
# The cosmic-ray / gamma-ray / synchrotron / magnetic field connection in the Galaxy : with new insights from Fermi-LAT

Andy Strong

*on behalf of Fermi-LAT collaboration*

Infrared emission, ISM and star formation

MPIA Heidelberg, 22-24 Feb 2010

Milky Way is a potentially interesting datum on FIR-radio correlation

because ...

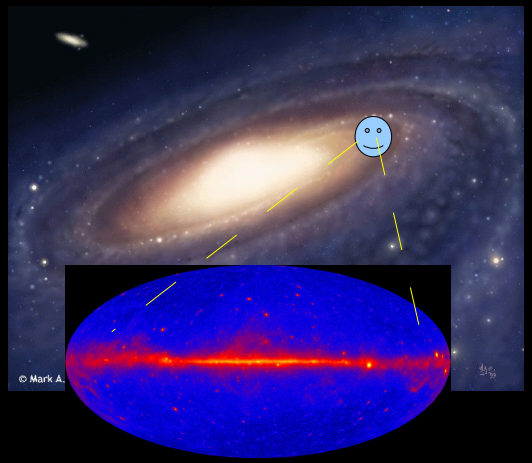
We know much more about our Galaxy than external galaxies:

* cosmic rays *directly* measured
* gamma rays mapped in detail
* synchrotron mapped in detail
* magnetic fields measured

so study of the Galaxy allows a better understanding of the detailed inner workings to clarify the overall picture

including e.g. CALORIMETRY

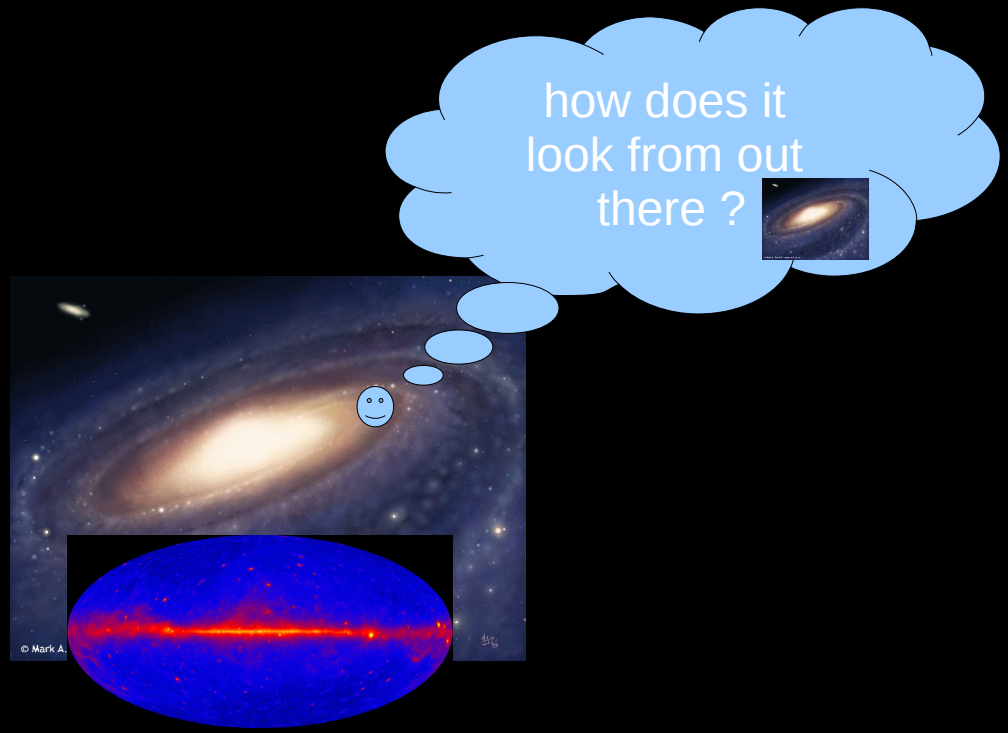
Since we live inside the Galaxy,
global properties e.g. luminosity
are not easy to deduce.



Since we live inside the Galaxy,
global properties e.g. luminosity
are not easy to deduce.

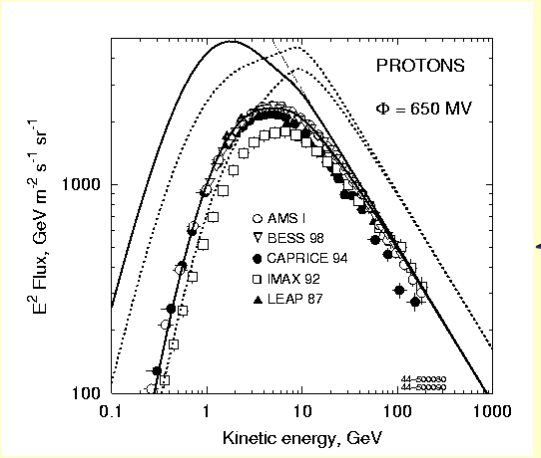
Model-dependent.

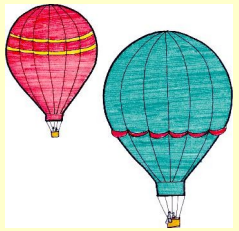
Need 3D models.

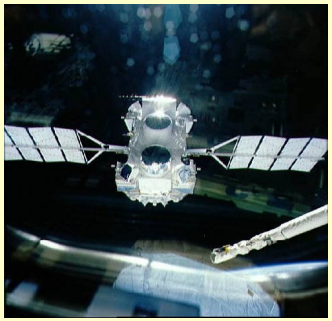


# The **goal** : use *all* types of data in self-consistent way to test models of cosmic-ray propagation.

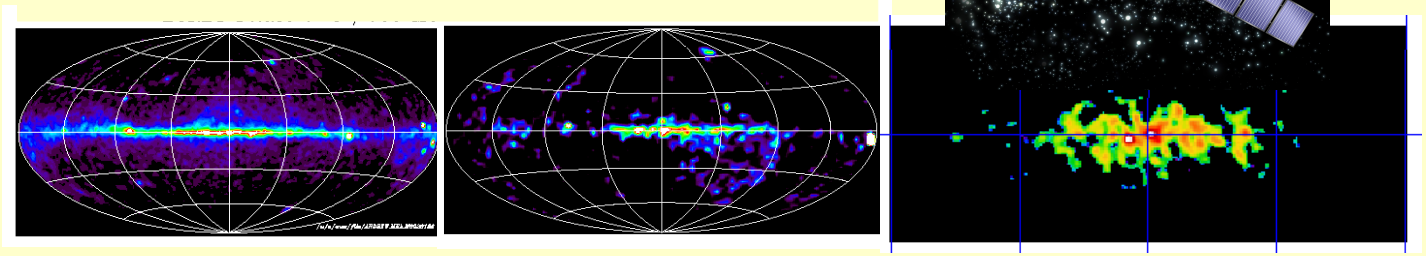
Observed *directly, near Sun:*
primary spectra (p, He ... Fe; $e^-$ )
secondary/primary (B/C etc)
secondary $e^+$ , antiprotons...



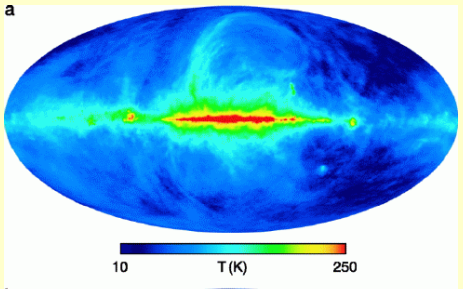



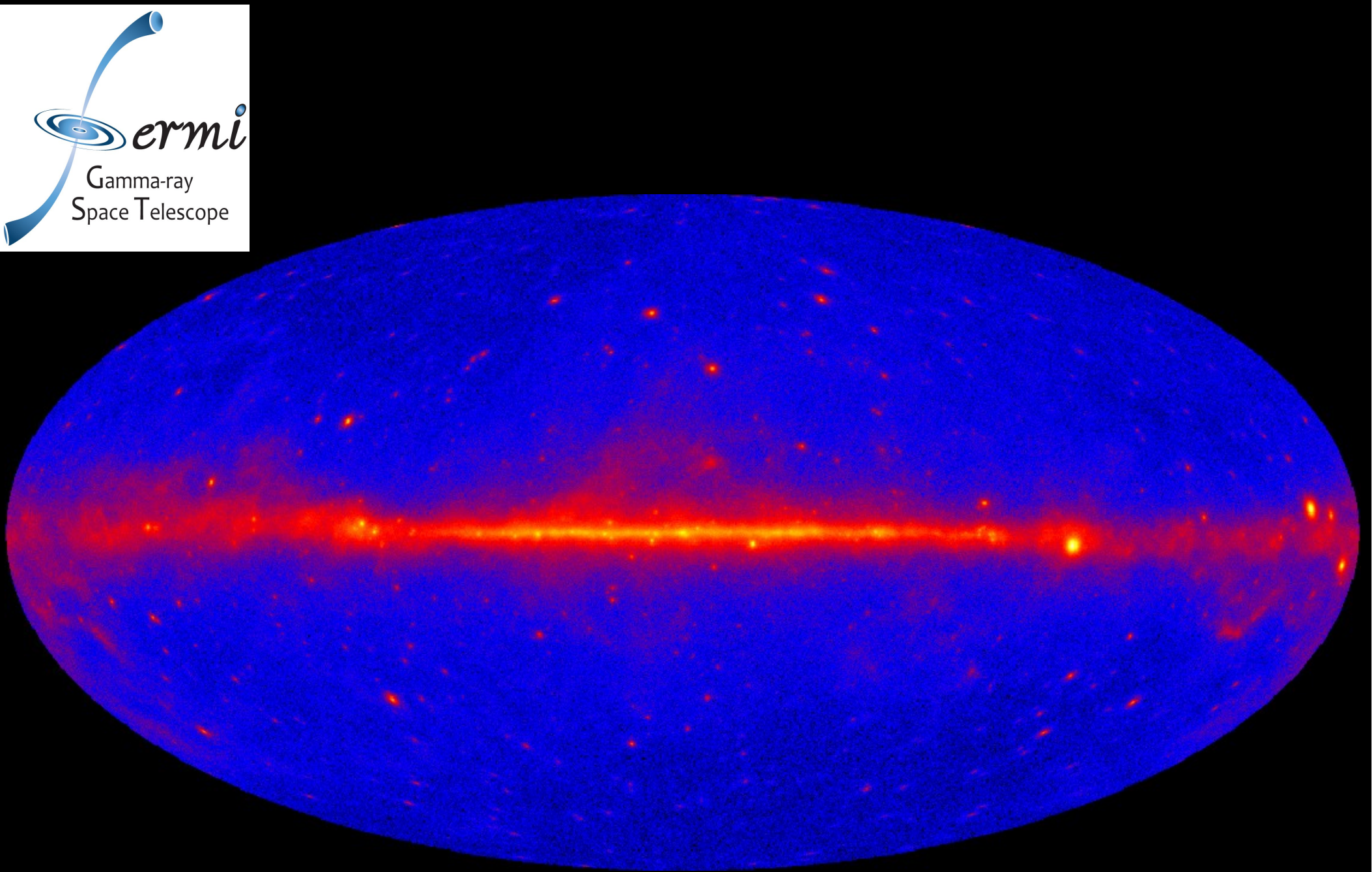


Observed *from whole Galaxy:*

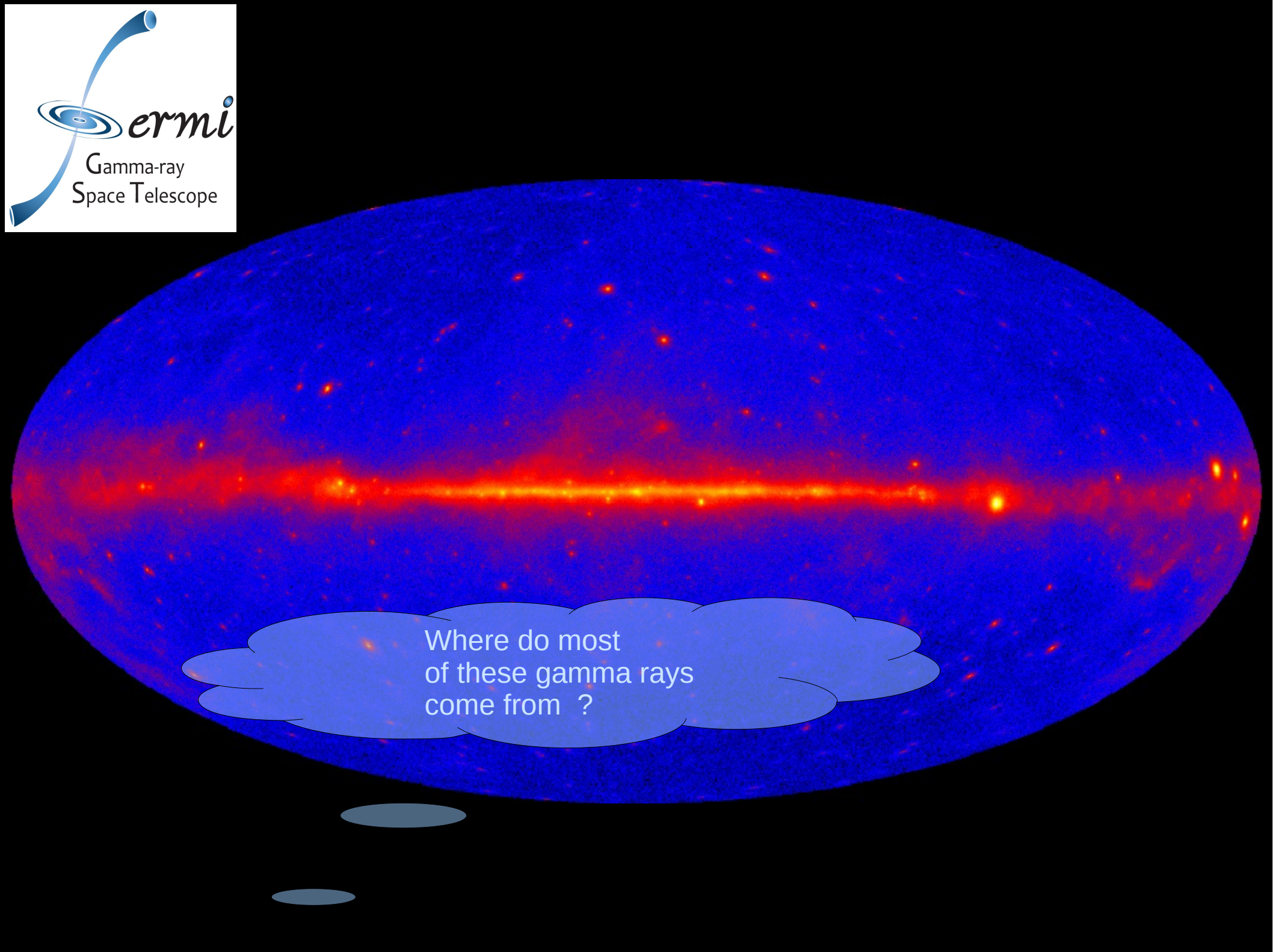


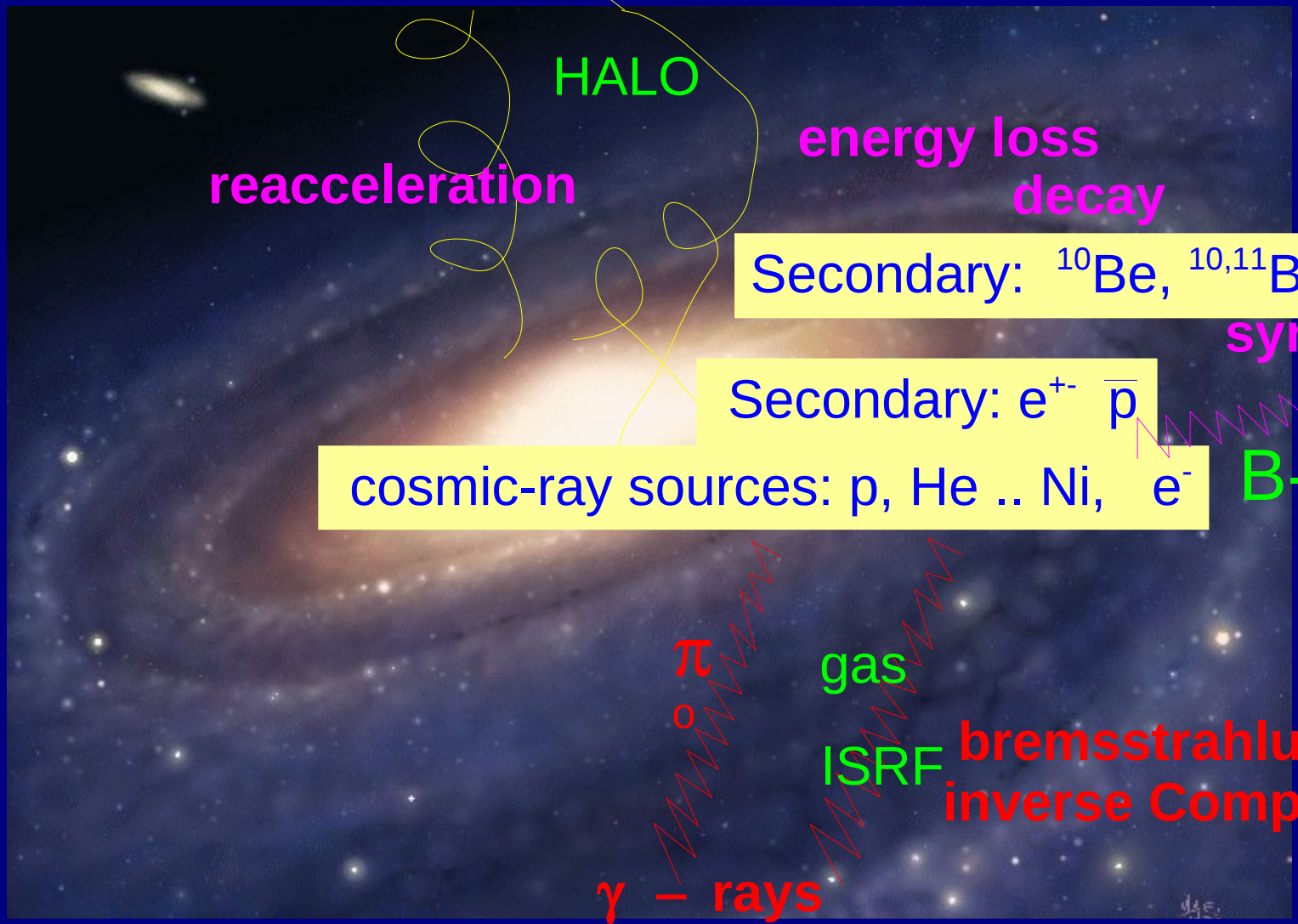
synchrotron




1st year skymap


Fermi
Gamma-ray
Space Telescope
Where do most
of these gamma rays
come from ?


