

GALPROP: B-fields, synchrotron, cosmic rays

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MPE Garching

ISSI Workshop on Testing Magnetic Field Models
ISSI, Berne, Dec 8-12 2014



High energy particles and radiation in the Galaxy

intergalactic space

HALO

cosmic-ray sources: electrons

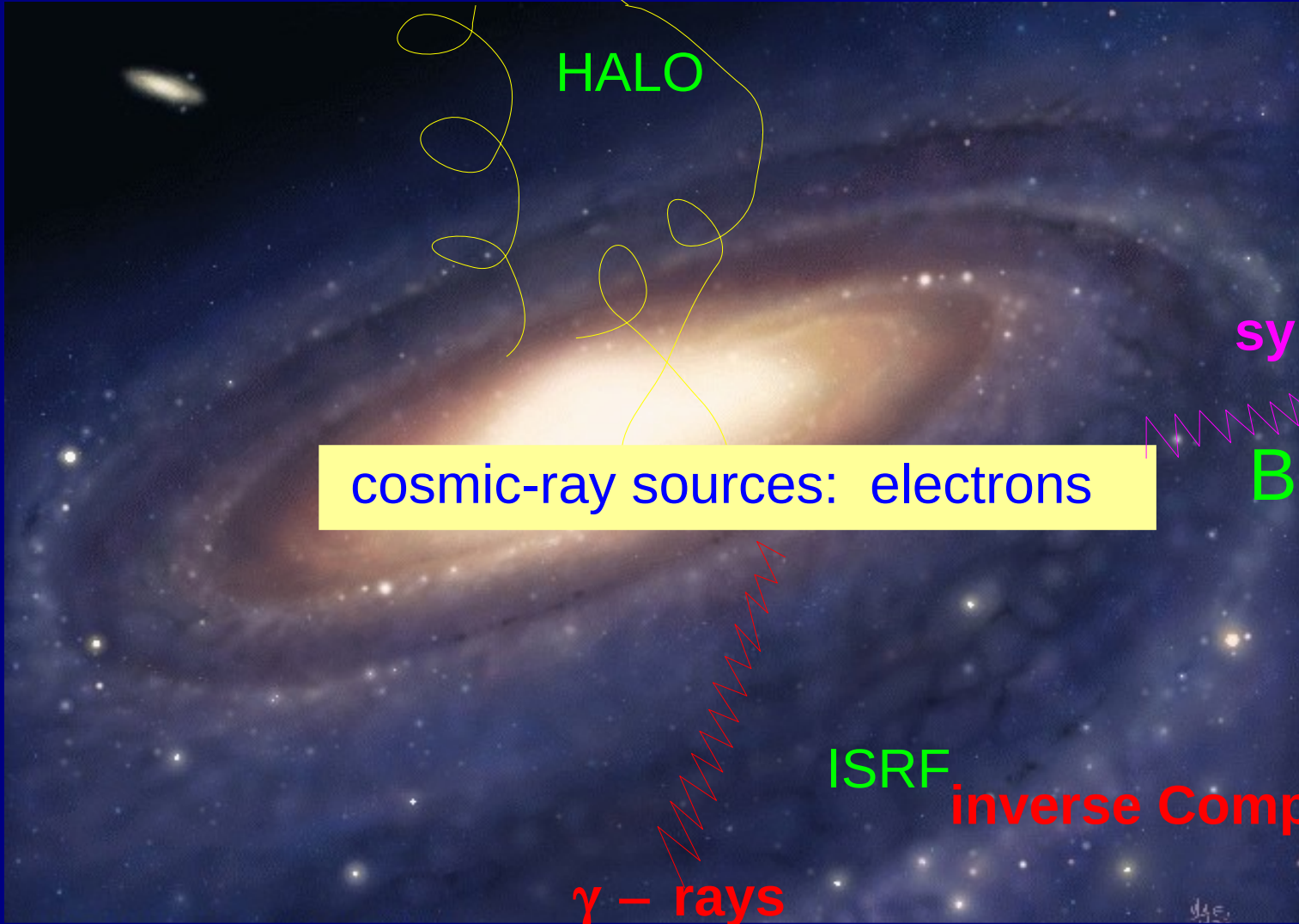
synchrotron

B-field

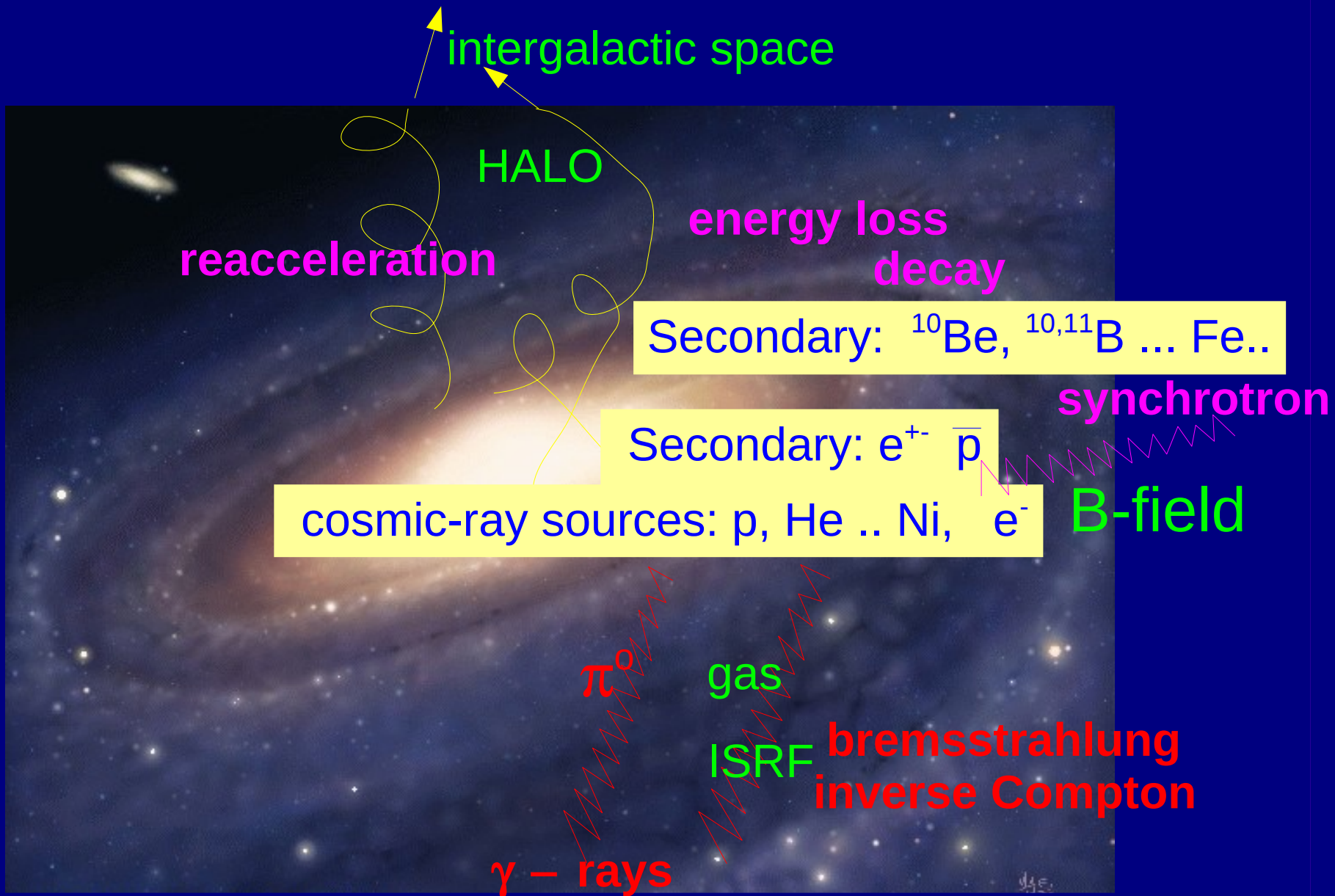
ISRF

inverse Compton

γ - rays

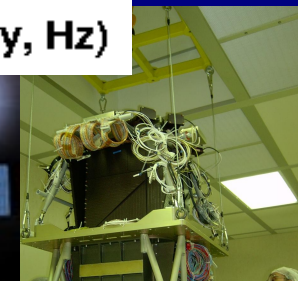
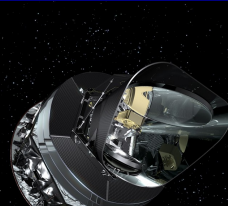
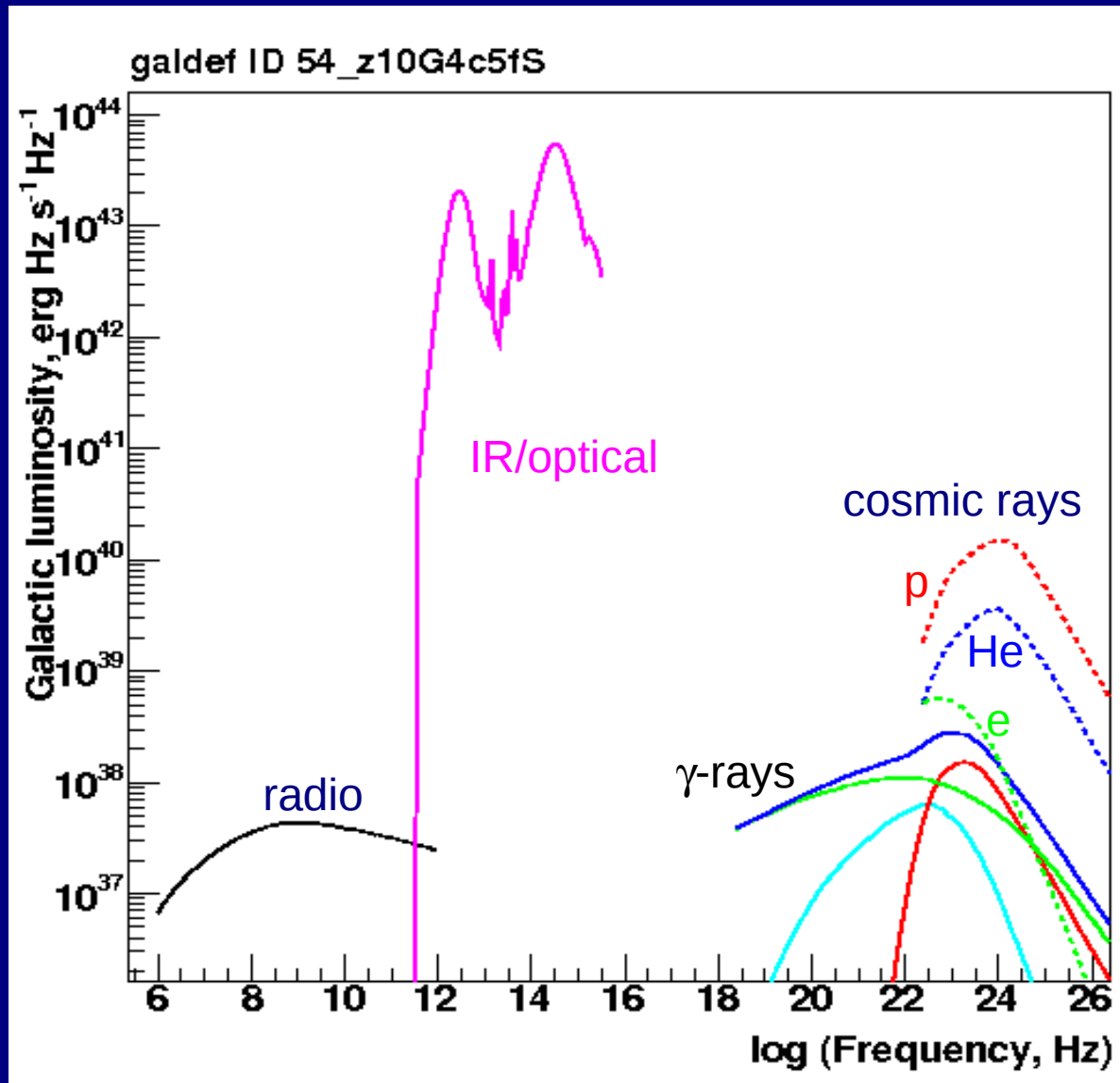


COSMIC RAYS produce many observables

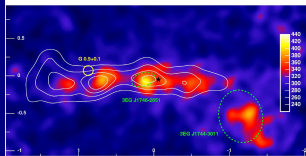


GALPROP model

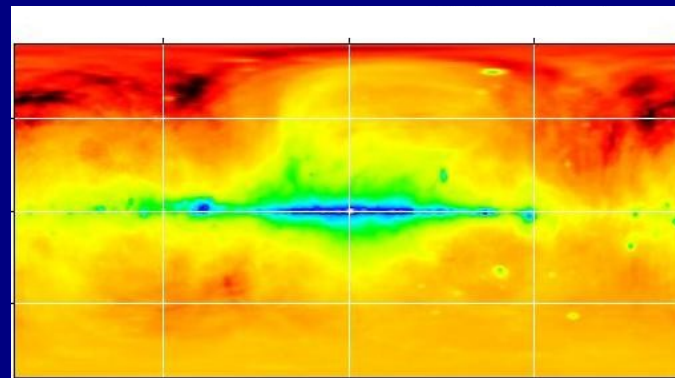
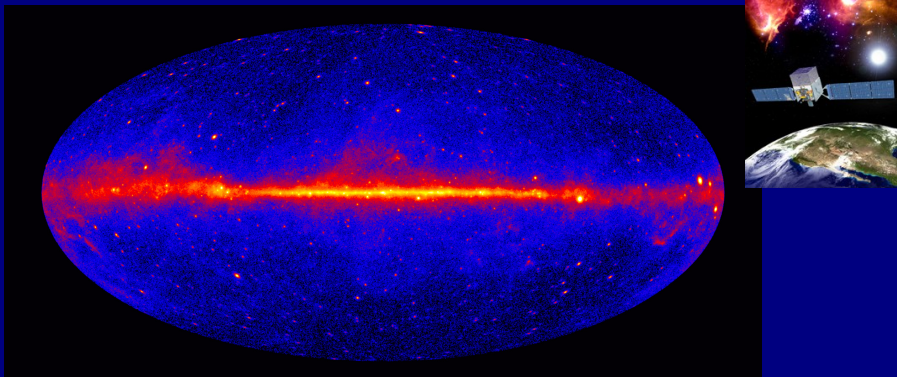
Galaxy luminosity over 20 decades of energy



TeV



GeV

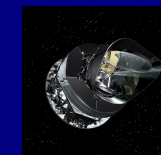
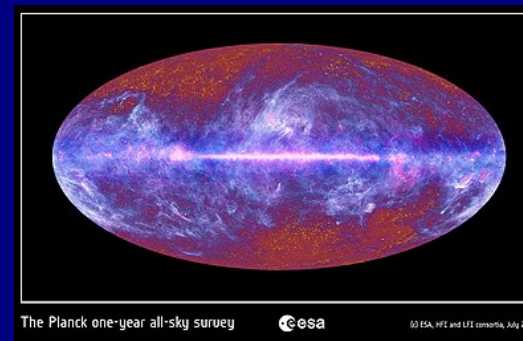
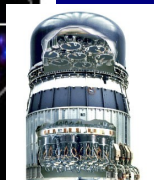
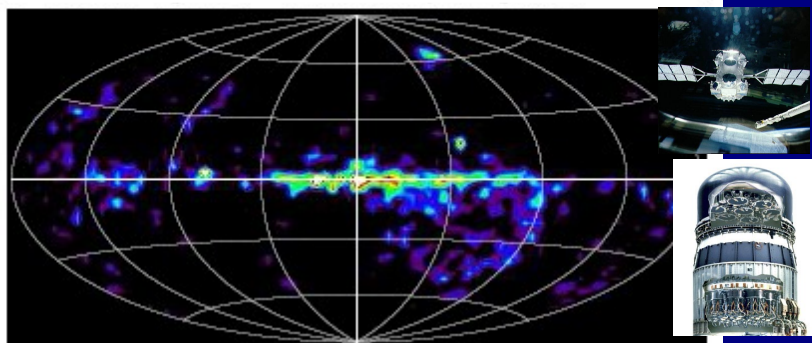


μeV

GHz

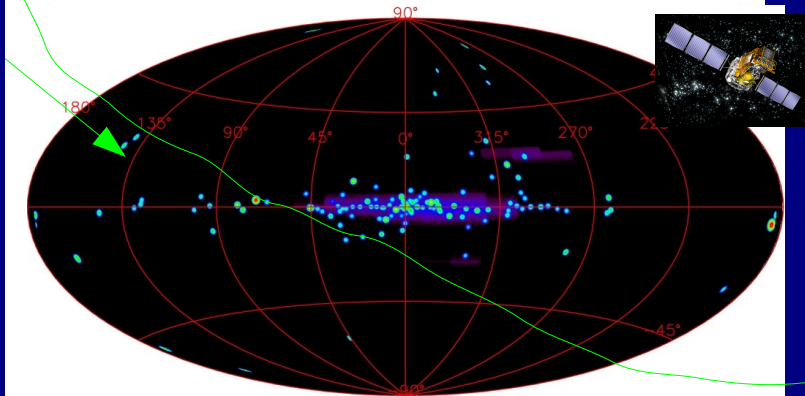
Cosmic-ray interactions probed by their photon emission

MeV



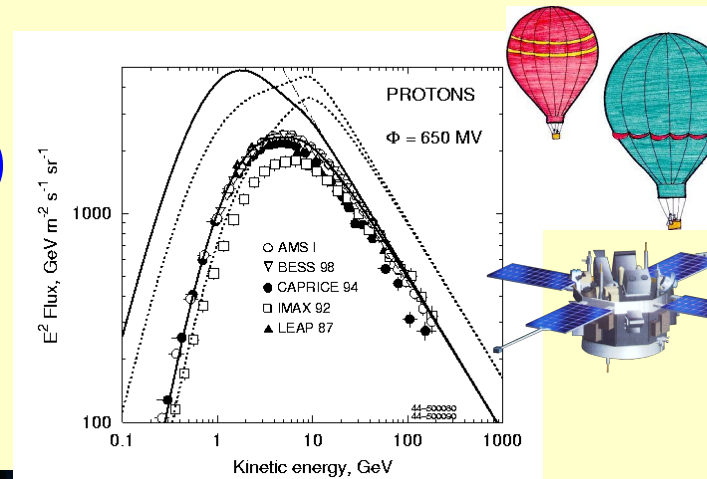
meV

THz



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...

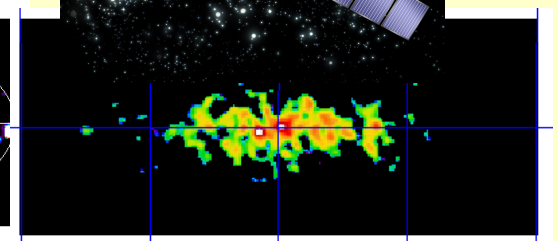
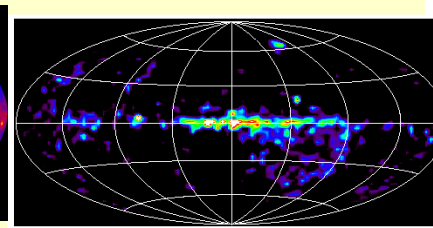
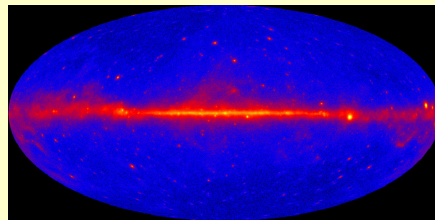


Victor Hess before his 1912 balloon in Austria, during which he discovered cosmic rays

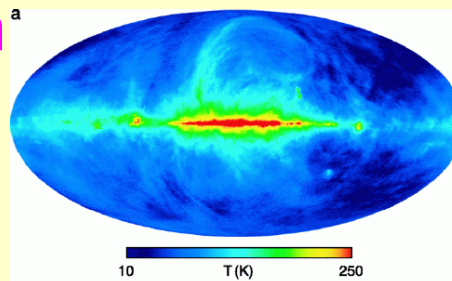


Observed
from whole Galaxy:
Galaxy:

γ - rays



synchrotron^a



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)

