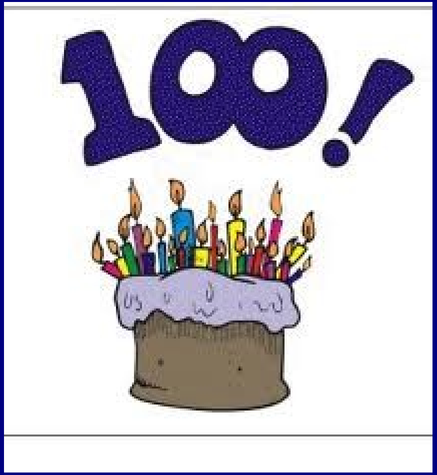
Synchrotron : exploiting the high-energy astrophysics connection

Andy Strong,

MPE Garching

Workshop on Polarized CMB Foregrounds,
MPA Garching 26-28 Nov 2012

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



WHY ?

This workshop is on polarized foregrounds for CMB.

So why consider the high-energy astrophysics connection ?

High-energy astrophysics = cosmic-rays, gamma rays, synchrotron

Gives insight into the synchrotron emission – spectral and spatial

Contributes to understanding synchrotron rather than to template generation.

Polarized synchrotron is essential part of the topic.

Topics

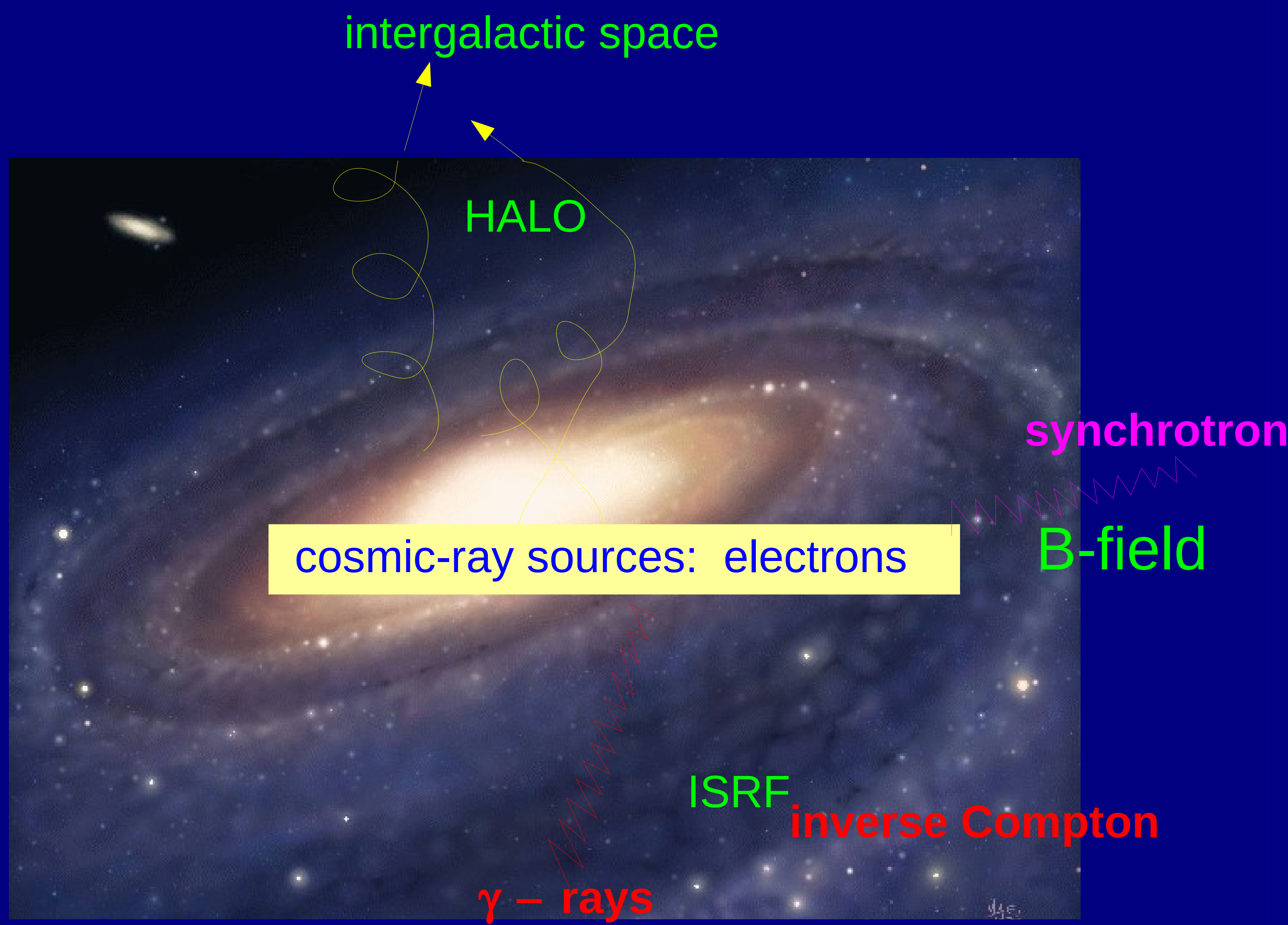
Synchrotron in high-energy context

Spectral aspects

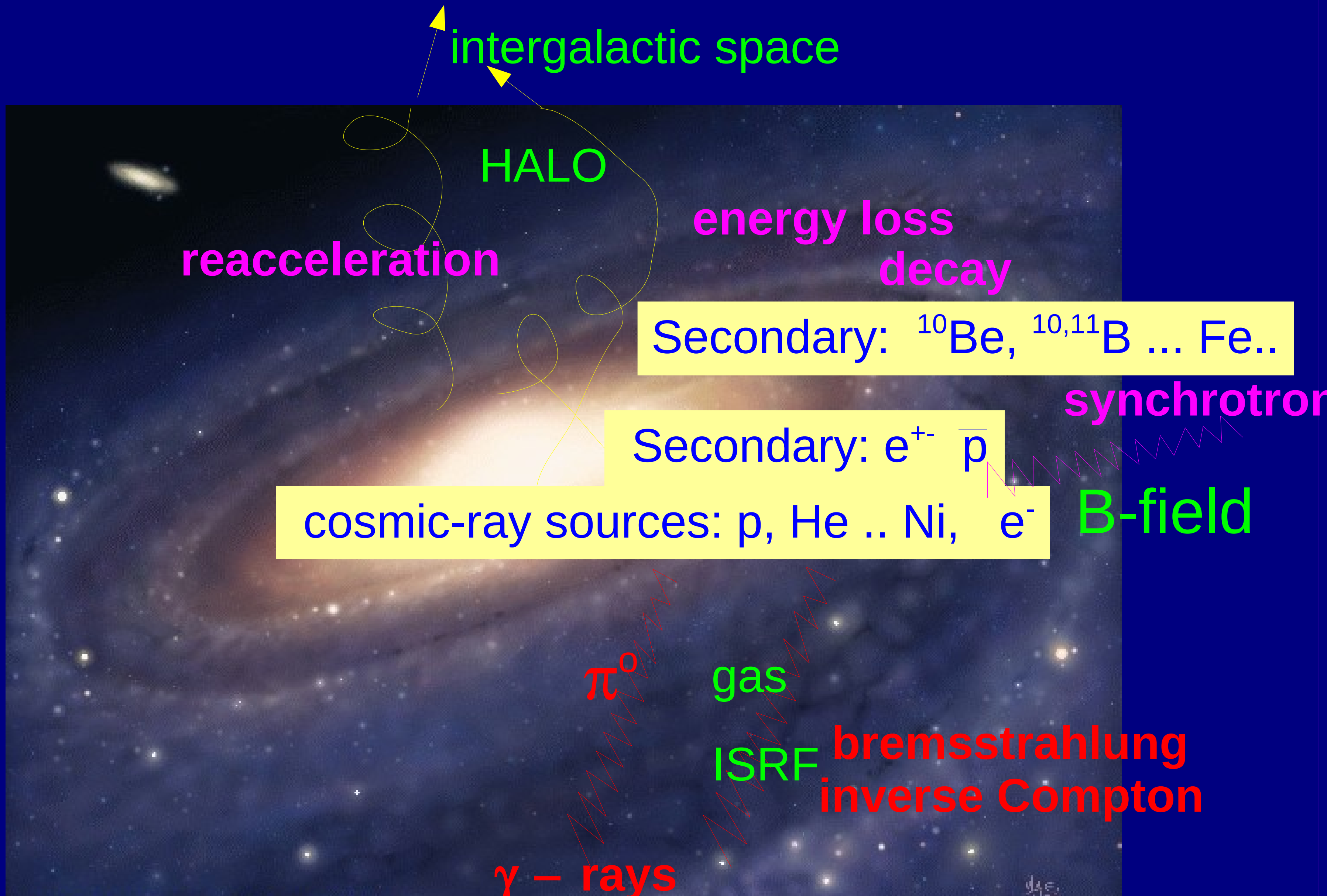
Polarization, magnetic fields

Gamma rays

High energy particles and radiation in the Galaxy

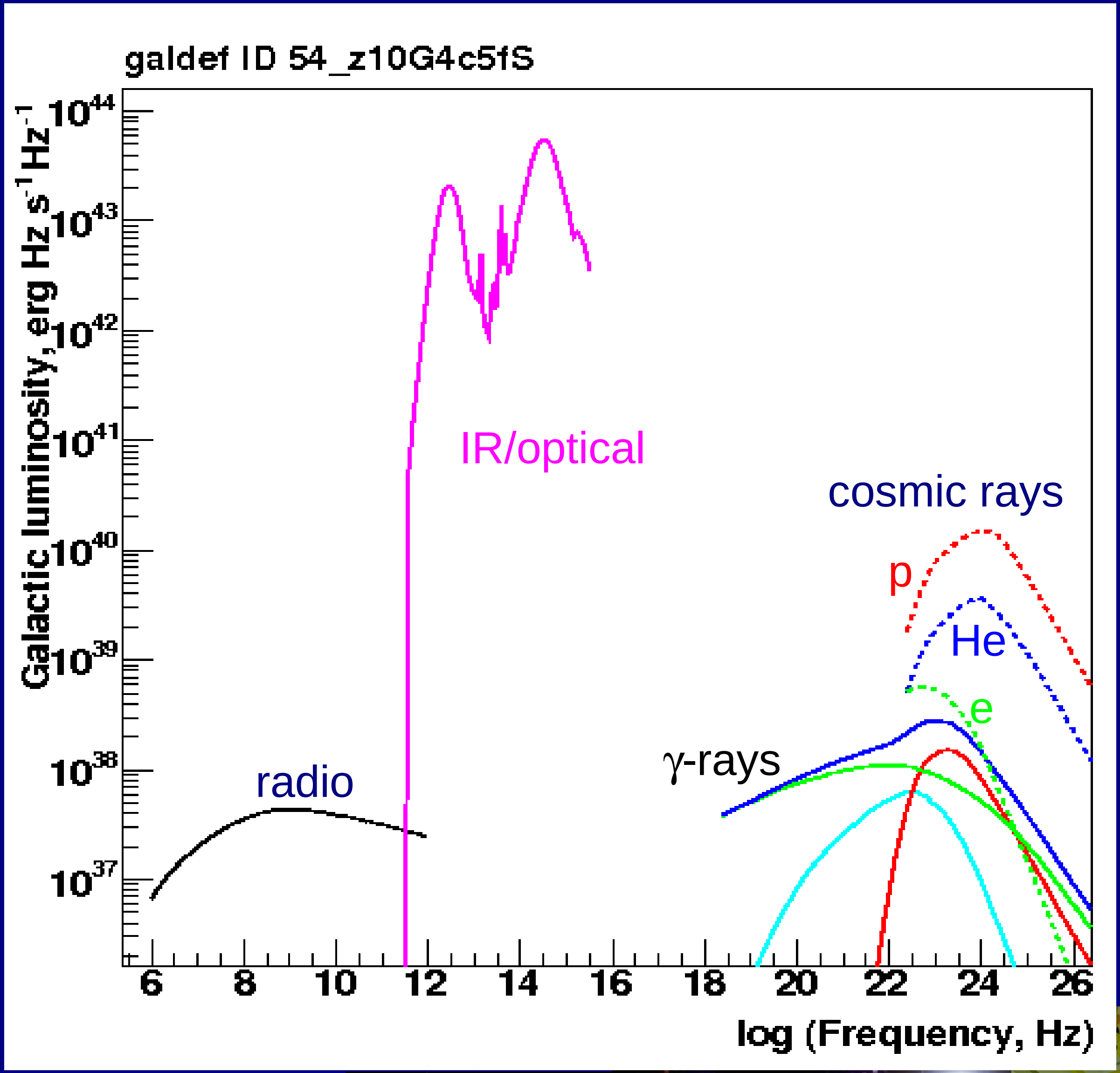

intergalactic space
HALO
synchrotron
cosmic-ray sources: electrons
B-field
ISRF
inverse Compton
γ – rays

