



Fermi  
Gamma-ray Space Telescope

# Interstellar gamma rays

## New insights from Fermi

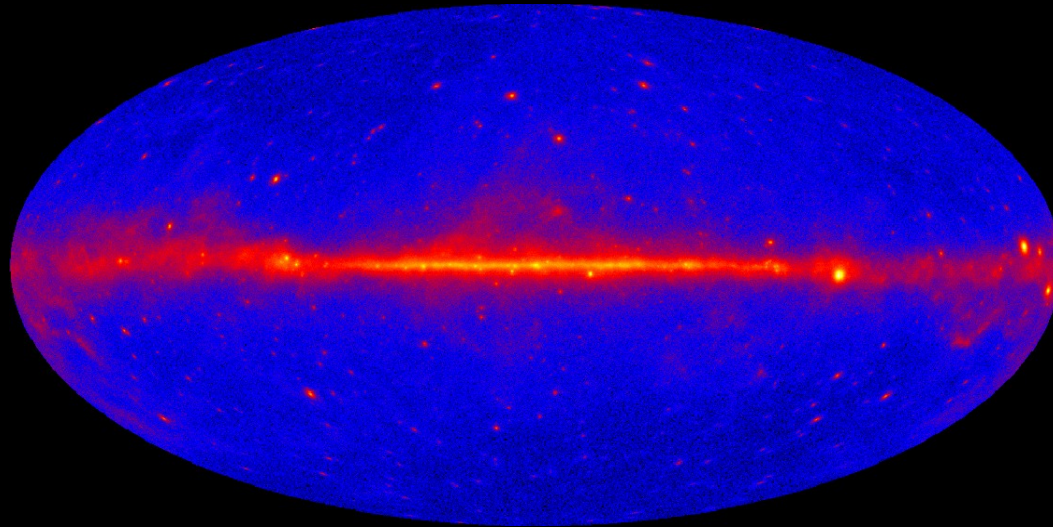
Andy Strong

*on behalf of Fermi-LAT collaboration*

COSPAR Scientific Assembly, Bremen, July 2010

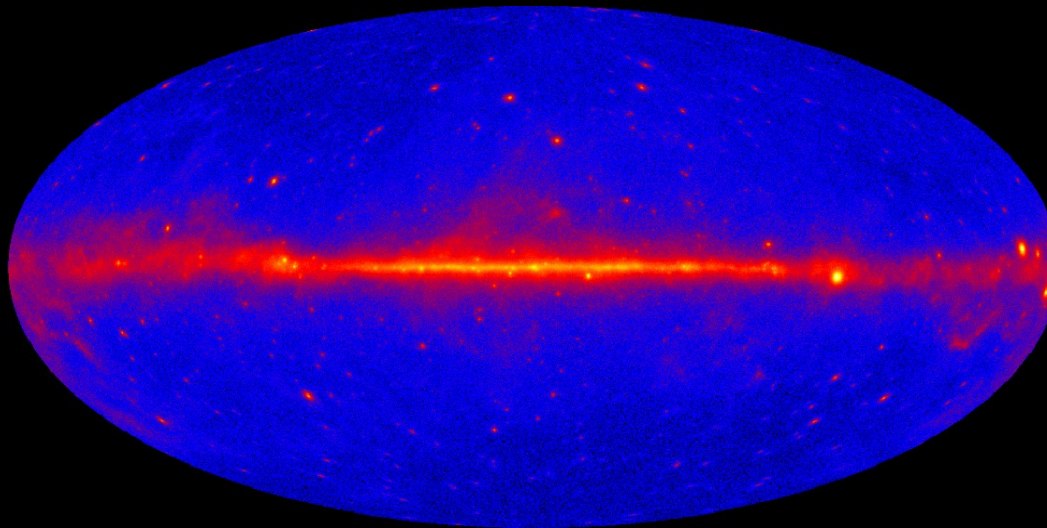
Session E110:

'The next generation of ground-based  
Cerenkov Telescopes'

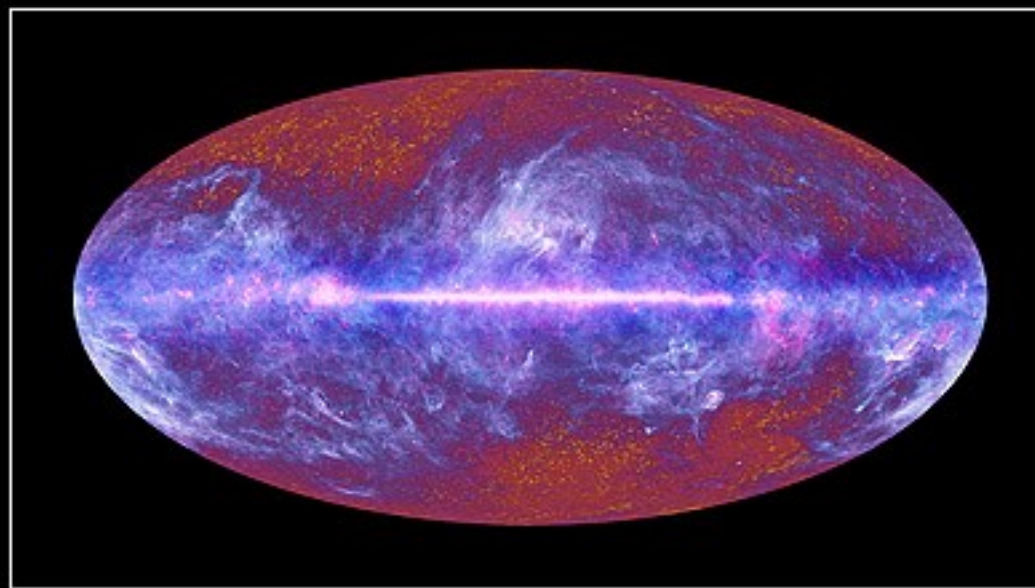
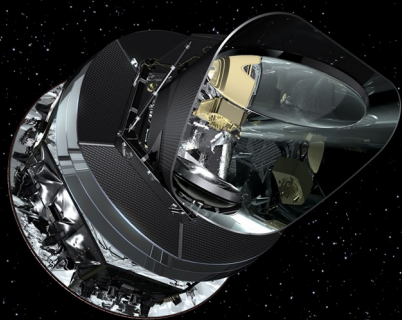


1 year





1 year



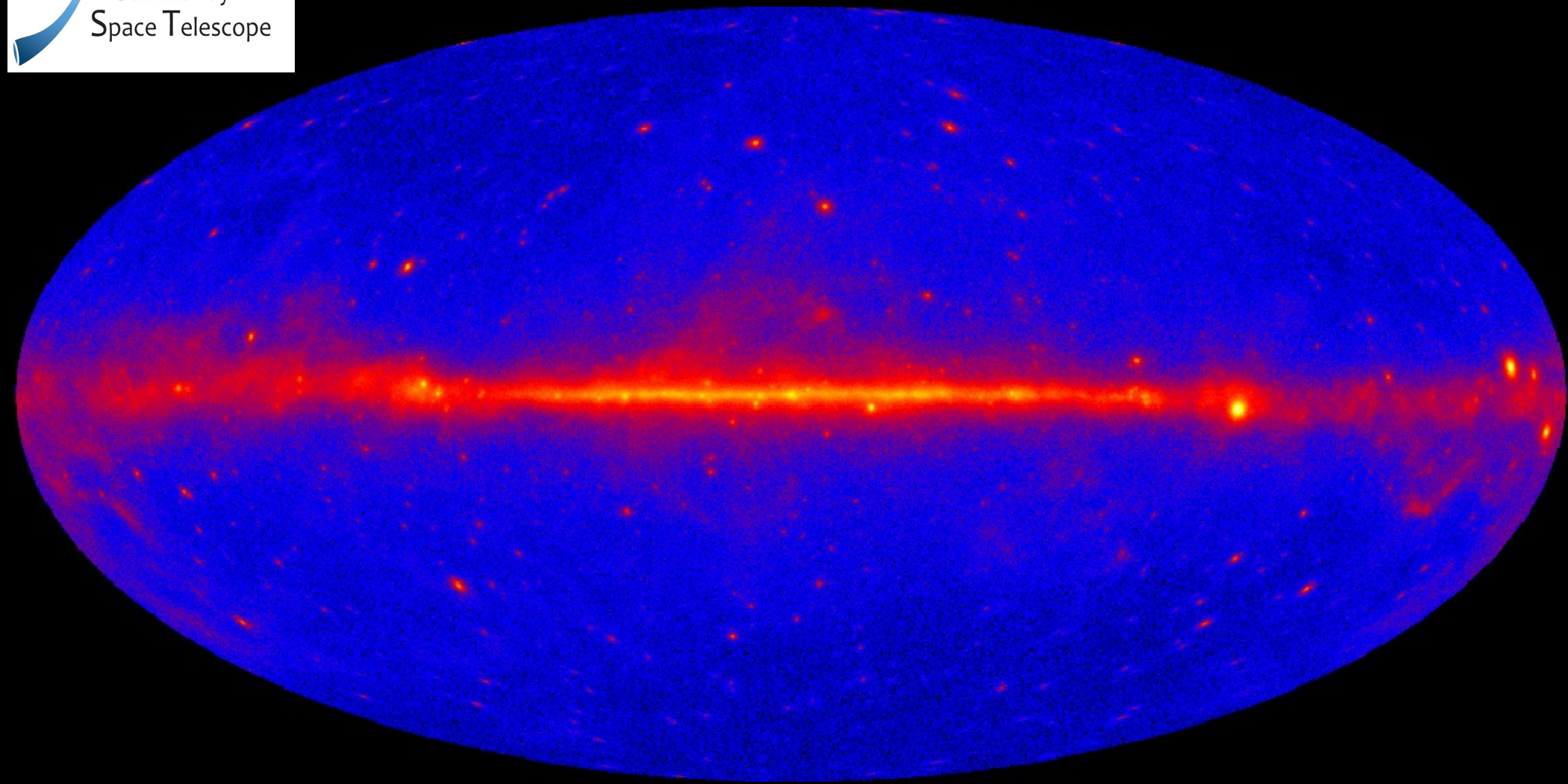
1 year

The Planck one-year all-sky survey



(c) ESA, IFFI and LFI consortia, July 2008

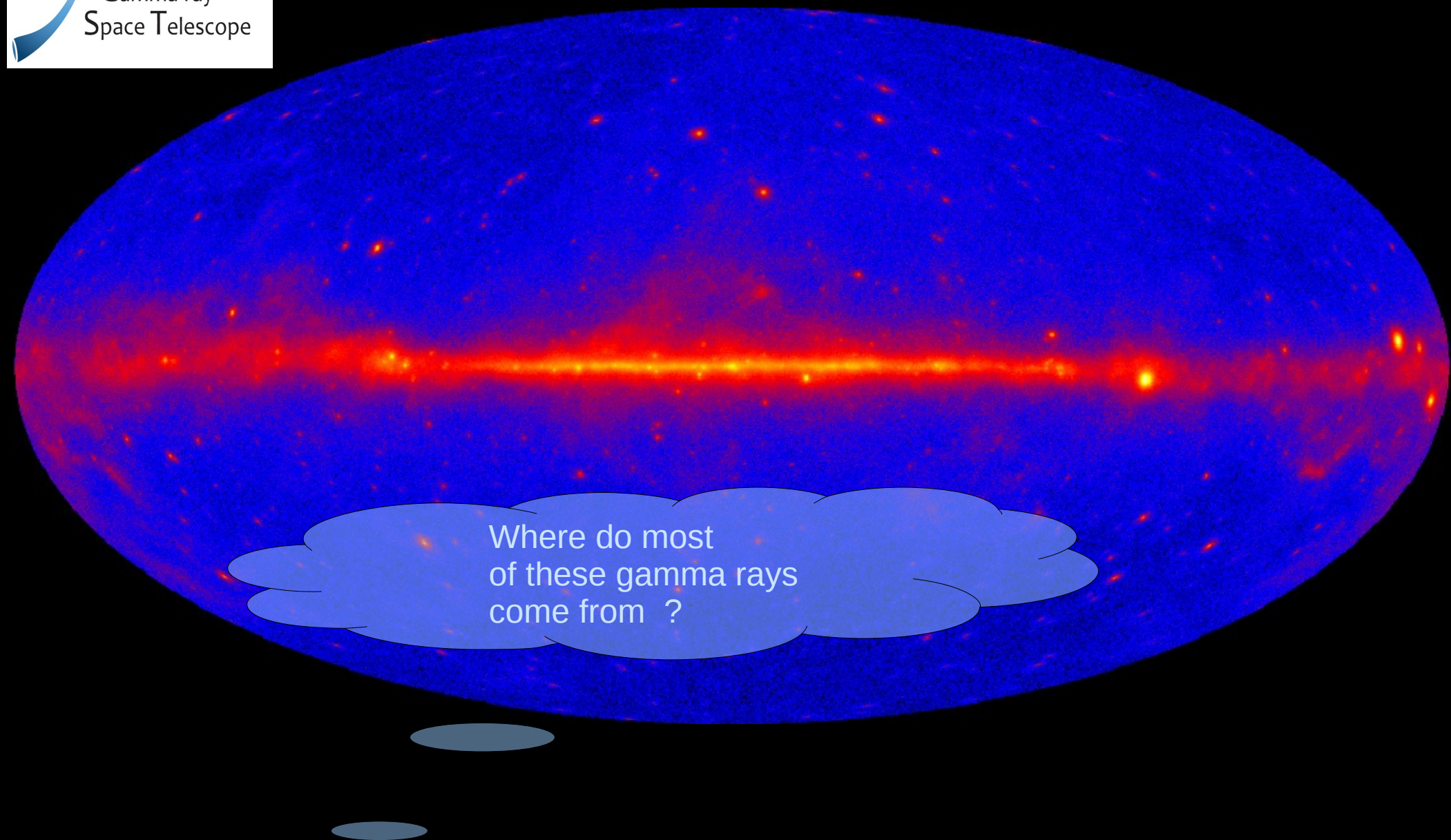




*see also talk by Eric Charles on Fermi results,*

**1<sup>st</sup> year skymap**





Where do most  
of these gamma rays  
come from ?

intergalactic space

HALO

reacceleration

energy loss  
decay

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

synchrotron

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

cosmic-ray sources:  $p$ ,  $\text{He}$  ..  $\text{Ni}$ ,  $e^-$

B-field

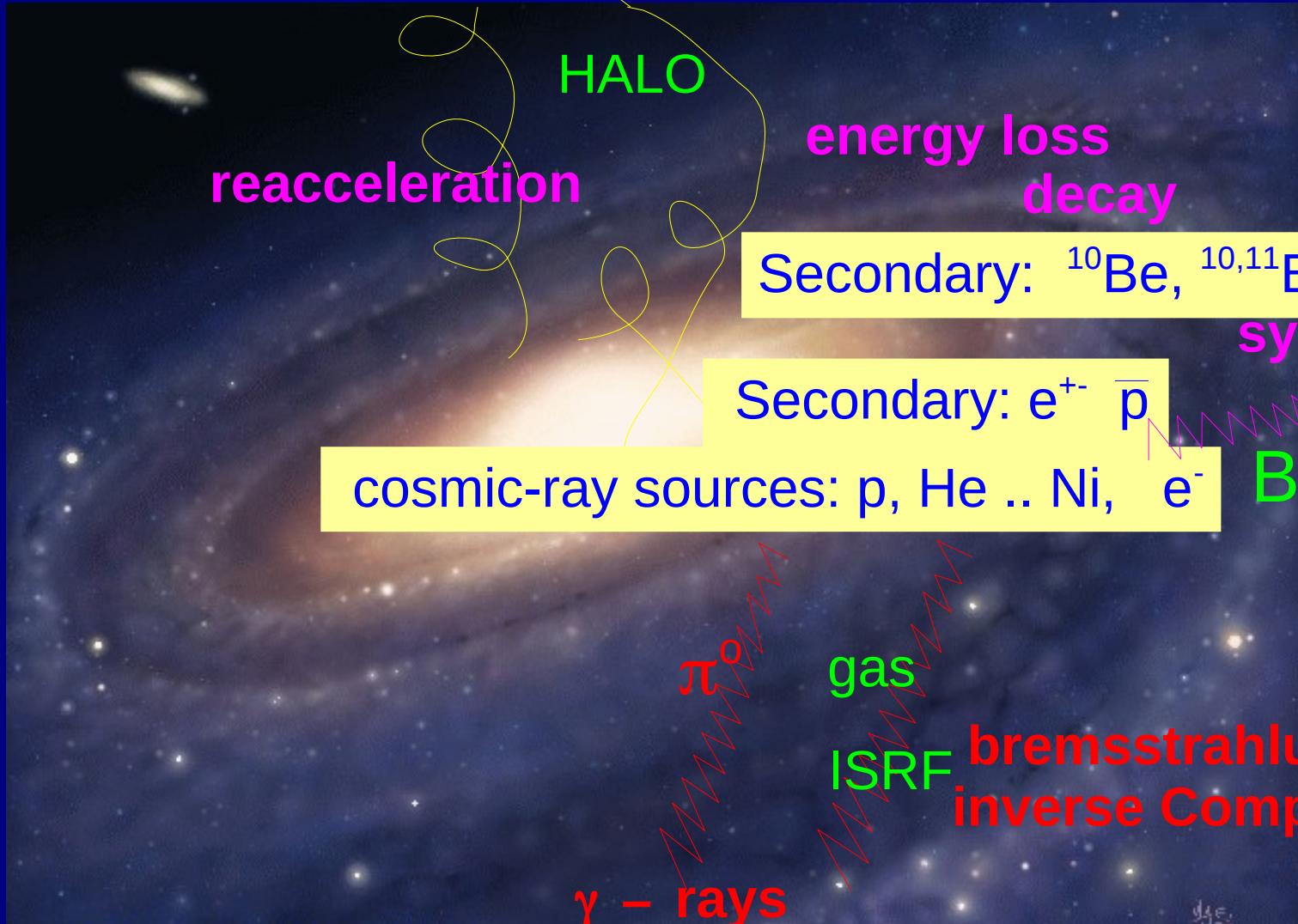
$\pi^0$

gas

ISRF

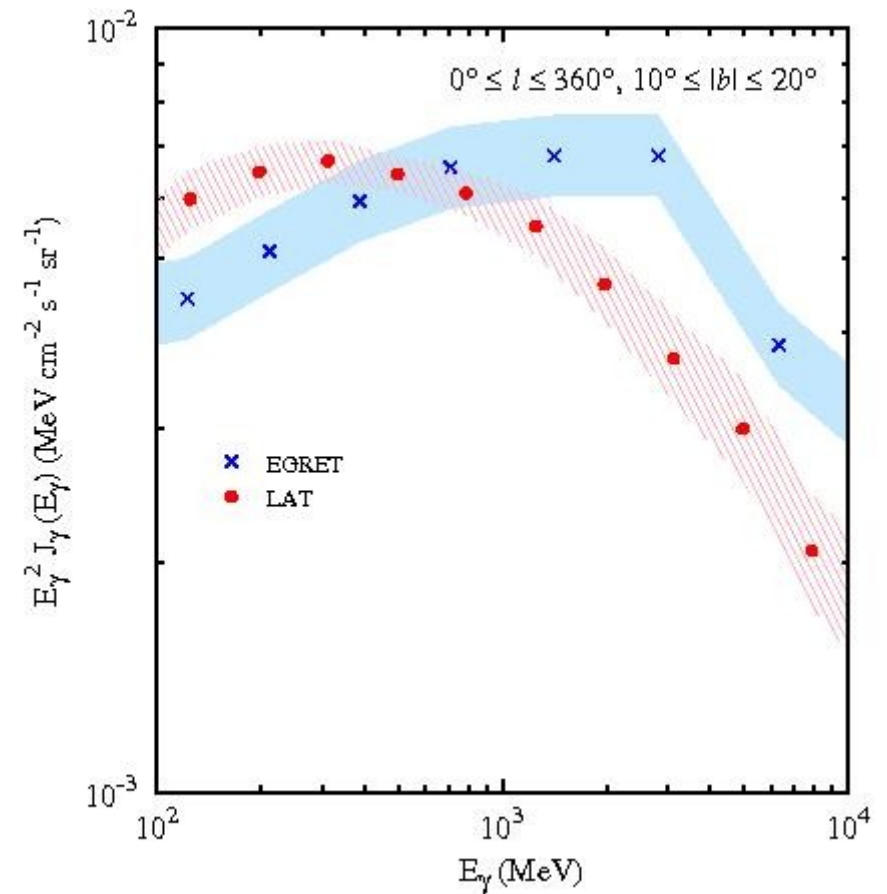
bremsstrahlung  
inverse Compton

$\gamma$  - rays



## EARLY CONCLUSIONS from Fermi-LAT

Fermi does *not* confirm EGRET GeV excess



*Abdo et al (2009) PRL 103, .251101*

*so back to the drawing board for models based on GeV excess !*

## LATEST DIFFUSE EMISSION RESULTS FROM FERMI-LAT

New:

- >1 year of data

- low background event class (developed for extragalactic background study)

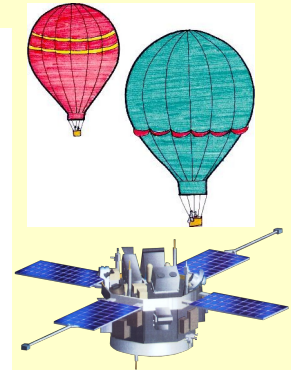
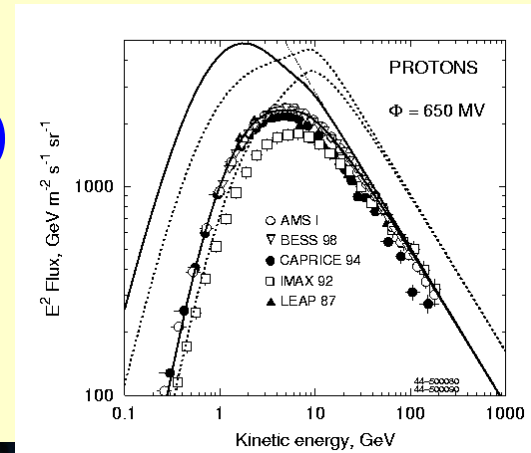
- Fermi-measured electron spectrum

- Improved gas tracer: dust emission

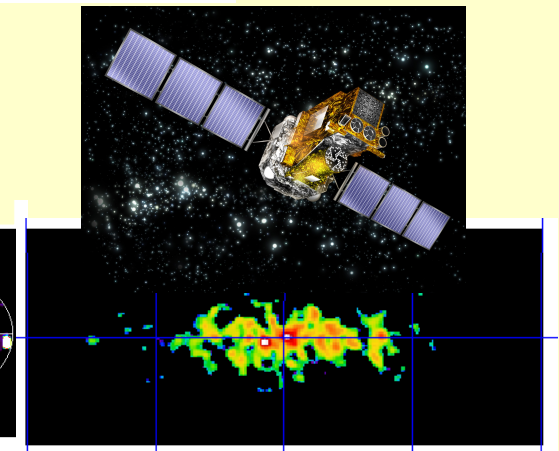
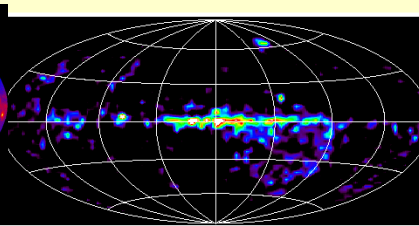
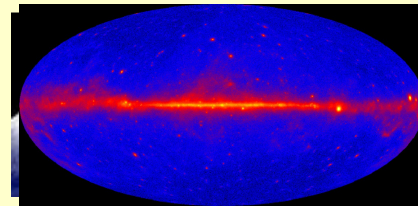


The **goal** : use *all* types of data in self-consistent way to test models of cosmic-ray propagation.