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

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

momentum loss adiabatic momentum loss
ionization, bremsstrahlung

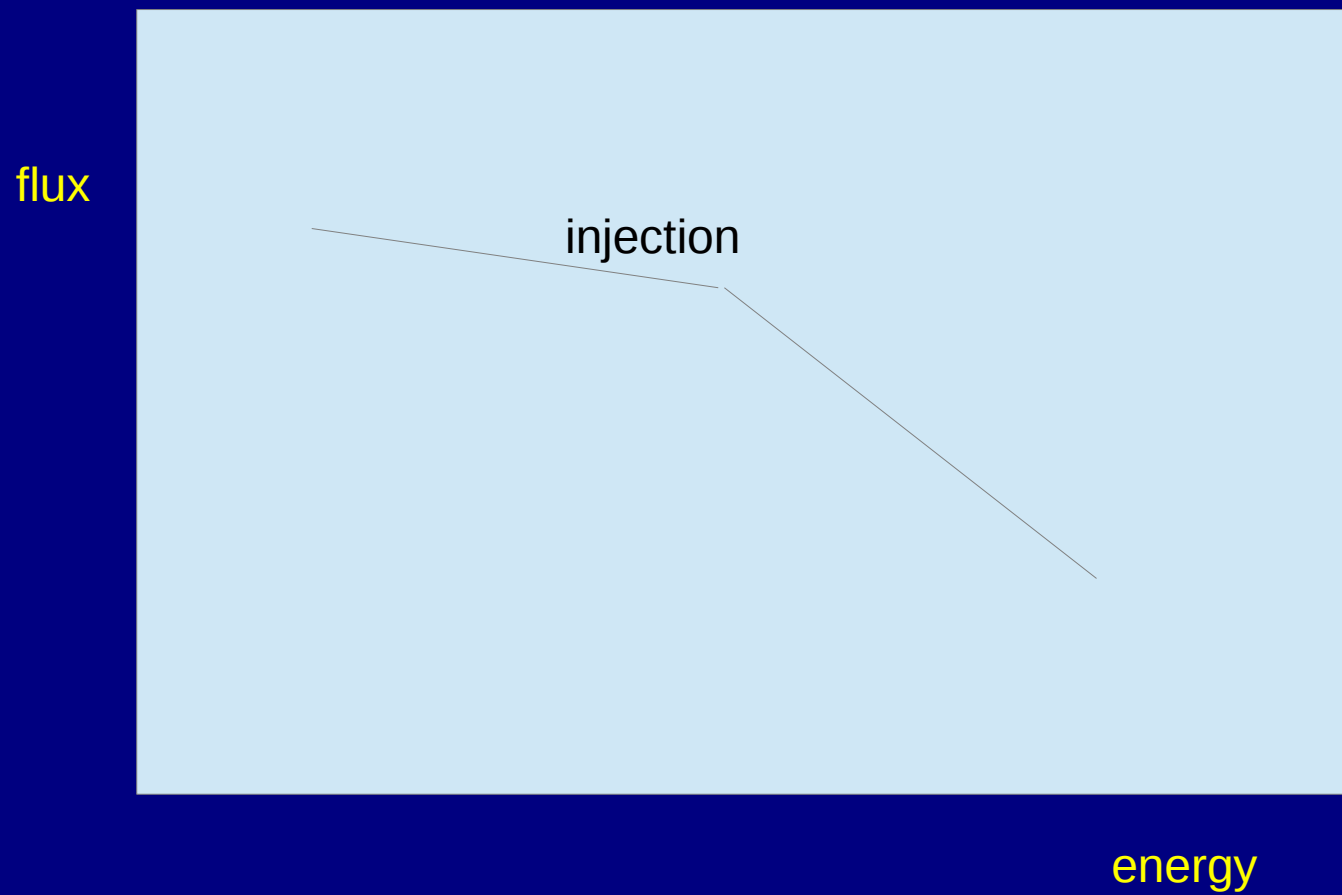
$$- \psi / \tau_f$$

nuclear fragmentation

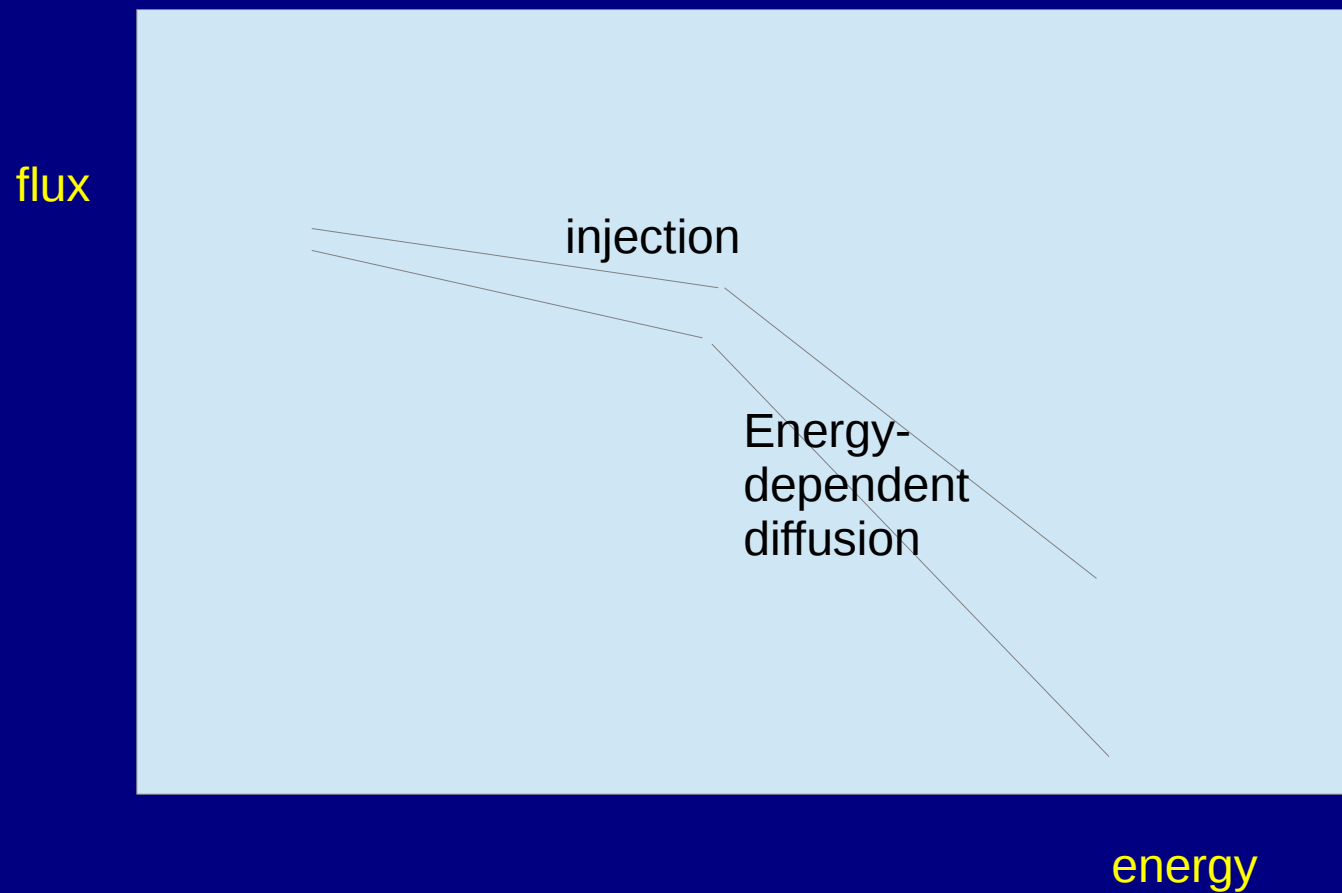
$$- \psi / \tau_r$$

radioactive decay

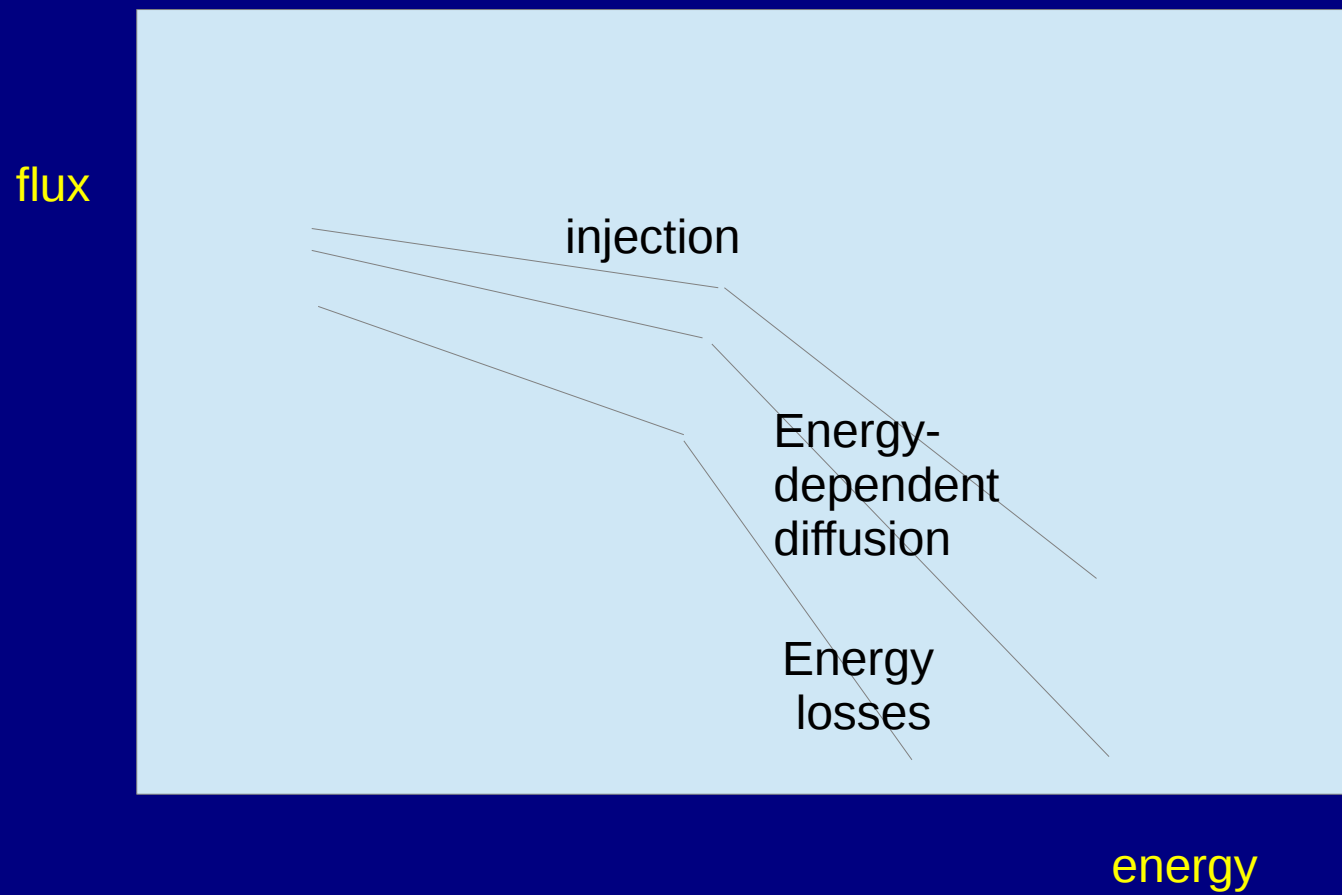
Producing the cosmic-ray electron spectrum



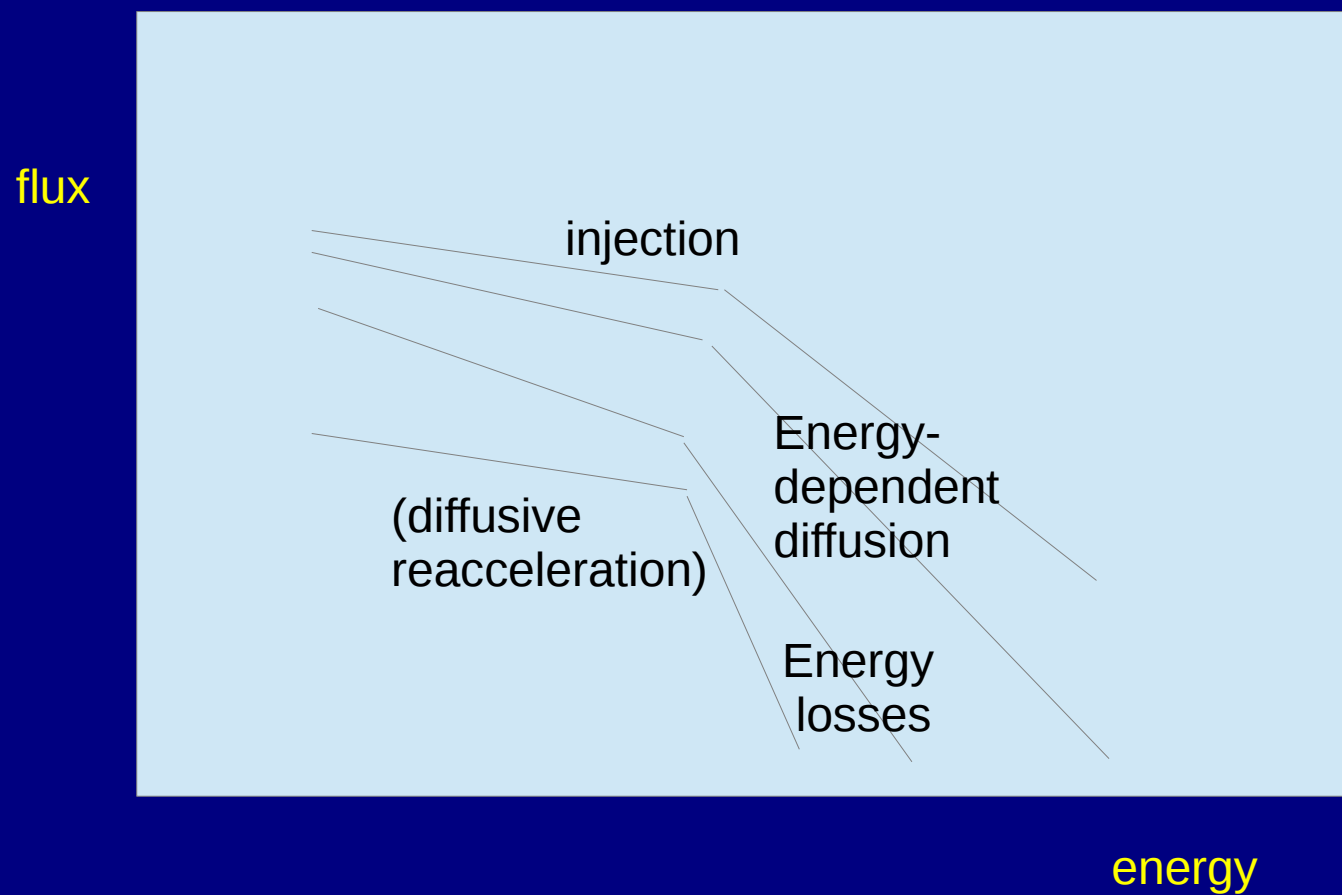
Producing the cosmic-ray electron spectrum



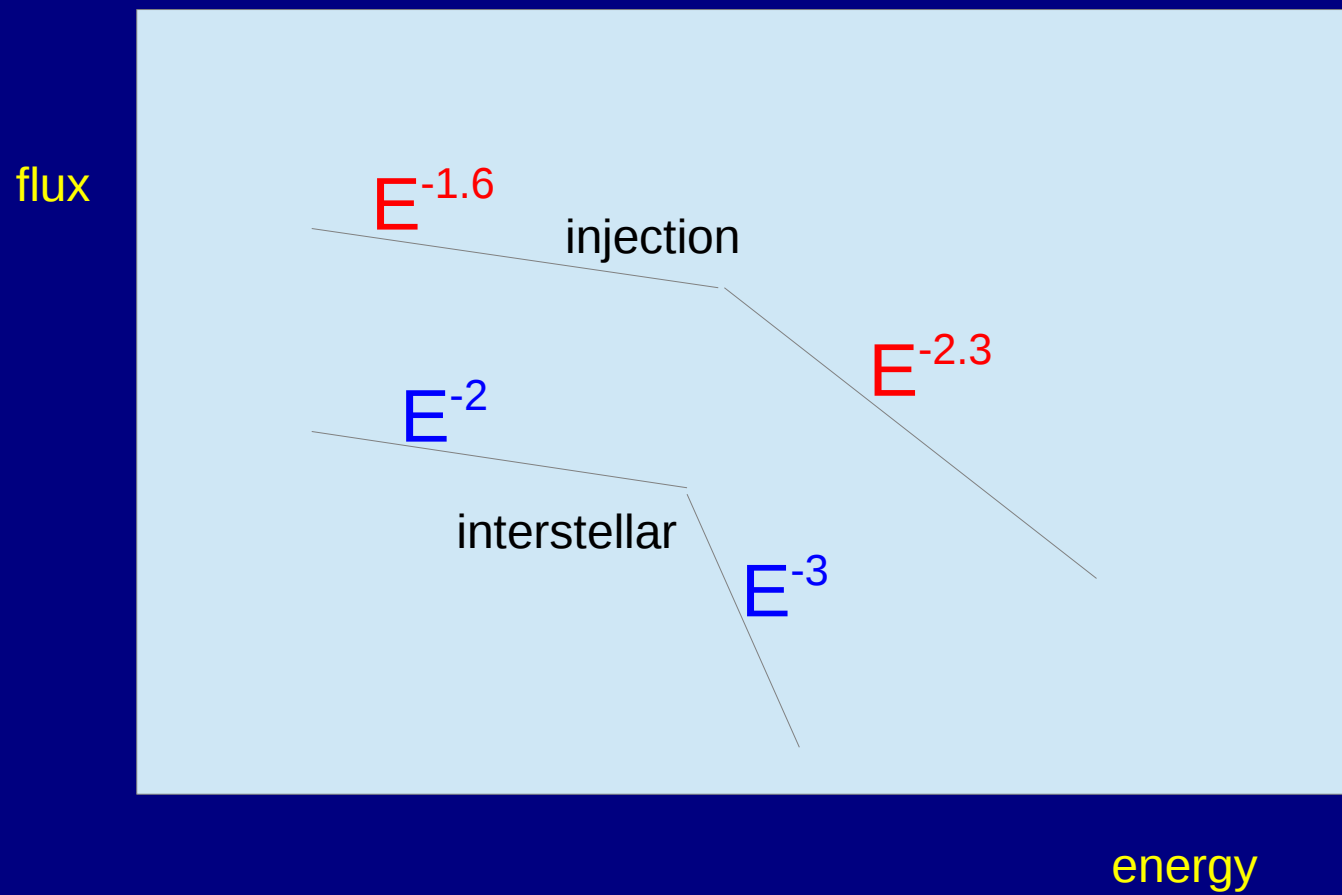
Producing the cosmic-ray electron spectrum



Producing the cosmic-ray electron spectrum

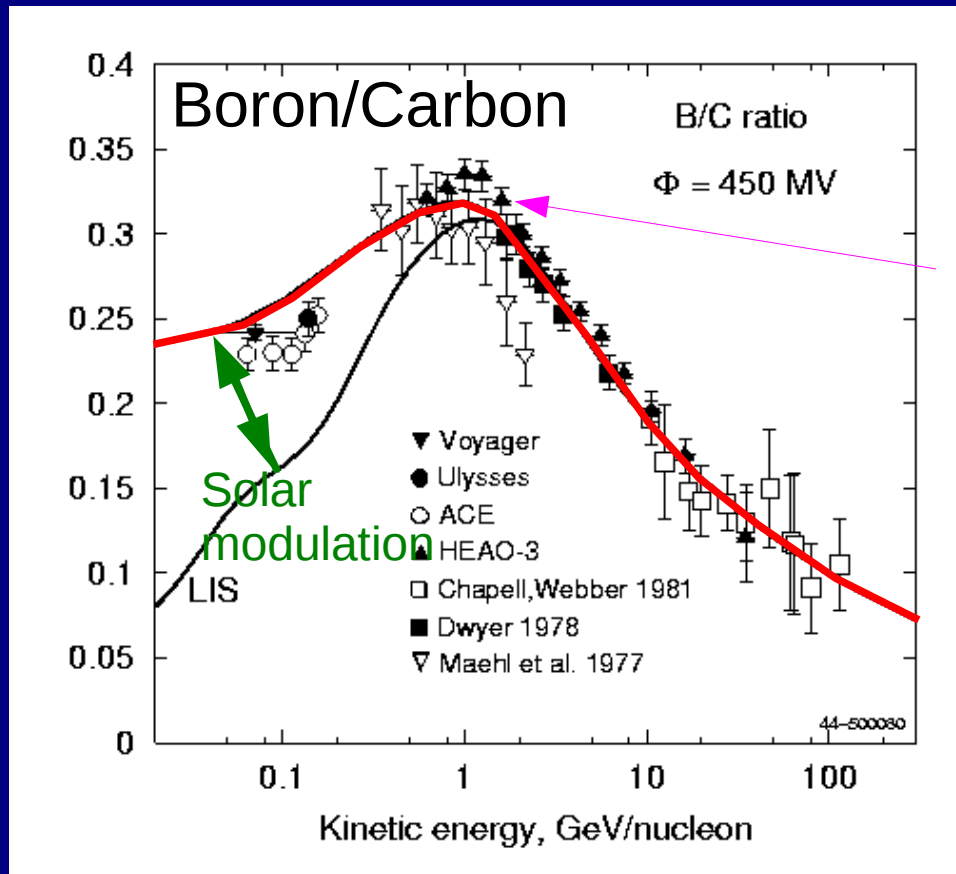


Producing the cosmic-ray electron spectrum



Cosmic-ray secondary/primary ratios: e.g. Boron/Carbon probes *cosmic-ray propagation*

Boron / Carbon



Peak in Boron/Carbon could be explained by **diffusive reacceleration** with Kolmogorov spectrum giving momentum-dependence of diffusion coefficient

Spatial diffusion

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

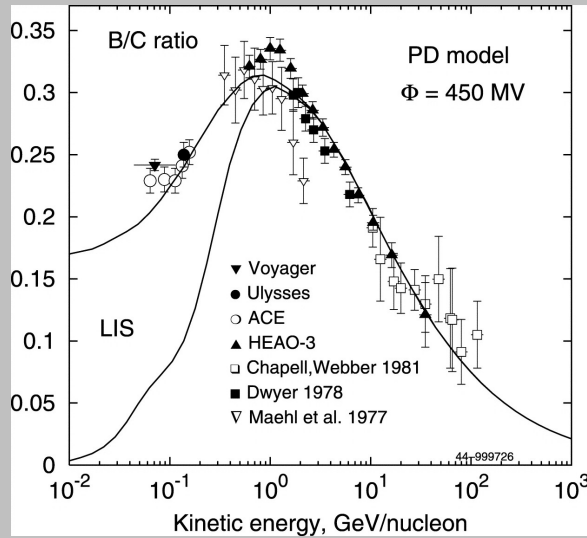
Momentum space diffusion

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

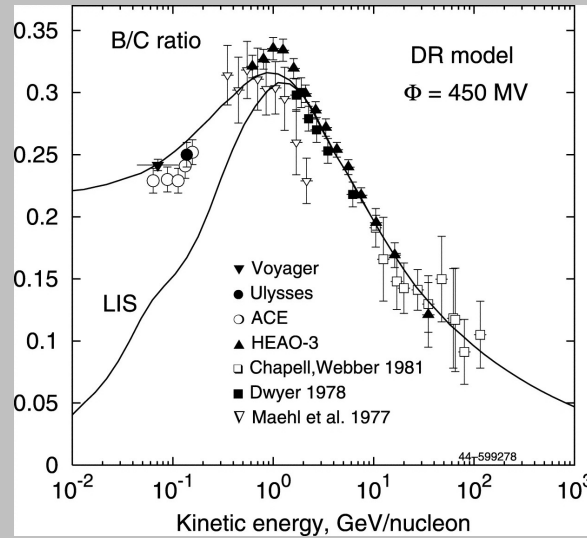
However reacceleration not proven, maybe does not happen

→ 'pure diffusion' model: $D_{xx}(p) \sim p^{0.5}$, constant < 3 GeV.

