Cosmic-ray Propagation with GALPROP

Andy Strong
Max-Planck Institut für extraterrestrische Physik
Munich, Germany

Workshop on indirect DM searches,
DESY, Hamburg
June 2011

The original motivation :

- to escape from the leaky-box

into the Galaxy

The original motivation :

- 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

REVIEWS IN ADVANCE

Cosmic-Ray Propagation and Interactions in the Galaxy

Andrew W. Strong,[1] Igor V. Moskalenko,[2] and Vladimir S. Ptuskin[3]

[1]Max-Planck-Institut für extraterrestrische Physik, 85741 Garching, Germany; email: aws@mpe.mpg.de

[2]Hansen Experimental Physics Laboratory and Kavli Institute for Particle Astrophysics and Cosmology, Stanford University, Stanford, California 94305; email: imos@stanford.edu

[3]Institute for Terrestrial Magnetism, Ionosphere and Radiowave Propagation of the Russian Academy of Sciences (IZMIRAN), Troitsk, Moscow region 142190, Russia; email: vptuskin@izmiran.ru

Annu. Rev. Nucl. Part. Sci. 2007. 57:285–327

The *Annual Review of Nuclear and Particle Science* is online at http://nucl.annualreviews.org

This article's doi: 10.1146/annurev.nucl.57.090506.123011

0163-8998/07/1123-0285$20.00

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 γ-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....

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....

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

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....

----------------- 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 for cosmic-ray source composition studies.

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

Leaky-box, path-length distribution models
these are numerical 0-D models

not discussed here since we regard them as outdated.

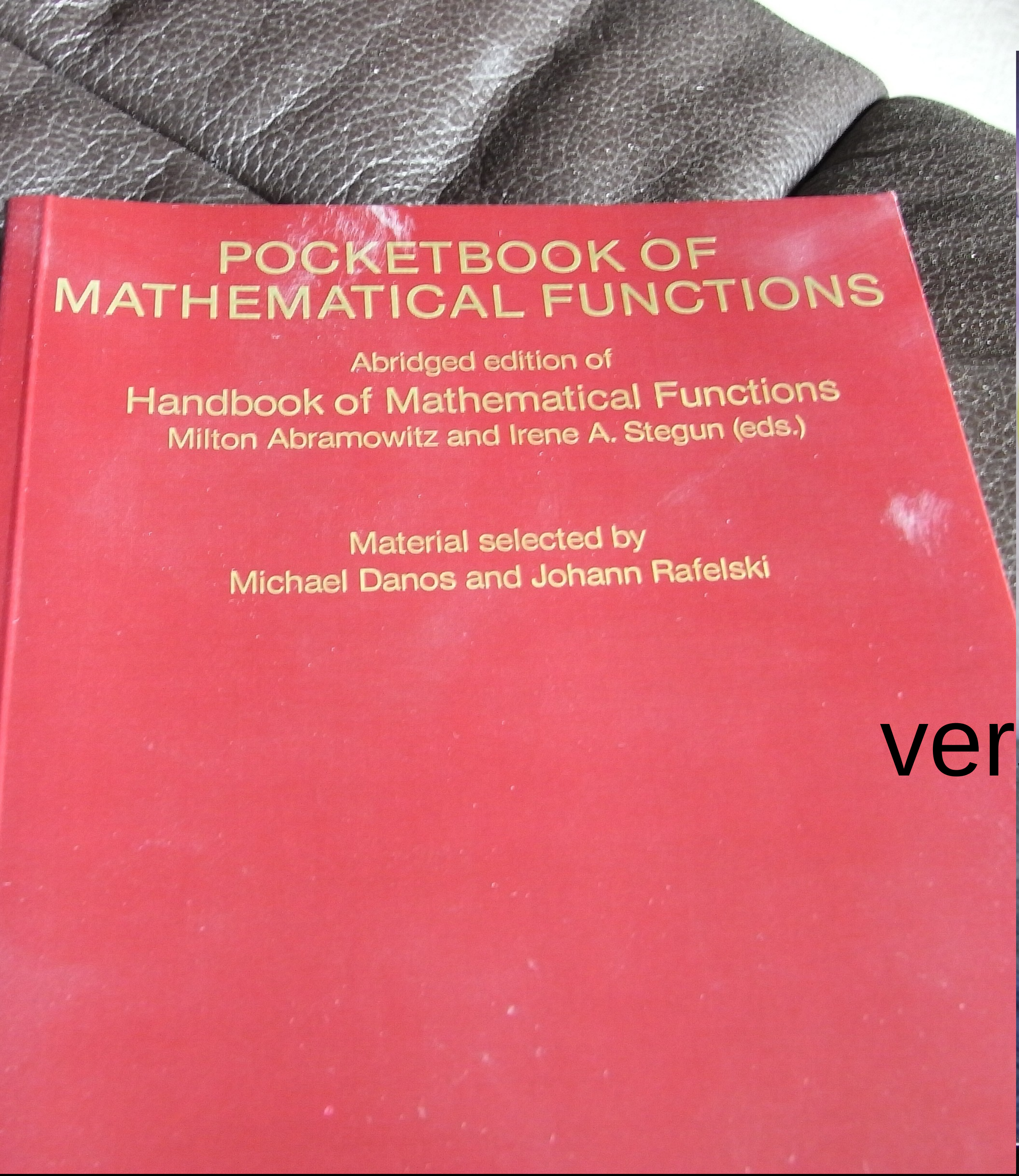
But it is a well-known fact that for stable nuclei without energy losses, these methods can be designed to produce the same results as propagation models,
So OK for for cosmic-ray source composition studies.
For unstable nuclei, electrons, positrons, gamma rays.... not realistic enough to be useful

Spatial Propagation models

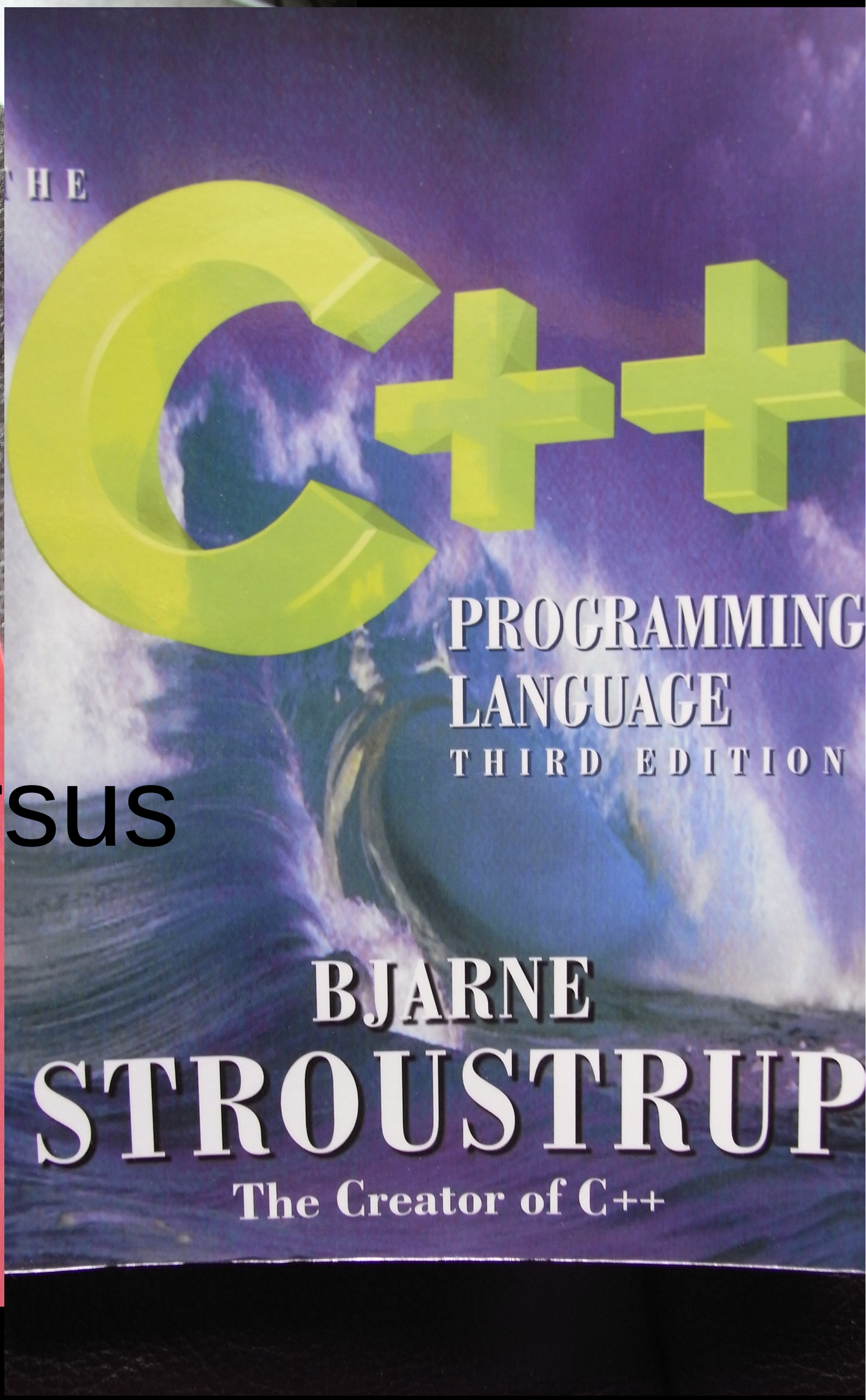
Advantage is the physical interpretation in terms of diffusion, convection etc.
related to the real Galaxy. Intuitive understanding of meaning of terms.

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
C++
PROGRAMMING
LANGUAGE
THIRD EDITION
BJARNE
STROUSTRUP
The Creator of C++

Propagation models

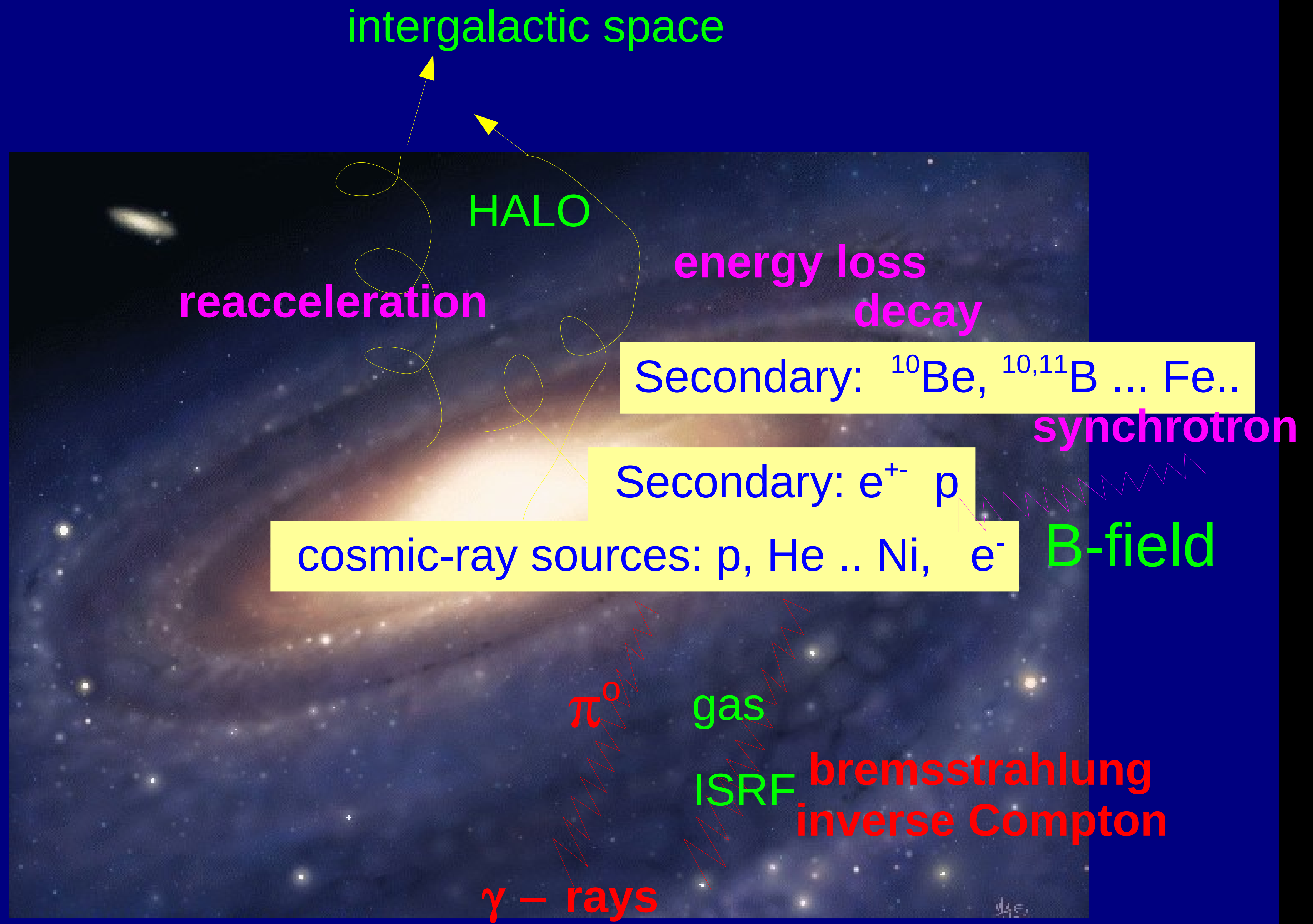
A main advantage is the physical interpretation in terms of diffusion, convection etc. related to the real Galaxy. Intuitive understanding of meaning of terms.

1D, 2D, or 3D
Both analytical and numerical, and hybrids, all have their proponents.

Analytical	**Numerical**
Mainly 1D, some 2D	2D or 3D
complex (but impressive) formulae	simple formulae (computer does the work)
simplified energy losses	full energy losses
simplified gas distribution	gas based on HI, CO surveys in 3D
simplified magnetic field	any magnetic field model
gamma rays only in simple way	full gamma ray calculation
synchrotron only in simple way	full synchrotron calculation

focus : cosmic-ray production & propagation in the Galaxy

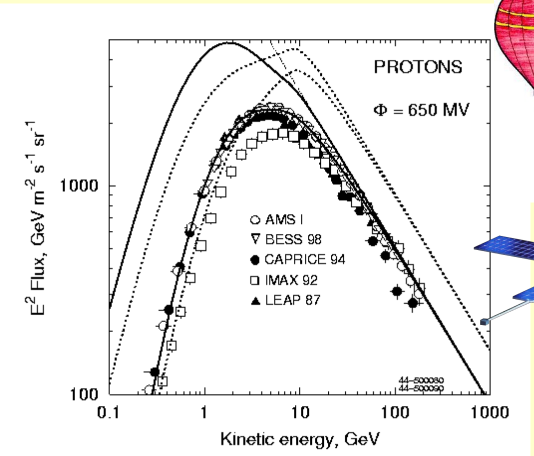
COSMIC RAYS

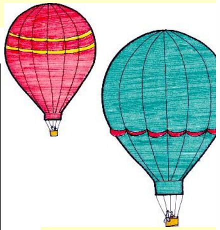

intergalactic space
HALO
reacceleration
energy loss
decay
Secondary: ^{10}Be, ^{10,11}B ... Fe..
synchrotron
Secondary: e^{+-} $\bar{p}$
cosmic-ray sources: p, He .. Ni, e^{-}
B-field
π^{o}
gas
ISRF
bremsstrahlung
inverse Compton
γ – rays

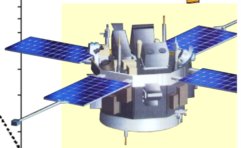
The **goal** : use *all* types of data in self-consistent way to test models of cosmic-ray propagation.

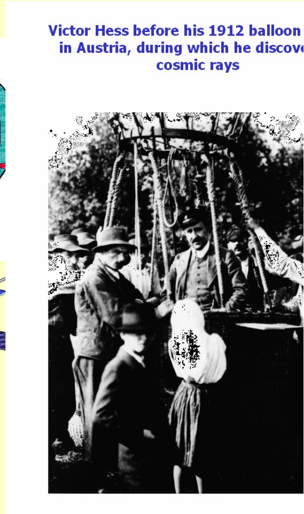
Observed *directly, near Sun:*

- primary spectra (p, He ... Fe; e^-)
- secondary/primary (B/C etc)
- secondary e^+ , antiprotons...



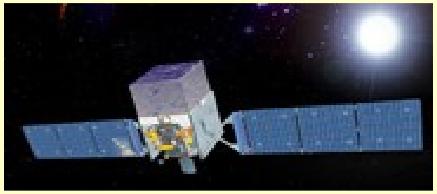


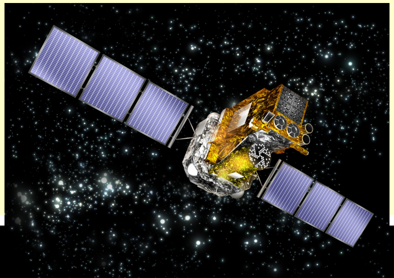


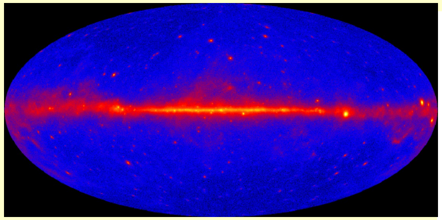


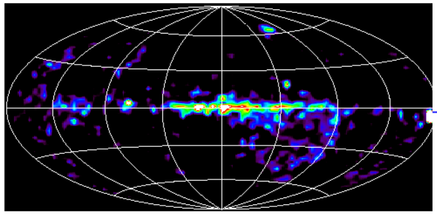
Observed *from whole Galaxy:*

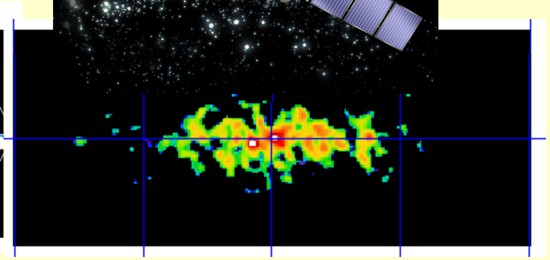
γ - rays



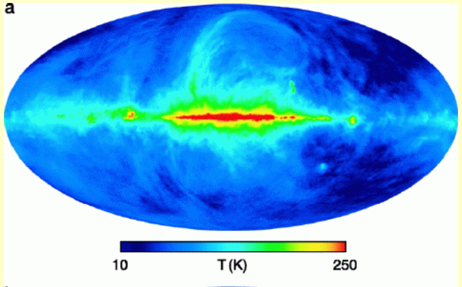








synchrotron



GALPROP project

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

Dramatis personae:

Igor Moskalenko (Stanford)

Troy Porter (Stanford)

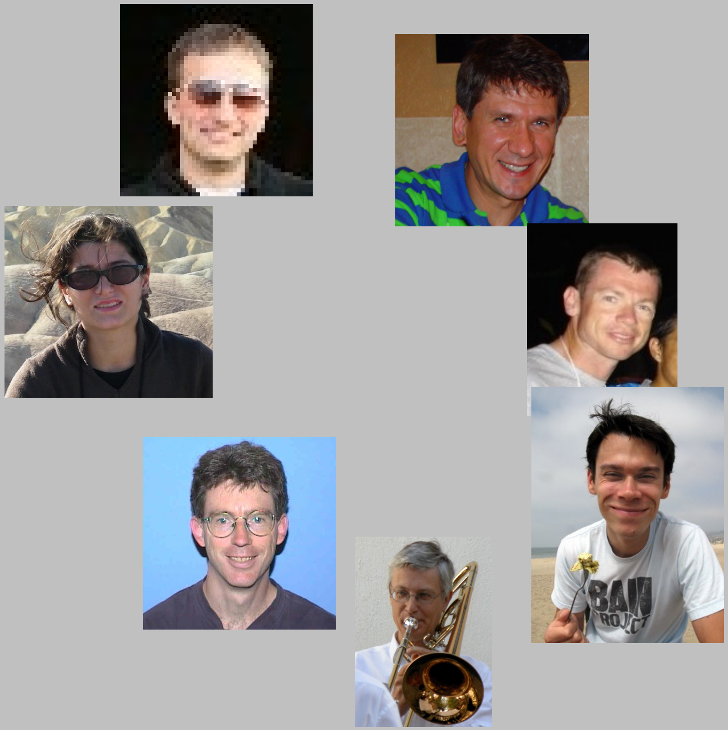
Gulli Johannesson (Iceland)

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

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

cosmic-ray sources (primary and secondary)

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

diffusion convection

$$+ \partial/\partial p \, [p^2 D_{pp} \partial/\partial p \, \psi / p^2]$$

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

diffusive reacceleration (diffusion in p)

$$- \partial/\partial p \, [dp/dt \, \psi - p/3 \, (\nabla \cdot v) \, \psi]$$

momentum loss 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 = source terms + propagation terms

$\Delta t \sim 1000$ yrs

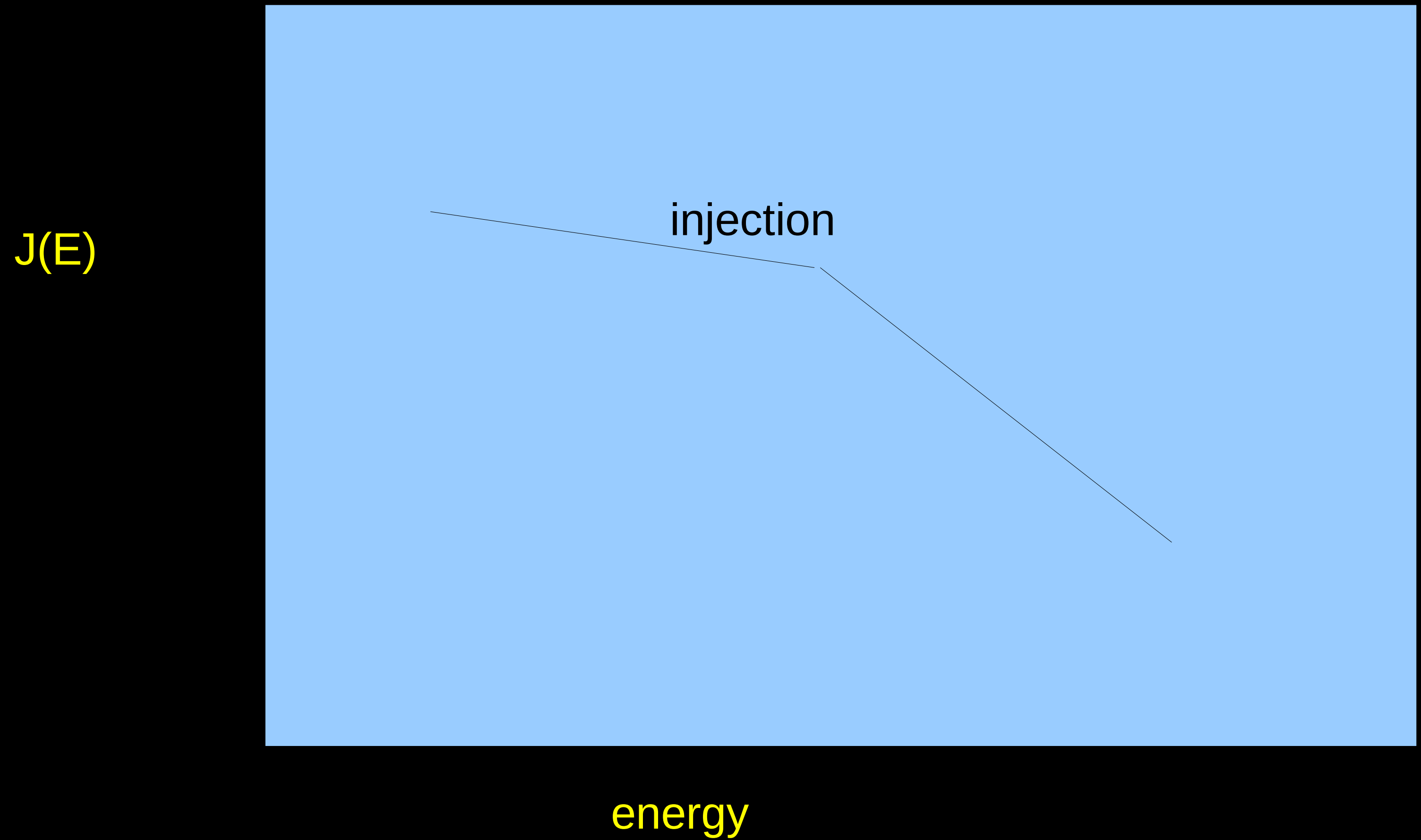
for steady-state, evolve until dn / dt = 0

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

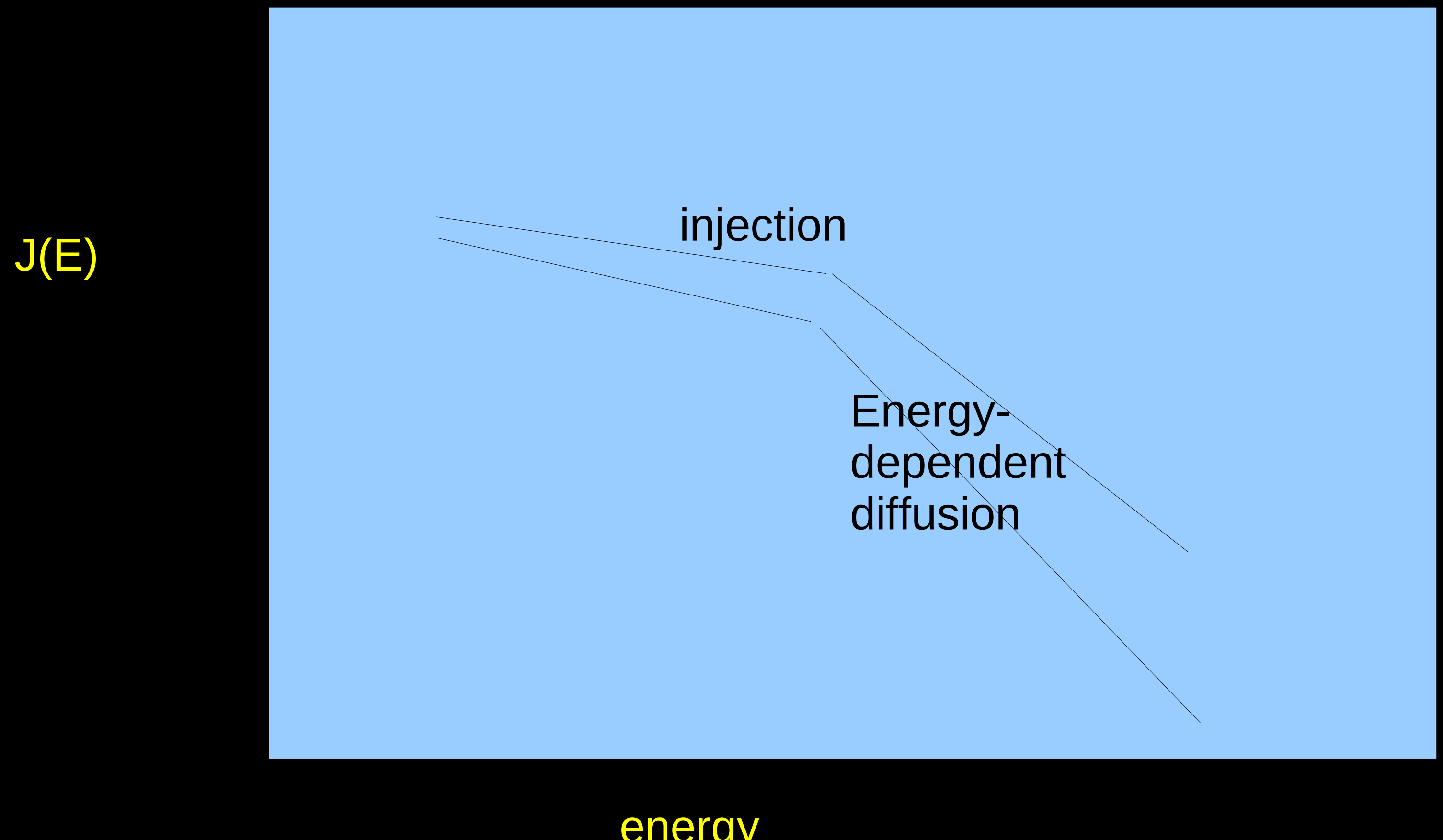
Cosmic-ray nuclei: start from ^{64}Ni and work down in (A, Z)
including secondary production
plus secondary positrons, electrons, antiprotons

primary electrons: separate species

Producing the cosmic-ray spectrum

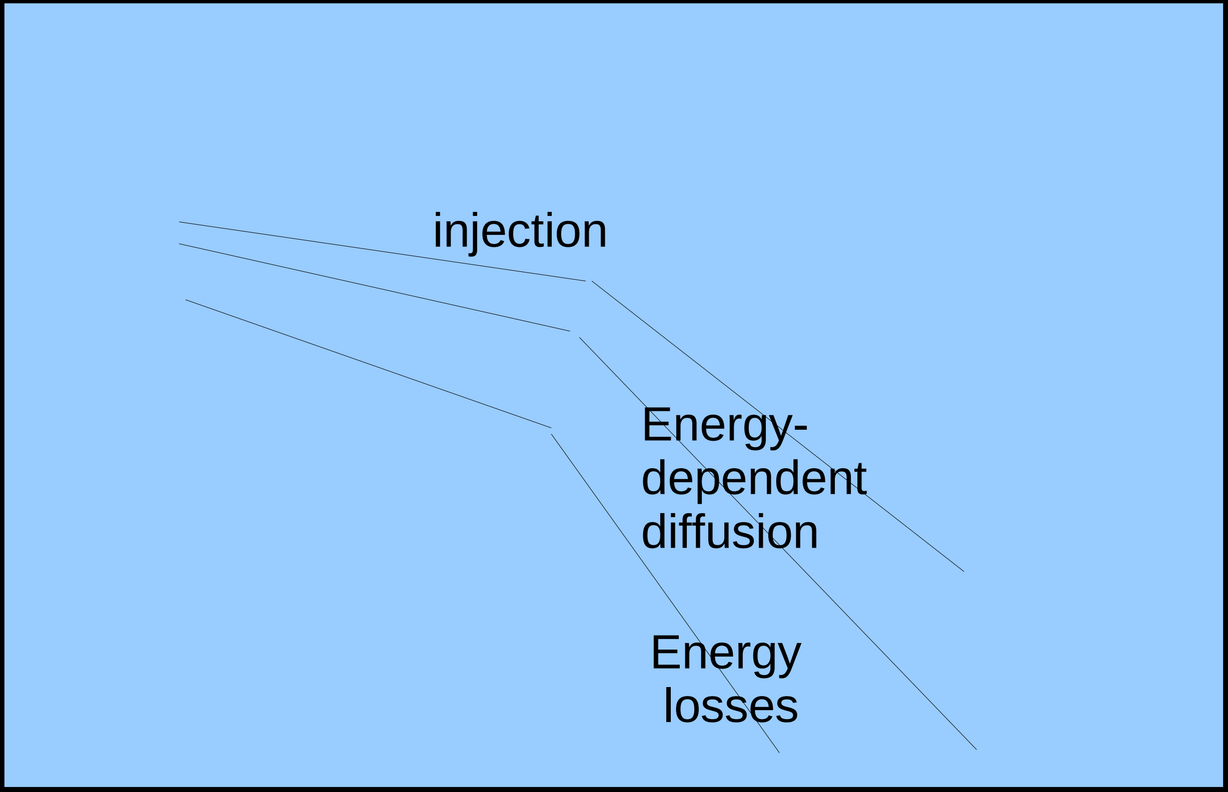


Producing the cosmic-ray spectrum



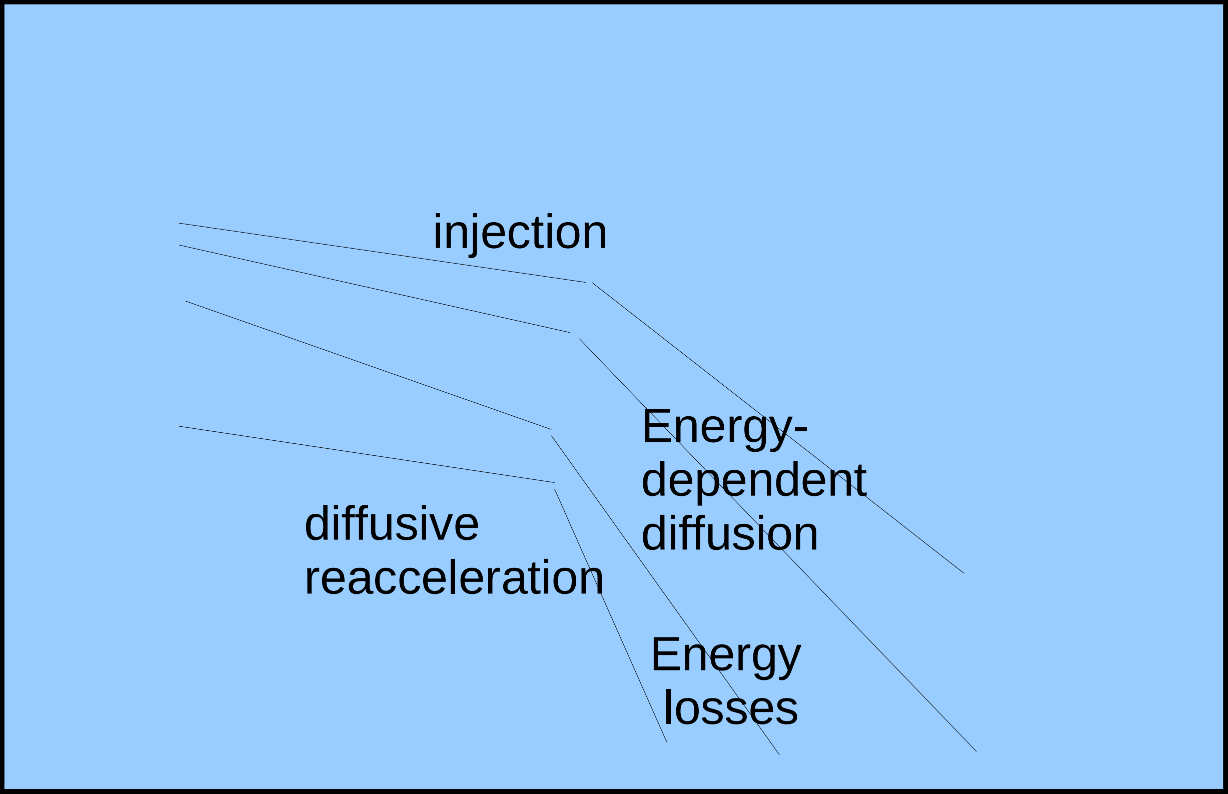
Producing the cosmic-ray spectrum

J(E)