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

# Modelling the gamma-ray sky

main ingredients of GALPROP model

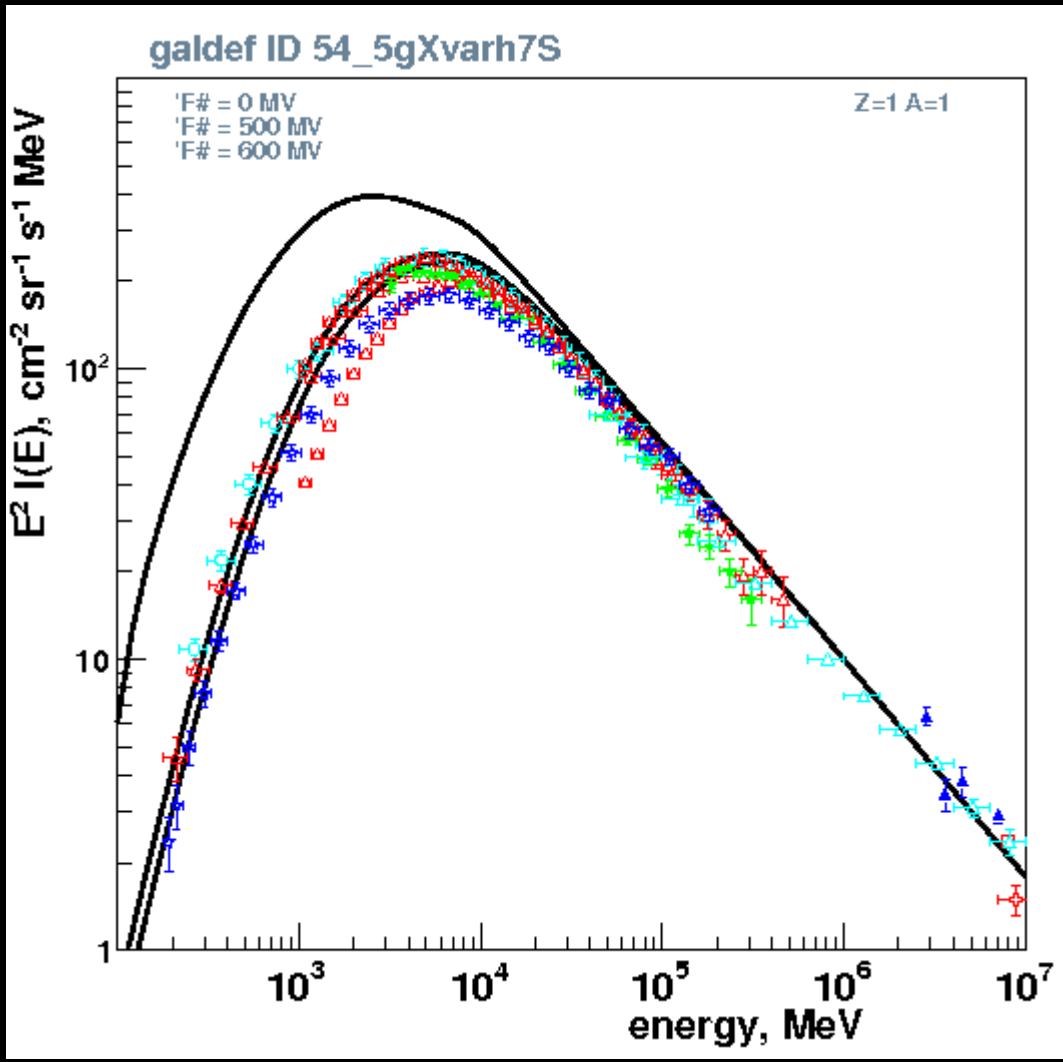
cosmic-ray spectra p , He , e- , e+ (including secondaries)
(+ *Fermi-measured* electrons)
cosmic-ray source distribution follows SNR/pulsars

B/C etc for propagation parameters
halo height = 4 - 10 kpc (from radioactive cosmic-ray nuclei)

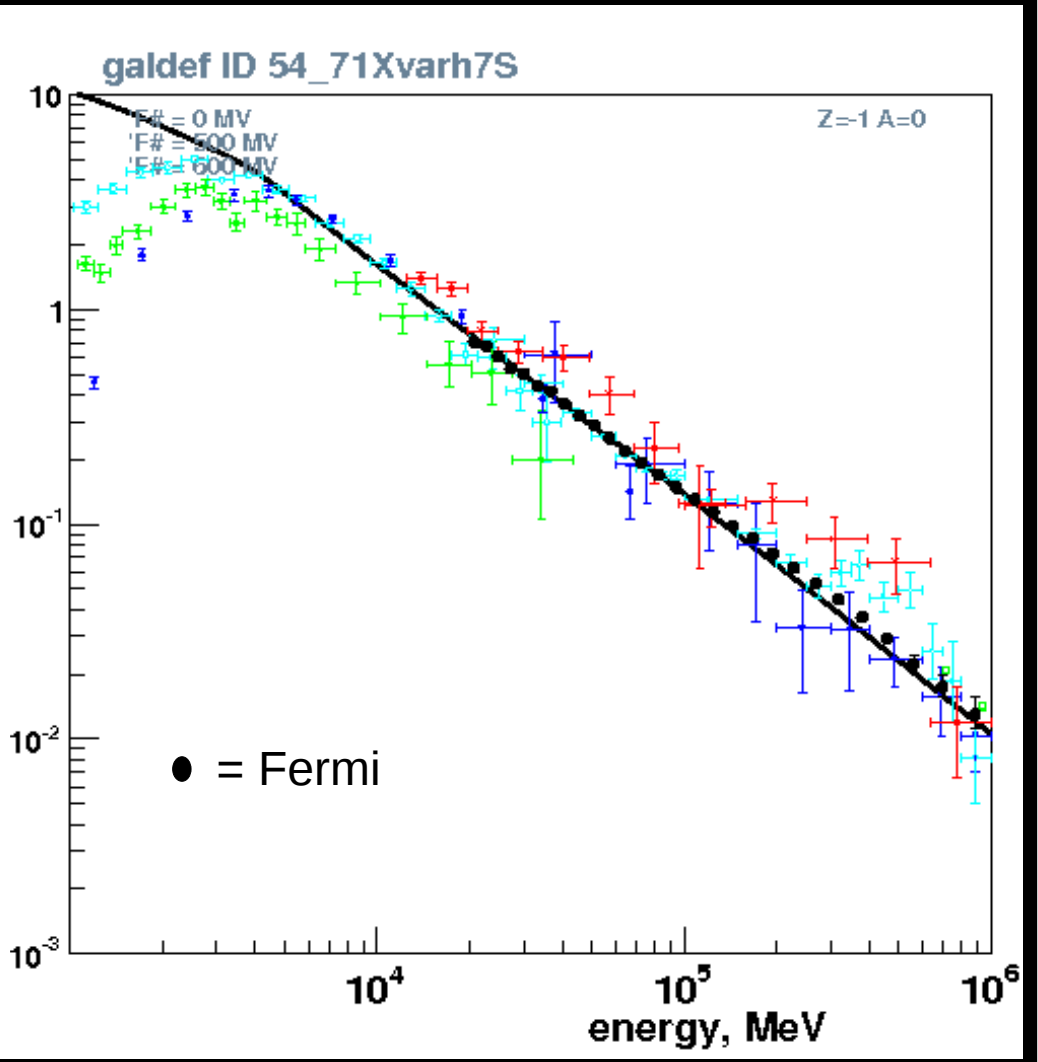
Interstellar radiation field
HI, CO surveys
CO-to-$H_2$ conversion a function of position in Galaxy
Fermi 1$^{st}$ Year Source Catalogue

# First use a model based on locally-measured cosmic rays

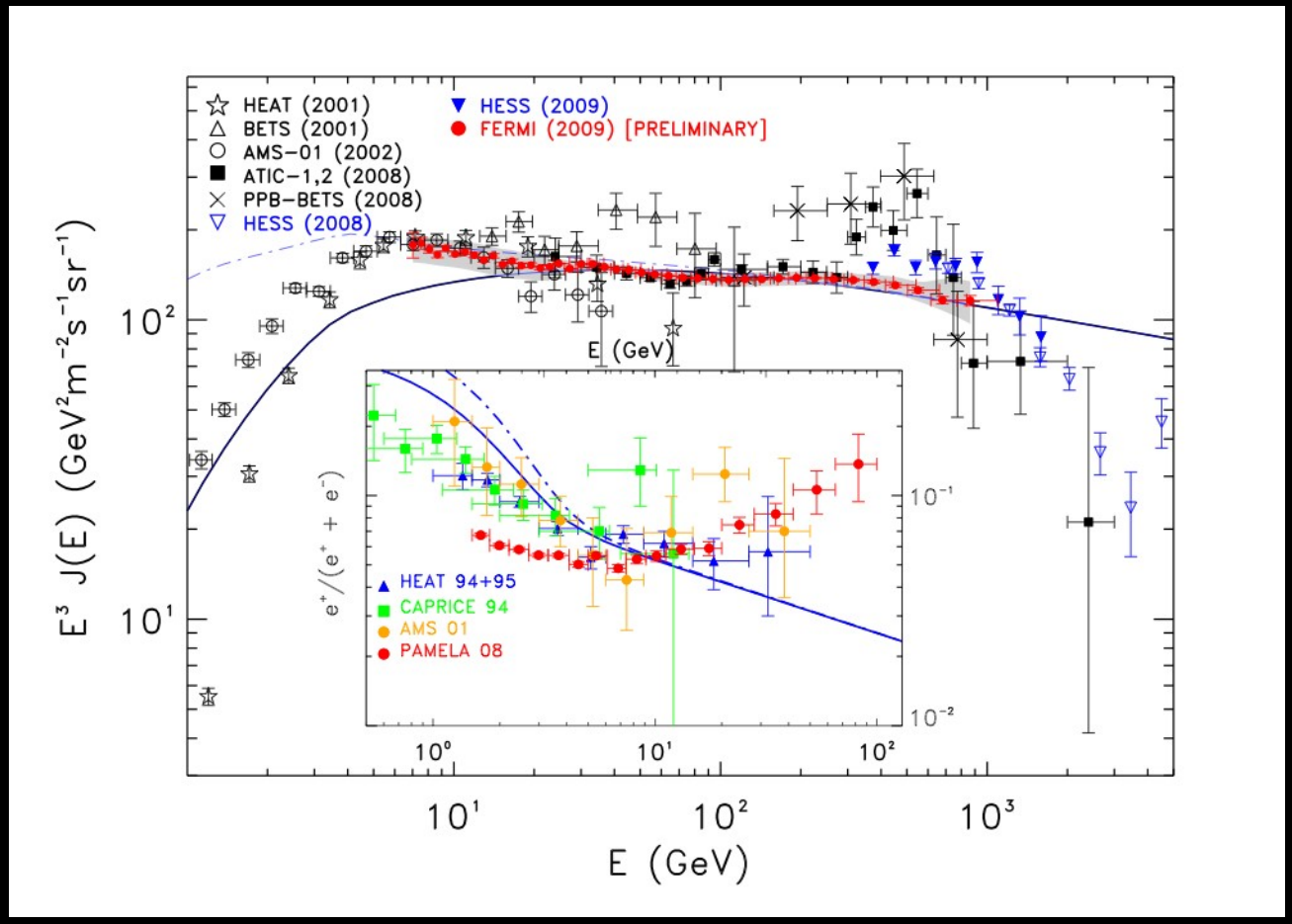
**PROTONS**




**ELECTRONS**



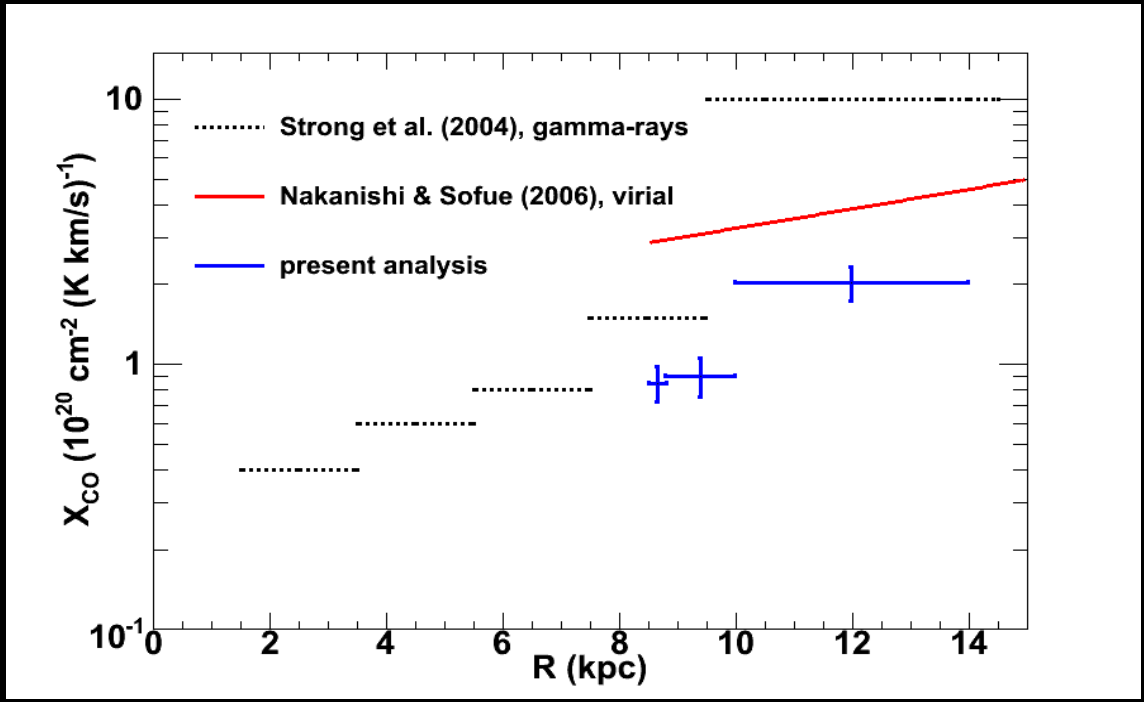
# Electron spectrum measured by Fermi-LAT extended down to 7 GeV