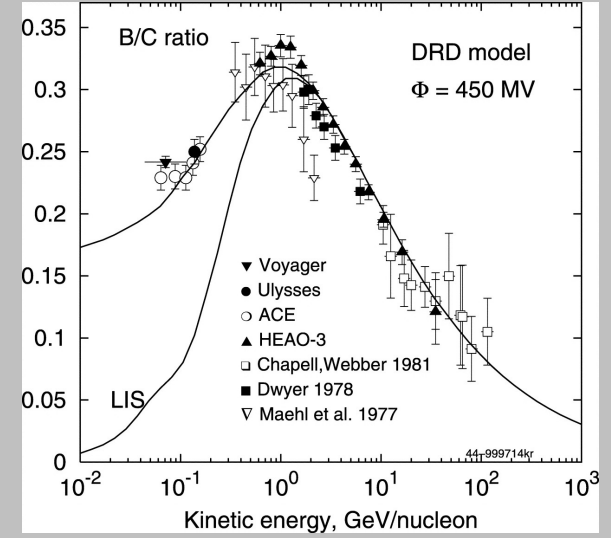
plain diffusion



diffusive reacceleration

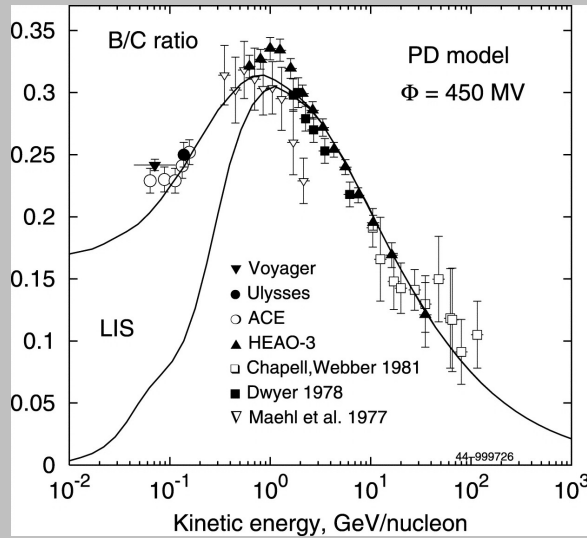


wave damping

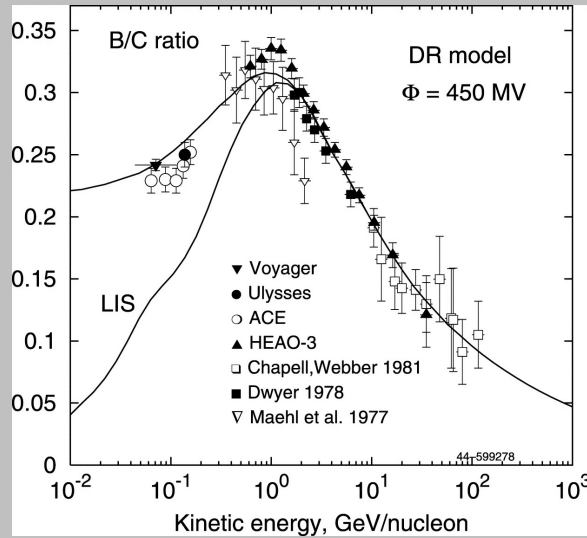


For any model, first adjust parameters to fit Boron/Carbon

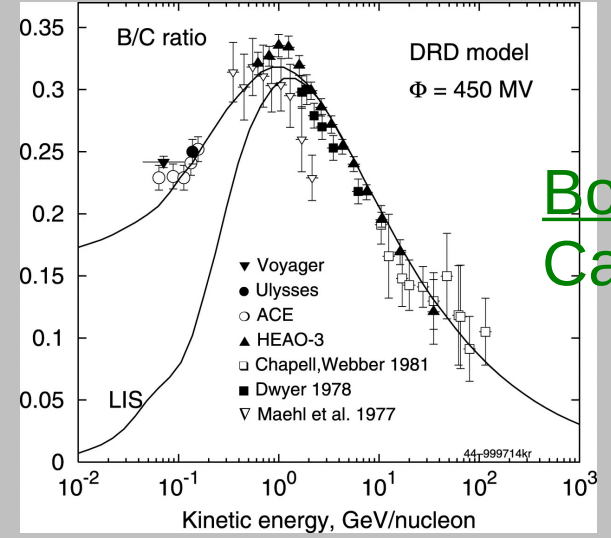
plain diffusion



diffusive reacceleration



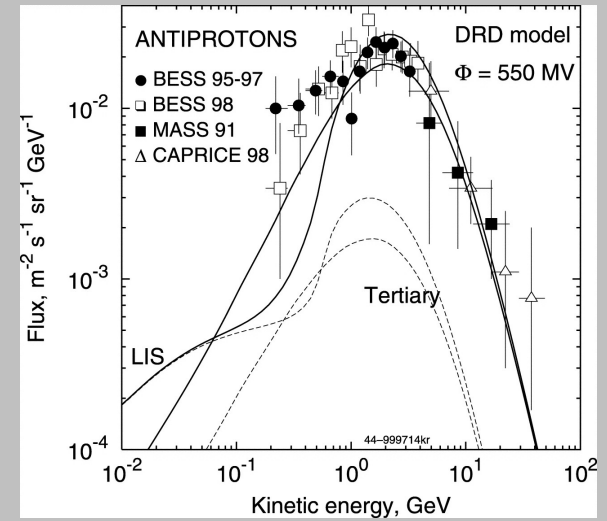
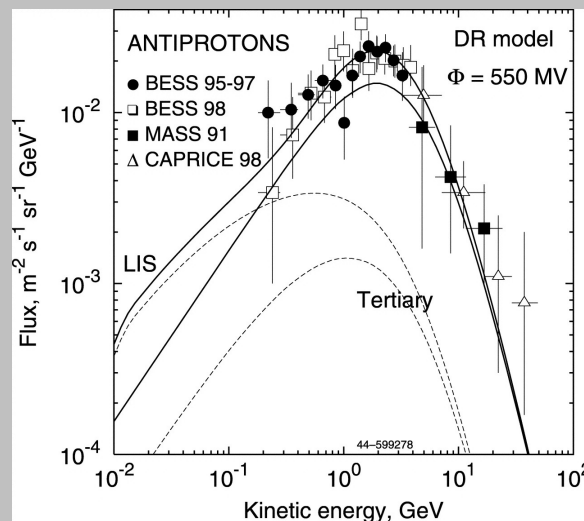
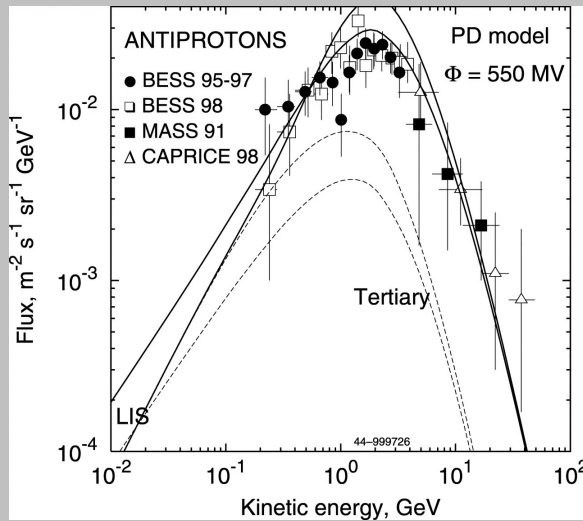
wave damping



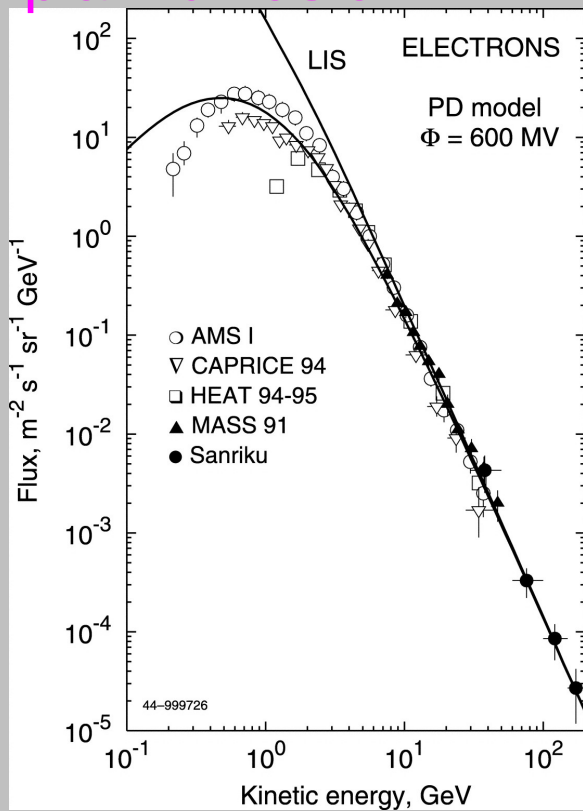
Boron/
Carbon

then predict the other cosmic-ray spectra

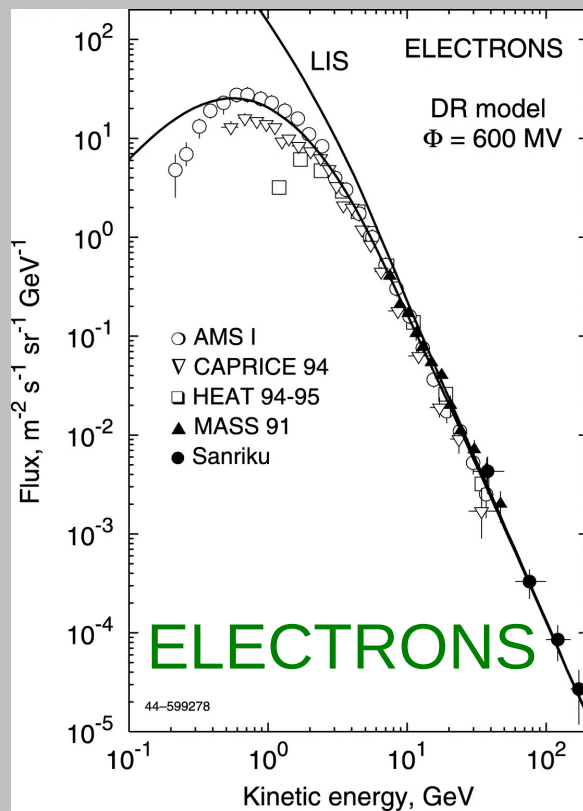
antiprotons



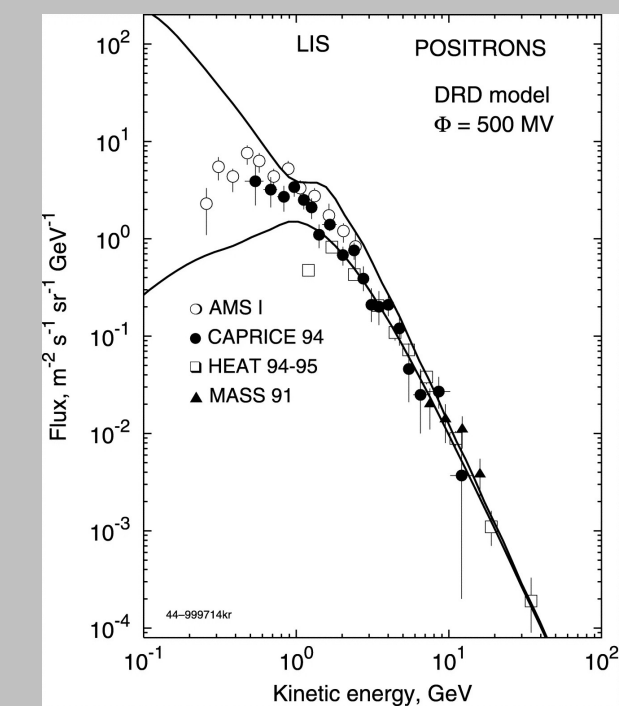
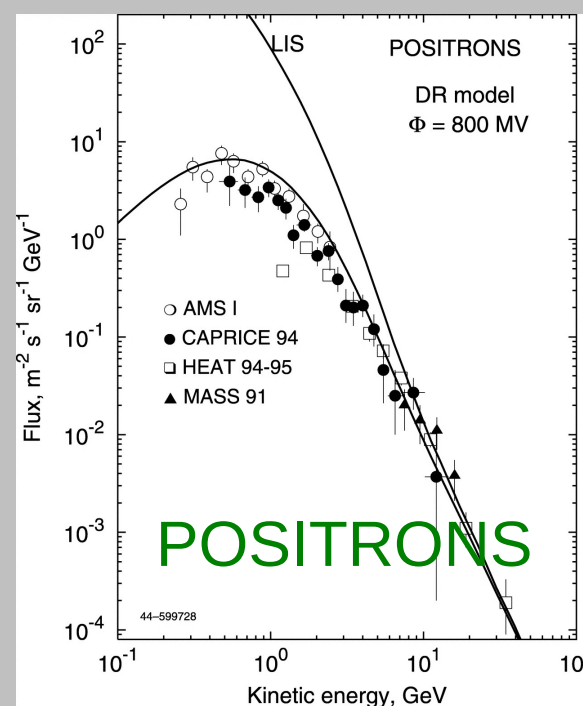
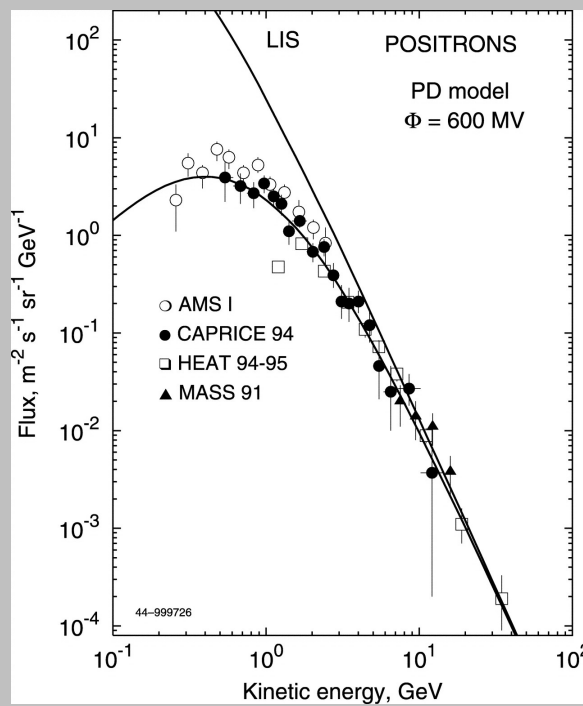
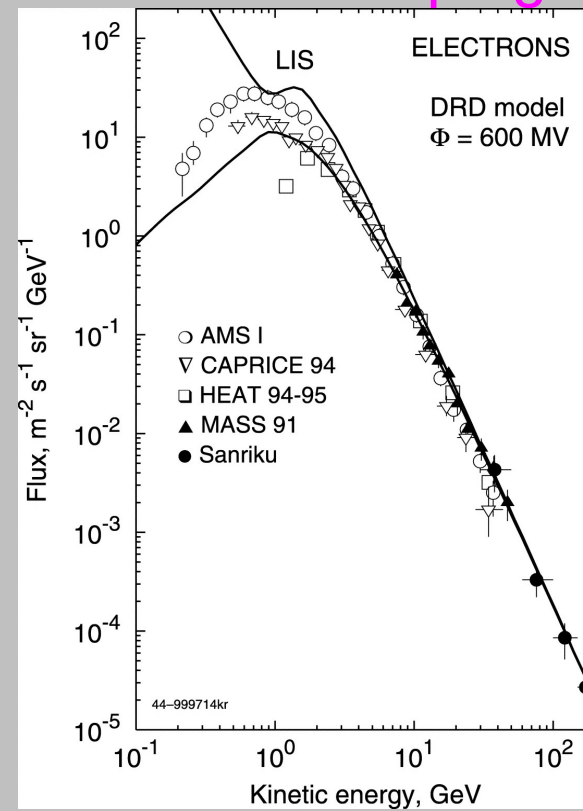
plain diffusion



diffusive reacceleration



wave damping



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

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MNRAS 416, 1152 (2011)

Uses RM, polarization, MCMC.

Cosmic-ray electrons from sources + propagation

The interstellar cosmic-ray electron spectrum from synchrotron radiation and direct measurements[★]

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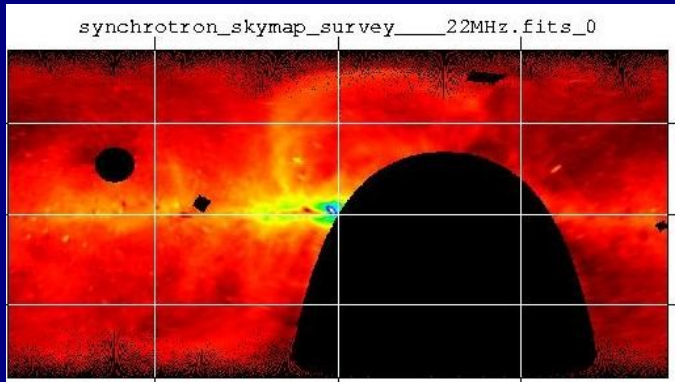
ABSTRACT

Aims. We exploit synchrotron radiation to constrain the low-energy interstellar electron spectrum, using various radio surveys and connecting with electron data from *Fermi*-LAT and other experiments.

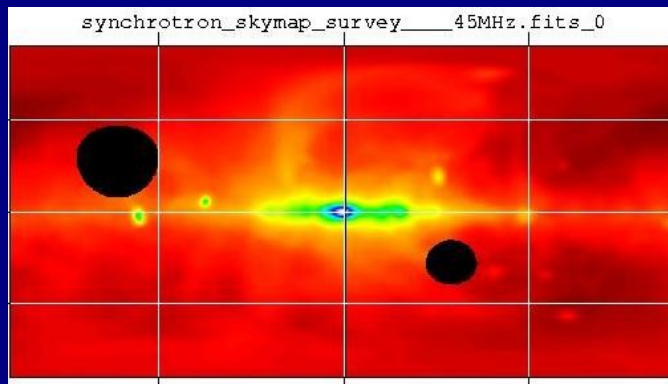
Methods. The GALPROP programme for cosmic-ray propagation, gamma-ray and synchrotron radiation is used. Secondary electrons and positrons are included. Propagation models based on cosmic-ray and gamma-ray data are tested against synchrotron data from 22 MHz to 94 GHz.

Results. The synchrotron data confirm the need for a low-energy break in the cosmic-ray electron injection spectrum. The interstellar spectrum below a few GeV has to be lower than standard models predict, and this suggests less solar modulation than usually assumed. Reacceleration models are more difficult to reconcile with the synchrotron constraints. We show that secondary leptons are important for the interpretation of synchrotron emission. We also consider a cosmic-ray propagation origin for the low-energy break.

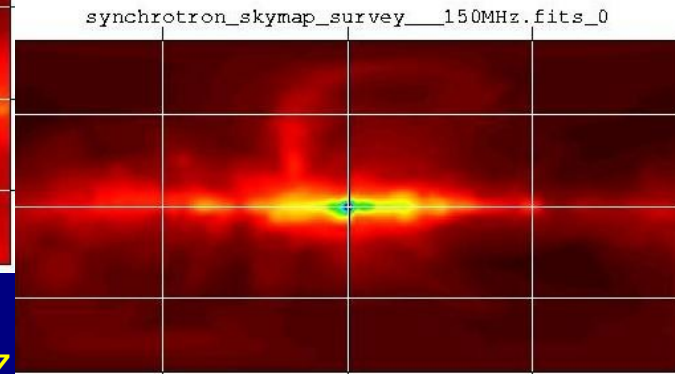
Conclusions. Exploiting the complementary information on cosmic rays and synchrotron gives unique and essential constraints on electrons, and has implications for gamma rays. This connection is especially relevant now in view of the ongoing *Planck* and *Fermi* missions.



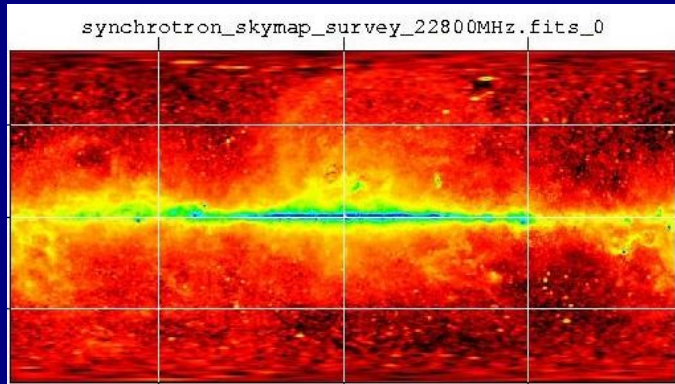
22 MHz



45 MHz



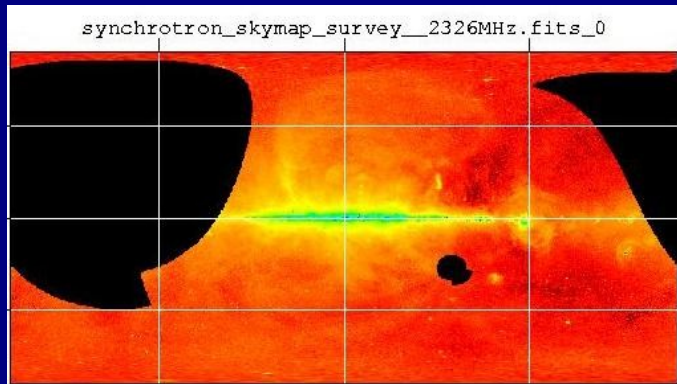
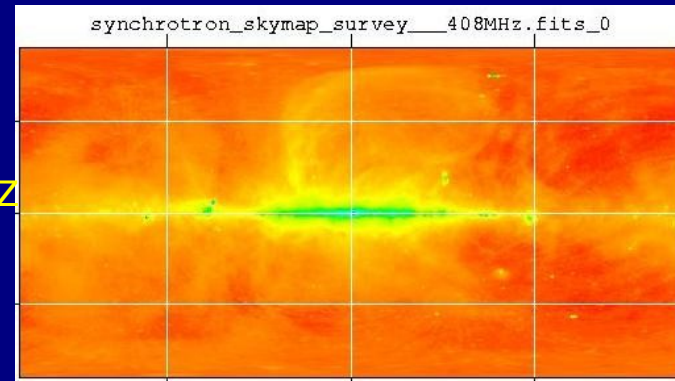
150 MHz



23 GHz

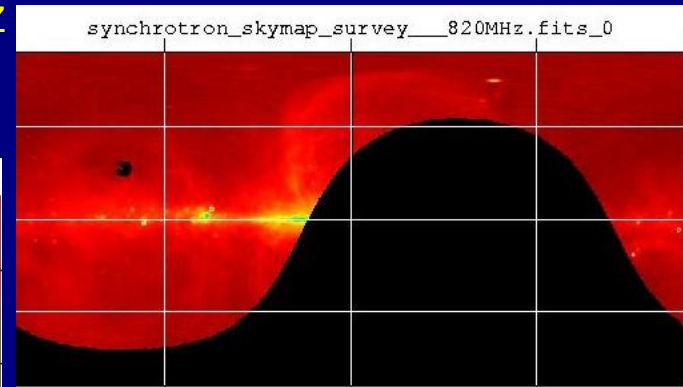
Continuum
sky surveys

408 MHz

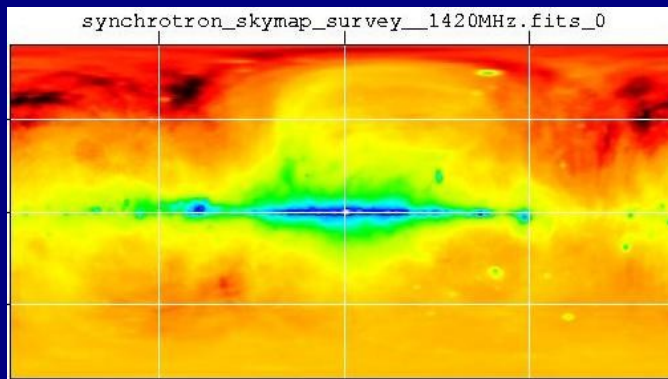


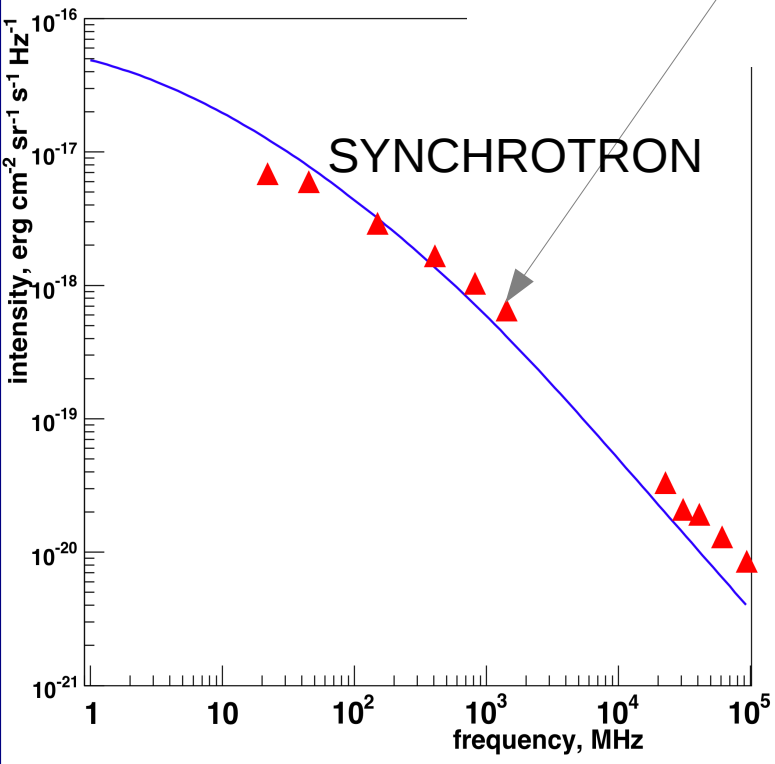
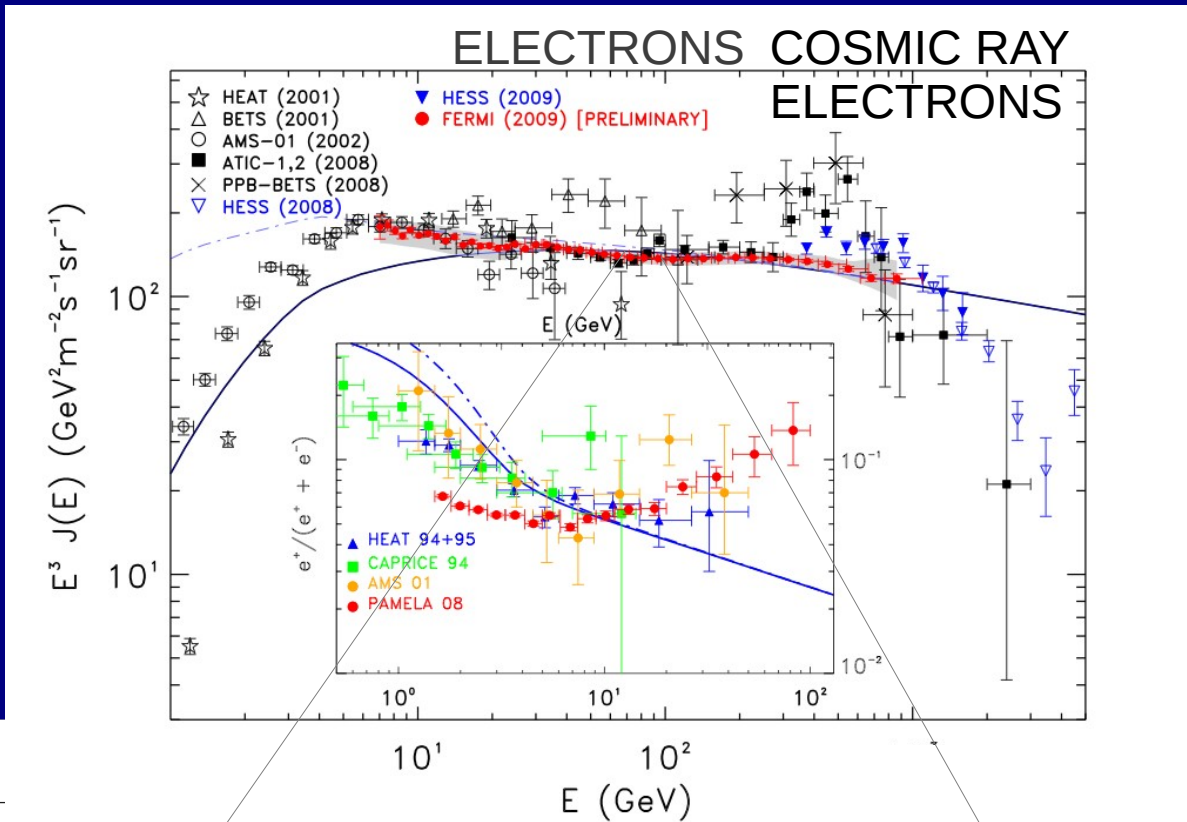
2.3 GHz

