# The cosmic-ray, gamma-ray, radio connection in the Galaxy

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Workshop on Galactic Centre,
Heidelberg
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This conference is about the GC

But  large-scale Galactic context is relevant to the interpretation

e.g.

Electron spectrum, synchrotron, B-field, gamma rays.

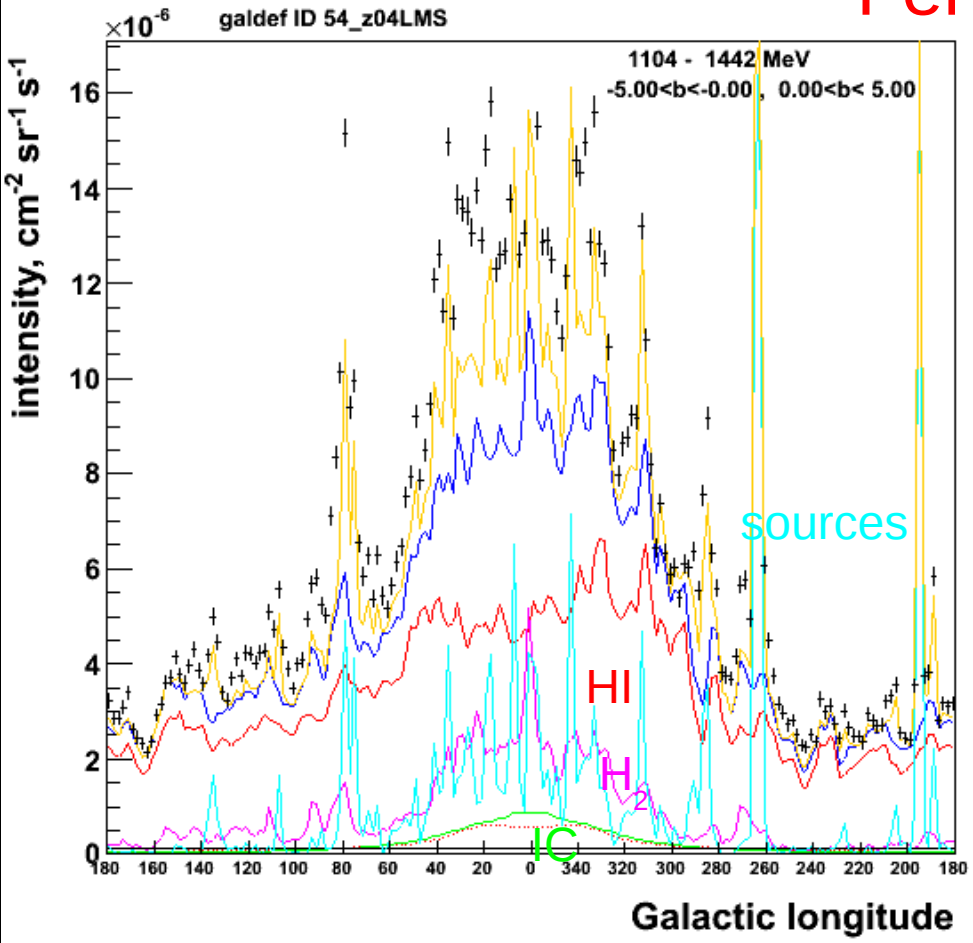
# Fermi-LAT
# Gamma rays >1 GeV
# 36 months

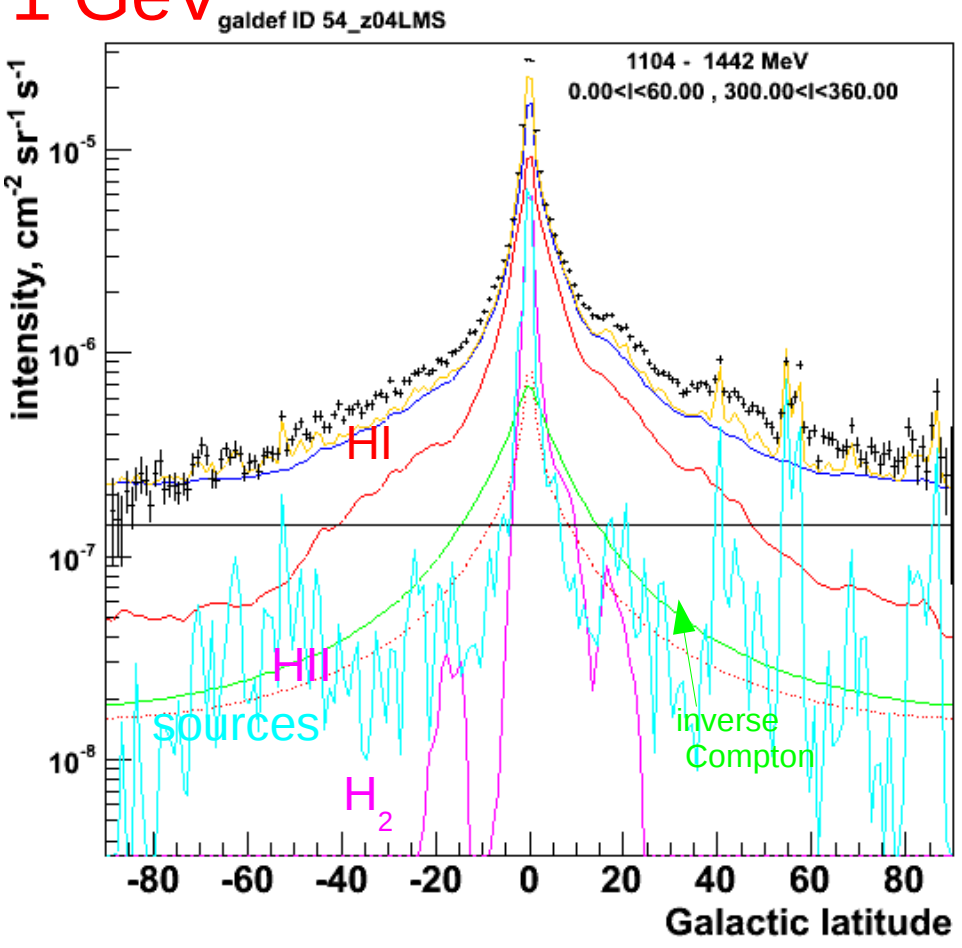
PRELIMINARY

LONGITUDE PROFILE LOW LATITUDES

LATITUDE PROFILE INNER GALAXY

# Fermi 1 GeV

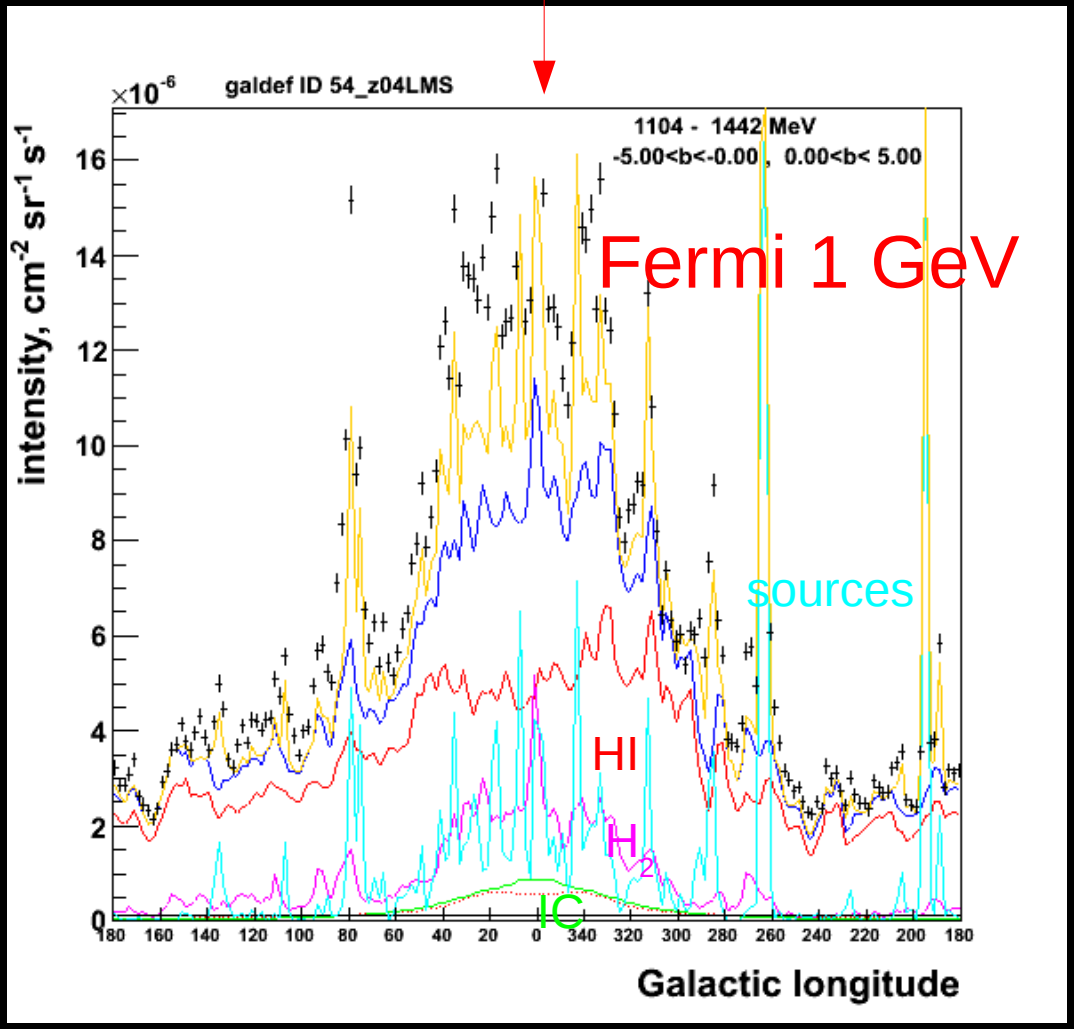


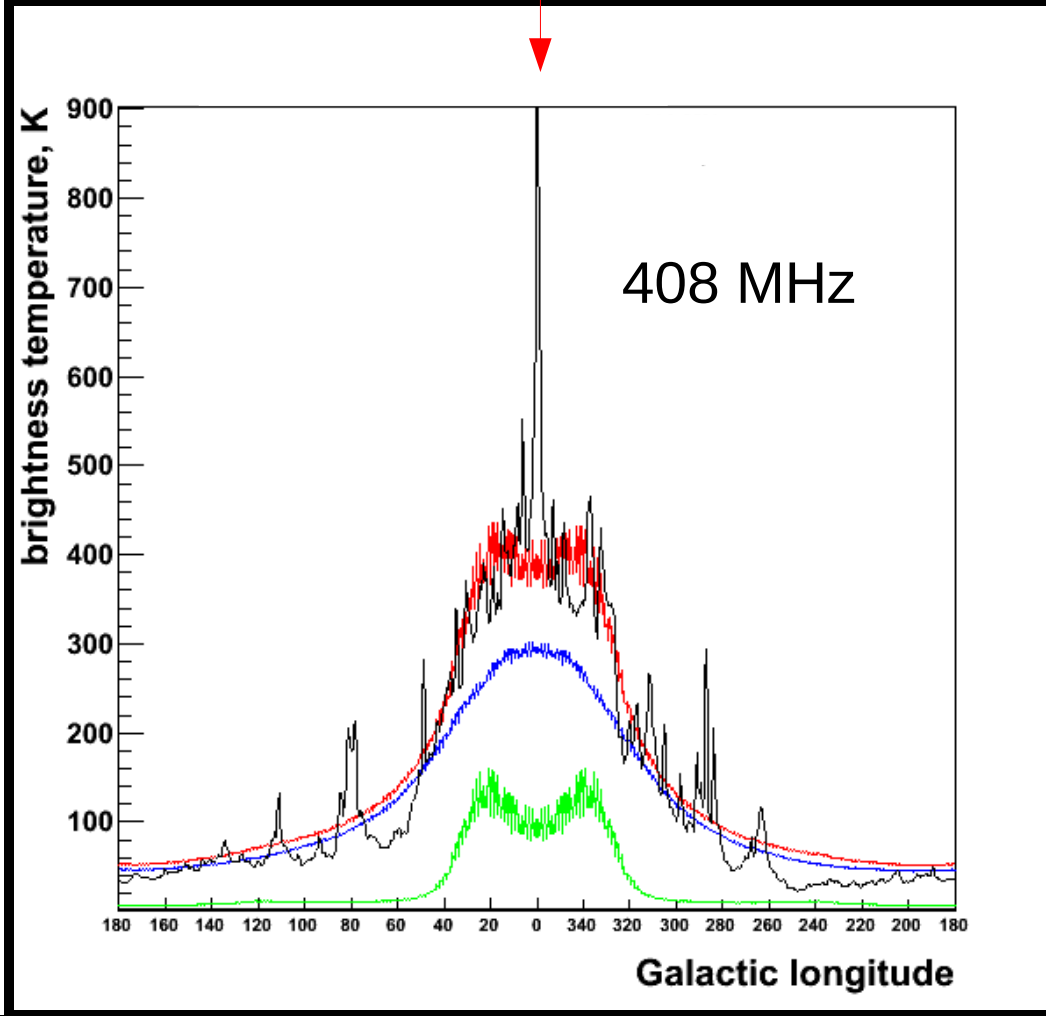



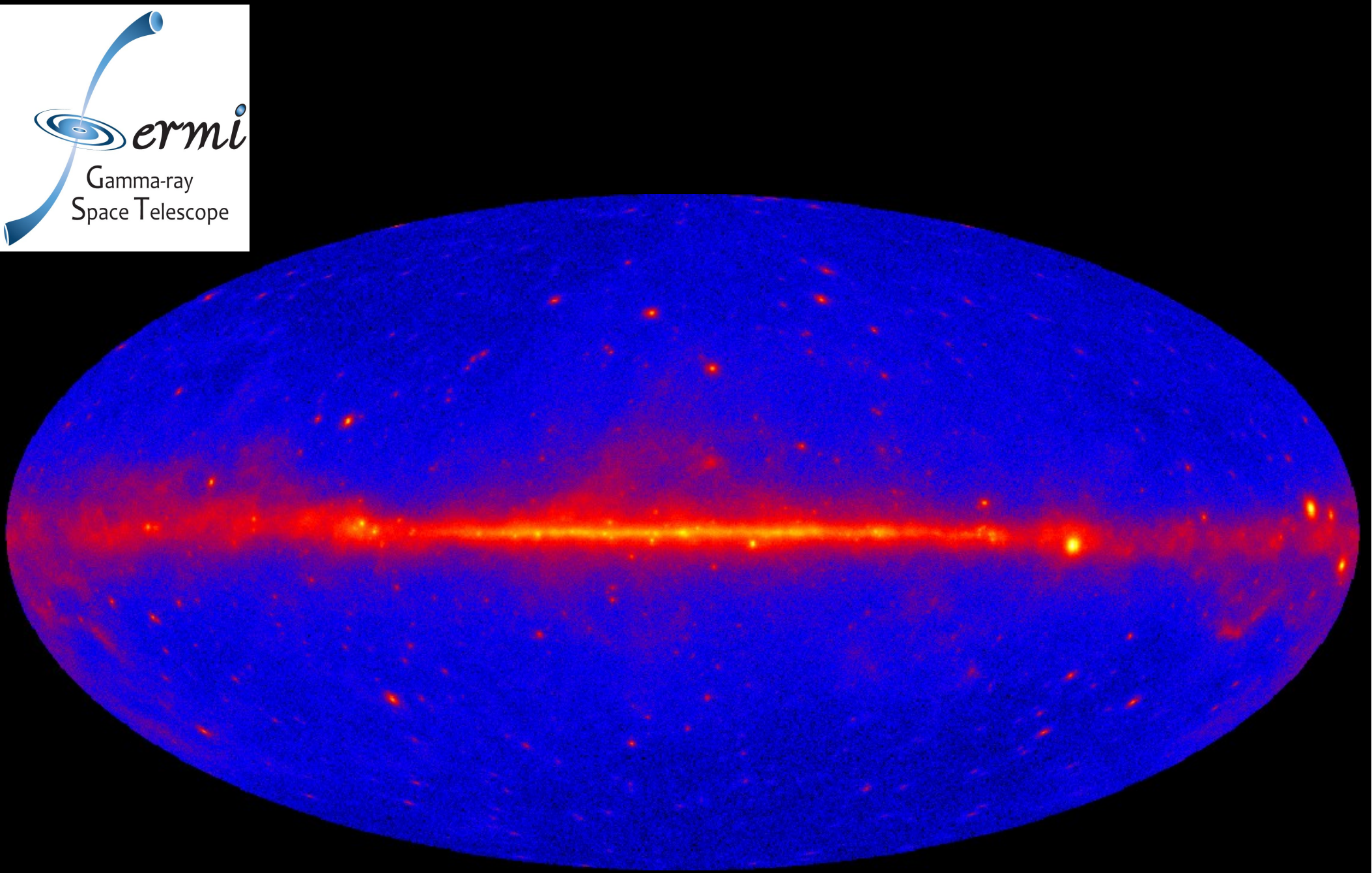

GALPROP Model agrees within 15% over 2 decades of dynamic range
The observed flux is the sum of many components:
importance of modelling them all !

*Strong 2011, Proc ICATPP Conf. Villa Olmo, arXiv:1101.1381*

GC is *not* a striking feature in gamma rays in large-scale map (unlike synchrotron) !

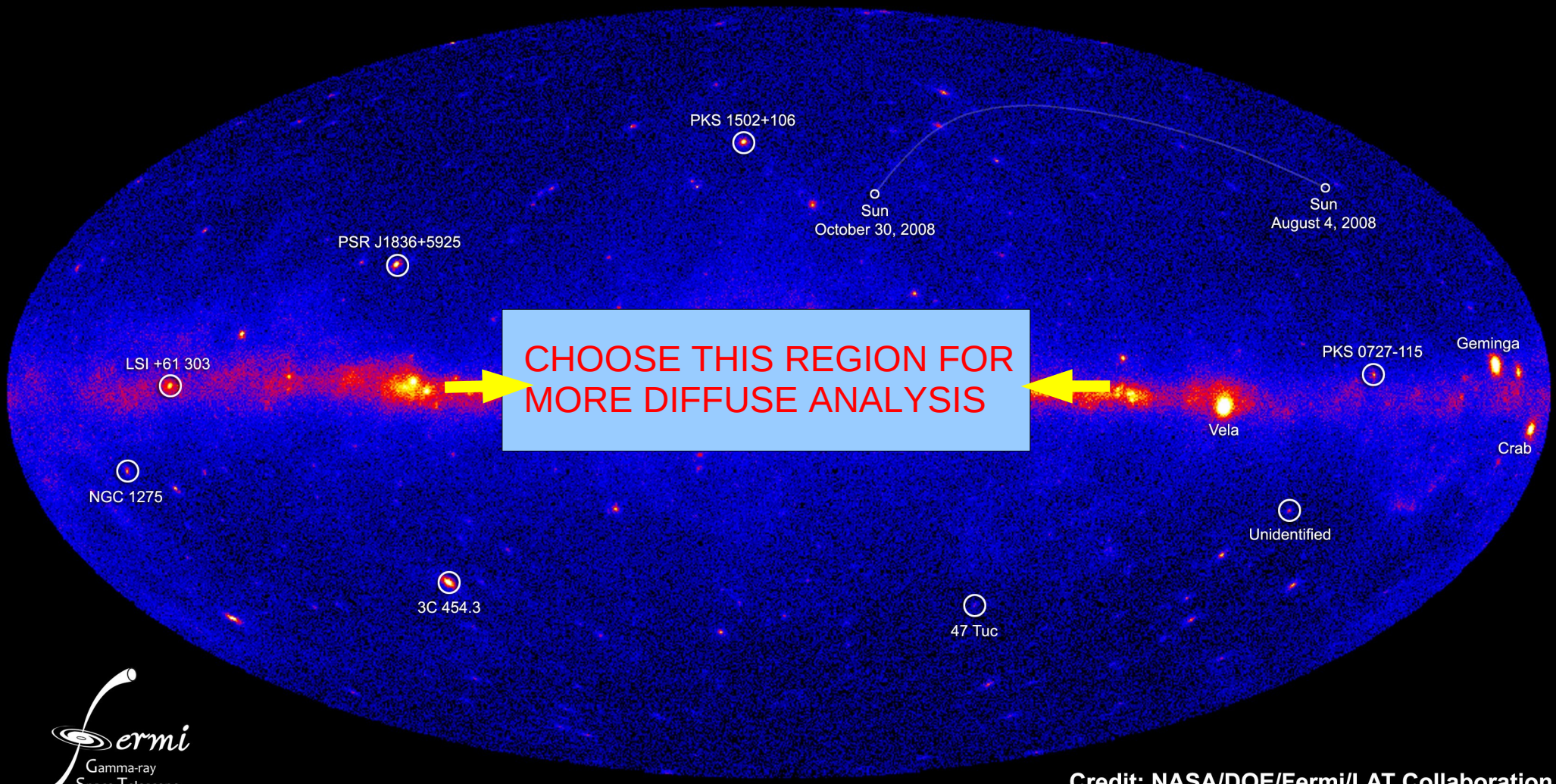



Fermi
Gamma-ray
Space Telescope

# MORE LIGHT ON DIFFUSE GAMMA RAYS

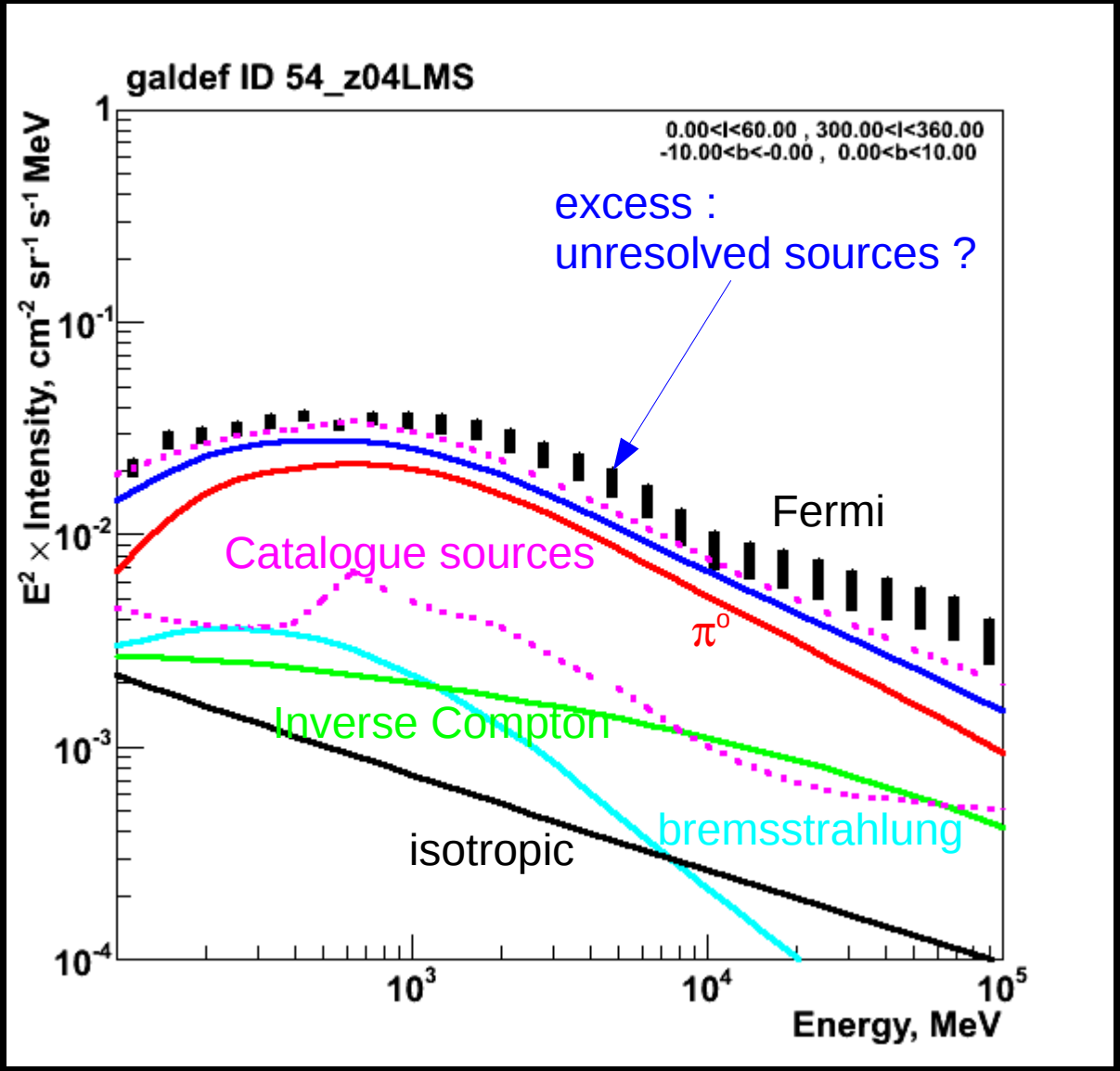
## NASA's Fermi telescope reveals best-ever view of the gamma-ray sky