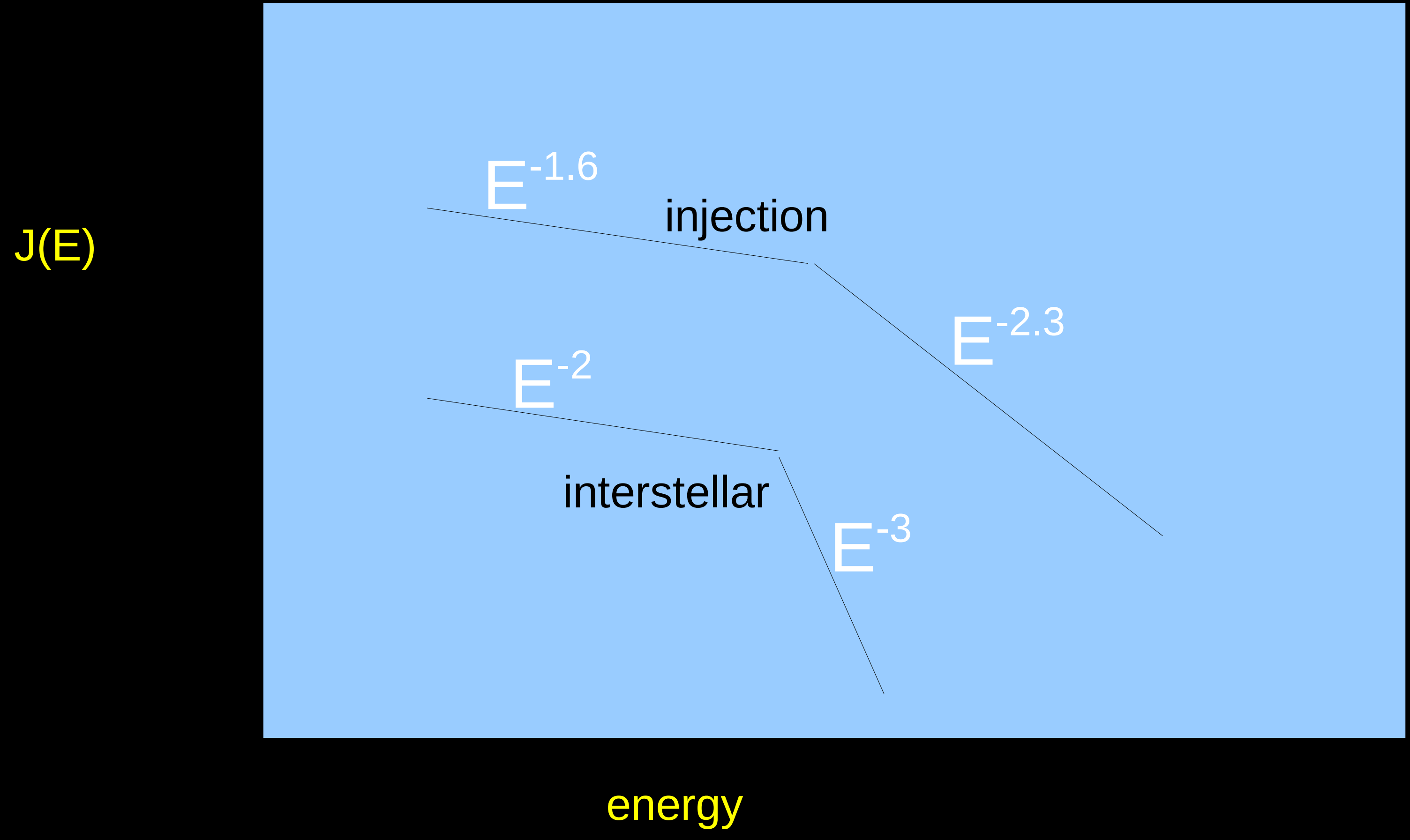
energy

Producing the cosmic-ray spectrum



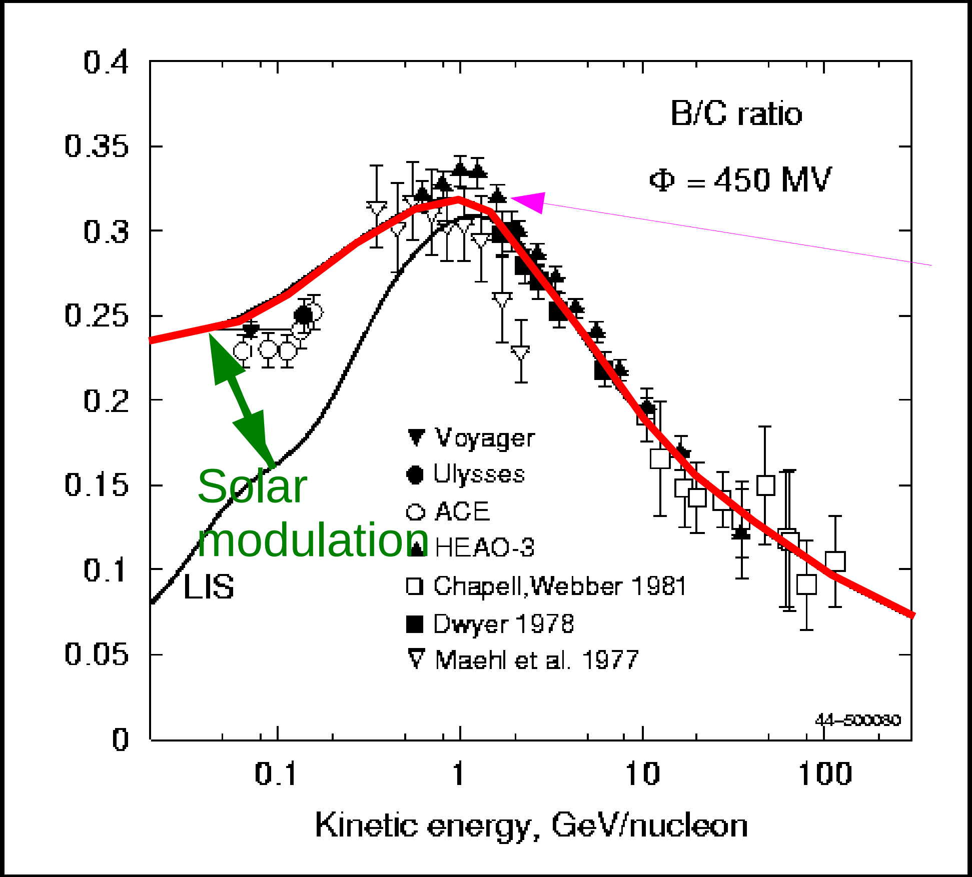
Producing the cosmic-ray spectrum

Example: electrons



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

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

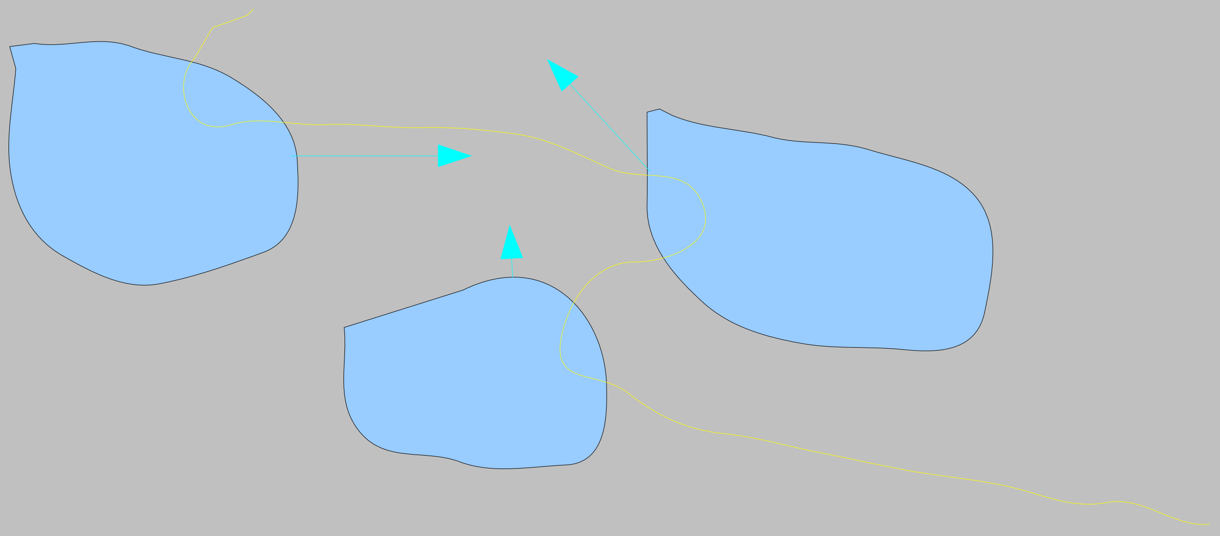
Without reacceleration, need a change to constant D at low energy to get B/C peak
However reacceleration not proven !

Diffusive reacceleration

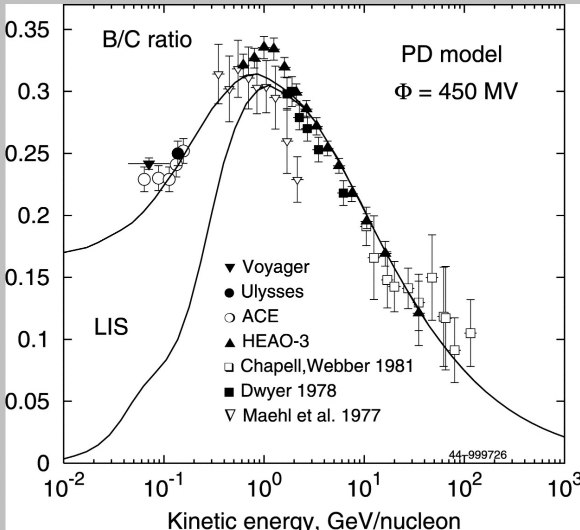
Cosmic rays diffuse by scattering on magnetic irregularies

'clouds'

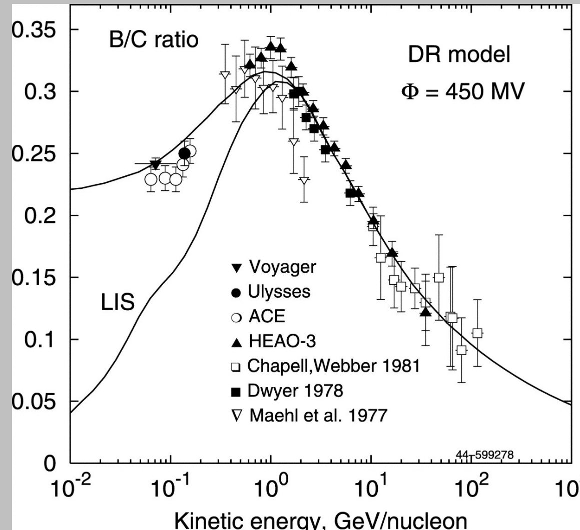
Moving clouds → momentum transfer
→ diffusion in momentum space = diffusive reacceleration



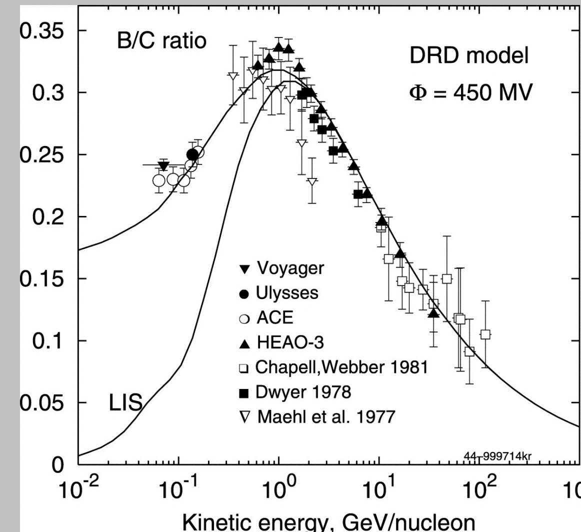
plain diffusion



diffusive reacceleration



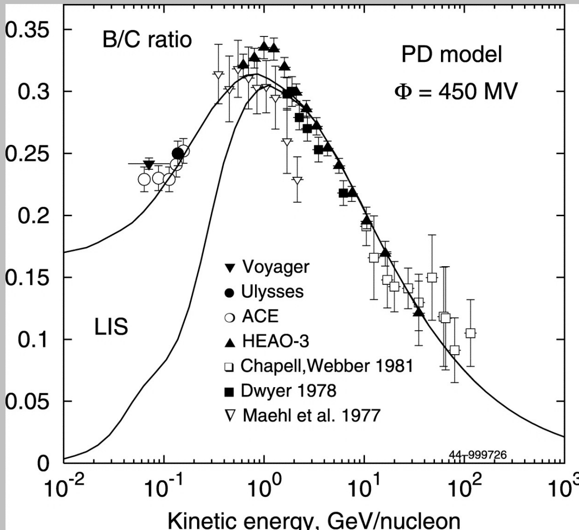
wave damping



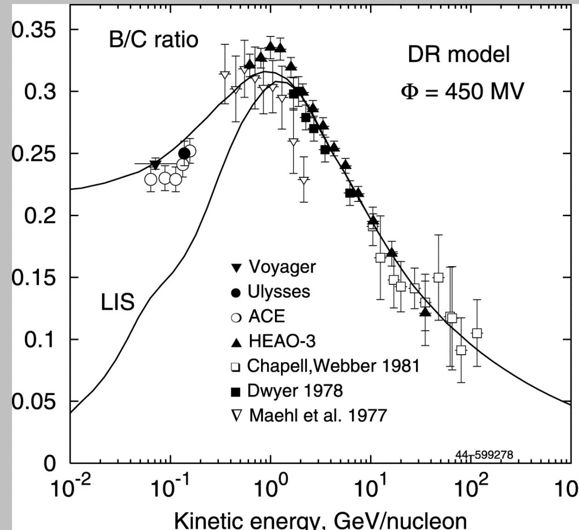
For any model, first adjust parameters to fit Boron/Carbon

Ptuskin et al. 2006 ApJ 642, 902

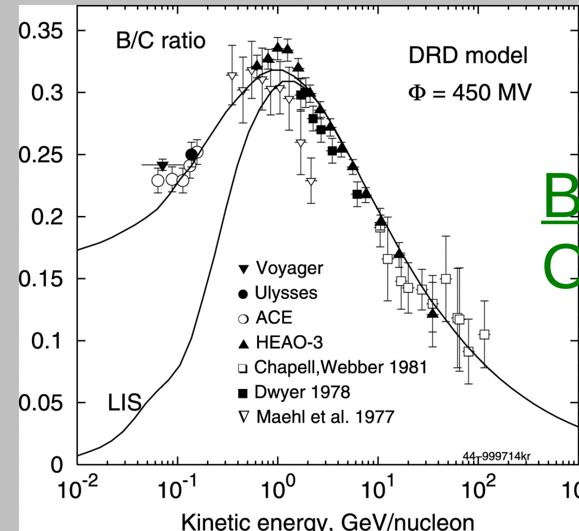
plain diffusion



diffusive reacceleration



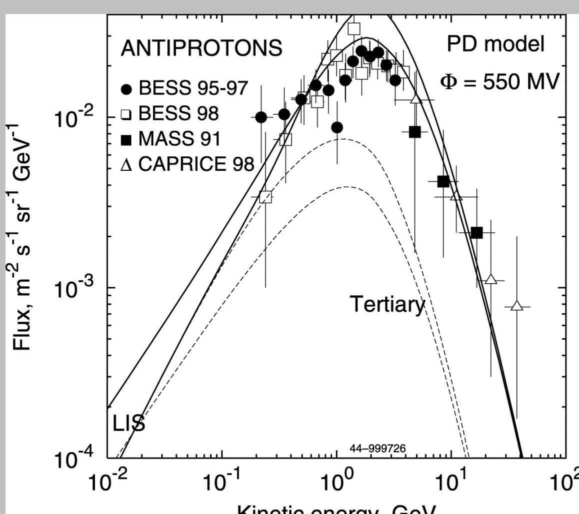
wave damping

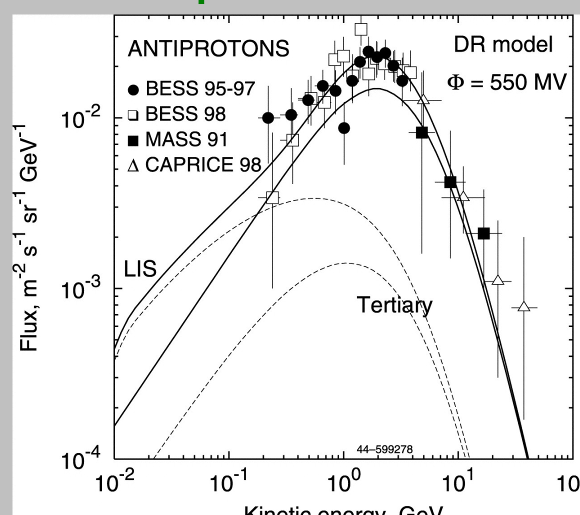


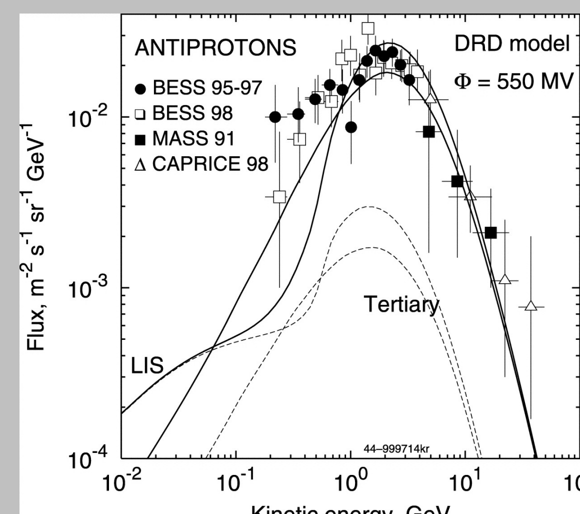
<u>Boron/</u>
Carbon

then predict the other cosmic-ray spectra

antiprotons

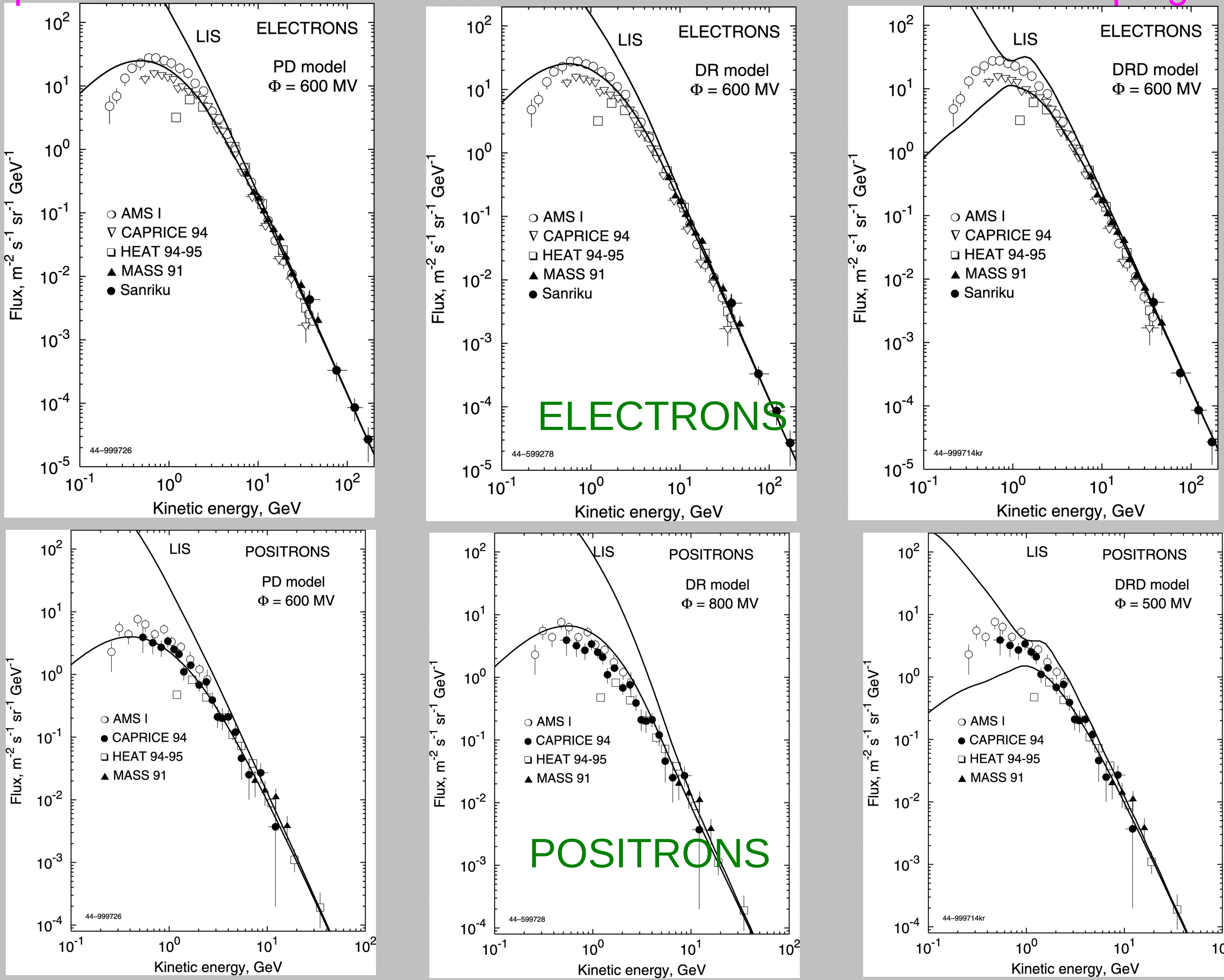




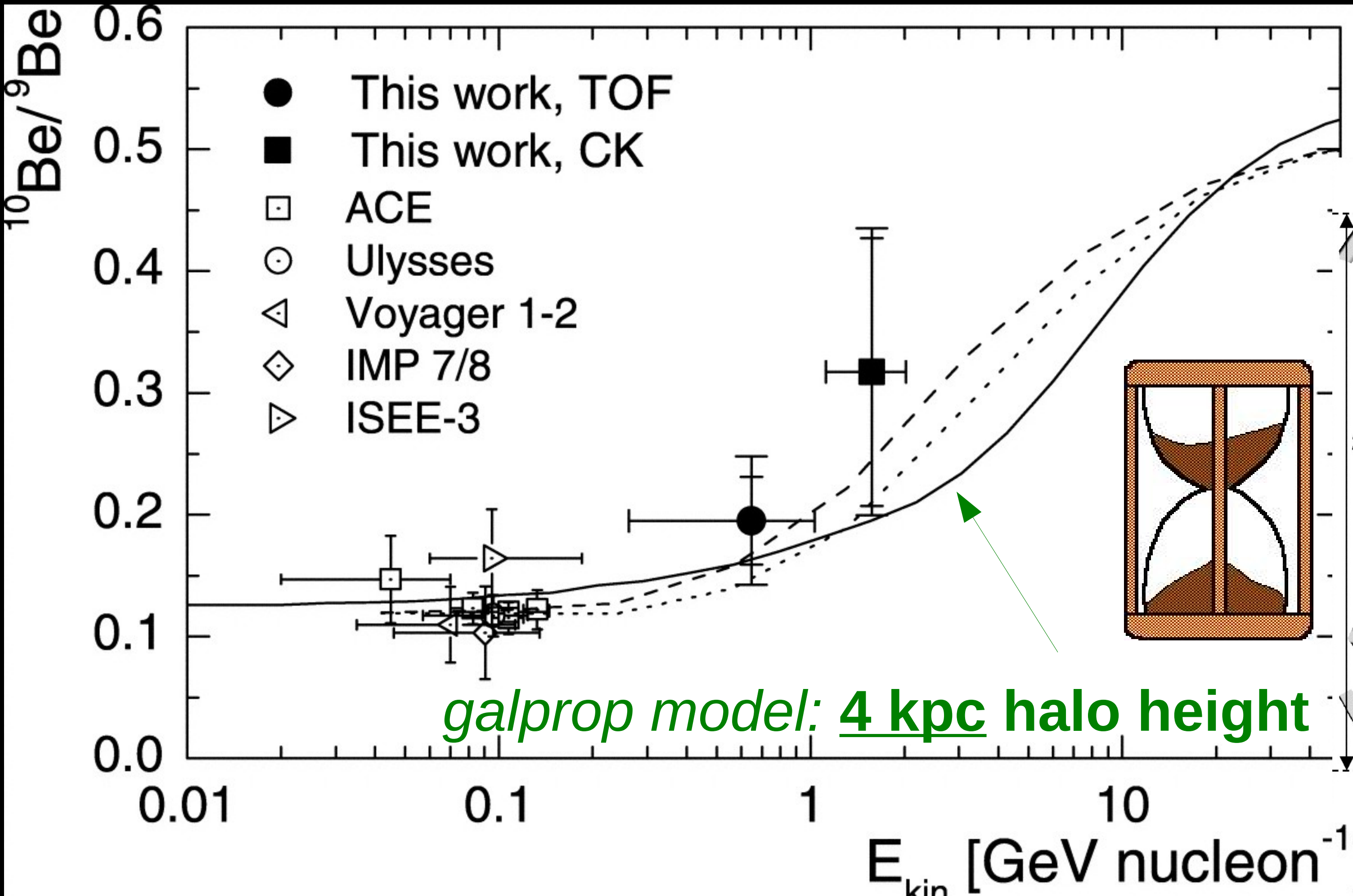


Ptuskin et al. 2006 ApJ 642, 902

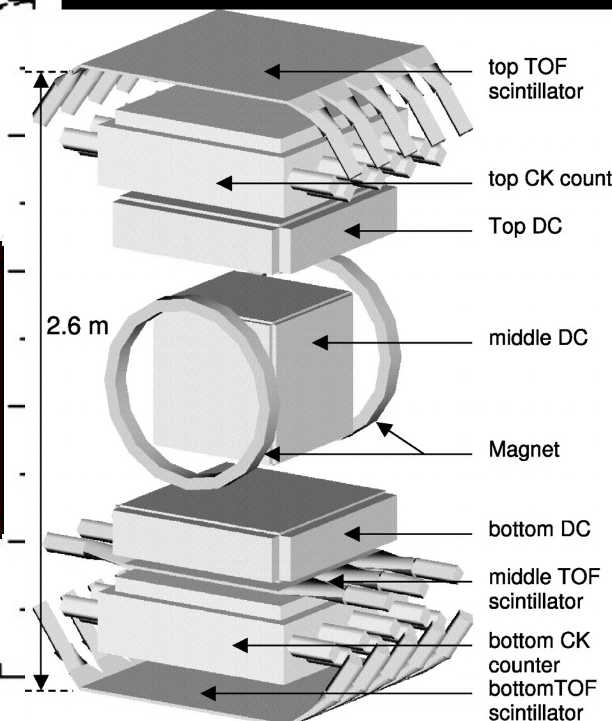
plain diffusion | diffusive reacceleration | wave damping



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



data:
ACE, ISOMAX

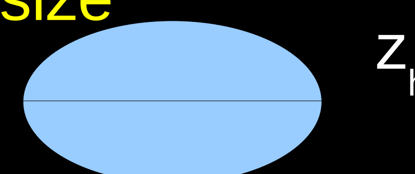


Hams et al. 2004 ApJ 611, 892

^{10}**Be** *decays* in 10^{6} years, ^{9}**Be** is *stable*

so ratio sensitive to cosmic-ray confinement time, halo size

Cosmic-ray halo height = 4 – 10 kpc

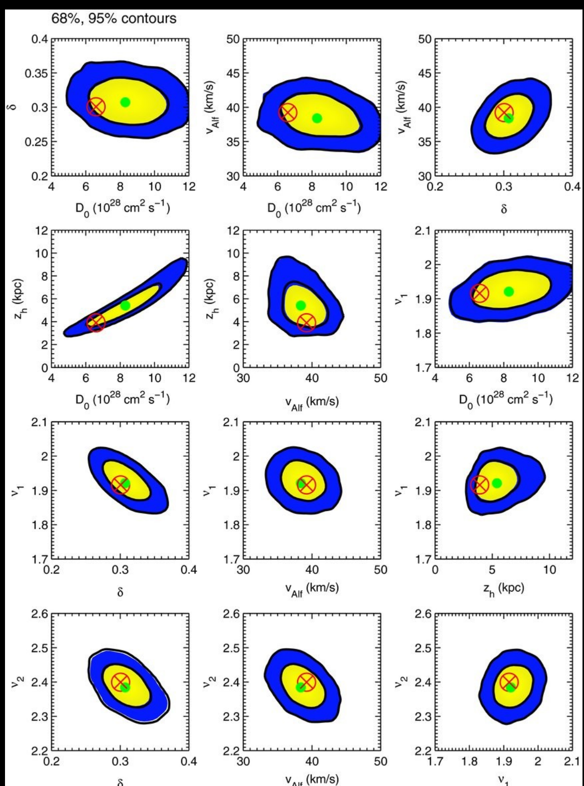


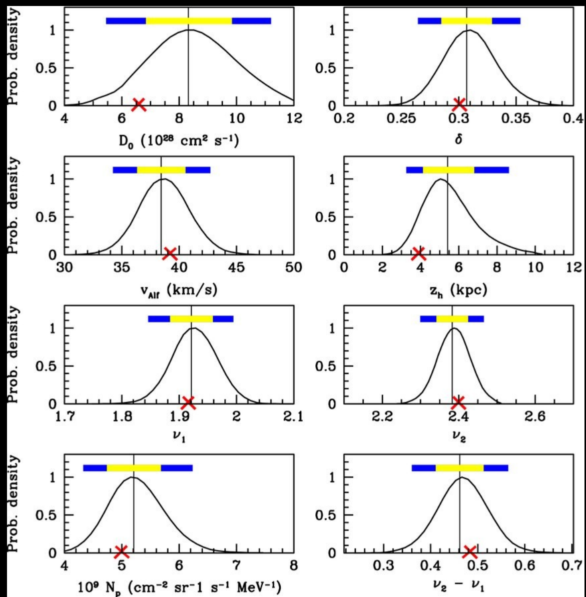
The Astrophysical Journal, 729:106 (16pp), 2011 March 10
doi:10.1088/0004-637X/729/2/106

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

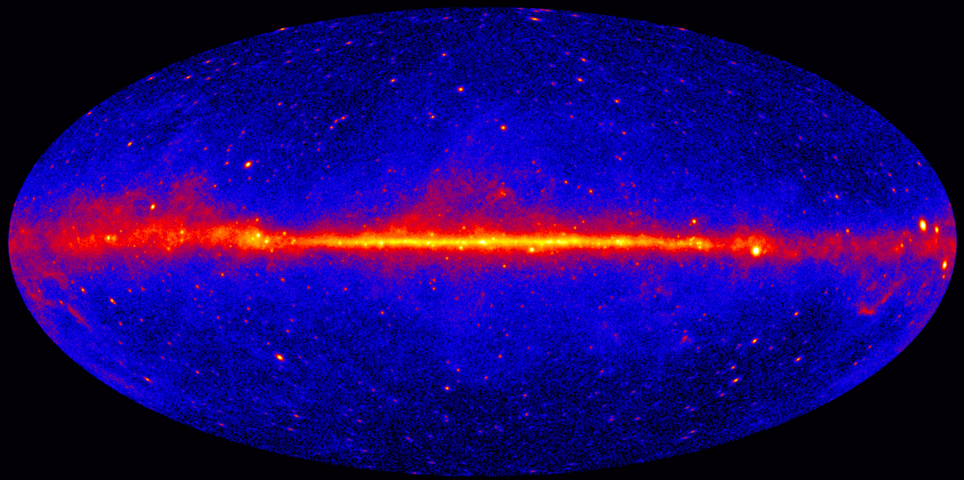
R. Trotta[1], G. Jóhannesson[2], I. V. Moskalenko[3,4], T. A. Porter[3], R. Ruiz de Austri[5], and A. W. Strong[6]
[1] Astrophysics Group, Imperial College London, Blackett Laboratory, Prince Consort Road, London SW7 2AZ, UK
[2] Science Institute, University of Iceland, Dunhaga 3, IS-107 Reykjavik, Iceland
[3] Hansen Experimental Physics Laboratory, Stanford University, Stanford, CA 94305, USA
[4] Kavli Institute for Particle Astrophysics and Cosmology, Stanford University, Stanford, CA 94305, USA
[5] Instituto de Física Corpuscular, IFIC-UV/CSIC, Valencia, Spain
[6] 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 !) .