2009 Fermi Symposium: Latronico; Pesce-Rollins; Grasso

Abdo et al 2009 PRL.102, 181101, Grasso et al 2009 Astropart.Ph. 32, 140

# Gamma rays depend on molecular gas content of the outer Galaxy

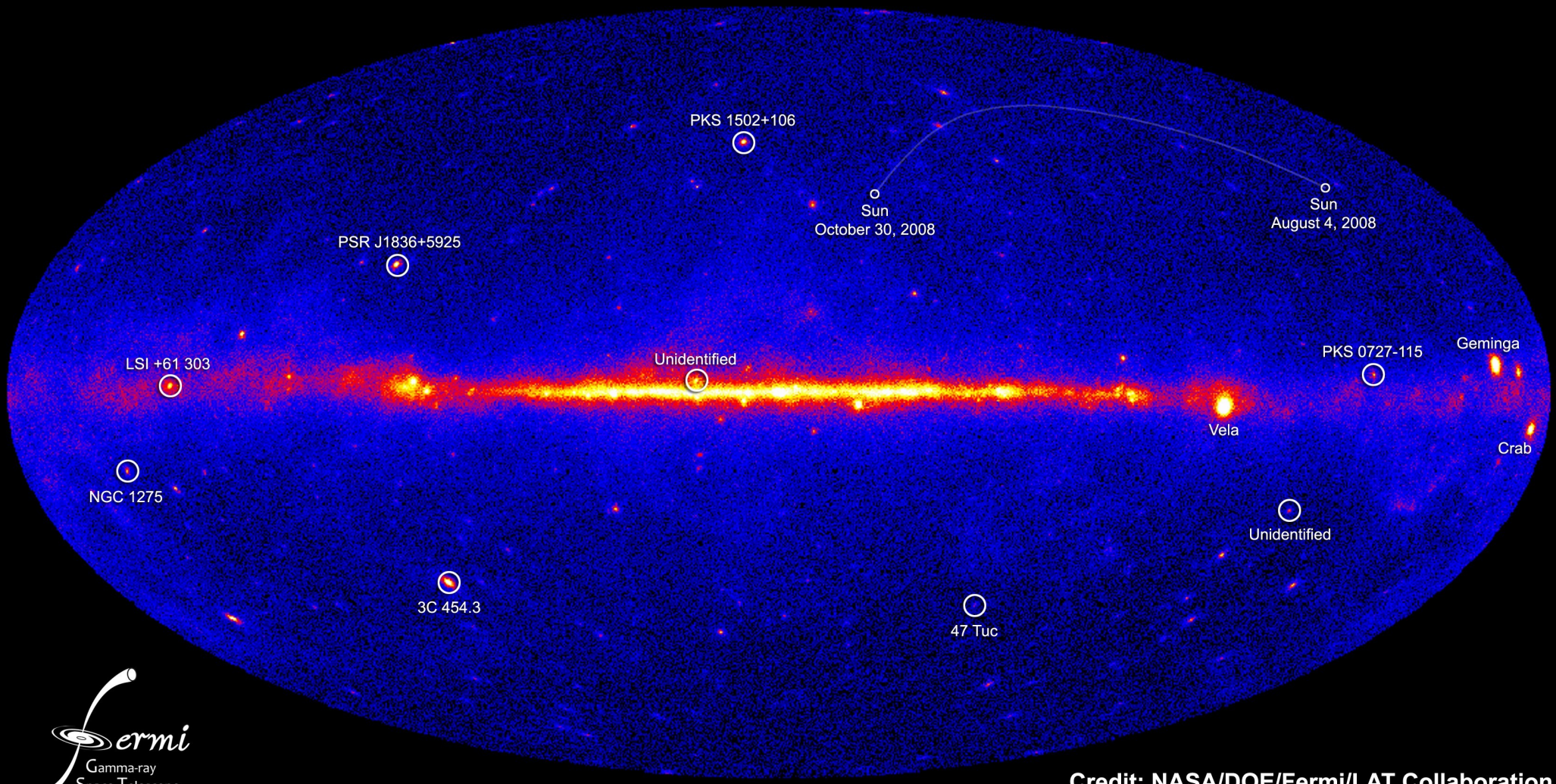



Conversion factor Xco from CO to $H_2$

Outer Galaxy

Luigi Tibaldo
Abdo etal (2010) ApJ 710, 133

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




Fermi Gamma-ray Space Telescope

Credit: NASA/DOE/Fermi/LAT Collaboration

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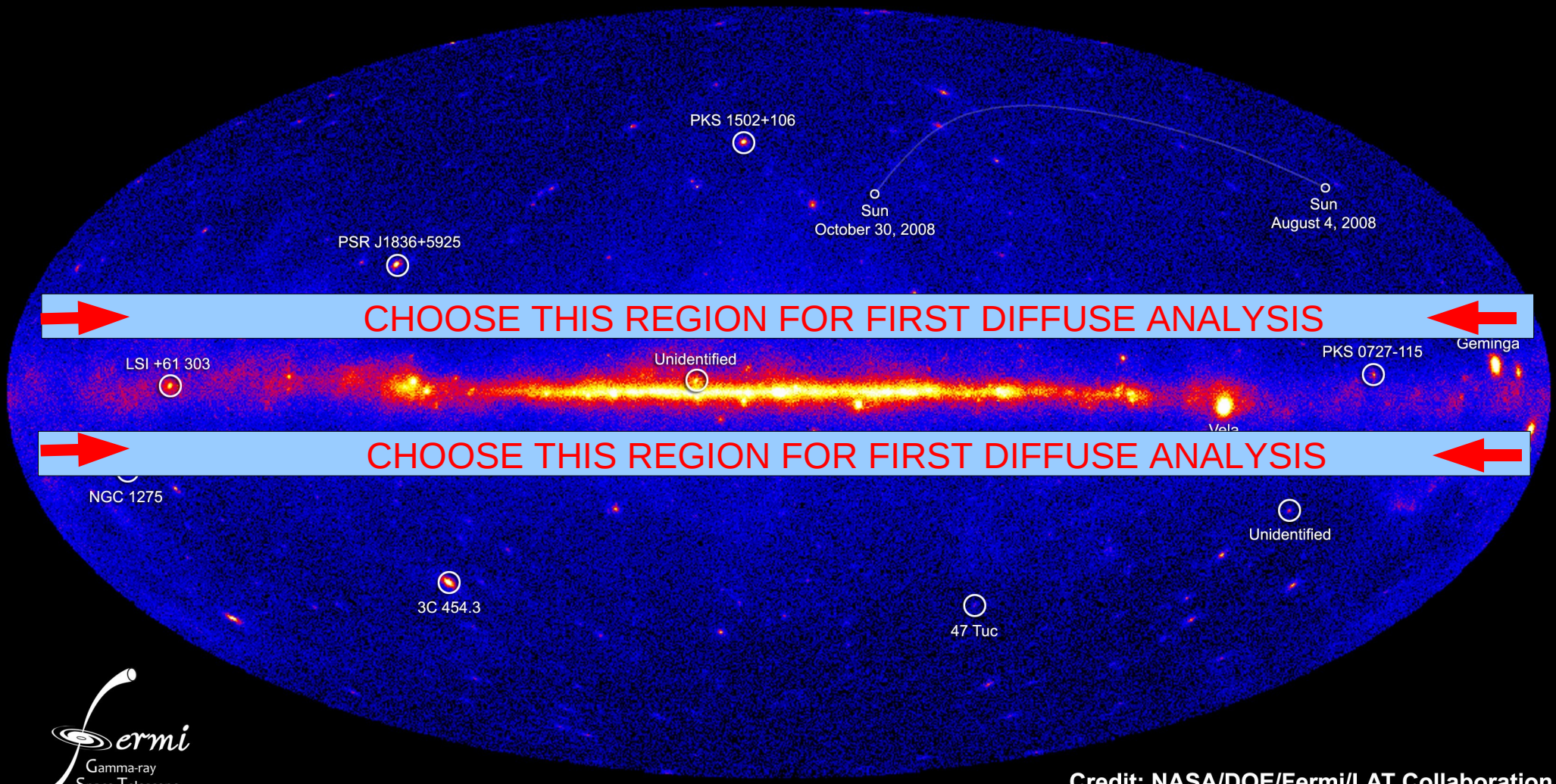
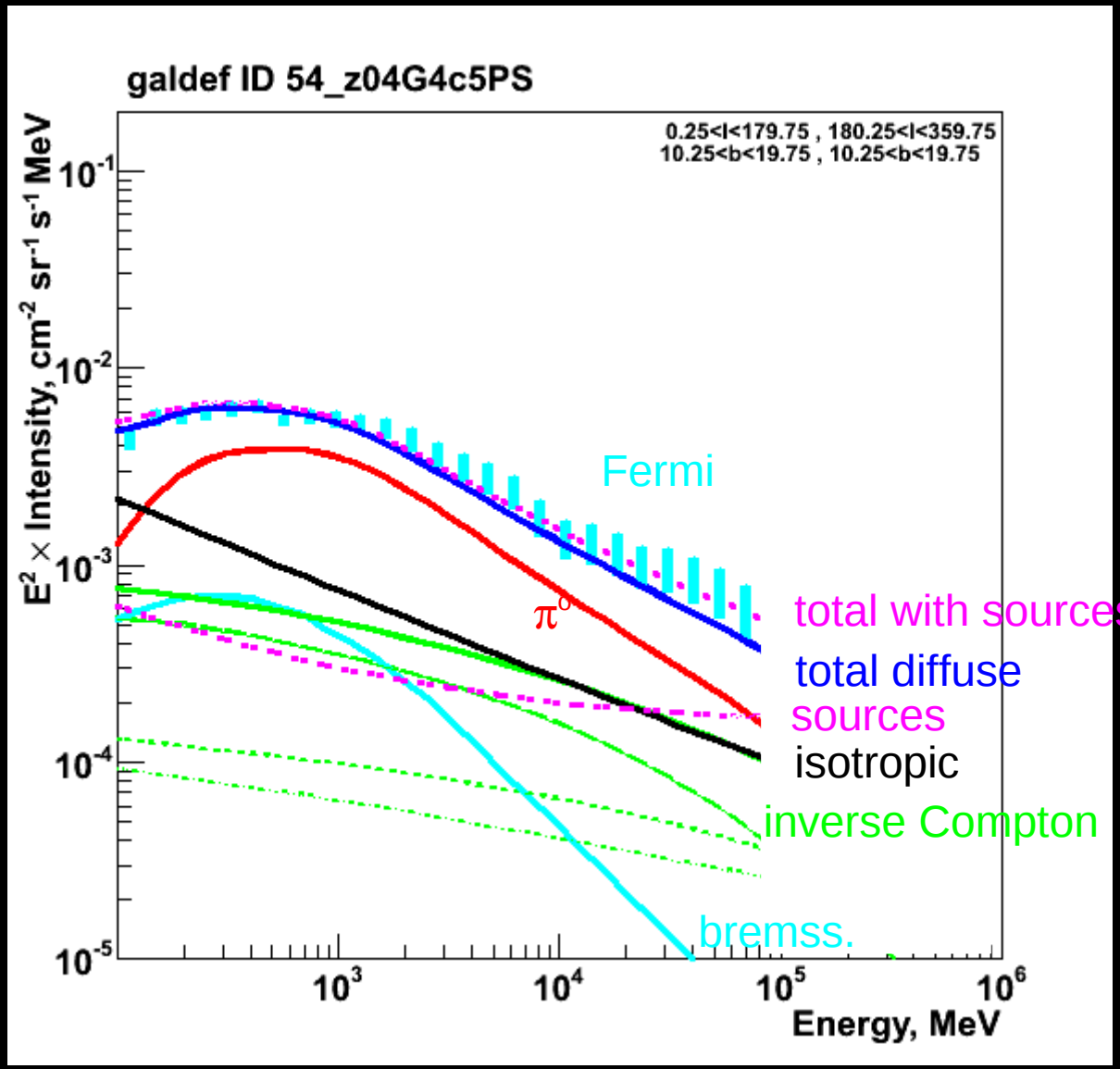



Fermi Gamma-ray Space Telescope

Credit: NASA/DOE/Fermi/LAT Collaboration

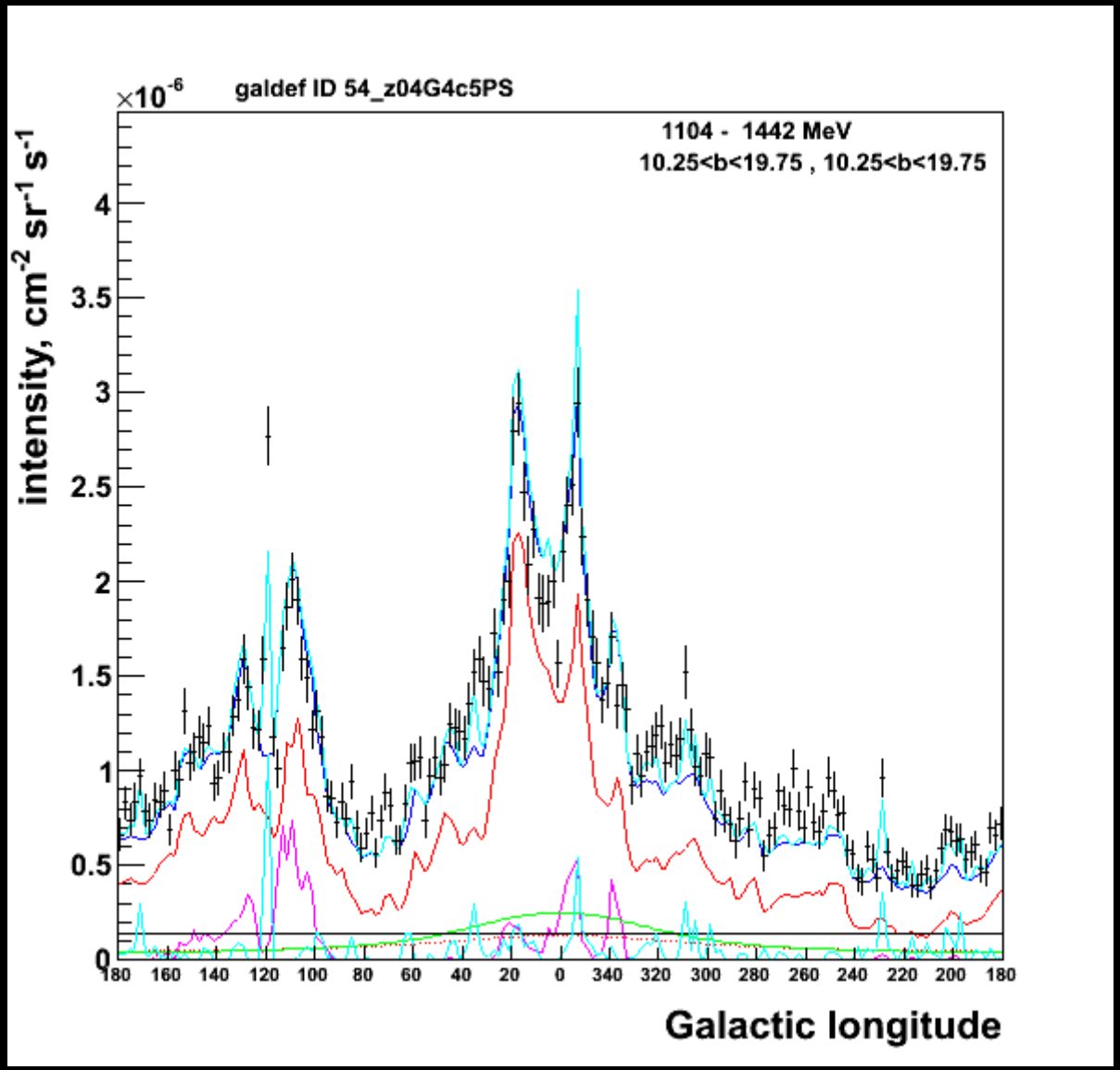
INTERMEDIATE LATITUDES
+10 < b < +20




PRELIMINARY

INTERMEDIATE LATITUDES
+10 < b < +20
1 GeV

total gas
traced by
dust from
IRAS+DIRBE
Finkbeiner etal 1999



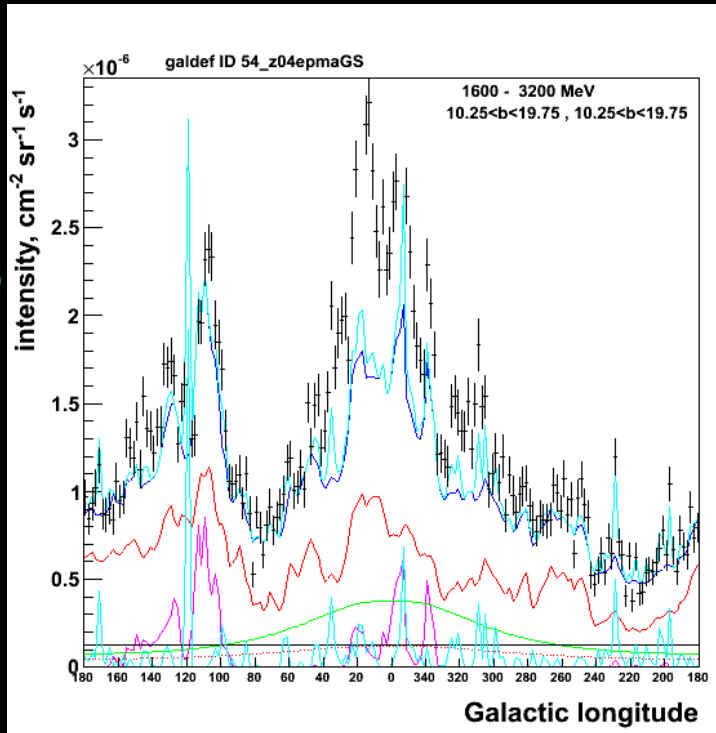

Remarkable agreement. Confirms that dust is a better tracer of local gas than HI+CO
(Grenier, Casandjian: found this in EGRET data)

