

# Cosmic-ray Propagation with GALPROP

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Workshop on indirect DM searches,  
DESY, Hamburg  
June 2011

# The original motivation :

- to escape  
from the  
leaky-box



into the Galaxy



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- to escape  
from the  
leaky-box



into the Galaxy



but now...

*precision* experiments e.g.

Fermi, PAMELA, ACE, AMS02, Planck

require correspondingly *detailed* – 'realistic' - models to do them justice.



## Annual Reviews of Nuclear and Particle Science, 2007

# Cosmic-Ray Propagation and Interactions in the Galaxy

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### Key Words

energetic particles, gamma rays, interstellar medium, magnetic  
fields, plasmas

### Abstract

We survey the theory and experimental tests for the propagation of cosmic rays in the Galaxy up to energies of  $10^{15}$  eV. A guide to the previous reviews and essential literature is given, followed by an exposition of basic principles. The basic ideas of cosmic-ray propagation are described, and the physical origin of its processes is explained. The various techniques for computing the observational consequences of the theory are described and contrasted. These include analytical and numerical techniques. We present the comparison of models with data, including direct and indirect—especially  $\gamma$ -ray—observations, and indicate what we can learn about cosmic-ray propagation. Some important topics, including electron and antiparticle propagation, are chosen for discussion.

Quote.....

*It is unclear whether one would wish to go much beyond the generalizations discussed here for an analytically soluble diffusion model. The added insight from any analytic solution of a purely numerical approaches is quickly cancelled by the growing complexity of the formulae. With rapidly developing computational capabilities, one could profitably employ numerical solutions....*

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----- J.M. Wallace, ApJ, 1981

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----- J.M. Wallace, ApJ, 1981

more than ¼ century ago

Propagation codes: ' We are not alone '.

**Other *numerical* propagation codes e.g.**

Evoli / Maccione / Gaggero / Grasso     **DRAGON** code (similar to GALPROP) **PUBLIC**

***Analytical* propagation code:**

Putze, Derome, Maurin

**USINE**: most advanced analytical code on the market

**Other codes emphasizing other aspects than GALPROP:**

Buesching/Pohl

Green's function approach

Hanasz, Lesch, Koturba

PIERNIK code: MHD, CR= fluid. CR-driven dynamo

DeMarco, Blasi, Stanev

Trajectory approach, for  $> 1$  PeV

## **Leaky-box, path-length distribution models**

these are numerical 0-D models

not discussed here since we regard them as outdated.

*But it is a well-known fact that for stable nuclei without energy losses, these methods can be designed to produce the same results as propagation models,*

*So OK for cosmic-ray source composition studies.*

*For unstable nuclei, electrons, positrons, gamma rays.... not realistic enough to be useful*

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## **Spatial Propagation models**

Advantage is the physical interpretation in terms of diffusion, convection etc. related to the real Galaxy. Intuitive understanding of meaning of terms.

Both analytical and numerical, and hybrids, all have their proponents.



# Workshop “Tango in Paris” 2009 Section on cosmic-ray codes

# POCKETBOOK OF MATHEMATICAL FUNCTIONS

Abridged edition of  
**Handbook of Mathematical Functions**  
Milton Abramowitz and Irene A. Stegun (eds.)

Material selected by  
Michael Danos and Johann Rafelski

versus

THE



**PROGRAMMING  
LANGUAGE**  
THIRD EDITION

**BJARNE  
STROUSTRUP**  
The Creator of C++

## Propagation models

A main advantage is the physical interpretation in terms of diffusion, convection etc. related to the real Galaxy. Intuitive understanding of meaning of terms.

1D, 2D, or 3D

Both analytical and numerical, and hybrids, all have their proponents.

### Analytical

Mainly 1D, some 2D

complex (but impressive) formulae

simplified energy losses

simplified gas distribution

simplified magnetic field

gamma rays only in simple way

synchrotron only in simple way

### Numerical

2D or 3D

simple formulae (computer does the work)

full energy losses

gas based on HI, CO surveys in 3D

any magnetic field model

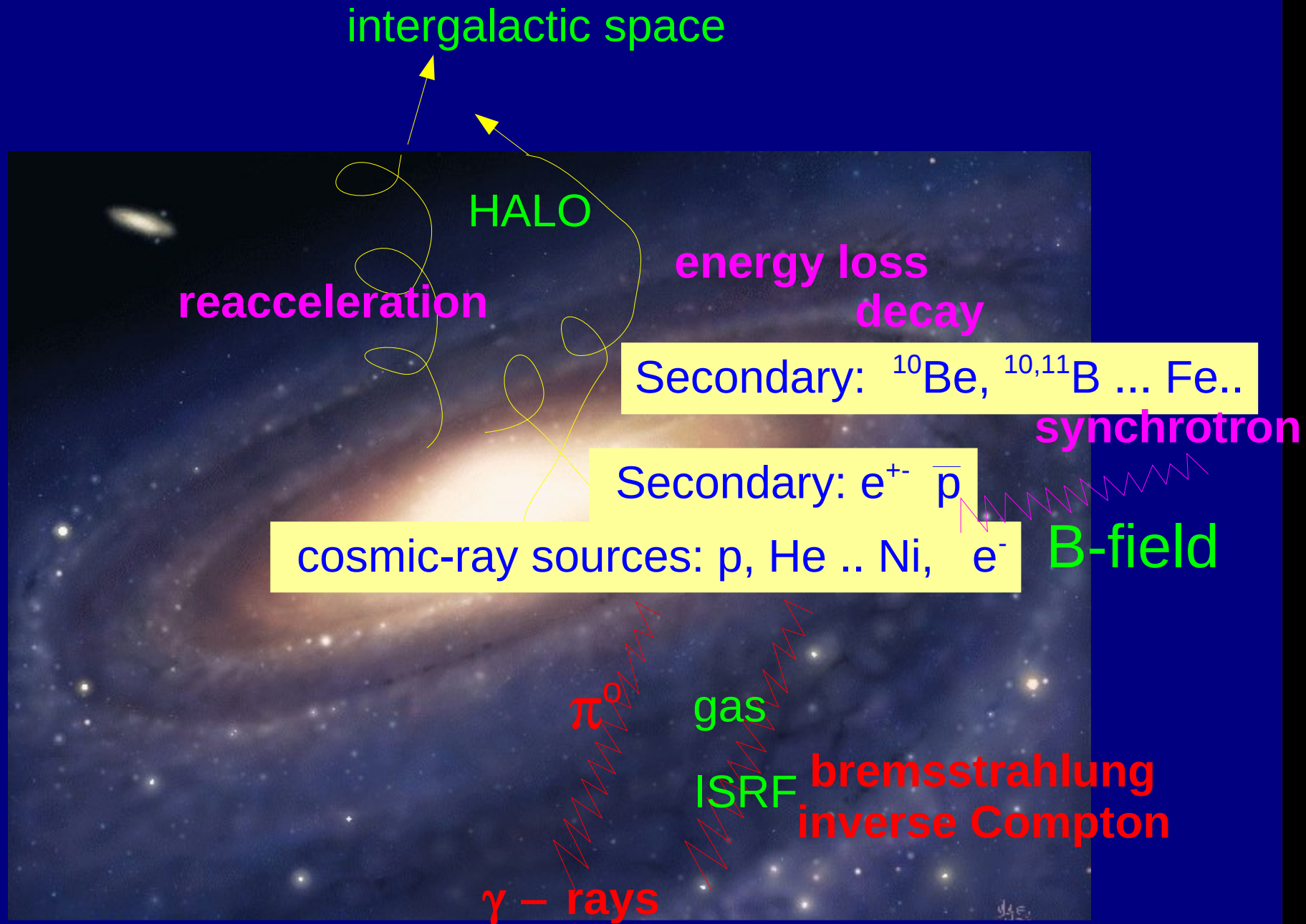
full gamma ray calculation

full synchrotron calculation



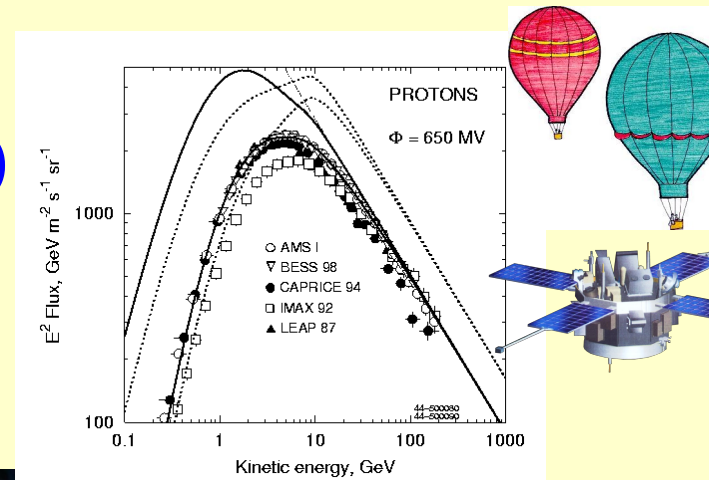
focus : cosmic-ray production & propagation in the Galaxy

# COSMIC RAYS



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

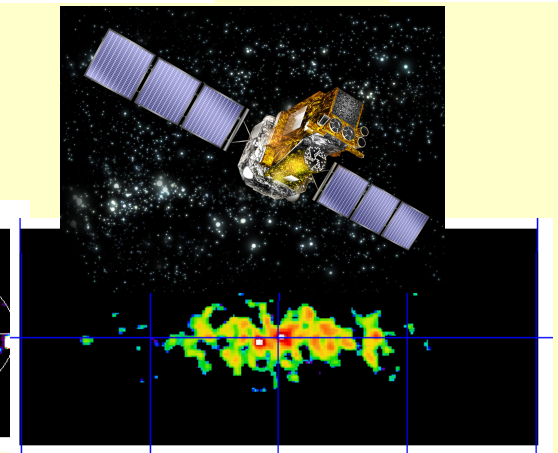
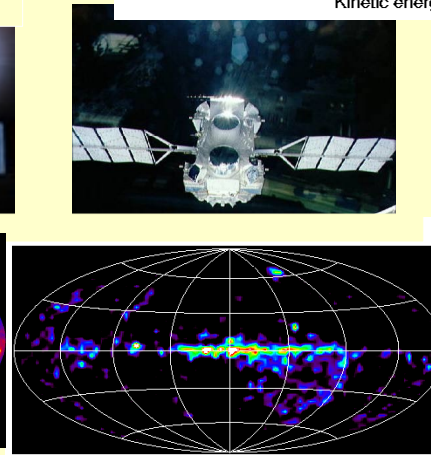
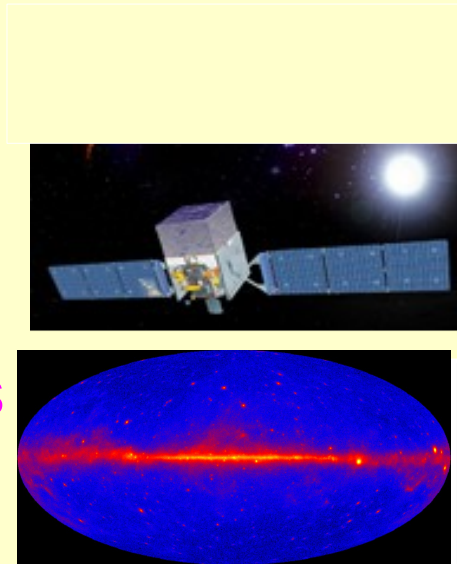
Observed *directly, near Sun*:  
primary spectra (p, He ... Fe;  $e^-$ )  
secondary/primary (B/C etc)  
secondary  $e^+$ , antiprotons...



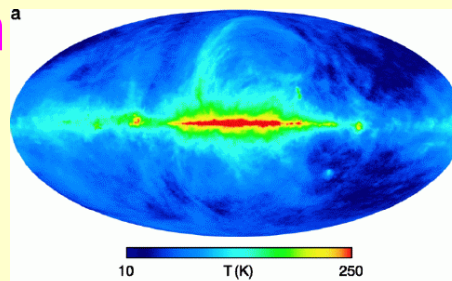
Victor Hess before his 1912 balloon in Austria, during which he discovered cosmic rays



Observed  
from whole  
Galaxy:  
 $\gamma$  - rays



synchrotron<sup>a</sup>



# GALPROP project

Built up over more than 15 years by a growing team.

## *Dramatis personae:*

Igor Moskalenko      (Stanford)

Troy Porter            (Stanford)

Gulli Johannesson (Iceland)

Elena Orlando        (Stanford, MPE)

Seth Digel            (Stanford)

Andy Strong          (MPE)

Andrey Vladimirov (Stanford)



# GALPROP

Public code

Dedicated website *galprop.stanford.edu* for code and forum  
Web-based runs without installing code ! Runs on dedicated server

Used in many papers / year

Adopted as standard model for Fermi

Need such a model to do justice to the quality of Fermi data

Also for WMAP, Planck .....

# Cosmic-ray propagation

$$\frac{\partial \psi(\underline{r}, p)}{\partial t} = q(\underline{r}, p)$$

cosmic-ray sources (primary and secondary)

$$+ \nabla \cdot (D_{xx} \nabla \psi - v \psi)$$

diffusion                      convection

$$+ \frac{\partial}{\partial p} \left[ p^2 D_{pp} \frac{\partial \psi}{\partial p} \right]$$

diffusive reacceleration (diffusion in p)

$D_{pp} D_{xx} \sim p^2 v_A^2$

$$- \frac{\partial}{\partial p} \left[ \frac{dp}{dt} \psi \right] - \frac{p}{3} (\nabla \cdot v) \psi$$

momentum loss                      adiabatic momentum loss

ionization, bremsstrahlung

$$- \psi / \tau_f$$

nuclear fragmentation

$$- \psi / \tau_r$$

radioactive decay

# How cosmic-ray propagation is computed

## GALPROP code

Linear equation, easy to solve.

2D or 3D grid, resolution down to 100 pc

$dn/dt = \text{source terms} + \text{propagation terms}$

$\Delta t \sim 1000 \text{ yrs}$

for steady-state, evolve until  $dn / dt = 0$

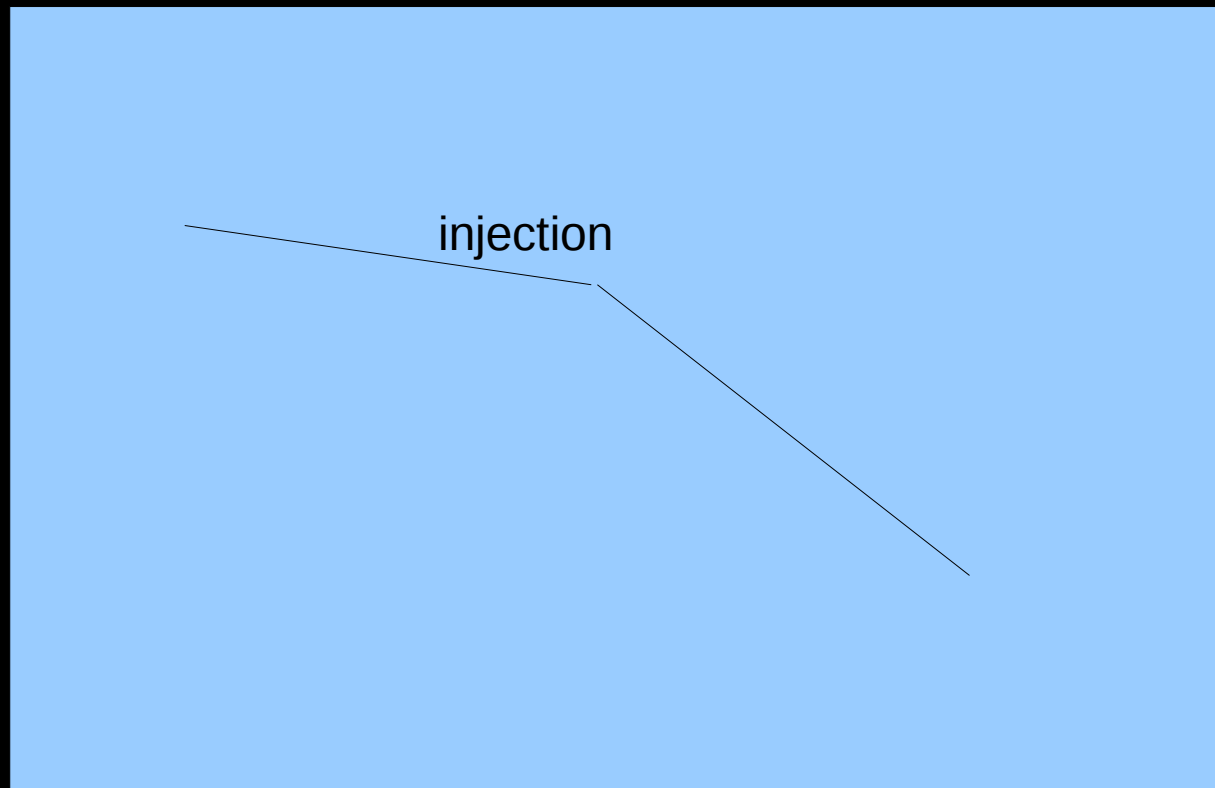
or time-dependent solution if required e.g. for stochastic sources.

Cosmic-ray nuclei: start from  $^{64}\text{Ni}$  and work down in (A, Z)  
including secondary production  
plus secondary positrons, electrons, antiprotons

primary electrons: separate species

# Producing the cosmic-ray spectrum

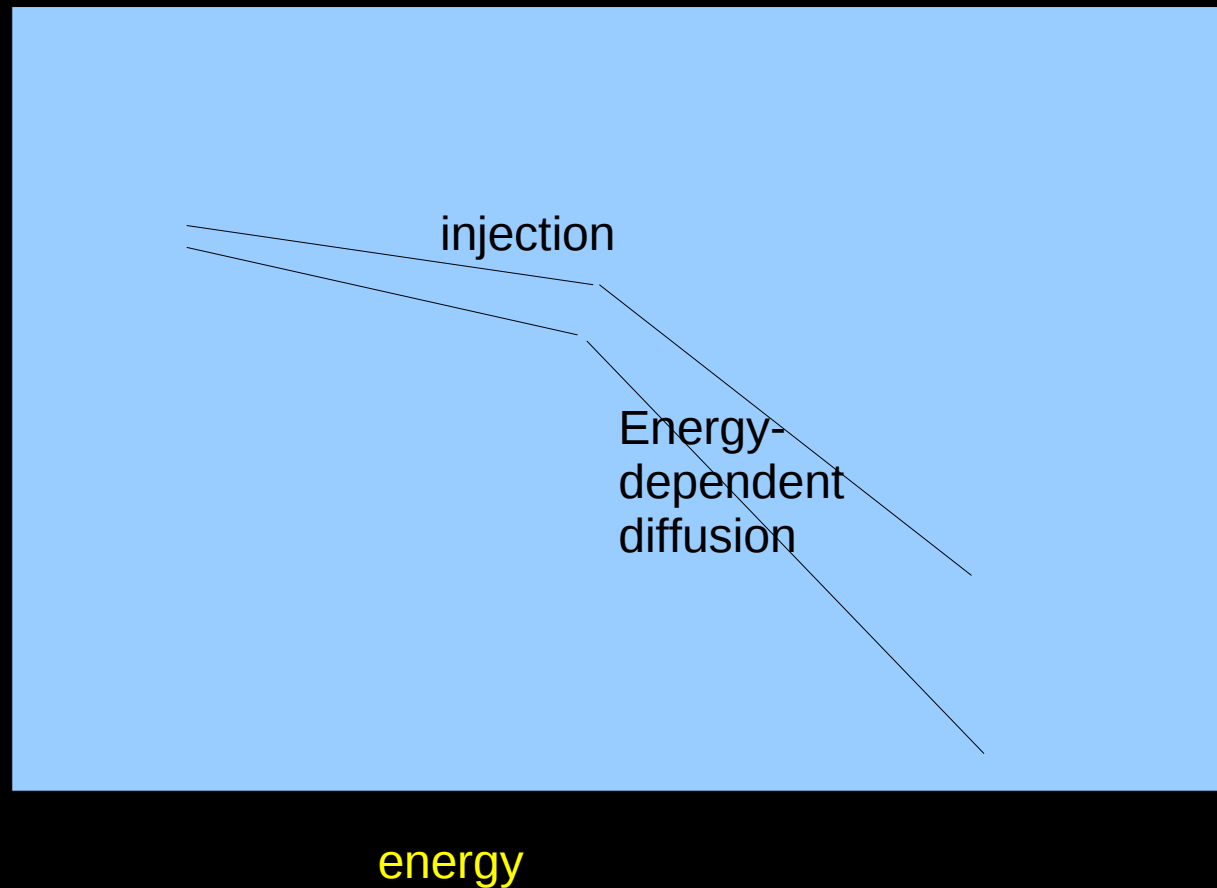
$J(E)$



energy

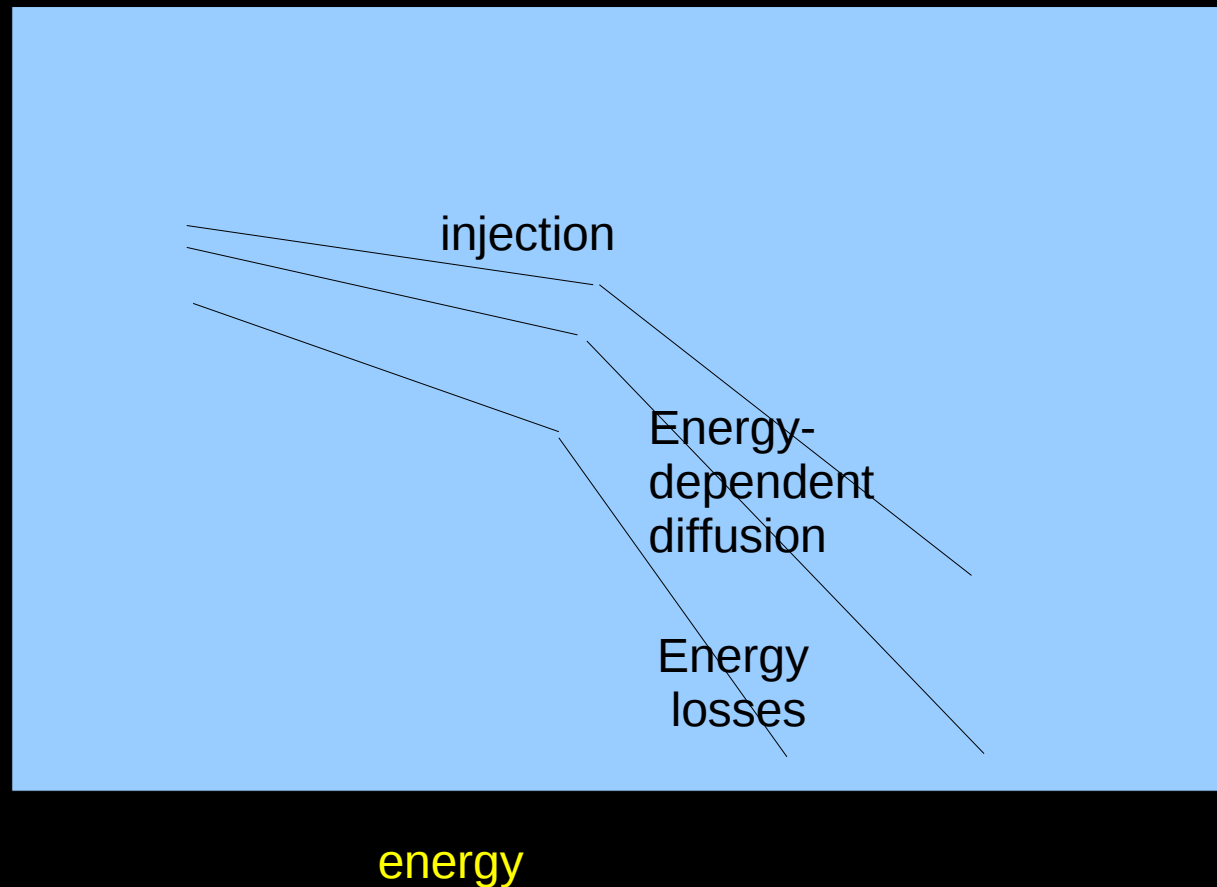
# Producing the cosmic-ray spectrum

$J(E)$



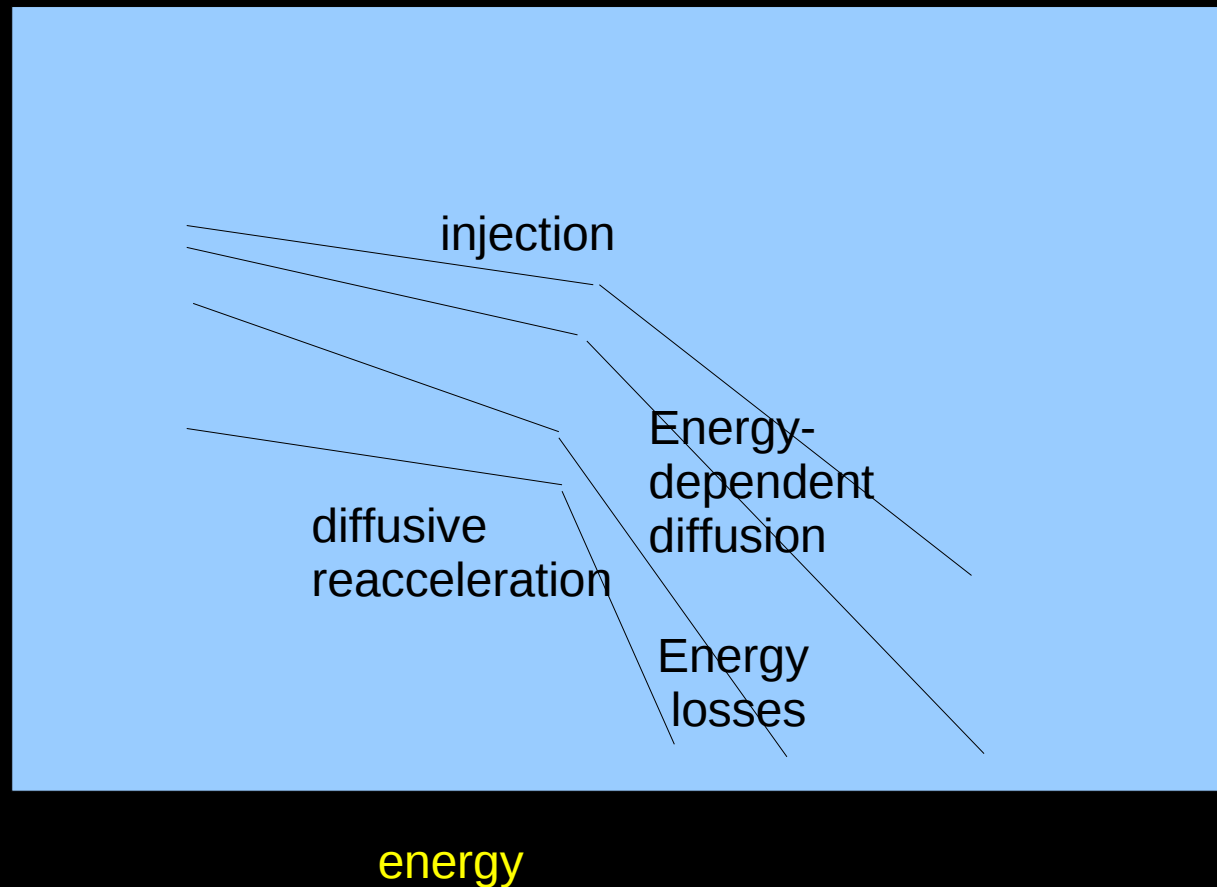
# Producing the cosmic-ray spectrum

$J(E)$



# Producing the cosmic-ray spectrum

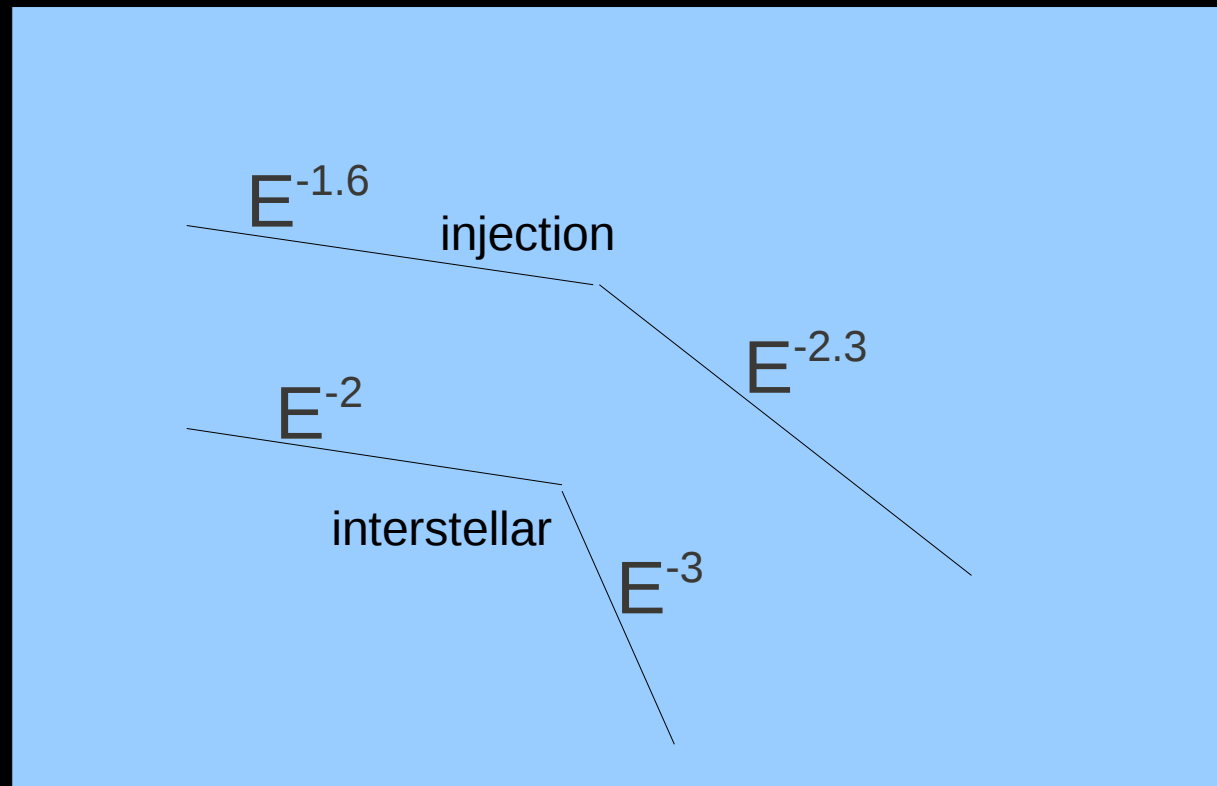
$J(E)$



# Producing the cosmic-ray spectrum

Example: electrons

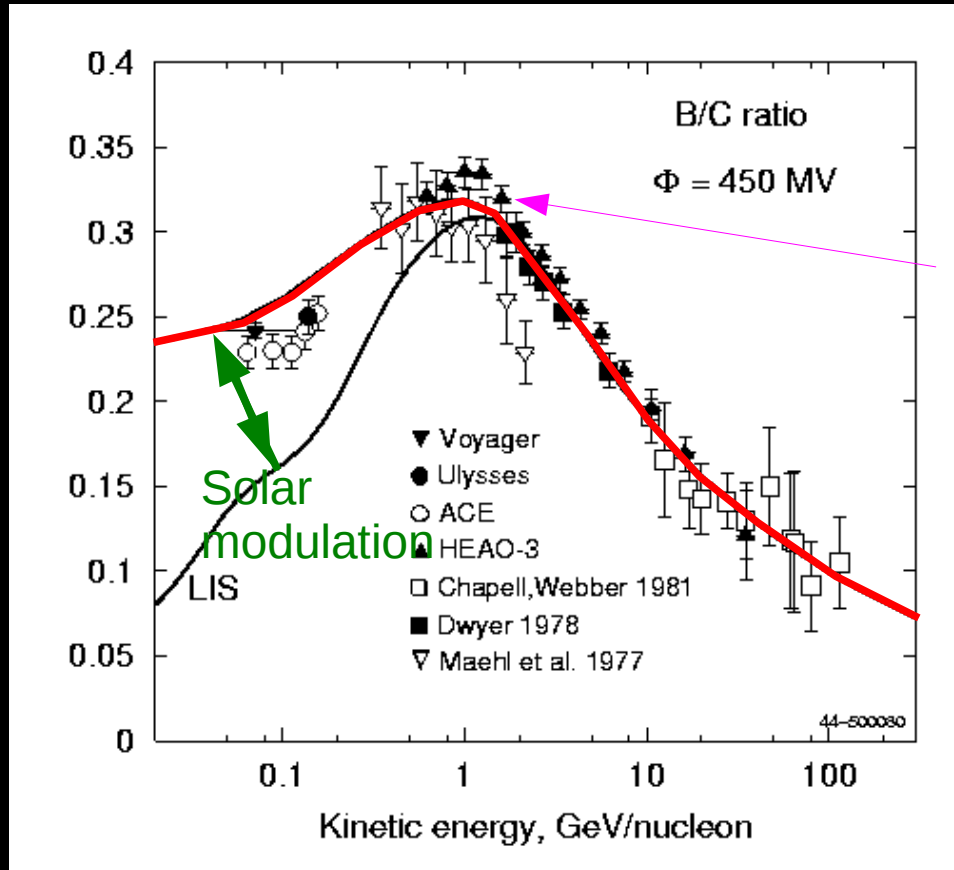
$J(E)$



energy

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

## Boron / Carbon



Peak in B/C can be explained by **diffusive reacceleration** with Kolmogorov spectrum giving diffusion coefficient energy dependence

Spatial diffusion

$$D_{xx} \sim \beta p^{1/3}$$

Momentum space diffusion

$$D_{pp} \sim 1 / D_{xx}$$

Without reacceleration, need a change to constant  $D$  at low energy to get B/C peak  
However reacceleration not proven !