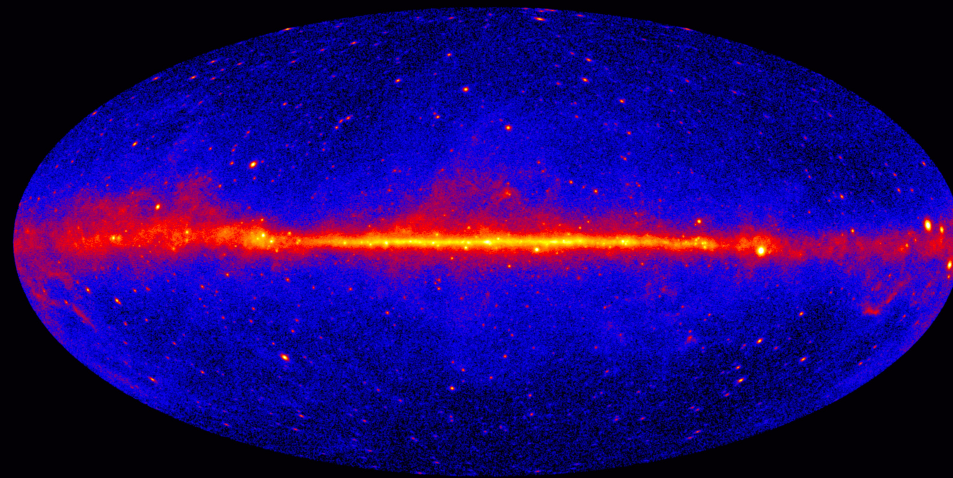




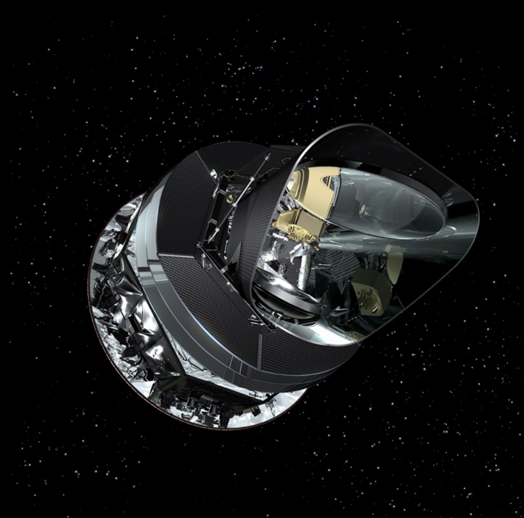

National Aeronautics and Space Administration
Fermi
Gamma-ray Space Telescope
www.nasa.gov/fermi

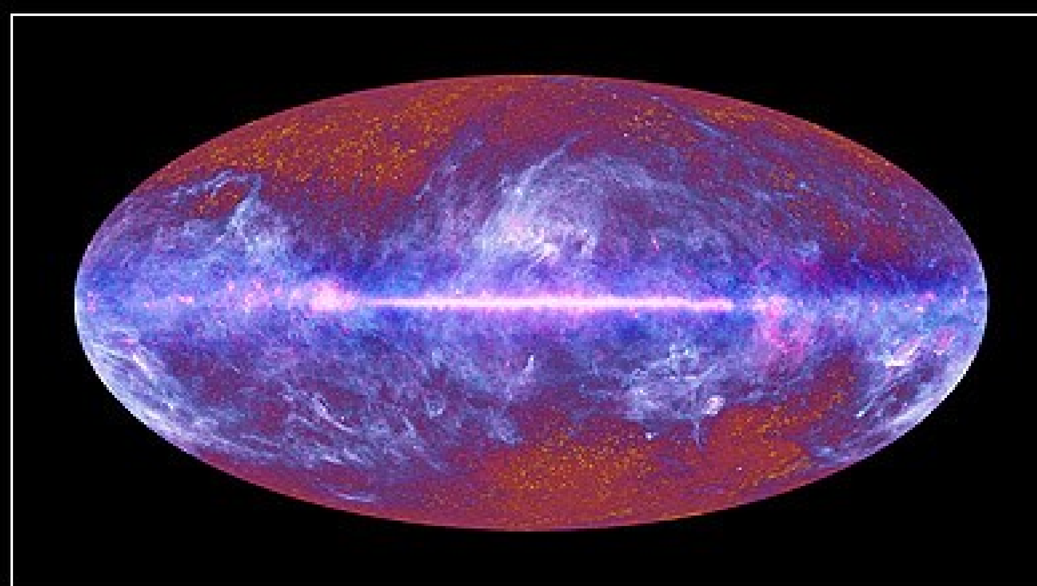


2 years



2 years





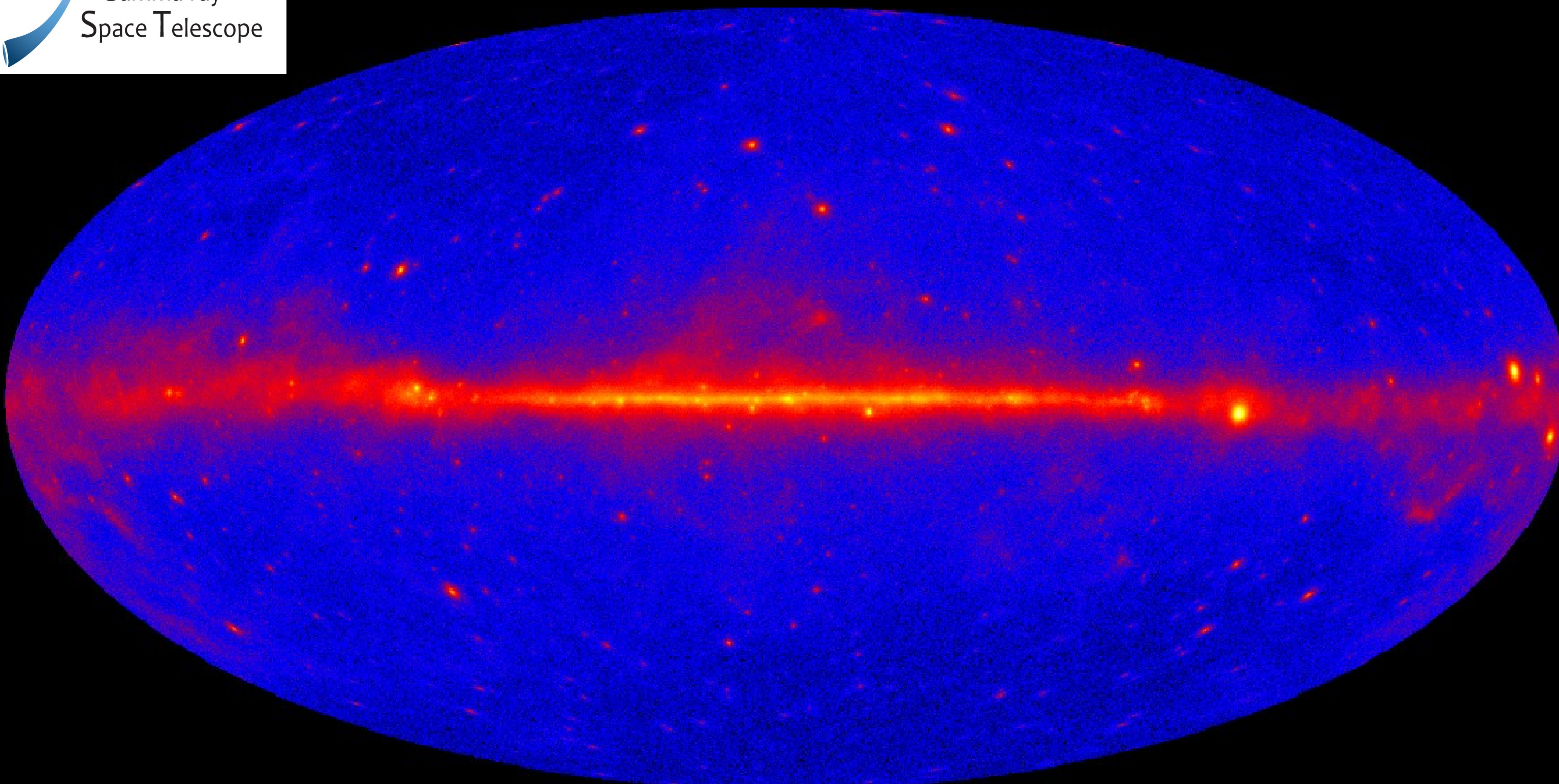
The Planck one-year all-sky survey   esa   (c) ESA, HFI and LFI consortia, July 2010

1 year

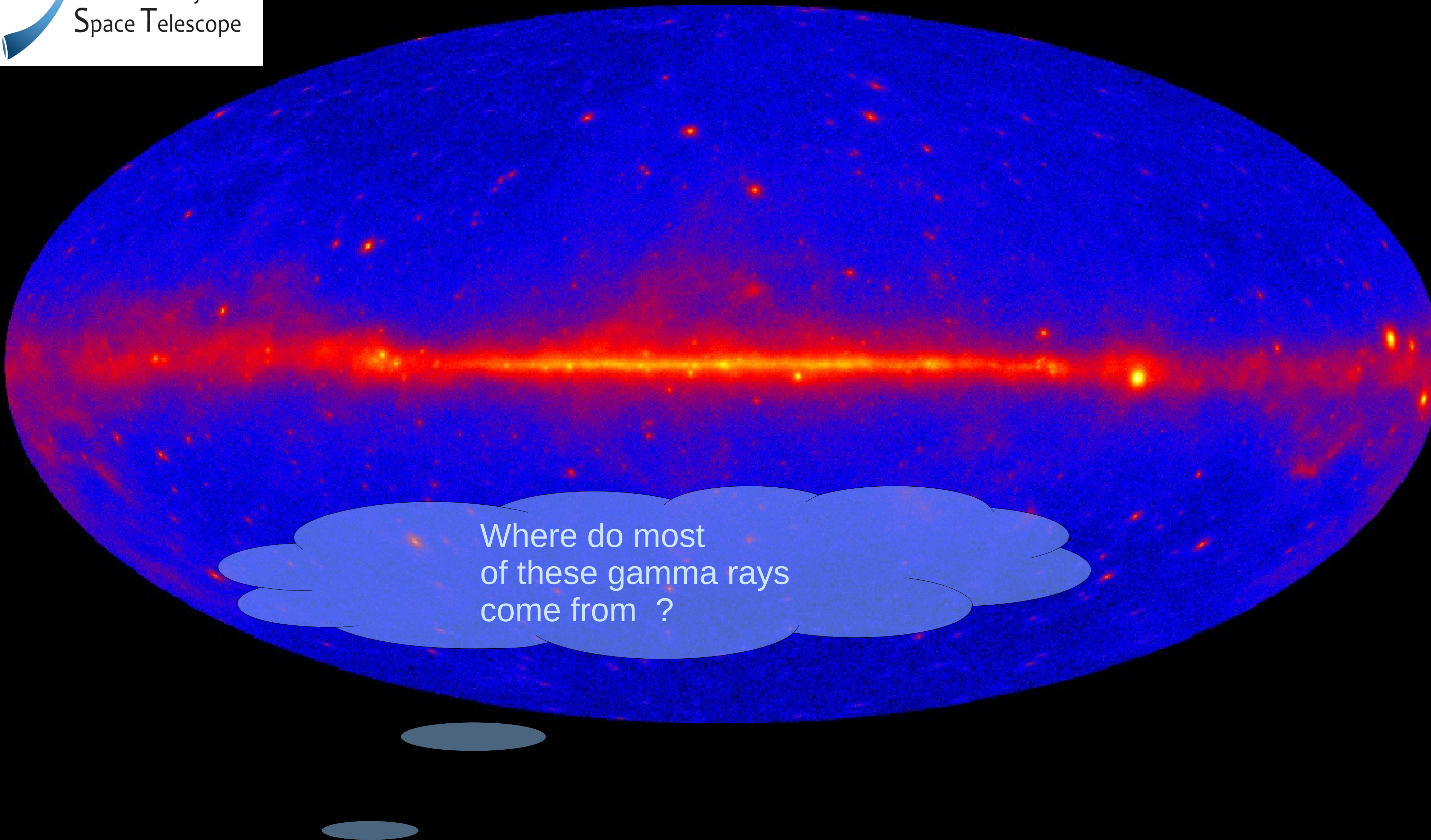
Both flying now. A lot of common astrophysics !

fermi

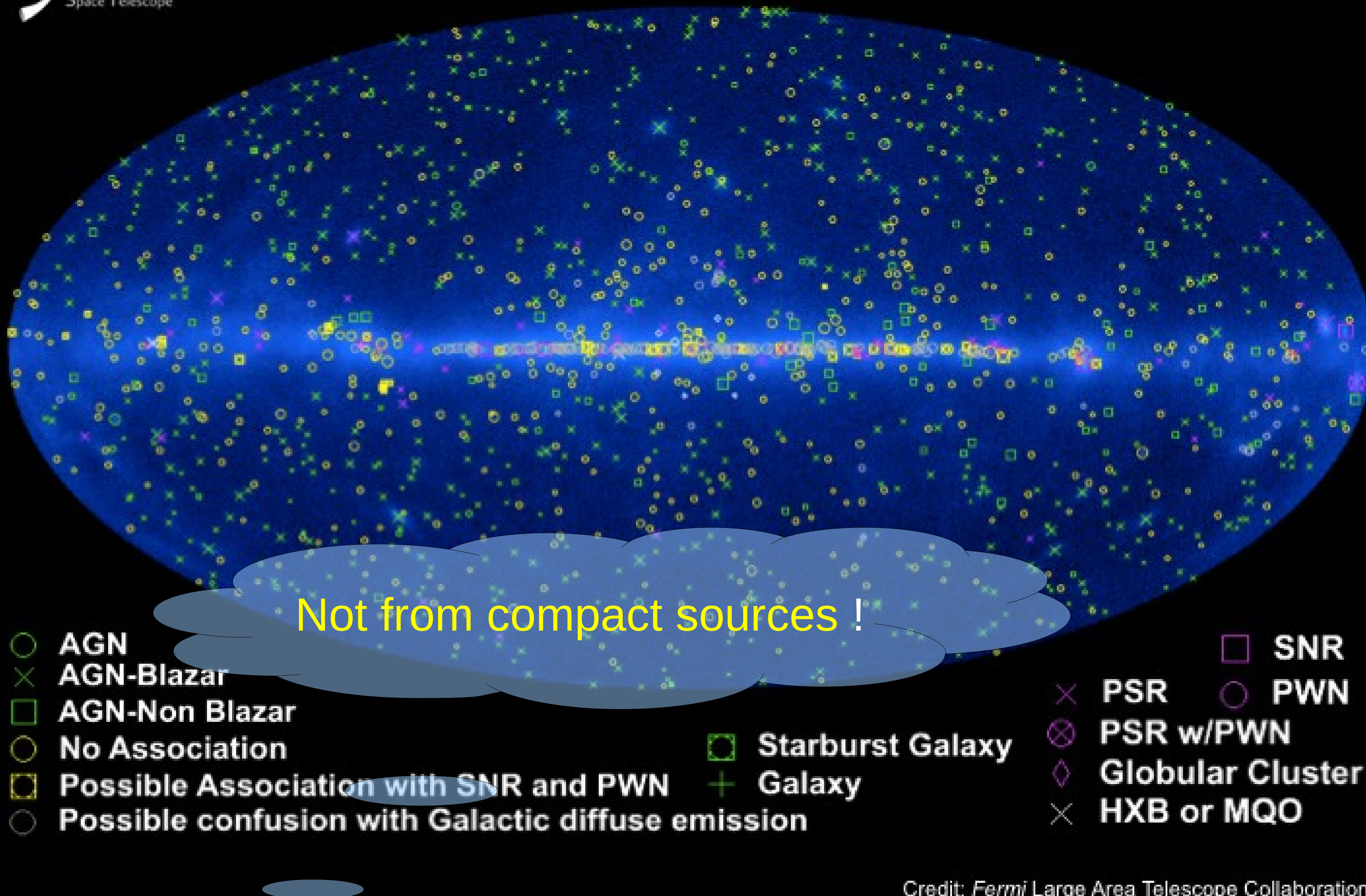
Gamma-ray Space Telescope



Fermi
Gamma-ray
Space Telescope



The Fermi LAT 1FGL Source Catalog

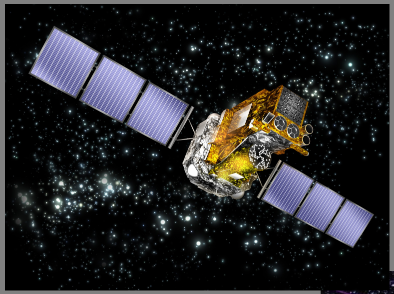


Credit: *Fermi* Large Area Telescope Collaboration

History of gamma-ray astronomy

'GeV astronomy'

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

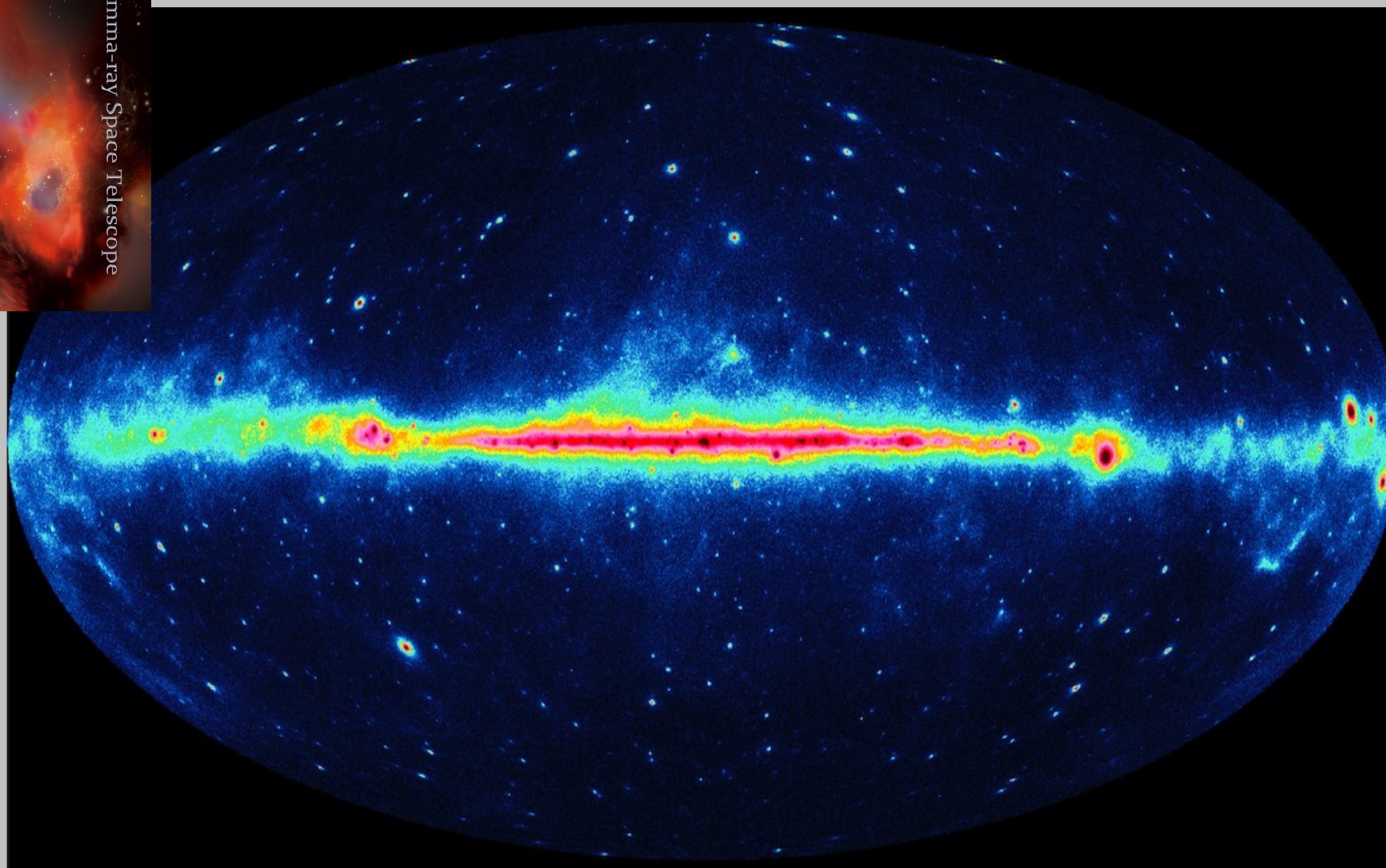
Launched 2008
maps the whole sky every 3 hours
30 MeV – 300 GeV
arcminute resolution
data public immediately

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_2) surveys

cosmic-ray sources *f* (r, E)

interstellar radiation field *f* (r, ν)

nuclear cross-sections database

energy-loss processes

B-field model

γ – ray, synchrotron

Modelling the gamma-ray sky

Main ingredients of **GALPROP** model

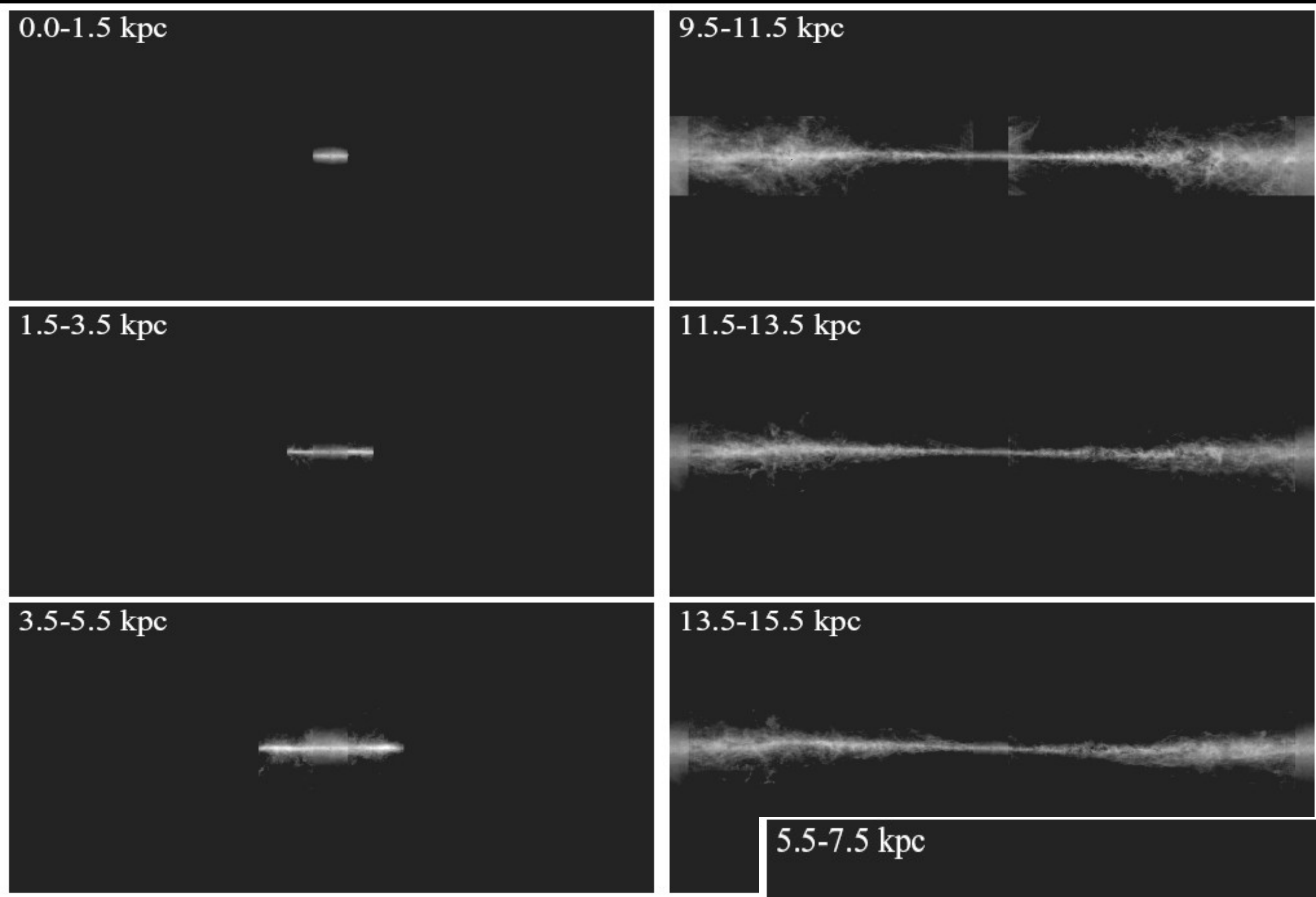
cosmic-ray spectra p , He , e- , e+ (including secondaries)

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

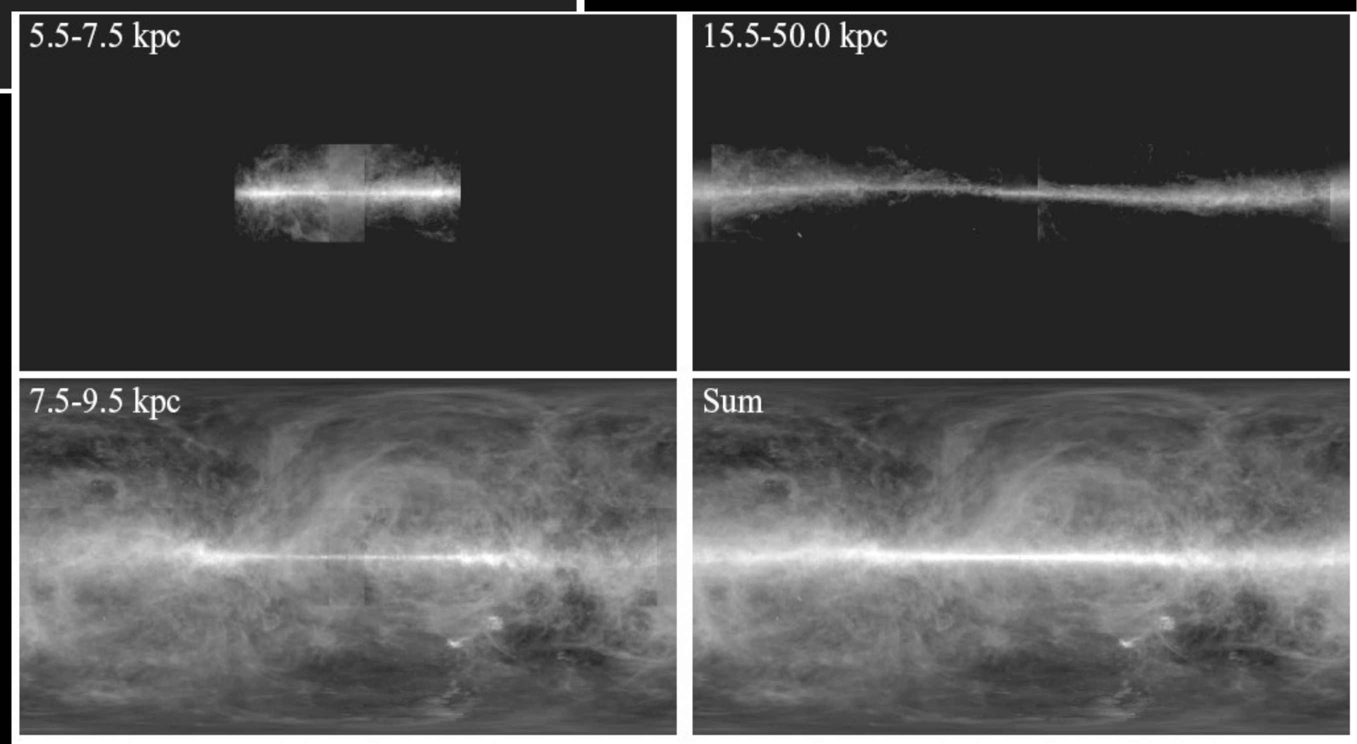
Secondary / primary ratios (B/C etc) for propagation parameters
halo height = 4 - 10 kpc (from radioactive cosmic-ray nuclei)

Interstellar radiation field (Frankie code) (-> inverse Compton)
B-field (electron energy losses, synchrotron emission)
HI, CO, dust surveys
CO-to-H_2 conversion a function of position in Galaxy
Fermi 1^{st} Year Source Catalogue

Gas Rings: HI Inner & Outer Galaxy



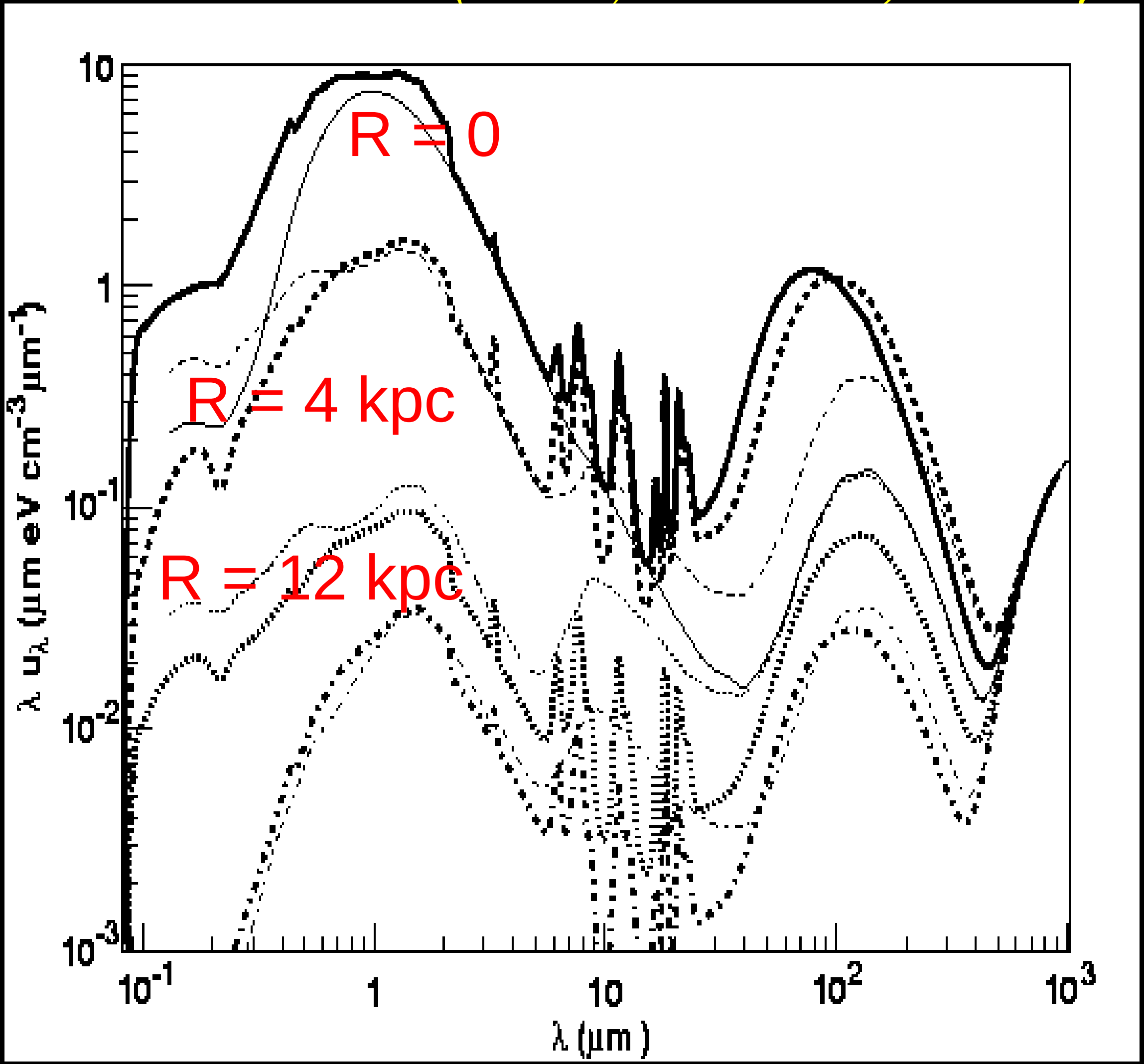
Gas Rings: HI Local Galaxy



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

***New** ISRF using latest information*

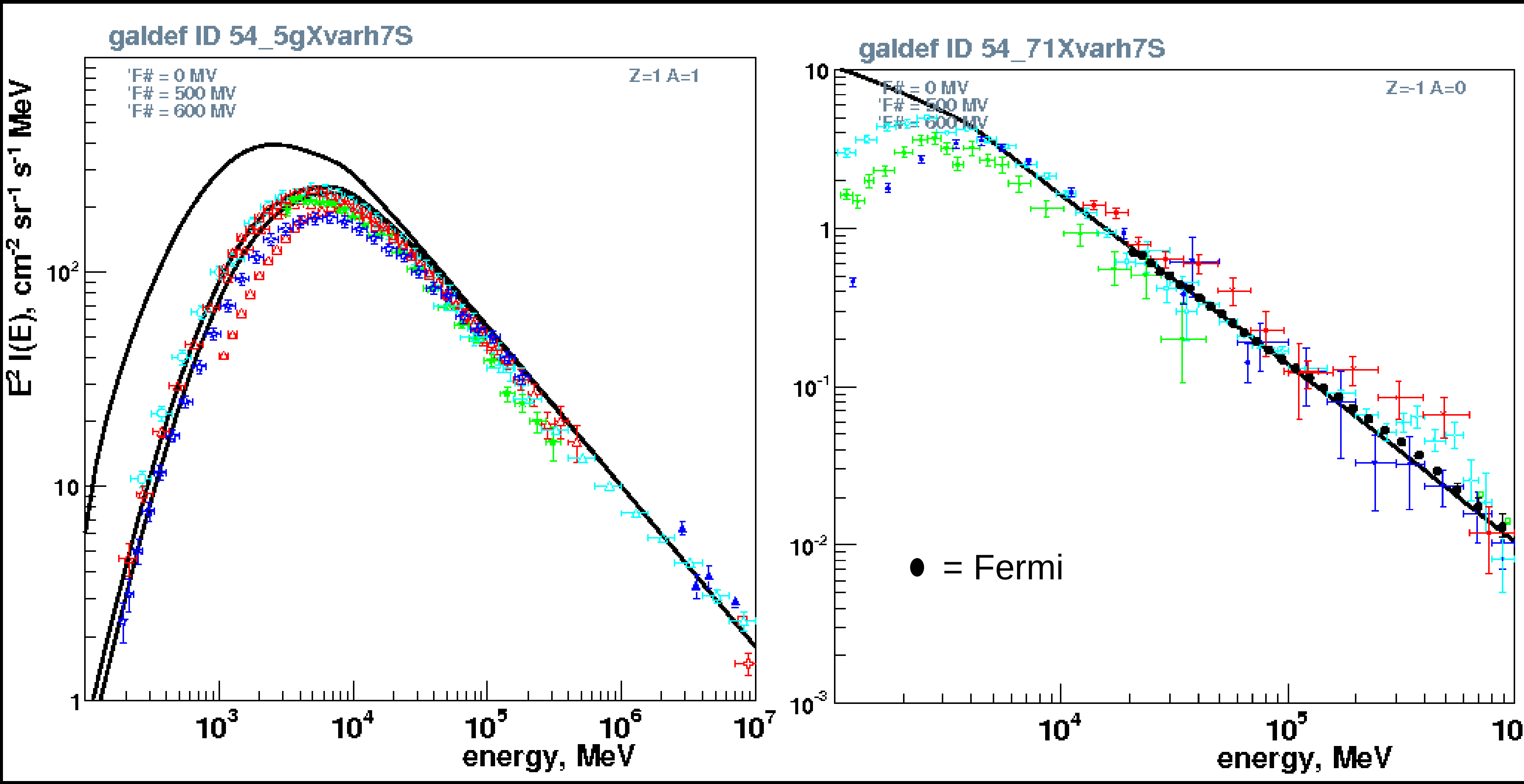
stellar populations, dust radiative transfer



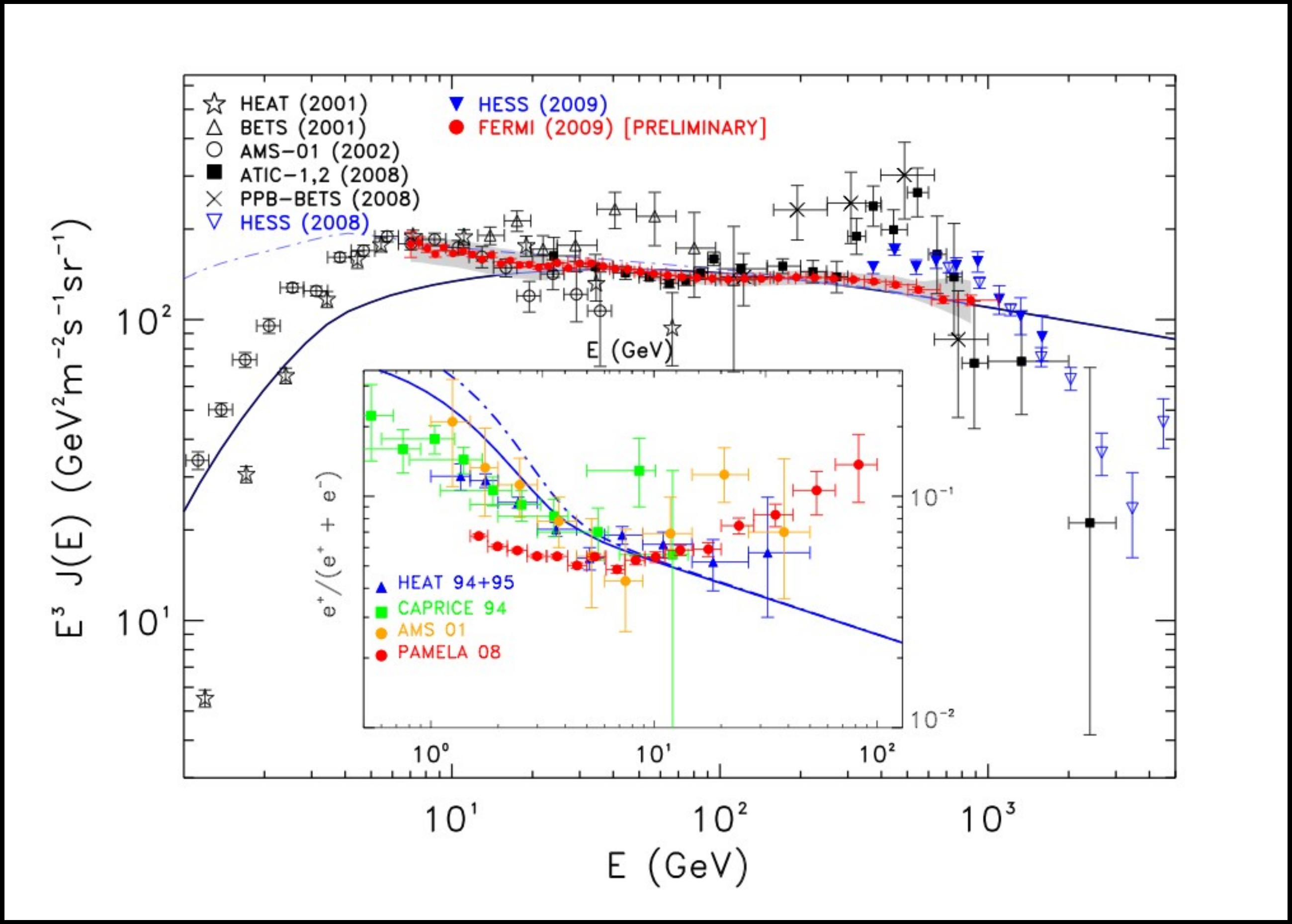
UV optical IR FIR CMB

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 over estimated, and an experimental check on them, if possible, is certainly worth while.

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

Very sincerely yours,

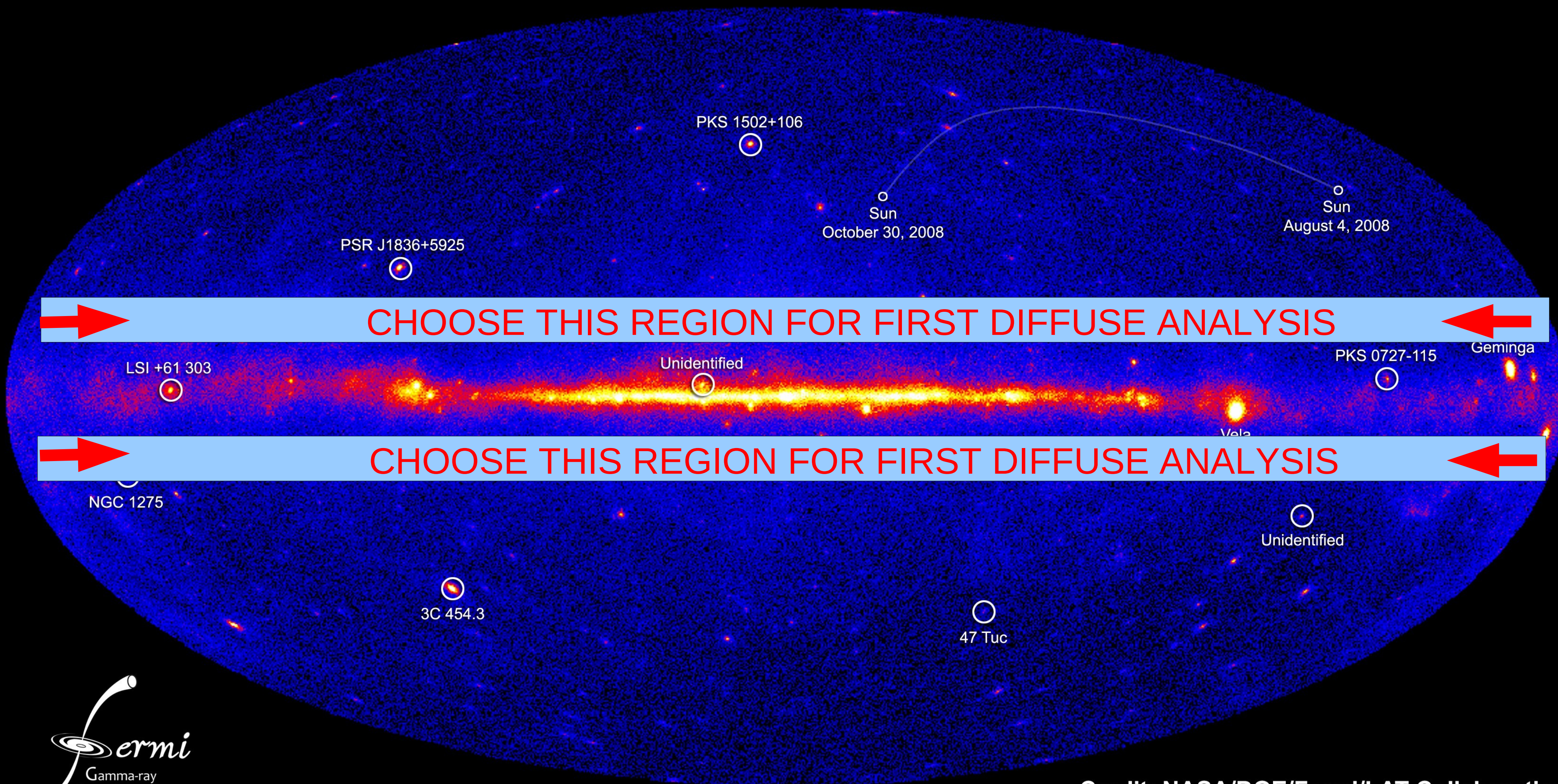
Enrico Fermi

Enrico Fermi

EF:al
encl.