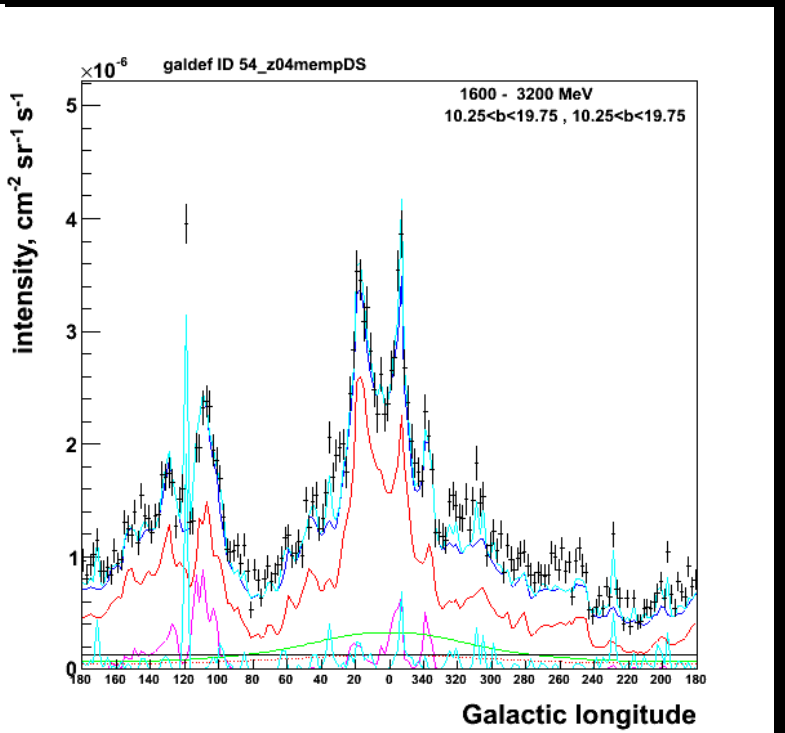
PRELIMINARY

**HI, CO** tracer of gas

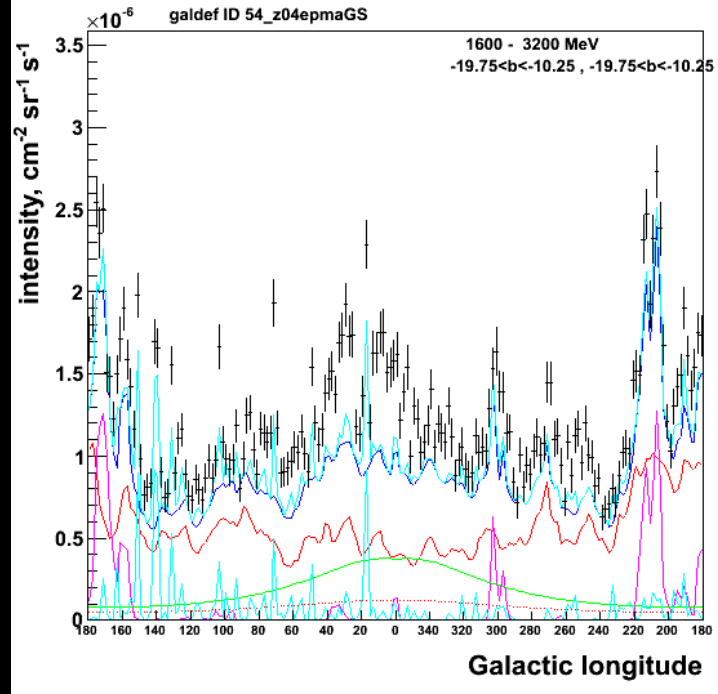
**dust** tracer of gas

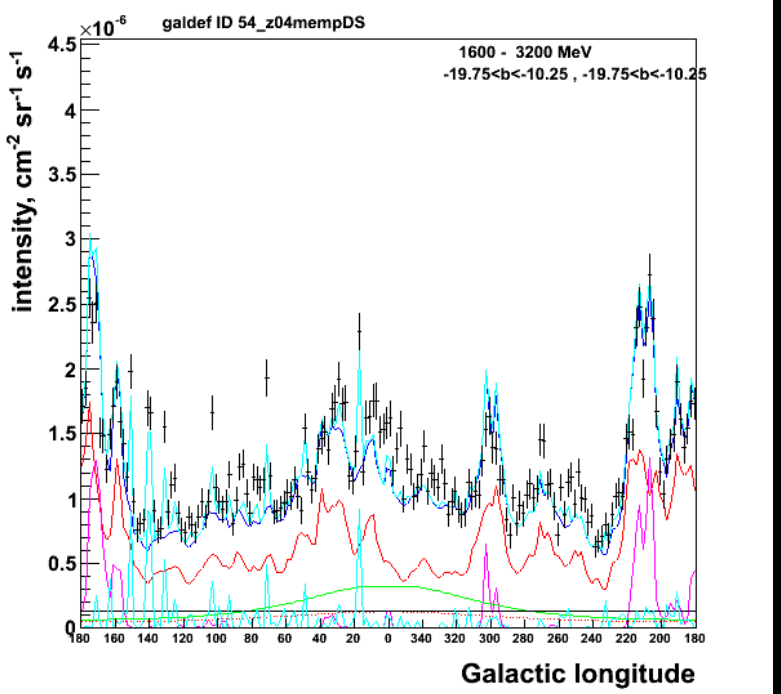
$+10^{o} < b < +20^{o}$



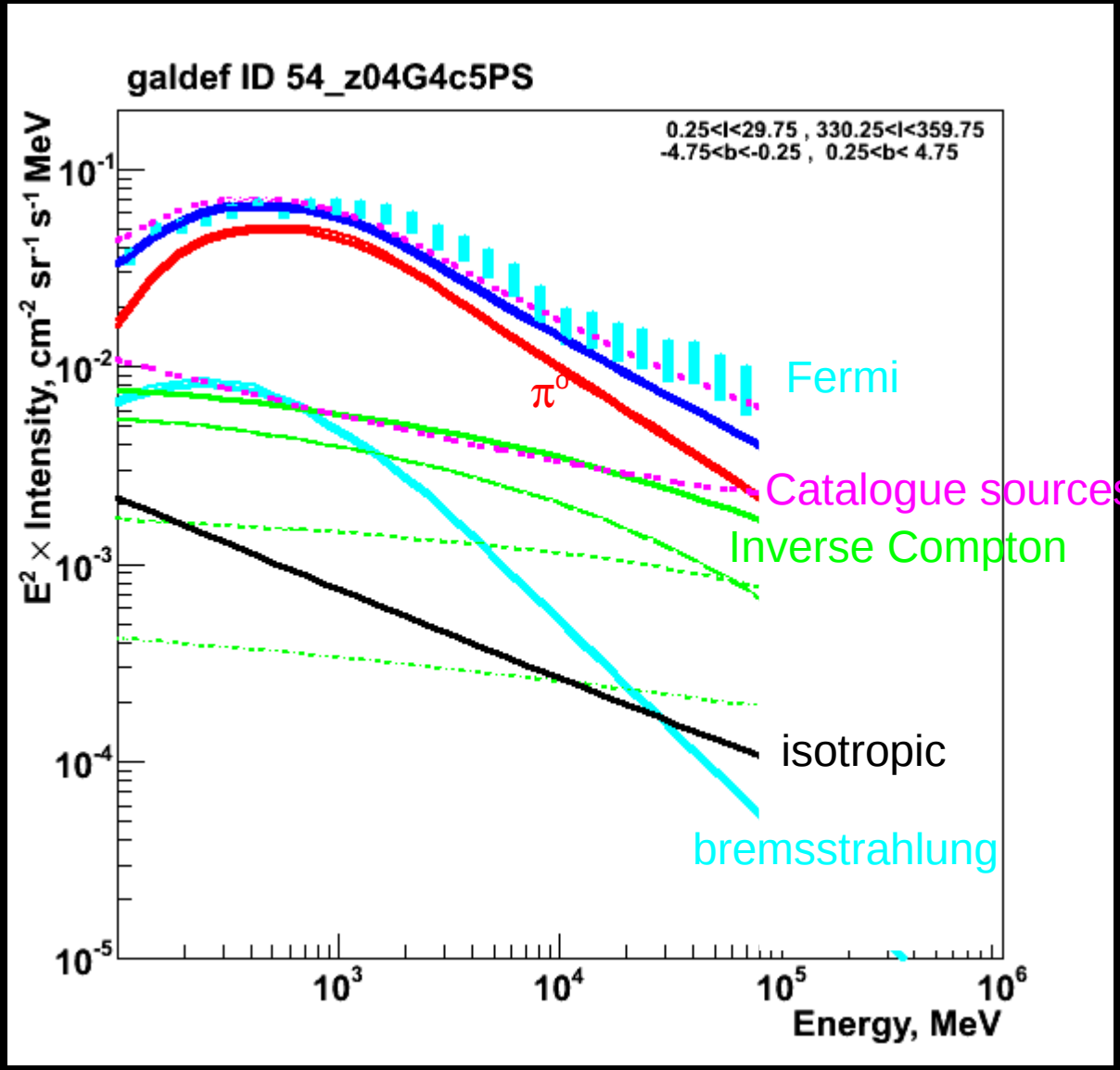

$-20^{o} < b < -10^{o}$




Confirms that dust is a better tracer of local gas than HI+CO in these regions !

# Inner Galaxy
# $330^o < l < 30^o$, $|b|<5^o$




PRELIMINARY

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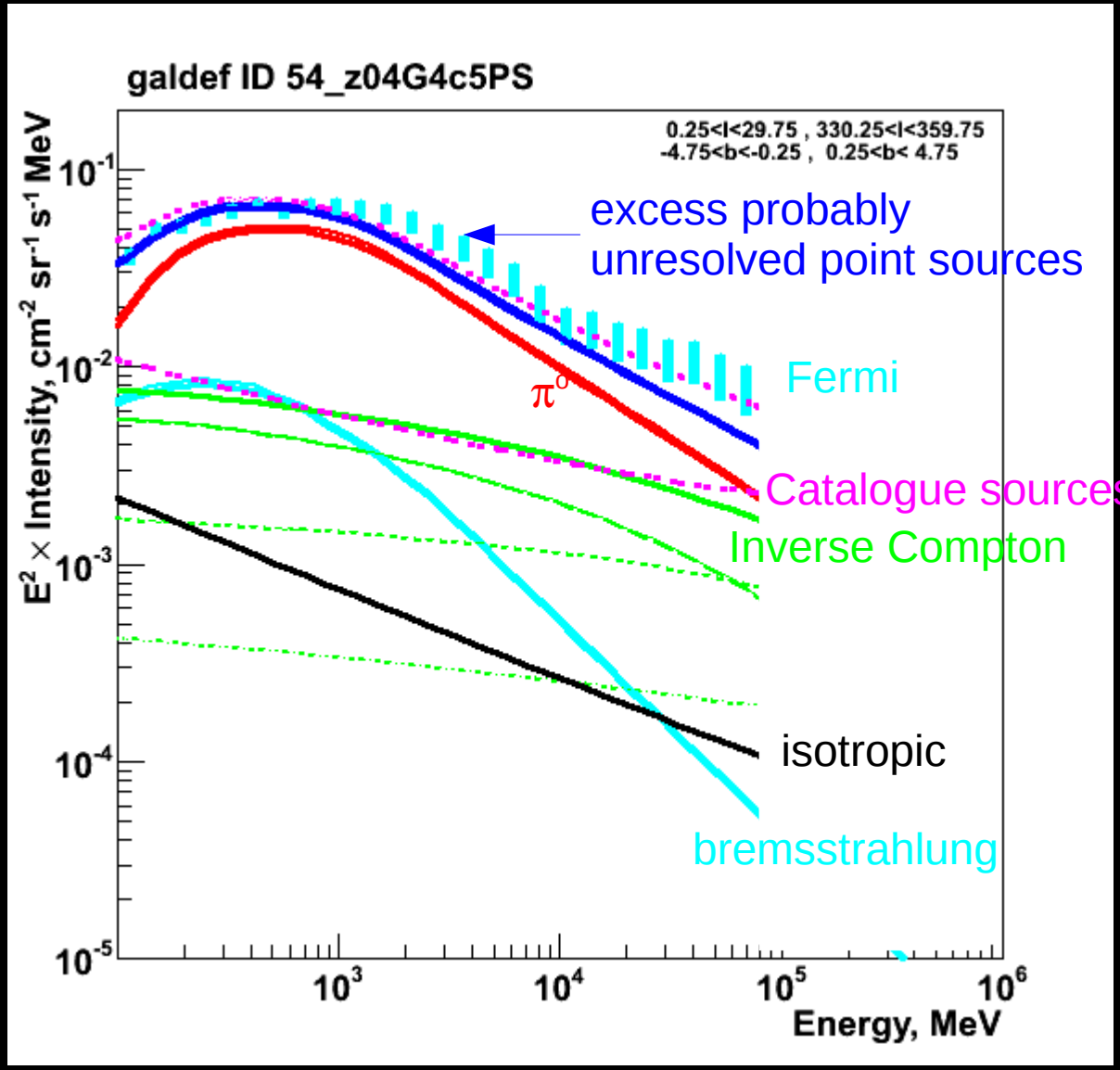
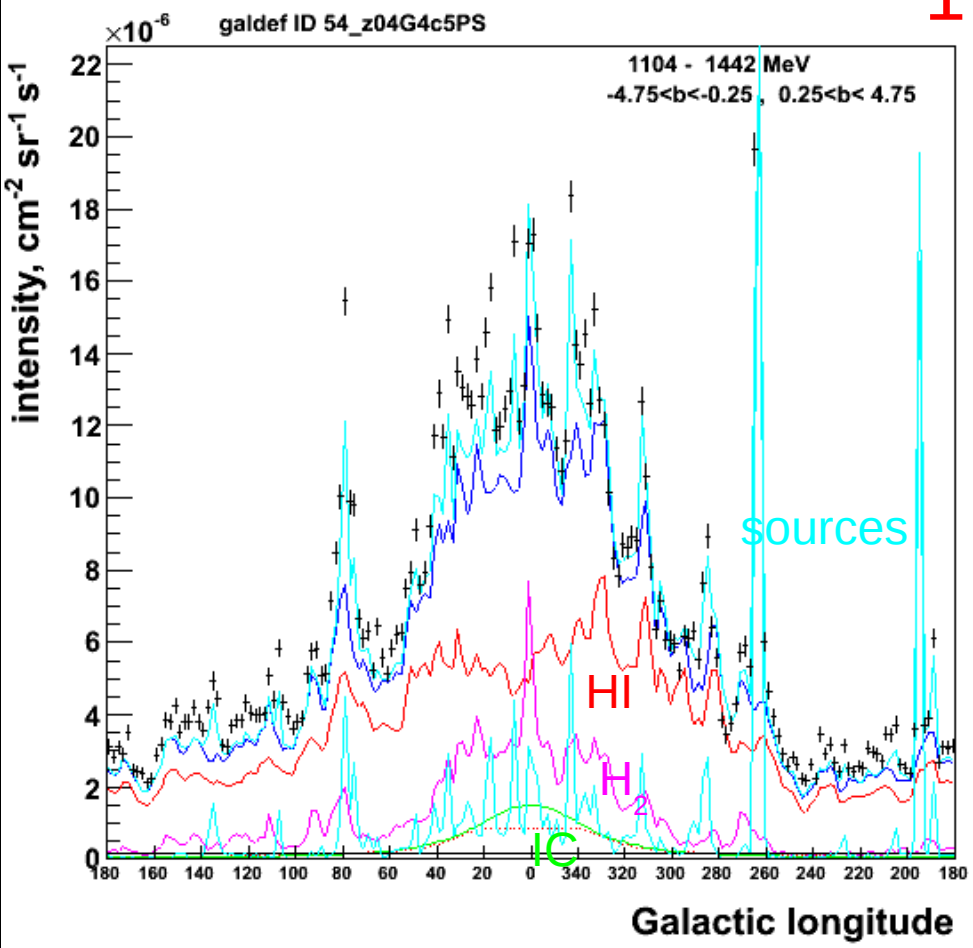


