Galactic diffuse gamma rays: experimental status

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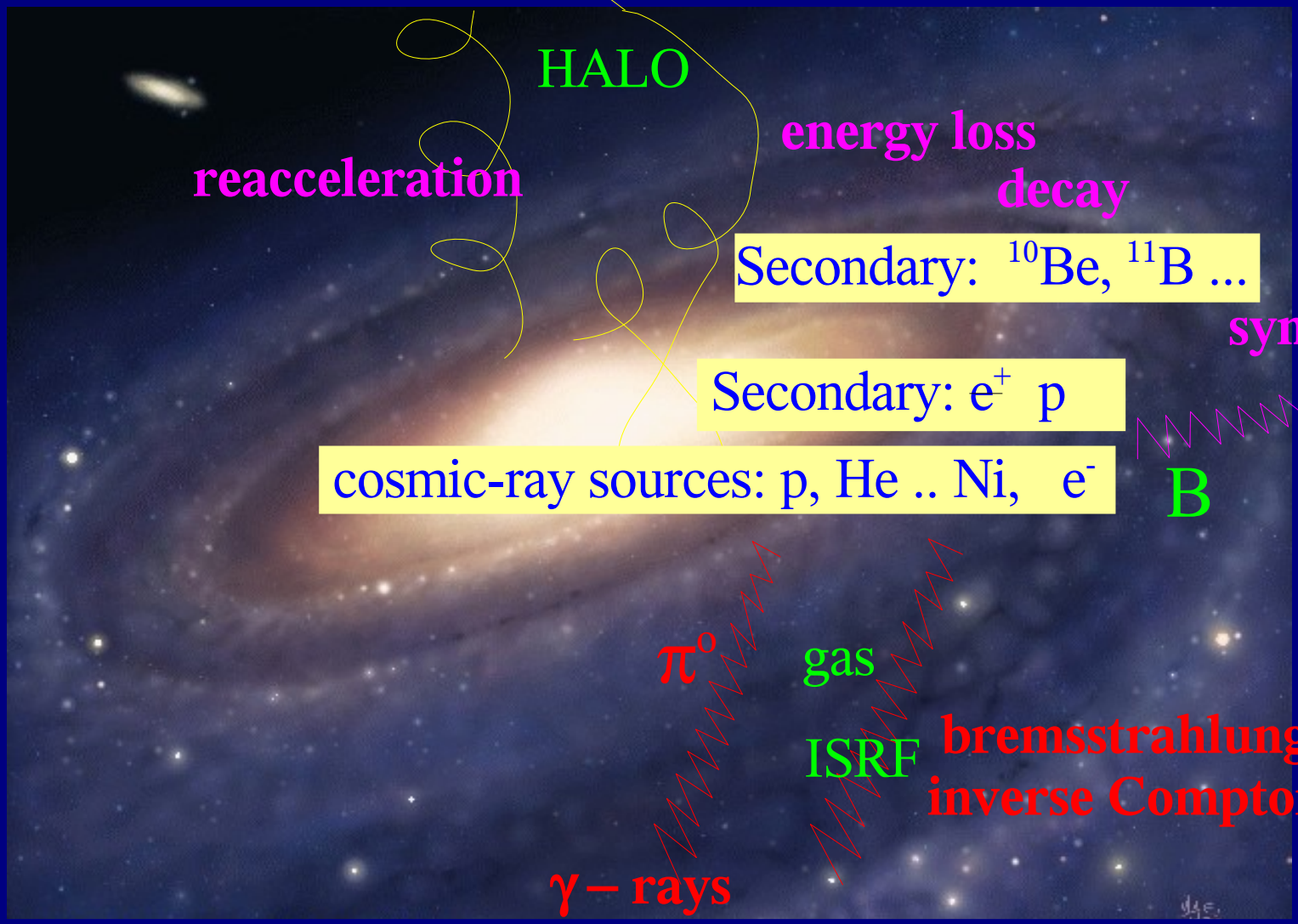
MPE Garching

CERN / ENTAPP Workshop, 2- 6 Feb 2008

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

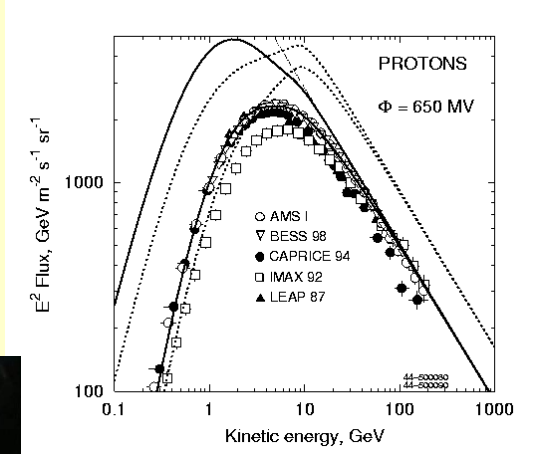
The **goal** : use *all* types of data in self-consistent way to test models of cosmic-ray propagation.

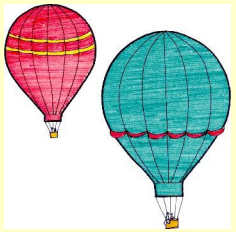
Observed *directly, near Sun:*

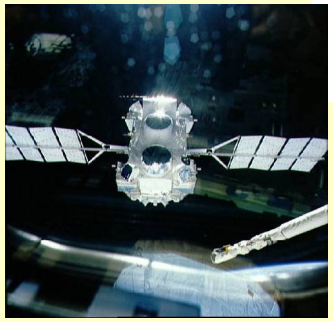
primary spectra (p, He ... Fe; e^-)

secondary/primary (B/C etc)

secondary e^+ , pbar

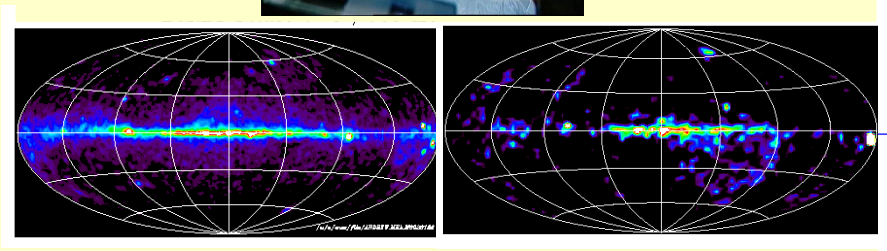


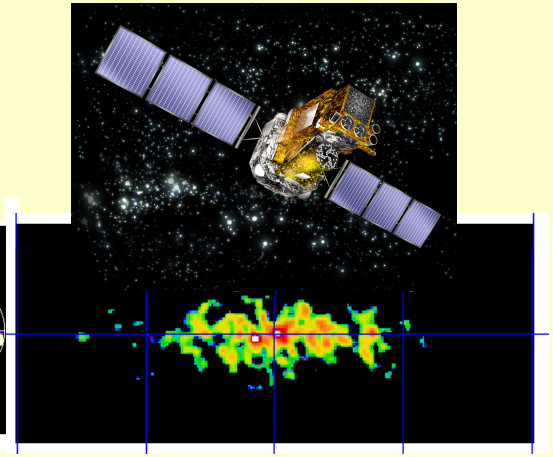




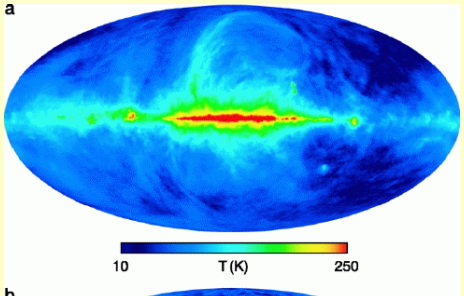
Observed *from whole Galaxy:*

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

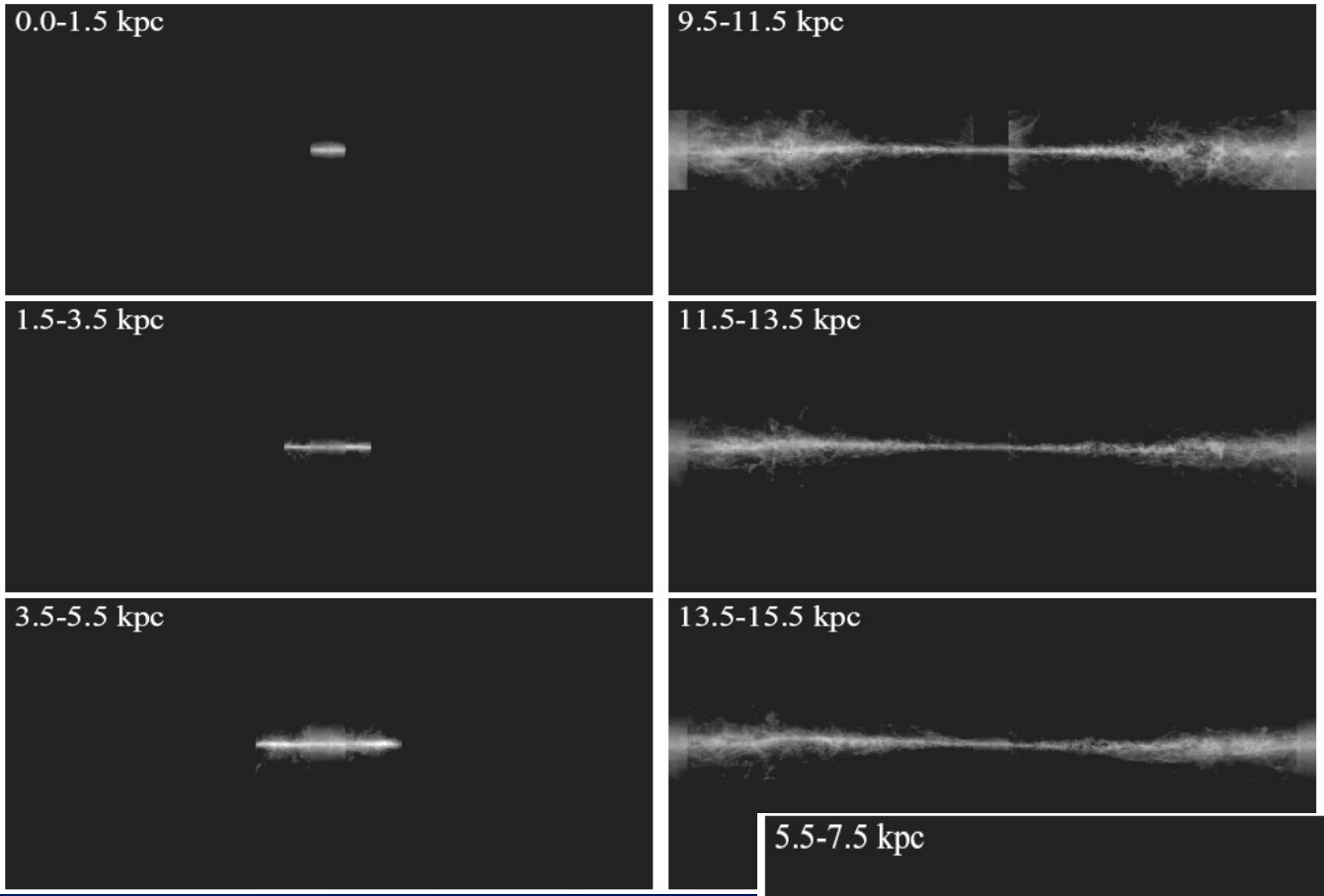
GALPROP code: publicly available

with dedicated Website galprop.stanford.edu

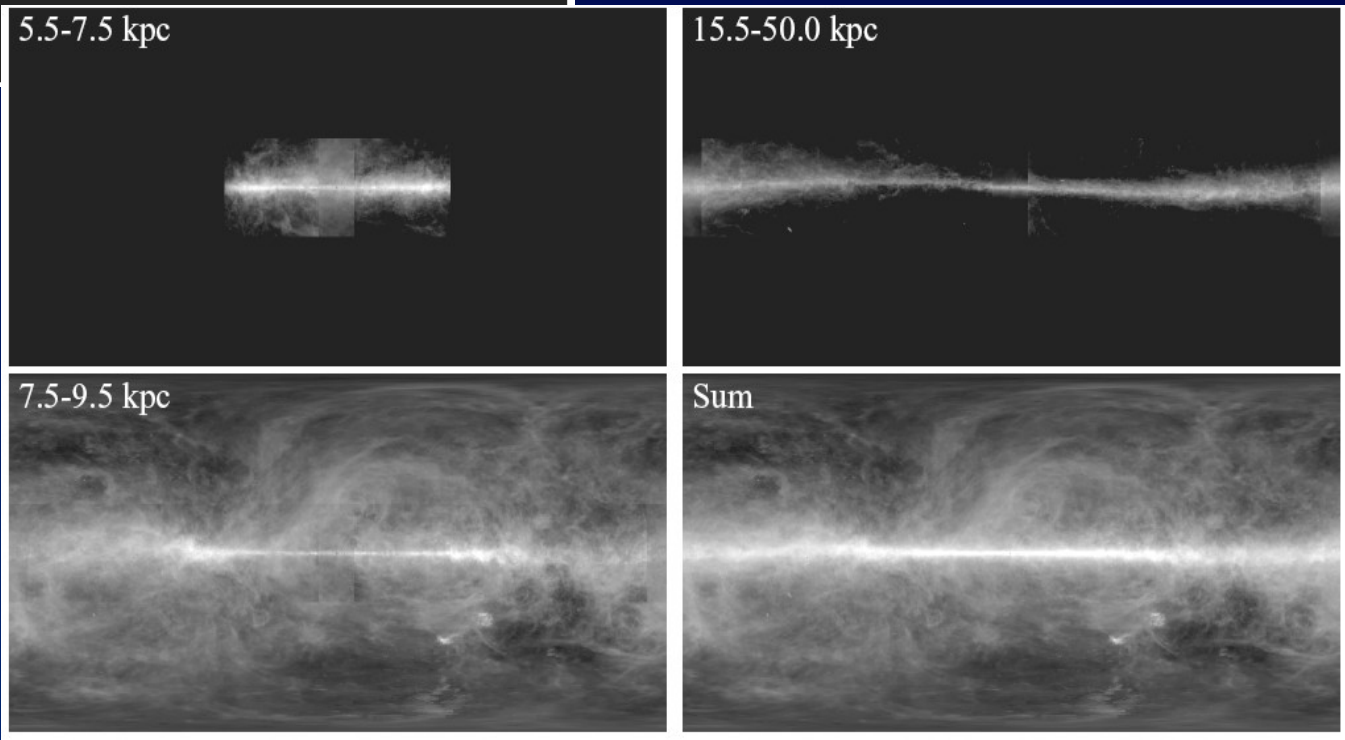
Reference Model for Fermi LAT

Gas Rings: HI Inner & Outer Galaxy

Seth Digel'05



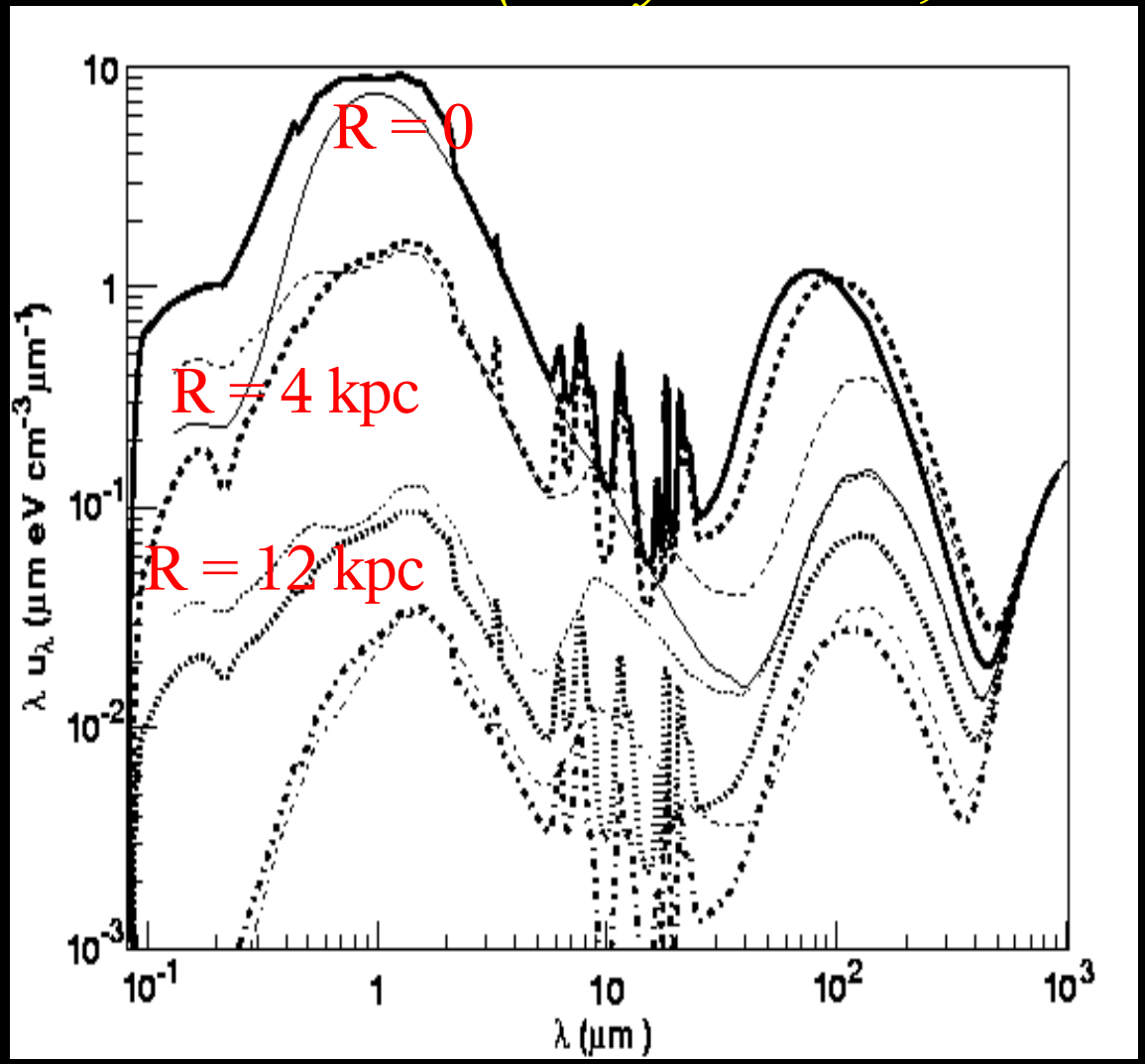
Gas Rings: HI Local Galaxy



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

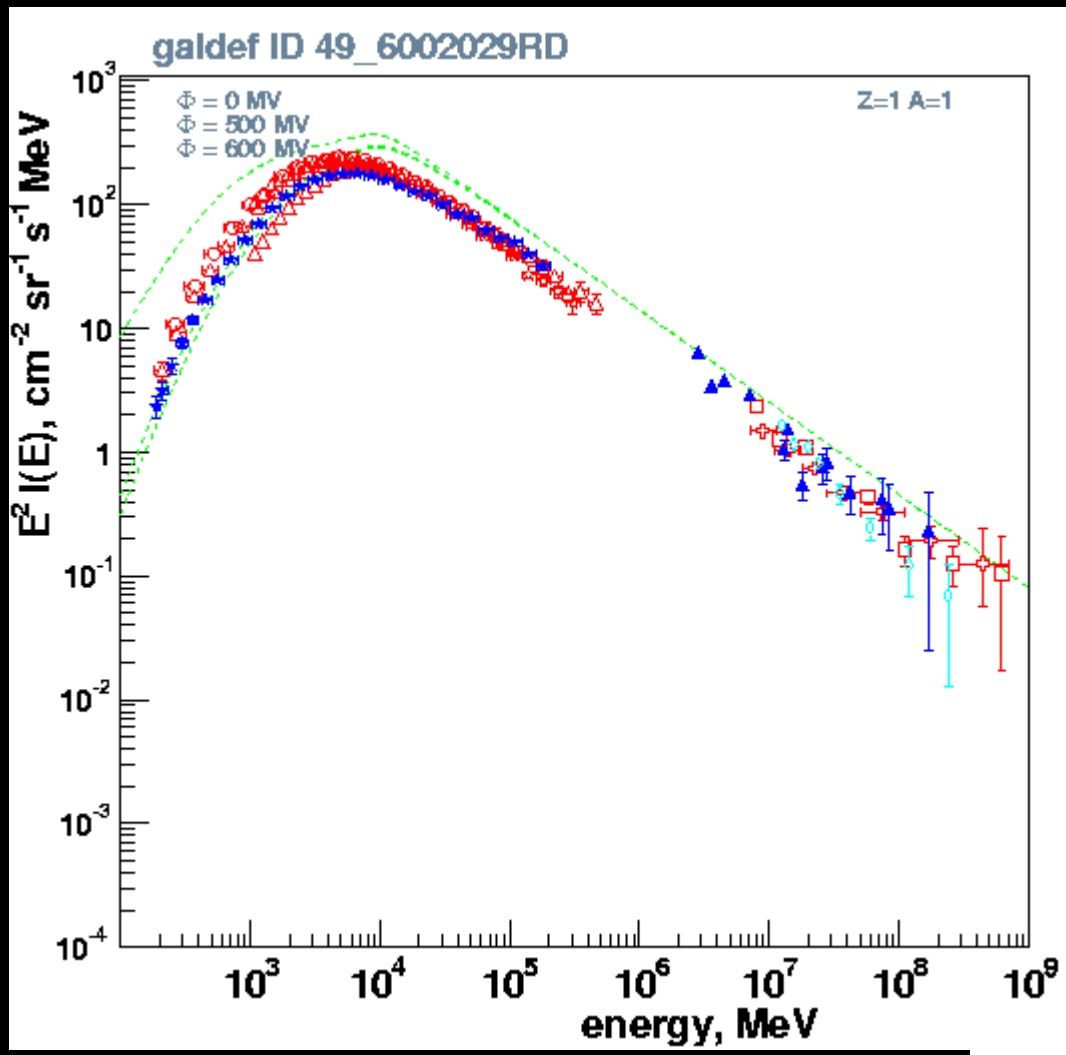
***New** ISRF using latest information*

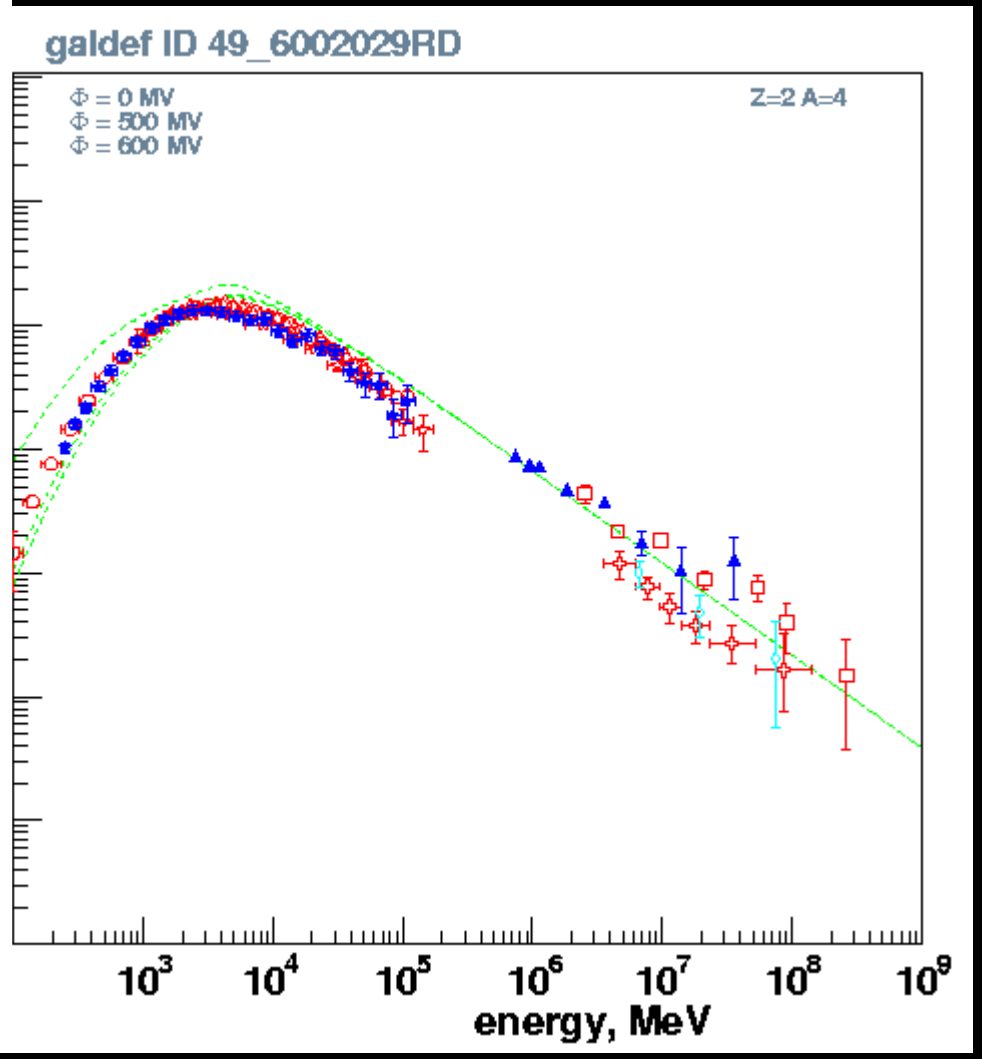
stellar populations, dust radiative transfer



UV optical IR FIR CMB

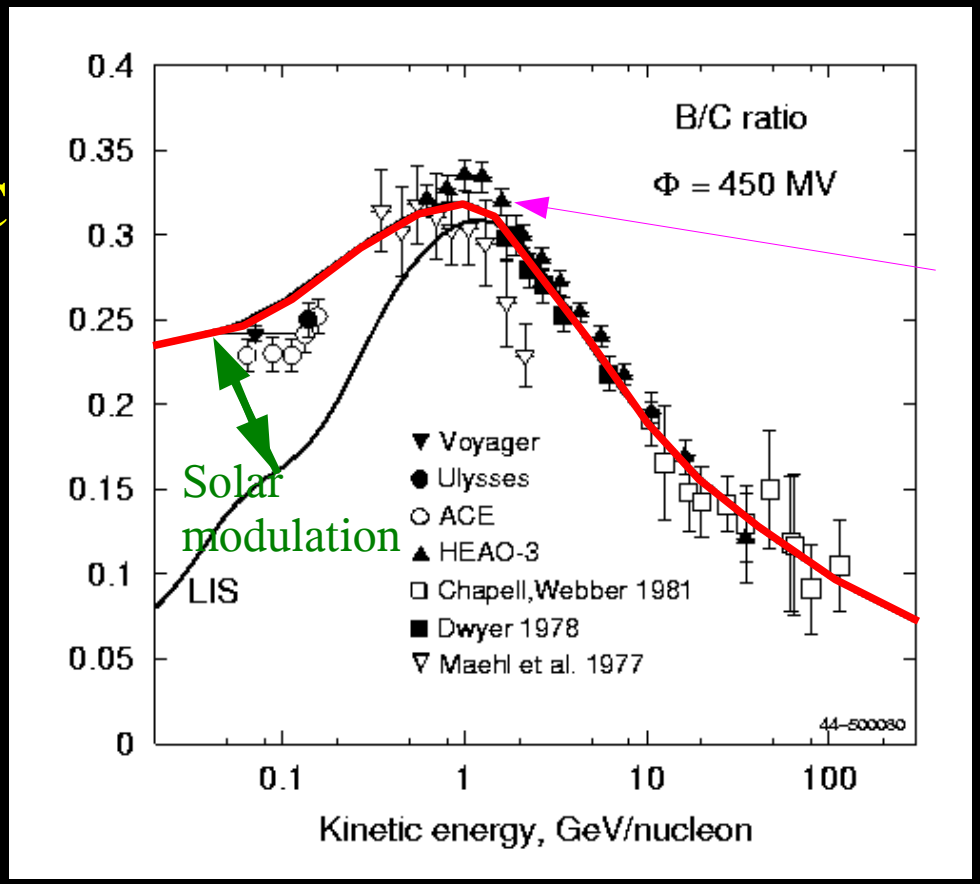
Key data : primary cosmic-ray nuclei spectra





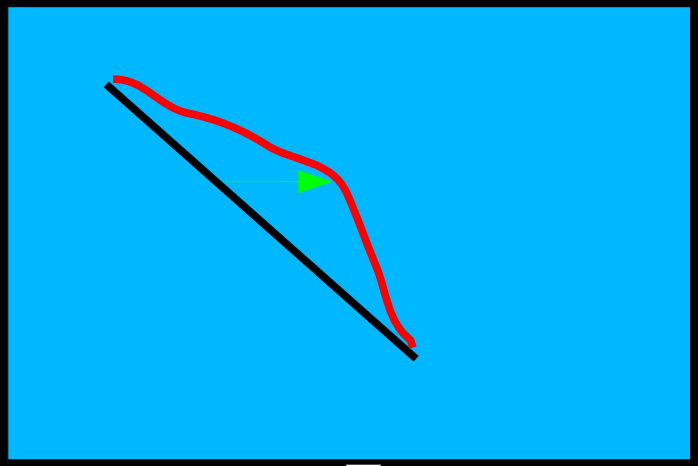
Key data cosmic-ray secondary/primary ratios: e.g. Boron/Carbon probes cosmic-ray propagation parameters