820 MHz

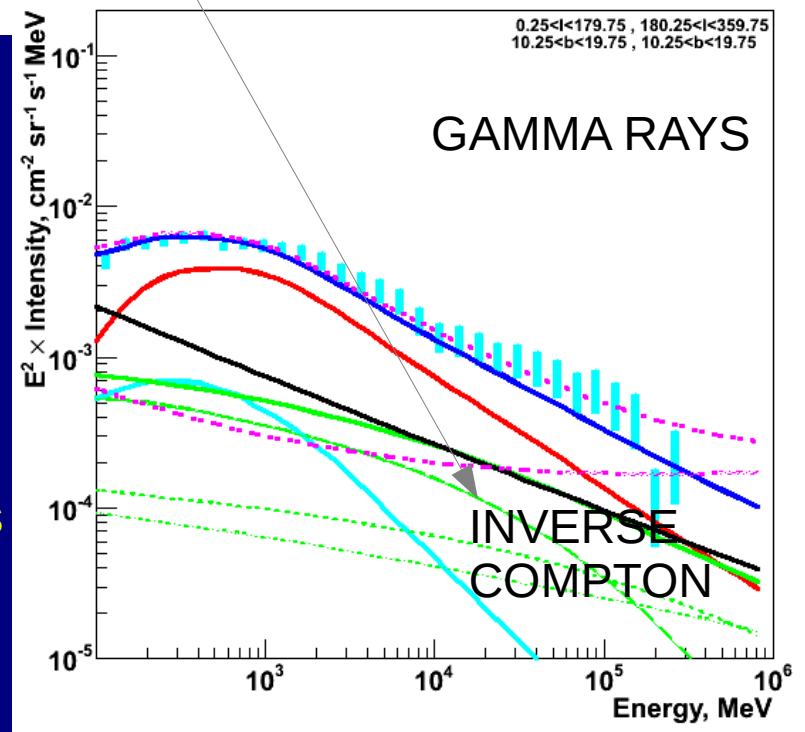


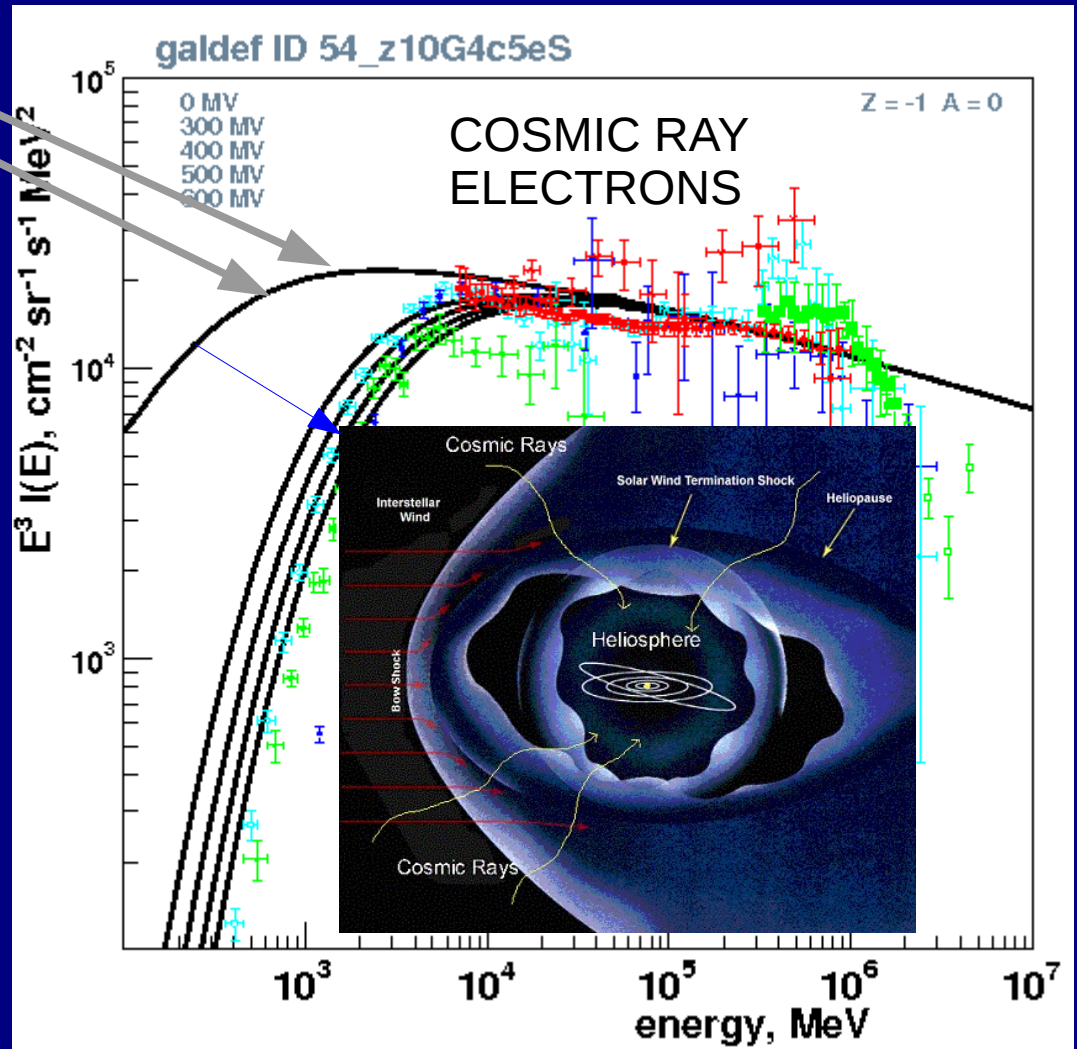
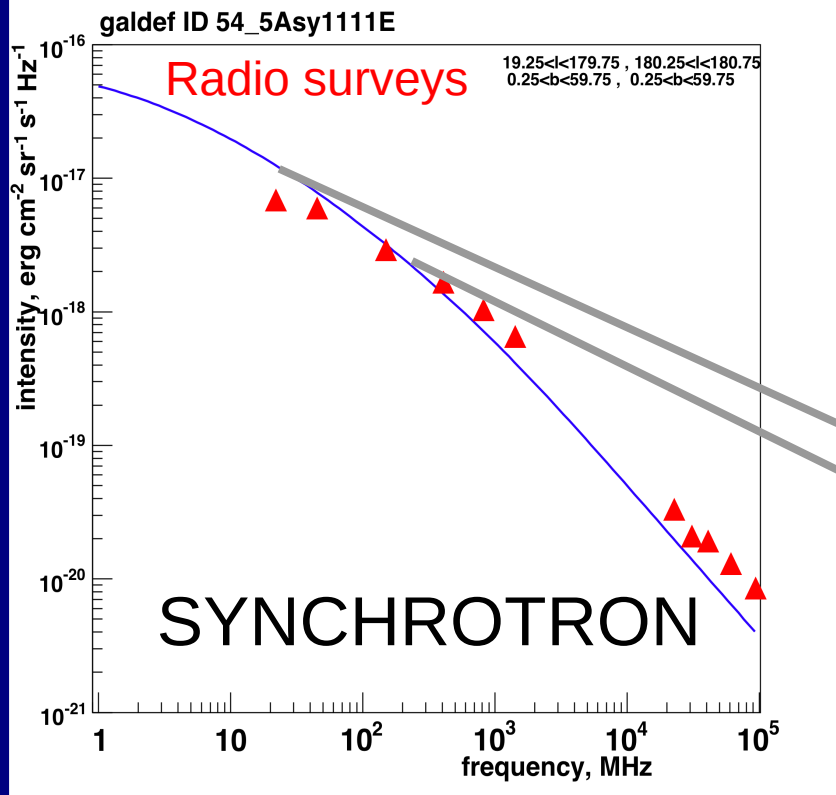
1.4 GHz





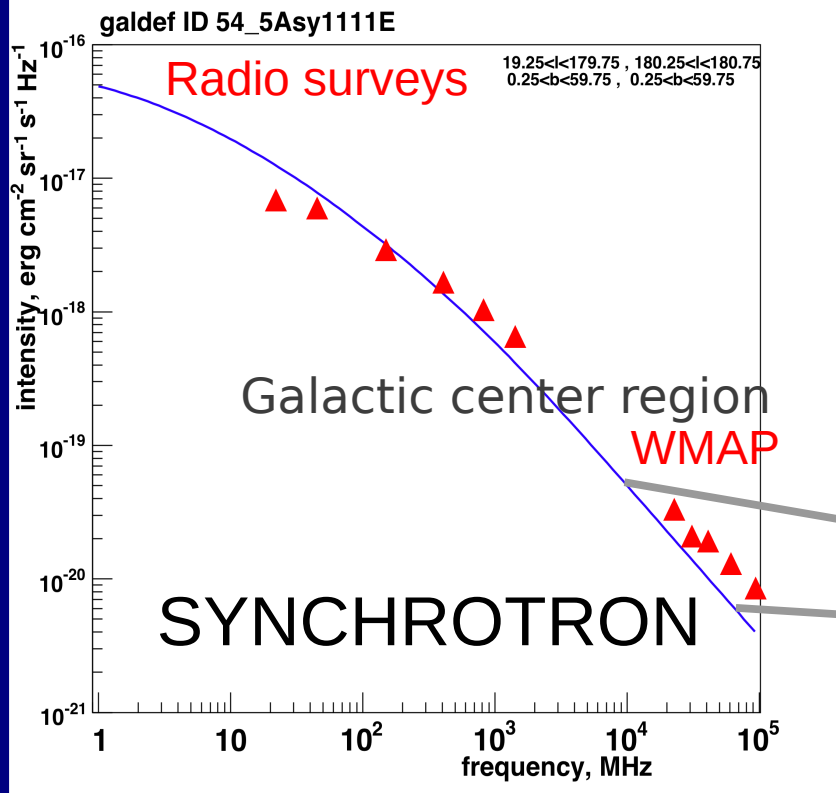
**SAME
 ELECTRONS
 for
 RADIO
 and
 GAMMA RAYS !**
 good constraints
 on models



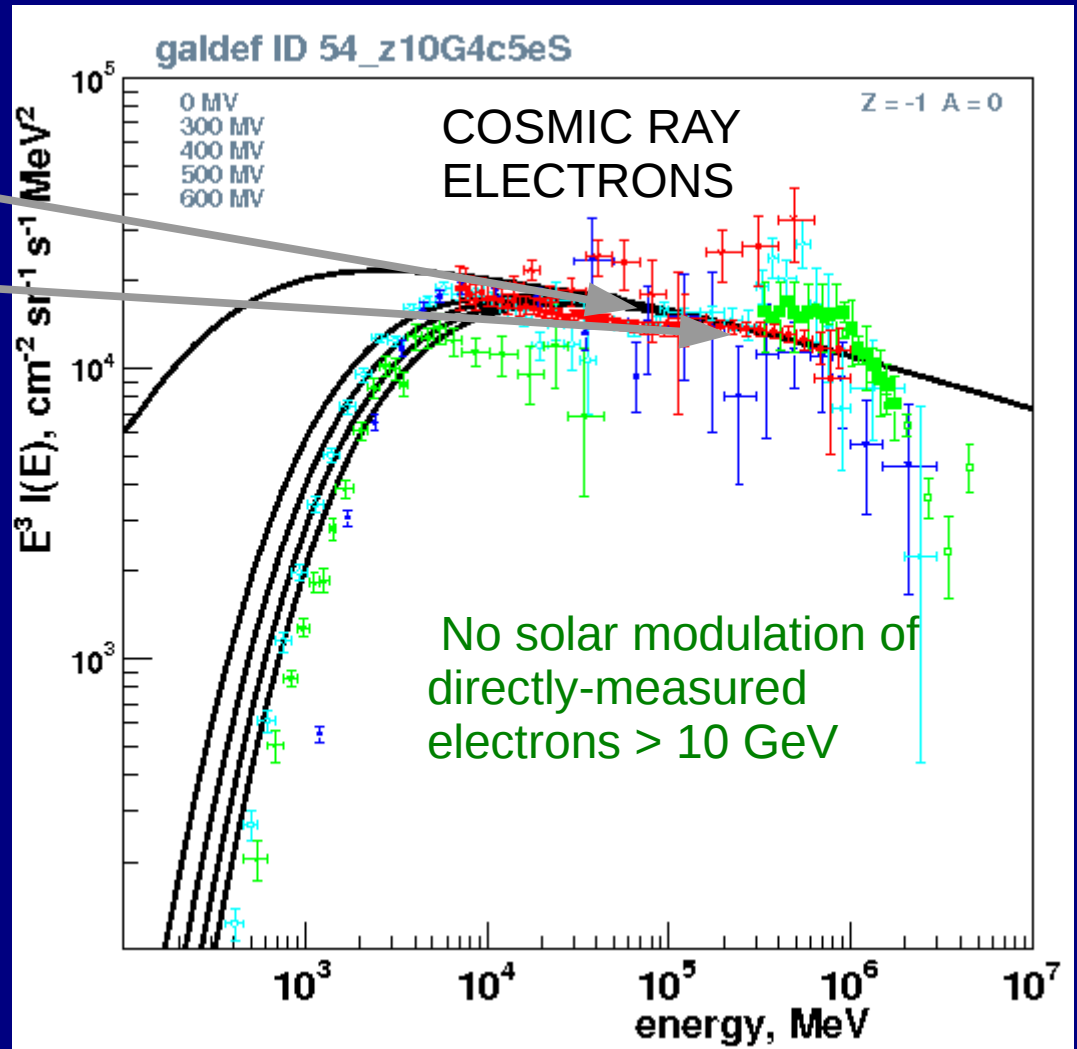


Radio provides essential probe of interstellar electron spectrum at $E < \text{few GeV}$ to complement direct measurements and determine solar modulation

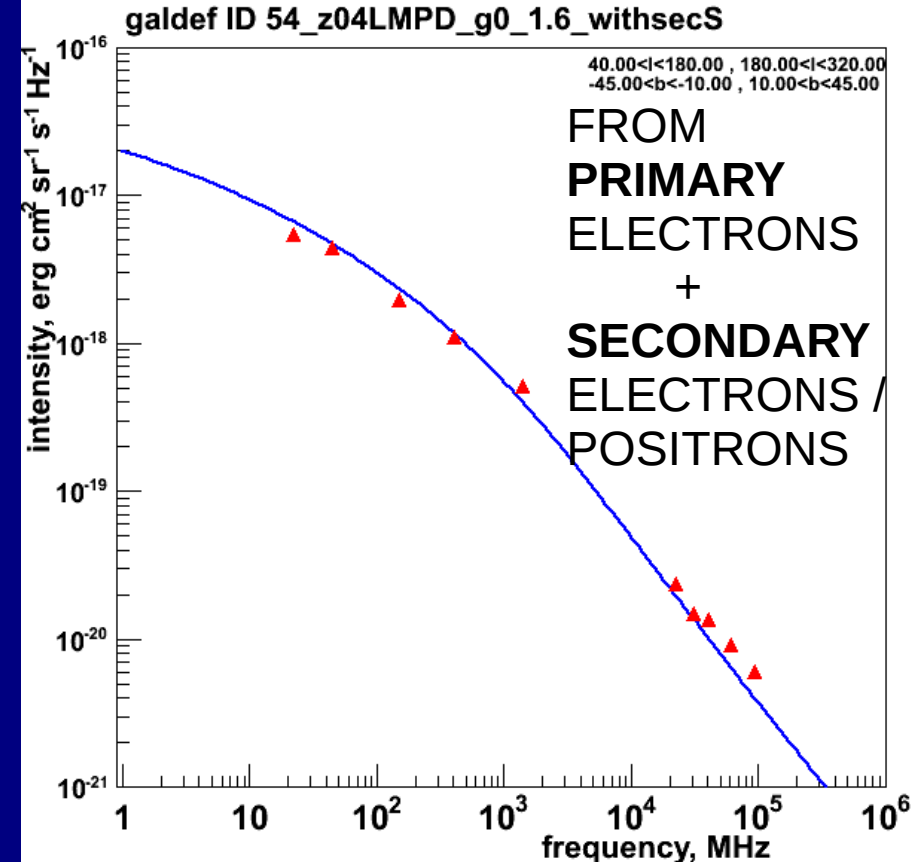
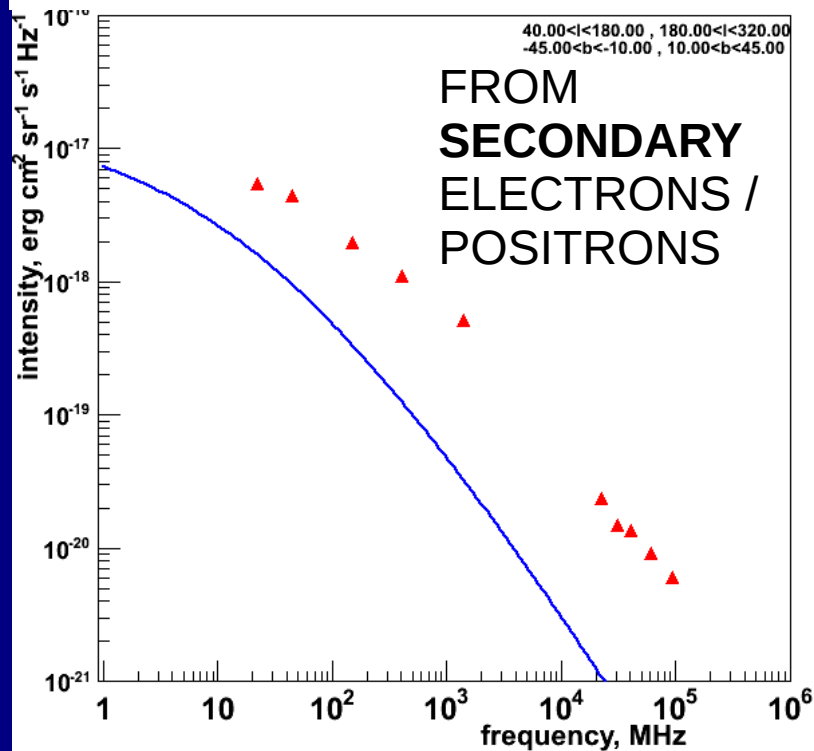
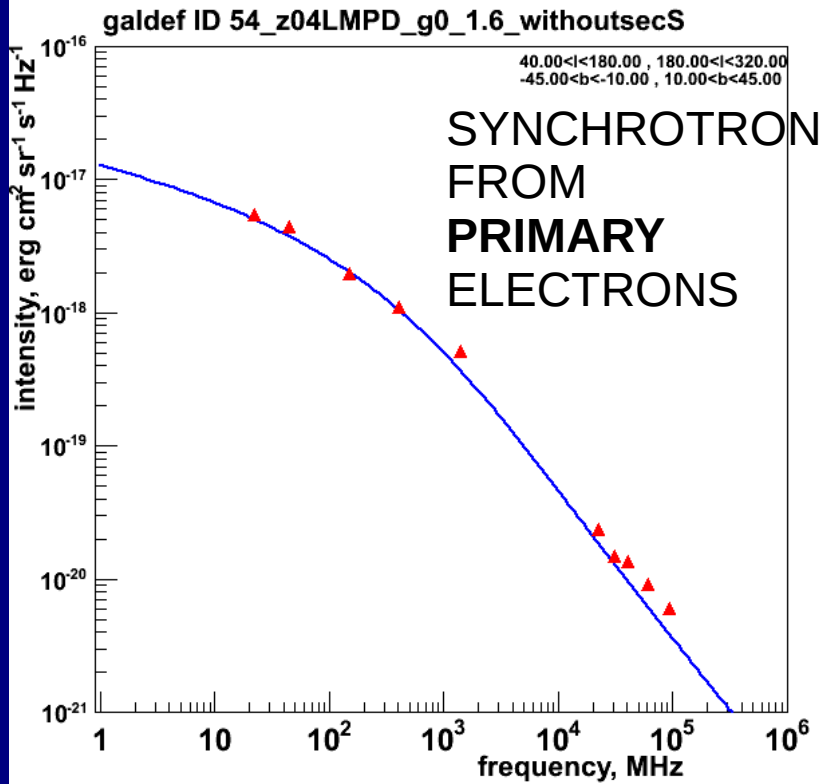
Electrons have huge uncertainty due to modulation here



microwaves probe
interstellar electron spectrum
10 - 100 GeV



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



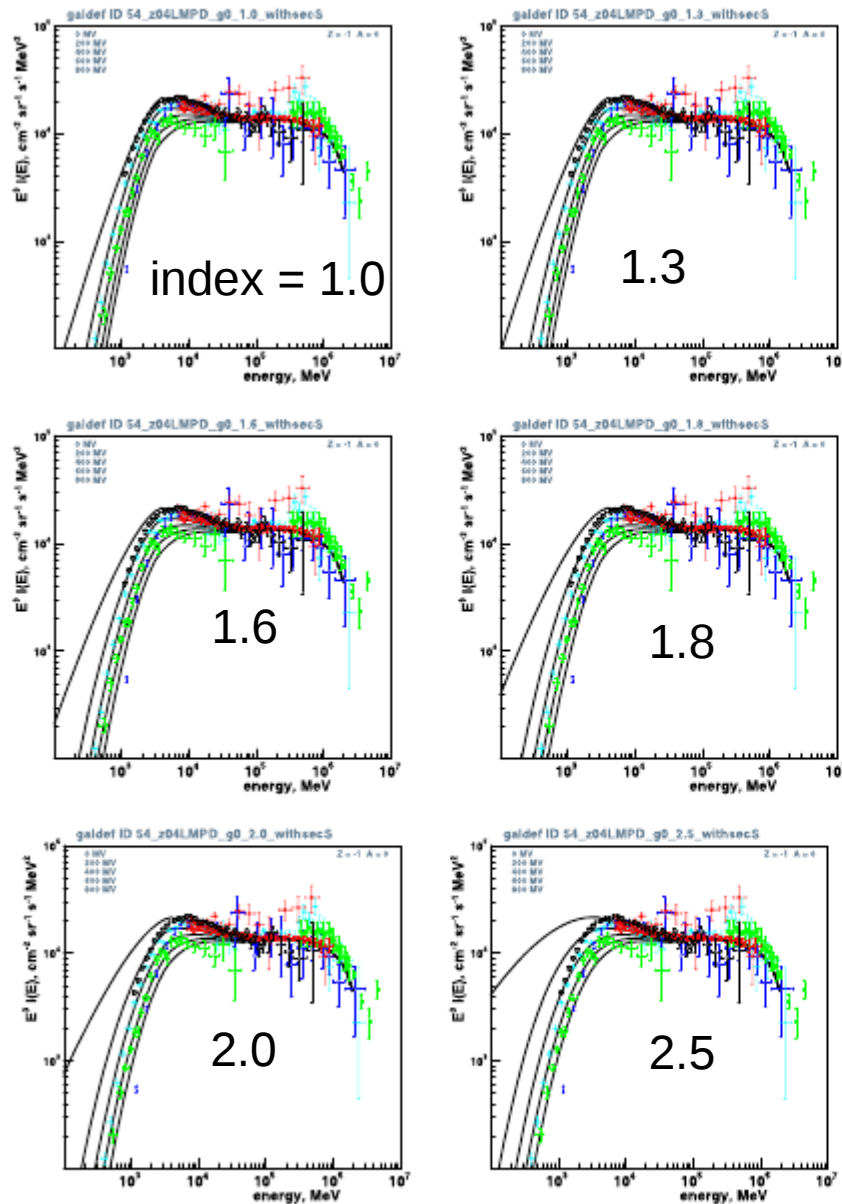


Fig. 4. Electron spectra for pure diffusion model, low-energy electron injection index 1.0, 1.3, 1.6, 1.8, 2.0, 2.5. Modulation $\Phi = 0, 200, 400, 600, 800$ MV. Data as in Fig. 1.

