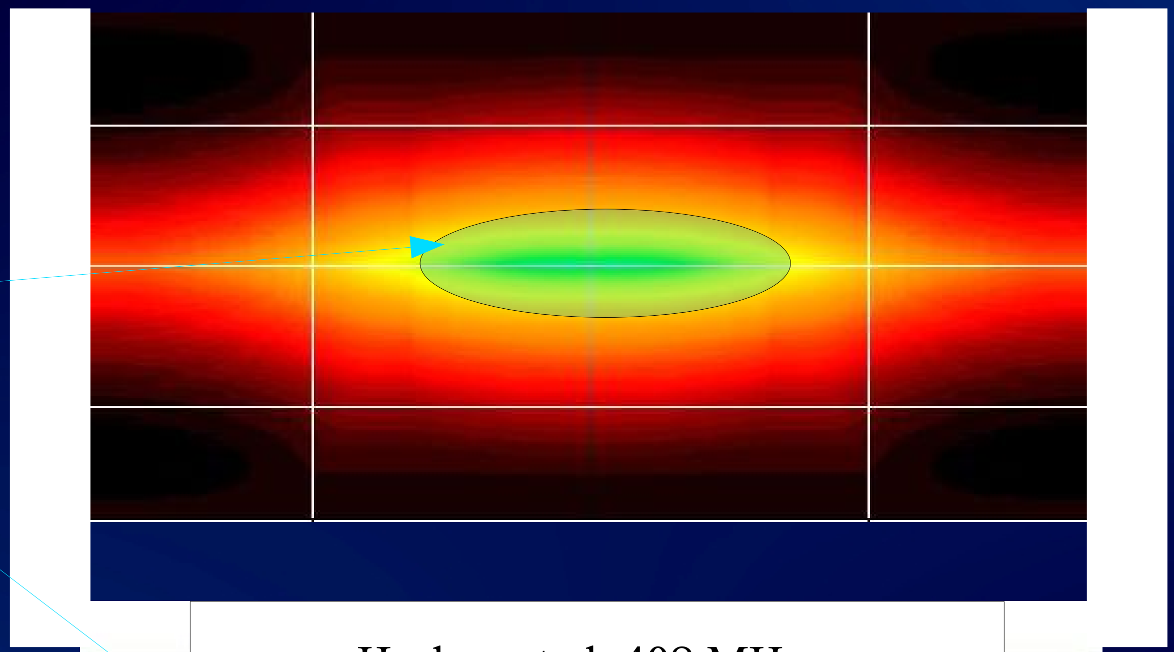


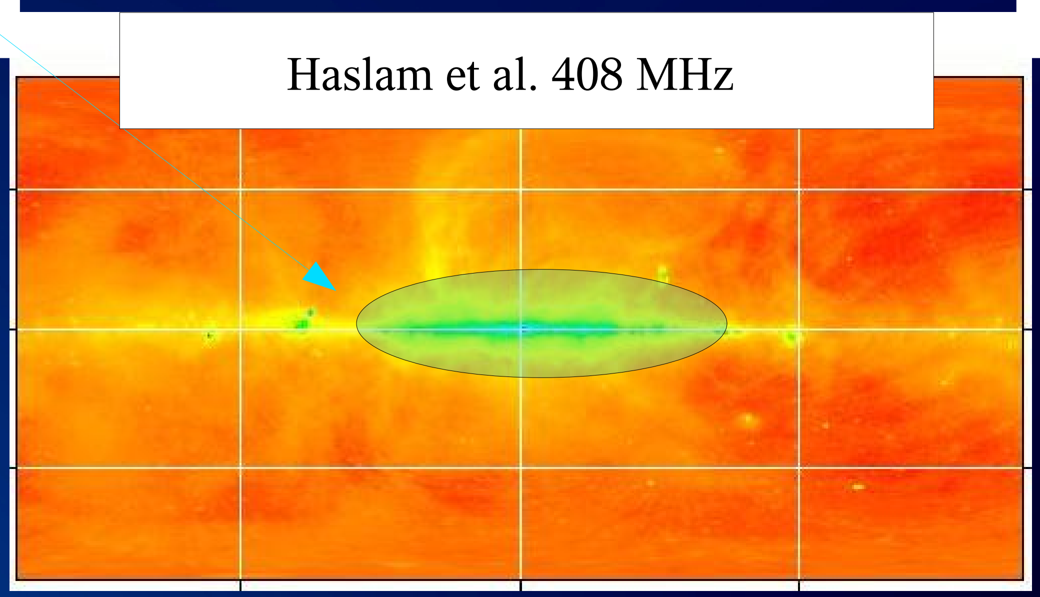
Haslam et al. 408 MHz



galprop synchrotron skymap @ 408 MHz

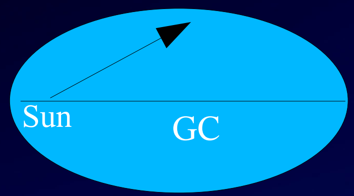




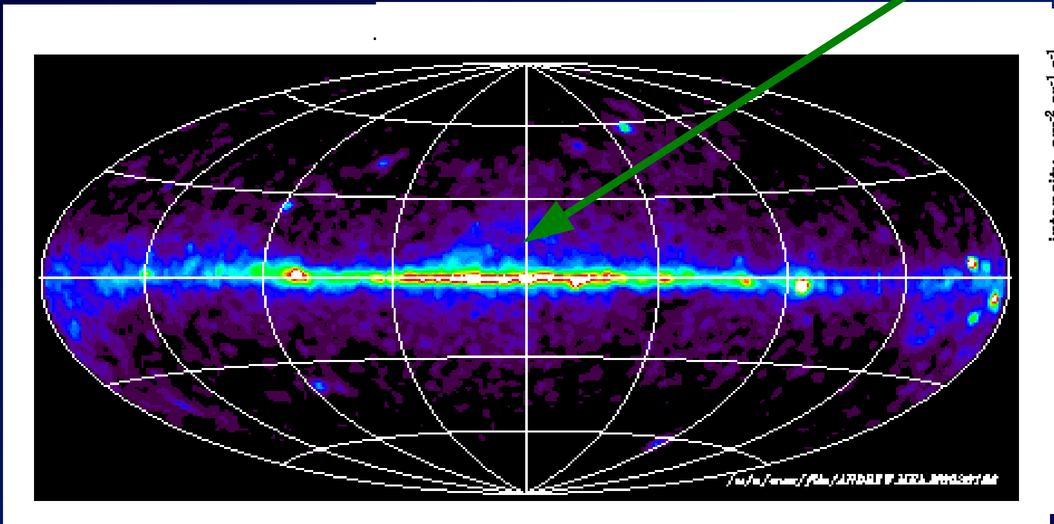


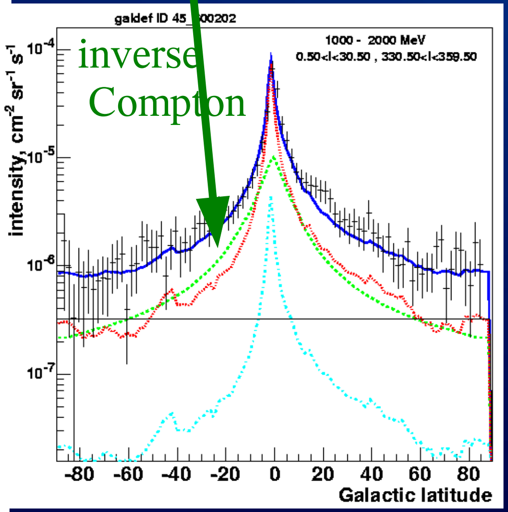
intermediate
latitudes
inner Galaxy:
we are seeing
kpc-wide halo

gamma-rays:
halo less evident but still there:
cosmic-rays + gas
+ ISRF

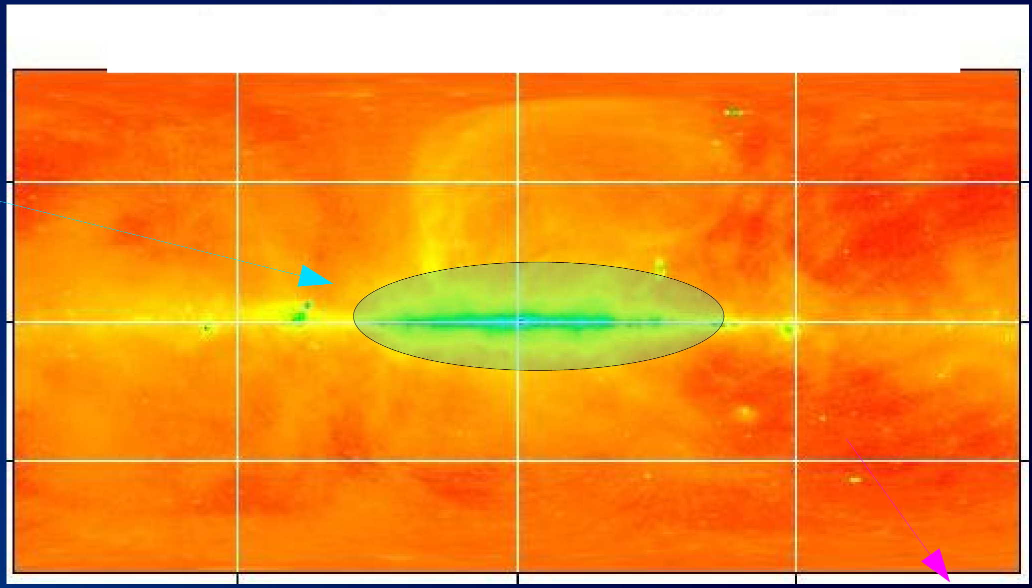


EGRET γ-rays





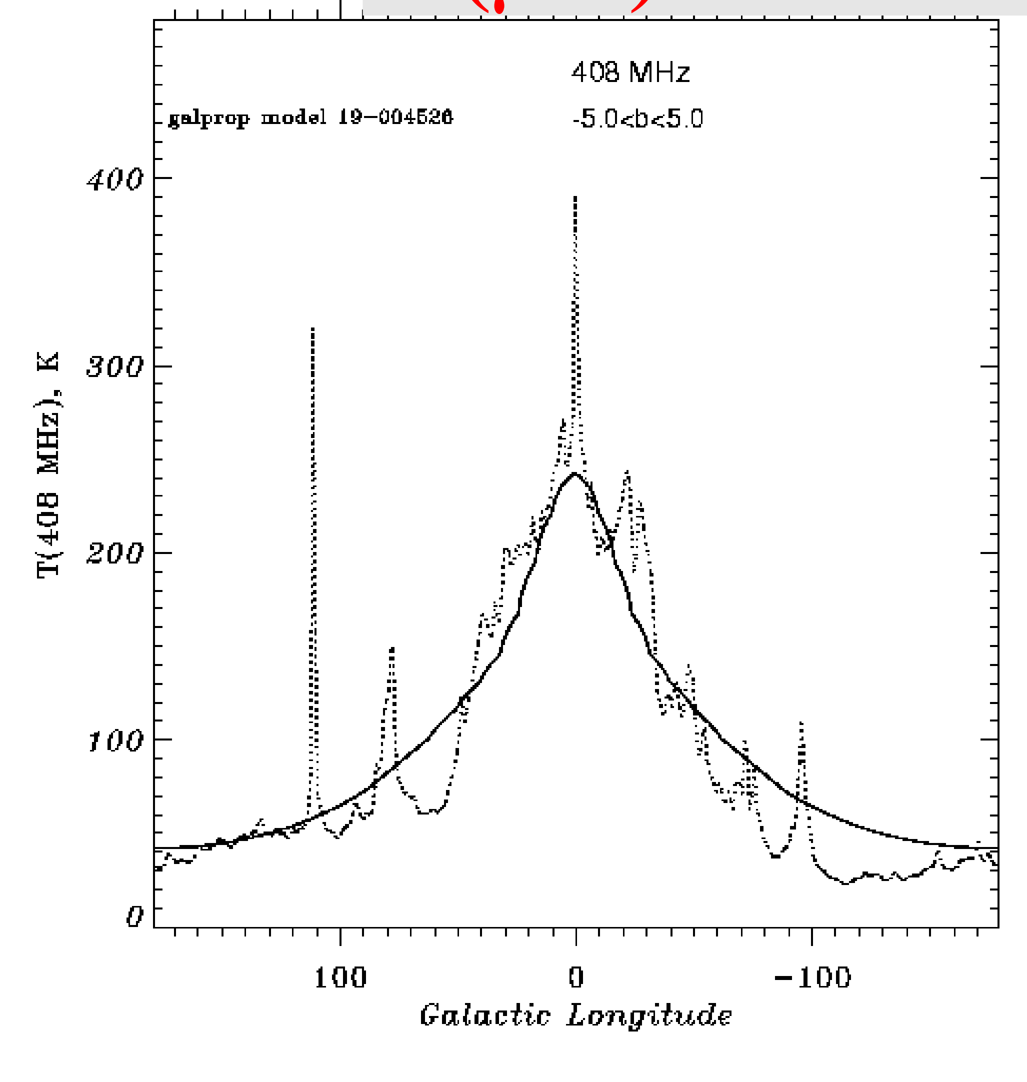
Haslam et al. 408 MHz

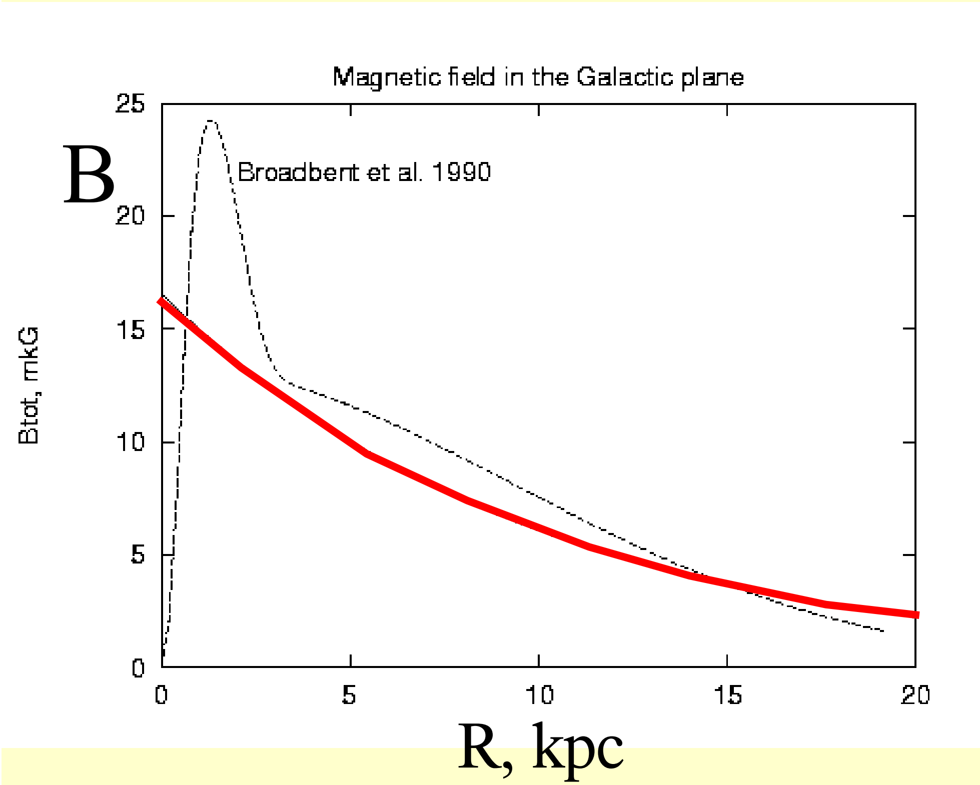


intermediate
latitudes
inner Galaxy:
seeing kpc-wide
halo:
cosmic-rays + B

Electrons: Synchrotron and B field

$B(\mu G) \sim 6\, e^{-(R - R_o)/10\ kpc\ -\ |z|/2\ kpc}$





B: rough agreement with pulsars, EG RM

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

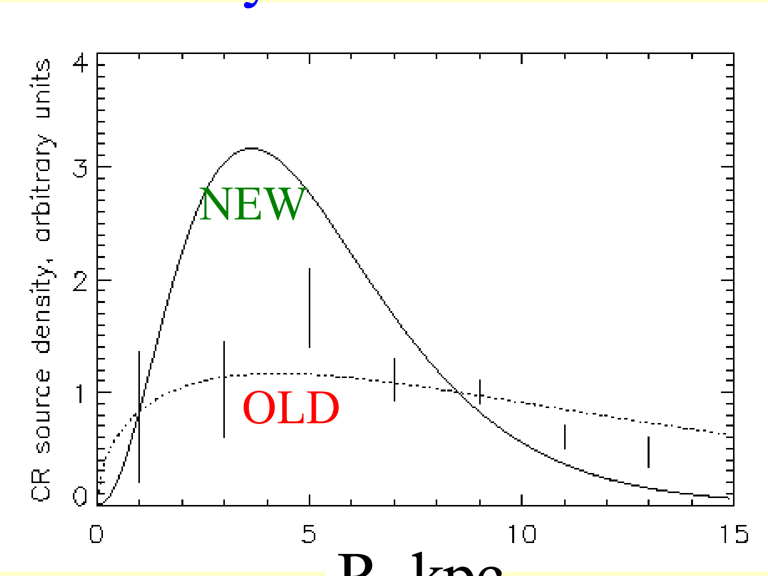
Strong, Moskalenko & Reimer 2000 ApJ 537, 763 *current* working model (no detailed parameter study yet):