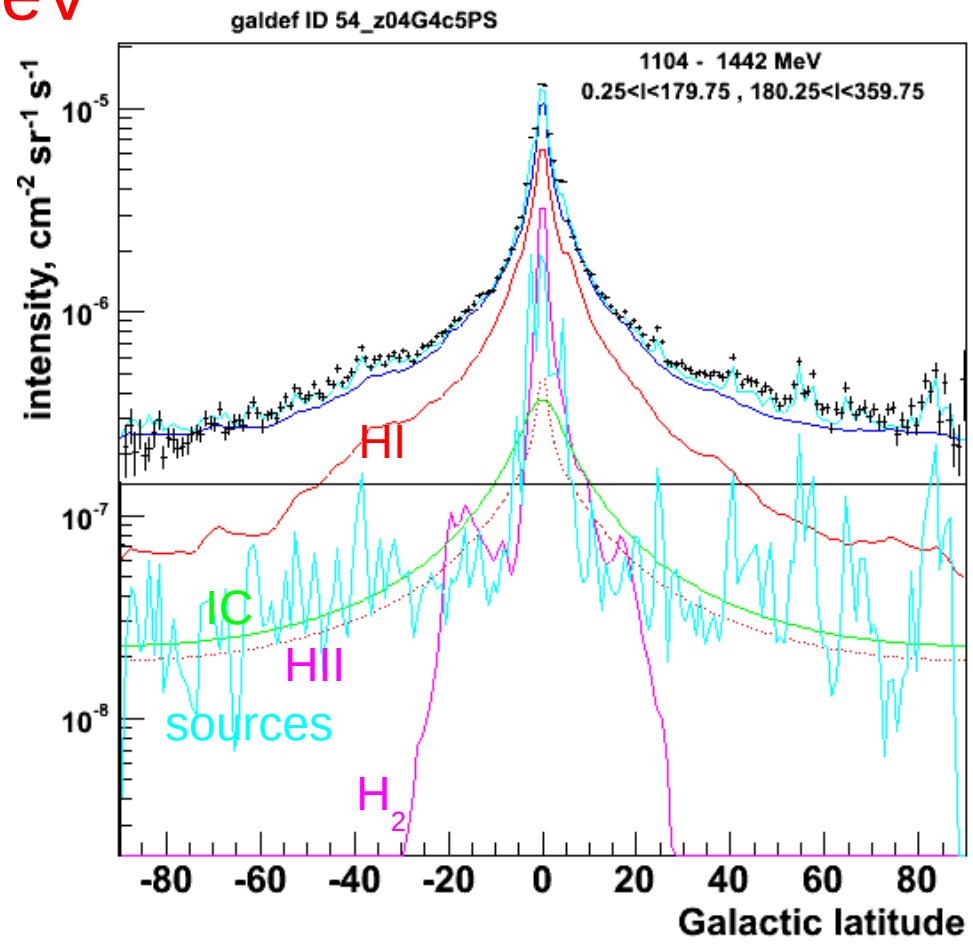

PRELIMINARY

LONGITUDE PROFILE LOW LATITUDES

LATITUDE PROFILE ALL LONGITUDES

1 GeV



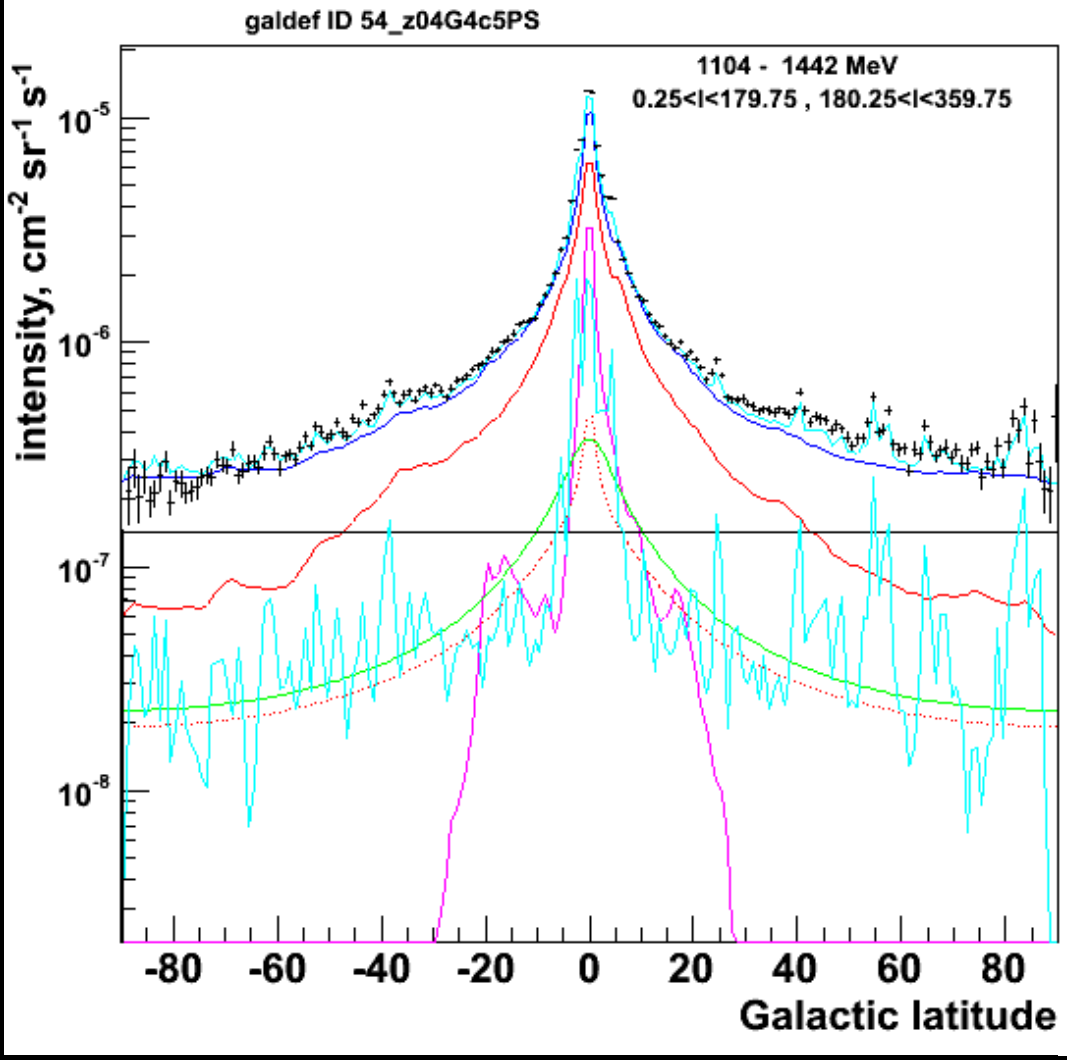




Agrees within 15% over 2 decades of dynamic range
The observed flux is the sum of many components:
importance of modelling them all !

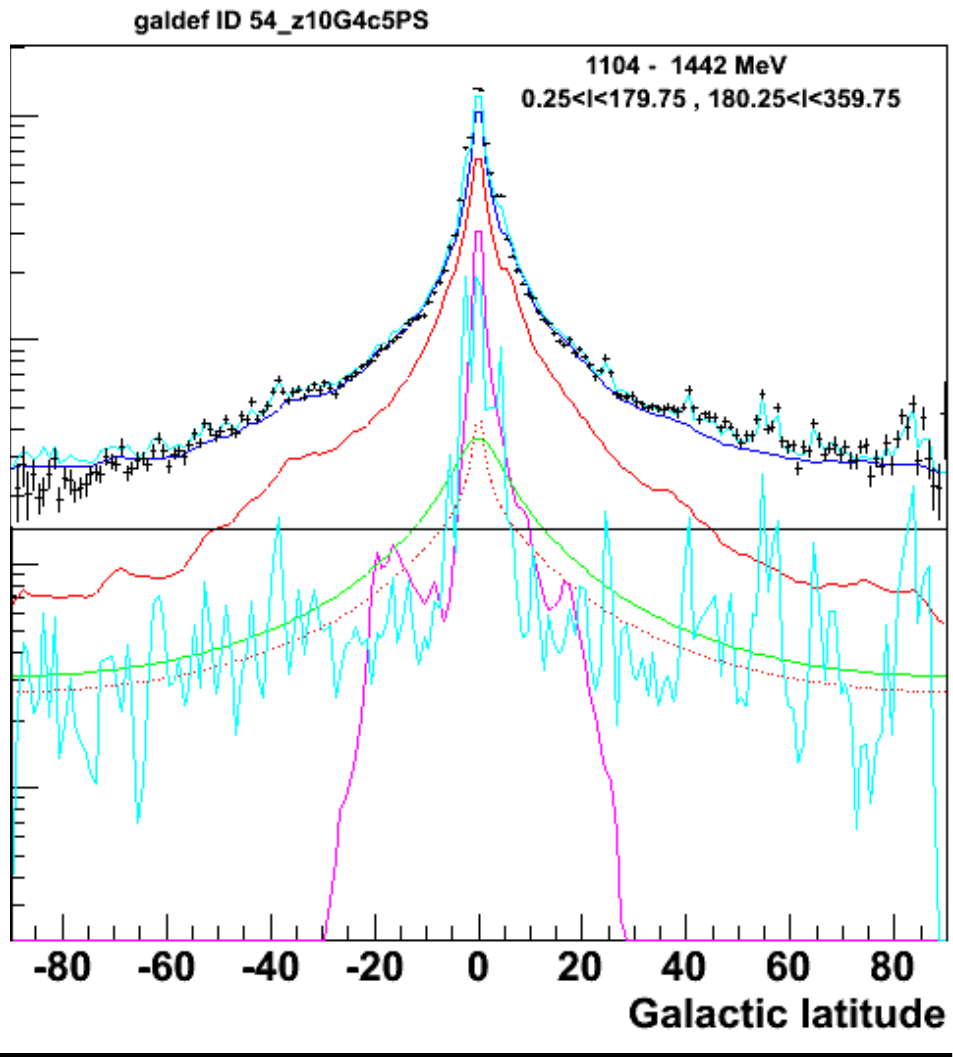
PRELIMINARY

# EVIDENCE FOR LARGE COSMIC-RAY HALO

## 4 kpc halo height




## 10 kpc halo height



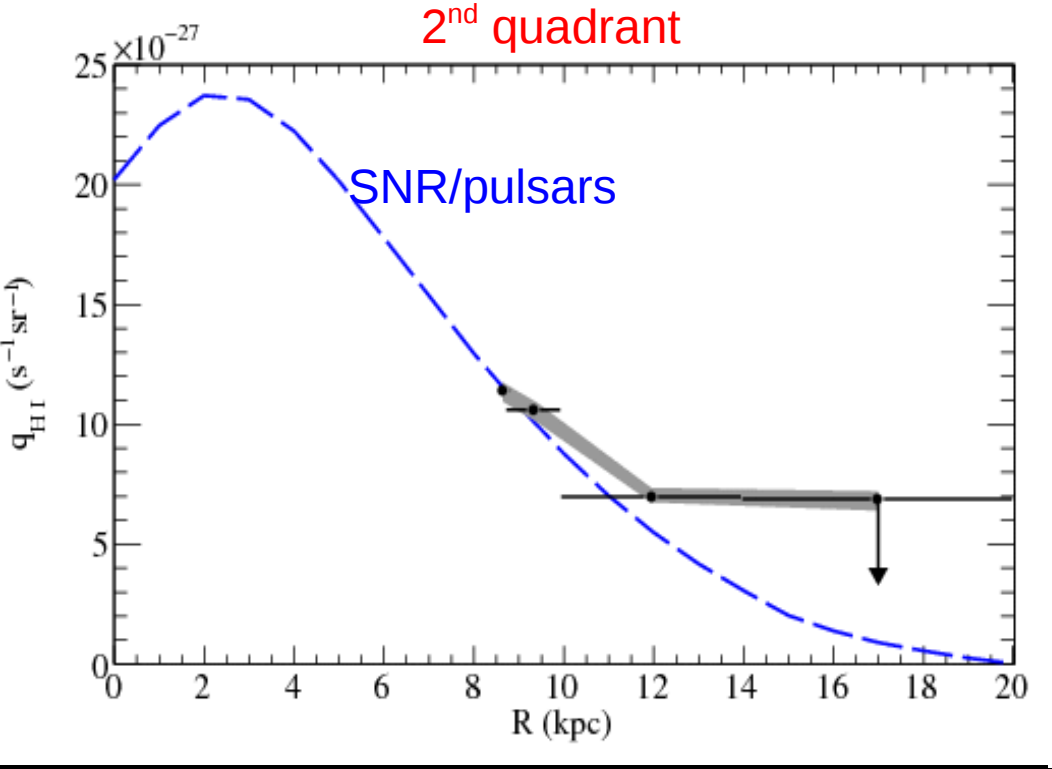

inverse Compton at high latitudes suggests a *large cosmic-ray halo*

PRELIMINARY

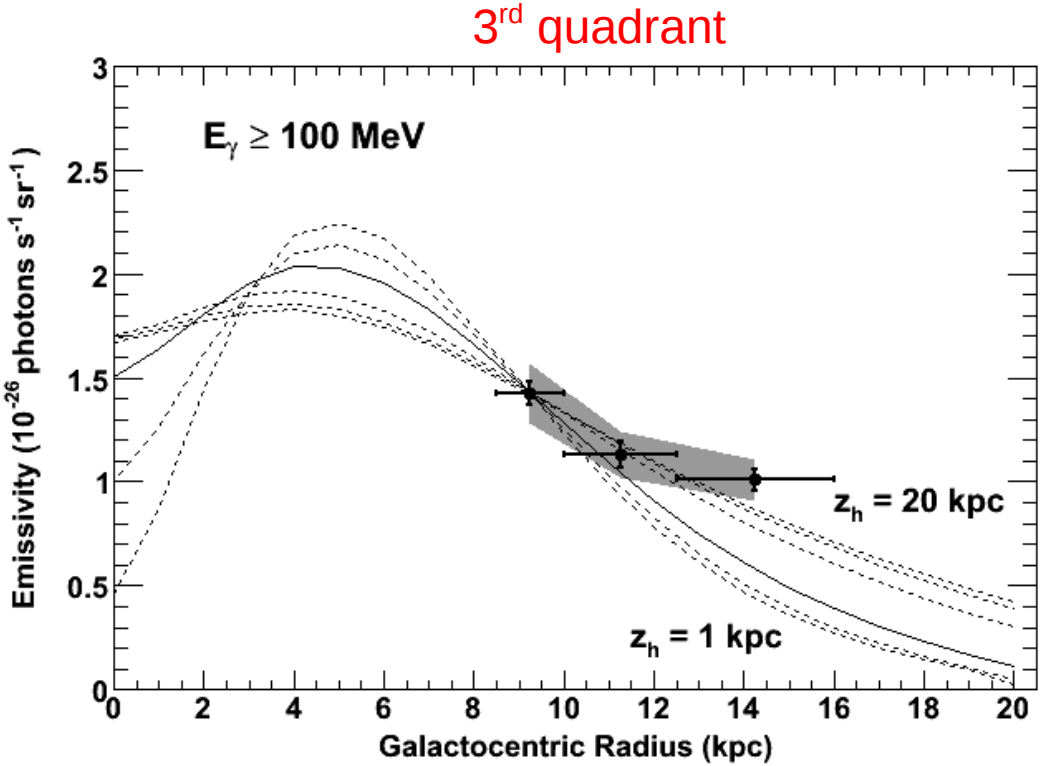
# Gamma-ray distribution in *outer* Galaxy

Gamma-ray emissivity falls off *slower than expected for SNR* source origin
Large halo will flatten it .... more evidence for large halo