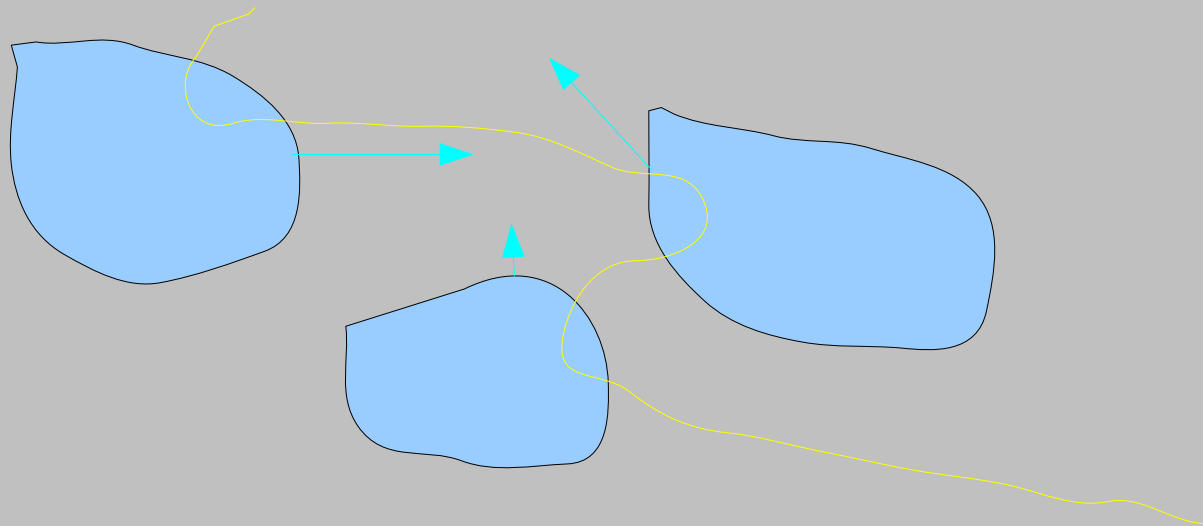
## Diffusive reacceleration

Cosmic rays diffuse by scattering on magnetic irregularities

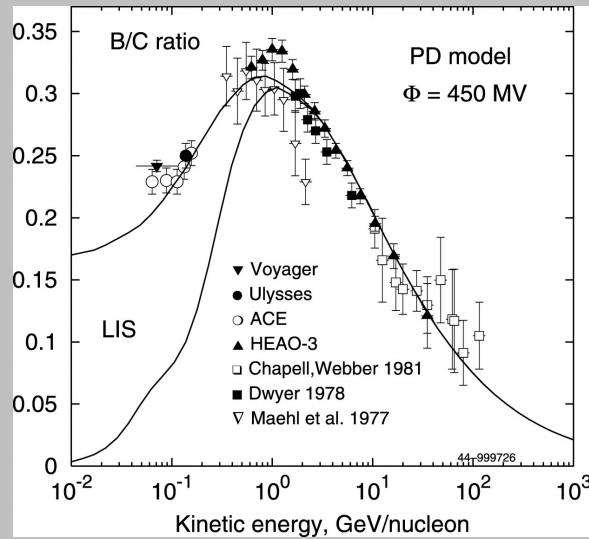
'clouds'

Moving clouds → momentum transfer

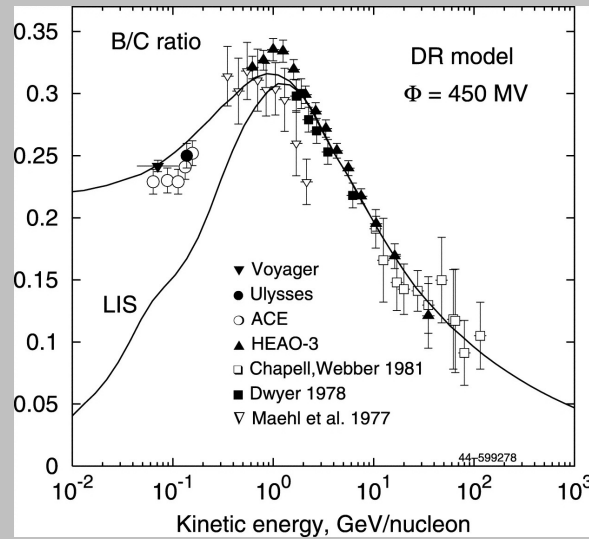
→ diffusion in momentum space = diffusive reacceleration



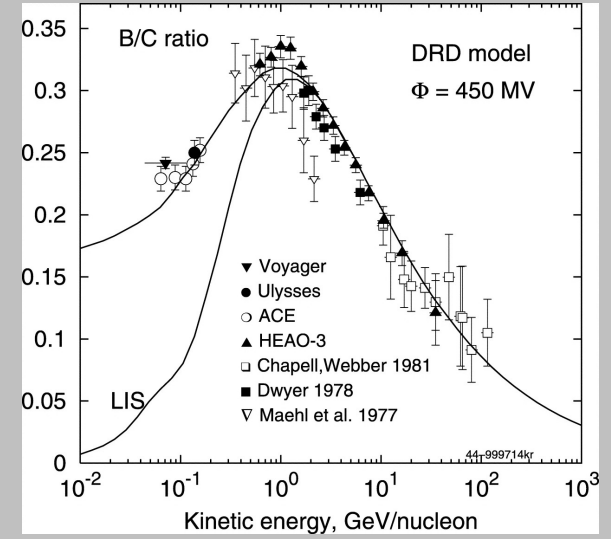
plain diffusion



diffusive reacceleration

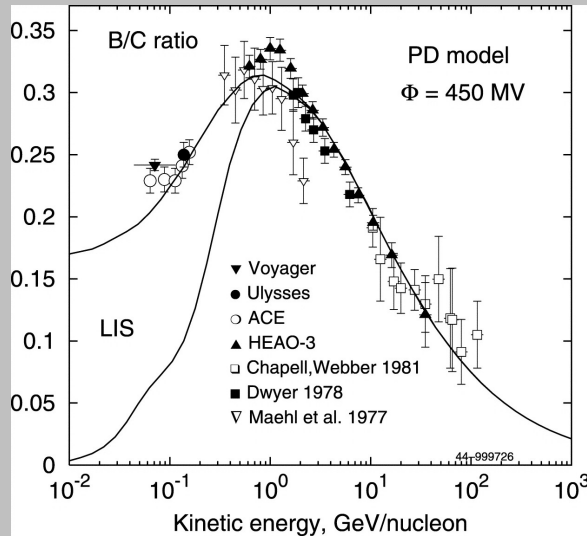


wave damping

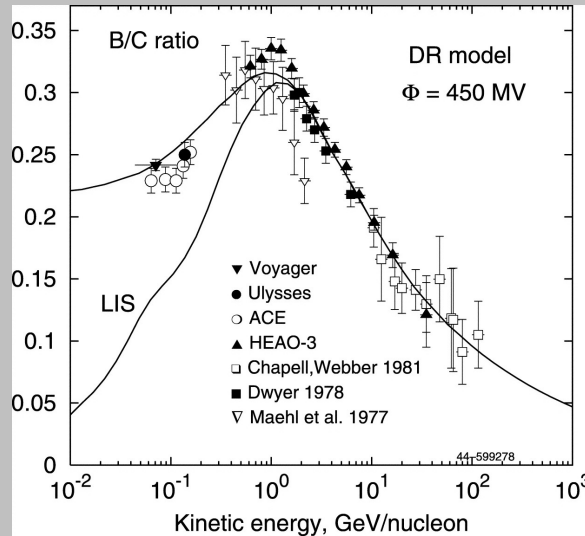


For any model, first adjust parameters to fit Boron/Carbon

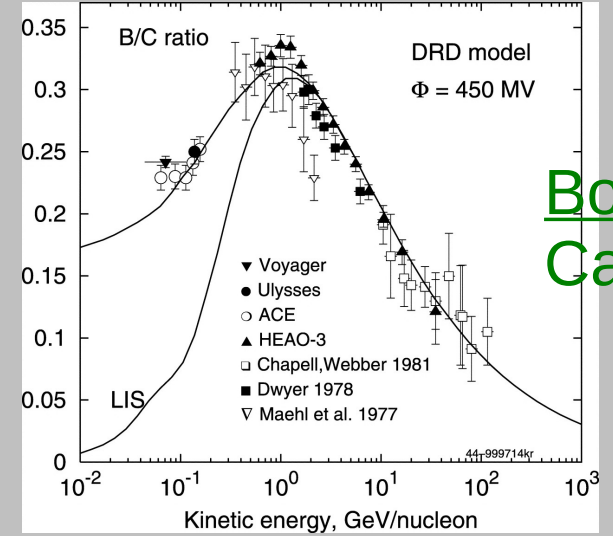
plain diffusion



diffusive reacceleration



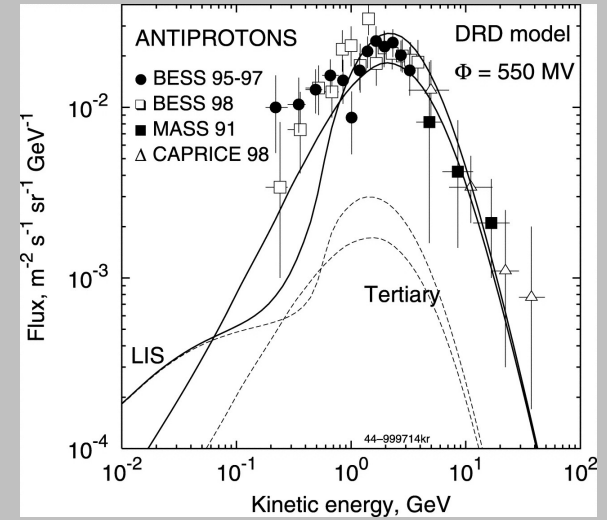
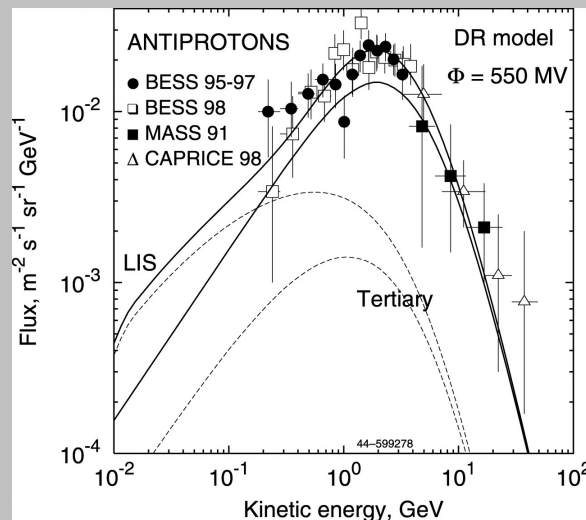
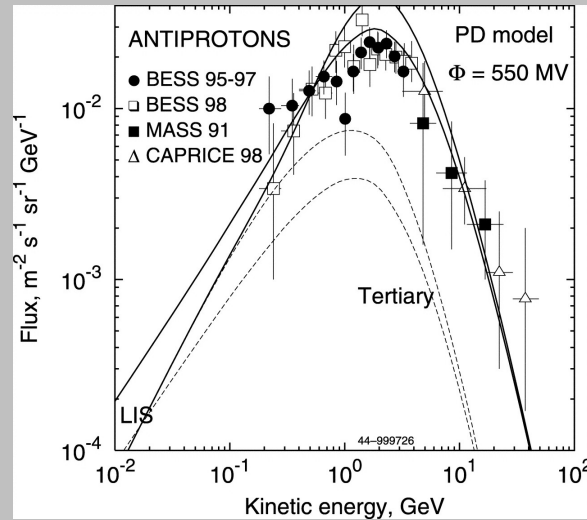
wave damping



Boron/  
Carbon

then predict the other cosmic-ray spectra

antiprotons

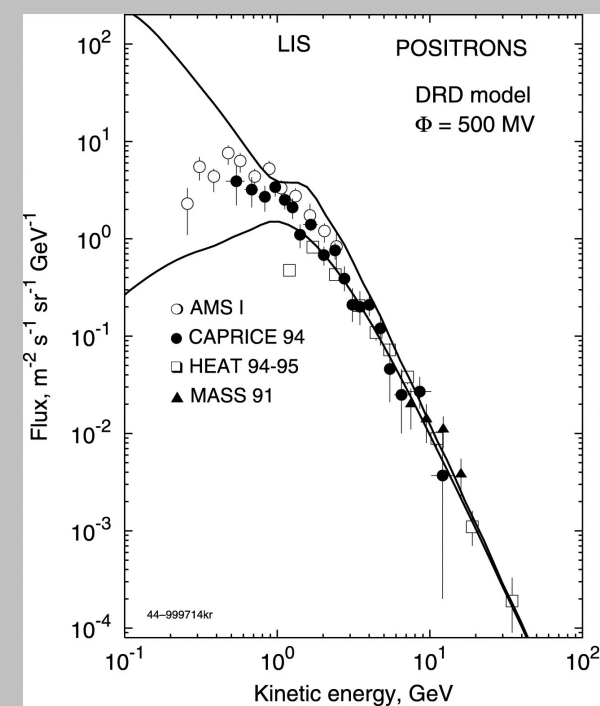
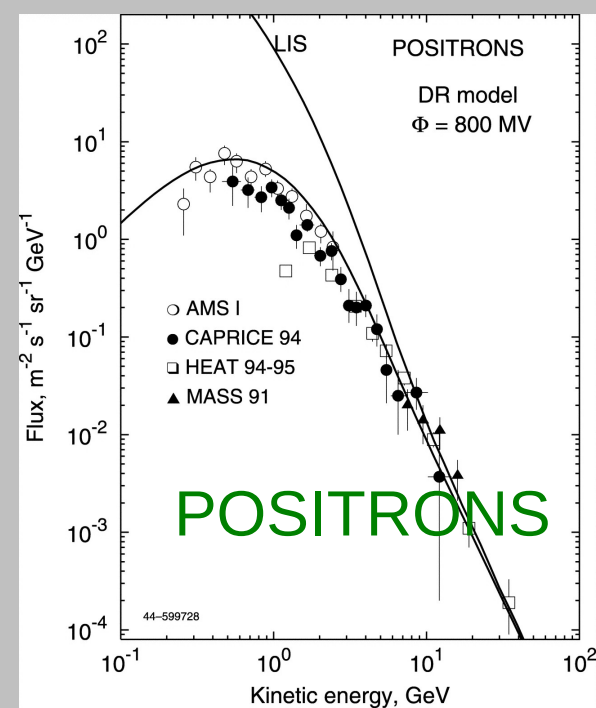
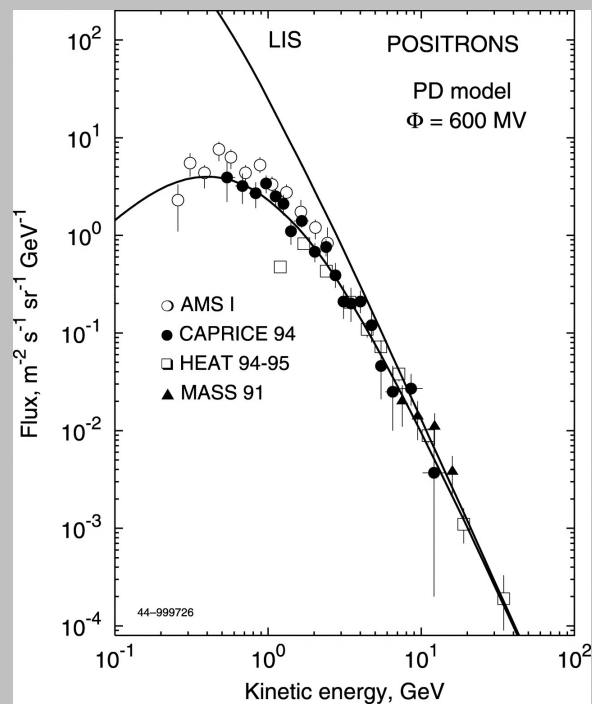
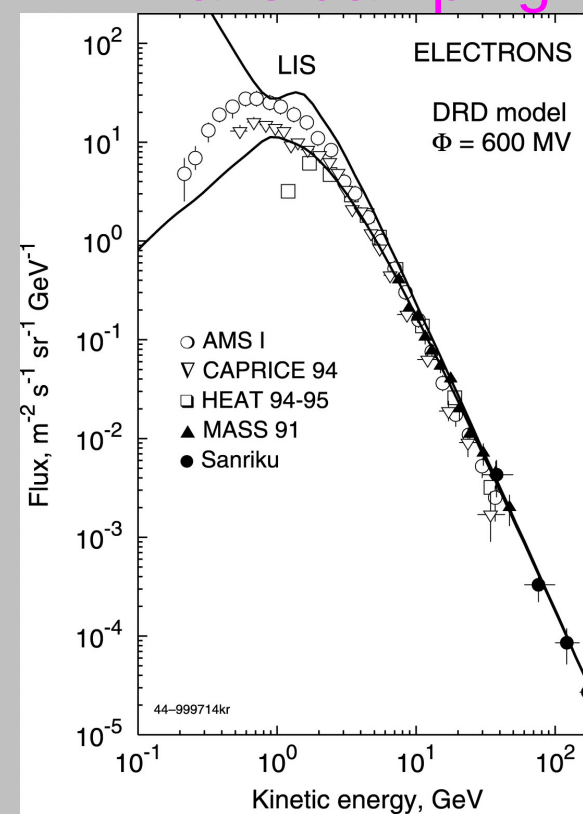
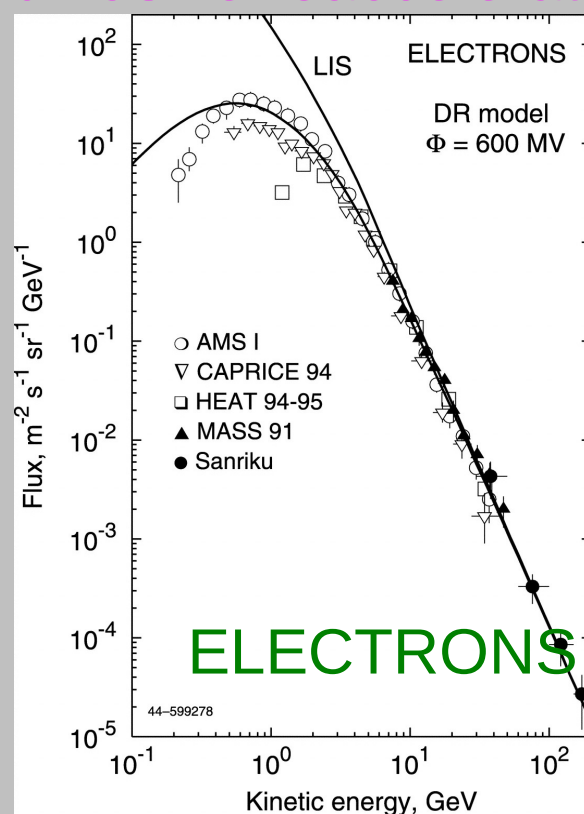
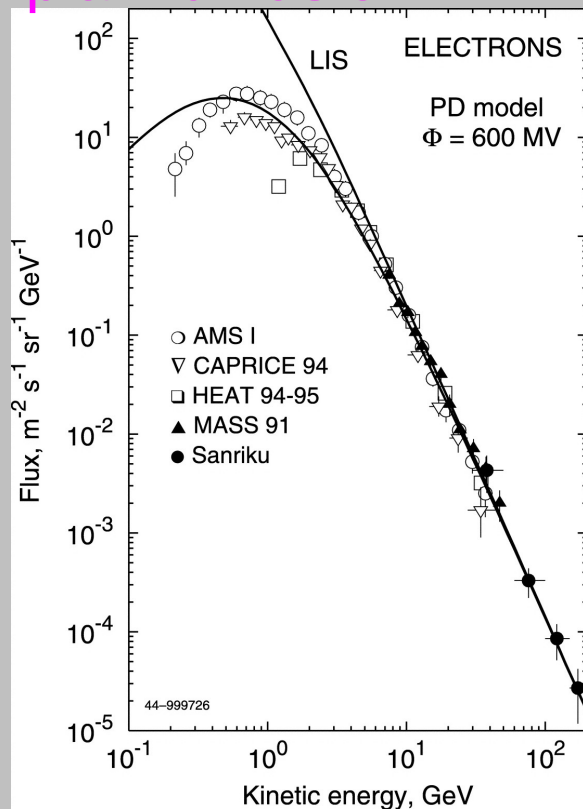


Ptuskin et al. 2006 ApJ 642, 902

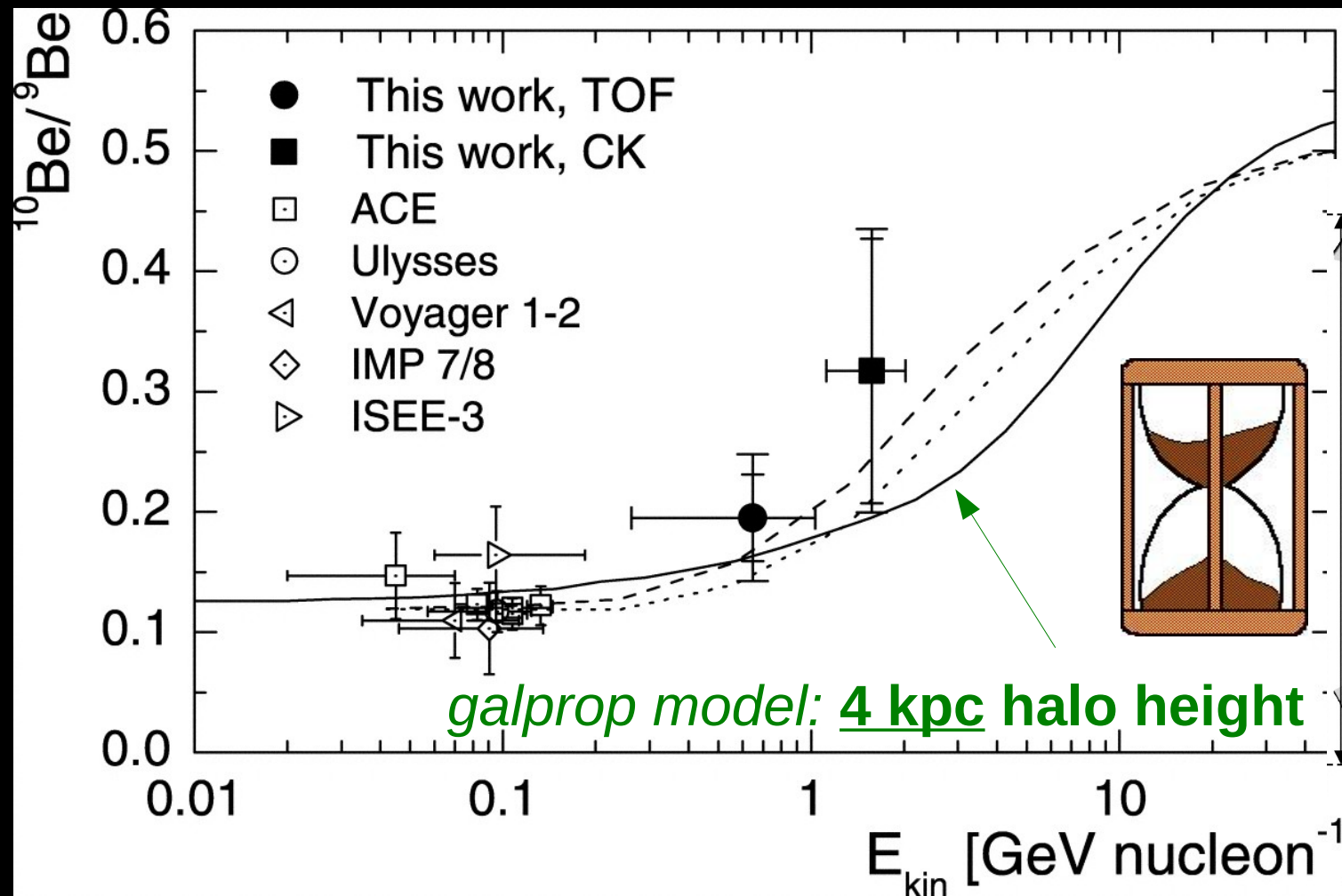
plain diffusion

diffusive reacceleration

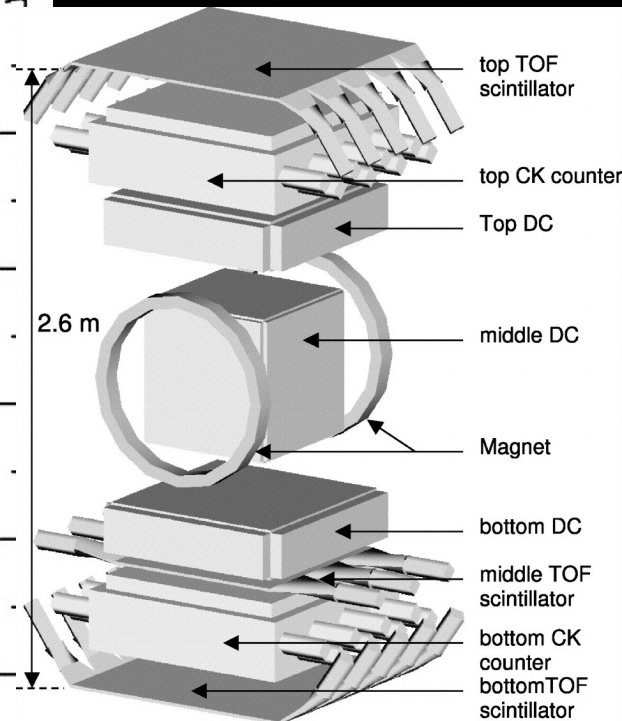
wave damping



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

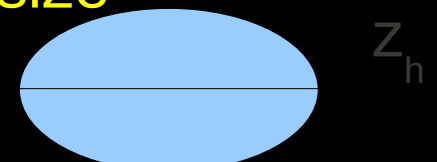


data:  
ACE, ISOMAX



Hams et al. 2004 ApJ 611, 892

$^{10}\text{Be}$  decays in  $10^6$  years,  $^9\text{Be}$  is stable  
 so ratio sensitive to cosmic-ray confinement time, halo size  
 Cosmic-ray halo height = 4 – 10 kpc



# CONSTRAINTS ON COSMIC-RAY PROPAGATION MODELS FROM A GLOBAL BAYESIAN ANALYSIS

R. TROTTA<sup>1</sup>, G. JÓHANNESSON<sup>2</sup>, I. V. MOSKALENKO<sup>3,4</sup>, T. A. PORTER<sup>3</sup>, R. RUIZ DE AUSTRI<sup>5</sup>, AND A. W. STRONG<sup>6</sup>

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<sup>2</sup> Science Institute, University of Iceland, Dunhaga 3, IS-107 Reykjavik, Iceland

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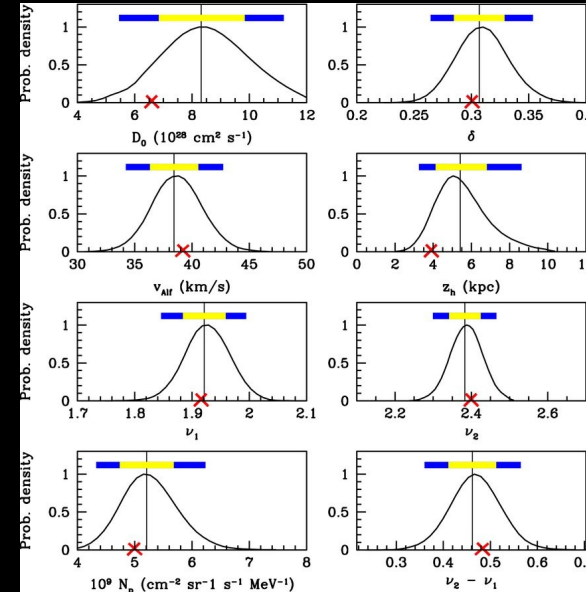
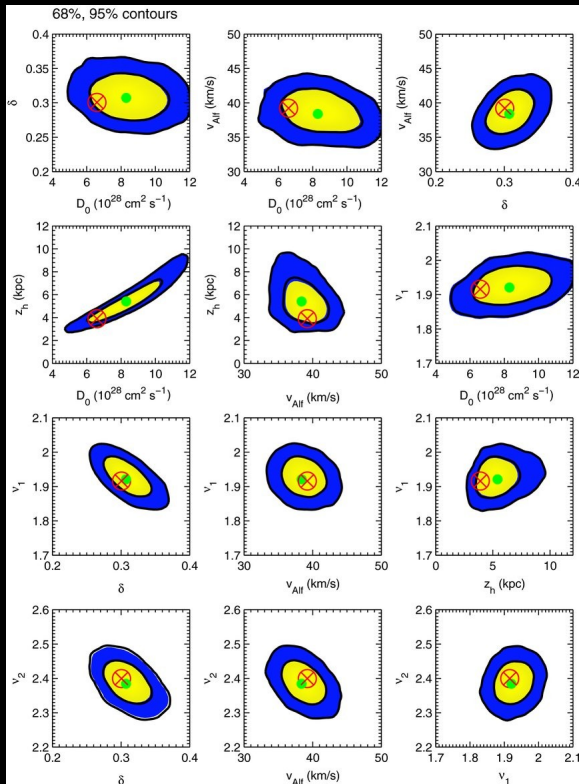
<sup>4</sup> Kavli Institute for Particle Astrophysics and Cosmology, Stanford University, Stanford, CA 94305, USA

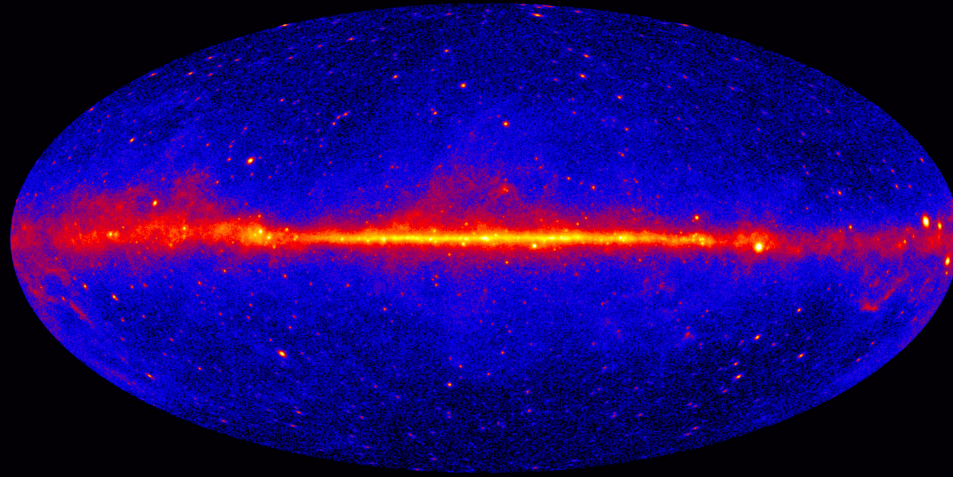
<sup>5</sup> Instituto de Física Corpuscular, IFIC-UV/CSIC, Valencia, Spain

<sup>6</sup> Max-Planck-Institut für extraterrestrische Physik, Postfach 1312, D-85741 Garching, Germany

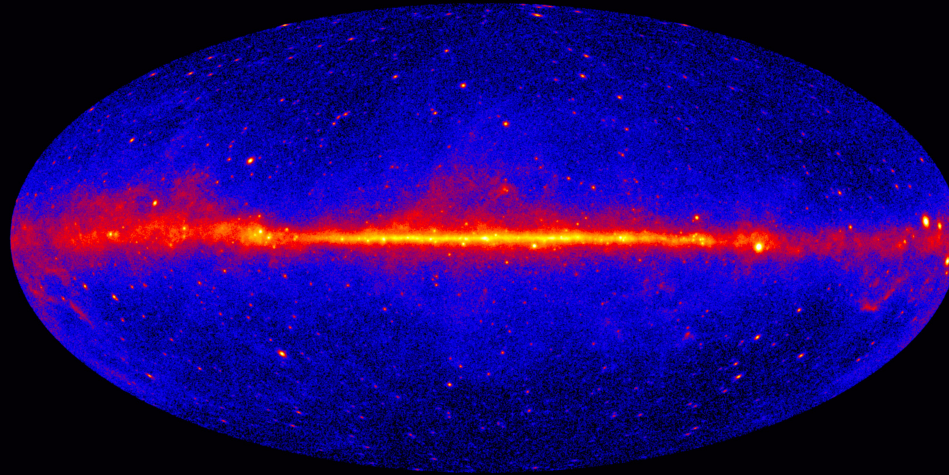
*Received 2010 October 28; accepted 2010 December 10; published 2011 February 15*

Getting more rigorous in parameter estimation....  
 GALPROP meets MCMC ( proves it can be done ! ) .

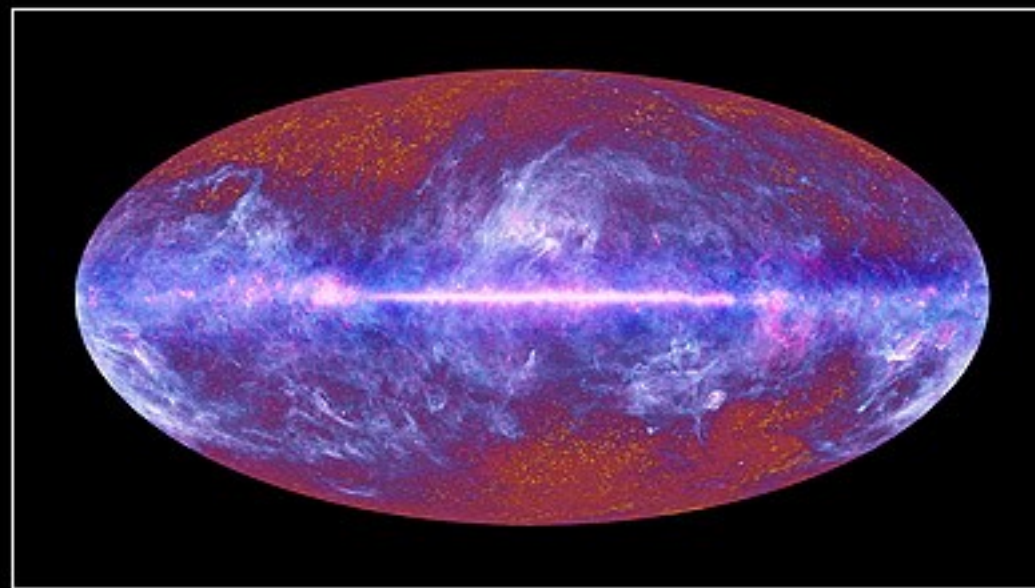
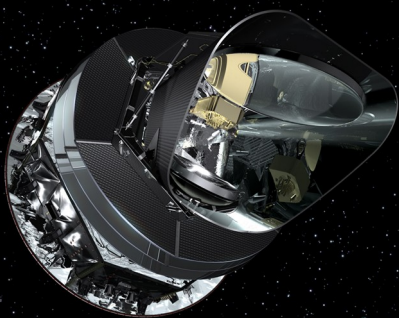




2 years



2 years



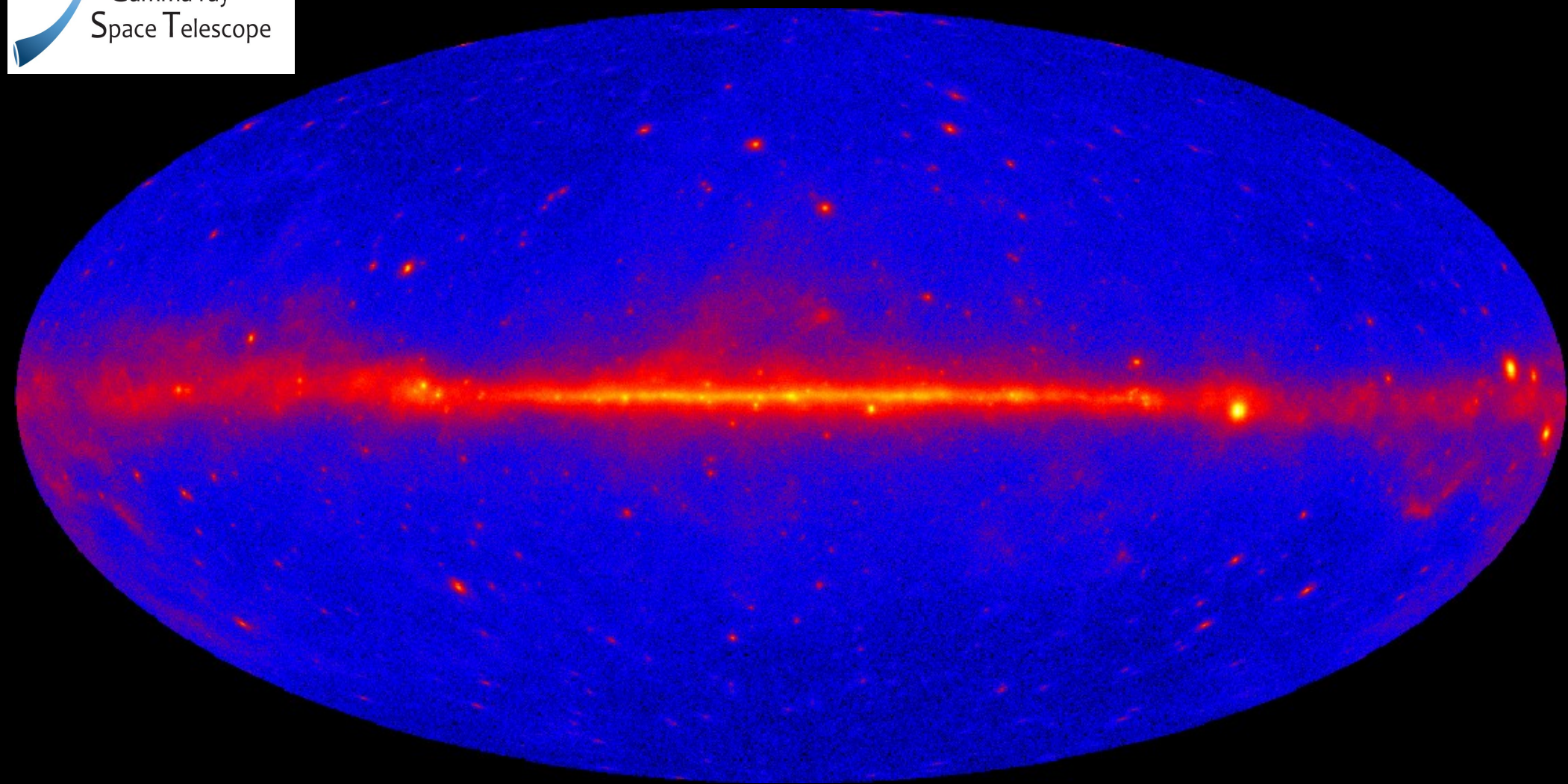
1 year

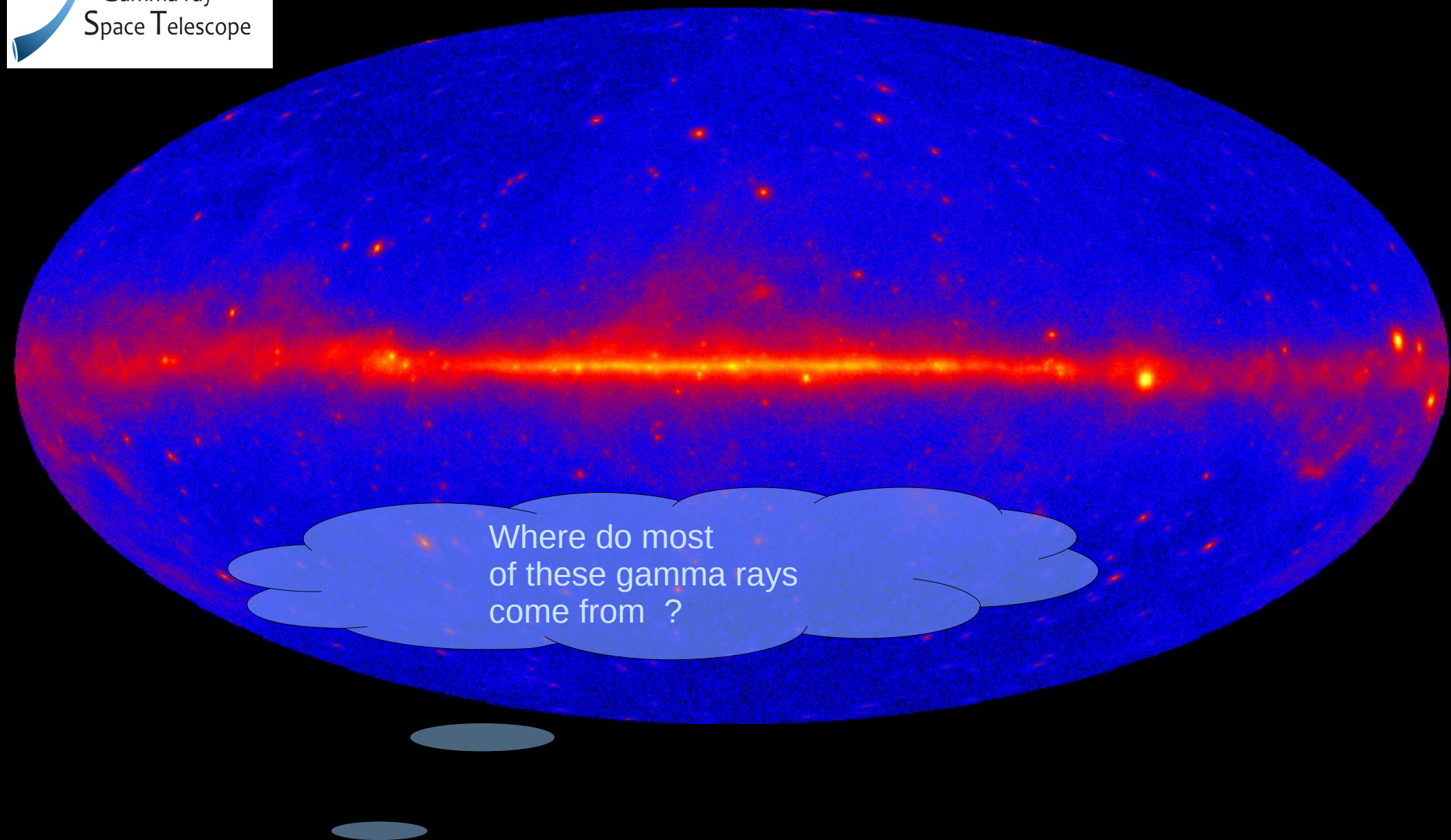
The Planck one-year all-sky survey



© ESA, IFFI and LFI consortia, July 2009

Both flying now. A lot of common astrophysics !