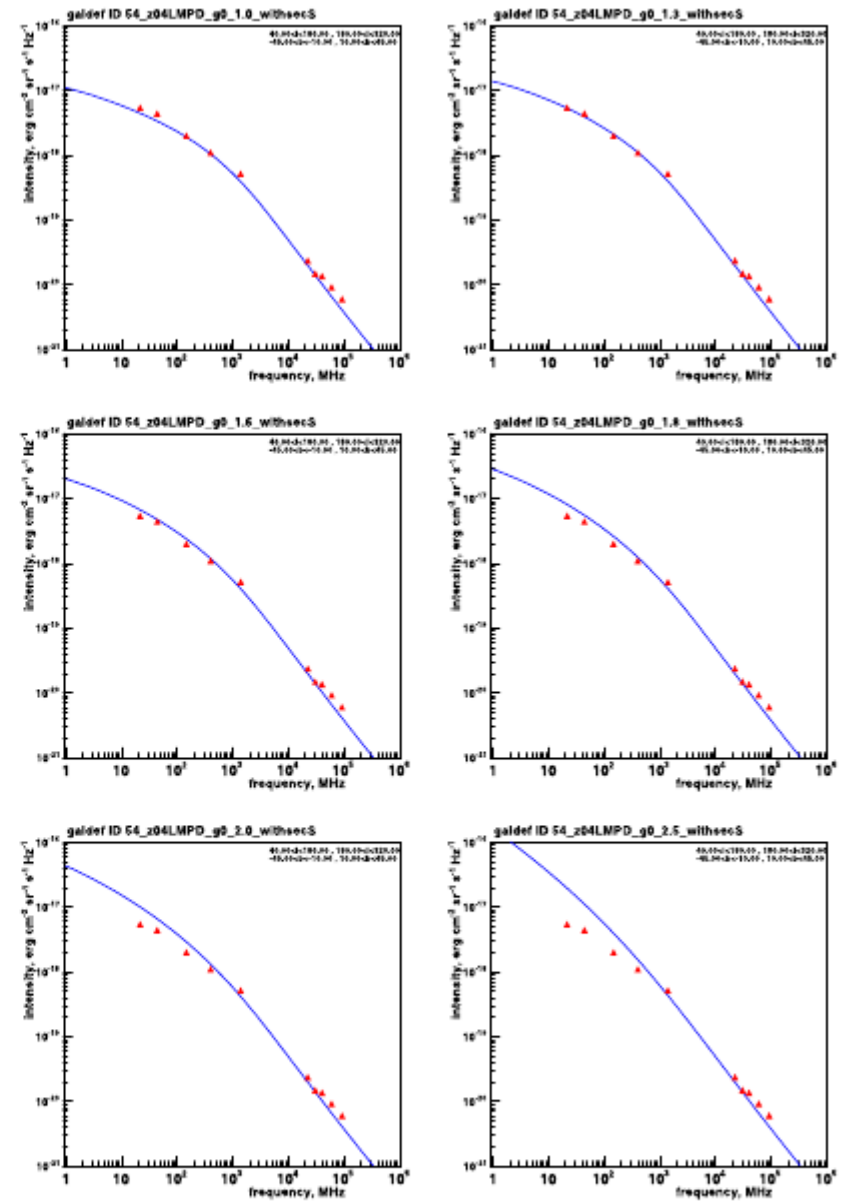


Fig. 5. Synchrotron spectra for pure diffusion model with low-energy electron injection index (left to right, top to bottom) 1.0, 1.3, 1.6, 1.8, 2.0, 2.5. Including secondary leptons. Data as in Fig. 2.

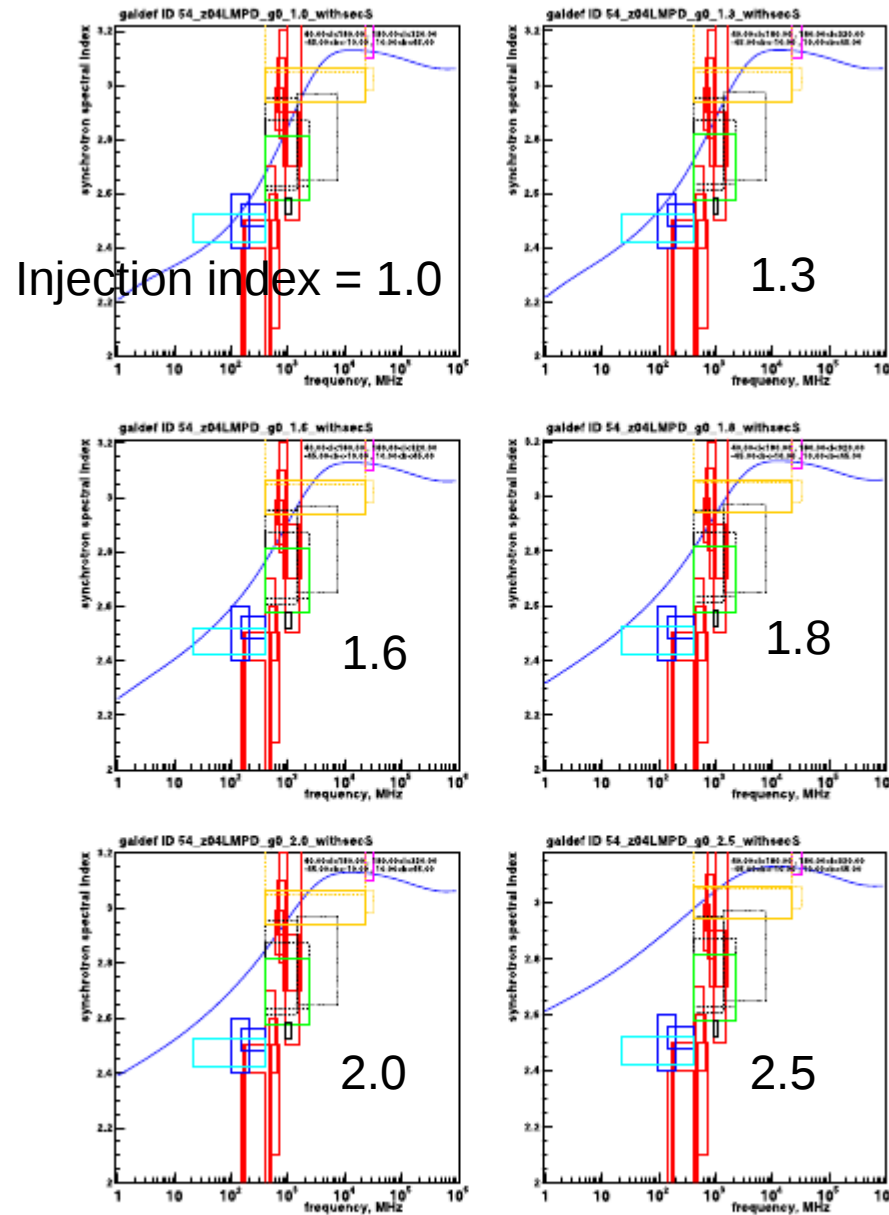
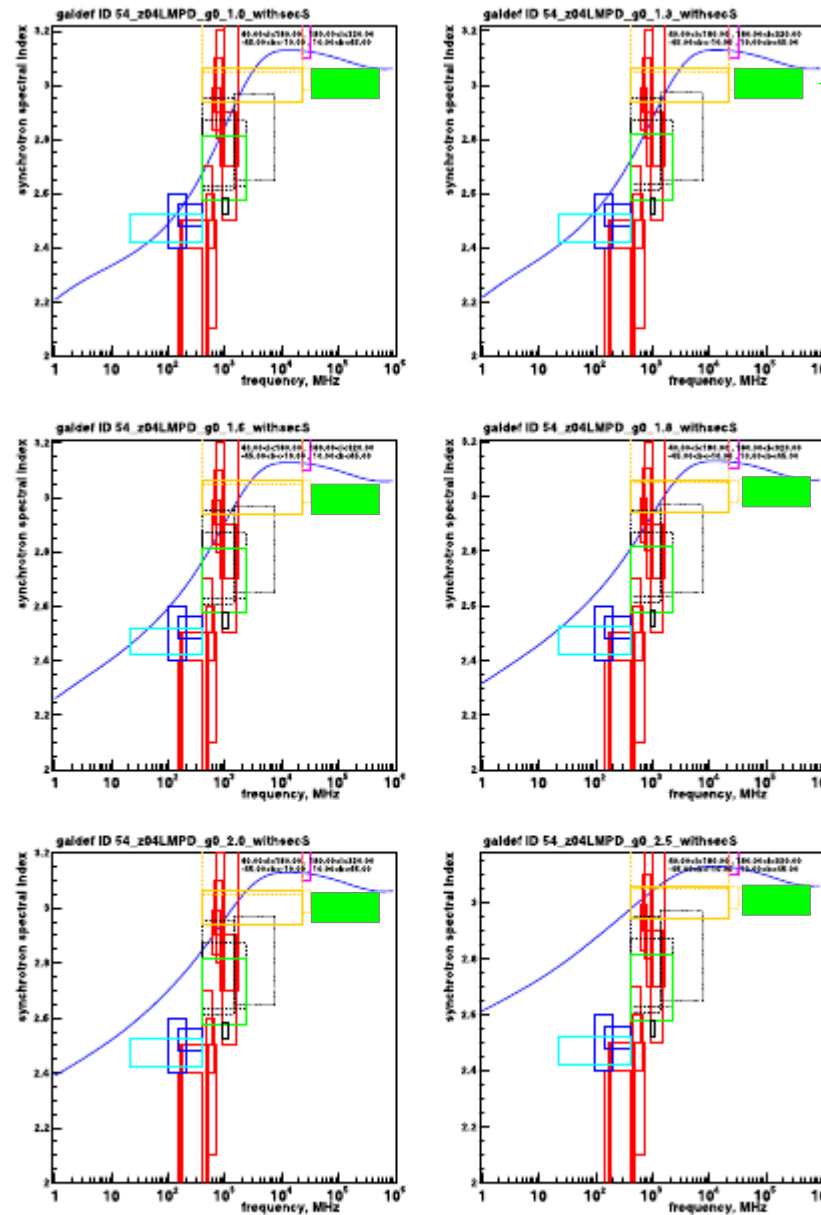
Galactic
Synchrotron
Spectral
Index

Fig. 6. Synchrotron spectral index for pure diffusion model with low-energy electron injection index (left to right, top to bottom) 1.0, 1.3, 1.6, 1.8, 2.0, 2.5. Including secondary leptons. Experimental ranges are based on the references reviewed in Sect. 4.1, and are intended to be representative not exhaustive. Data as in Fig. 3.

Effect of electron injection spectral index



Planck

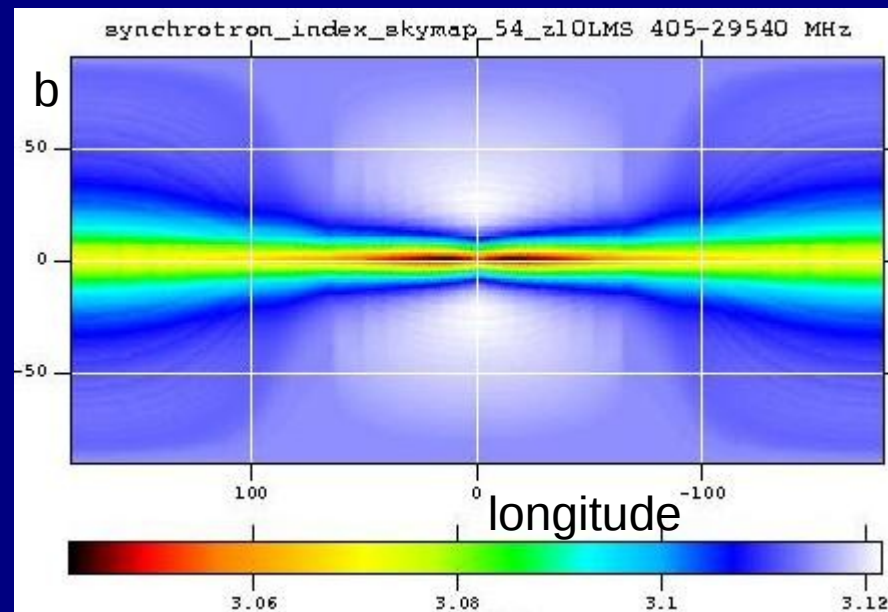
A&A 536, A21 (2011)

Galactic
Synchrotron
Spectral
Index

Fig. 6. Synchrotron spectral index for pure diffusion model with low-energy electron injection index (left to right, top to bottom) 1.0, 1.3, 1.6, 1.8, 2.0, 2.5. Including secondary leptons. Experimental ranges are based on the references reviewed in Sect. 4.1, and are intended to be representative not exhaustive. Data as in Fig. 3.

Model Synchrotron spectral index

408 MHz – 23 GHz



Model predicts small but systematic variations due to propagation effects.

Reality is of course much more complex (Loop I etc not modelled).

The model gives a minimum underlying variation from electron propagation.

Total B (local) = 7.5 μ G from this analysis

Using high latitudes only, avoiding Loop I etc

Orlando and Strong 2013 (A&A 436, 2127)

What is new :

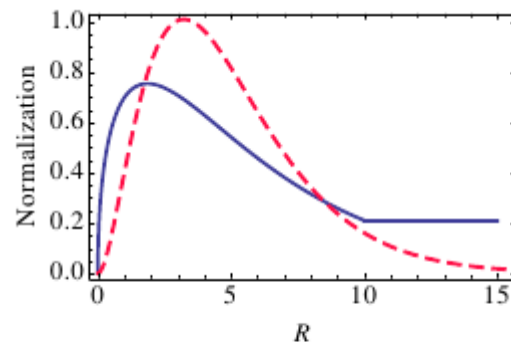
Polarized synchrotron

Separates regular from random B

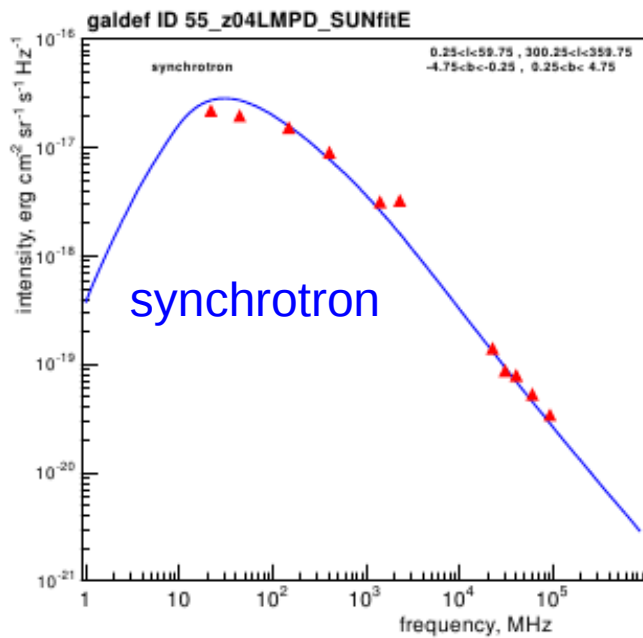
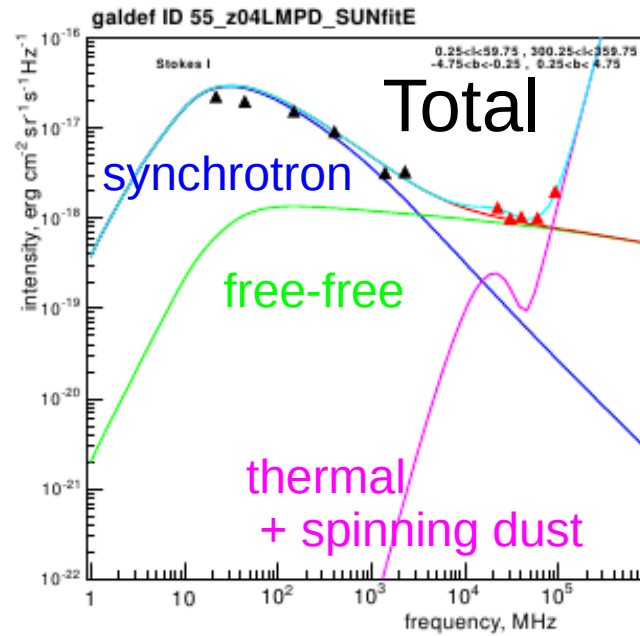
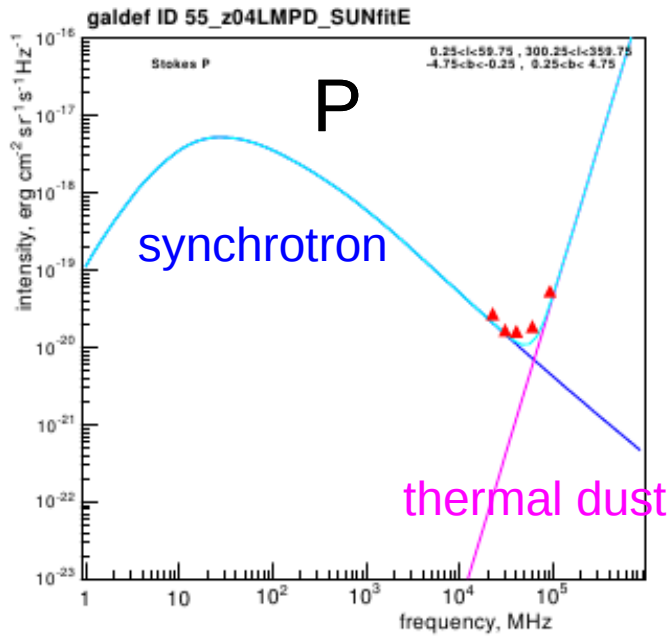
Now modelled in GALPROP

B-fields from literature, basic modifications to fit data.

Cosmic-ray electron distribution is a main input from gamma rays.

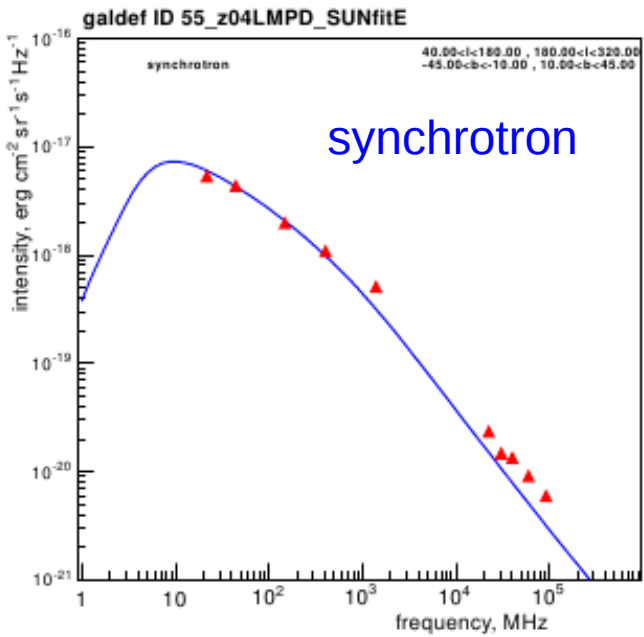
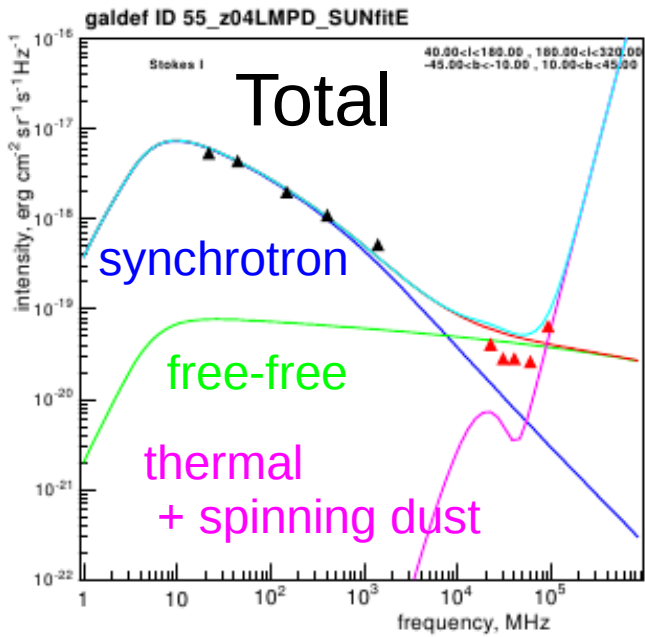
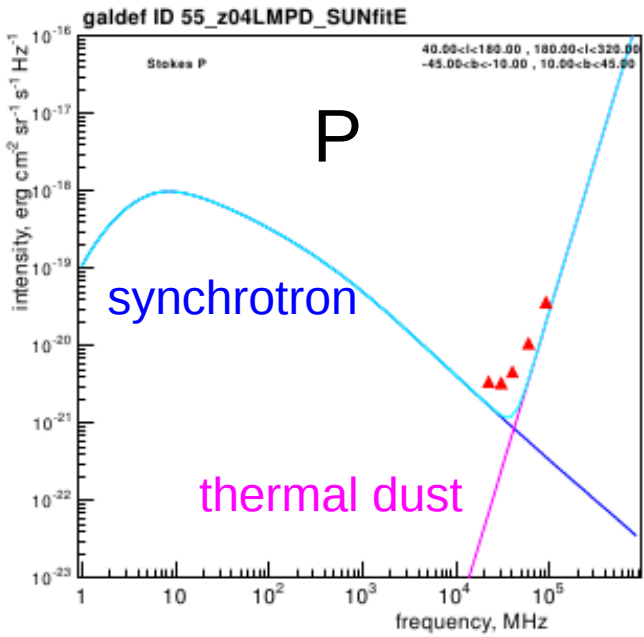


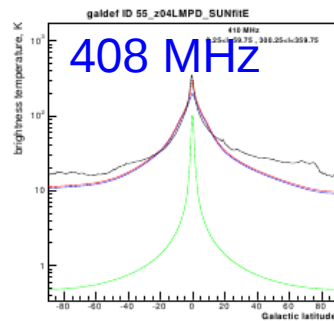
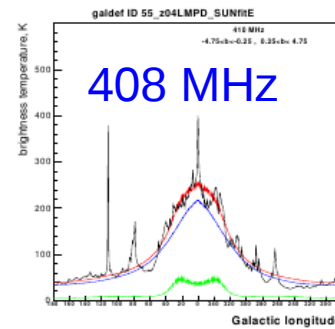
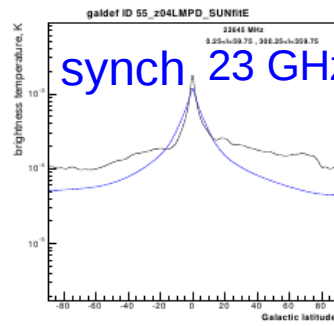
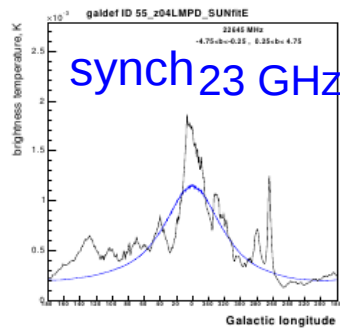
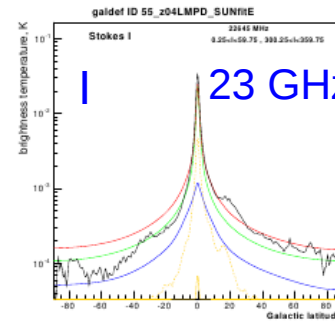
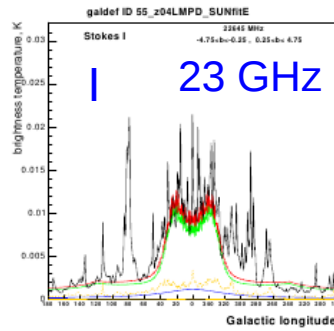
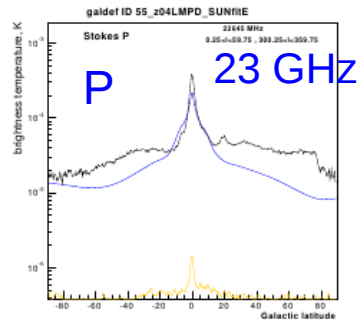
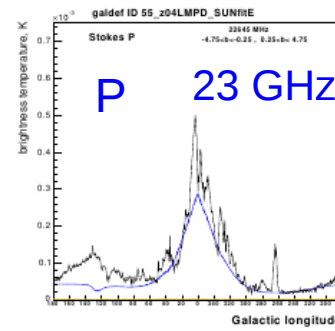
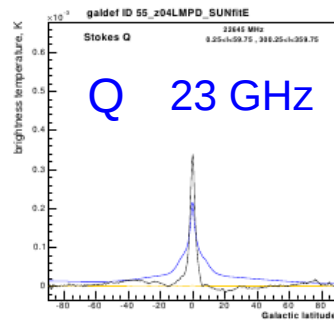
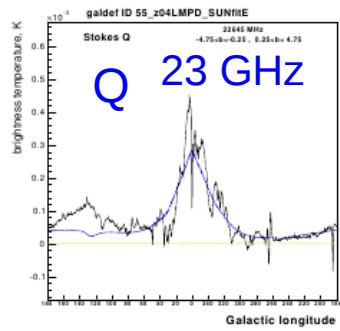
CR source distributions from Strong et al. (2010) (blue line) and pulsar-based Lorimer et al. (2006) (red dashed line). R is the Galactocentric radius in kpc. The distributions are normalized at $R= 8.5$ kpc.