FIRST LIGHT ON DIFFUSE GAMMA RAYS

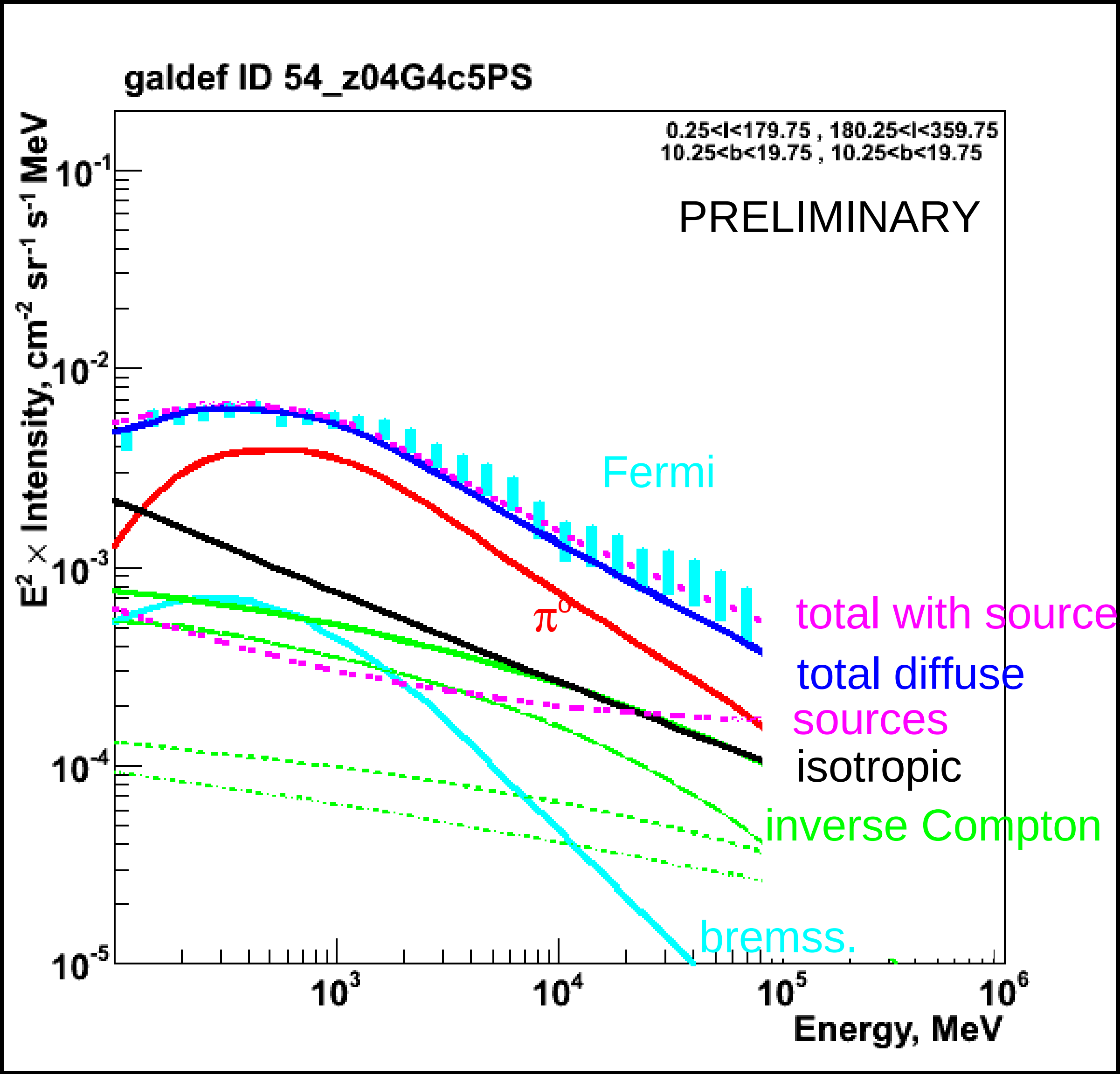
NASA's Fermi telescope reveals best-ever view of the gamma-ray sky



fermi
Gamma-ray
Space Telescope

Credit: NASA/DOE/Fermi/LAT Collaboration

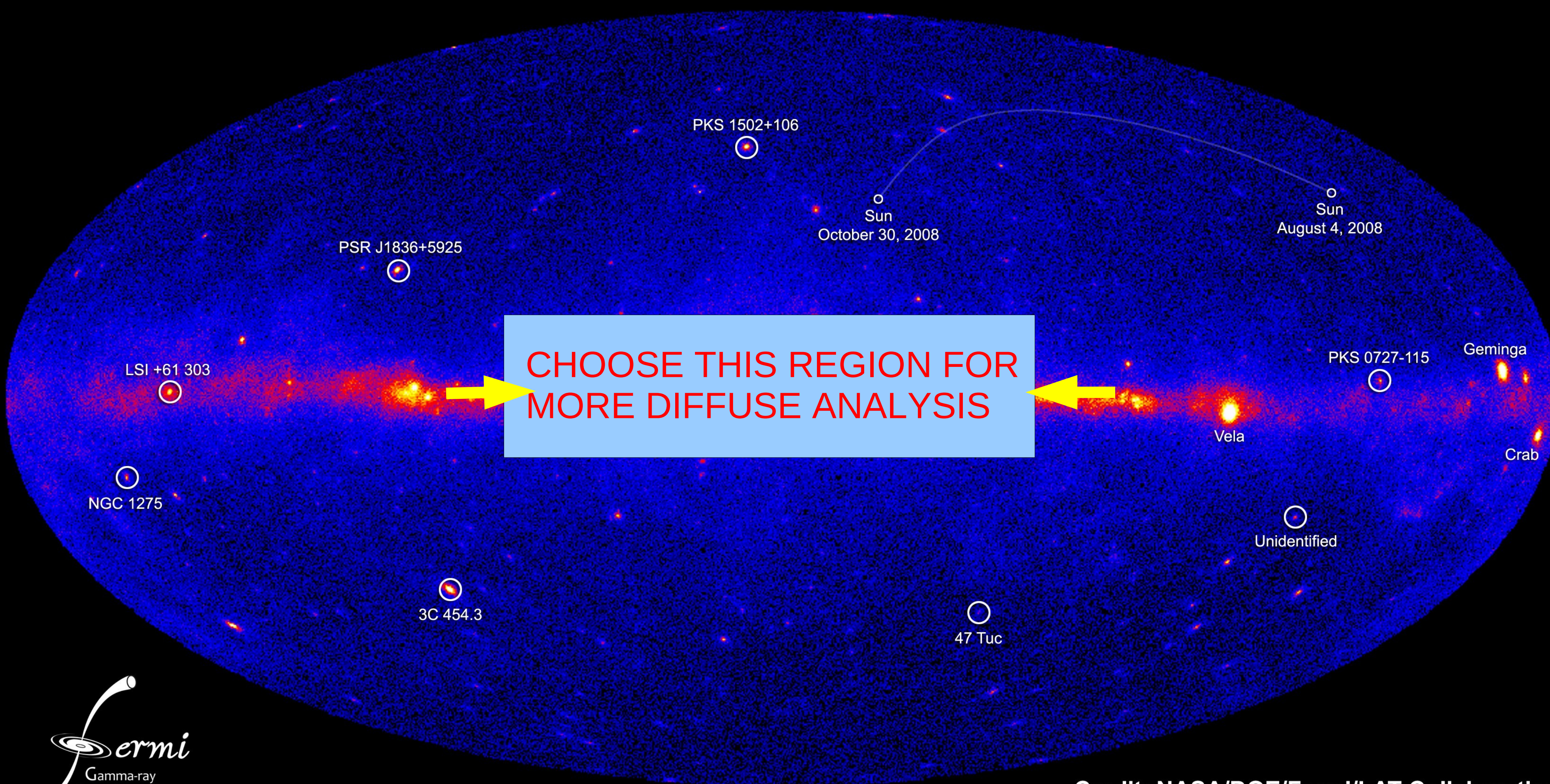
INTERMEDIATE LATITUDES
+10 < b < +20



Good agreement overall with *a-priori GALPROP* model

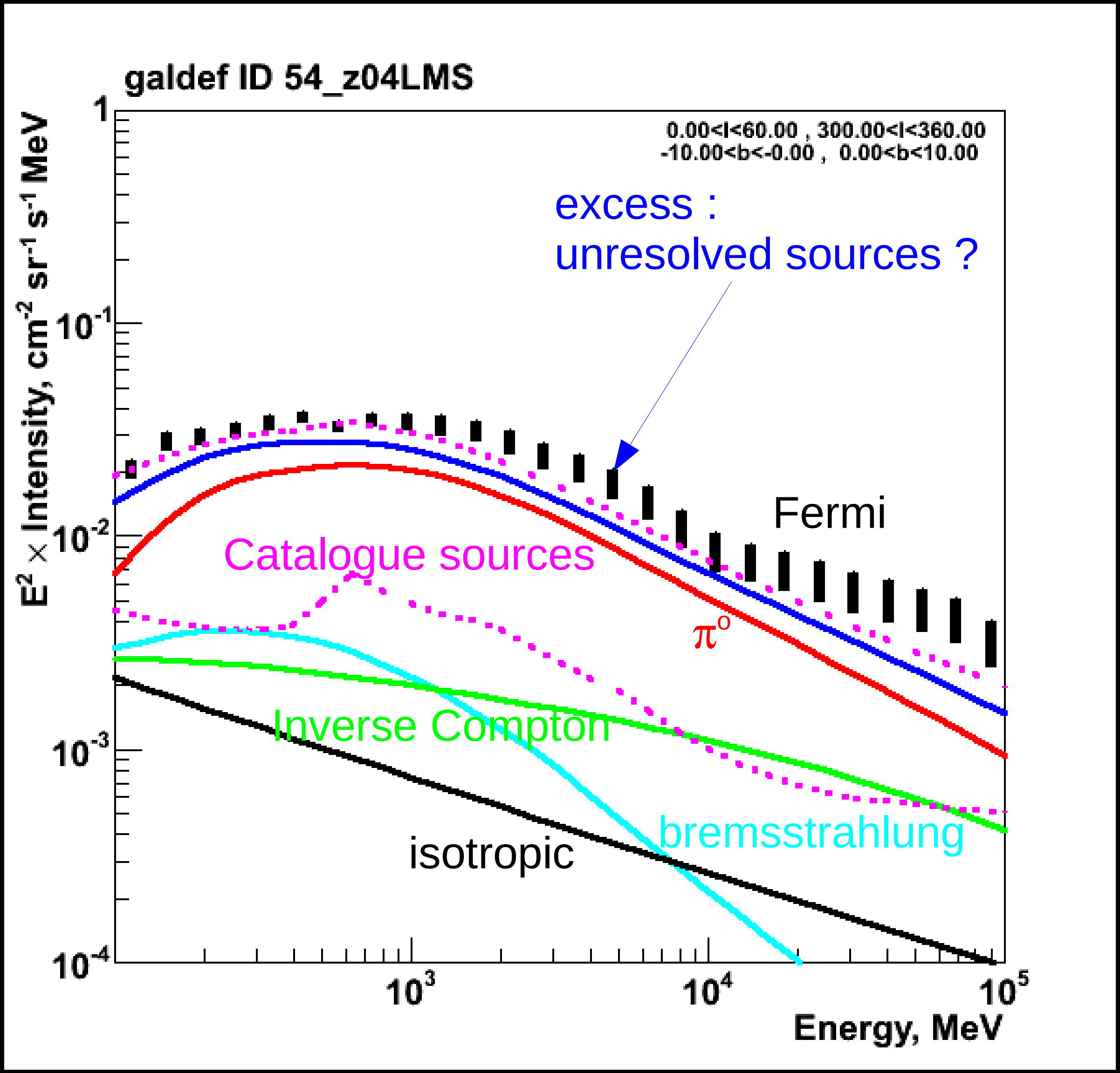
MORE LIGHT ON DIFFUSE GAMMA RAYS

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



Credit: NASA/DOE/Fermi/LAT Collaboration

Inner Galaxy
300° < l < 60°, |b|<10°



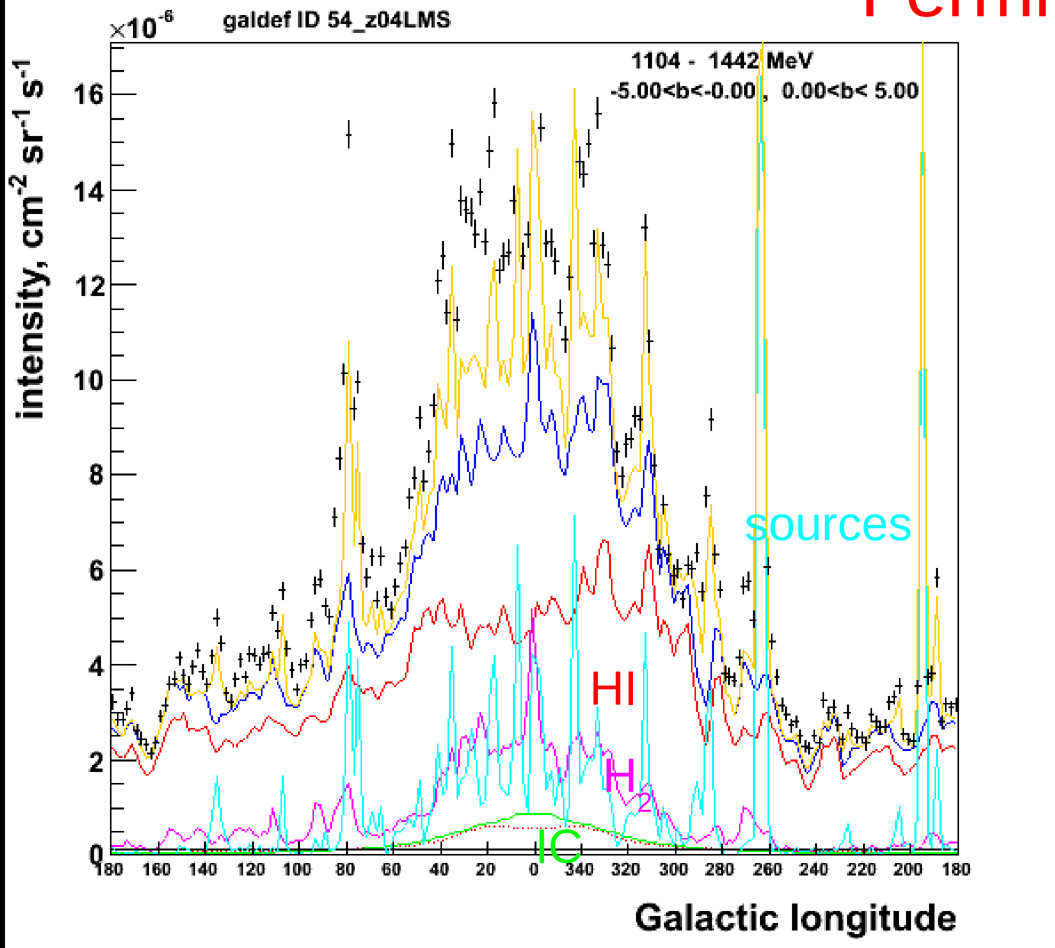
Good agreement overall with *a-priori* GALPROP model

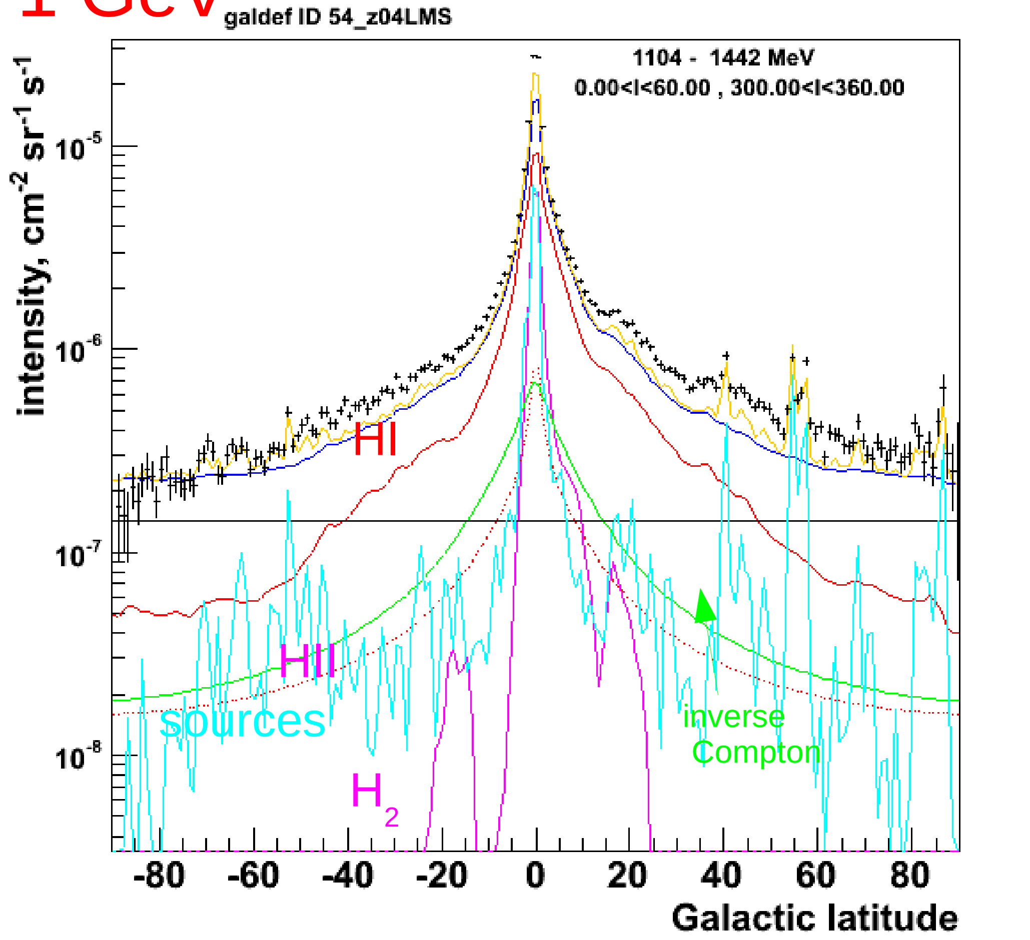
Strong 2010, Proc ICATPP Conf. Villa Olmo, arXiv:1101.1381

LONGITUDE PROFILE LOW LATITUDES

LATITUDE PROFILE INNER GALAXY

Fermi 1 GeV



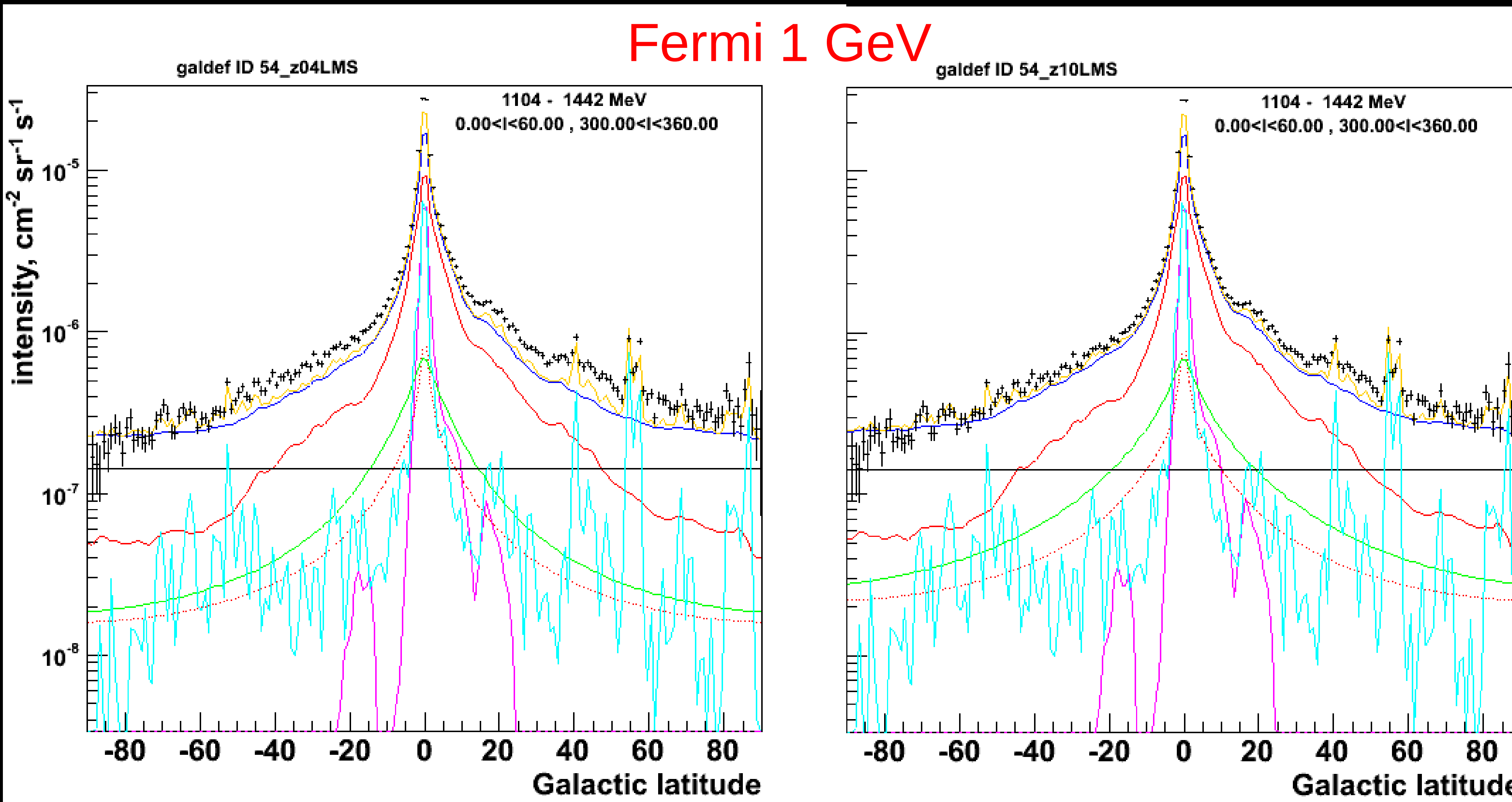


Agrees within 15% over 2 decades of dynamic range
The observed flux is the sum of many components:
importance of modelling them all !

Strong 2010, Proc ICATPP Conf. Villa Olmo, arXiv:1101.1381

EVIDENCE FOR LARGE COSMIC-RAY HALO

4 kpc halo height 10 kpc halo height

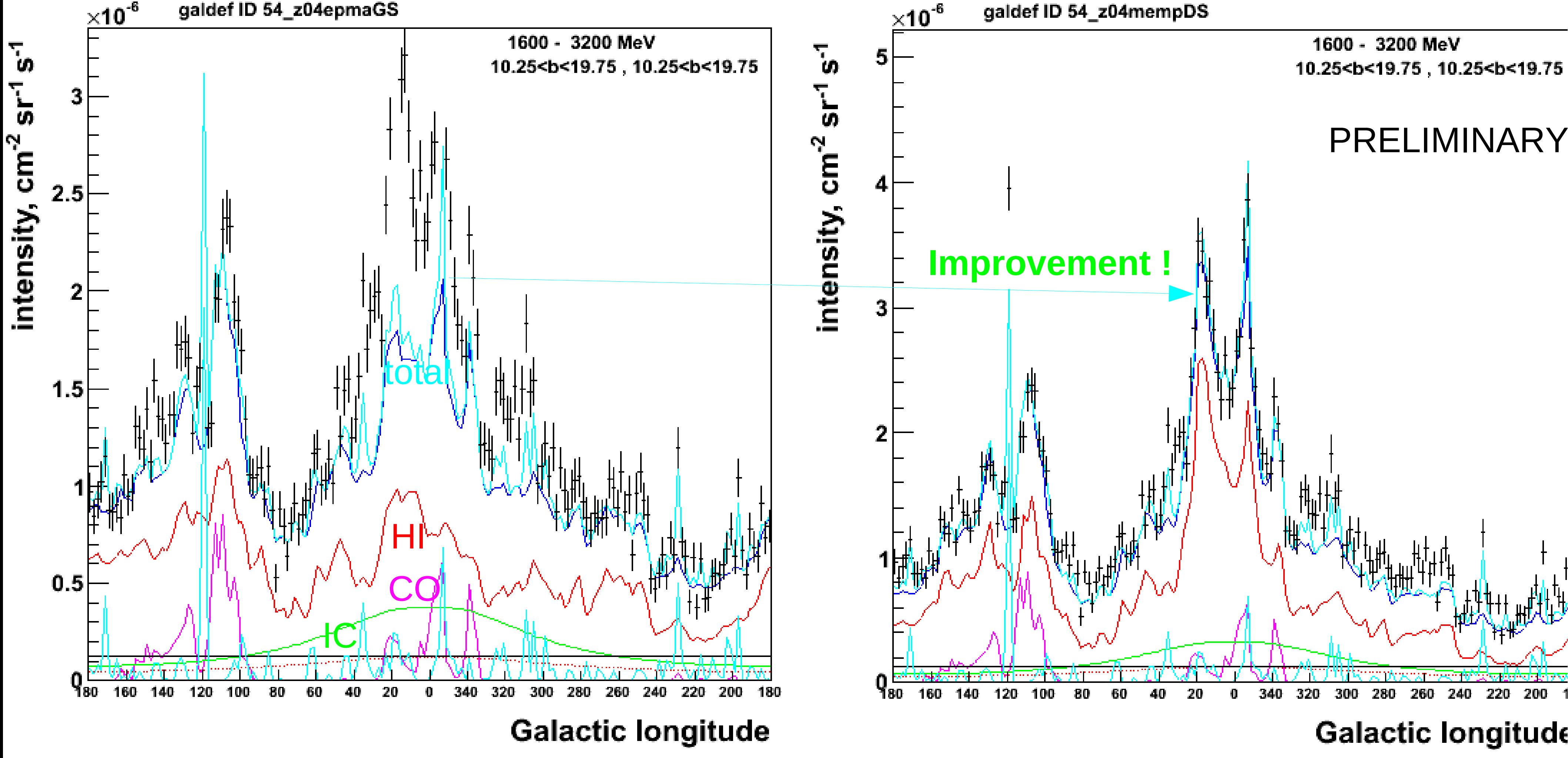


inverse Compton at high latitudes suggests a *large cosmic-ray halo*
Important for halo magnetic field ! Relevant to Planck !

Strong 2010, Proc ICATPP Conf. Villa Olmo, arXiv:1101.1381

HI + CO   GAS TRACER   dust

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

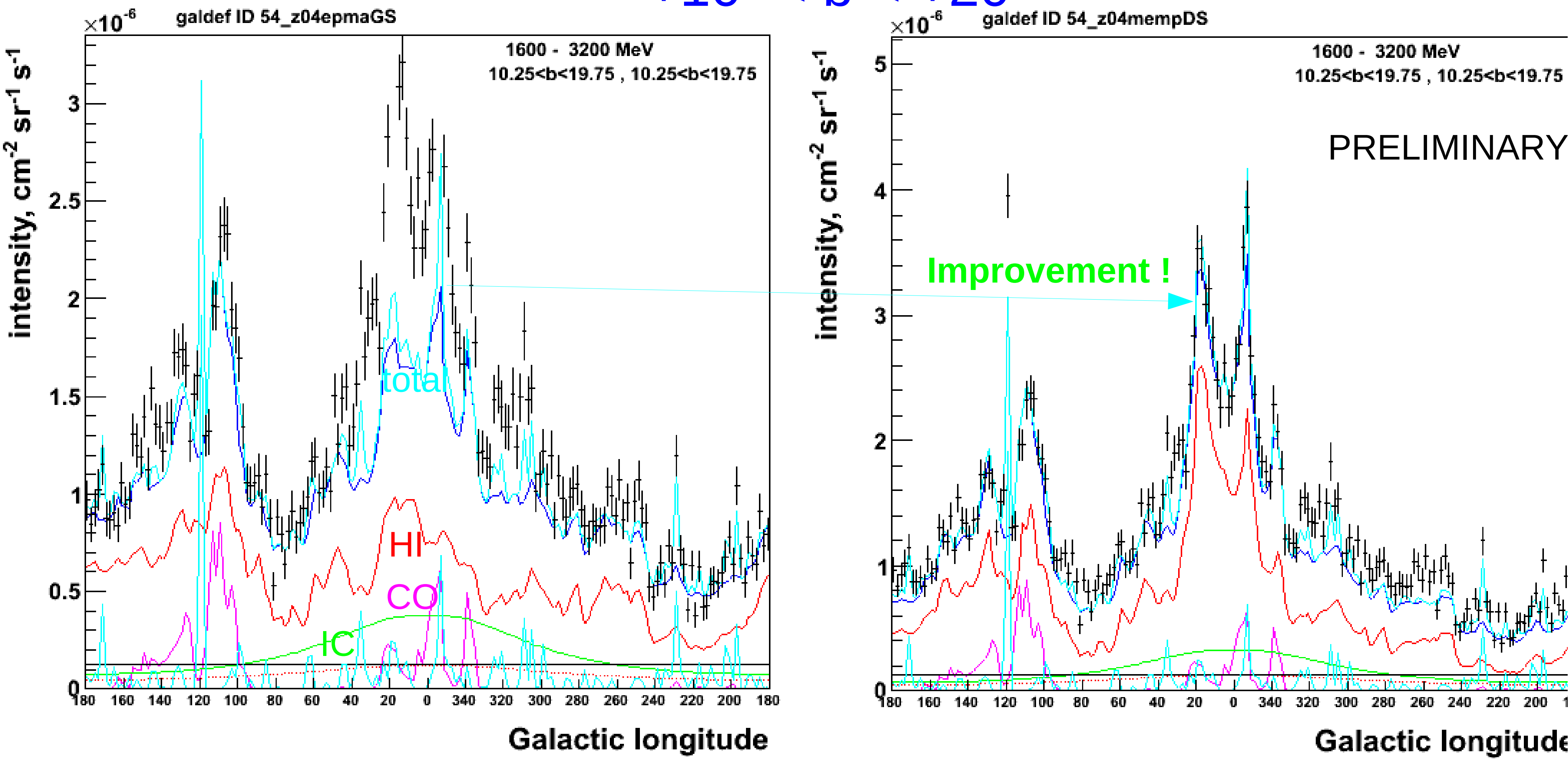


Fermi: GeV gamma rays from cosmic-ray + gas interactions

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

HI + CO GAS TRACER dust

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



Fermi: GeV gamma rays from cosmi

'dark gas' : independent evidence from
Planck (arXiv:1101.2029)

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

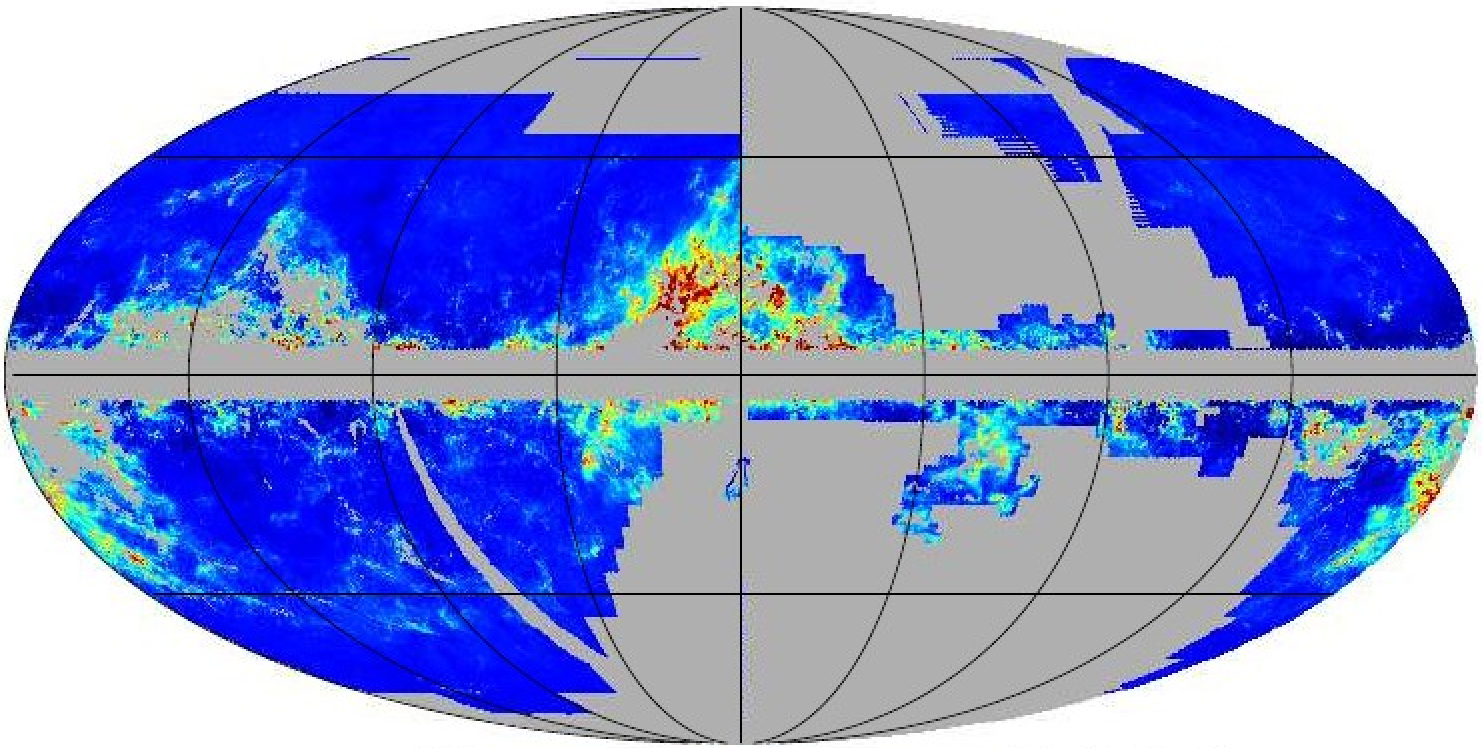


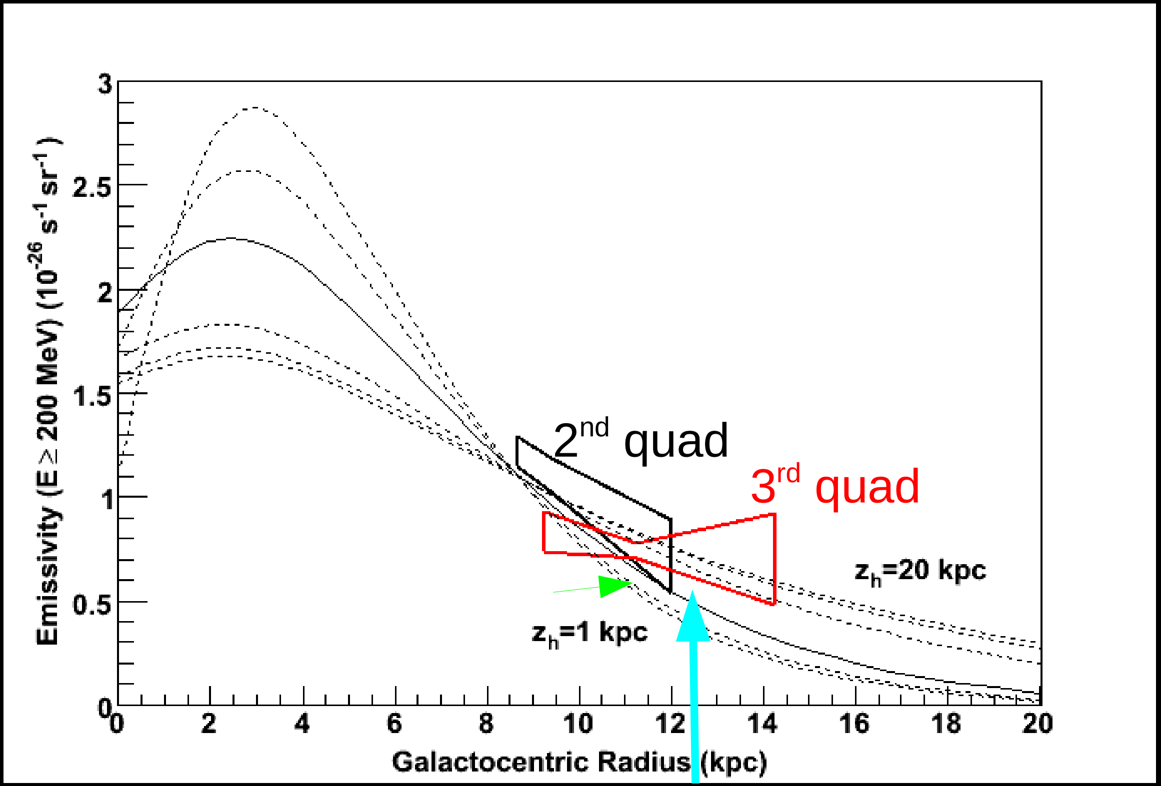
Fig. 8. Map of the excess column density derived from the 857 GHz data. The map is shown in Galactic coordinates with the Galactic centre at the centre of the image. The grey regions correspond to those where no *IRAS* data are available, regions with intense CO emission ($W_{CO} > 1$ Kkms^{-1}) and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