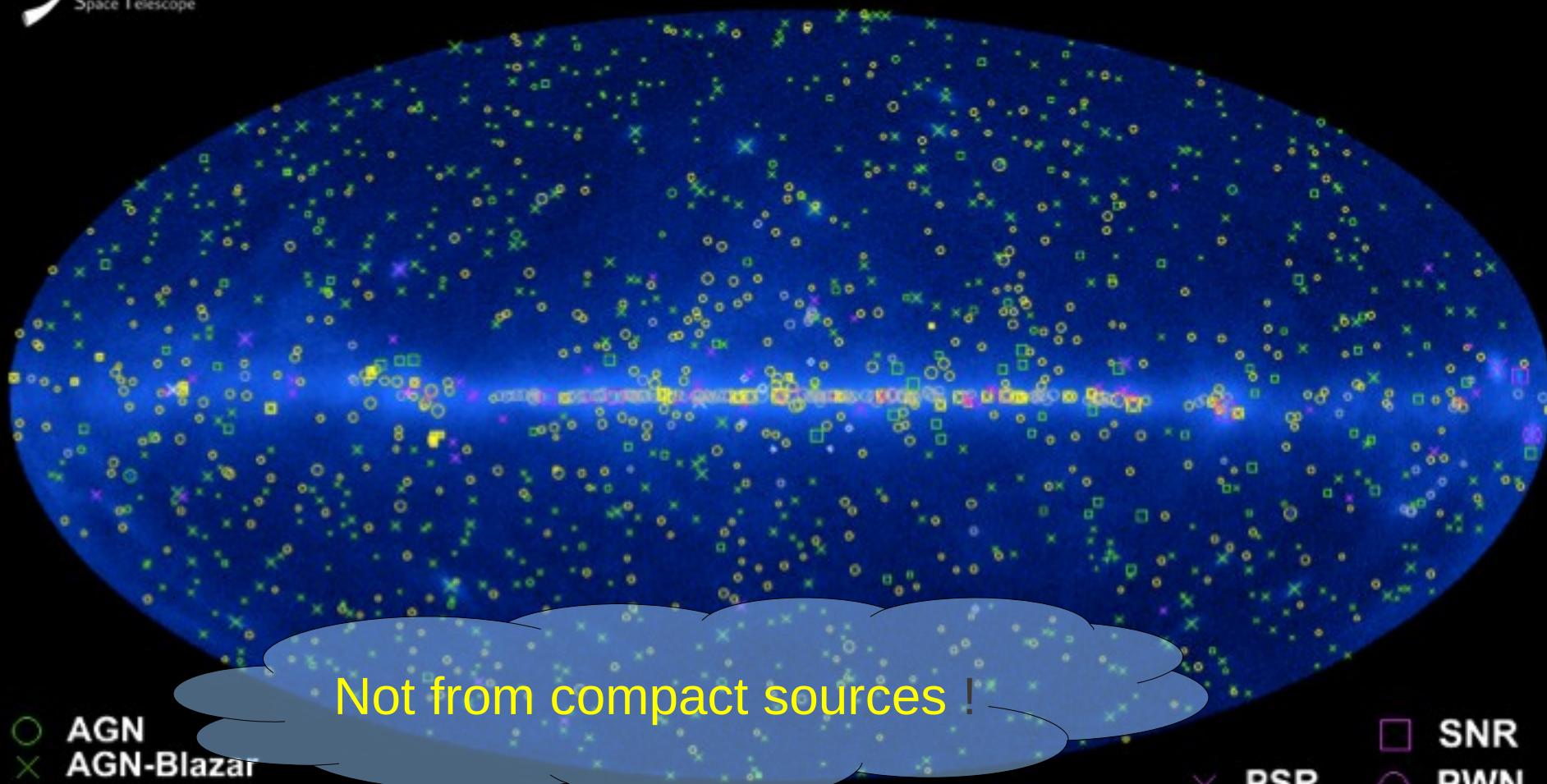




Where do most  
of these gamma rays  
come from ?



# The Fermi LAT 1FGL Source Catalog



Not from compact sources !

- |                                                     |                    |
|-----------------------------------------------------|--------------------|
| ○ 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                                            |                    |



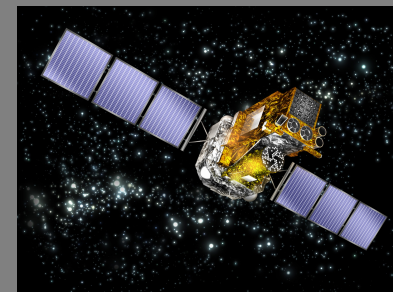
## History of gamma-ray astronomy



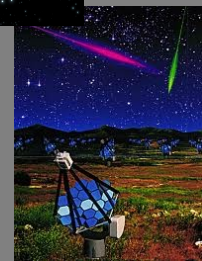
### 'GeV astronomy'

|            | Detector      | energy        | resolution | photons | sources |
|------------|---------------|---------------|------------|---------|---------|
| 1968 OSO-3 | NaI           | 50-100 MeV    | 30°        | 500     | 1       |
| 1972 SAS-2 | spark chamber | 30-200 MeV    | 5°         | 5000    | 3       |
| 1975 COS-B | spark chamber | 70-500 MeV    | 3°         | 100K    | 13      |
| 1991 CGRO  | spark chamber | 30 MeV-10 GeV | 1°         | 1M      | 200     |
| 2008 Fermi | Si            | 30 MeV- 1 TeV | 0.1°       | 40M+    | 1500+   |

'MeV astronomy' CGRO-COMPTEL, INTEGRAL  
NB no more MeV missions planned !



'TeV astronomy' Cerenkov: Whipple.....HESS, MAGIC..CTA



# INTERSTELLAR EMISSION RESULTS FROM FERMI-LAT



Fermi Gamma Ray Observatory  
Launched 2008  
maps the whole sky every 3 hours  
30 MeV – 300 GeV  
arcminute resolution  
data public immediately



The Photon database currently holds 519001463 photons collected between 2008-08-04T15:43:37 and 2011-03-28T18:59:22

For the results shown here:

1-2 years of data

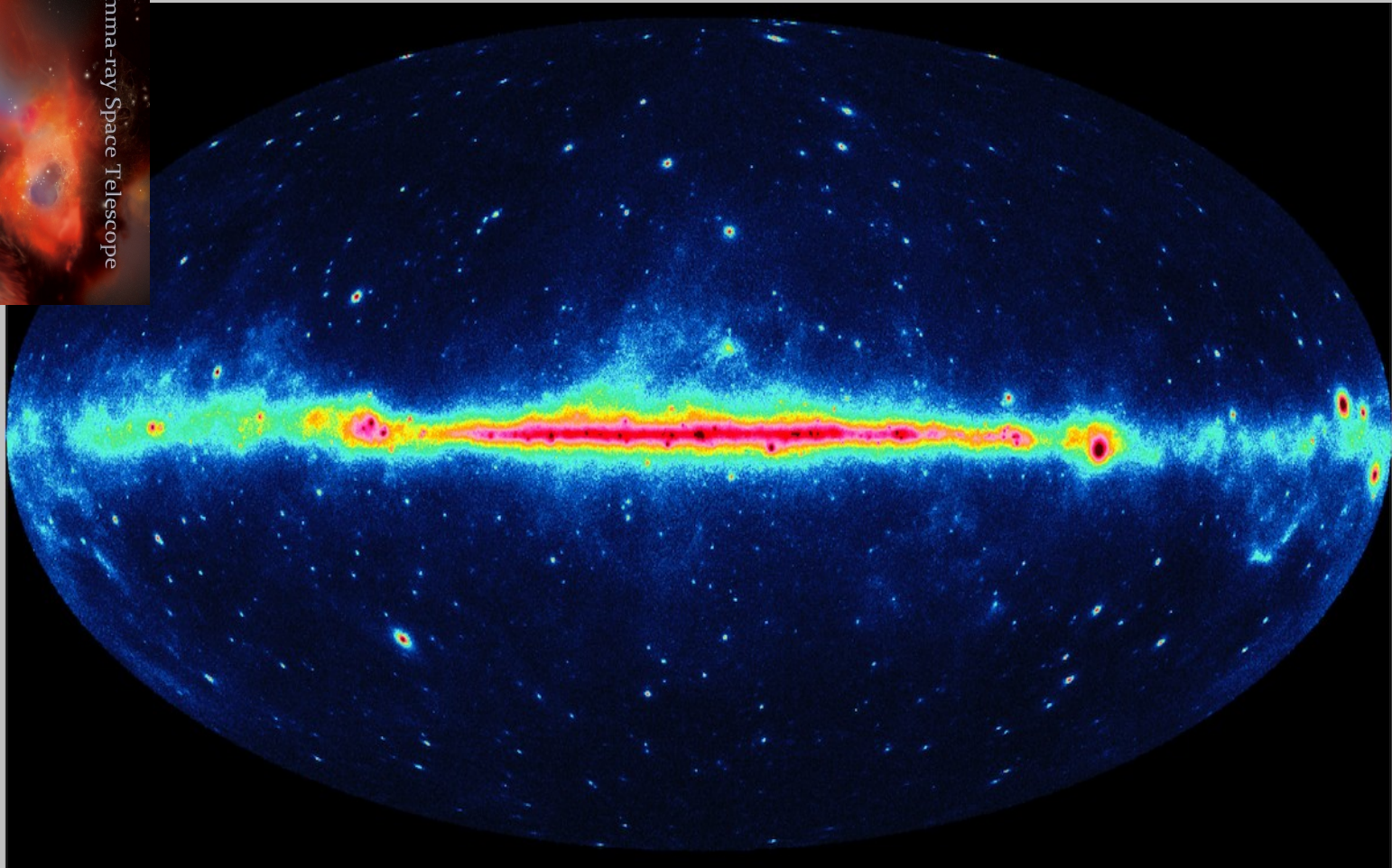
Low background event class (developed for extragalactic background study)

+ Fermi-measured cosmic-ray electron spectrum



# Fermi-LAT

## Gamma rays 1-10 GeV



PRELIMINARY

# *Modelling*

## *Cosmic-ray propagation*

### *Gamma rays*

### *Synchrotron*

3D gas model based on 21-cm (atomic H), CO (tracer of H<sub>2</sub>) 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

$\gamma$  – ray, synchrotron

# Modelling the gamma-ray sky

## Main ingredients of **GALPROP** model

cosmic-ray spectra  $p$  ,  $He$  ,  $e^-$  ,  $e^+$  (including secondaries)

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

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

Interstellar radiation field (Frankie code) (-> inverse Compton)

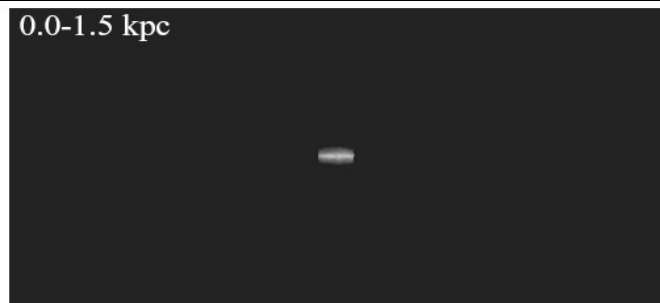
B-field (electron energy losses, synchrotron emission)

HI, CO, dust surveys

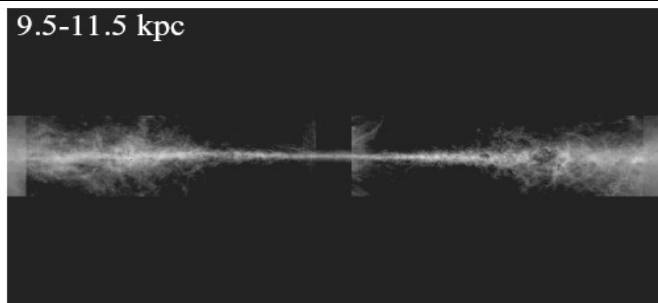
CO-to-H<sub>2</sub> conversion a function of position in Galaxy

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

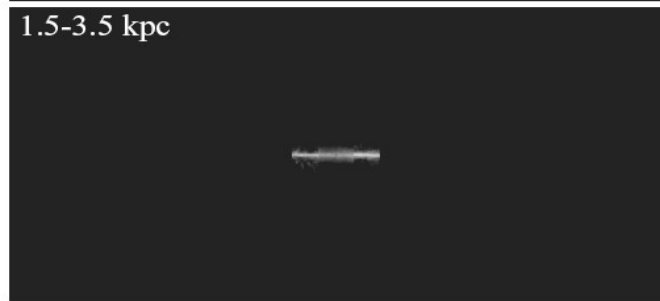
0.0-1.5 kpc



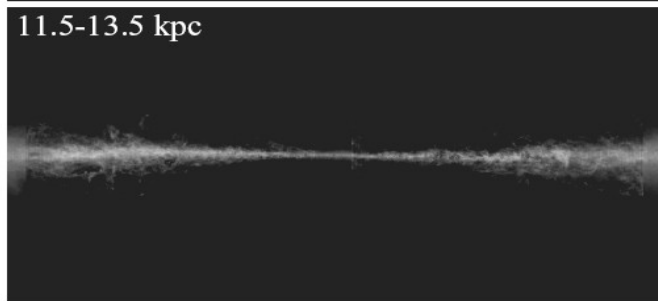
9.5-11.5 kpc



1.5-3.5 kpc



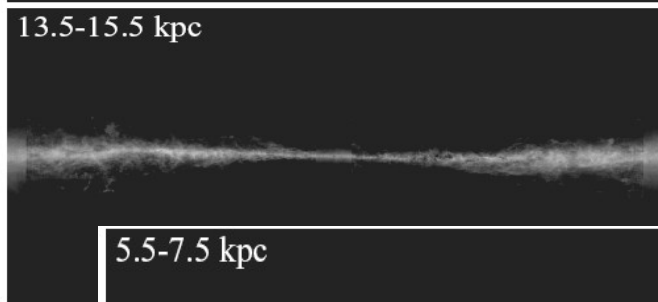
11.5-13.5 kpc



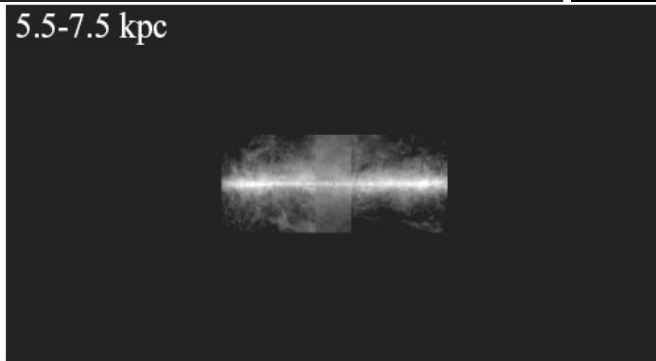
3.5-5.5 kpc



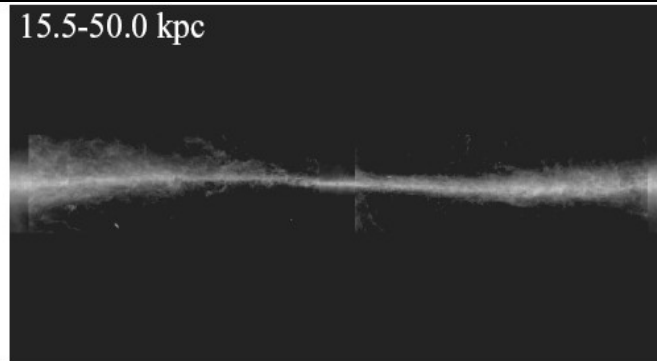
13.5-15.5 kpc



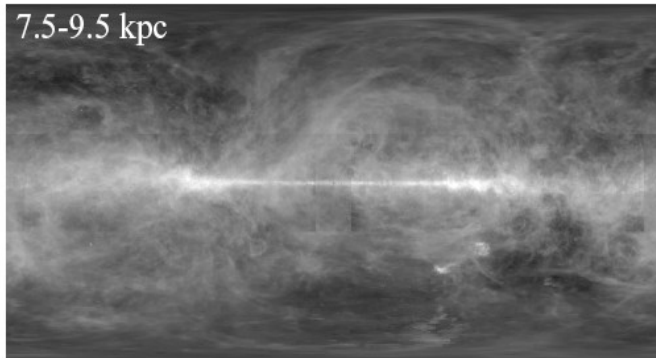
5.5-7.5 kpc



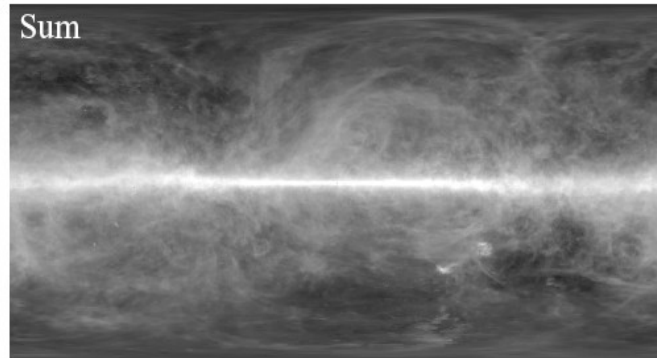
15.5-50.0 kpc



7.5-9.5 kpc



Sum



Gas Rings: HI  
Inner &  
Outer Galaxy

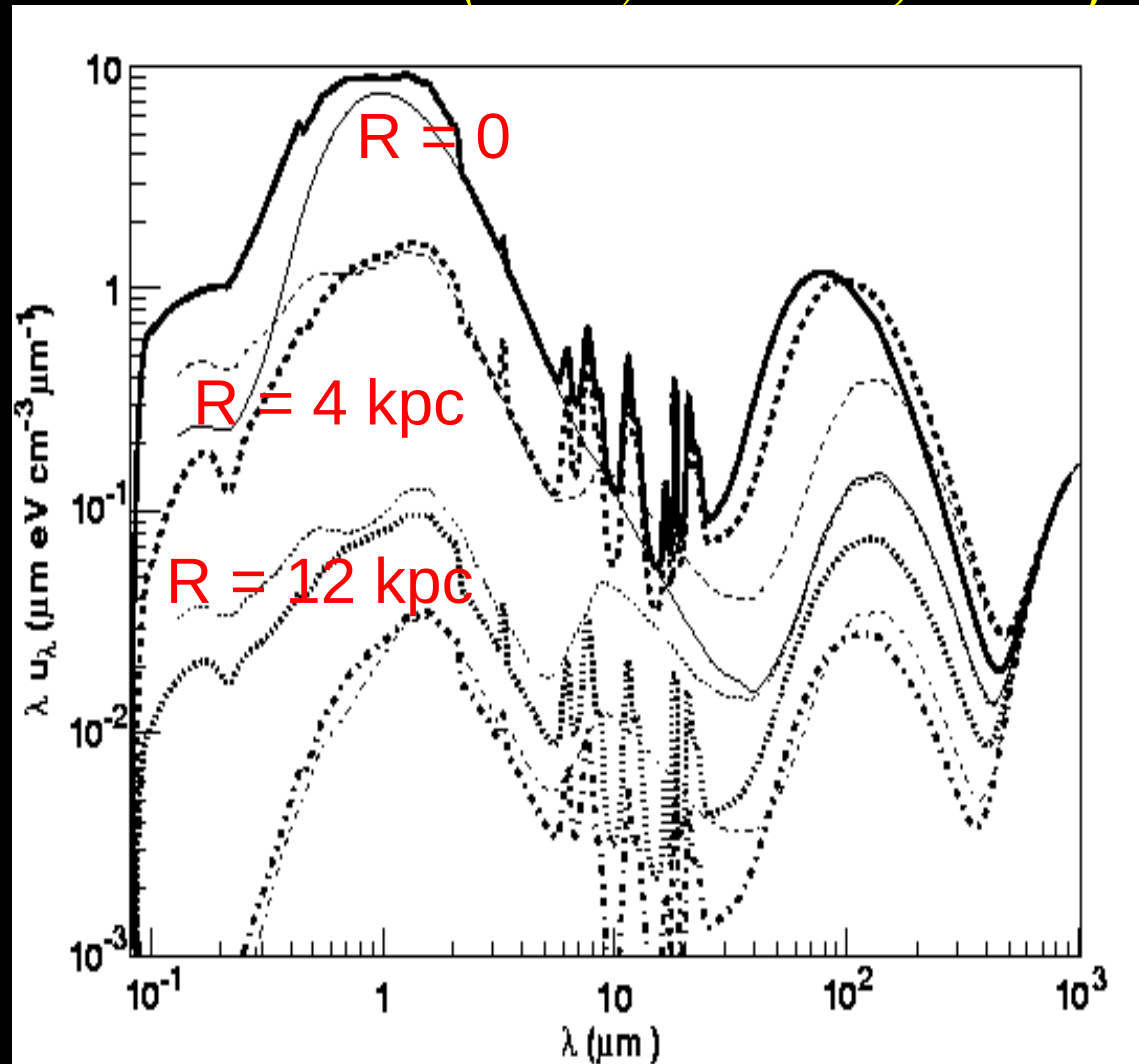
Gas Rings: HI  
Local Galaxy

# Interstellar Radiation Field

(for electron  $dE/dt$ , inverse Compton  $\gamma$ -rays):  
new model (*Troy Porter, Stanford*)

**New ISRF**  
using latest  
information

stellar  
populations,  
dust  
radiative  
transfer



UV optical

IR

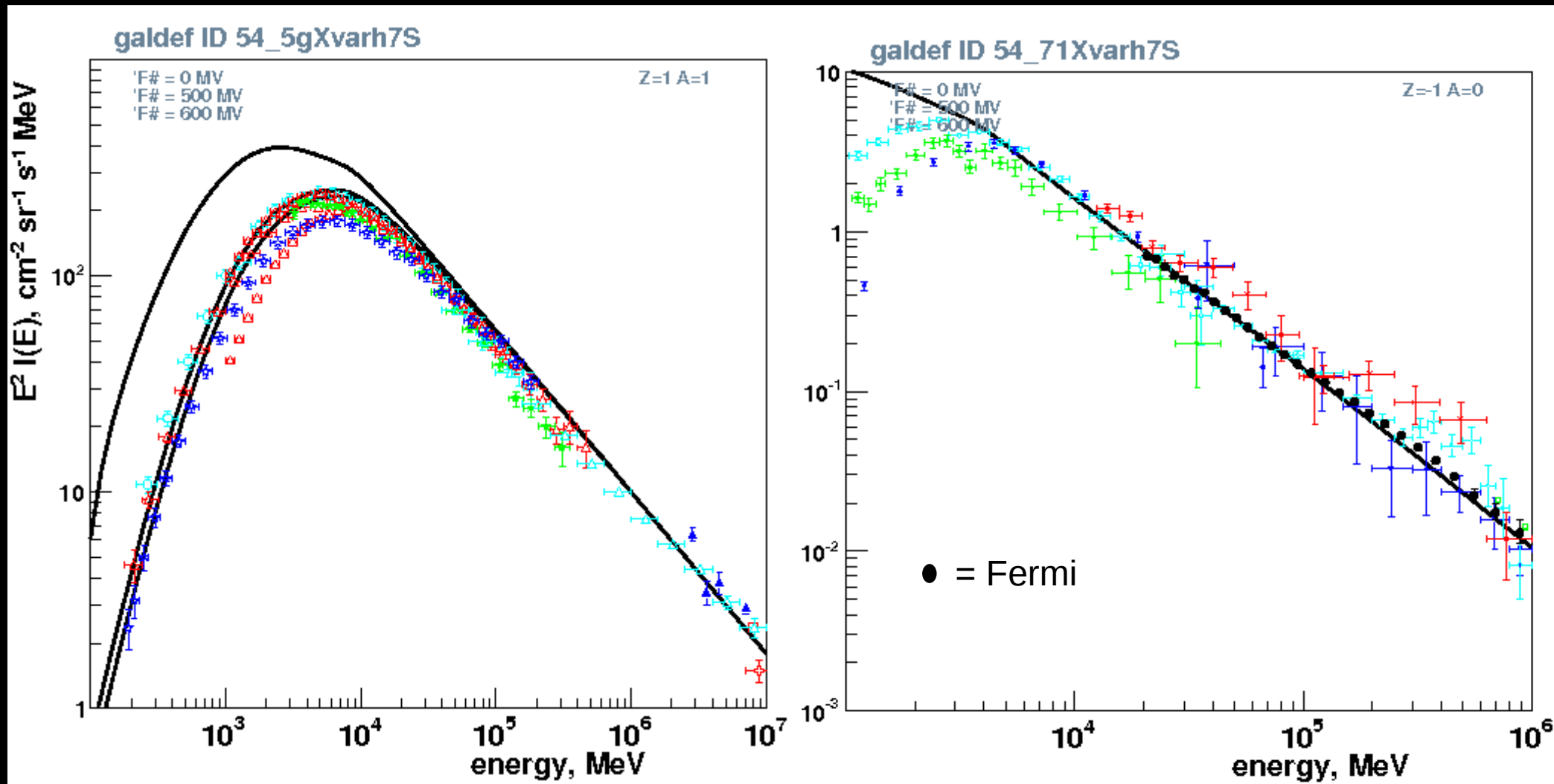
FIR

CMB

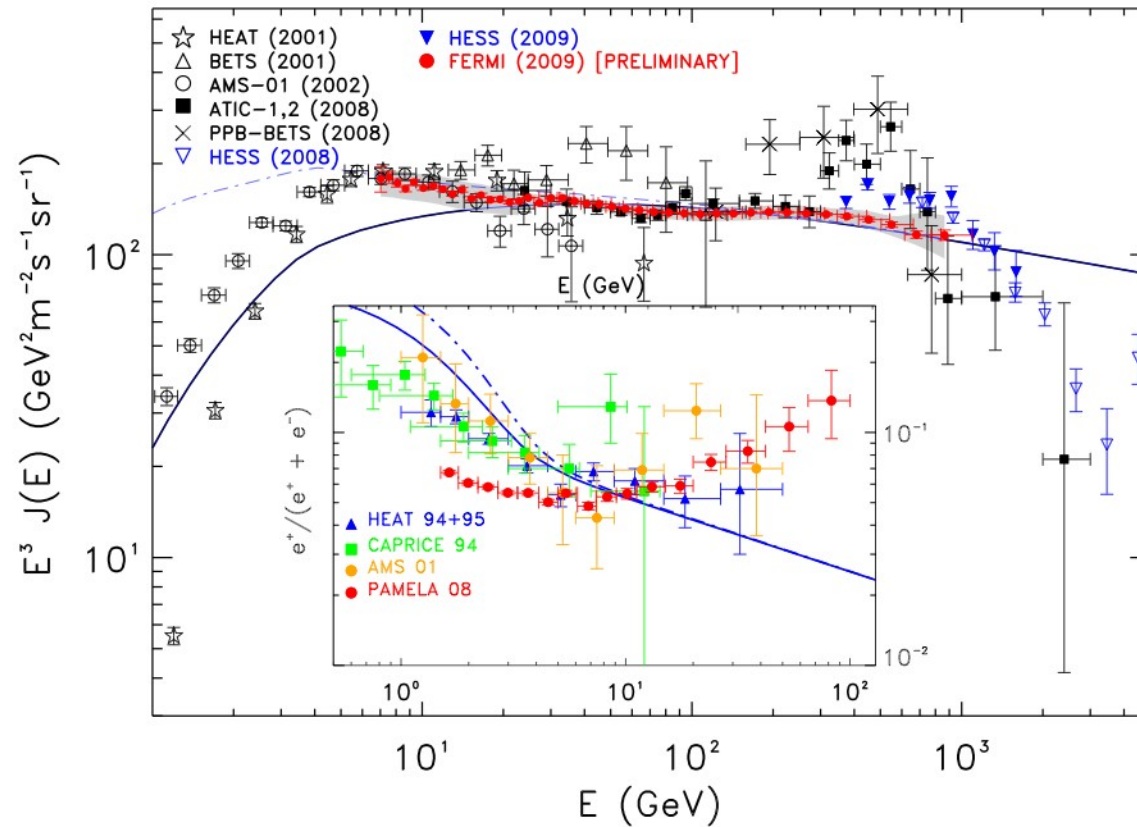
# Use a model based on *locally-measured* cosmic rays

## PROTONS

## ELECTRONS



# Electron spectrum measured by Fermi-LAT 7 GeV – 1 TeV



THE UNIVERSITY OF CHICAGO  
CHICAGO 37, ILLINOIS  
INSTITUTE FOR NUCLEAR STUDIES

March 12, 1949

Professor G. Cocconi  
Cornell University  
Laboratory of Nuclear Studies  
Ithaca, New York

Dear Cocconi:

Excuse my answering in English your letter, since by doing so I can dictate to my secretary. I have been very much interested by your statement that you have evidence of the existence of large showers up to  $10^{17}$  eV.

The reason why, according to the theory on the origin of cosmic rays that I have proposed, no electrons should be found, is that I postulate the existence throughout the interstellar space of a magnetic field with an intensity of about  $10^{-5}$  -  $10^{-6}$  gauss. If this assumption is correct, the radiation loss for a fast electron is quite large and prevents it from acquiring a sizeable energy. This mechanism of energy loss by electrons is much more efficient in removing fast electrons than the mechanism of the inverse Compton effects discussed by Feenberg and Primakoff. On the other hand, the existence of this last effect is much less hypothetical because all that is needed to produce it is the existence of the stellar light in the space traversed by the cosmic rays during their life. I have not read the article of Feenberg and Primakoff with particularly great attention, but as far as I can see, their conclusions seem to me to be sound.

You probably know that Teller recently has maintained that the cosmic radiation may be of solar origin and may be held within the limits of the planetary system by some suitable kind of magnetic field. Even if this hypothesis is correct, one could hardly expect to find electrons of high energy in the cosmic radiation. Probably the main reason to eliminate them is the same inverse Compton effect considered by Feenberg and Primakoff, which becomes much stronger because the particles are supposed to travel in the vicinity of the sun and are exposed, therefore, to a much stronger radiation than they would be in the interstellar space.

For all these reasons, it seems to me highly improbable that electrons of as high energy as you mention could be found in the cosmic radiation. On the other hand, all these arguments should not be overestimated, and an experimental check on them, if possible, is certainly worth while.

I will send  
I am sending to you a copy of my manuscript, as soon as reprints are available.

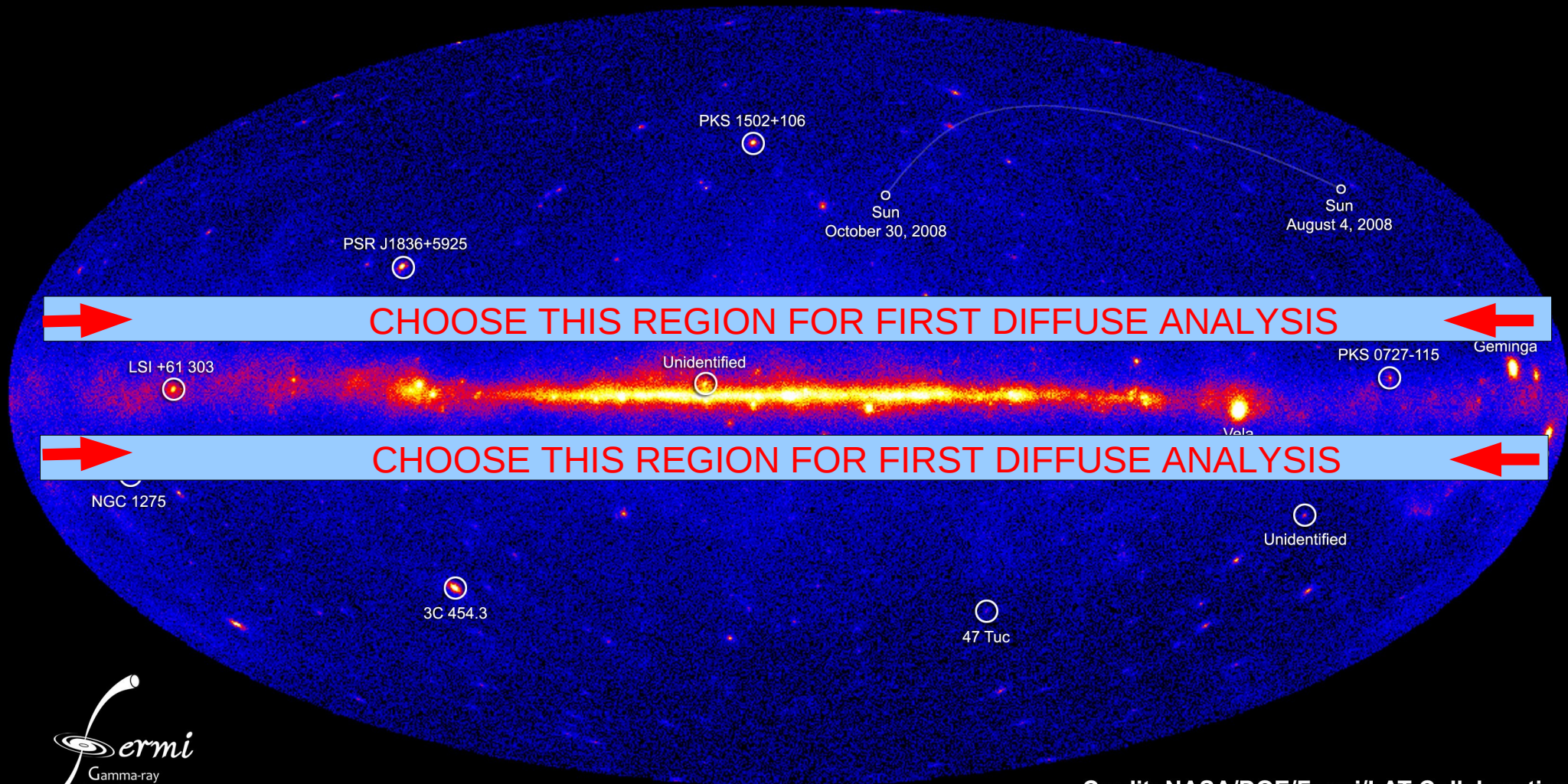
Very sincerely yours,

*Enrico Fermi*  
Enrico Fermi

EF:al  
encl.