Fermi Gamma-ray Space Telescope

**Credit: NASA/DOE/Fermi/LAT Collaboration**

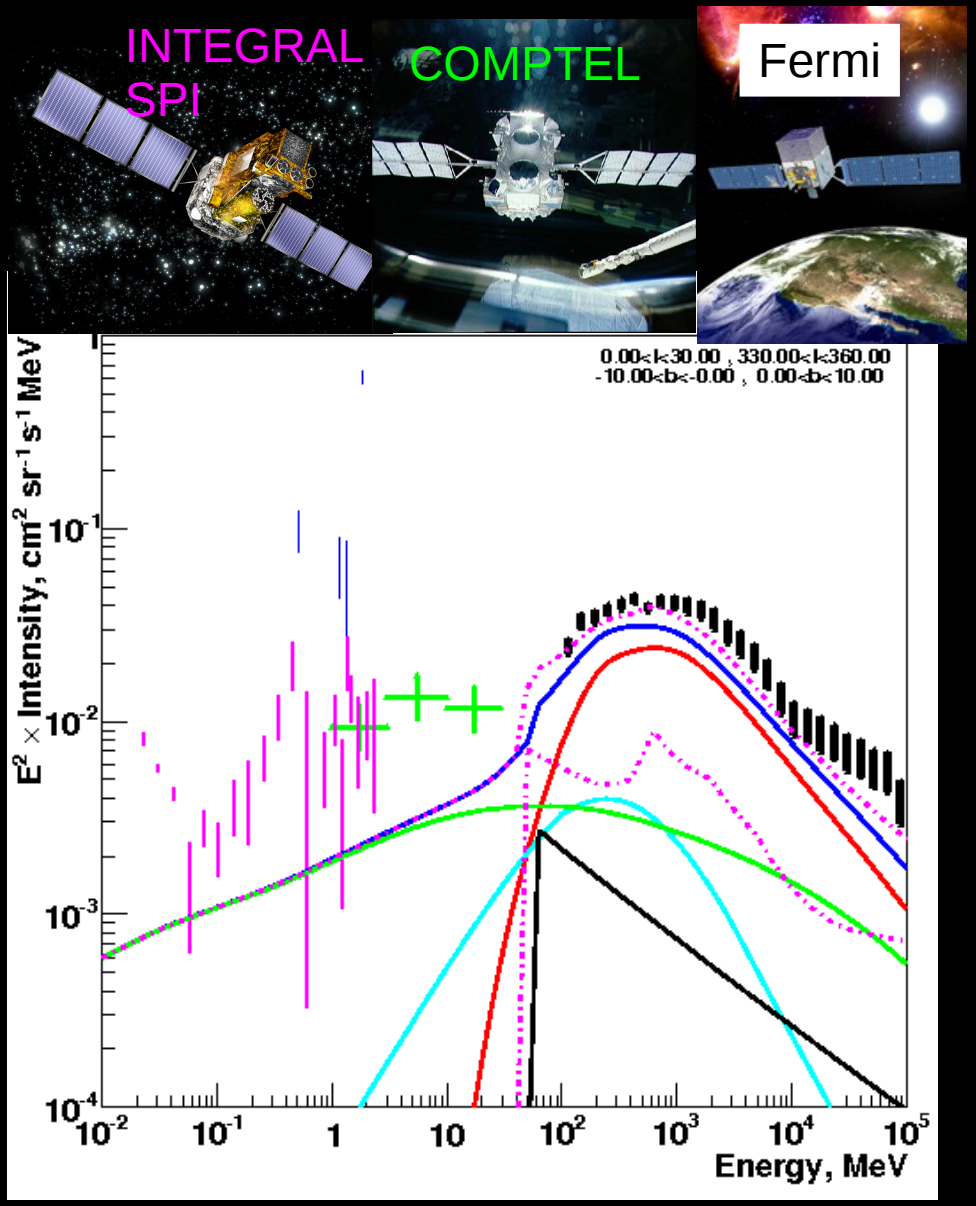
# Inner Galaxy
# $300^o < l < 60^o$, $|b|<10^o$



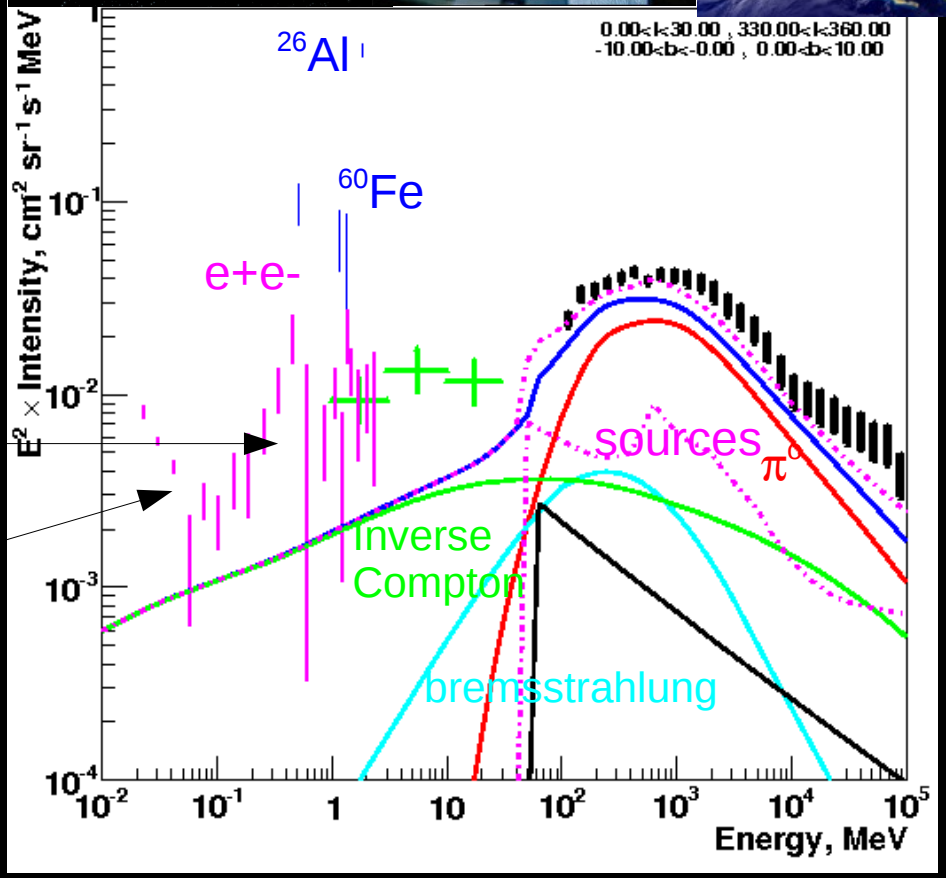

Good agreement overall with *a-priori* GALPROP model

*Strong 2011, Proc ICATPP Conf. Villa Olmo, arXiv:1101.1381*

# Inner Galaxy: keV to TeV



# Inner Galaxy: keV to TeV




positronium

sources

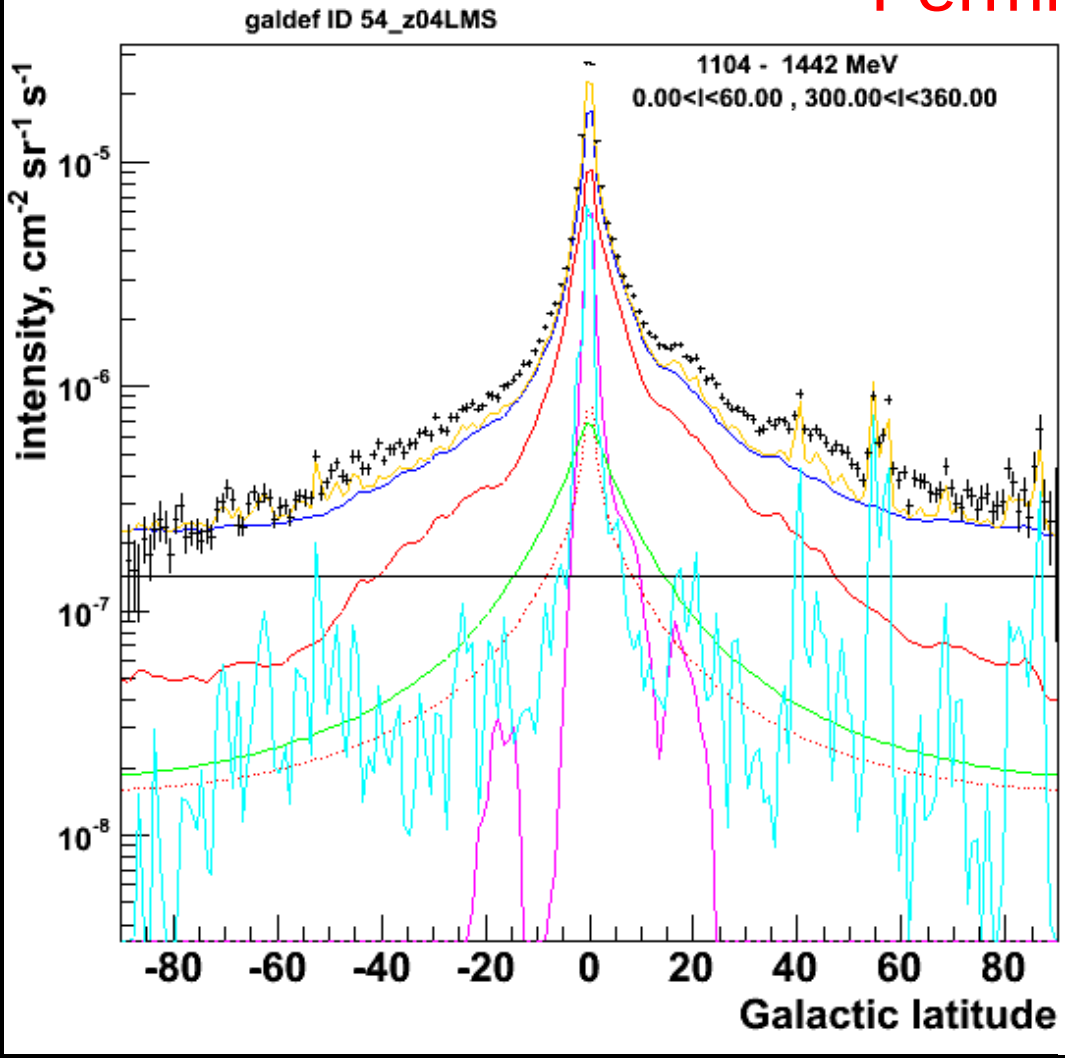
GeV electrons – inverse Compton - important for MeV gamma rays !
For latest on this see Bouchet et al. 2011 ApJ 739, 29

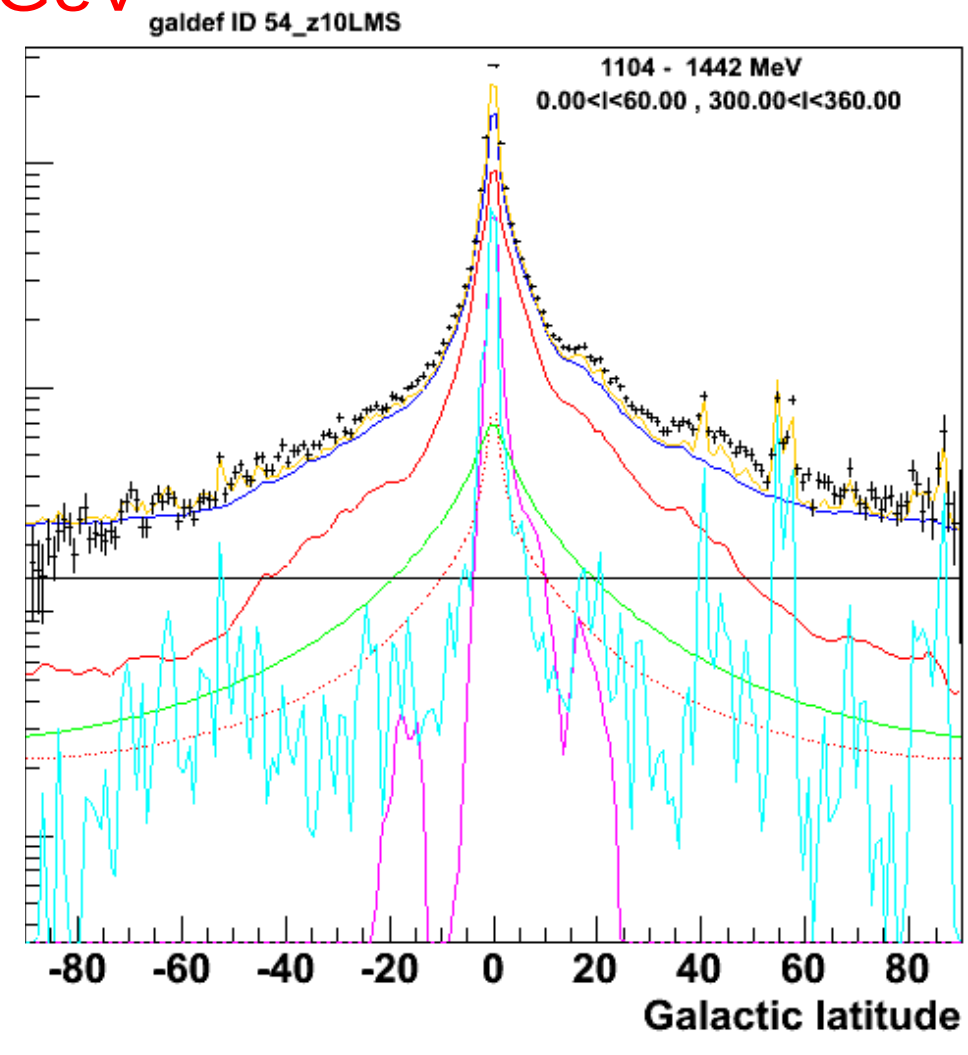
# EVIDENCE FOR LARGE COSMIC-RAY HALO

4 kpc halo height

10 kpc halo height

## Fermi 1 GeV



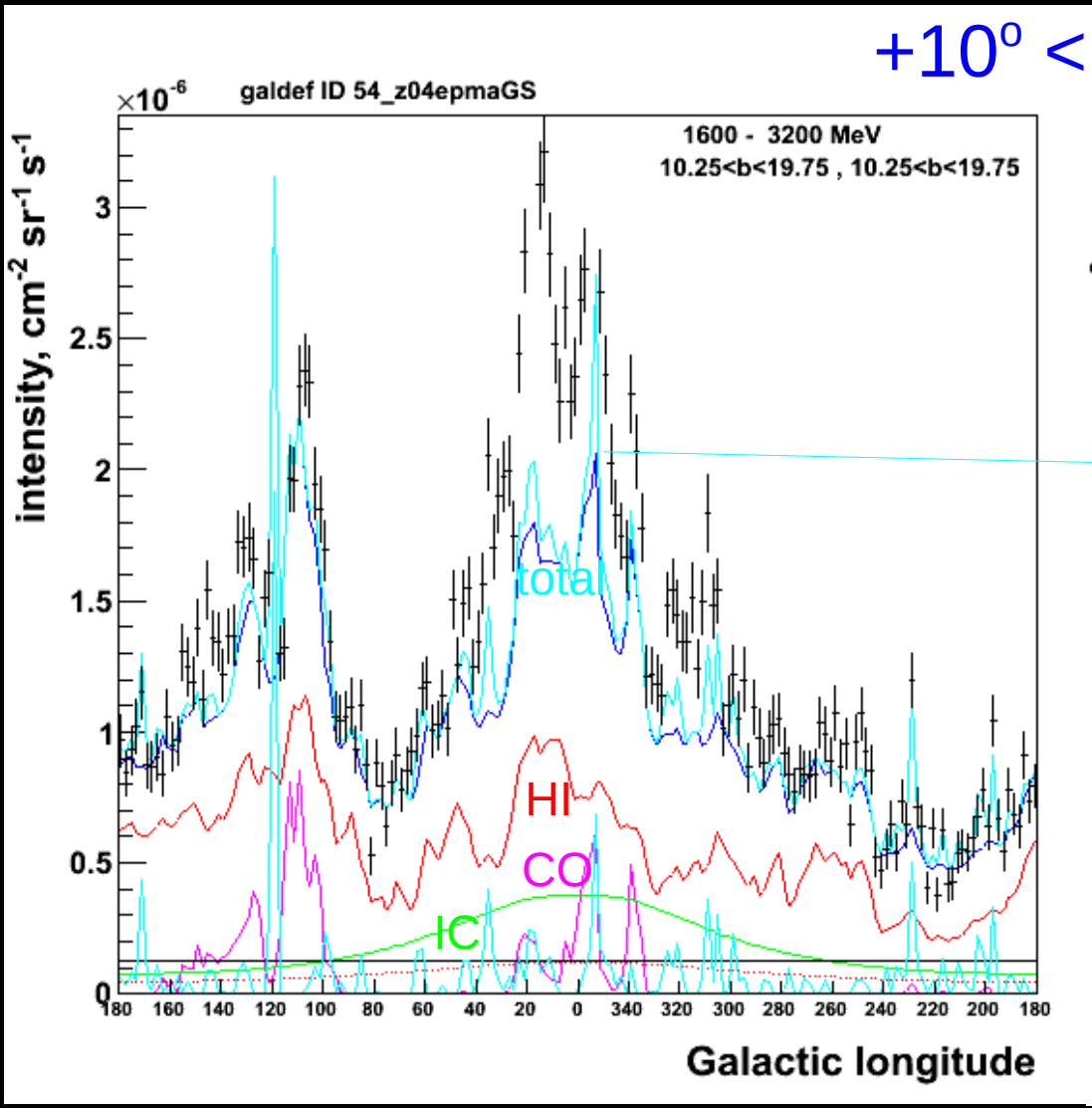



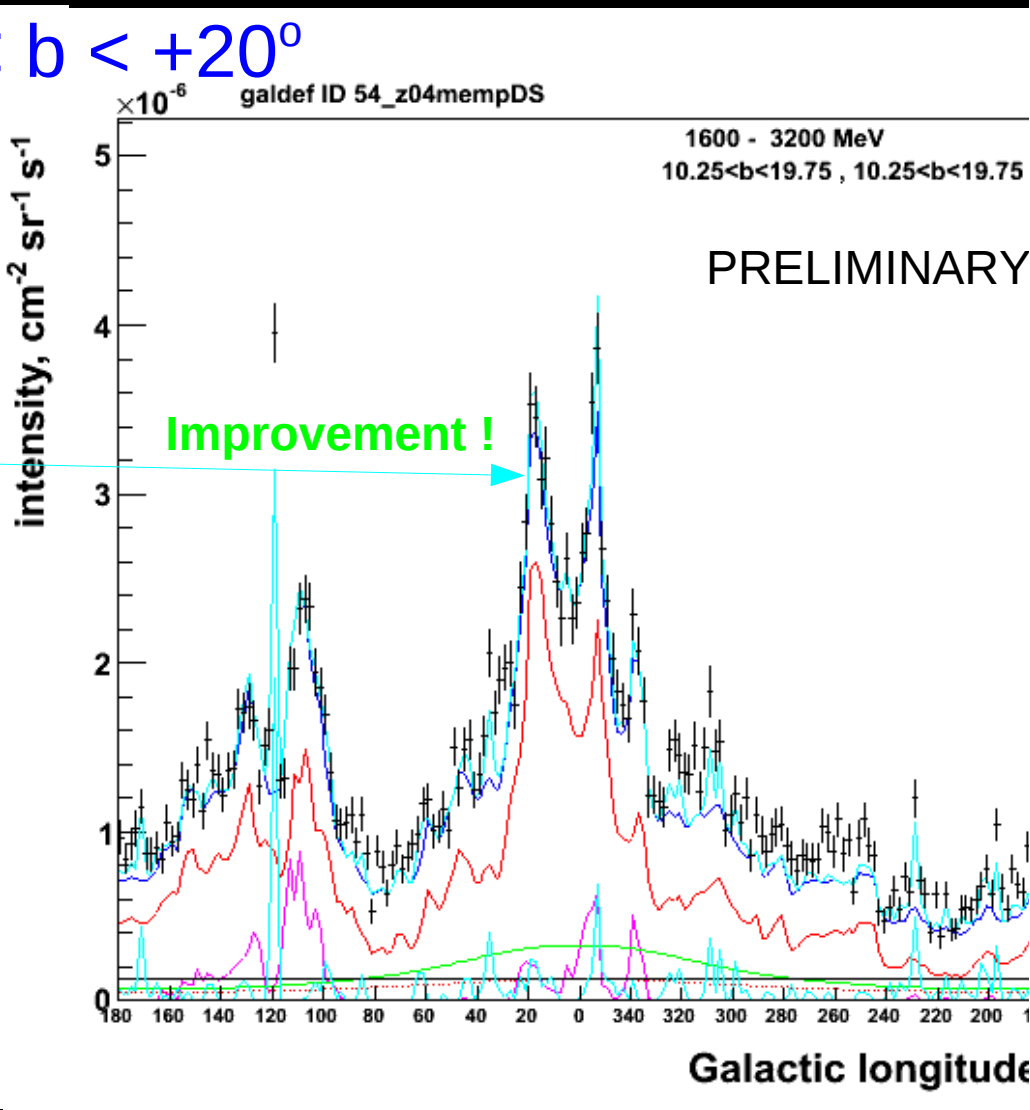

inverse Compton at high latitudes suggests a *large cosmic-ray halo*
*Important for halo magnetic field ! Relevant to Planck !*