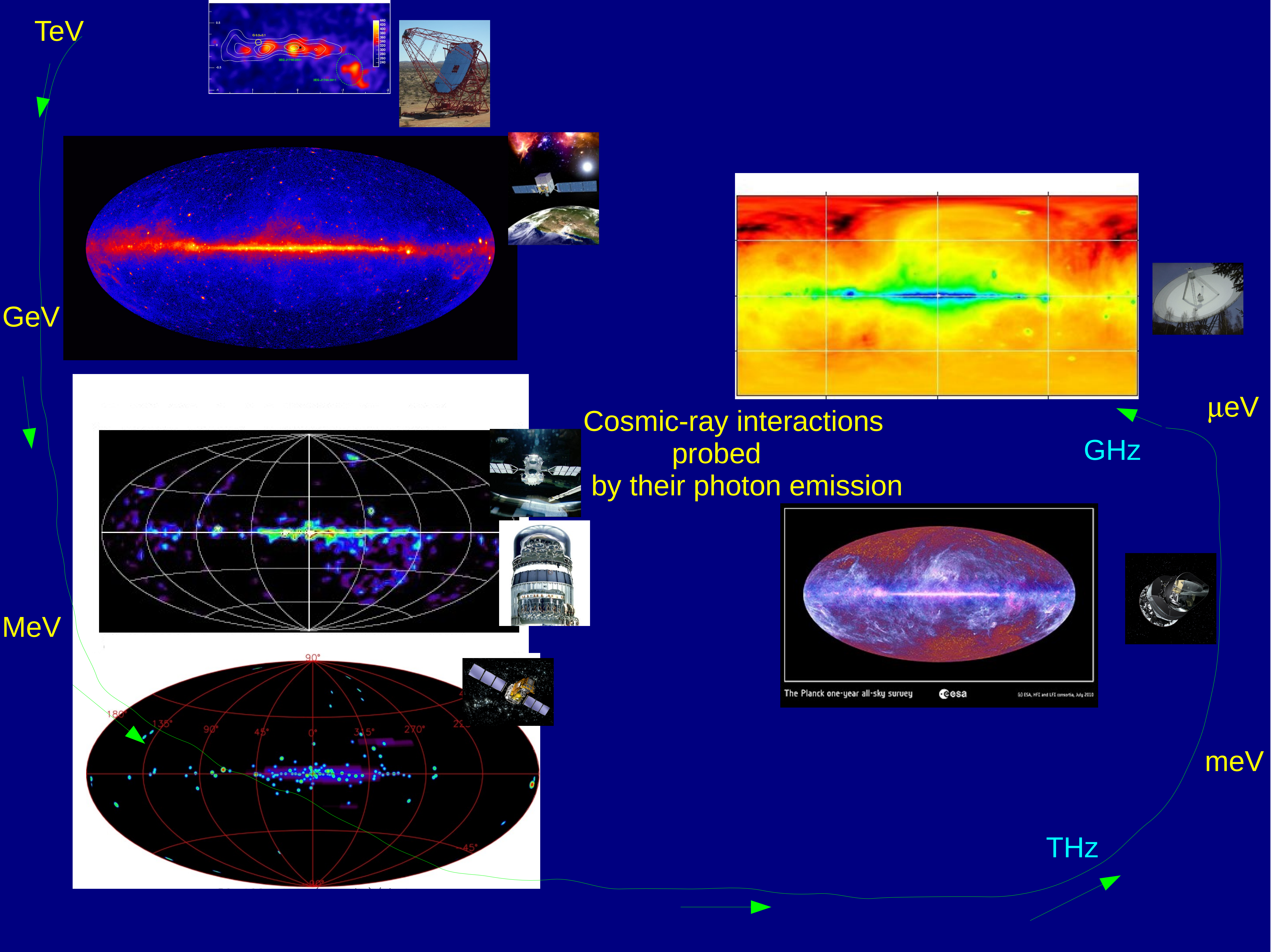
COSMIC RAYS produce many observables



GALPROP model

Galaxy luminosity over 20 decades of energy




TeV
GeV
MeV
Cosmic-ray interactions
probed
by their photon emission
μeV
GHz
meV
THz
The Planck one-year all-sky survey
esa
90°
135°
90°
45°
0°
315°
270°
-45°

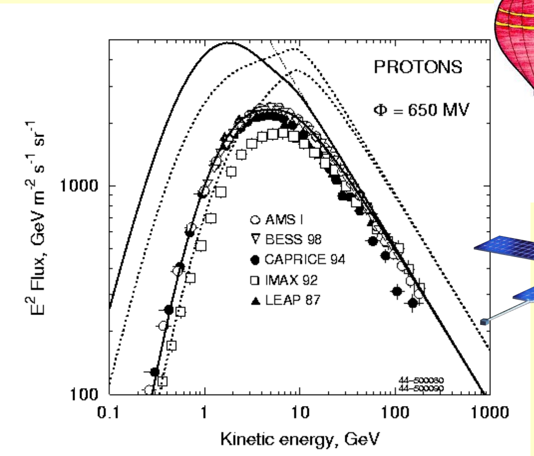
The **goal** : use *all* types of data in self-consistent way to test models of cosmic-ray propagation.

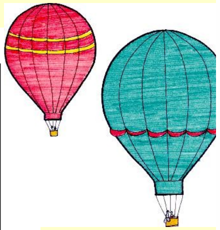
Observed *directly, near Sun:*

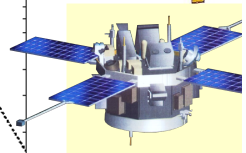
primary spectra (p, He ... Fe; e^-)

secondary/primary (B/C etc)

secondary e^+ , antiprotons...

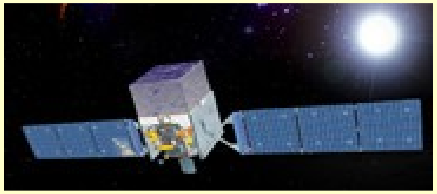


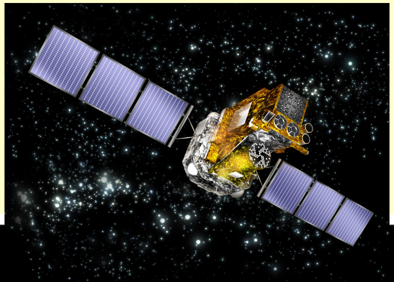


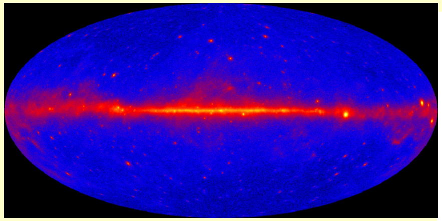


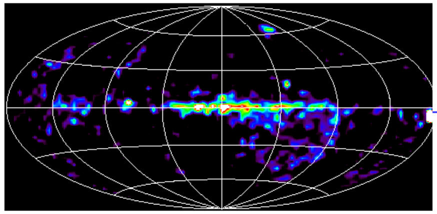
Observed *from whole Galaxy:*

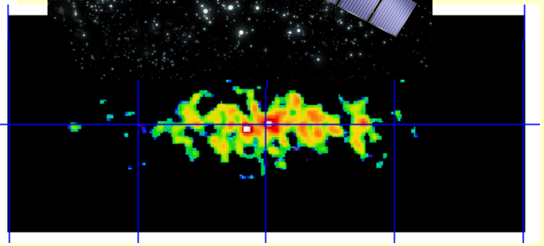
γ - rays



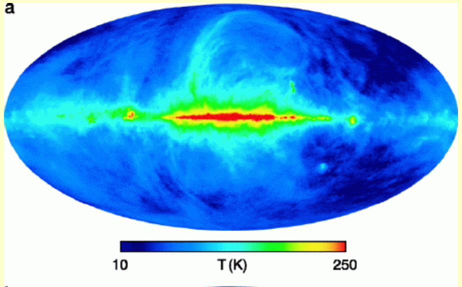








synchrotron



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)

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

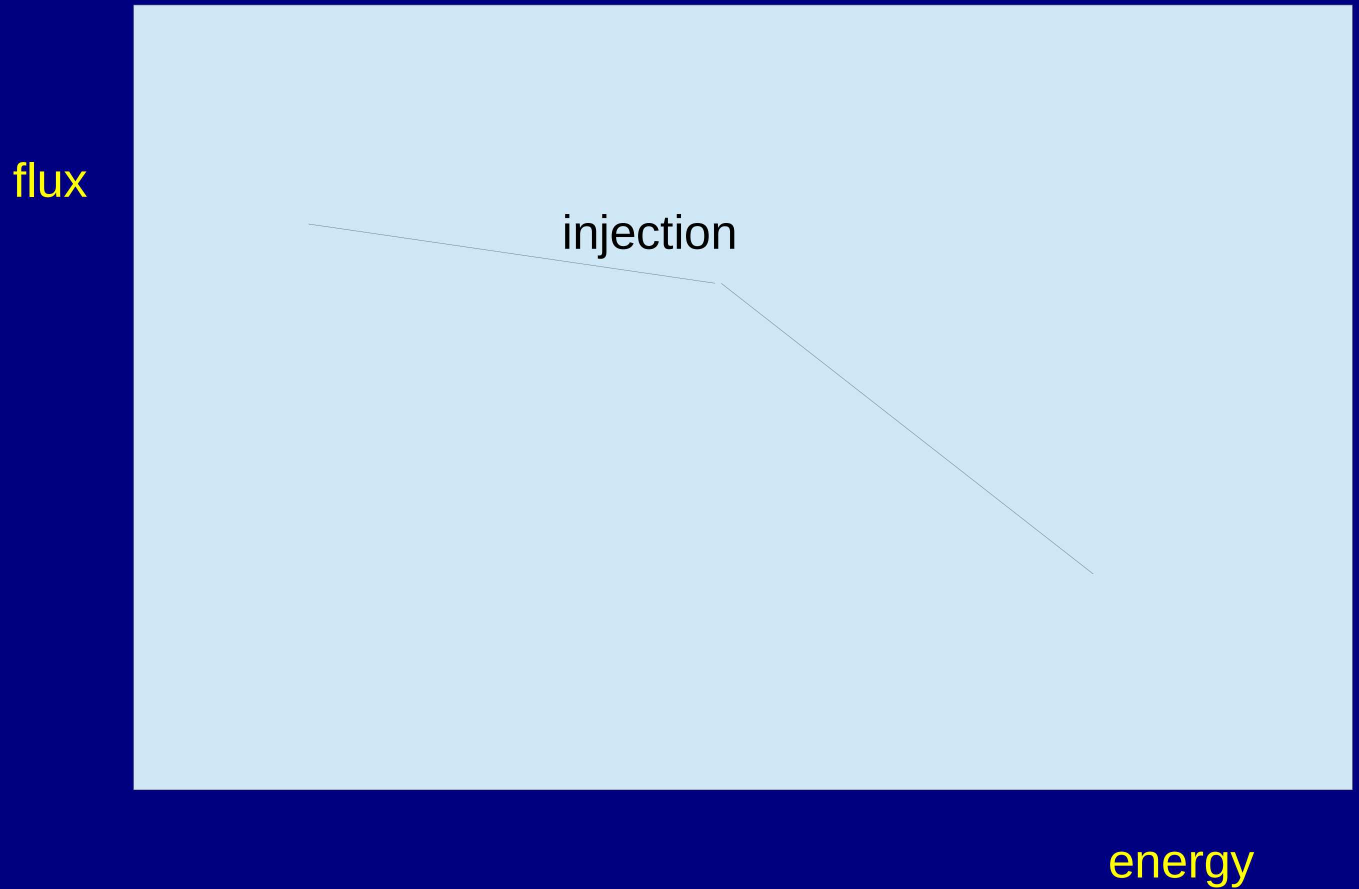
momentum loss
ionization, bremsstrahlung