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

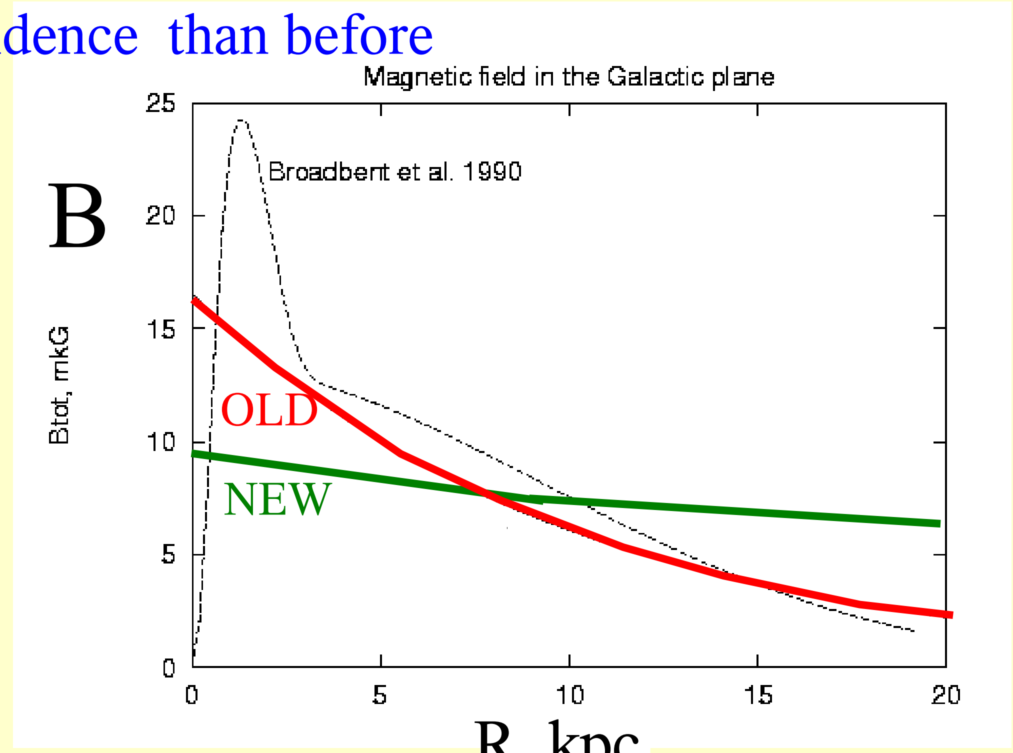
NEW

essentially no R- dependence of B:
since the electrons have a steeper R-dependence than before

cosmic-ray source distribution



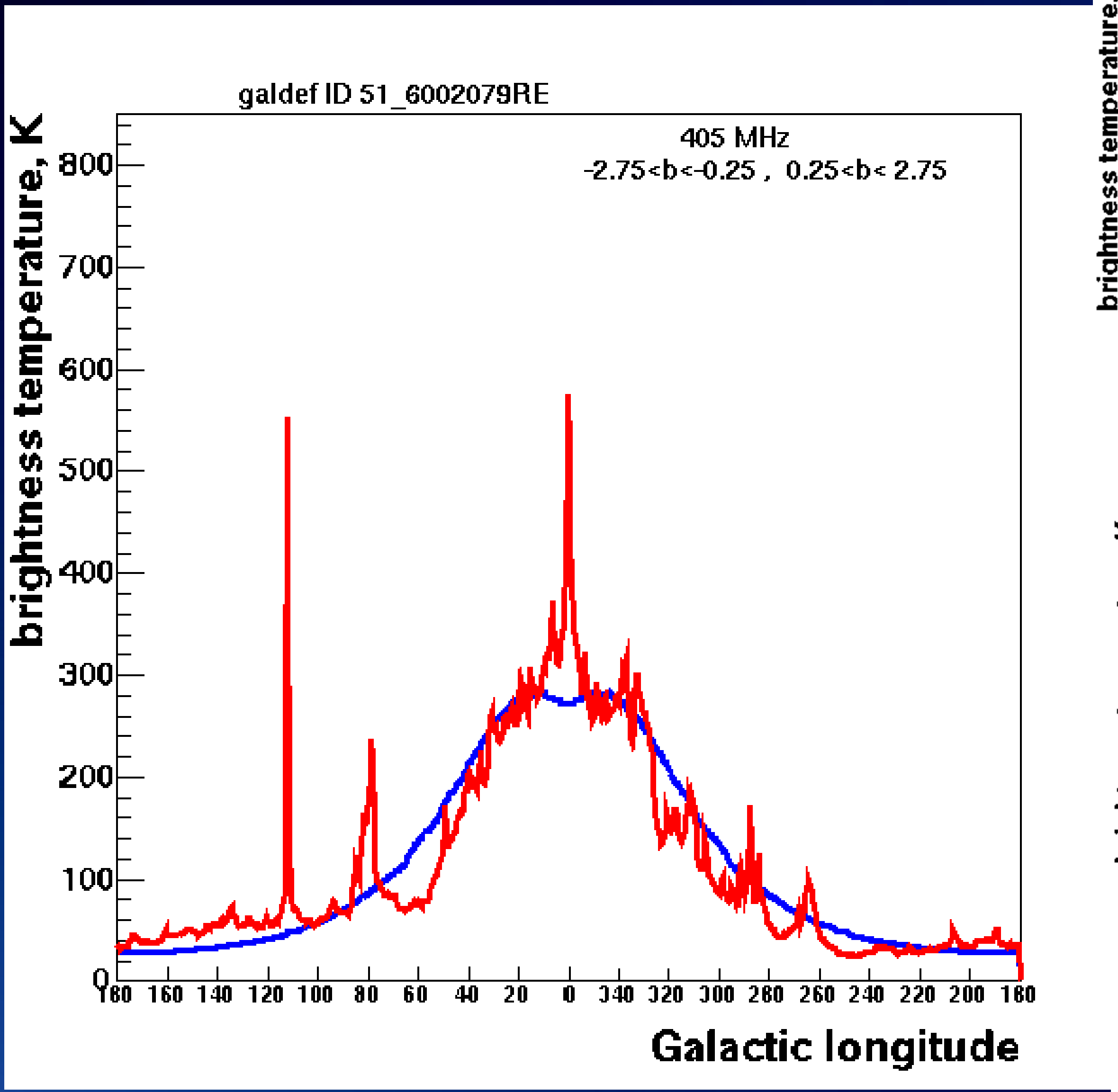
R, kpc

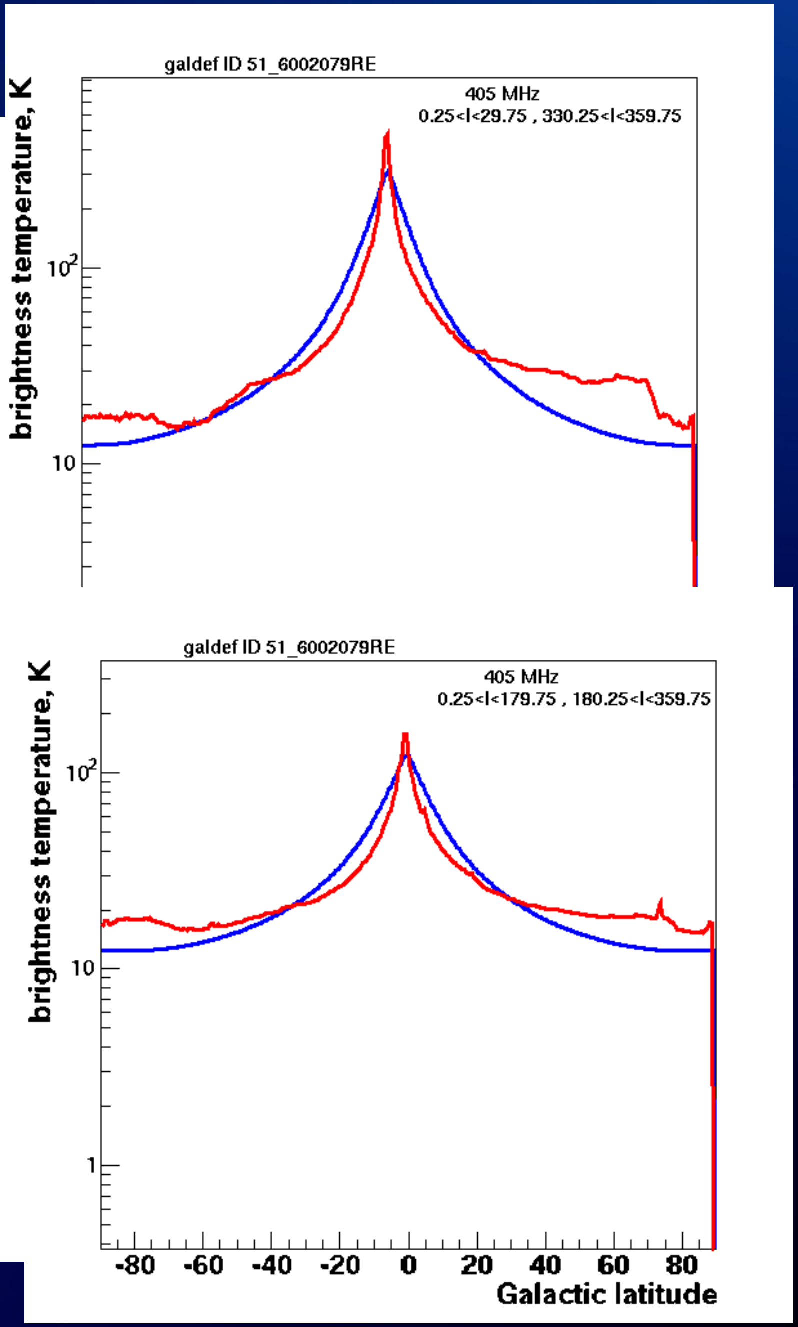


R, kpc

z-dependence: scale height cannot be >> electrons, best is 3 kpc, cf halo height 4 kpc

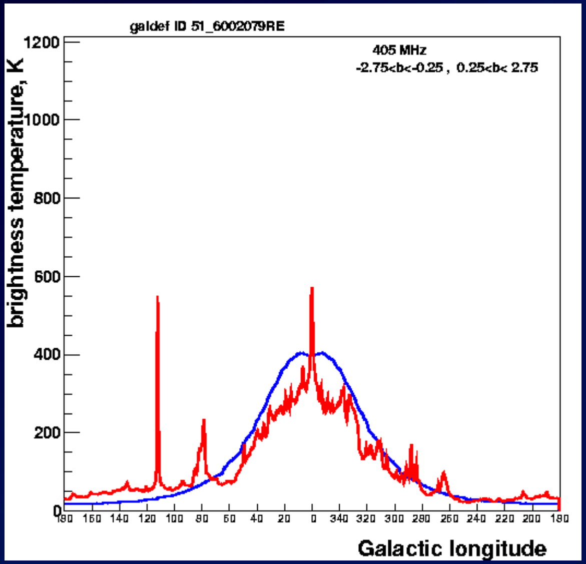
Best-fit **B** model



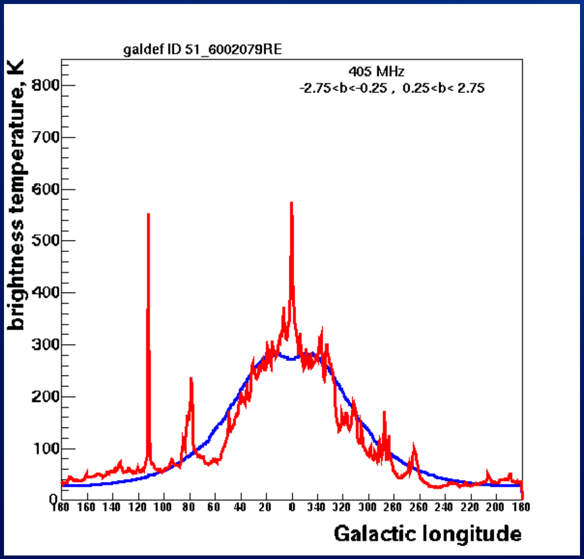


Sensitivity to **B** parameters

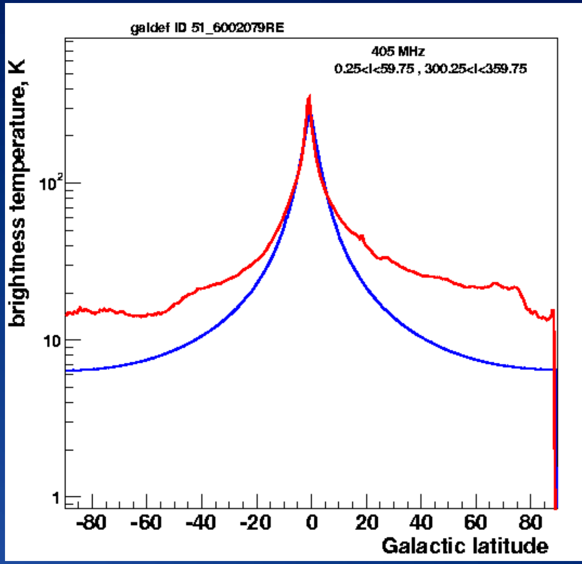
R-scale: 10 kpc too small



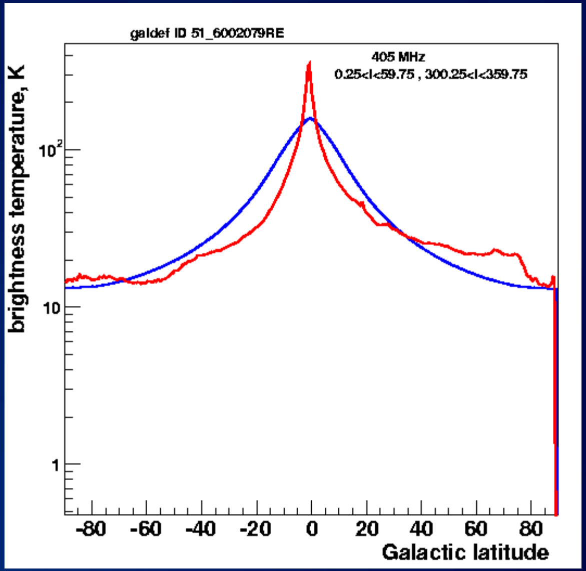
best (still not great)