Planck (arXiv:1101.2032)

Gamma-ray emissivity distribution in *outer* Galaxy

From Fermi-LAT

2nd and 3rd Galactic Quadrants



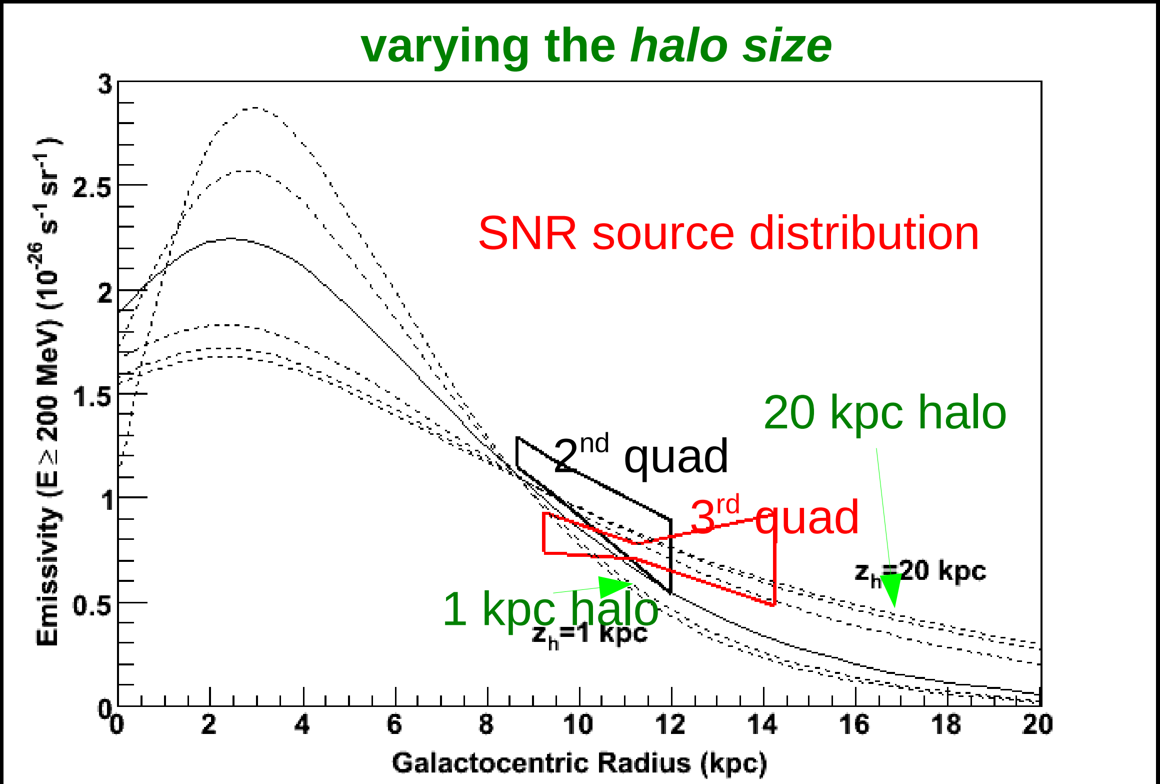
More cosmic-rays in outer Galaxy than expected !

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

Gamma-ray emissivity distribution in outer Galaxy

From Fermi-LAT

2^{nd} and 3^{rd} Galactic Quadrants



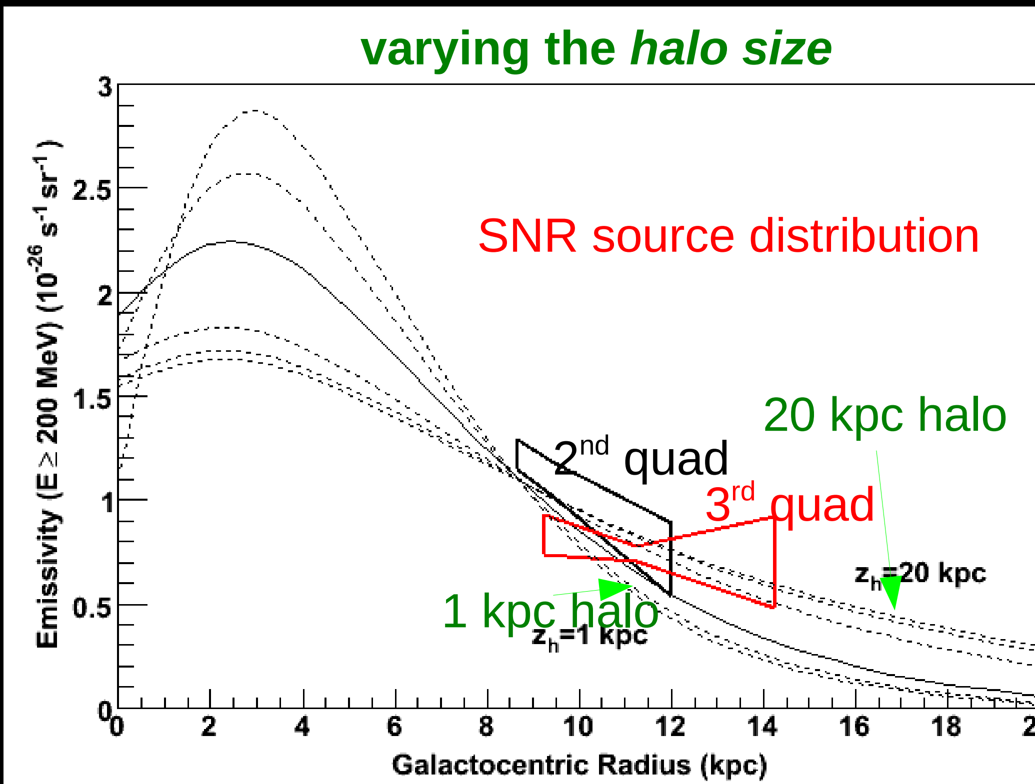
More cosmic-rays in outer Galaxy than expected !

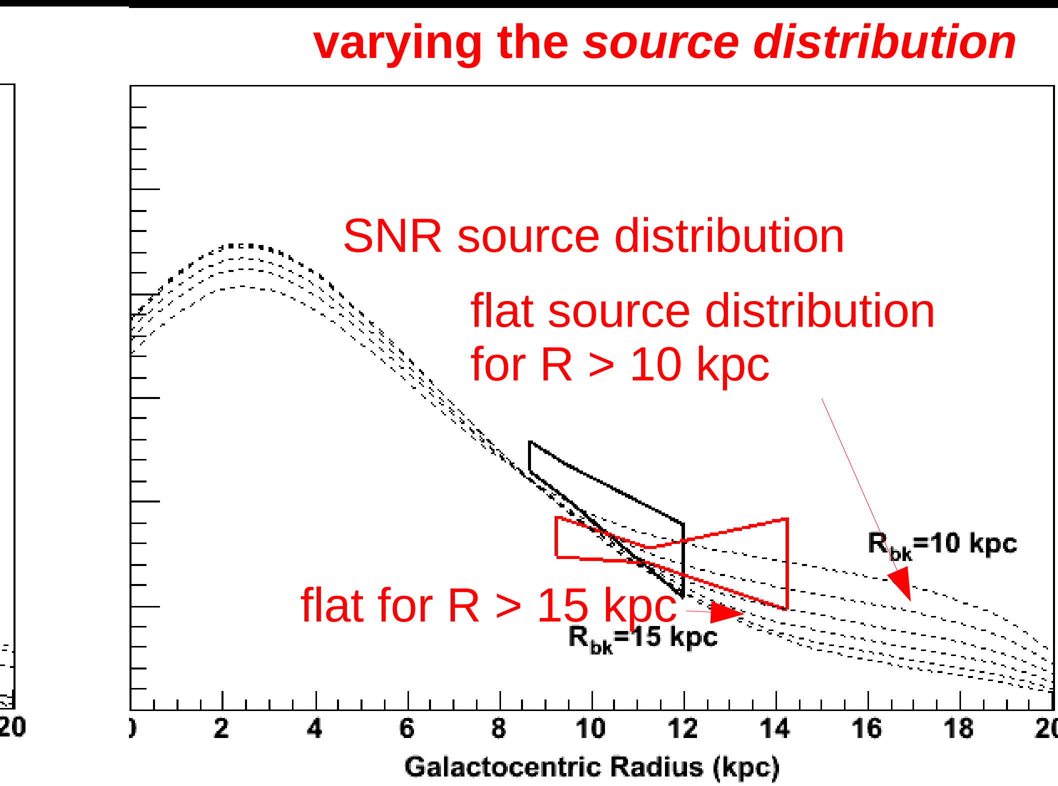
More evidence for large halo, which widens the distribution ?

Gamma-ray emissivity distribution in outer Galaxy

From Fermi-LAT

2^{nd} and 3^{rd} Galactic Quadrants





More cosmic-rays in outer Galaxy than expected !

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

Or **more gas** than traced by HI + CO ?

'dark gas' : independent evidence from Planck (arXiv:1101.2029)

but not enough to explain the gamma rays ?

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

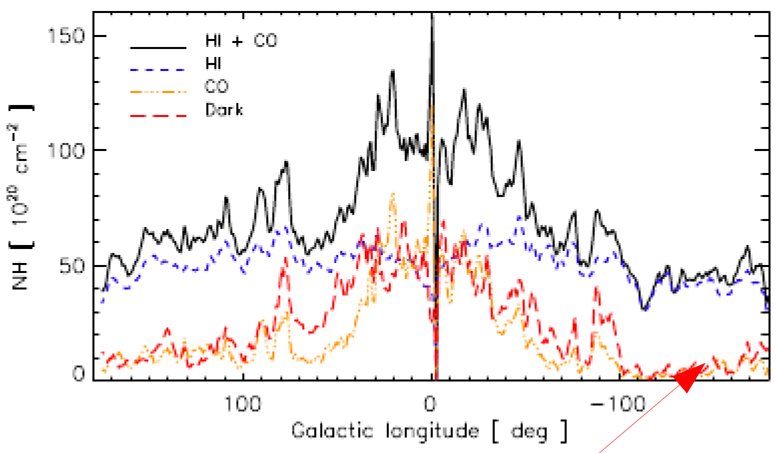


Fig. 2. Longitude profile of H I, CO and dark gas. The dark gas represents a significant fraction of the gas column density, and dominates the CO outside of the molecular ring.

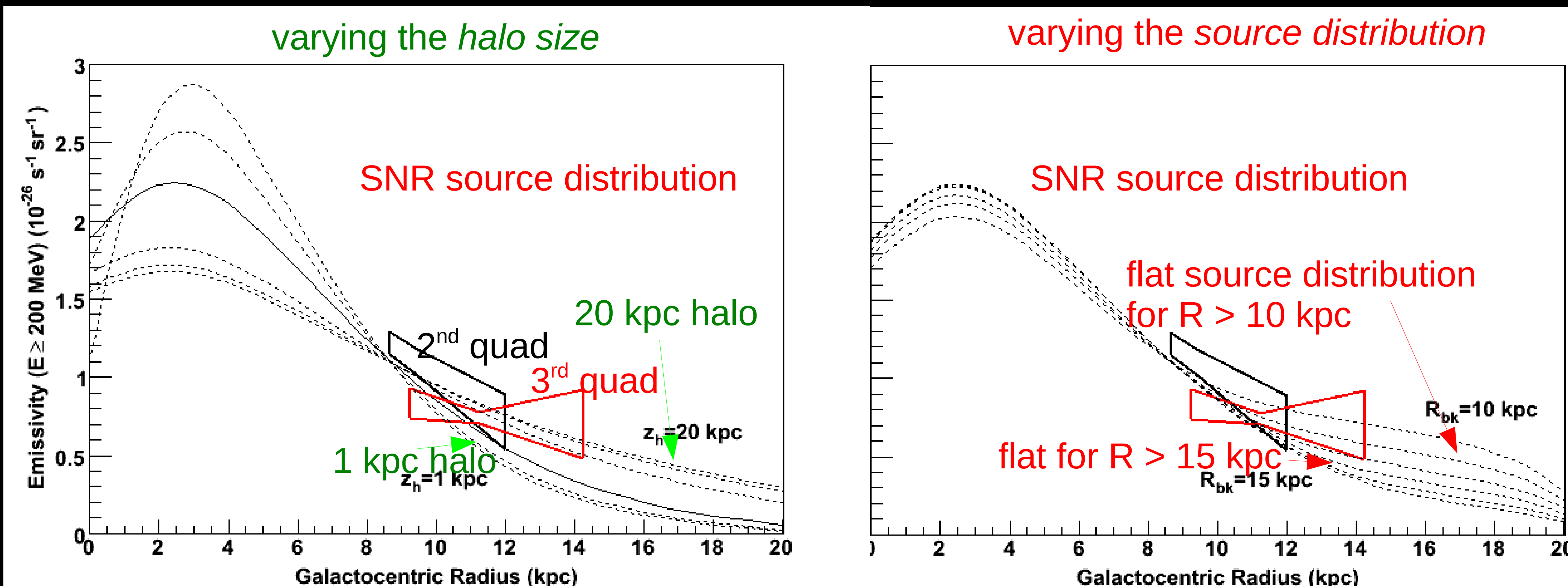
Planck (arXiv:1101.2032)

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

Gamma-ray emissivity distribution in outer Galaxy

From Fermi-LAT

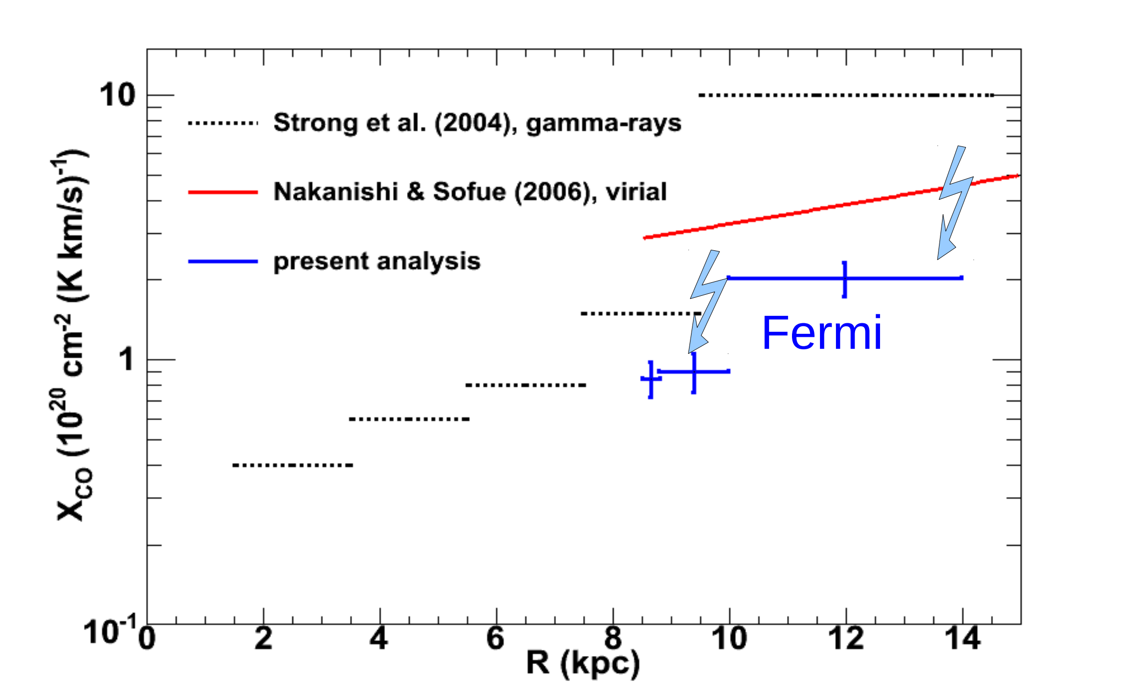
2^{nd} and 3^{rd} Galactic Quadrants



Implications for synchrotron / B-field models

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

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

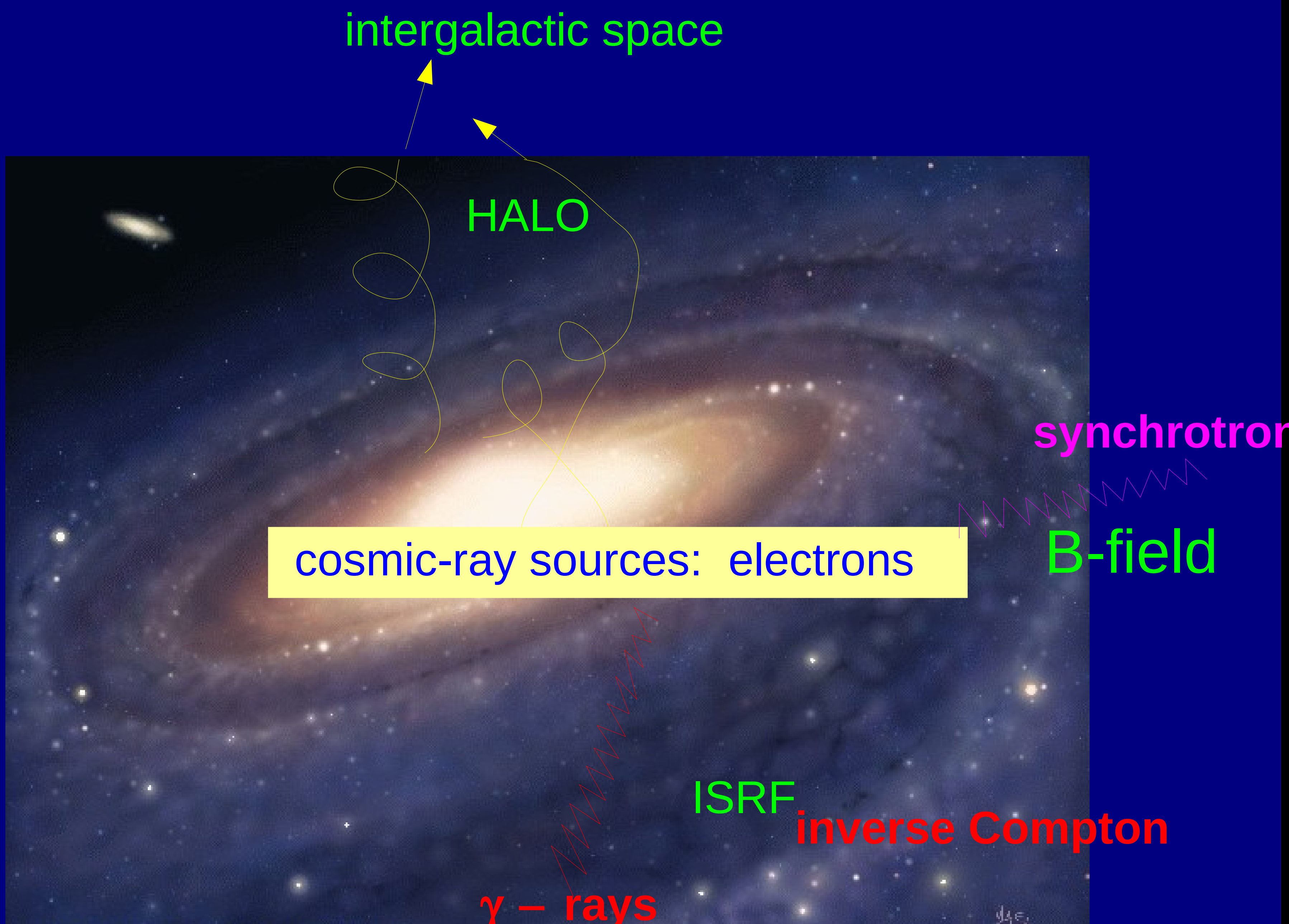


Scaling factor Xco from ^{12}CO to H_2
Local and Outer Galaxy (2nd quadrant)

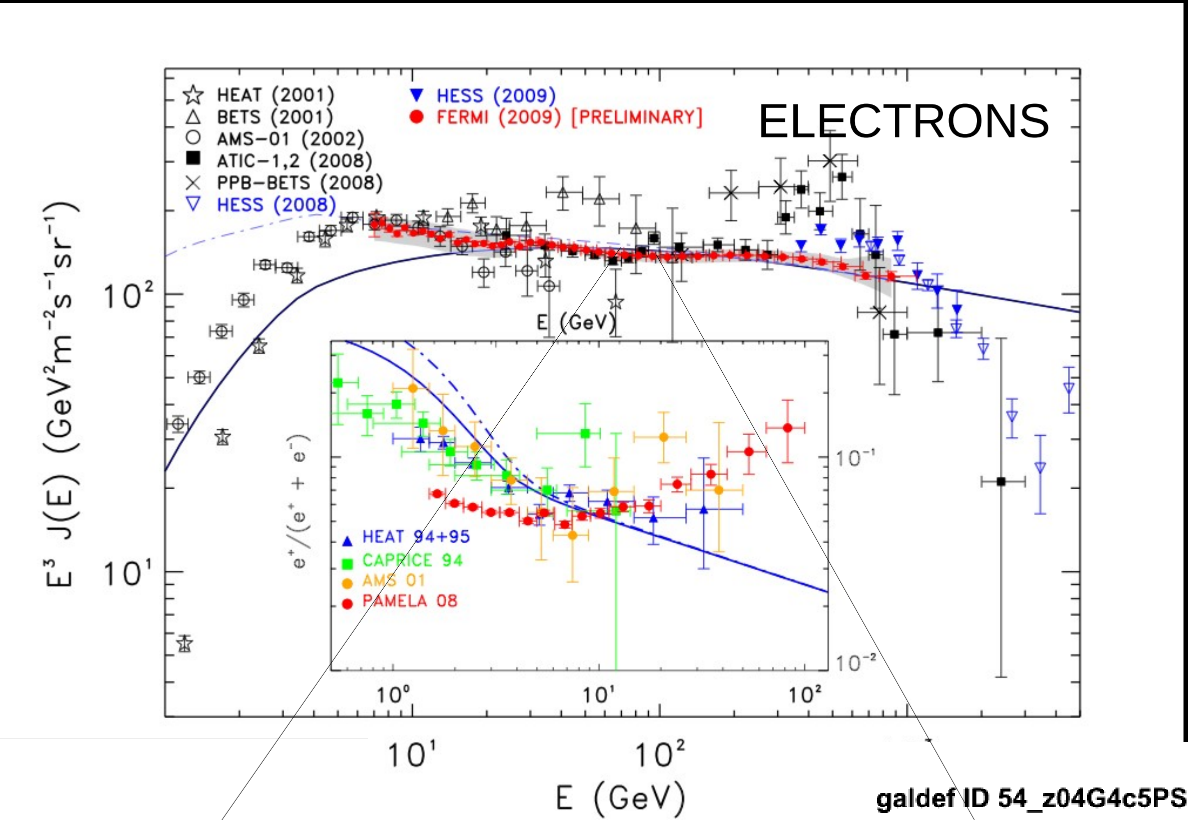
Confirms *increase* from inner to outer Galaxy

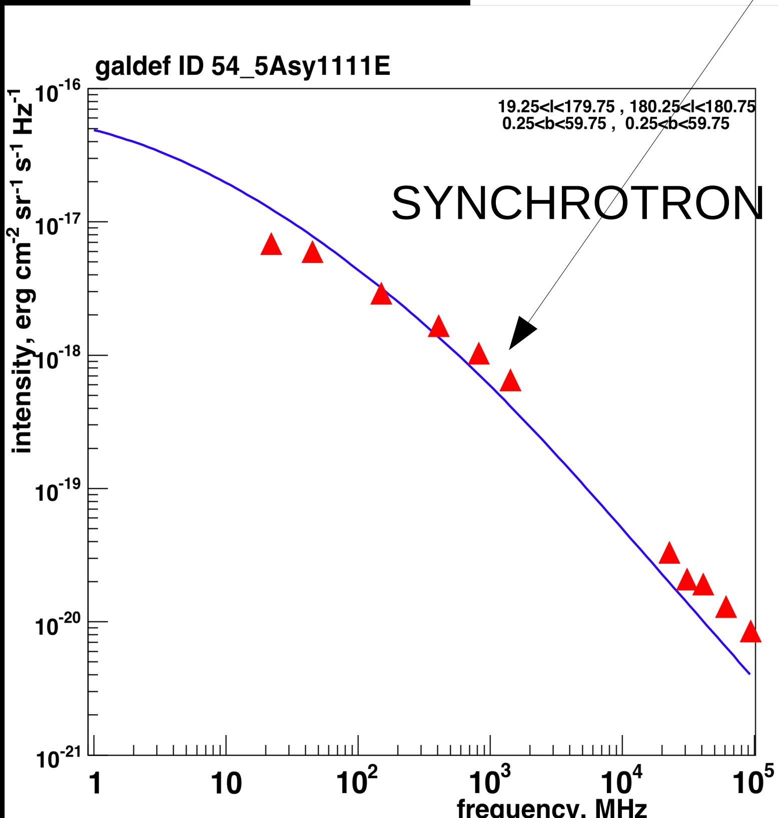
Abdo etal (2010) ApJ 710, 133

Cosmic Ray Electrons Synchrotron and Magnetic Fields



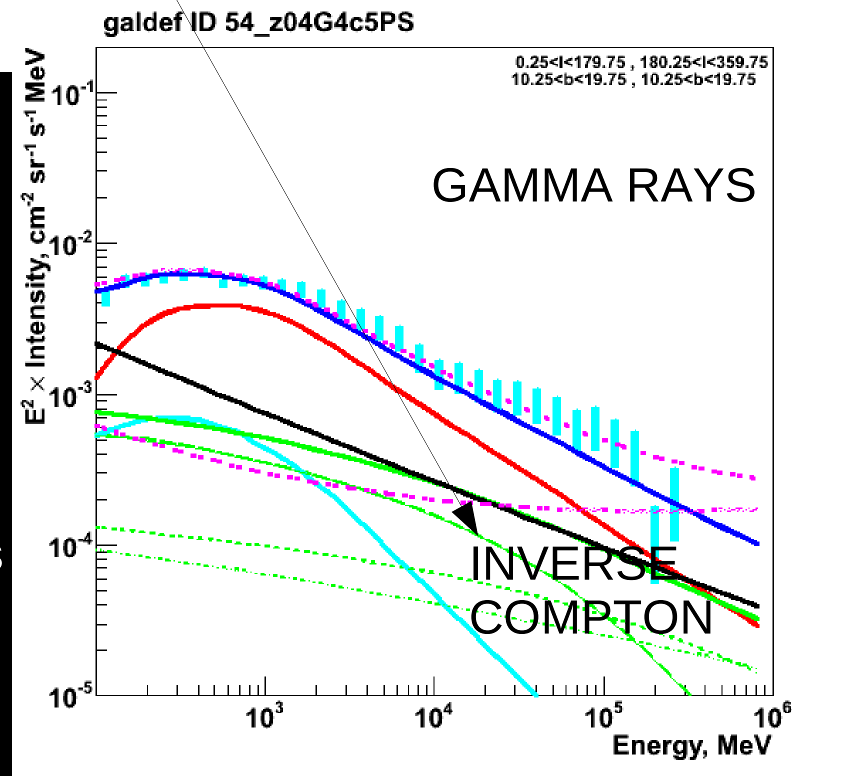
Cosmic-ray electrons provide the link radio – gamma ray
Hence (one of the) Fermi – Planck connection(s) !

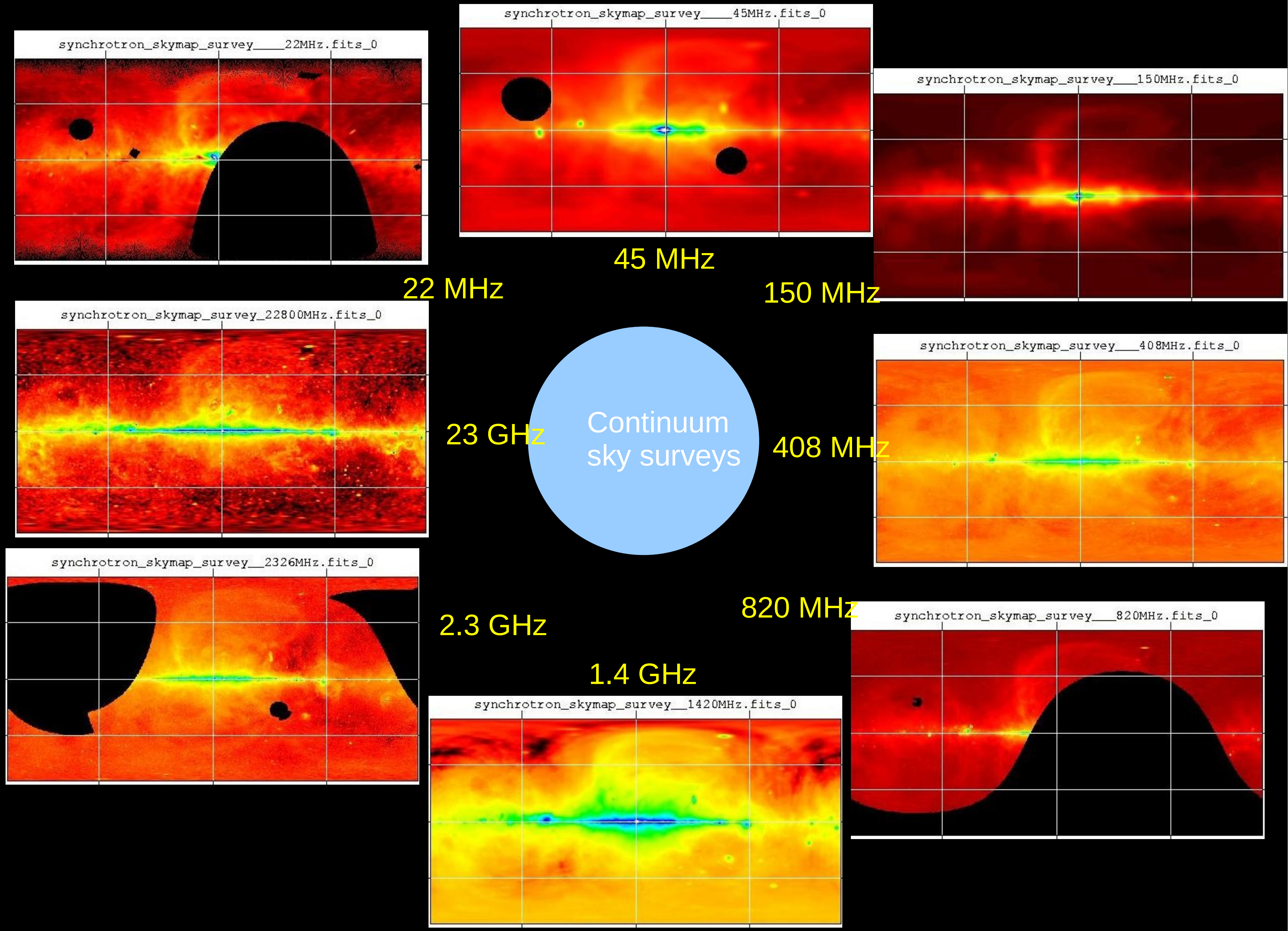


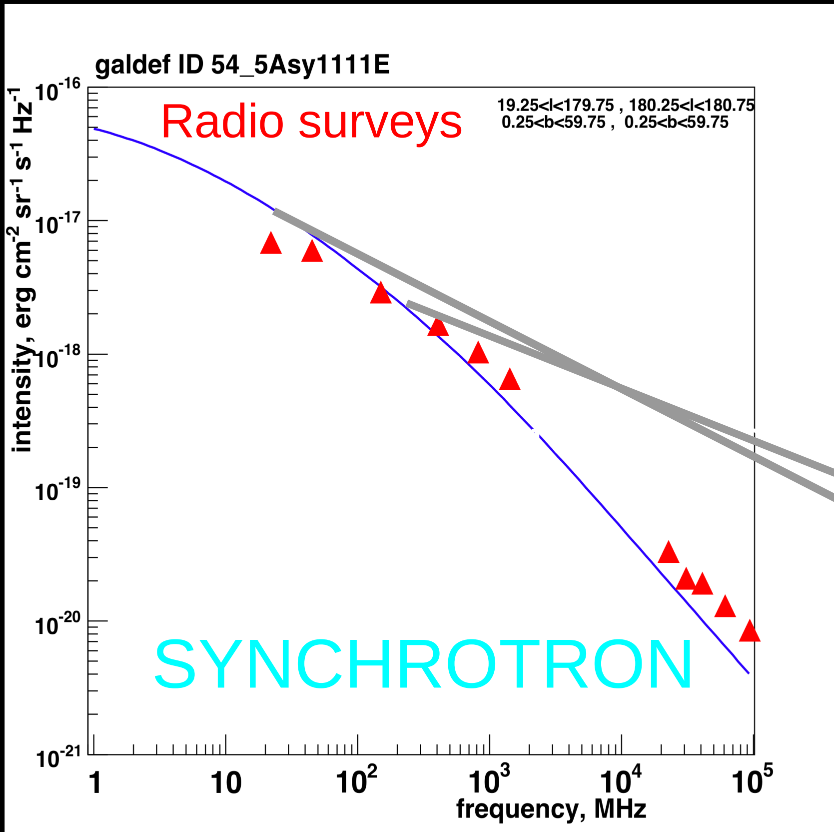


SAME
ELECTRONS
for
RADIO
and
GAMMA RAYS !