B/C



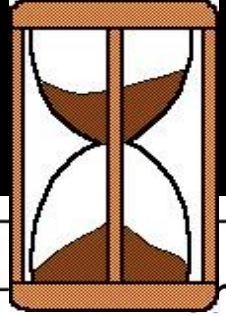
Peak in B/C can be explained by **diffusive reacceleration** with Kolmogorov $D \sim \beta p^{1/3}$

flux

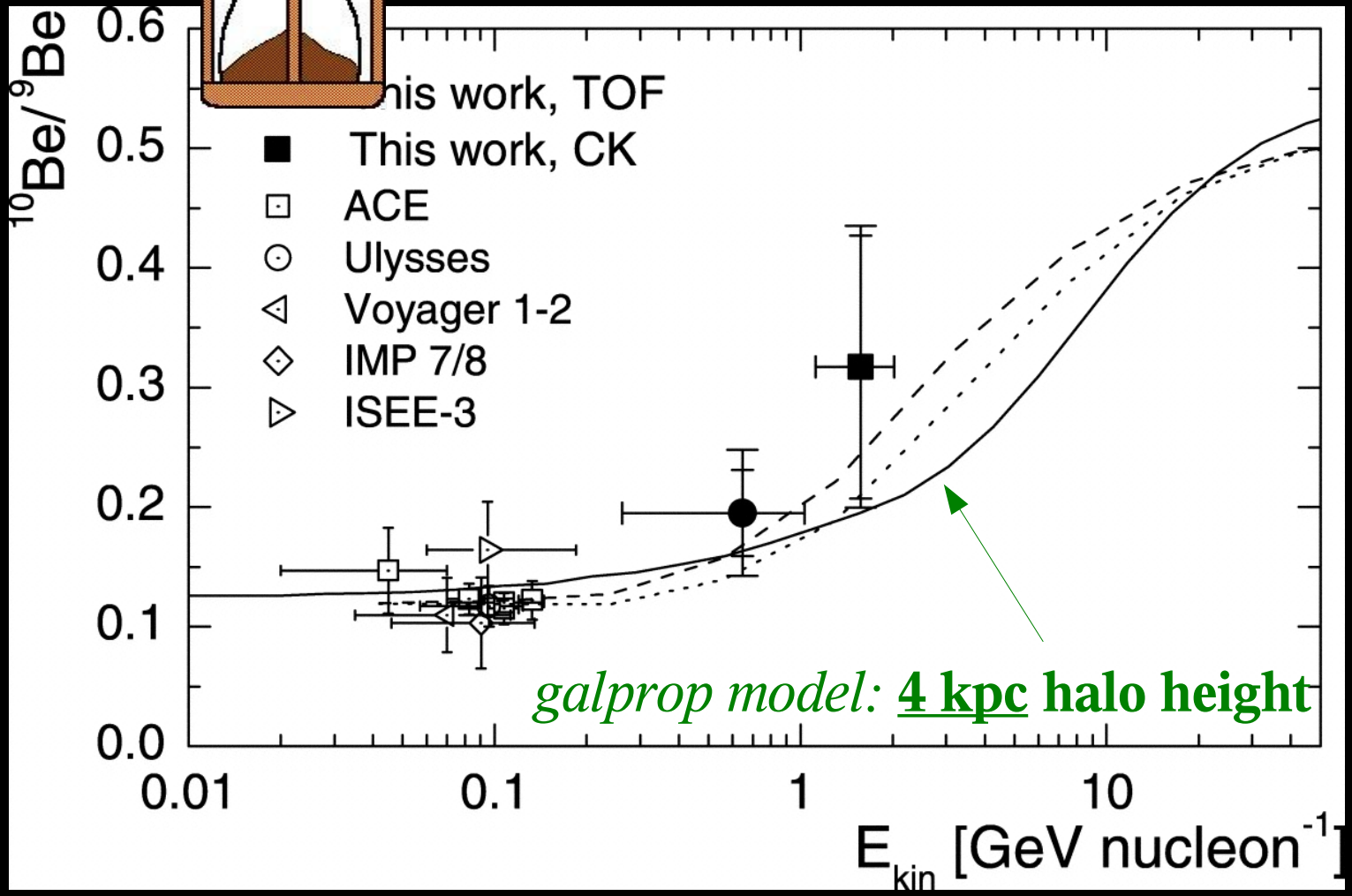


E

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

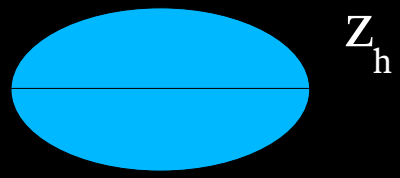


Key data III: Radioactive nuclei: cosmic-ray clocks set limits on size of Galactic halo



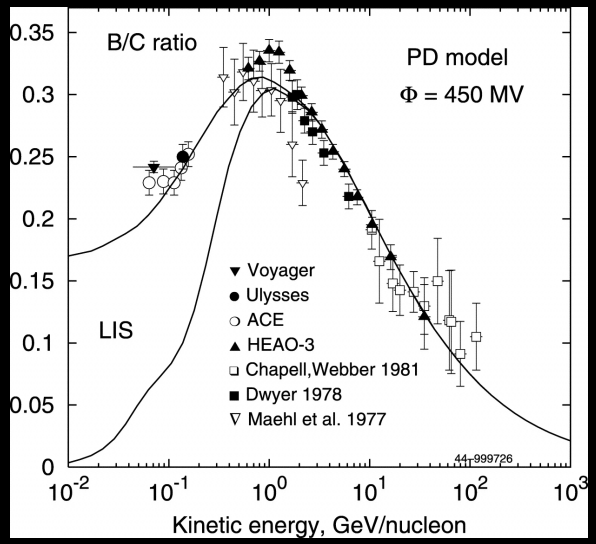
recent data:
ACE, ISOMAX

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

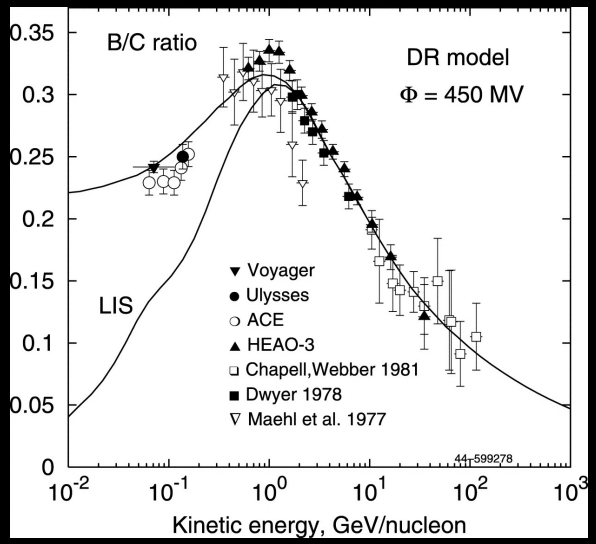


Hams et al. 2004 ApJ 611, 892

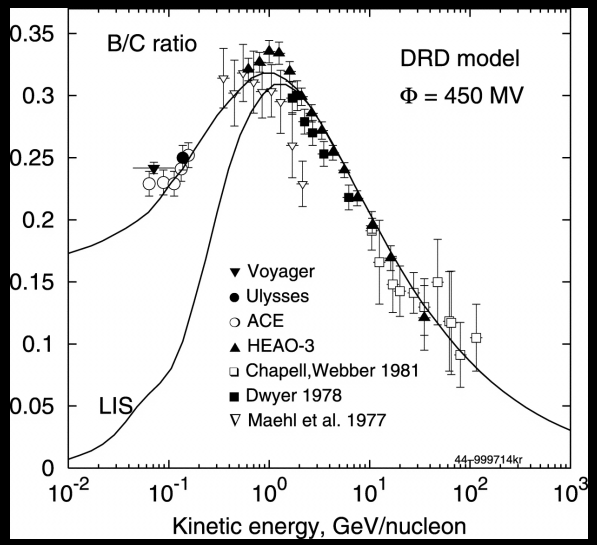
plain diffusion



diffusive reacceleration



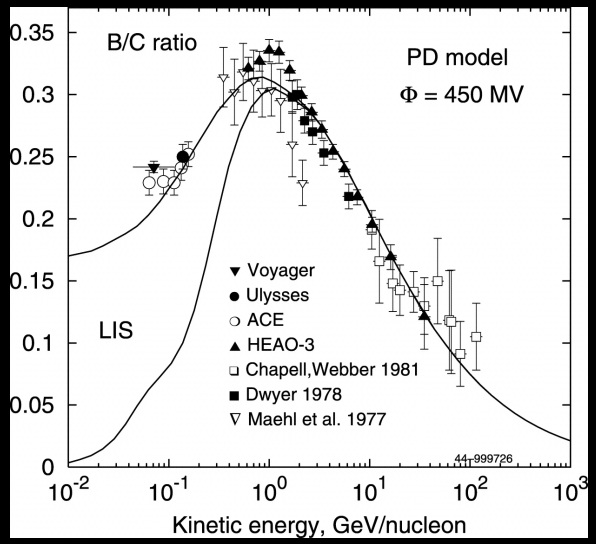
wave damping



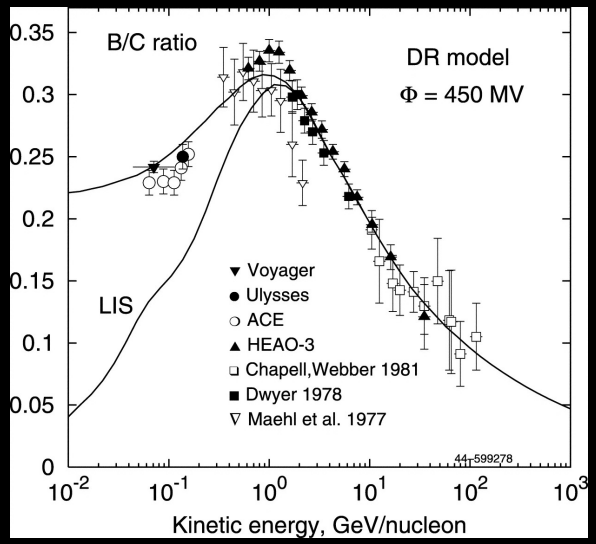
For any model, first adjust parameters to fit Boron/Carbon

Ptuskin et al. 2006 ApJ 642, 902

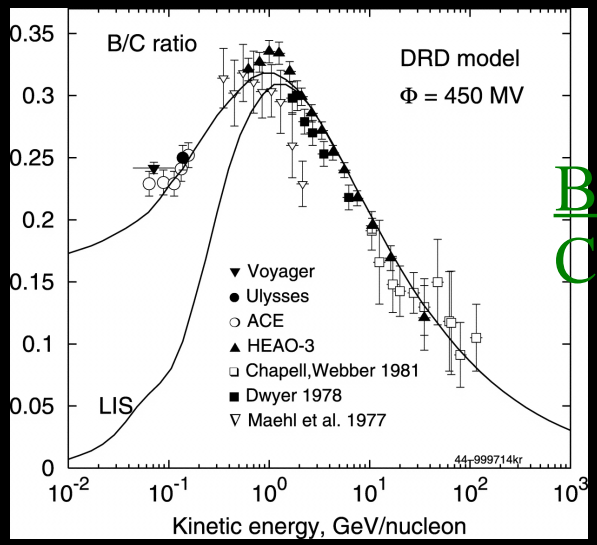
plain diffusion



diffusive reacceleration



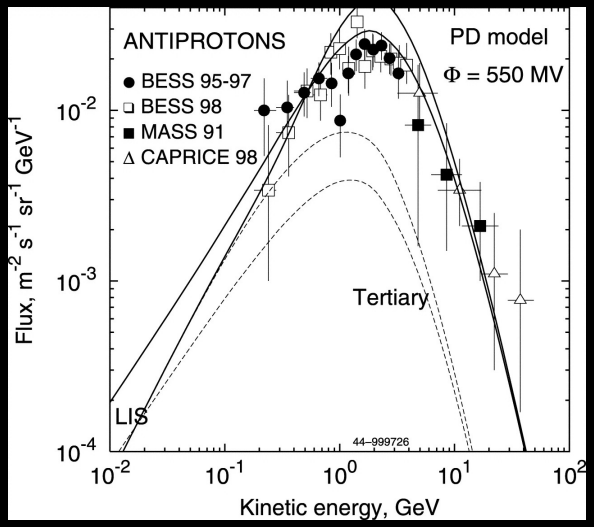
wave damping

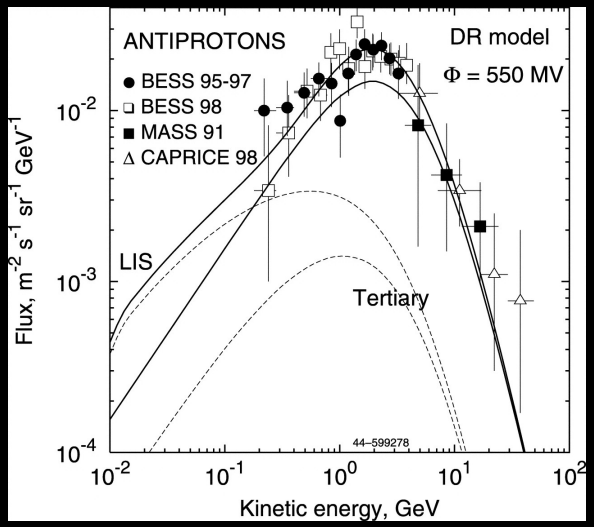


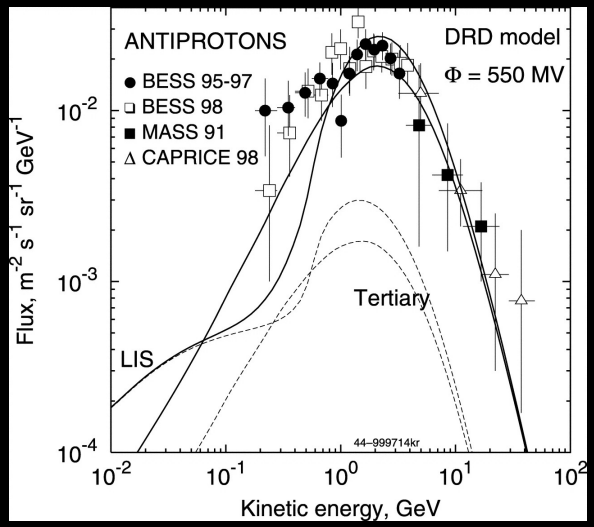
Boron/ Carbon

then predict the other cosmic-ray spectra

antiprotons

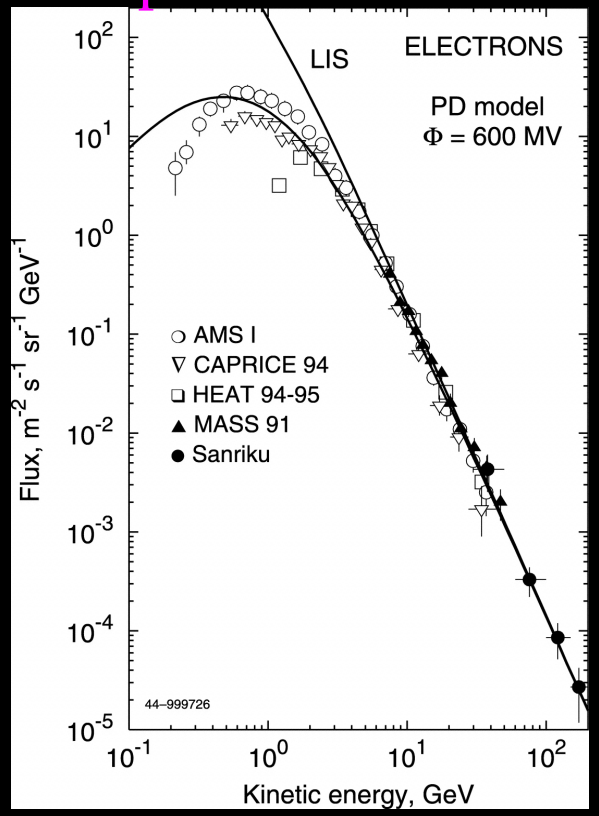


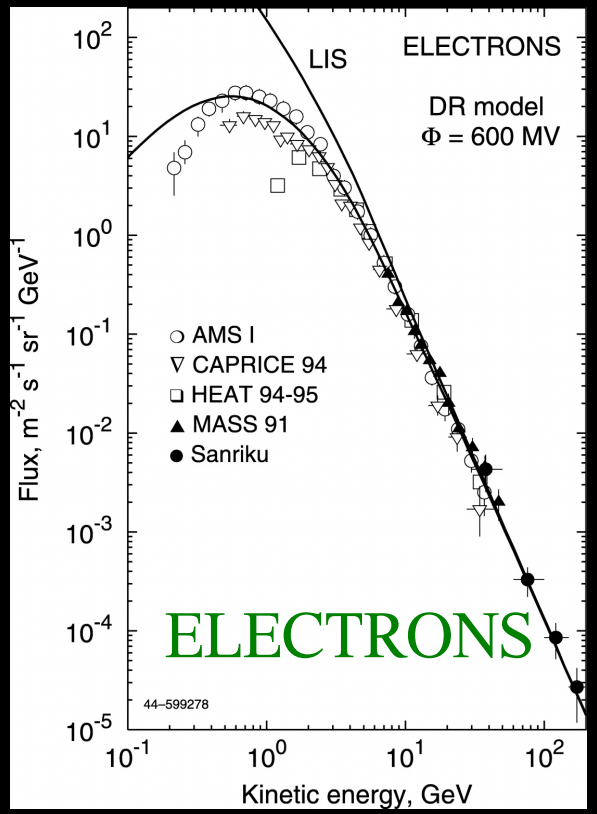


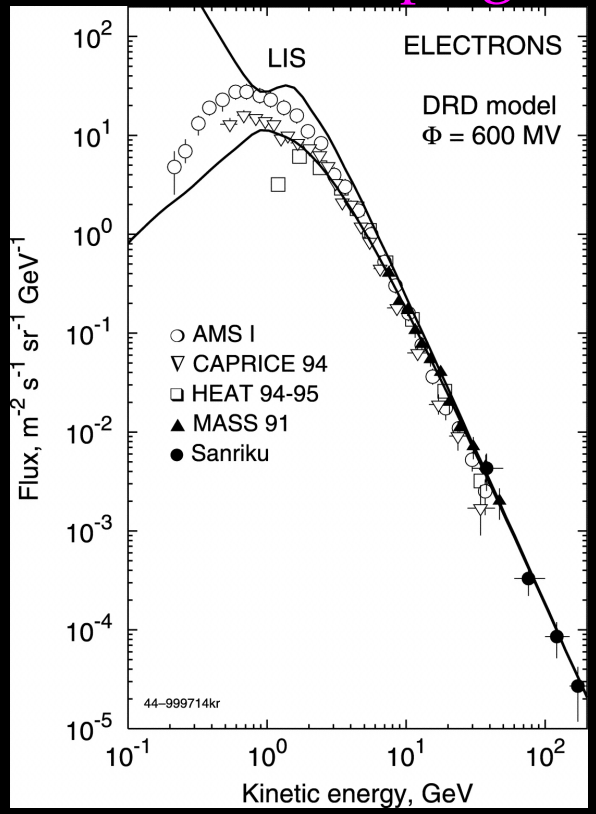


Ptuskin et al. 2006 ApJ 642, 902

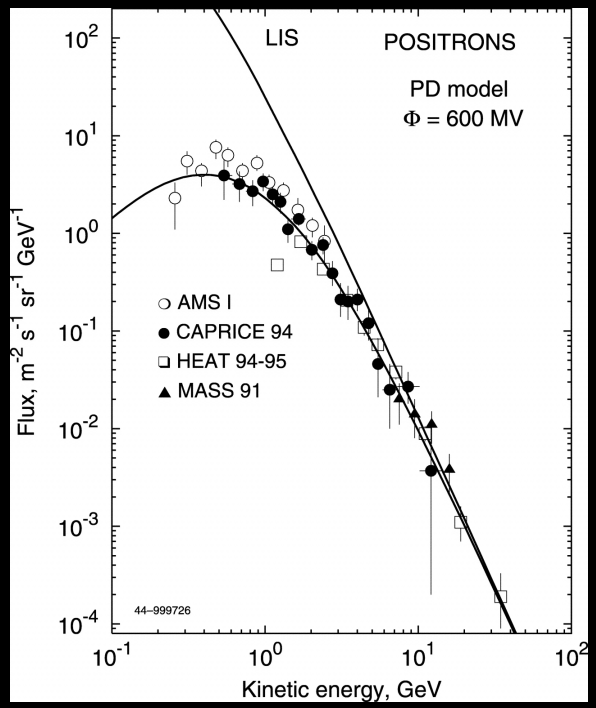
plain diffusion | diffusive reacceleration | wave damping

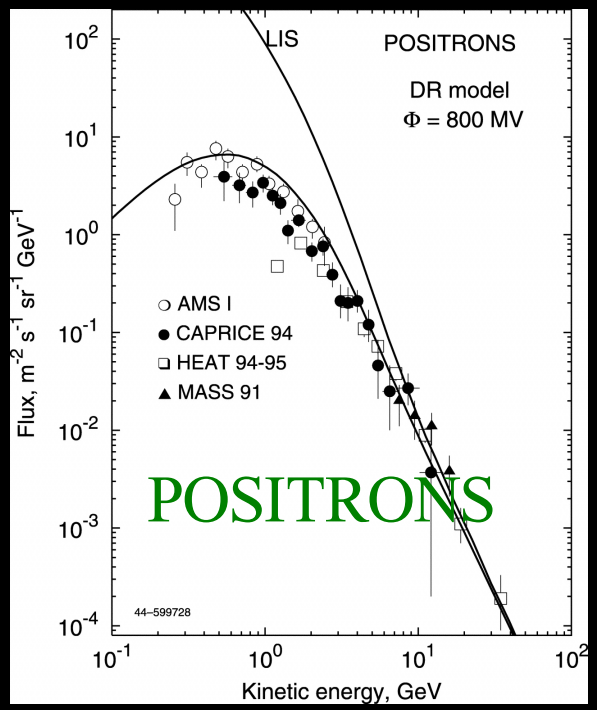


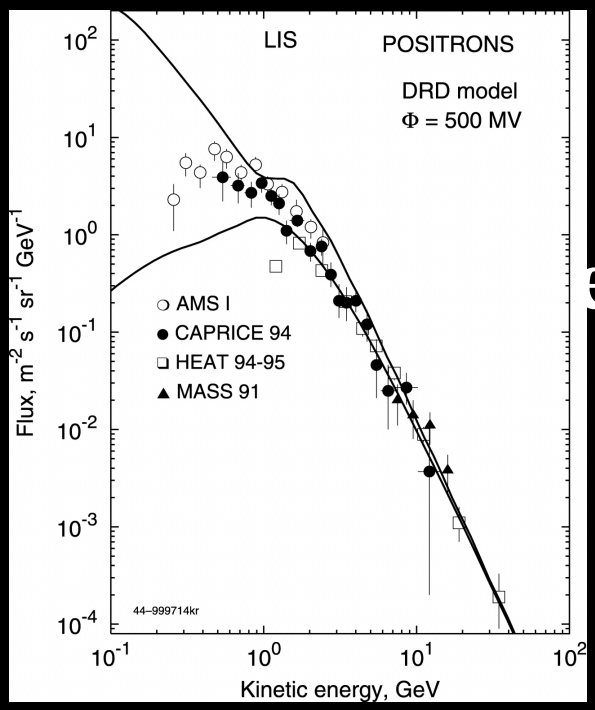




e^-





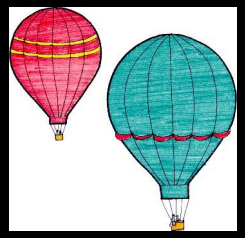


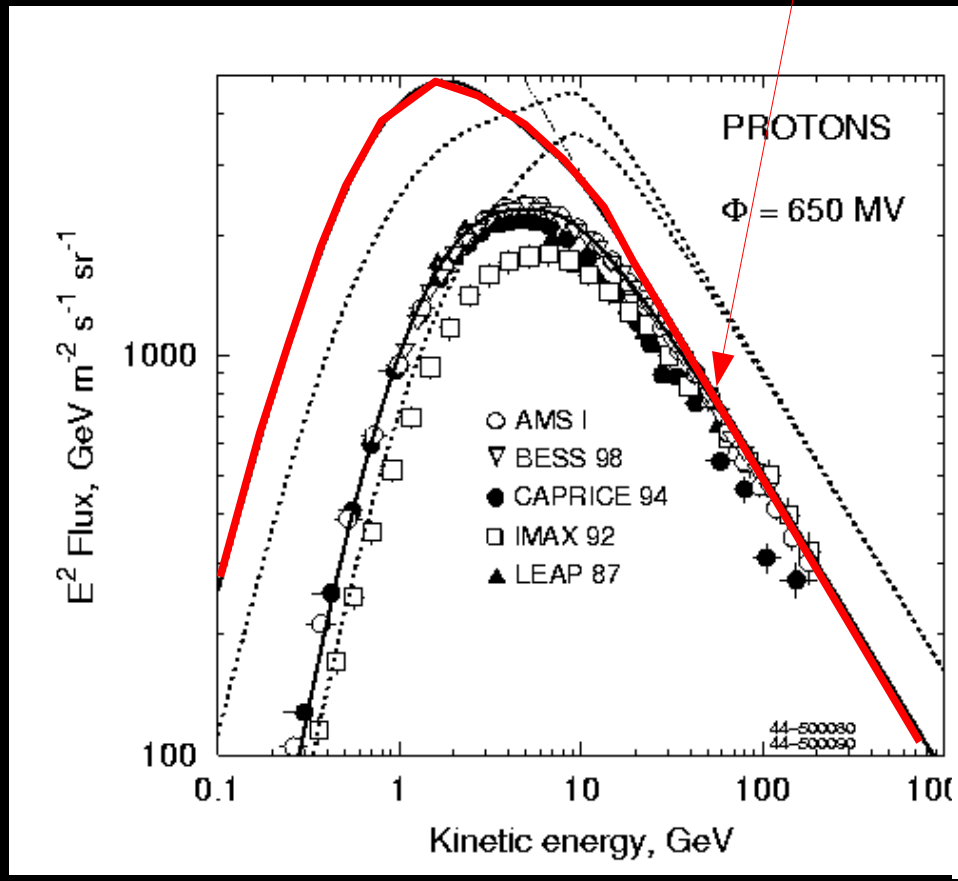
e^+

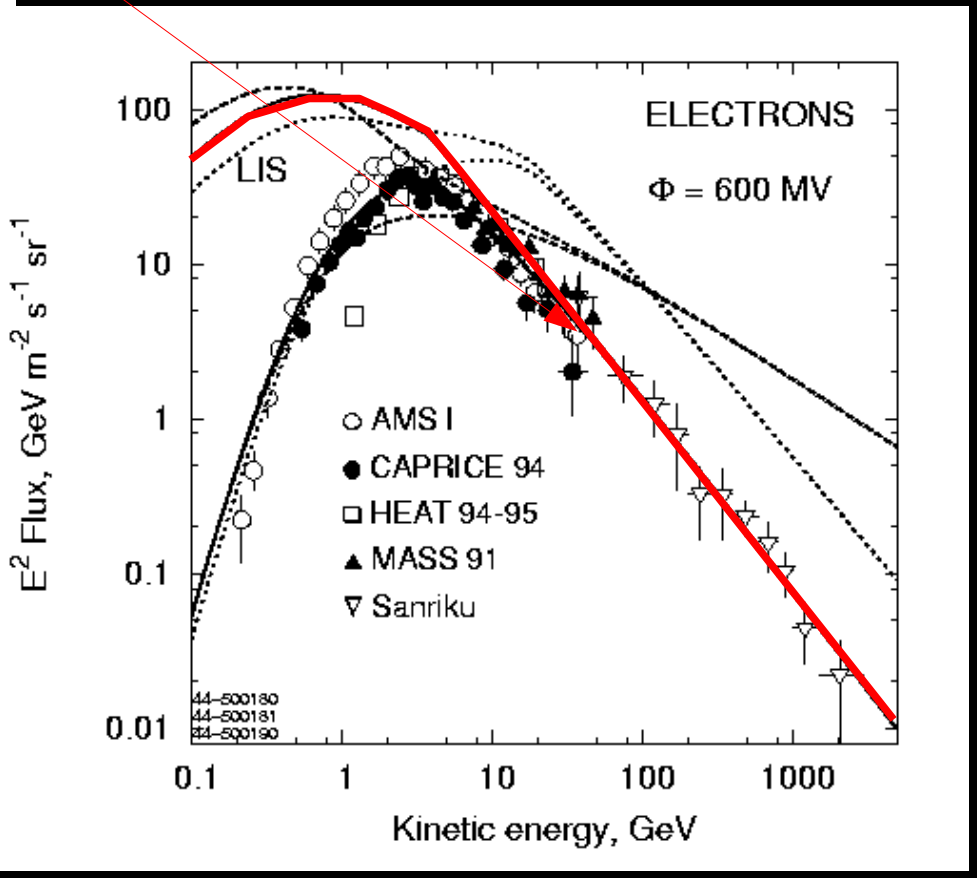
γ - rays

Modelling diffuse Galactic γ - rays:

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

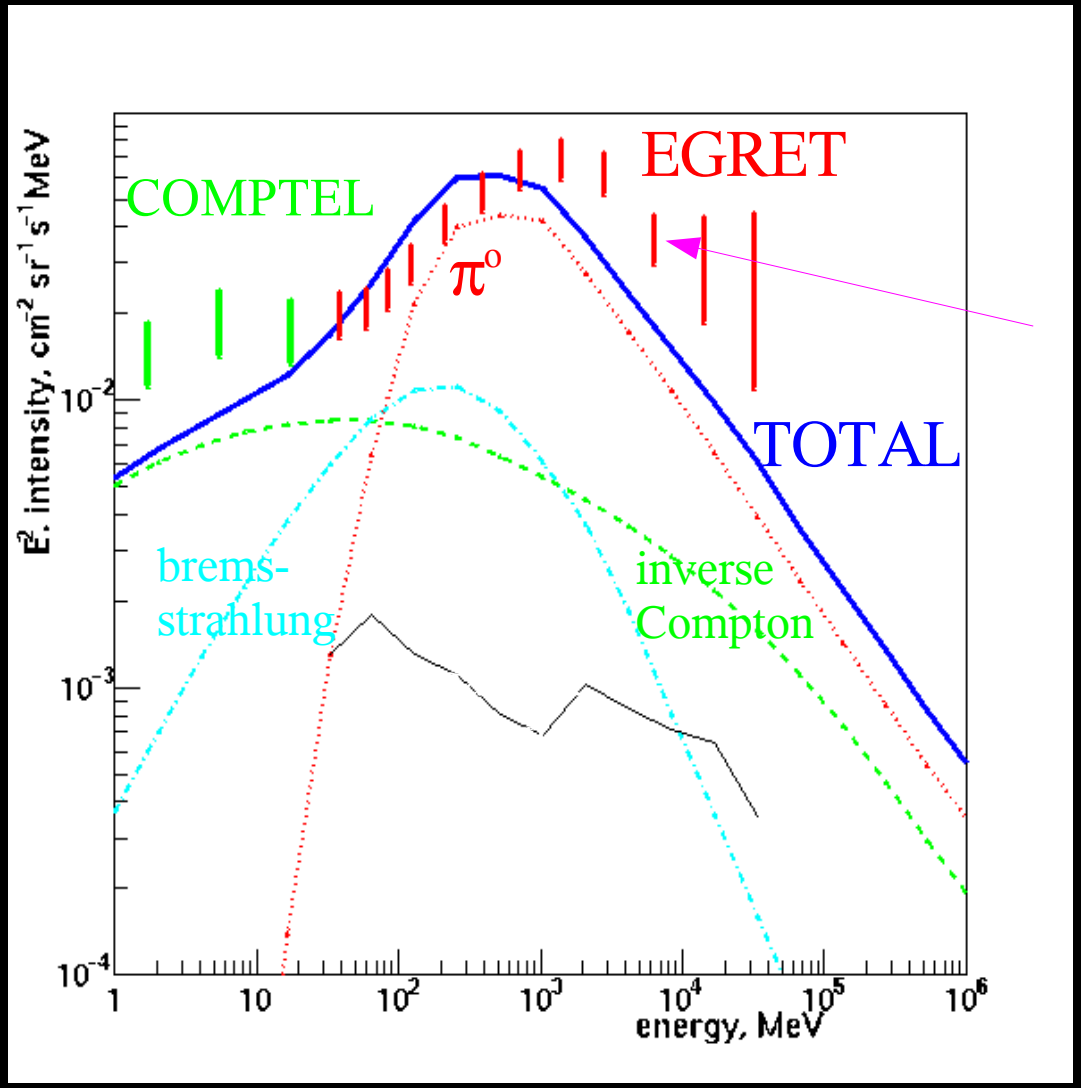






'Conventional' model:
cosmic-ray protons (+He) and electrons as *directly measured*

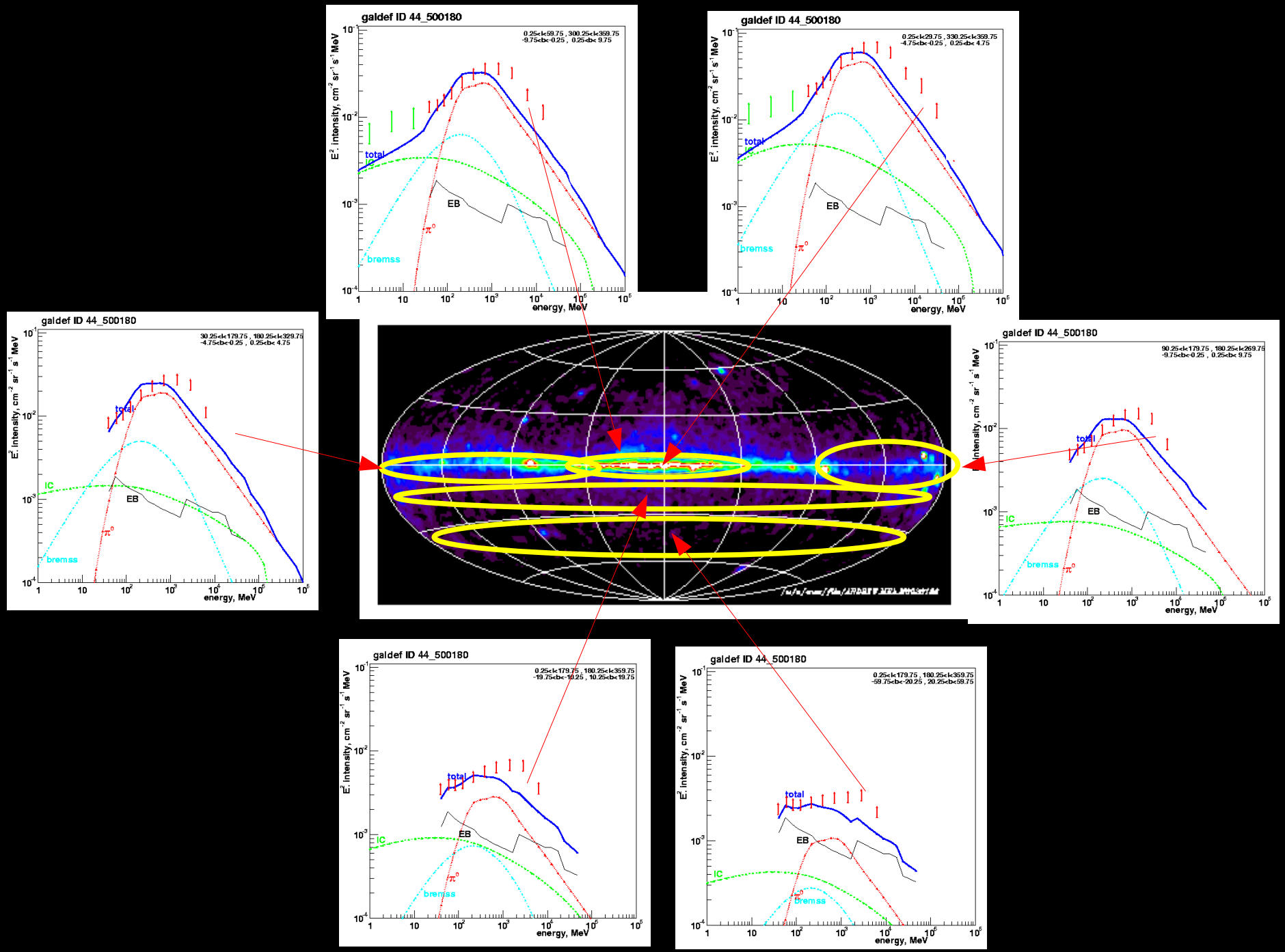
γ - ray spectrum
of inner Galaxy



GeV excess

EGRET saw a big excess over prediction !