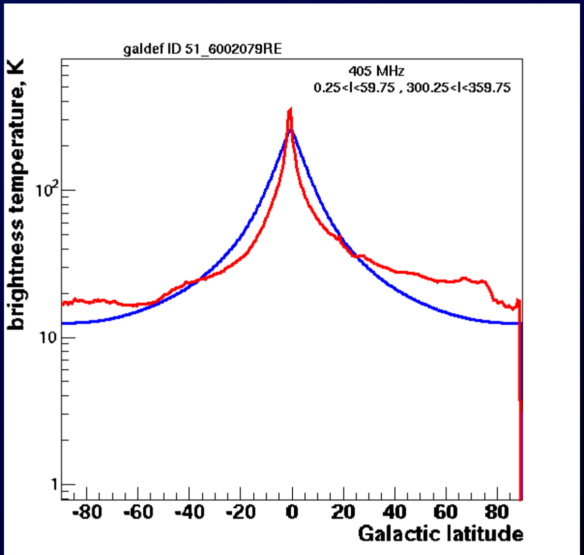


z - scale : 1 kpc too small

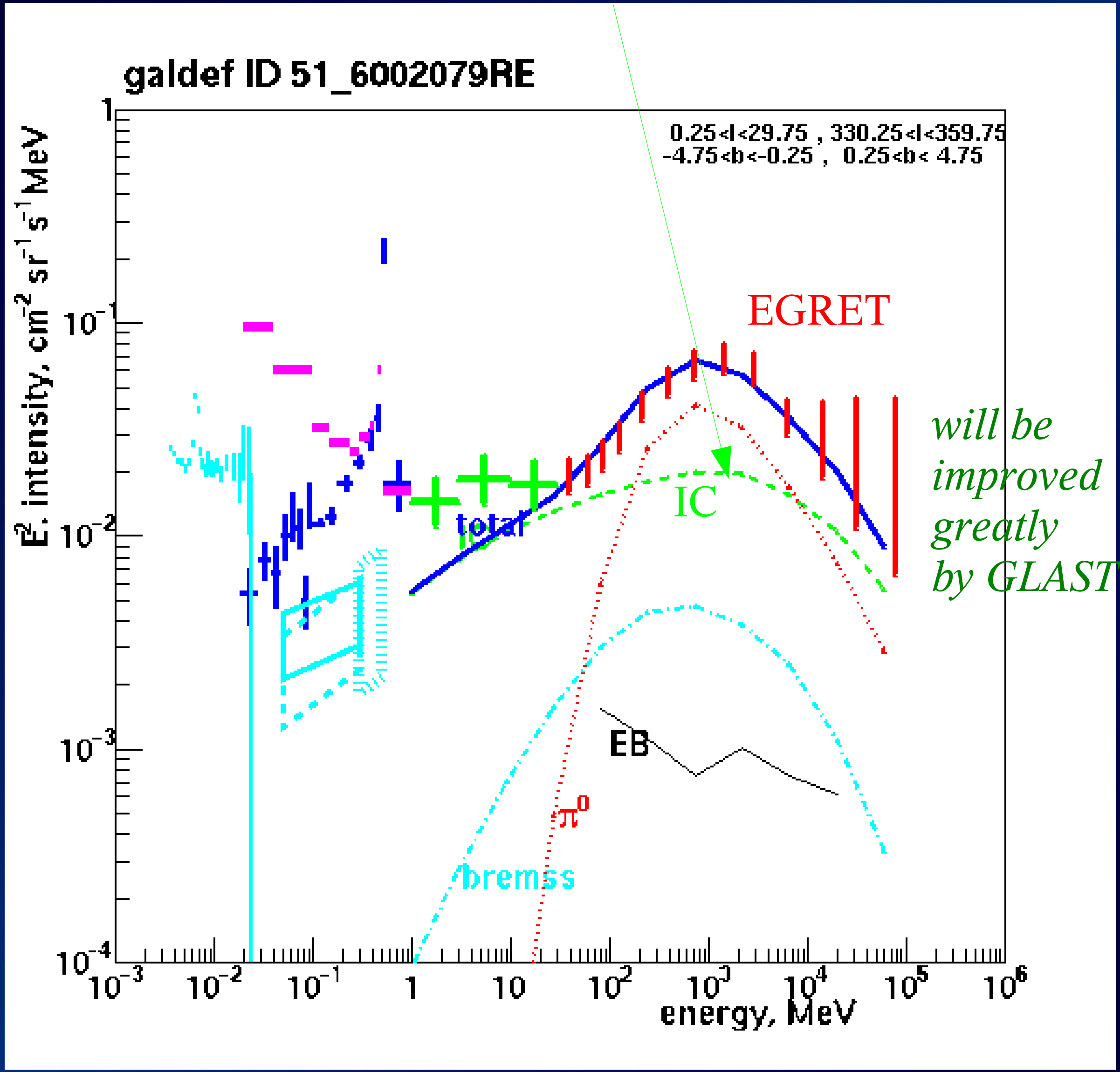


>> electron halo too large





GAMMA RAYS FROM INNER GALAXY

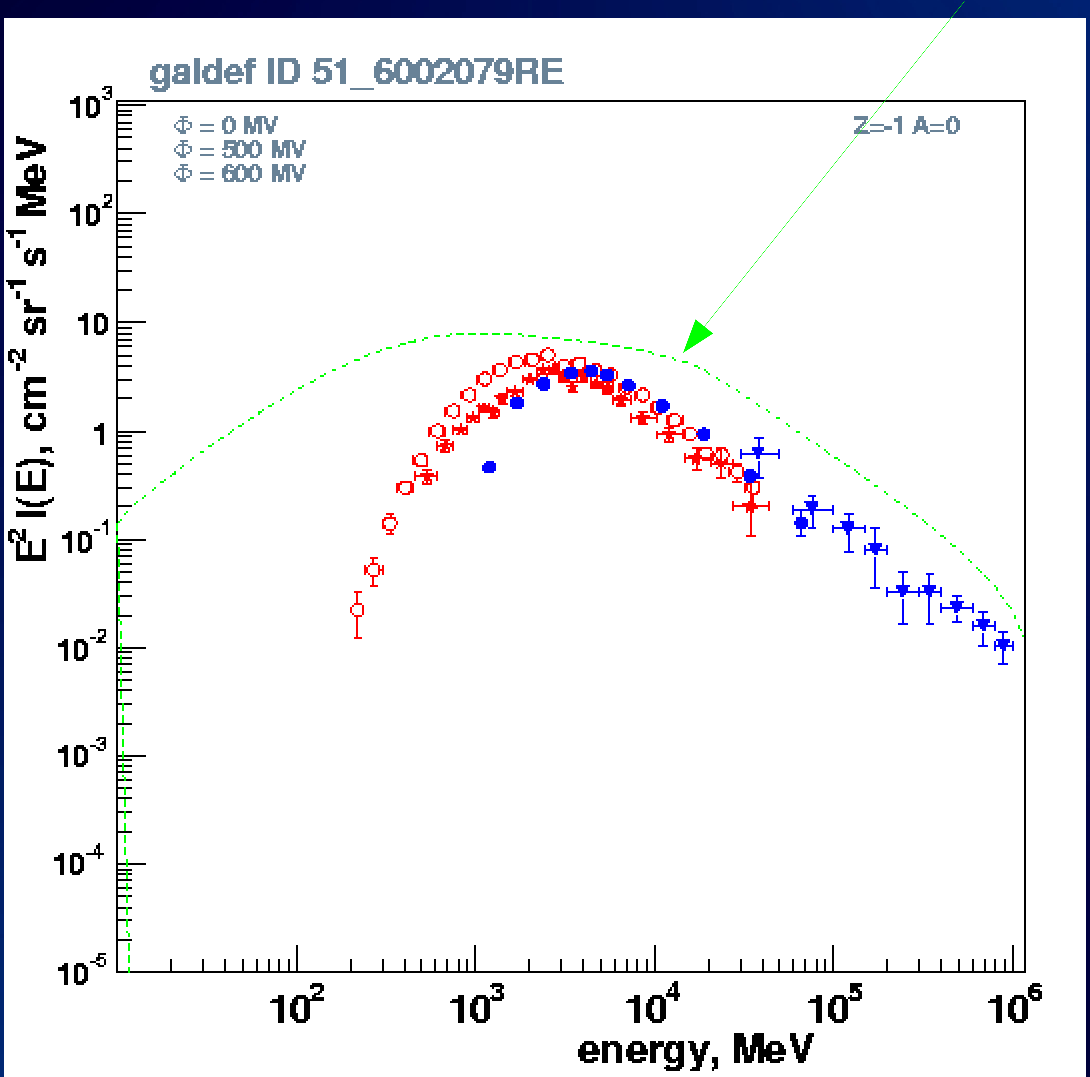


will be improved greatly by GLAST

γ - rays constrain electron spectrum
via inverse Compton emission

COSMIC RAY ELECTRONS

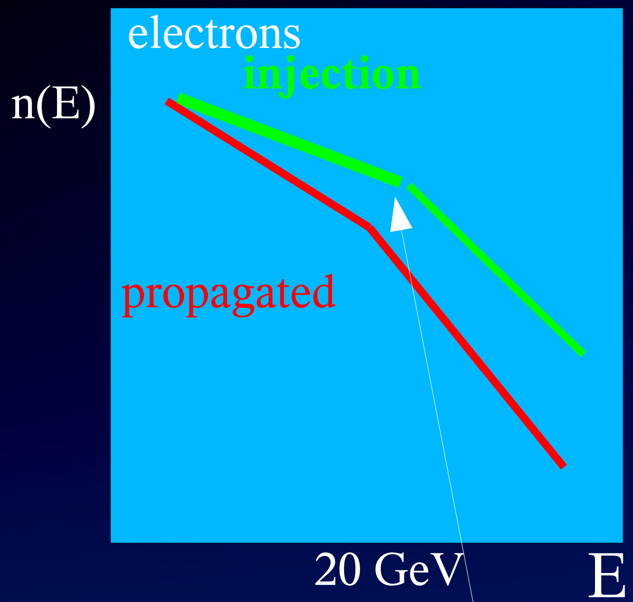
ELECTRON SPECTRUM



need a BREAK in electron spectrum derived from γ-rays

also need a factor ~ 4 more electrons than observed locally to be consistent with γ - rays

Producing the electron/synchrotron spectrum



a *break* is required here by gamma-rays, in interesting range for synchrotron

propagation includes energy losses and energy-dependent diffusion combine in complicated way determined by detailed model

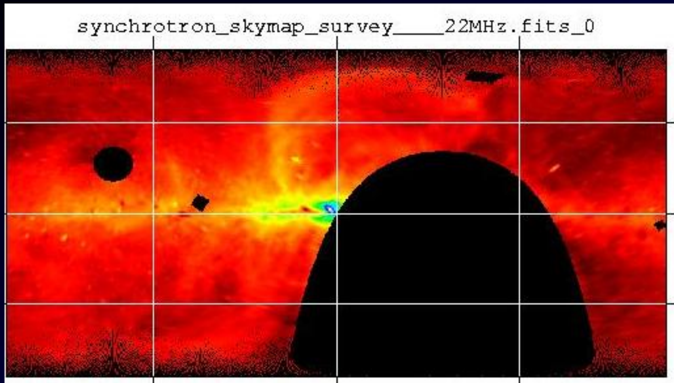
B = 6 μG, sin θ = 0.5

electron E_e	synch. ν_{max}
1 GeV	15 MHz
2	50 MHz
5	350 MHz
10	1.5 GHz
20	5 GHz
30	13 GHz

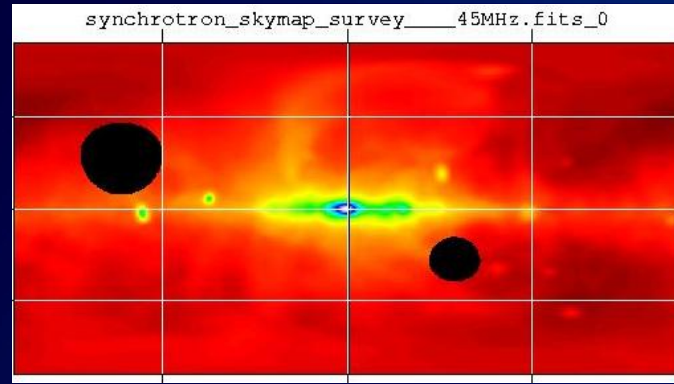
electrons	index: injection	index: propagated	synchrotron	
E < 20 GeV	1.6	2.1	ν < 5 GHz	2.55
E > 20 GeV	2.4	2.9	ν > 5 GHz	2.95

to 0th order as observed

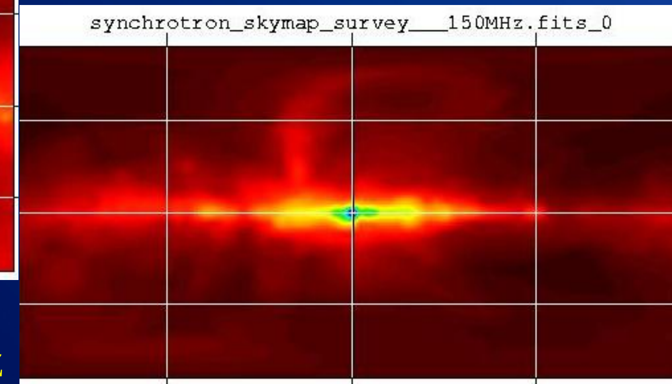
Continuum
sky surveys



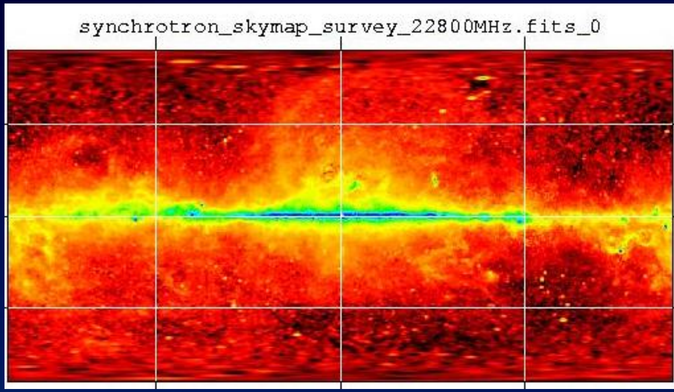
22 MHz



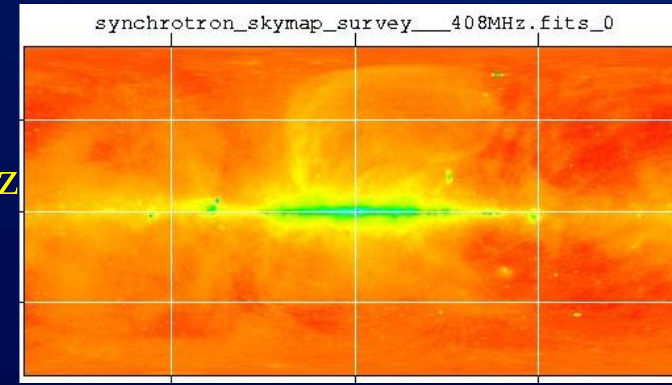
45 MHz



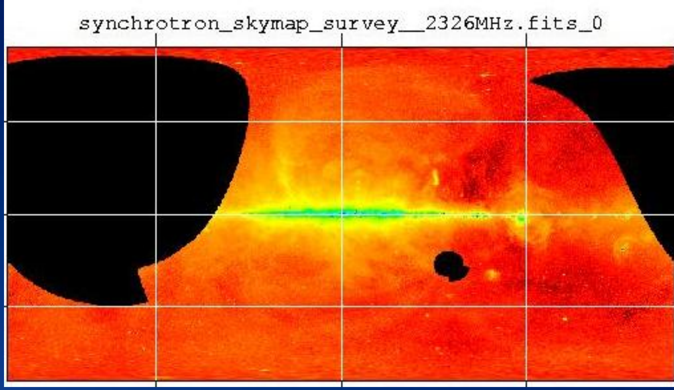
150 MHz



23 GHz

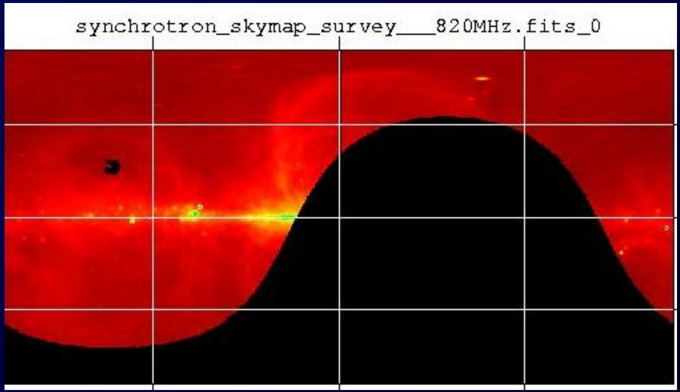


408 MHz

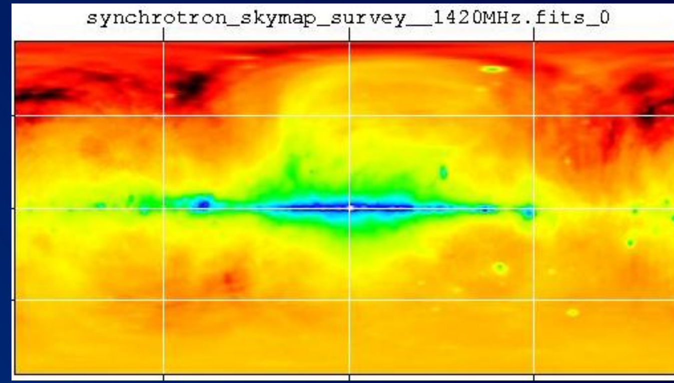


2.3 GHz

820 MHz



1.4 GHz

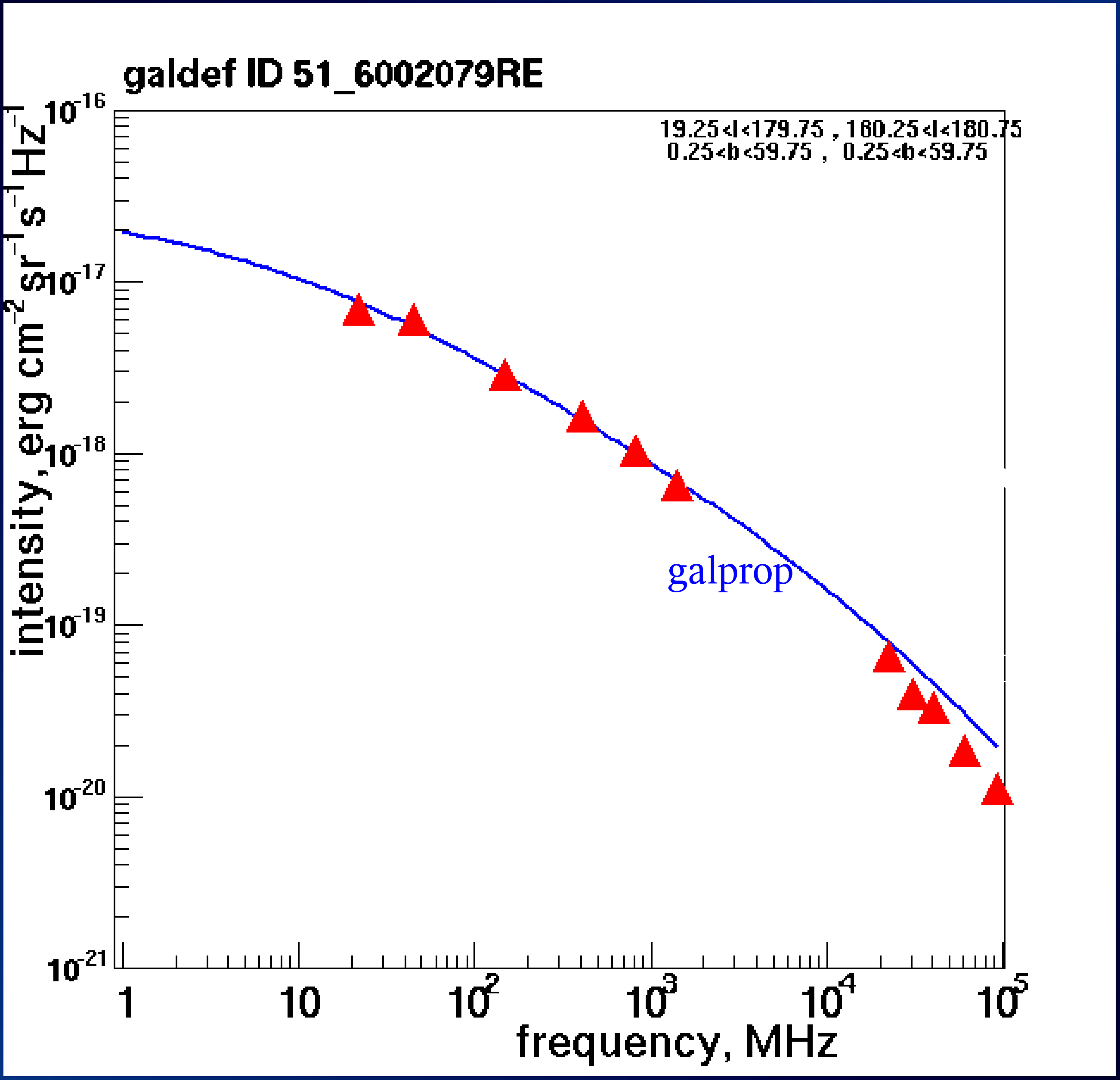


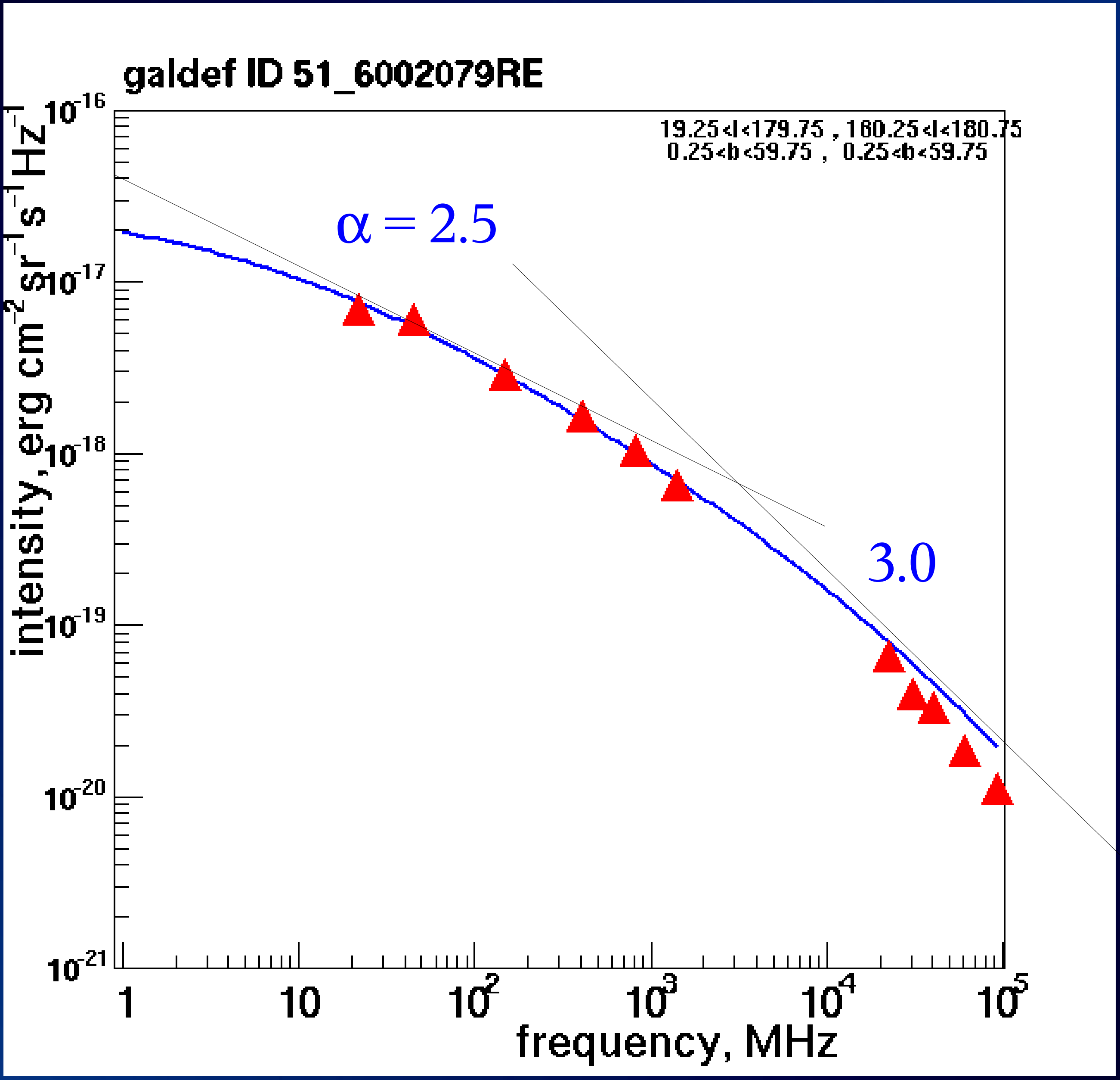
using large areas of sky we should be immune to local effects

but beware of loops, spurs et al

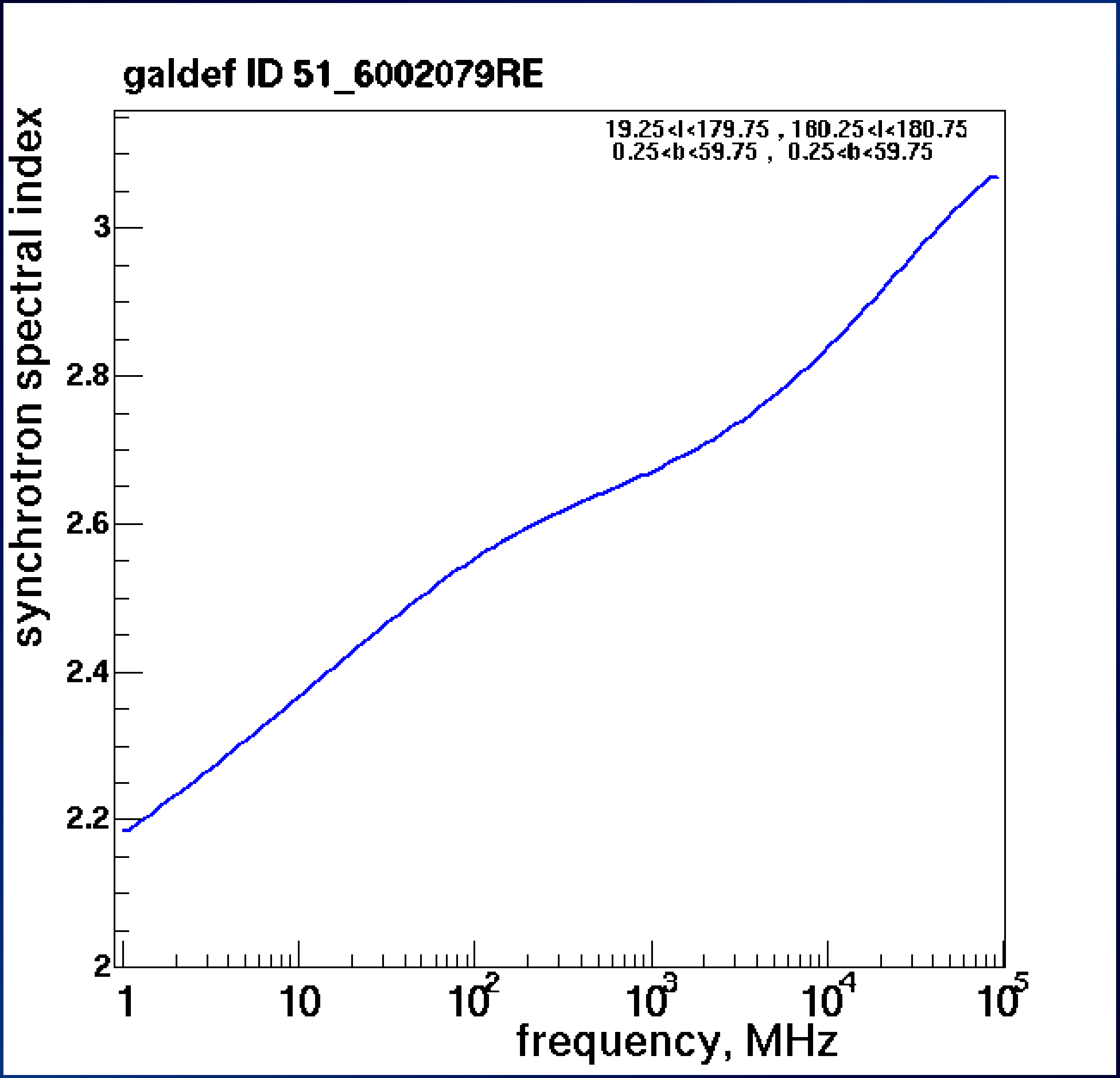
(can eventually be included in model) !