# FIRST LIGHT ON DIFFUSE GAMMA RAYS

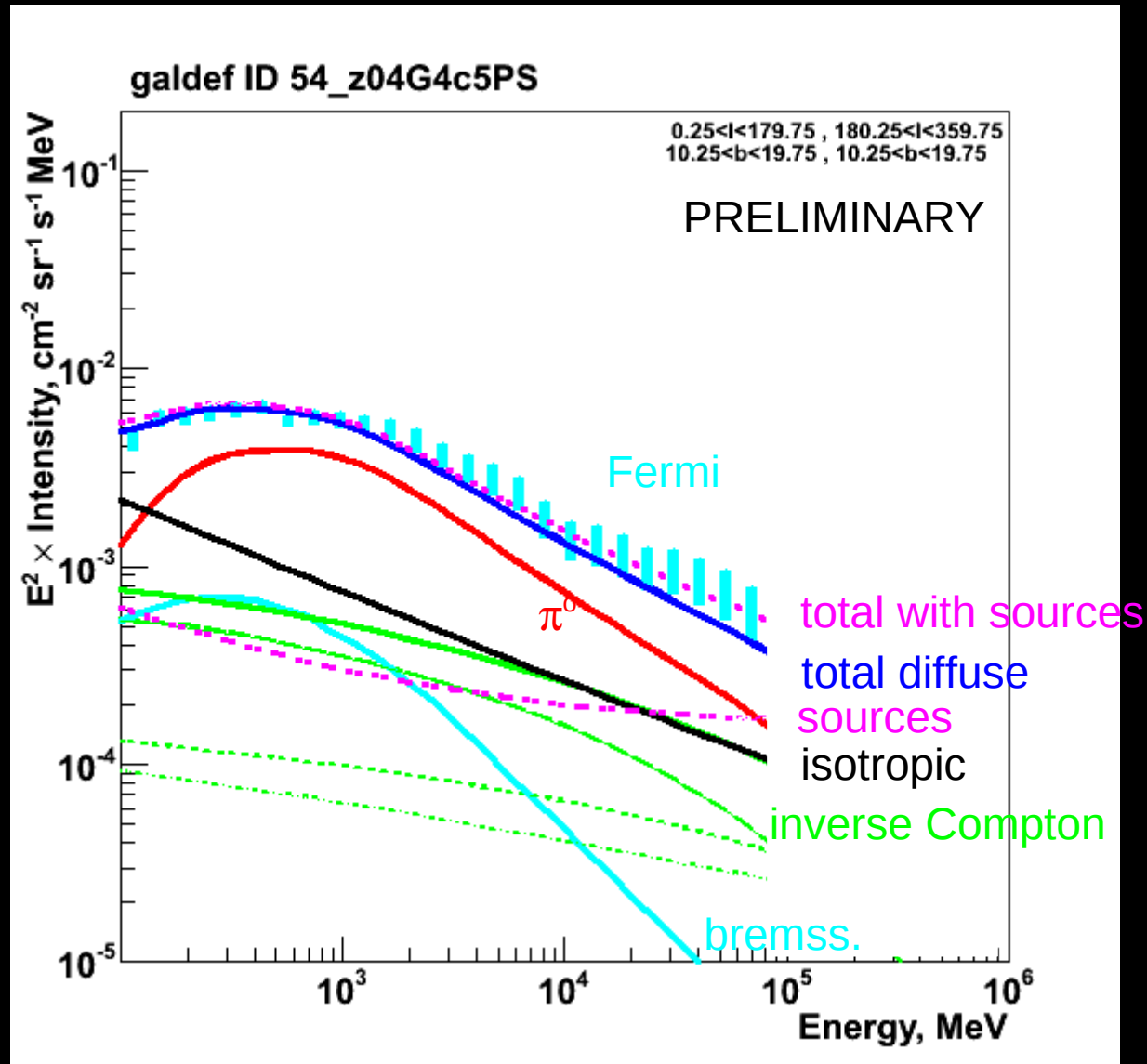
NASA's Fermi telescope reveals best-ever view of the gamma-ray sky



Credit: NASA/DOE/Fermi/LAT Collaboration

# INTERMEDIATE LATITUDES

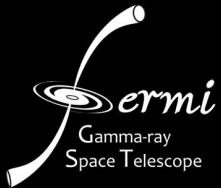
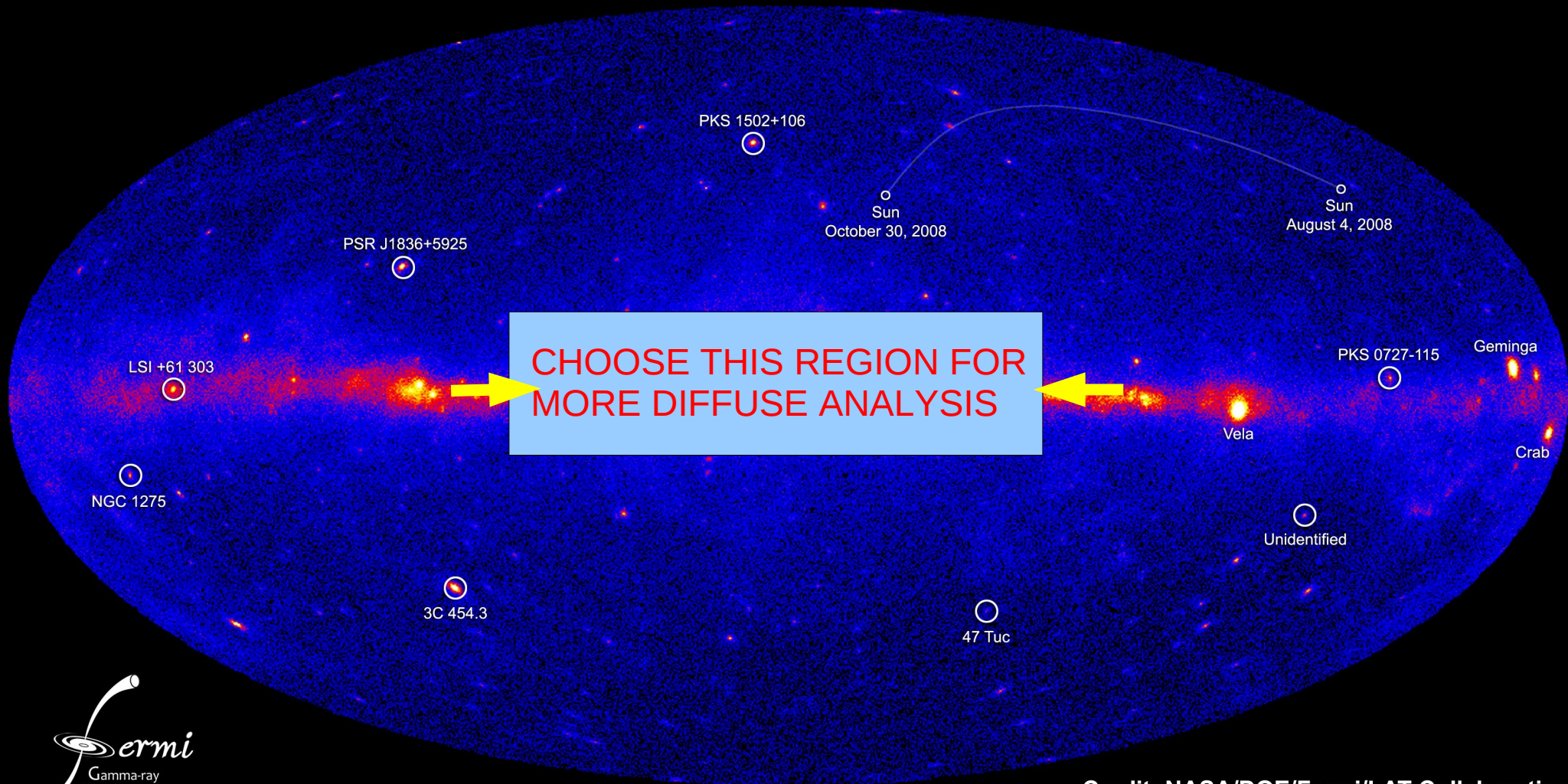
$$+10 < b < +20$$



Good agreement overall with *a-priori* GALPROP model

## MORE LIGHT ON DIFFUSE GAMMA RAYS

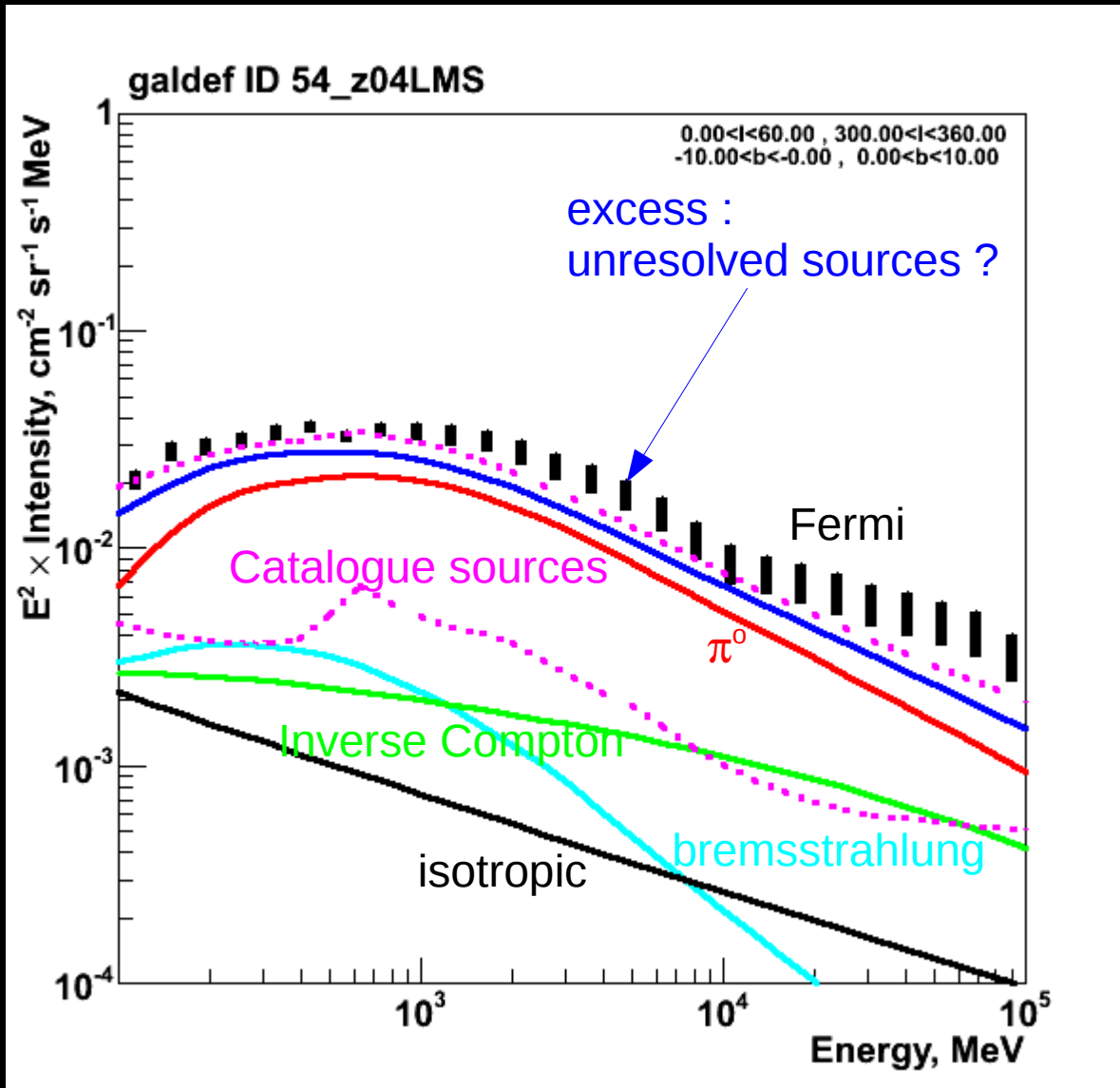
NASA's Fermi telescope reveals best-ever view of the gamma-ray sky



Credit: NASA/DOE/Fermi/LAT Collaboration

# Inner Galaxy

$300^\circ < l < 60^\circ, |b| < 10^\circ$

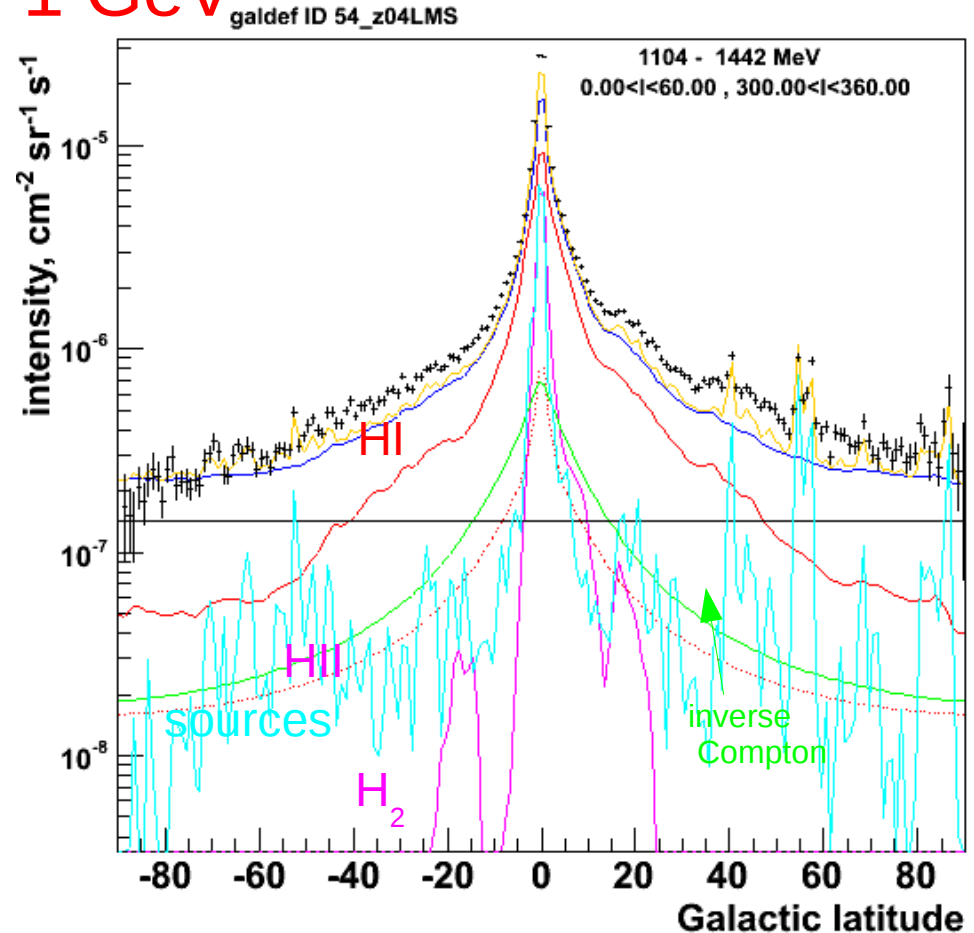
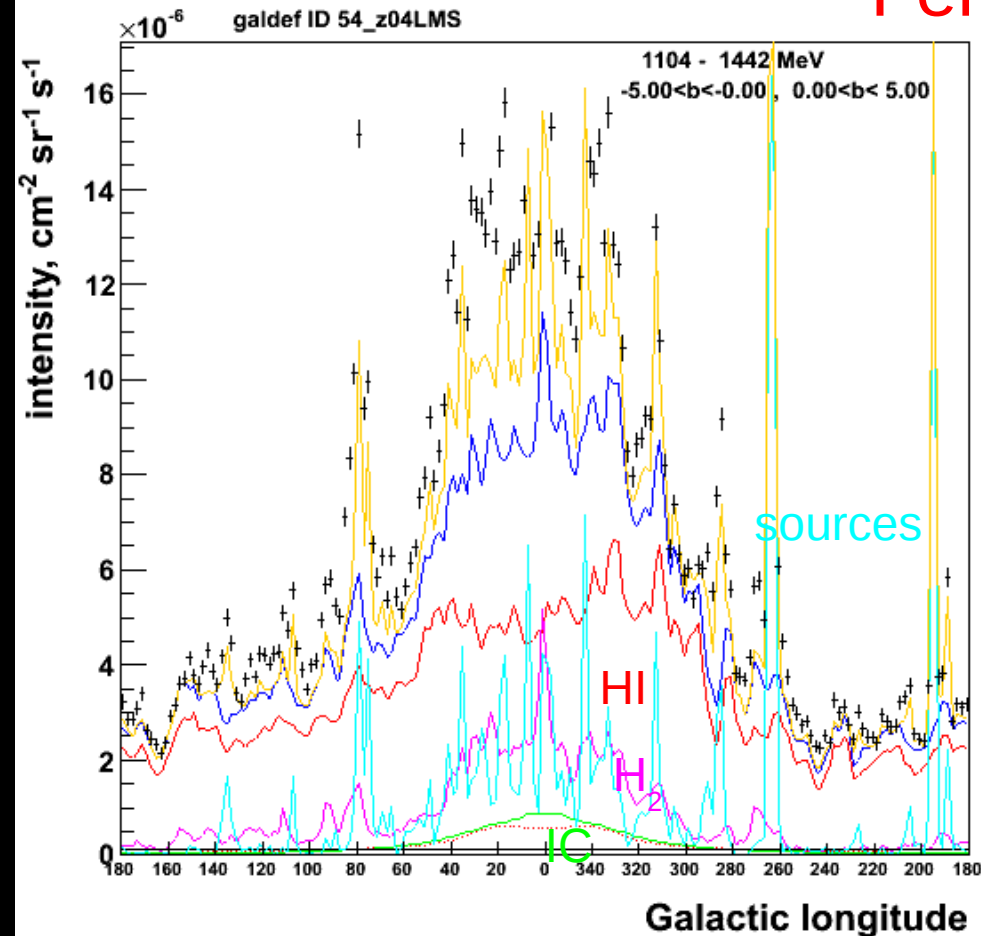


Good agreement overall with *a-priori* GALPROP model

## LONGITUDE PROFILE LOW LATITUDES

## LATITUDE PROFILE INNER GALAXY

Fermi 1 GeV



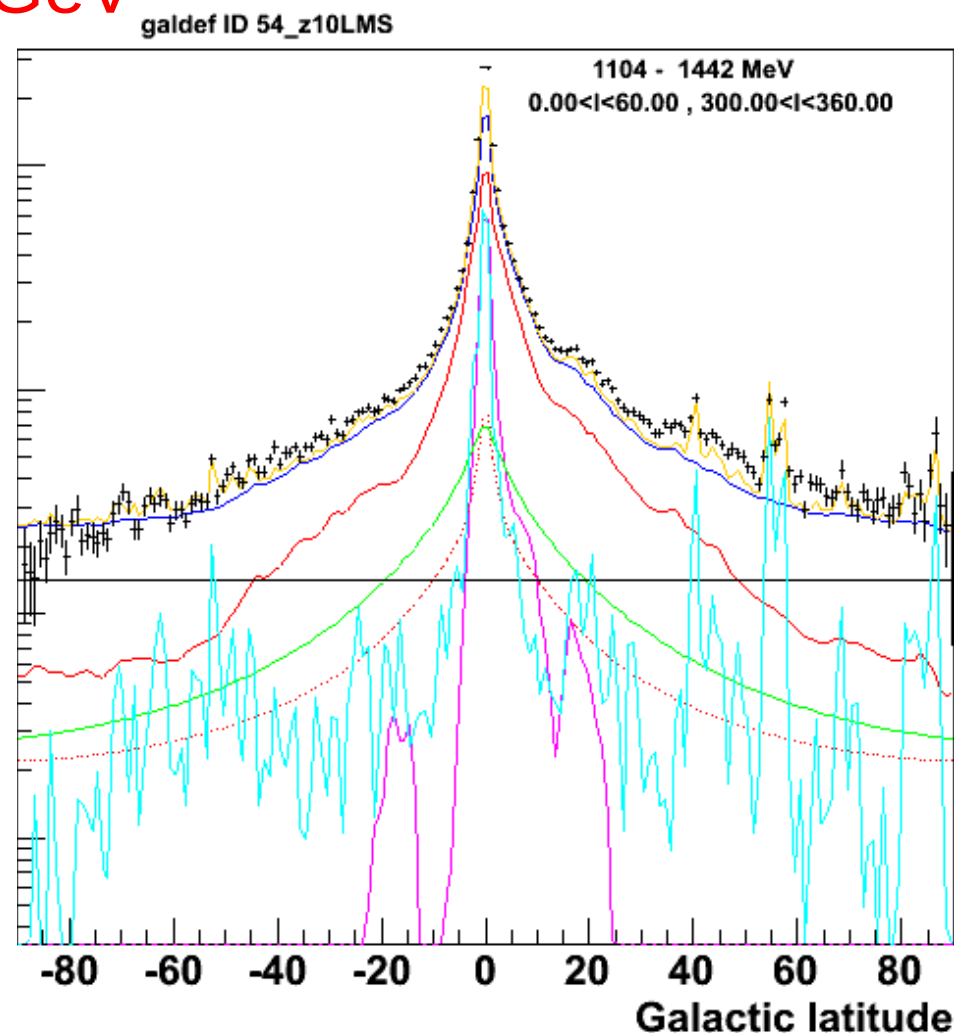
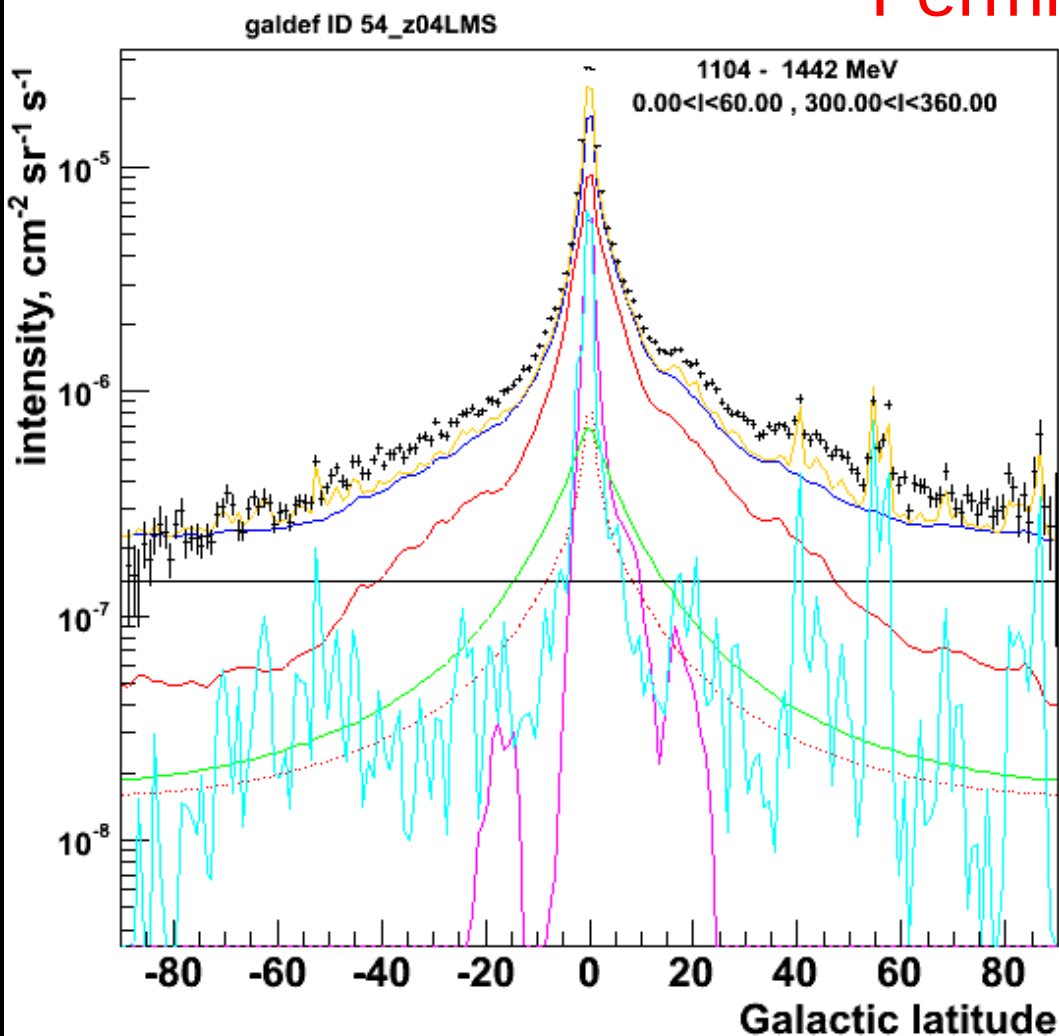
Agrees within 15% over 2 decades of dynamic range  
The observed flux is the sum of many components:  
importance of modelling them all !

# EVIDENCE FOR LARGE COSMIC-RAY HALO

4 kpc halo height

10 kpc halo height

Fermi 1 GeV



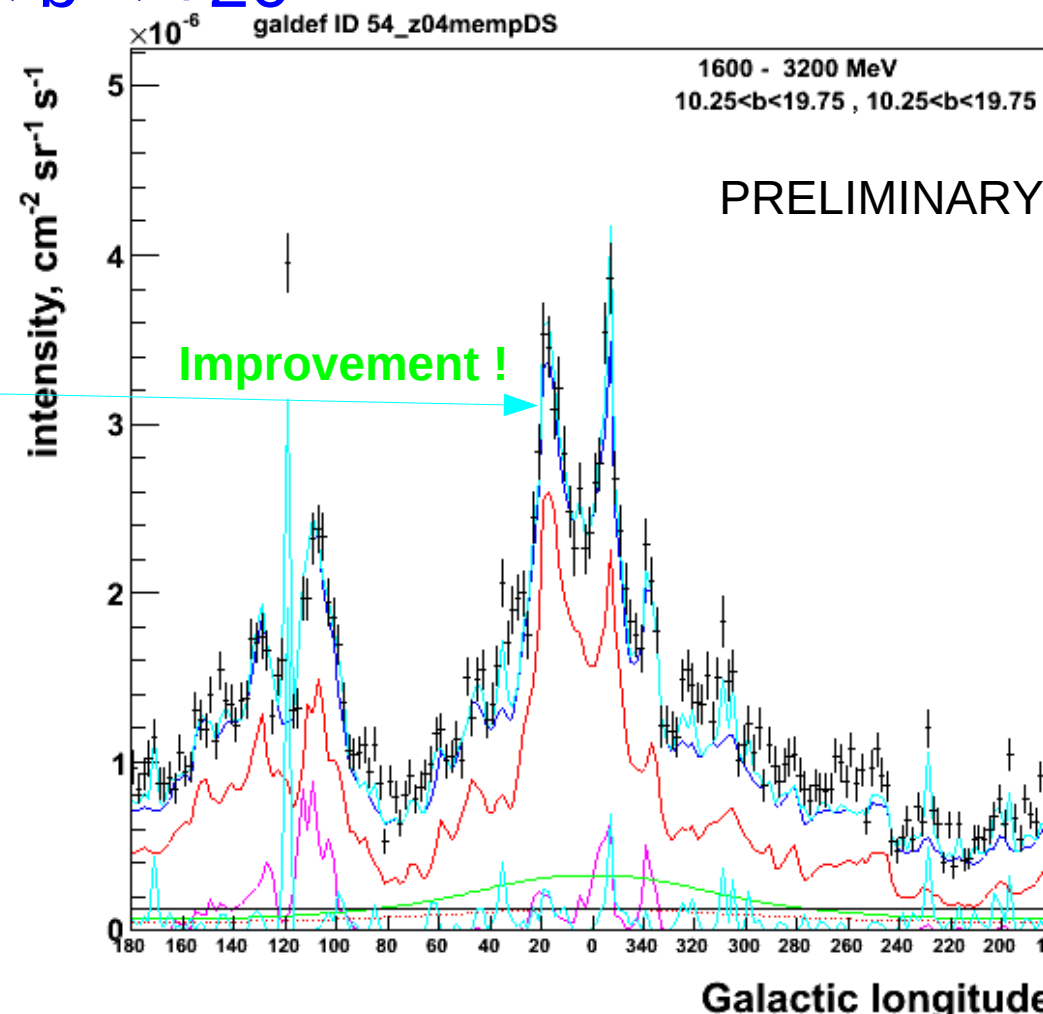
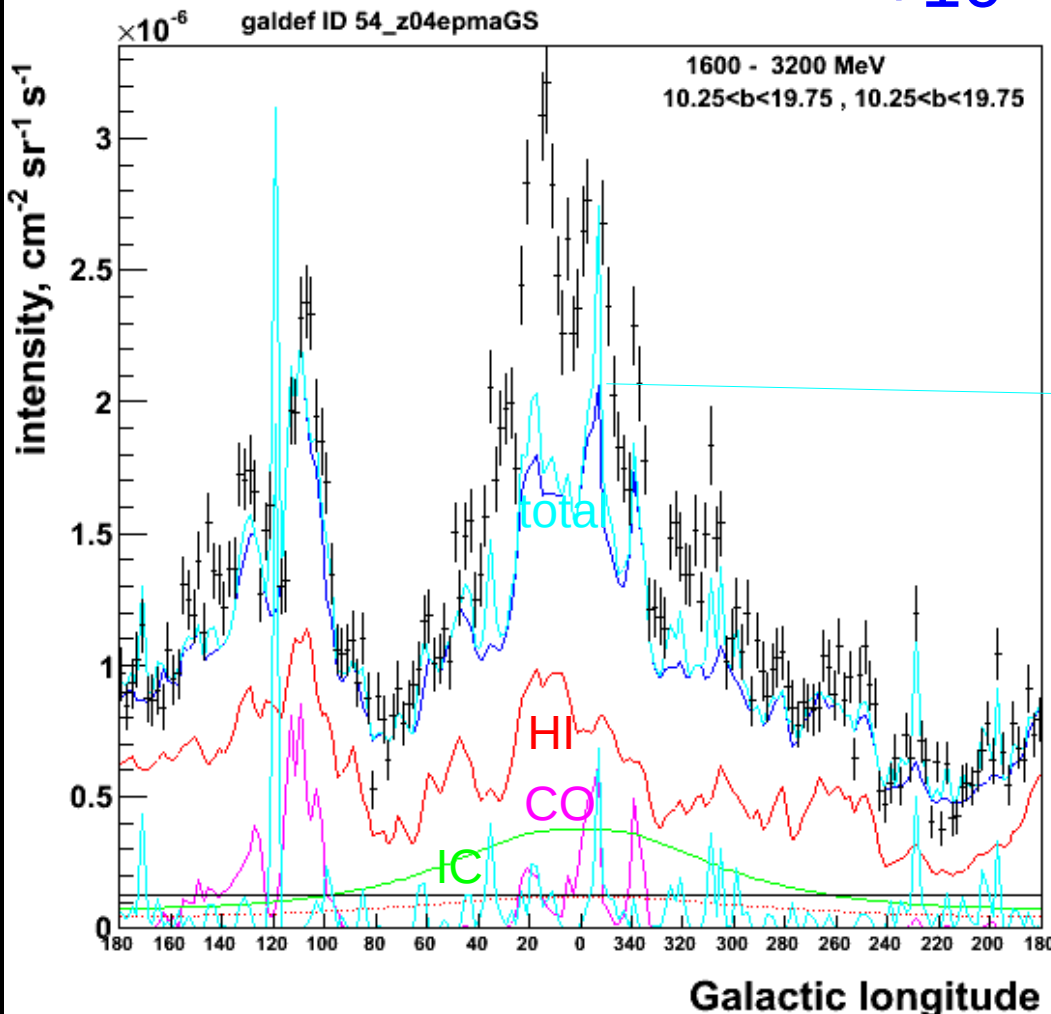
inverse Compton at high latitudes suggests a large cosmic-ray halo  
Important for halo magnetic field ! Relevant to Planck !

HI + CO

GAS TRACER

dust

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



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

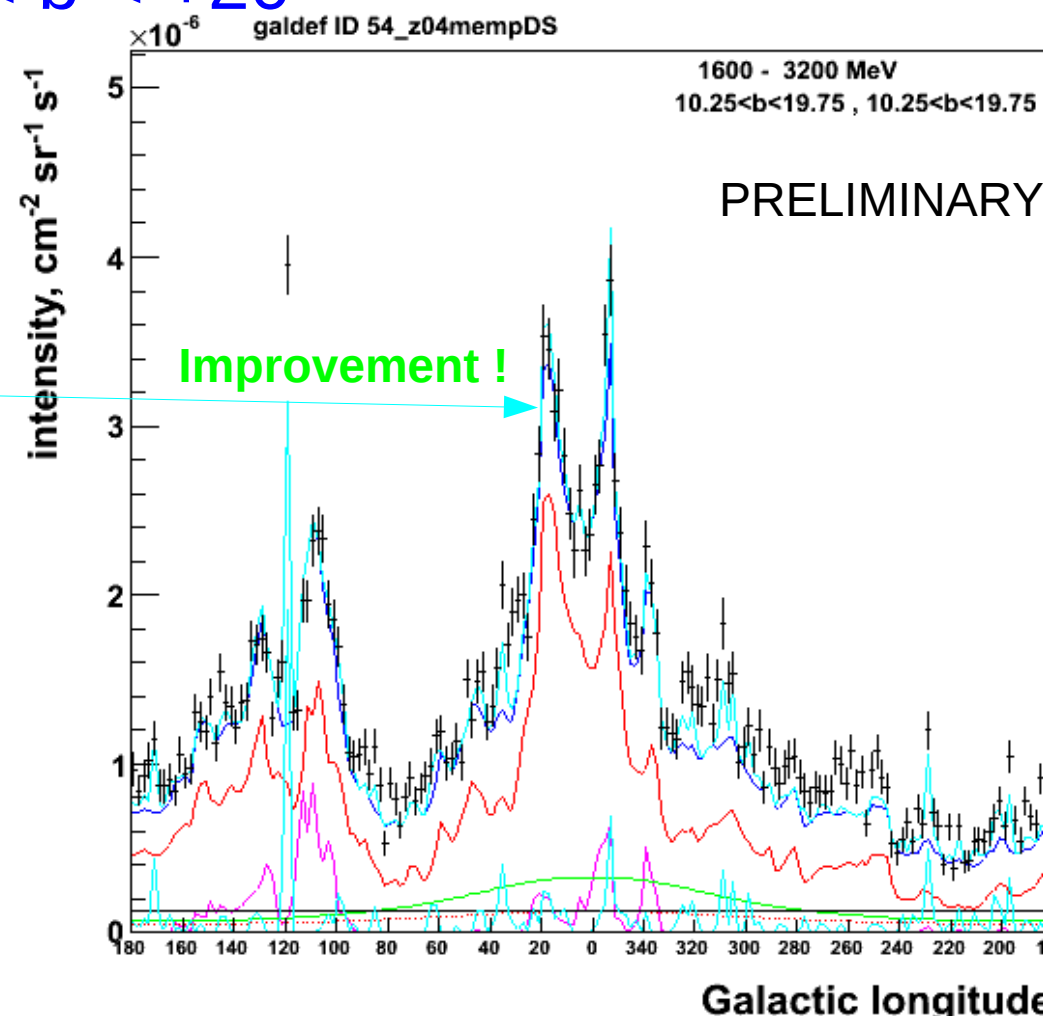
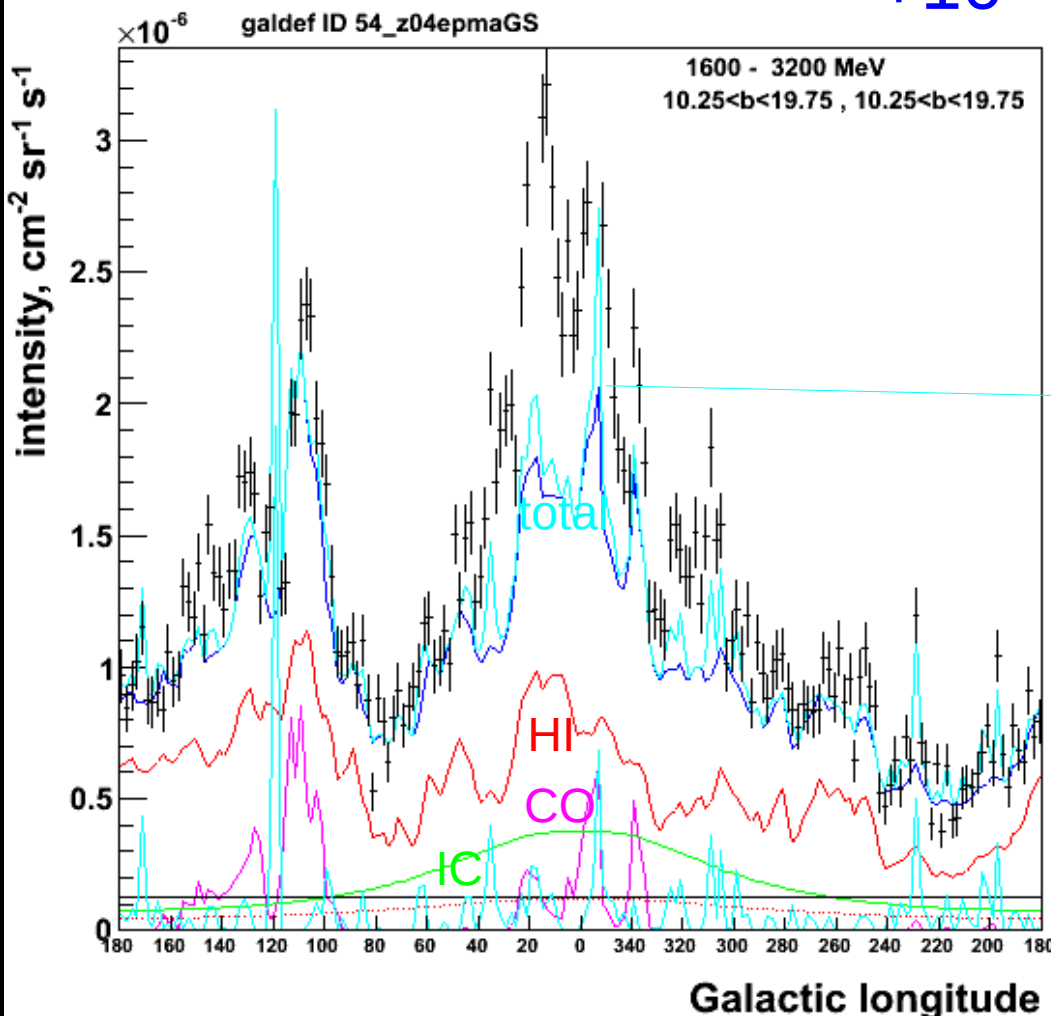
Dust emission (IRAS + DIRBE) is a better tracer of local gas than HI+CO !  
(Grenier, Casandjian: found this in EGRET data: 'dark gas')

HI + CO

GAS TRACER

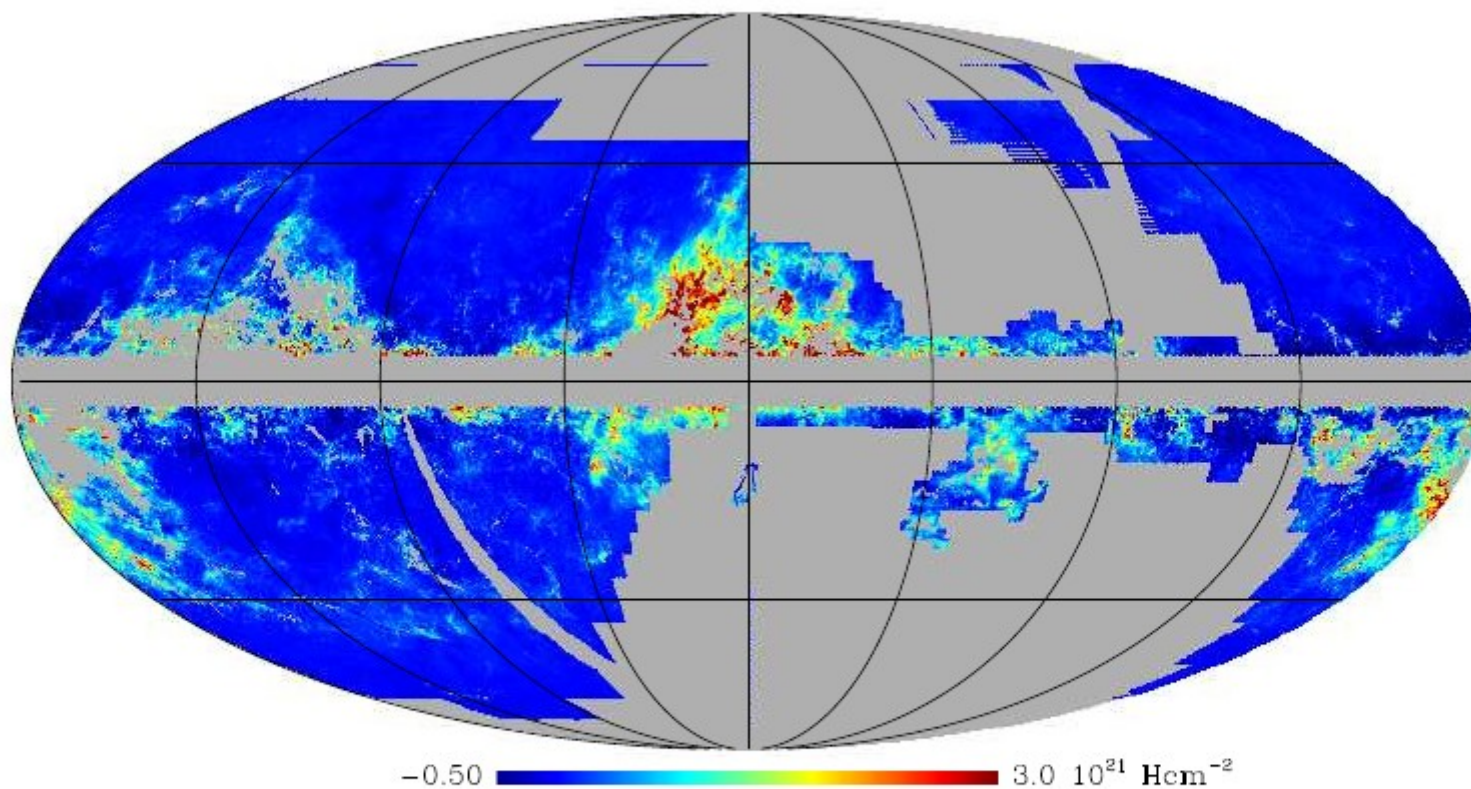
dust

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



Fermi: GeV gamma rays from cosmic rays  
'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  $\approx 28\%$  of the atomic mass and  $\approx 118\%$  of the molecular gas mass. The comparison of this value with the recent

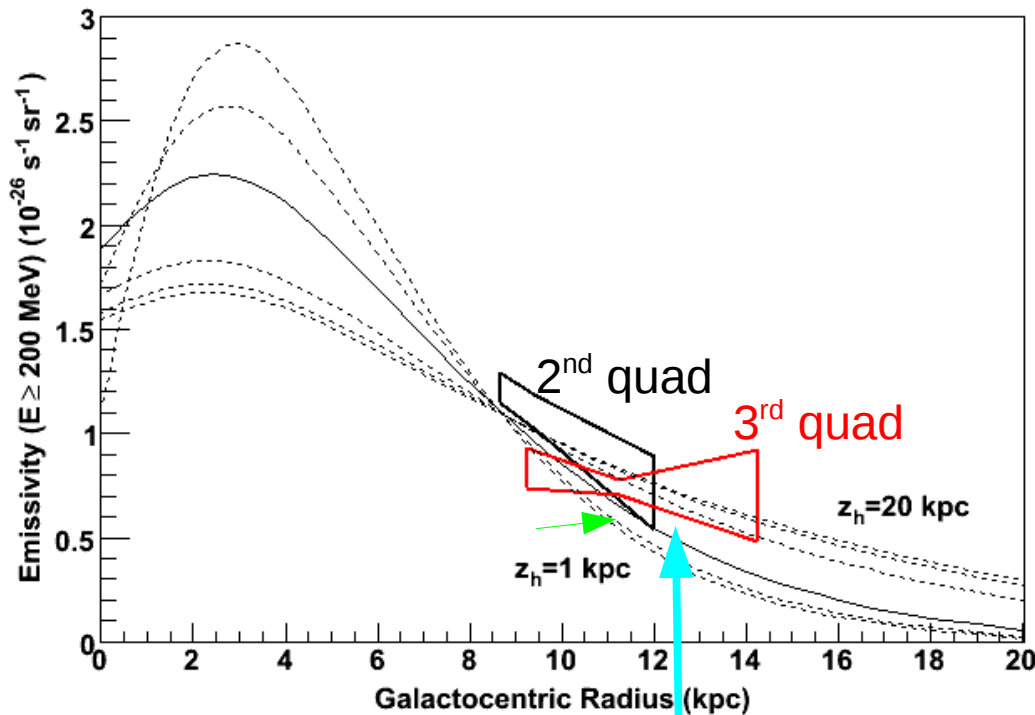


**Fig. 8.** Map of the excess column density derived from the 857 GHz data. The map is shown in Galactic coordinates with the Galactic centre at the centre of the image. The grey regions correspond to those where no *IRAS* data are available, regions with intense CO emission ( $W_{\text{CO}} > 1 \text{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

# Gamma-ray emissivity distribution in *outer* Galaxy

From Fermi-LAT

## 2<sup>nd</sup> and 3<sup>rd</sup> Galactic Quadrants



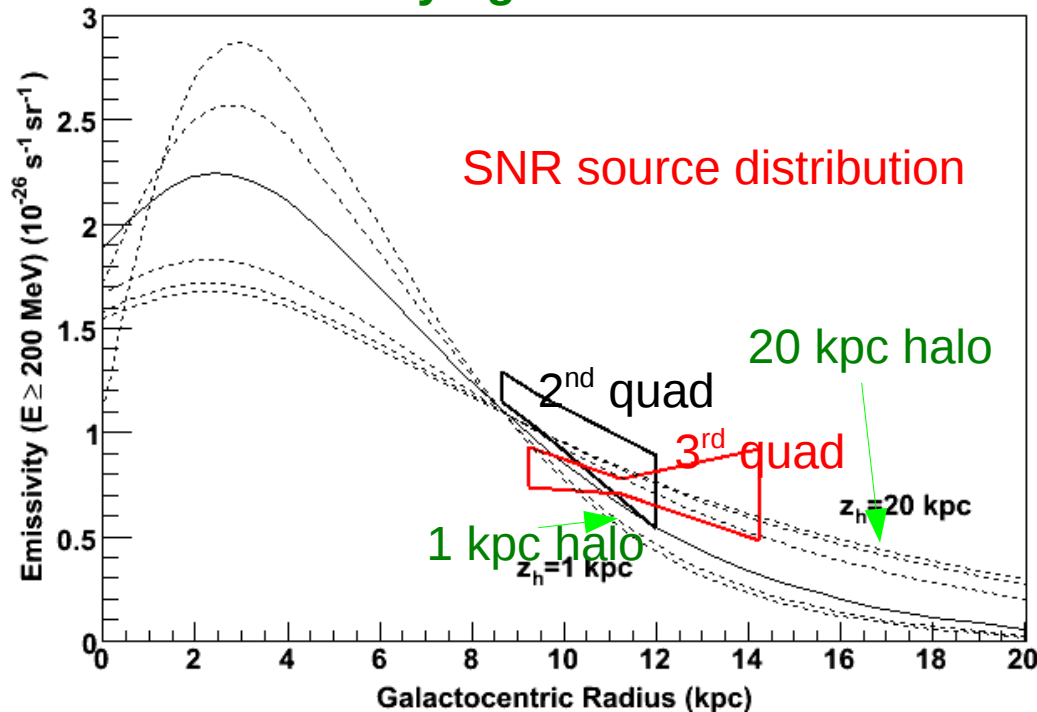
More cosmic-rays in outer Galaxy than expected !