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



Proposed explanations of EGRET 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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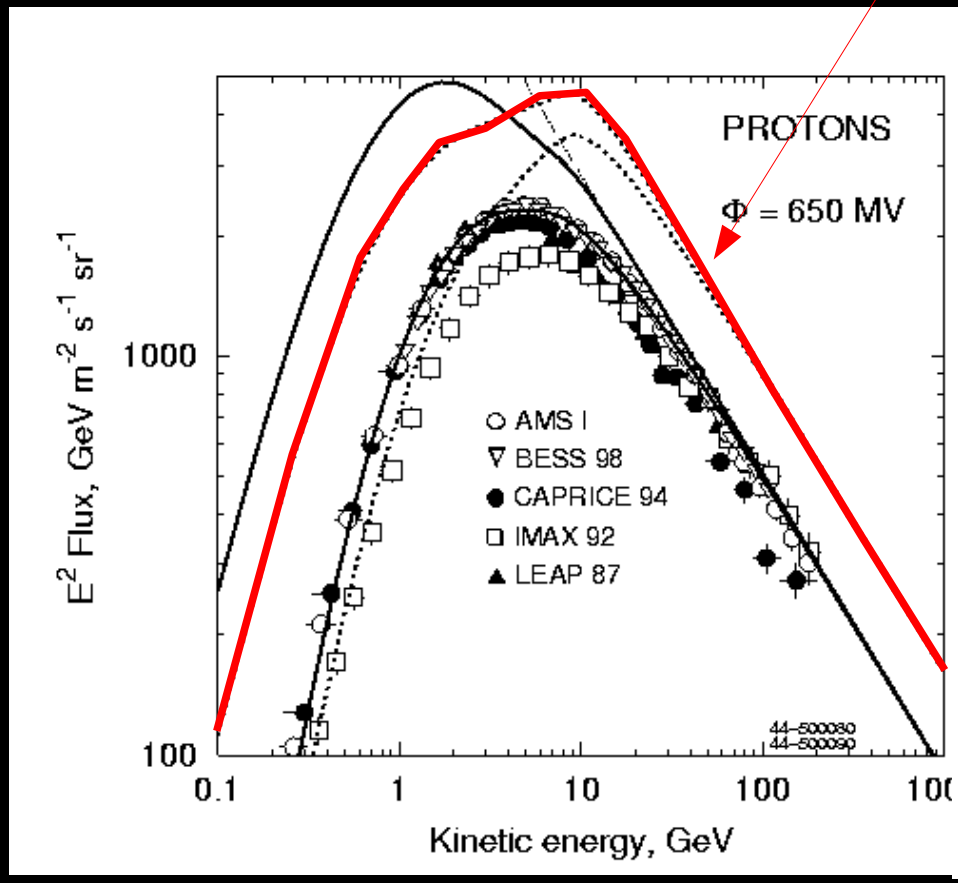
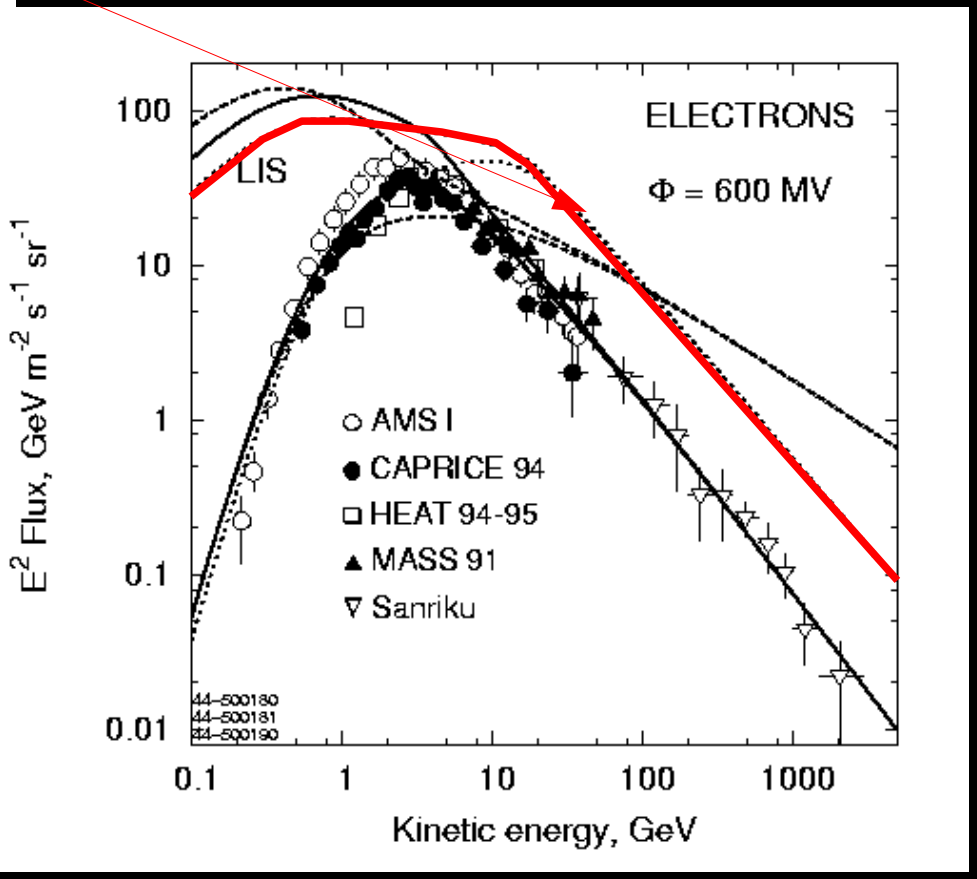
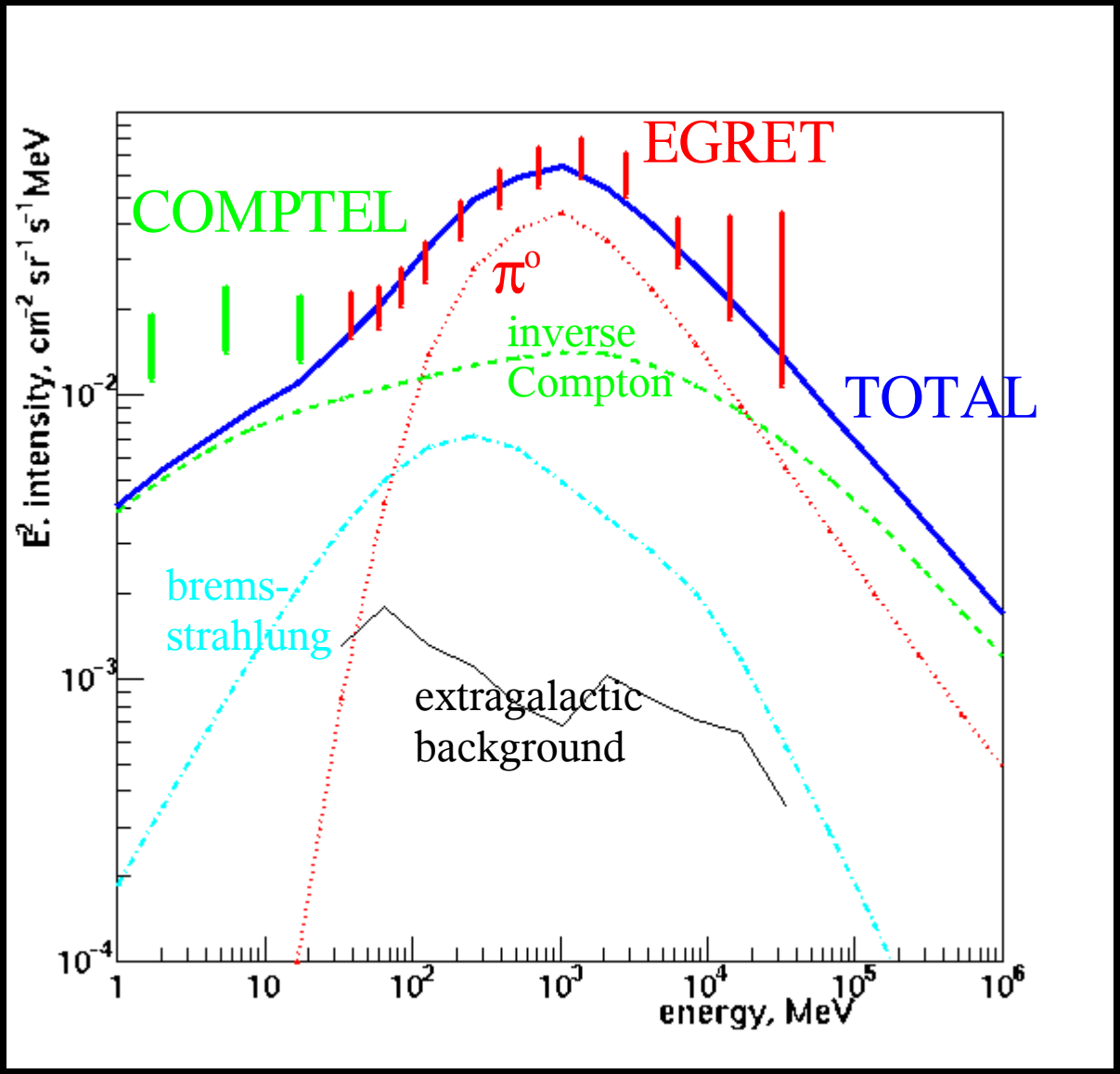
'Optimized' model:

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



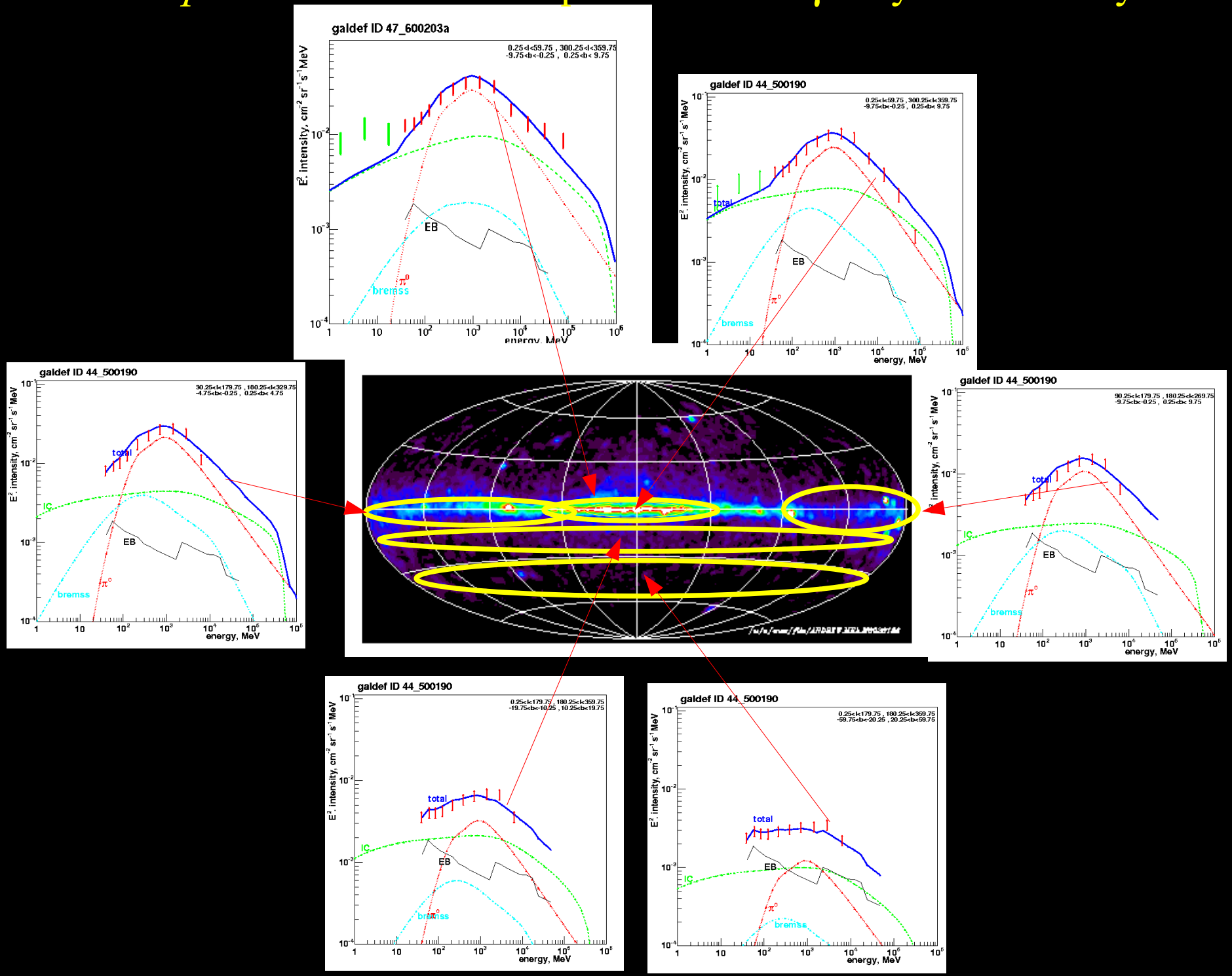


Optimized model: vary cosmic-ray proton, electron spectra but keep compatible with expected spatial variations



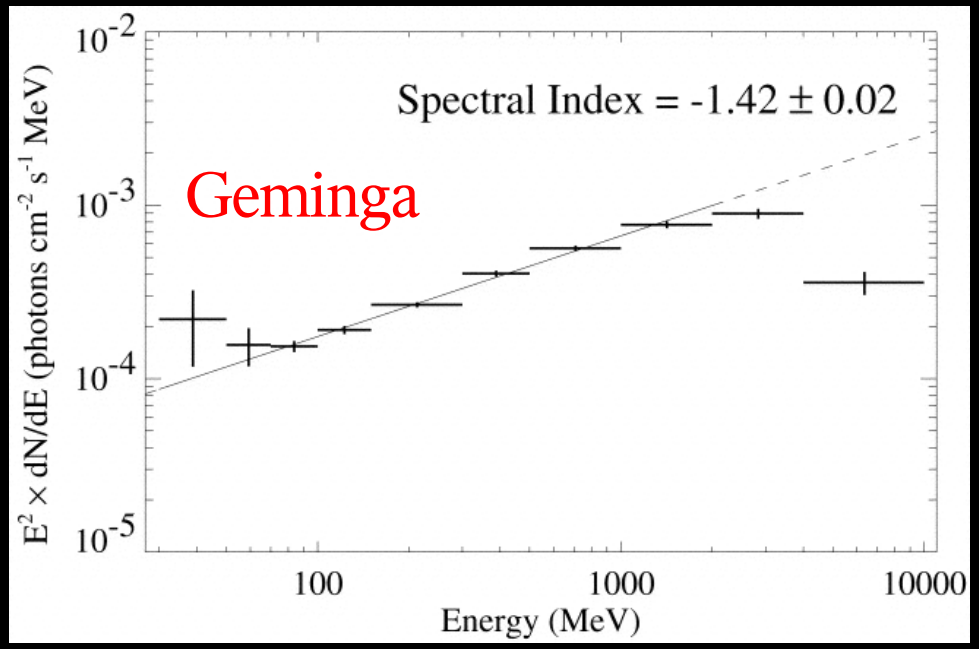
Satisfactory fit above 10 MeV: no more GeV excess

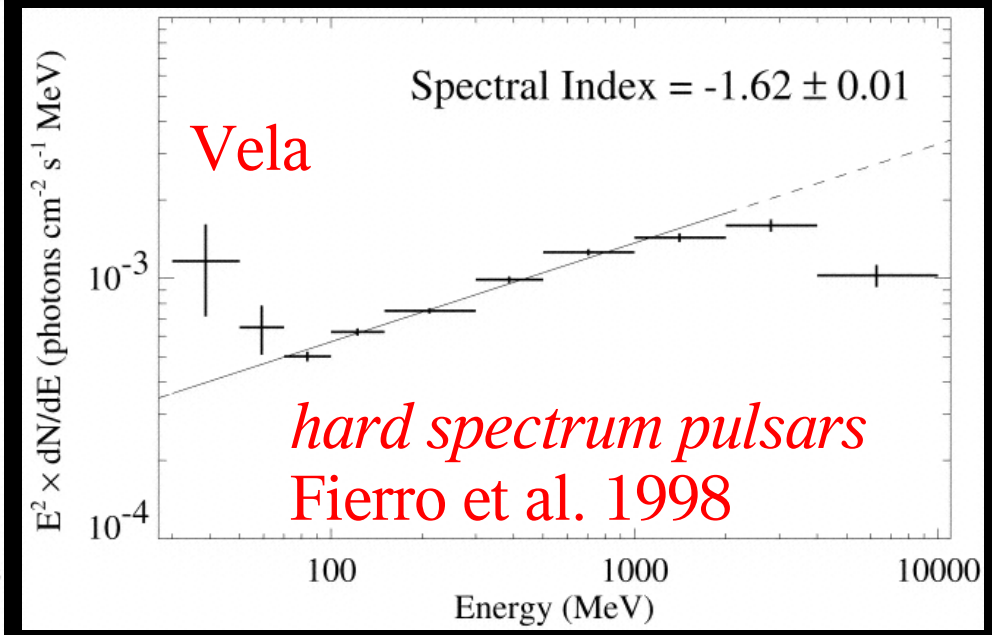
Optimized model can explain the GeV γ - ray excess everywhere!



ALTERNATIVE EXPLANATION of GeV excess

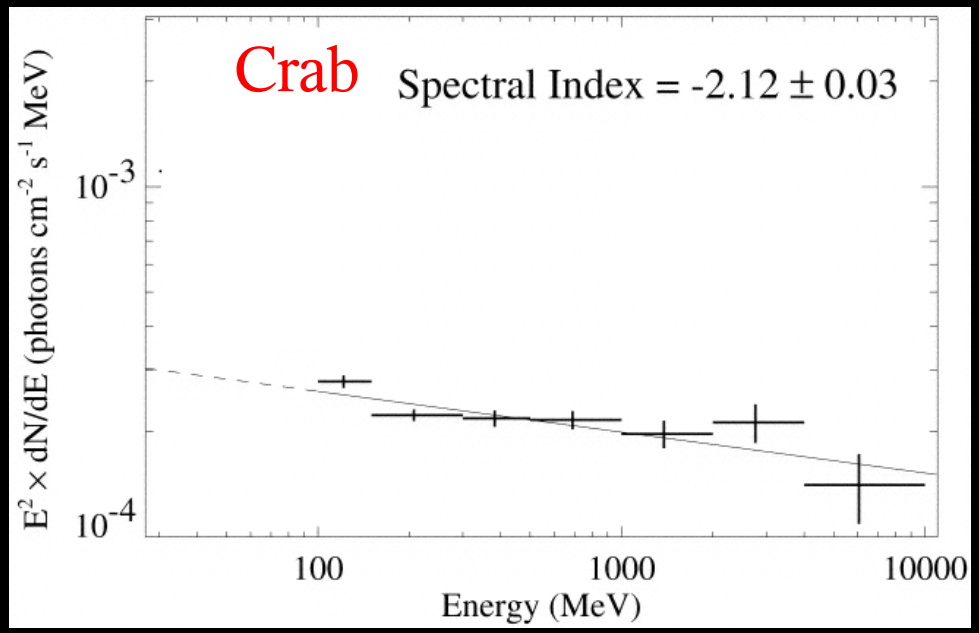
γ-ray pulsars: spectrum very reminiscent of the Galactic emission !





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:



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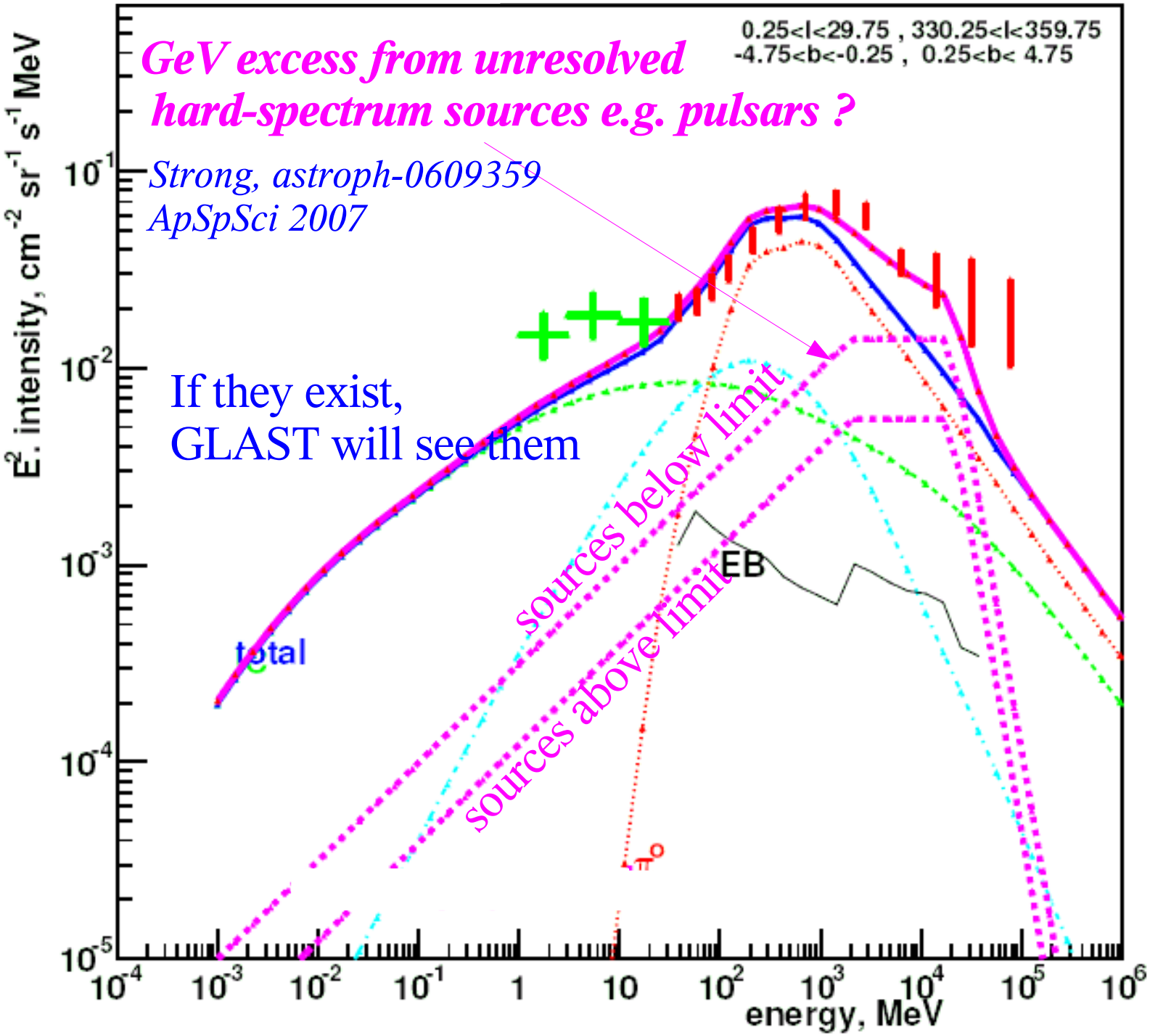
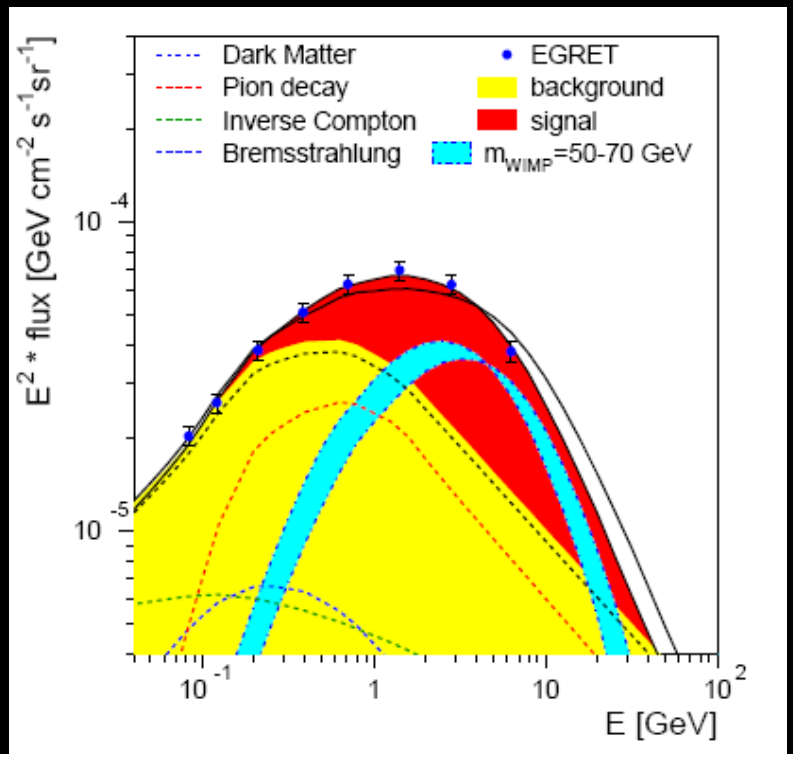


OR .....

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 ← *pre-Fermi* 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

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6. Hard spectrum SOURCES — quite plausible

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

8. Instrumental – EGRET response ← now comes Fermi

Fermi now begins to shed new light on the matter

Fermi LAT Collaboration

France
- CNRS/IN2P3, CEA/Saclay

Italy
- INFN, ASI, INAF

Japan
- Hiroshima University
- ISAS/JAXA
- RIKEN
- Tokyo Institute of Technology

Sweden
- Royal Institute of Technology (KTH)
- Stockholm University

United States
- Stanford University (SLAC and HEPL/Physics)
- University of California, Santa Cruz - Santa Cruz Institute for Particle Physics
- Goddard Space Flight Center
- Naval Research Laboratory
- Sonoma State University
- The Ohio State University
- University of Washington

PI: Peter Michelson (Stanford)

~390 Scientific Members (including 96 Affiliated Scientists, plus 68 Postdocs and 105 Students)

Cooperation between NASA and DOE, with key international contributions from France, Italy, Japan and Sweden.

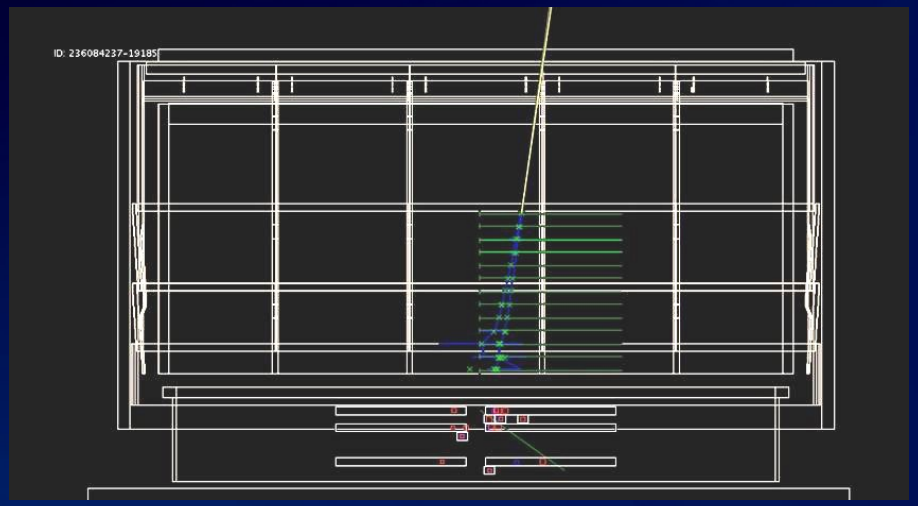
http://www.youtube.com/watch?v=W0aGzO2Fw90

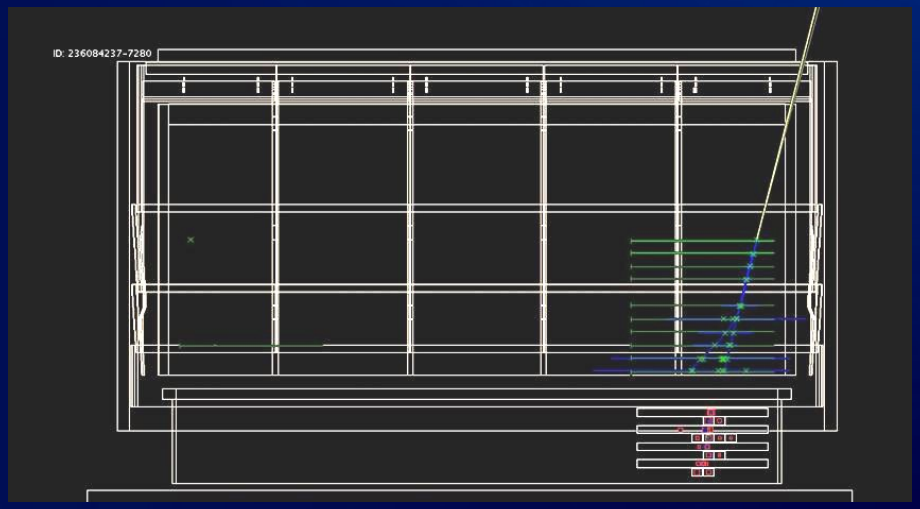
Peter Michelson & Bill Atwood lighting the fuse!