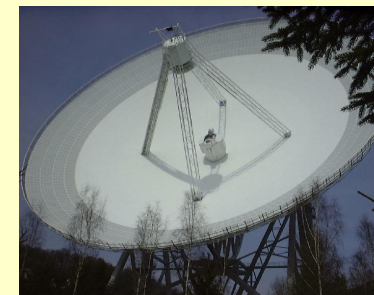
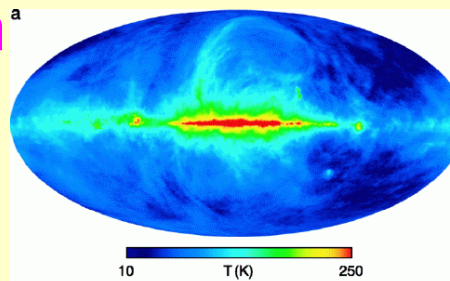
Observed *directly, near Sun*:  
primary spectra (p, He ... Fe;  $e^-$ )  
secondary/primary (B/C etc)  
secondary  $e^+$ , antiprotons...



Observed  
from whole  
Galaxy:  
 $\gamma$  - rays



synchrotron<sup>a</sup>



# Modelling the gamma-ray sky

## Main ingredients of GALPROP model

cosmic-ray spectra  $p$  ,  $He$  ,  $e^-$  ,  $e^+$  (including secondaries)  
(including *Fermi-measured* electrons)

cosmic-ray source distribution follow e.g. SNR/pulsars

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

Interstellar radiation field (-> inverse Compton)

HI, CO, dust surveys

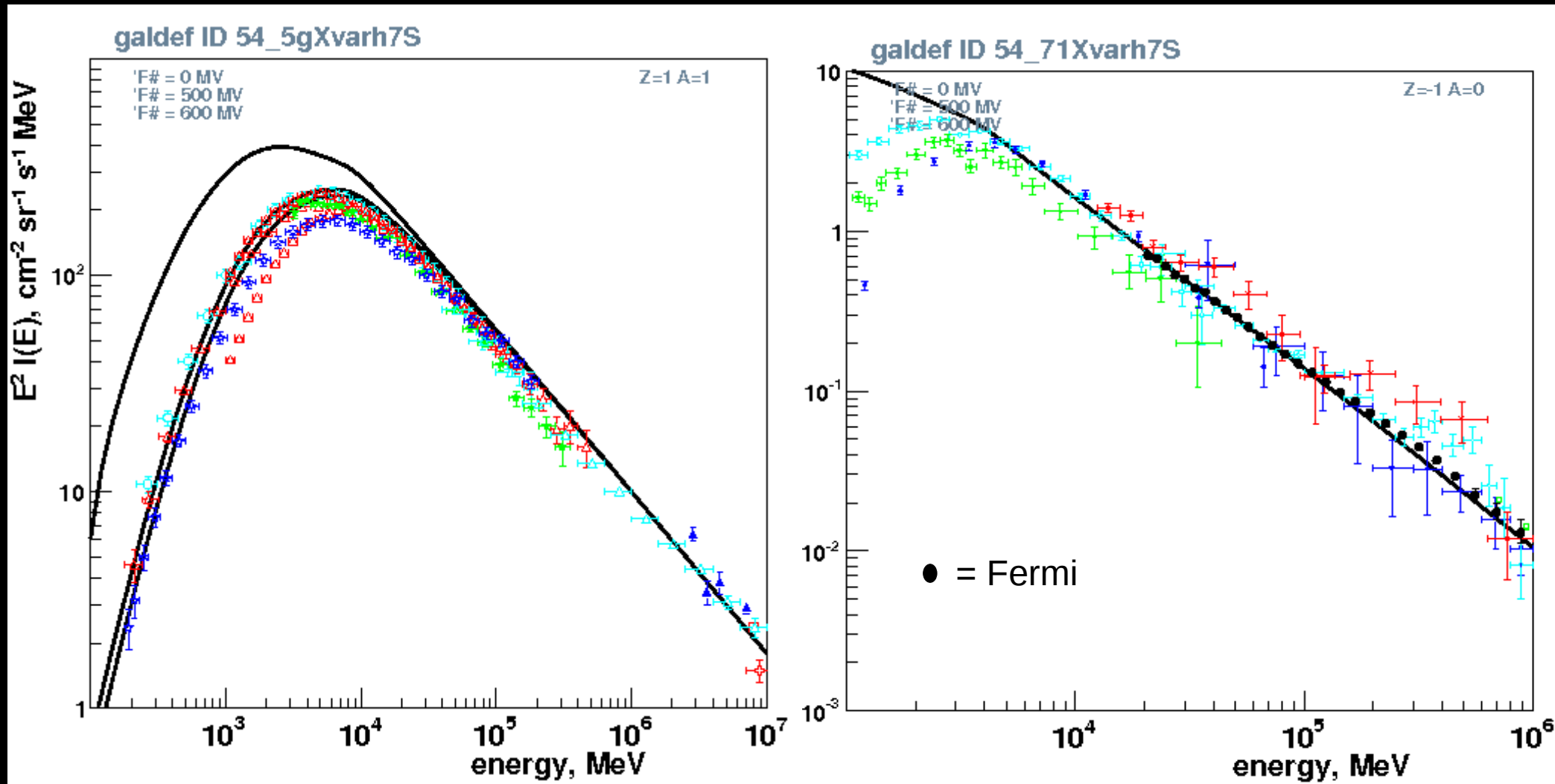
CO-to- $H_2$  conversion a function of position in Galaxy

Fermi 1<sup>st</sup> Year Source Catalogue

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

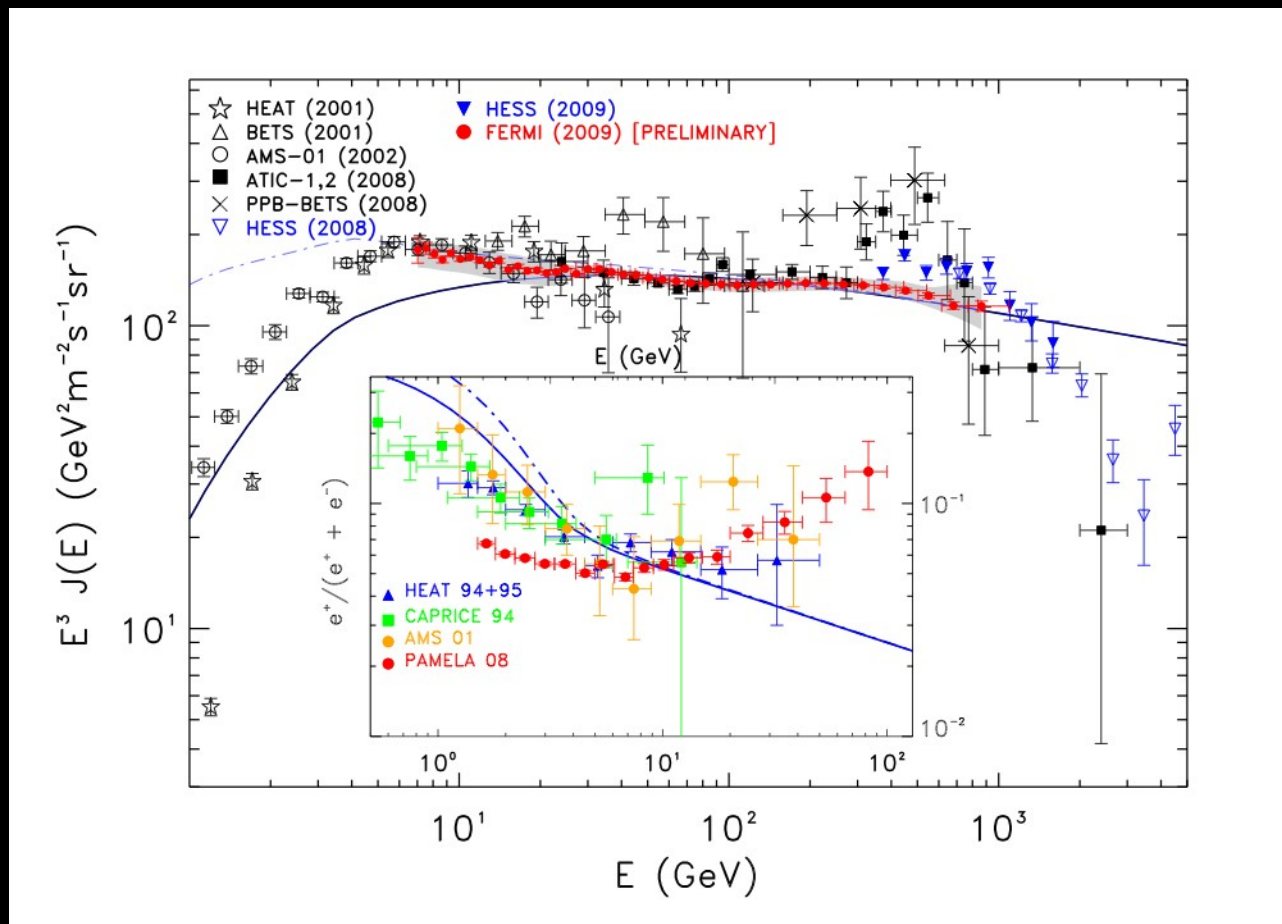
## PROTONS

## ELECTRONS



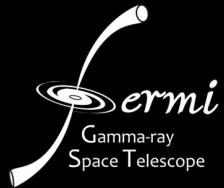
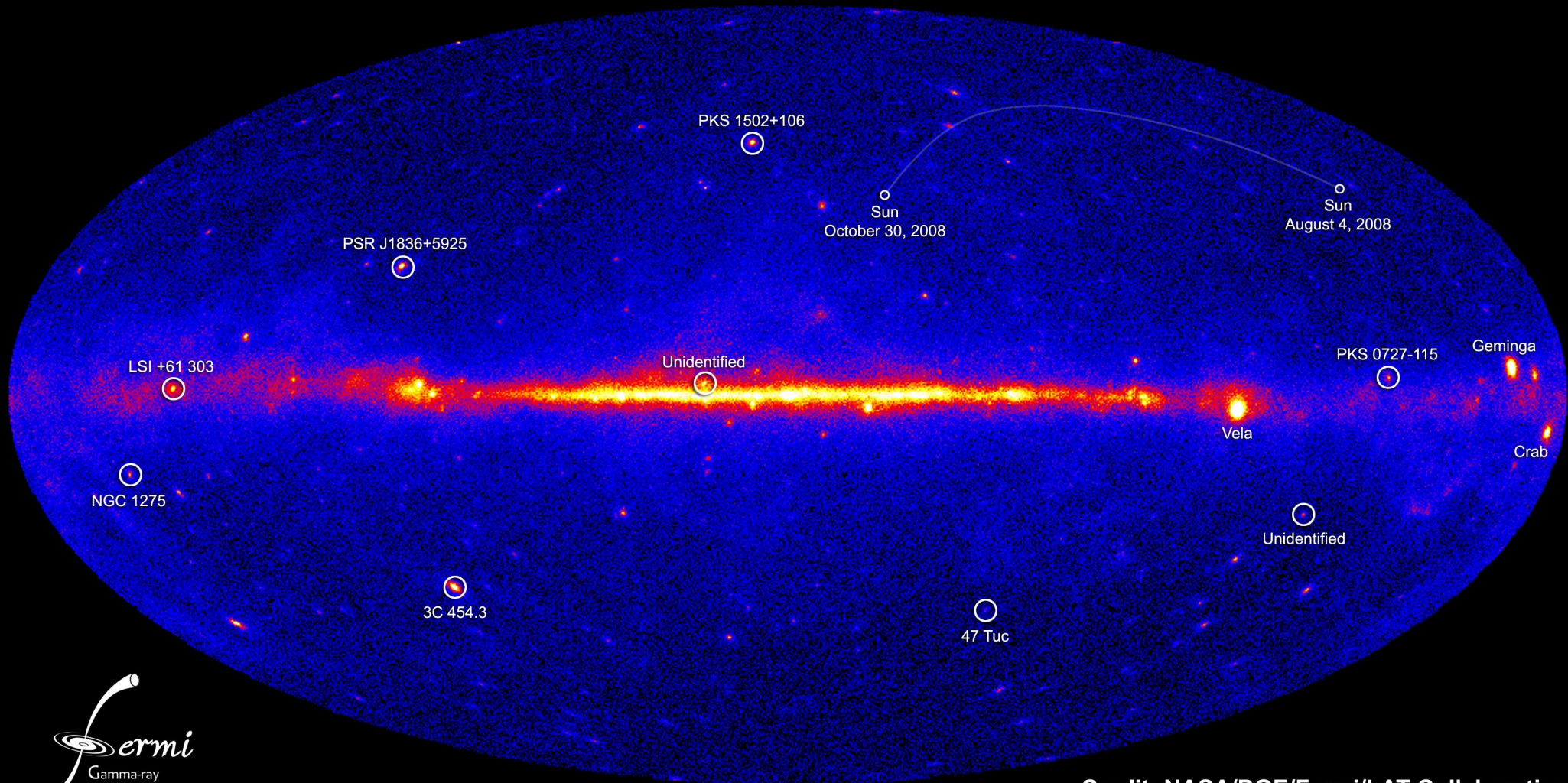


# Electron spectrum measured by Fermi-LAT extended down to 7 GeV



Abdo et al in preparation

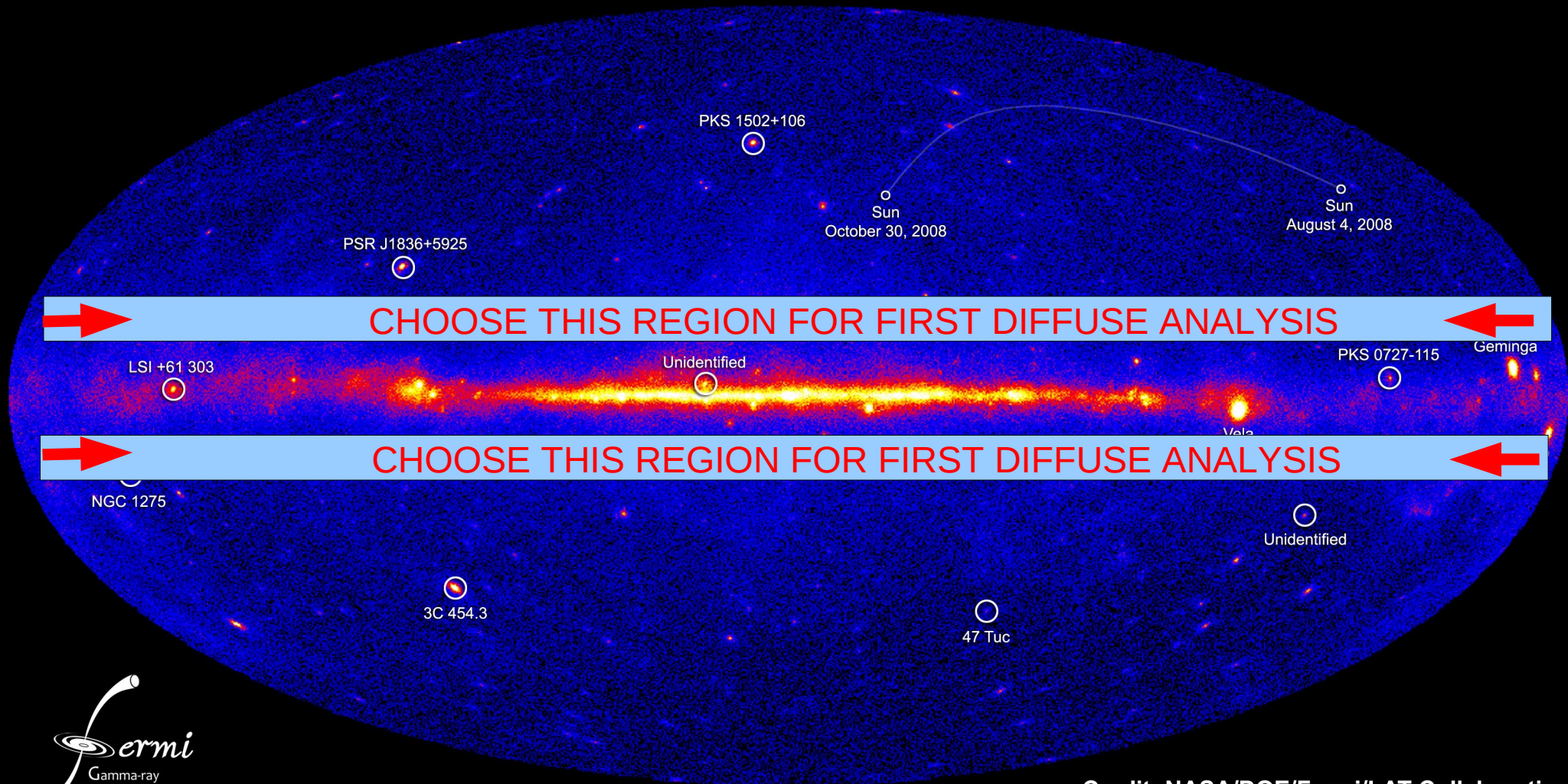
# NASA's Fermi telescope reveals best-ever view of the gamma-ray sky