# Gamma-ray emissivity distribution in outer Galaxy

From Fermi-LAT

## 2<sup>nd</sup> and 3<sup>rd</sup> Galactic Quadrants

varying the *halo size*



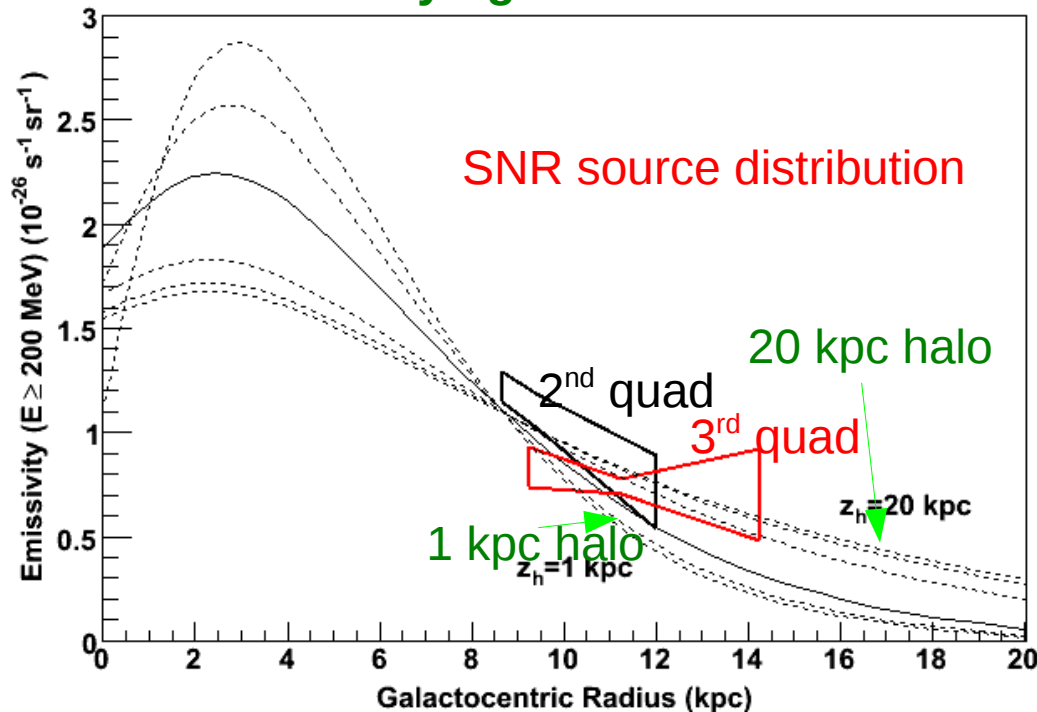
More cosmic-rays in outer Galaxy than expected !  
More evidence for large halo, which widens the distribution ?

# Gamma-ray emissivity distribution in outer Galaxy

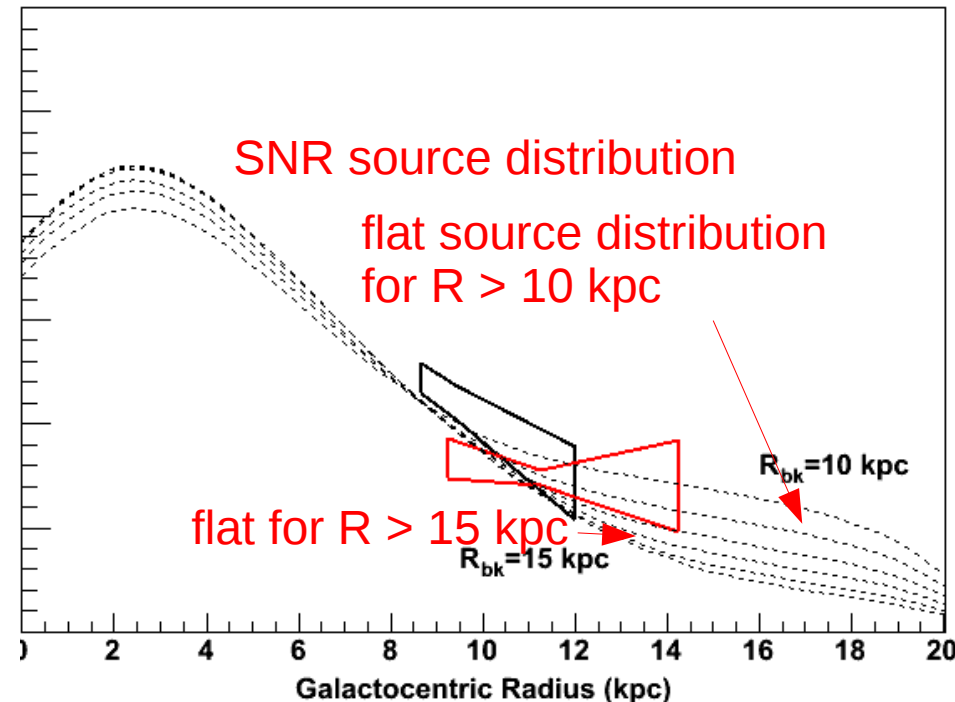
From Fermi-LAT

## 2<sup>nd</sup> and 3<sup>rd</sup> Galactic Quadrants

varying the *halo size*



varying the *source distribution*



More cosmic-rays in outer Galaxy than expected !

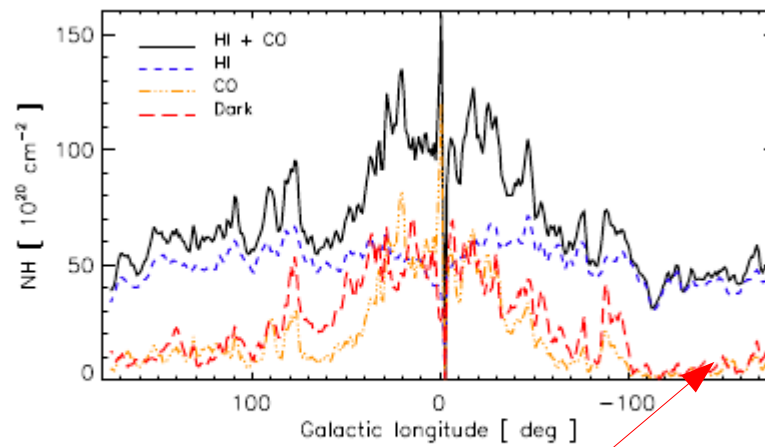
More evidence for large halo ? More sources in outer Galaxy (what are they ?)

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  $\approx 28\%$  of the atomic mass and  $\approx 118\%$  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)

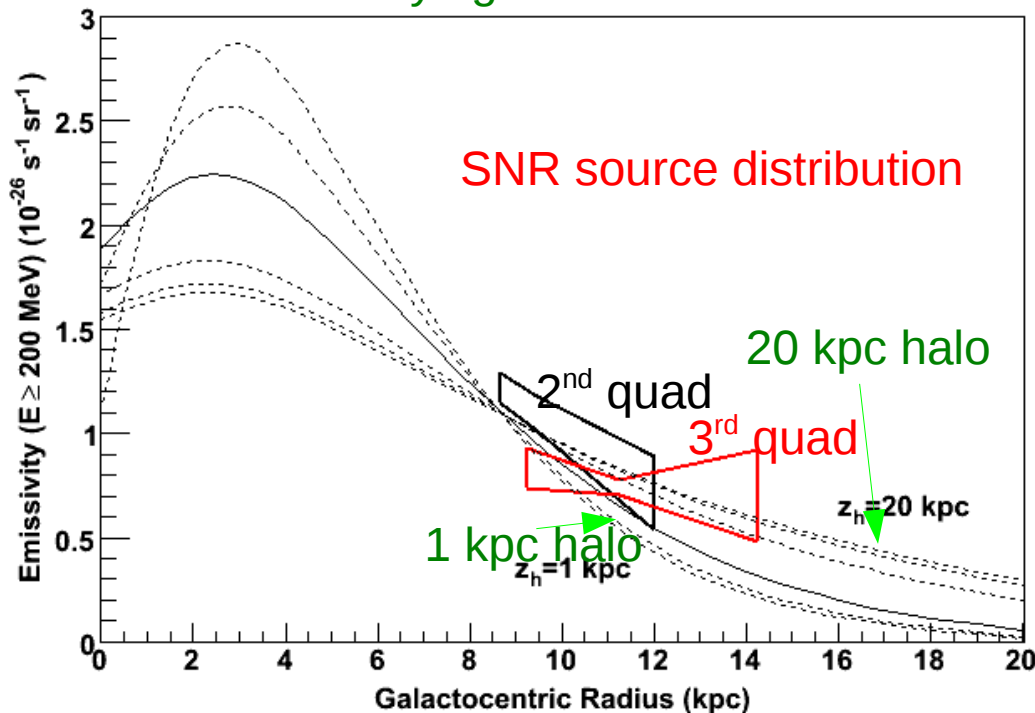
Not enough dark gas in outer Galaxy to explain Fermi gamma rays ?

# Gamma-ray emissivity distribution in outer Galaxy

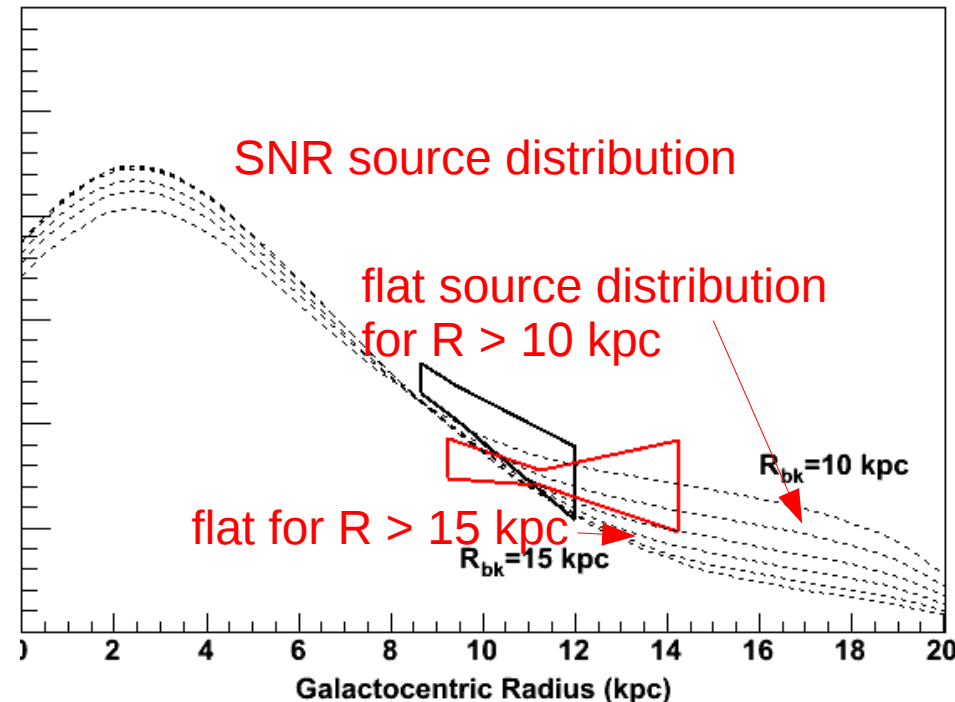
From Fermi-LAT

## 2<sup>nd</sup> and 3<sup>rd</sup> Galactic Quadrants

varying the *halo size*



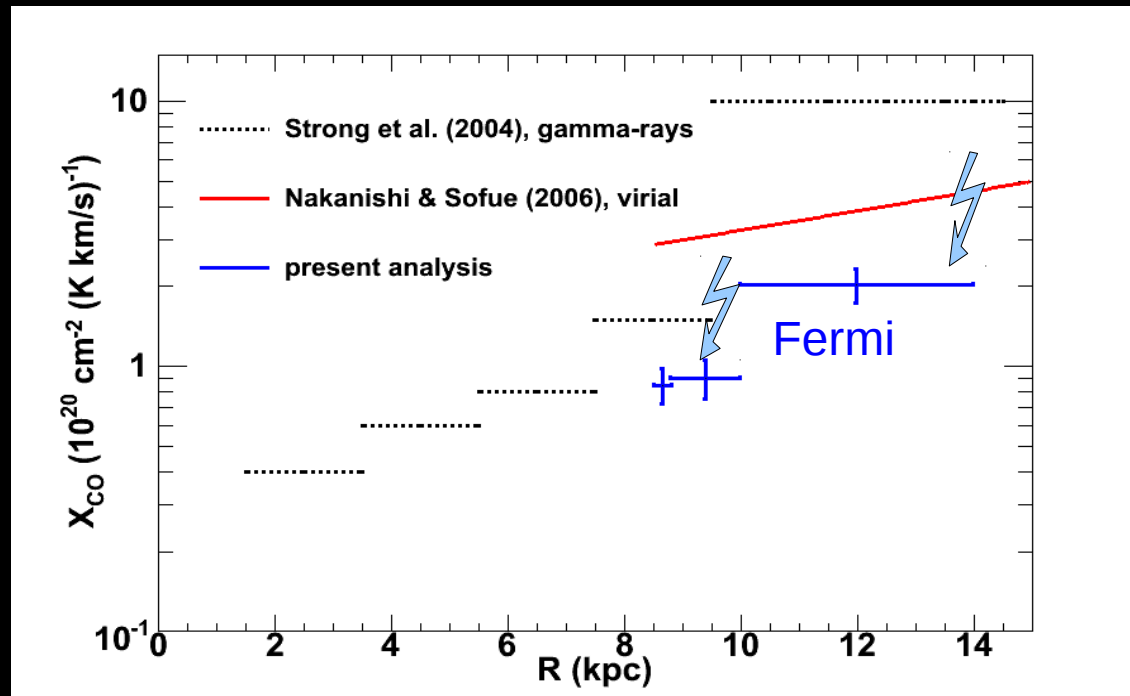
varying the *source distribution*



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

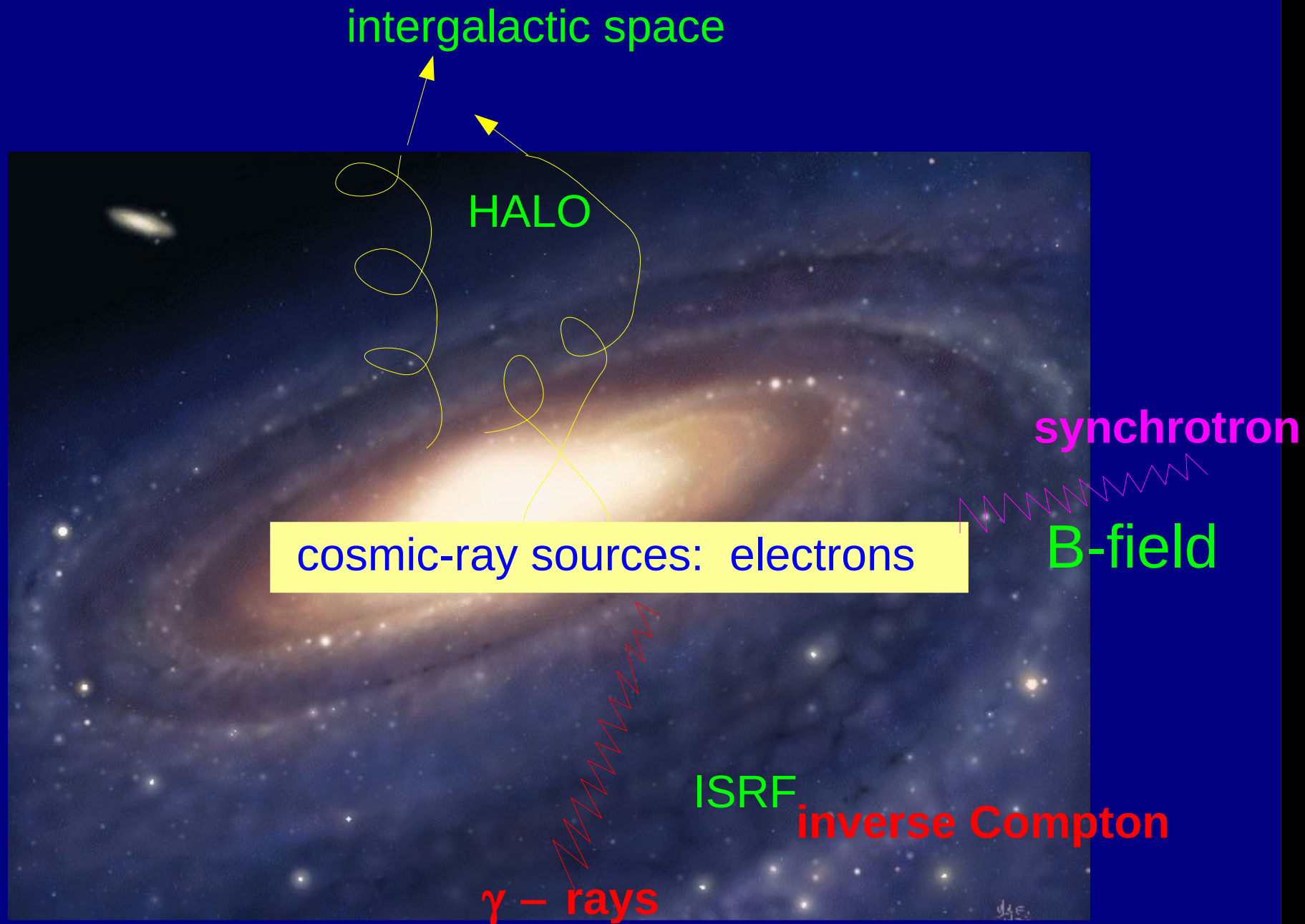


Scaling factor  $X_{\text{CO}}$  from  $^{12}\text{CO}$  to  $\text{H}_2$   
Local and Outer Galaxy (2<sup>nd</sup> quadrant)

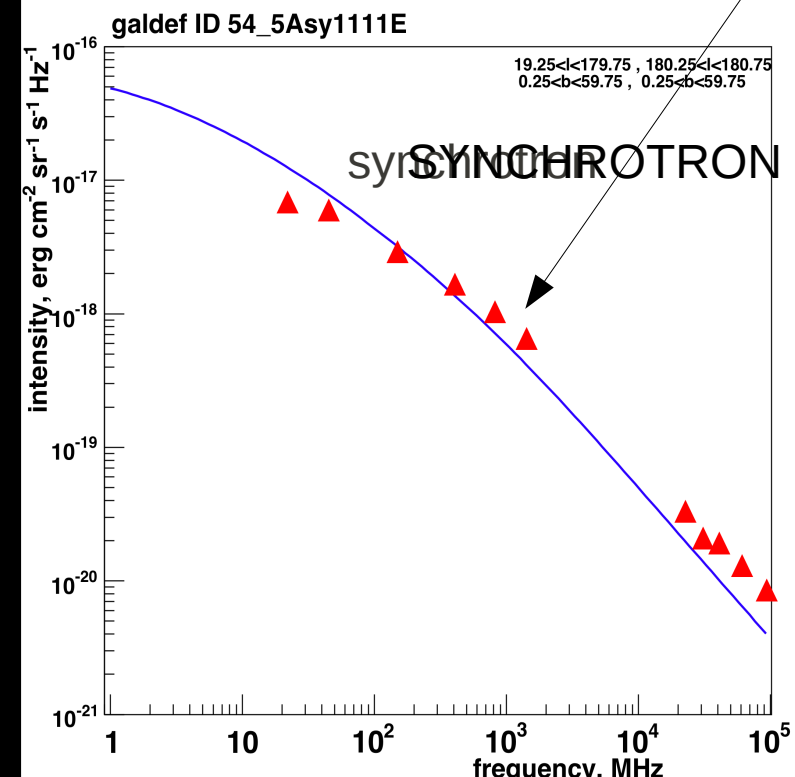
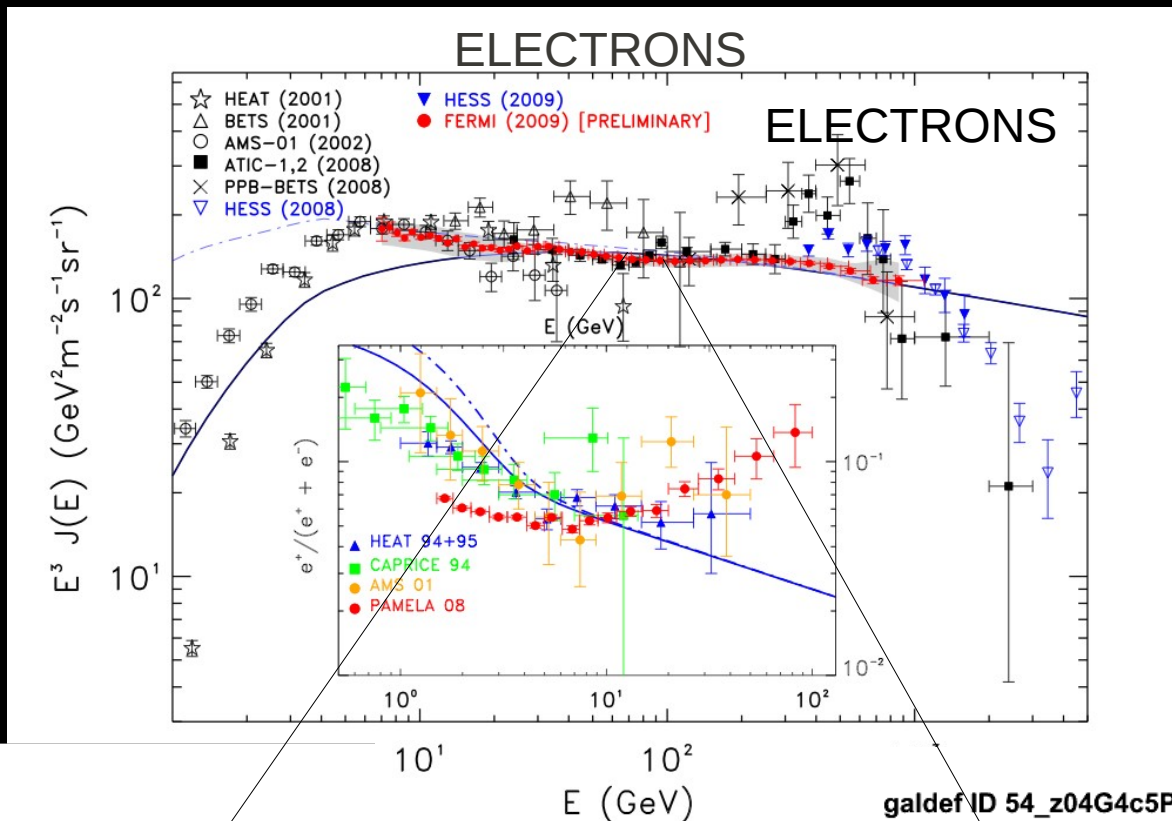
Confirms *increase* from inner to outer Galaxy

Abdo et al (2010) ApJ 710, 133

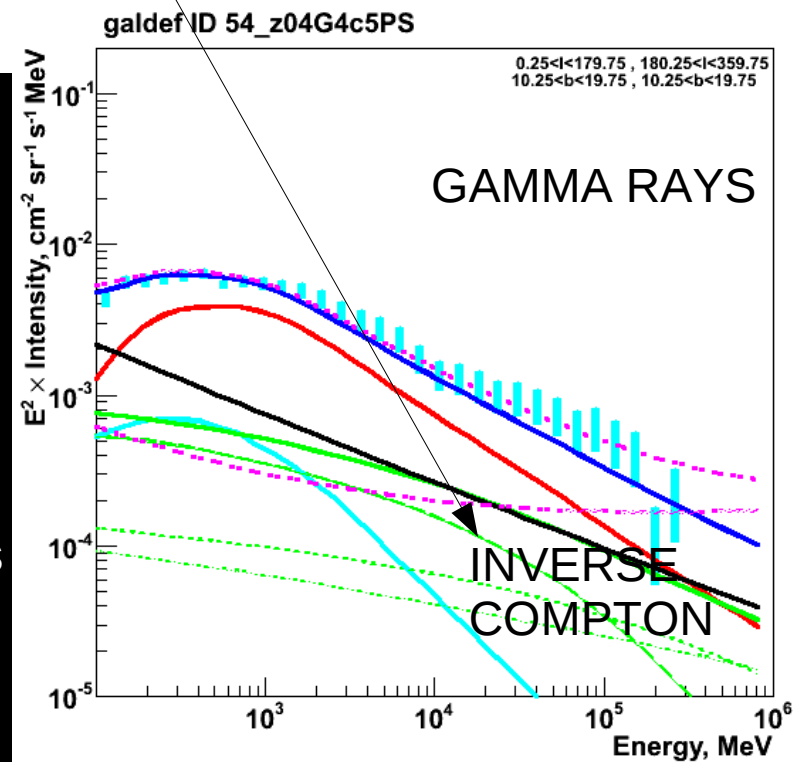
# Cosmic Ray Electrons Synchrotron and Magnetic Fields

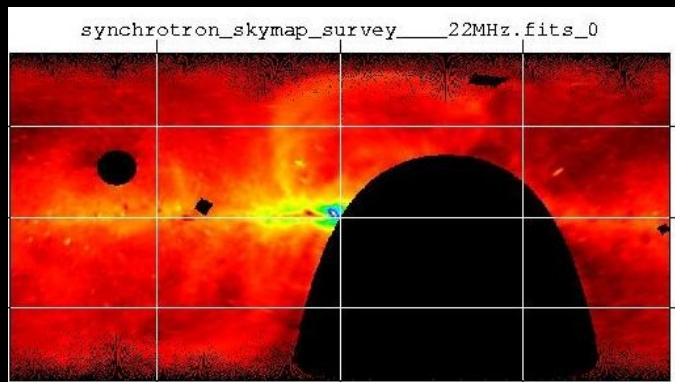


Cosmic-ray electrons provide the link radio – gamma ray  
Hence (one of the) Fermi – Planck connection(s) !

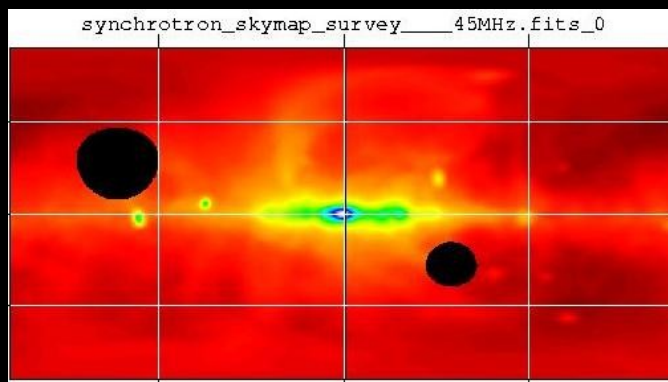


SAME  
 ELECTRONS  
 for  
 RADIO  
 and  
 GAMMA RAYS !  
 good constraints  
 on models

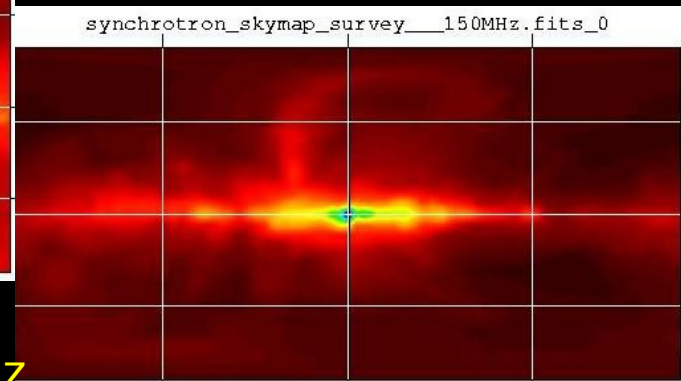




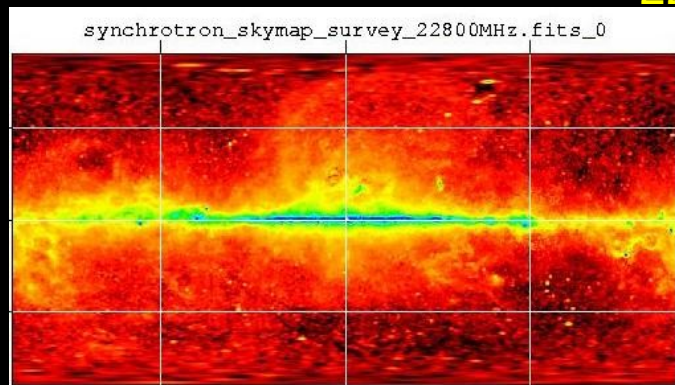
22 MHz



45 MHz



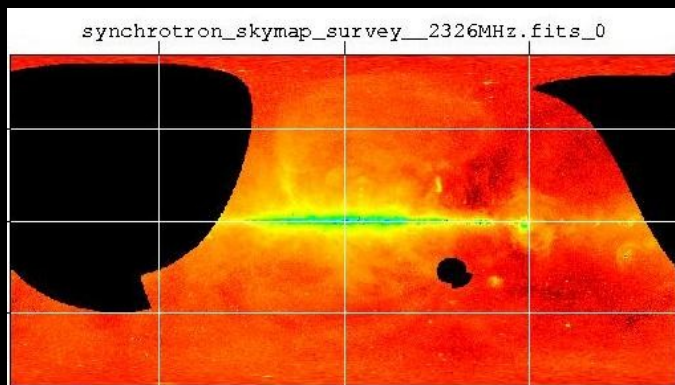
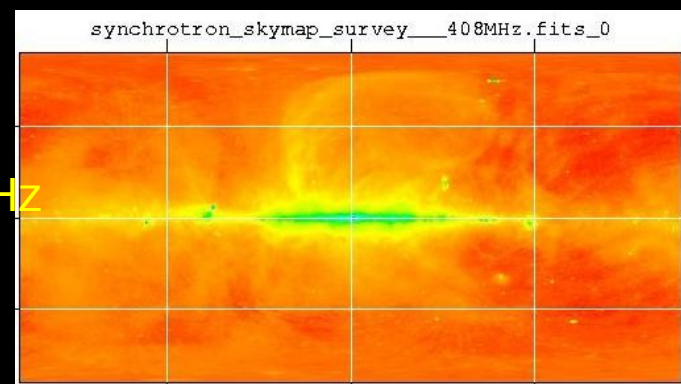
150 MHz