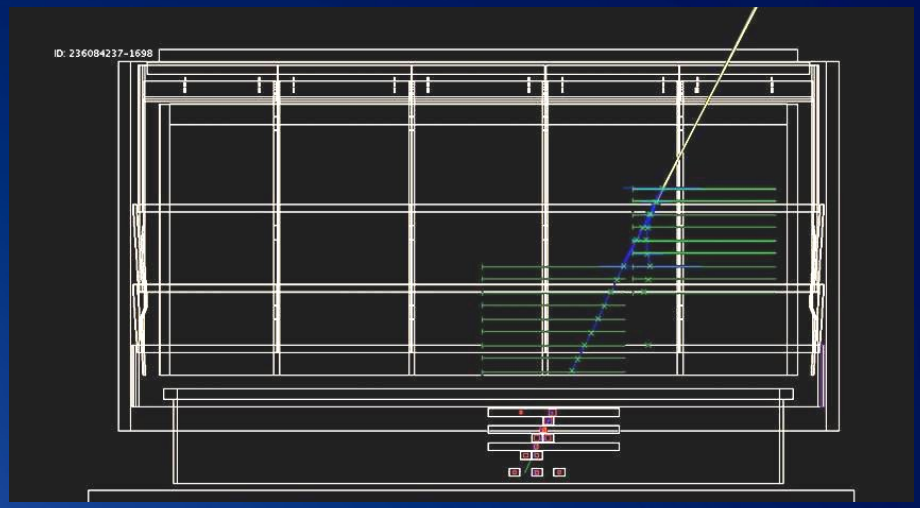
June 11 2008 11.30 am EST

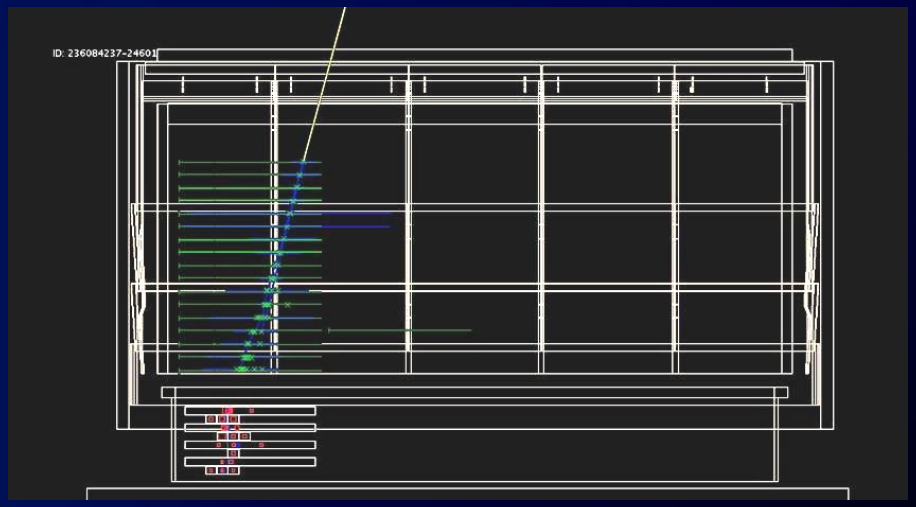
Photon Events on Orbit!

Immediately upon being powered on, the LAT began taking data flawlessly!

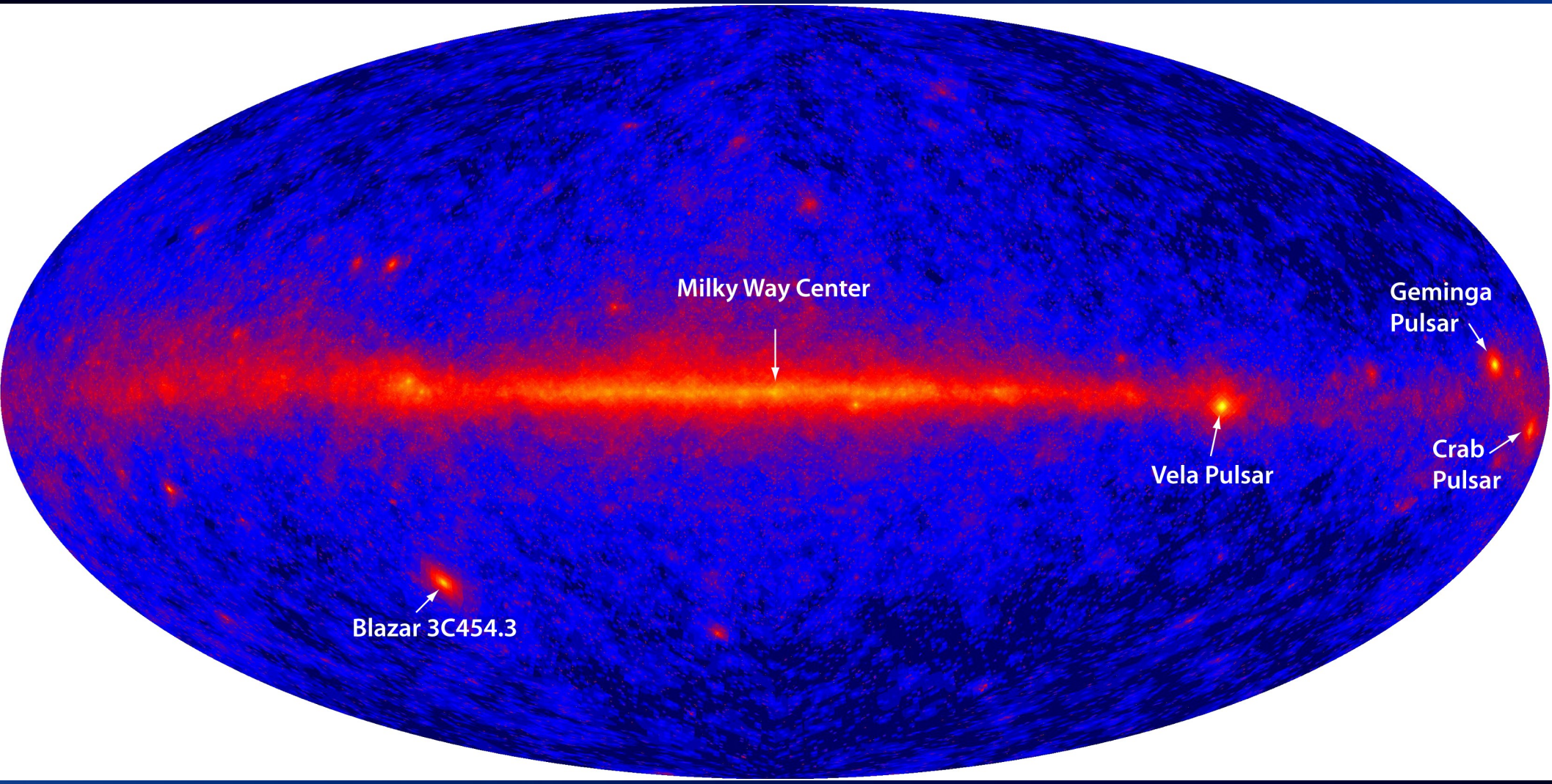






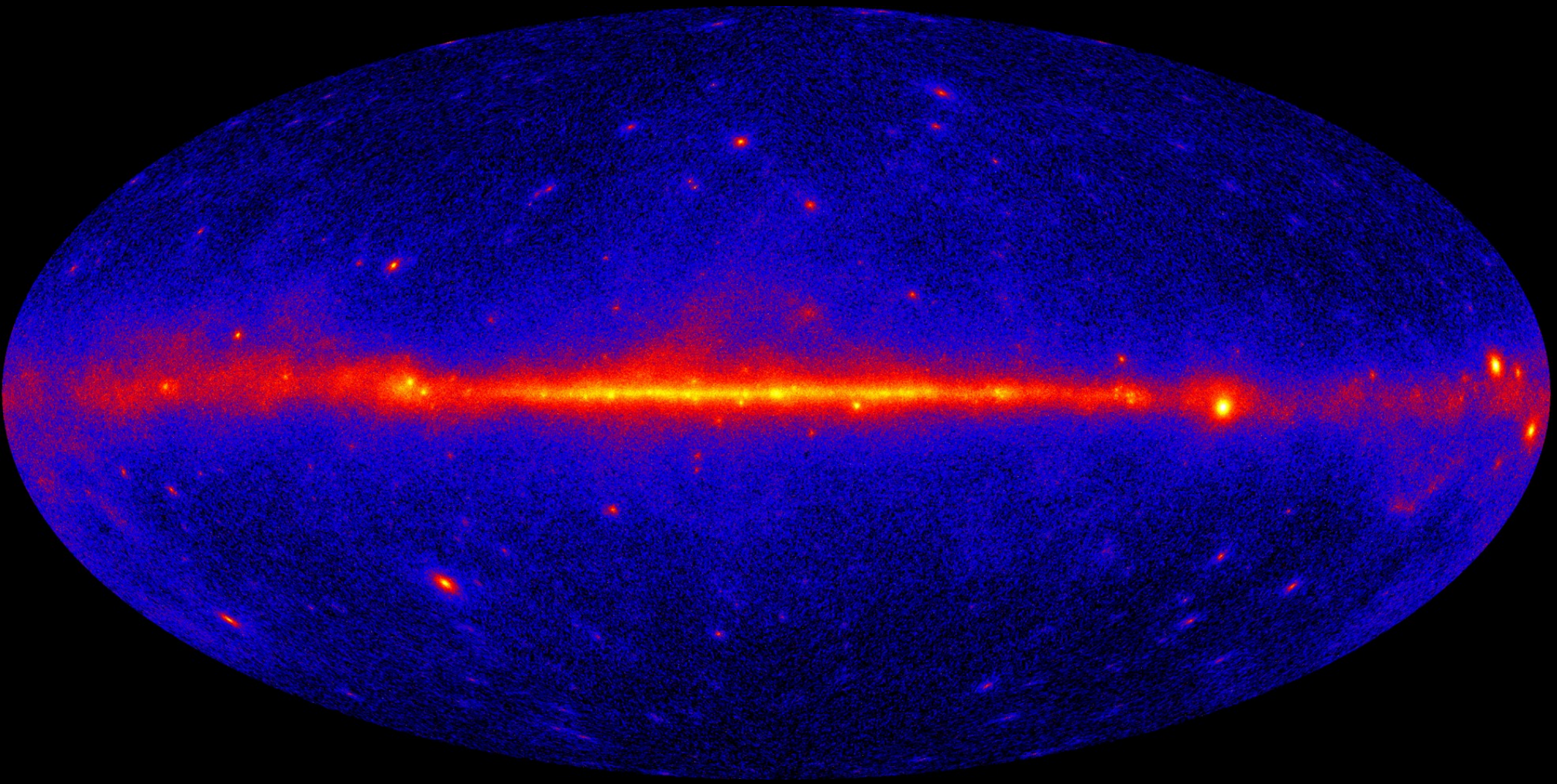


First Light!



Four days of all-sky survey engineering data

3-Month All-Sky Count Map



Not exposure corrected, but the exposure in all-sky scan mode is fairly uniform averaged over 3 months.

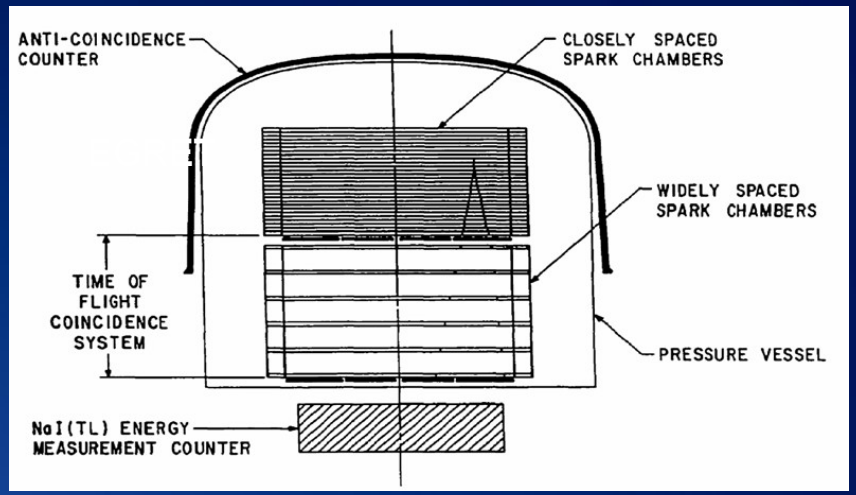
LAT Performance as a Telescope

	Years	Ang. Res. (100 MeV)	Ang. Res. (10 GeV)	Energy (GeV)	*Aeff* Ω (cm2 sr)	# γ-rays
EGRET	1991–00	5.8°	0.5°	0.03–10	750	1.4 M
AGILE	2007–	4.7°	0.2°	0.03–50	1,500	4 M /y
***Fermi* LAT**	**2008–**	**3.5°**	**0.1°**	**0.02–300**	**25,000**	100 M /y

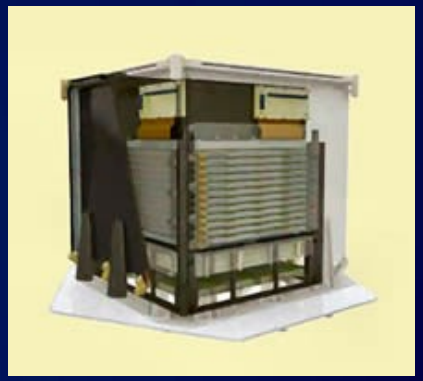
LAT has already surpassed EGRET and AGILE celestial gamma-ray totals

Unlike EGRET and AGILE, LAT is an effective All-Sky Monitor

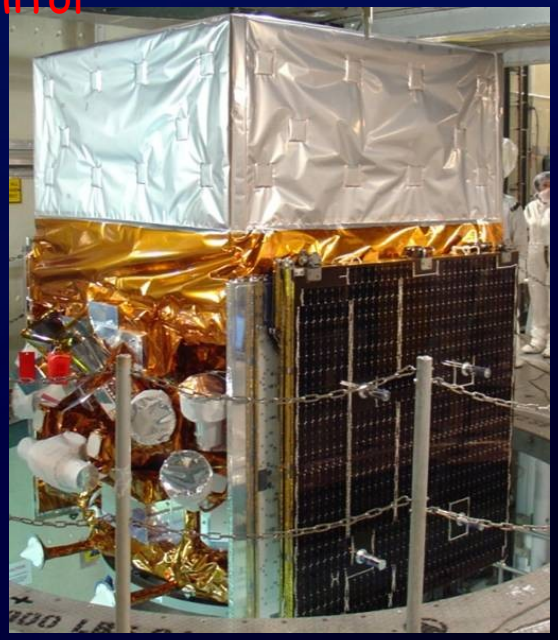
The ***whole sky*** is viewed every ~3 hours



CGRO EGRET



AGILE (ASI)

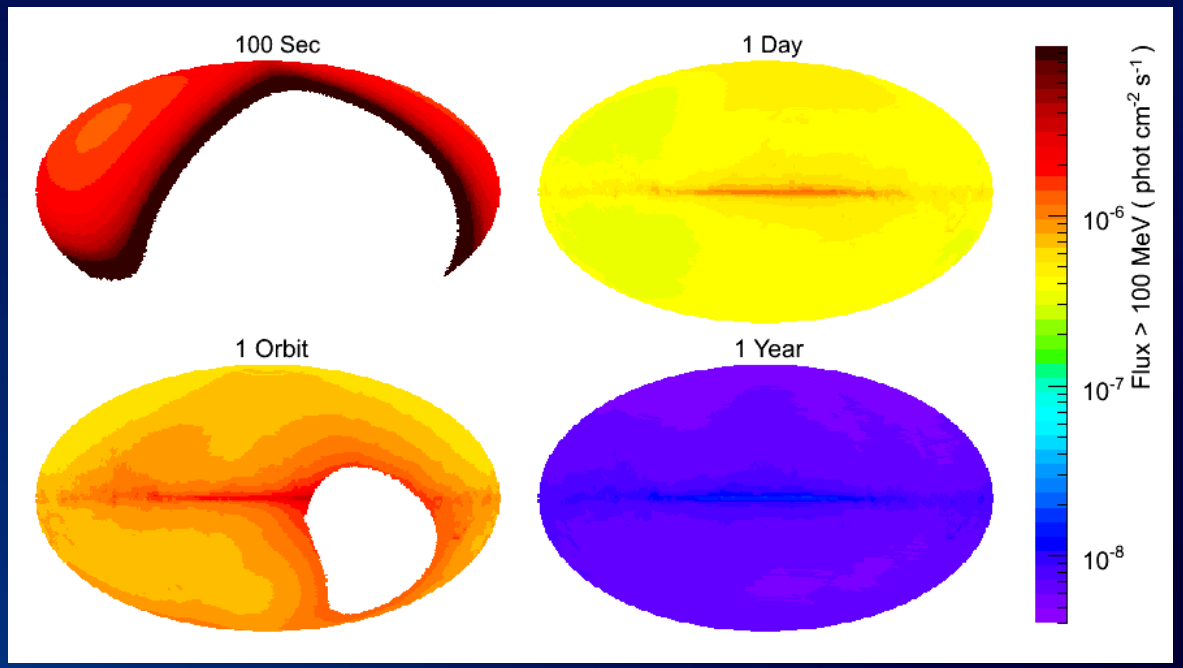


Fermi / LAT

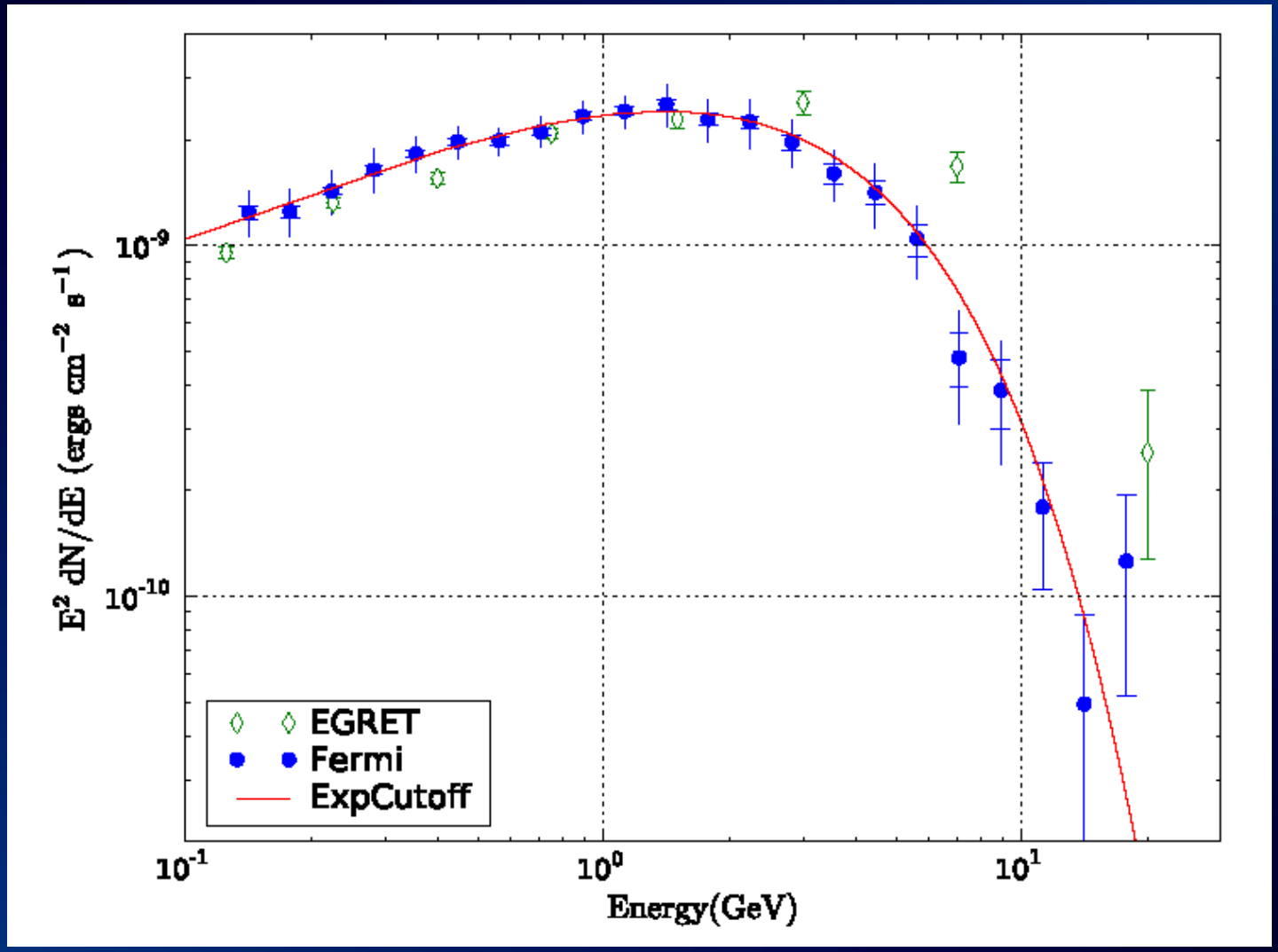
Operating modes

Primary observing mode is Sky Survey

- Full sky every 2 orbits (3 hours)
- Uniform exposure, with each region viewed for ~30 minutes every 2 orbits
- Best serves majority of science, facilitates multiwavelength observation planning
- Exposure intervals commensurate with typical instrument integration times for sources
- EGRET sensitivity reached in days

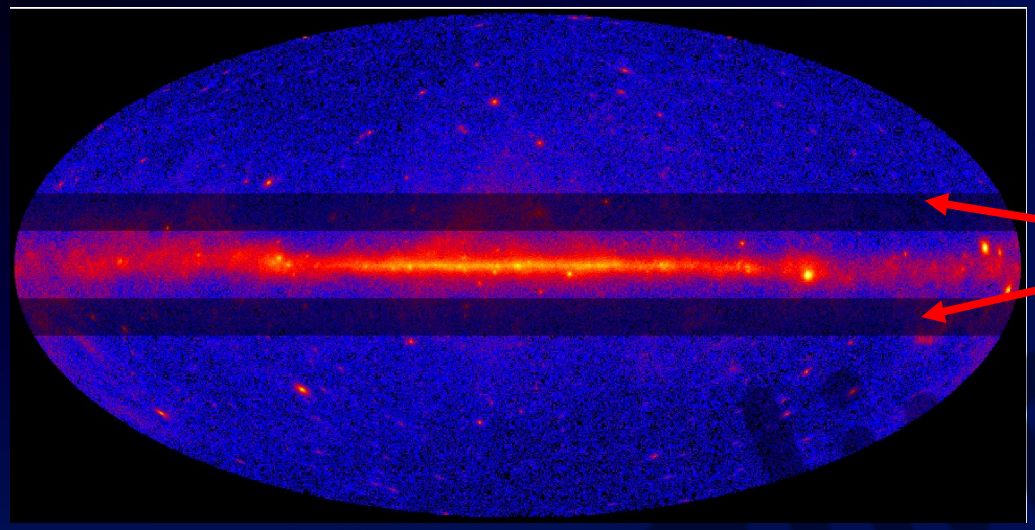


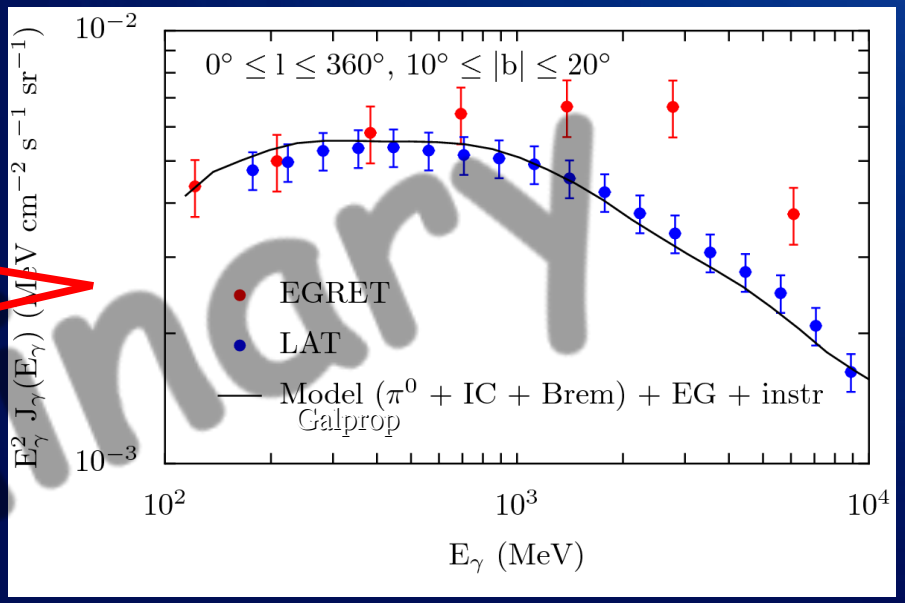
Vela Pulsar – Phase-averaged spectrum



Abdo etal. 2009 ApJ in press, arXiv: **0812.2960**
first hint of a difference with EGRET at GeV energies!

Galactic Diffuse: Fermi LAT View



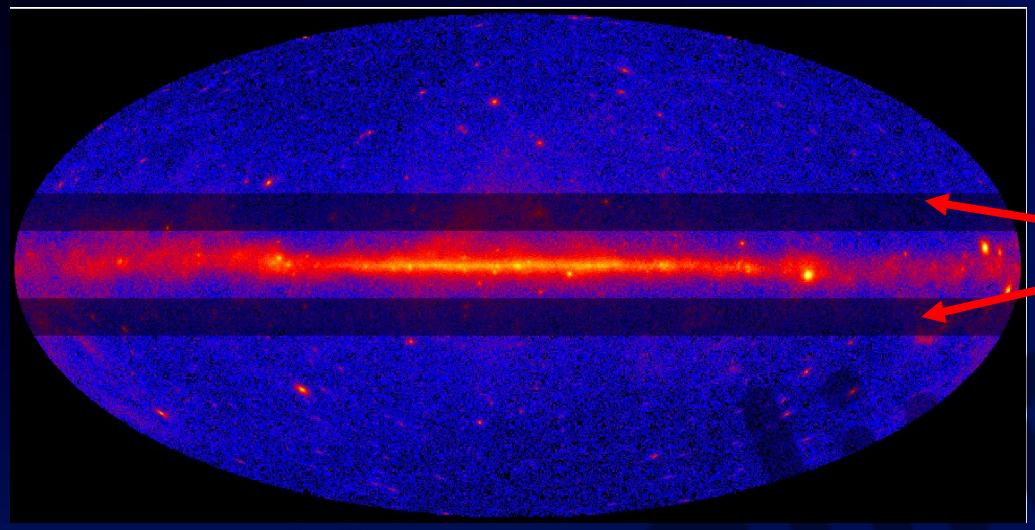


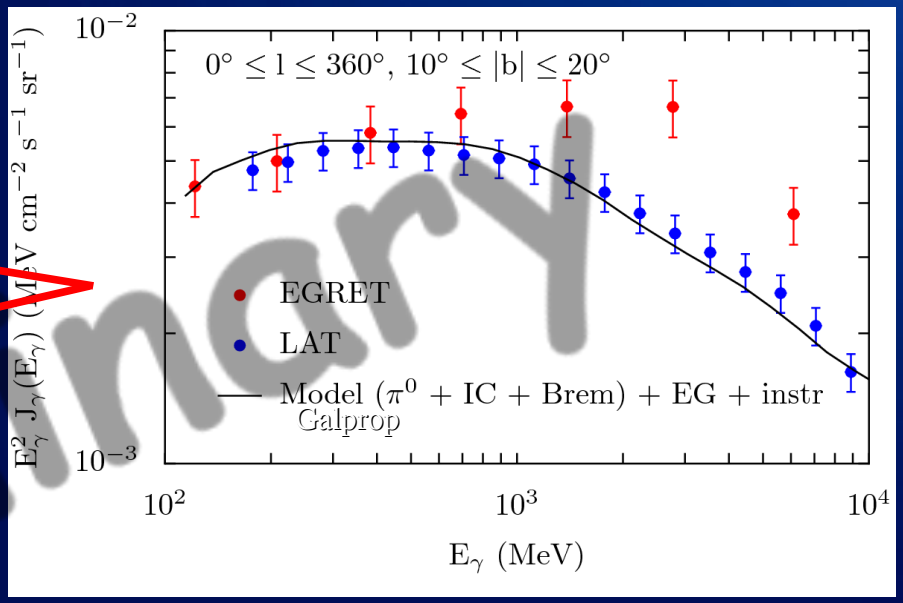
Choose mid-latitudes because:

* gamma-rays from local 1 kpc where CR spectrum should be similar to directly-measured one
* avoids gamma-ray sources in the plane
* the Galactic emission still dominates over instrumental + extragalactic backgrounds

Model: GALPROP, 'conventional': uses locally measured CR spectrum

The Fermi LAT View





Spectra shown for mid-latitude range → EGRET GeV excess in this region of the sky is not confirmed.