adiabatic momentum loss

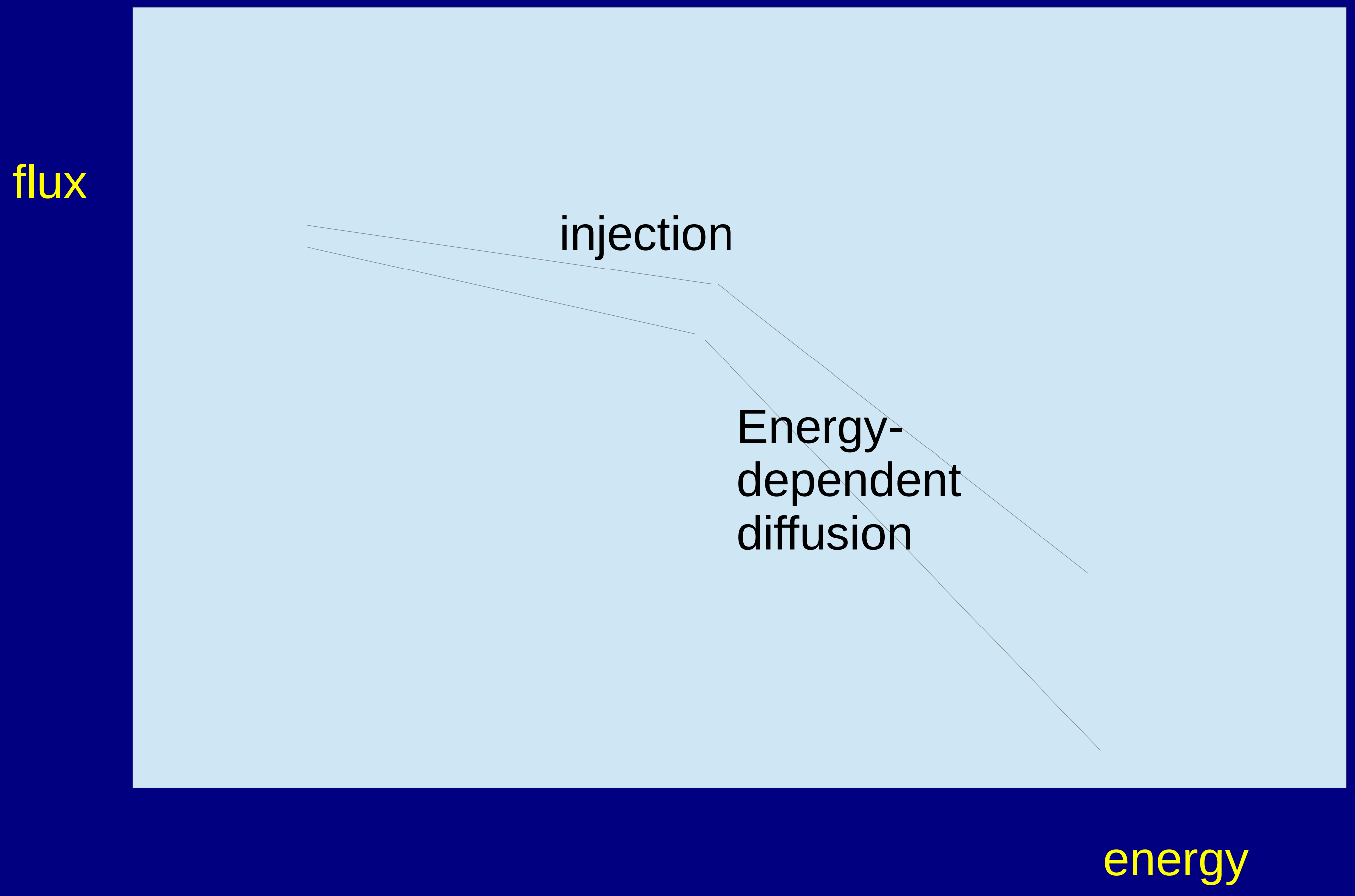
$- \psi / \tau_f$ nuclear fragmentation

$- \psi / \tau_r$ radioactive decay

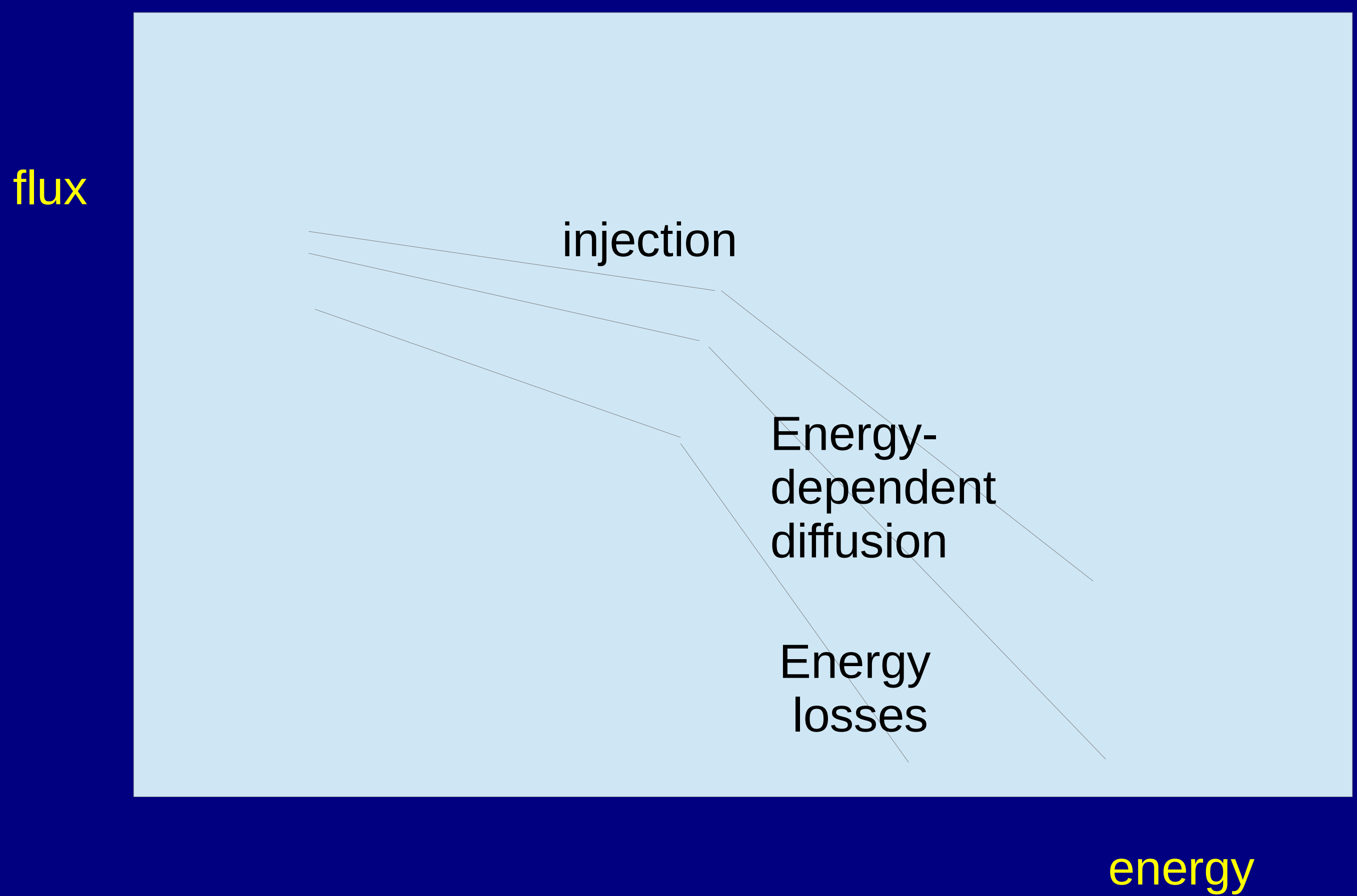
Producing the cosmic-ray electron spectrum



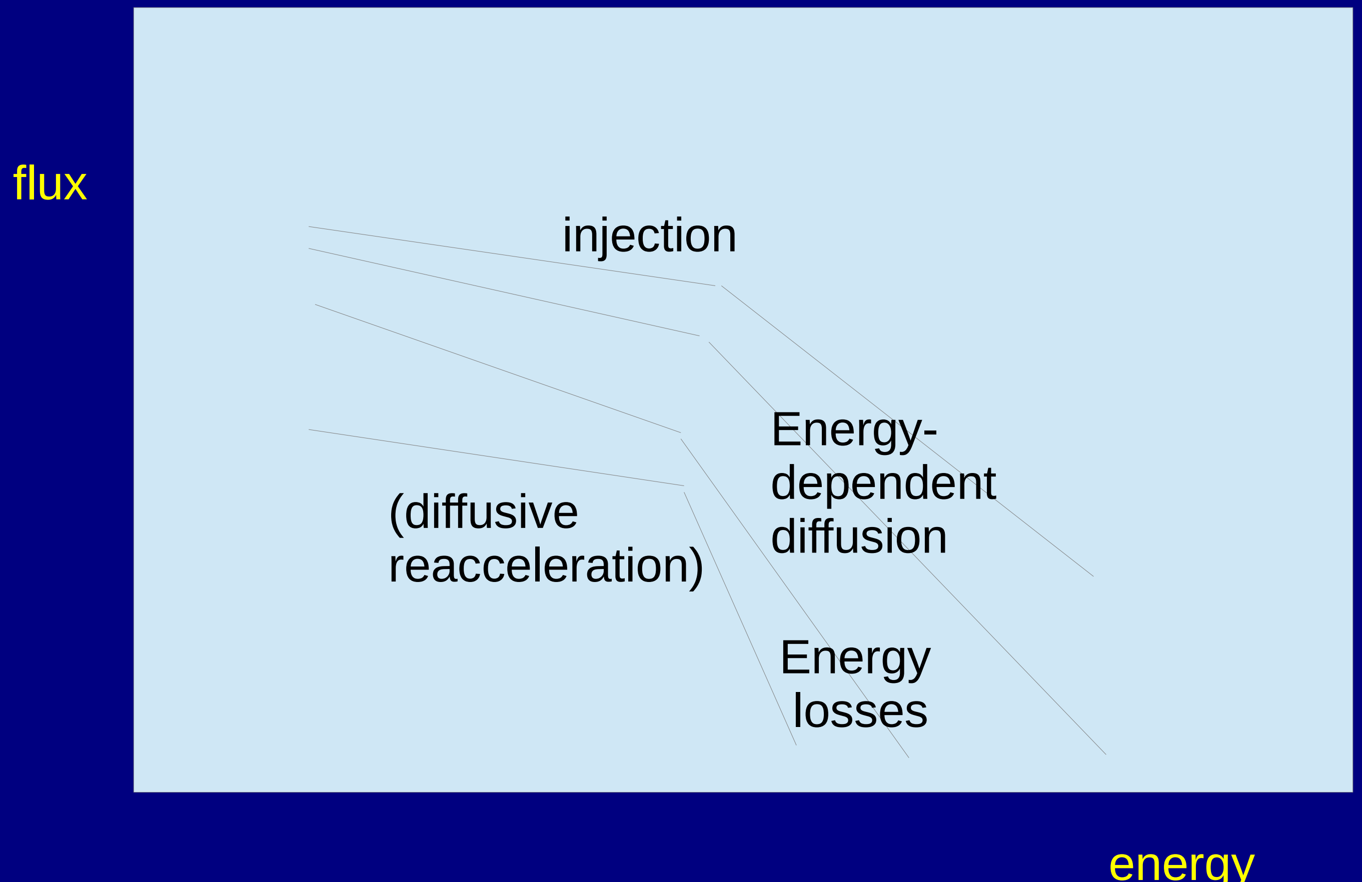
Producing the cosmic-ray electron spectrum



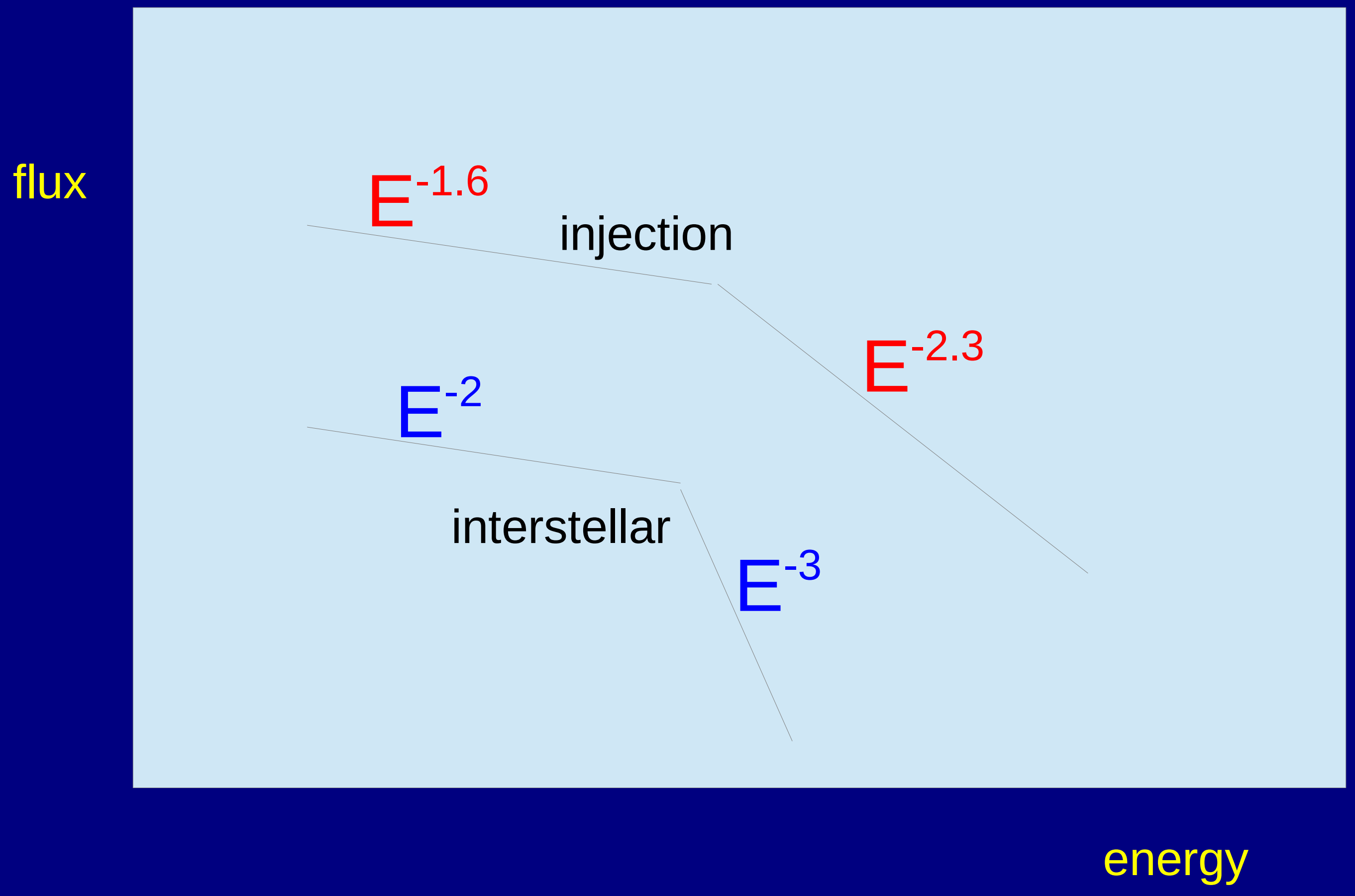
Producing the cosmic-ray electron spectrum



Producing the cosmic-ray electron spectrum

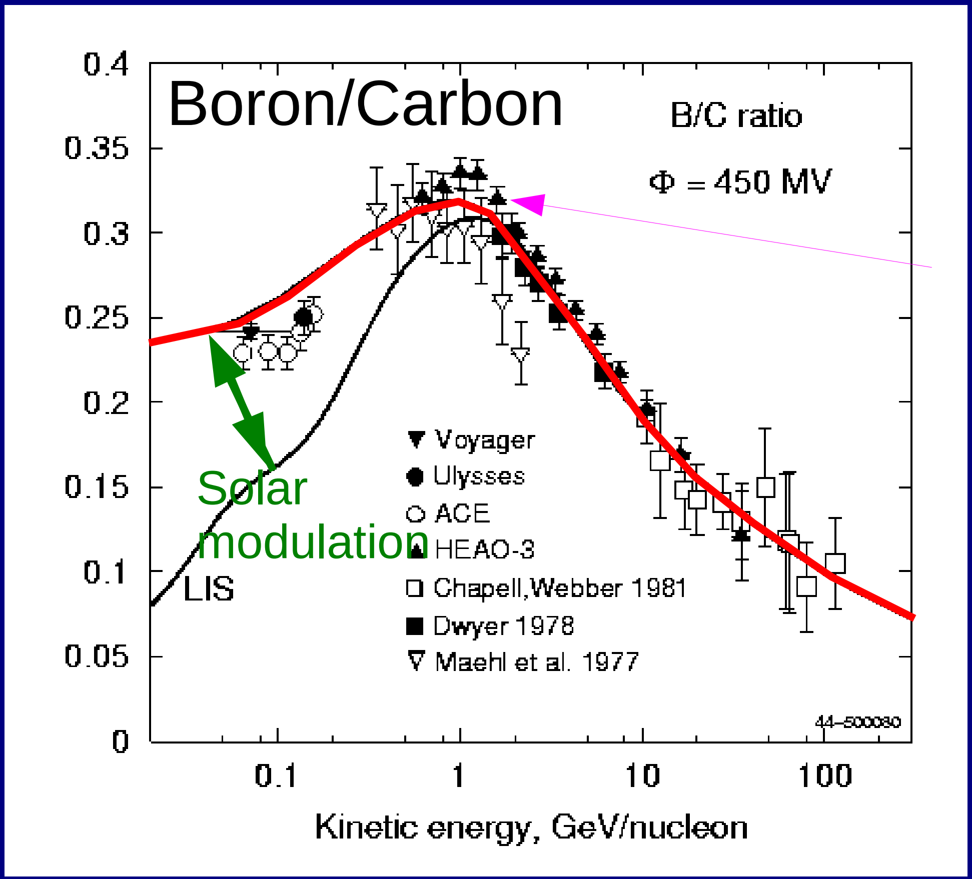


Producing the cosmic-ray electron spectrum



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

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

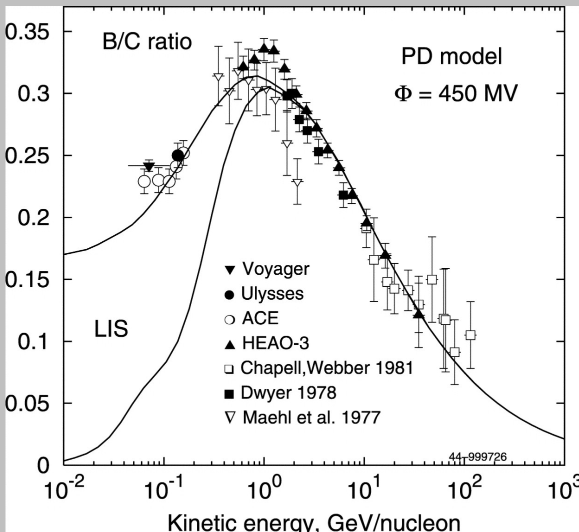
Momentum space diffusion

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

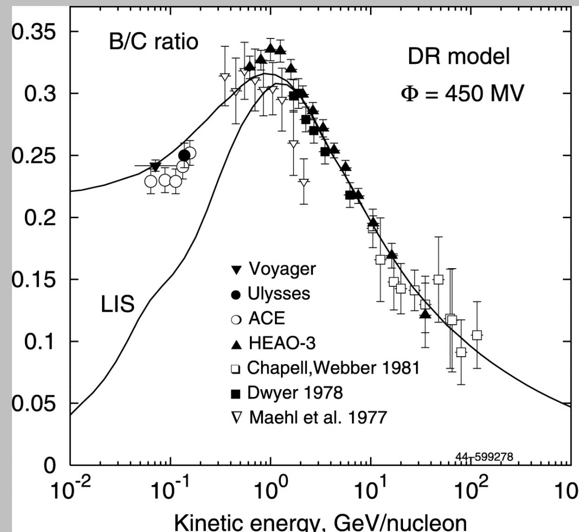
However reacceleration not proven, maybe does not happen