SYNCHROTRON, NORTHERN GALAXY

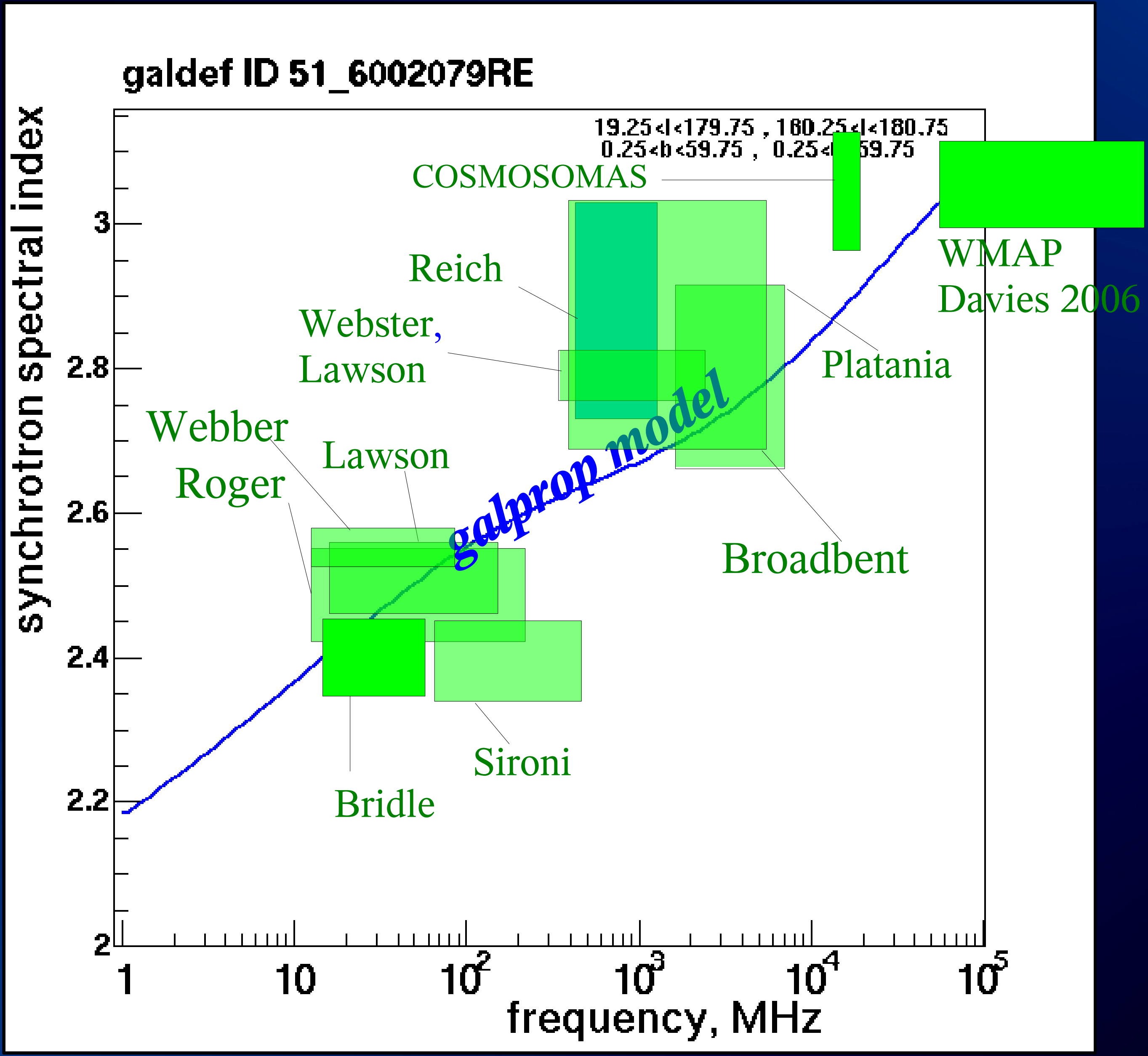



galdef ID 51_6002079RE
19.25<l<179.75 , 180.25<l<180.75
0.25<b<59.75 , 0.25<b<59.75
α = 2.5
3.0
intensity, erg cm^-2 sr^-1 s^-1 Hz^-1
frequency, MHz

NORTHERN SKY SPECTRAL INDEX

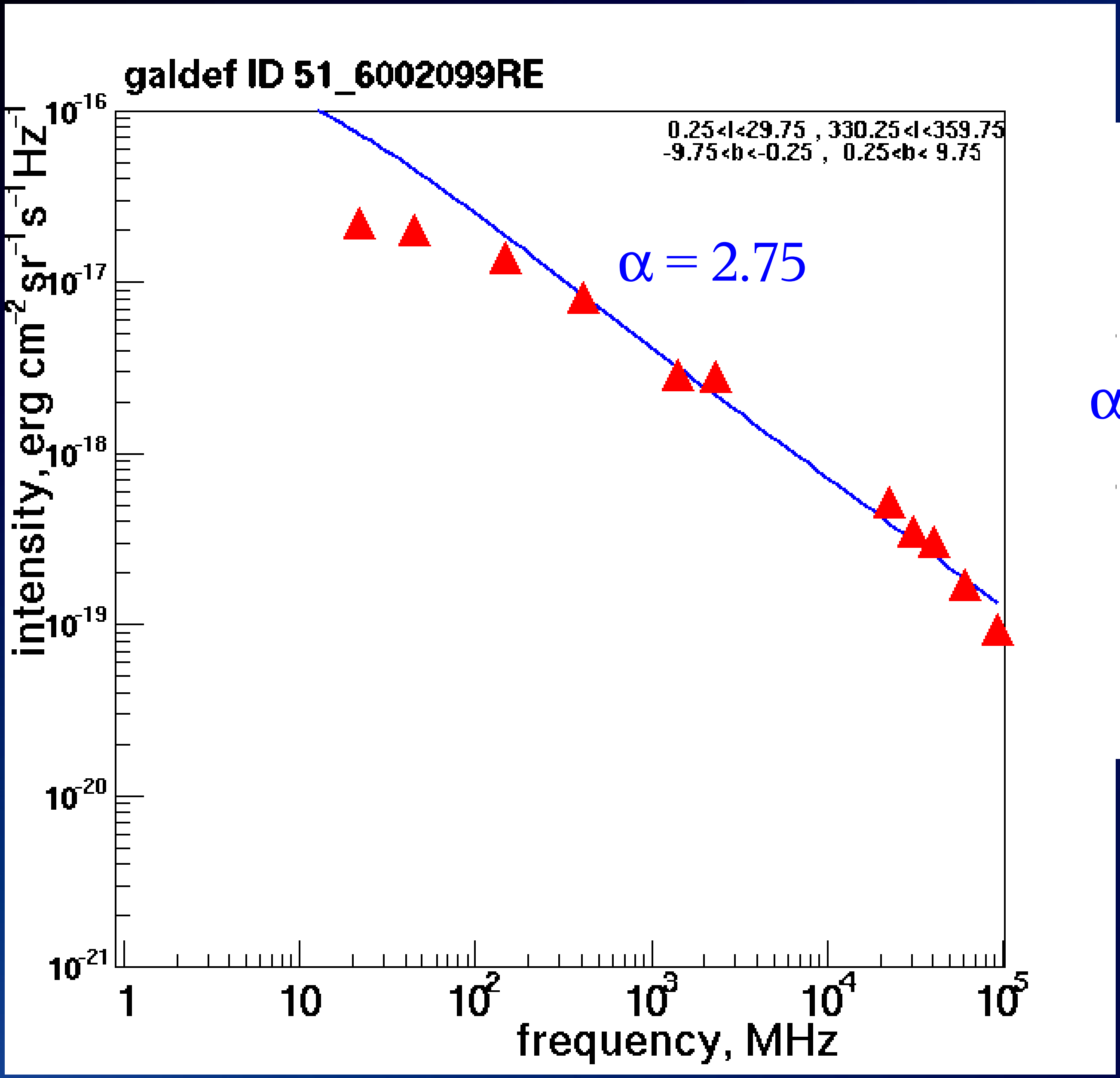


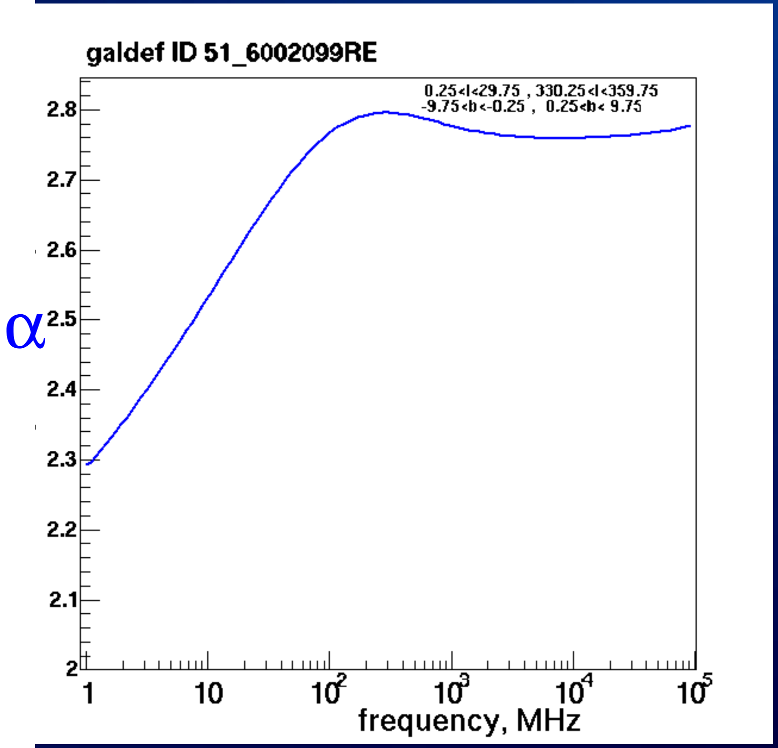
NORTHERN SKY SPECTRAL INDEX



data are just indicative, schematic

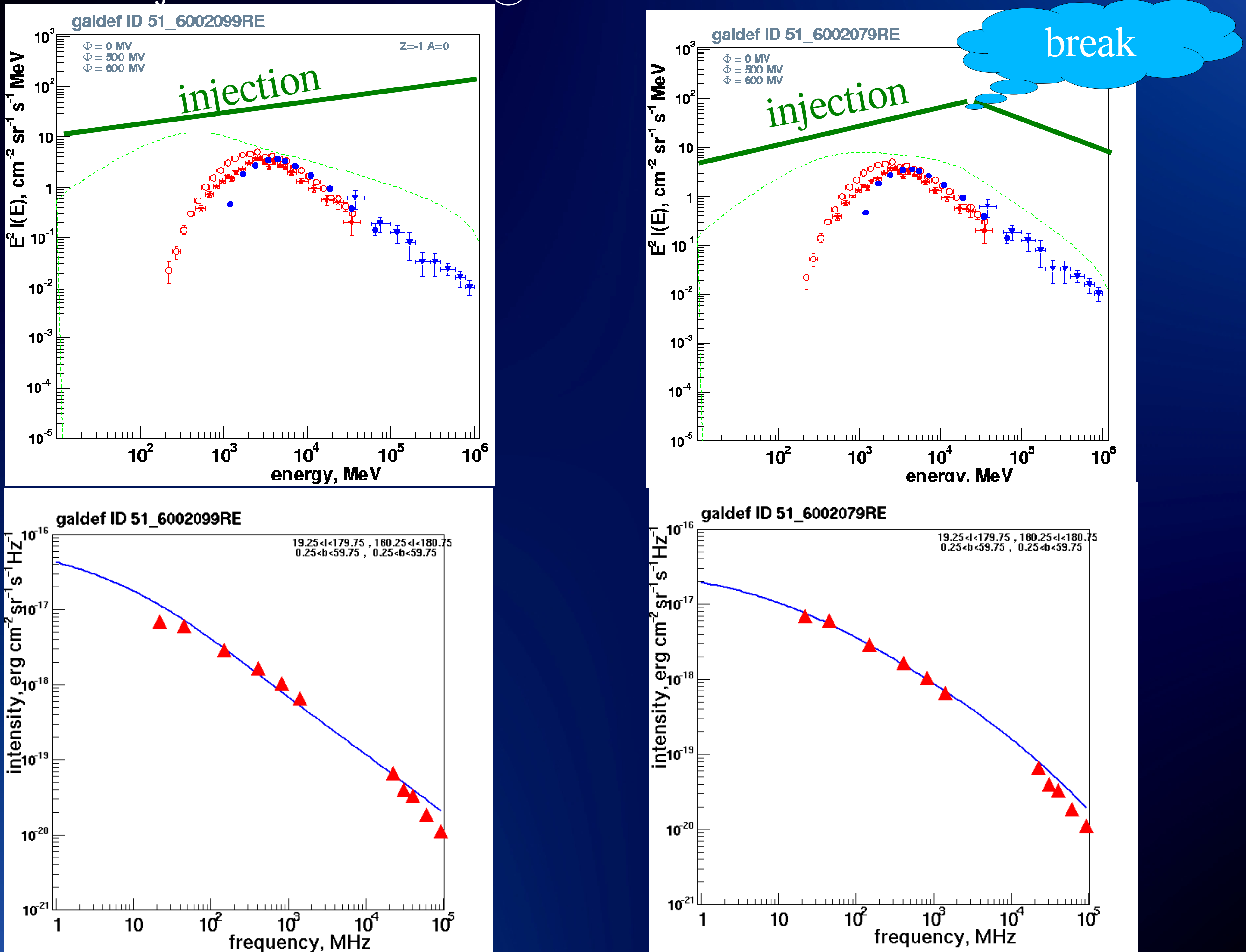
cosmic-ray electron injection index = 1.8





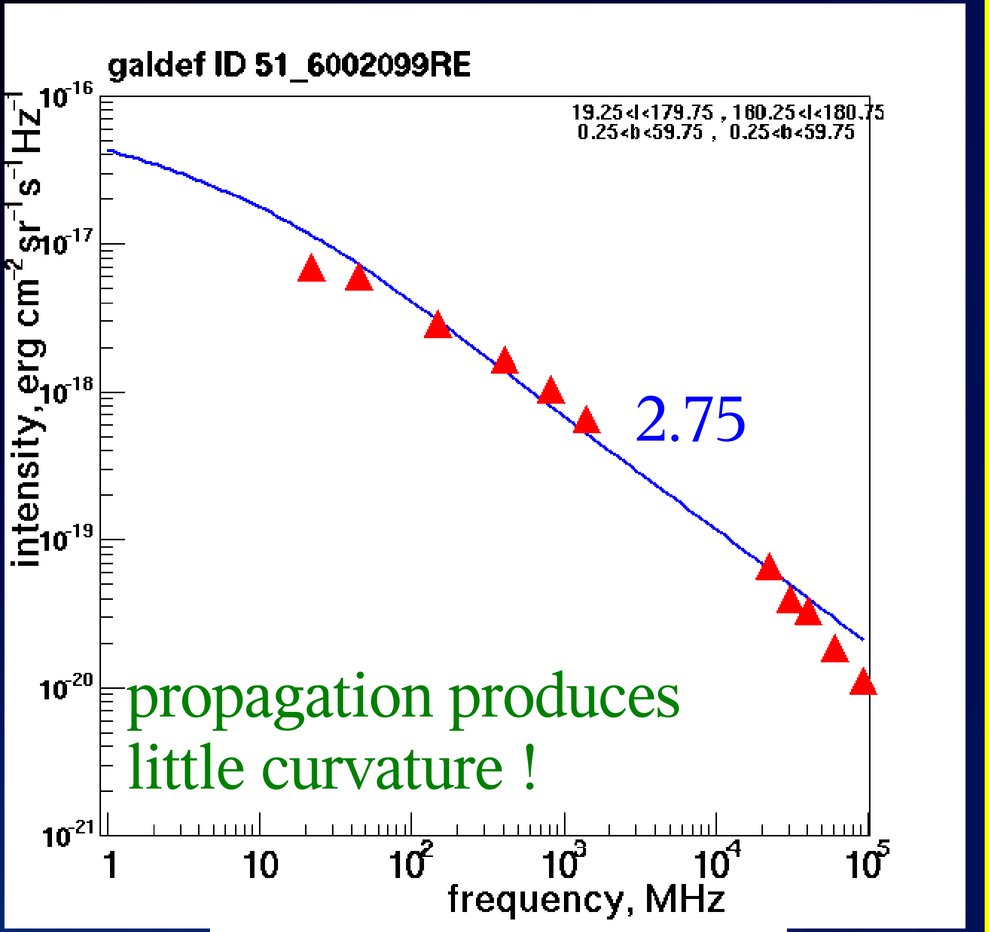
propagation produces *little curvature* at high frequencies !