INNER GALAXY

HIGH LATITUDES





Data: WMAP

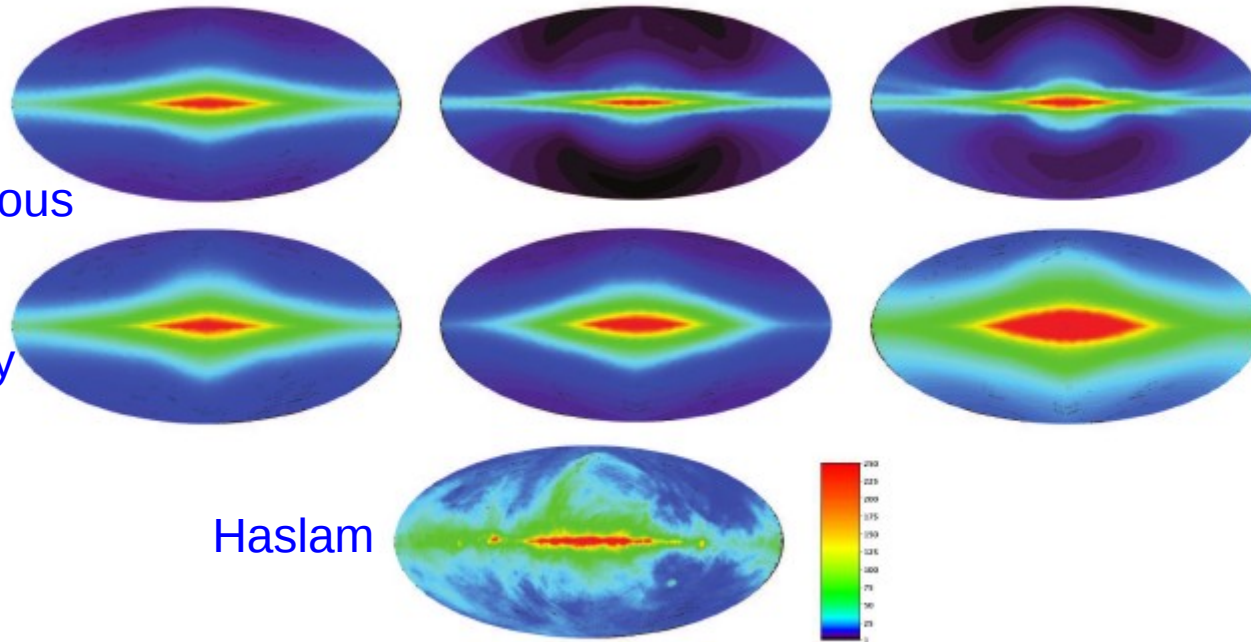
Data: Haslam

408 MHz

Interstellar radio emission

19

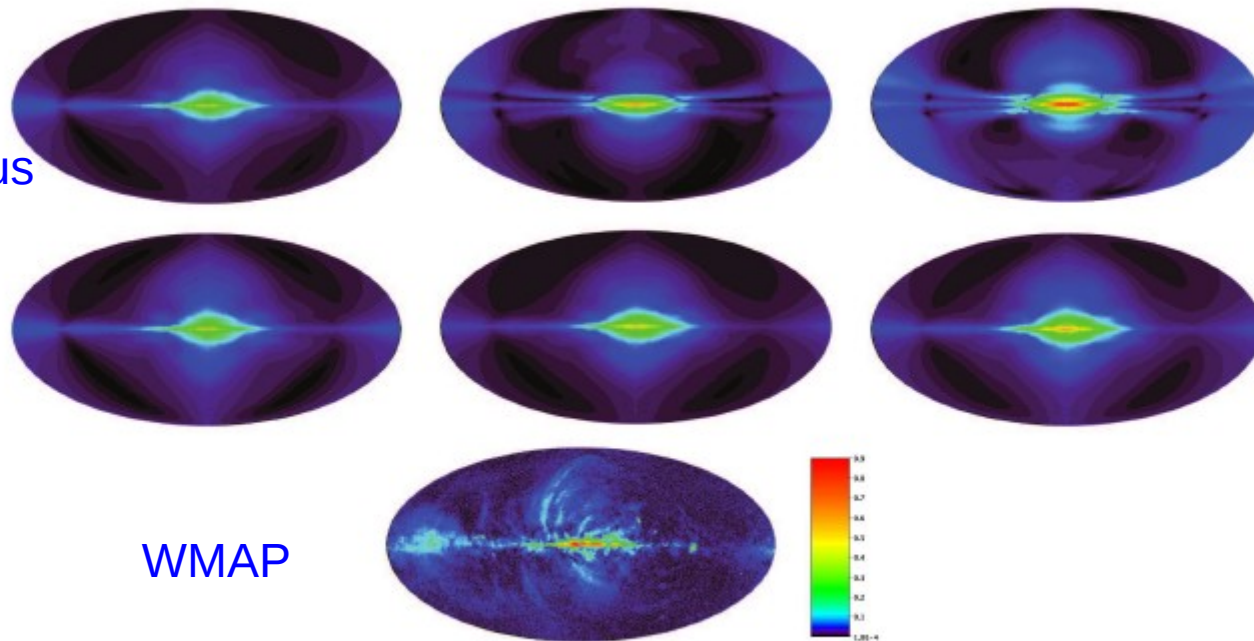
Using various
B-field
and
cosmic-ray
models



Regular B-field models from Sun et al, Pshirkov et al.
Scaling factor applied.

23 GHz
P

Using various
B-field
and
cosmic-ray
models



WMAP

Regular B-field models from Sun et al, Pshirkov et al.
Scaling factor applied.

B- field from Orlando & Strong 2013

Using :

Fermi-LAT cosmic-ray electrons

408 MHz

23 GHz WMAP polarized

Local B-field:

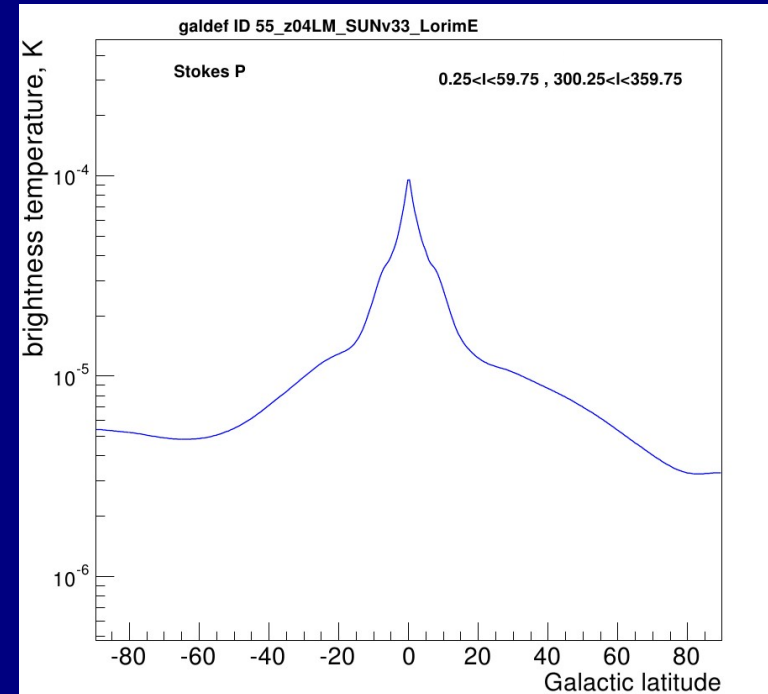
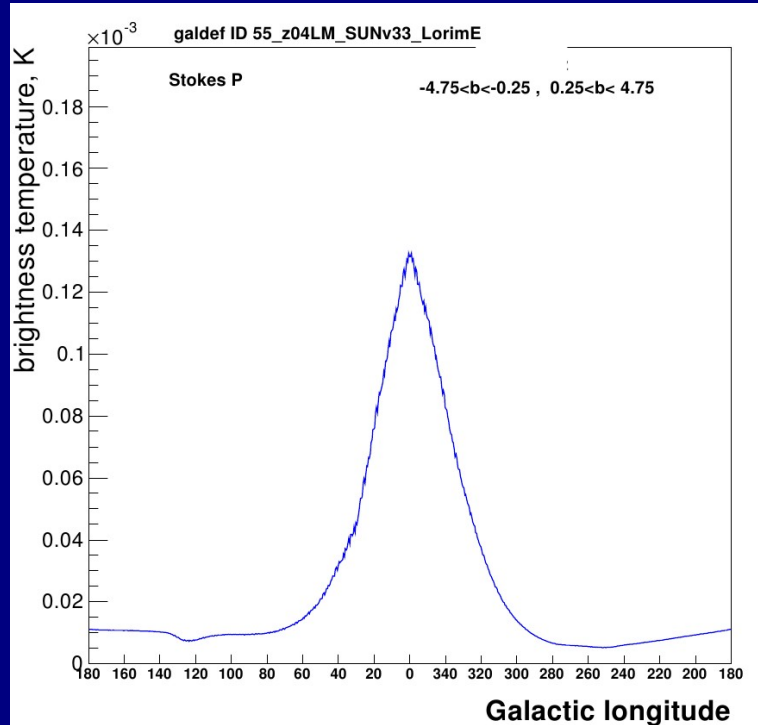
Regular : 3-4 μG :

factor 1.5-2 higher than original models of Sun, Pshirkov

Attribute to anisotropic field which contributes to synchrotron but not to rotation measures.

Random : 6 μG

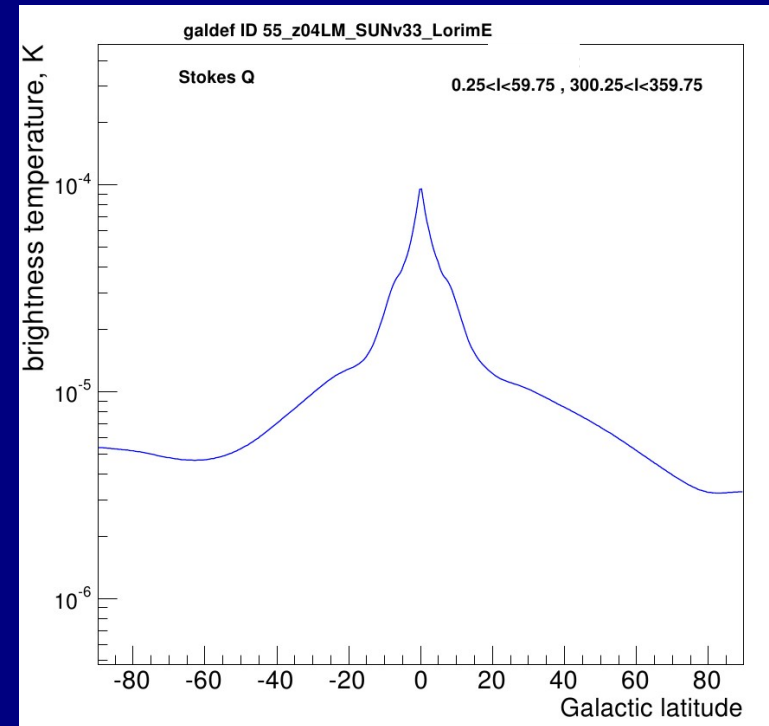
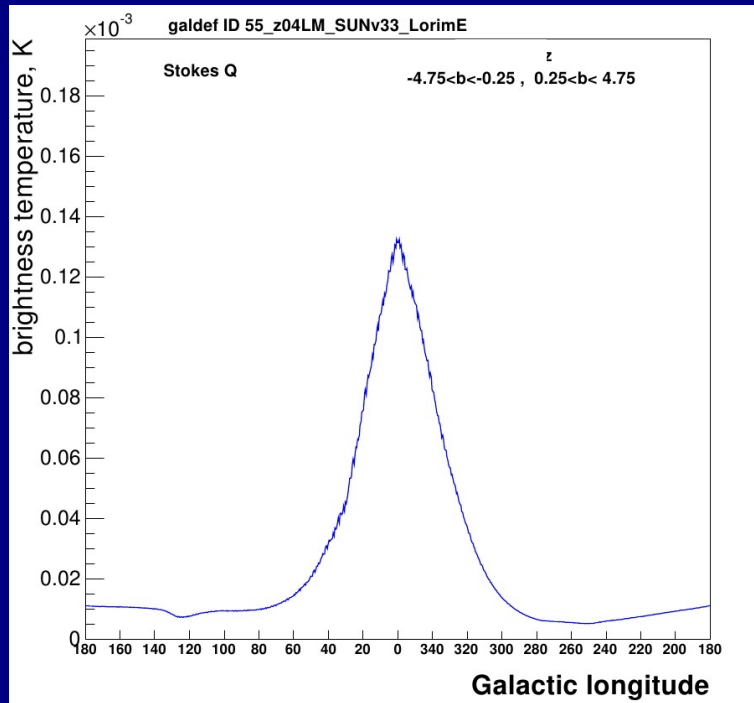
Illustrative model for 30 GHz Stokes P



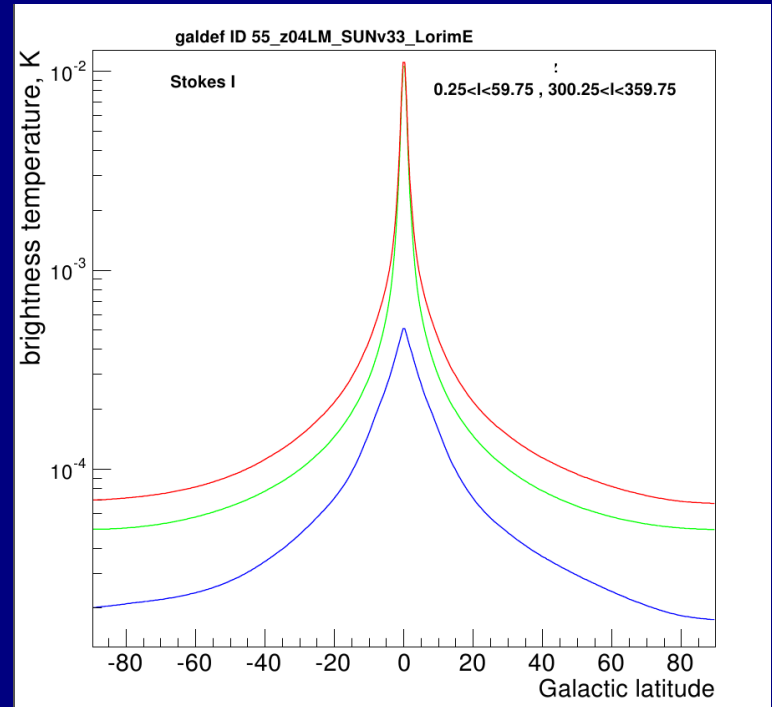
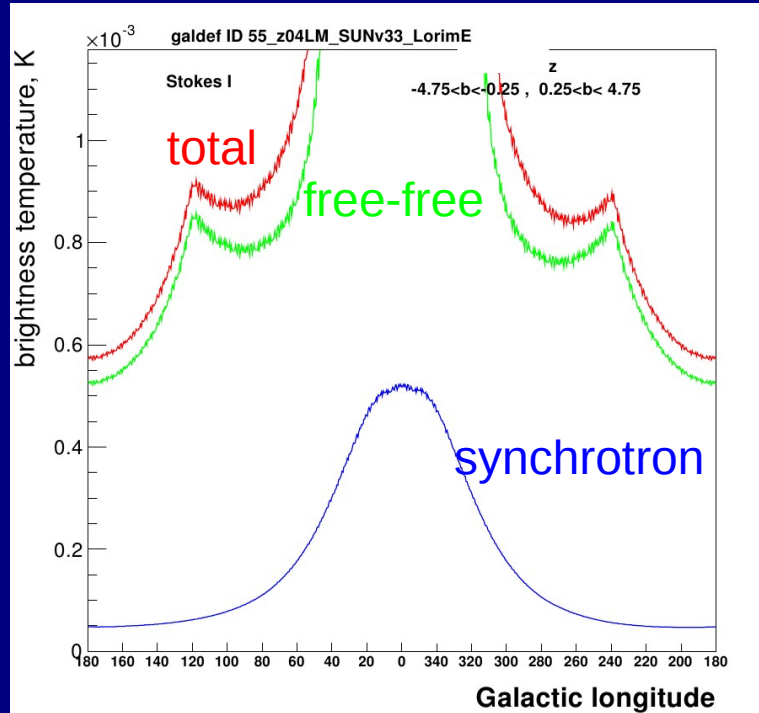
B_{reg} : Sun et al., scaled
 B_{rand} : double exponential

Cosmic-ray electrons based on gamma rays and locally measured spectrum

Illustrative model for 30 GHz Stokes Q



Illustrative model for 30 GHz Stokes I



Free-free from NE2001, illustrative

NOTES on use of GALPROP for synchrotron calculations

1. Computes synchrotron using full formulae and electron + positron spectra. no power law or $p=-3$ approximations (unlike Hammurabi).
2. 3D mode used for B-field and synchrotron.
3. Any B-field model can be incorporated, latest is Jansson & Farrar 2012.
4. Random and regular fields, Stokes Q, U, P, I for any frequencies.
5. No Faraday depolarization (unlike Hammurabi).
6. Only large-scale B, does not attempt Loops and other details. No pc-scale random structures (unlike Hammurabi).
7. Electron and positron spectra based on cosmic-ray propagation and locally measured spectra, and synchrotron data, also gamma ray constraints.
8. Updated in public domain, <http://sourceforge.net/projects/galprop> (217 downloads since start in October 2013).

New development: **PICARD** Cosmic-ray propagation package.

Uni Innsbruck: Ralf Kissmann, Michael Werner, Olaf Reimer
with AWS@MPE

Fully 3D from outset.

Modern numerical techniques for solving cosmic-ray propagation.

Accurate and fast. Full MPI parallelization.

This allows fine spatial resolution (e.g. 10 pc) with reasonable CPU resources.

Spiral structure incorporated.

Uses *hdf5* for model storage (more flexible than *FITS* for 3D models)

Werner, M. et al. 2015, *Astroparticle Physics* 64, 18 : CR Protons and spiral arms

Kissmann, R. et al. submitted: secondary/primary ratios

Synchrotron, B-fields: not yet, but foreseen. Fits well into 3D scheme.

Will allow all components to be accurately included.

A public version is planned sometime in the not-too-distant future.

Probably PICARD will replace GALPROP in the long term.

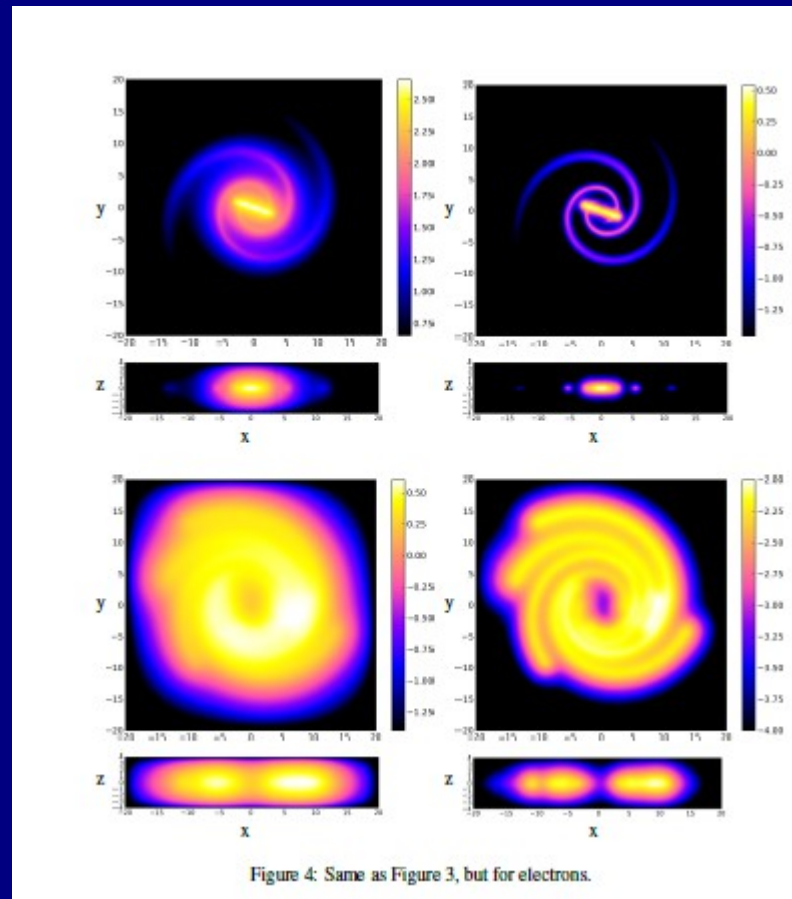
Anyway good to have multiple CR propagation packages:

e.g. GALPROP, DRAGON, PICARD

for cross-checks and healthy competition.