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

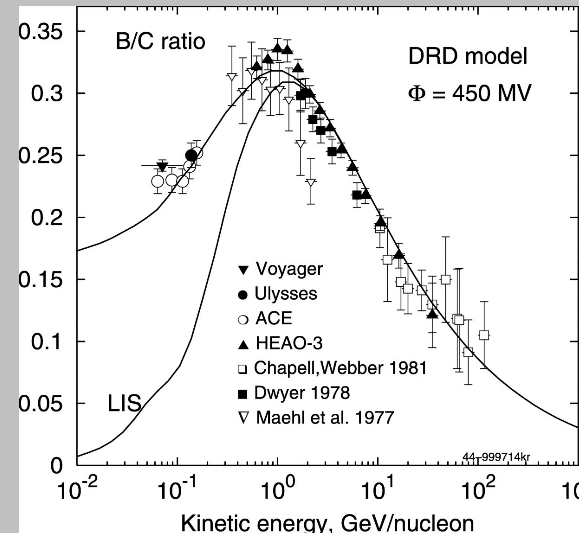
plain diffusion



diffusive reacceleration



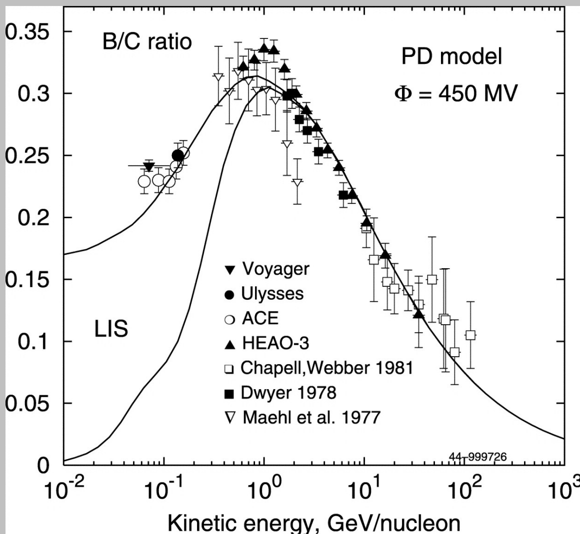
wave damping

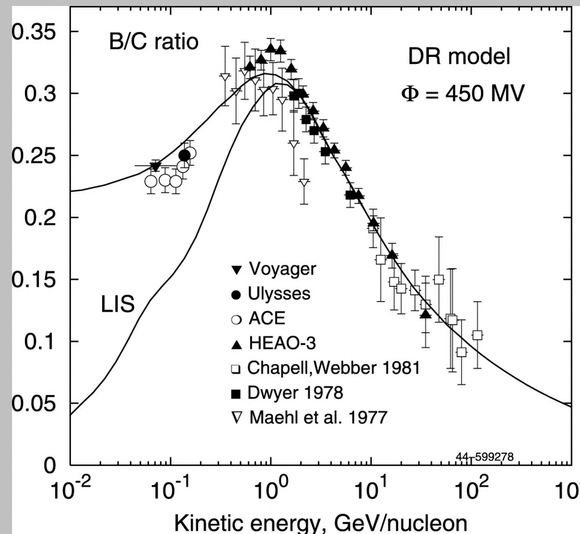


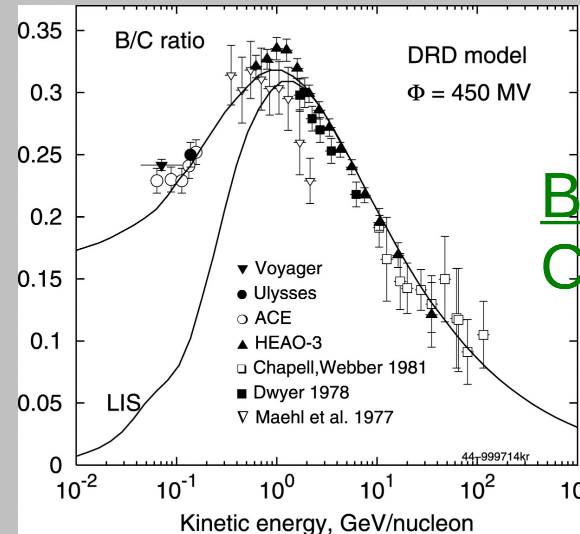
For any model, first adjust parameters to fit Boron/Carbon

Ptuskin et al. 2006 ApJ 642, 902

plain diffusion diffusive reacceleration wave damping



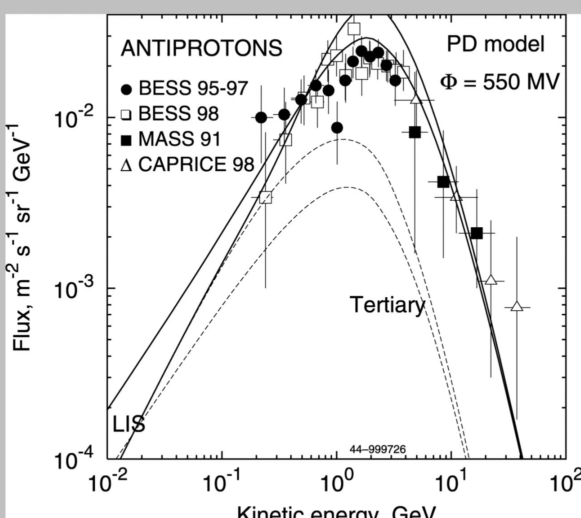


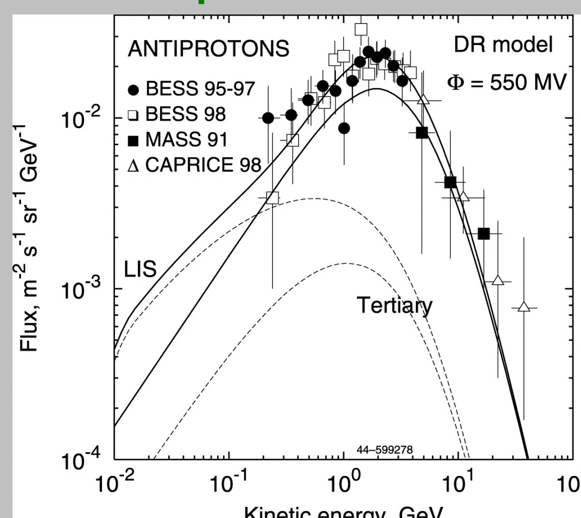


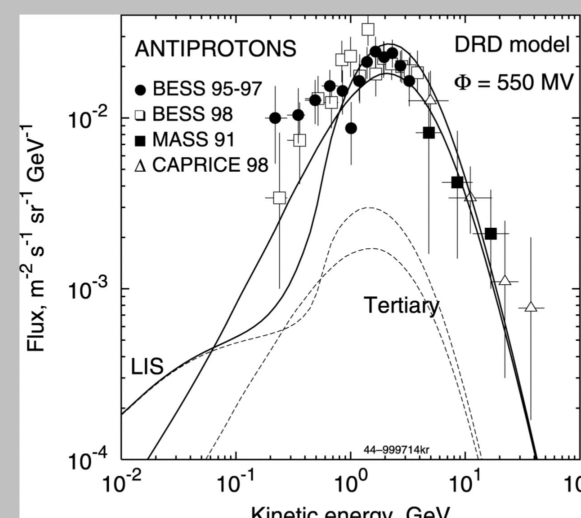
<u>Boron/</u>
Carbon

then predict the other cosmic-ray spectra

antiprotons

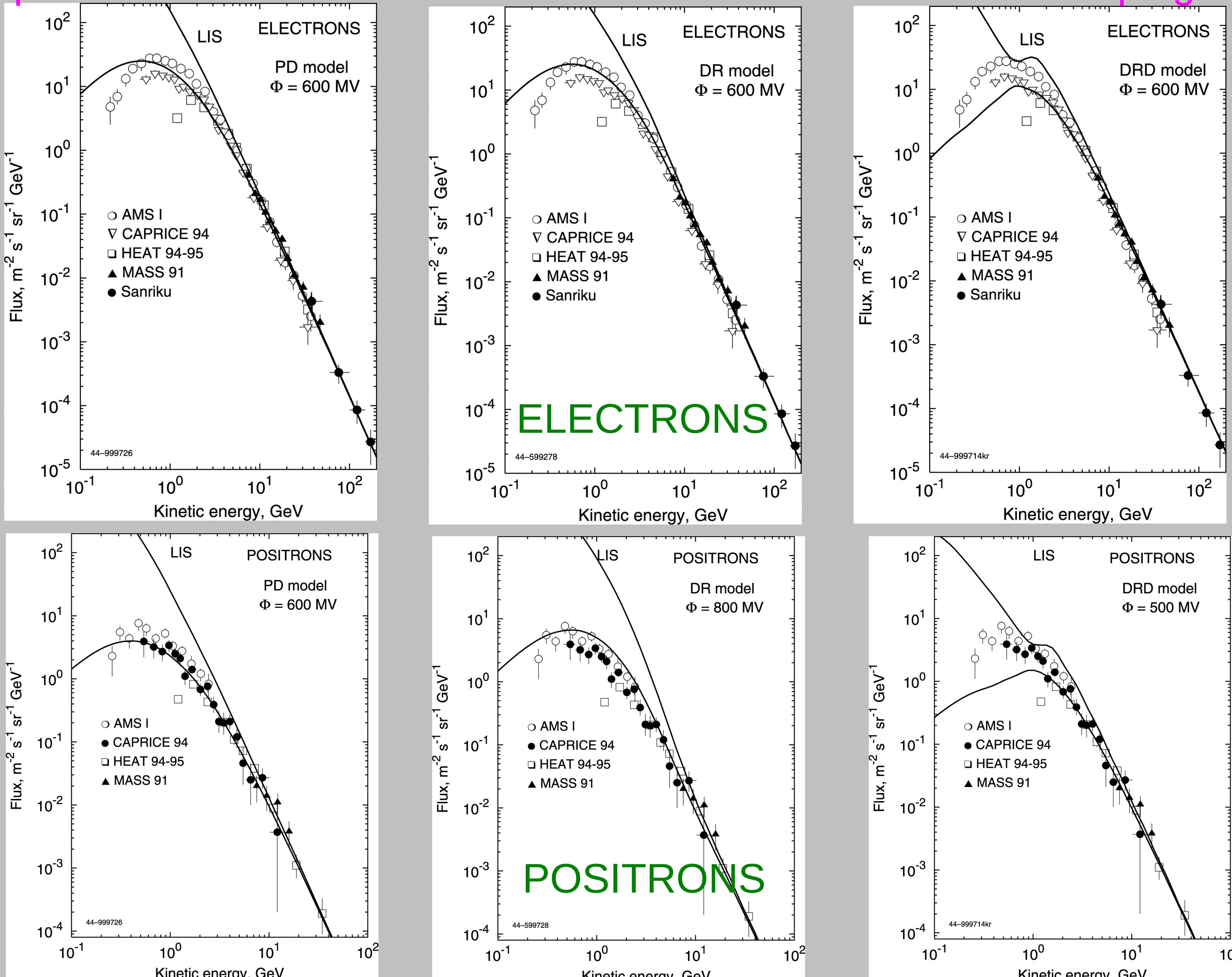






Ptuskin et al. 2006 ApJ 642, 902

plain diffusion diffusive reacceleration wave damping



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

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Uses RM, polarization, MCMC.
Cosmic-ray electrons from sources + propagation

See talk by Tess Jaffe, this workshop.

A&A 534, A54 (2011)
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Astronomy & Astrophysics

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

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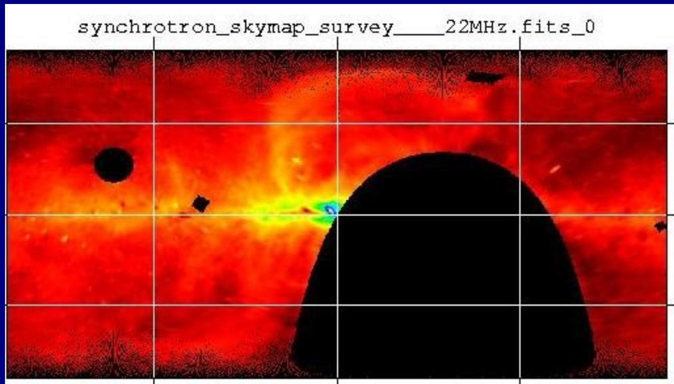
ABSTRACT

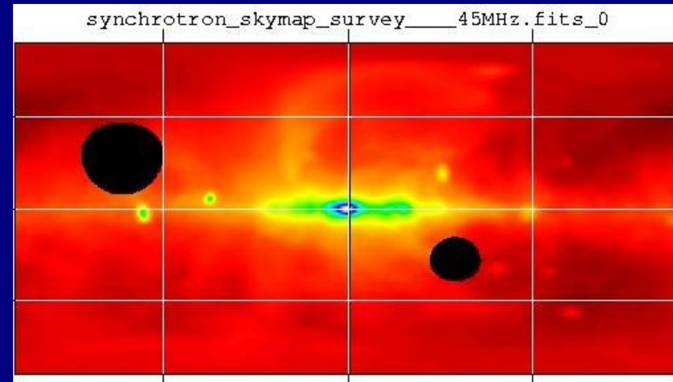
Aims. We exploit synchrotron radiation to constrain the low-energy interstellar electron spectrum, using various radio surveys and connecting with electron data from *Fermi*-LAT and other experiments.
Methods. The GALPROP programme for cosmic-ray propagation, gamma-ray and synchrotron radiation is used. 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.

Following results based on this paper.