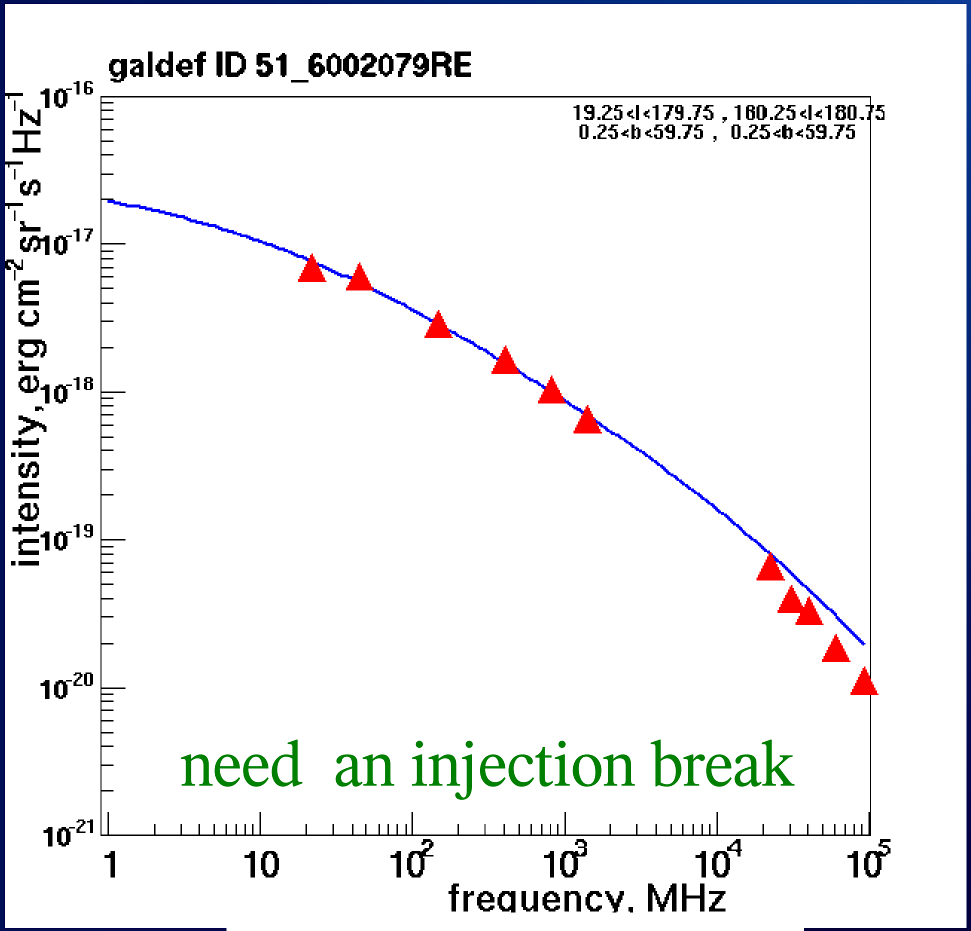
electron injection index: const @ 1.8 with break 1.5 / 2.4 at 20 GeV



electron injection index: const @ 1.8

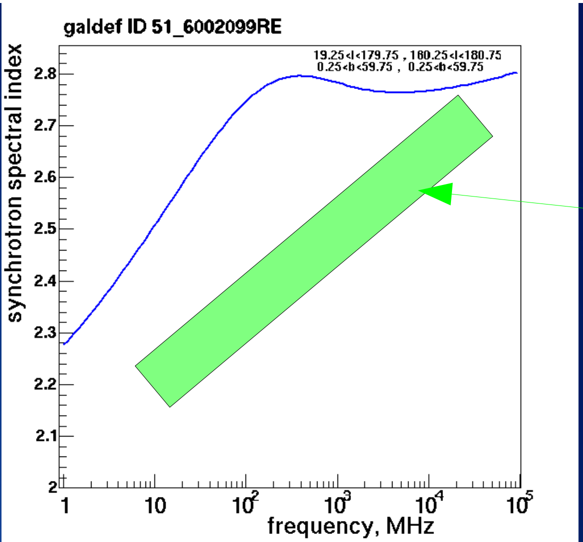
with break 1.5 / 2.4 at 20 GeV





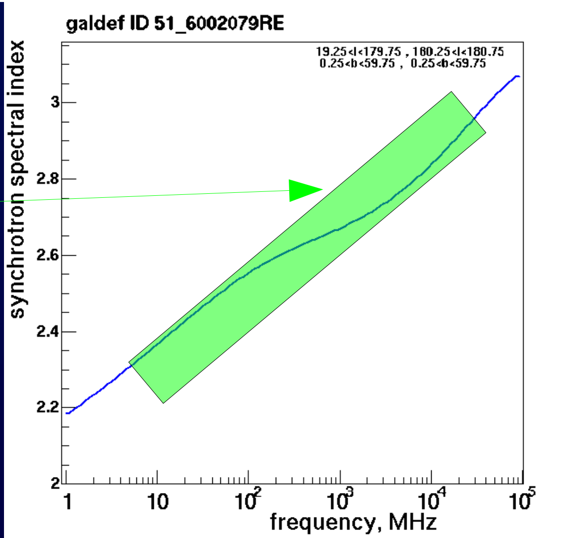
to fit in this case need B=50μG !

$\nu \sim BE^2$



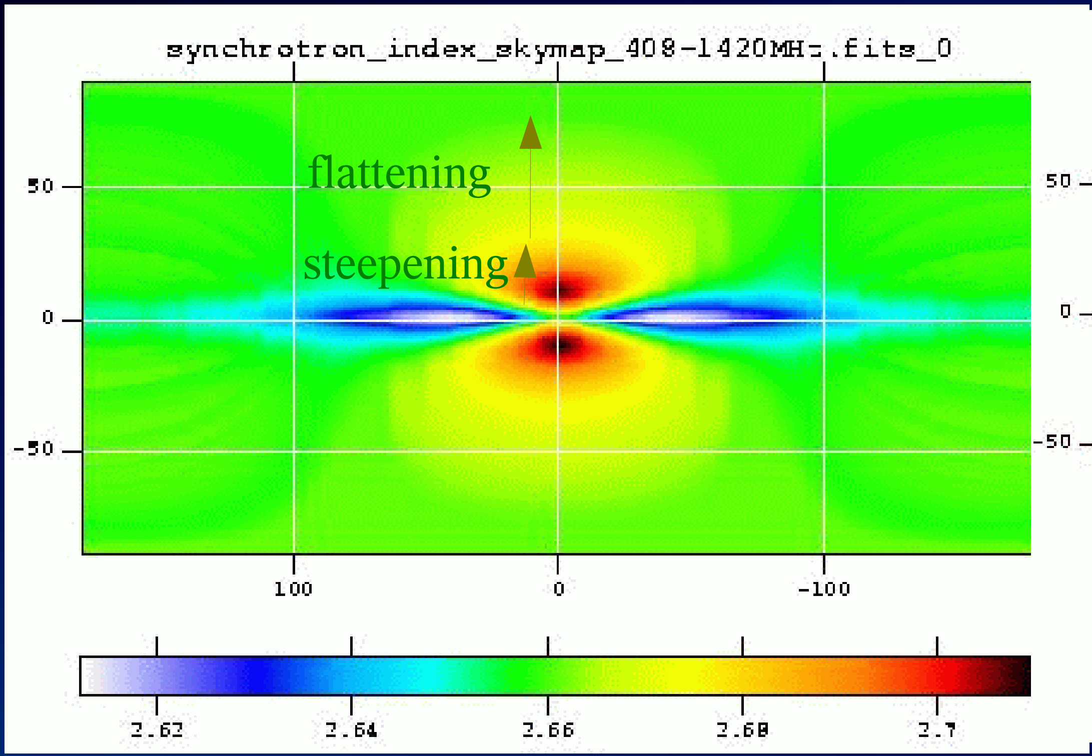
fits nicely:

observed trend

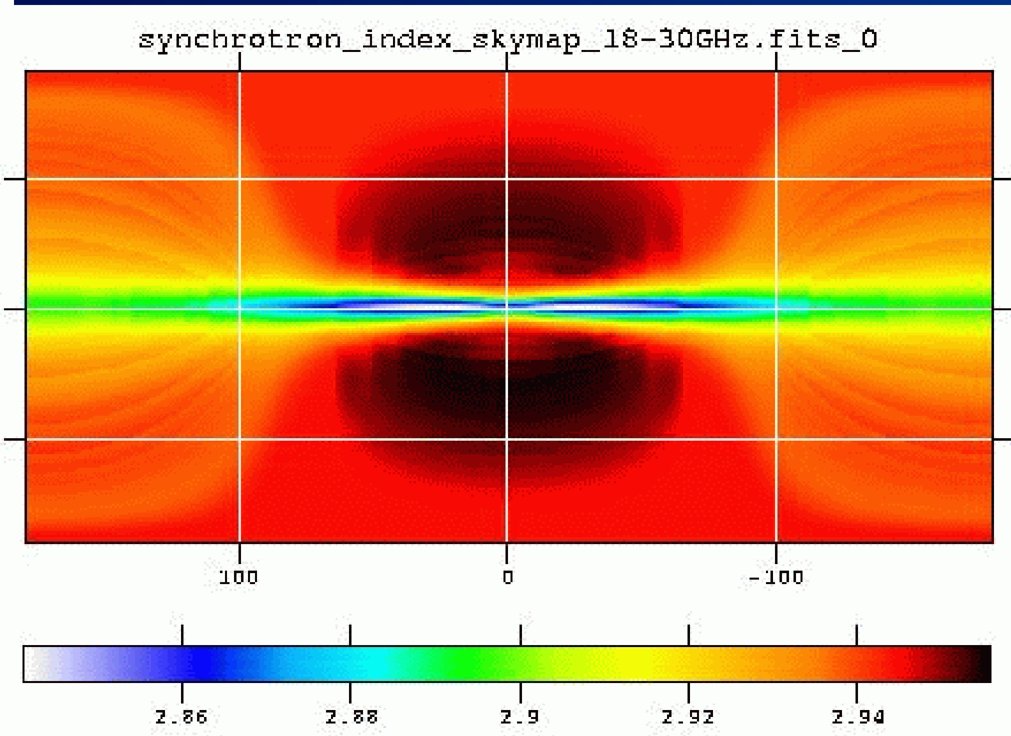


MODEL SPECTRAL INDEX VARIATIONS

408-1420 MHz



18 - 30 GHz



Propagation model predicts some interesting structure but variations are small, and not really as observed. Easily masked by other effects: loops etc.
Some flattening to high *b*, but less than observed.

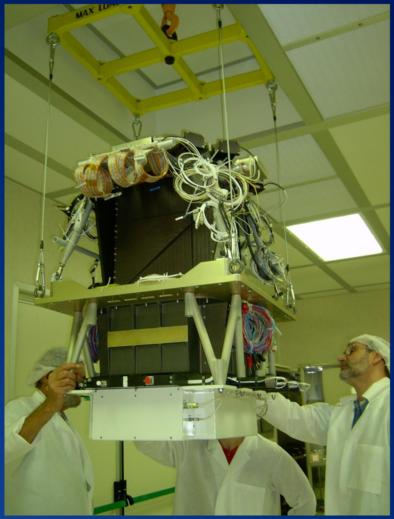
Outlook

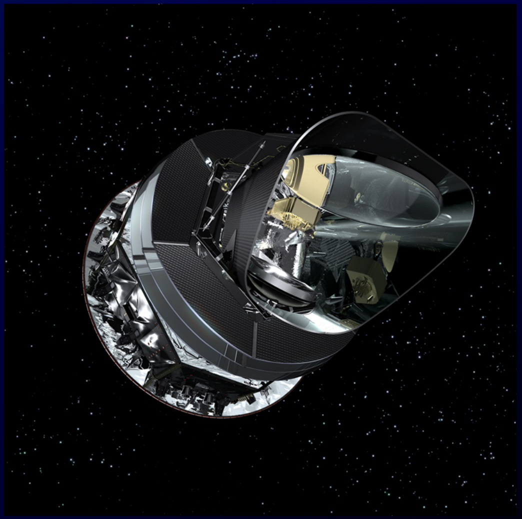
more realistic **B** in *galprop*, including regular component

compare with all radio survey data, spectral index maps

this impacts on cosmic-ray, γ - ray models

exploit synergy
cosmic-ray - GLAST – radio - Planck





END

backup slides

SPECTRAL INDEX SPATIAL VARIATIONS

ALWAYS TRICKY !

BUT TRY ANYWAY

Bloemen et al 1988 based on Reich&Reich 1988

spectral hardening with increasing latitude: surprising (Galactic wind?)

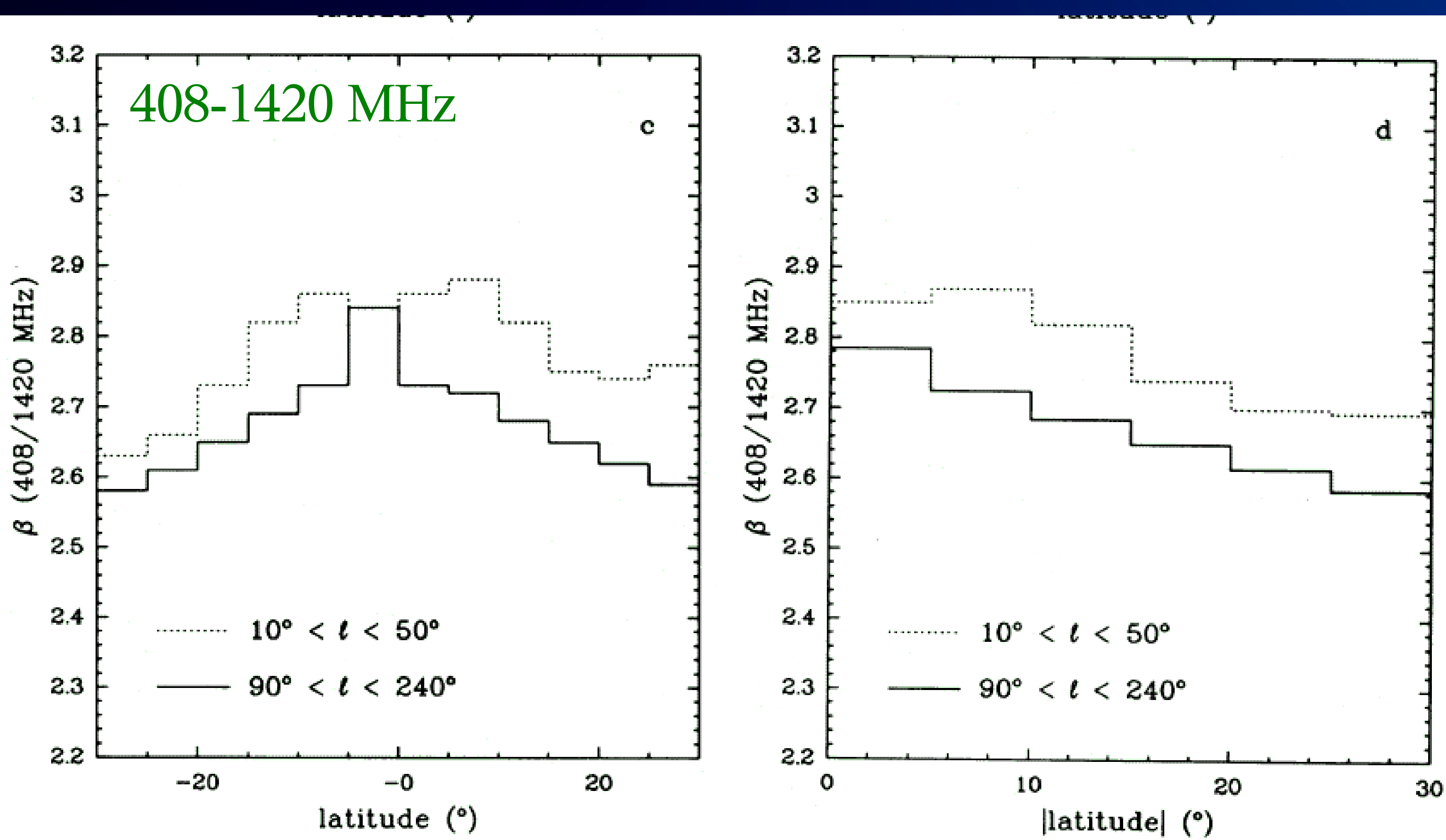
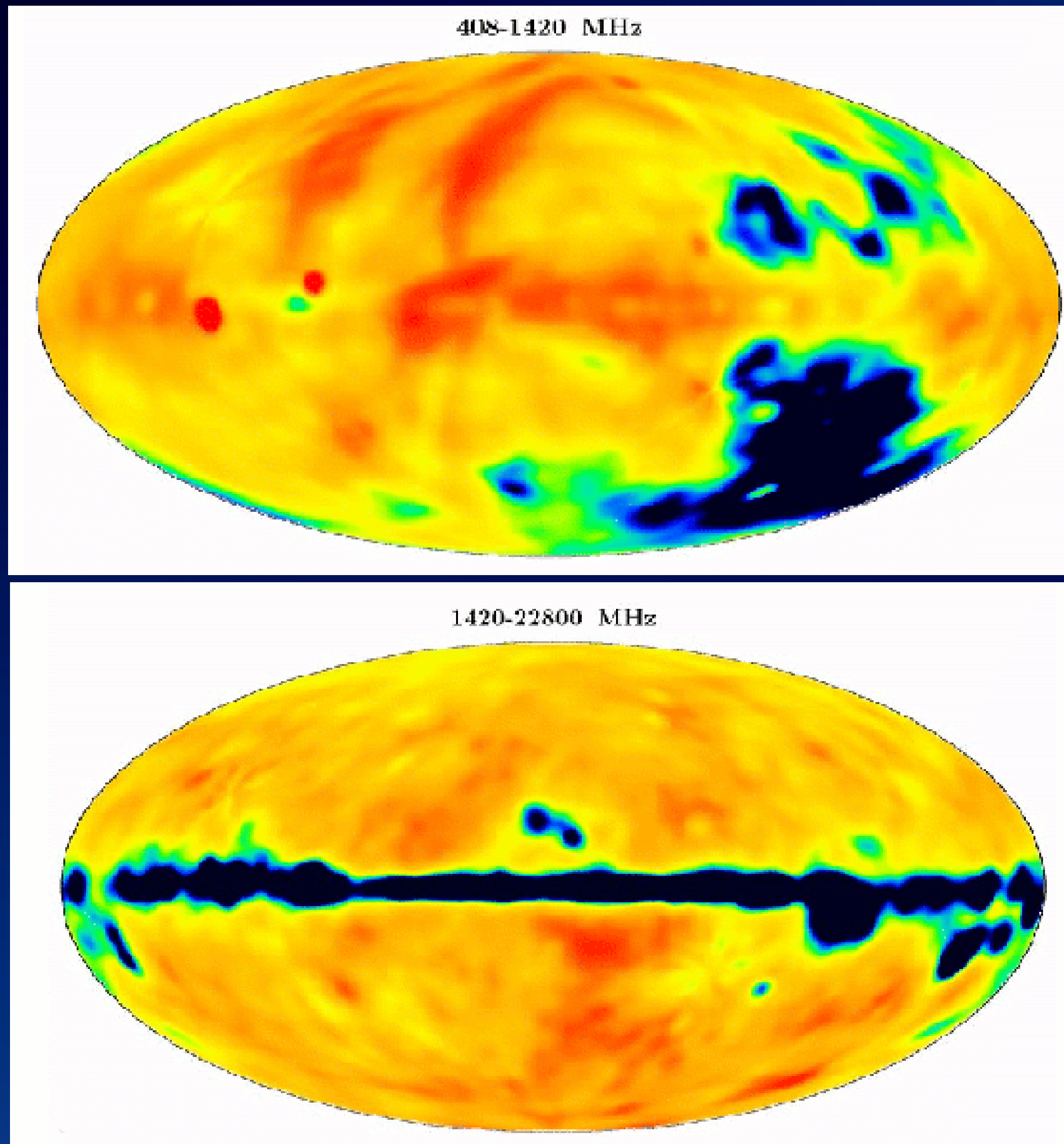