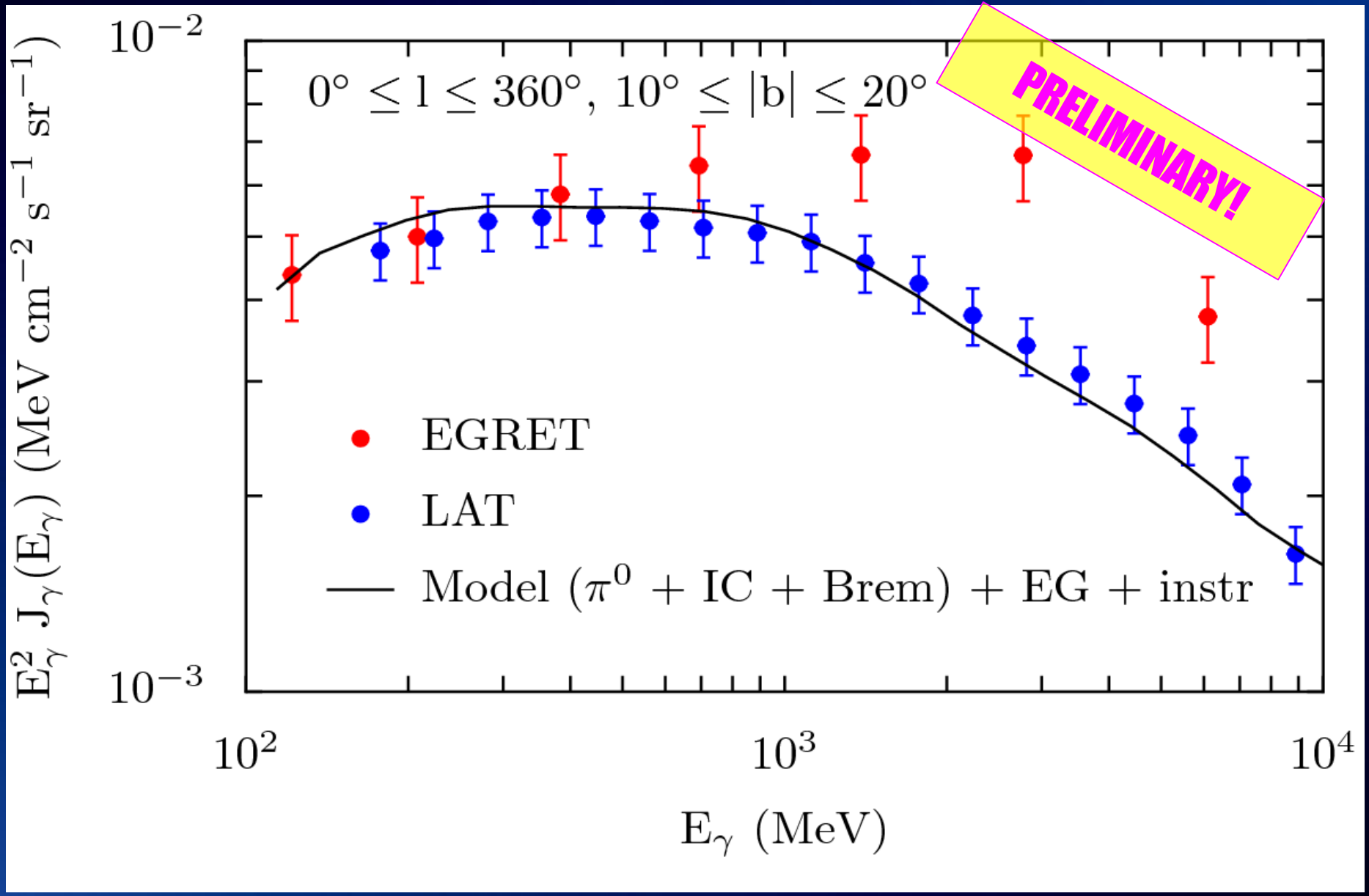
Sources are not subtracted but are a minor component.

LAT errors are dominated by systematic uncertainties and are currently estimated to be ~10% → this is preliminary.

EGRET data iincludes a 15% systematic error assumed to dominate (Esposito, et al. 1999).

EG + instrumental is assumed to be isotropic and determined from fitting the data at $|b| > 10°$.

Fermi LAT mid-latitudes



Current Fermi View of Diffuse Emission

Intermediate latitude γ-ray spectra can be explained by cosmic-ray propagation models based on local cosmic-ray nuclei and electron spectra.

The EGRET GeV excess is not seen in this region of the sky with the LAT.

The Vela spectrum also displays a discrepancy between the EGRET and LAT spectrum

This result applies to intermediate latitudes (local ~ 1 kpc) only

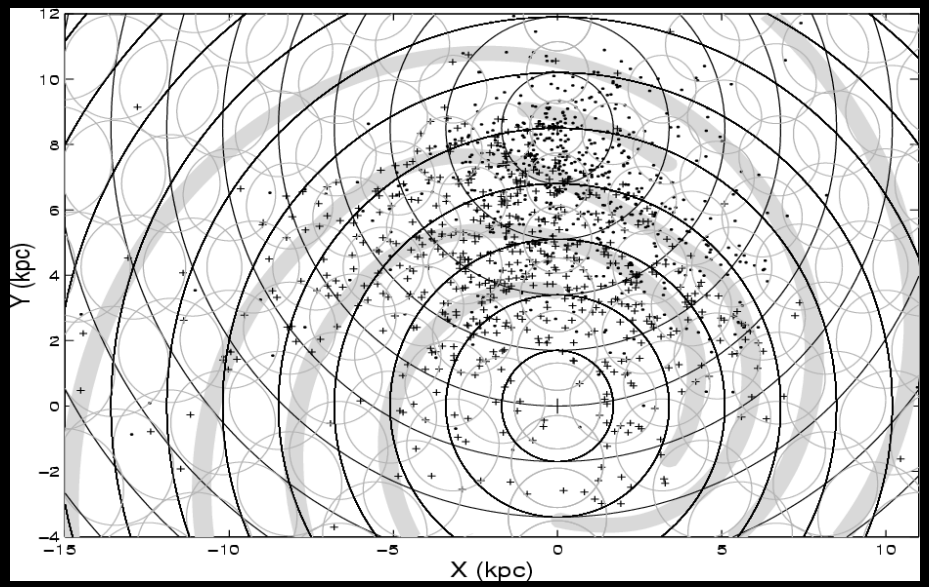
Work to analyse and understand diffuse emission over the entire sky is in progress.

Stay tuned !

For spatial analysis the EGRET data remain valid since not affected by spectral problems.

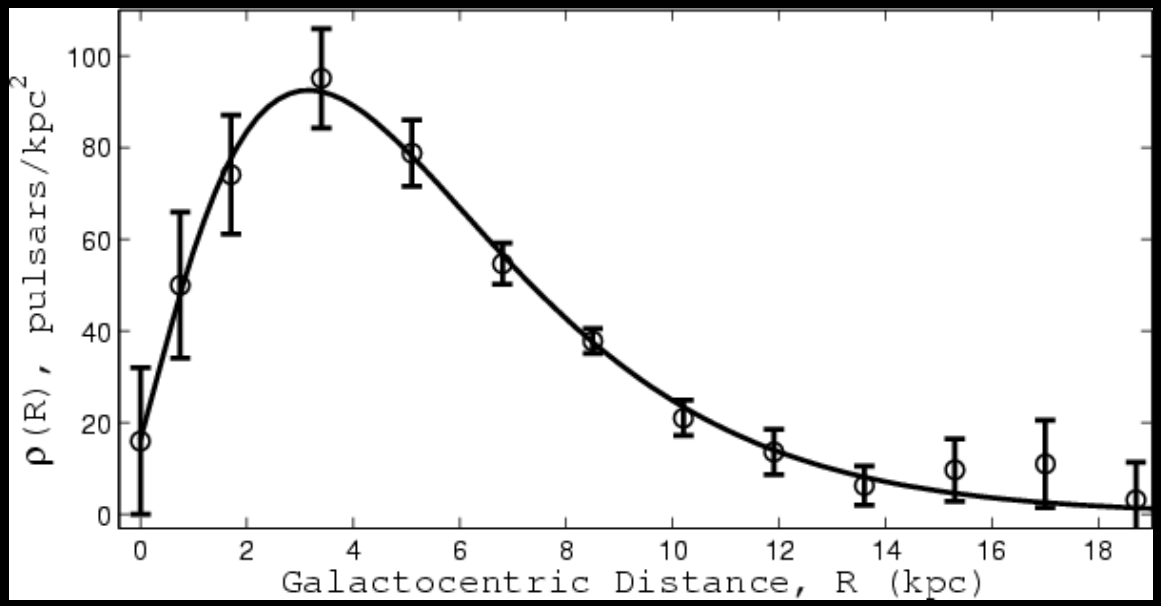
Hence now look at this aspect.

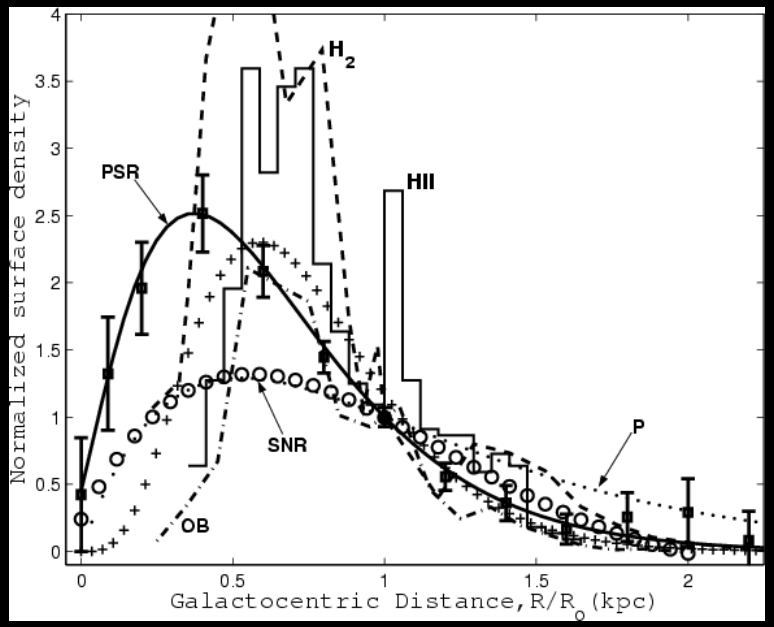
Tracer of SNR cosmic-ray sources: Pulsar distribution



Parkes Deep Survey

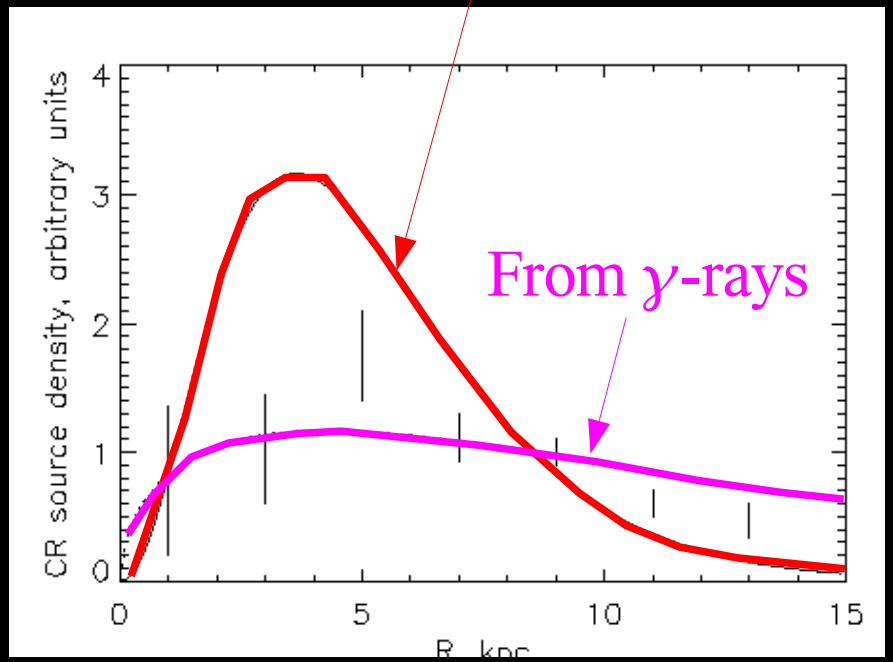
Yusifov & Kücük 2004
Lorimer 2004





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

SNR (traced by latest pulsar surveys: Lorimer 2004)

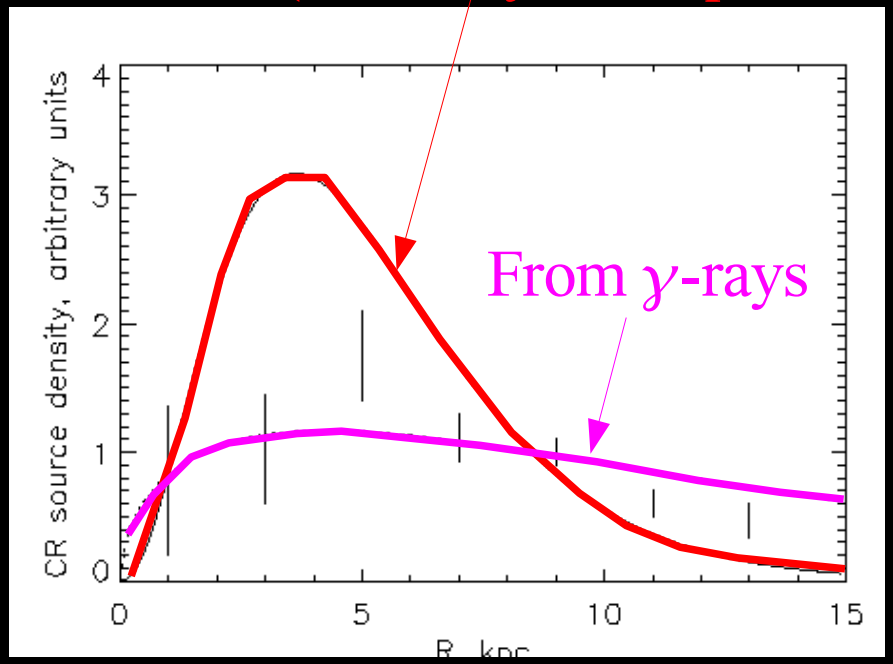


R (kpc)

might be wind gradient (Völk, Breidschwerdt) 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)

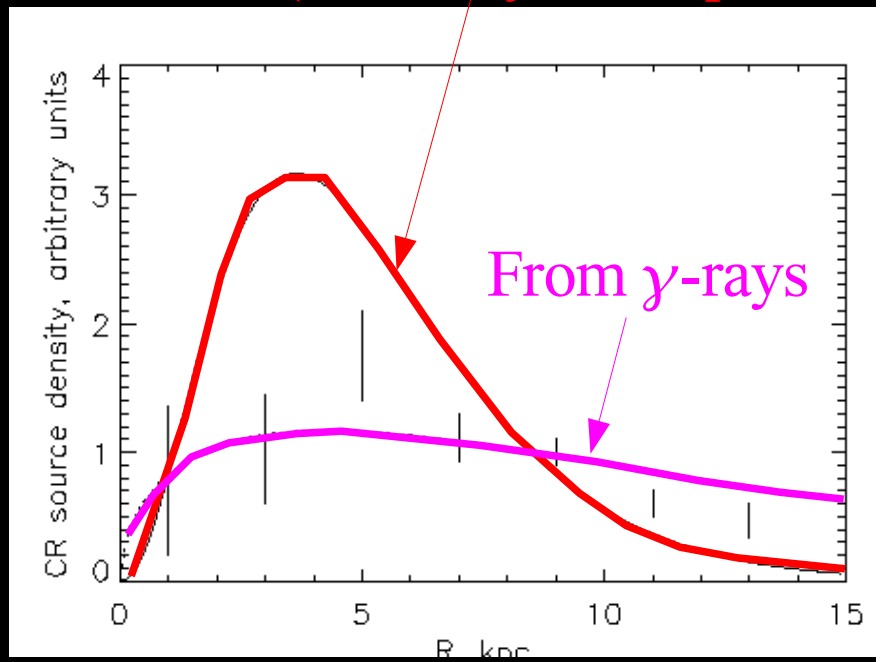


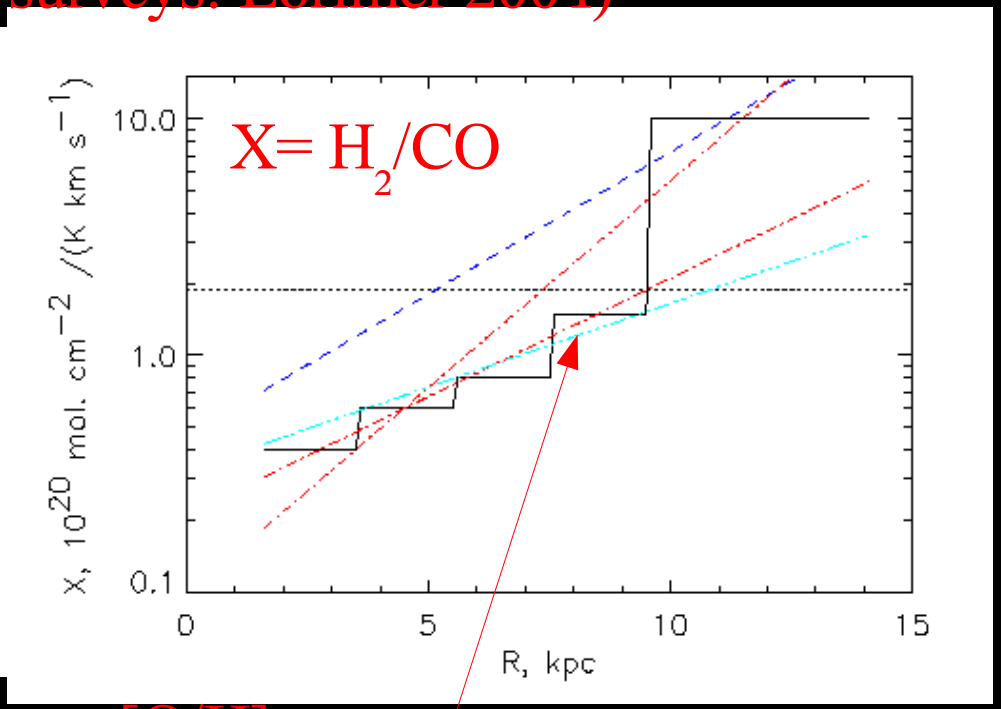
Clue: Galactic metallicity gradient e.g. [O/H]

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*

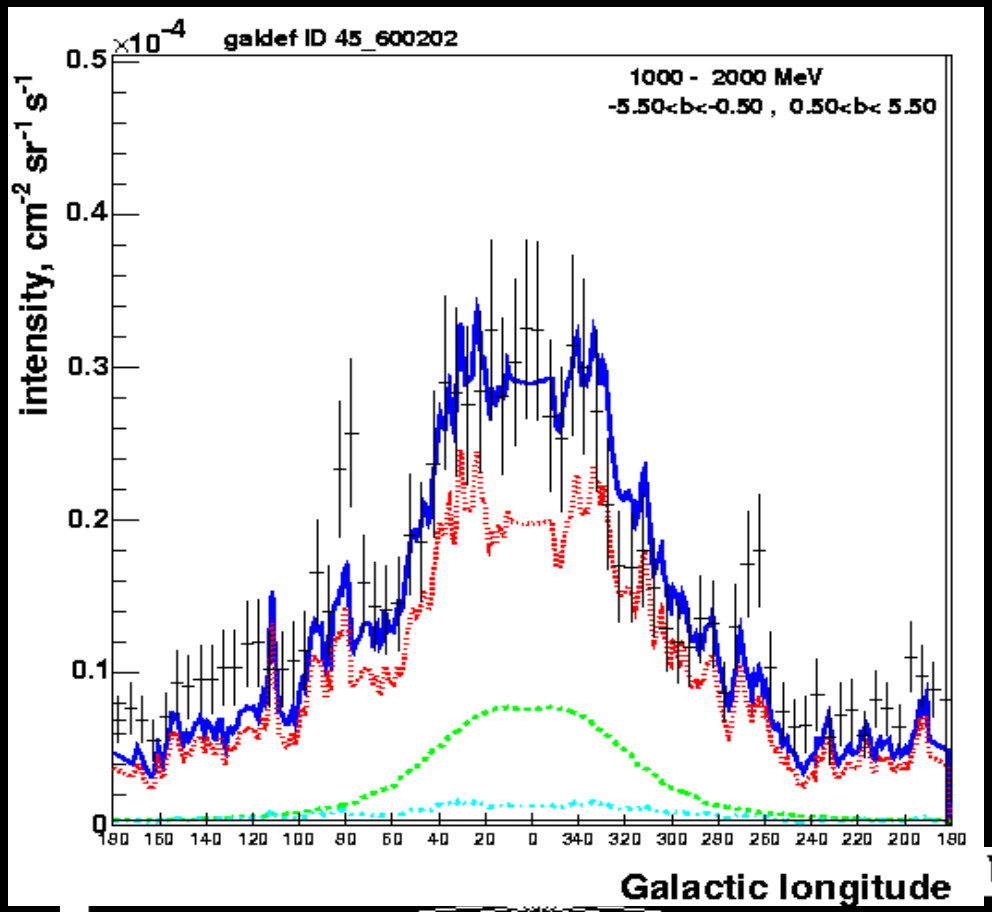
>>>>>>> ***X = H_2 / CO increases with radius***

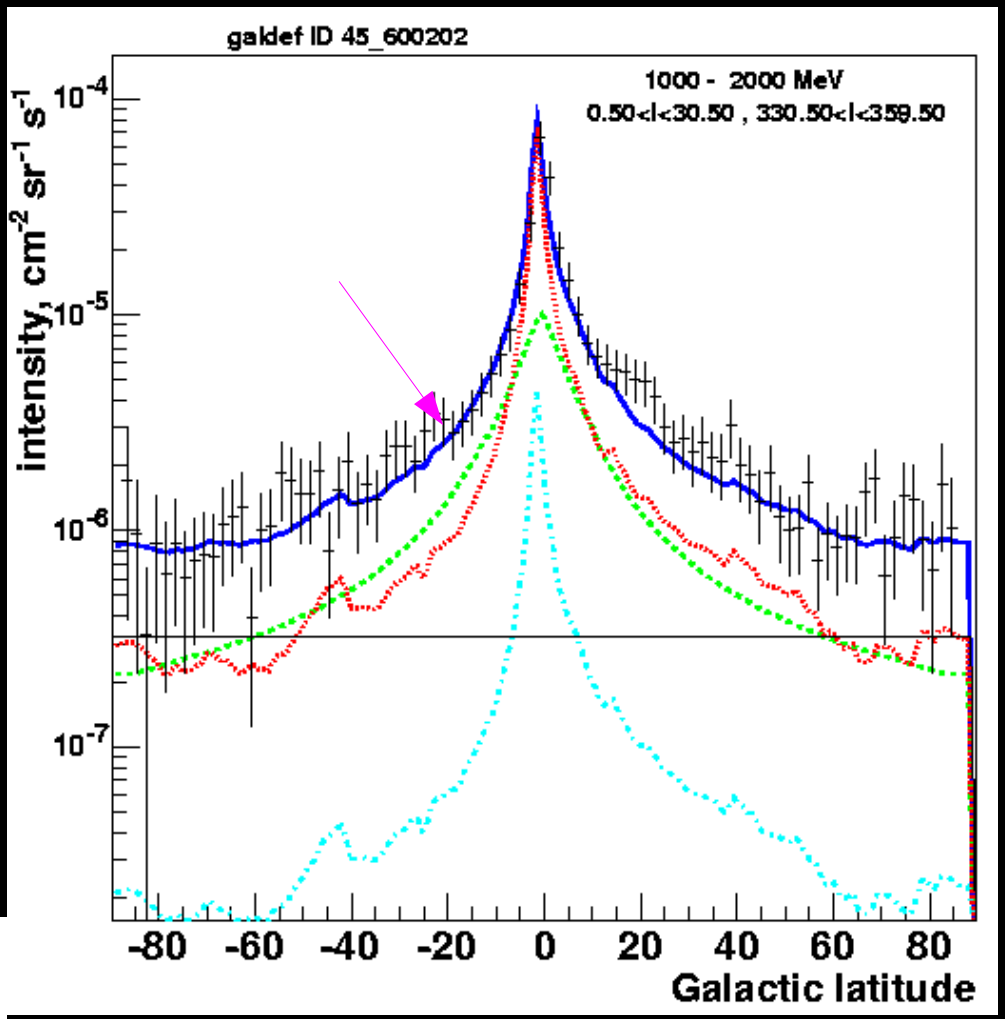
γ-rays = sources(R) * X(R) *CO(R) (+ HI, inverse Compton terms)

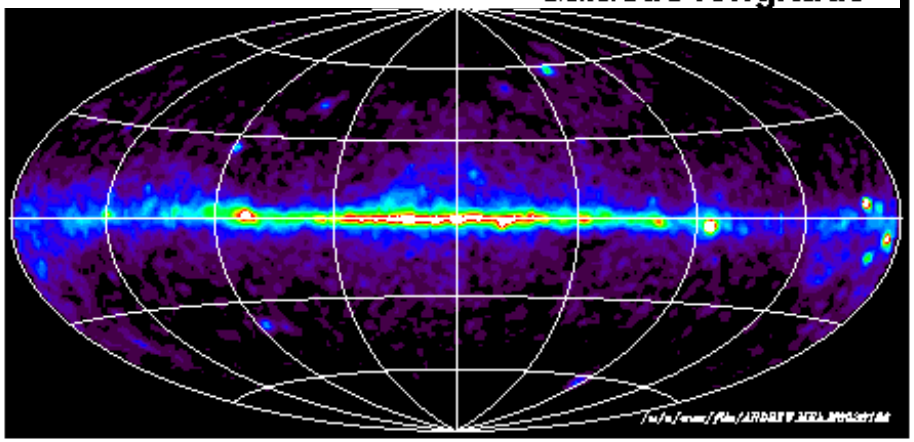
Steeper sources * flatter X = observed gamma-rays

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

EGRET γ -ray data







broadening the energy coverage:

INTEGRAL : down to 20 keV

MILAGRO: up to 15 TeV

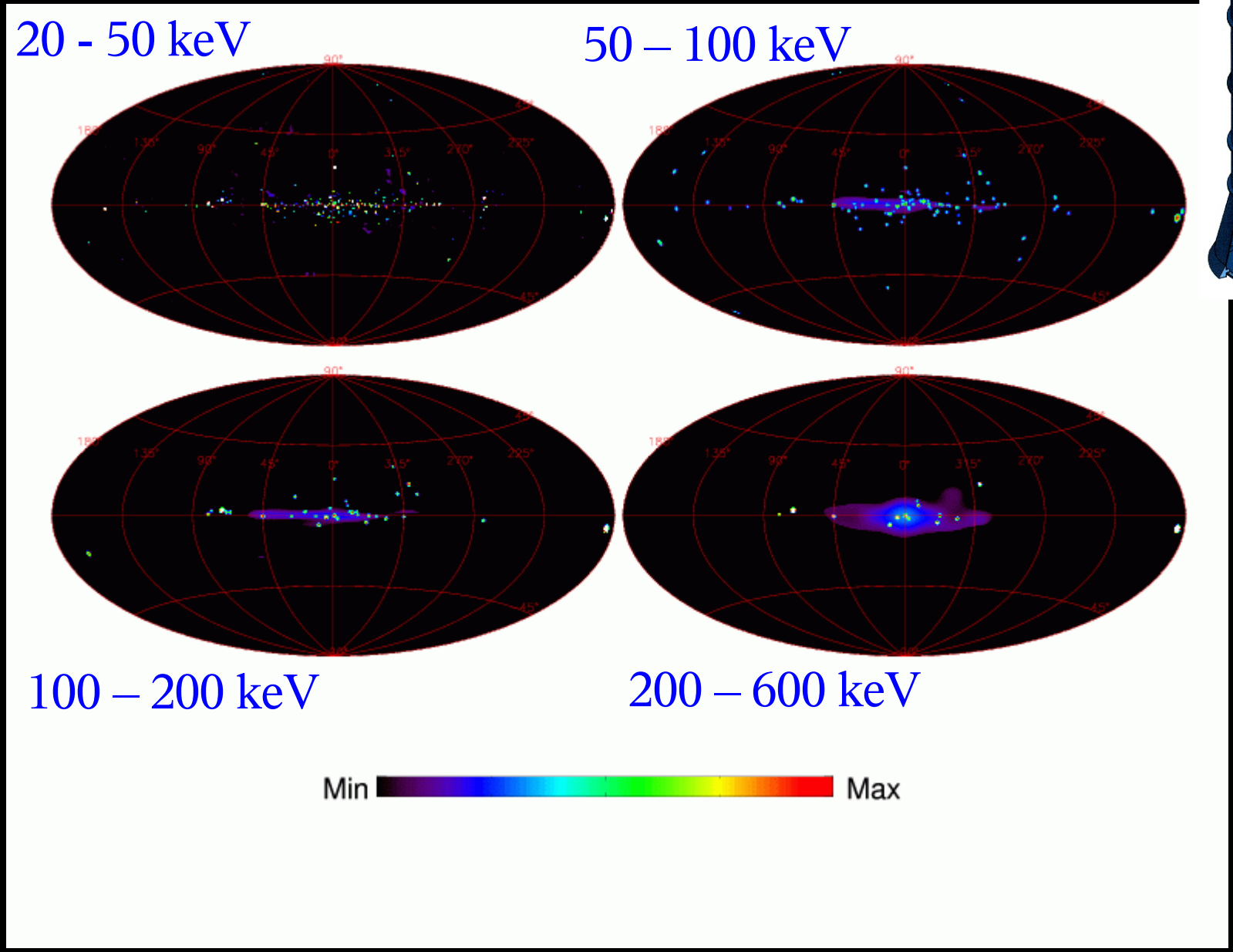
it's mainly about cosmic-ray electrons !