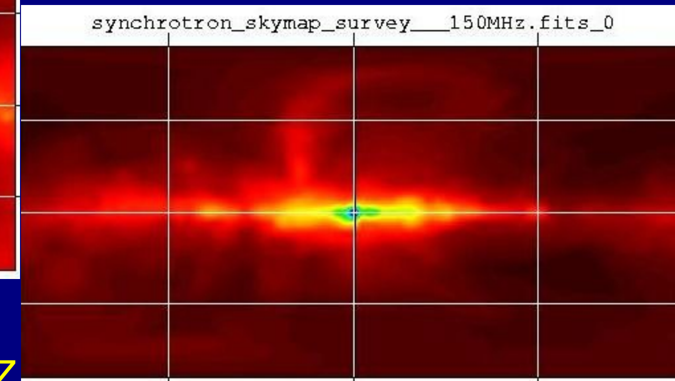
Continuum sky surveys



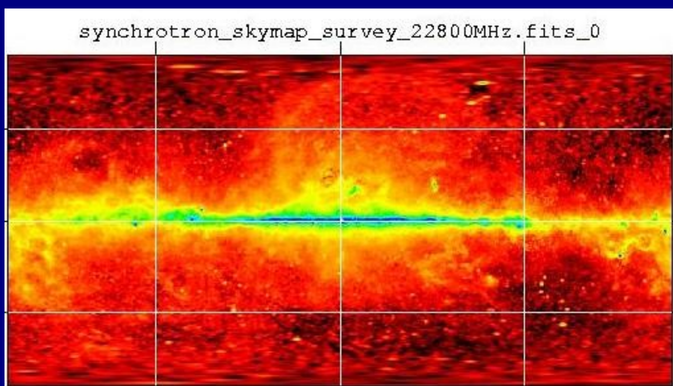
22 MHz



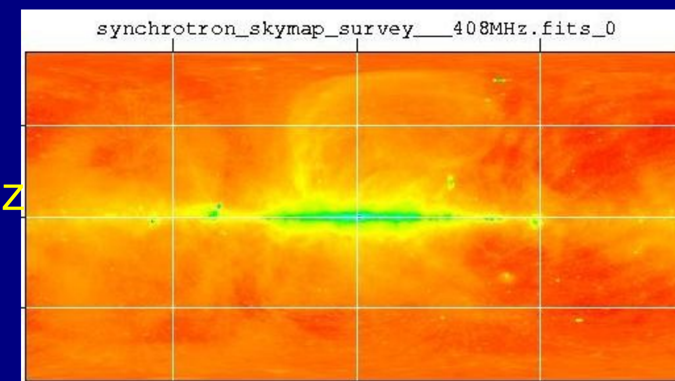
45 MHz



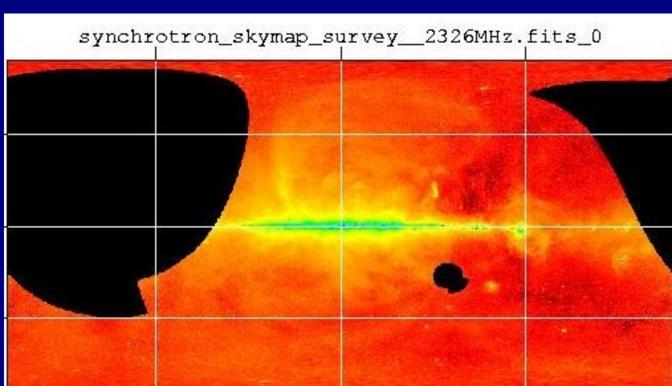
150 MHz



23 GHz

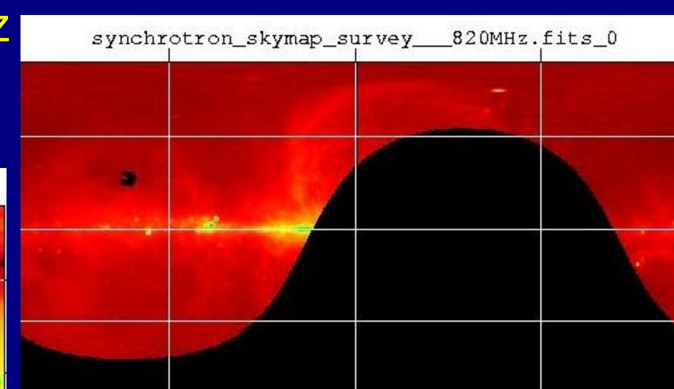


408 MHz

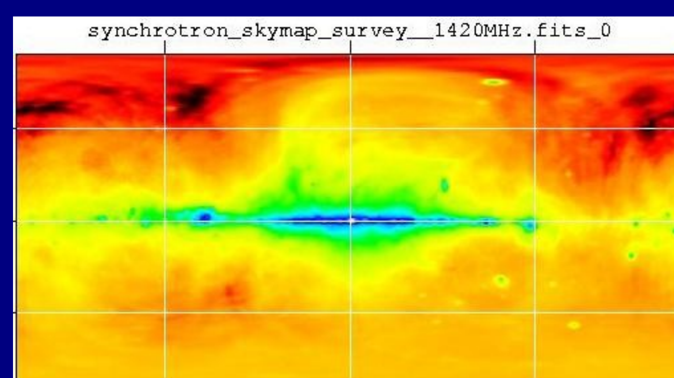


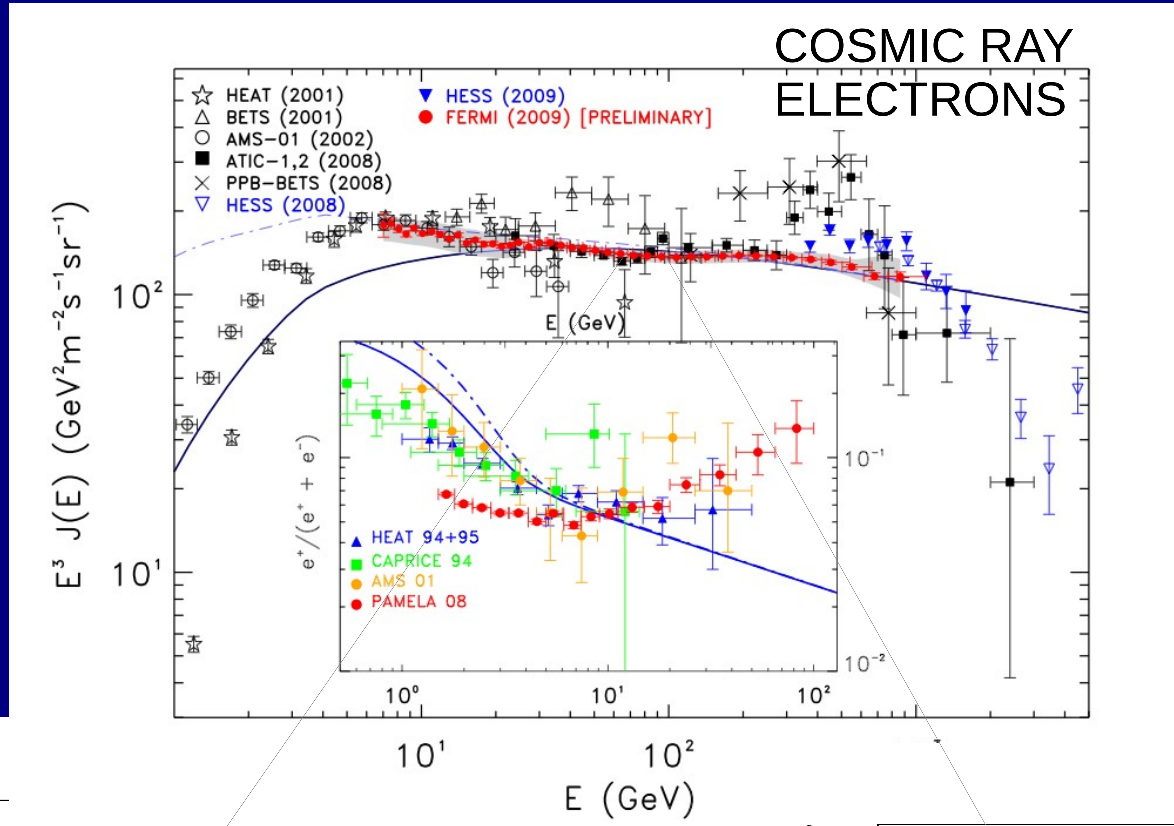
2.3 GHz

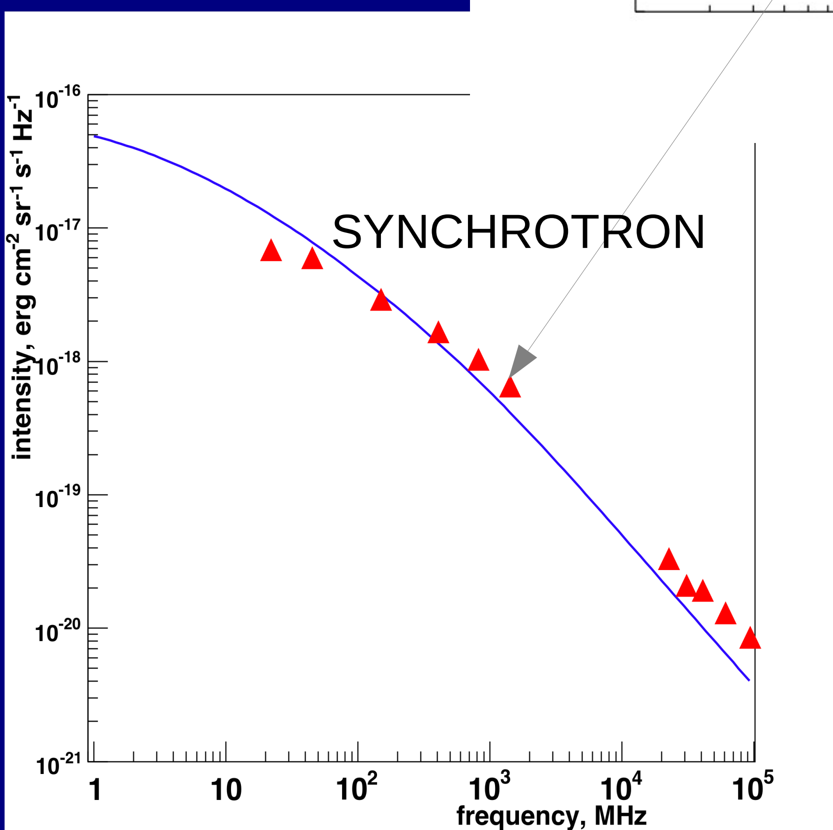
820 MHz



1.4 GHz

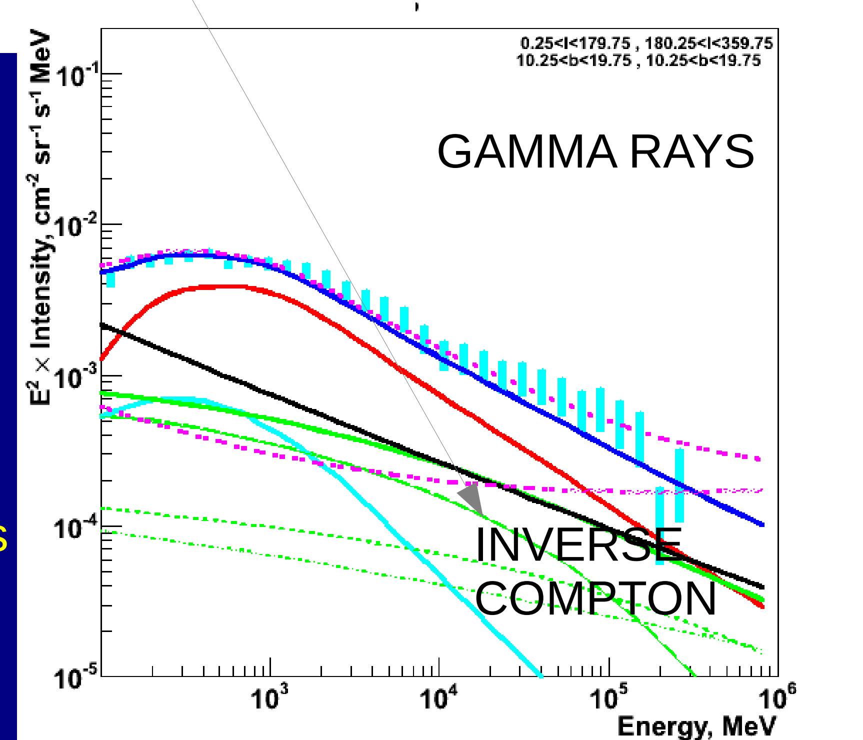