Credit: NASA/DOE/Fermi/LAT Collaboration



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

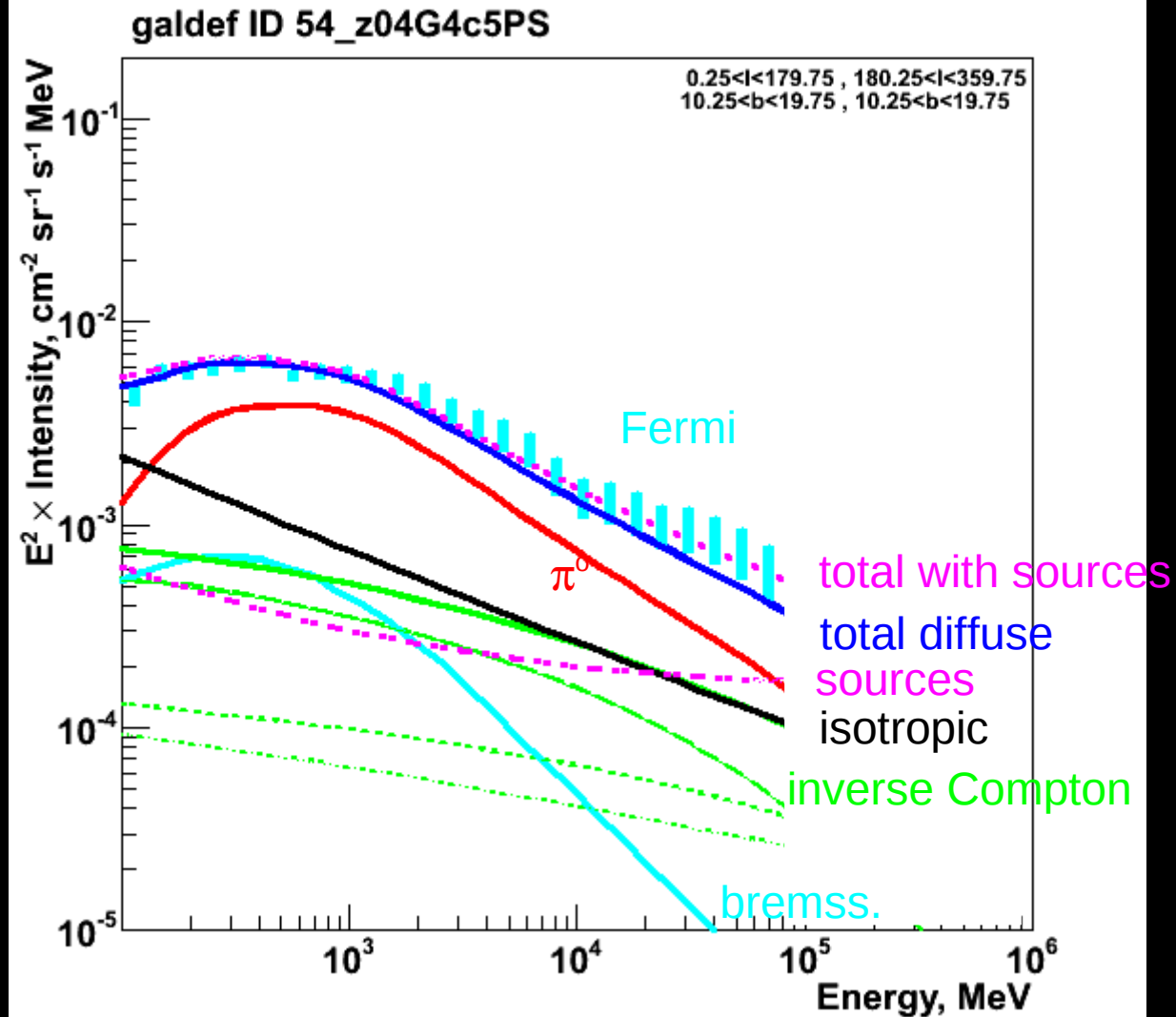


Credit: NASA/DOE/Fermi/LAT Collaboration



# INTERMEDIATE LATITUDES $+10 < b < +20$

good  
agreement  
with  
basic  
model



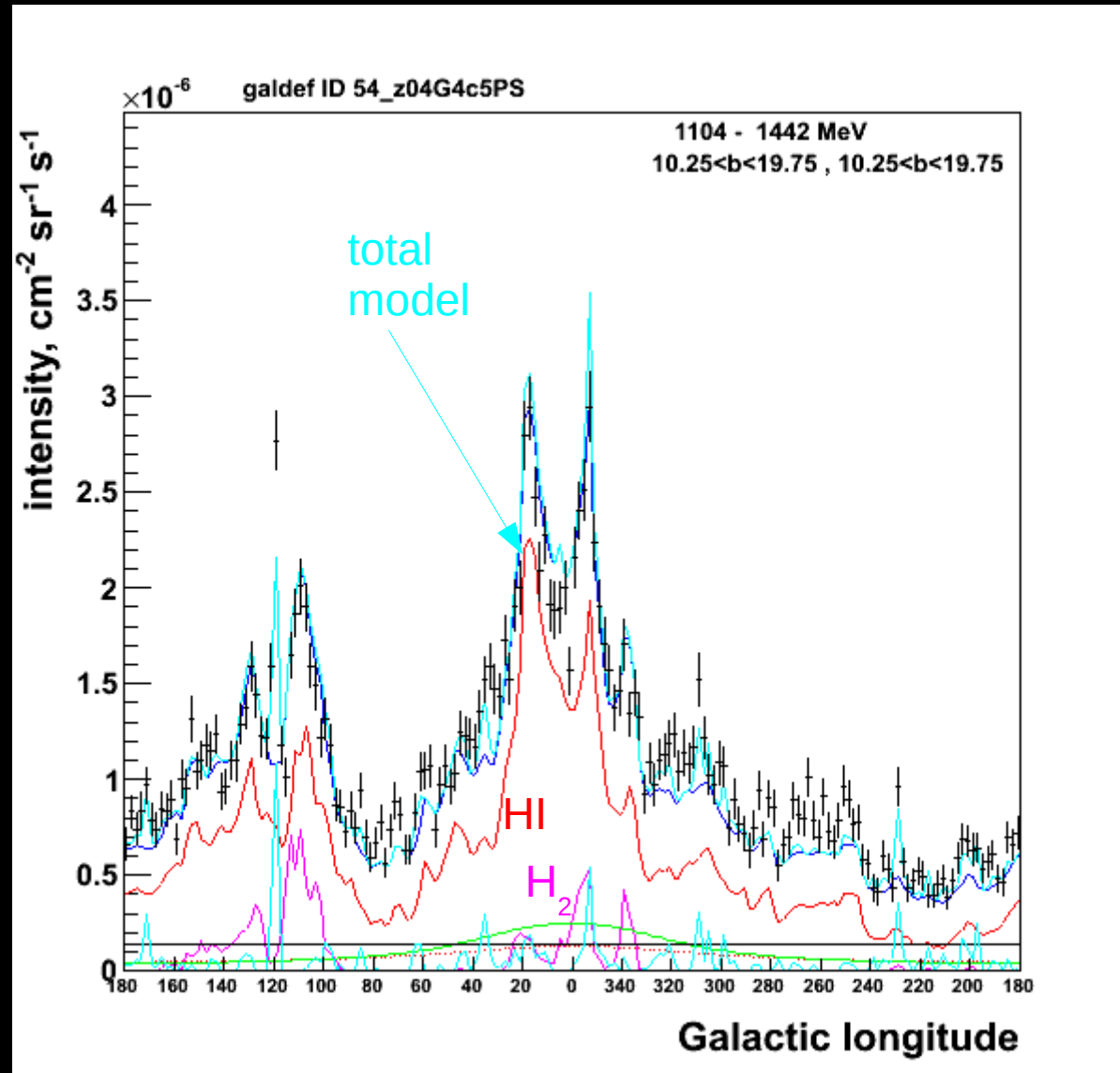
PRELIMINARY

## INTERMEDIATE LATITUDES

$$+10 < b < +20$$

1 GeV

total gas  
traced by  
dust from  
IRAS+DIRBE



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

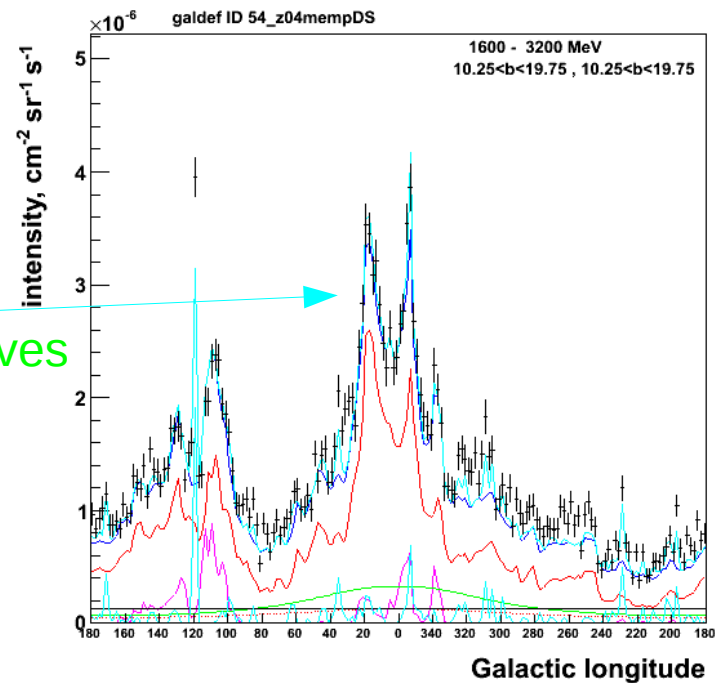
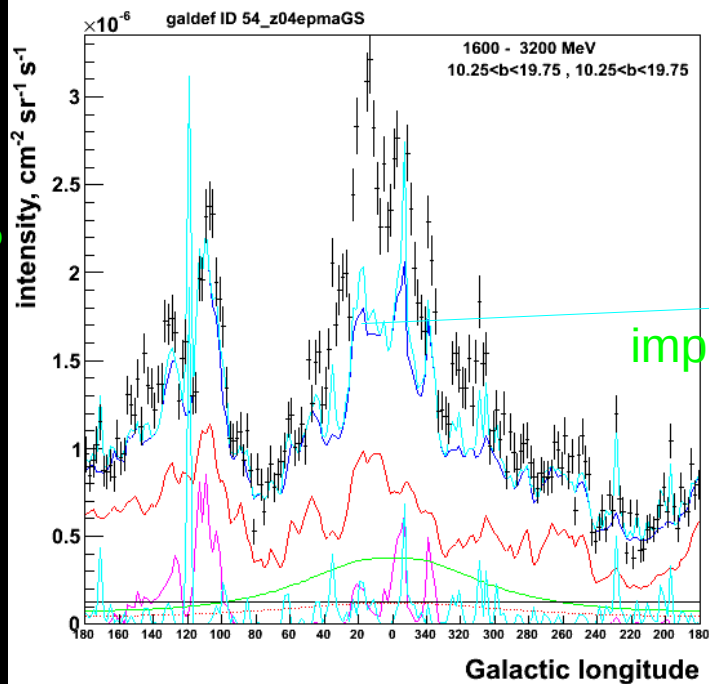
**PRELIMINARY**

# GAS TRACER: HI, CO

# GAS TRACER: dust

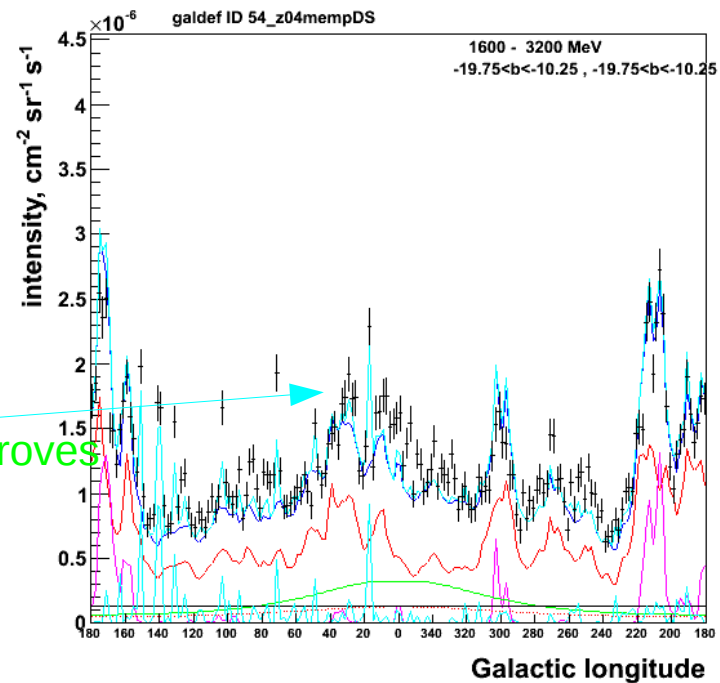
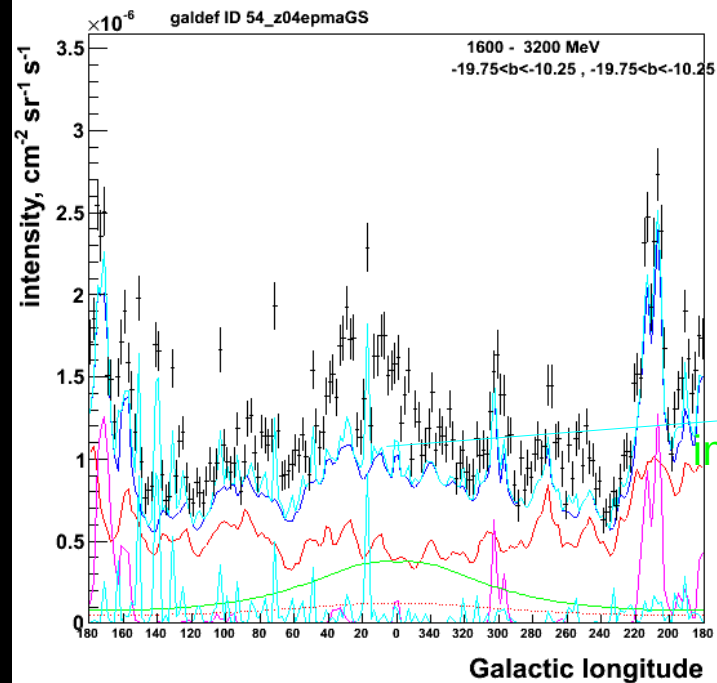
North

$+10^\circ < b < +20^\circ$



South

$-20^\circ < b < -10^\circ$

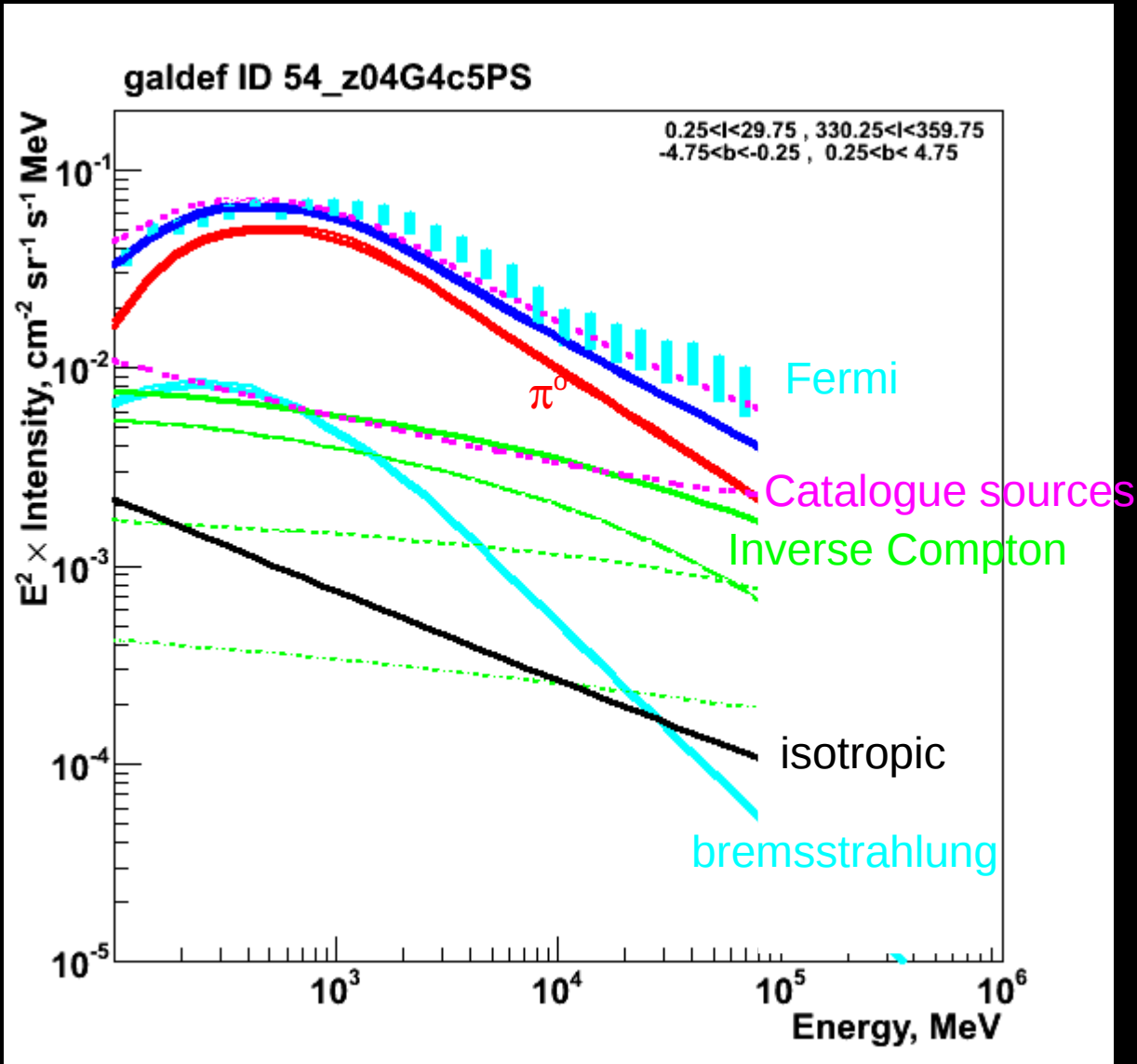


Dust emission is a better tracer of local gas than HI+CO !



# Inner Galaxy

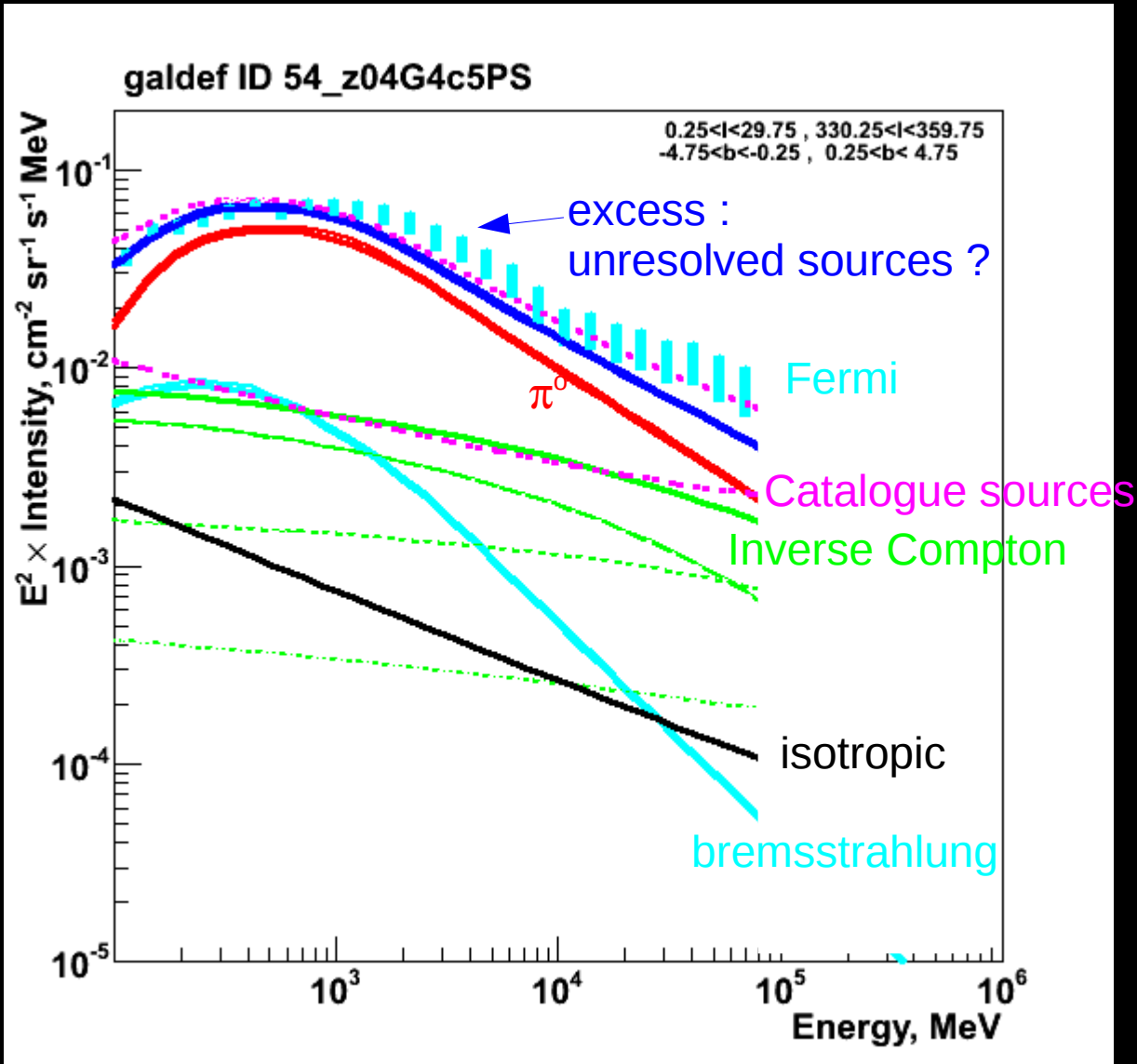
$330^\circ < l < 30^\circ, |b| < 5^\circ$