*Strong 2011, Proc ICATPP Conf. Villa Olmo, arXiv:1101.1381*

# HI + CO  GAS TRACER  dust

$+10^{o} < b < +20^{o}$



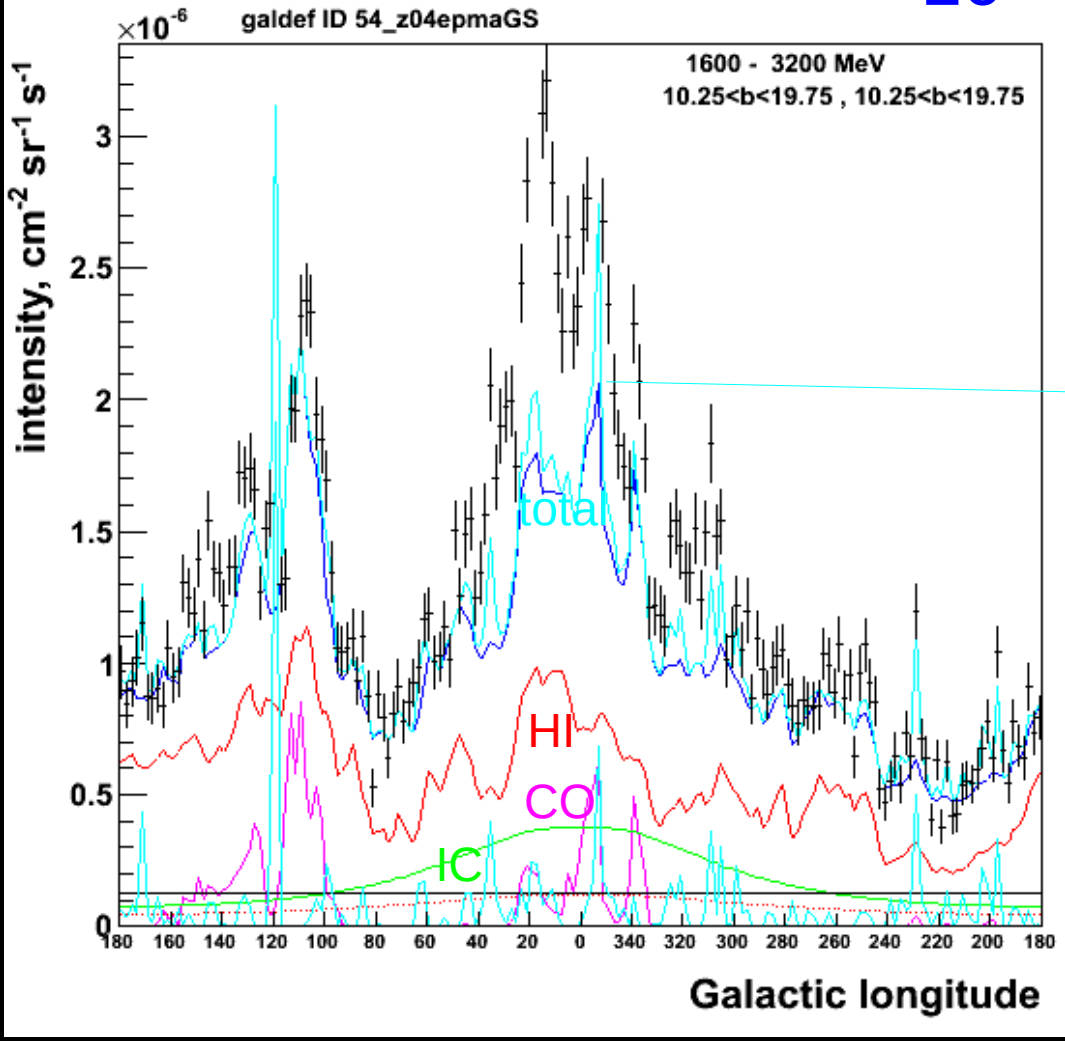



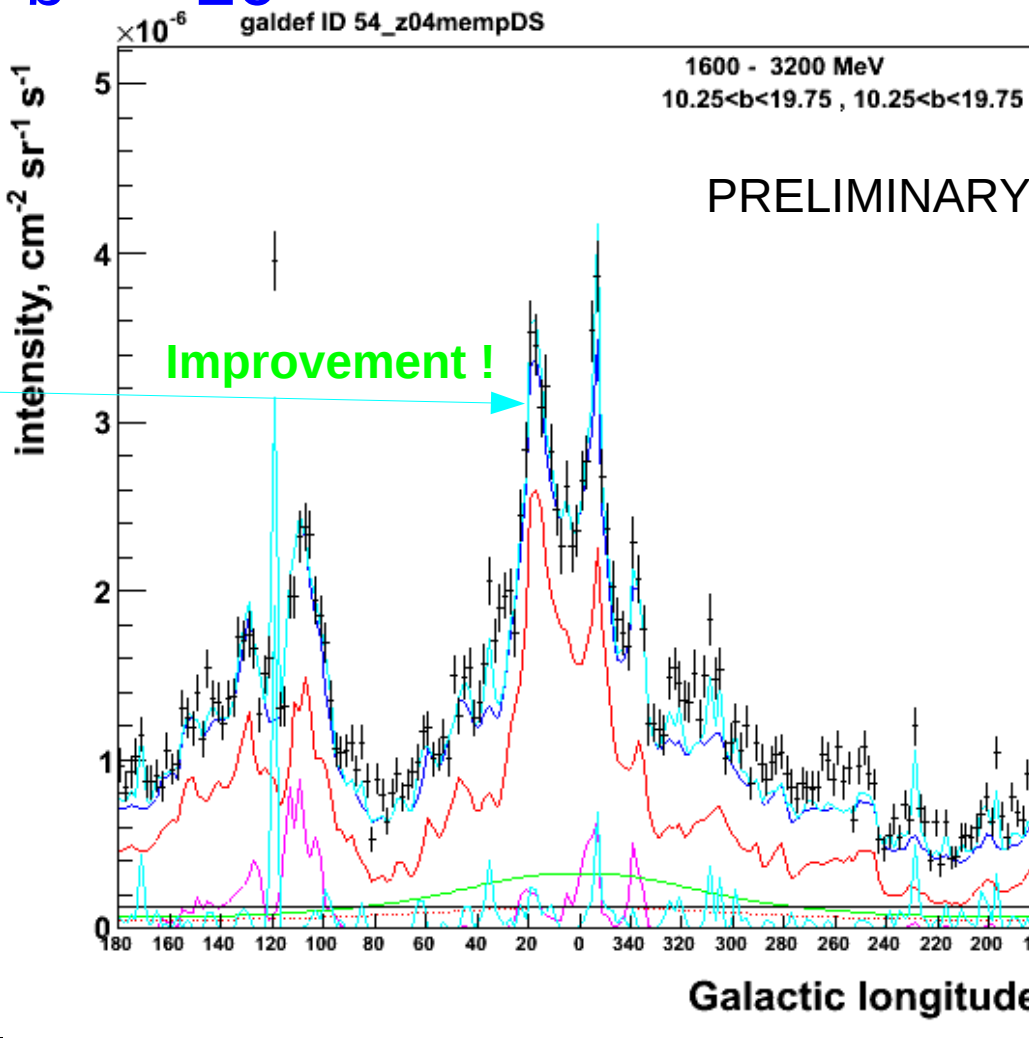

Fermi: GeV gamma rays from cosmic-ray + gas interactions

Dust emission (IRAS + DIRBE) is a better tracer of local gas than HI+CO !
(Grenier, Casandjian: found this in EGRET data: 'dark gas')

# HI + CO GAS TRACER dust

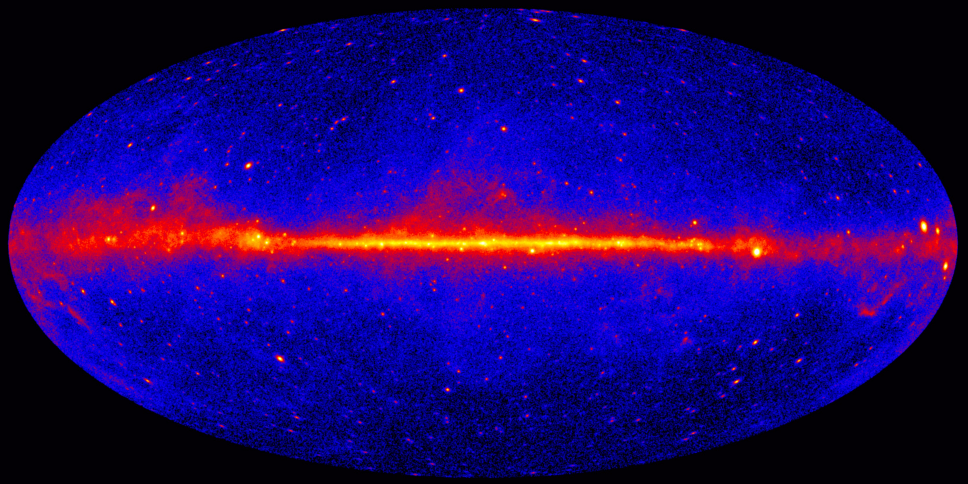
$+10^o < b < +20^o$



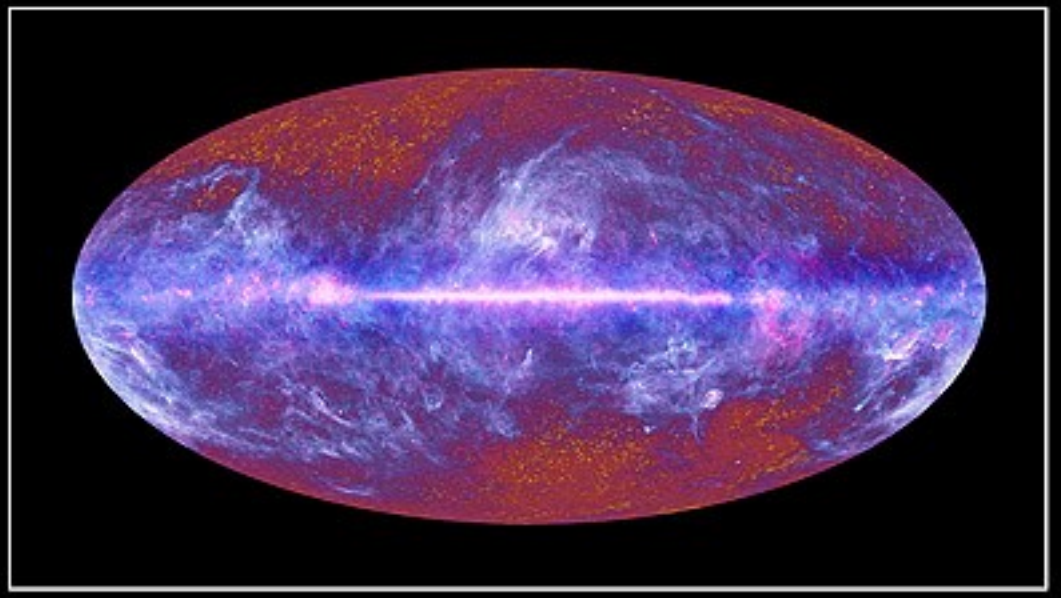




Fermi: GeV gamma rays from cosmi
'dark gas' : independent evidence from
Planck (arXiv:1101.2029)

In the solar neighbourhood, the derived mass of the dark gas, assuming the same dust emissivity as in the H I phase is found to correspond to ≃ 28%% of the atomic mass and ≃ 118%% of the molecular gas mass. The comparison of this value with the recent



2 years




1 year

Both operational now. A lot of common astrophysics !

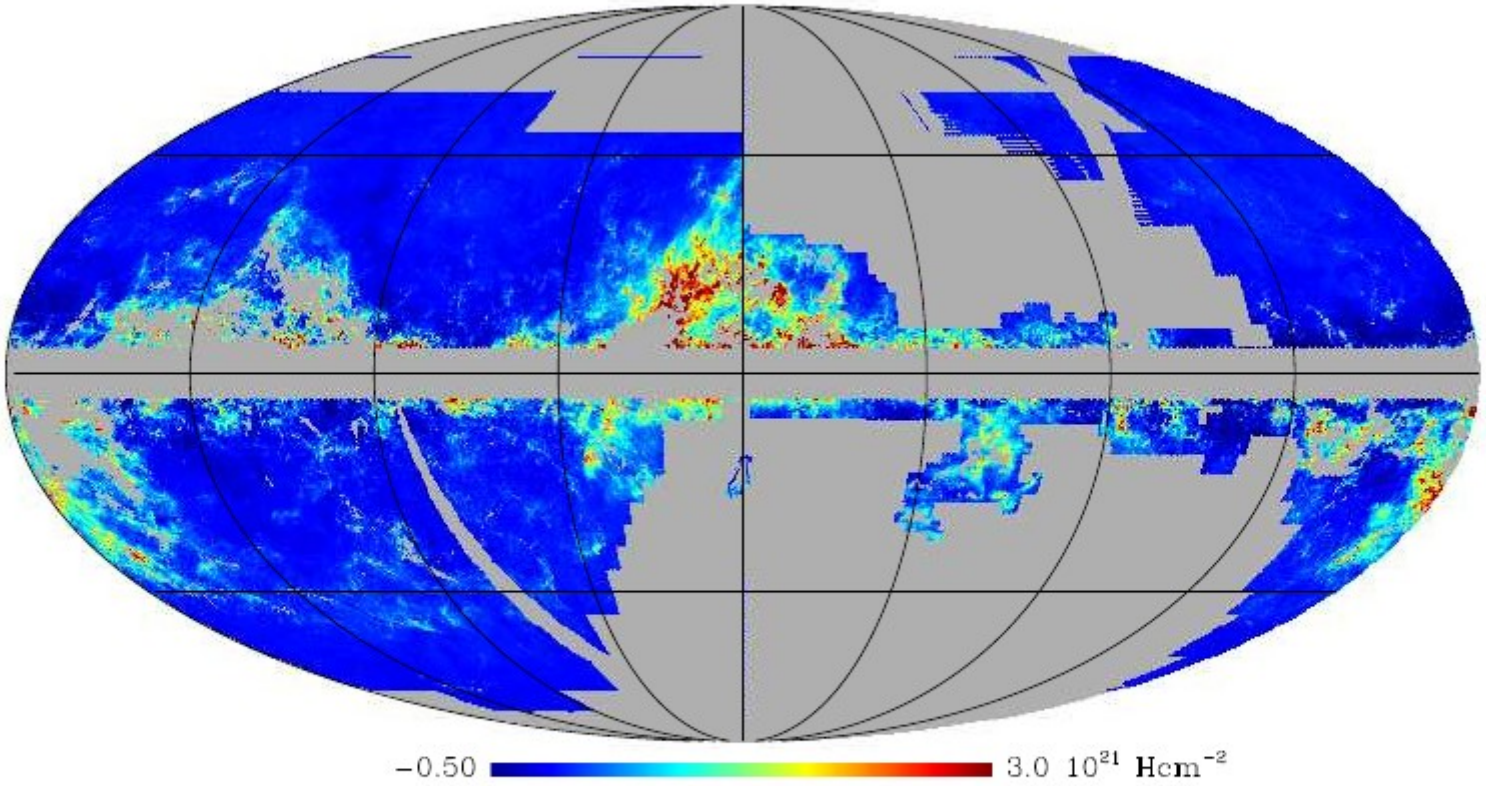


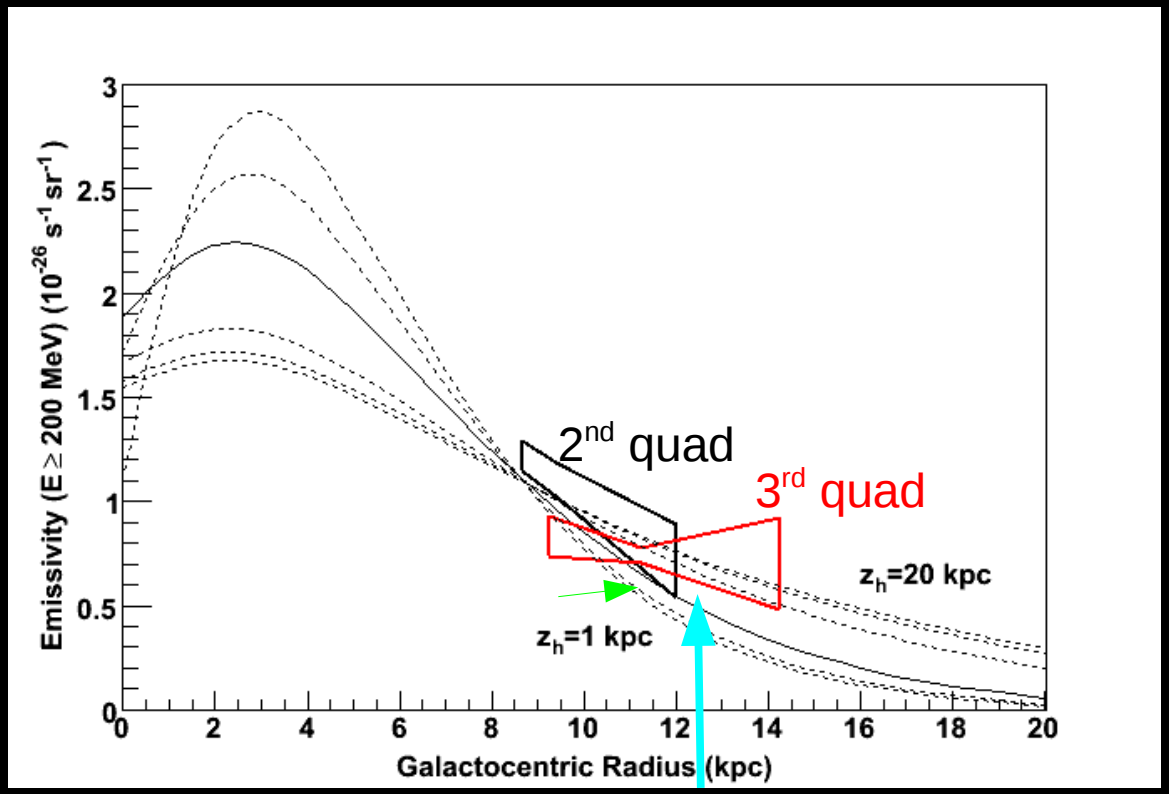

**Fig. 8.** Map of the excess column density derived from the 857 GHz data. The map is shown in Galactic coordinates with the Galactic centre at the centre of the image. The grey regions correspond to those where no *IRAS* data are available, regions with intense CO emission ($W_{CO} > 1$ Kkms$^{-1}$) and the Galactic plane ($|b_{II}| < 5°$).

Planck (arXiv:1101.2032)

# Gamma-ray emissivity distribution in *outer* Galaxy

From Fermi-LAT

## 2nd and 3rd Galactic Quadrants




More cosmic-rays in outer Galaxy than expected !

Abdo et al. (2010) ApJ 710, 133, Ackermann etal, ApJ 726, 81 (2011)

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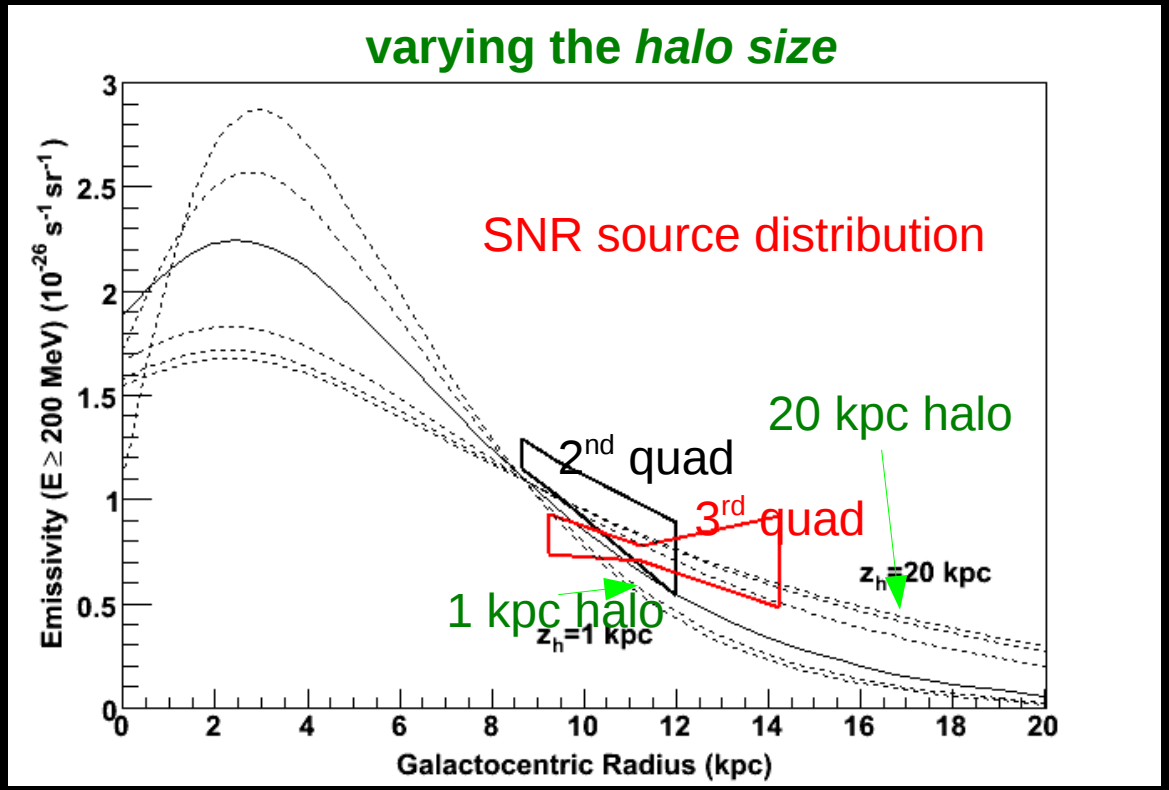


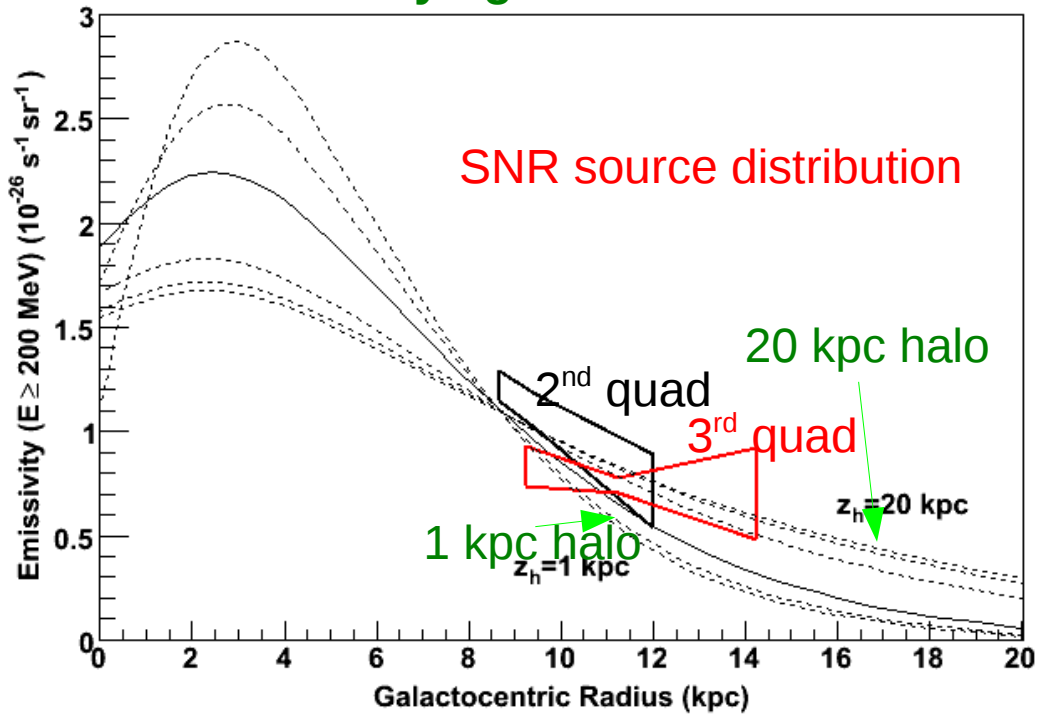

More cosmic-rays in outer Galaxy than expected !
More evidence for large halo, which widens the distribution ?

# Gamma-ray emissivity distribution in outer Galaxy

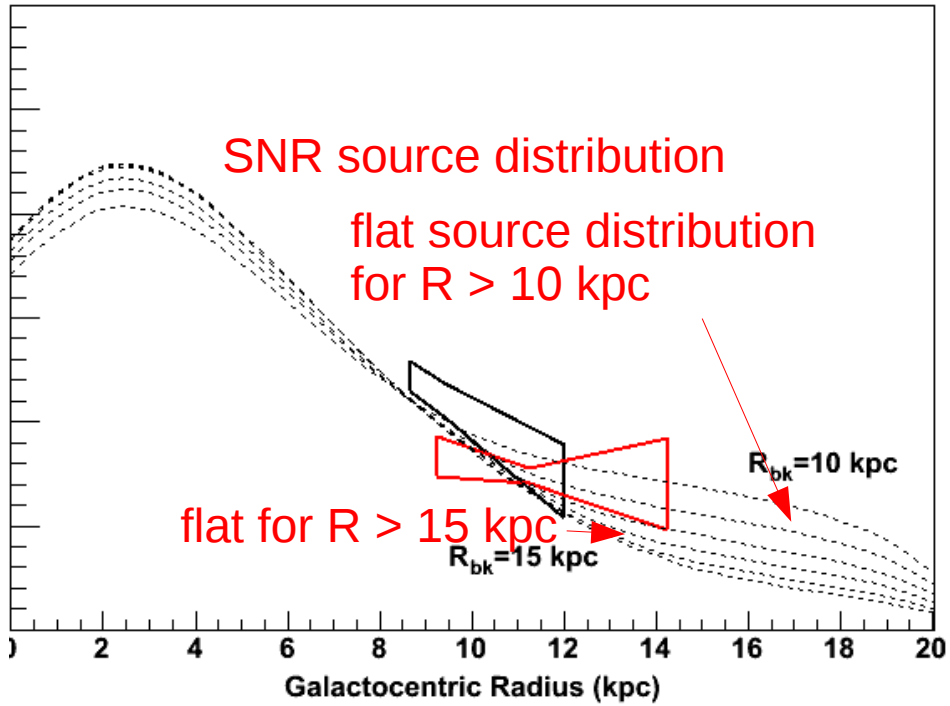
From Fermi-LAT

## 2nd and 3rd Galactic Quadrants

**varying the *halo size***




**varying the *source distribution***




More cosmic-rays in outer Galaxy than expected !
More evidence for large halo ? More sources in outer Galaxy (what are they ?)
Or **more gas** than traced by HI + CO ?
'dark gas' : independent evidence from Planck (arXiv:1101.2029)
but not enough to explain the gamma rays ?