Fig. 1. **a** Latitude distributions of the brightness temperatures at 408 MHz toward the inner and outer Galaxy. The dashed lines indicate the background level of 3.7 K (Reich and Reich 1988a). **b** As **a**, but for 1420 MHz. The background level is 2.8 K. **c** Latitude distribution of the spectral index β of the galactic radio emission at 408 and 1420 MHz ($T_b(\nu) \propto \nu^{-\beta}$). **d** As **c**, but the regions below and above the galactic plane are combined

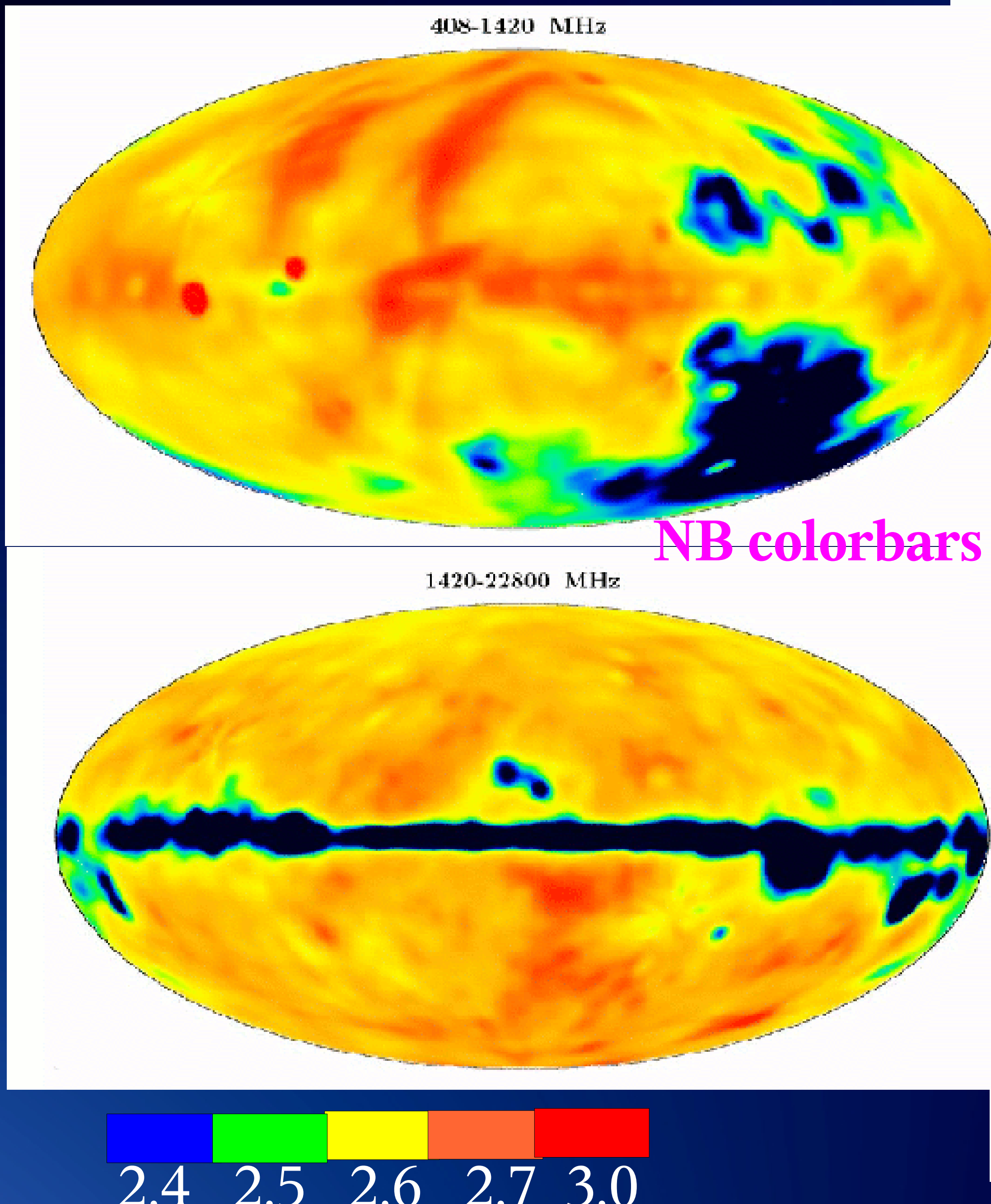
diffusion model does NOT predict this behaviour !

Reich, Reich and Testori spectral index maps
from The Magnetized Interstellar Medium Conference, 2003

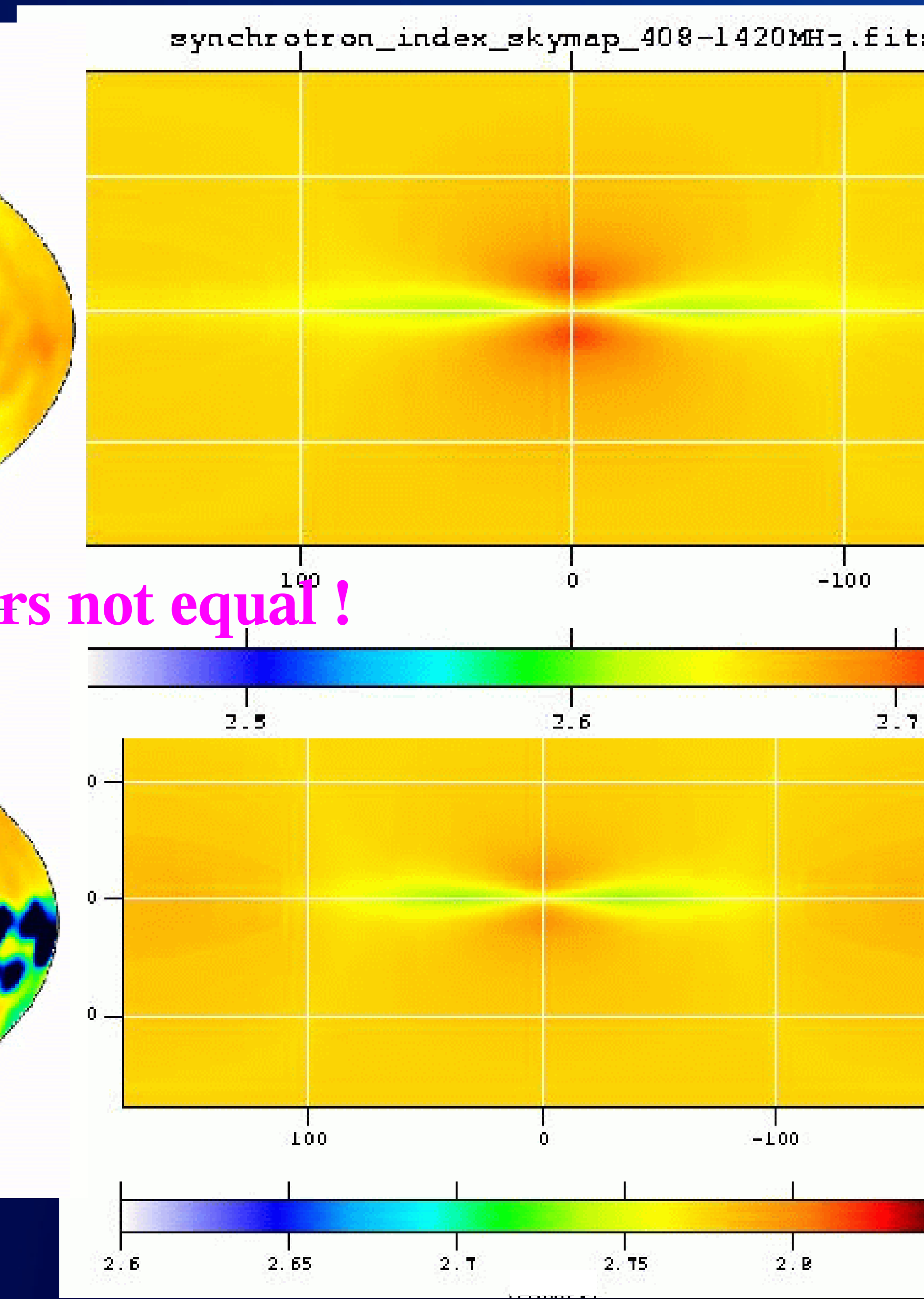


Reich, Reich and Testori spectral index maps from The Magnetized Interstellar Medium Conference, 2003

galprop model



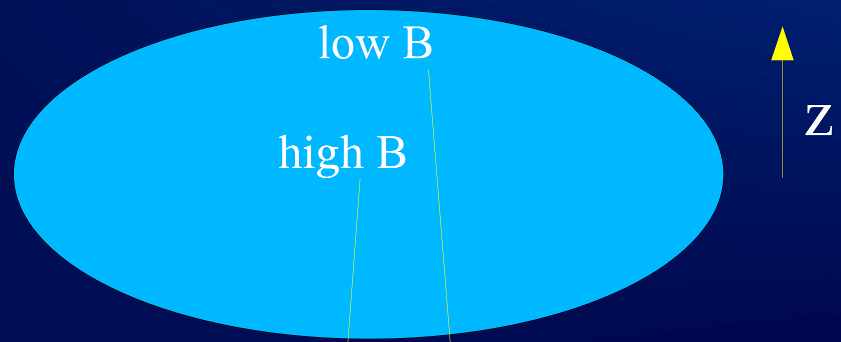
NB colorbars not equal !

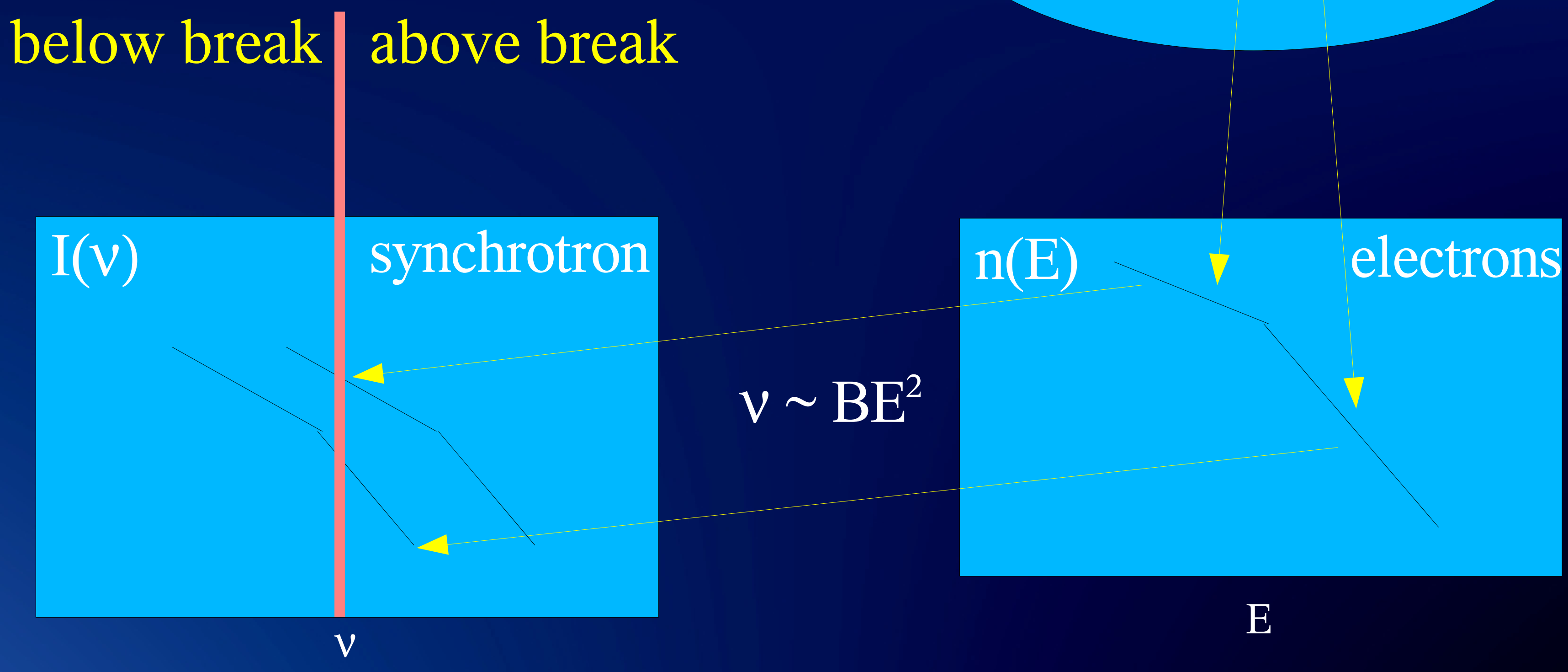


electron spectrum: has breaks, complex form ?

importance of detailed models !

B(*z*) – see different electron energies
are we seeing the break as we move up
into the halo ?





Reich & Reich
408 -1420 MHz

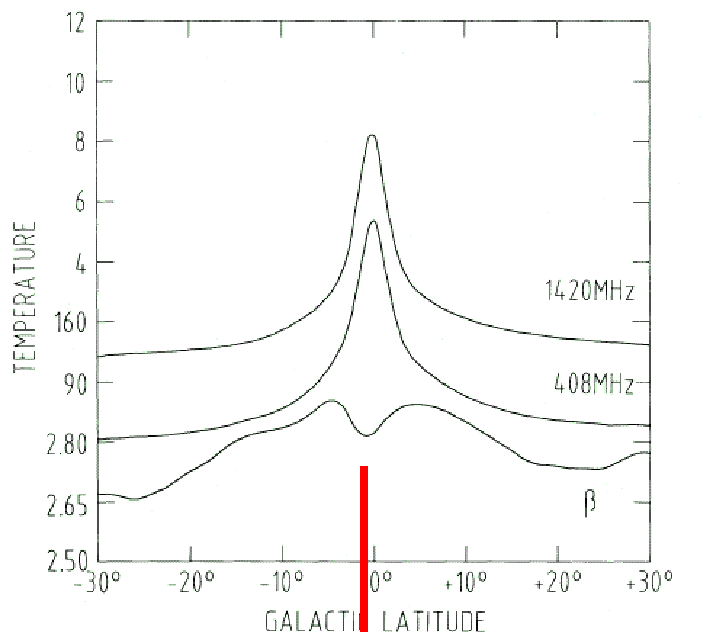
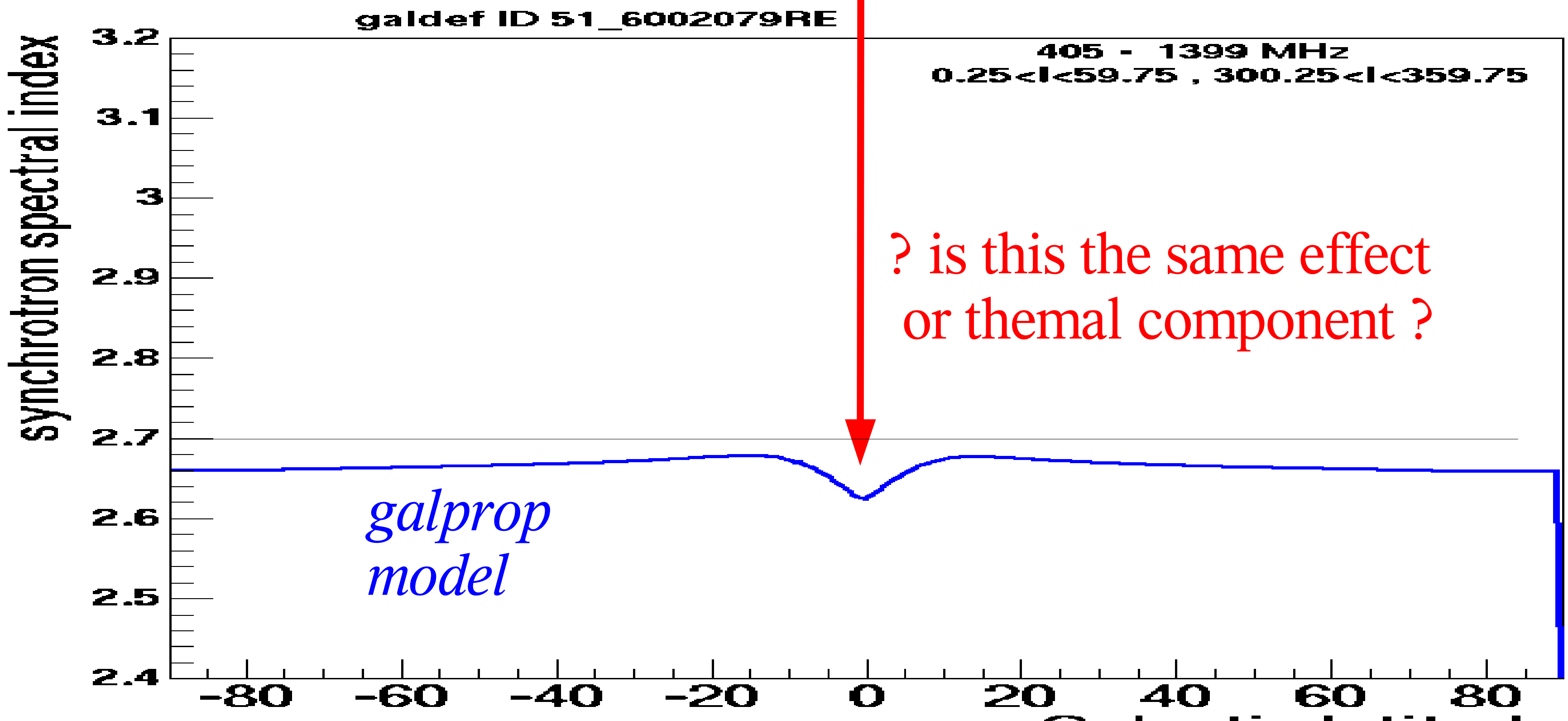
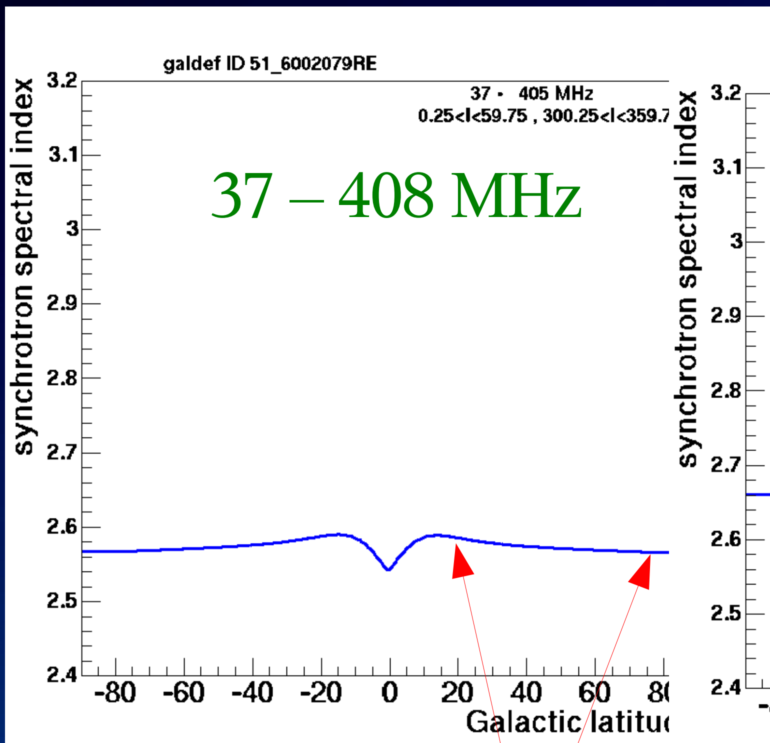