PRELIMINARY

# Inner Galaxy

$330^\circ < l < 30^\circ, |b| < 5^\circ$

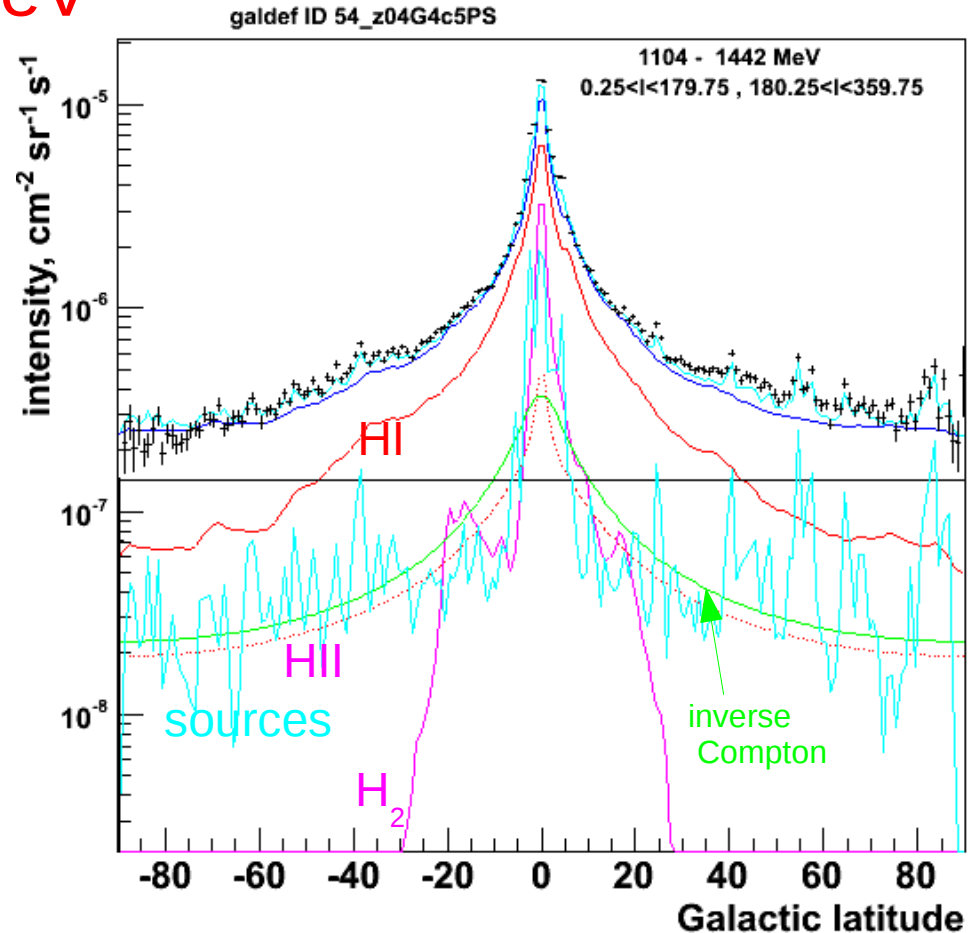
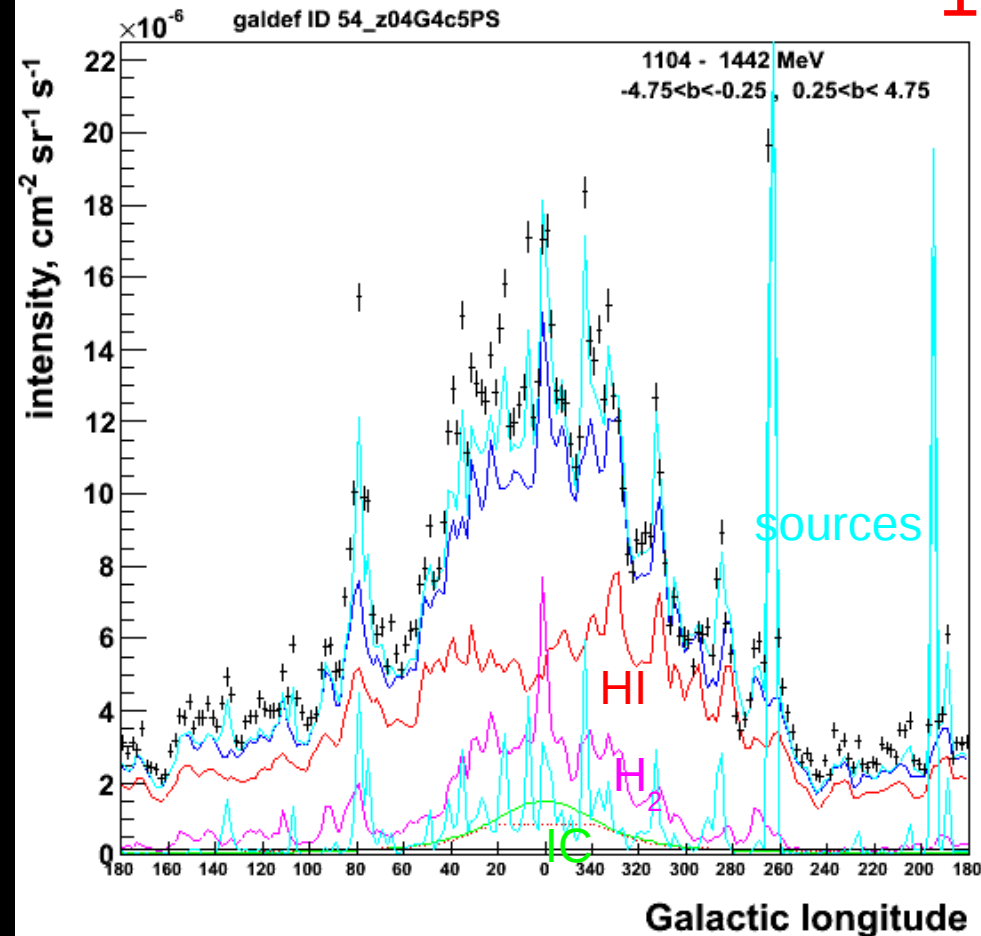


PRELIMINARY

# 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

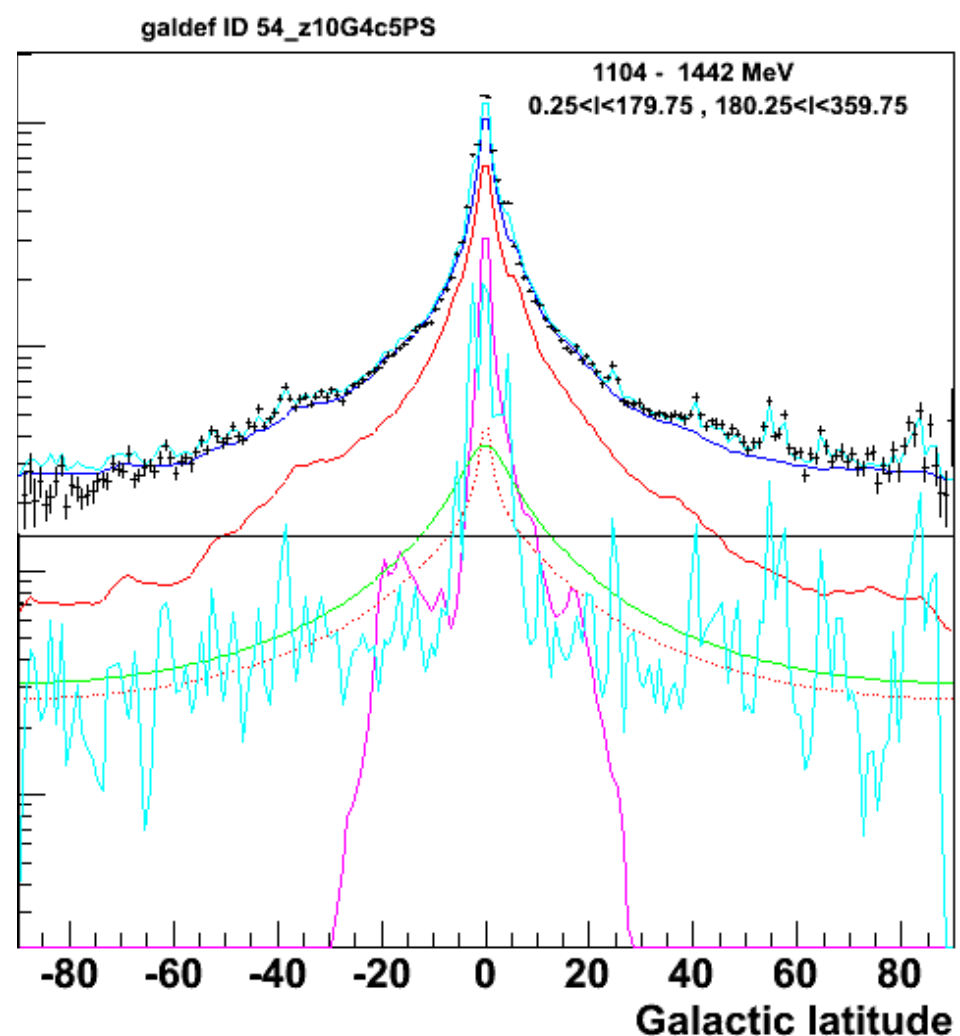
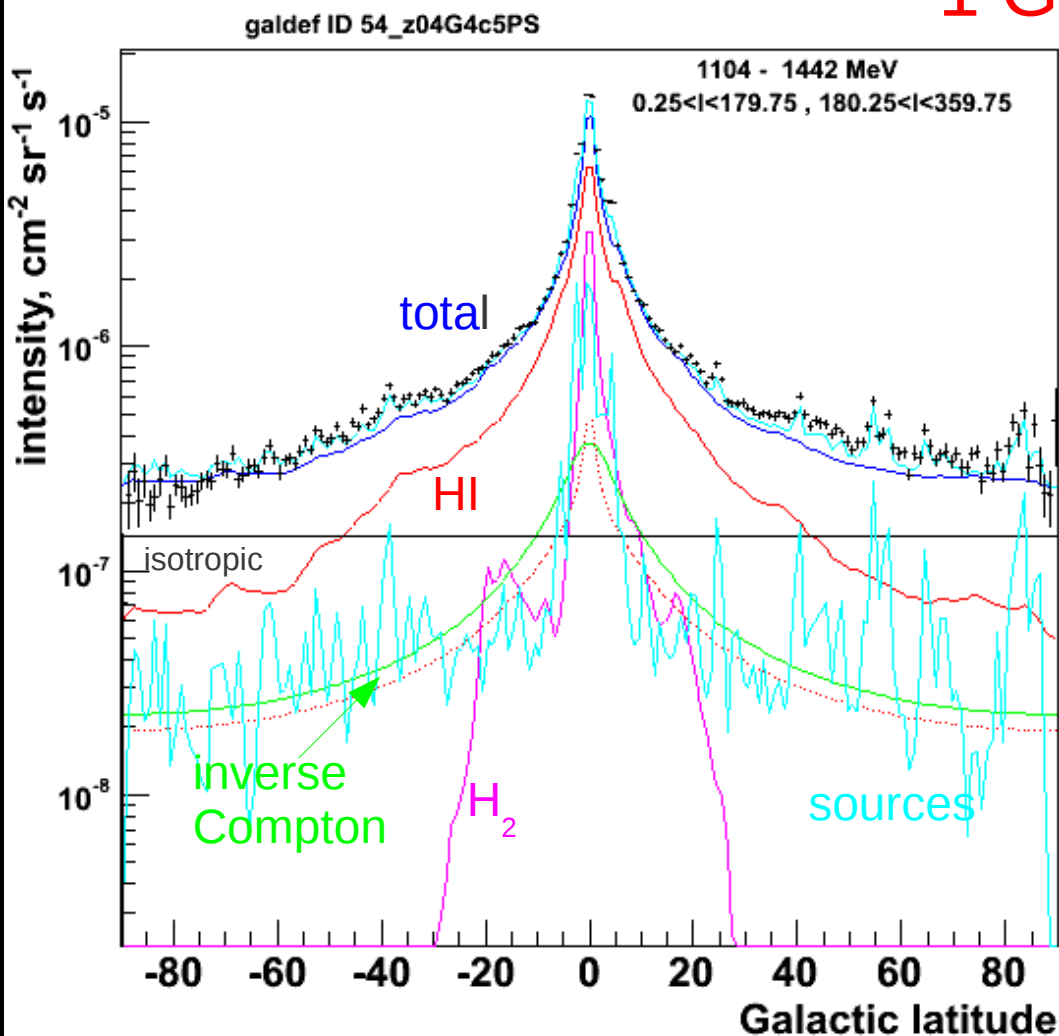


# EVIDENCE FOR LARGE COSMIC-RAY HALO

4 kpc halo height

10 kpc halo height

1 GeV



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

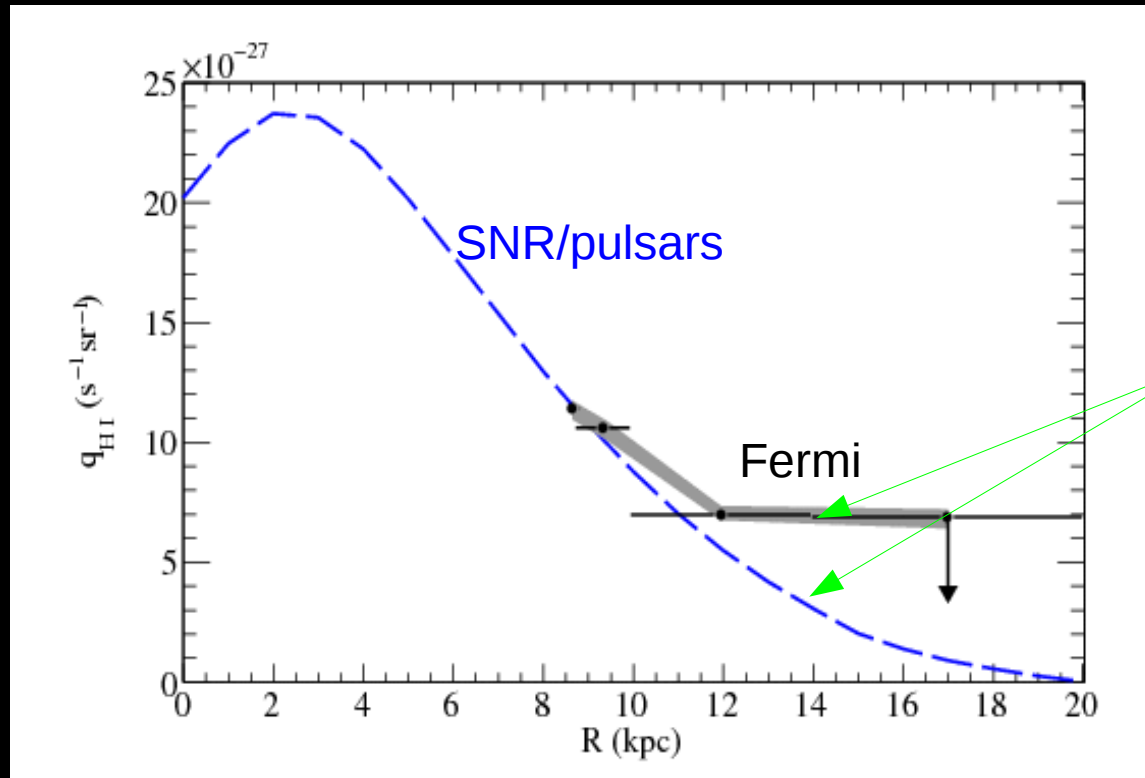
PRELIMINARY

# 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

## 2<sup>nd</sup> Galactic quadrant



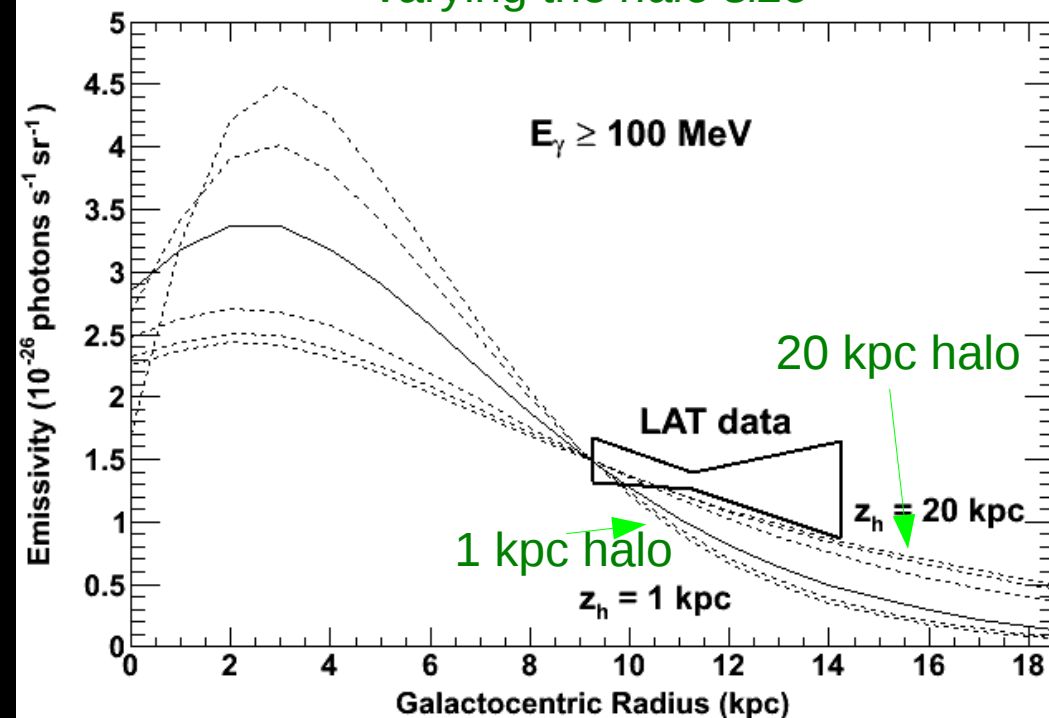
more  
cosmic rays  
than  
expected !

Abdo et al (2010) ApJ 710, 133

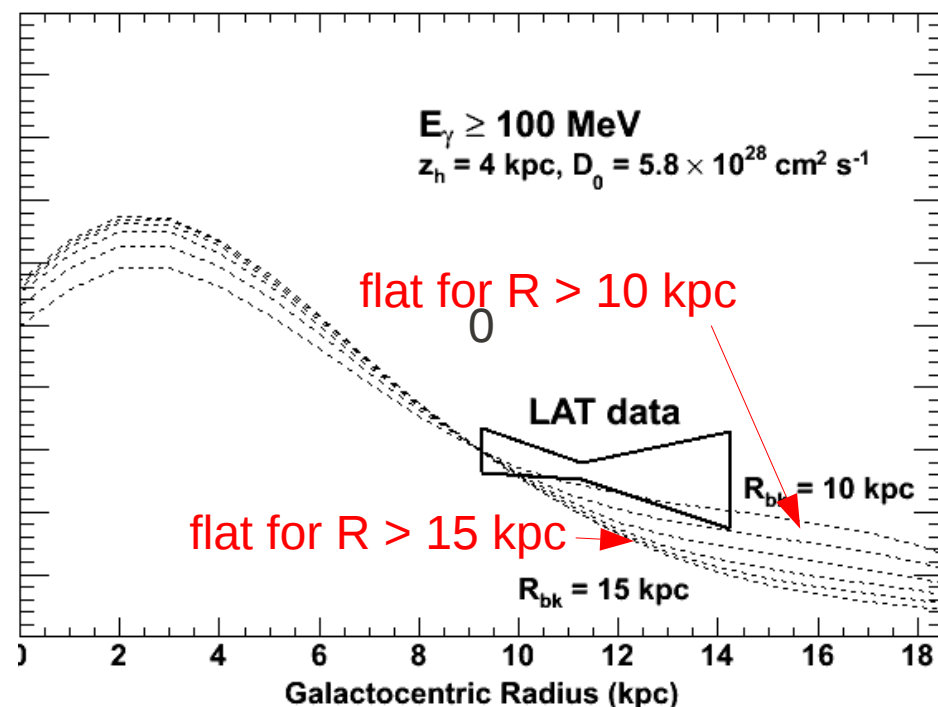
# Gamma-ray emissivity distribution in outer Galaxy