> In the solar neighbourhood, the derived mass of the dark gas, assuming the same dust emissivity as in the H I phase is found to correspond to ≃ 28%% of the atomic mass and ≃ 118%% of the molecular gas mass. The comparison of this value with the recent

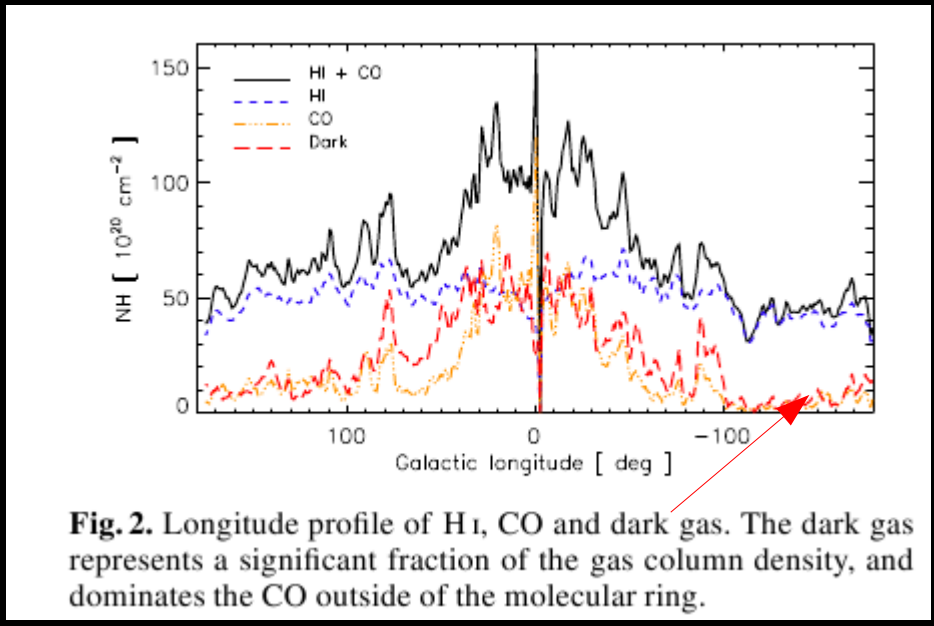



**Fig. 2.** Longitude profile of H I, CO and dark gas. The dark gas represents a significant fraction of the gas column density, and dominates the CO outside of the molecular ring.

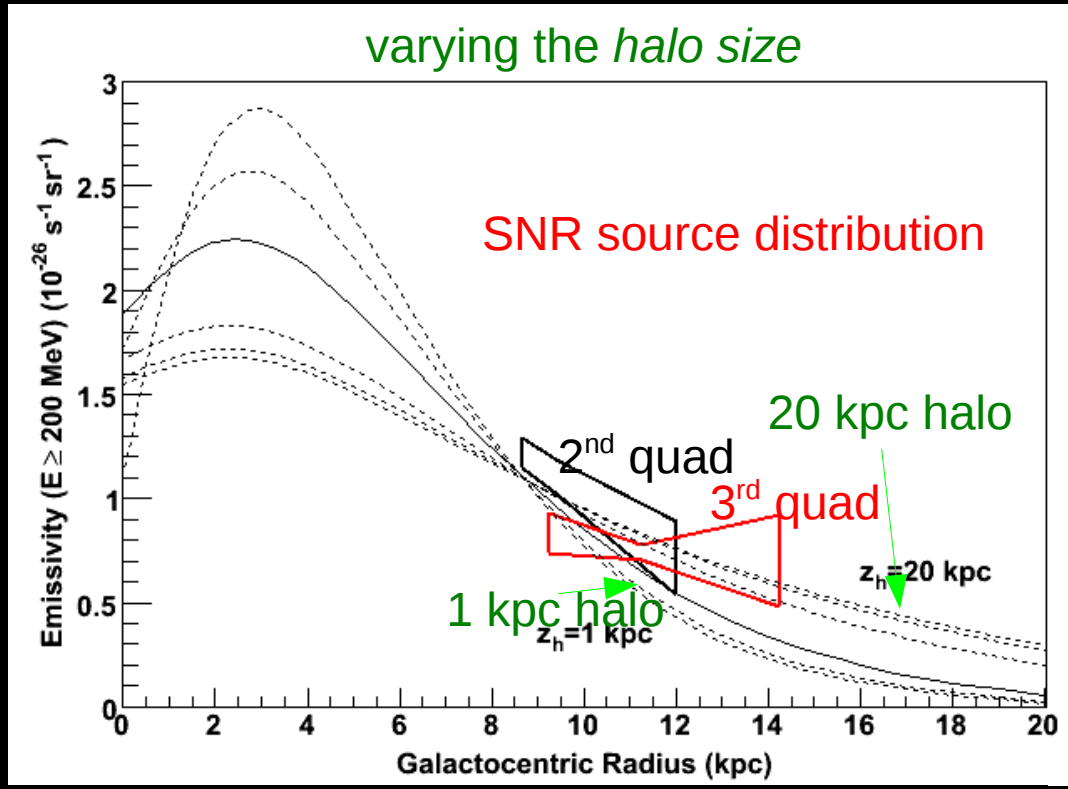
Planck (arXiv:1101.2032)

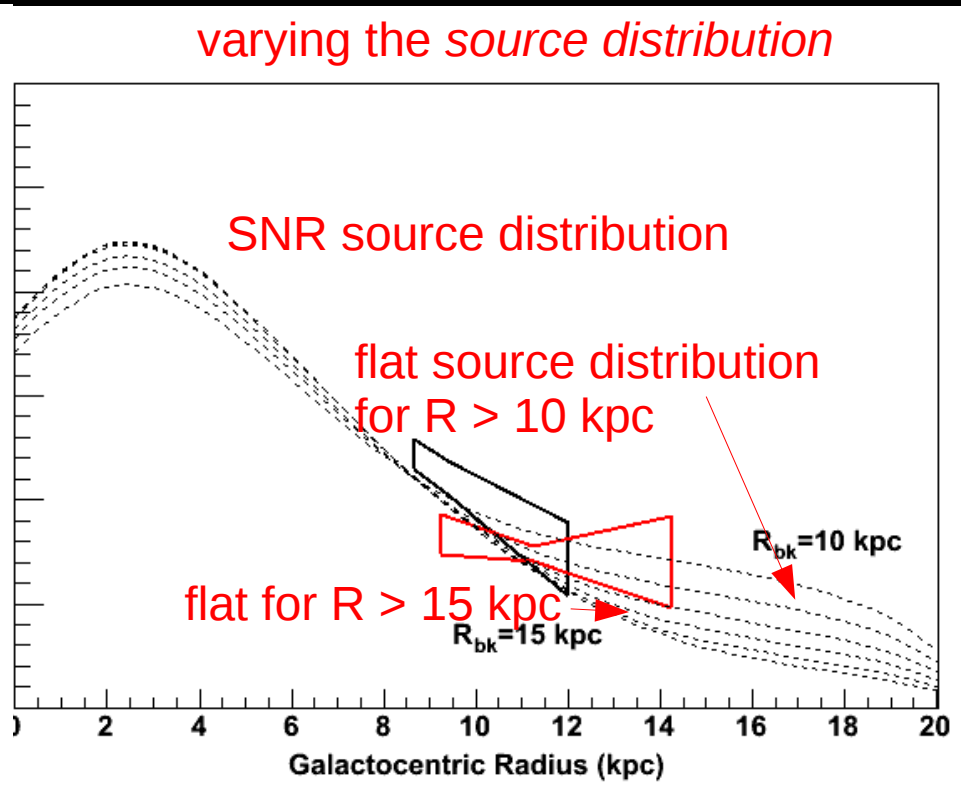
Not enough dark gas in outer Galaxy to explain Fermi gamma rays ?

# Gamma-ray emissivity distribution in outer Galaxy

From Fermi-LAT

## 2nd and 3rd Galactic Quadrants

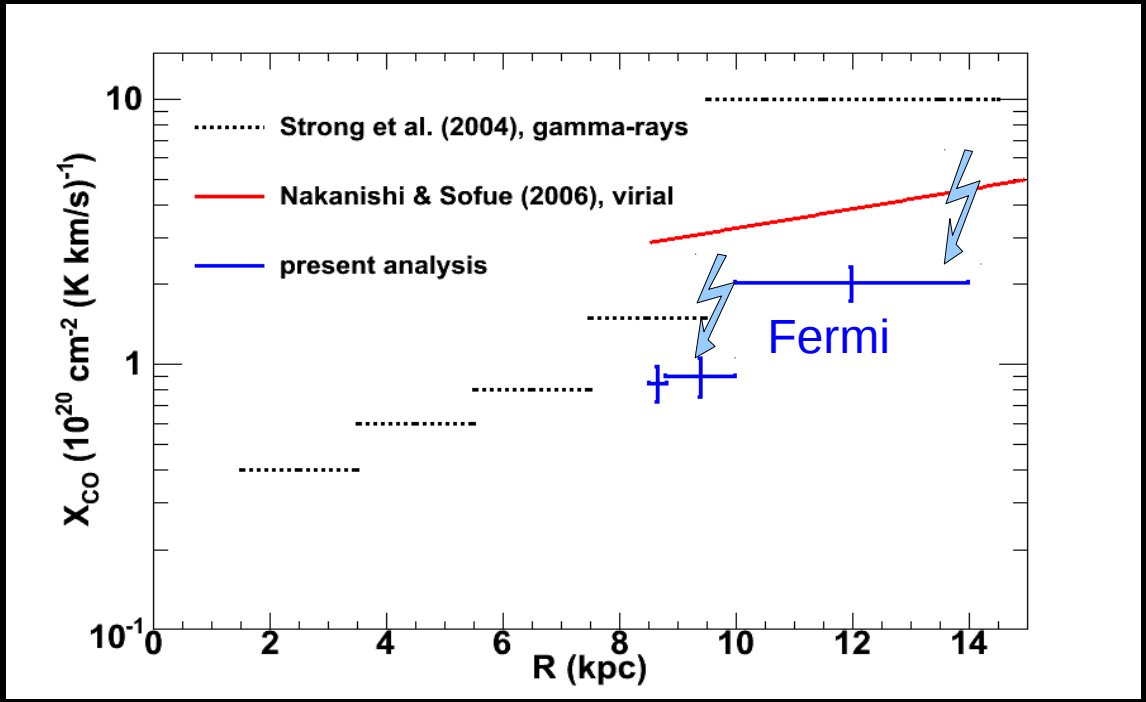



Implications for synchrotron / B-field models

Important for Planck ! Maybe can break degeneracy cosmic rays /gas

# Fermi measures molecular gas content of the outer Galaxy by comparing gamma-ray emissivities of molecular and atomic hydrogen




Scaling factor Xco from $^{12}$CO to $H_2$

Local and Outer Galaxy (2$^{nd}$ quadrant)

Confirms *increase* from inner to outer Galaxy

Abdo etal (2010) ApJ 710, 133

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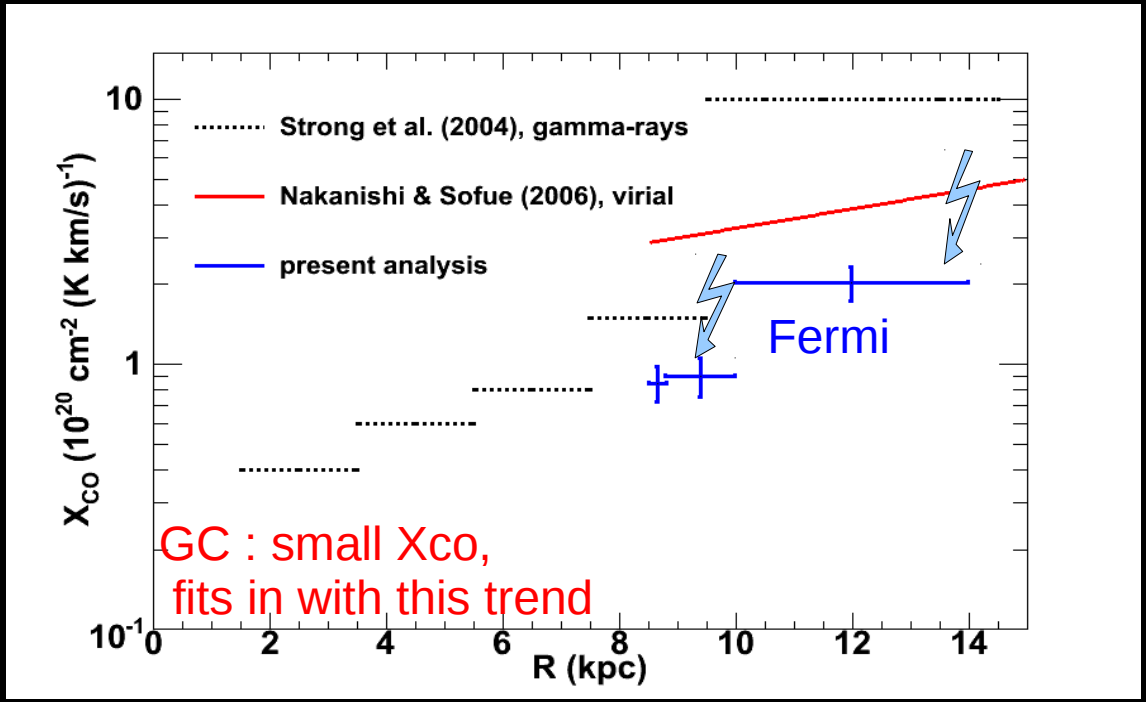


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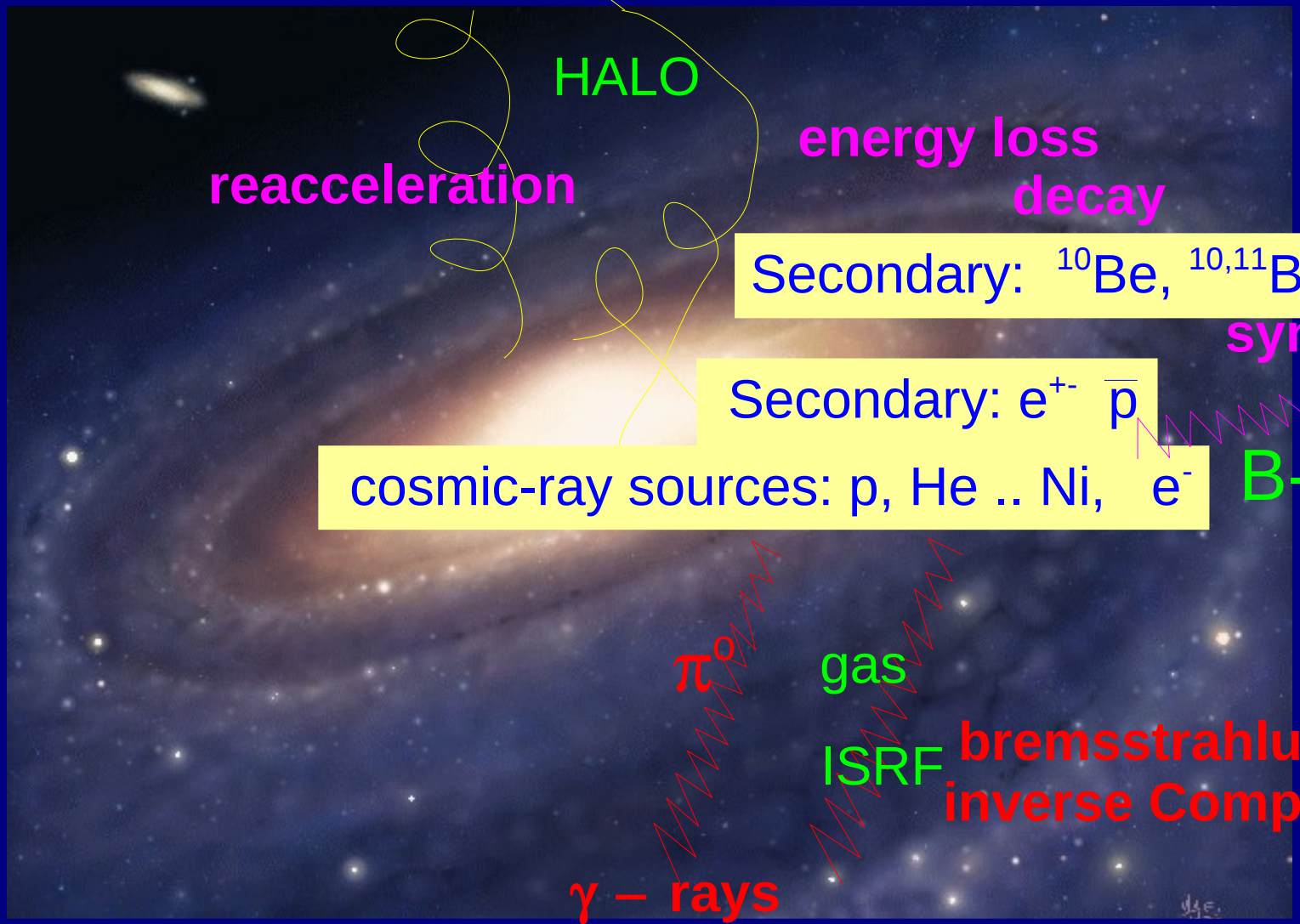
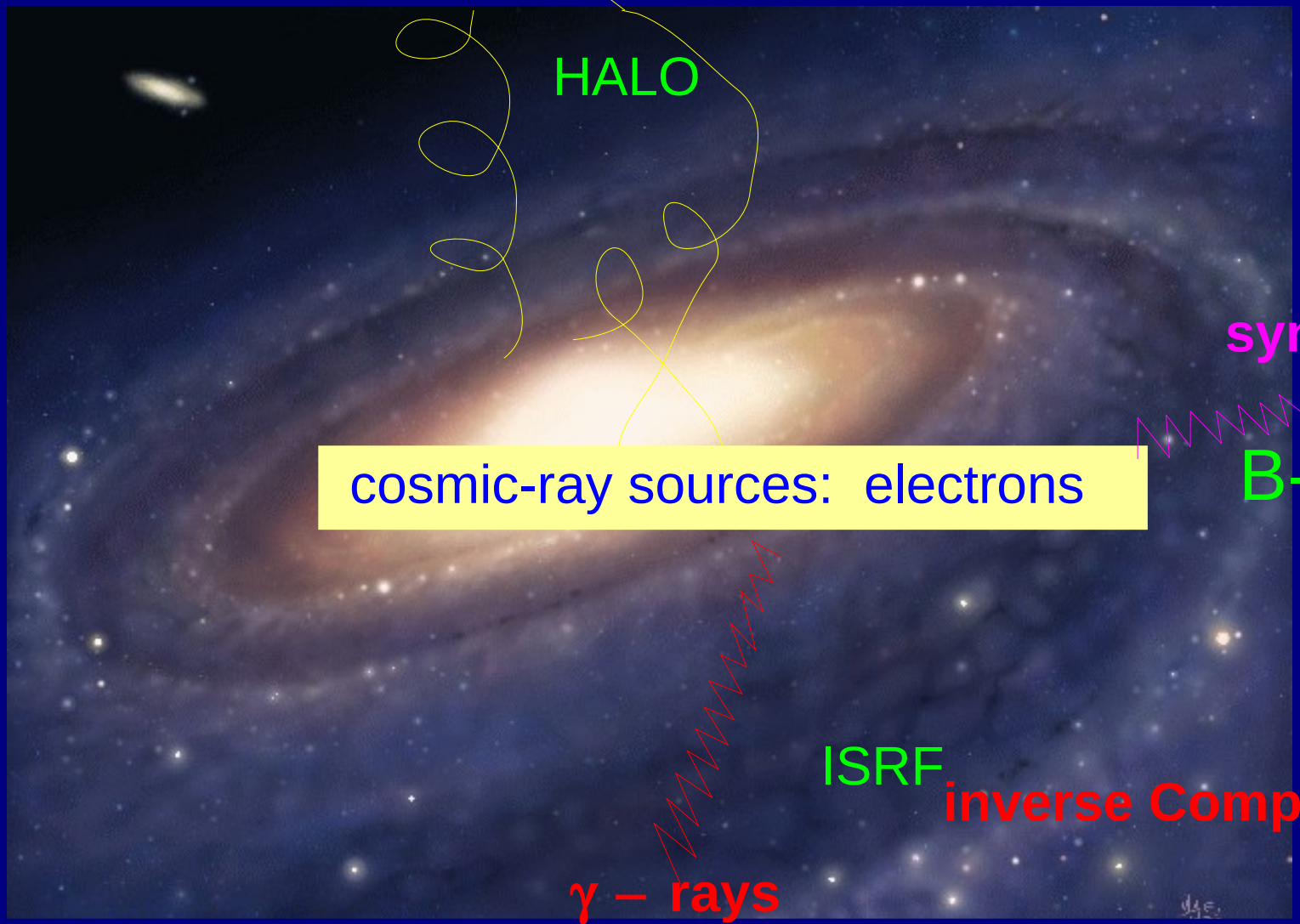
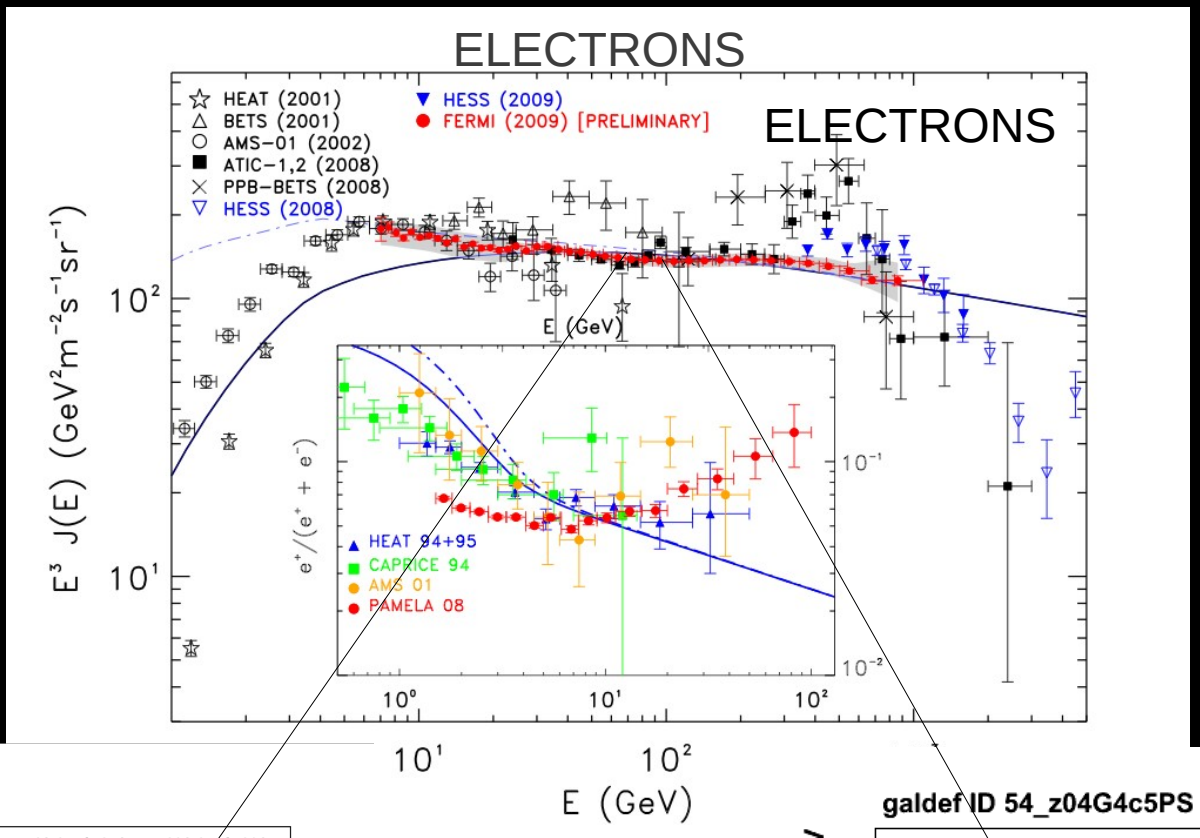
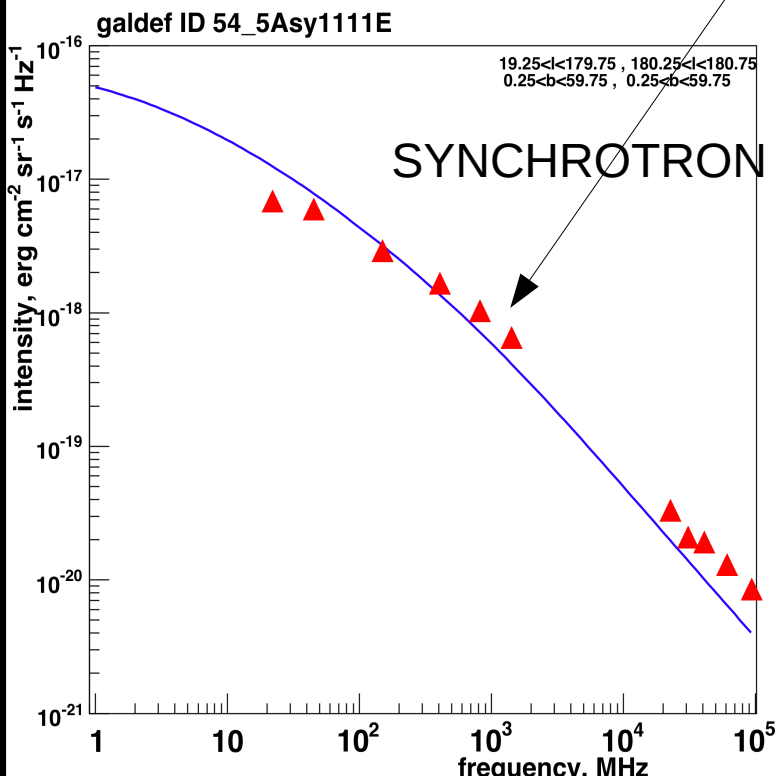
# Cosmic Ray Electrons Synchrotron and Magnetic Fields


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



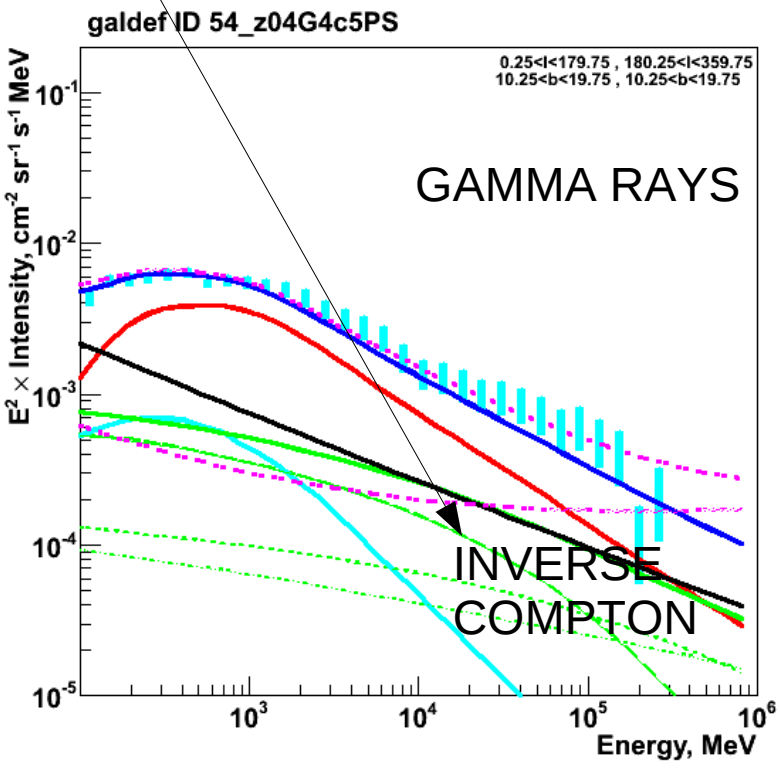

Cosmic-ray electrons provide the link radio – gamma ray
Hence (one of the) Fermi – Planck connection(s) !