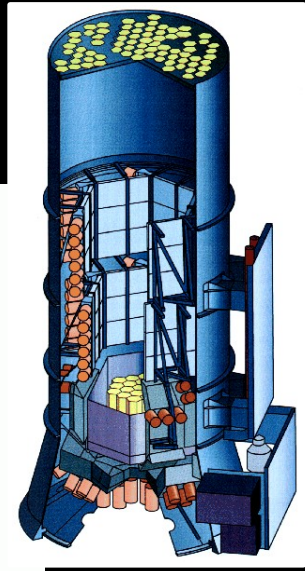
radio, hard X, soft gamma sensitive to GeV electrons

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



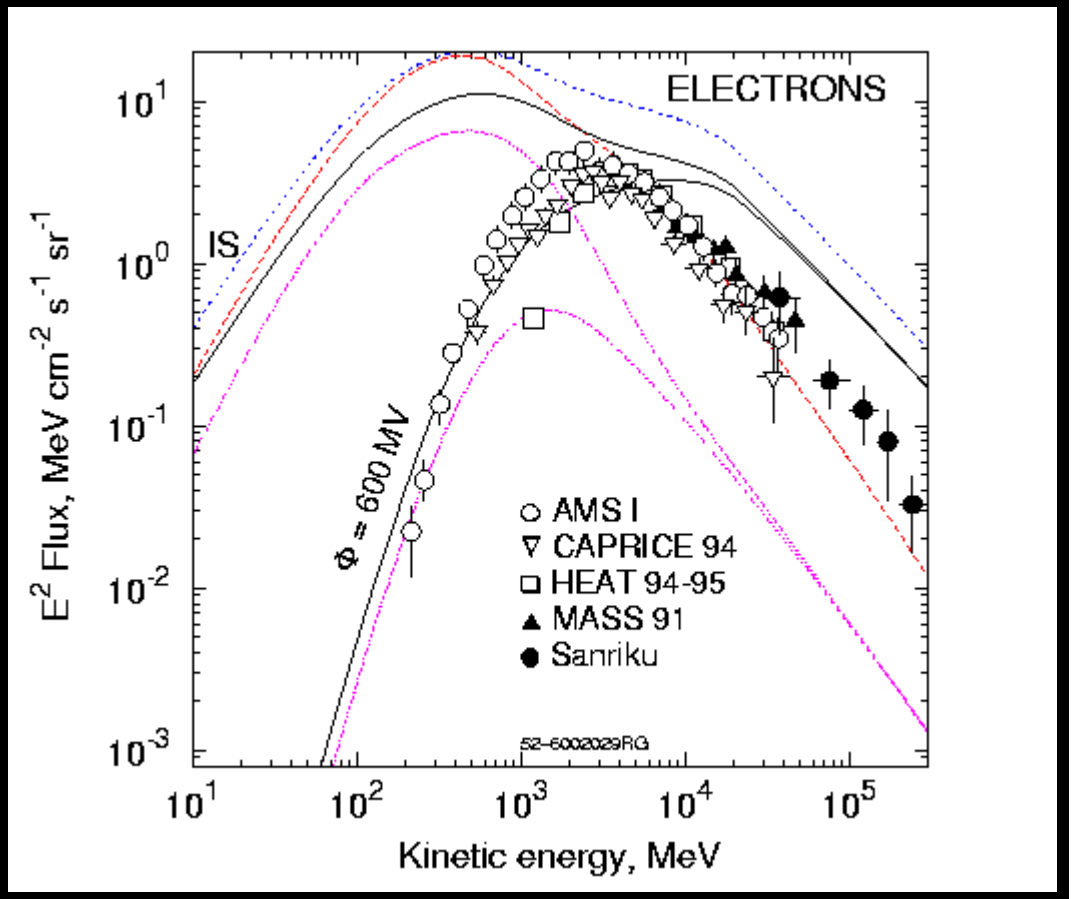


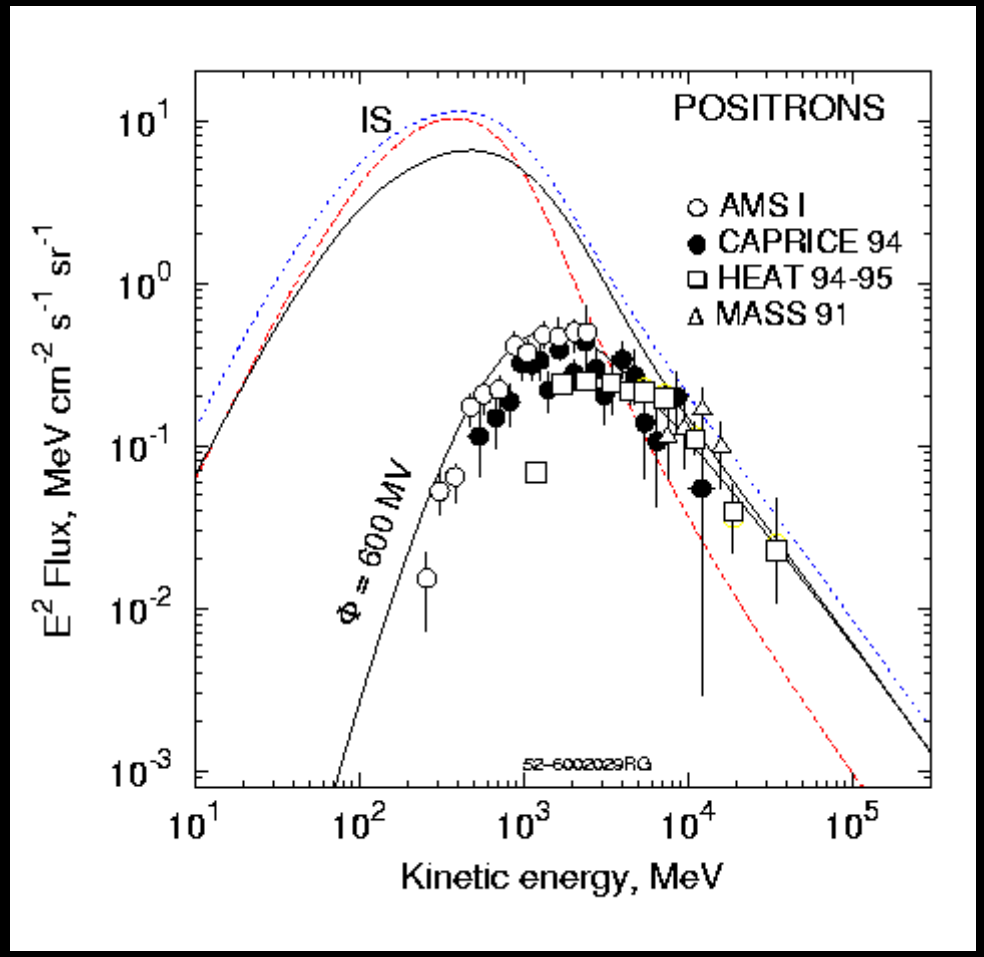
Bouchet et al 2008 ApJ 679,1315

primary cosmic-ray electrons

secondary cosmic-ray positrons

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





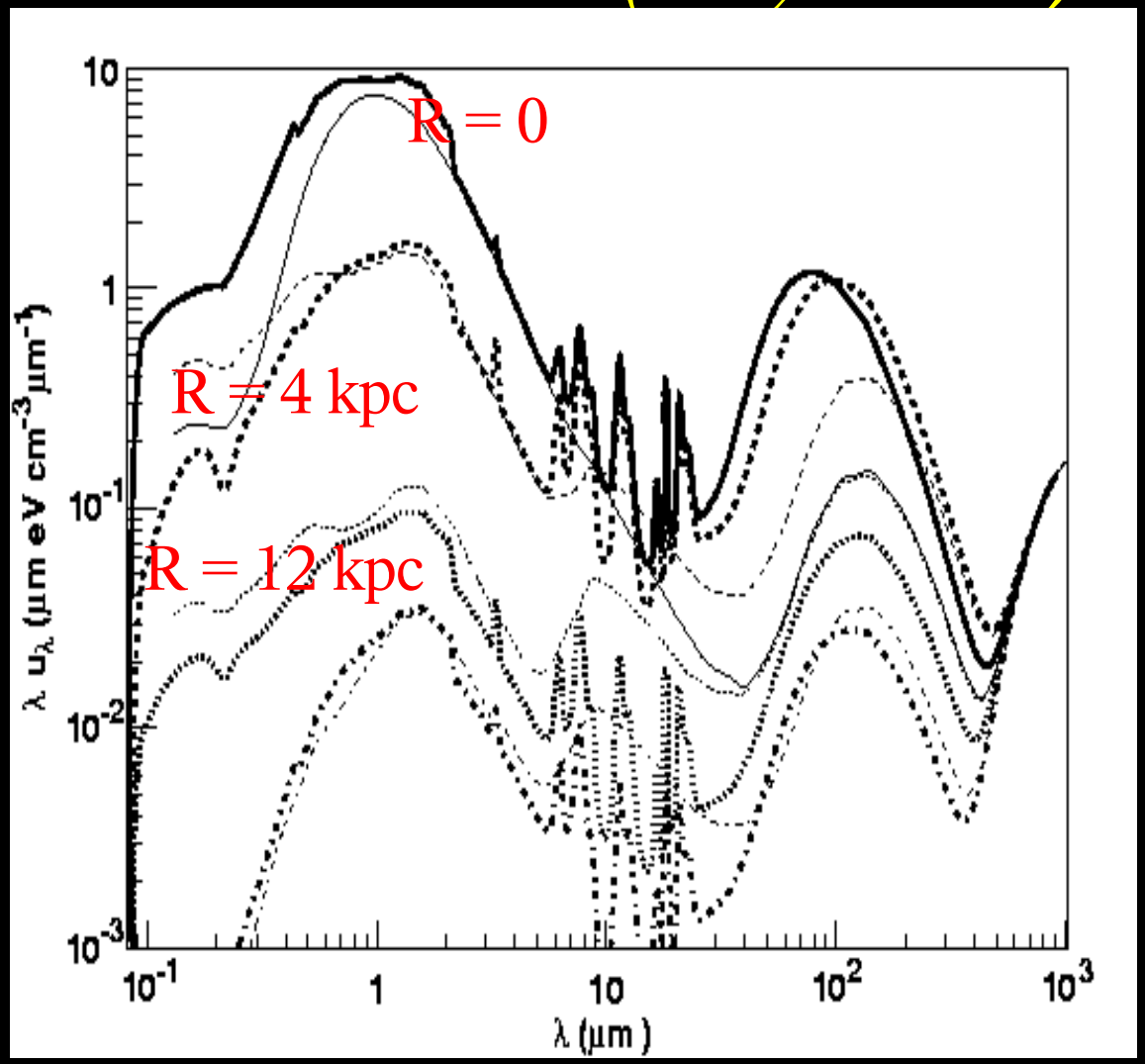
those electrons & positrons can explain a lot !

Porter, Moskalenko, Strong, Orlando, Bouchet 2008 ApJ 682, 400

Interstellar Radiation Field

new model *(Troy Porter)*

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

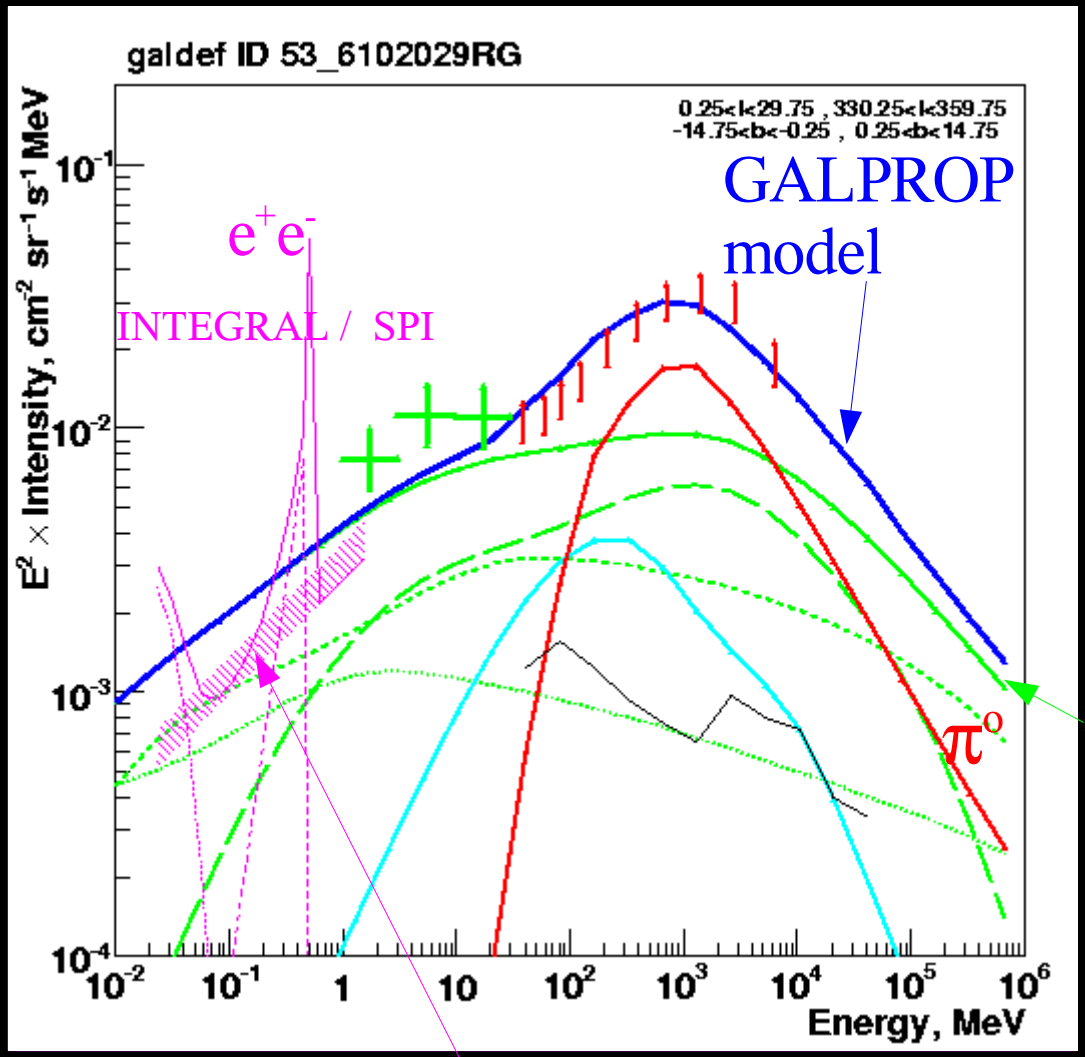


essential for inverse Compton gamma rays

UV optical IR FIR CMB

Gamma-rays, inner Galaxy

inverse Compton
from primary electrons, secondary electrons, positrons

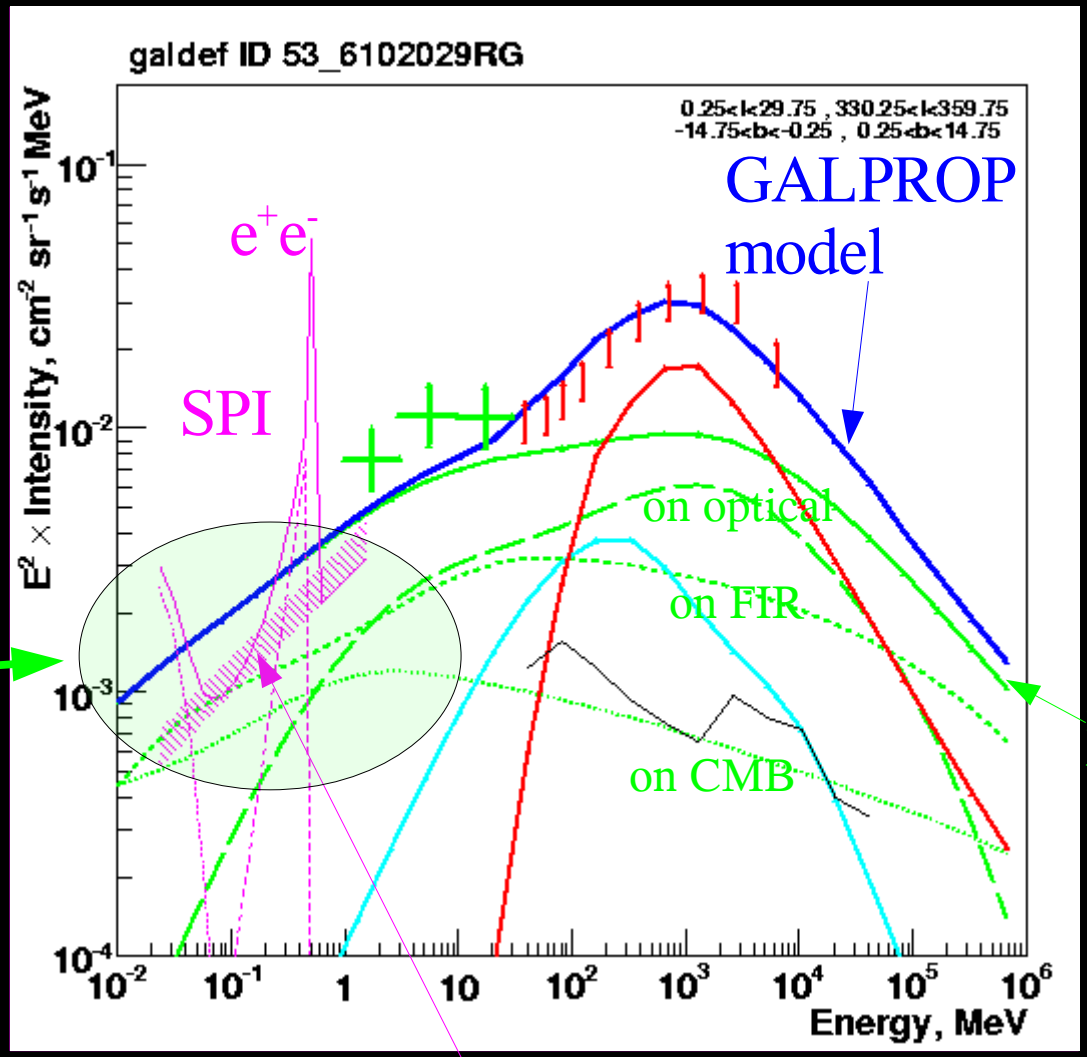


Bouchet et al power-law continuum

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

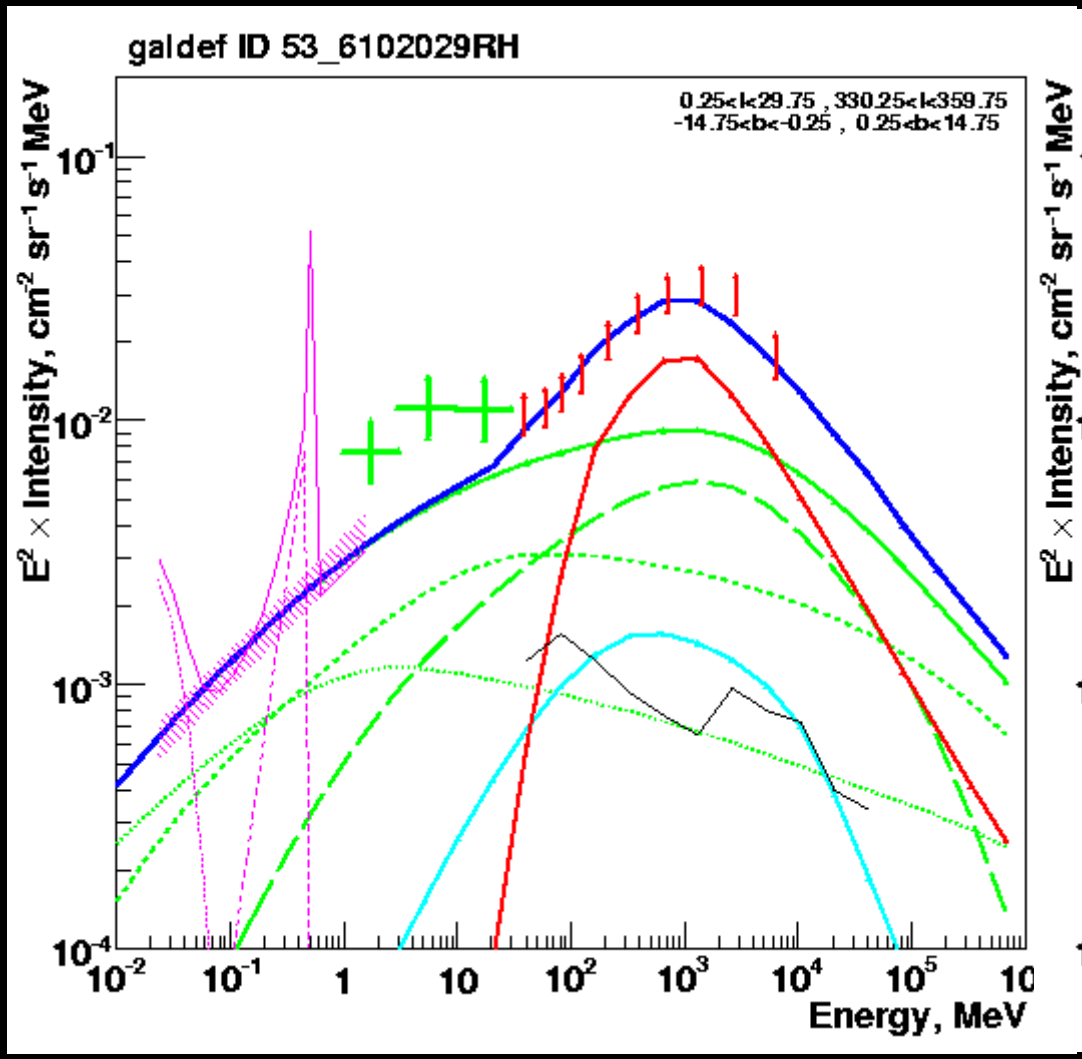
Porter, Moskalenko, Strong, Orlando, Bouchet ApJ 682, 400

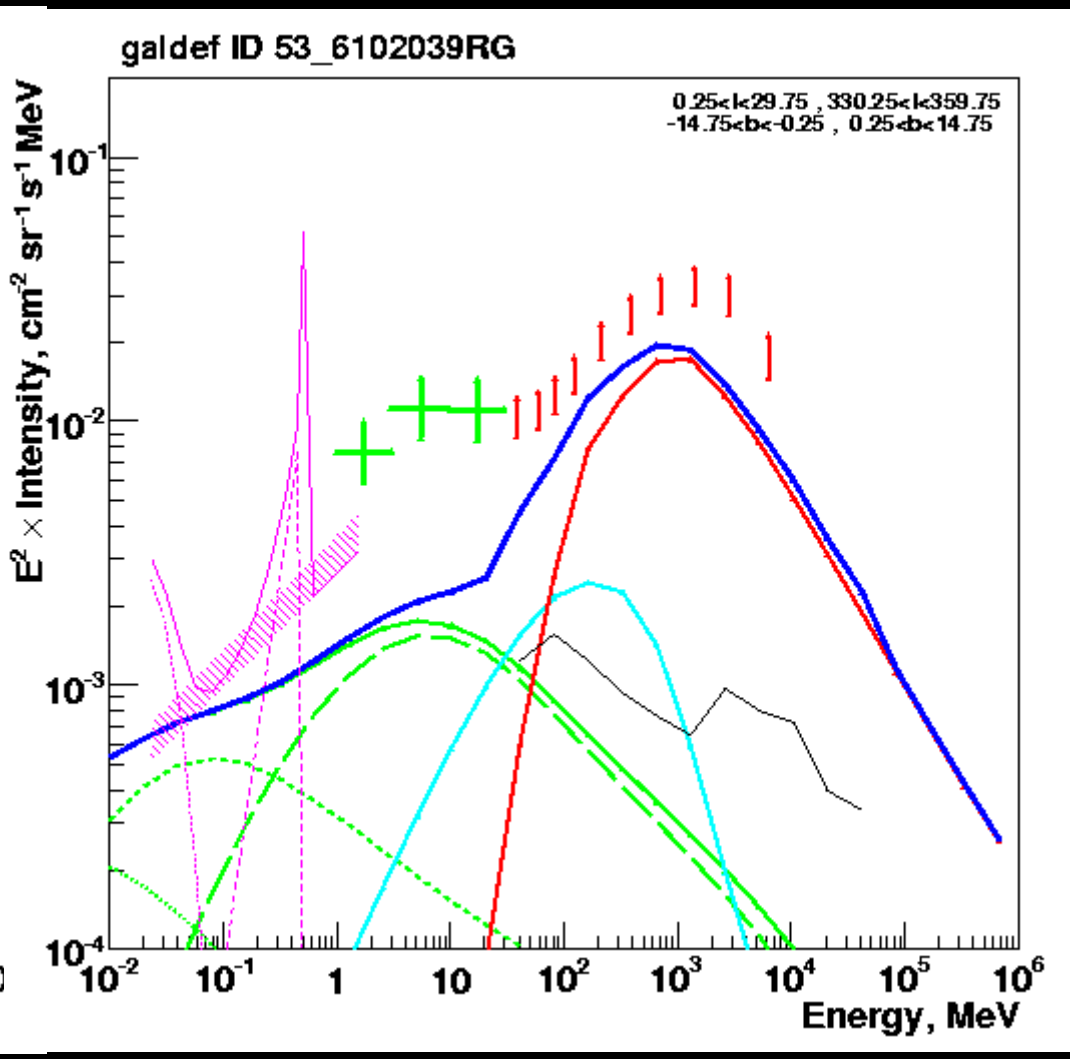
Gamma-rays, inner Galaxy

inverse Compton from

primary electrons only

secondary electrons, positrons only



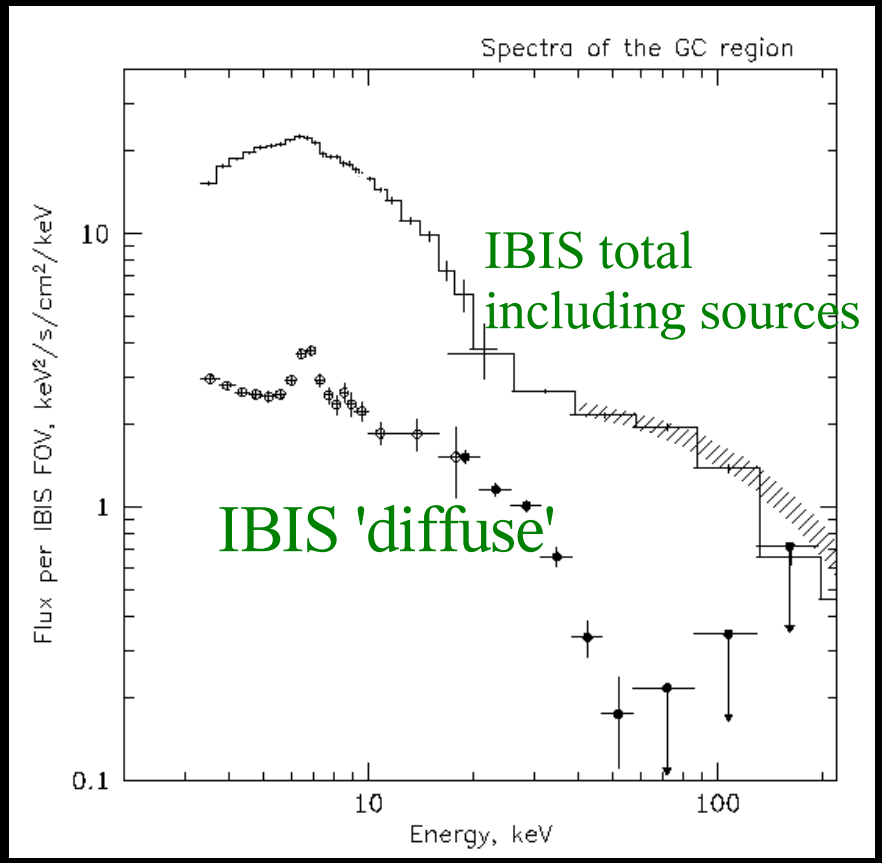


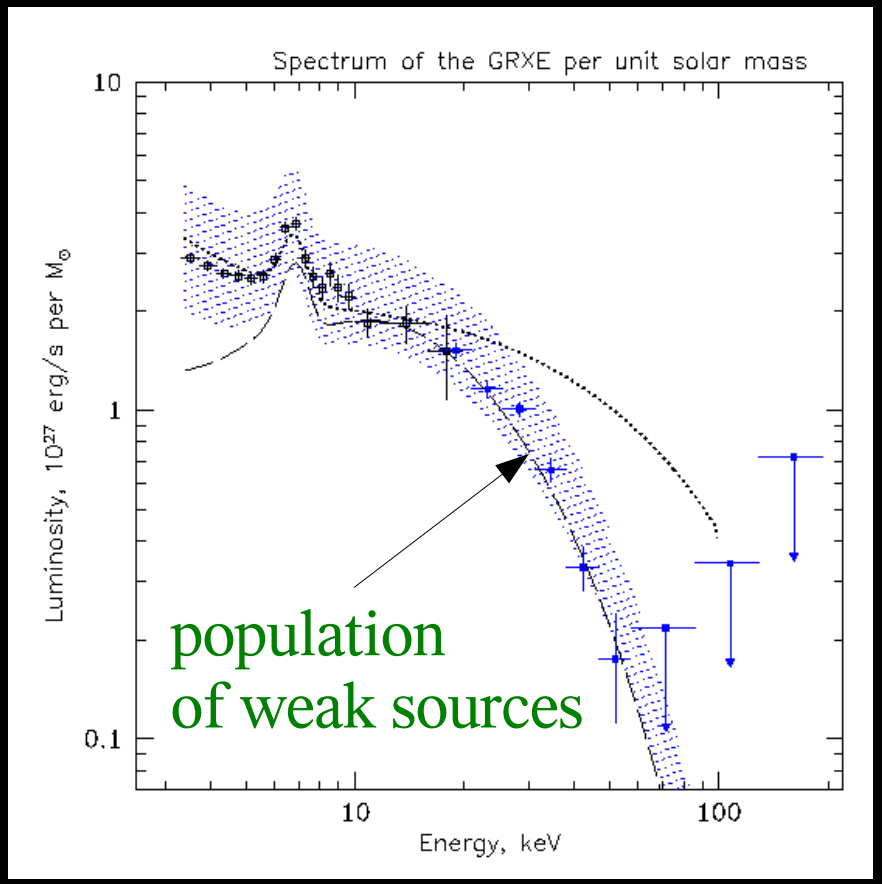
inverse Compton origin of hard X and gamma-rays

secondary positrons, electrons important

even hard X-rays trace cosmic rays !!