23 GHz

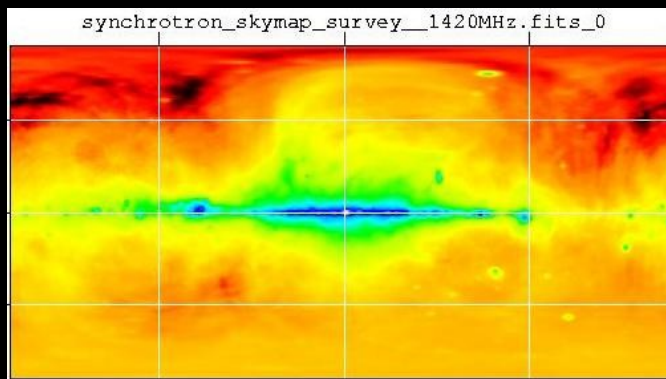
Continuum  
sky surveys

408 MHz

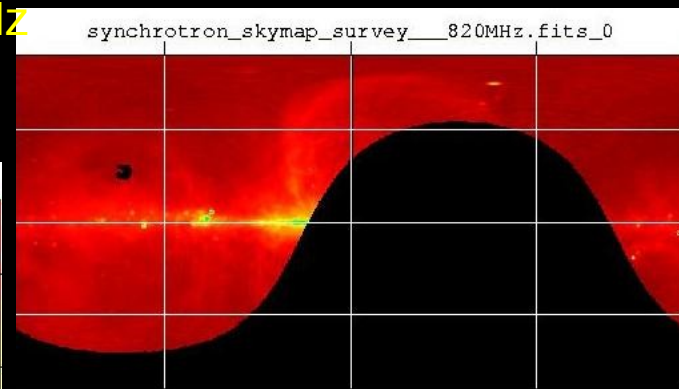


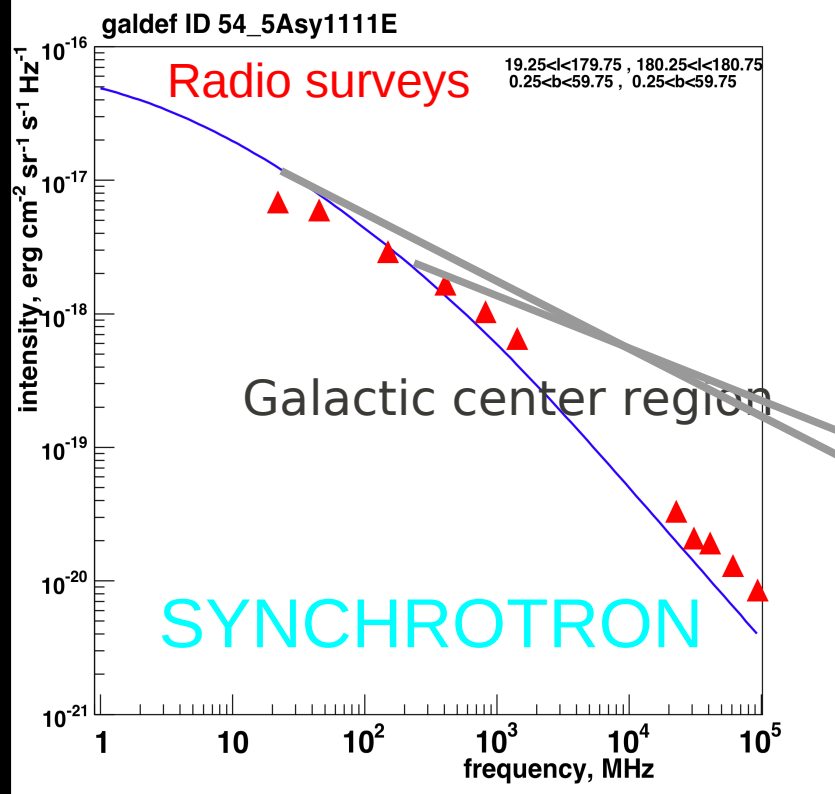
2.3 GHz

1.4 GHz

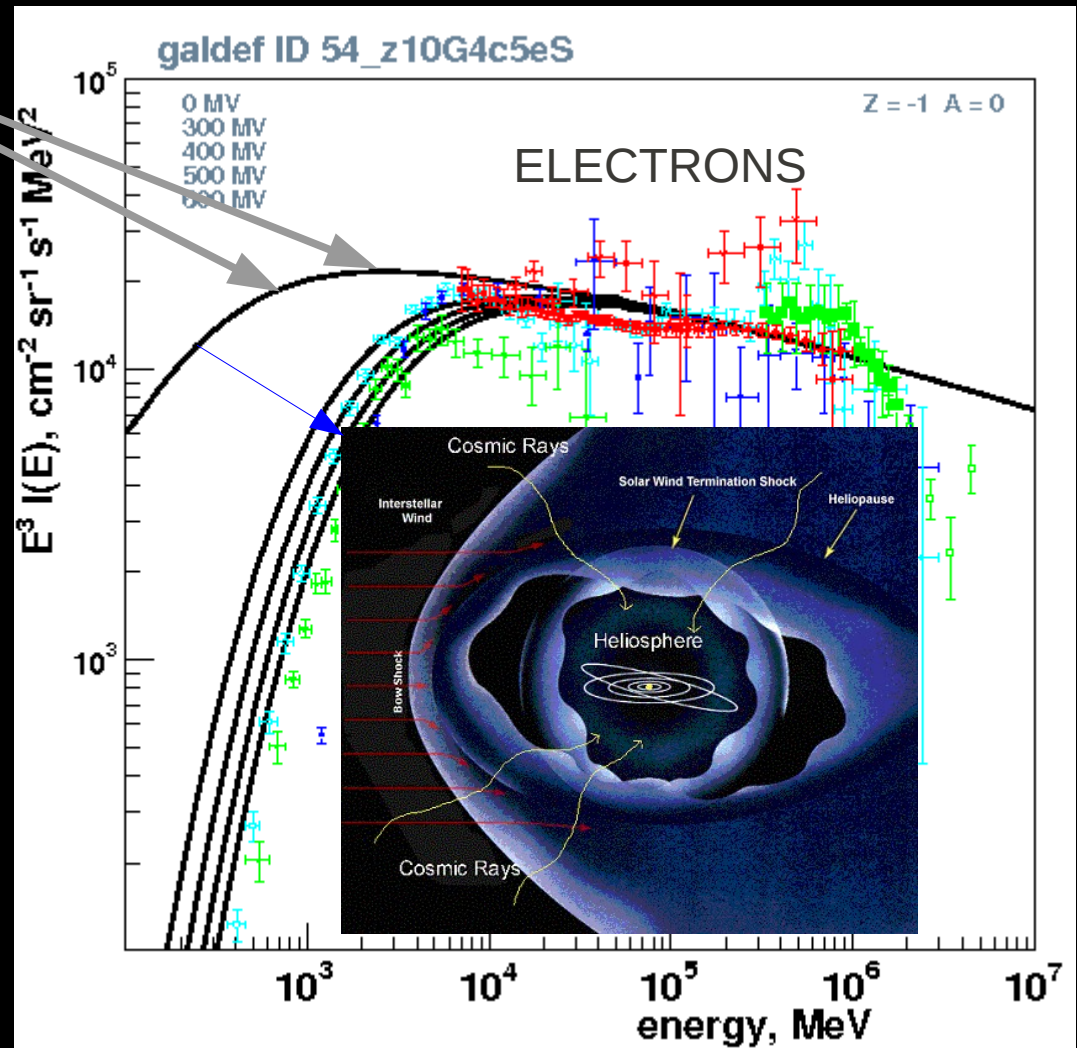


820 MHz



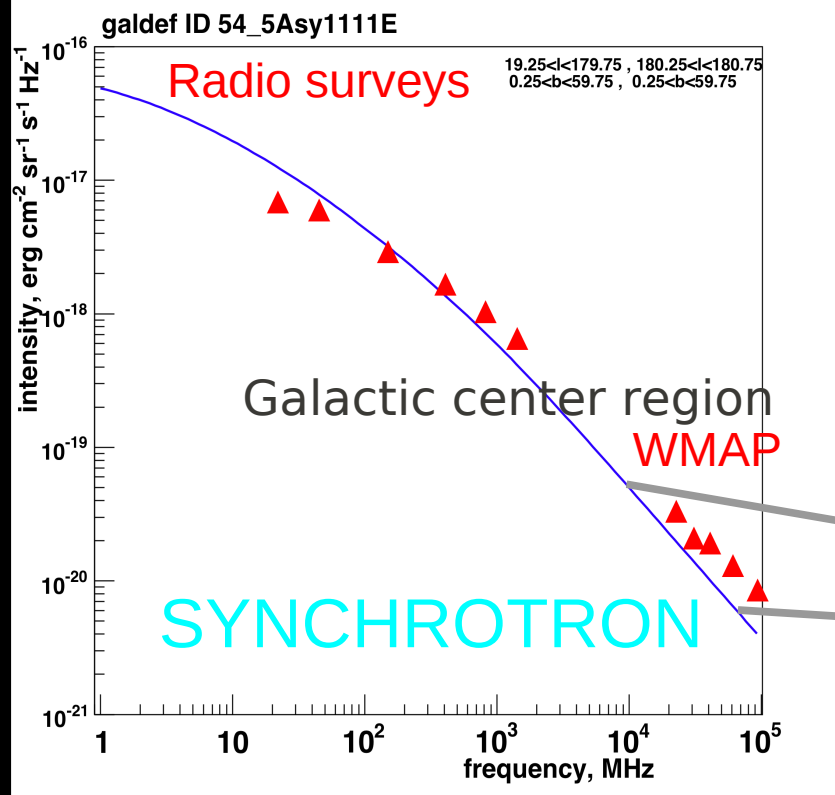


GALPROP  
model



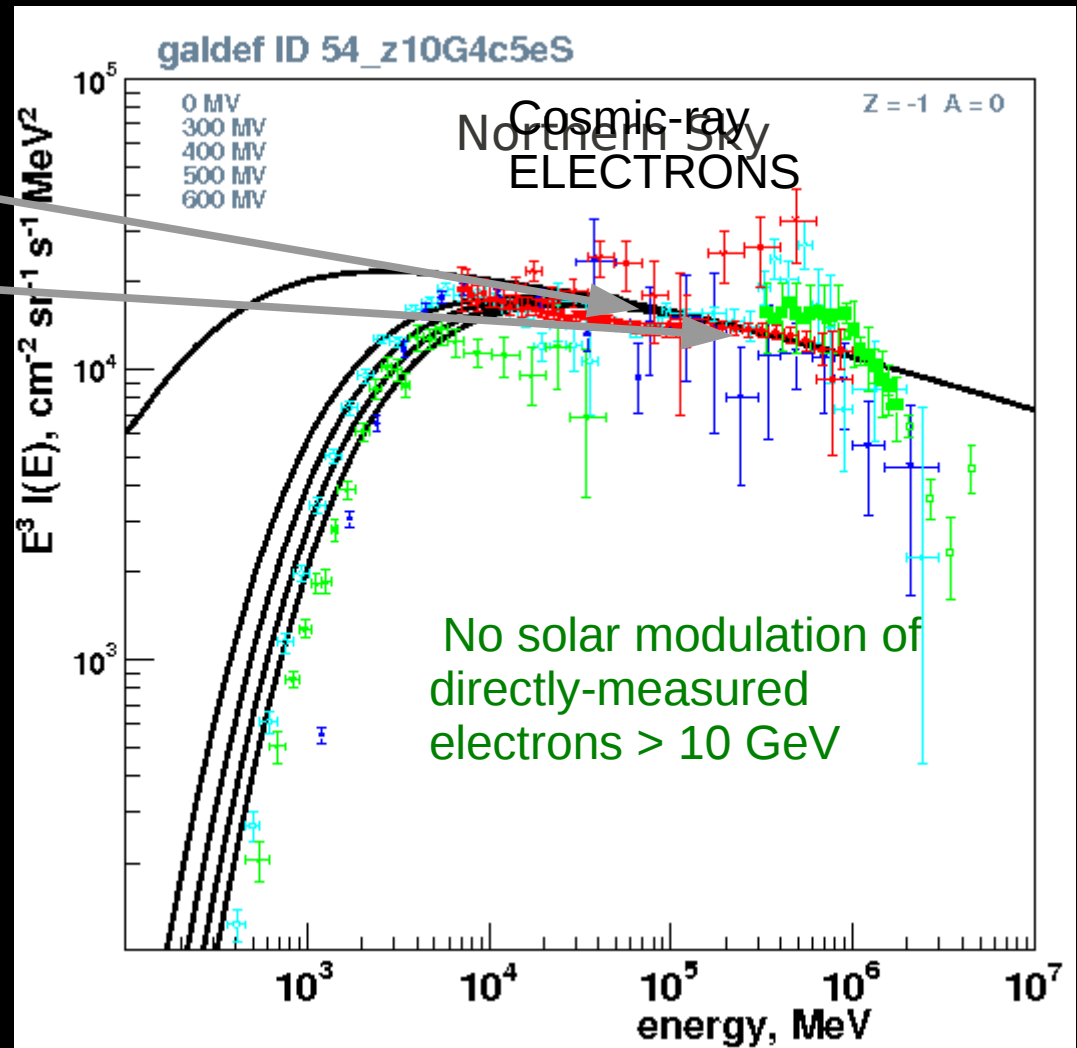
radio provides essential probe of  
interstellar electron spectrum at  
 $E < \text{few GeV}$   
to complement direct measurements  
and determine solar modulation

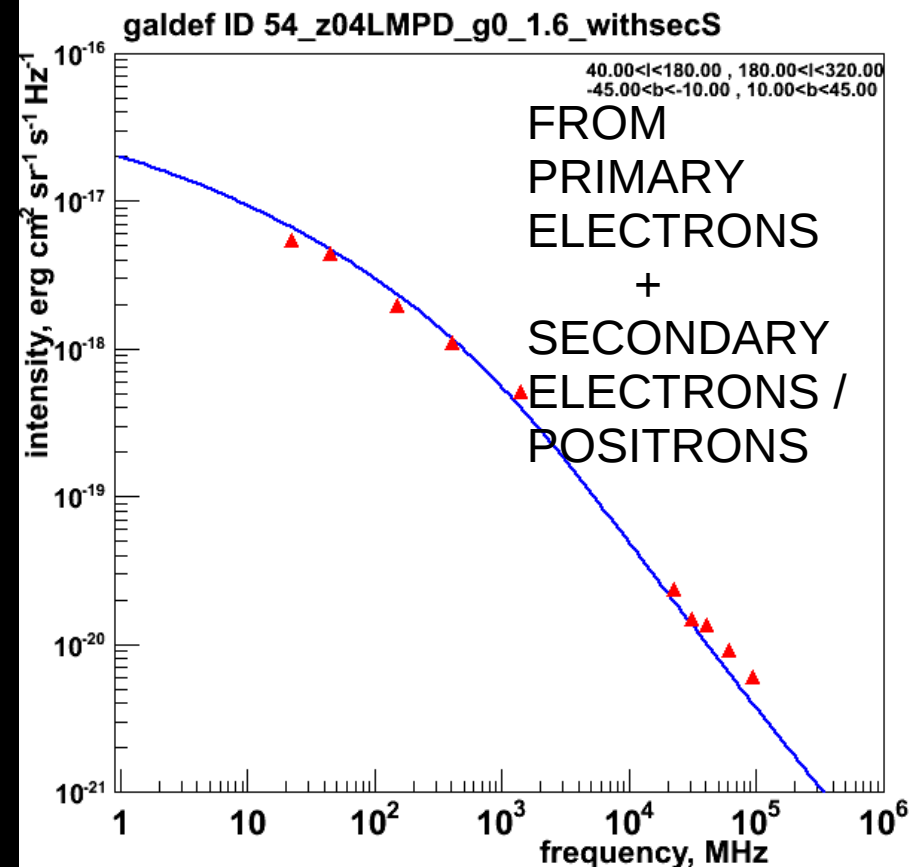
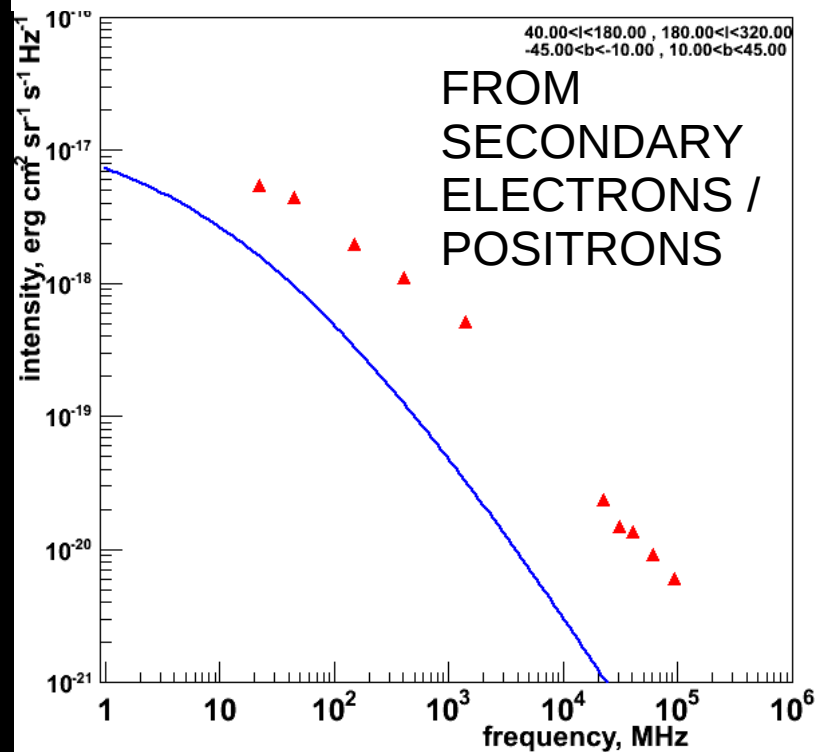
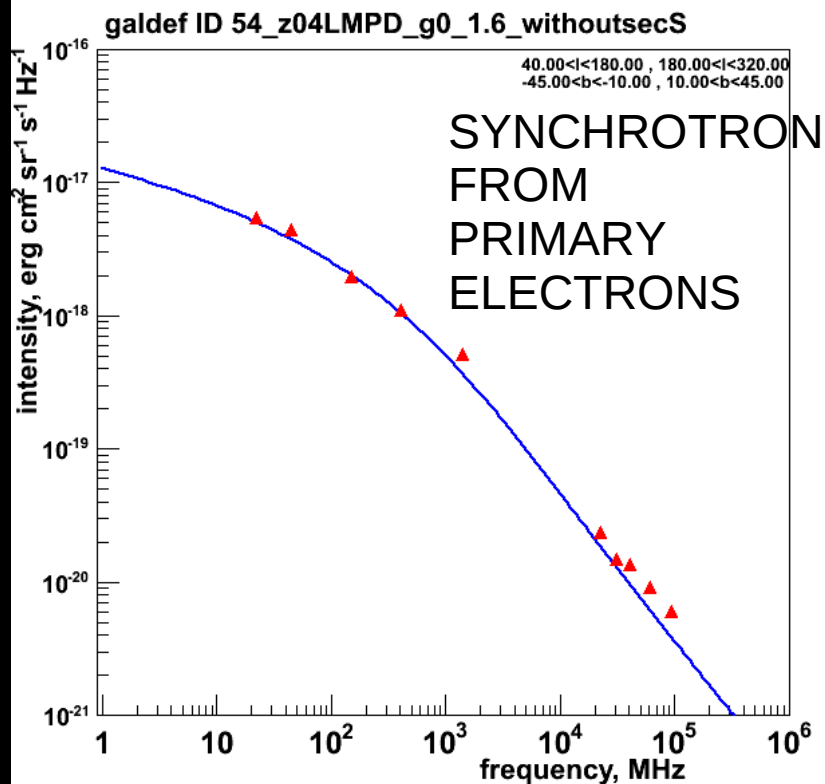
electrons have huge uncertainty  
due to modulation here



GALPROP  
model

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

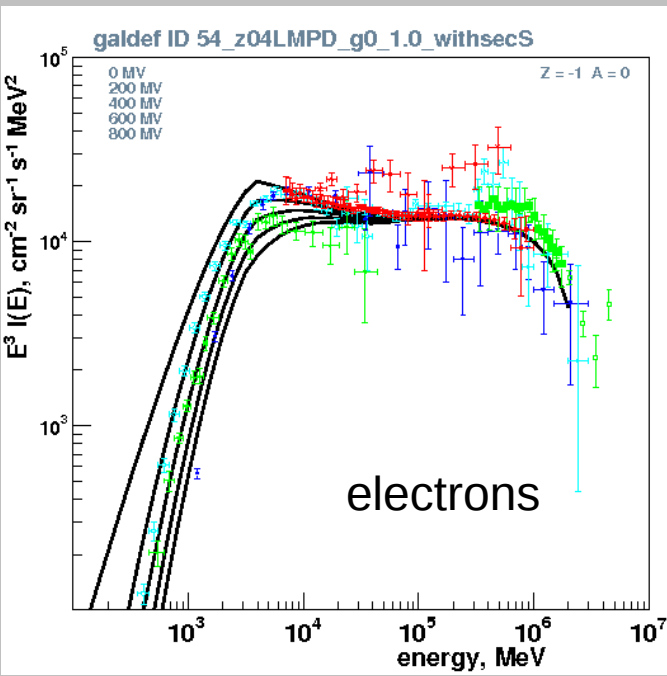




*Secondary positrons  
(and secondary electrons)  
are important for synchrotron*

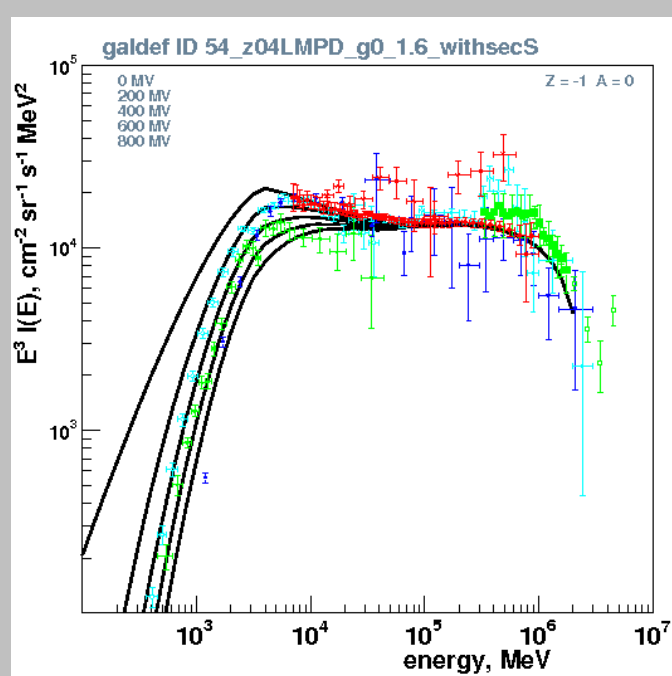
# Electron injection index

-1.0



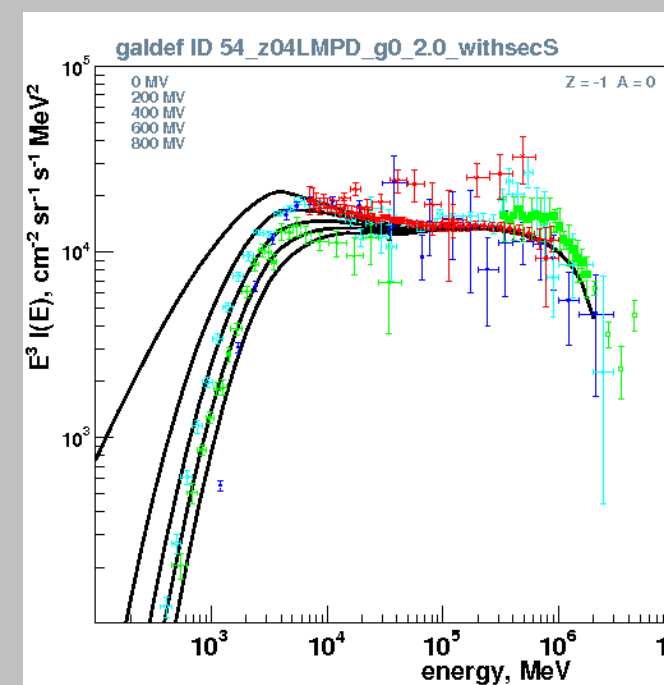
OK

-1.6

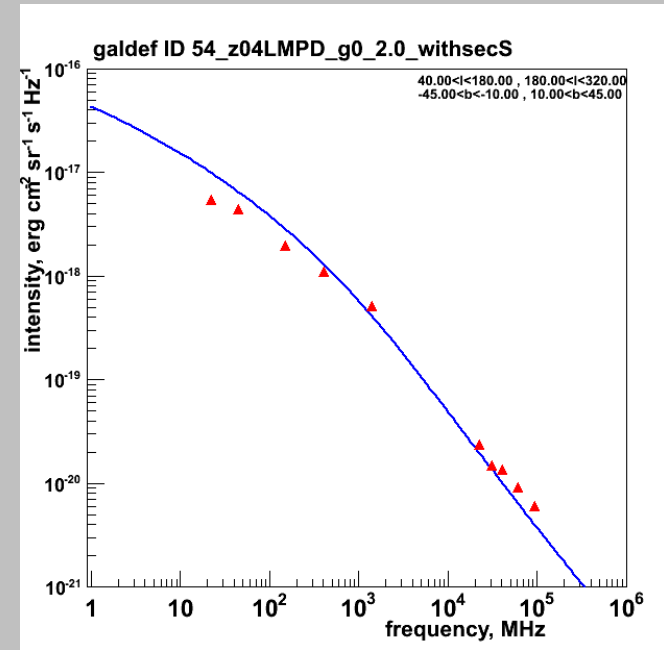
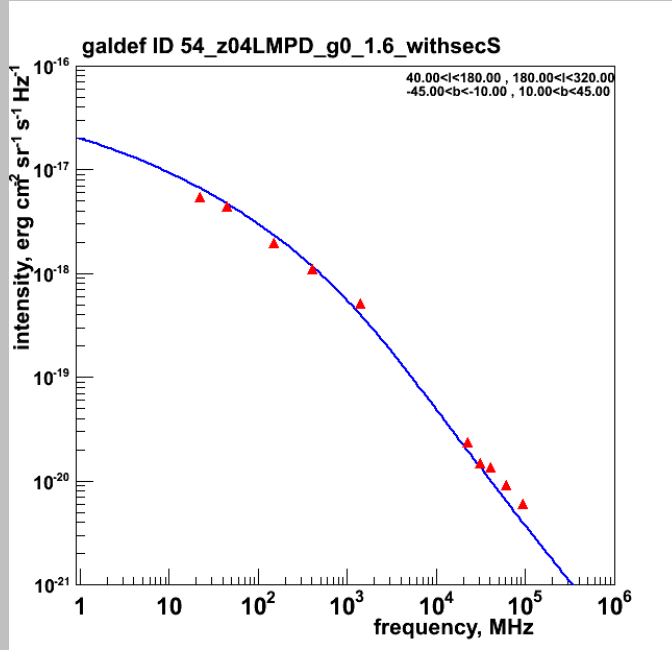
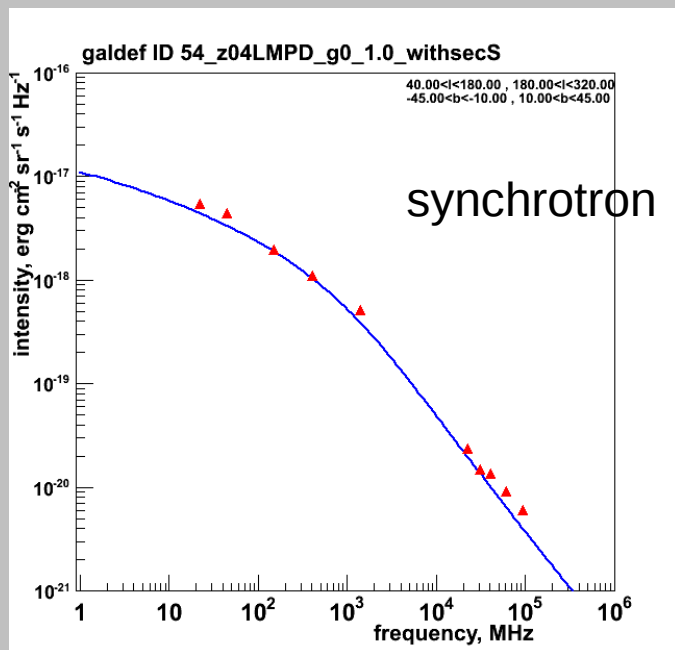


OK

-2.0

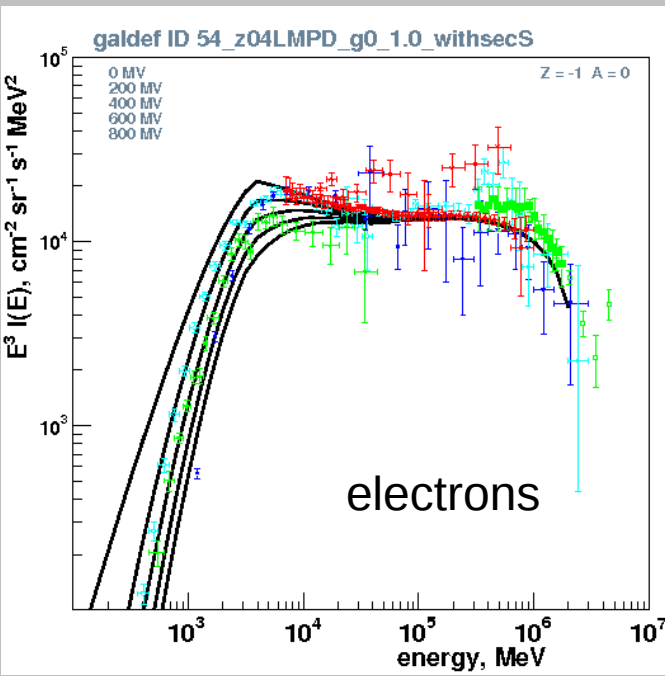


excluded by synchrotron !



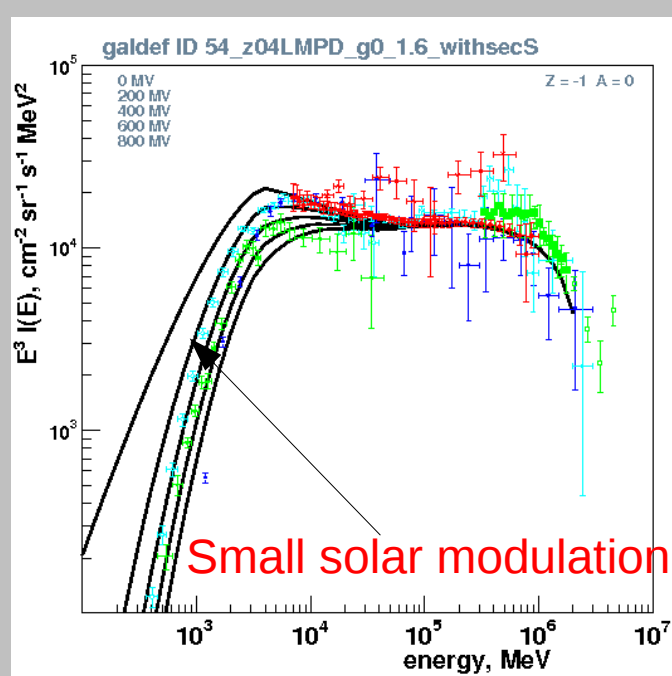
# Electron injection index

-1.0



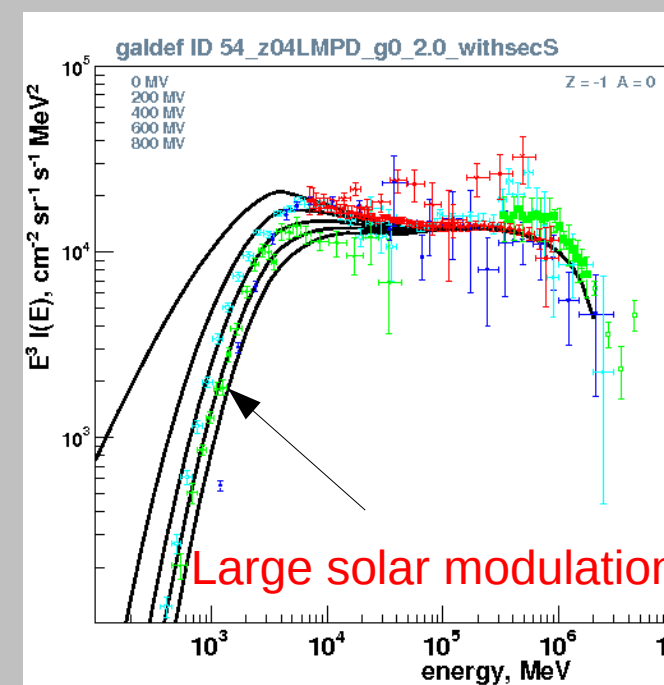
OK

-1.6

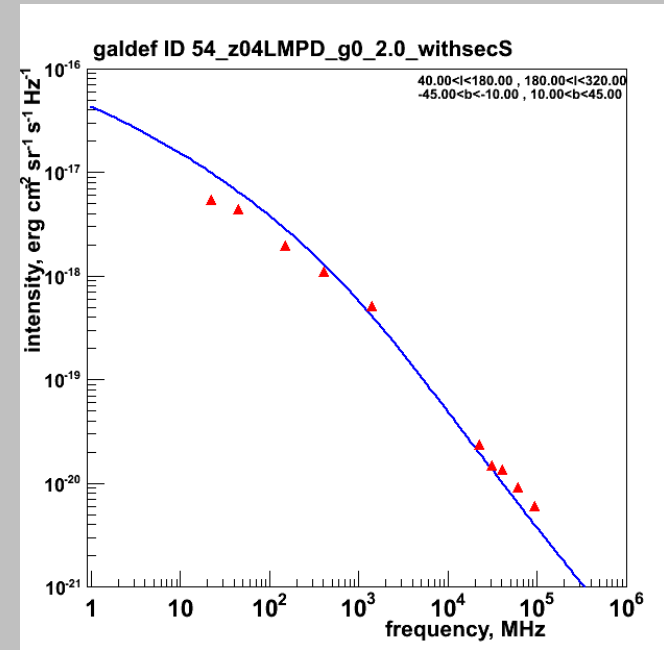
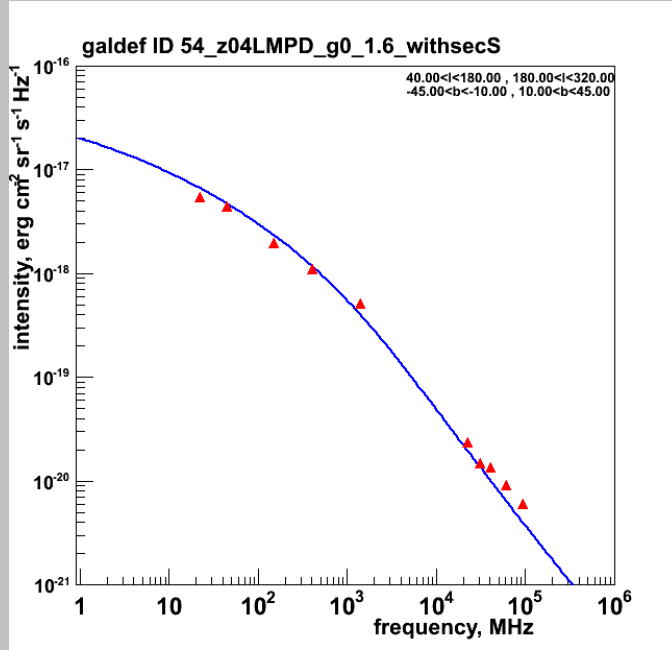
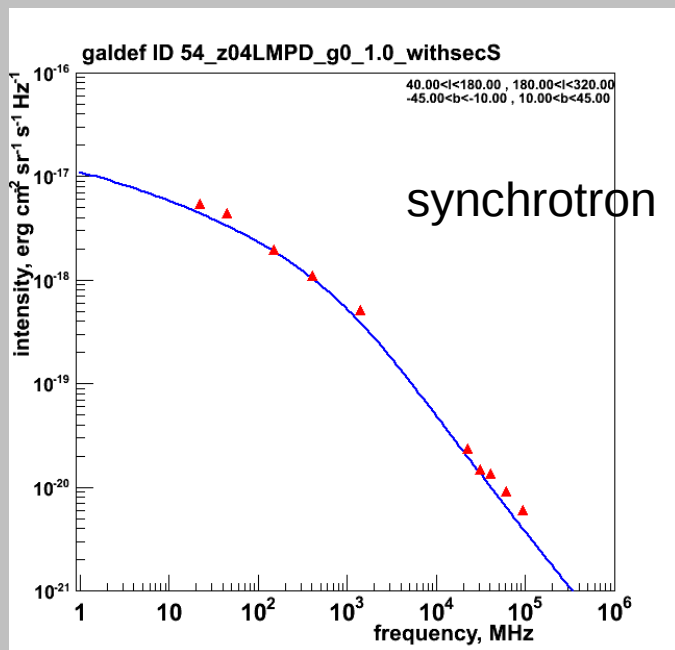


OK

-2.0

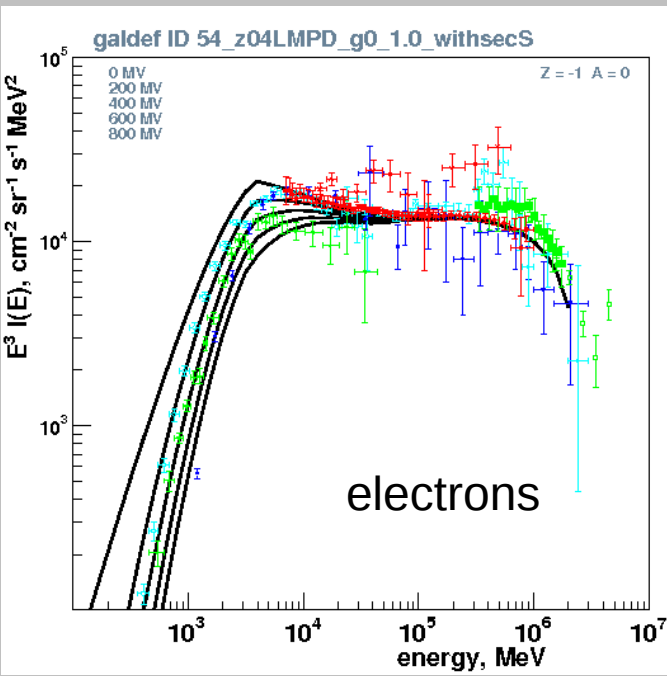


excluded by synchrotron !