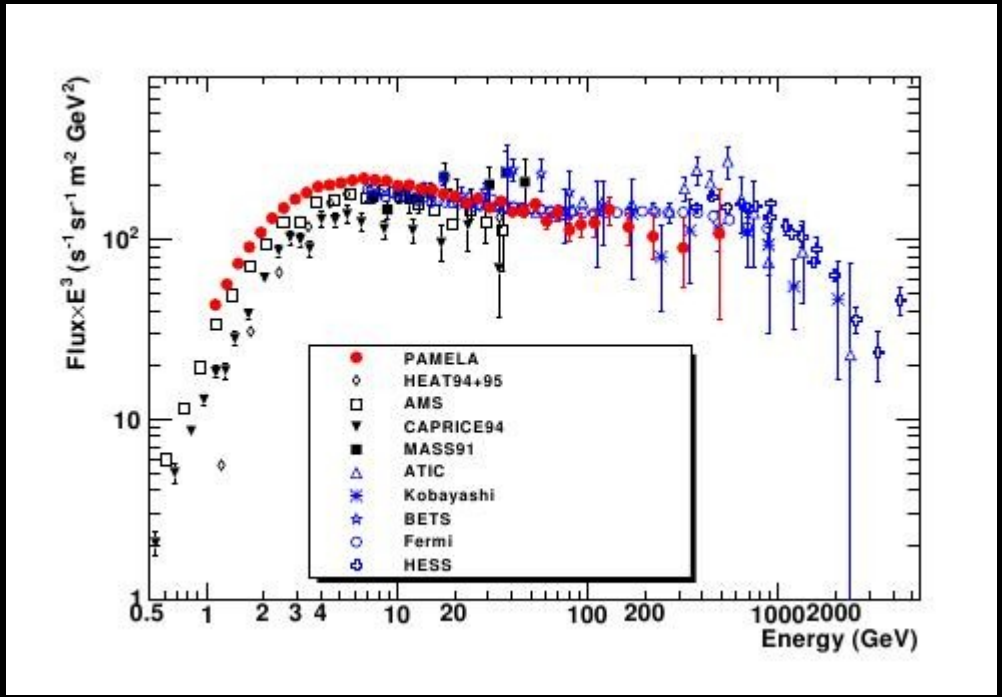




SAME ELECTRONS for RADIO and GAMMA RAYS !

good constraints on models



New !
PAMELA satellite measures cosmic-ray electrons
Phys Rev Letter March 2011




Down to 1 GeV ( c.f.  Fermi > 7 GeV)
Consisistent, a bit higher than Fermi at low energies
Slightly steeper, as expected since Fermi includes positrons

Now: AMS-02, launched May 16, operational.

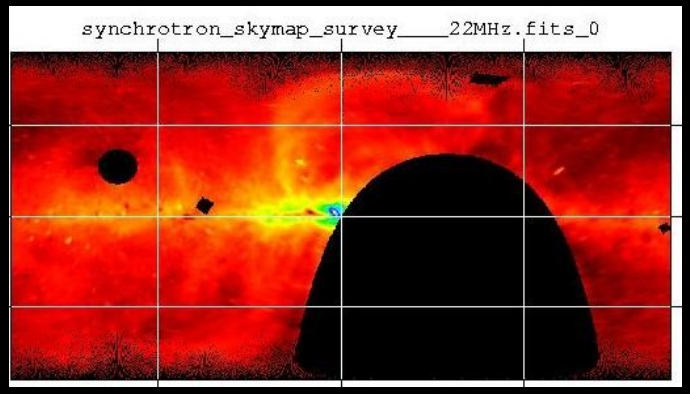
Facit for electrons - synchrotron

Synchrotron spectral break by 0.5 at GHz,
→ Electron spectral break by 1 at few GeV

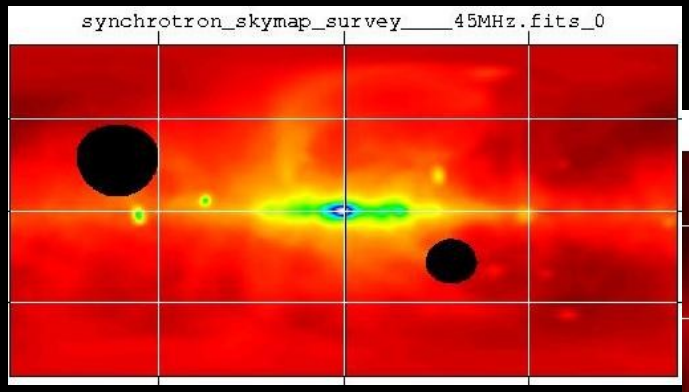
Hard to explain by propagation or energy loss

Instead need:
Injection spectrum break from 1.3 to 2.3 at few GeV

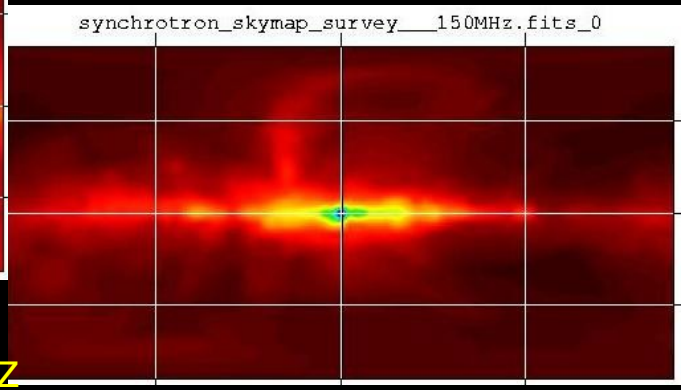
Relevant to GC !



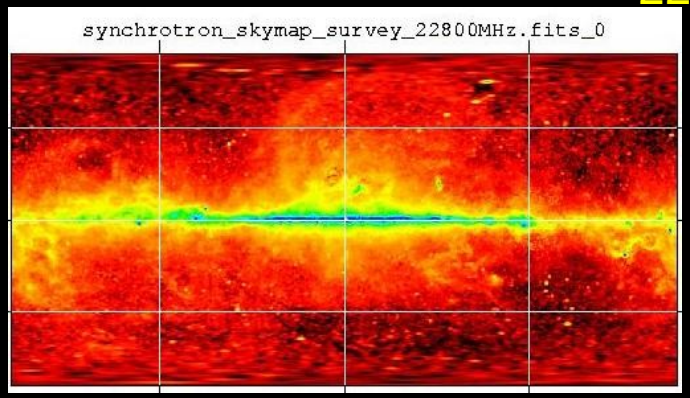

22 MHz




45 MHz



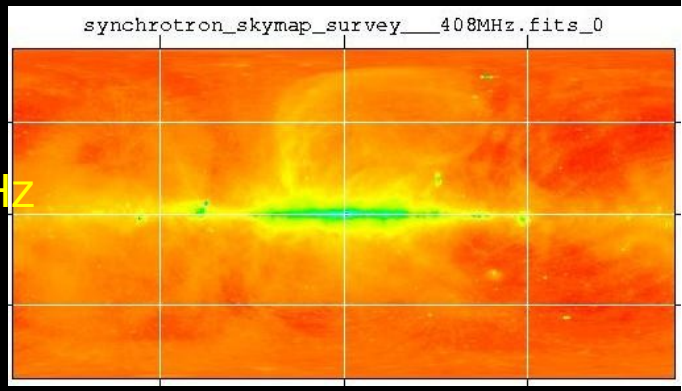

150 MHz

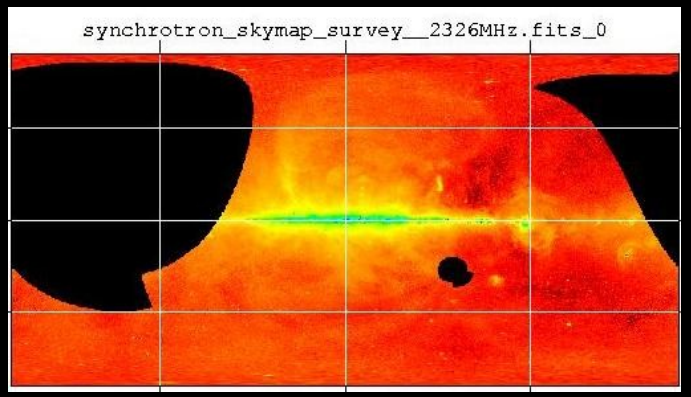



23 GHz

Continuum sky surveys

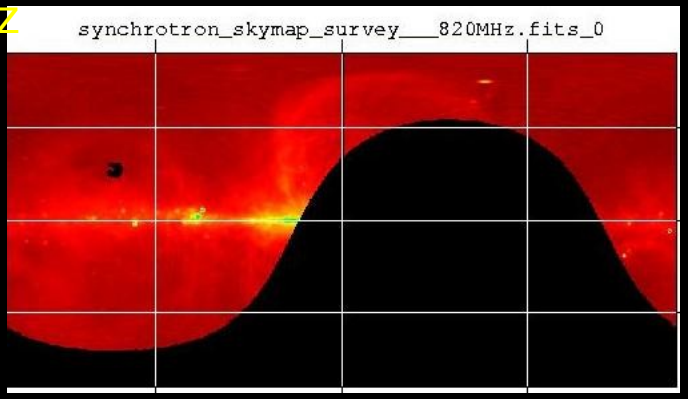
408 MHz



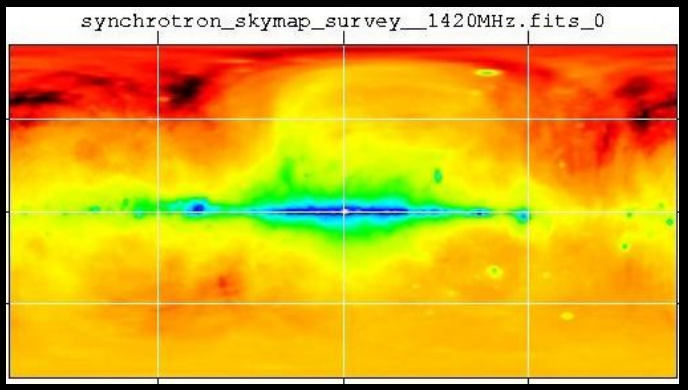



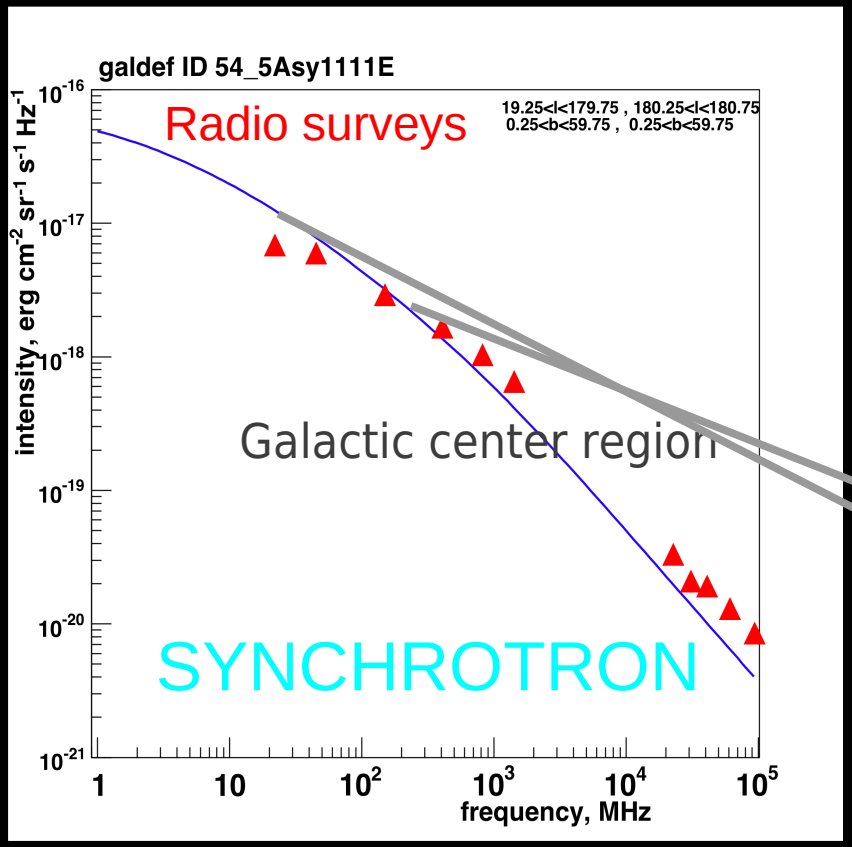

2.3 GHz

820 MHz

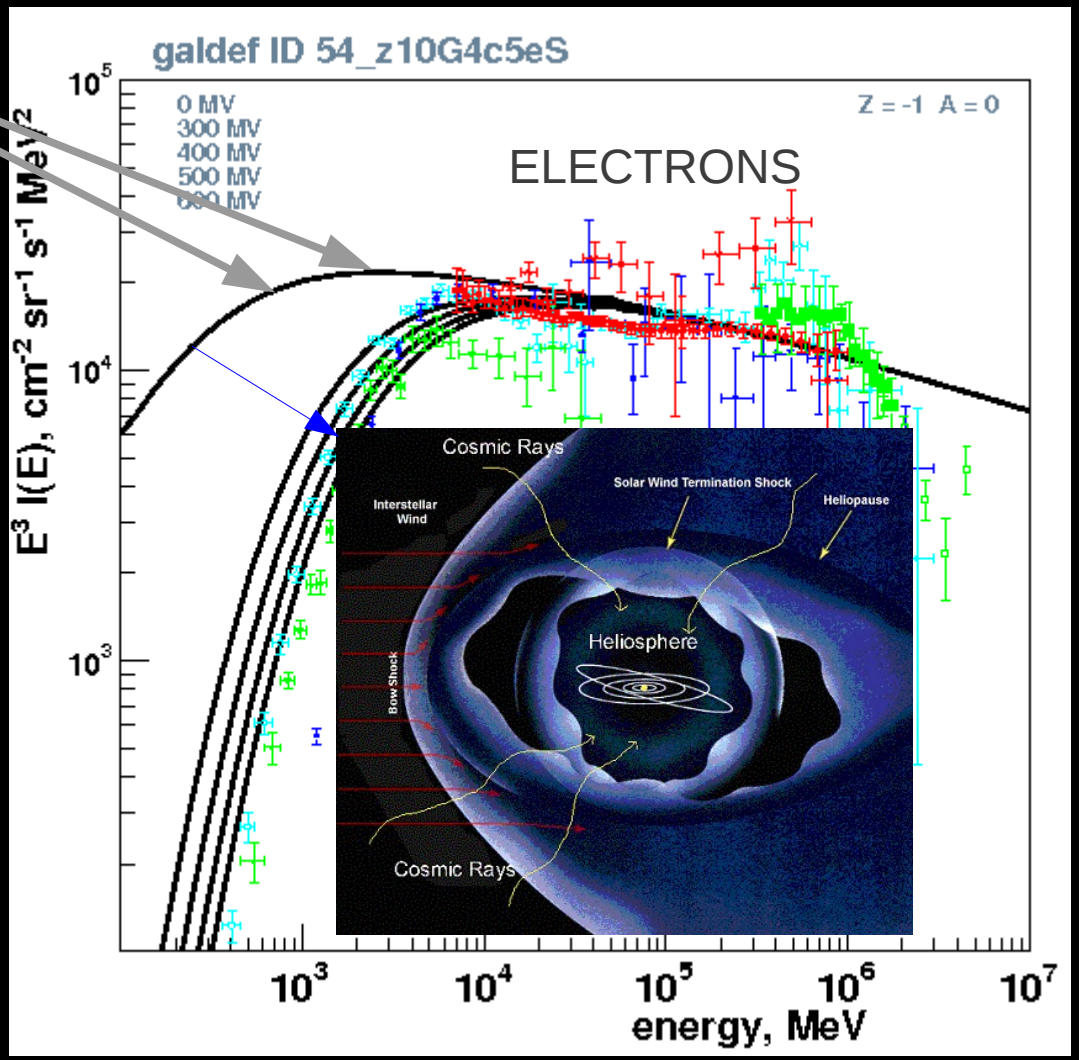



1.4 GHz



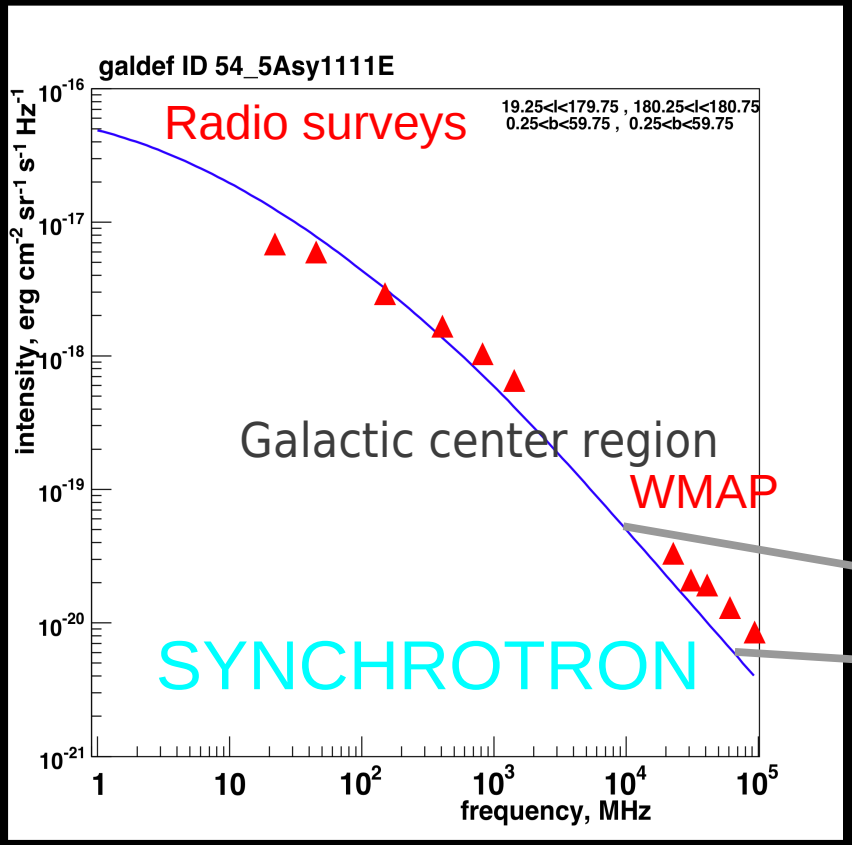



GALPROP
model



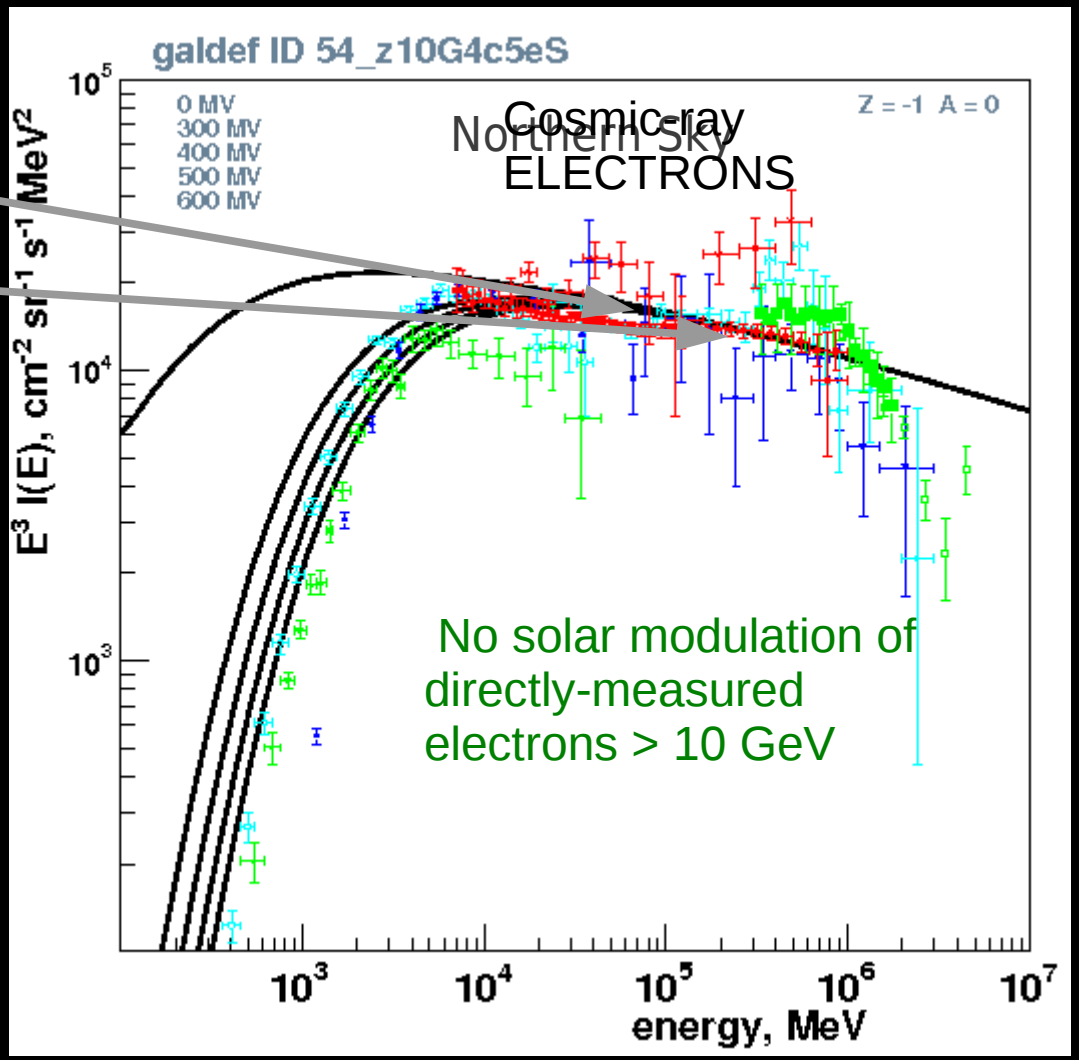

radio provides essential probe of interstellar electron spectrum at E < few GeV
to complement direct measurements and determine solar modulation