New development: **PICARD** Cosmic-ray propagation package.

Werner, M. et al. 2015, Astroparticle Physics 64, 18 : CR and spiral arms

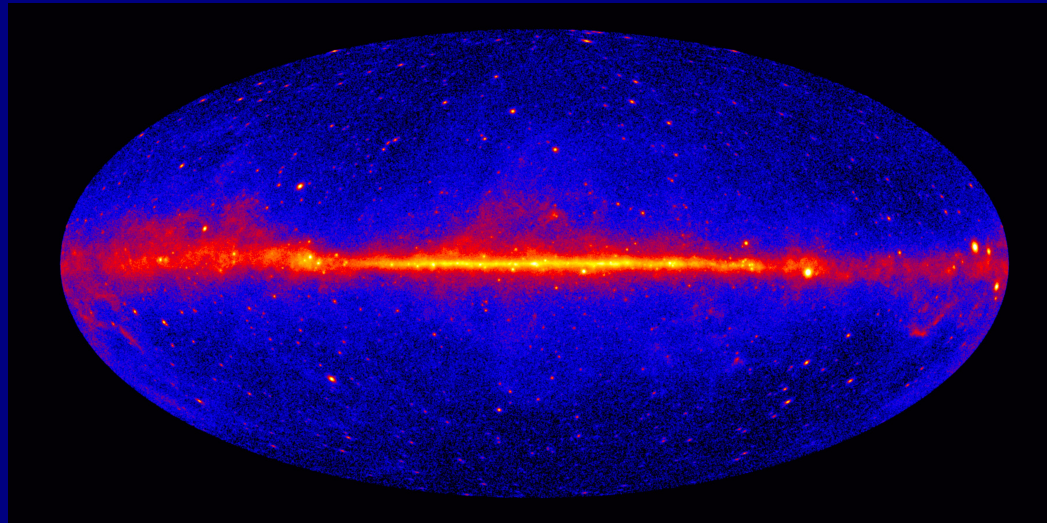


Cosmic-ray electrons, for 4 different spiral-arm source distributions



Exploiting gamma rays

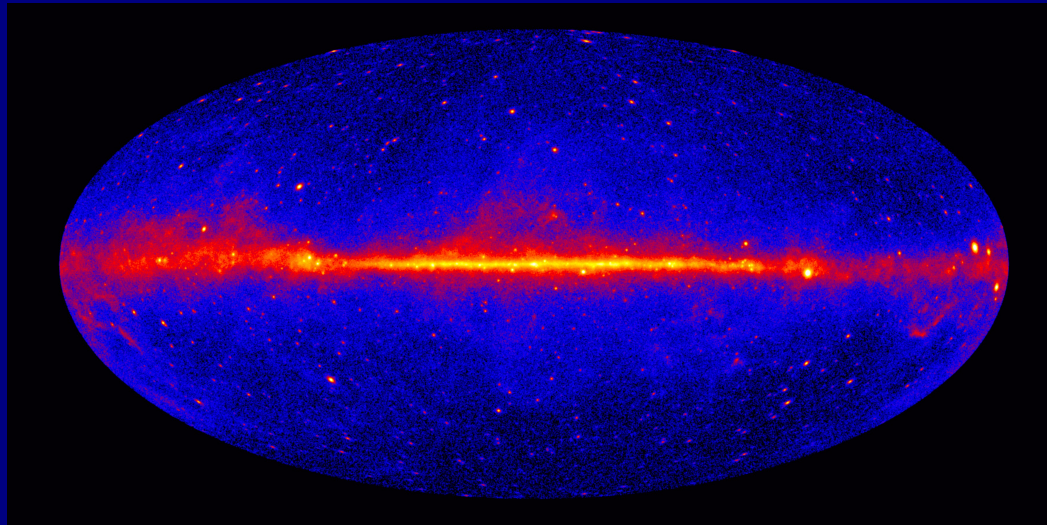
1 – 10 GeV



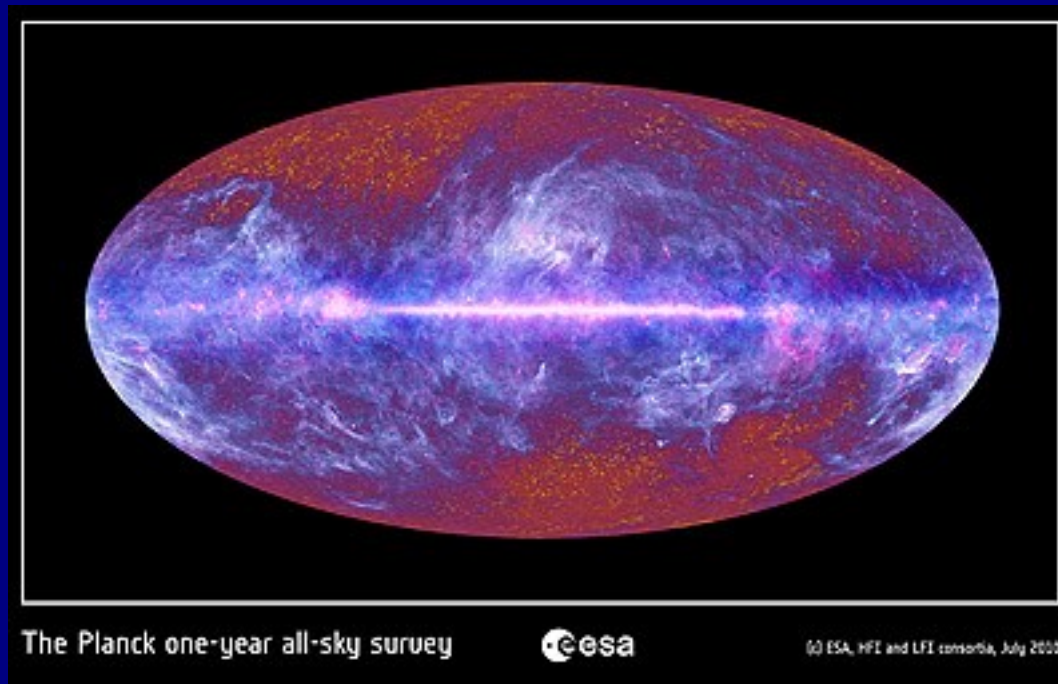
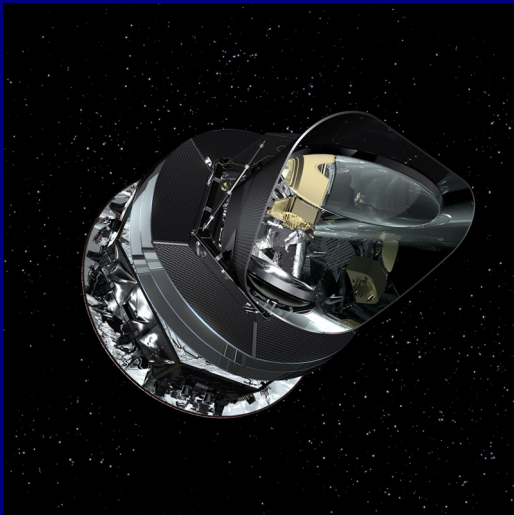
Cosmic-ray protons interacting with gas : hadronic (pion-decay)

Cosmic-ray electrons and positrons interacting with gas : bremsstrahlung

interacting with interstellar radiation : inverse Compton



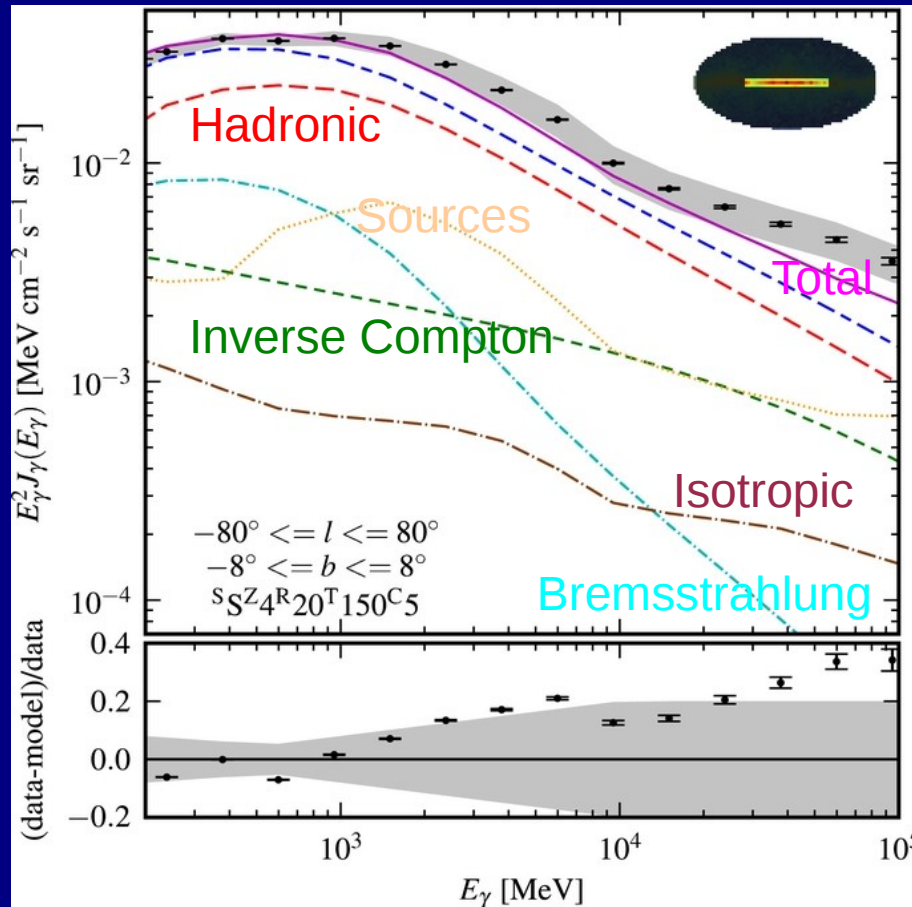
2 years



1 year

A lot of common astrophysics, cosmic rays, gas, magnetic fields !

Fermi-LAT Inner Galaxy Gamma Ray Spectrum



Ackermann et al. ApJ 750, 3 (2012)

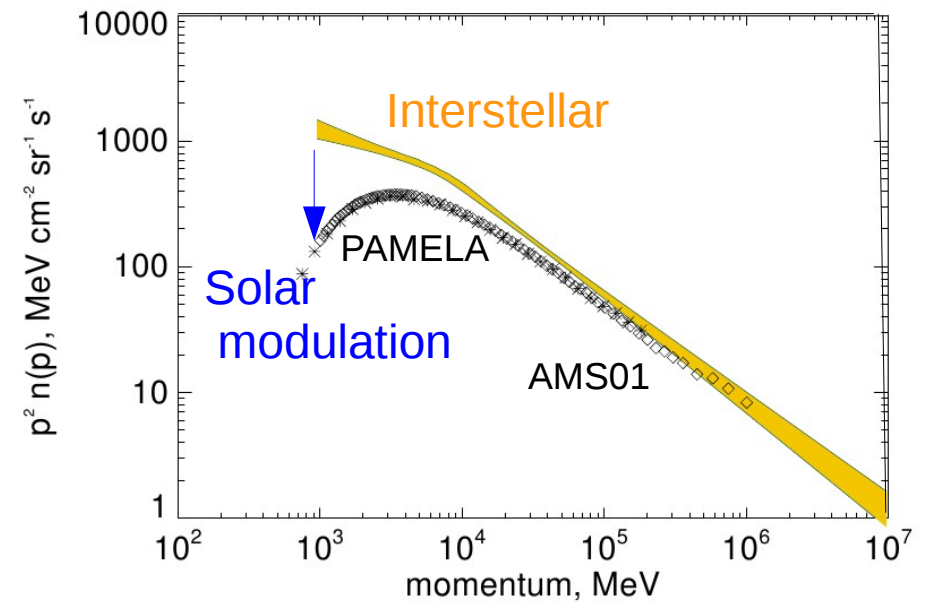
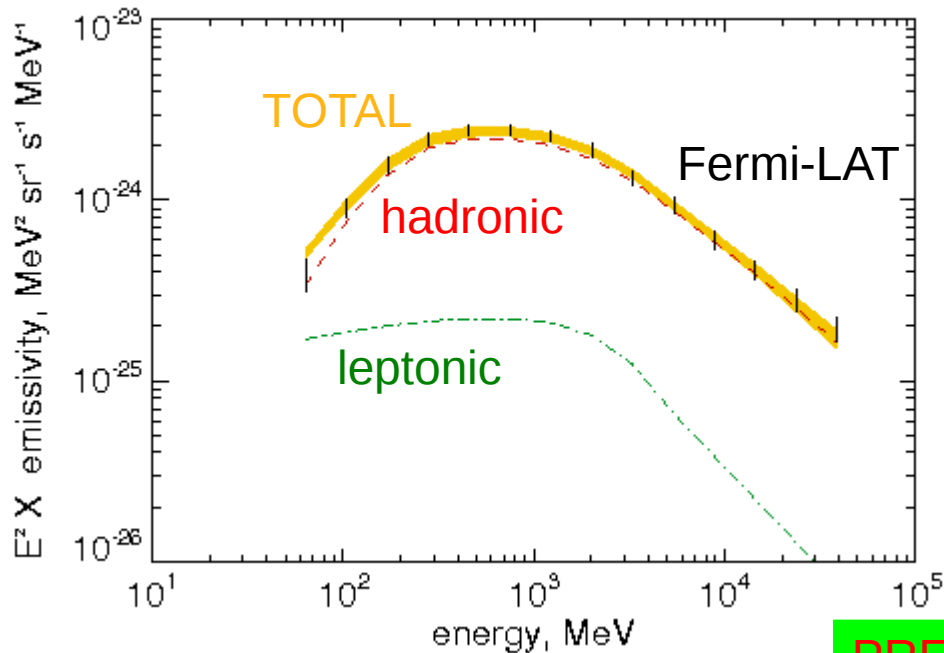
Interstellar Cosmic ray spectra derived from gamma rays

Method : Bayesian analysis

Gamma-ray gas emissivity

used to derive

Cosmic-ray protons



PRELIMINARY

Below 10 GeV affected by solar modulation, but gamma rays probe the interstellar spectrum.

Emissivity of local interstellar gas – Jean-Marc Casandjian (Fermi-LAT Collab).

Power-law in momentum overall, but low-energy break ?

e.g. from power-law injection and interstellar propagation (diffusion = $f(E)$)

Interstellar spectrum essential to test heliospheric modulation models.

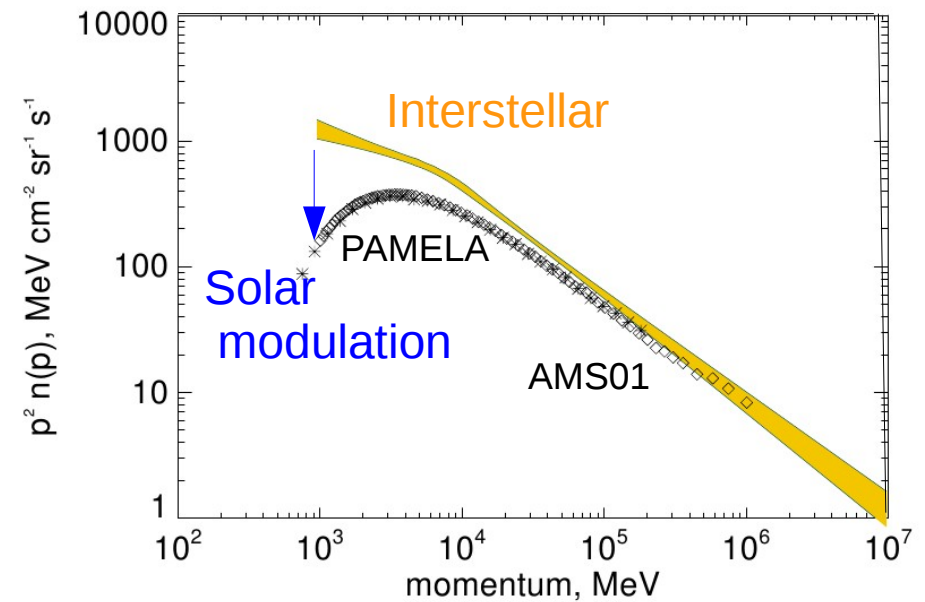
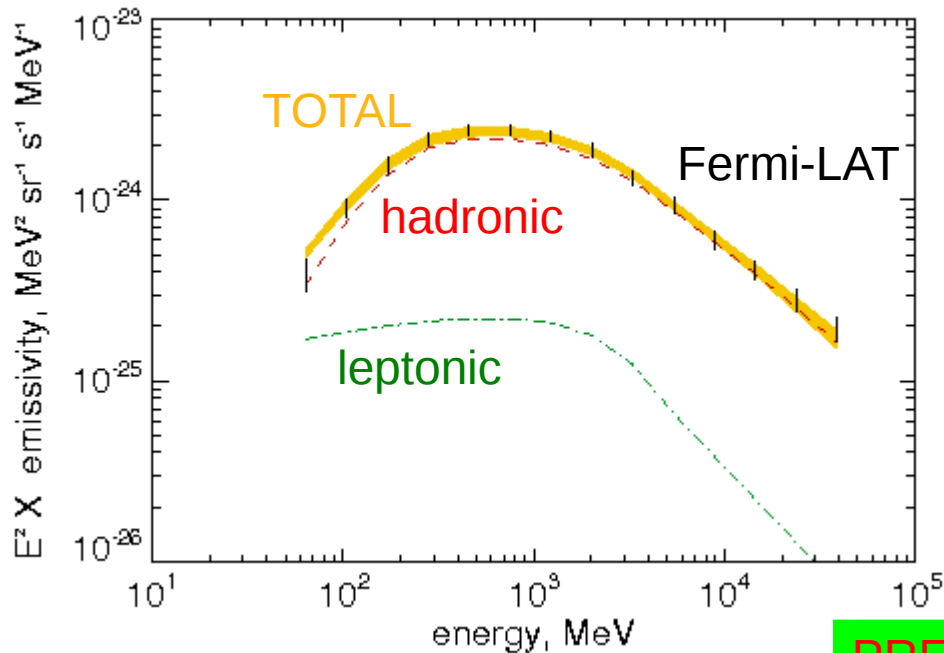
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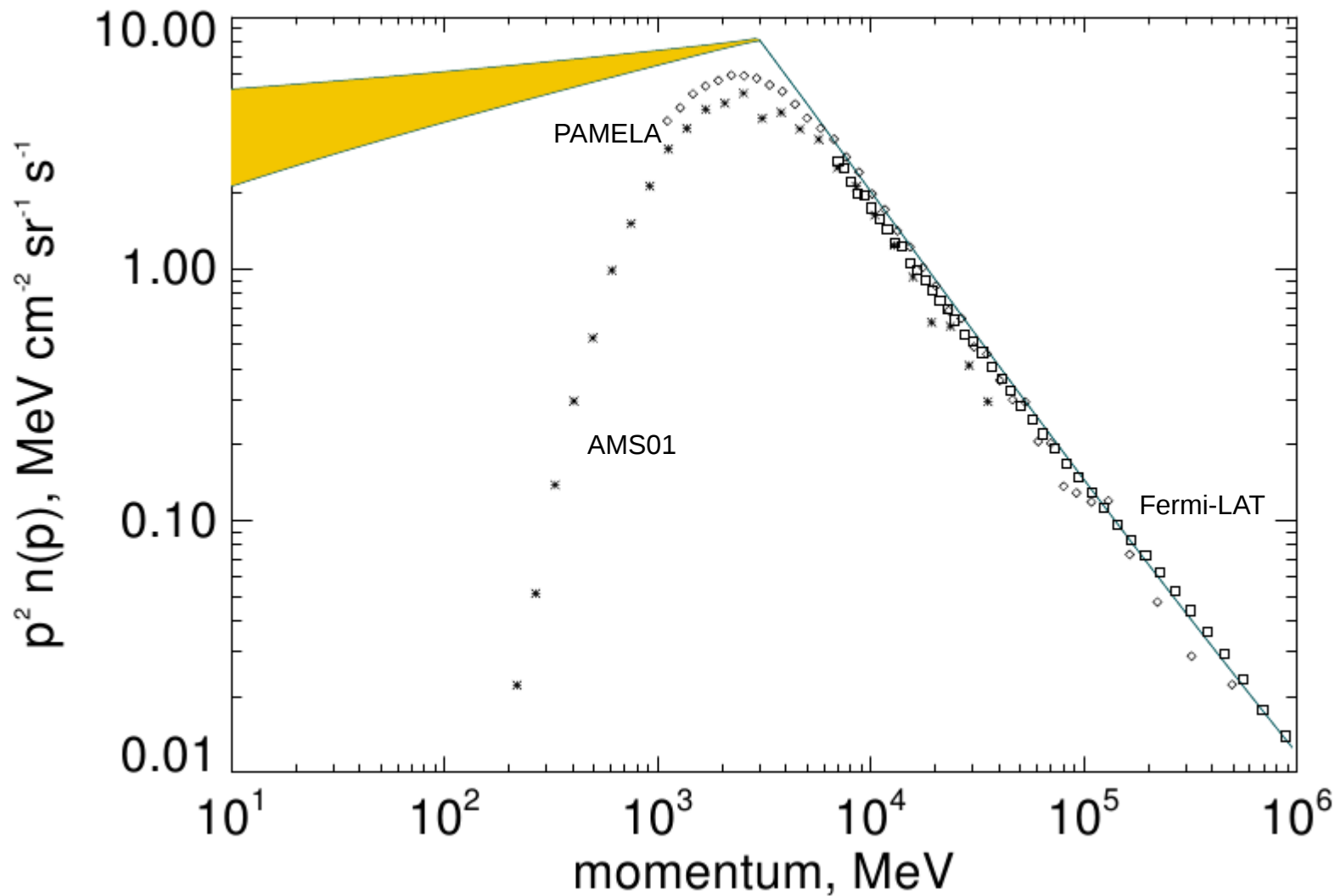
e.g. from power-law injection and interstellar propagation (diffusion = $f(E)$)

Interstellar spectrum essential to test heliospheric modulation models.