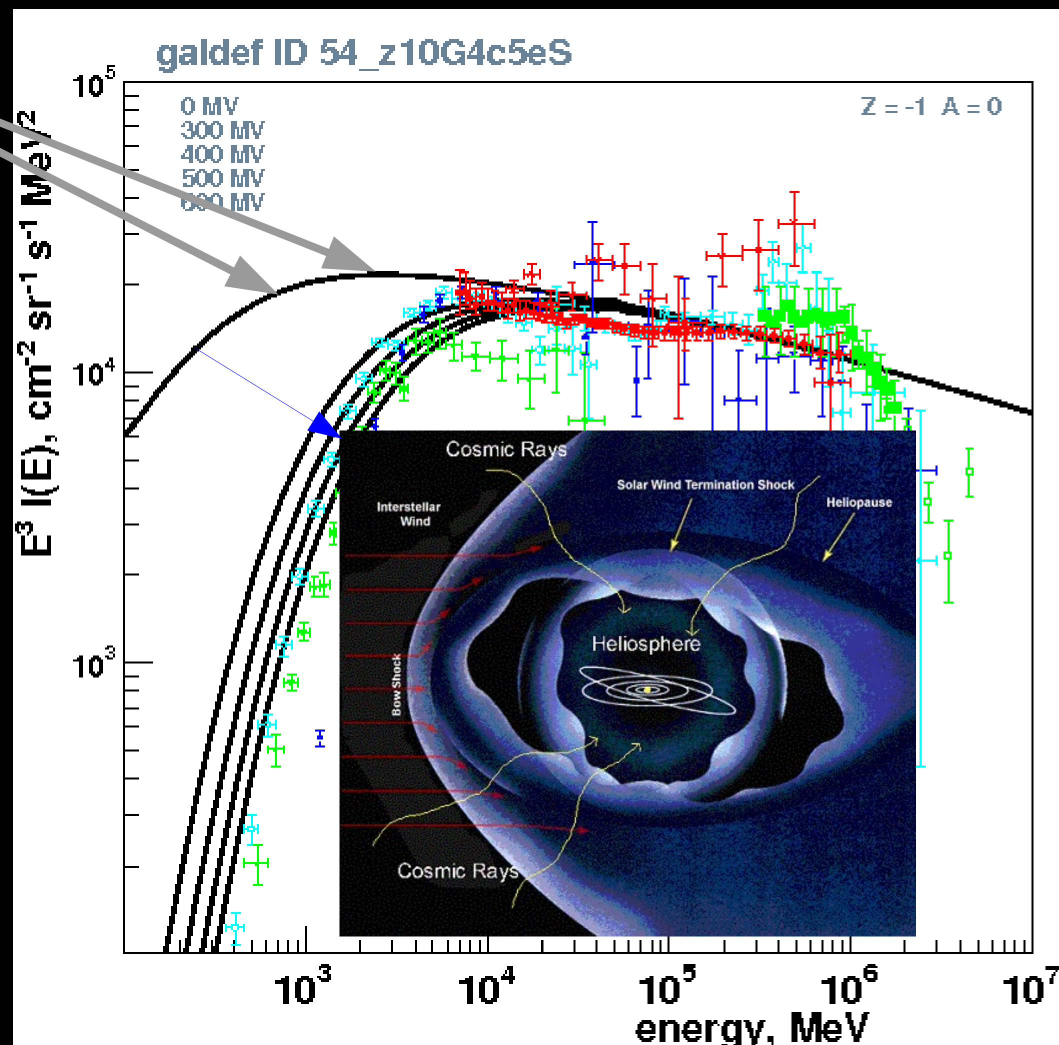
good constraints
on models




synchrotron_skymap_survey____22MHz.fits_0
synchrotron_skymap_survey____45MHz.fits_0
synchrotron_skymap_survey___150MHz.fits_0
45 MHz
22 MHz
150 MHz
synchrotron_skymap_survey_22800MHz.fits_0
synchrotron_skymap_survey___408MHz.fits_0
23 GHz
Continuum
sky surveys
408 MHz
synchrotron_skymap_survey__2326MHz.fits_0
820 MHz
synchrotron_skymap_survey___820MHz.fits_0
2.3 GHz
1.4 GHz
synchrotron_skymap_survey__1420MHz.fits_0



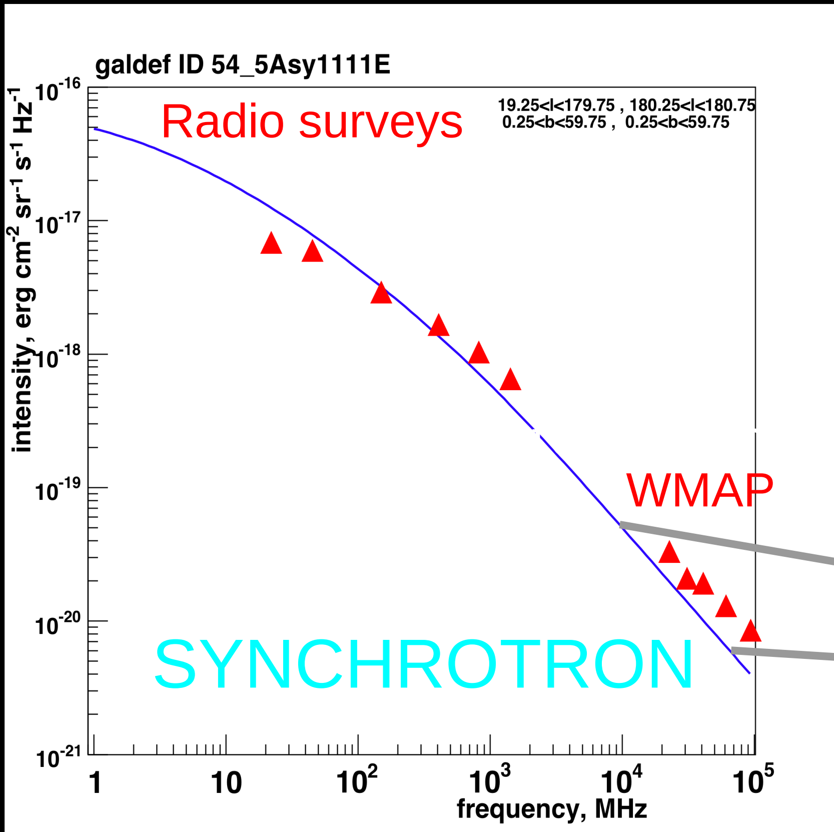
GALPROP
model

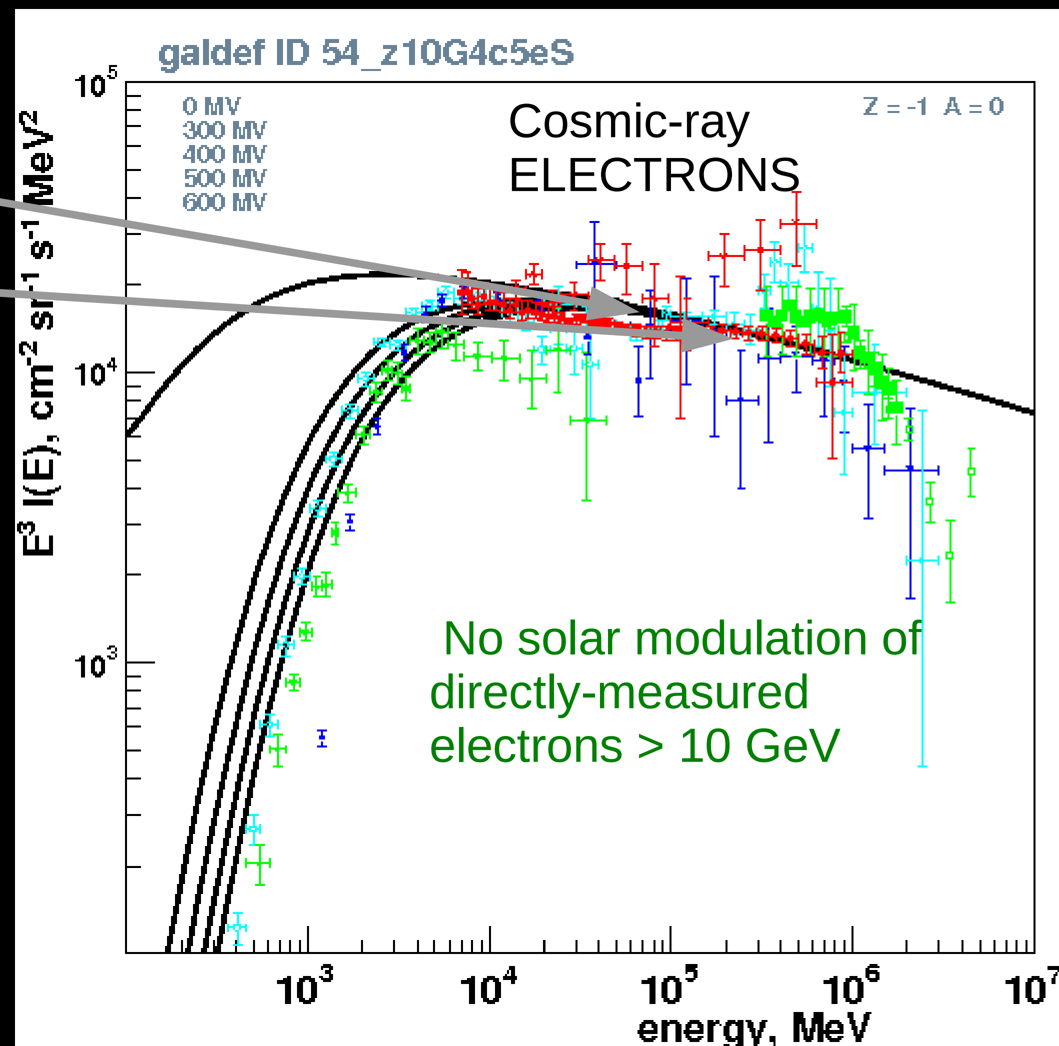


radio provides essential probe of interstellar electron spectrum at
E < few GeV
to complement direct measurements and determine solar modulation

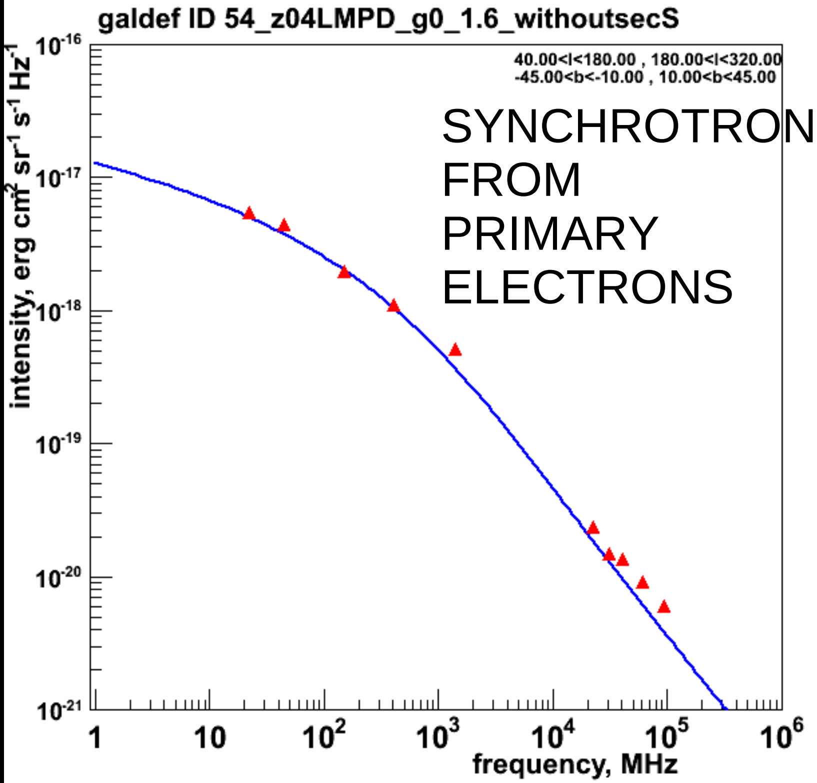
electrons have huge uncertainty due to modulation here

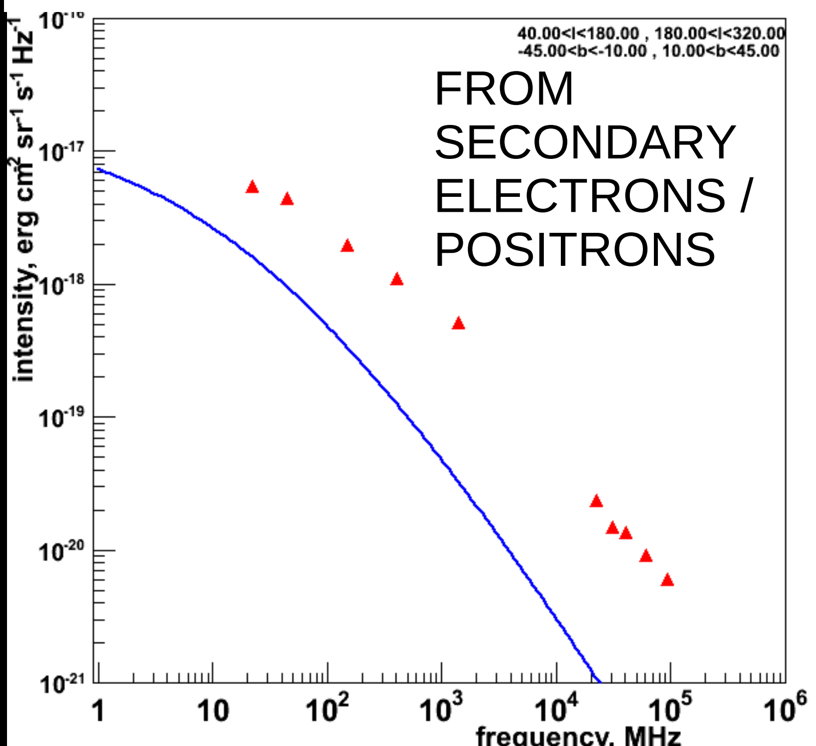
GALPROP
model

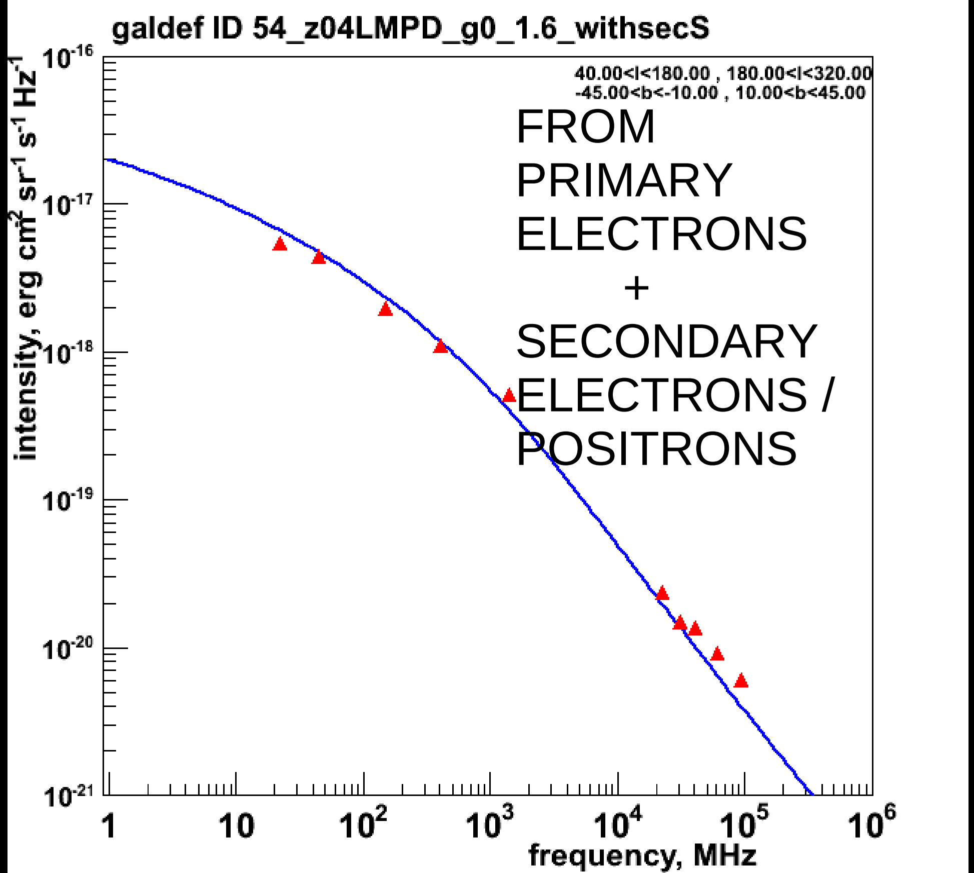




microwaves provide essential probe of
interstellar electron spectrum
10 - 100 GeV



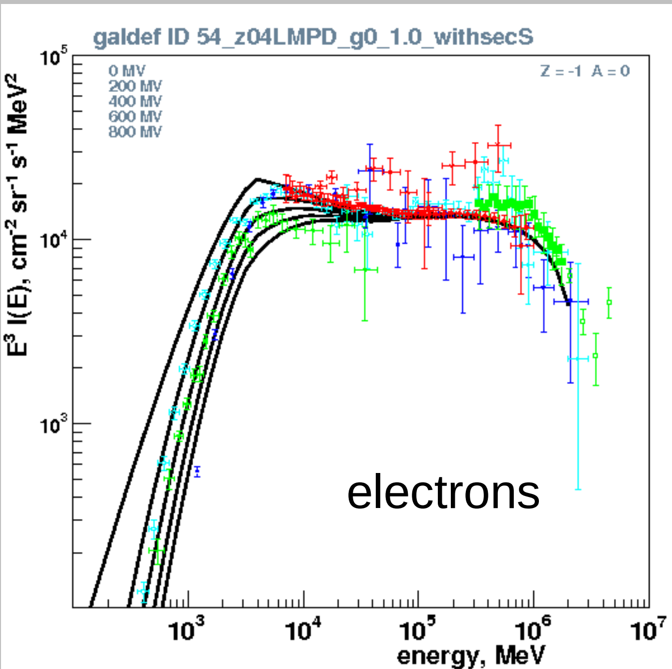


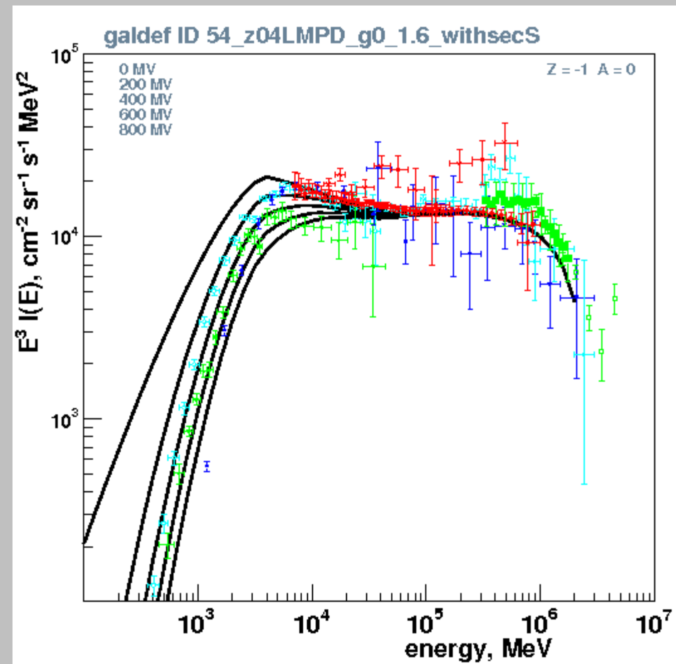


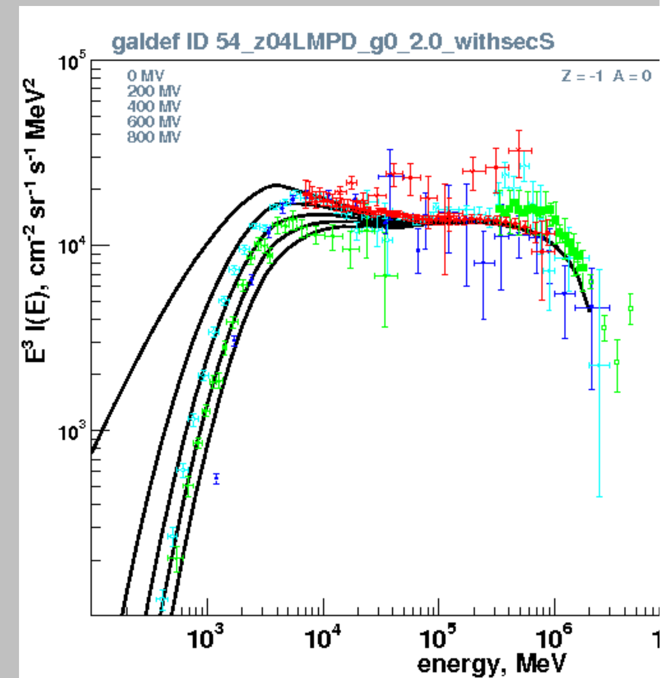
Secondary positrons
(and secondary electrons)
are important for synchrotron

Electron injection index

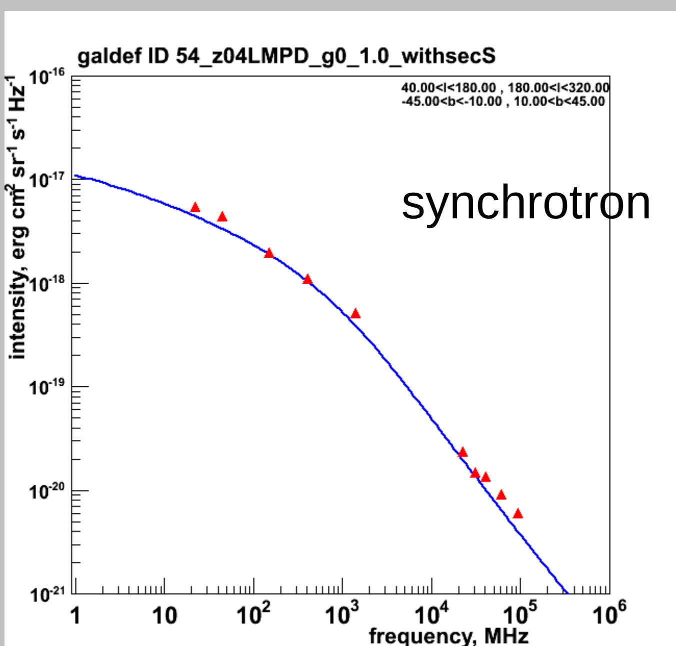
-1.0 -1.6 -2.0

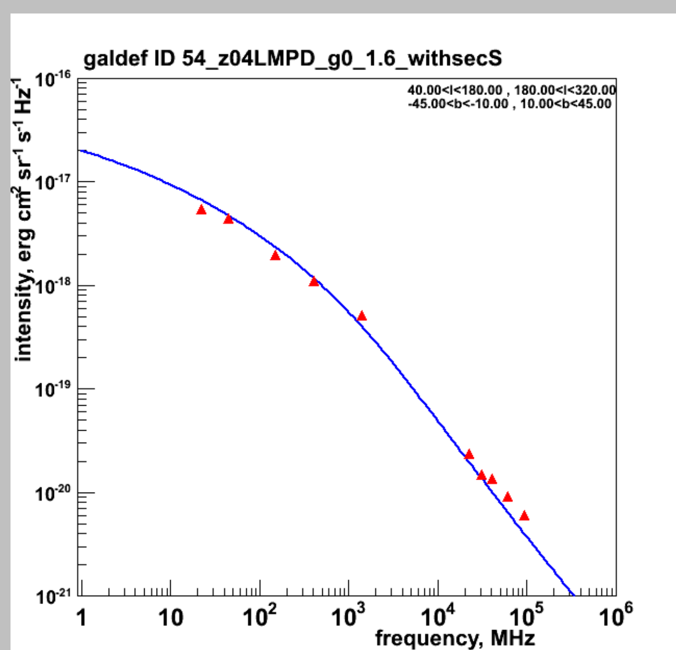


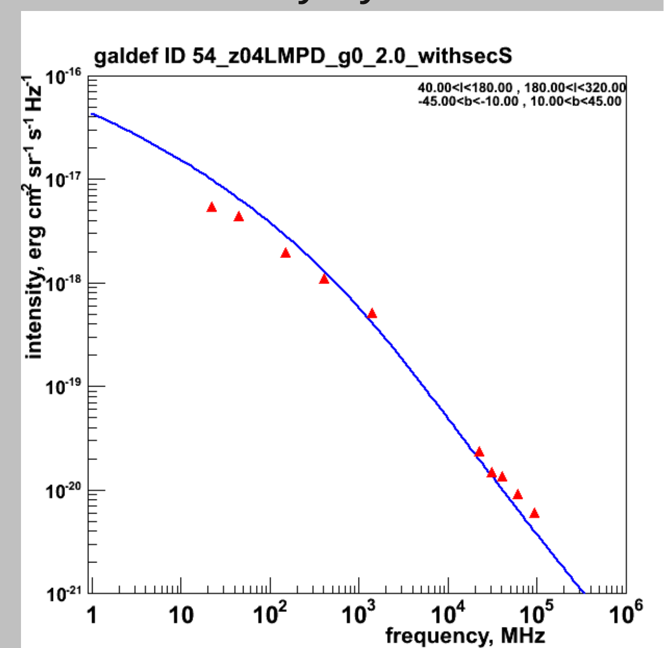




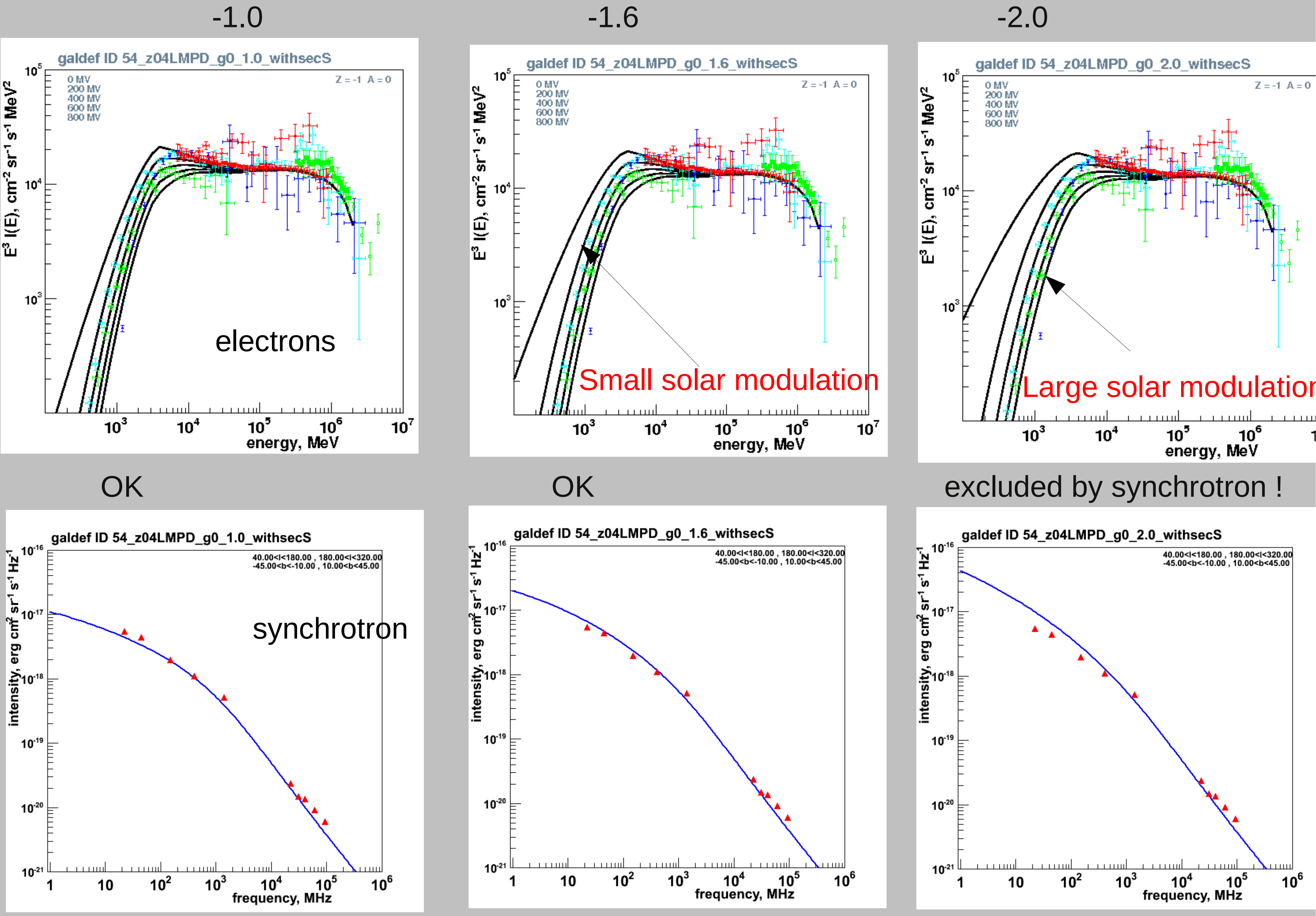
OK OK excluded by synchrotron !





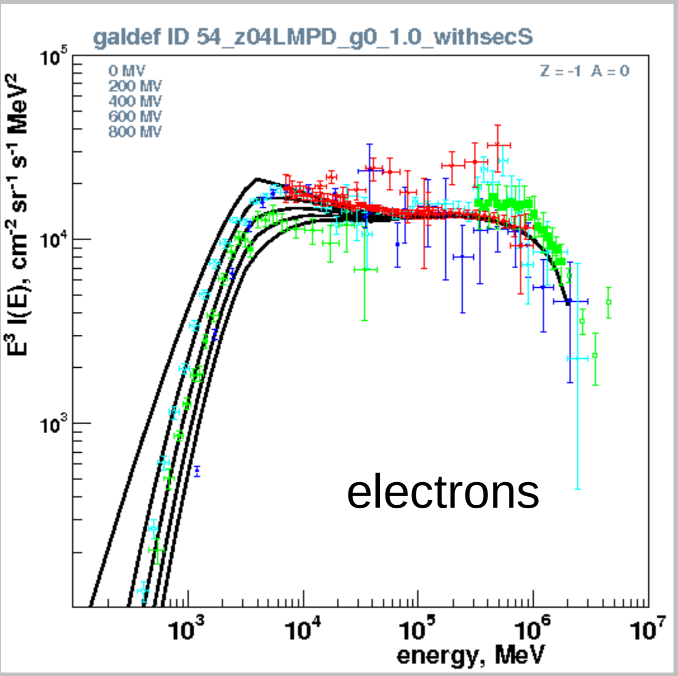


Electron injection index

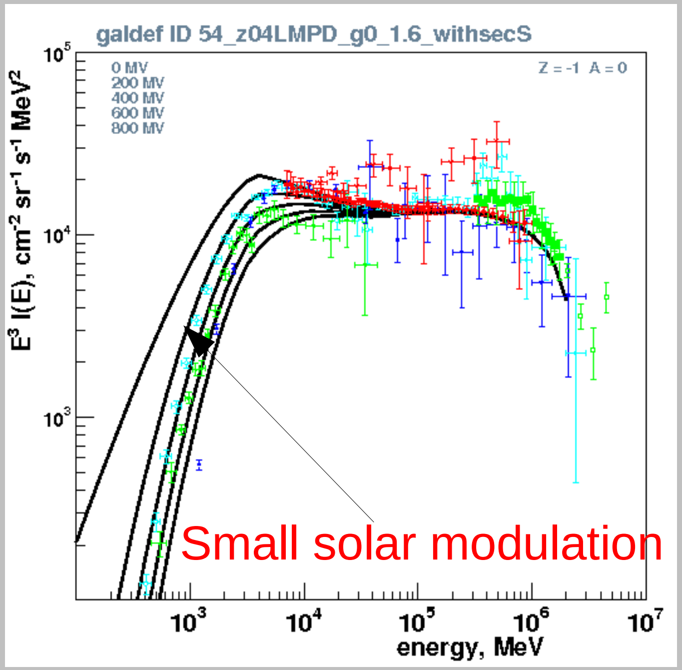


Electron injection index

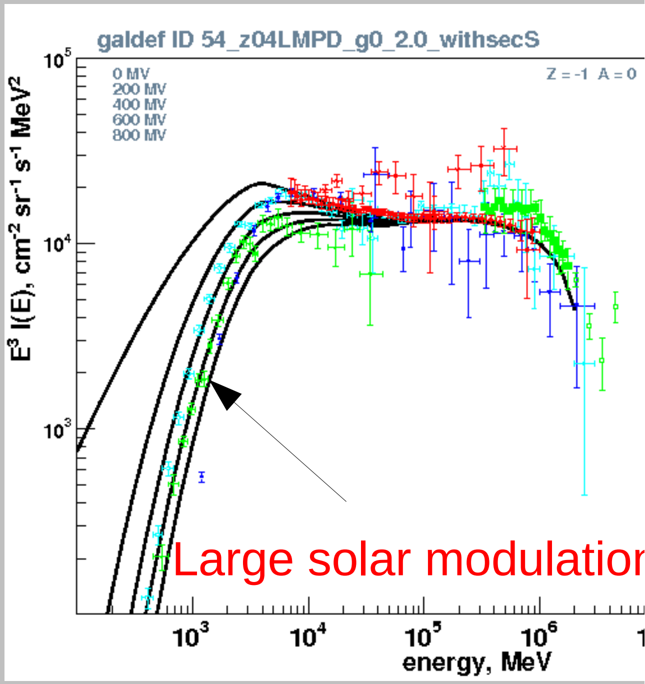
-1.0



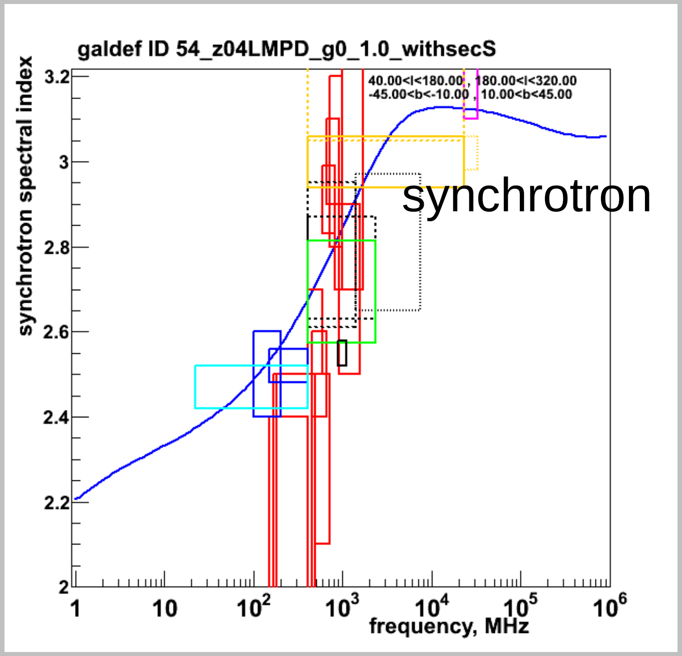
-1.6



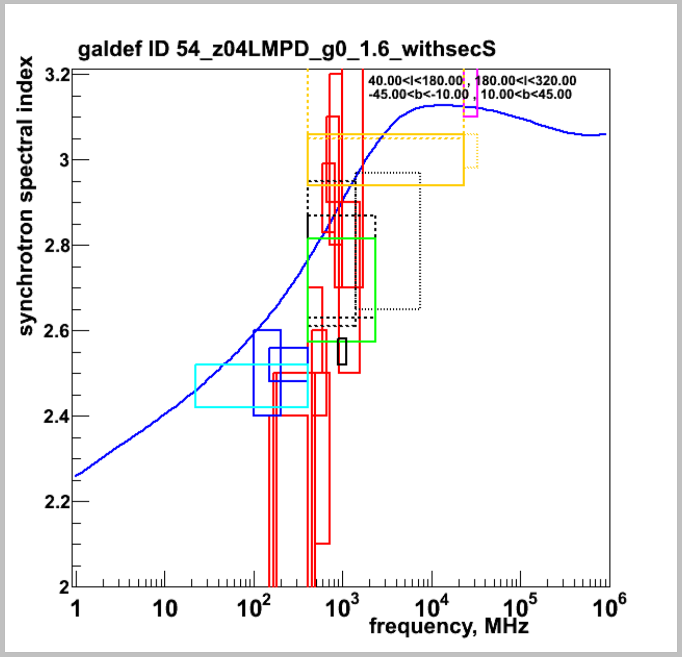
-2.0



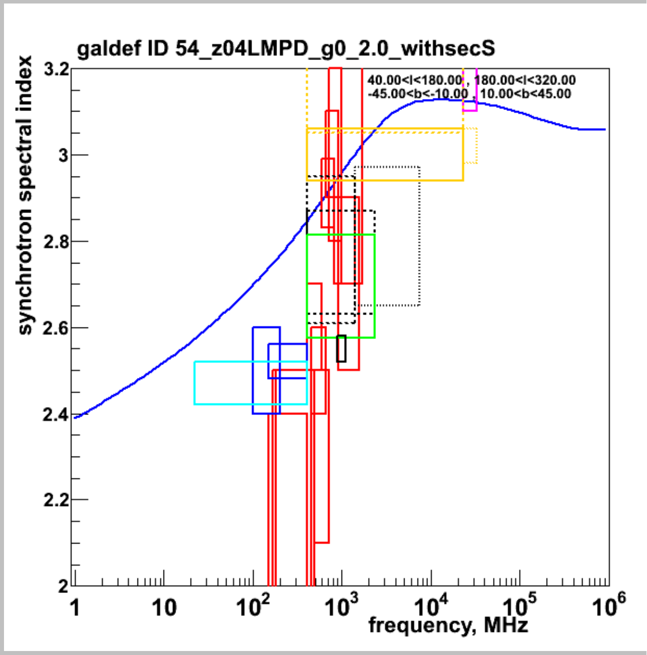
OK



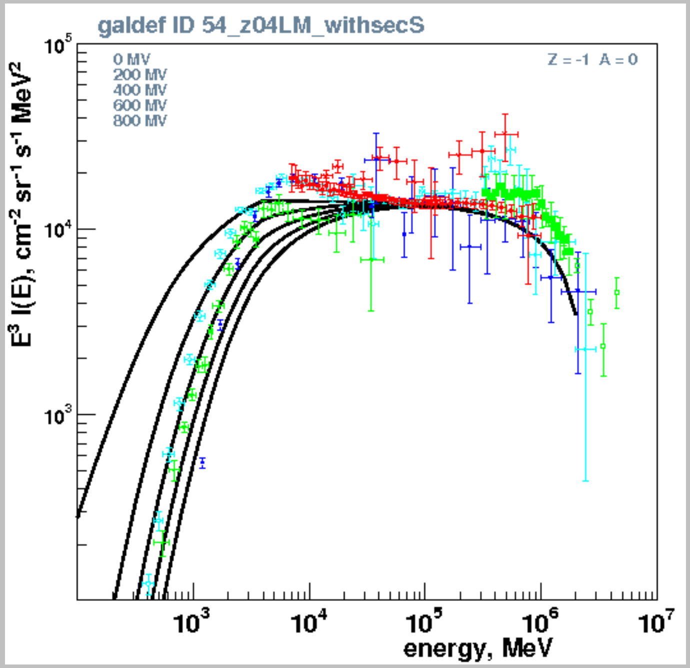
OK



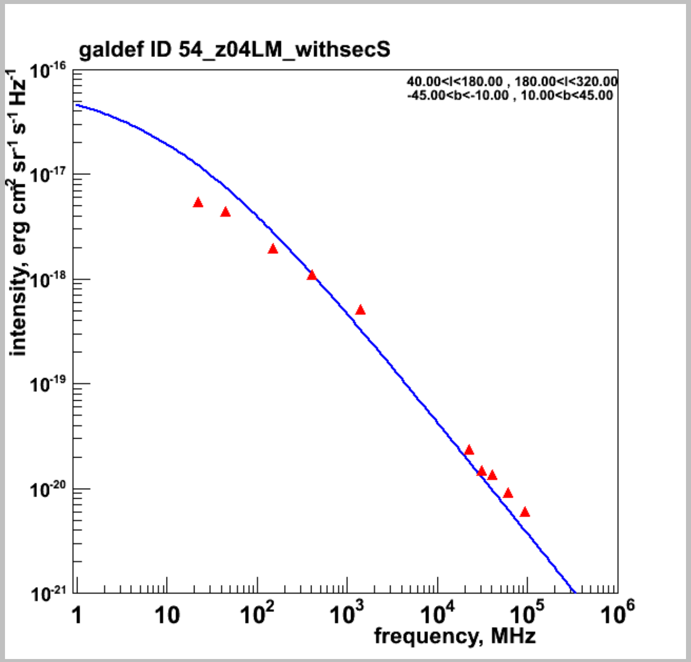
excluded by synchrotron !