IBIS: Krivonos et al. 2007



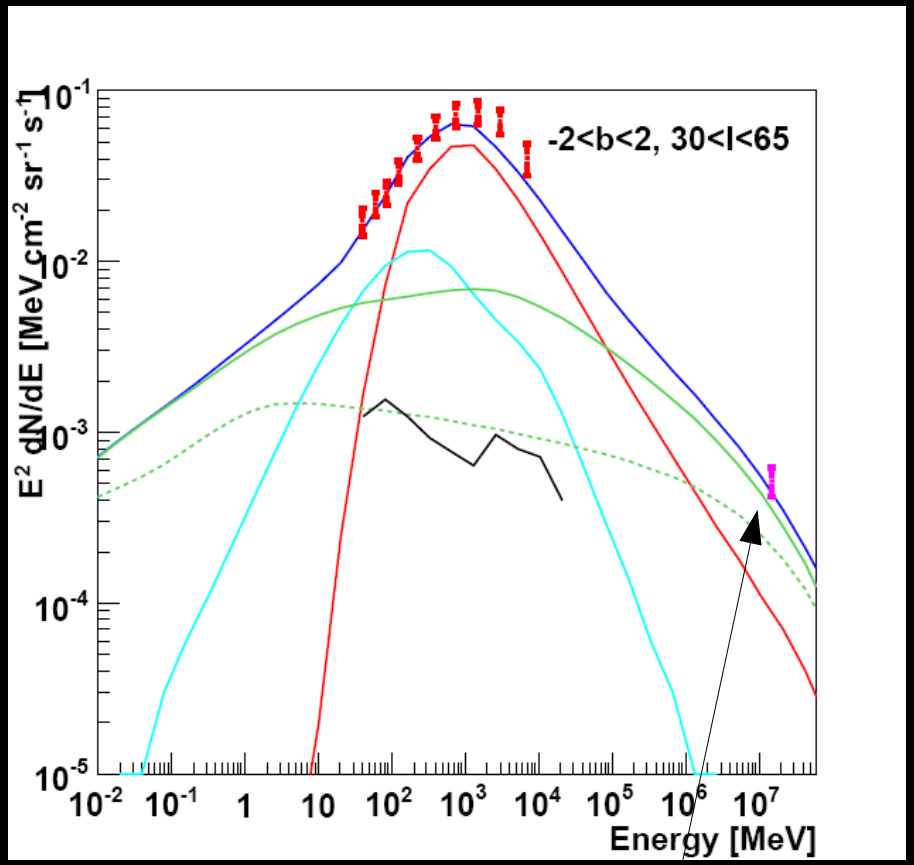


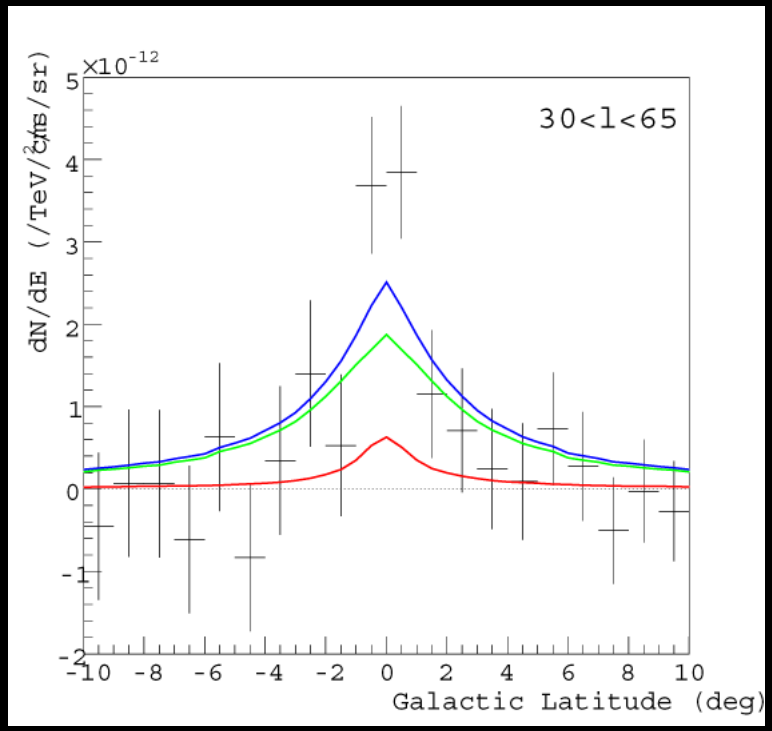
inner Galaxy as seen by an instrument with IBIS FOV, with diffuse traced by 4.9μ DIRBE map

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

Inner Galaxy

same model, extended to > TeV



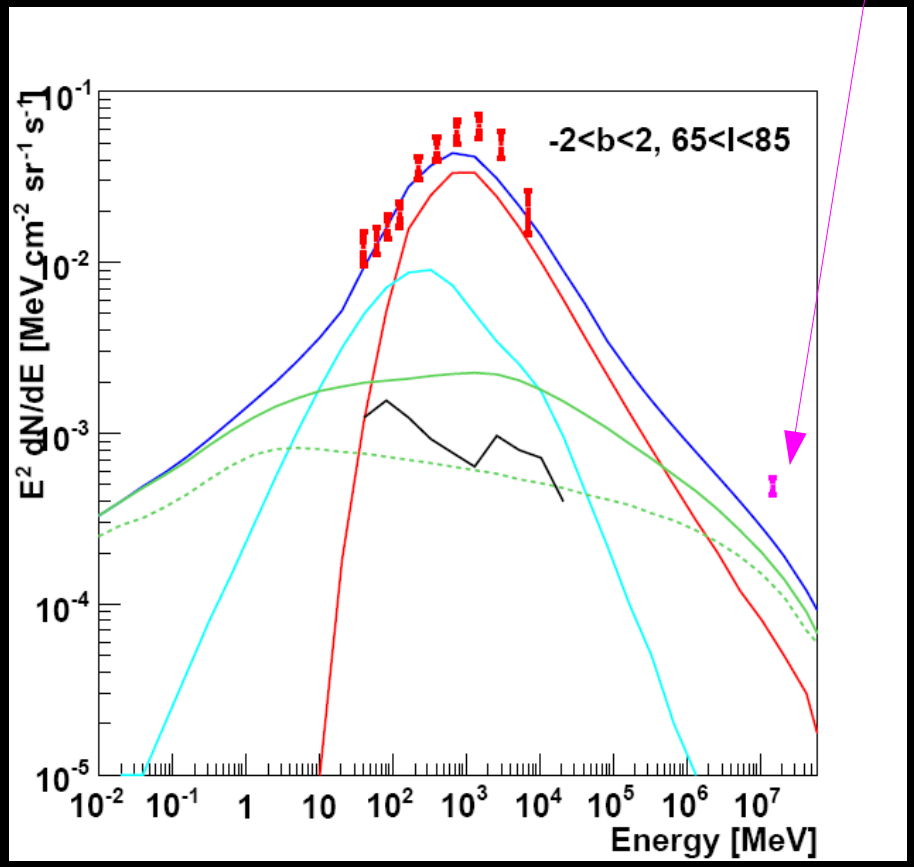


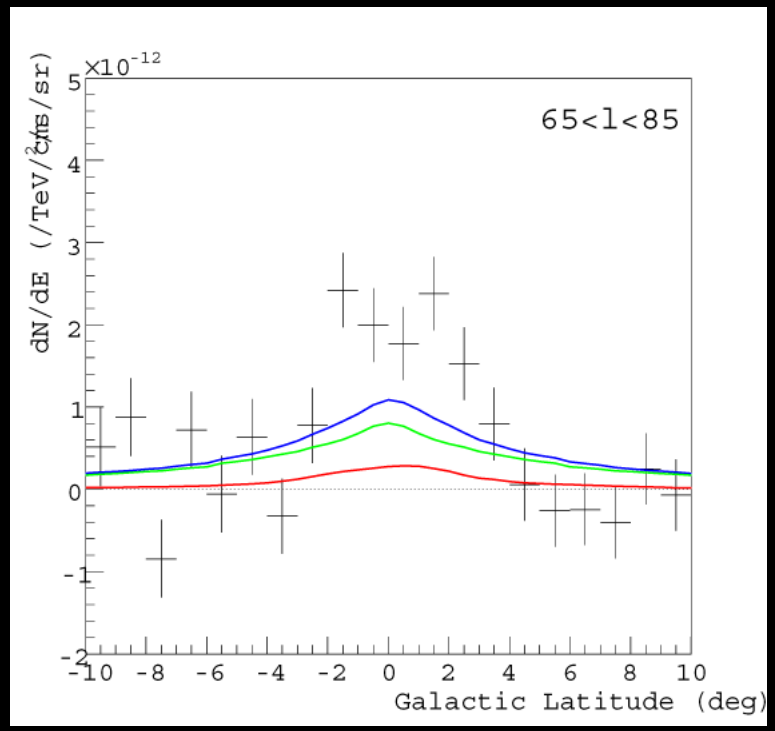
- **ApJ 688, 1078**
  Milagro, Abdo et al. 2008

Cygnus Region

Excess over prediction

more CR in Cygnus ?



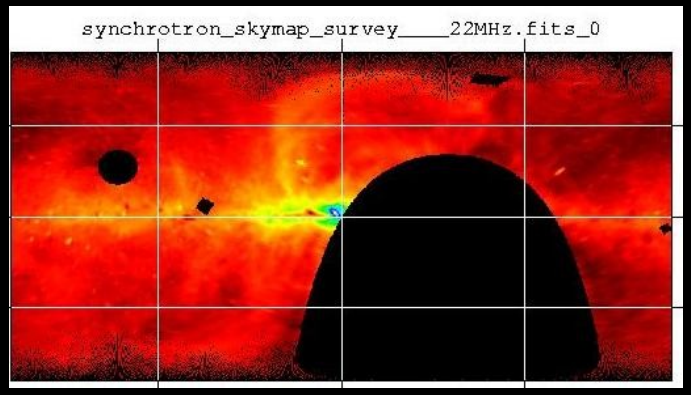


Milagro, Abdo et al. 2008

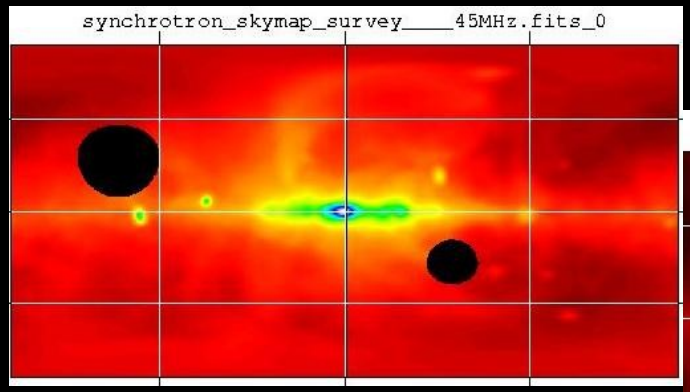
- **ApJ 688, 1078**

The final link...

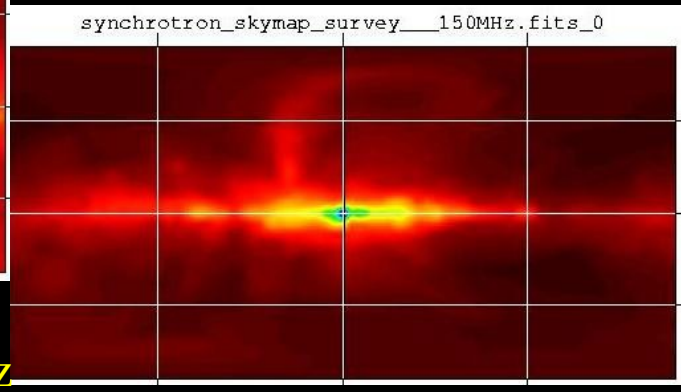
radio .....



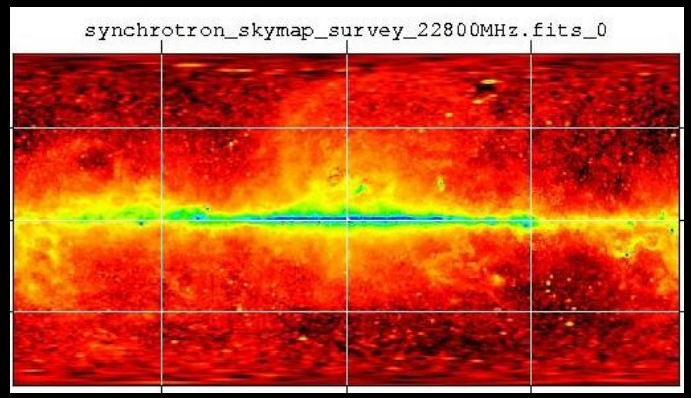
22 MHz



45 MHz



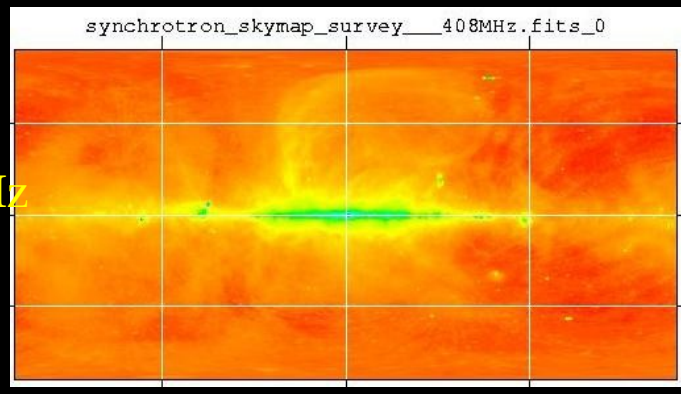
150 MHz

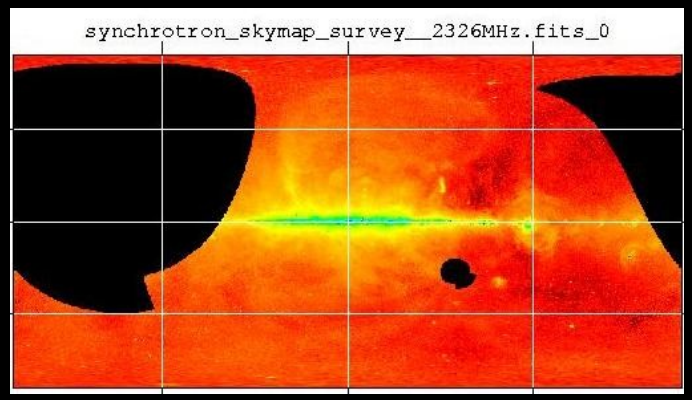


23 GHz

Continuum sky surveys

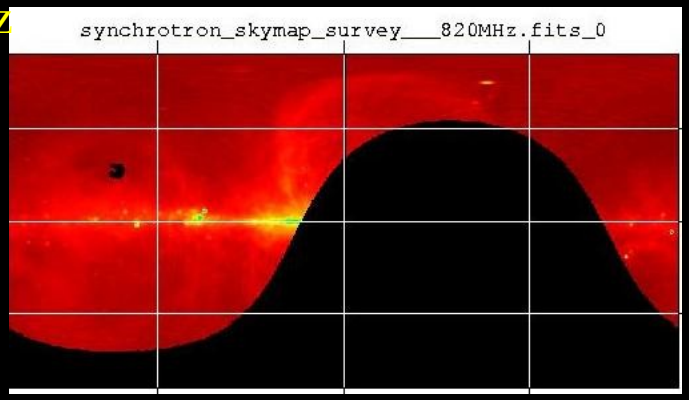
408 MHz



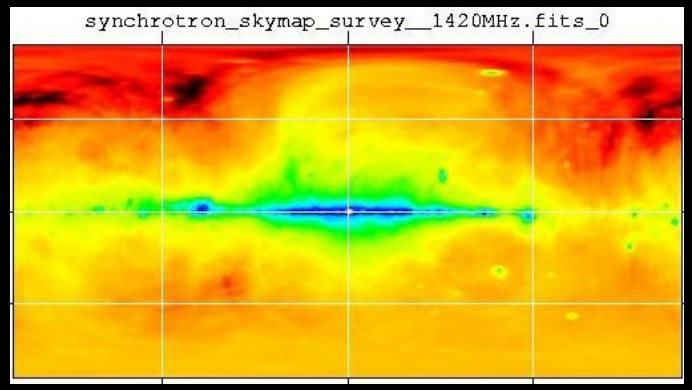


2.3 GHz

820 MHz

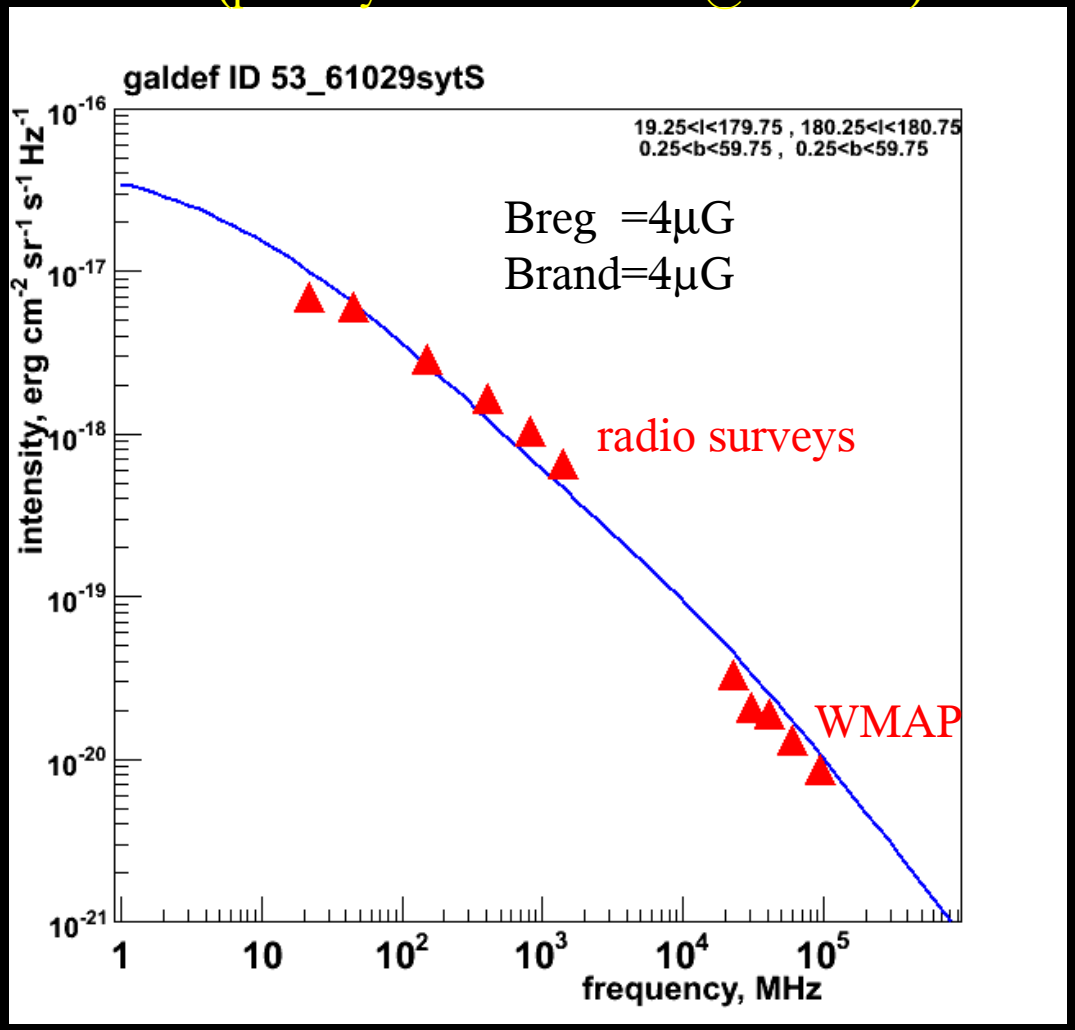


1.4 GHz



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

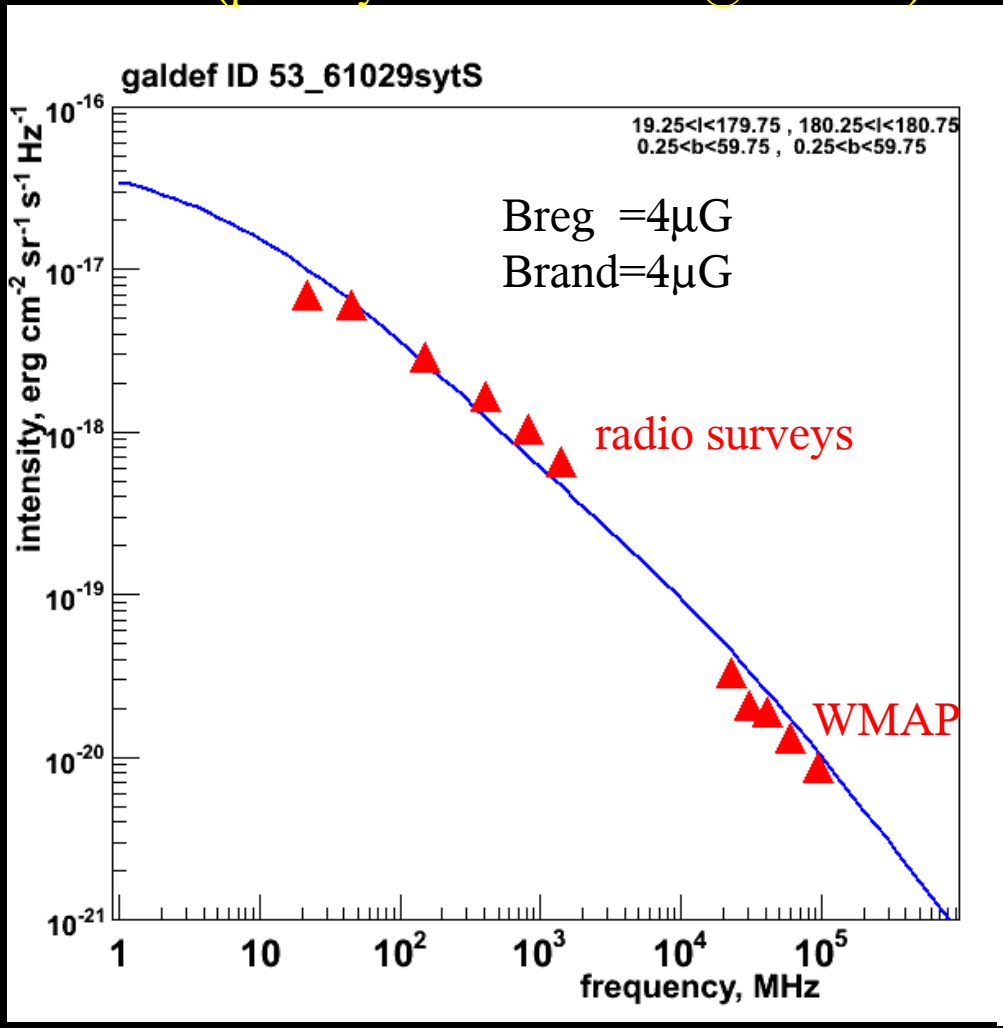
optimized model
(primary electrons break @ 20 GeV)

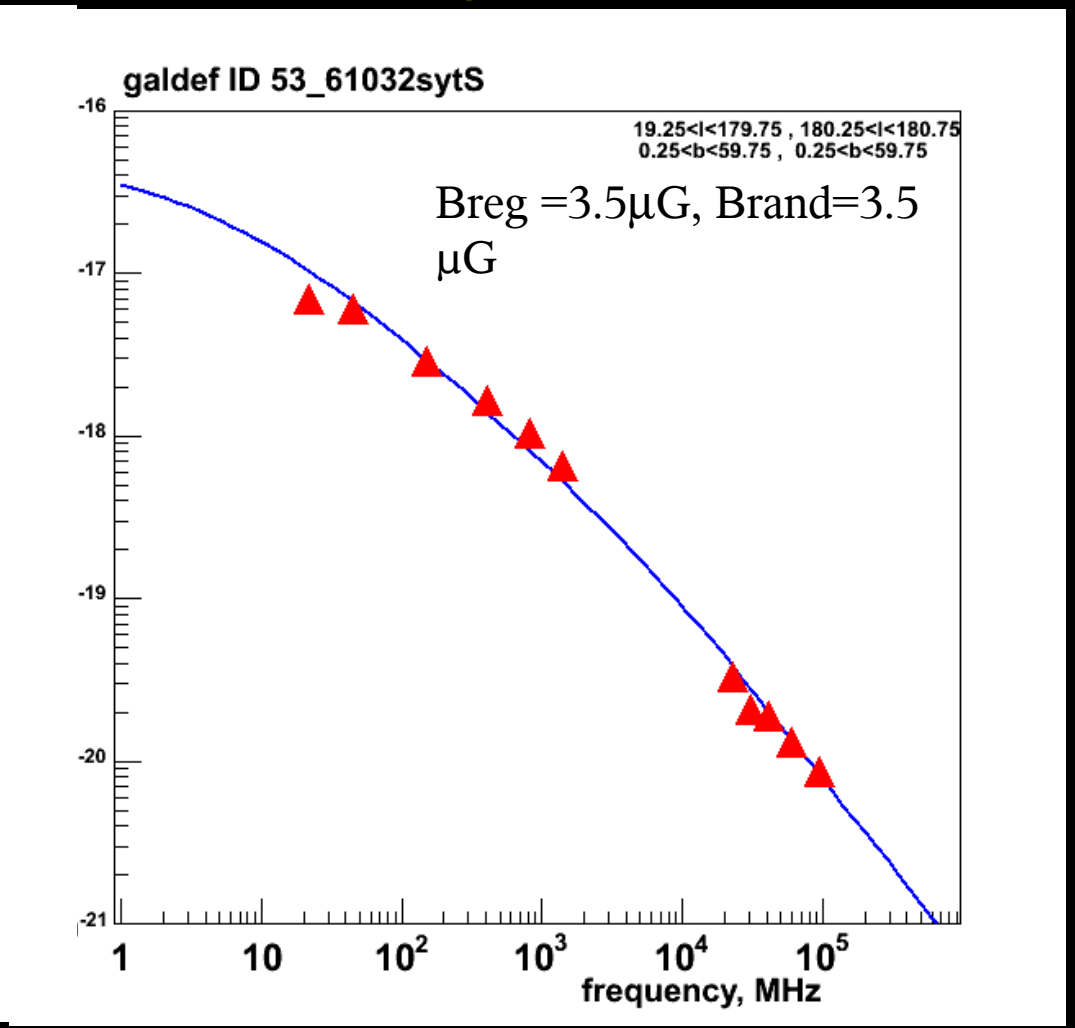


B-field: spiral + random, :with cosmic-ray electrons + positrons

optimized model
(primary electrons break @ 20 GeV)

optimized-modified
break @ 10 GeV



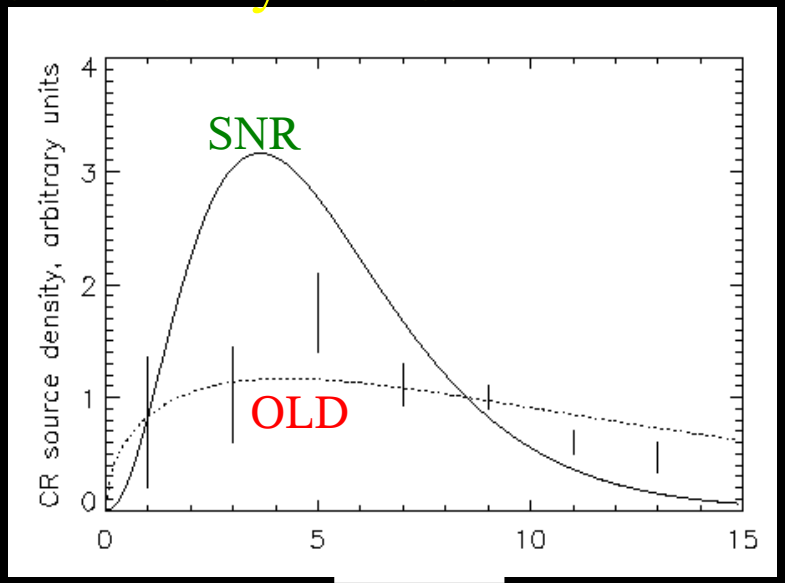


A slightly modified electron spectral break allows an essentially perfect fit to the radio data

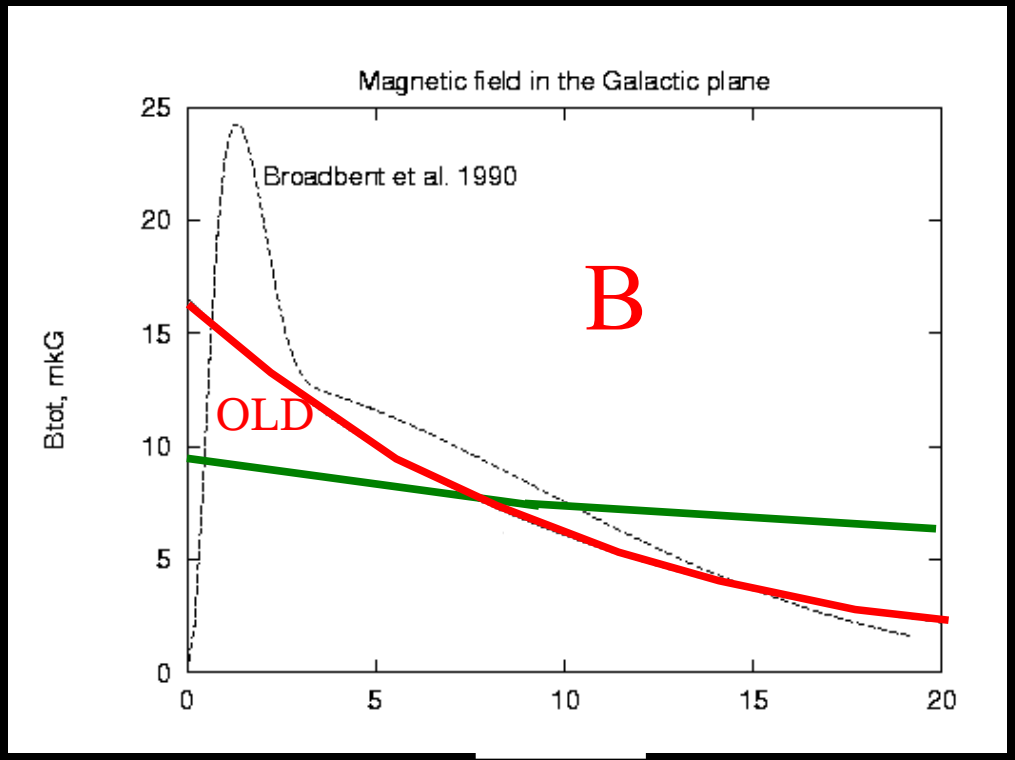
$$B(\mu G) = 8\, e^{-(R - Ro)/50\ kpc\ -\ |z|/3\ kpc}$$