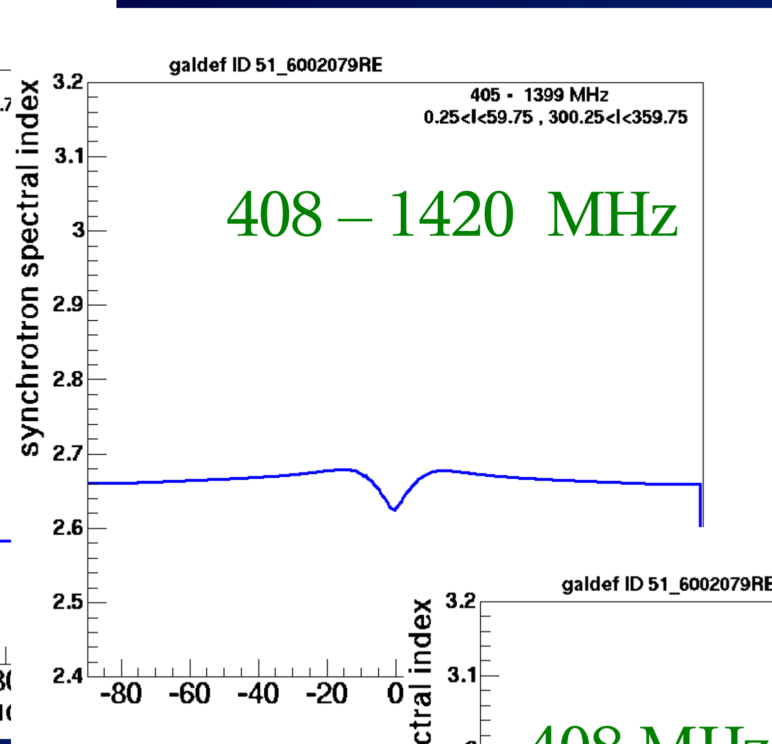
Fig. 6. The same latitude profiles as in Fig. 5 for an angular resolution of 2°5

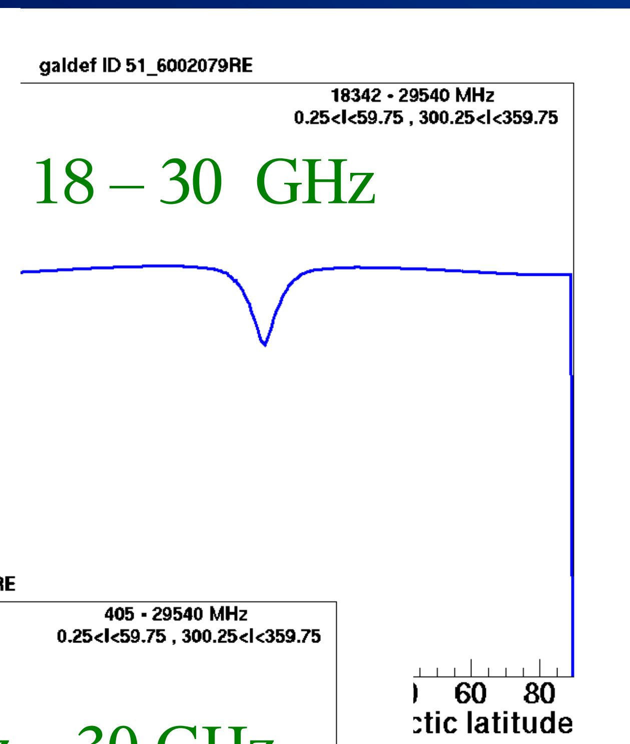


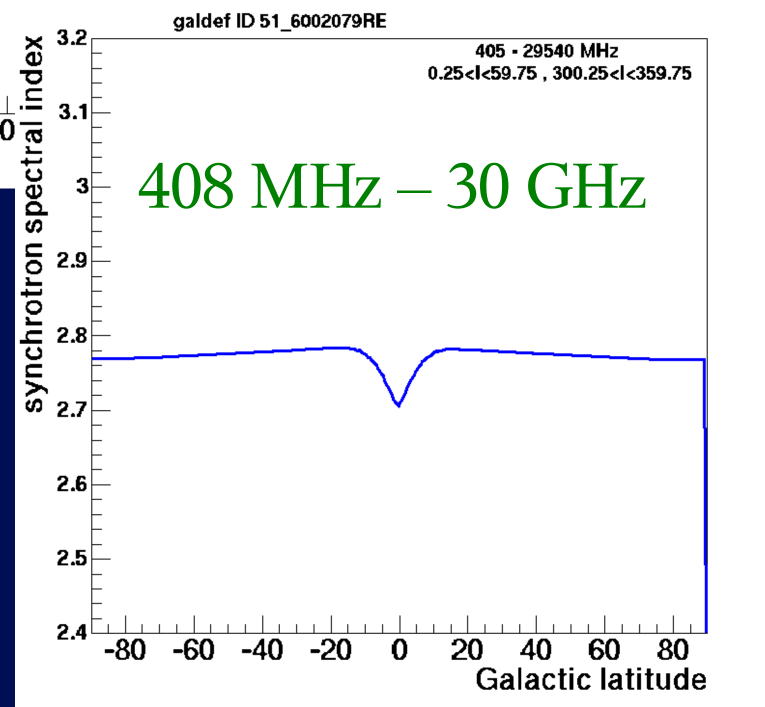
? is this the same effect
or themal component ?

SPECTRAL INDEX AS FUNCTION OF LATITUDE









predicts slight flattening,
hardly detectable

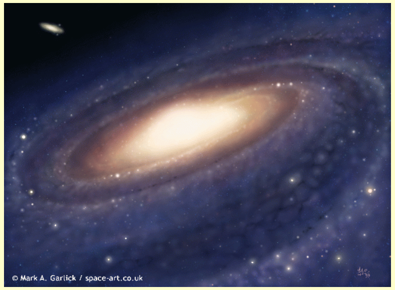
guiding principle:

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, AMS, long-duration balloon flights
require correspondingly *detailed* models.

astronomical input

compared to 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
(cf. complex formulae of analytical methods)

uses only observable quantities (cosmic-ray spectrum, secondary/primary ratios)

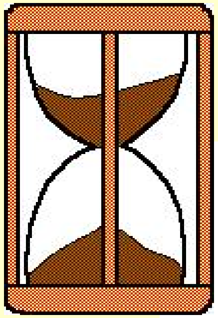
for *nuclei* it is possible to treat semi-analytically
but for e.g. *electrons*, *positrons* it's **impossible** to do it properly
(rapid energy losses on 3D interstellar radiation field)

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

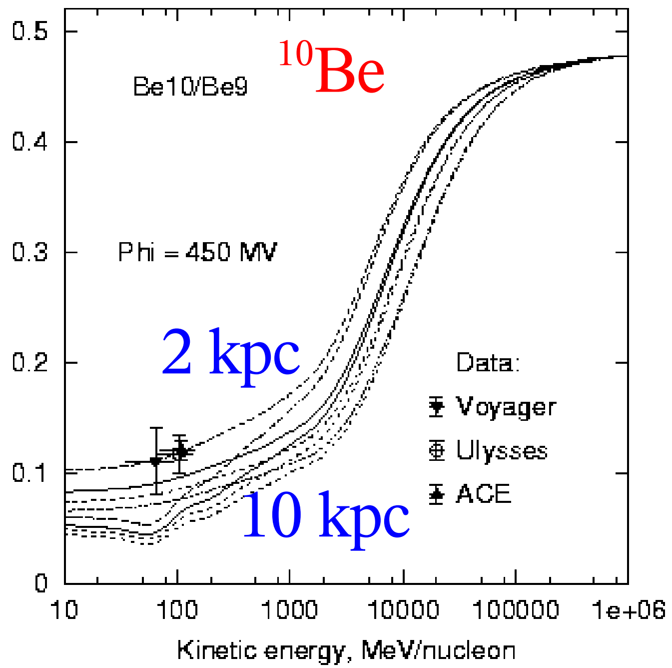
an example of a *galprop* application:

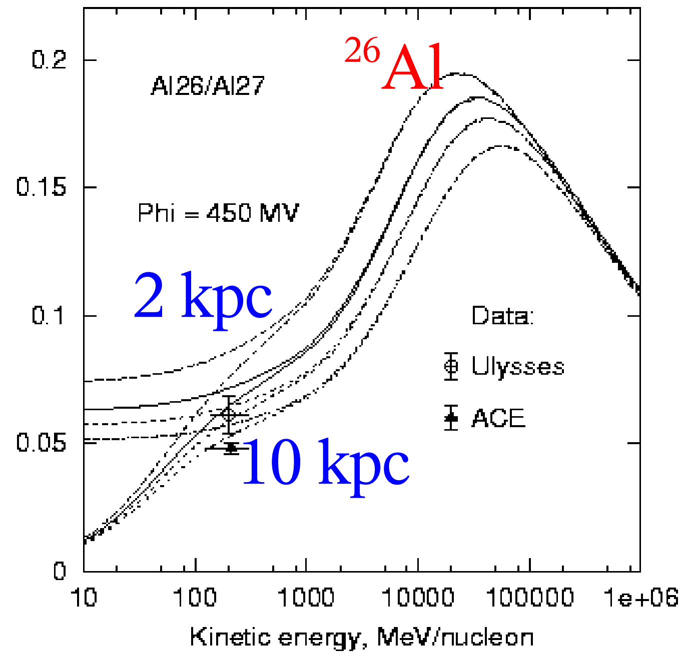
study of cosmic-ray diffusion theories:
wave-damping by cosmic rays

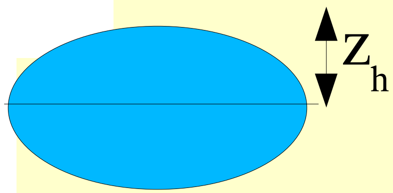
Ptuskin et al. 2006 ApJ 642, 902



More Cosmic-ray Clocks: Radioactive nuclei set limits on size of halo







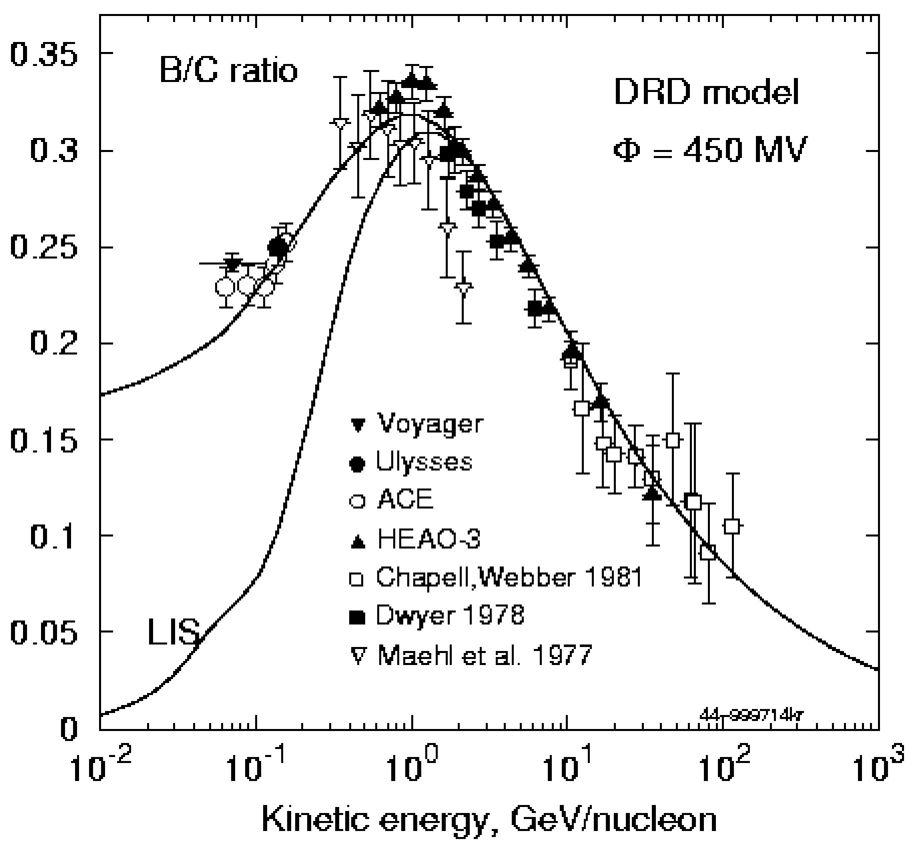
$3 < z < 7$ kpc

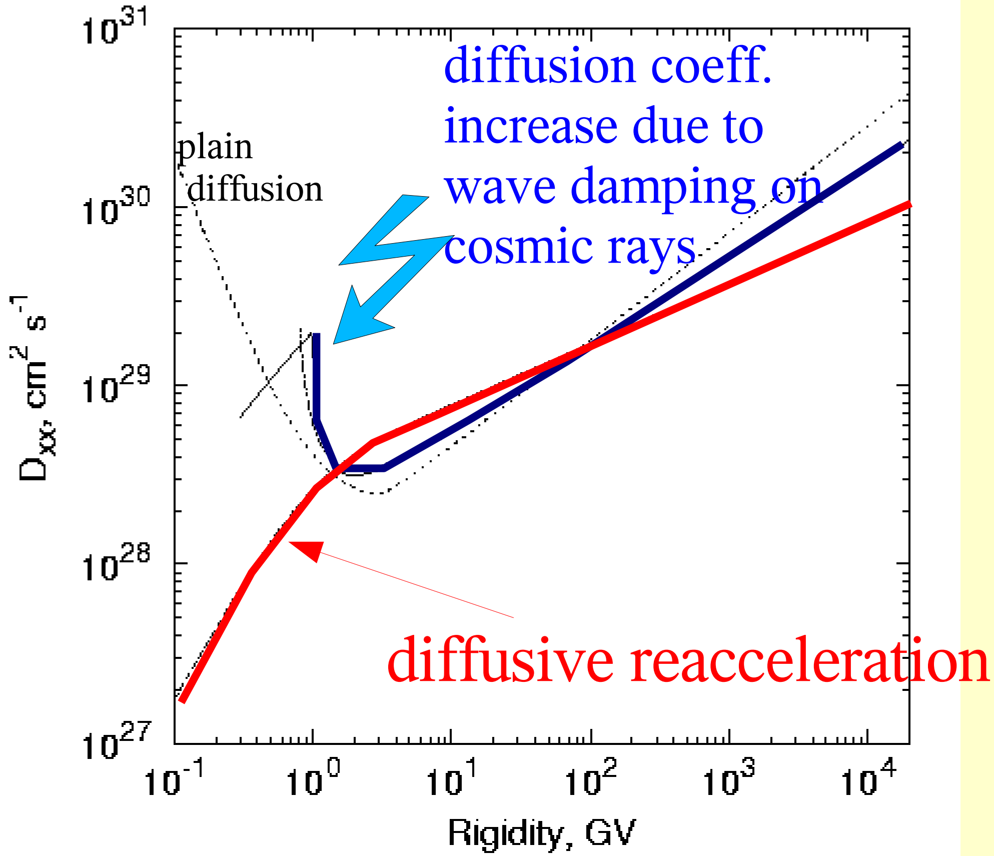
kpc

secondary/primary ratio: Boron/Carbon

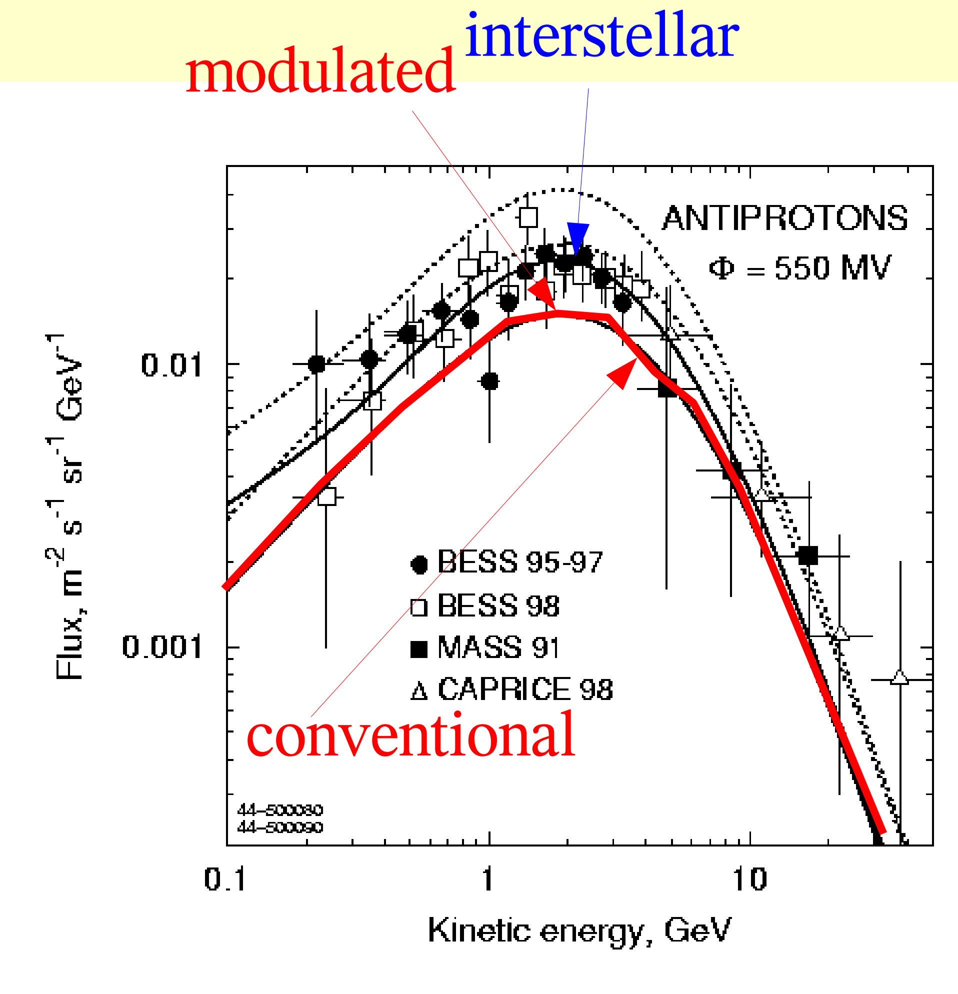
.... another explanation of peak in B/C :
dissipation of MHD waves by cosmic rays
Ptuskin et al. 2006, ApJ 642, 902
Effect included in galprop code.