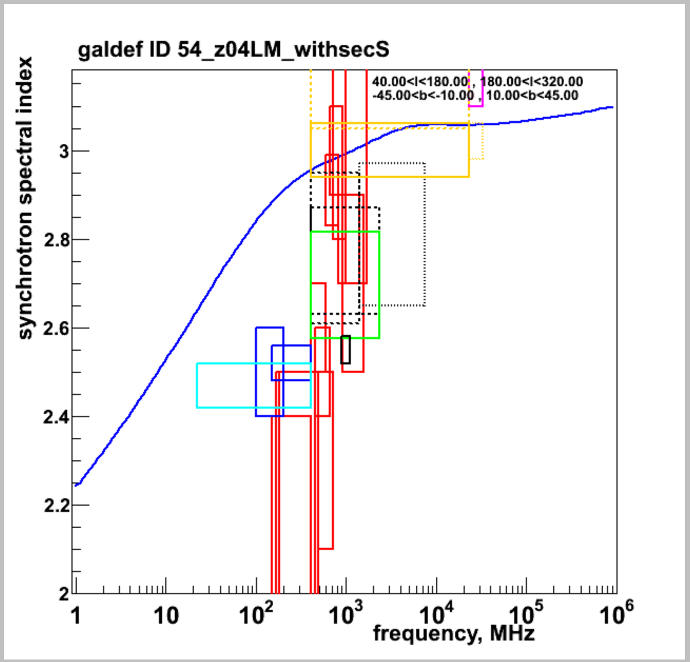
Reacceleration model – in trouble with synchrotron



ELECTRONS



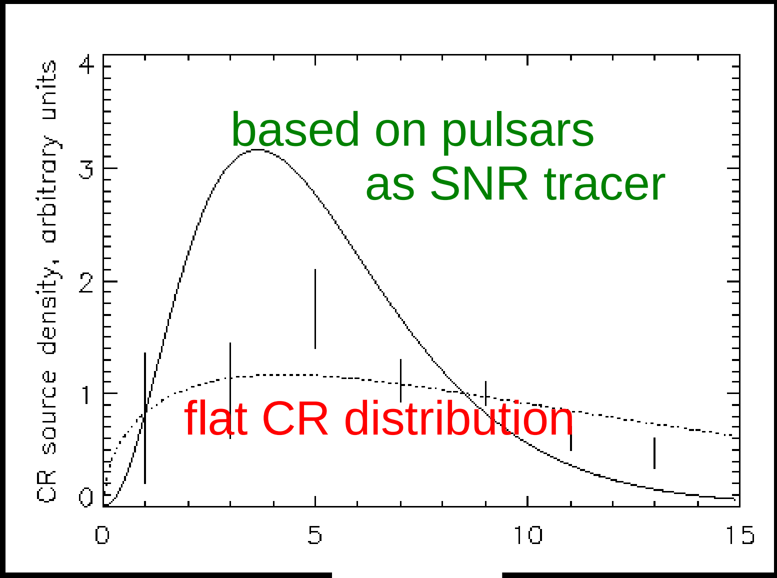
SYNCHROTRON



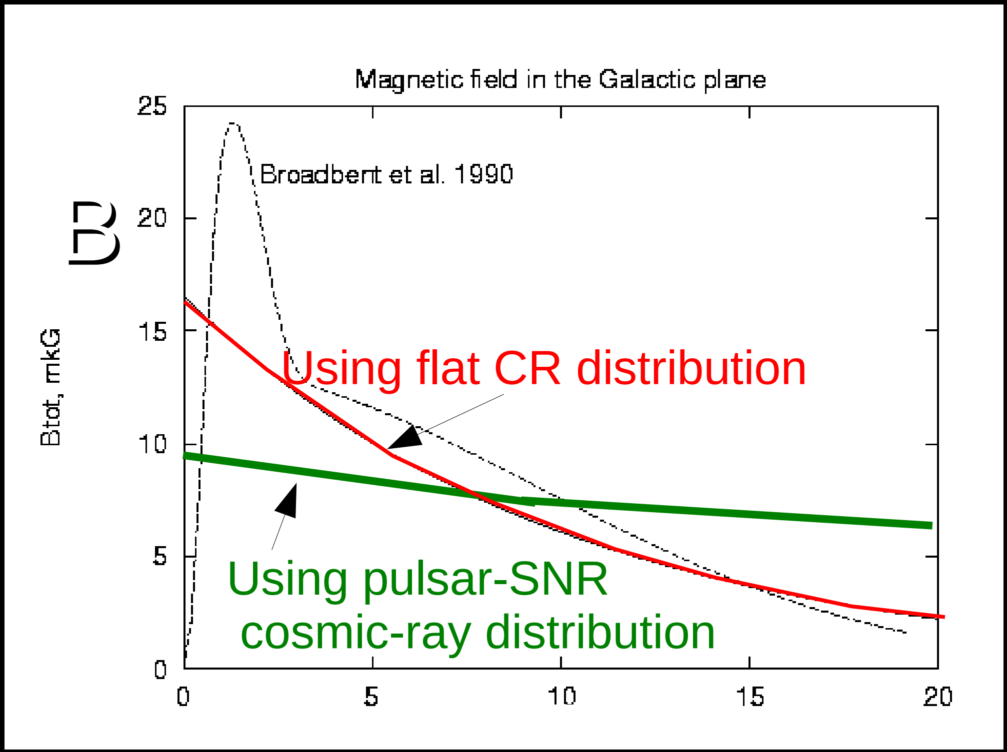
from synchrotron and cosmic-ray propagation model :

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

cosmic-ray source distribution



R, kpc



R, kpc

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

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

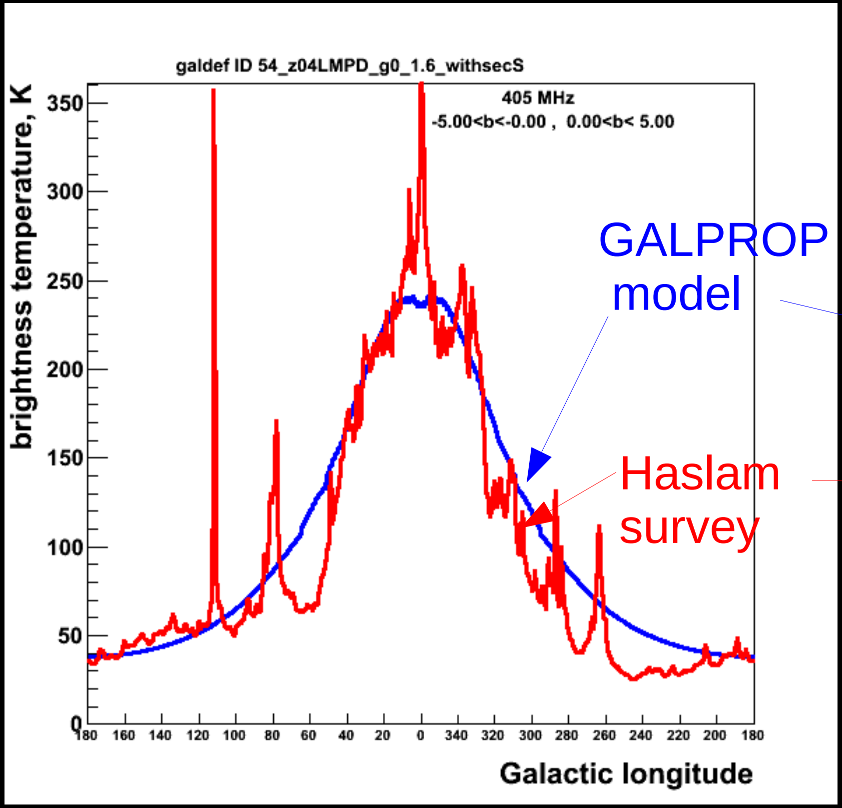
Relevant to Planck !

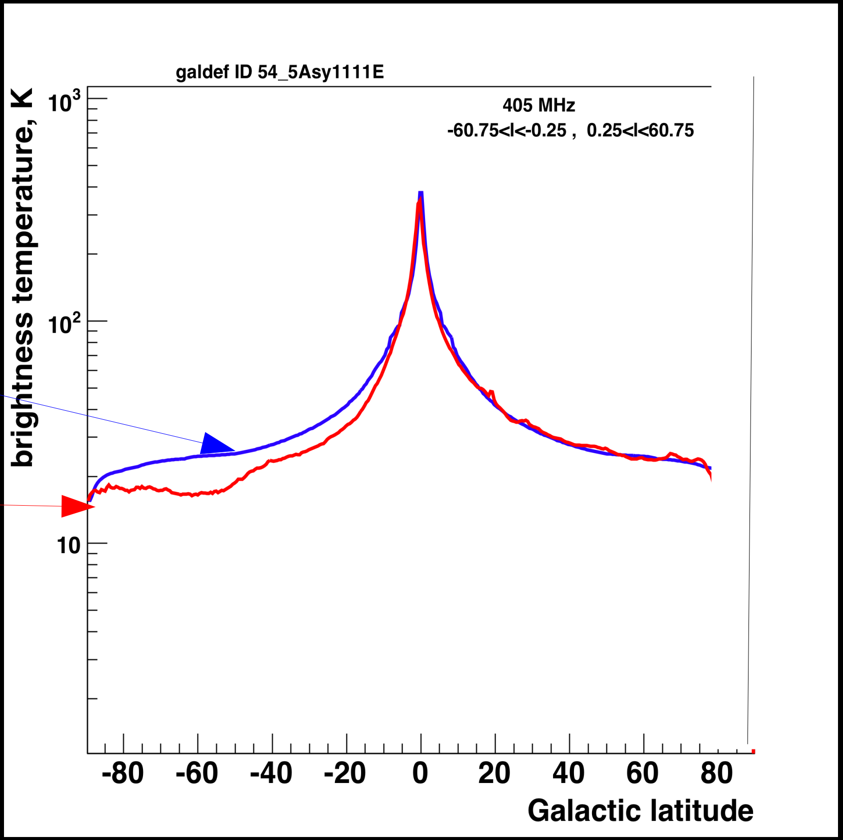
SYNCHROTRON

408 MHz

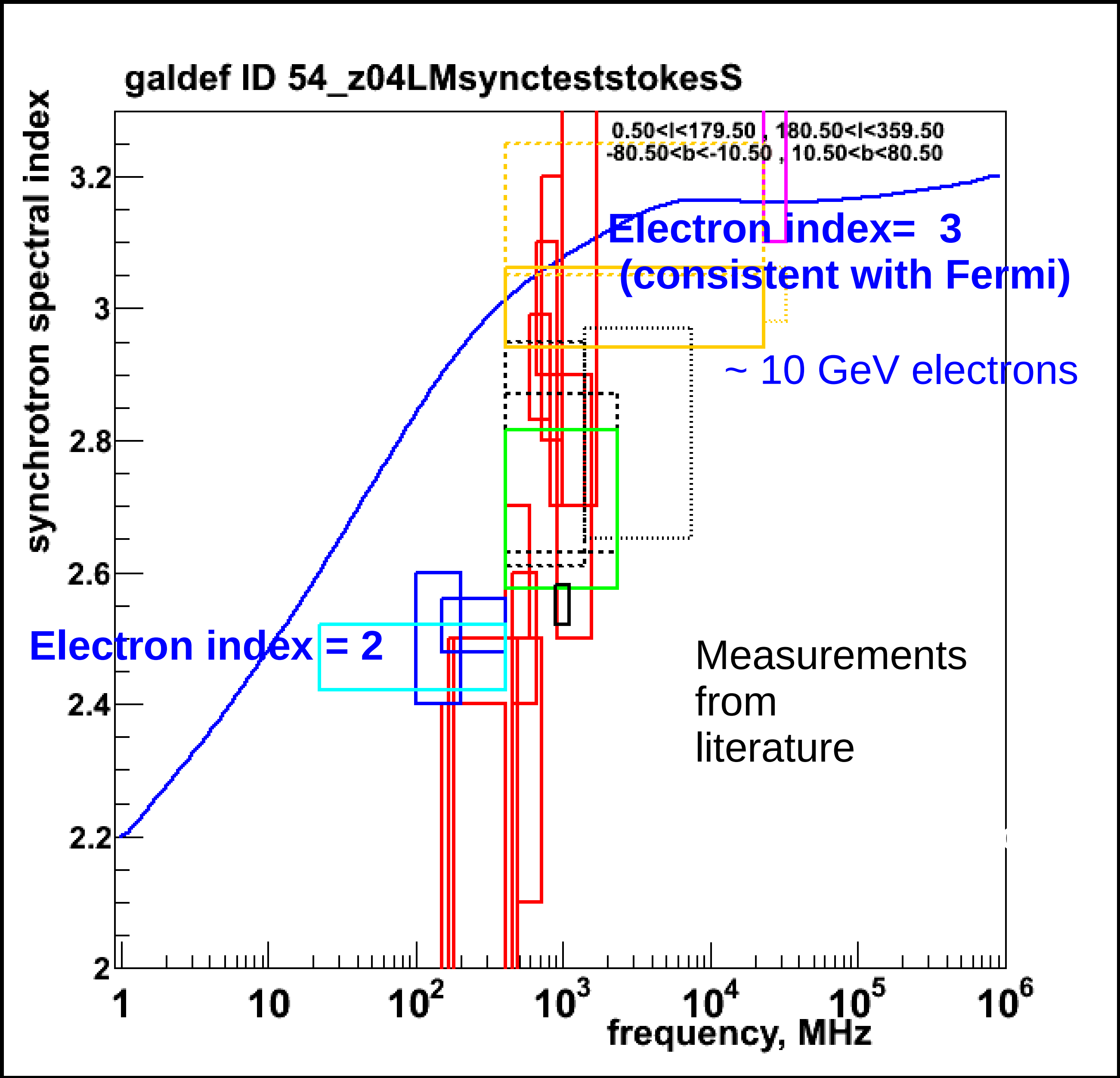
|b| < 5°

| *l* | < 60°

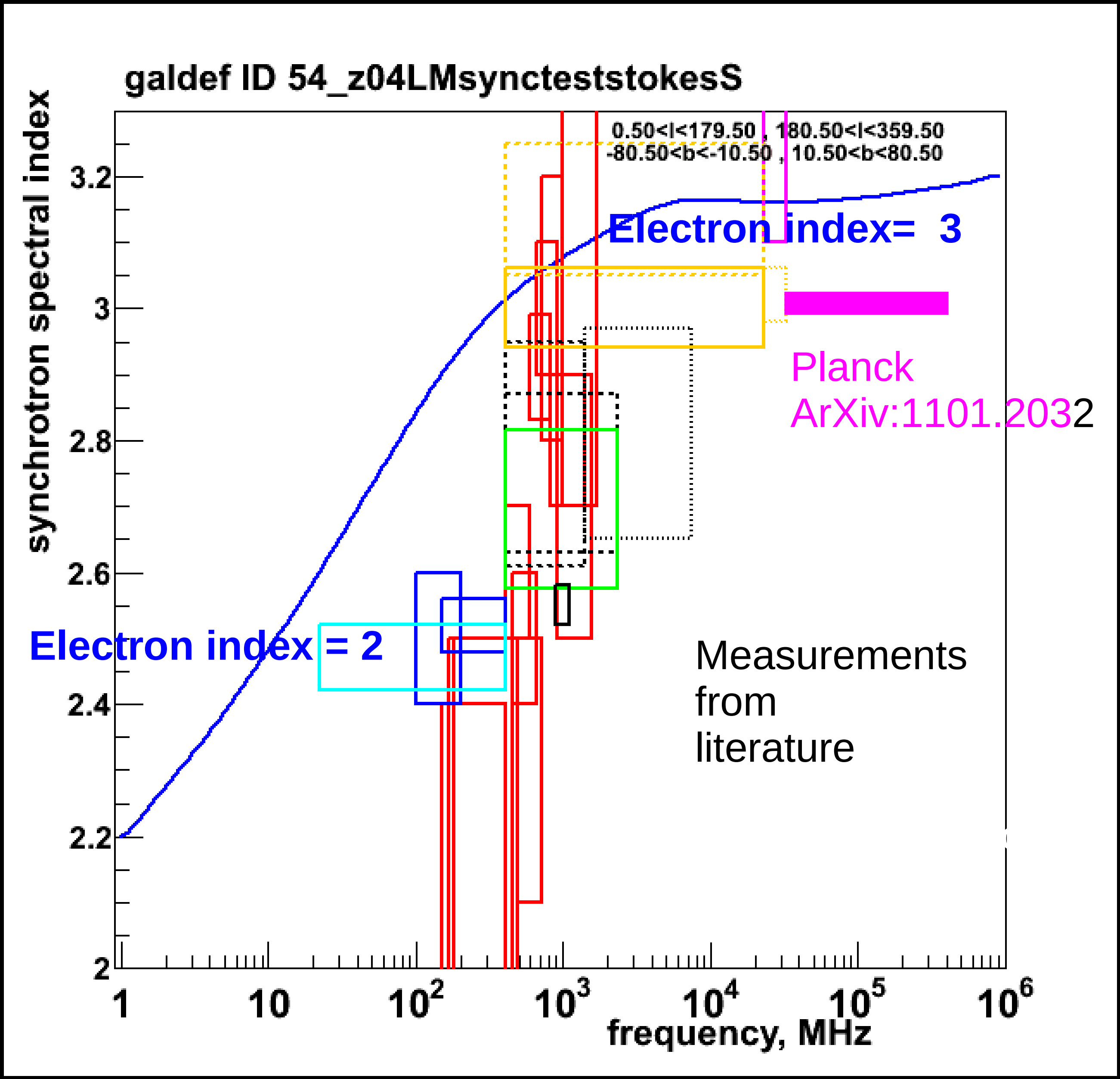




Synchrotron Spectral index vs frequency

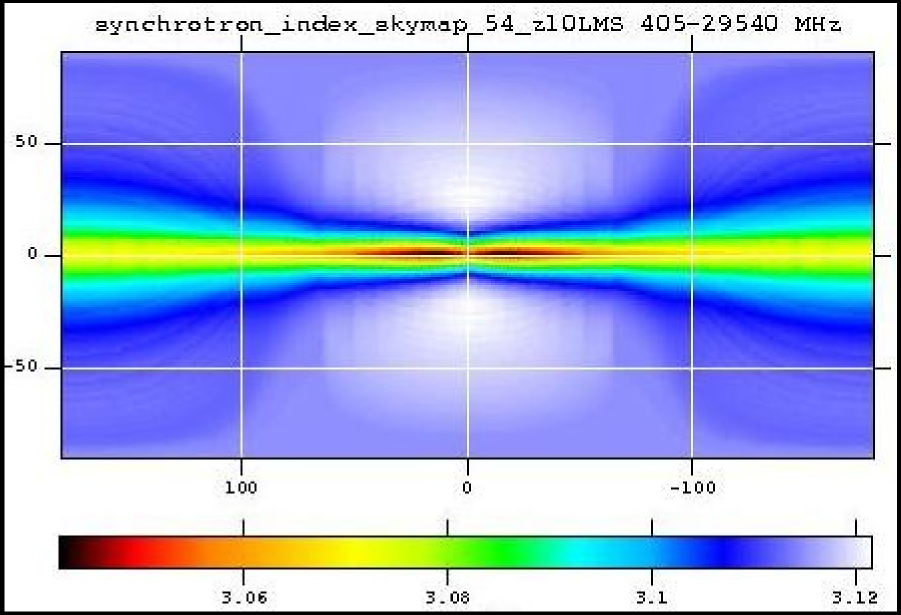


Synchrotron Spectral index vs frequency



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

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

MNRAS, in press
arXiv:1105.5885

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

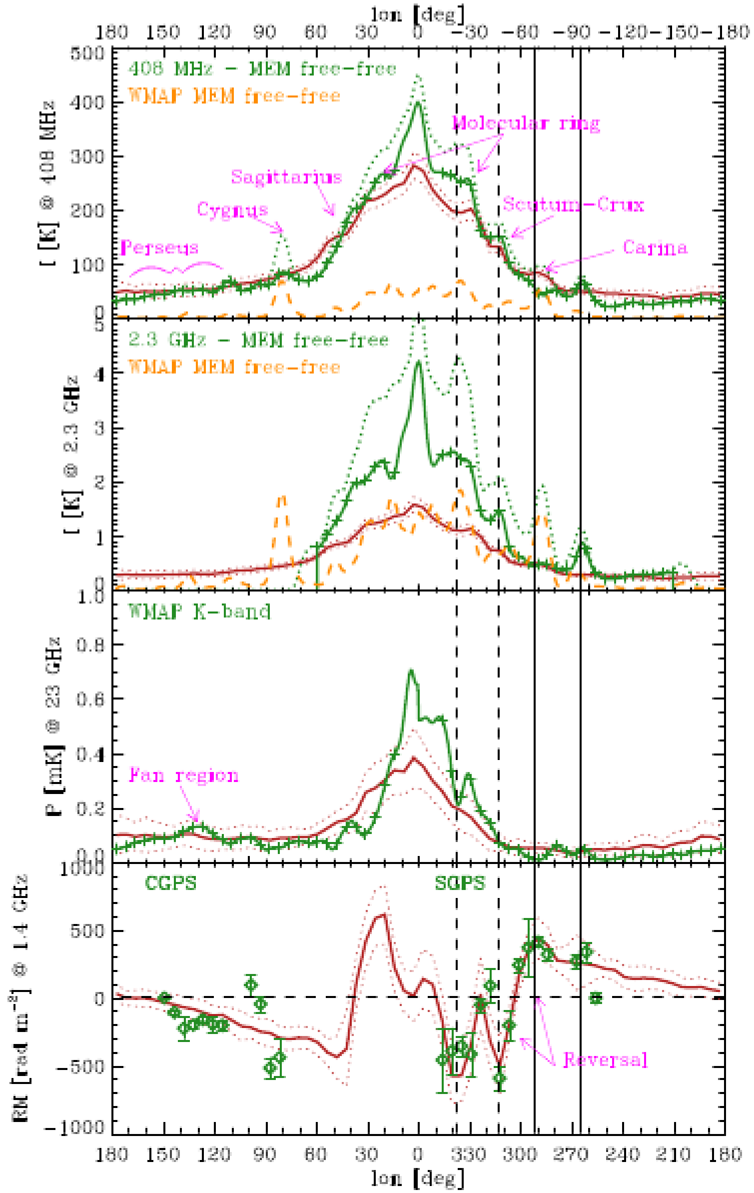
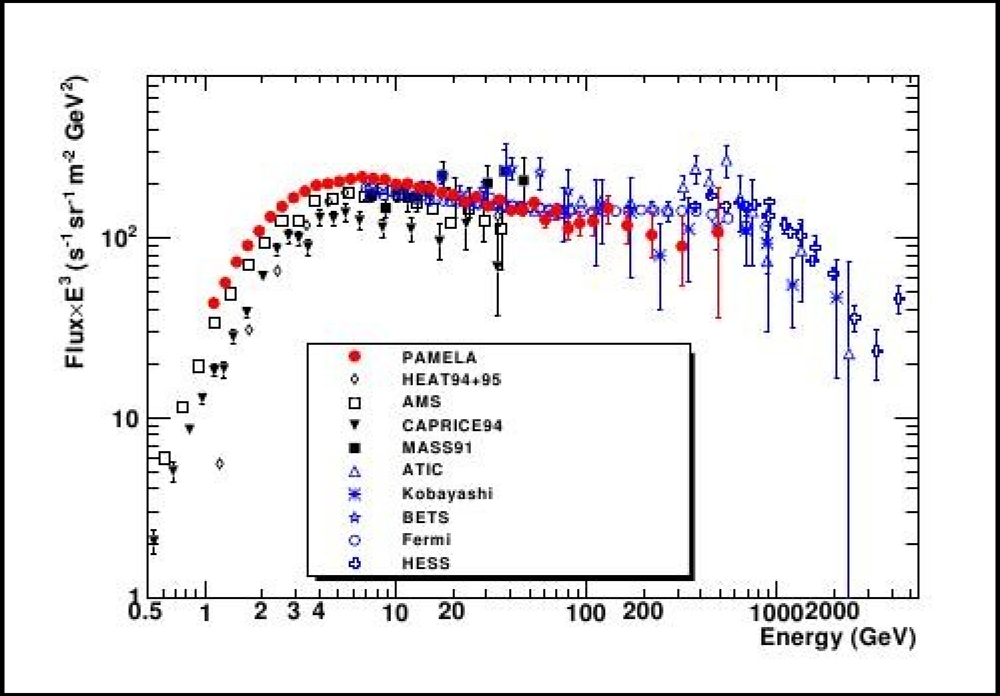


Figure 1. The available observables (*green*) tracing the Galactic magnetic field. The over-plotted model (*red*) is the original model from Paper I, while the data have been updated somewhat. See text in § 2. Furthermore, we have added the 2.3 GHz frequency which clearly shows that the power-law CRE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

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



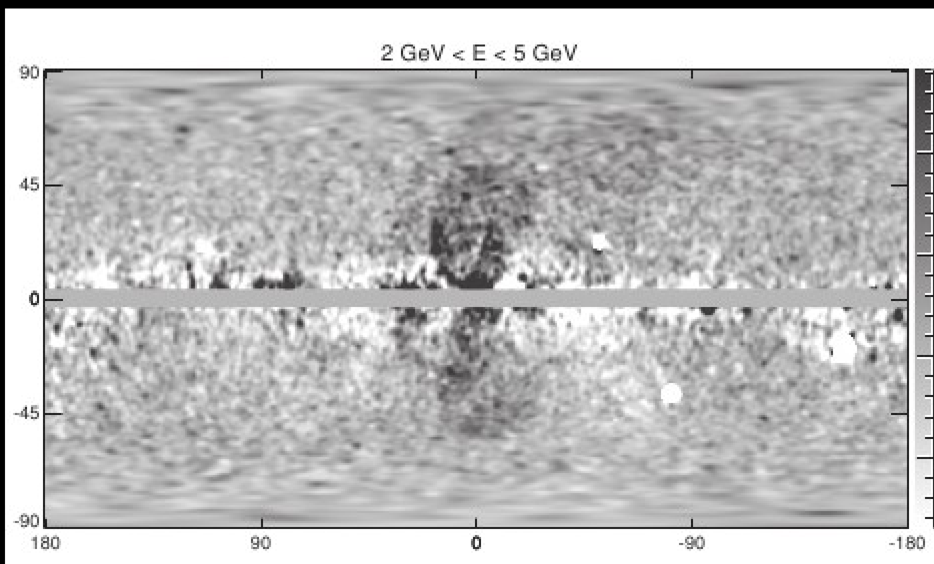
Down to 1 GeV (c.f. Fermi > 7 GeV)
Consisistent, a bit higher than Fermi at low energies
Slightly steeper, as expected since Fermi includes positrons

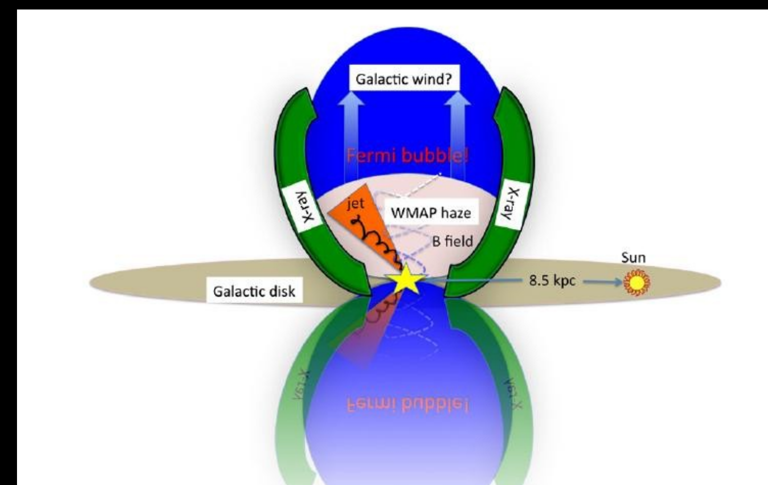
Now: AMS-02, launched May 16, operational.

THE ASTROPHYSICAL JOURNAL, 724:1044–1082, 2010 December 1 doi:10.1088/0004-637X/724/2/1044

GIANT GAMMA-RAY BUBBLES FROM *FERMI*-LAT: ACTIVE GALACTIC NUCLEUS ACTIVITY OR BIPOLAR GALACTIC WIND?

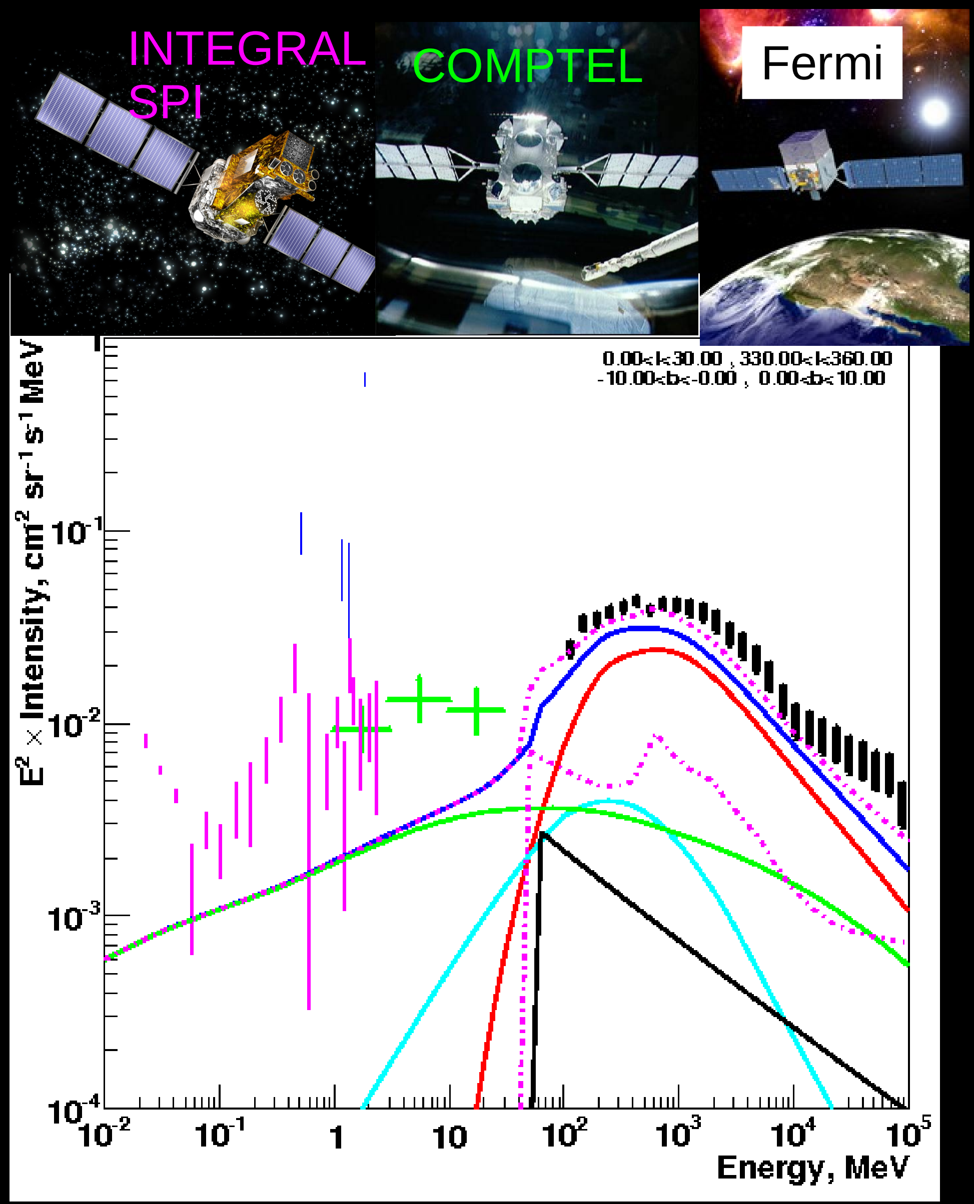
MENG SU[1], TRACY R. SLATYER[1,2], AND DOUGLAS P. FINKBEINER[1,2]



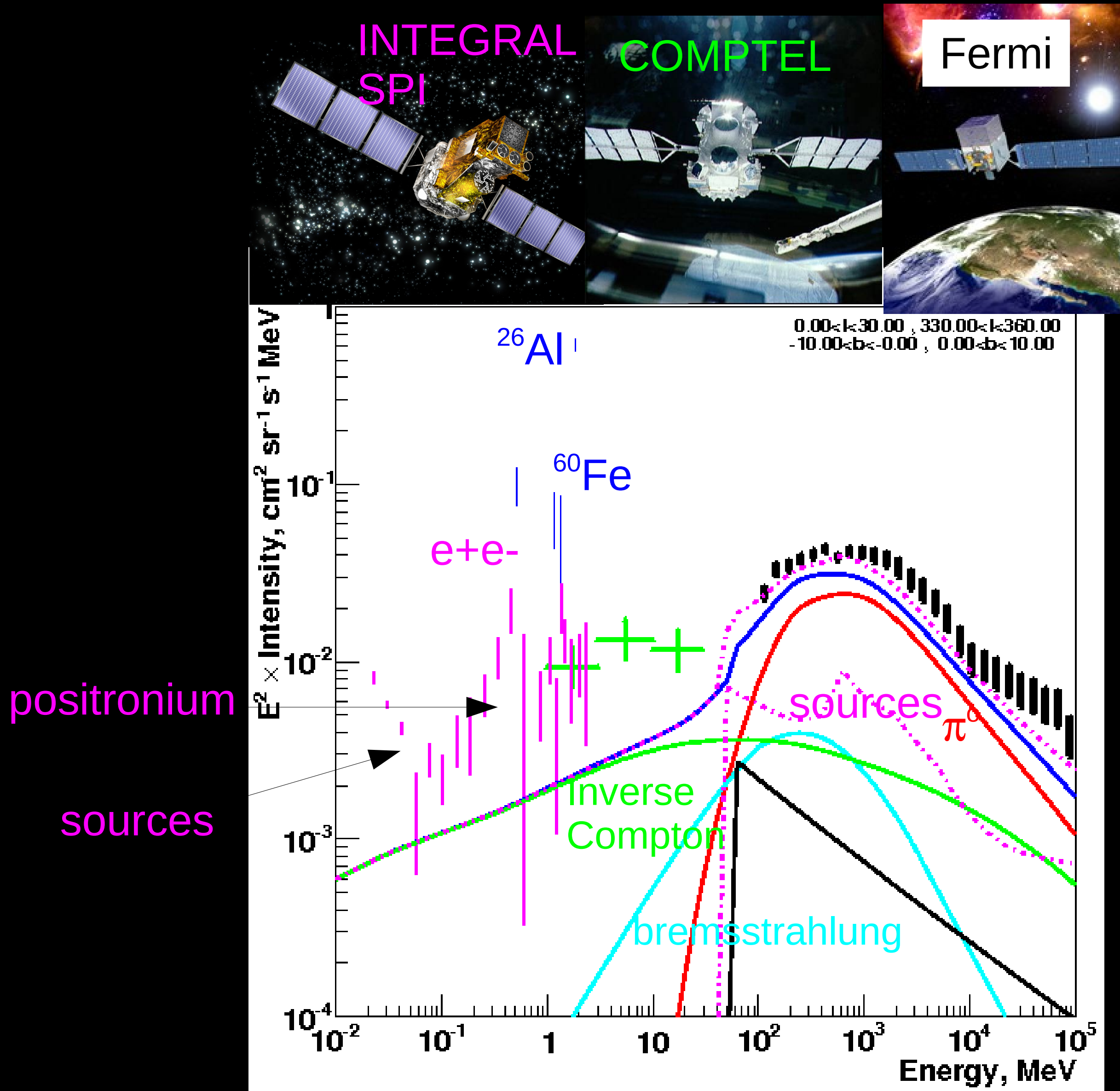


kpc-scale features centred on GC
Details depend on foreground model used (features ~ 10% of total intensity) !
Presumably inverse Compton – electrons -> radio –> relevant to Planck
.