## 3<sup>rd</sup> Galactic Quadrant

varying the *halo* size



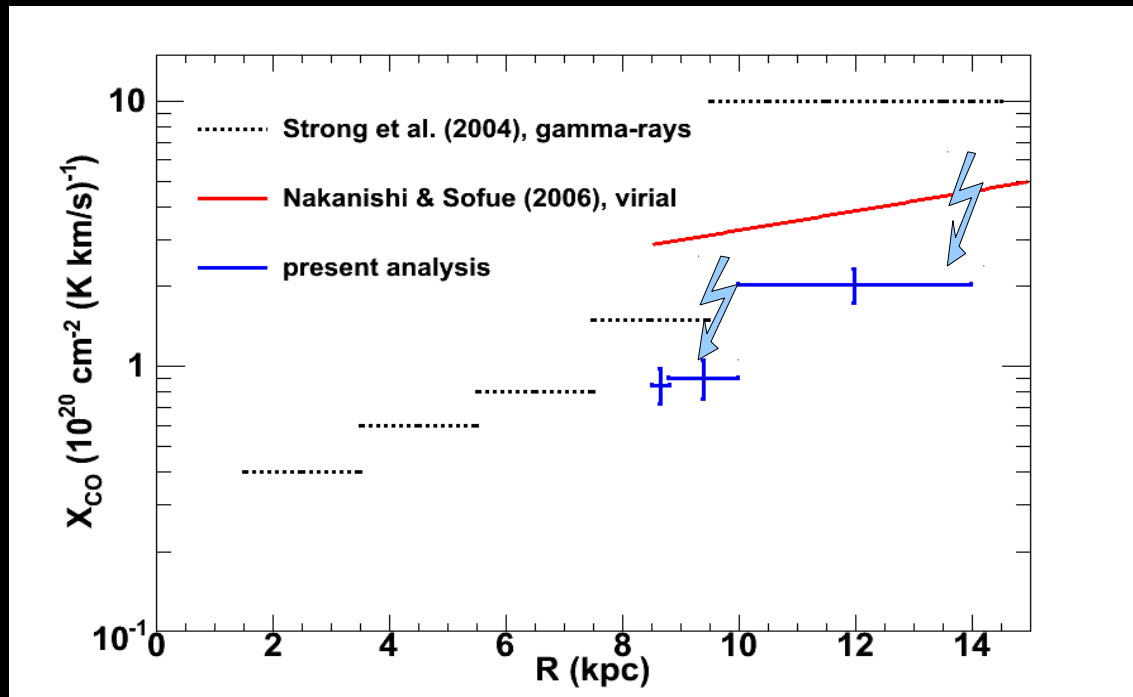
varying the *source distribution*



Abdo et al 2010, ApJ submitted

NEW: PRELIMINARY

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



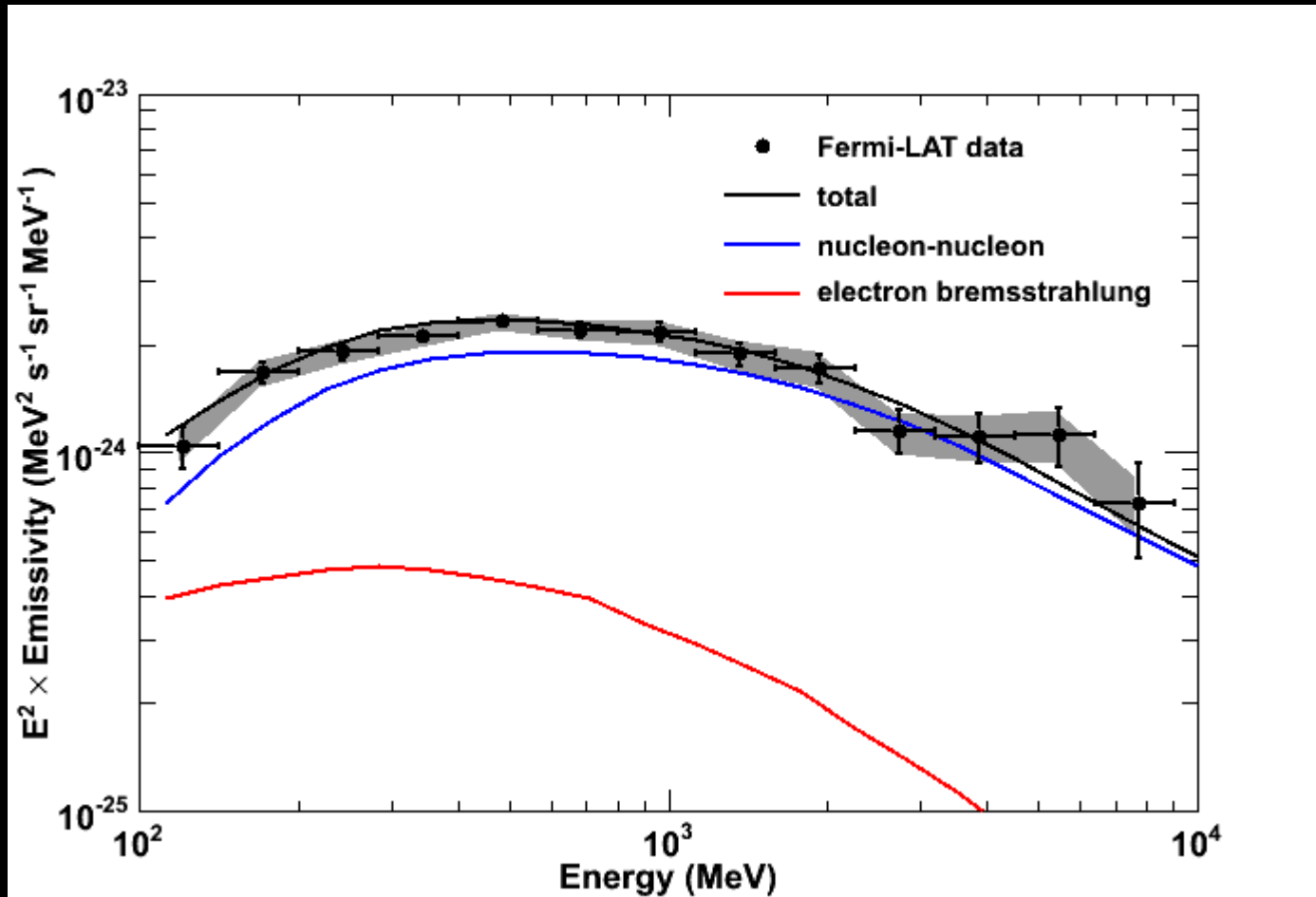
Scaling factor  $X_{\text{CO}}$  from  $^{12}\text{CO}$  to  $\text{H}_2$   
Local and Outer Galaxy (2<sup>nd</sup> quadrant)

Confirms *increase* from inner to outer Galaxy

Abdo et al (2010) ApJ 710, 133



## Local HI gamma-ray emissivity



Agrees well with pion-decay calculation !

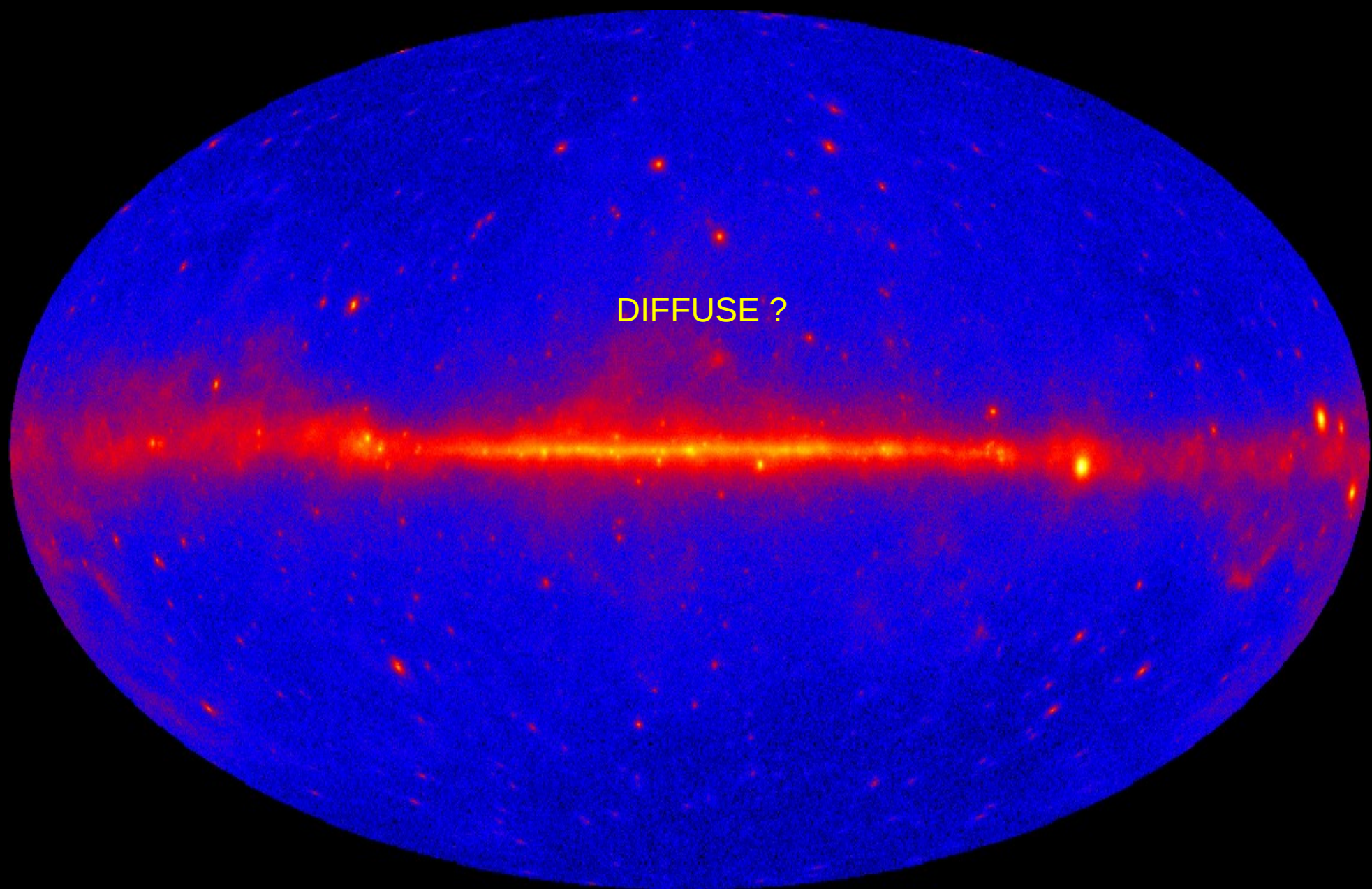
Abdo et al. ApJ 2009

# Facit

Large Scale Diffuse Gamma Ray Emission:

The diffuse emission model reproduces the Fermi data remarkably well.

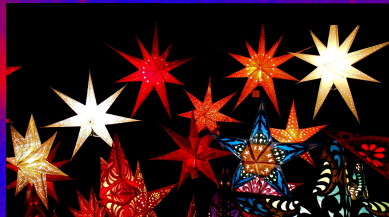
The remaining residuals have many possible origins:  
this is where the current action and interest is focussed.



DIFFUSE ?



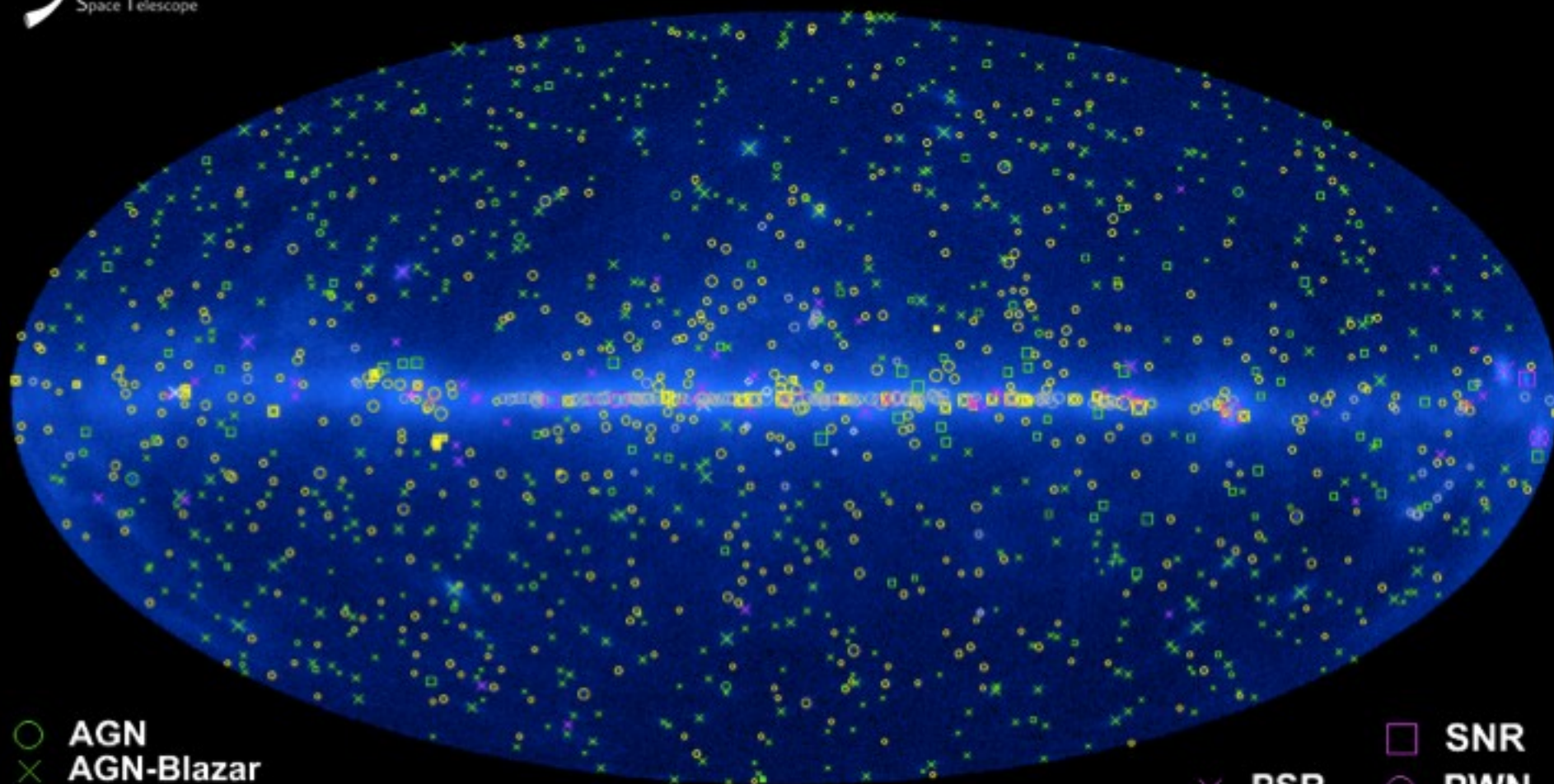
OR PARTLY UNRESOLVED SOURCES ?







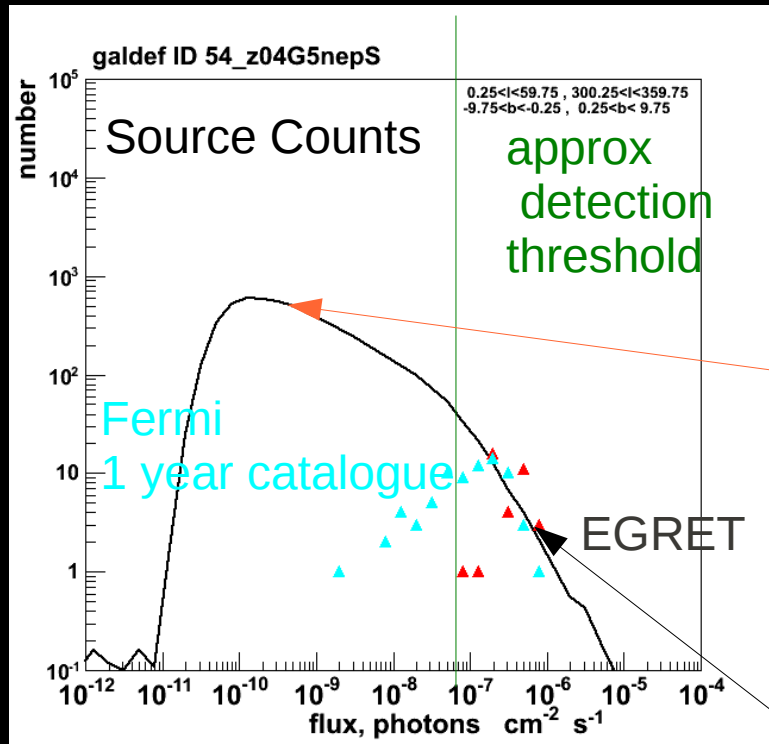
# The Fermi LAT 1FGL Source Catalog



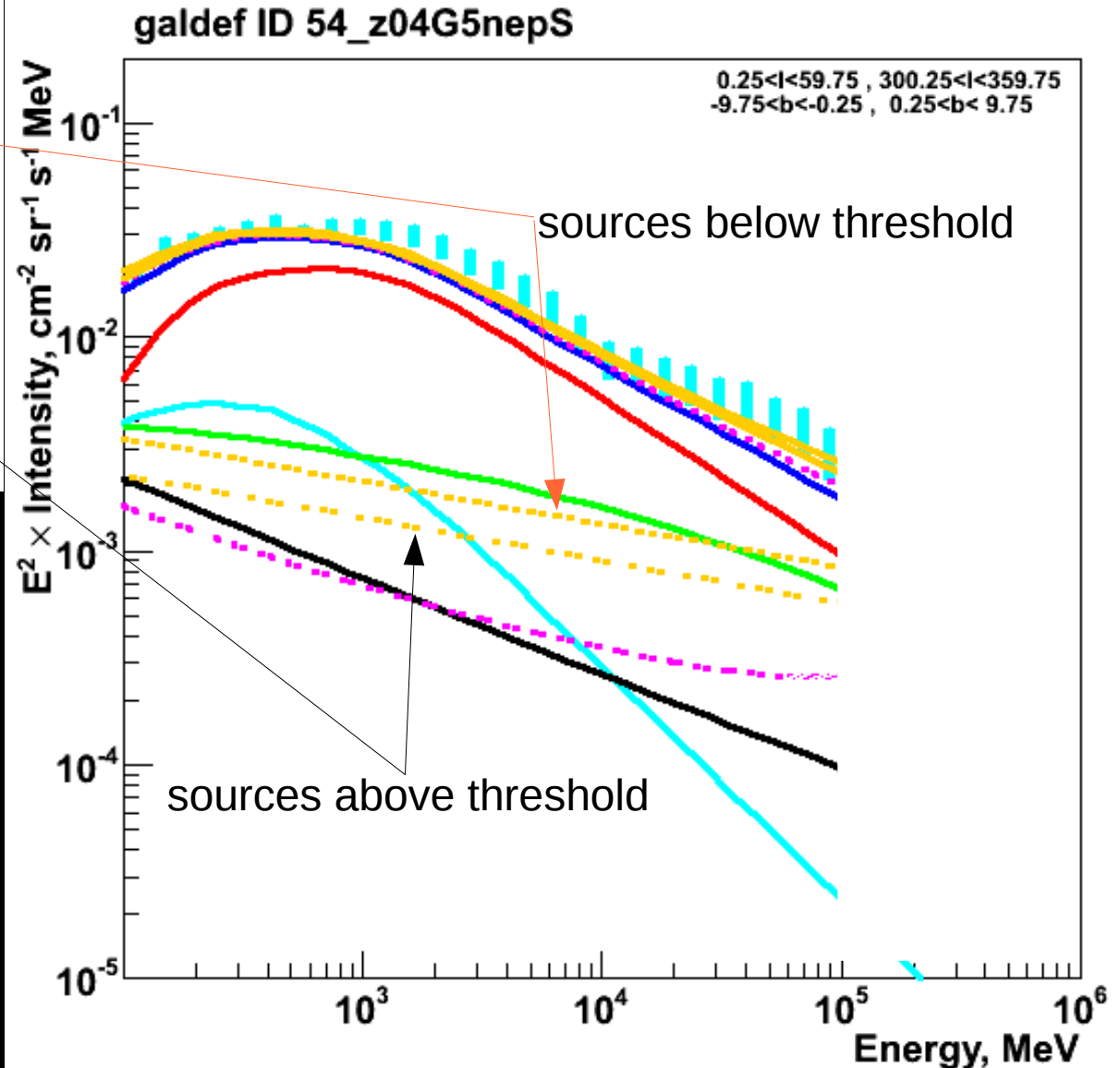
- |   |                    |
|---|--------------------|
| ○ AGN   | □ SNR              |
| × AGN-Blazar  | ○ PWN              |
| □ AGN-Non Blazar                                    | × PSR              |
| ○ No Association                                    | ⊗ PSR w/PWN        |
| □ Possible Association with SNR and PWN             | ◇ Globular Cluster |
| ○ Possible confusion with Galactic diffuse emission | × HXB or MQO       |
| □ Starburst Galaxy                                  |                    |
| + Galaxy  |                    |