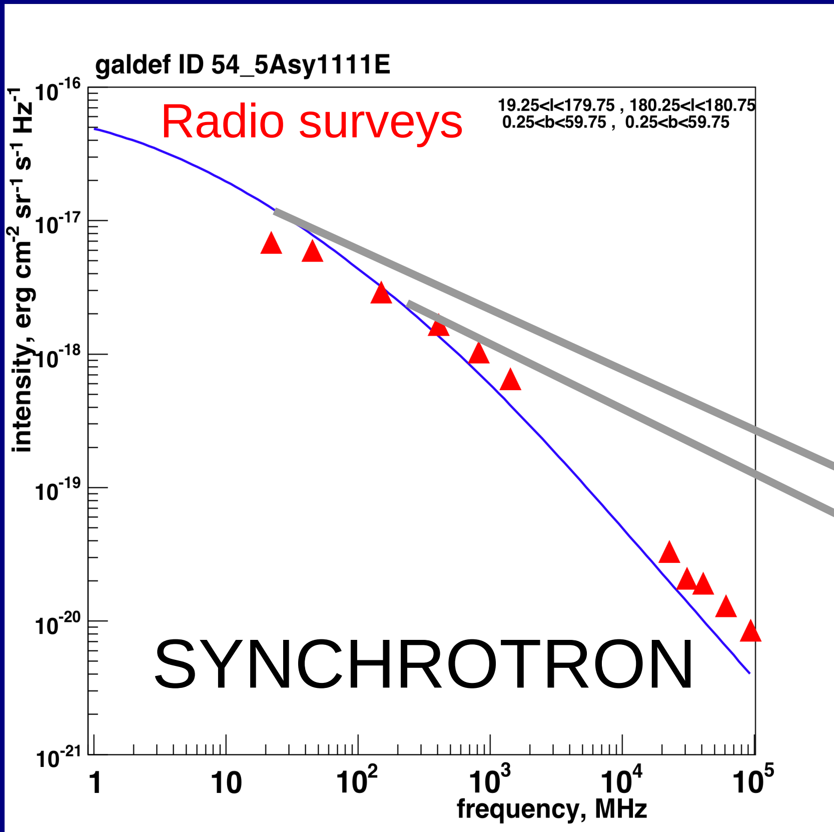


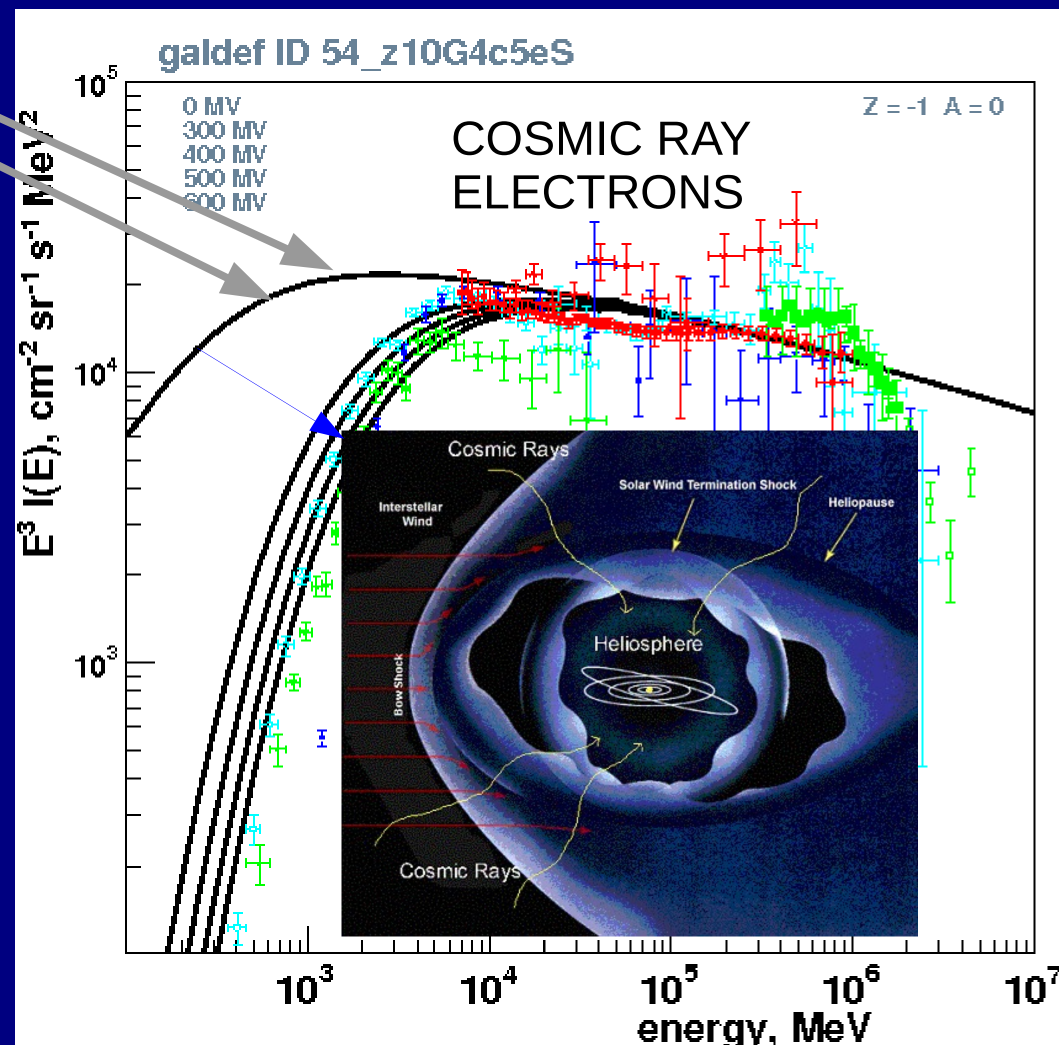


SAME
ELECTRONS
for
RADIO
and
GAMMA RAYS !

good constraints
on models

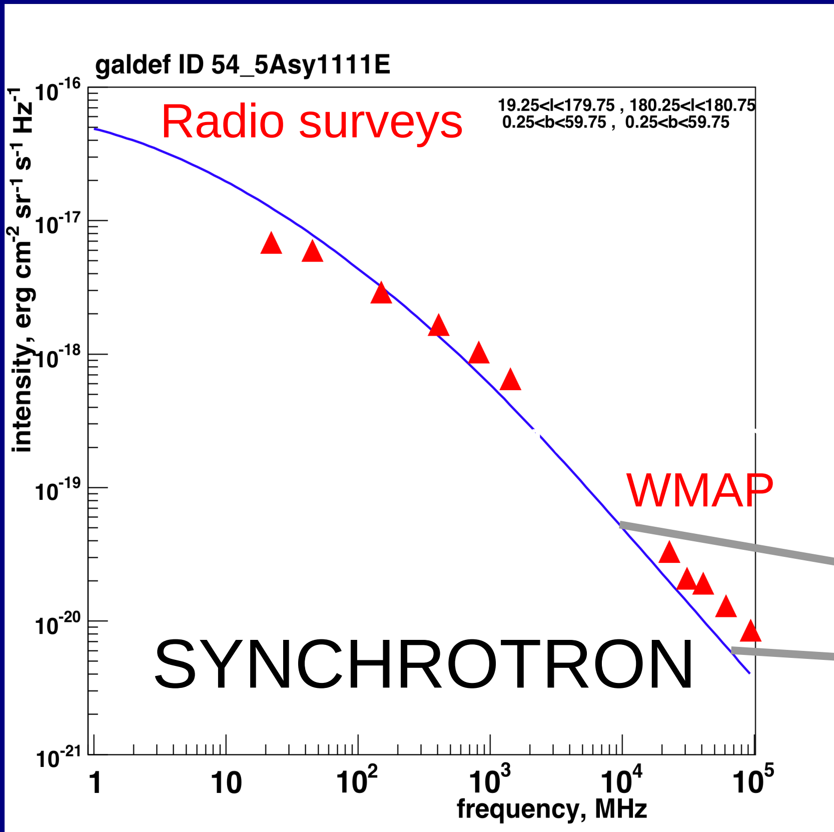


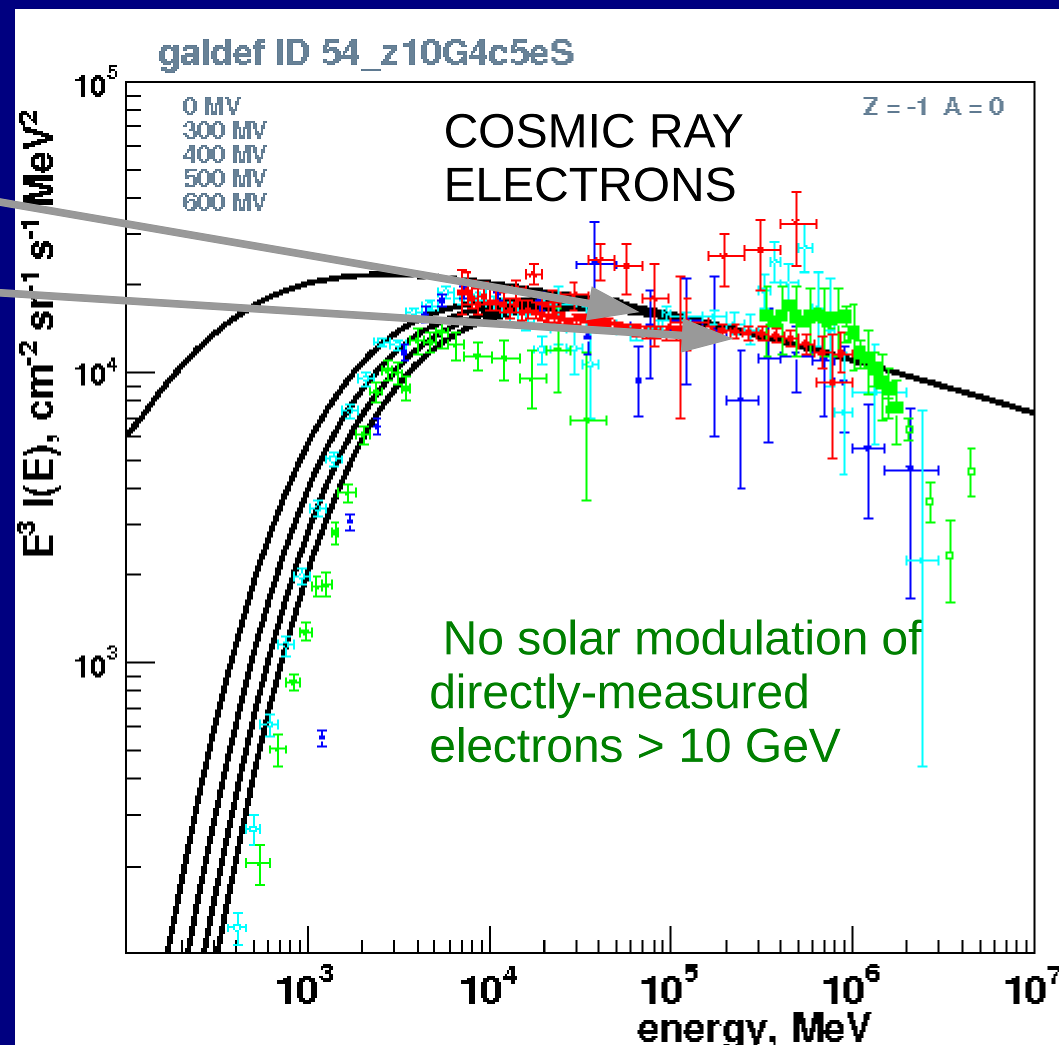




Radio provides essential probe of interstellar electron spectrum at
E < few GeV
to complement direct measurements and determine solar modulation

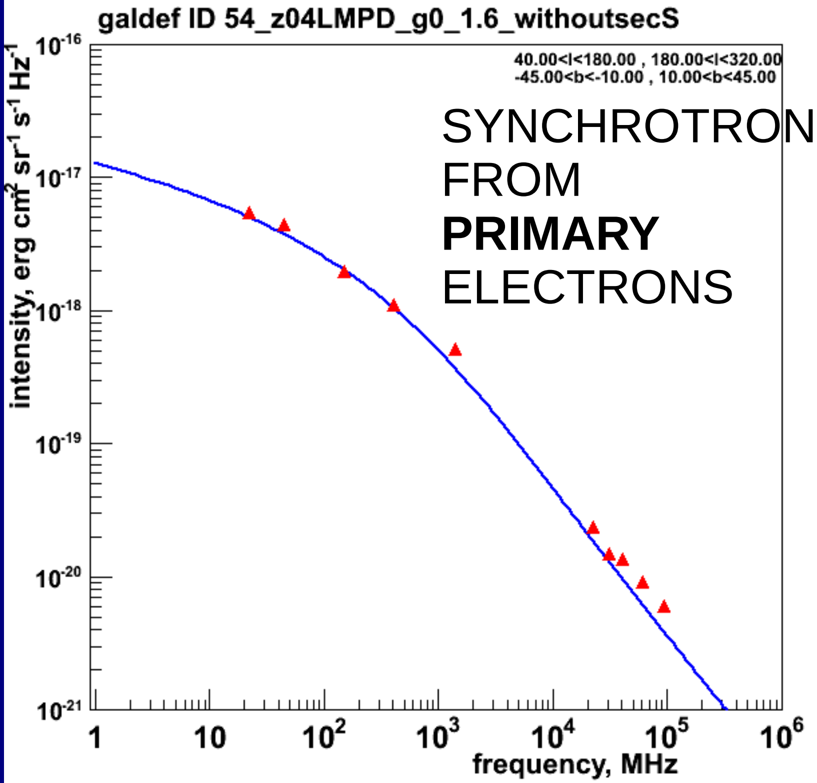
Electrons have huge uncertainty due to modulation here