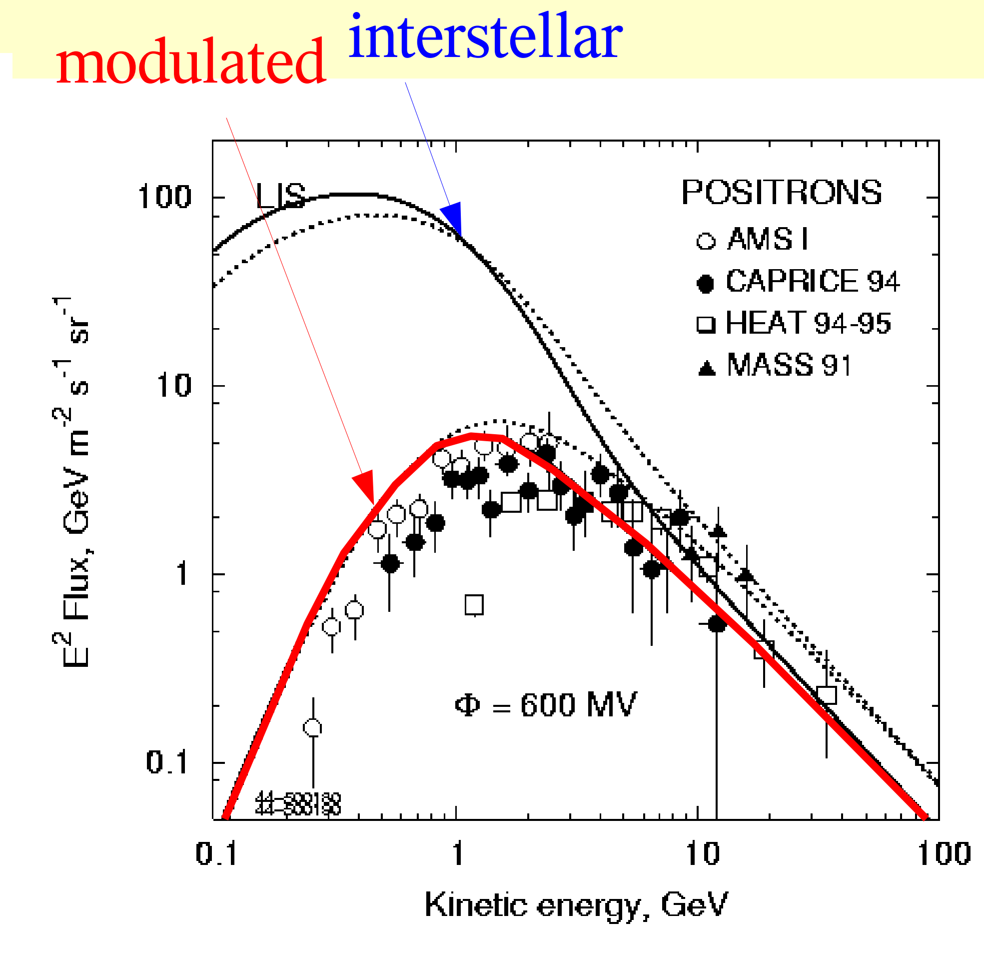
Boron/Carbon





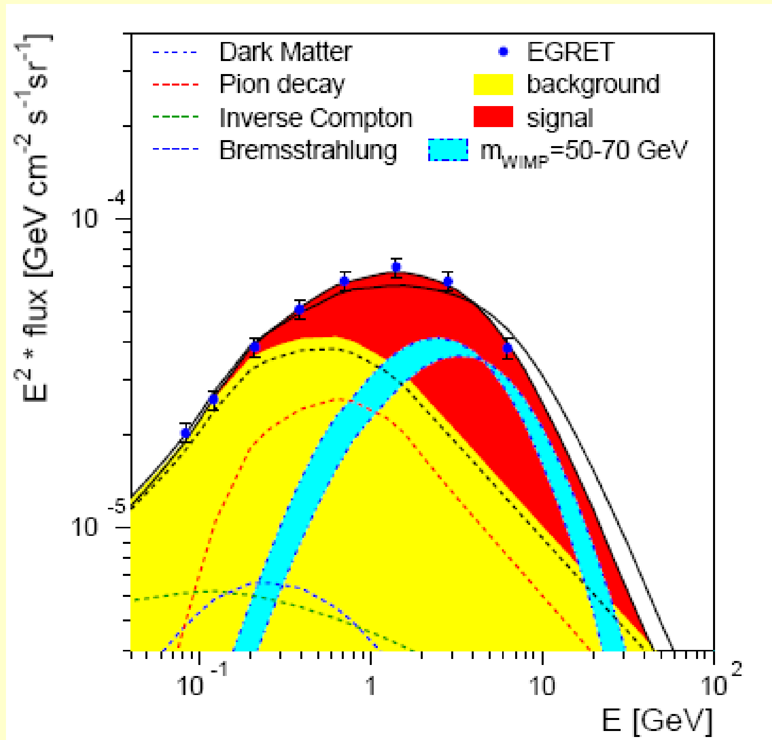
Conventional model underpredicts secondary antiprotons





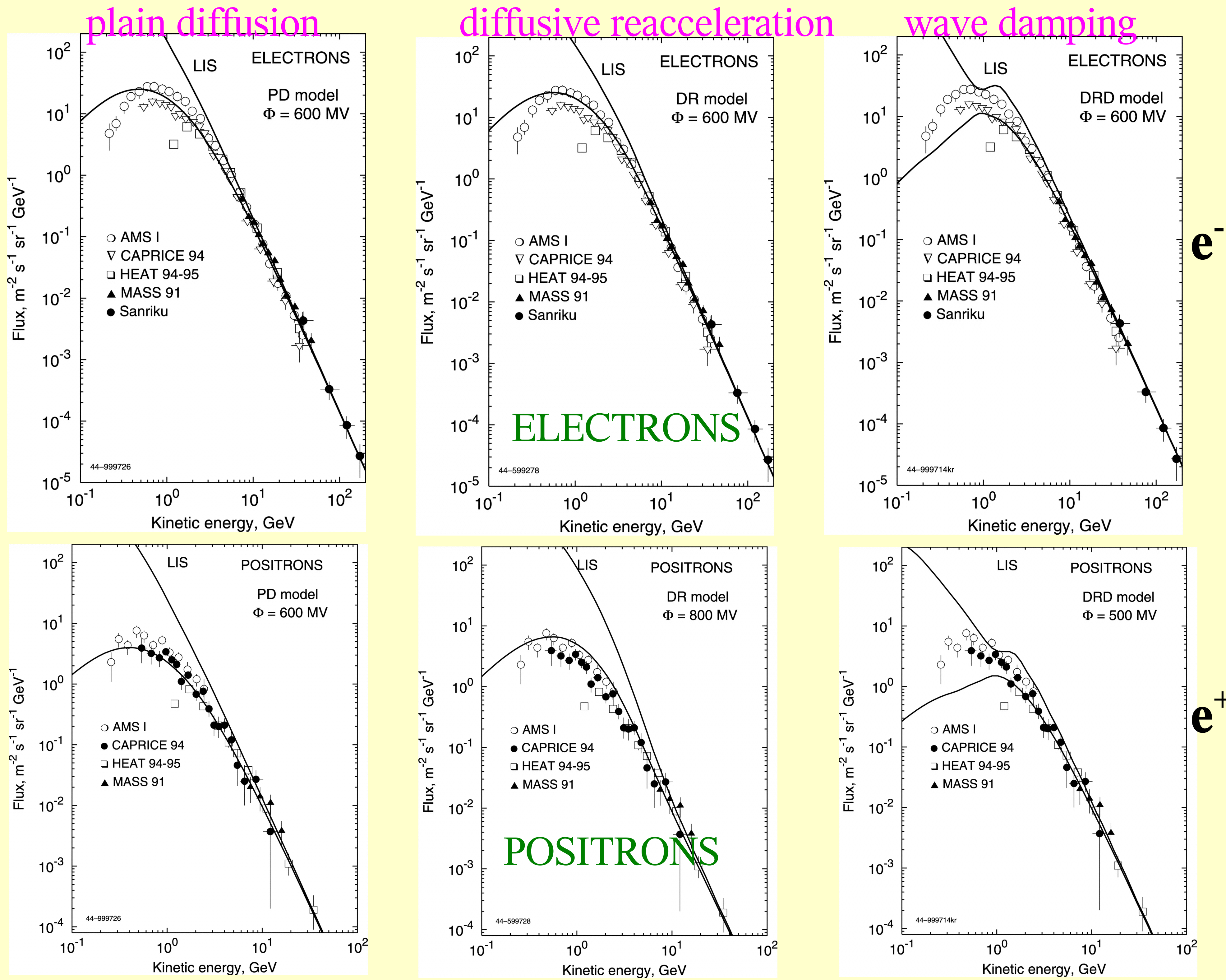
When you have eliminated the impossible whatever remains, however improbable, must be the truth.

- 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]


plain diffusion
diffusive reacceleration
wave damping
ELECTRONS
LIS
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
ELECTRONS
e-
POSITRONS
PD model
Φ = 600 MV
DR model
Φ = 800 MV
DRD model
Φ = 500 MV
POSITRONS
e+
Flux, m-2 s-1 sr-1 GeV-1
Kinetic energy, GeV
44–999726
44–599278
44–999714kr
44–599728

Comparison with observations problematic

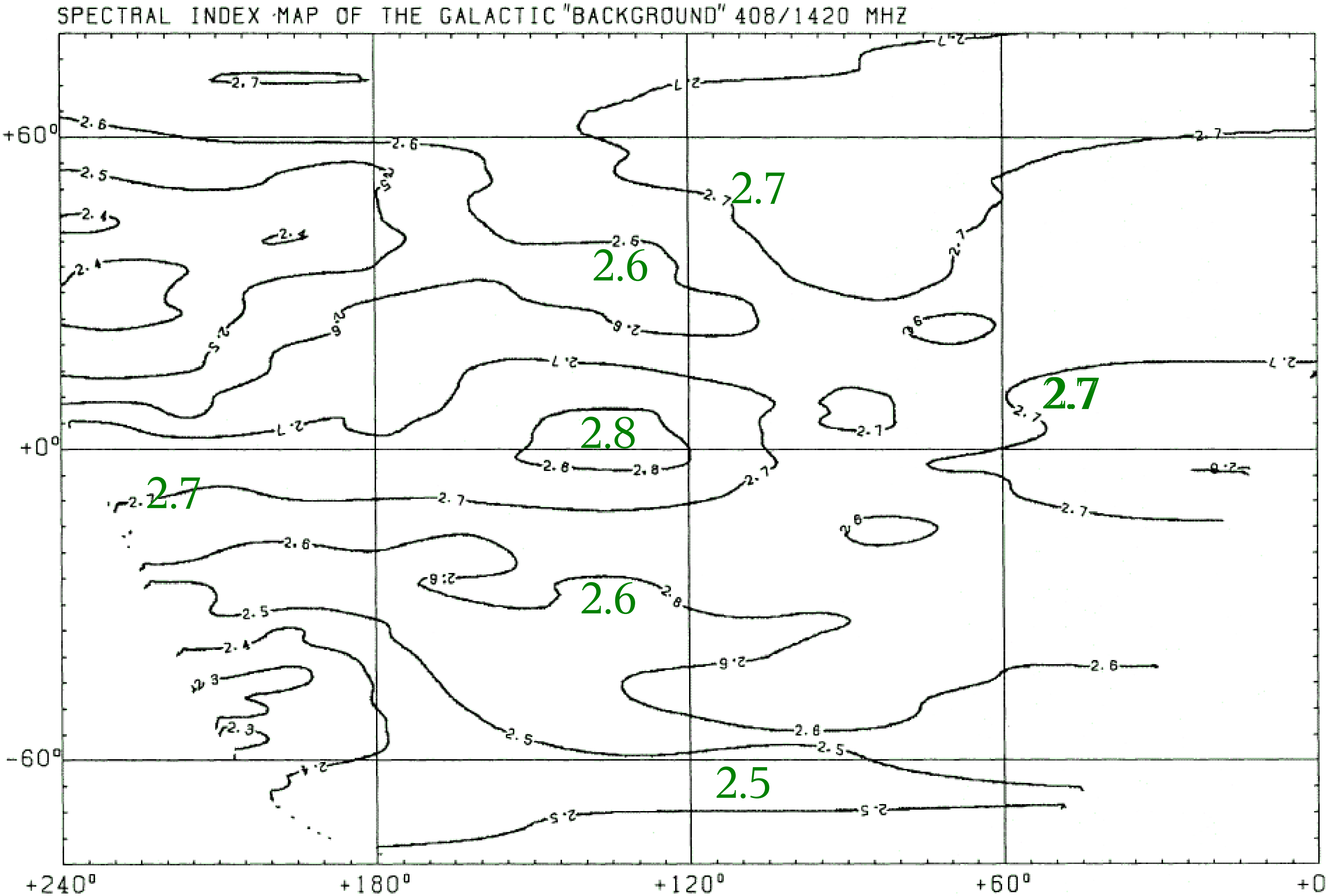


Fig. 8. Spectral index map between 408 MHz (3.7 K subtracted) and 1420 MHz (2.8 K subtracted) of the galactic "background" emission at a resolution of 10° × 3°

Reich & Reich 1988

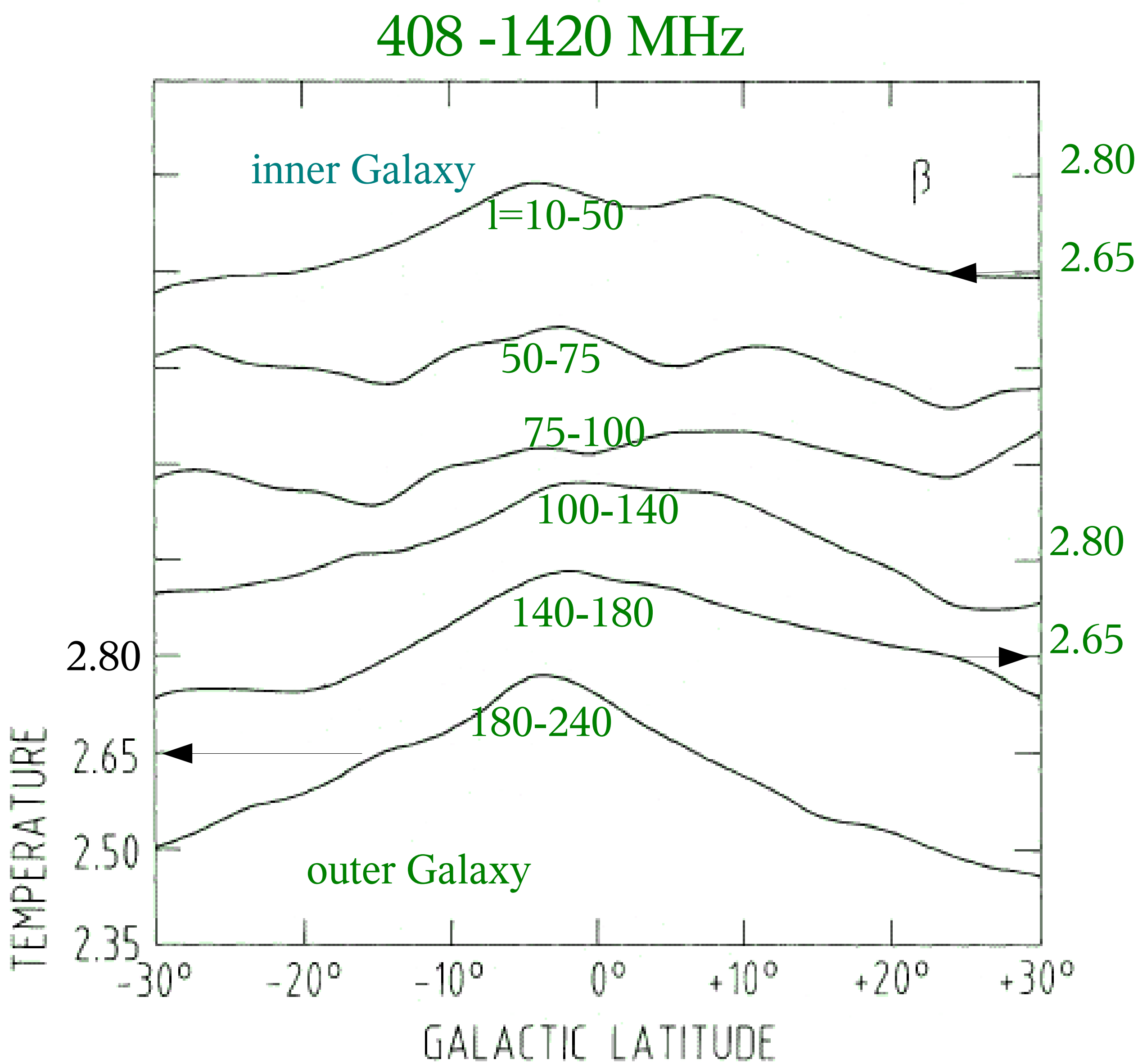


Fig. 11. Same latitude profiles as in Fig. 9, but for the spectral index data between 408 MHz (Fig. 9) and 1420 MHz (Fig. 10). The offset between the profiles is $\Delta\beta = 0.15$

resolution 10° x 3°

(Early work thoroughly reviewed by Lawson etal 1987)
Bridle 1967 drift scans 17.5-81.5 Mhz 2.4
Berkhuijsen 1971 240-820 Mhz 2.66
Sironi 1974 : drift scans 81.5-151-408 Mhz 2.41
Webster 1974 drift scans 408-610-1407 Mhz 2.8
Strong 1977 evaluation of drift scans in halo model 17.5-81.5 Mhz 2.4 (disc) 2.6 (halo)
Webber 1980 10-100 Mhz : 2.57
Lawson etal 1987 38-408-820-1420 maps: 2.5(38-408) -2.8 (408-1420) , summary of previous drift scans.
Reich&Reich 1988b 408-1420 map,l,b-profiles. 2.65-2.8. Flattens with b esp. in outer Galaxy
Bloemen et al. 1988 408-1420 based on Reich&Reich, 408-1420:convenient b plots:2.6-2.85
Broadbent et al. 1989: 408 Mhz – 5 Ghz : 2.7 -3
Davies et al 1996 408-1420-10GHz high-lat 408-1420: 2.8-3.2. no correlation with 10GHz!
Kogut et al1996 408-31.5: >2.9
Platania et al. 1998 1.4-7.5 Ghz high-lat 2.81, 408 Mhz-7.5 Ghz: 2.76
Jonas et al. 1998 and thesis1999:map (plate C5) 408-2326: 2.5-2.8. 2.326-31.5GHz:2.95
Roger et al. 1999 22-408Mhz: 2.4-2.55
Giardino et al 2001 408-1420:2.78 (with full sky map:2.5-3.2), 408-2326:2.75
Bennett et al 2003 408-23: low b (near SFR: 2.5, high b: 3. Near 20GHz:break to >3
Finkbeiner 2004 408-2326-8...93GHz : uses 3.05 for high-freq model
Davies et al 2006 408MHz-WMAP (22-41 Ghz) 408-22:3.18
Fernandez-Cerezo et al 2006 408-COSMOSOMAS (12.7-14.7-16.3 Ghz) high b: 2.94-3.2
Singal et al 2006 8GHz 408-81.5: 2.6+-.2, 1420-81.5: 2.7+-.2 (!)
Borka 2007 408-820-1420 loops 1-VI 2.68-3.03

General comment: results not often presented in user-friendly (digital) form for comparison with models !

SYNCHROTRON, INNER GALAXY