Credit: *Fermi* Large Area Telescope Collaboration

# Source contribution from luminous (pulsars etc) sources

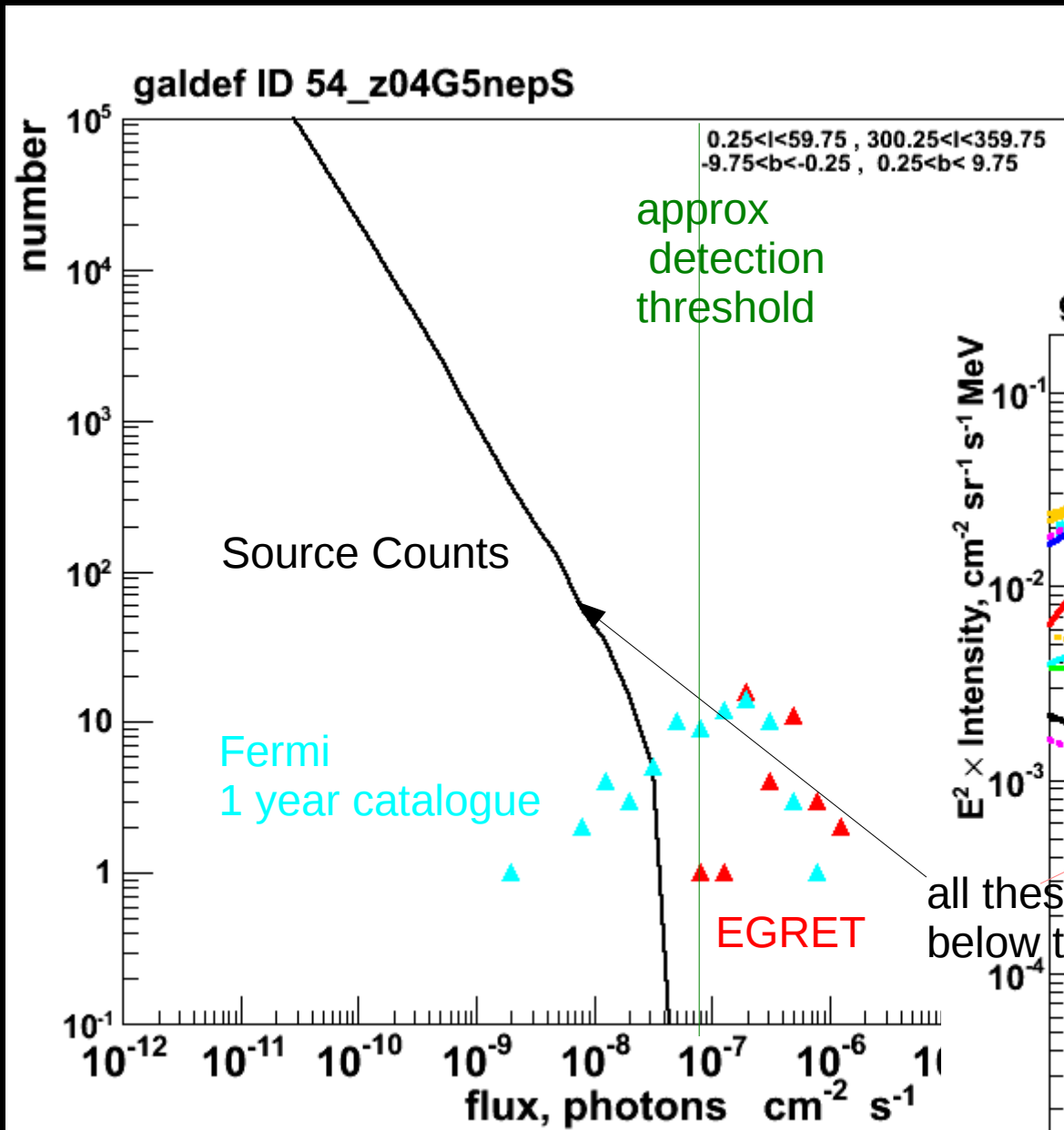


Due to Fermi sensitivity,  
unresolved source flux will finally be at percent level

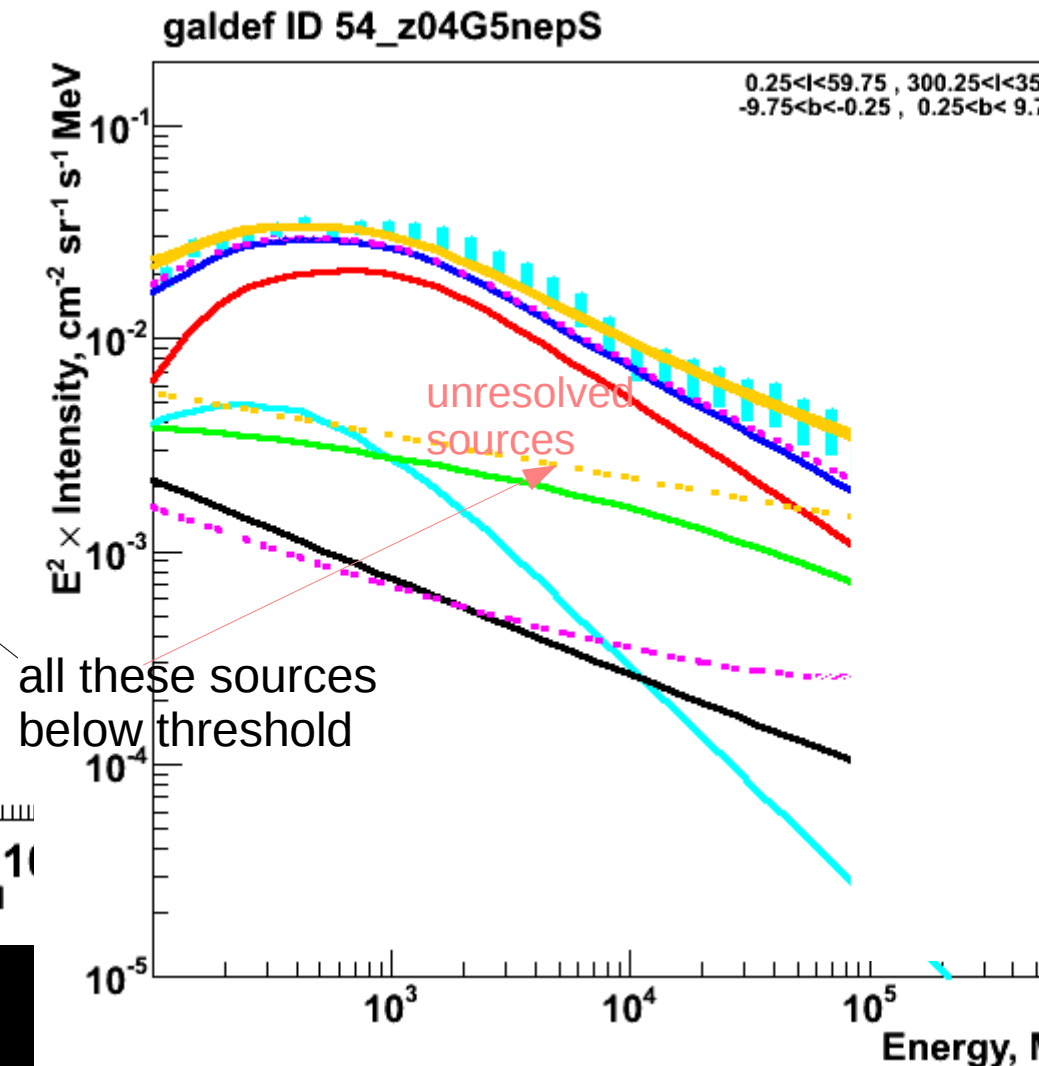


population synthesis  
model consistent with  
Fermi year 1 Catalogue

# Source contribution from possible low-luminosity sources

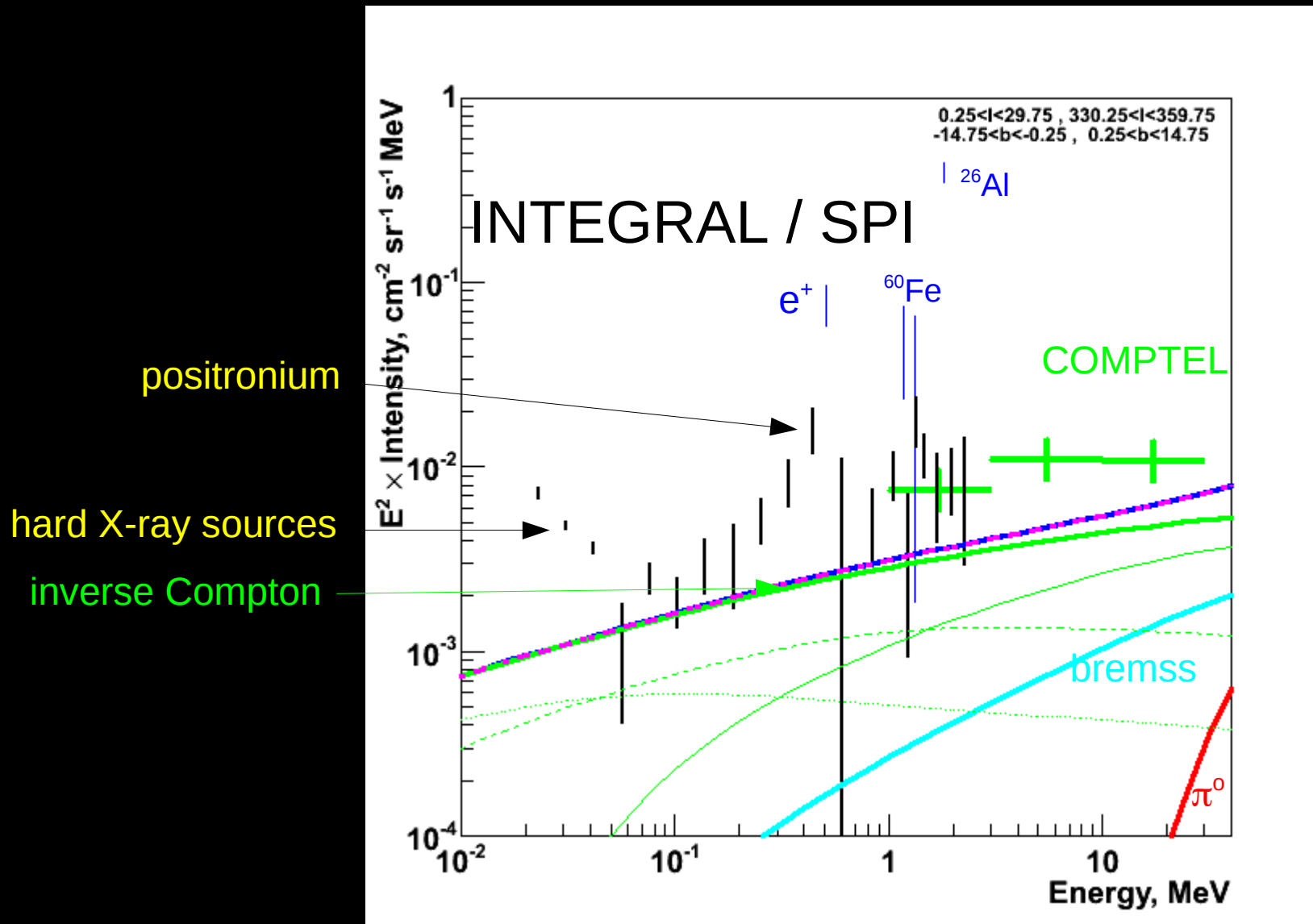


Many more dim sources can hide.  
Just limits can be set on  
their contribution.



# INTEGRAL / SPI

## spectrum of inner Galaxy



**NEW**

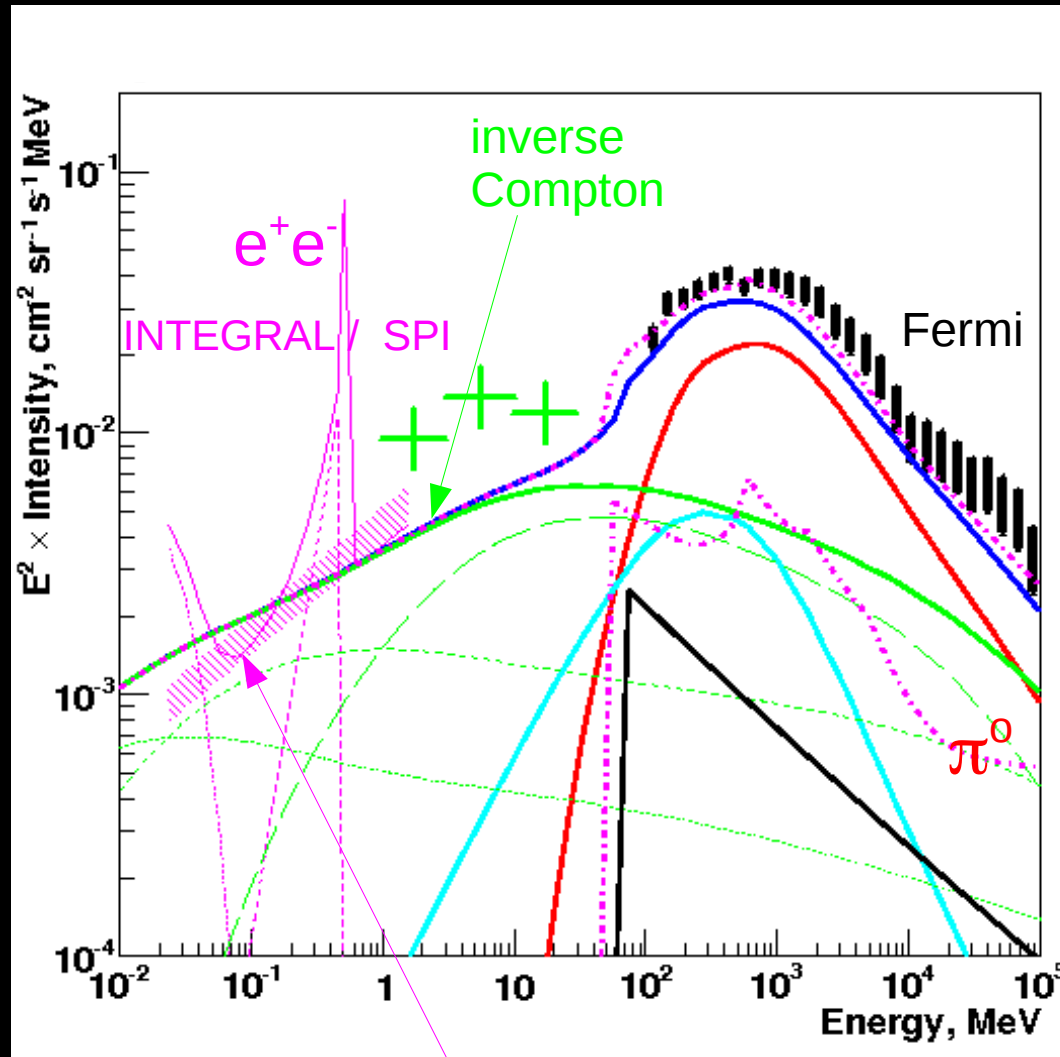
*Bouchet et al 2010, in preparation  
this conference: E18 Poster #65*



# Gamma-rays, inner Galaxy

inverse Compton

from primary electrons, secondary electrons + positrons

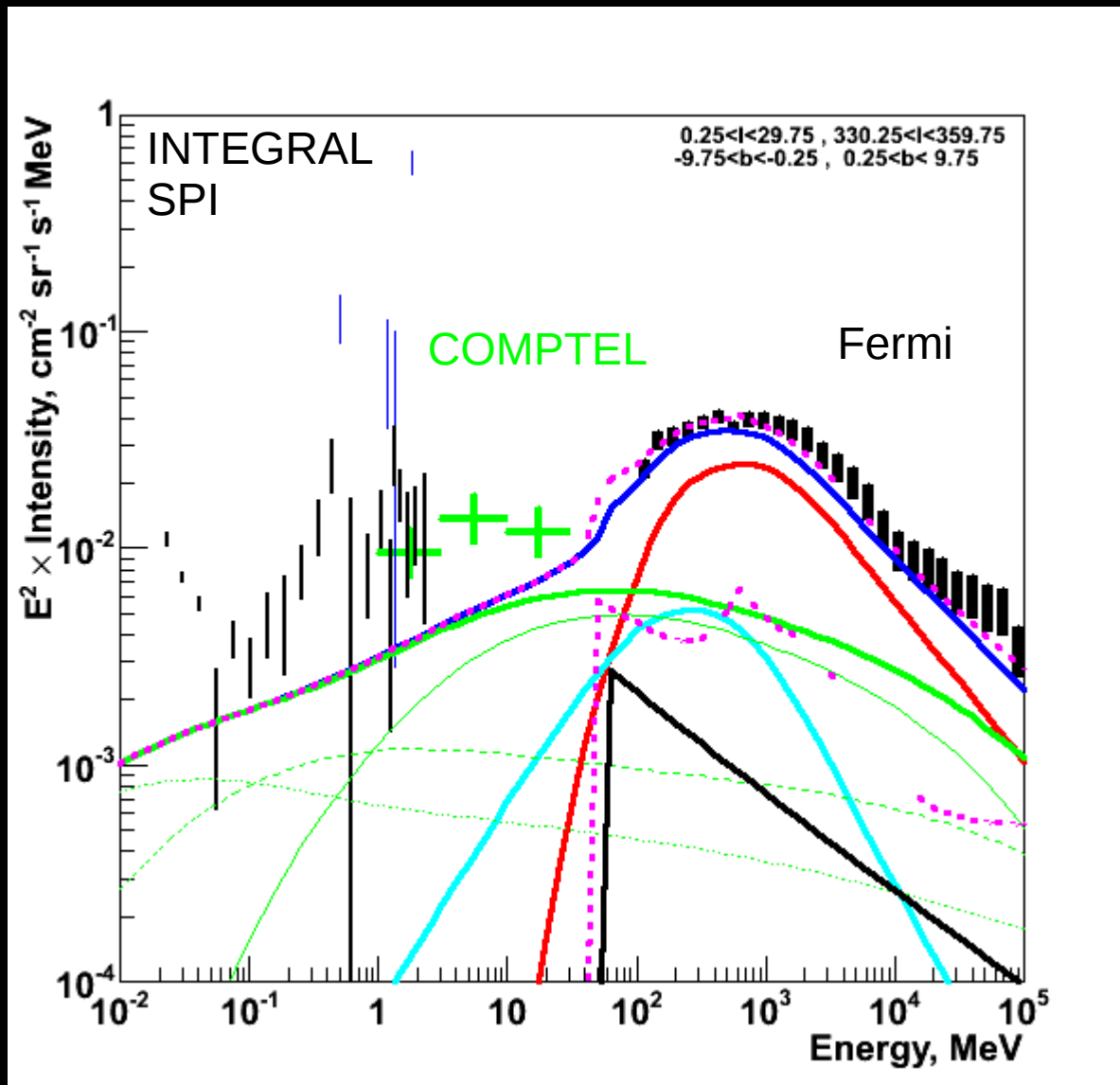


These processes  
are very relevant  
down to hard X-rays !

power-law continuum measured by INTEGRAL / SPI  
Bouchet et al 2008, Porter et al 2008

large fraction of the inverse Compton power comes out in hard X-rays !

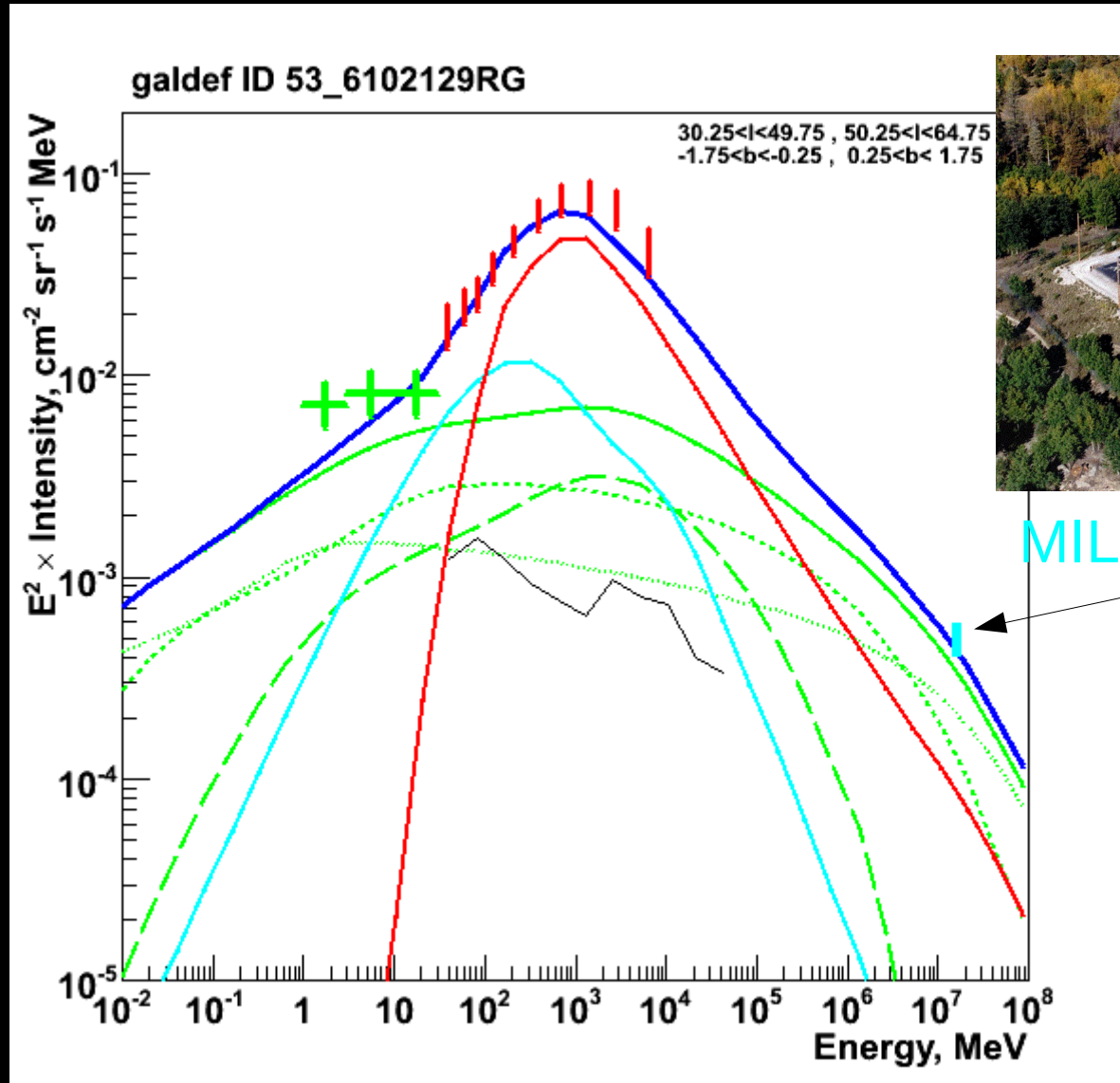
a glimpse of things to come....



PRELIMINARY

and towards the highest energies...