2nd quadrant




3rd quadrant




Luigi Tibaldo

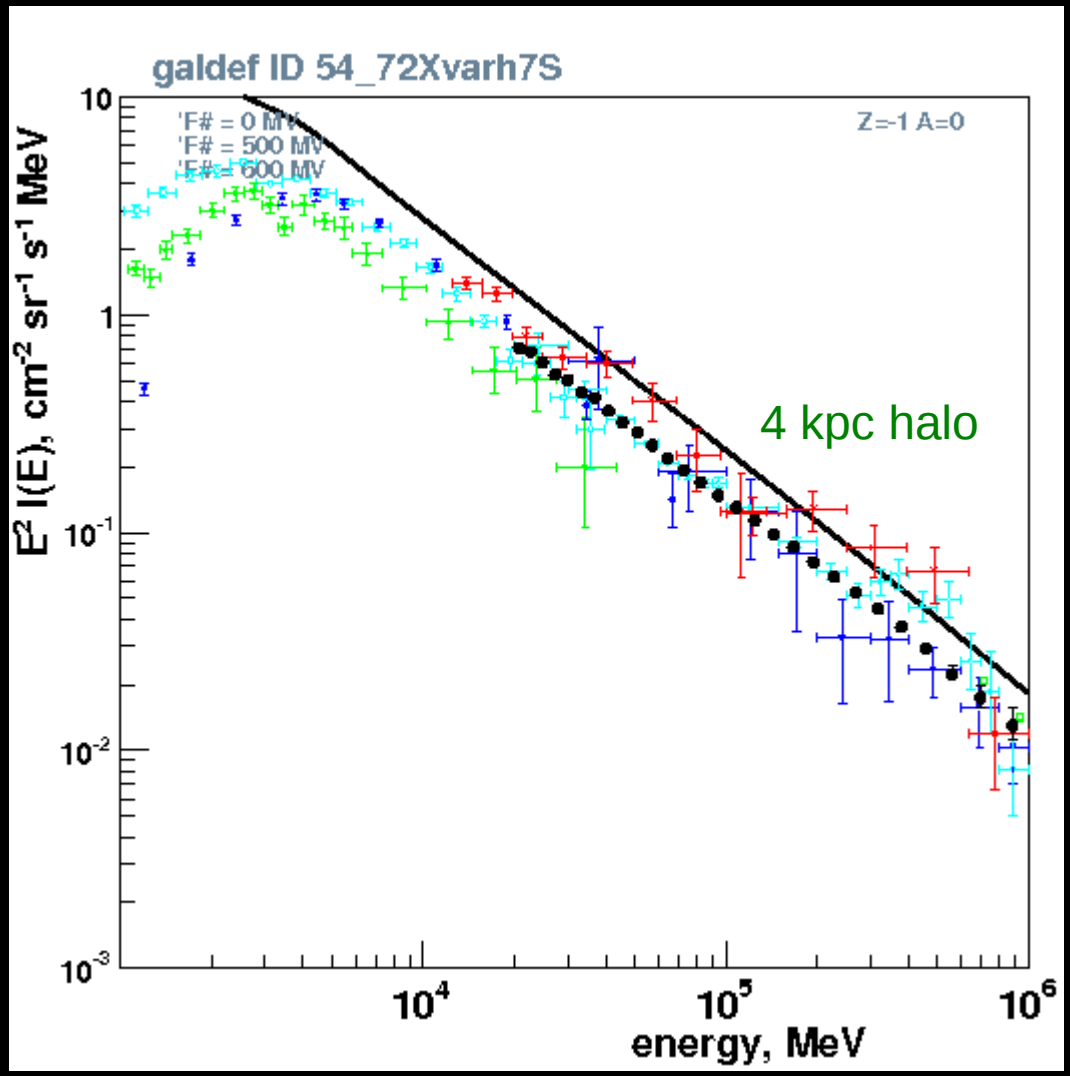
Abdo etal (2010) ApJ 710, 133

2009 Fermi Symposium

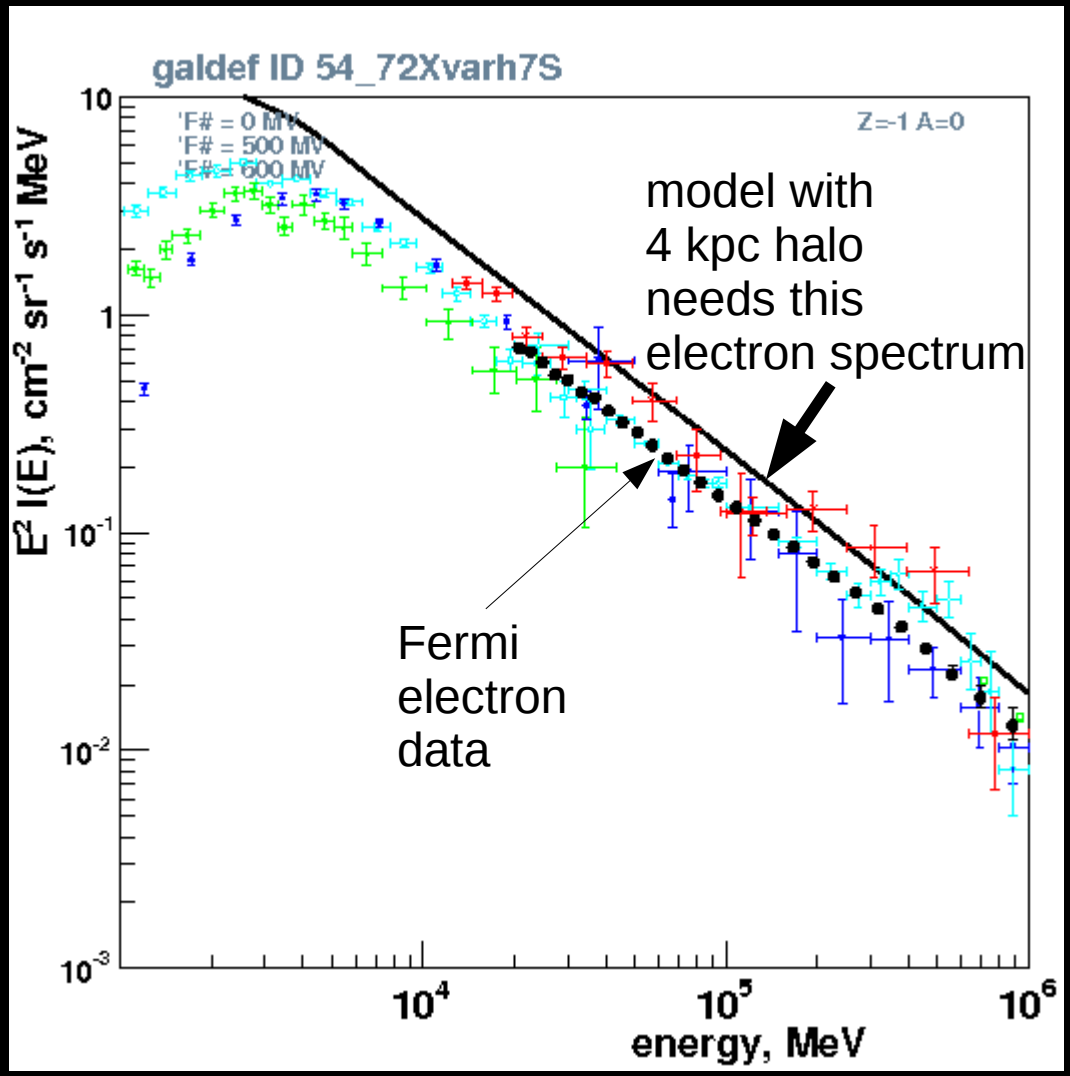
Tsufune Mizuno

PRELIMINARY

BONUS:
Large cosmic-ray halo also reduces the need to increase
electron spectrum over Fermi-LAT measurements, to give gamma rays



BONUS:
Large cosmic-ray halo also reduces the need to increase
electron spectrum over Fermi-LAT measurements, to give high-latitude gamma rays



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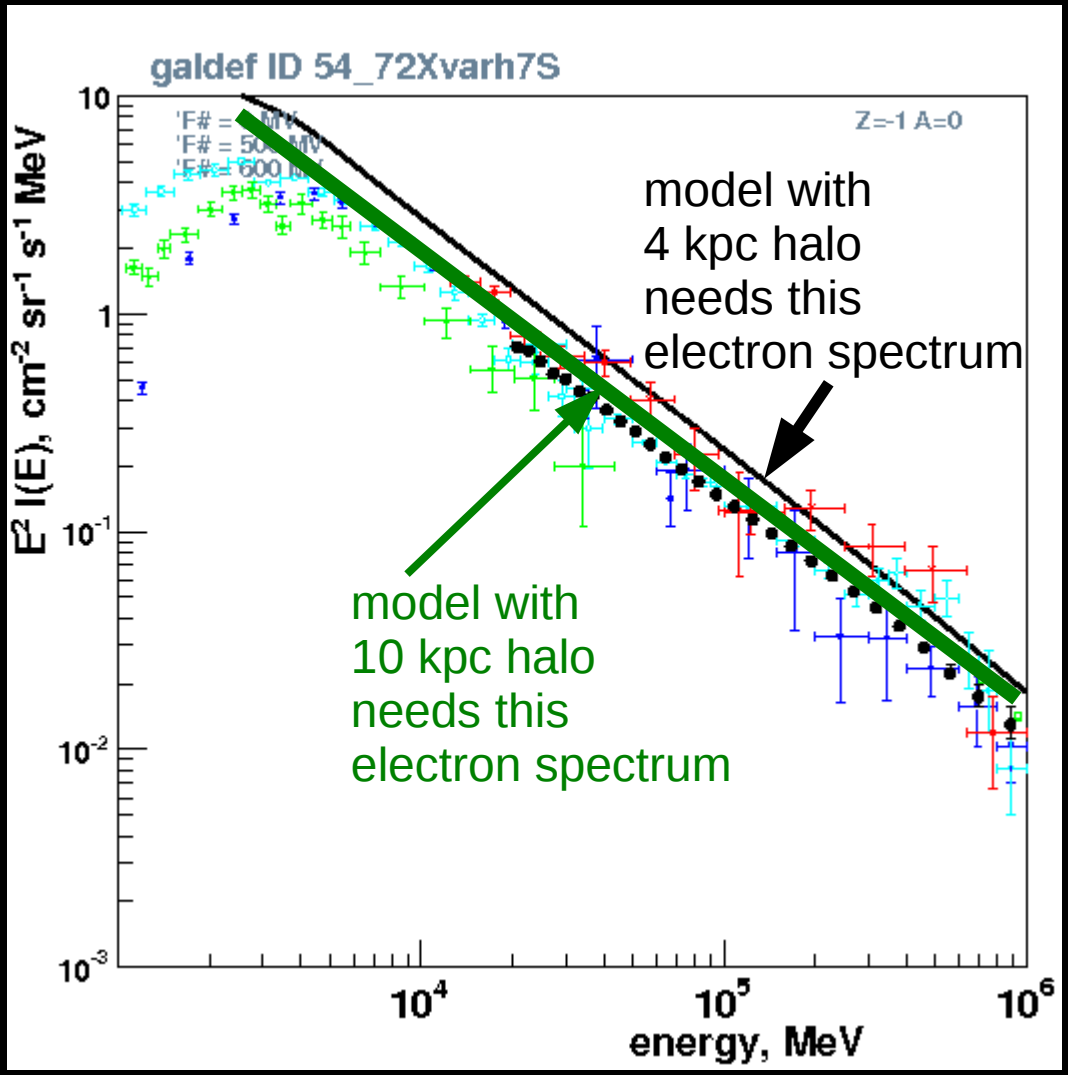
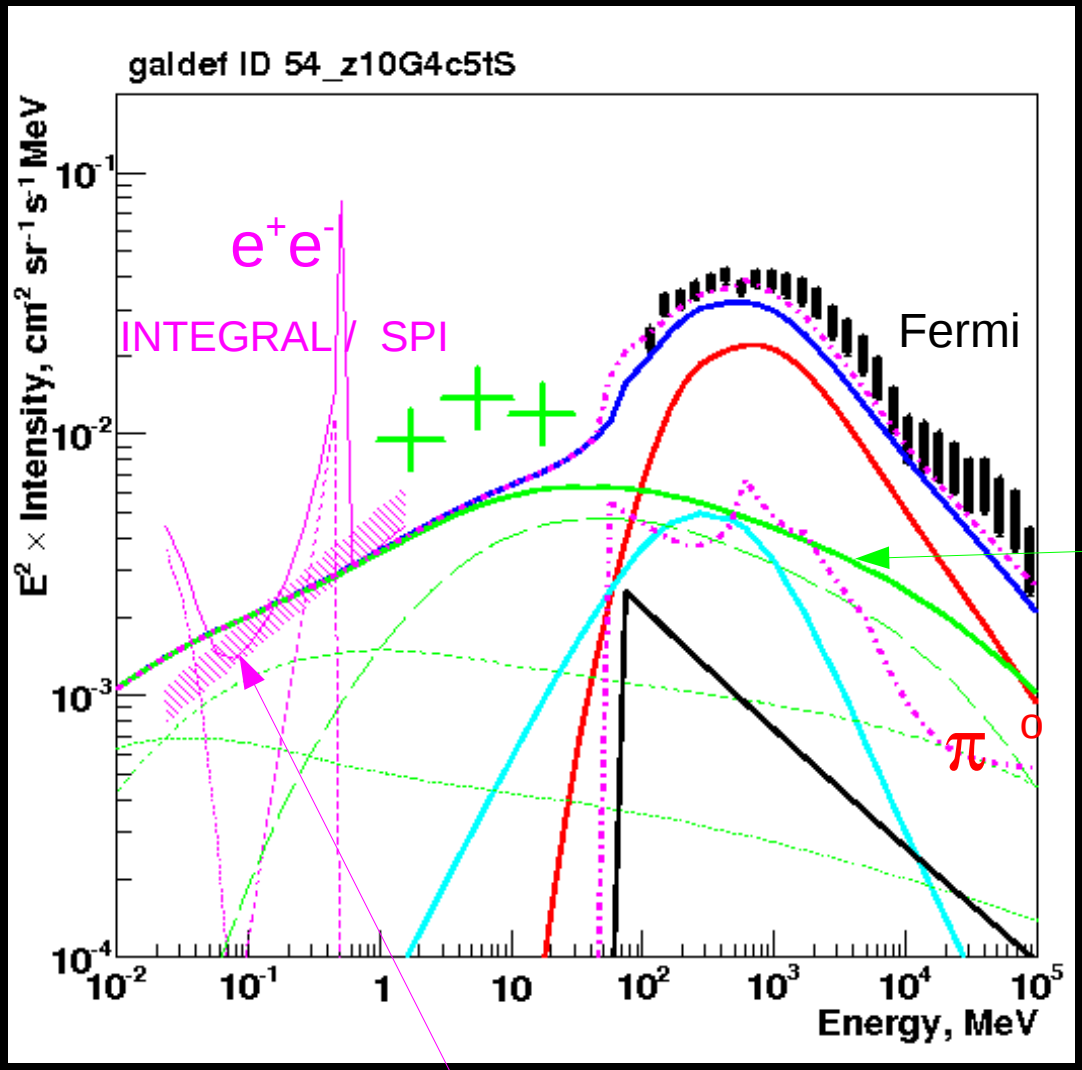


# Gamma-rays, inner Galaxy

inverse Compton
from primary electrons, secondary electrons + positrons

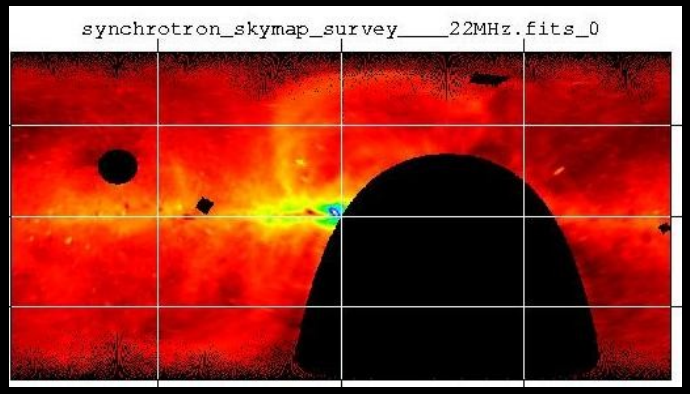
**These processes are very relevant down to hard X-rays !**



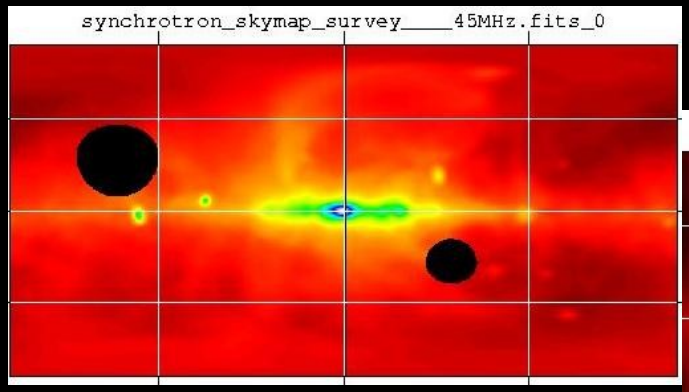

inverse Compton

Bouchet et al 2008 power-law continuum

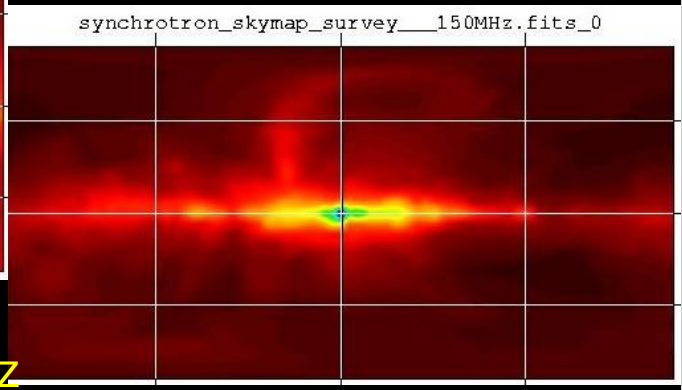
**¼ of the inverse Compton power comes out in hard X-rays !**