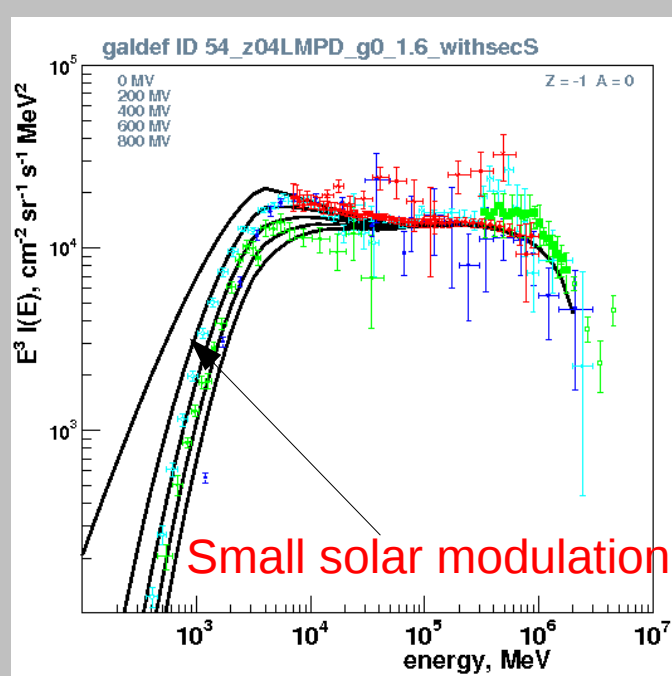
# Electron injection index

-1.0



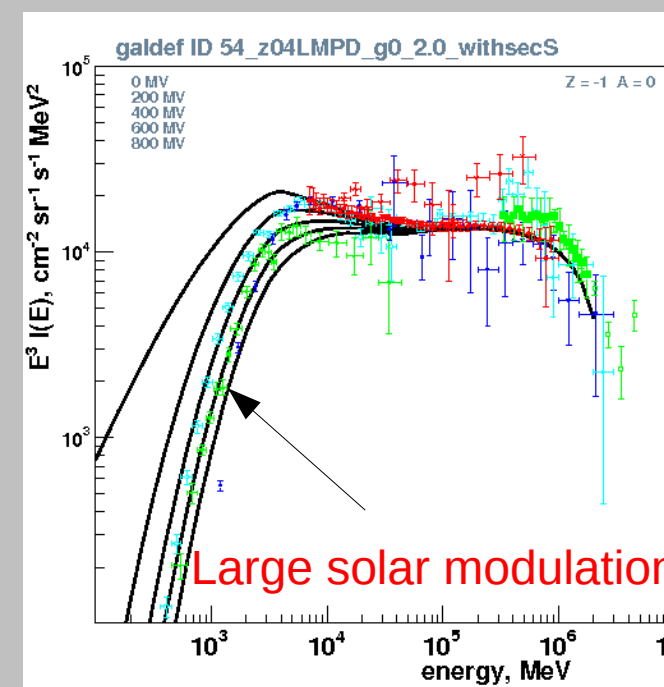
OK

-1.6

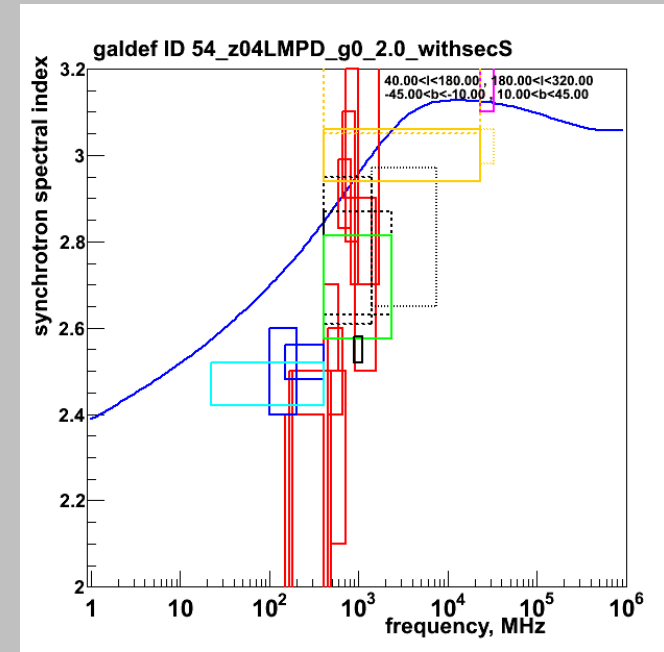
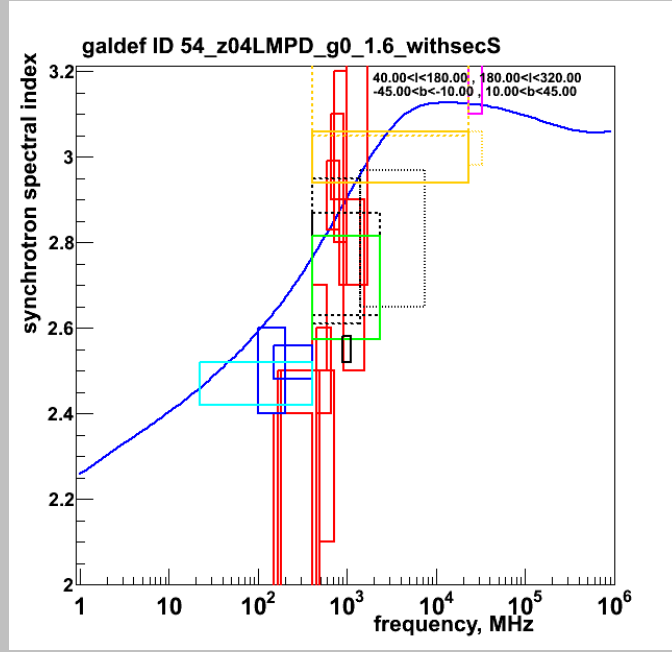
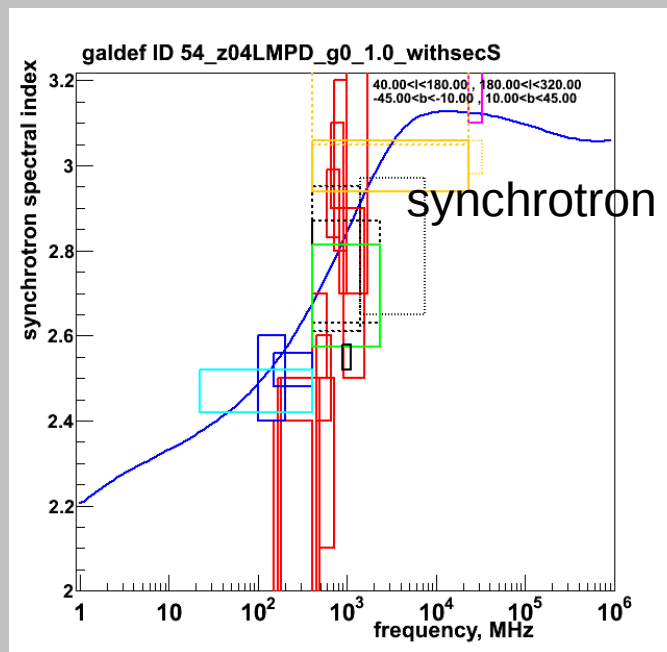


OK

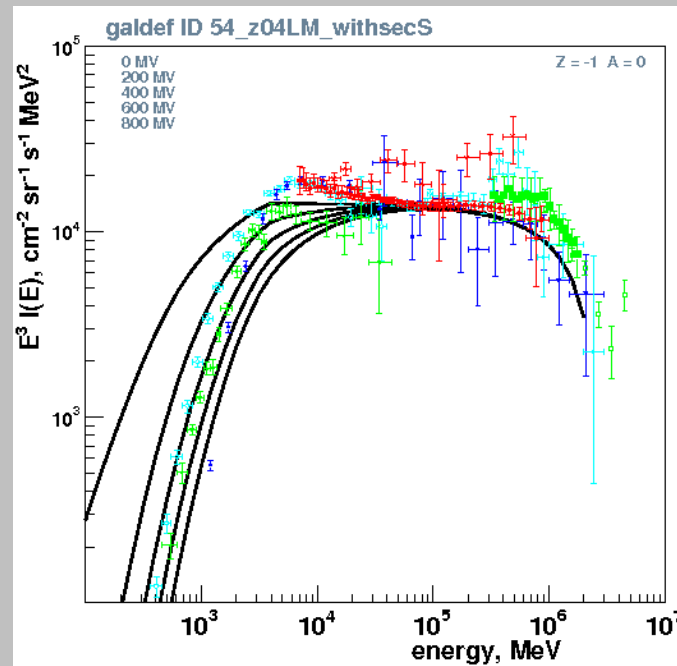
-2.0



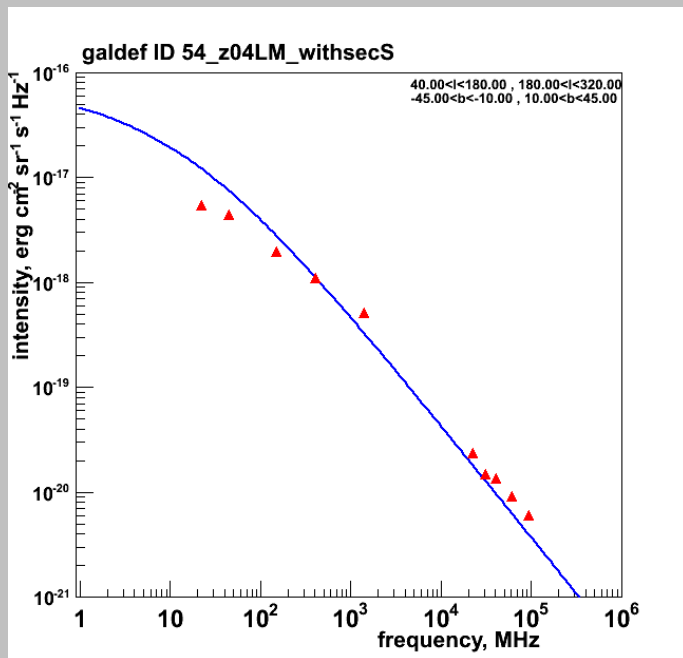
excluded by synchrotron !



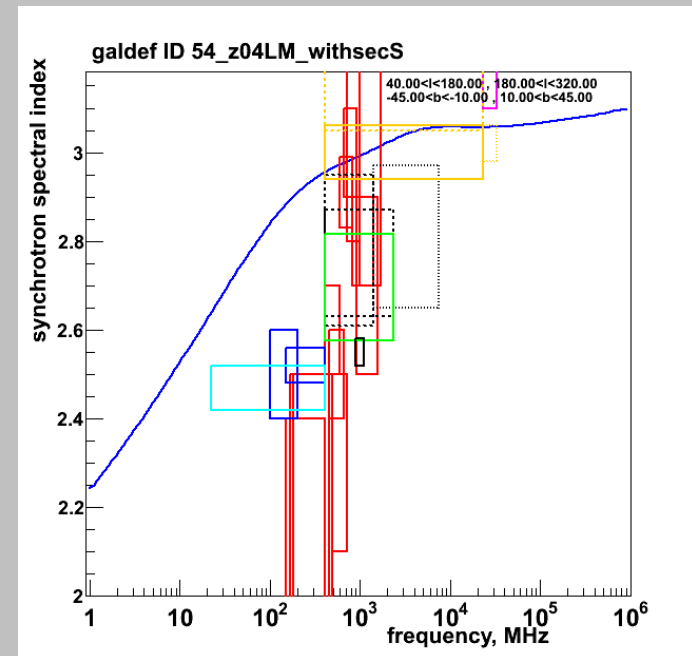
# Reacceleration model – in trouble with synchrotron



ELECTRONS



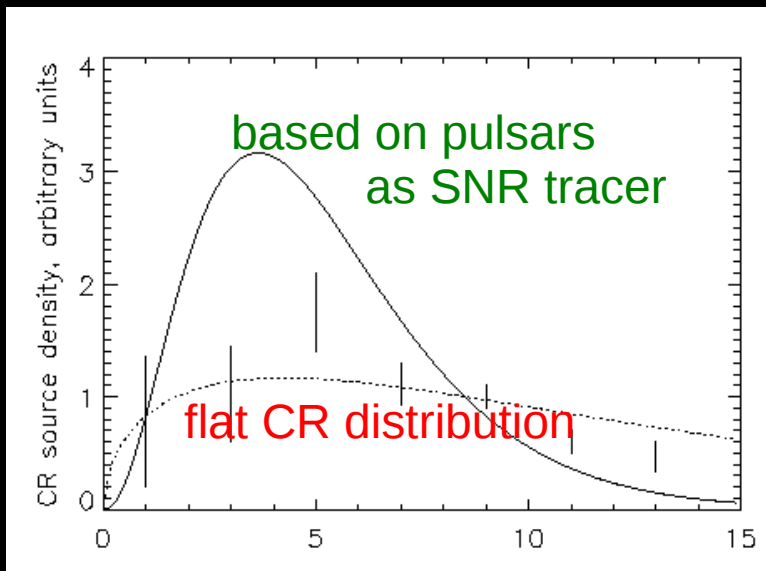
SYNCHROTRON



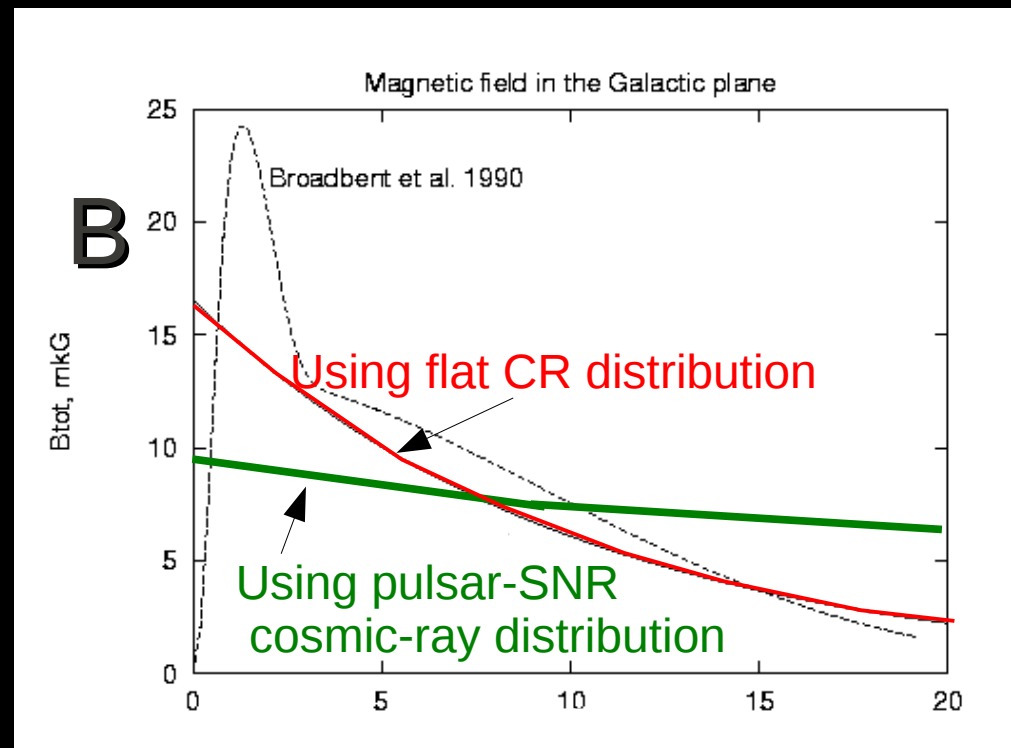
*from synchrotron and cosmic-ray propagation model :*

$$B_{\text{tot}} (\mu\text{G}) = 7 e^{- (R - R_0) / 30 \text{ kpc} - |z| / 4 \text{ kpc}}$$

**cosmic-ray source distribution**



$R$ , kpc



$R$ , kpc

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

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

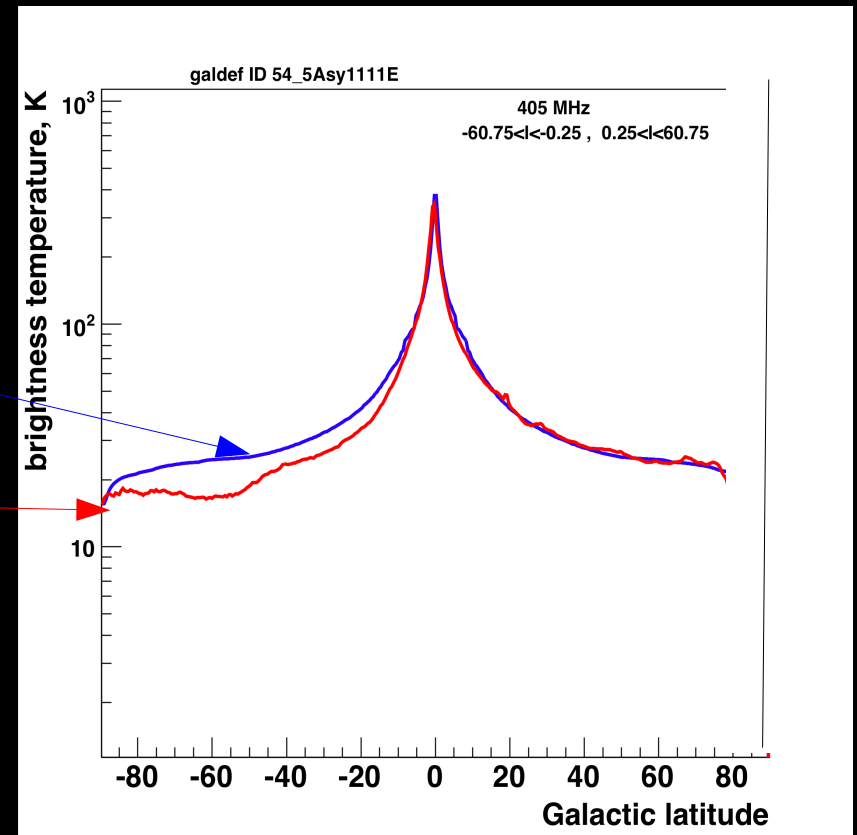
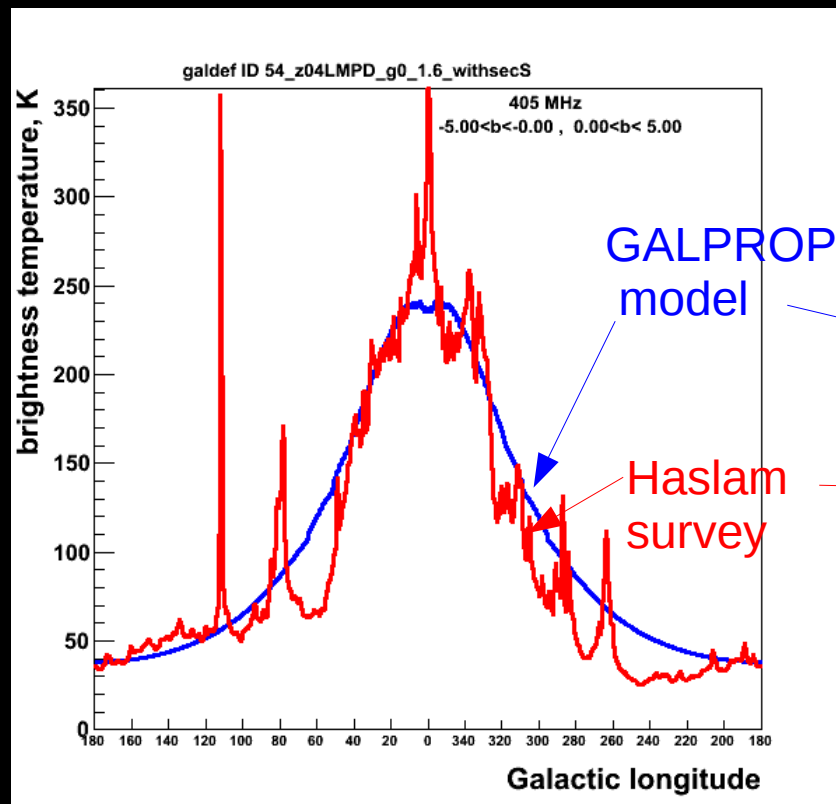
Relevant to Planck !

# SYNCHROTRON

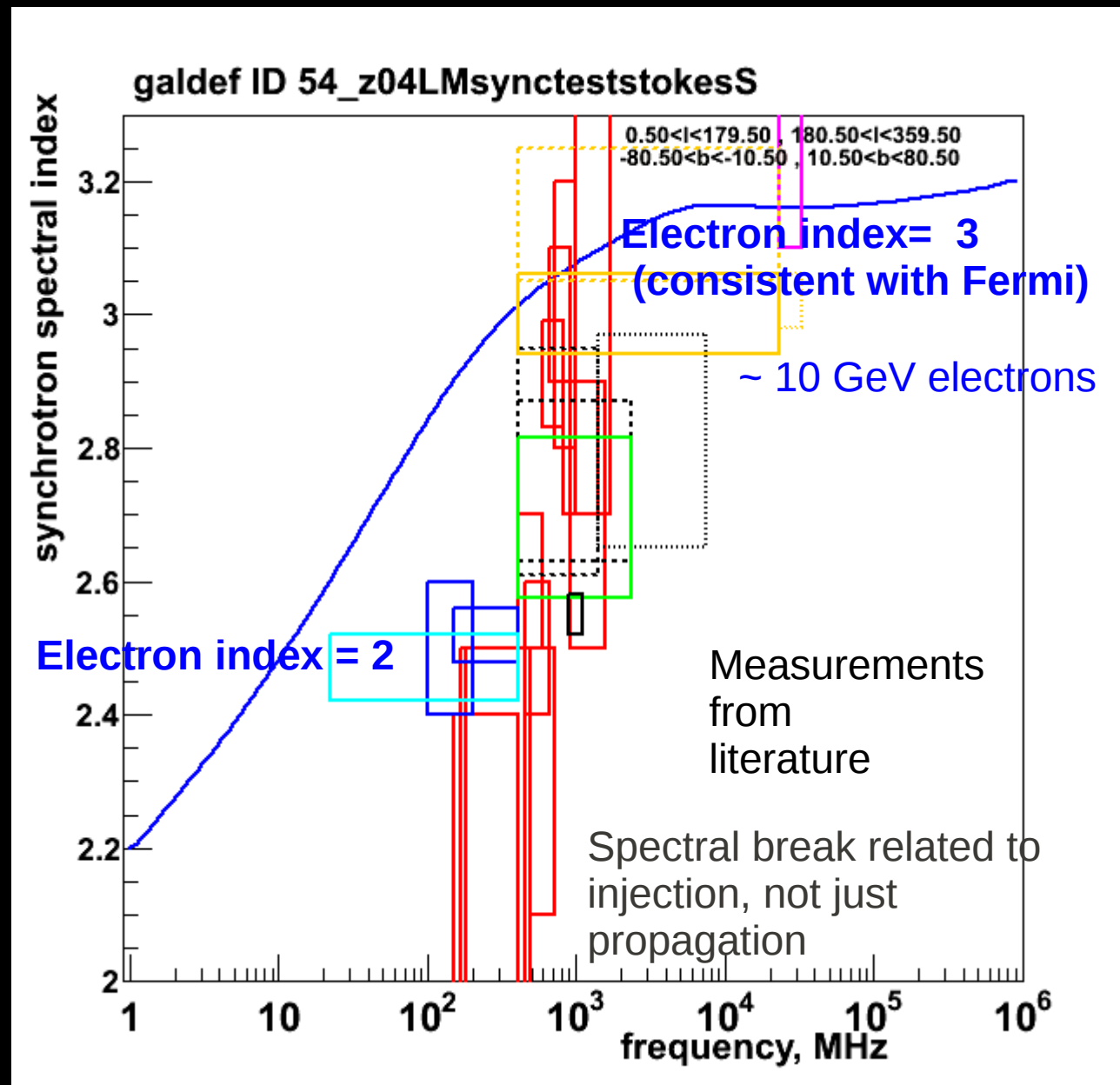
$|b| < 5^\circ$

408 MHz

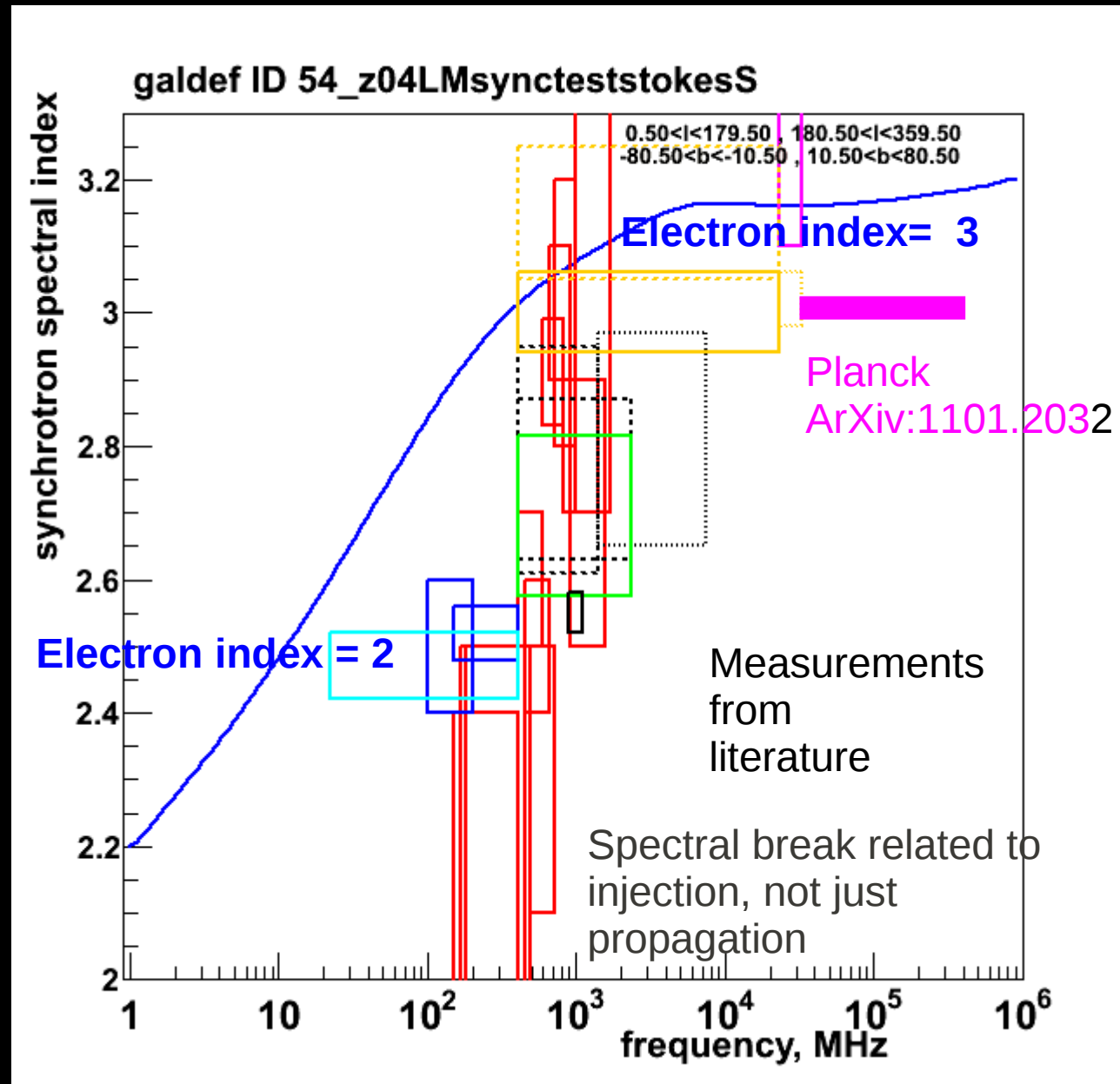
$|l| < 60^\circ$



# Synchrotron Spectral index vs frequency

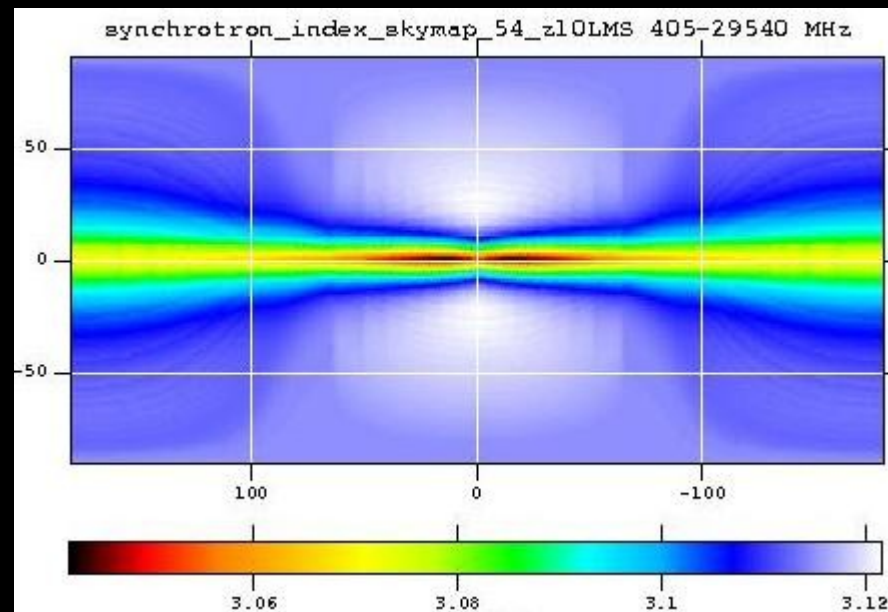


# Synchrotron Spectral index vs frequency



## Model Synchrotron spectral index

408 MHz – 23 GHz



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 <sup>1,2\*</sup>, A. J. Banday <sup>1,2,3†</sup>, J. P. Leahy <sup>4‡</sup>, S. Leach <sup>5,6§</sup>, A. W. Strong <sup>7¶</sup>

<sup>1</sup> Université de Toulouse; UPS-OMP; IRAP; Toulouse, France

<sup>2</sup> CNRS; IRAP; 9 Av. colonel Roche, BP 44346, F-31028 Toulouse cedex 4, France

<sup>3</sup> Max Planck Institute for Astrophysics, Karl-Schwarzschild Str. 1, D-85741 Garching, Germany

<sup>4</sup> Jodrell Bank Centre for Astrophysics, School of Physics and Astronomy, The University of Manchester, Oxford Road, Manchester, M13 9PL, United Kingdom

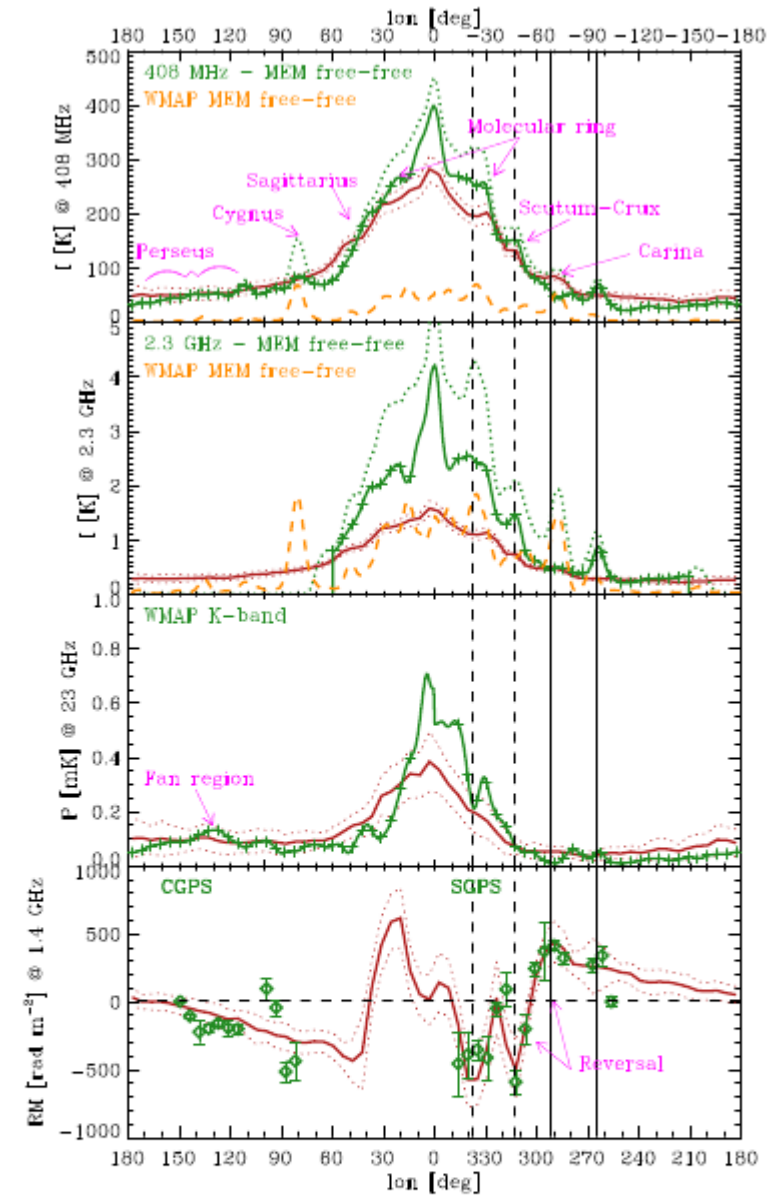
<sup>5</sup> SISSA, Astrophysics Sector, via Beirut 2-4, I-34014 Trieste, Italy.

<sup>6</sup> INFN, Sezione di Trieste, I-34014 Trieste, Italy.

<sup>7</sup> Max-Planck-Institut für Extraterrestrische Physik, Postfach 1312, D-85741 Garching, Germany

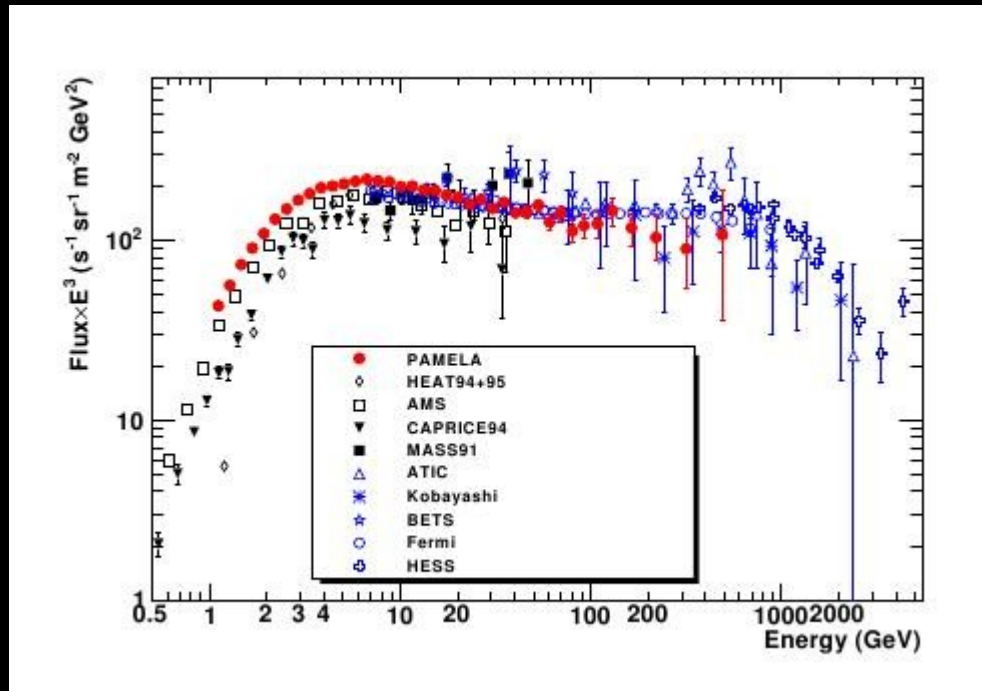
MNRAS, in press  
arXiv:1105.5885

Uses RM, polarization, MCMC.  
Cosmic-ray electrons using GALPROP.



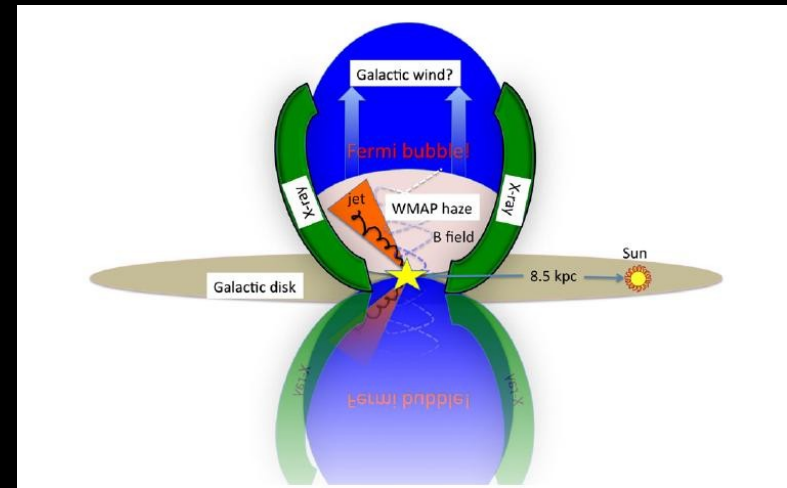
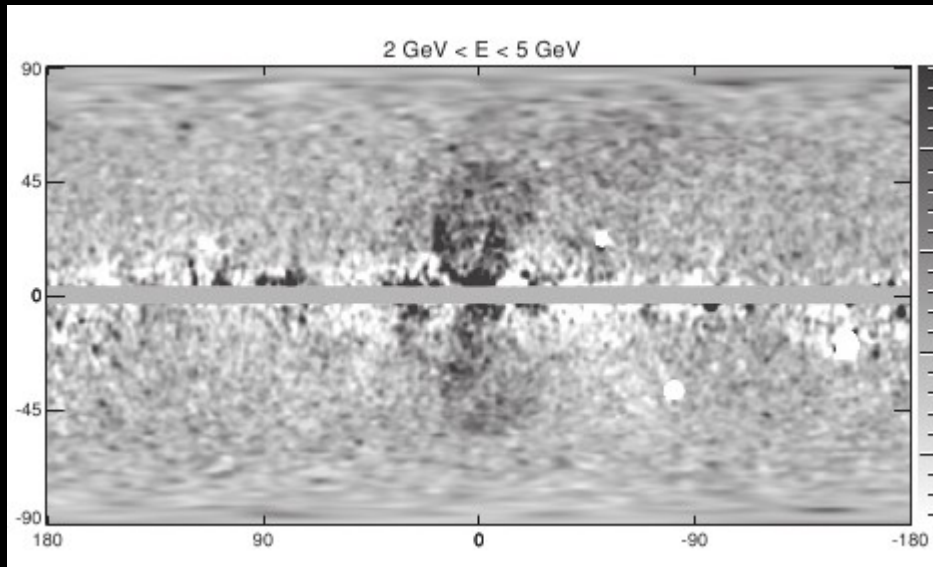
**Figure 1.** The available observables (green) tracing the Galactic magnetic field. The over-plotted model (red) is the original model from Paper I, while the data have been updated somewhat. See text in § 2. Furthermore, we have added the 2.3 GHz frequency which clearly shows that the power-law CRE 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, shown in dashed orange, is subtracted. See § 2.3.)