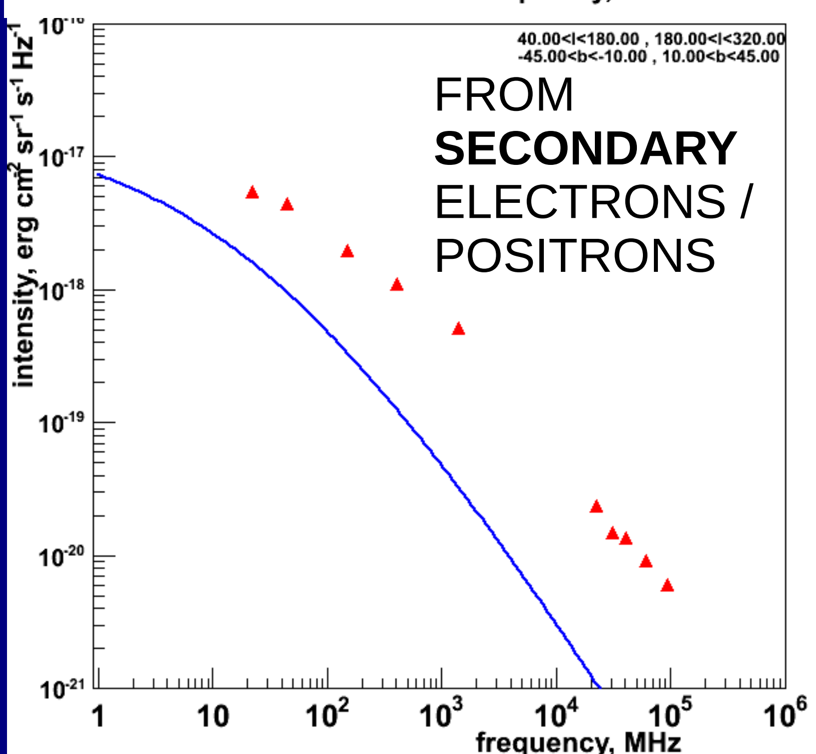


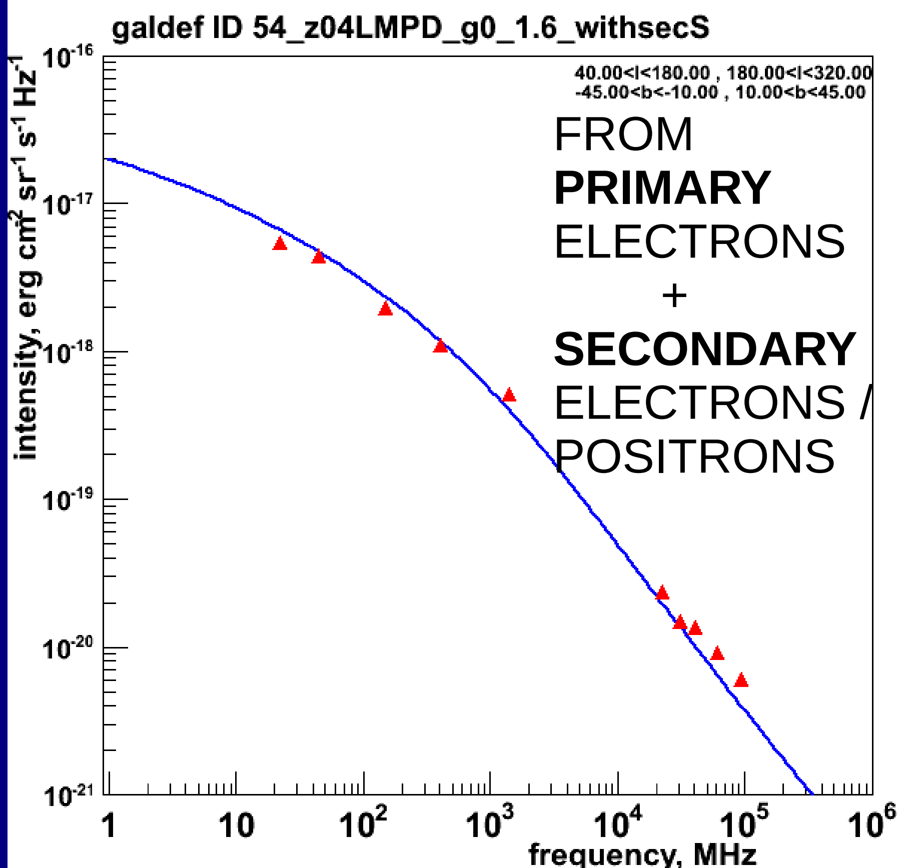


microwaves probe
interstellar electron spectrum
10 - 100 GeV

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







Cosmic-ray electrons

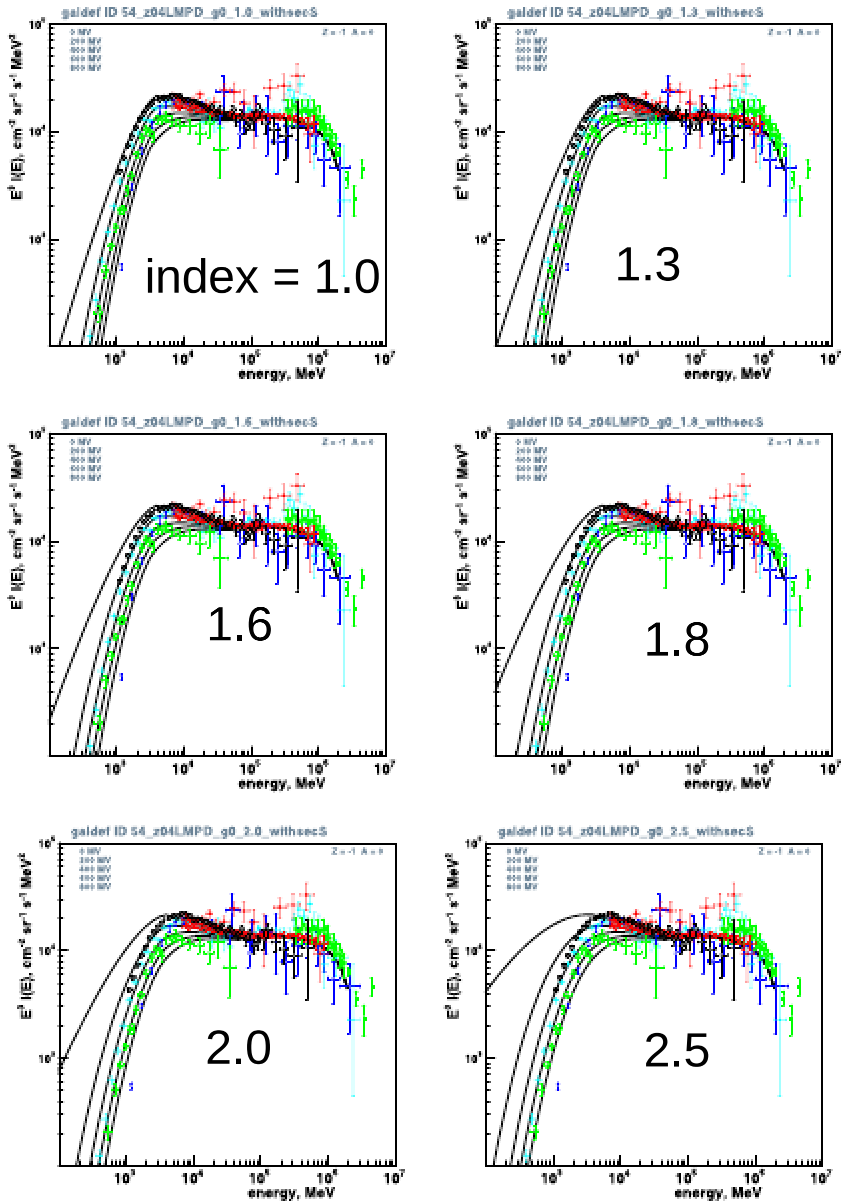


Fig. 4. Electron spectra for pure diffusion model, low-energy electron injection index 1.0, 1.3, 1.6, 1.8, 2.0, 2.5. Modulation Φ = 0, 200, 400, 600, 800 MV. Data as in Fig. 1.

Synchrotron

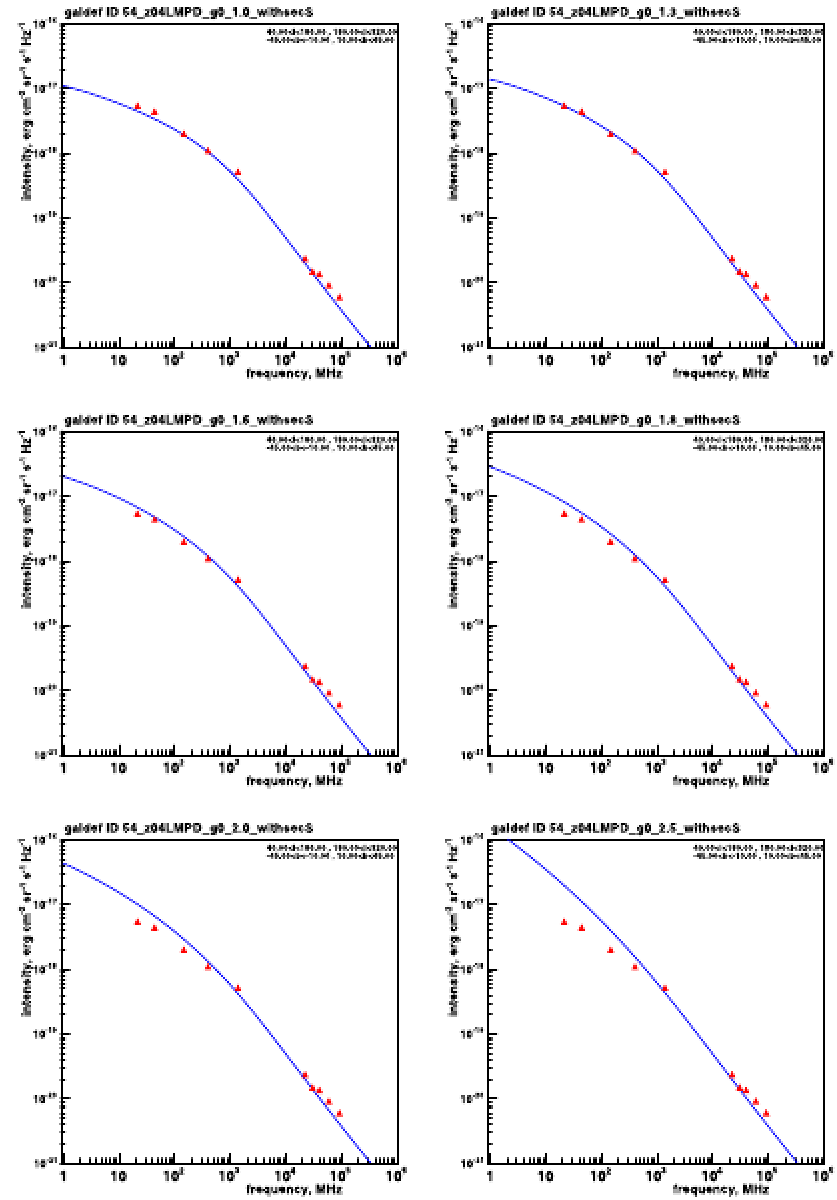


Fig. 5. Synchrotron spectra for pure diffusion model with low-energy electron injection index (*left to right, top to bottom*) 1.0, 1.3, 1.6, 1.8, 2.0, 2.5. Including secondary leptons. Data as in Fig. 2.

Effect of electron injection spectral index

Strong, Orlando & Jaffe, A&A 534, A54 (2011)

Galactic Synchrotron Spectral Index

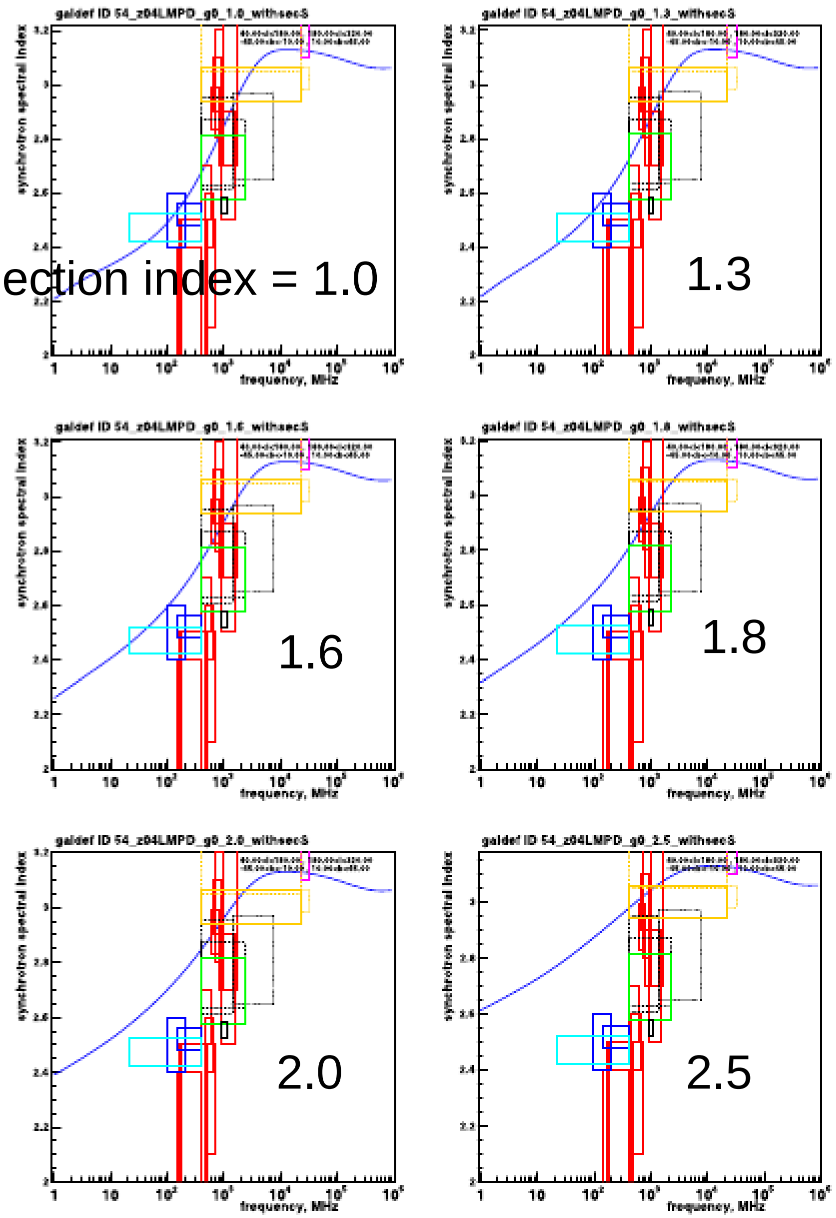


Fig. 6. Synchrotron spectral index for pure diffusion model with low-energy electron injection index (*left to right, top to bottom*) 1.0, 1.3, 1.6, 1.8, 2.0, 2.5. Including secondary leptons. Experimental ranges are based on the references reviewed in Sect. 4.1, and are intended to be representative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

Effect of electron injection spectral index

Strong, Orlando & Jaffe (2011)

Galactic Synchrotron Spectral Index

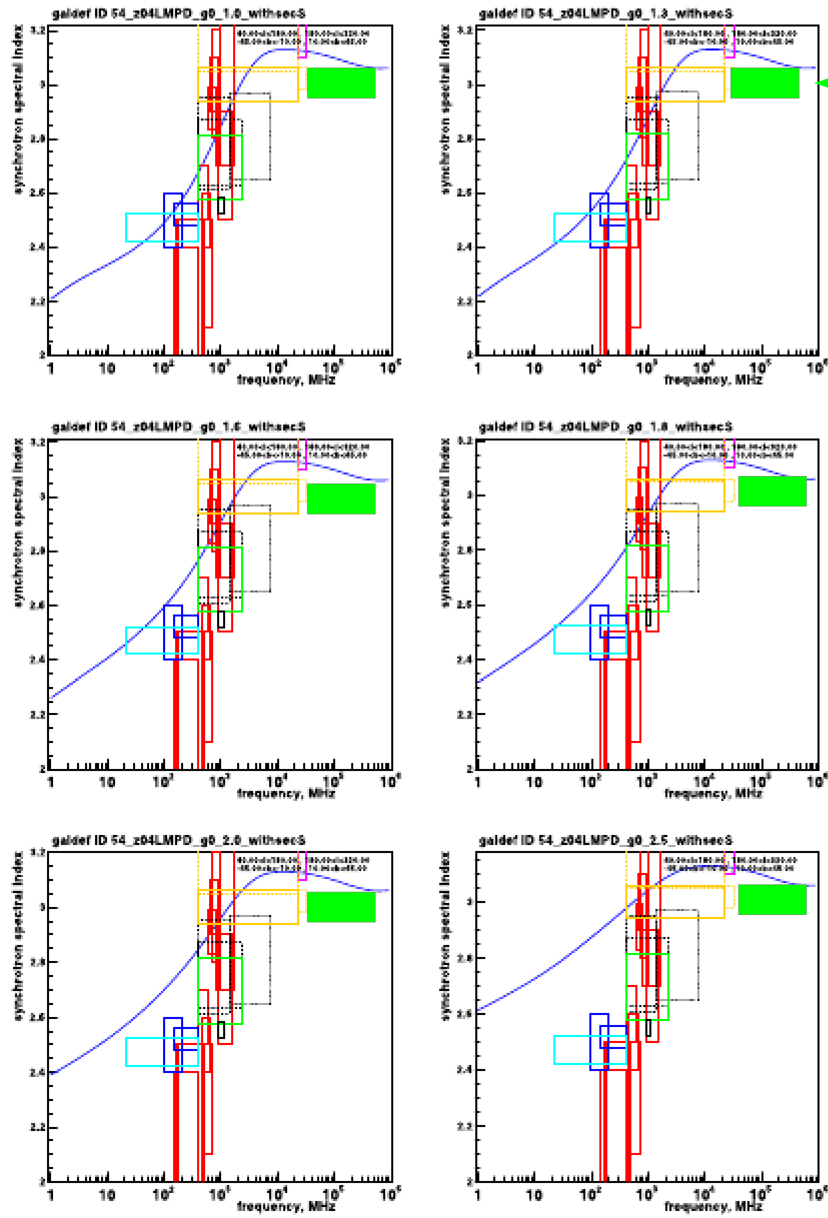


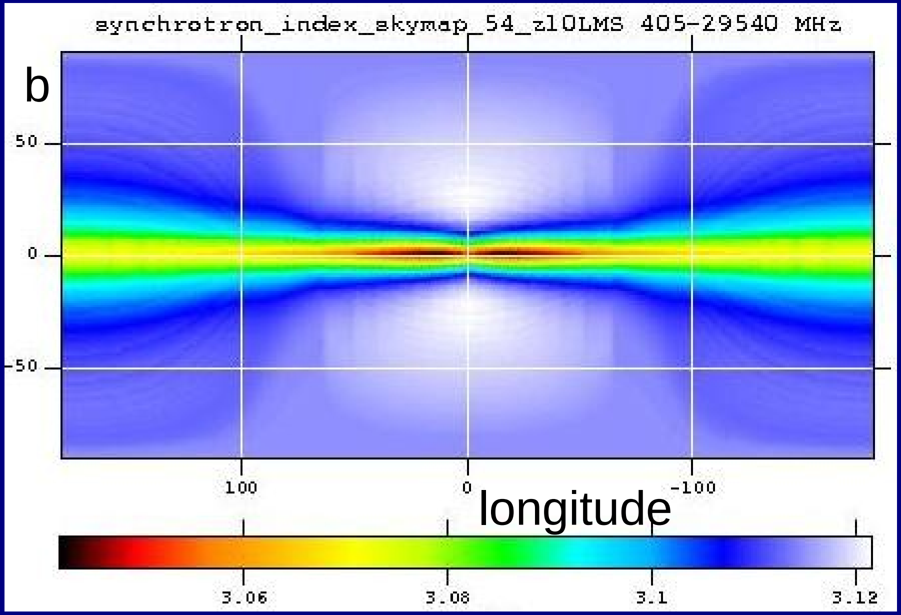
Fig. 6. Synchrotron spectral index for pure diffusion model with low-energy electron injection index (*left to right, top to bottom*) 1.0, 1.3, 1.6, 1.8, 2.0, 2.5. Including secondary leptons. Experimental ranges are based on the references reviewed in Sect. 4.1, and are intended to be representative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