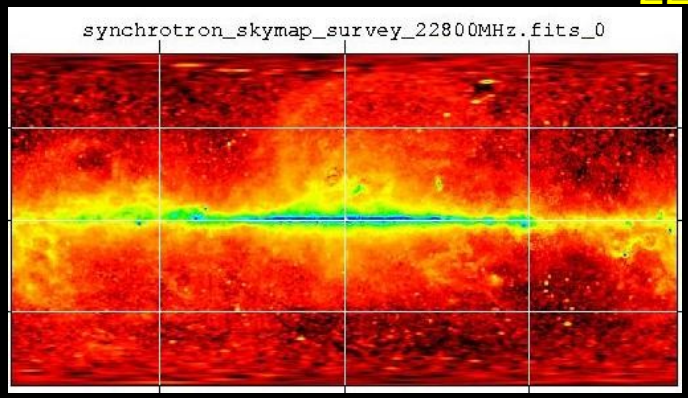

22 MHz




45 MHz



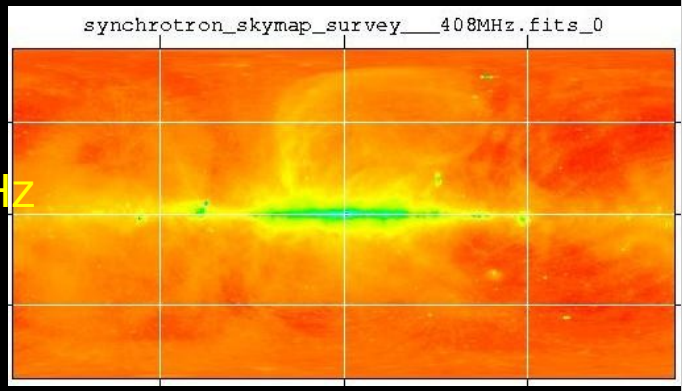

150 MHz

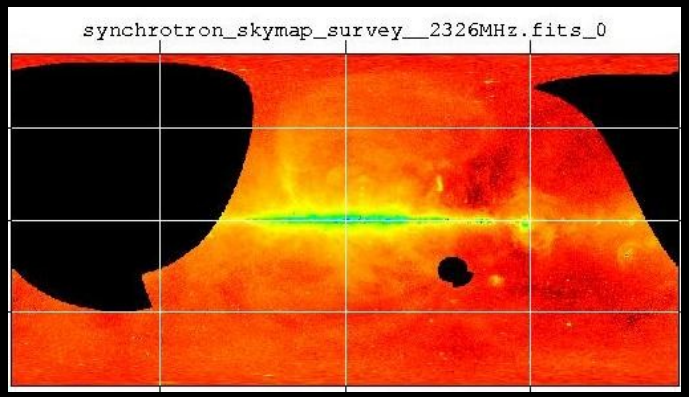



23 GHz

Continuum sky surveys

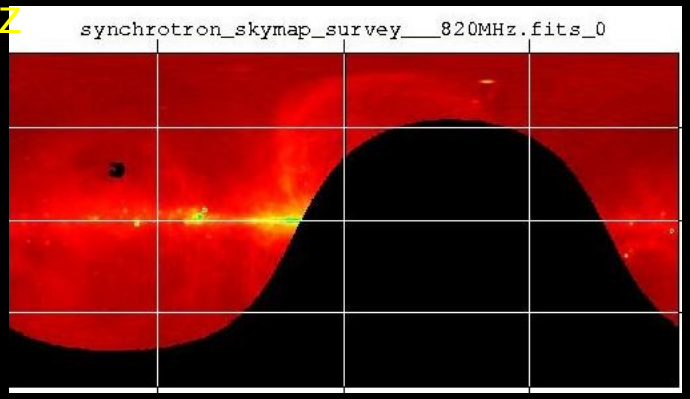
408 MHz



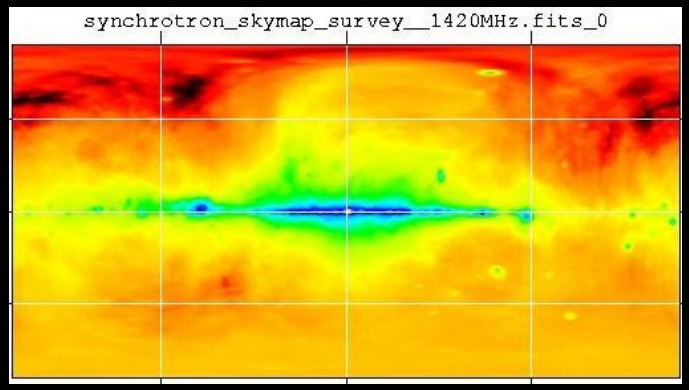




2.3 GHz

820 MHz



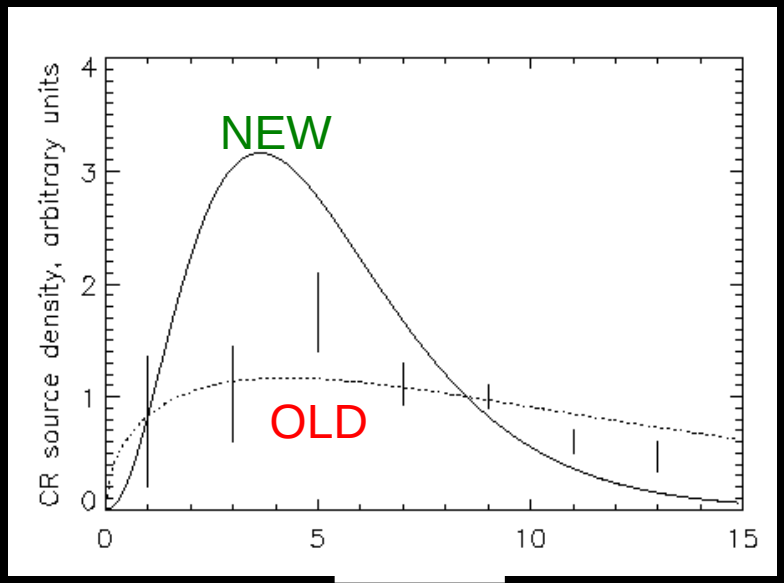

1.4 GHz



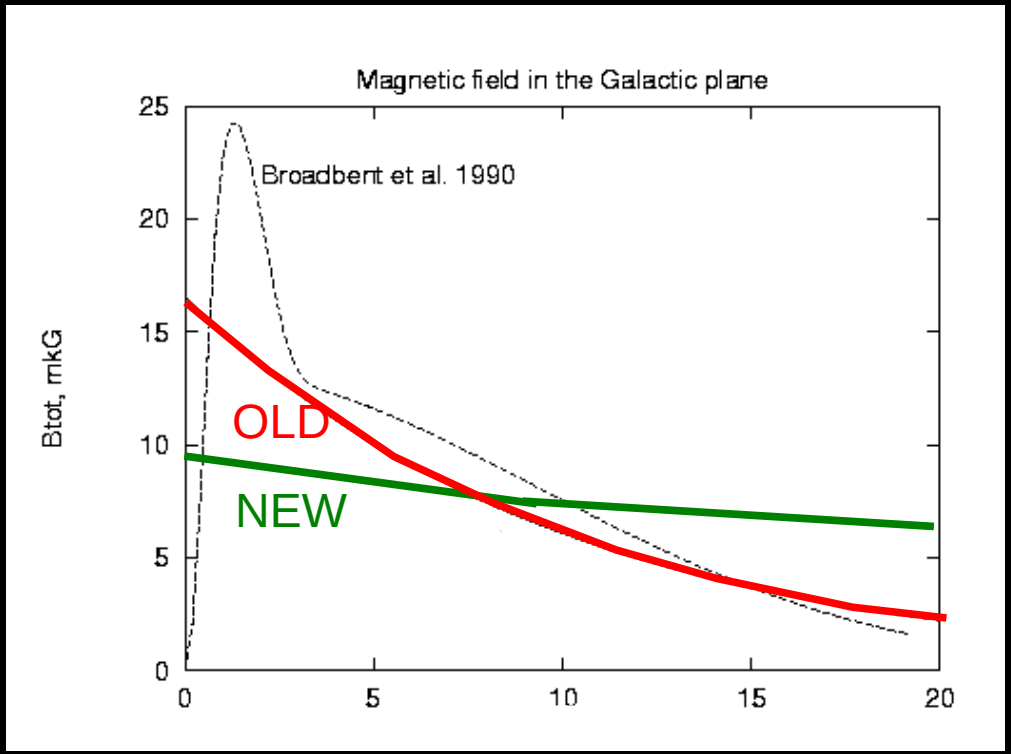
*from synchrotron and cosmic-ray propagation model:*

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

cosmic-ray source distribution

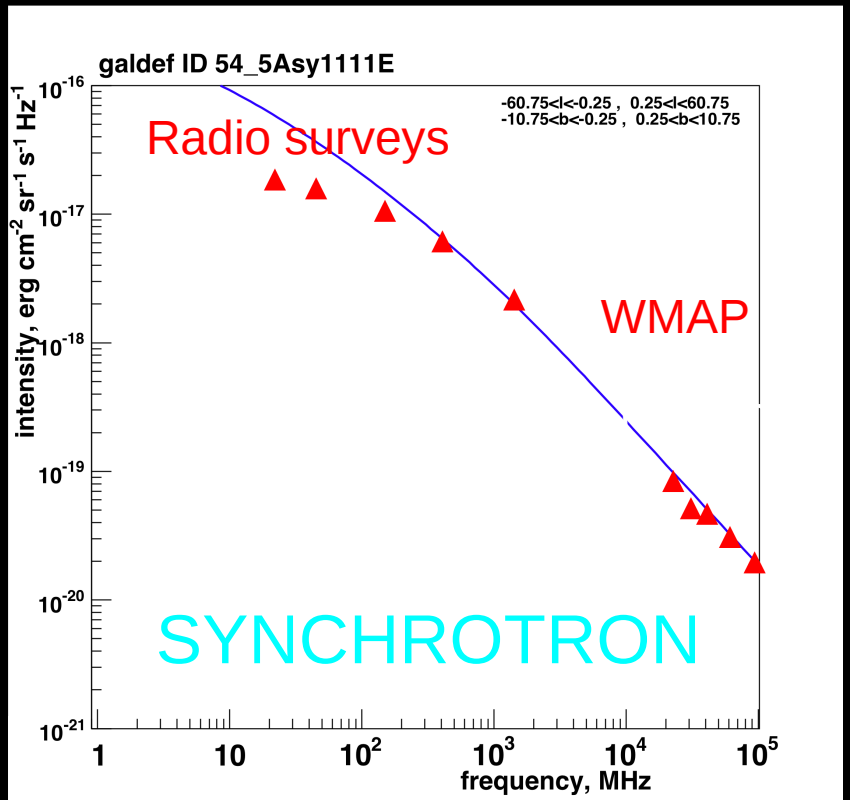



R, kpc

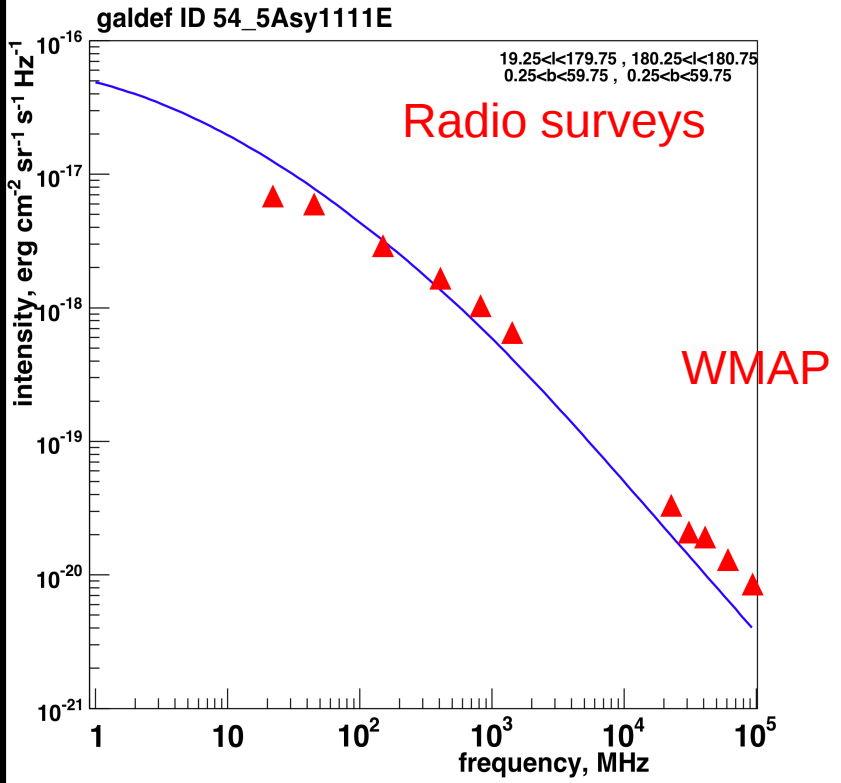


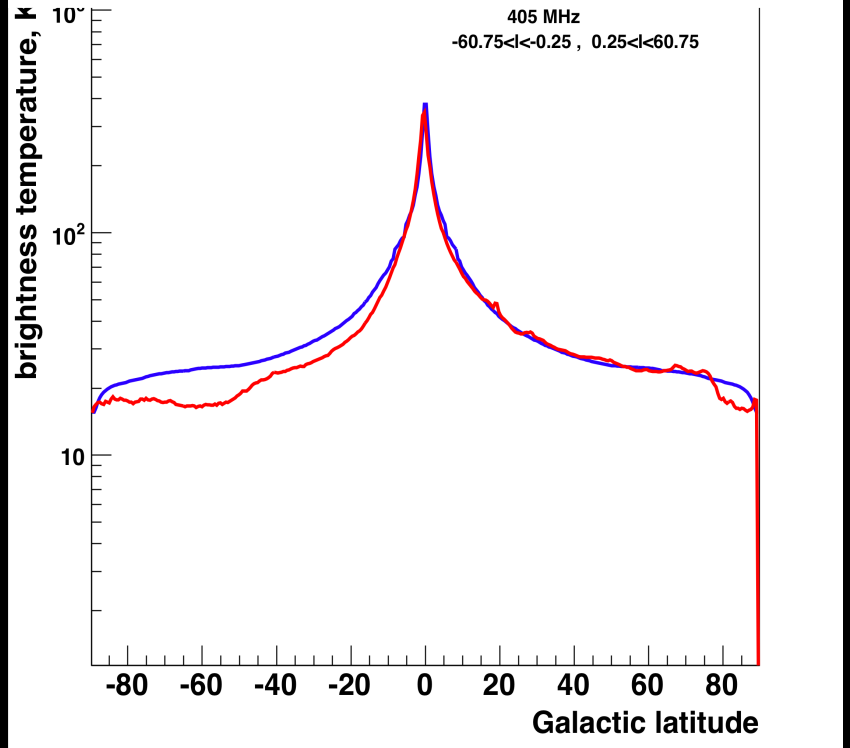

R, kpc

essentially no R- dependence of B:
since the cosmic-ray electrons have a
*steep R-dependence*