## Diffuse Galactic Emission



Abdo et al, (2008) ApJ 688

This model was adapted to EGRET GeV-excess, gave a good fit to MILAGRO but now with Fermi situation will change !

Milky Way Galaxy is a special target for multi-wavelength studies because ...

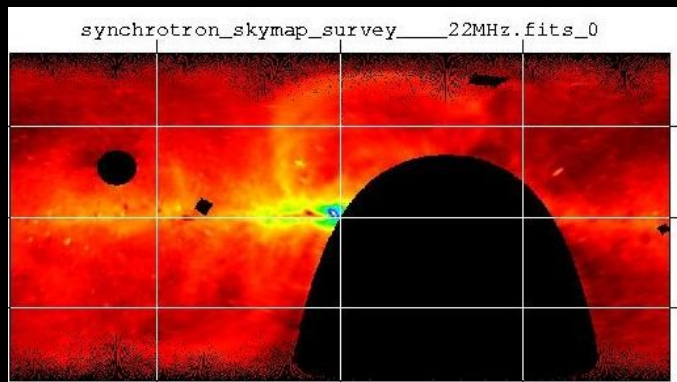
We know much more about our Galaxy than external galaxies:

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

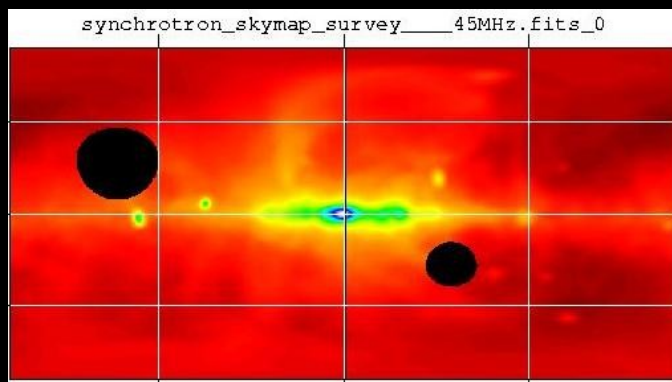
so study of the Galaxy allows a better understanding of the detailed inner workings to clarify the overall picture

including e.g. cosmic-ray CALORIMETRY

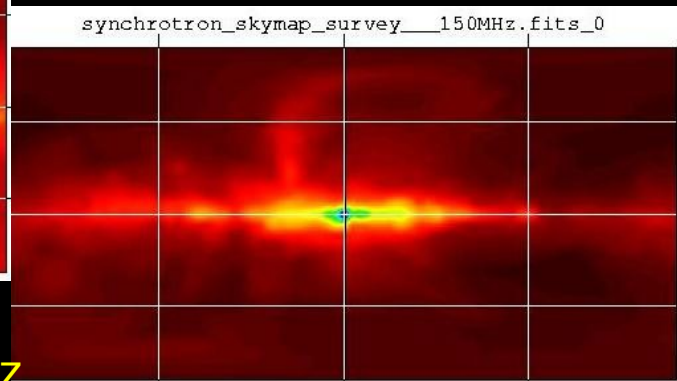




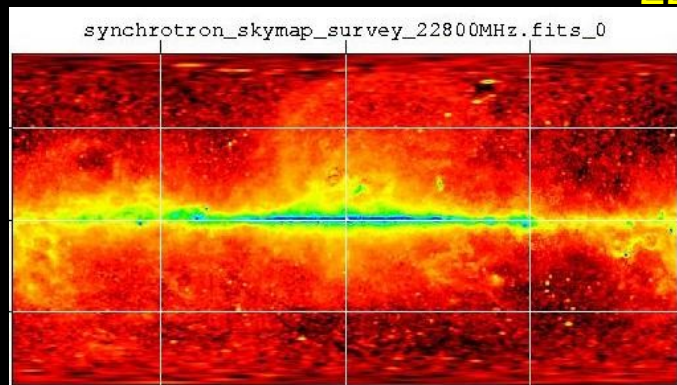
22 MHz



45 MHz



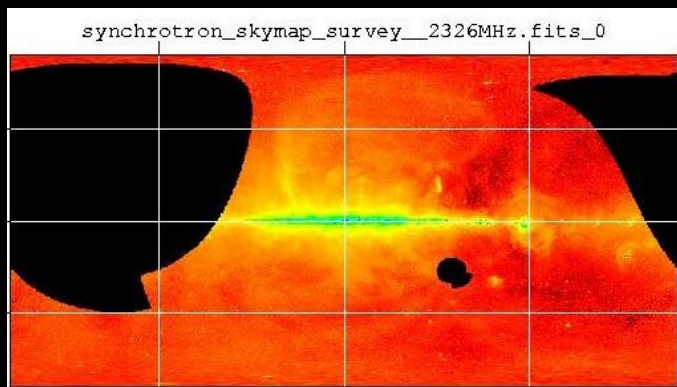
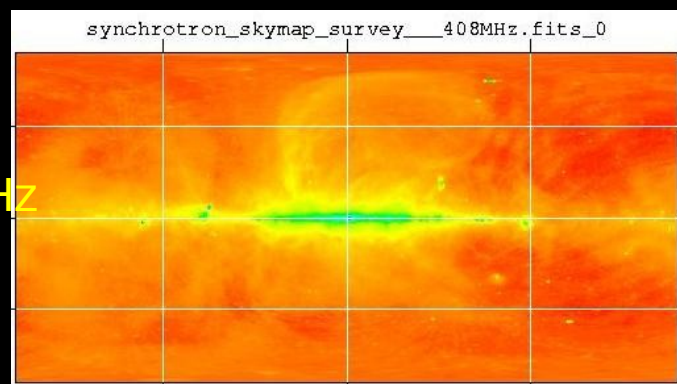
150 MHz



23 GHz

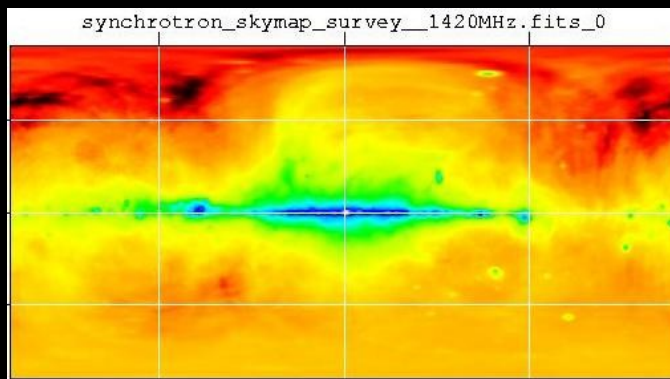
Continuum  
sky surveys

408 MHz

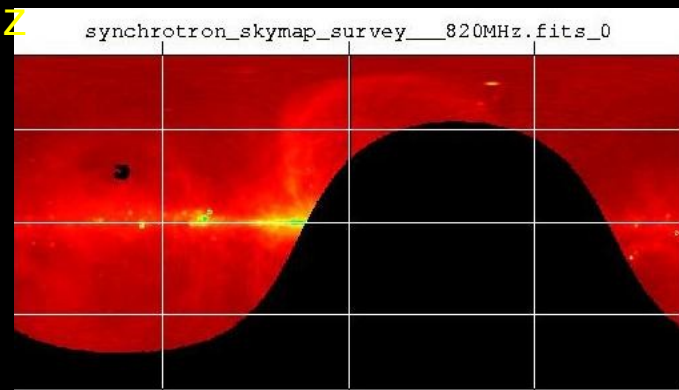


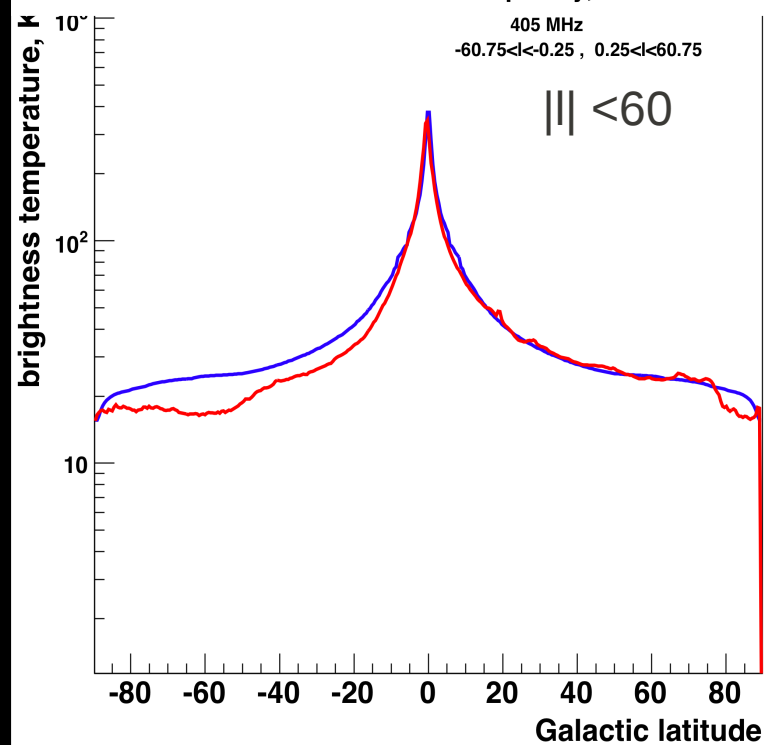
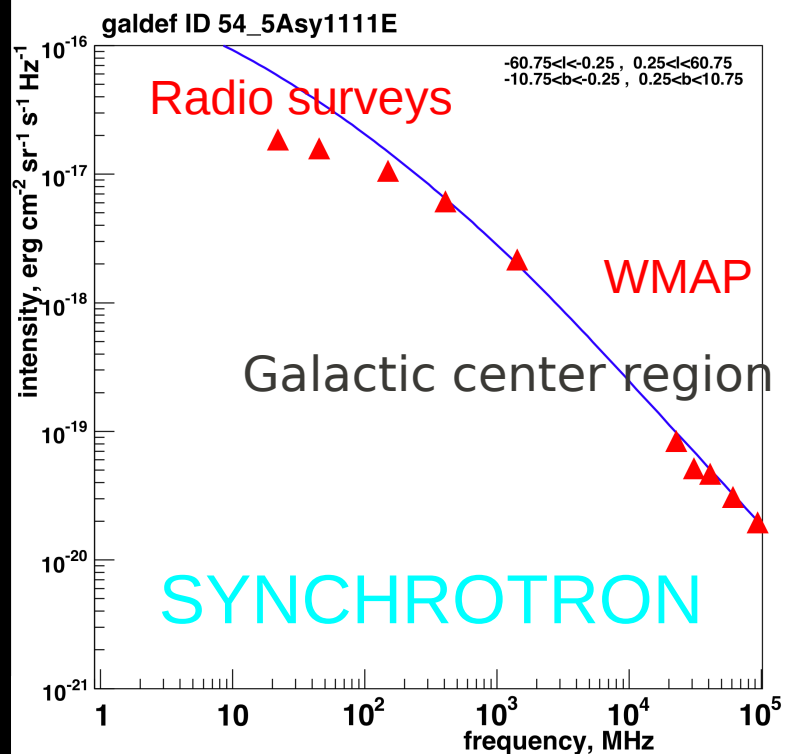
2.3 GHz

1.4 GHz



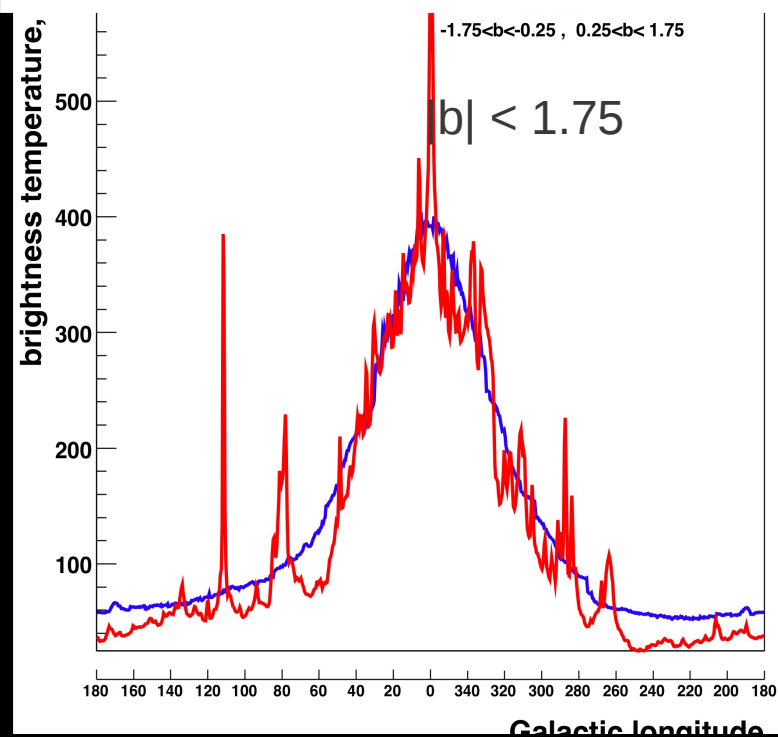
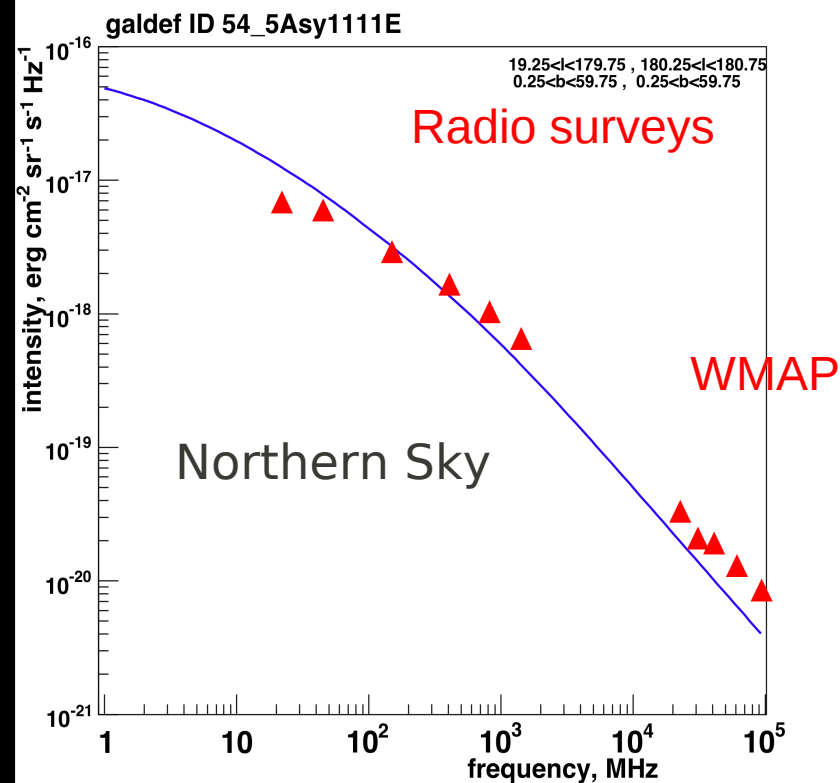
820 MHz



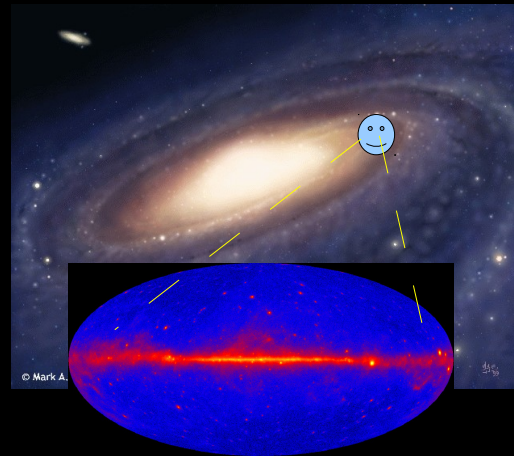


GALPROP  
model

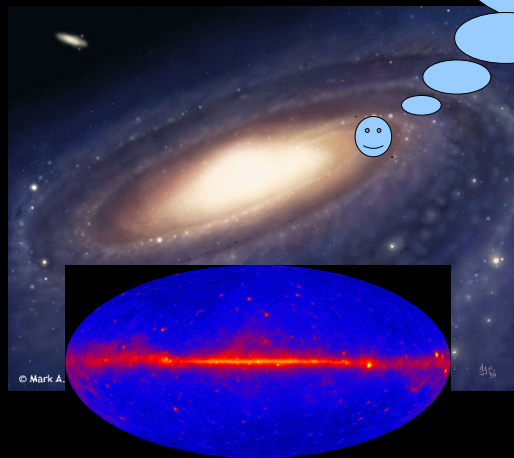
408 MHz



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



how does it  
look from out  
there ?

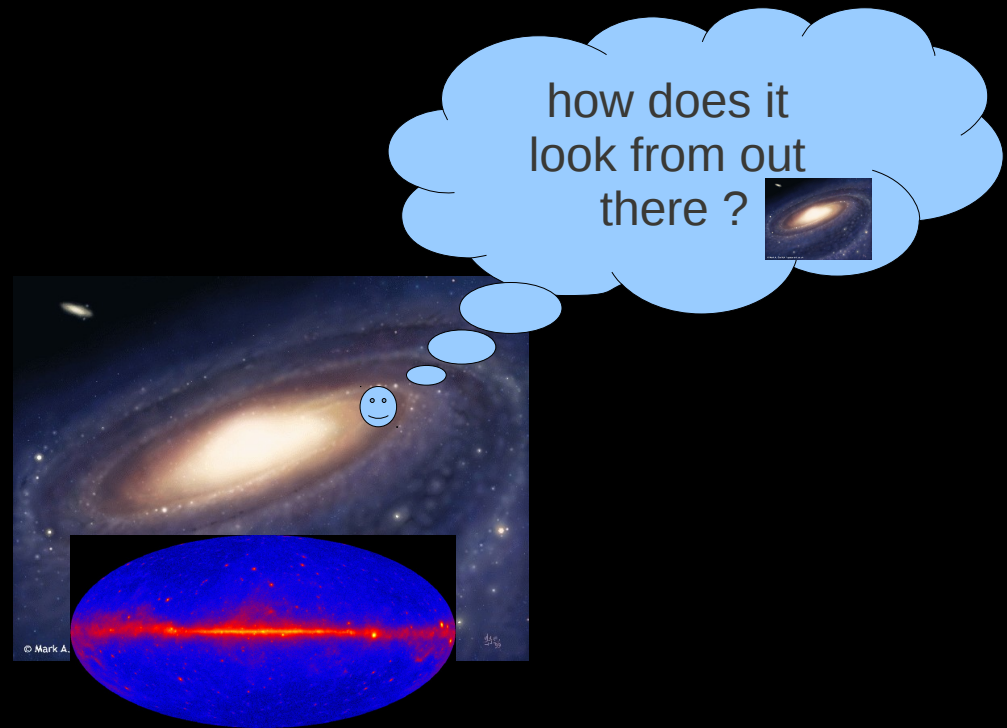




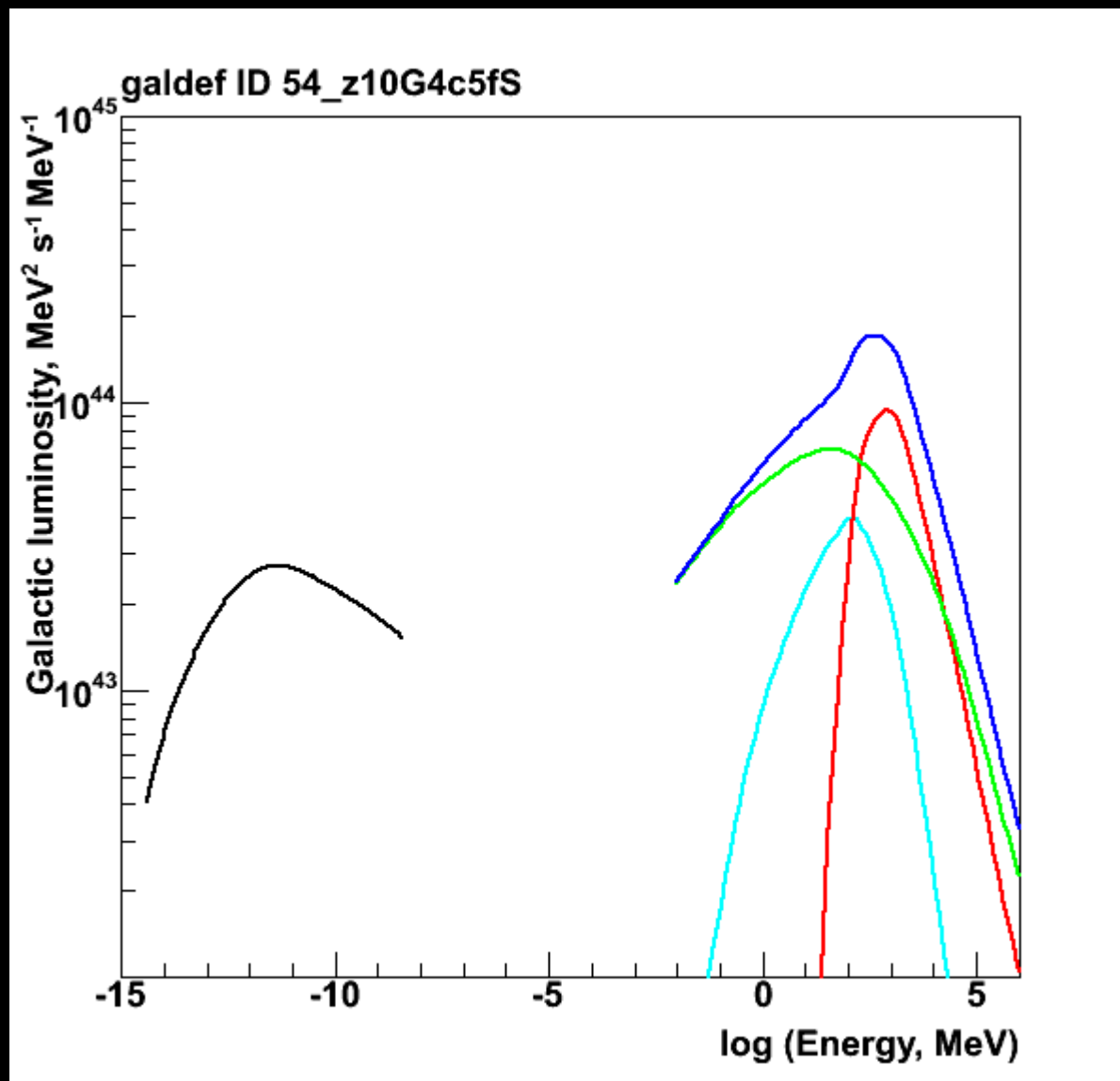
Since we live inside the Galaxy,  
global properties e.g. luminosity  
are not easy to deduce.