electrons have huge uncertainty due to modulation here

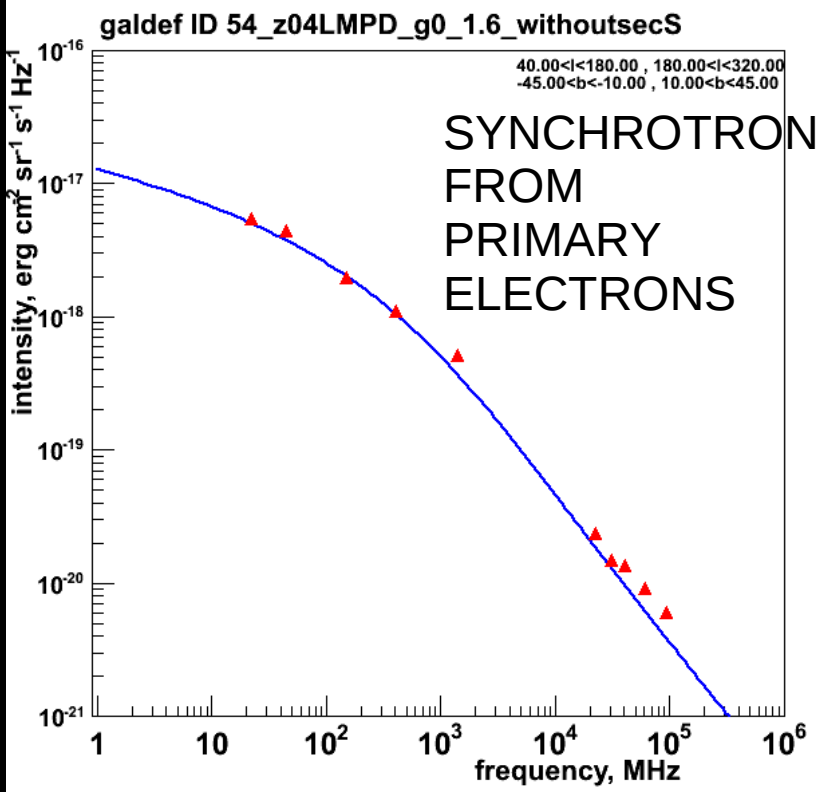


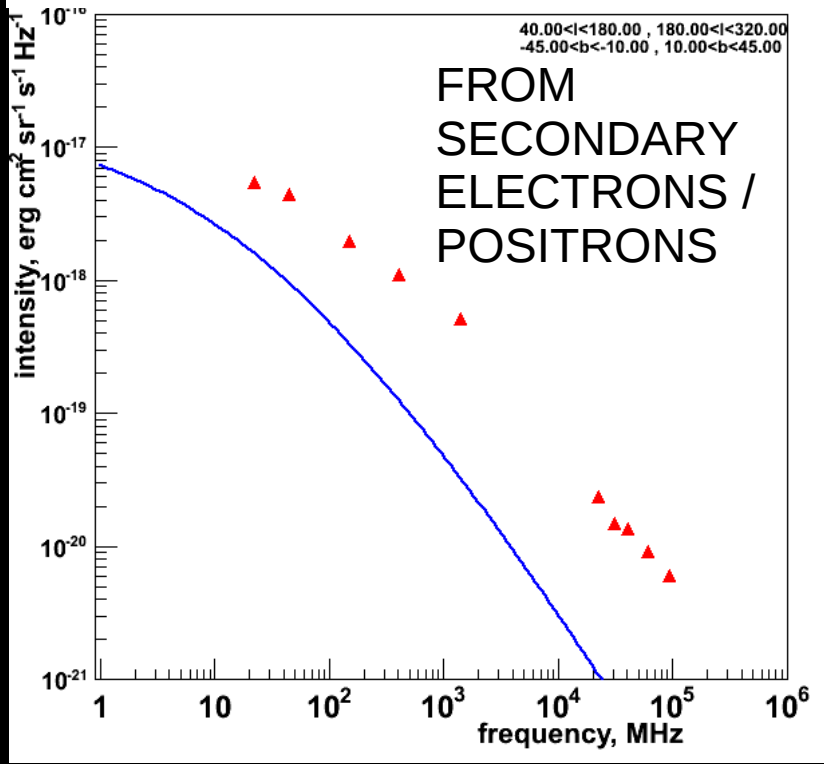

GALPROP model

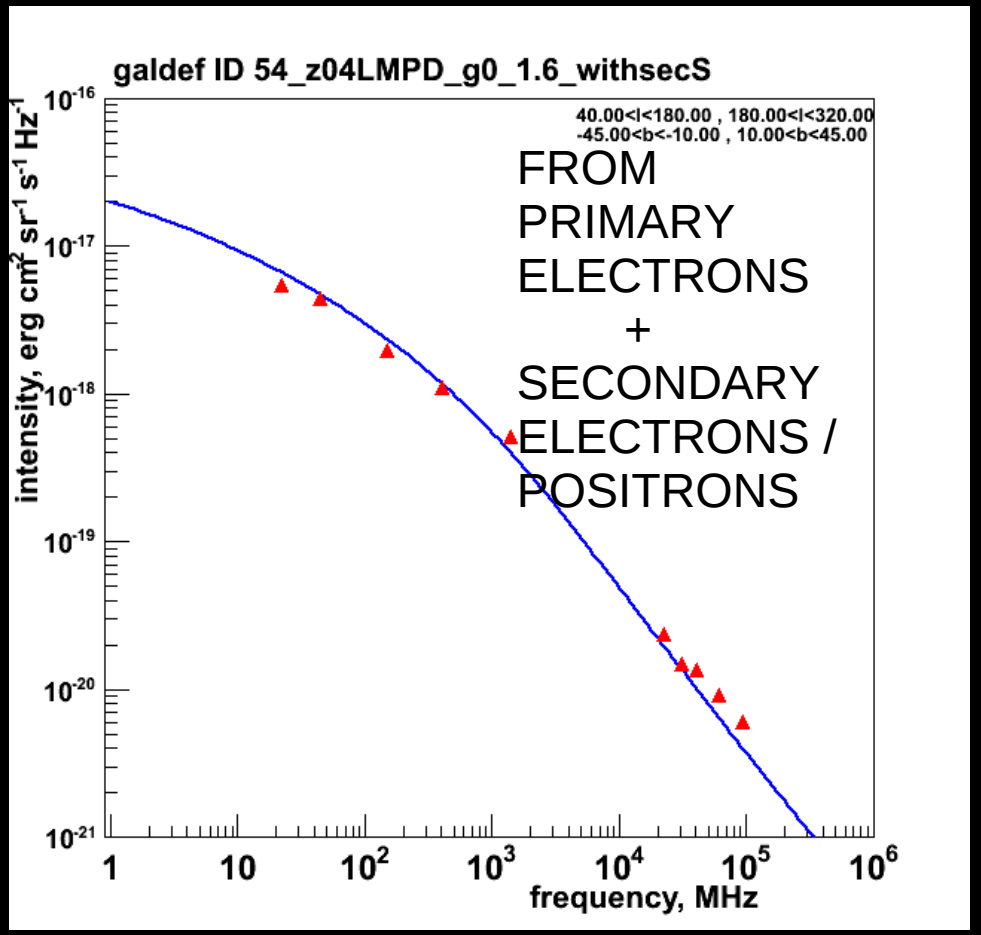
Electron spectrum must have break at ~4 GeV
~ 1 in spectral index




microwaves provide essential probe of interstellar electron spectrum
10 - 100 GeV



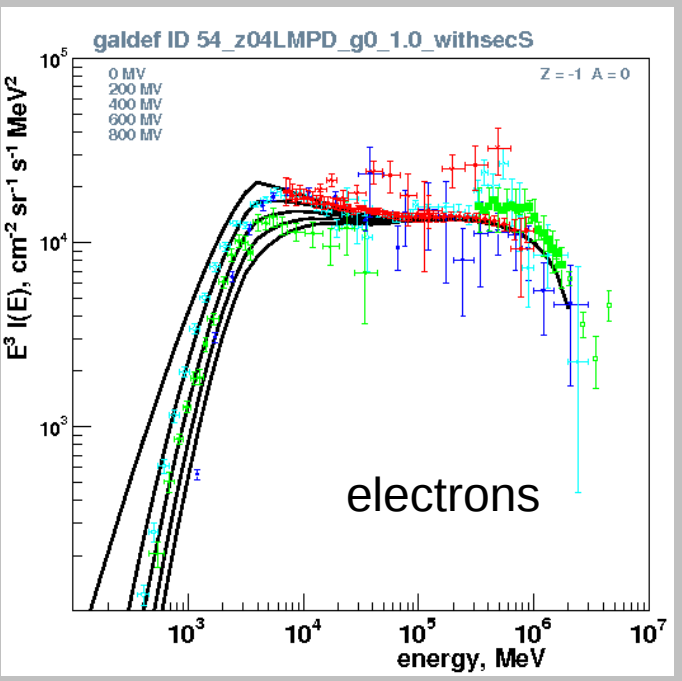



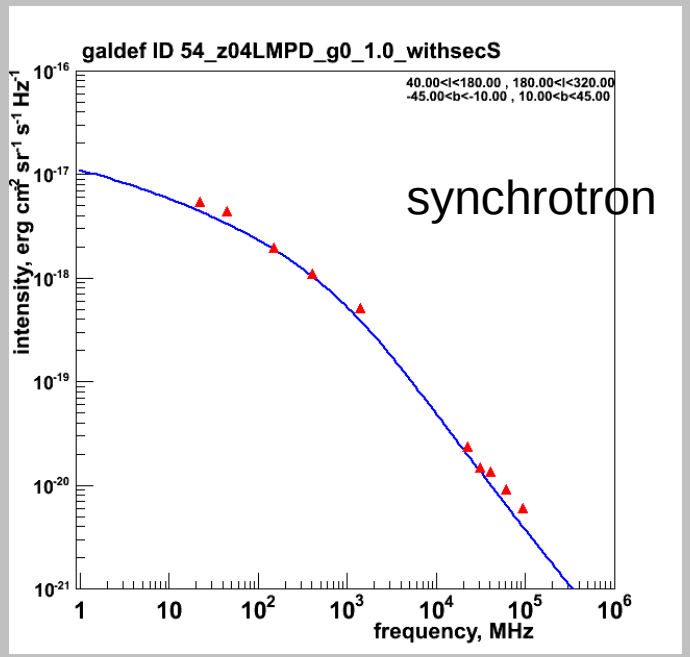

*Secondary* positrons
(and secondary electrons)
are important for synchrotron

Electron injection index E < 4 GeV (-2.3 > 4 GeV)

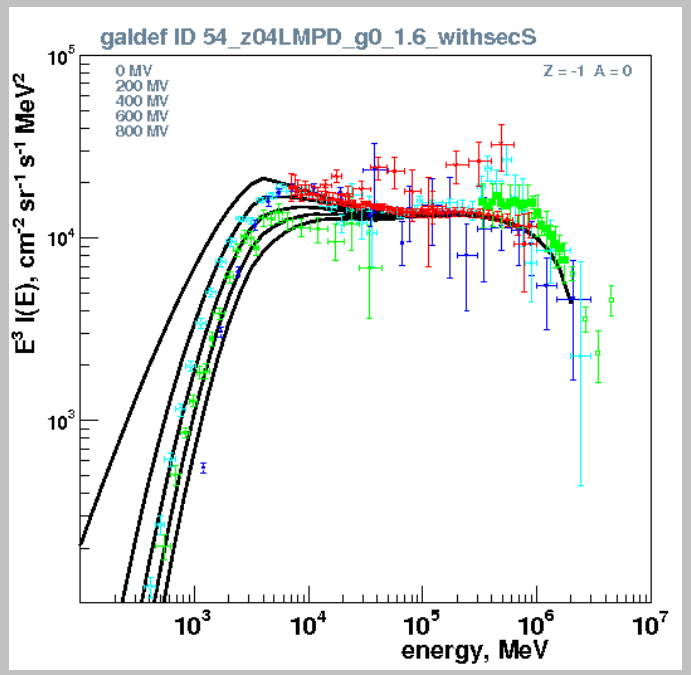
-1.0



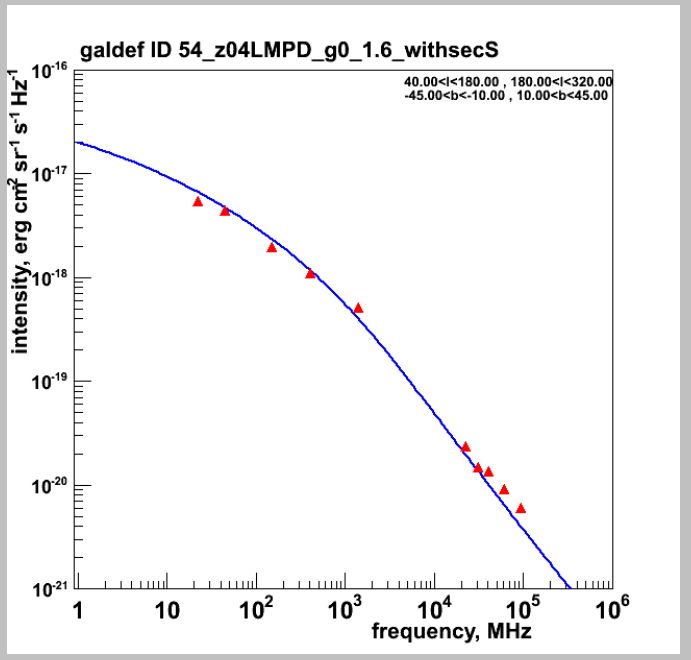

OK



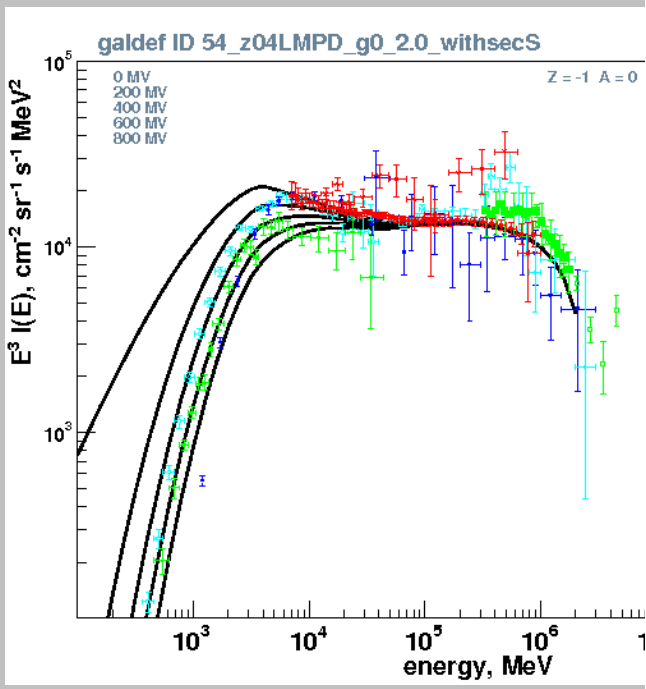

-1.6



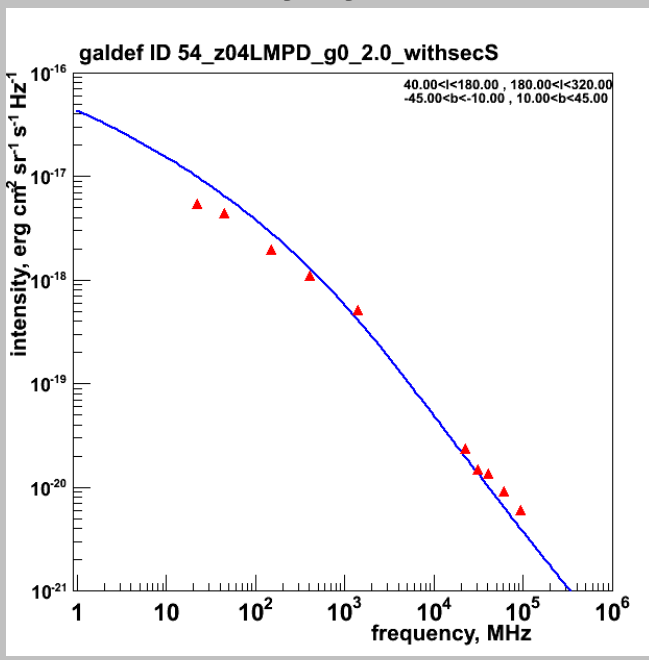

OK




-2.0



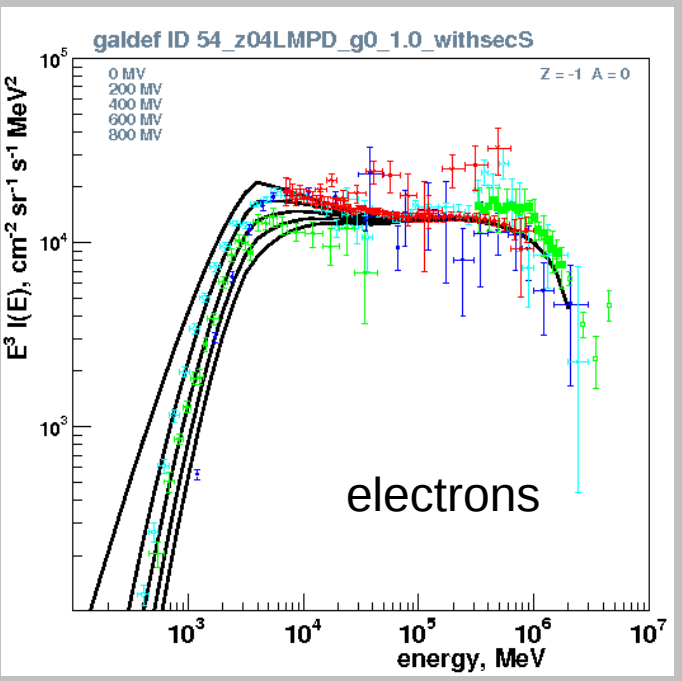

excluded by synchrotron !




Strong, Orlando & Jaffe (2011) A&A 534, A54

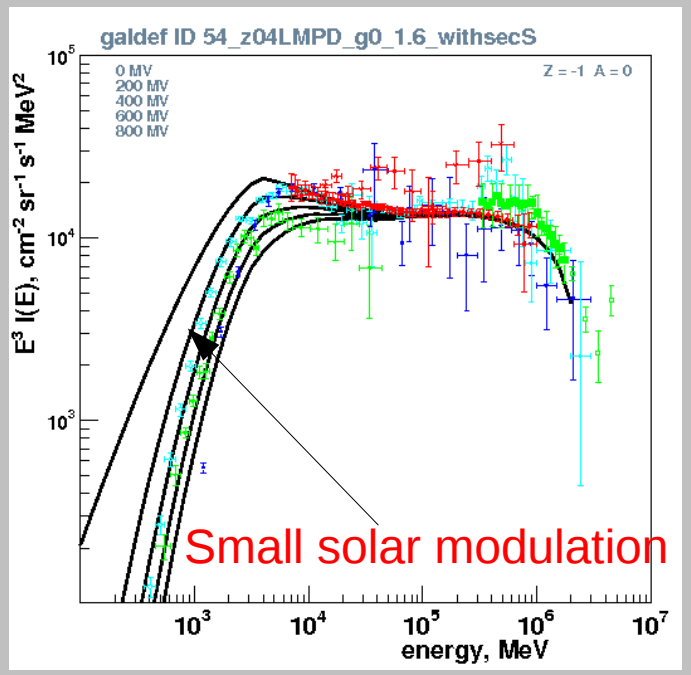
Electron injection index E < 4 GeV

-1.0



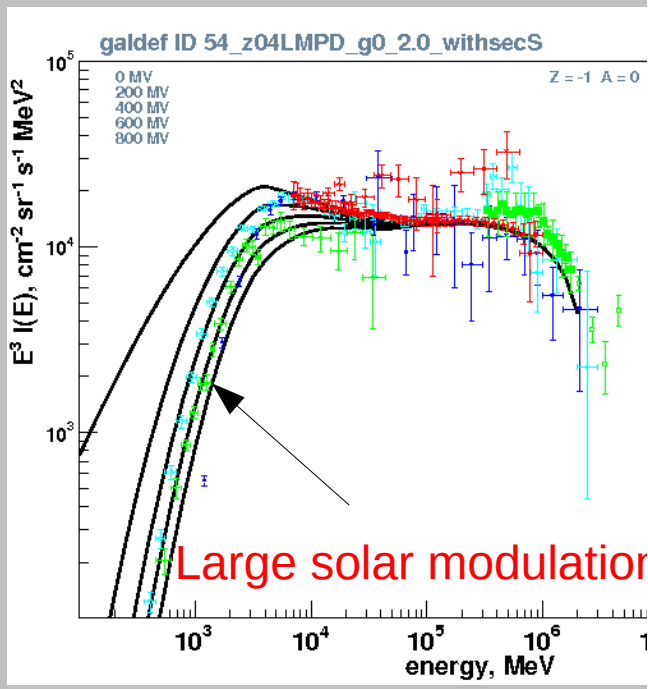

OK

-1.6

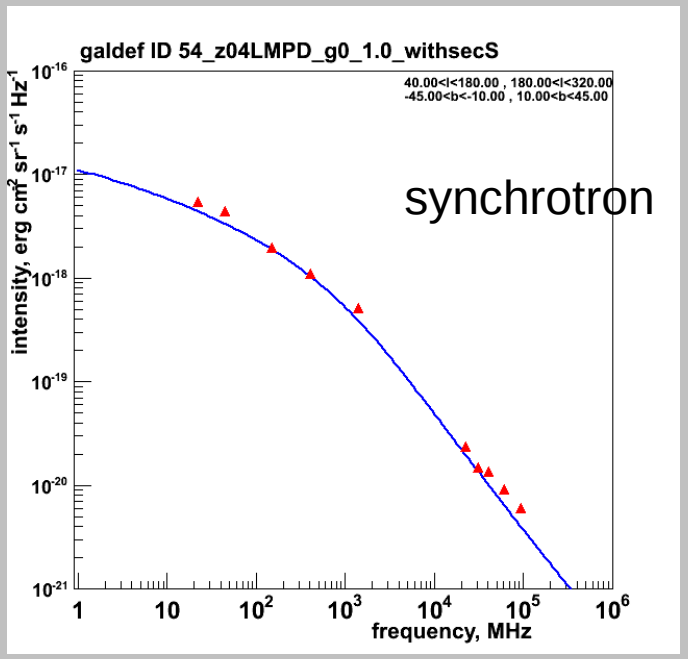


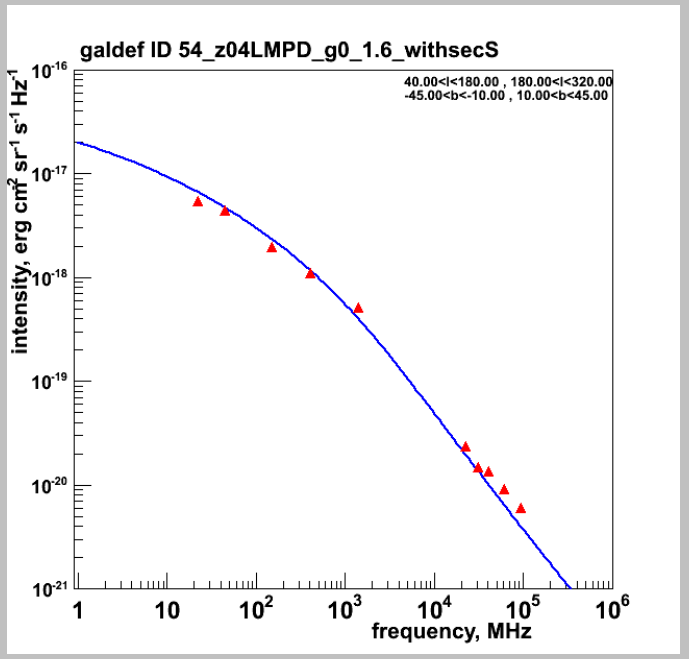

OK

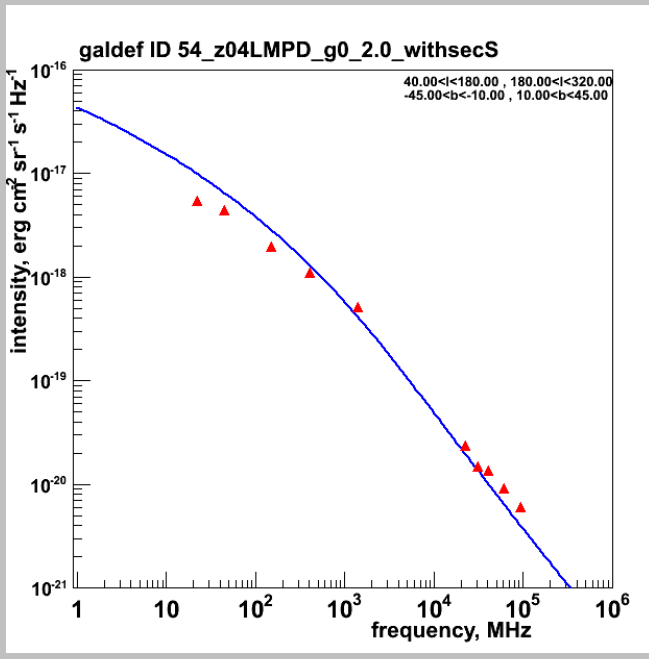
-2.0




excluded by synchrotron !