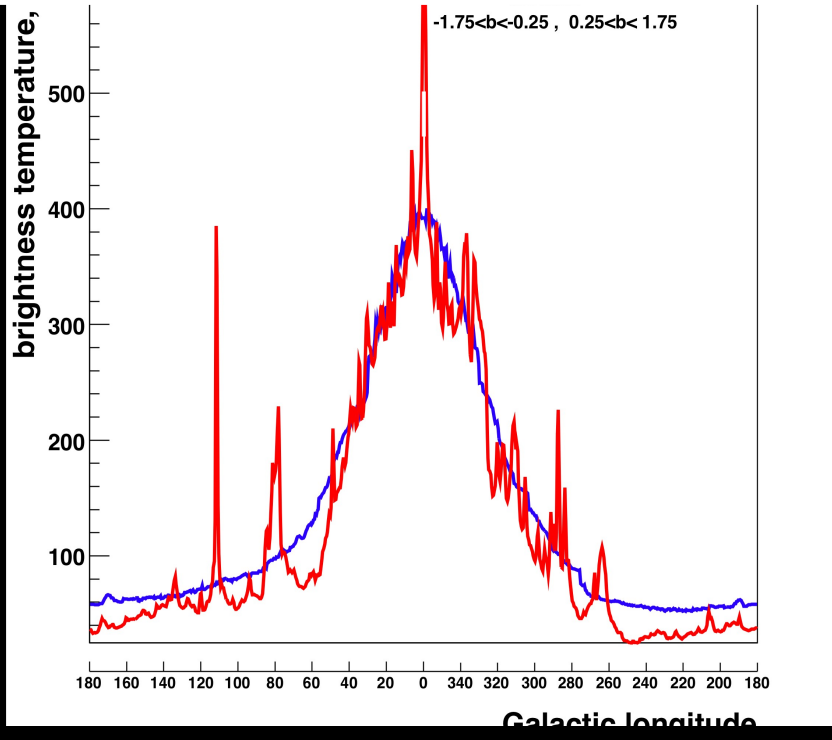


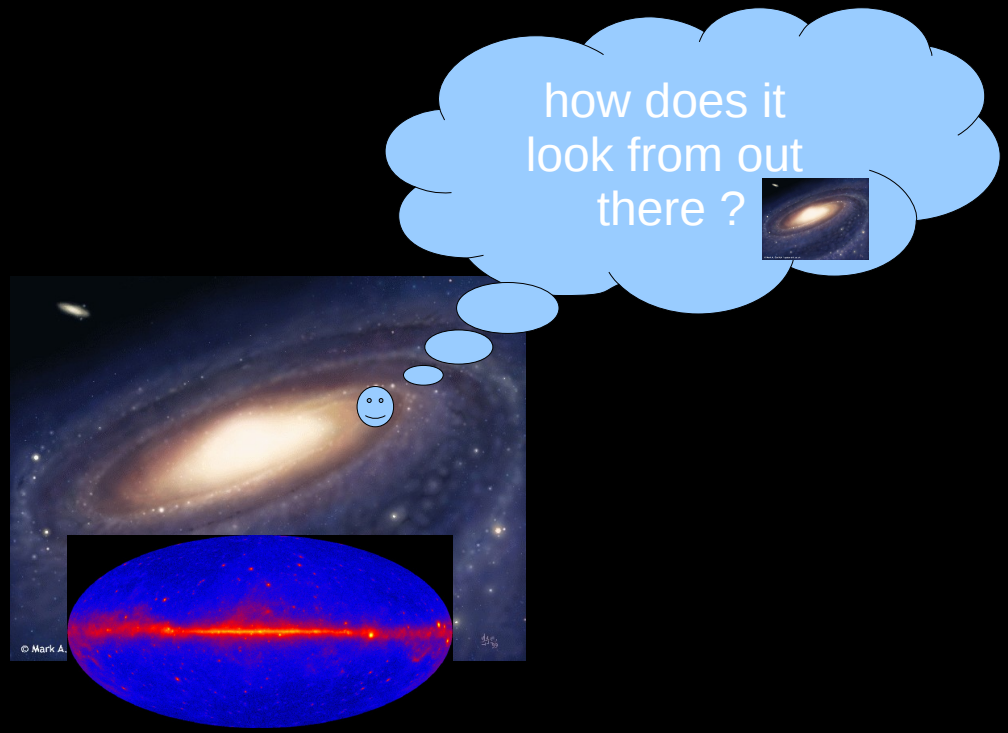

GALPROP model



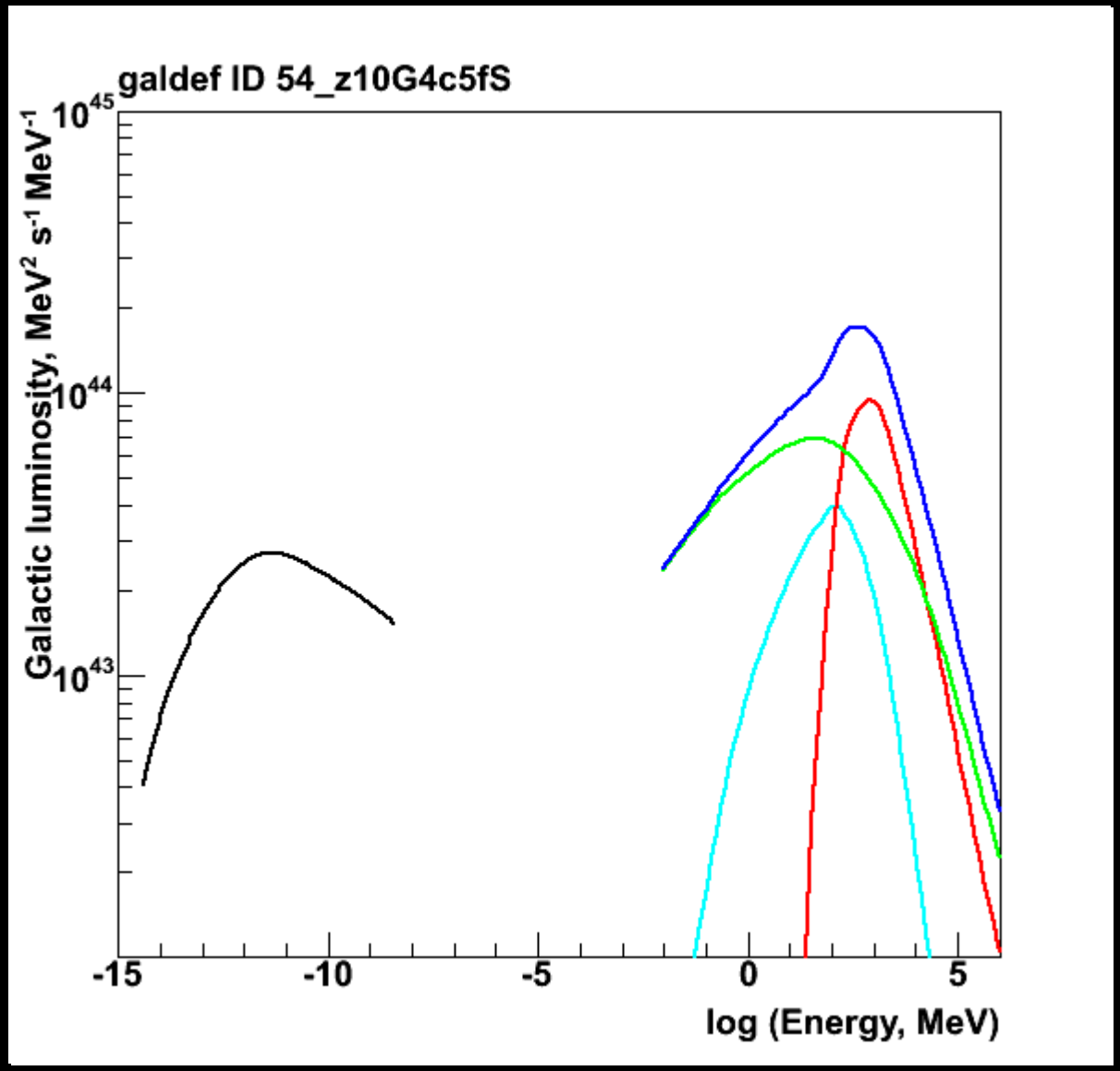




408 MHz



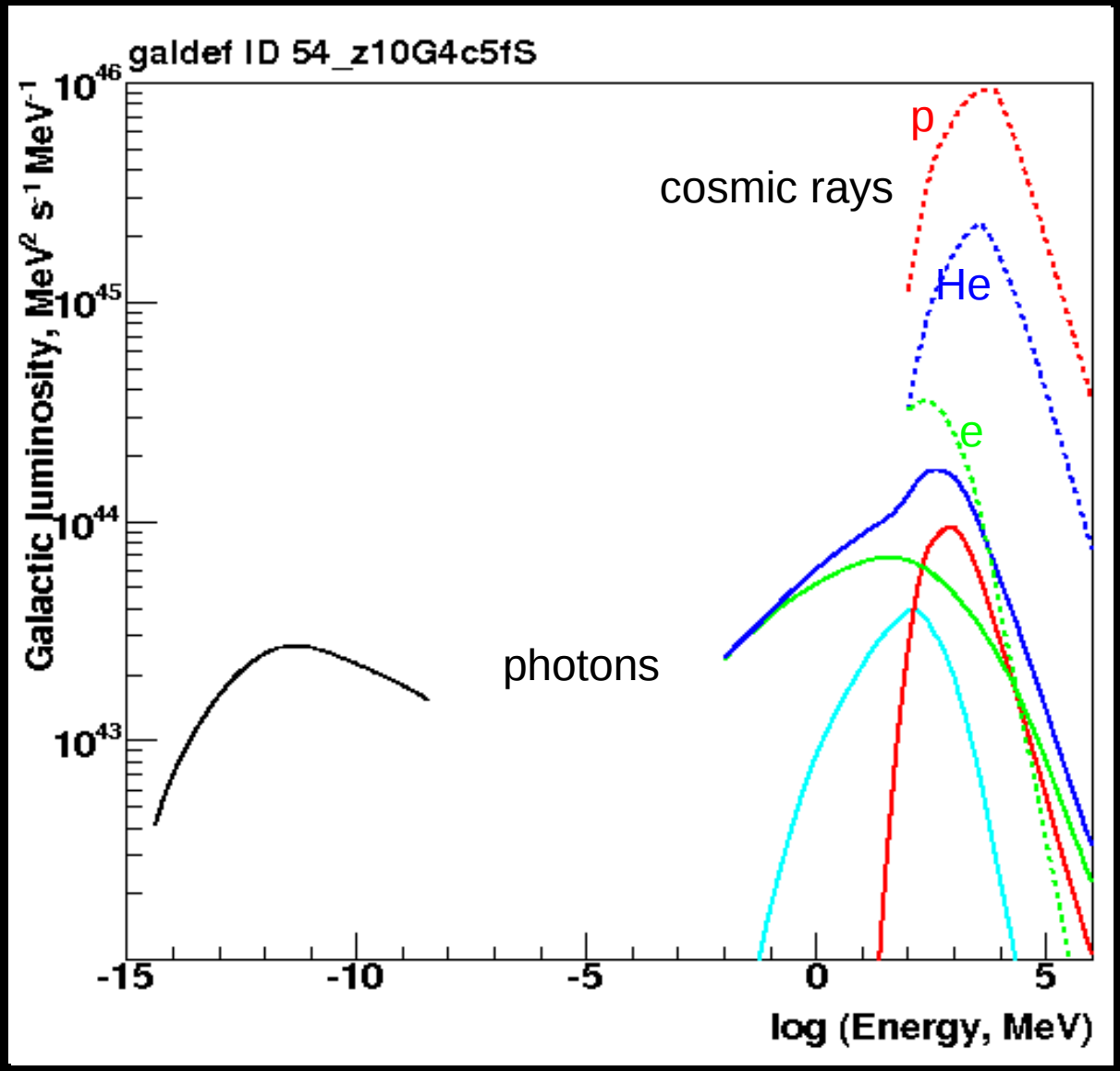

how does it look from out there ?
© Mark A.

# Galaxy luminosity over 20 decades of energy




radio CMB IR optical X γ

# Galaxy luminosity over 20 decades of energy

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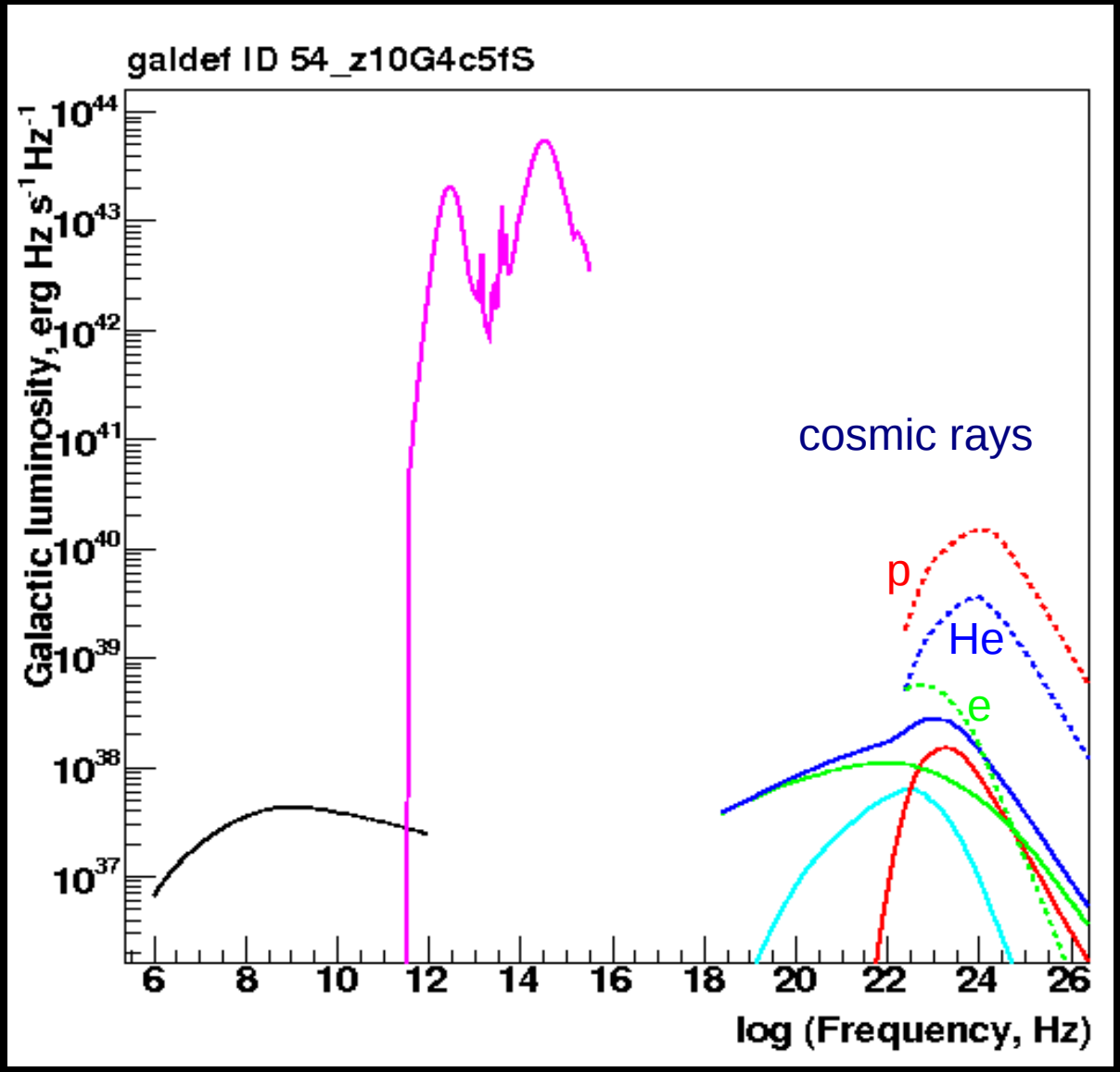



radio CMB IR optical X γ

# Galaxy luminosities

## based on GALPROP model and Fermi data

| | |
|---|---|
| Cosmic-ray nuclei | $10^{41}$ |
| Cosmic-ray electrons | $1.6\ 10^{39}$ |
| Gamma rays > 100 MeV | $1.2\ 10^{39}$ |
| $\pi^0$-decay | $7\ 10^{38}$ |
| bremsstrahlung | $1\ 10^{38}$ |
| inverse Compton | $4\ 10^{38}$ |
| < 100 MeV: | $8\ 10^{38}$ |
| Synchrotron | $4\ 10^{38}$ |
| Optical + IR | $10^{44}$ |

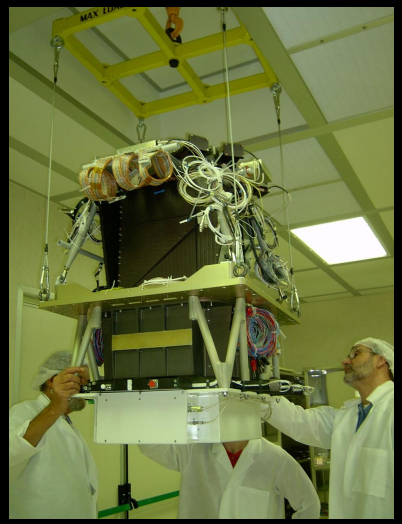
erg $s^{-1}$

1% of nuclei energy converts to gamma rays
75% of electron energy converts to inverse Compton gamma rays
25% of electron energy converts to synchrotron radiation
inverse Compton gamma rays ~ synchrotron
Galaxy is electron calorimeter ! But most energy goes into inverse Compton !

# Outlook

Fermi operational , results coming out fast
The fine data challenges the models.

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



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