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



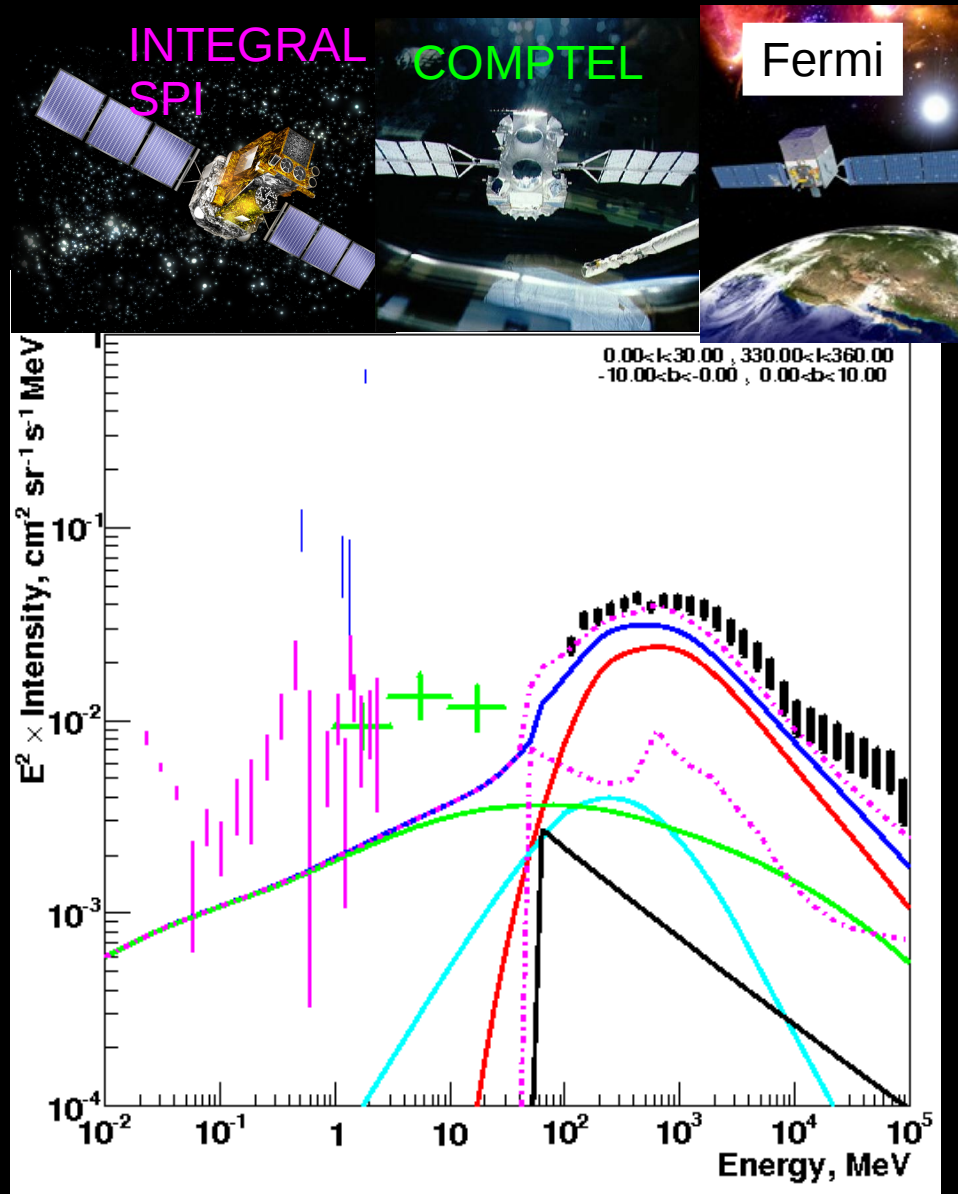
Down to 1 GeV ( c.f. Fermi  $> 7$  GeV)  
Consistent, a bit higher than Fermi at low energies  
Slightly steeper, as expected since Fermi includes positrons

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

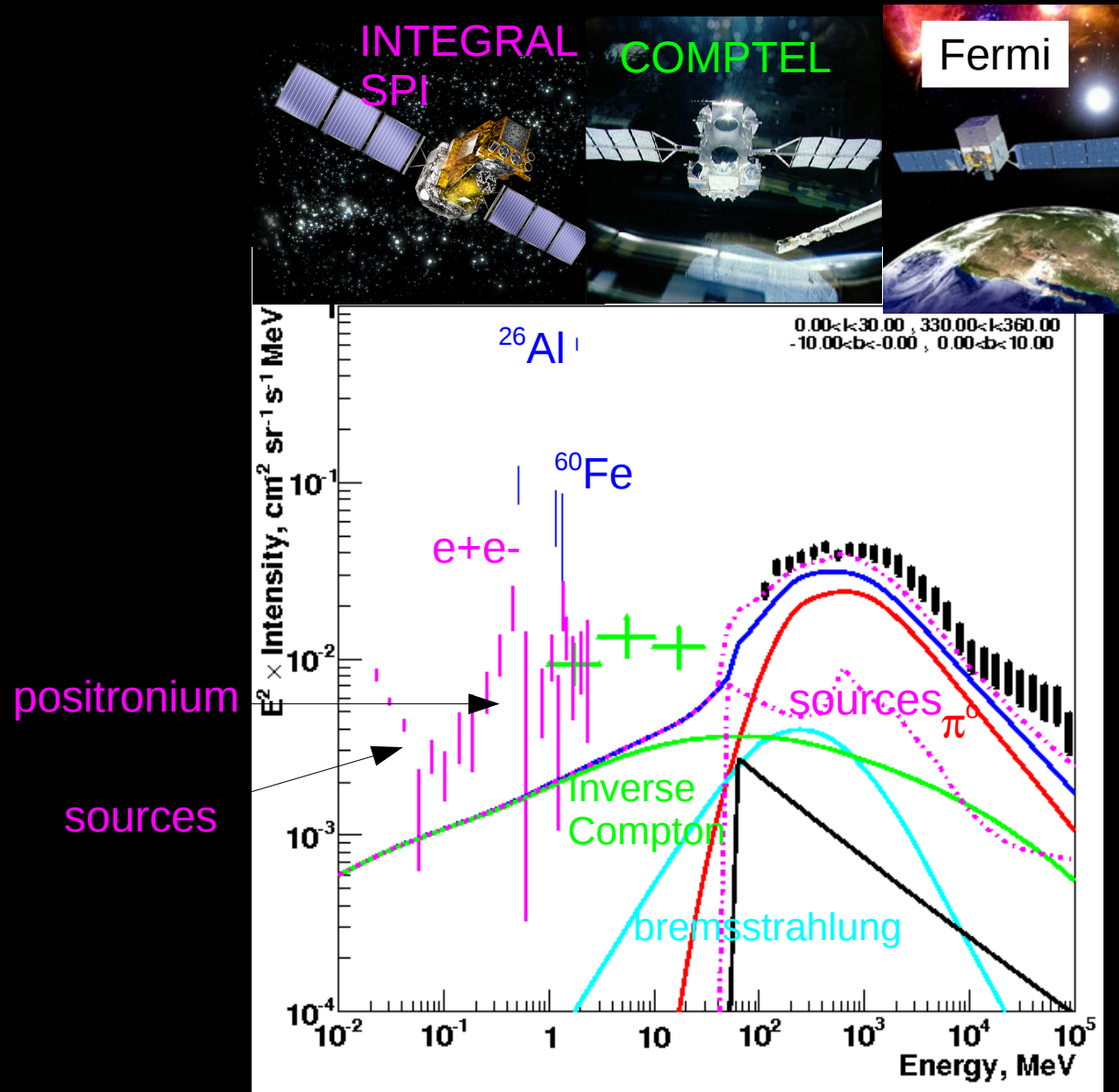
MENG SU<sup>1</sup>, TRACY R. SLATYER<sup>1,2</sup>, AND DOUGLAS P. FINKBEINER<sup>1,2</sup>

Details depend on foreground model used (features ~ 10% of total intensity) !  
Presumably inverse Compton – electrons  $\rightarrow$  radio  $\rightarrow$  relevant to Planck

# Inner Galaxy: keV to TeV



# Inner Galaxy: keV to TeV



GeV electrons – inverse Compton - important for MeV gamma rays !

# AN ALIEN'S VIEW OF THE GALAXY

A. W. STRONG<sup>1</sup>, T. A. PORTER<sup>2</sup>, S. W. DIGEL<sup>3,4</sup>, G. JÓHANNESSON<sup>2</sup>, P. MARTIN<sup>1</sup>, I. V. MOSKALENKO<sup>2,4</sup>, E. J. MURPHY<sup>5</sup>,  
AND E. ORLANDO<sup>1</sup>

<sup>1</sup> Max-Planck-Institut für extraterrestrische Physik, Postfach 1312, D-85741 Garching, Germany; [aws@mpe.mpg.de](mailto:aws@mpe.mpg.de)

<sup>2</sup> Hansen Experimental Physics Laboratory, Stanford University, Stanford, CA 94305, USA; [tporter@stanford.edu](mailto:tporter@stanford.edu)

<sup>3</sup> SLAC National Accelerator Laboratory, 2575 Sand Hill Road, Menlo Park, CA 94025, USA; [digel@slac.stanford.edu](mailto:digel@slac.stanford.edu)

<sup>4</sup> Kavli Institute for Particle Astrophysics and Cosmology, Stanford University, Stanford, CA 94305, USA

<sup>5</sup> Spitzer Science Center, California Institute of Technology, Pasadena, CA 91125, USA; [emurphy@ipac.caltech.edu](mailto:emurphy@ipac.caltech.edu)

*Received 2010 June 14; accepted 2010 August 24; published 2010 September 20*

## ABSTRACT

We use the GALPROP code for cosmic-ray (CR) propagation to calculate the broadband luminosity spectrum of the Milky Way related to CR propagation and interactions in the interstellar medium. This includes  $\gamma$ -ray emission from the production and subsequent decay of neutral pions ( $\pi^0$ ), bremsstrahlung, and inverse Compton scattering, and synchrotron radiation. The Galaxy is found to be nearly a CR electron calorimeter, but only if  $\gamma$ -ray emitting processes are taken into account. Synchrotron radiation alone accounts for only one-third of the total electron energy losses with  $\sim 10\%$ – $20\%$  of the total synchrotron emission from secondary CR electrons and positrons. The relationship between far-infrared and radio luminosity that we find from our models is consistent with that found for galaxies in general. The results will be useful for understanding the connection between diffuse emissions from radio through  $\gamma$ -rays in “normal” (non-active galactic nucleus dominated) galaxies as well as for estimating the broadband extragalactic diffuse background from these kinds of galaxies.

# GLOBAL COSMIC-RAY-RELATED LUMINOSITY AND ENERGY BUDGET OF THE MILKY WAY

A. W. STRONG<sup>1</sup>, T. A. PORTER<sup>2</sup>, S. W. DIGEL<sup>3,4</sup>, G. JÓHANNESSON<sup>2</sup>, P. MARTIN<sup>1</sup>, I. V. MOSKALENKO<sup>2,4</sup>, E. J. MURPHY<sup>5</sup>,  
AND E. ORLANDO<sup>1</sup>

<sup>1</sup> Max-Planck-Institut für extraterrestrische Physik, Postfach 1312, D-85741 Garching, Germany; [aws@mpe.mpg.de](mailto:aws@mpe.mpg.de)

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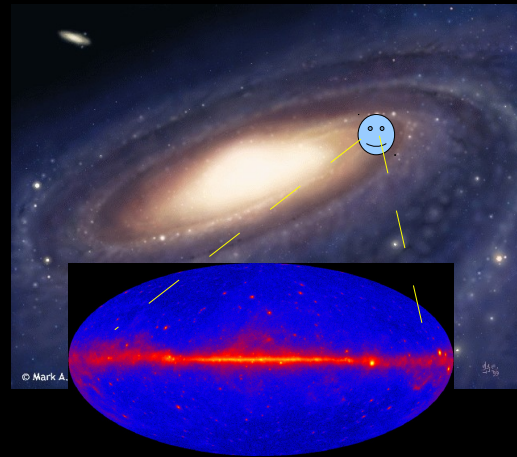
<sup>5</sup> Spitzer Science Center, California Institute of Technology, Pasadena, CA 91125, USA; [emurphy@ipac.caltech.edu](mailto:emurphy@ipac.caltech.edu)

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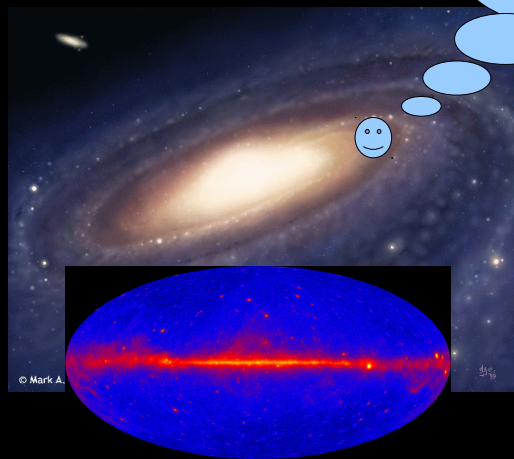
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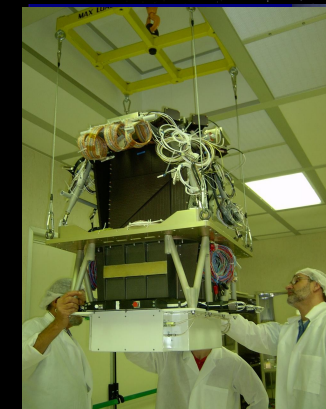
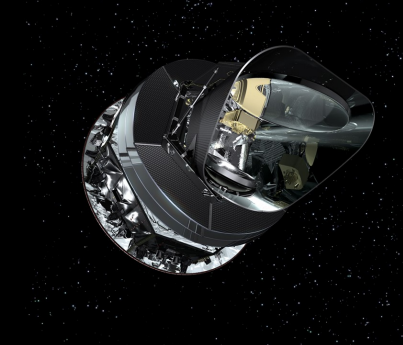
Since we live inside the Galaxy,  
global properties like  
multiwavelength luminosity (SED)  
are not easy to deduce.



what does it  
look from out  
there ?



EXPERIMENTS



THEORY

intergalactic space

HALO

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

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

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

synchrotron

B-field

$\pi^0$

gas

ISRF

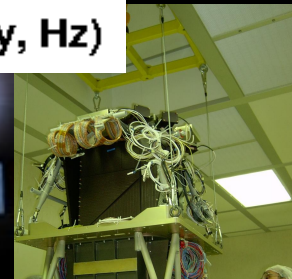
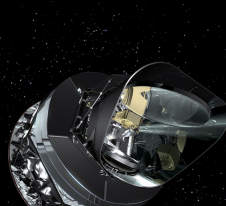
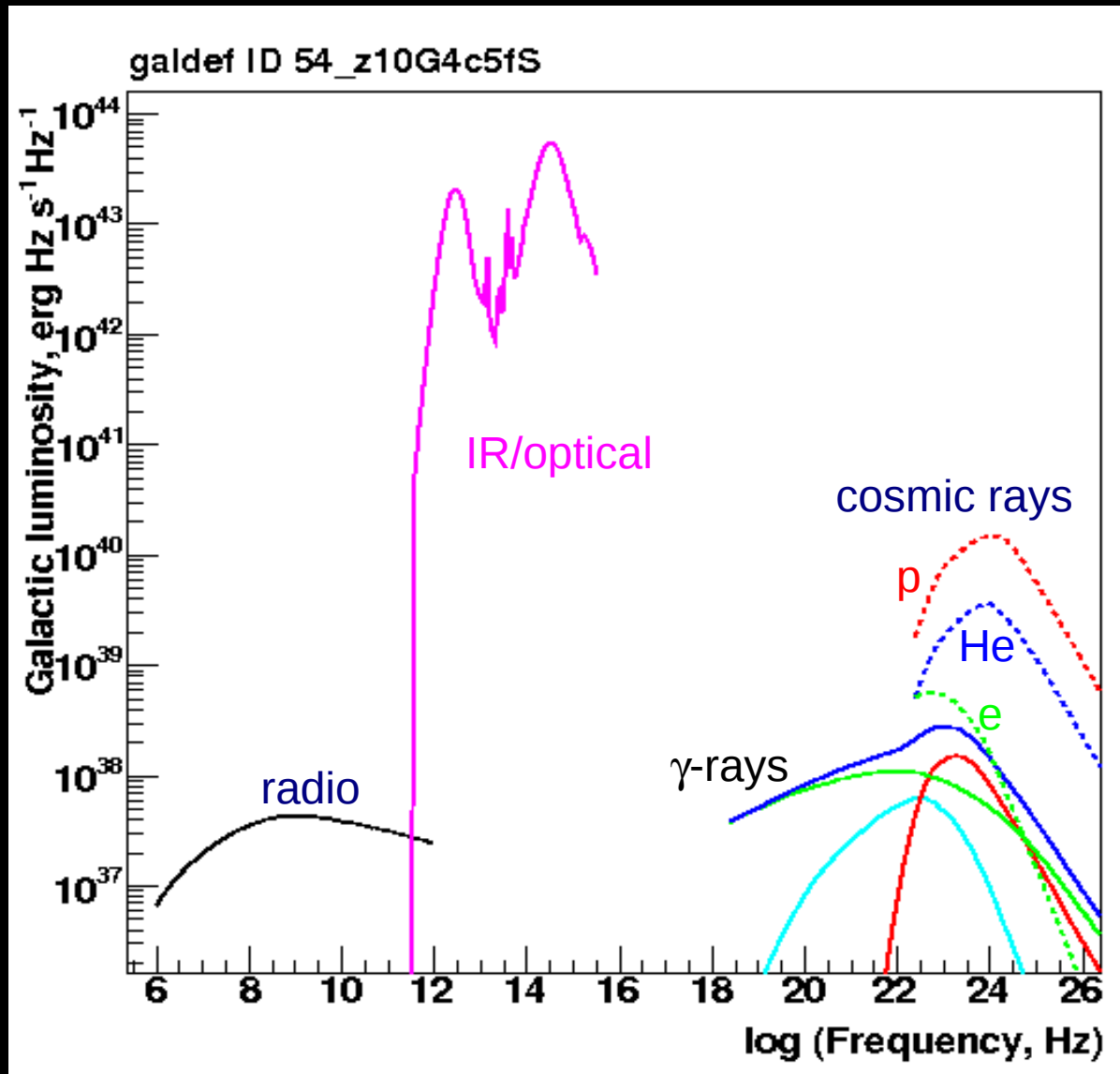
bremsstrahlung

inverse Compton

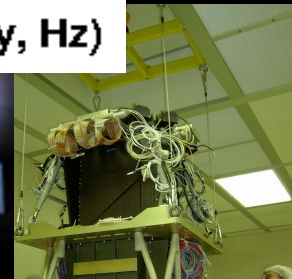
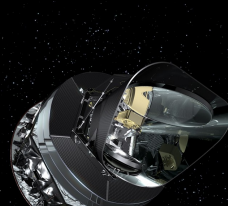
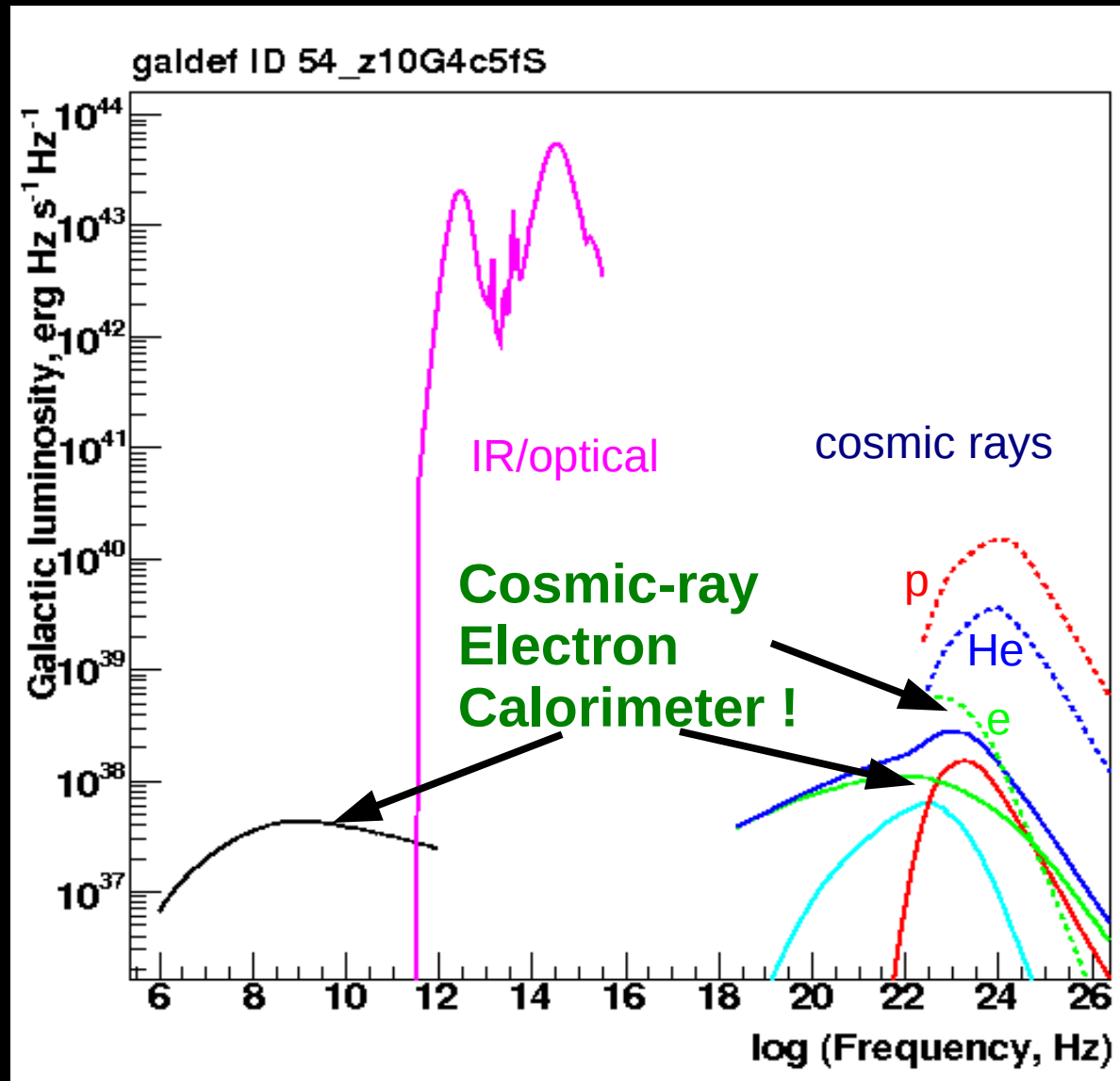
$\gamma$  - rays

GALPROP : models all that !

# Galaxy luminosity over 20 decades of energy



# Galaxy luminosity over 20 decades of energy



# 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

Emerging field:

Cosmic-ray ionization in molecular clouds.

New impetus due to chemistry and observational methods.

$\text{H}_3^+$  : produced only via cosmic-ray ionization (UV absorbed). Observed in IR.

Low-energies: MeV protons and electrons

(not traced by other methods, solar modulation prevents direct measurements)

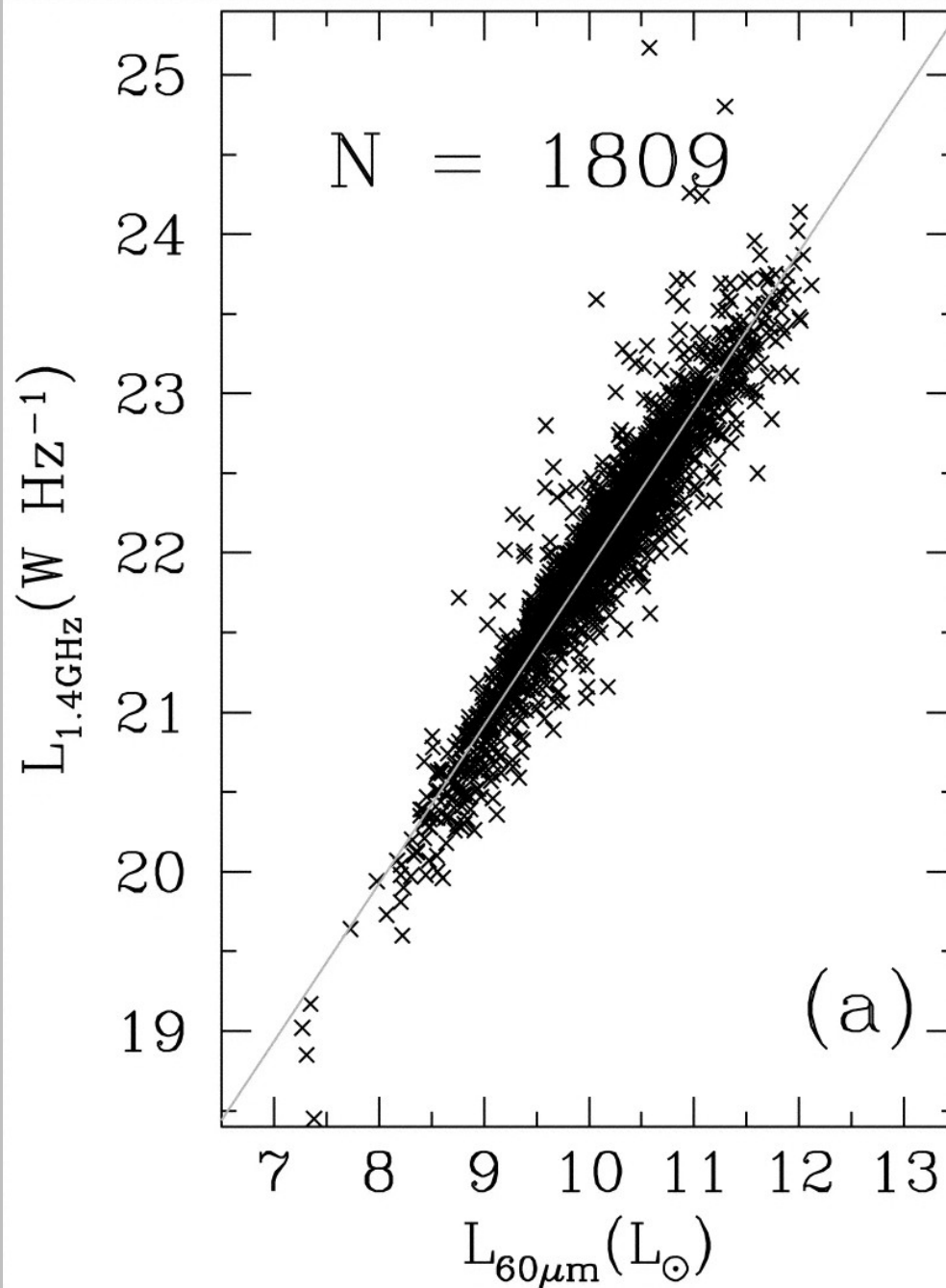
See presentations at this conference:

Cosmic Ray Interactions: Bridging High and Low Energy Astrophysics (March 2011)

[www.lorentzcenter.nl](http://www.lorentzcenter.nl)

Should be added to list of observables in future cosmic-ray studies.

## FIR / radio correlation



**Cosmic ray electron  
Calorimetry**

**Star-formation**

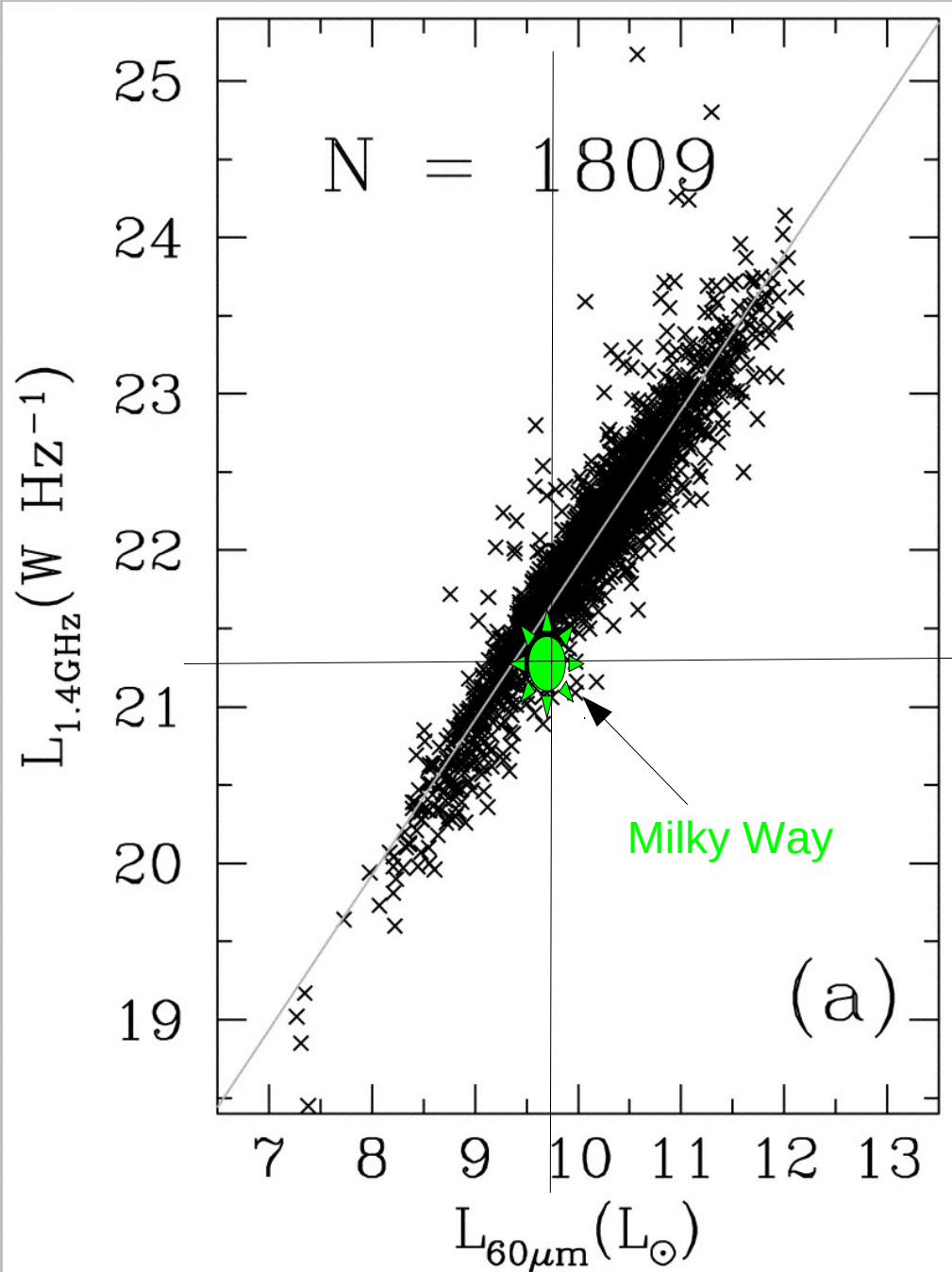
**V**

**Cosmic rays**

**V**

**Synchrotron**

## FIR / radio correlation



**Cosmic ray electron  
Calorimetry**

**Star-formation**

**V**

**Cosmic rays**

**V**

**Synchrotron**

# Nearby galaxies detected by Fermi

Large Magellanic Cloud

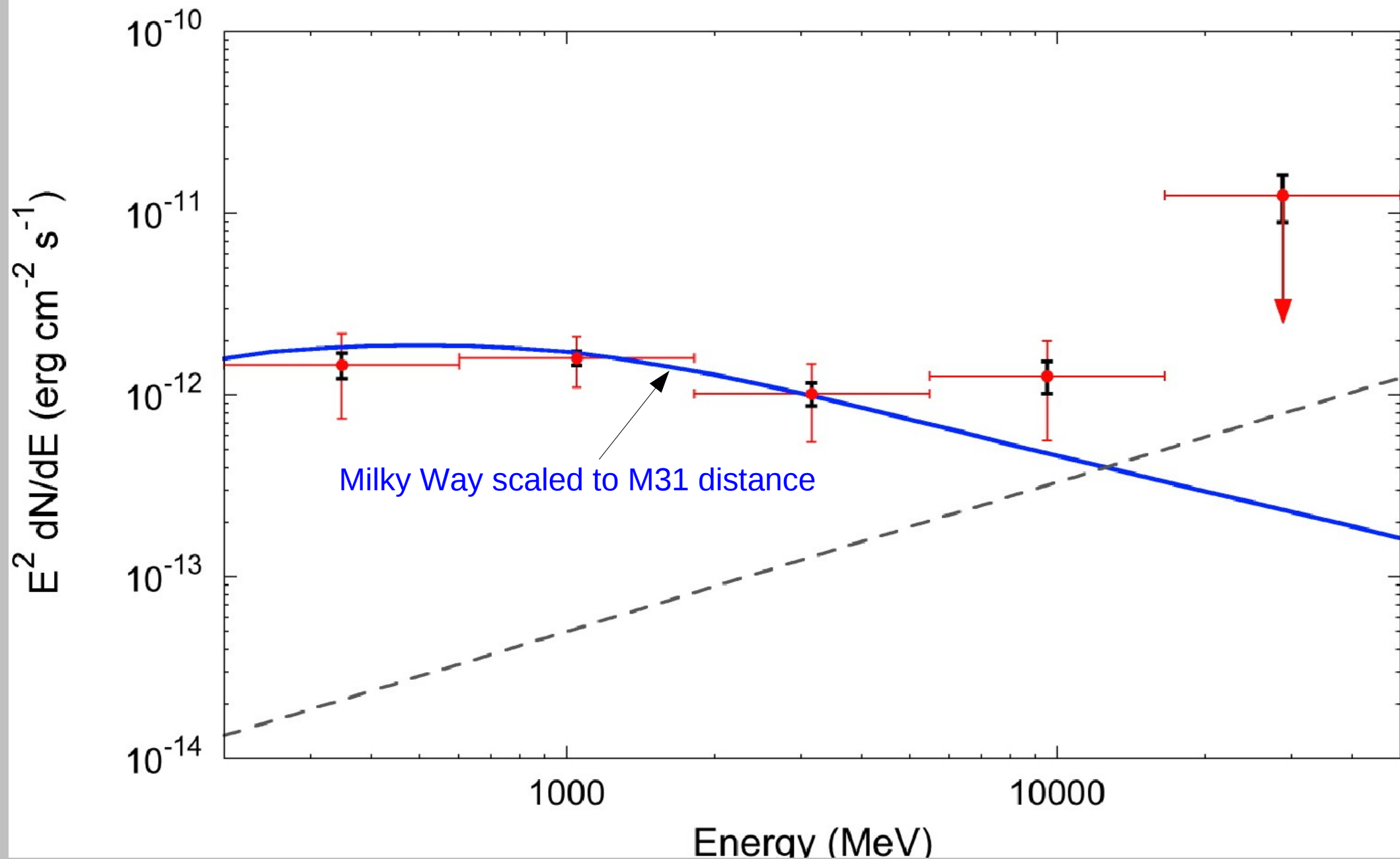
Small Magellanic Cloud

M31          Andromeda: normal Galaxy

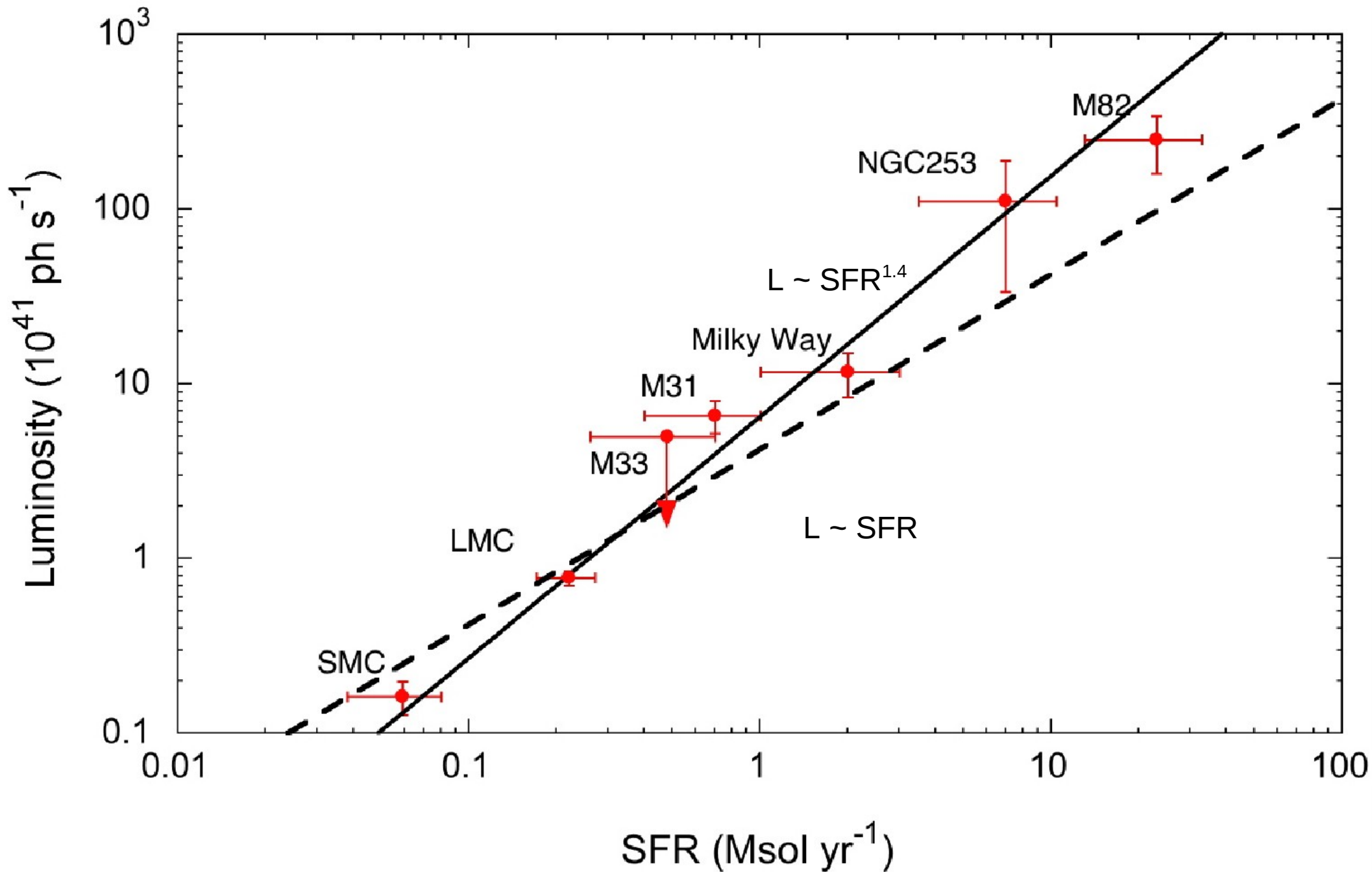
NGC253 starburst

M82          starburst

# M31 – first external galaxy detected in gamma rays !



# Gamma-ray luminosity correlates with star-formation rate



Search for more normal + starburst galaxies with Fermi underway !

# Outlook

## GALPROP development continues

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