Inner Galaxy: keV to TeV



Inner Galaxy: keV to TeV



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

THE ASTROPHYSICAL JOURNAL LETTERS, 722:L58–L63, 2010 October 10 doi:10.1088/2041-8205/722/1/L58

AN ALIEN'S VIEW OF THE GALAXY

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

[1] Max-Planck-Institut für extraterrestrische Physik, Postfach 1312, D-85741 Garching, Germany; aws@mpe.mpg.de
[2] Hansen Experimental Physics Laboratory, Stanford University, Stanford, CA 94305, USA; tporter@stanford.edu
[3] SLAC National Accelerator Laboratory, 2575 Sand Hill Road, Menlo Park, CA 94025, USA; digel@slac.stanford.edu
[4] Kavli Institute for Particle Astrophysics and Cosmology, Stanford University, Stanford, CA 94305, USA
[5] Spitzer Science Center, California Institute of Technology, Pasadena, CA 91125, USA; 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 γ-ray emission from the production and subsequent decay of neutral pions (π^0), bremsstrahlung, and inverse Compton scattering, and synchrotron radiation. The Galaxy is found to be nearly a CR electron calorimeter, but only if γ-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 γ-rays in "normal" (non-active galactic nucleus dominated) galaxies as well as for estimating the broadband extragalactic diffuse background from these kinds of galaxies.

The Astrophysical Journal Letters, 722:L58–L63, 2010 October 10 doi:10.1088/2041-8205/722/1/L58

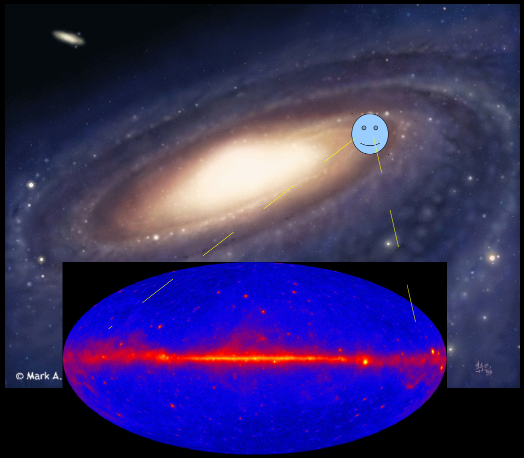
GLOBAL COSMIC-RAY-RELATED LUMINOSITY AND ENERGY BUDGET OF THE MILKY WAY

A. W. Strong[1], T. A. Porter[2], S. W. Digel[3,4], G. Jóhannesson[2], P. Martin[1], I. V. Moskalenko[2,4], E. J. Murphy[5], and E. Orlando[1]
[1] Max-Planck-Institut für extraterrestrische Physik, Postfach 1312, D-85741 Garching, Germany; aws@mpe.mpg.de
[2] Hansen Experimental Physics Laboratory, Stanford University, Stanford, CA 94305, USA; tporter@stanford.edu
[3] SLAC National Accelerator Laboratory, 2575 Sand Hill Road, Menlo Park, CA 94025, USA; digel@slac.stanford.edu
[4] Kavli Institute for Particle Astrophysics and Cosmology, Stanford University, Stanford, CA 94305, USA
[5] Spitzer Science Center, California Institute of Technology, Pasadena, CA 91125, USA; emurphy@ipac.caltech.edu
Received 2010 June 14; accepted 2010 August 24; published 2010 September 20

ABSTRACT

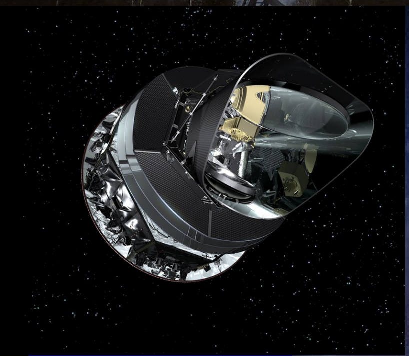
We use the GALPROP code for cosmic-ray (CR) propagation to calculate the broadband luminosity spectrum of the Milky Way related to CR propagation and interactions in the interstellar medium. This includes γ-ray emission from the production and subsequent decay of neutral pions (π^0), bremsstrahlung, and inverse Compton scattering, and synchrotron radiation. The Galaxy is found to be nearly a CR electron calorimeter, but only if γ-ray emitting processes are taken into account. Synchrotron radiation alone accounts for only one-third of the total electron energy losses with ∼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 γ-rays in "normal" (non-active galactic nucleus dominated) galaxies as well as for estimating the broadband extragalactic diffuse background from these kinds of galaxies.

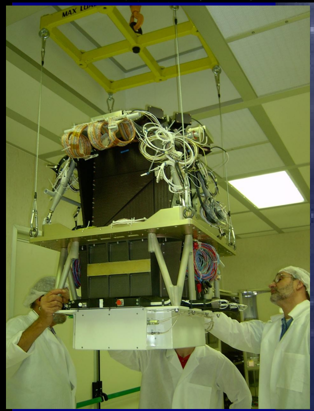
Since we live inside the Galaxy, global properties like multiwavelength luminosity (SED) are not easy to deduce.



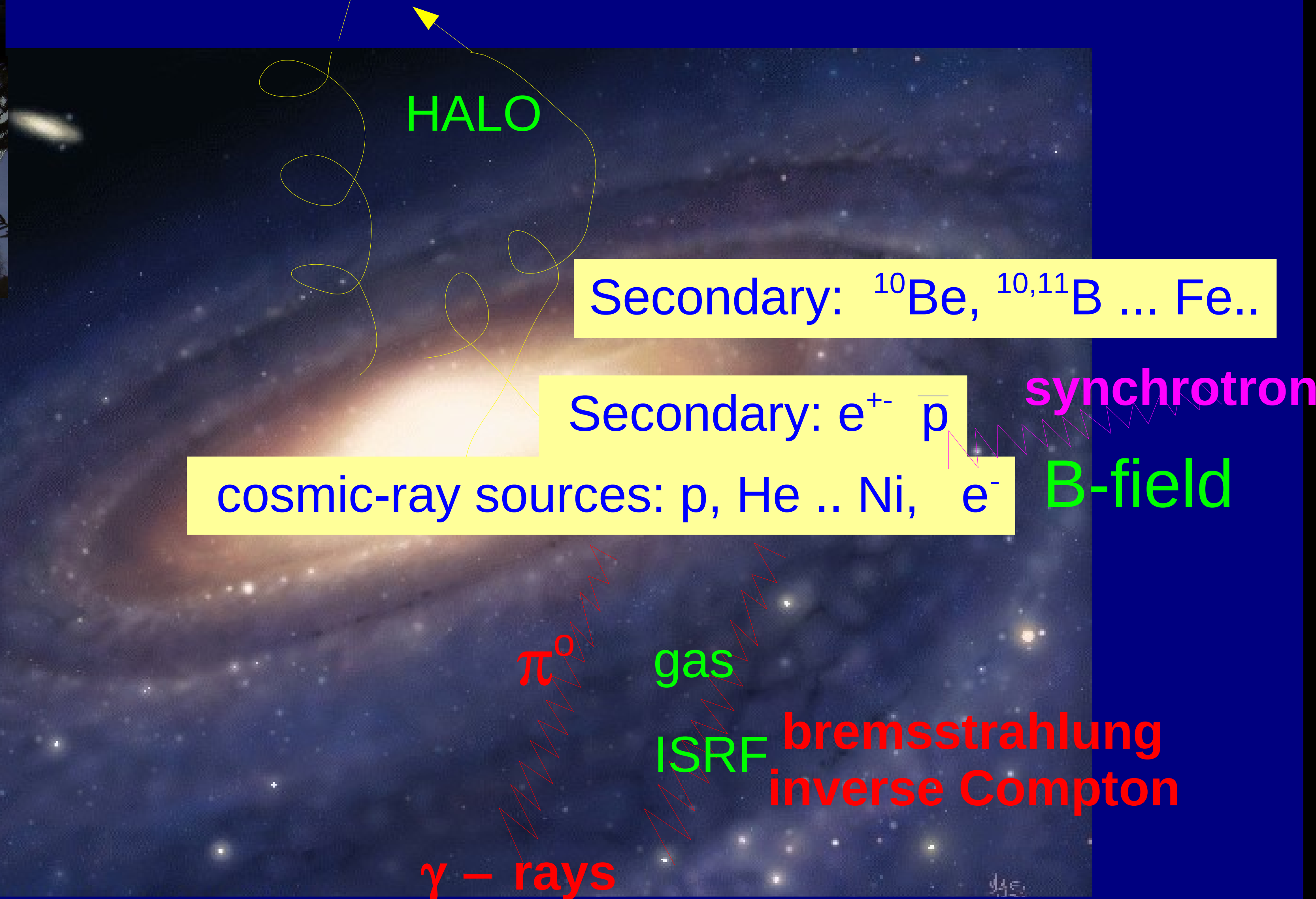

what does it look from out there ?
© Mark A.

EXPERIMENTS **THEORY**



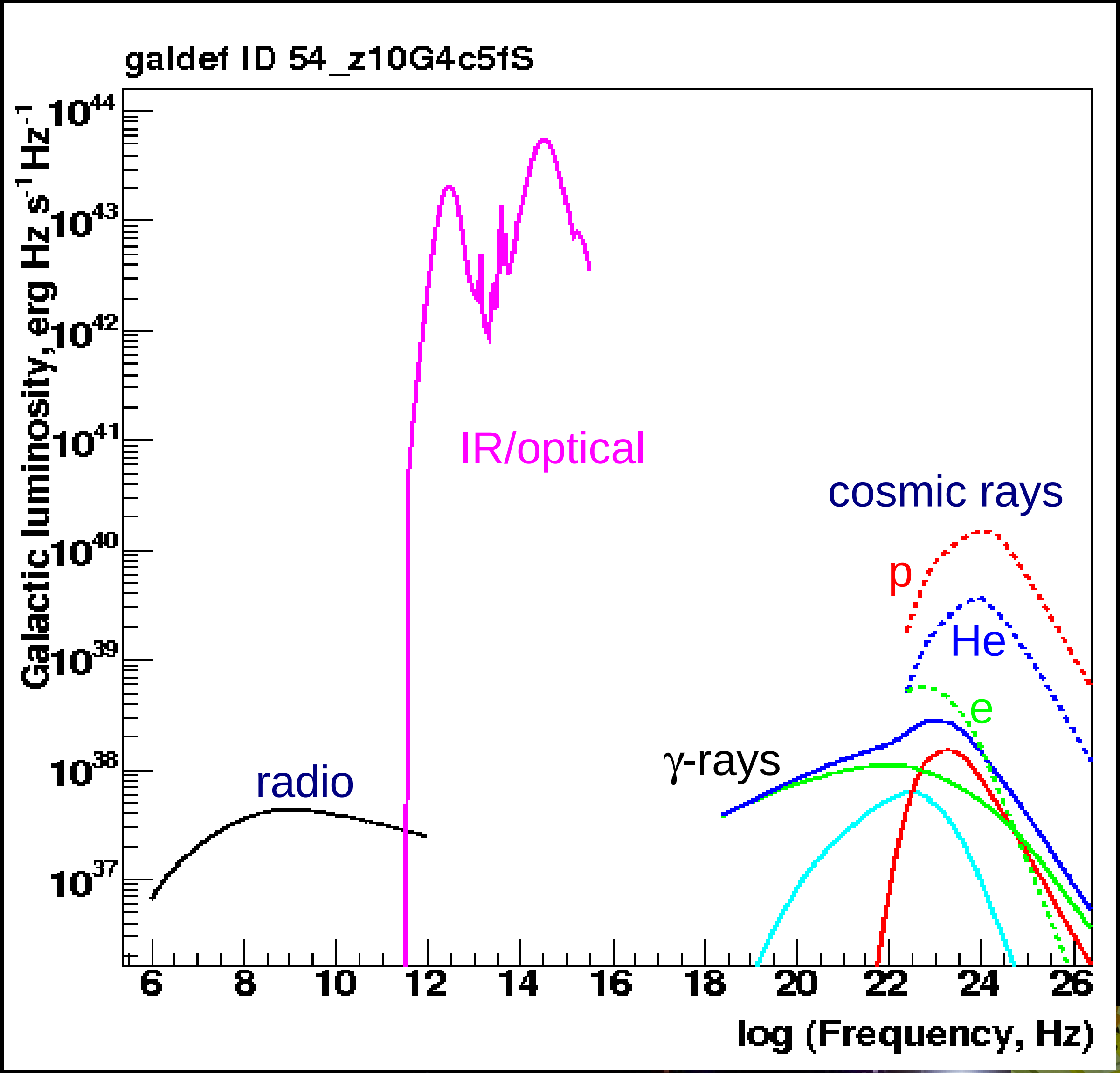


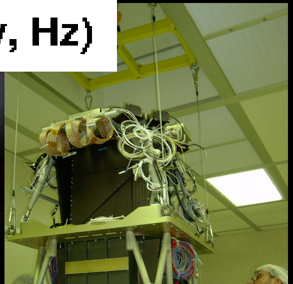
intergalactic space



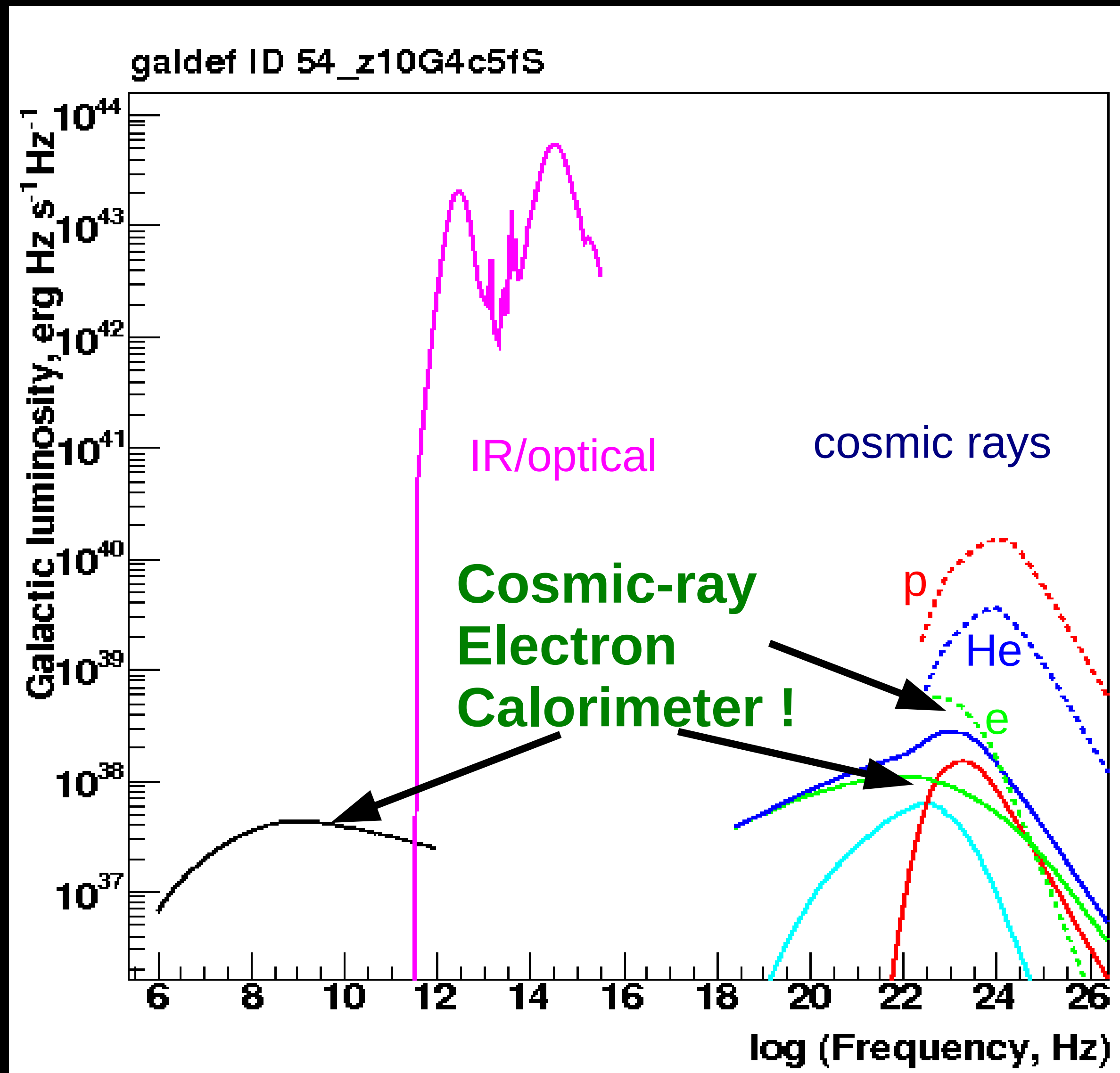
GALPROP : models all that !

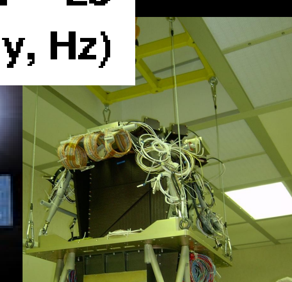
Galaxy luminosity over 20 decades of energy





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	$1.6\ 10^{39}$	erg s^{-1}
Gamma rays > 100 MeV	$1.2\ 10^{39}$	
π^o-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}	

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:

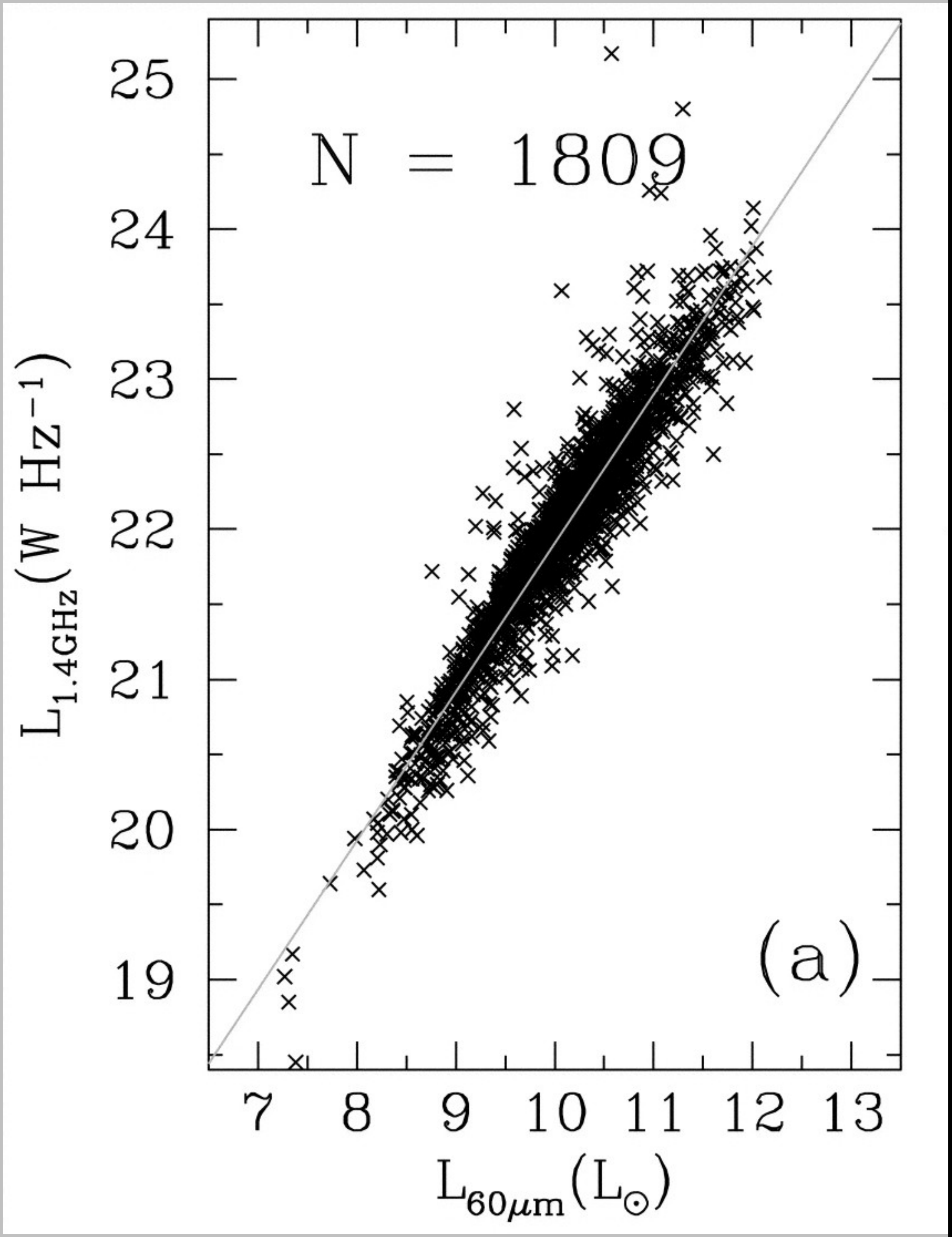
Cosmic-ray ionization in molecular clouds.
New impetus due to chemistry and observational methods.

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

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

FIR / radio correlation



Cosmic ray electron
Calorimetry

Star-formation

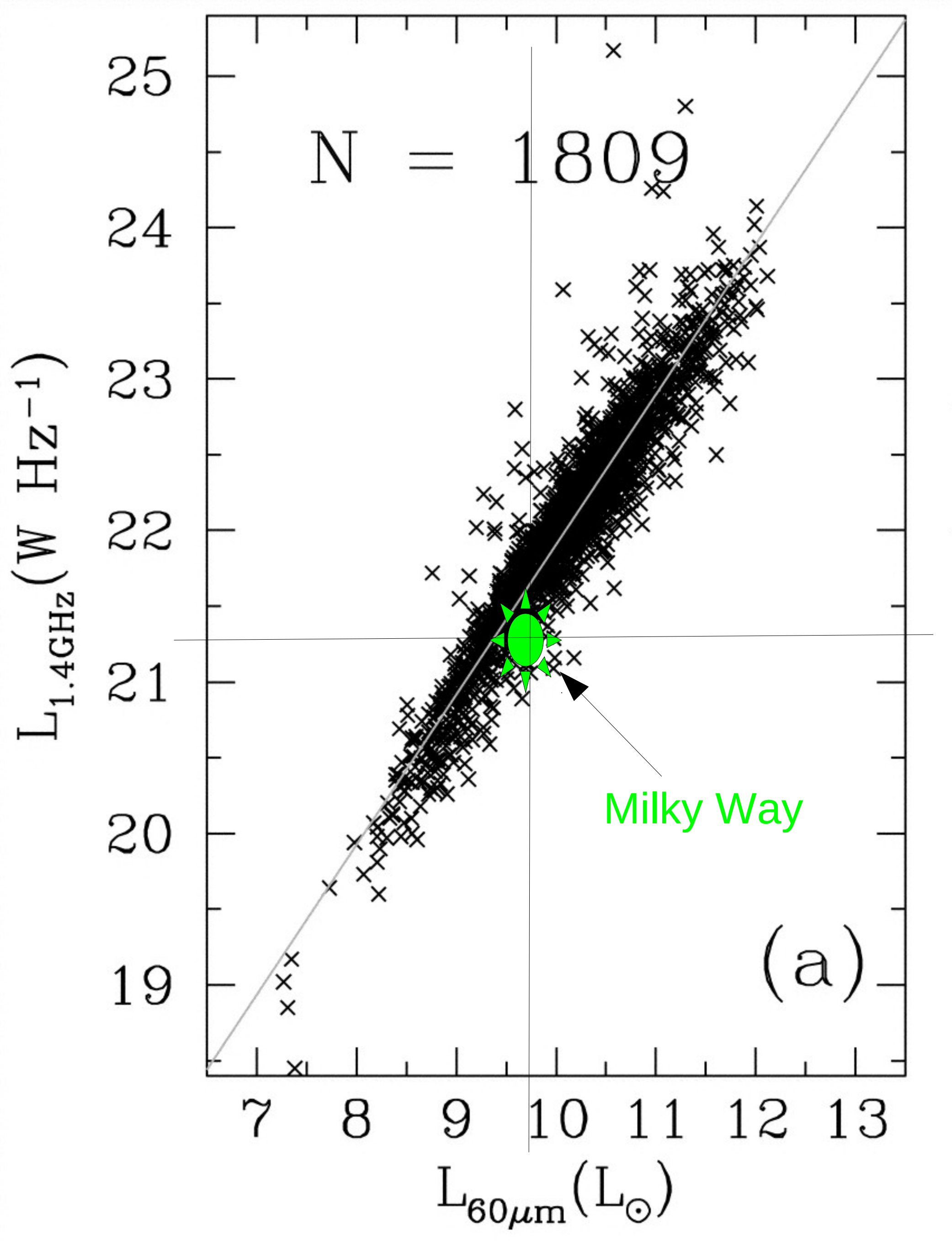
V

Cosmic rays

V

Synchrotron

FIR / radio correlation



Cosmic ray electron Calorimetry

Star-formation

V

Cosmic rays

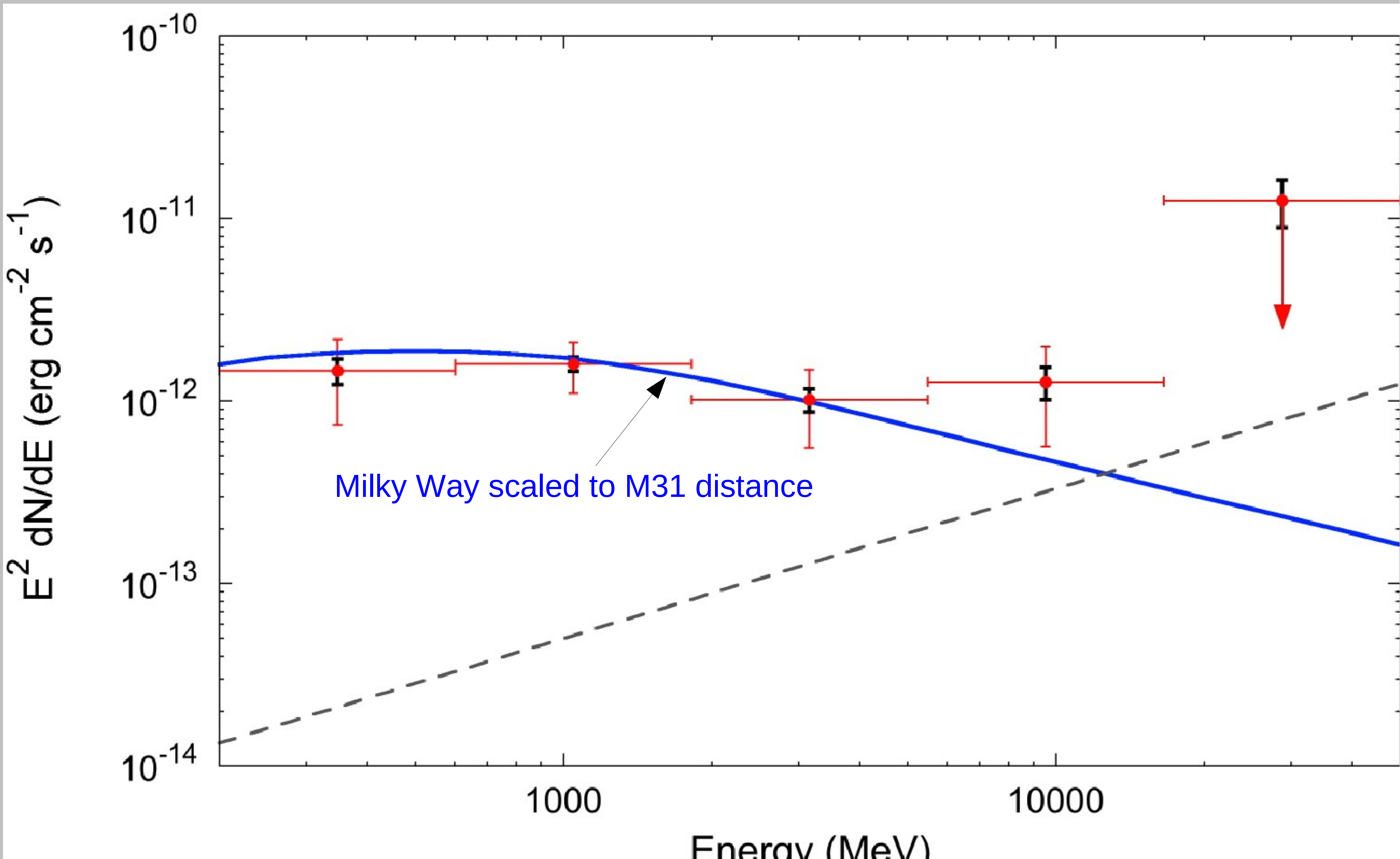
V

Synchrotron

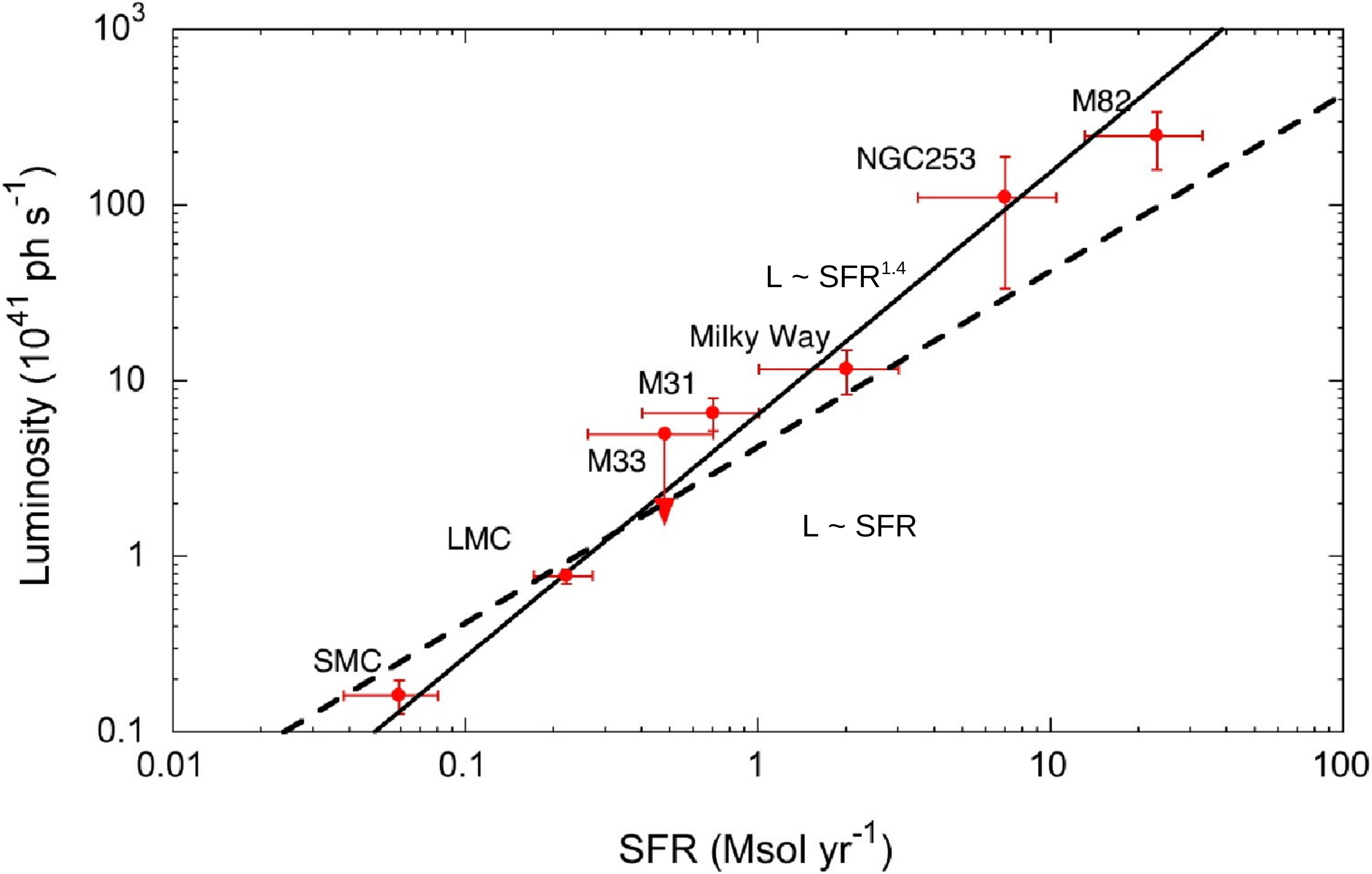
Nearby galaxies detected by Fermi

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