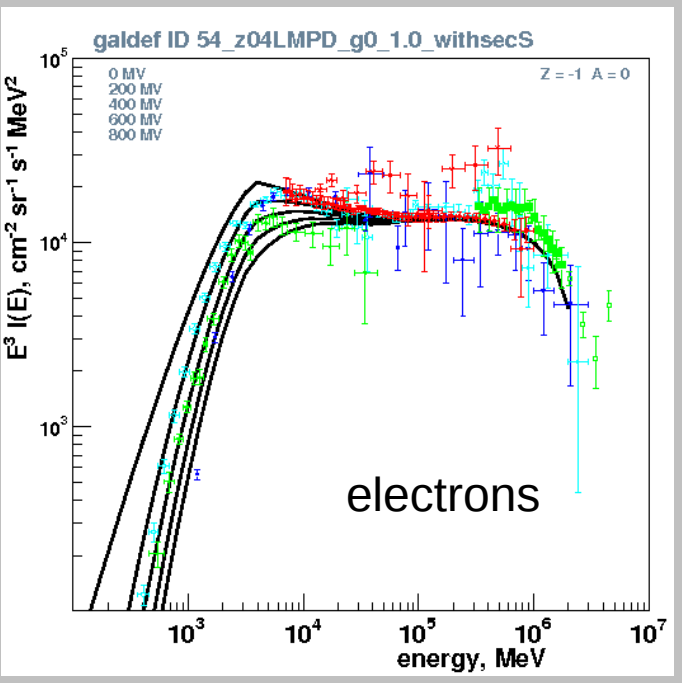




Strong, Orlando & Jaffe (2011) A&A 534, A54

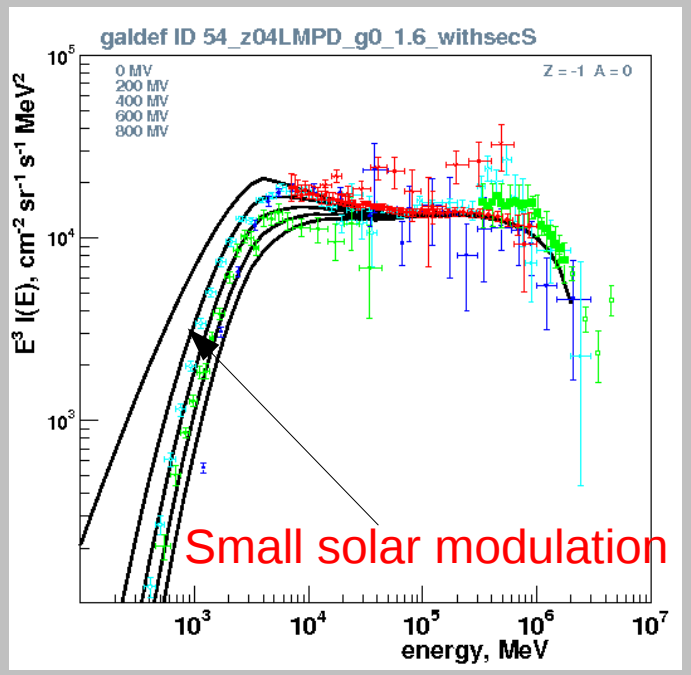
# Electron injection index E < 4 GeV

-1.0



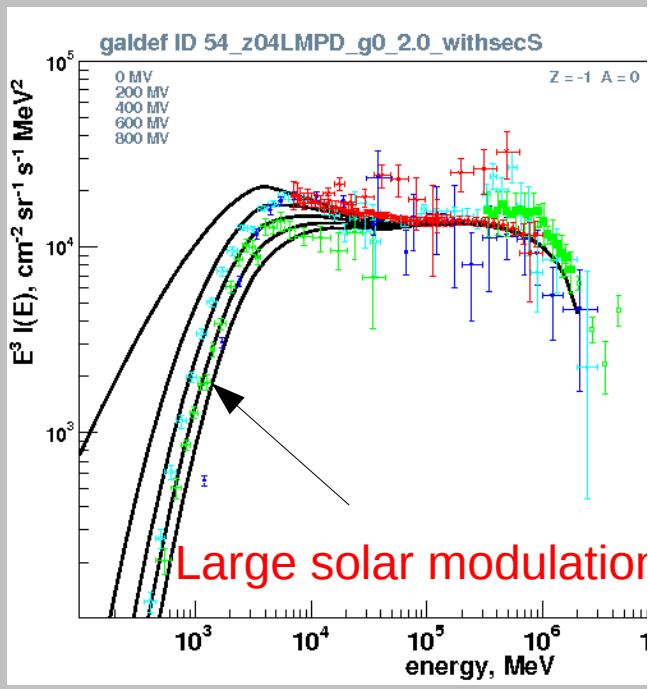

OK

-1.6

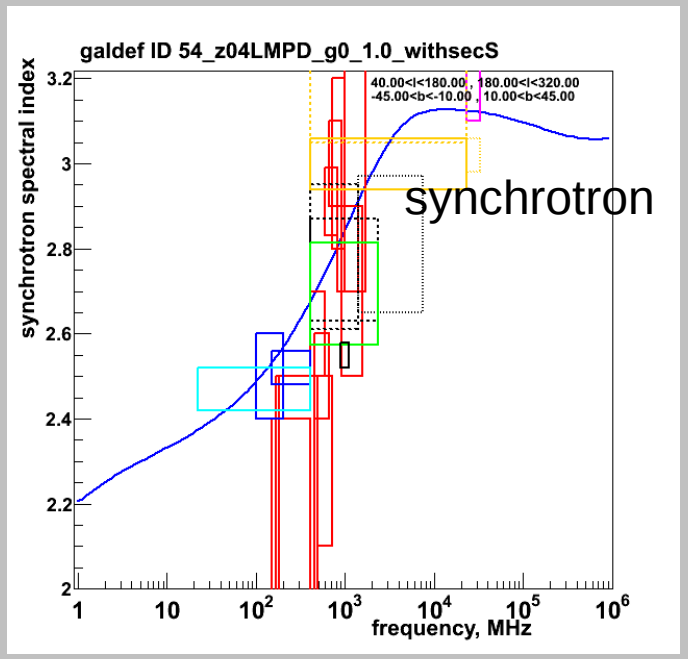


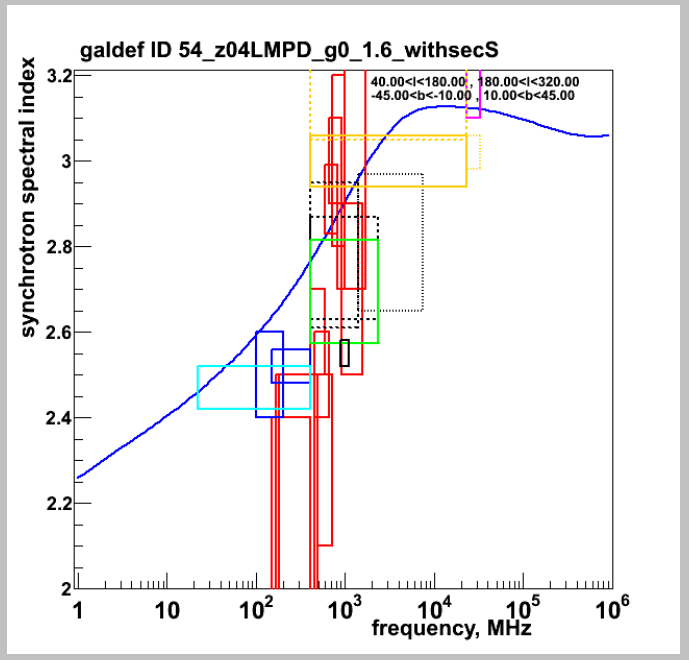

OK

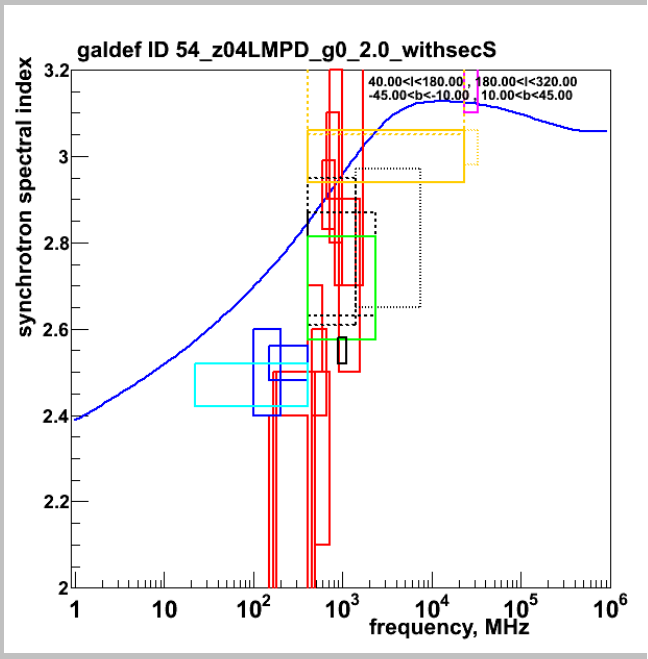
-2.0




excluded by synchrotron !

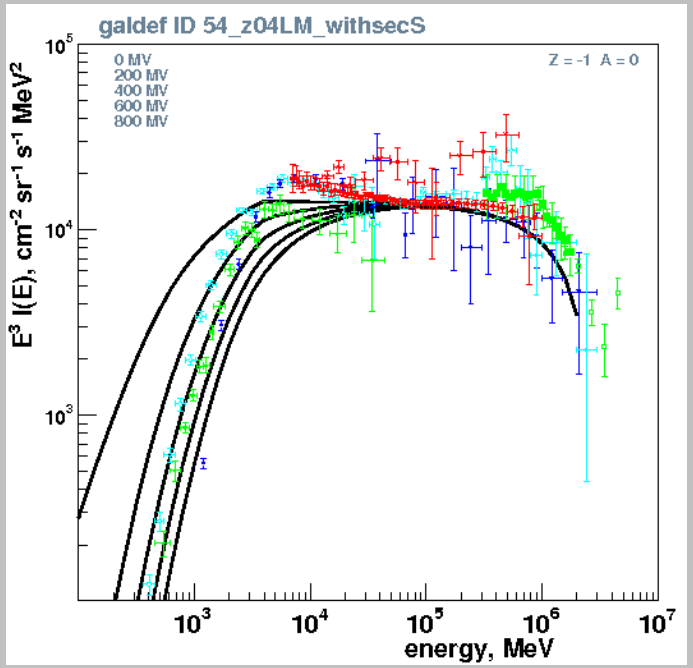


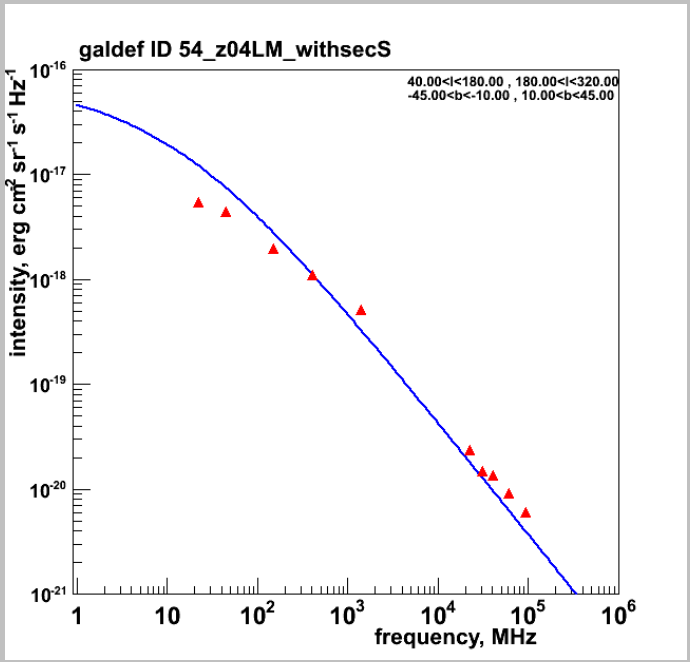




Strong, Orlando & Jaffe (2011) A&A 534, A54

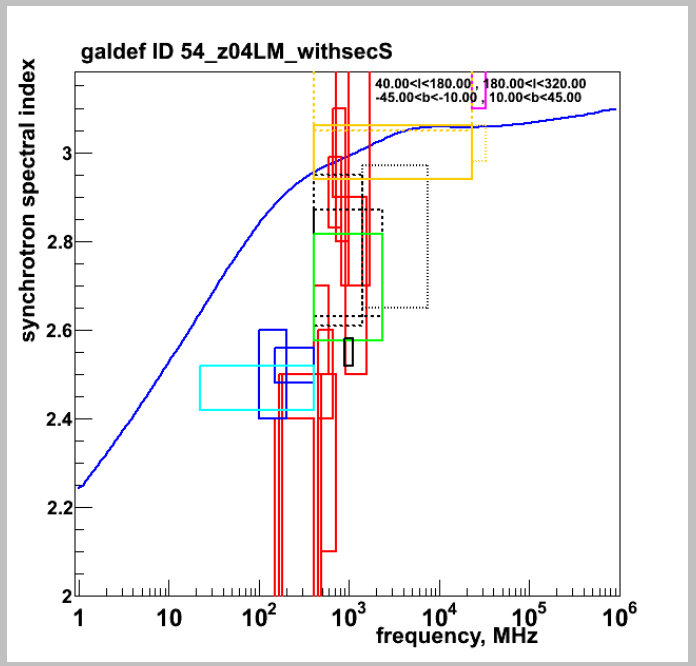
# Reacceleration model – in trouble with synchrotron




ELECTRONS




SYNCHROTRON

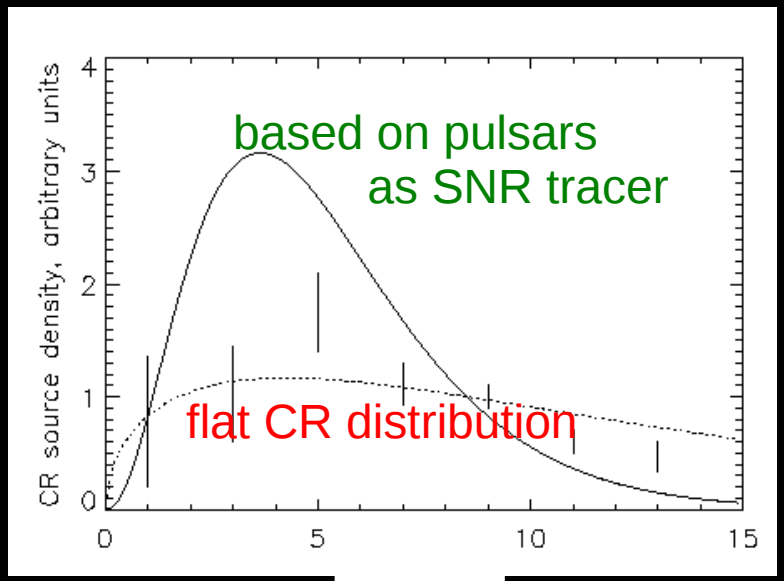



Strong, Orlando & Jaffe (2011) A&A 534, A54

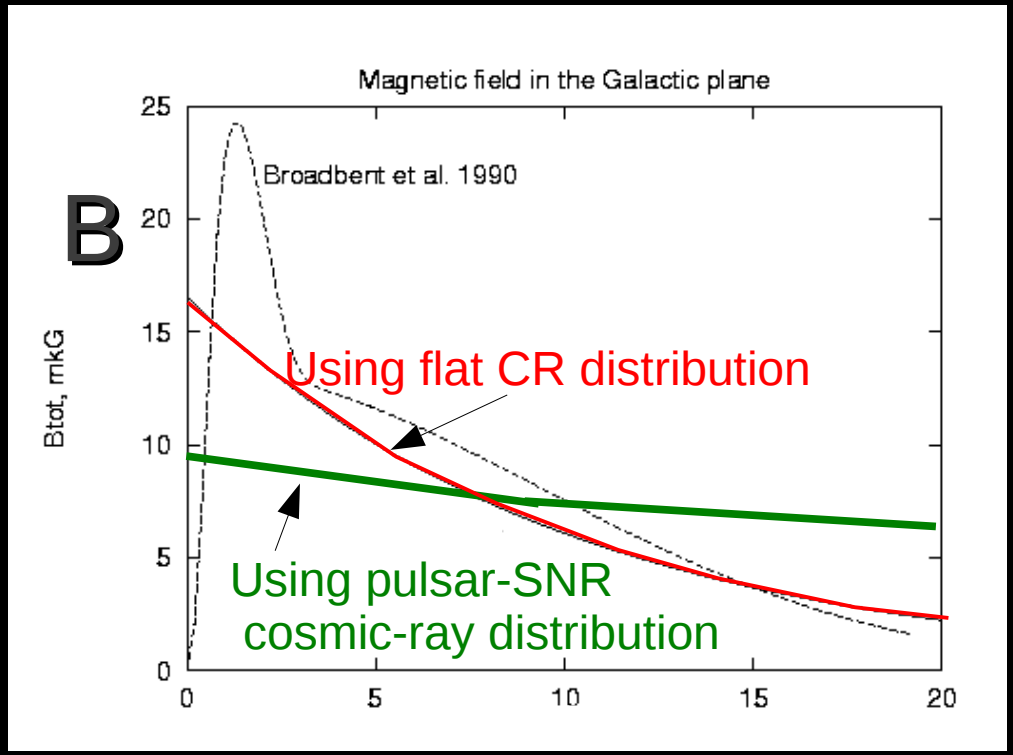
*from synchrotron and cosmic-ray propagation model :*

$$B_{tot}(\mu G) = 7\, e^{-(R - Ro)/30\ kpc\ -\ |z|/4\ kpc}$$

cosmic-ray source distribution




R, kpc




R, kpc

Using cosmic-ray distribution consistent with Fermi data, essentially no R- dependence of $B_{tot}$

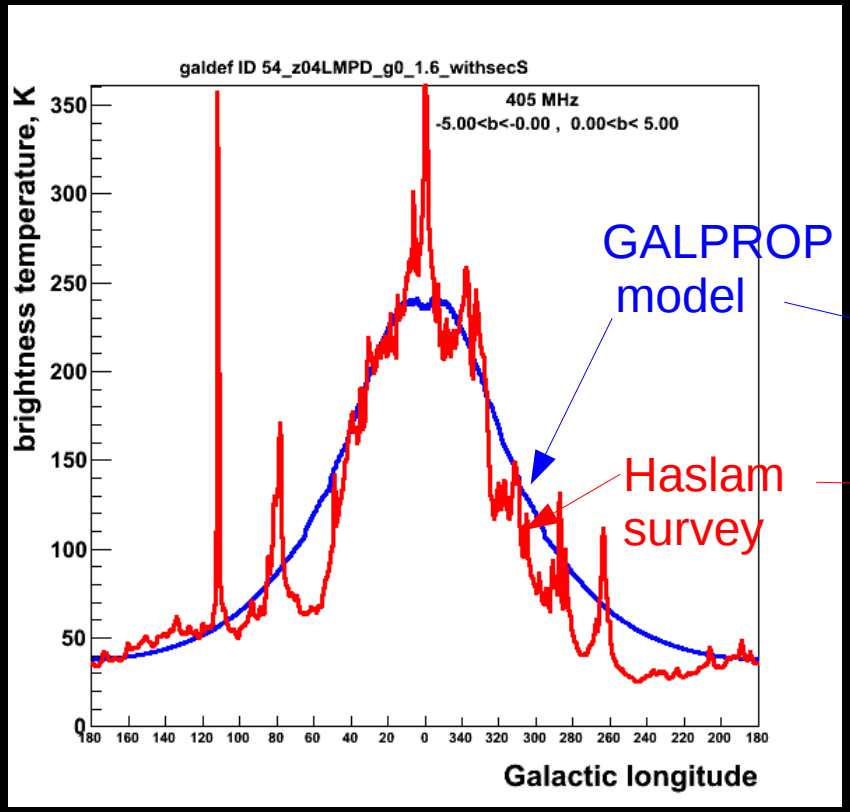
Only by combining gammas, electrons and synchrotron data can we get $B_{tot}$ !