Interstellar electrons from synchrotron, gamma rays and direct measurements



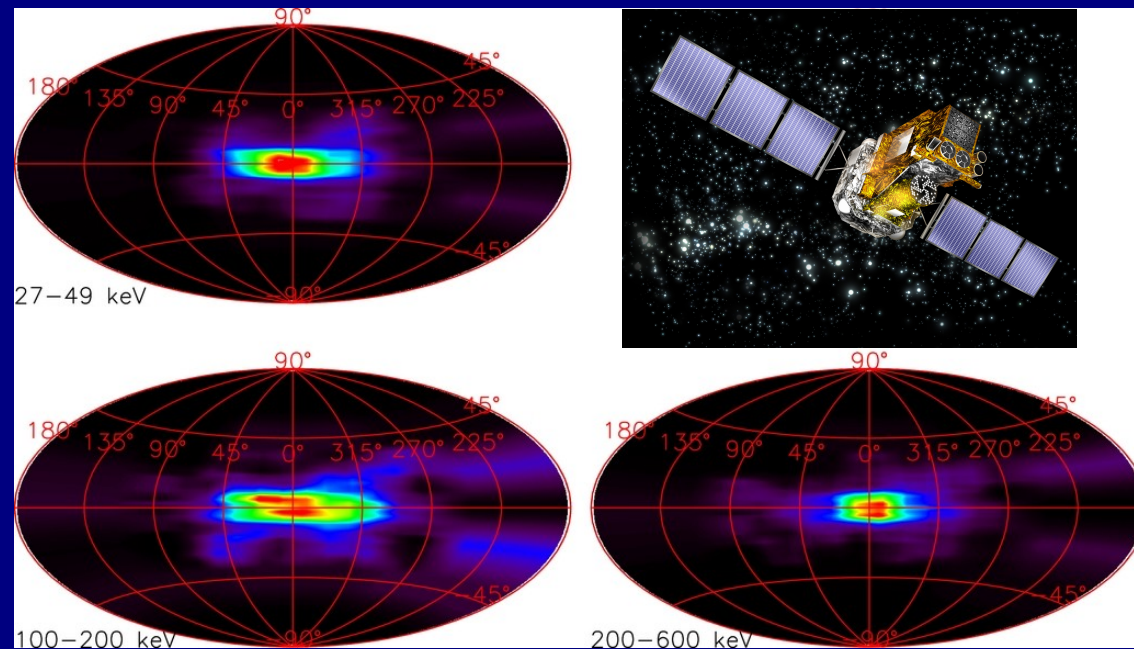
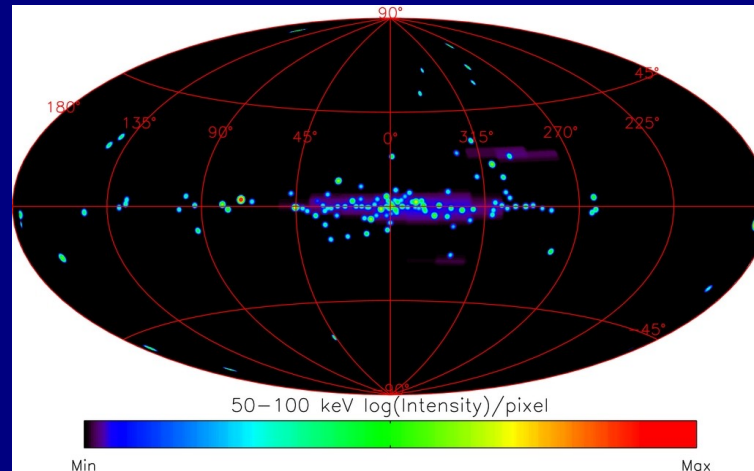
Same model as in previous slide



PRELIMINARY

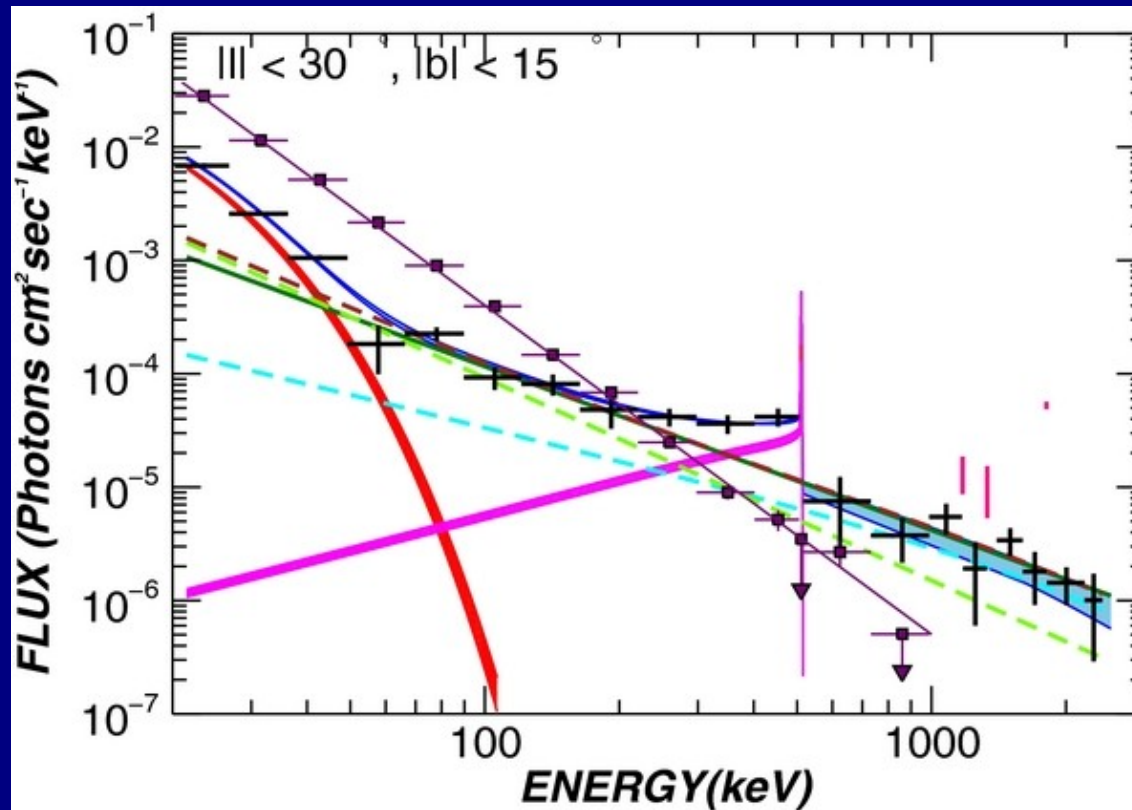
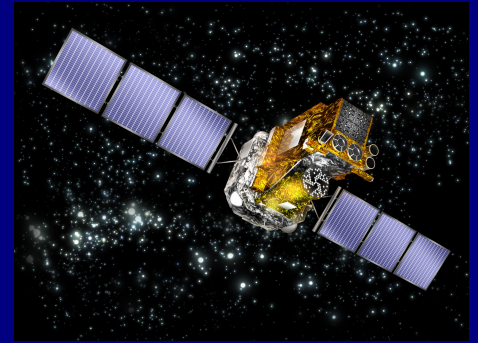
INTEGRAL / SPI Continuum skymaps

Bouchet et al.
ApJ 739, 29 (2011)

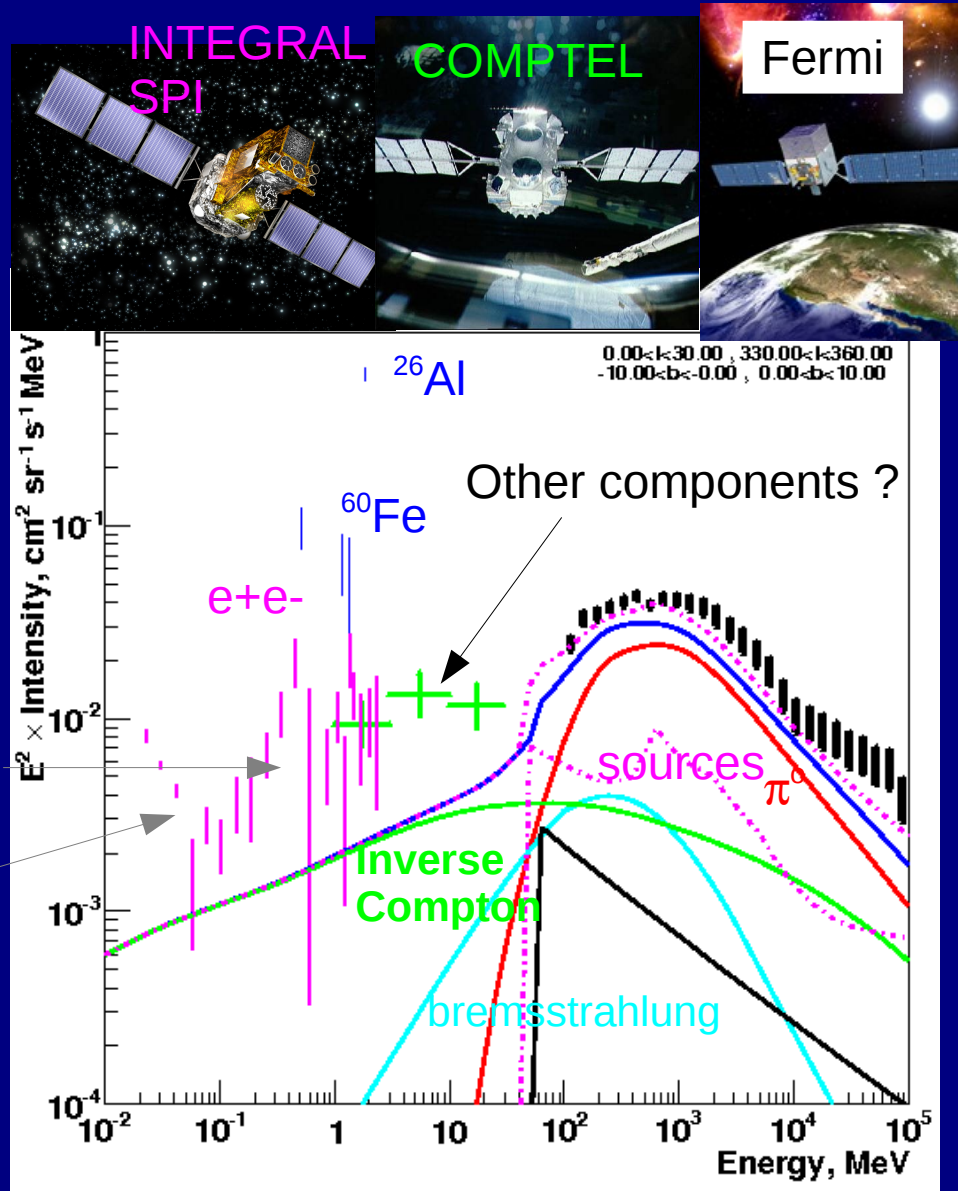


A real mix of processes !

Inner Galaxy
INTEGRAL / SPI
Bouchet et al. ApJ 739, 29 (2011)



Inner Galaxy: keV to TeV

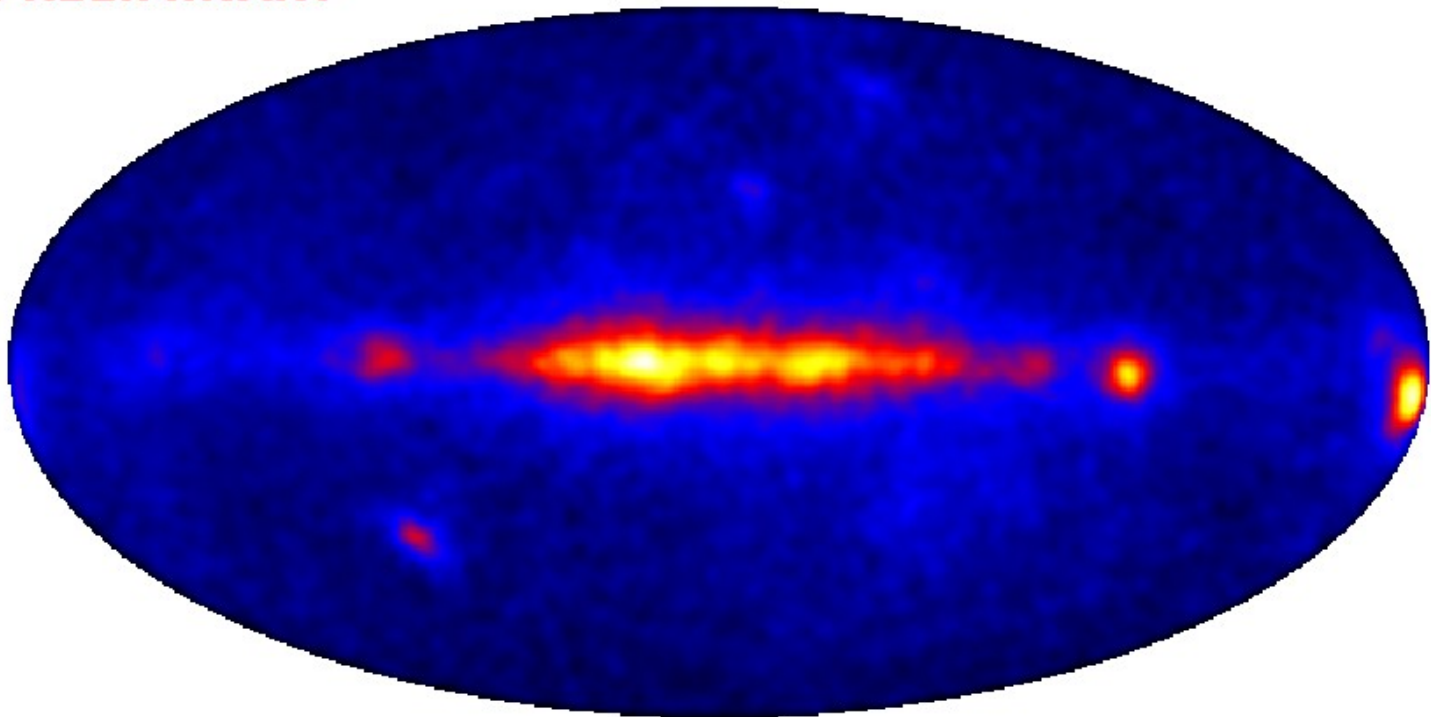


GeV electrons – inverse Compton - important for MeV gamma rays !



Fermi-LAT 25 – 40 MeV

PRELIMINARY

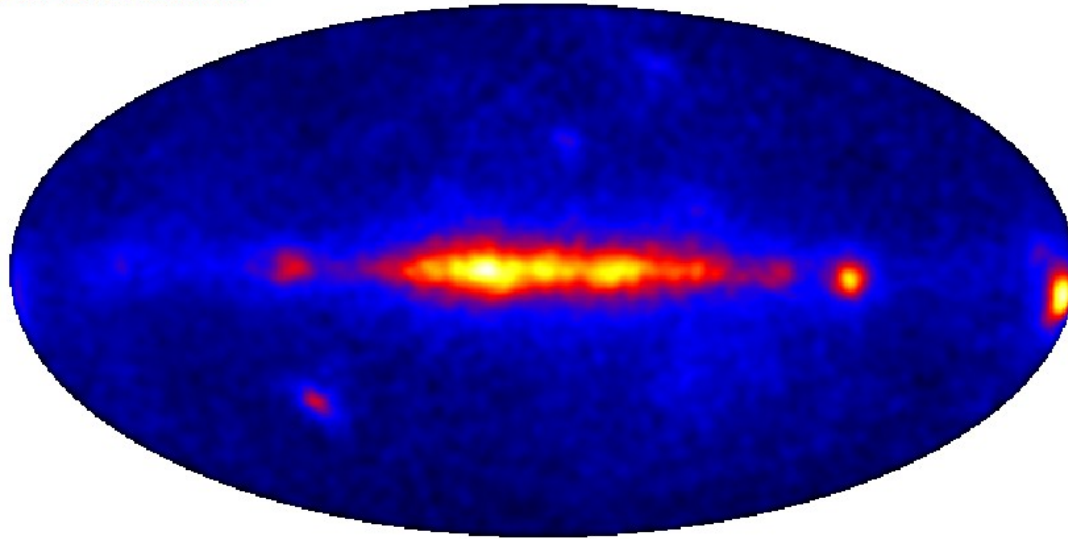


NB low angular and energy resolution !
Nominal energy range: photons may originate from range 10 to <100 MeV.
But valuable to bridge the MeV gap.



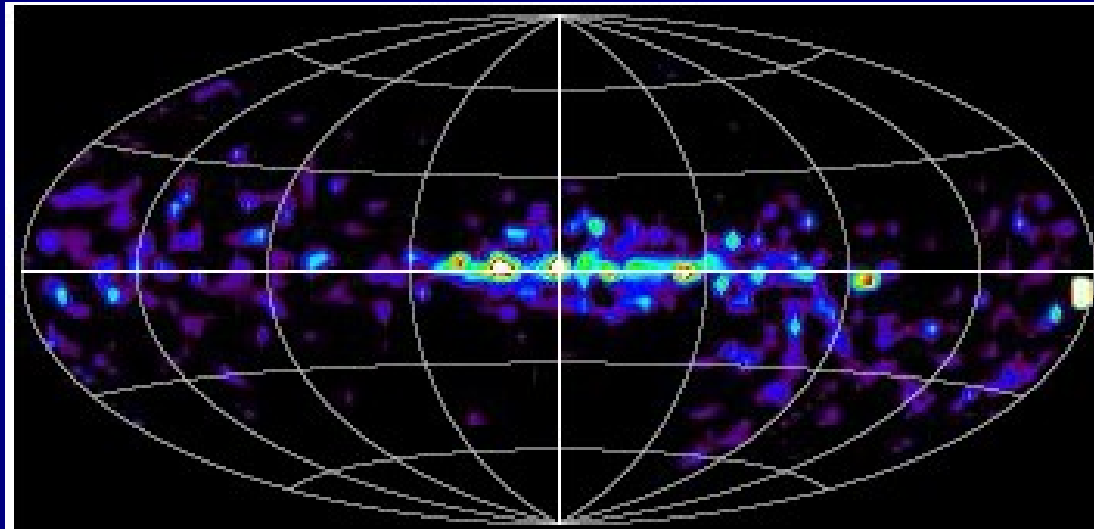
Fermi-LAT 25-40 MeV

PRELIMINARY



meets

COMPTEL 10-30 MeV



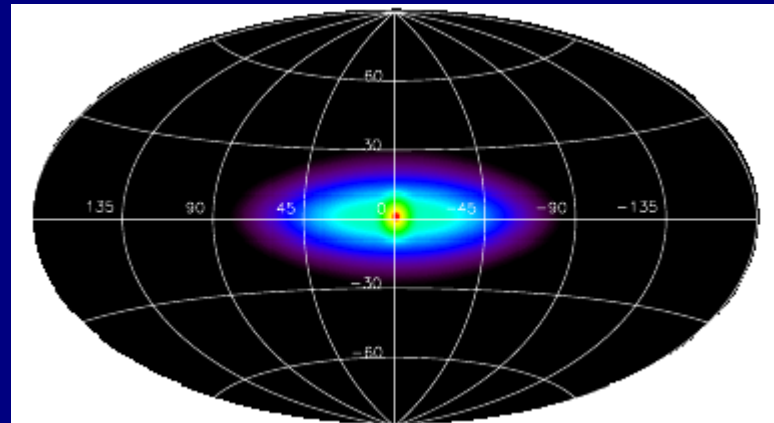
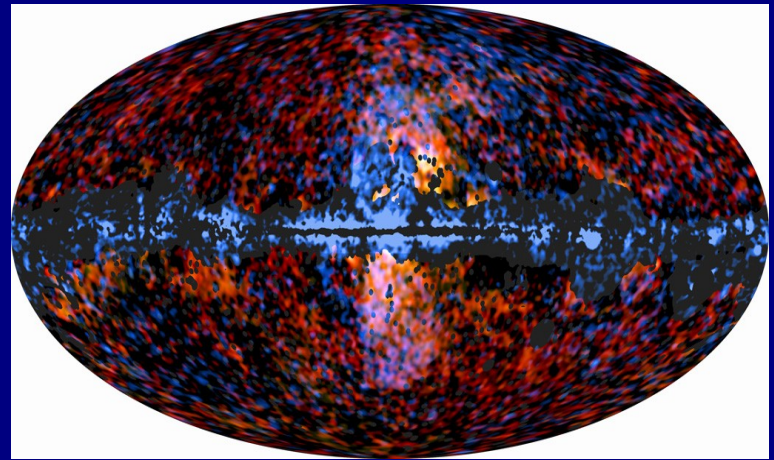
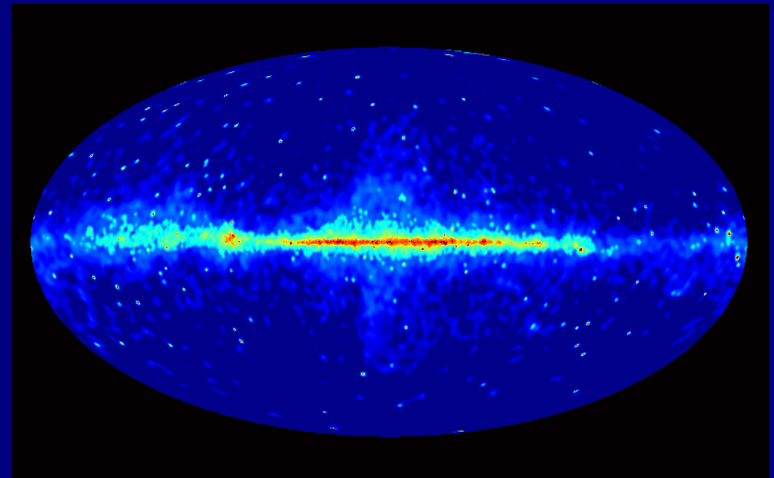
Fermi Bubbles

(related to WMAP Haze ?)

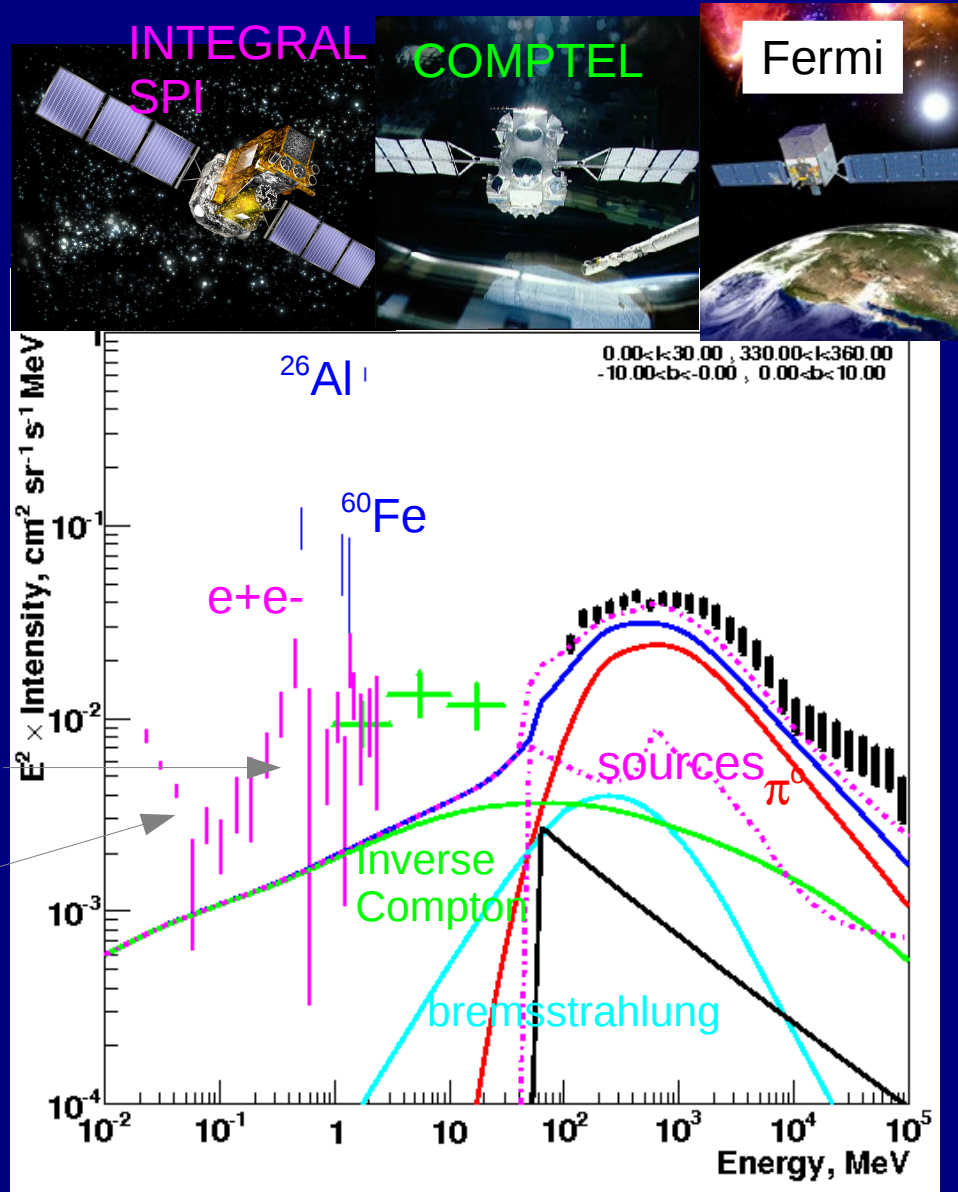
Planck haze (arXiv:1208.5483)
Overlaid on Fermi Bubbles

connection to 511 keV line ?

All are -
centred on Galactic Centre
leptonic
unknown origin



Inner Galaxy: keV to TeV



END