essentially no R- dependence of B

cosmic-ray source distribution

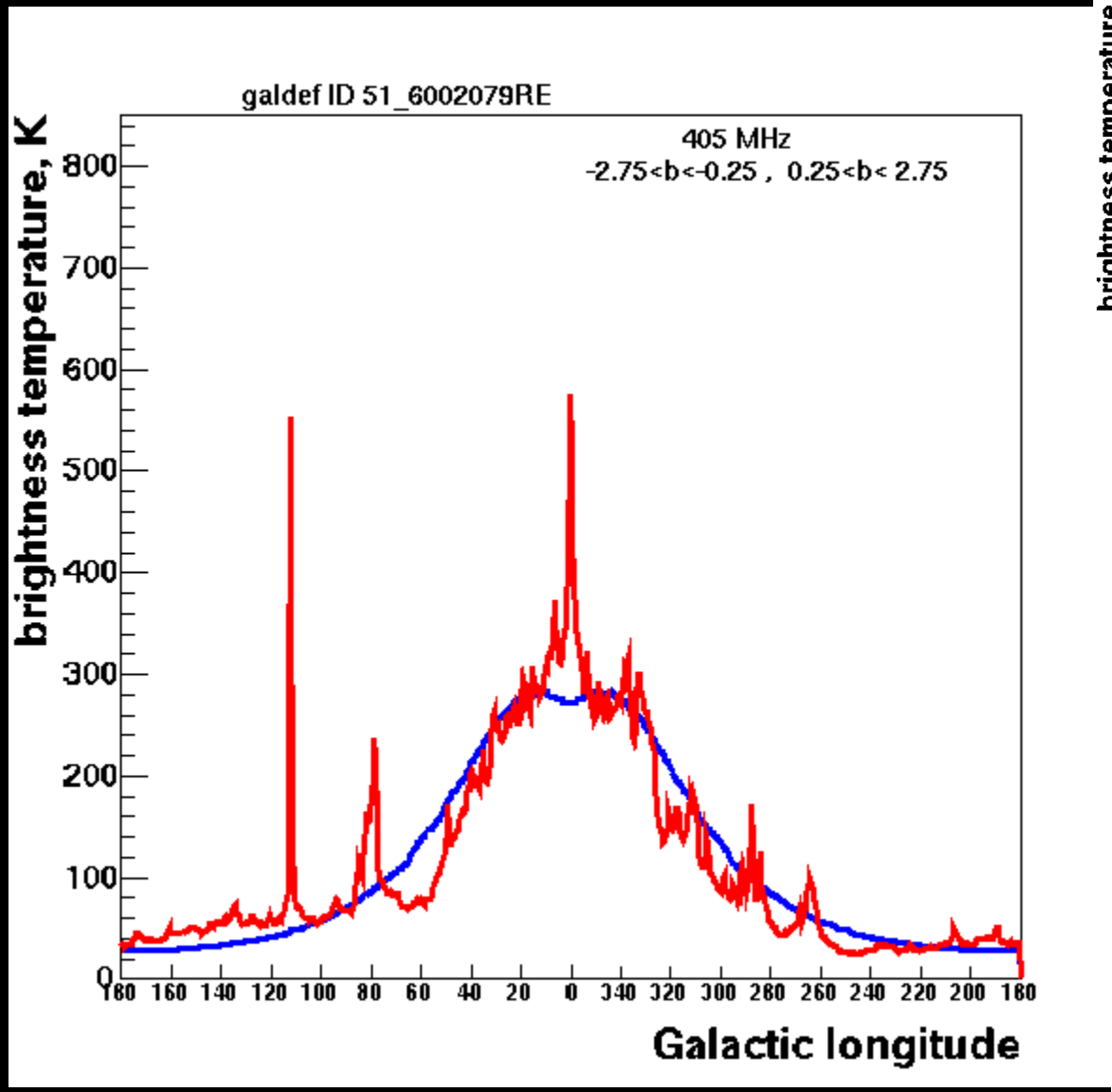


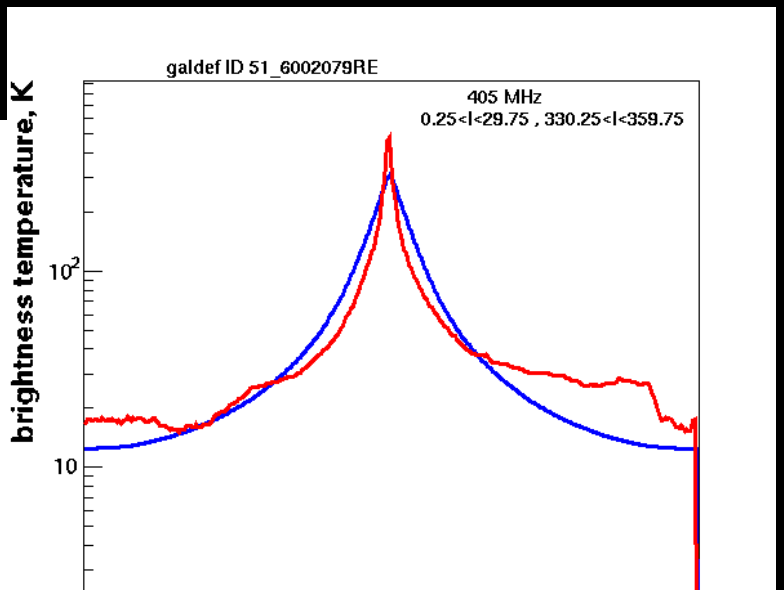
R, kpc

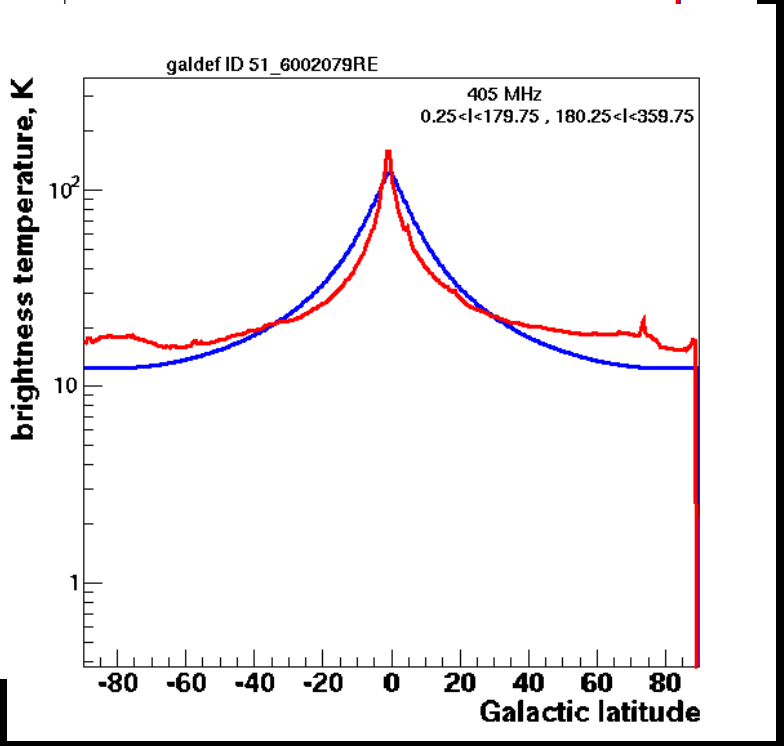


R, kpc

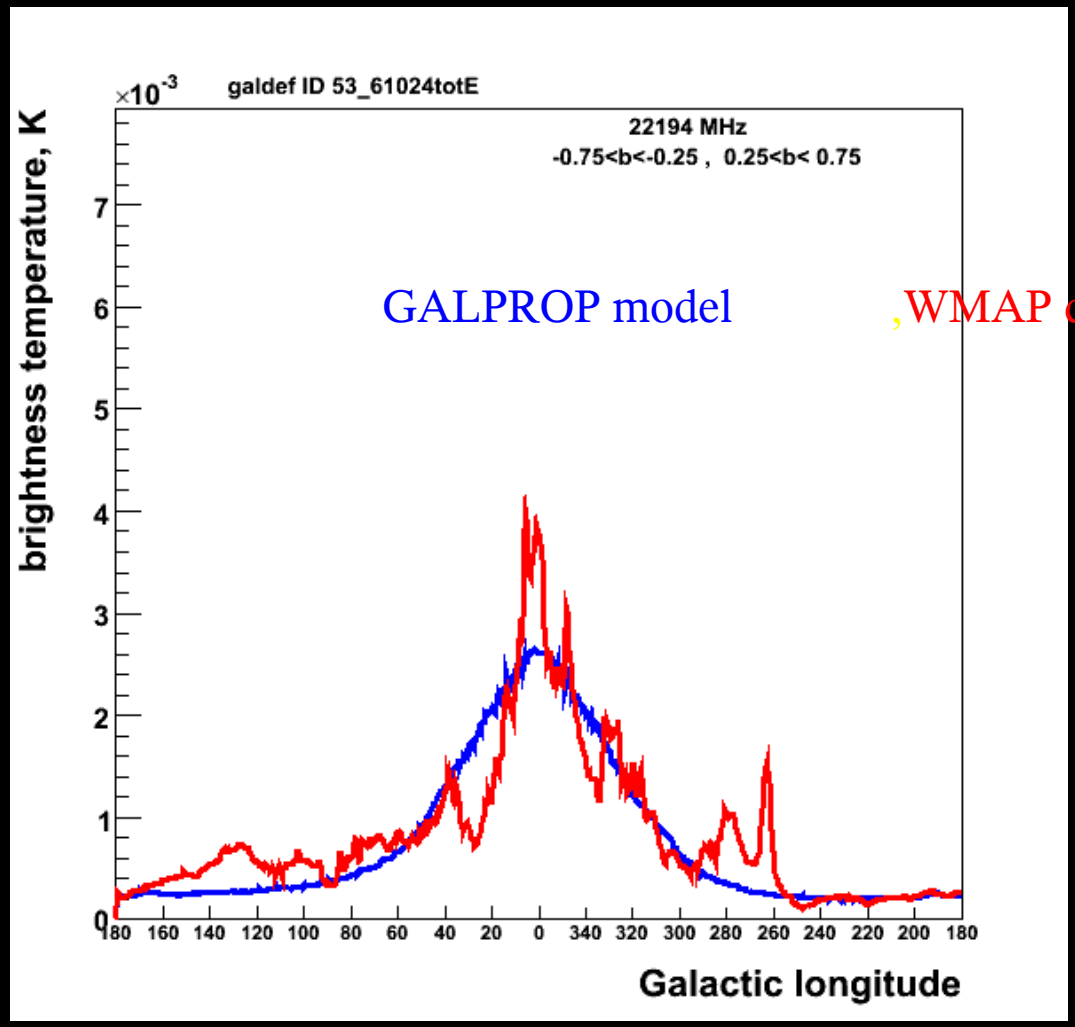
Best-fit **B** model using *galprop* analysis



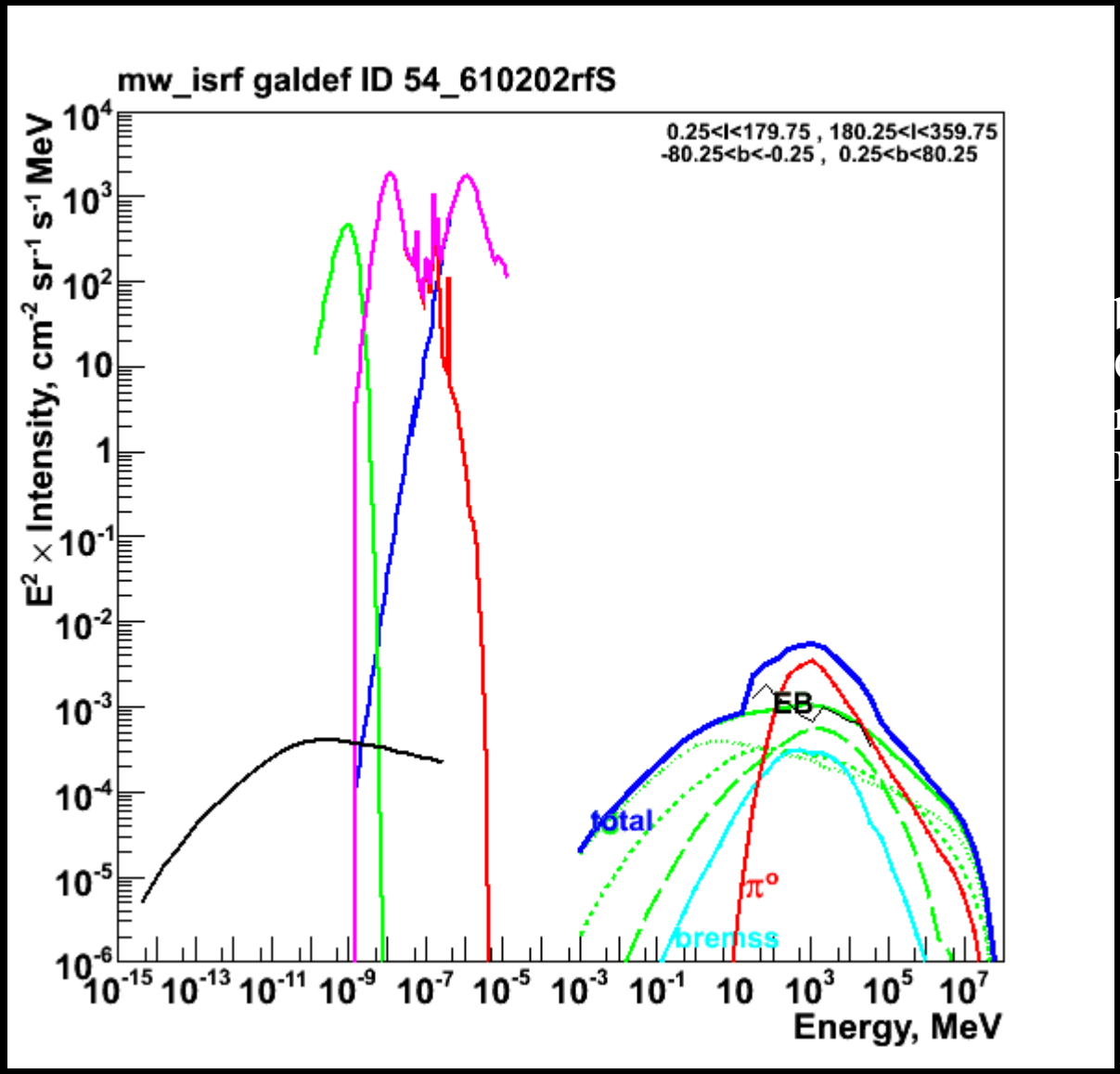




B-field: bisymmetric spiral + random component
23 GHz WMAP



Interstellar radiation over 20 decades of energy

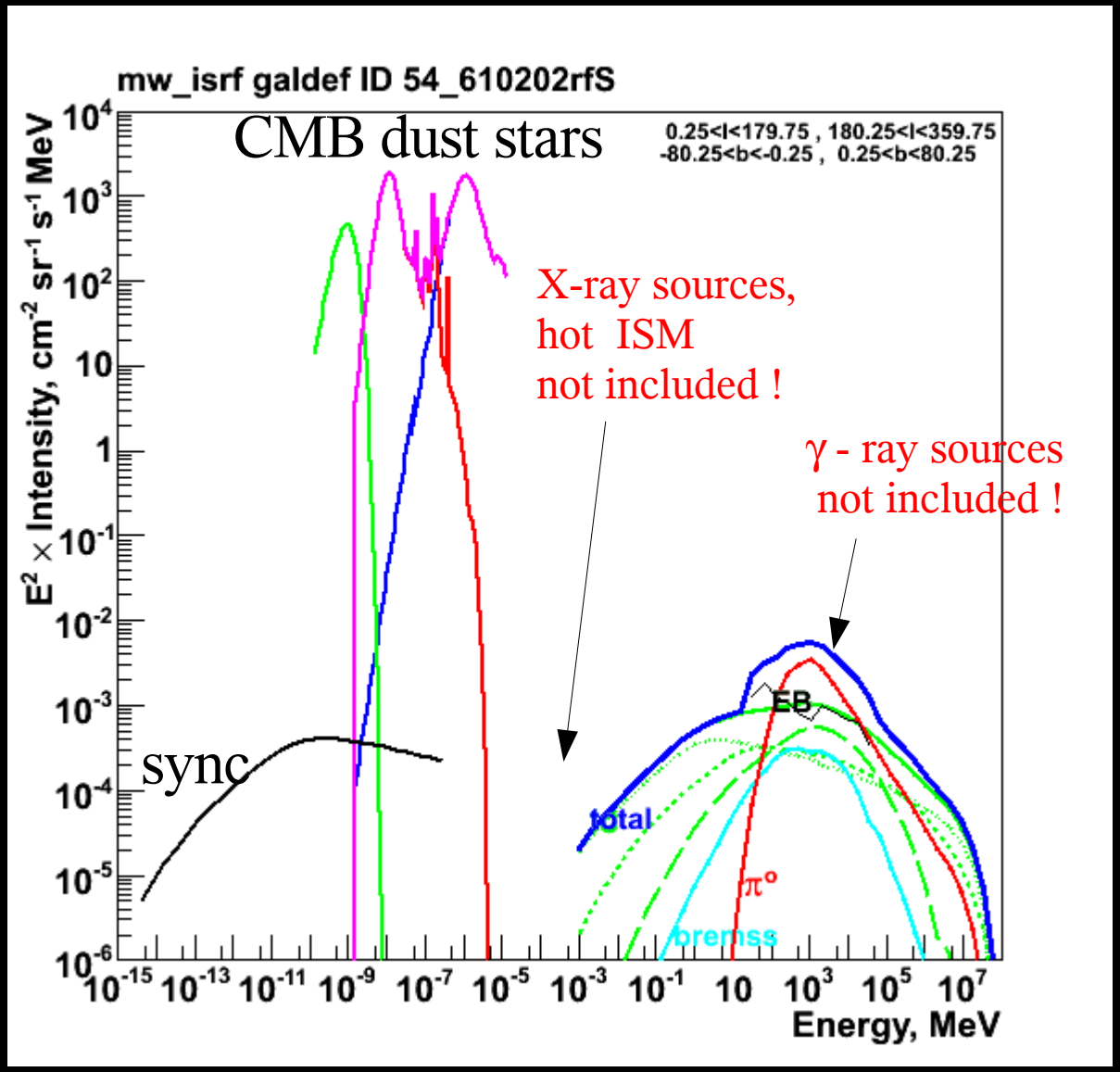


based on GALPROP model fitted to MW data

radio IR optical X γ

μwave

Interstellar radiation over 20 decades of energy

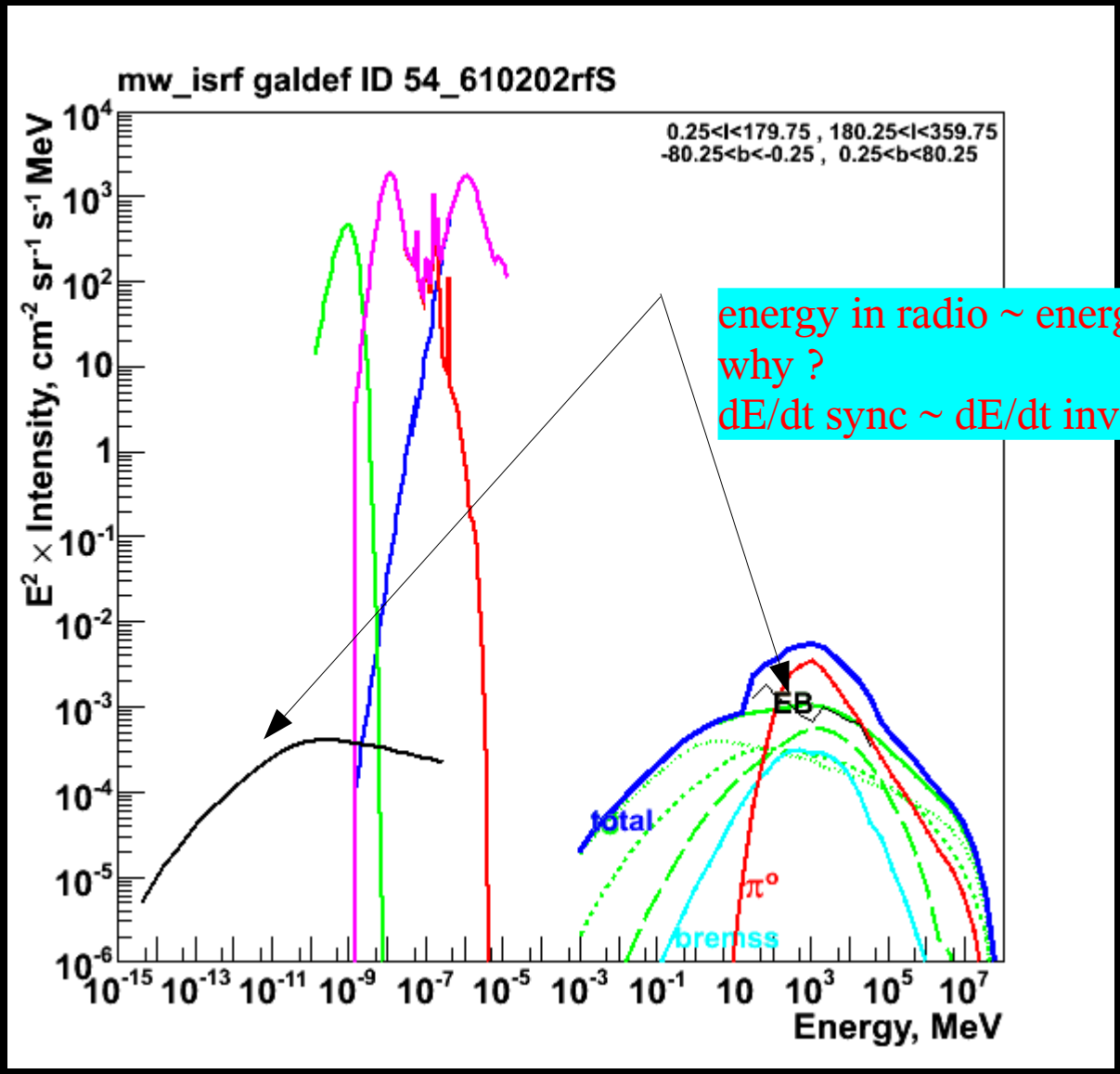


it's incomplete, obviously (in progress)

radio IR optical X γ

μwave

Interstellar radiation over 20 decades of energy



energy in radio ~ energy in gammas
why ?
dE/dt sync ~ dE/dt inverse Compton

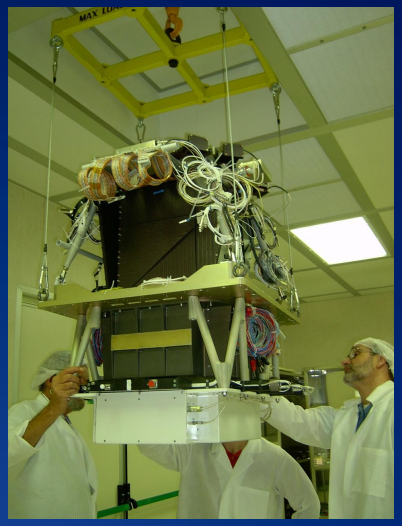
radio IR optical X γ
μwave

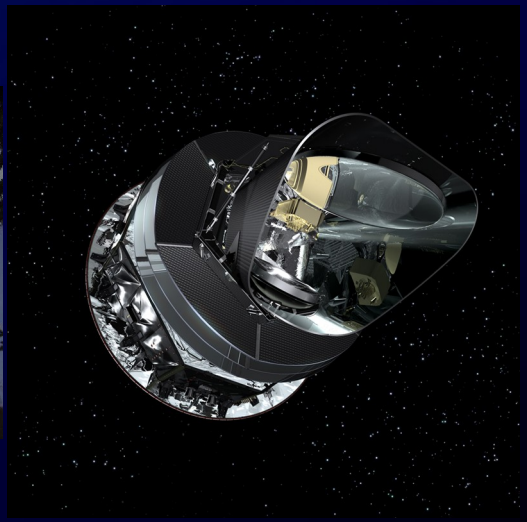
Outlook

Fermi operational , further results soon

continue to exploit synergy

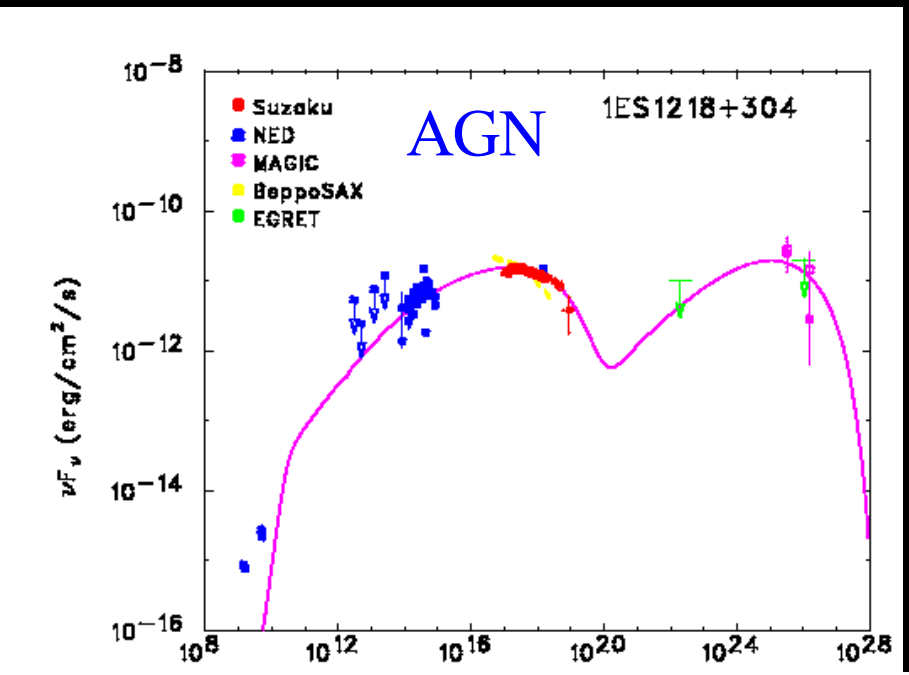
cosmic-rays - gammas – radio - microwave

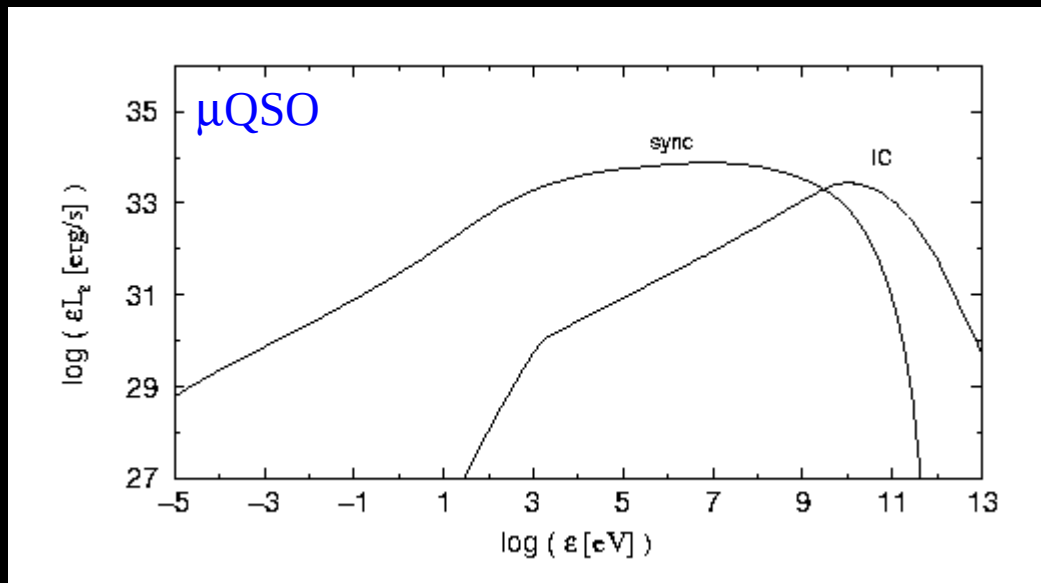




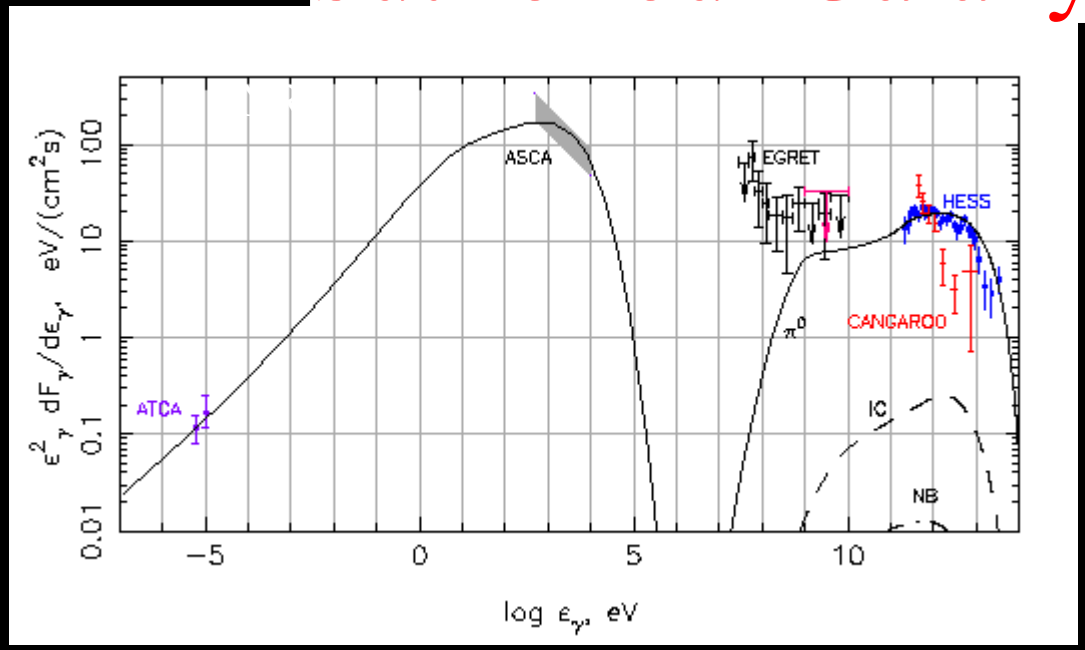
END

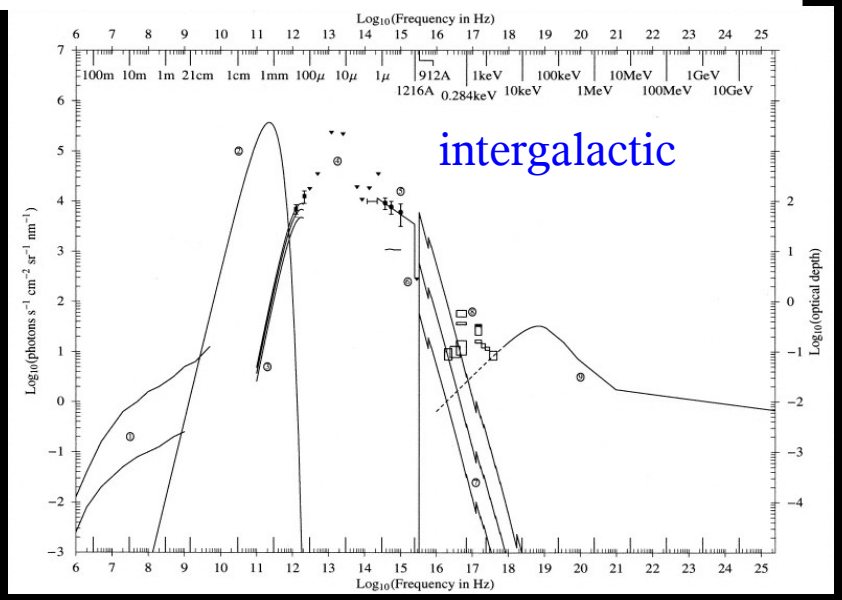
plenty of SED's

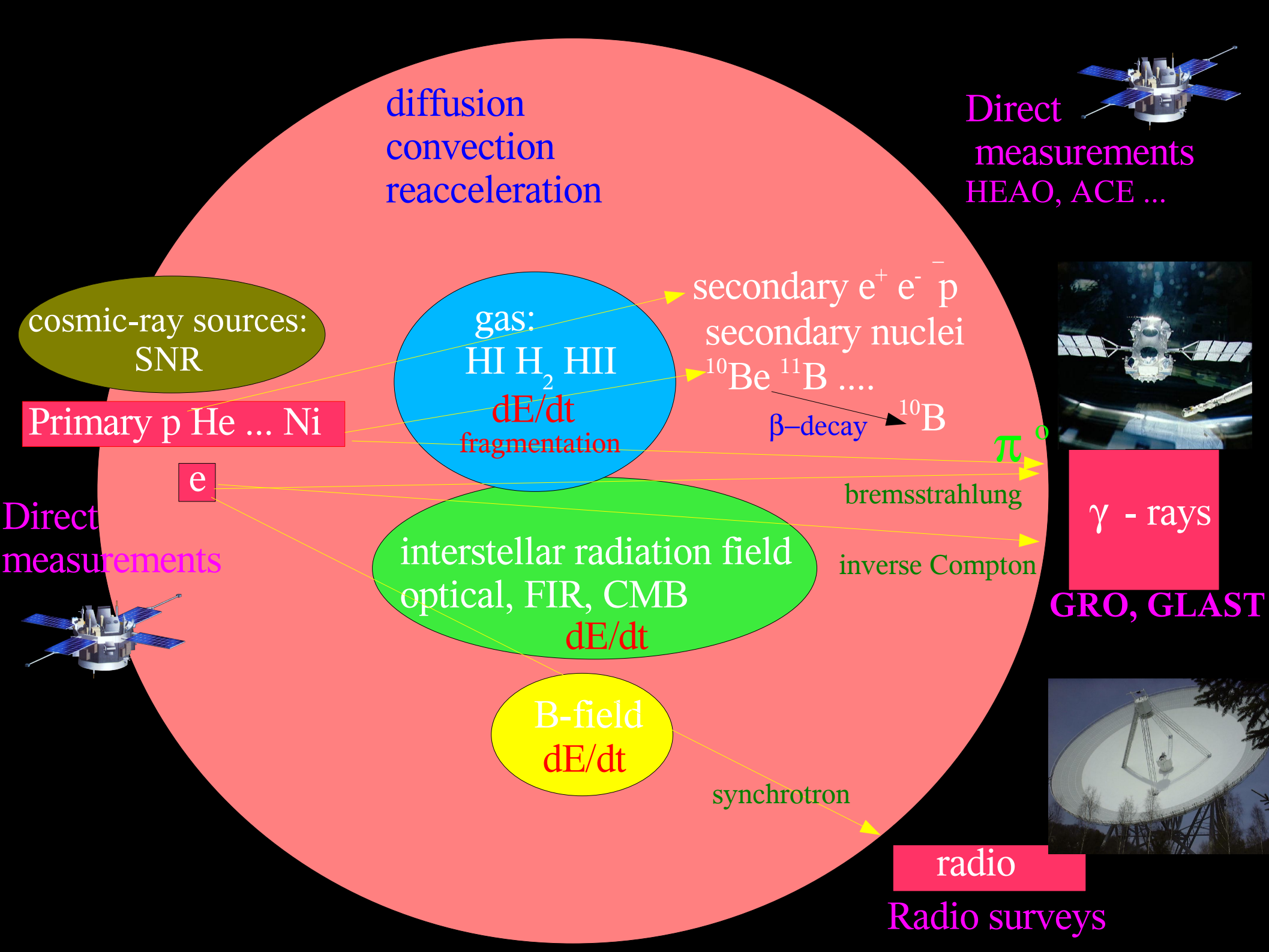




but for our Galaxy, harder to find....






diffusion
convection
reacceleration
Direct measurements
HEAO, ACE ...
cosmic-ray sources: SNR
gas:
HI H2 HII
dE/dt
fragmentation
secondary e+ e- p̄
secondary nuclei
10Be 11B ....
β–decay
10B
Primary p He ... Ni
π0
e
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