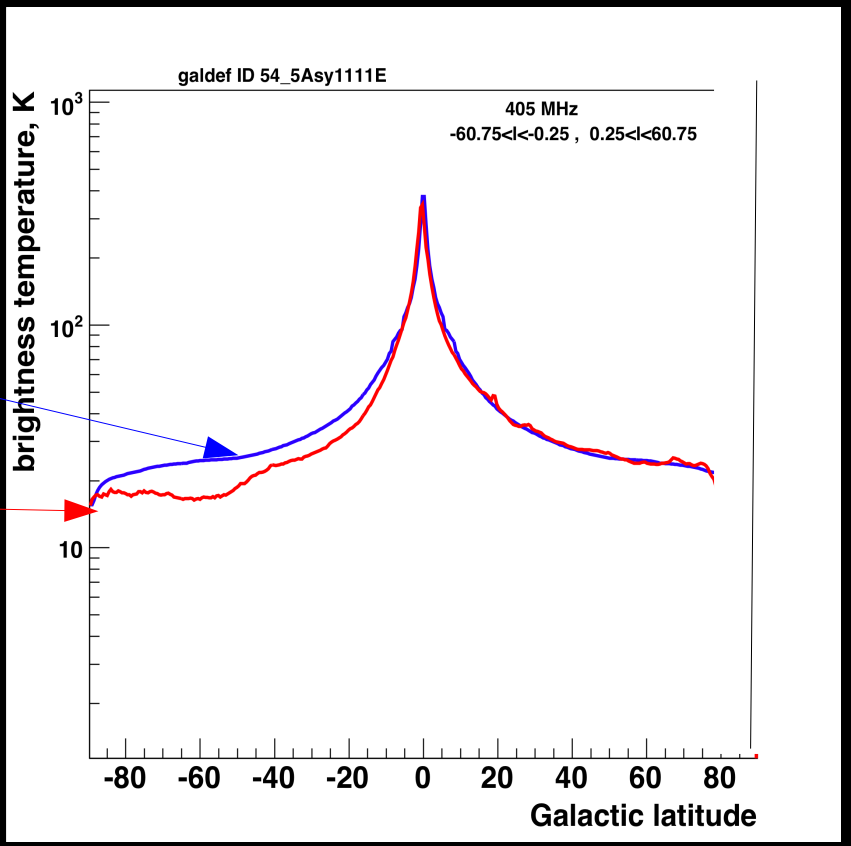
# SYNCHROTRON

408 MHz

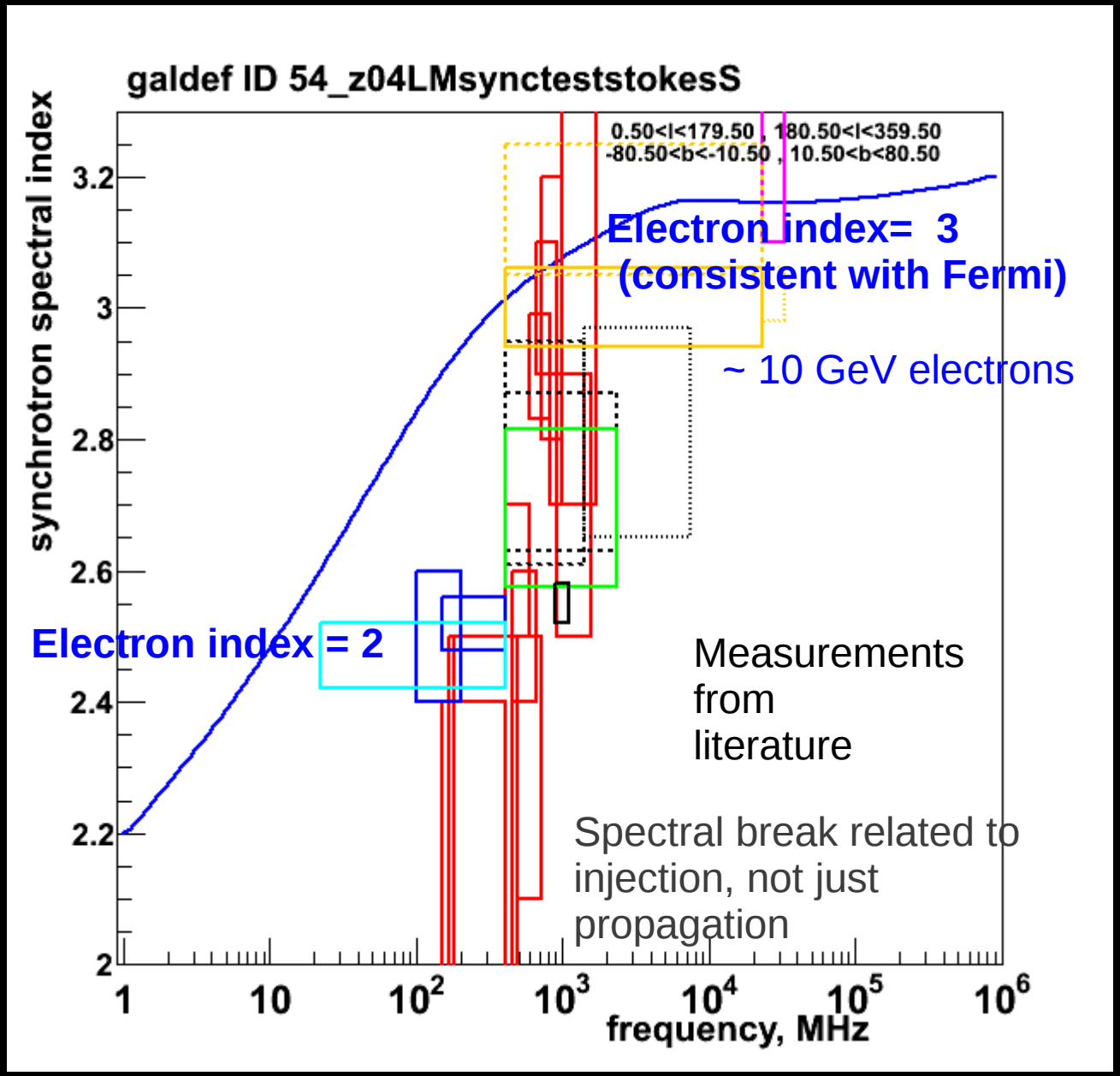
|b| < 5°

| *l* | < 60°

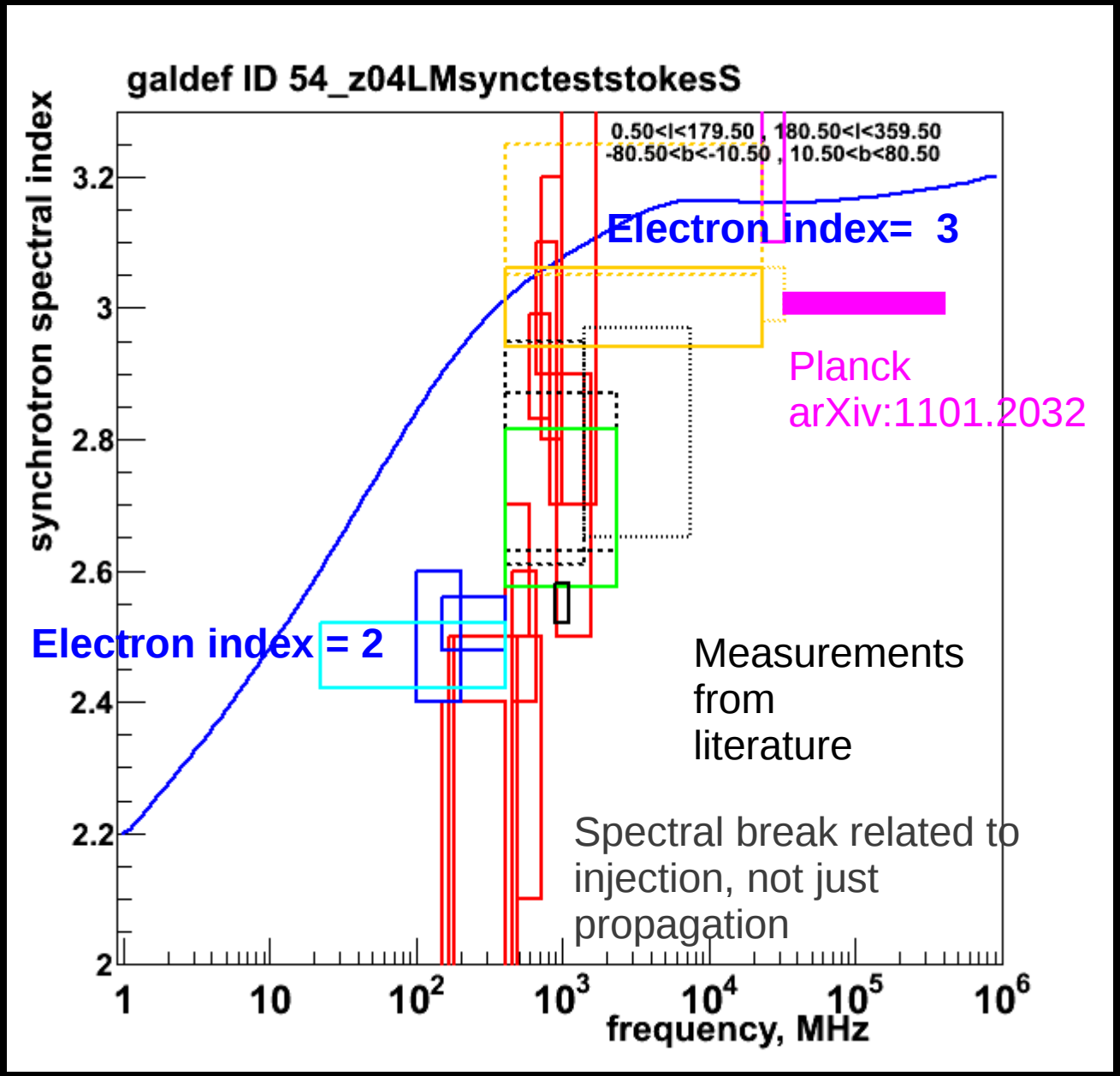


# Synchrotron Spectral index vs frequency



# Synchrotron Spectral index vs frequency



Facit for electrons - synchrotron

Synchrotronl apectra break by 0.5  at GHz,
→  Electron spectral break 1 at  few  GeV

Hard to explain  by propagation or energy loss

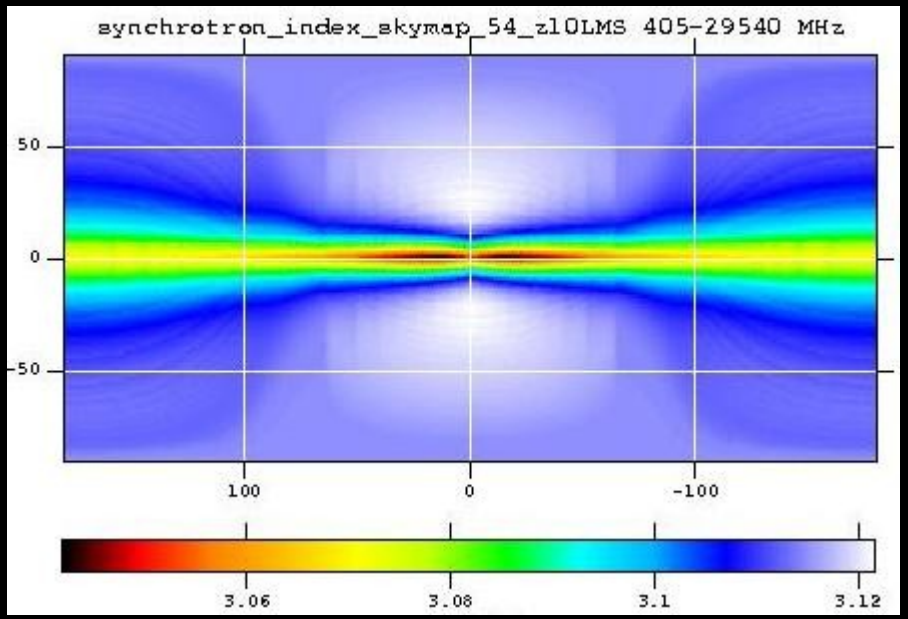
Instead need:
Injection spectrum break from 1.3 to 2.3 at  few GeV

Relevant to GC !

Model Synchrotron spectral index

408 MHz – 23 GHz

latitude




longitude

Model predicts  small but systematic variations.
Reality is of course much more complex.
The model gives a minimum underlying variation from electron propagation.

# Connecting Synchrotron, Cosmic Rays, and Magnetic Fields in the Plane of the Galaxy

T. R. Jaffe [1,2⋆], A. J. Banday[1,2,3]†, J. P. Leahy[4]‡, S. Leach[5,6]§, A. W. Strong[7]¶

[1] *Université de Toulouse; UPS-OMP; IRAP; Toulouse, France*
[2] *CNRS; IRAP; 9 Av. colonel Roche, BP 44346, F-31028 Toulouse cedex 4, France*
[3] *Max Planck Institute for Astrophysics, Karl-Schwarzschild Str. 1, D-85741 Garching, Germany*
[4] *Jodrell Bank Centre for Astrophysics, School of Physics and Astronomy, The University of Manchester, Oxford Road, Manchester, M13 9PL, United Kingdom*
[5] *SISSA, Astrophysics Sector, via Beirut 2-4, I-34014 Trieste, Italy.*
[6] *INFN, Sezione di Trieste, I-34014 Trieste, Italy.*
[7] *Max-Planck-Institut für Extraterrestrische Physik, Postfach 1312, D-85741 Garching, Germany*

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Uses RMs, polarization.
Cosmic-ray electrons using GALPROP.

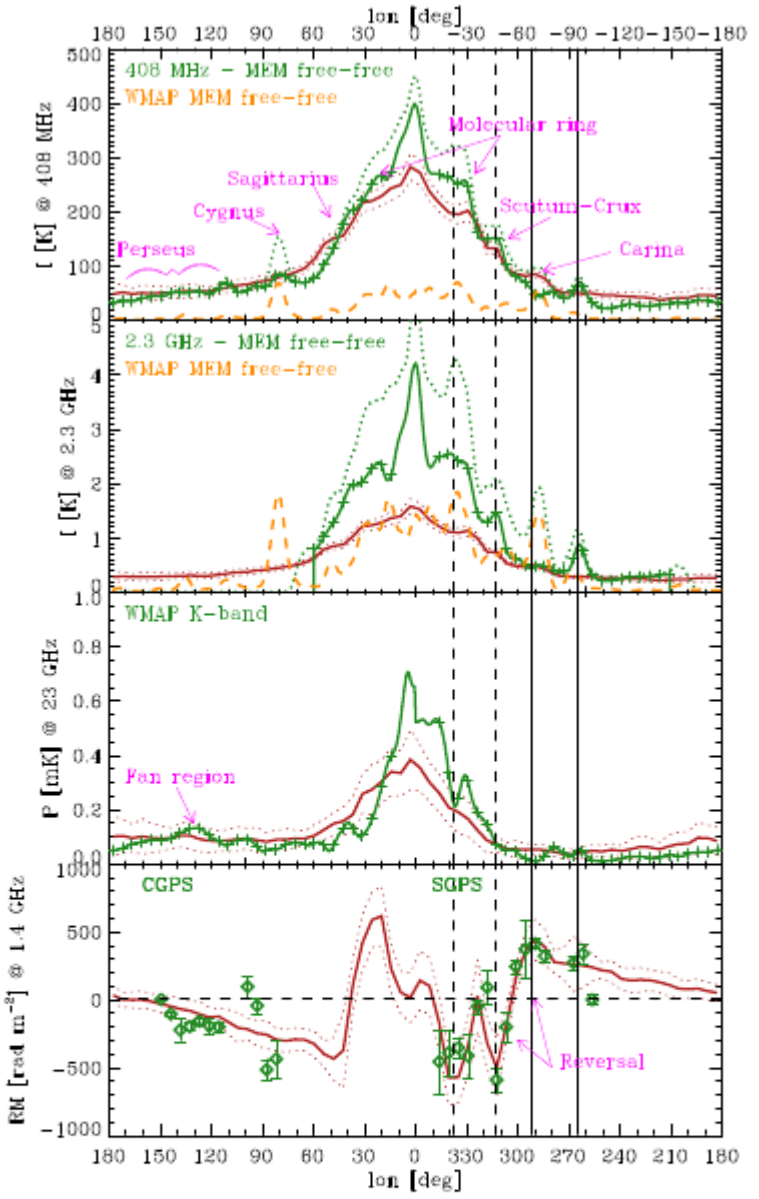
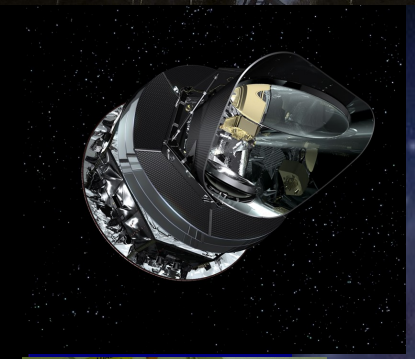
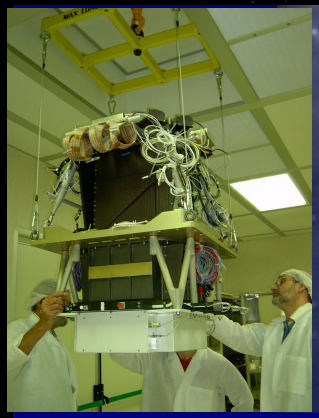



**Figure 1.** The available observables (*green*) tracing the Galactic magnetic field. The over-plotted model (*red*) is the original model from Paper I, while the data have been updated somewhat. See text in § 2. Furthermore, we have added the 2.3 GHz frequency which clearly shows that the power-law CRE spectrum does not match all of the data. (The *dotted green* line is the raw data, while the *solid* is that after a free-free estimate, show in *dashed orange*, is subtracted. See § 2.3.)

EXPERIMENTS





THEORY

intergalactic space

HALO

Secondary: $^{10}$Be, $^{10,11}$B ... Fe..

Secondary: $e^{+-}$ $\bar{p}$

cosmic-ray sources: p, He .. Ni, $e^-$

synchrotron

B-field

$\pi^o$ gas

ISRF

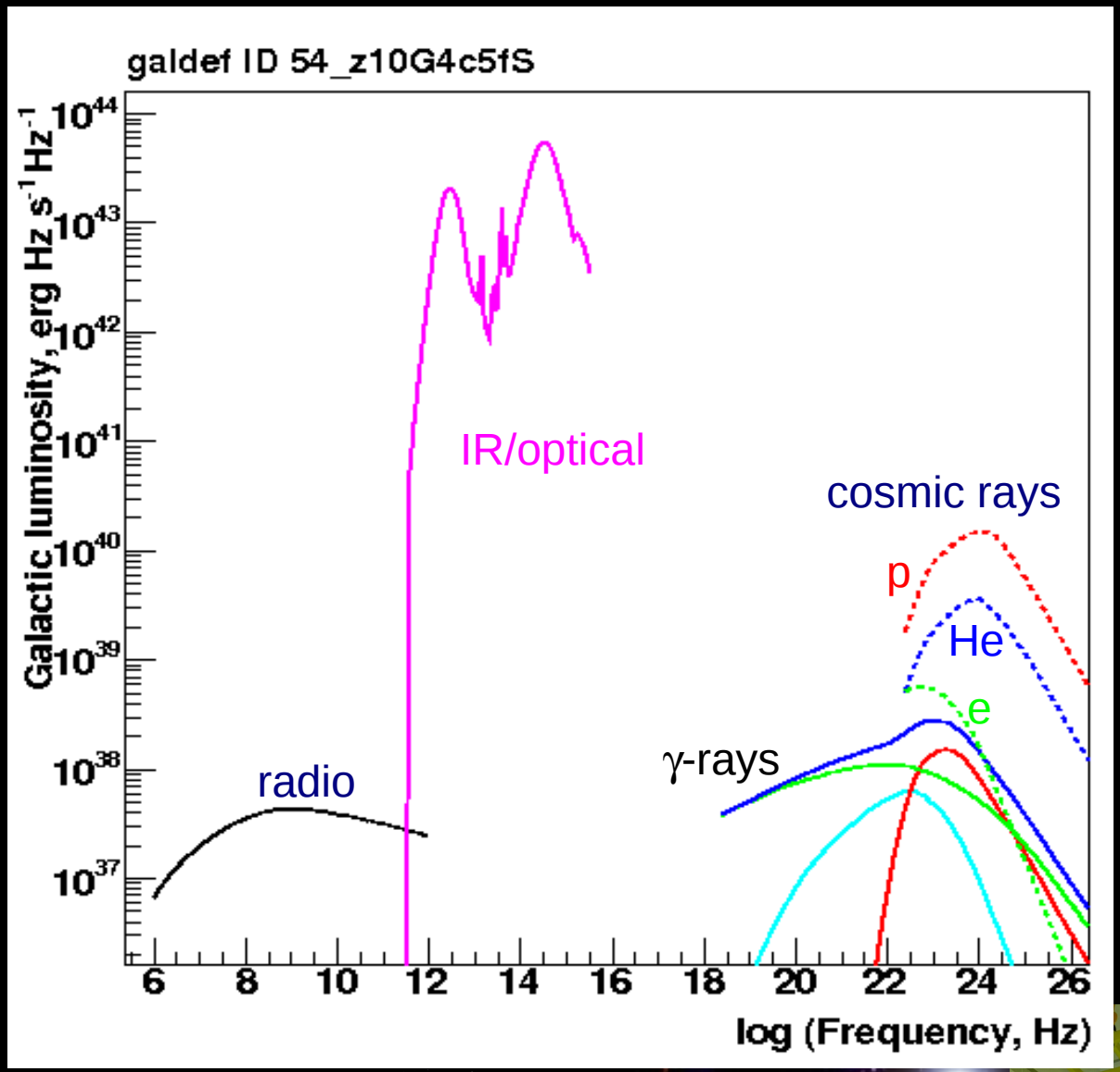
bremsstrahlung

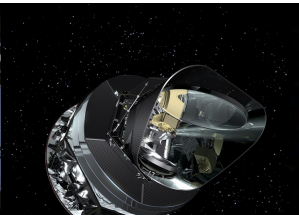
inverse Compton

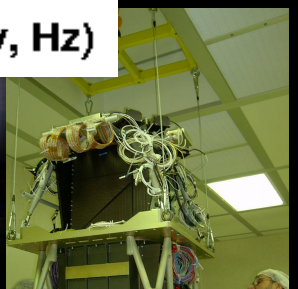
$\gamma$ – rays

GALPROP : models all that !

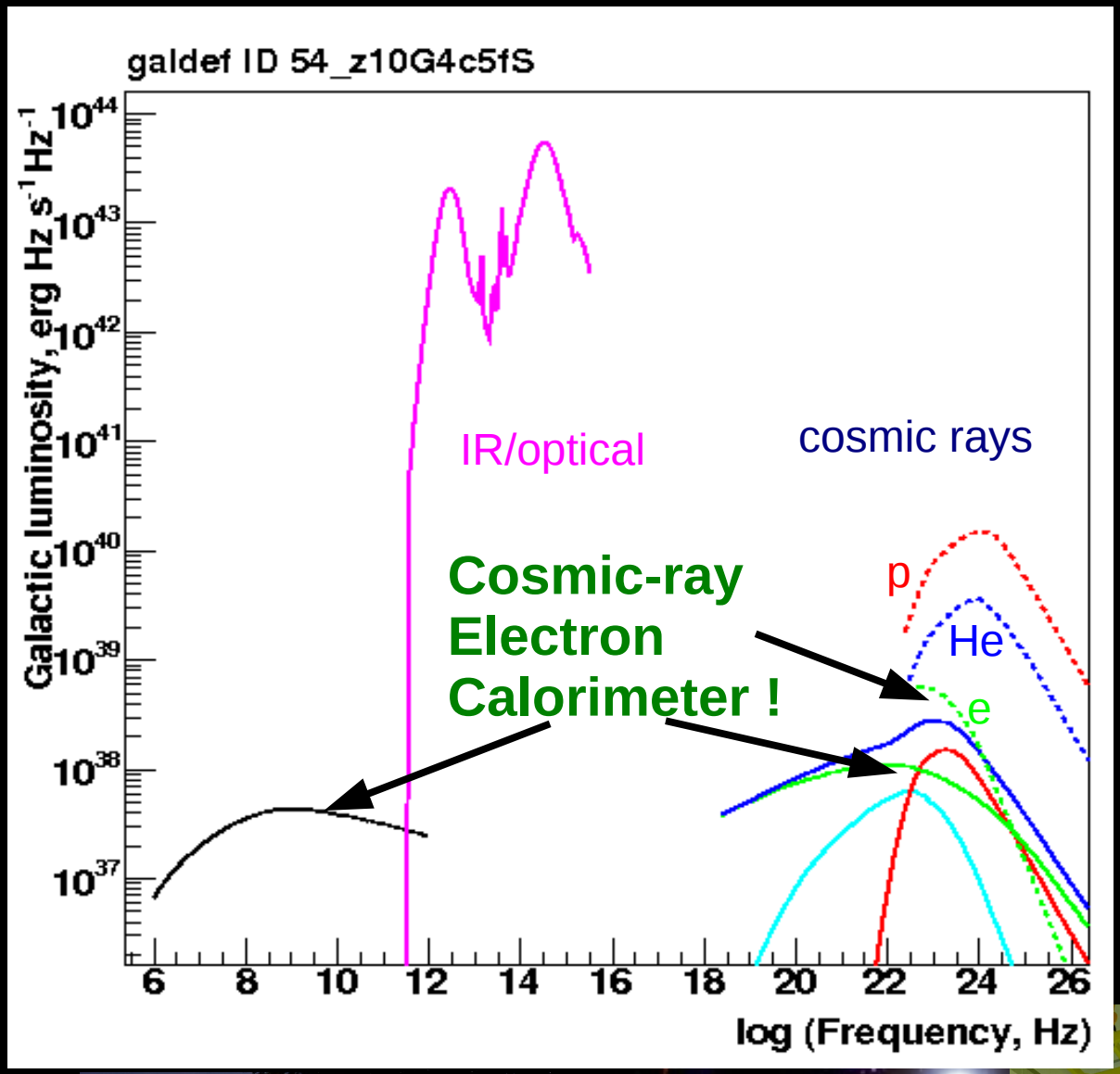
# Galaxy luminosity over 20 decades of energy





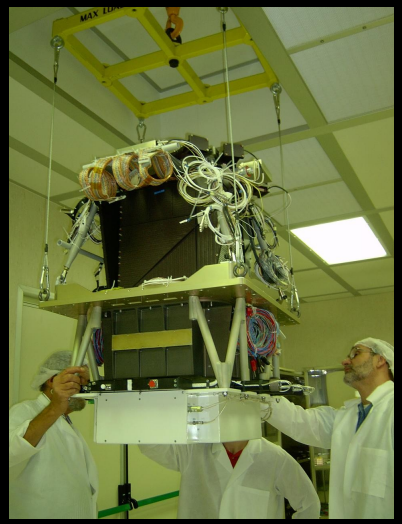


# Galaxy luminosity over 20 decades of energy



# Conclusion

## We can use Galactic-scale data to help understand the GC

.

Essential to exploit synergy between
cosmic-rays - gammas – microwave - radio