Model-dependent.

Need 3D models.

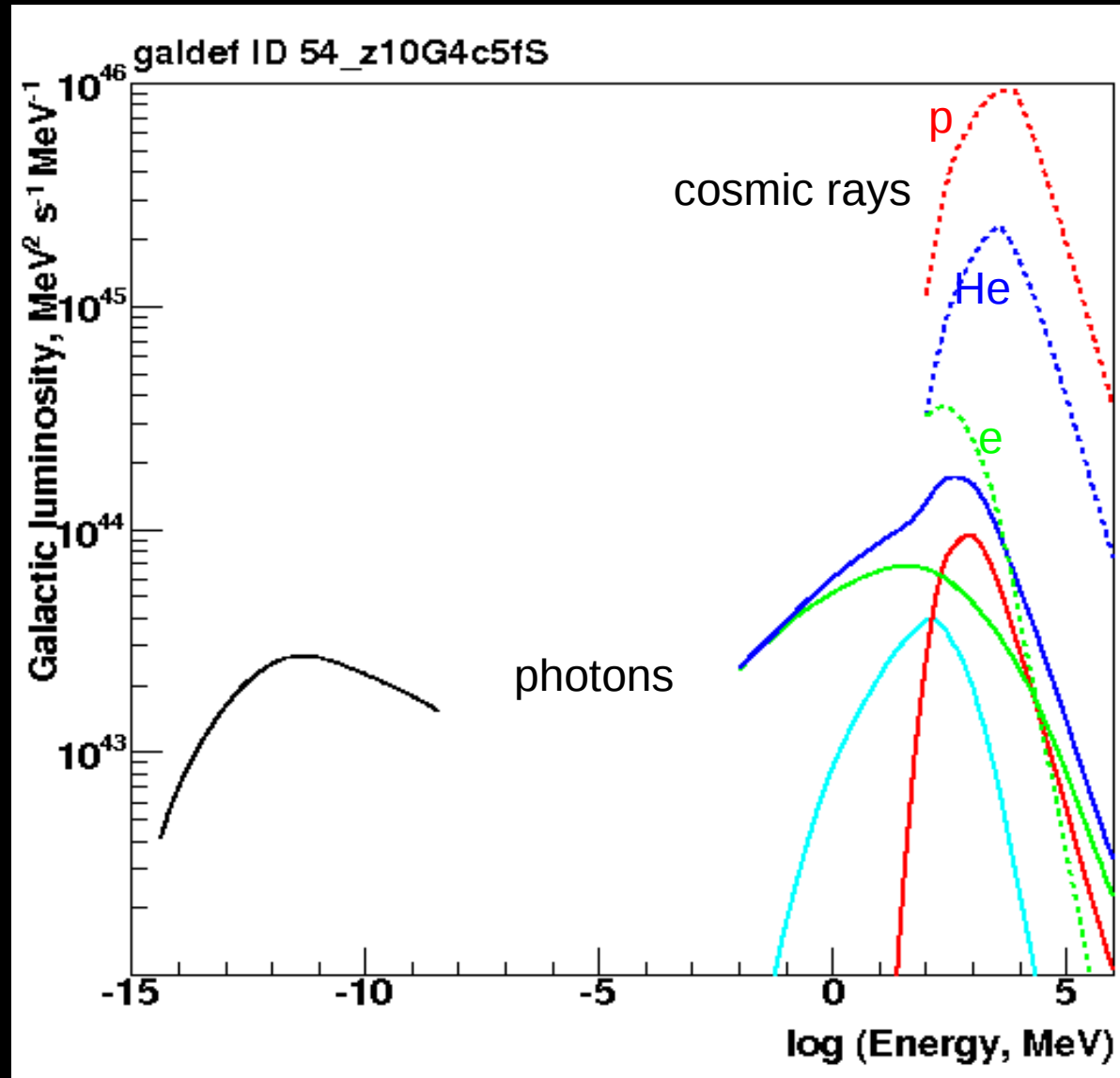


# Galaxy luminosity over 20 decades of energy



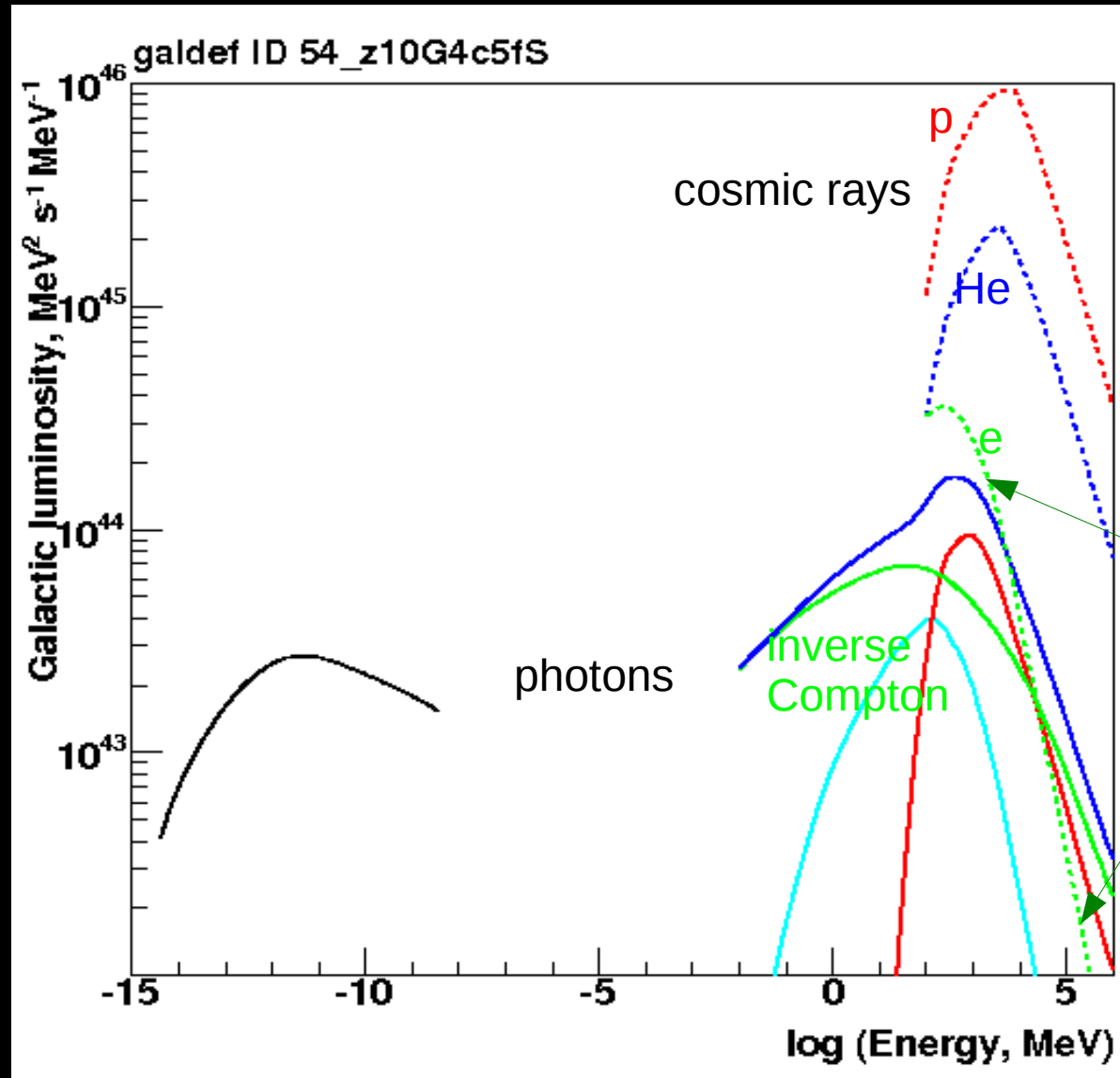
radio CMB IR optical X  $\gamma$

# Galaxy luminosity over 20 decades of energy



radio CMB IR optical X  $\gamma$

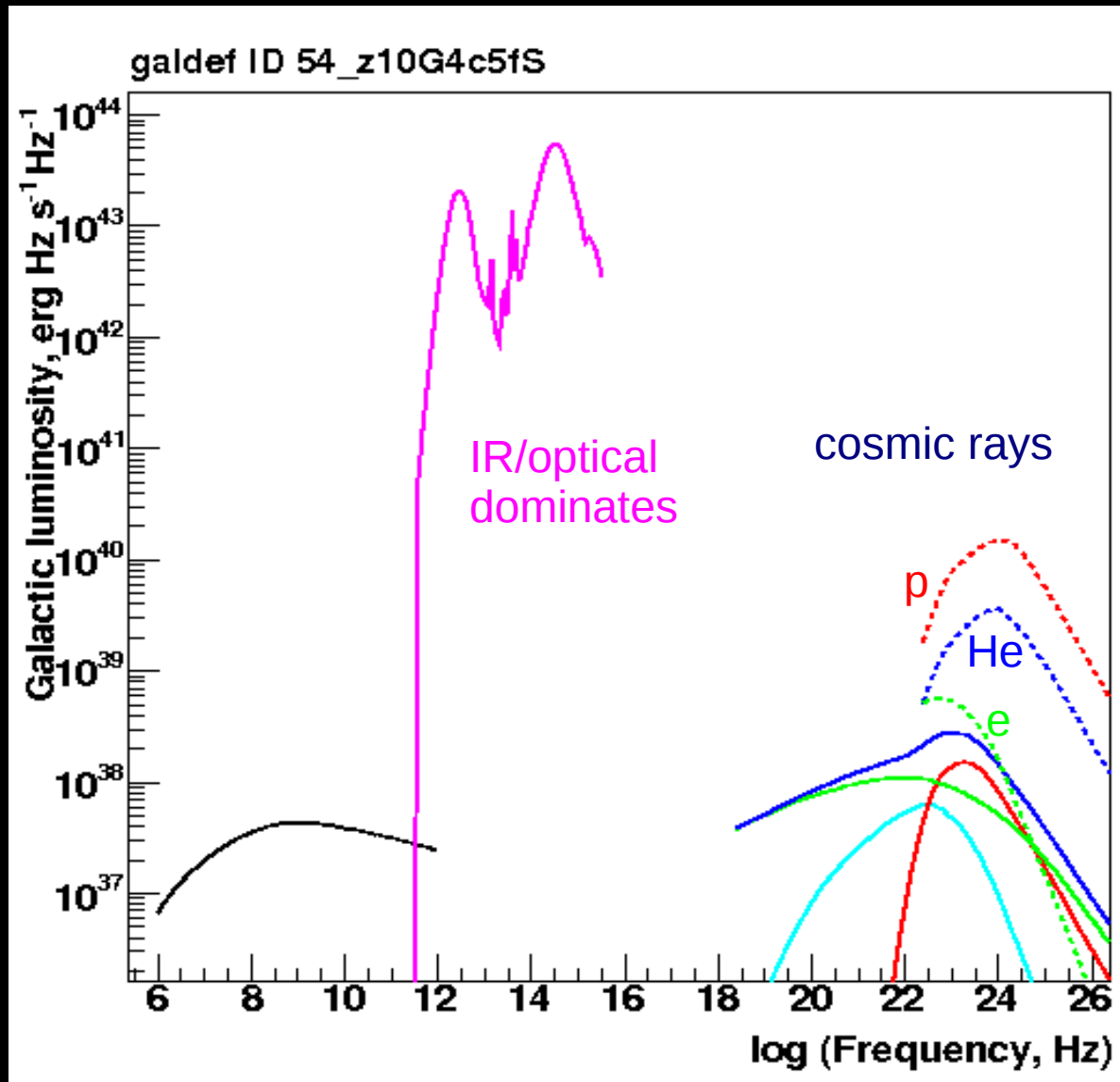
# Galaxy luminosity over 20 decades of energy



radio CMB IR optical X  $\gamma$



# Galaxy luminosity over 20 decades of energy



radio CMB IR optical X  $\gamma$

# Galaxy luminosities

based on GALPROP model

Fermi gamma rays and electrons

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

erg s<sup>-1</sup>

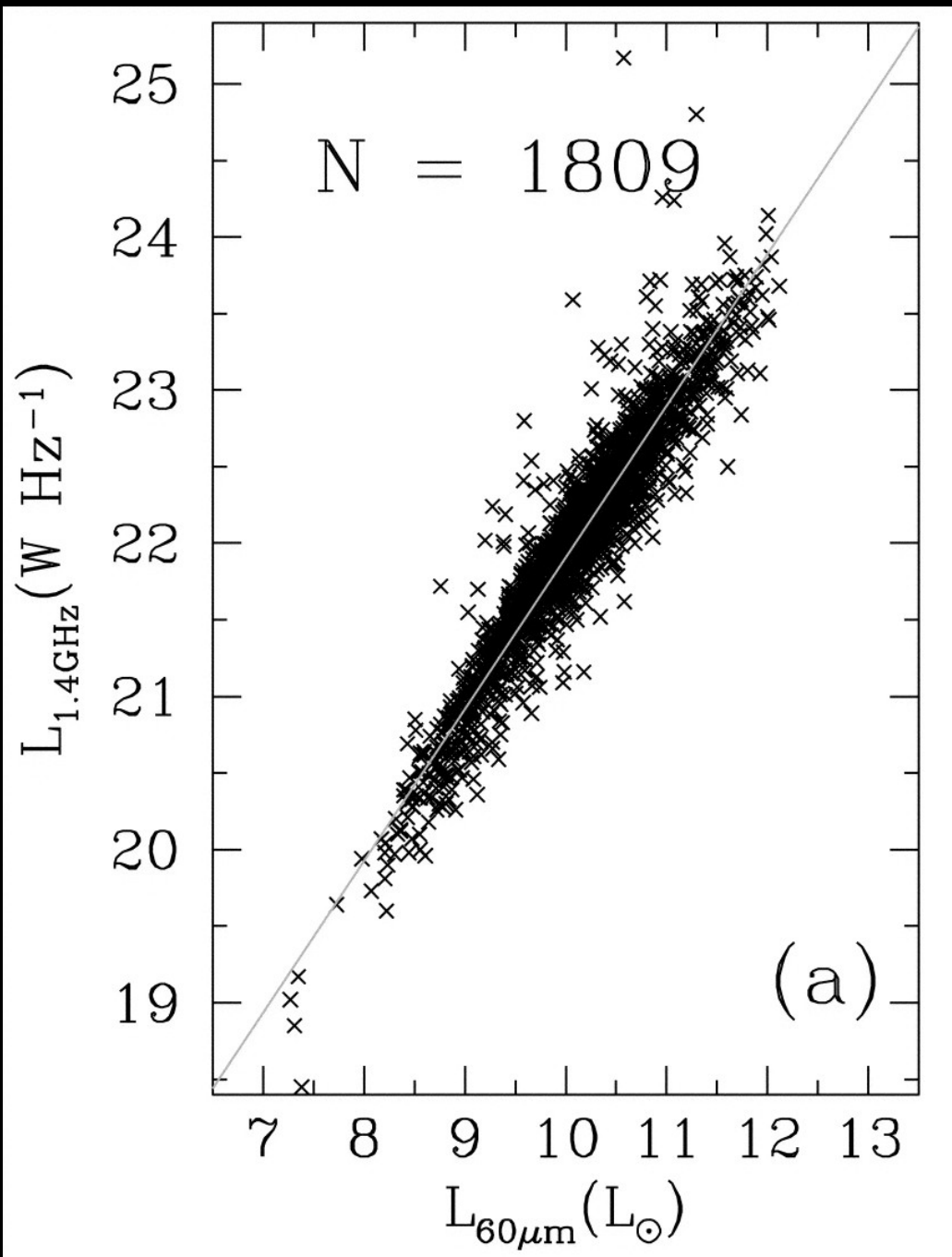
1% of nuclei energy converts to gamma rays

75% of electron energy converts to inverse Compton gamma rays

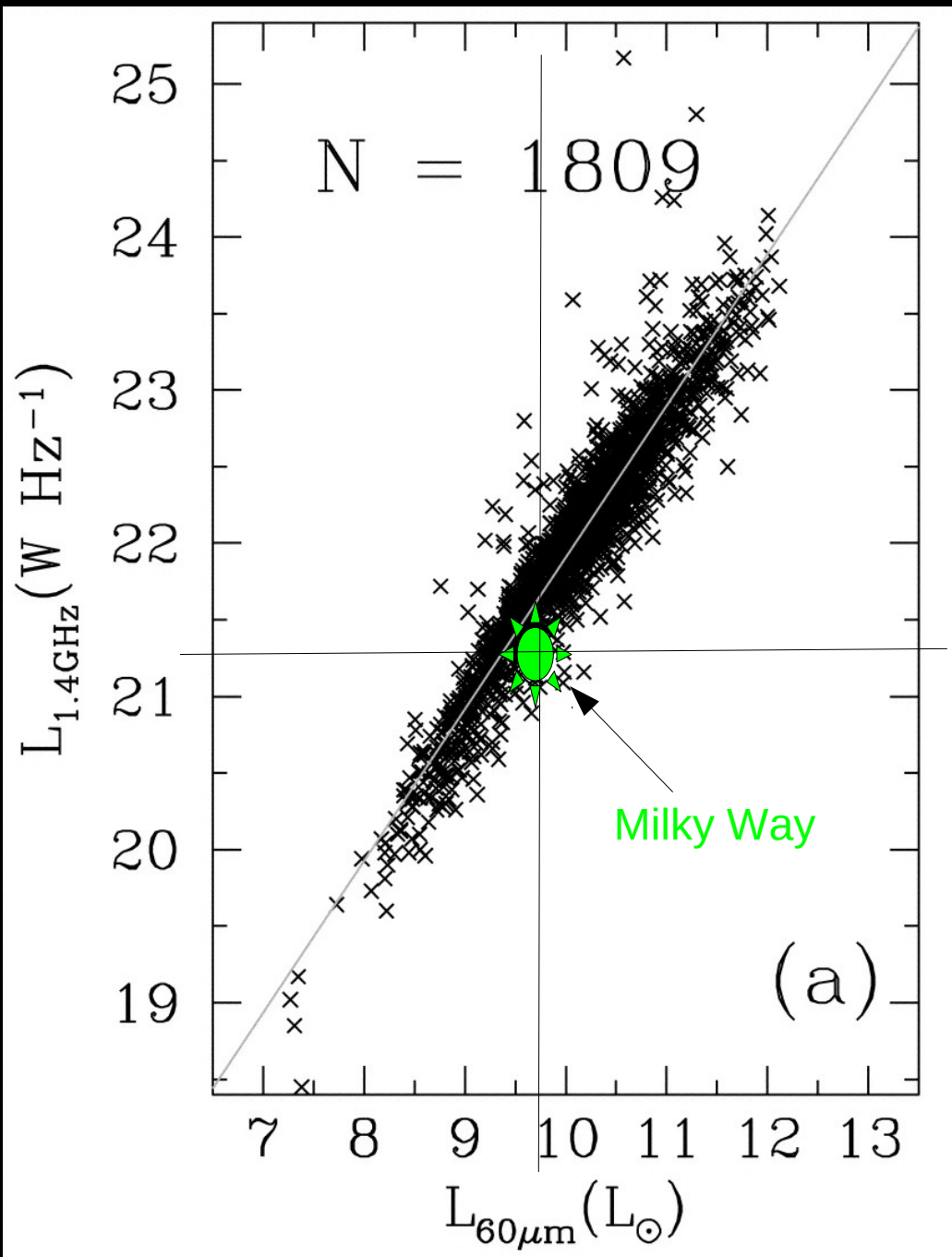
25% of electron energy converts to synchrotron radiation

Galaxy is electron calorimeter ! - but only if inverse Compton is included, not just synchrotron

# FIR/radio correlation IRAS Galaxies



# FIR/radio correlation IRAS Galaxies





# Outlook

Fermi operational, 2 years so far.  
Diffuse emission results appearing.  
The fine data challenges the models.

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