Planck

A&A 536, A21 (2011)

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 μG from this analysis

Using high latitudes only, avoiding Loop I etc

Orlando and Strong 2012, submitted

What is new :

Polarized synchrotron

Separates regular from random B

Now modelled in GALPROP

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

Orlando and Strong 2012, submitted

What is new :

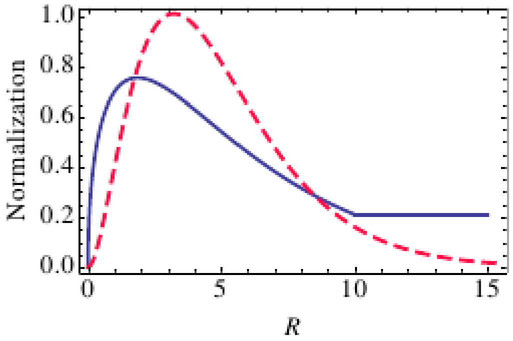
Polarized synchrotron

Separates regular from random B

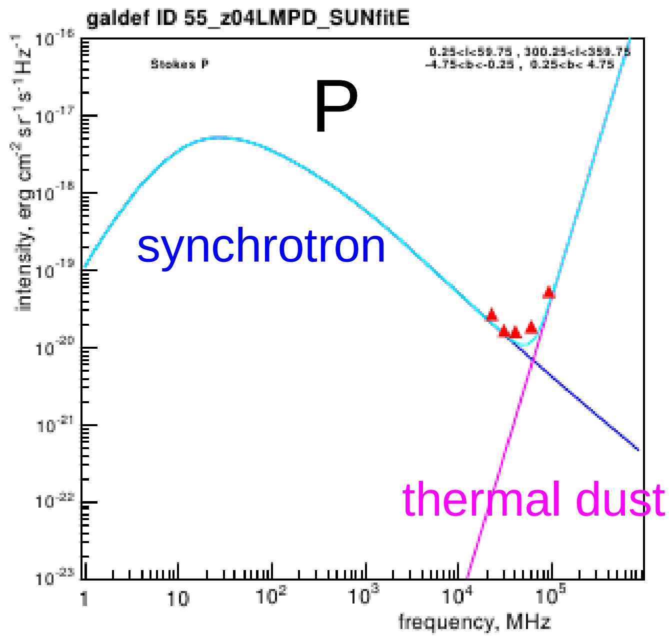
Now modelled in GALPROP

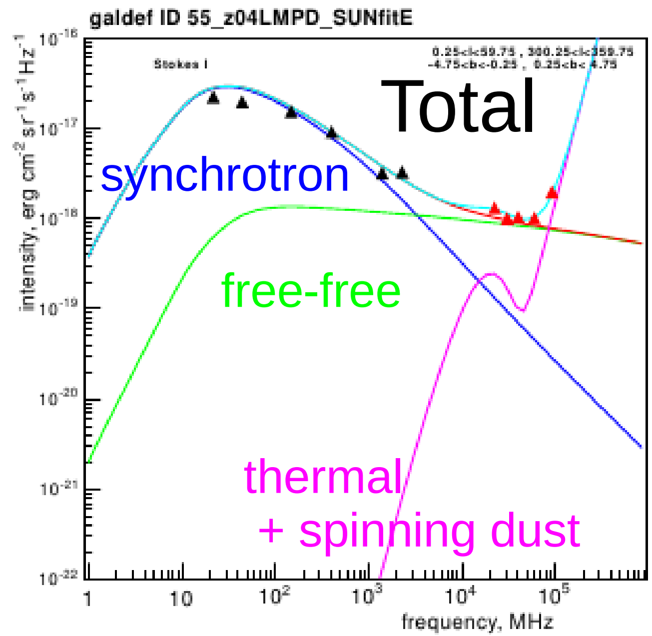
B-fields from literature, basic modifications to fit data.

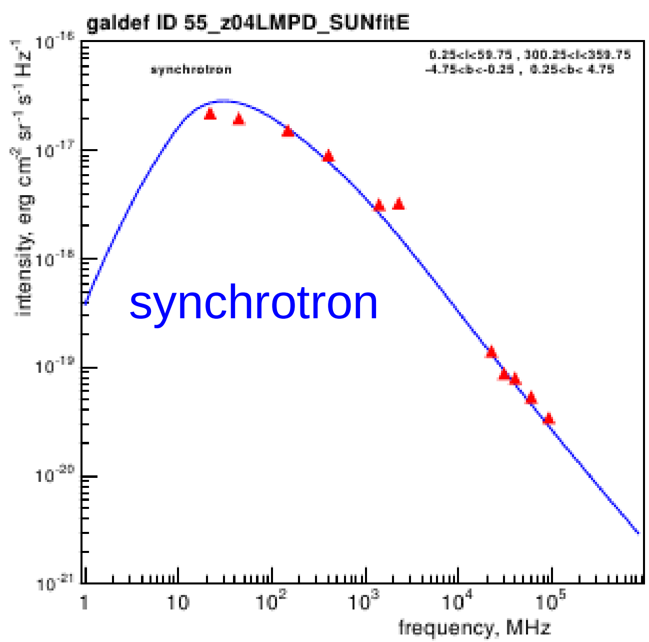
Cosmic-ray electron distribution is a main input from gamma rays.



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.

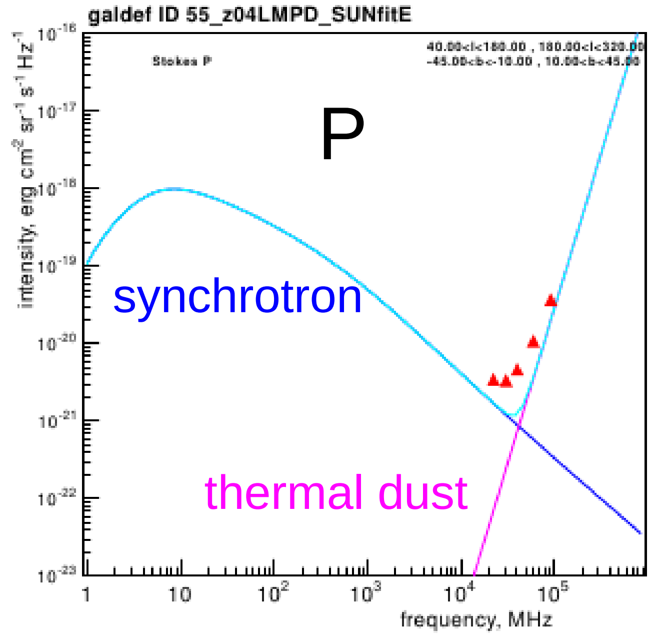


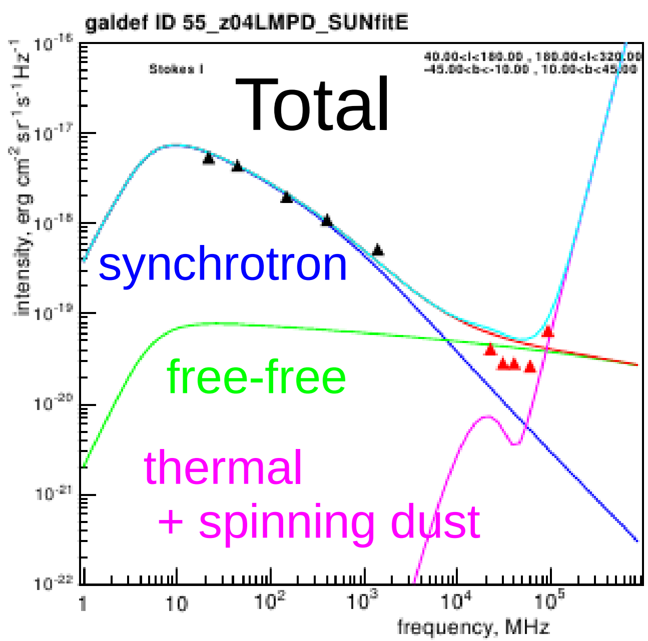


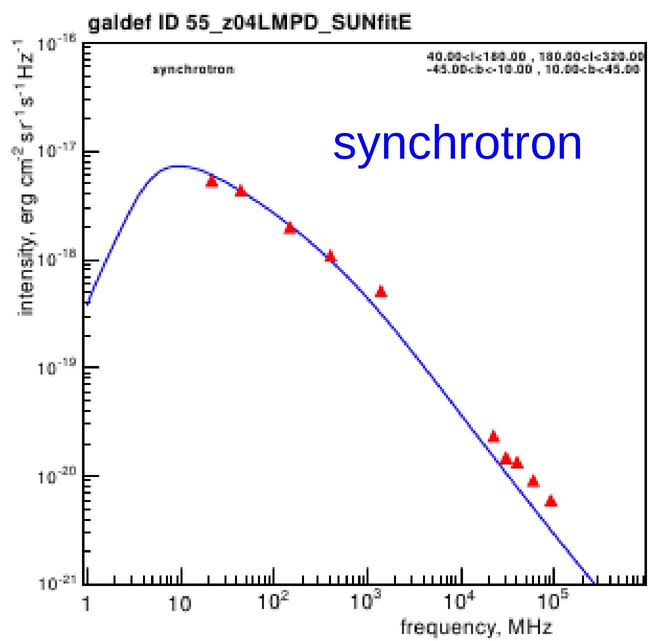


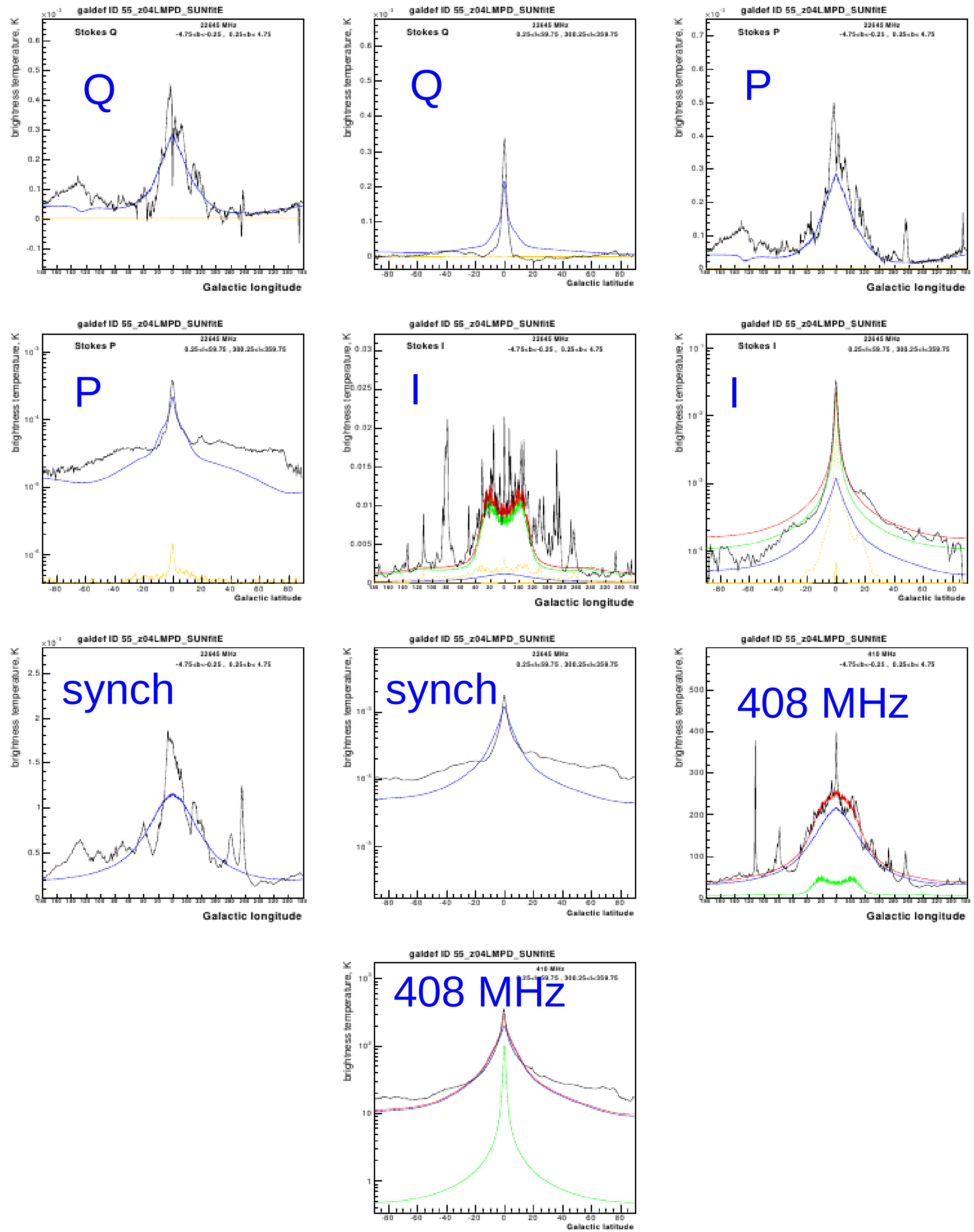
INNER GALAXY

HIGH LATITUDES

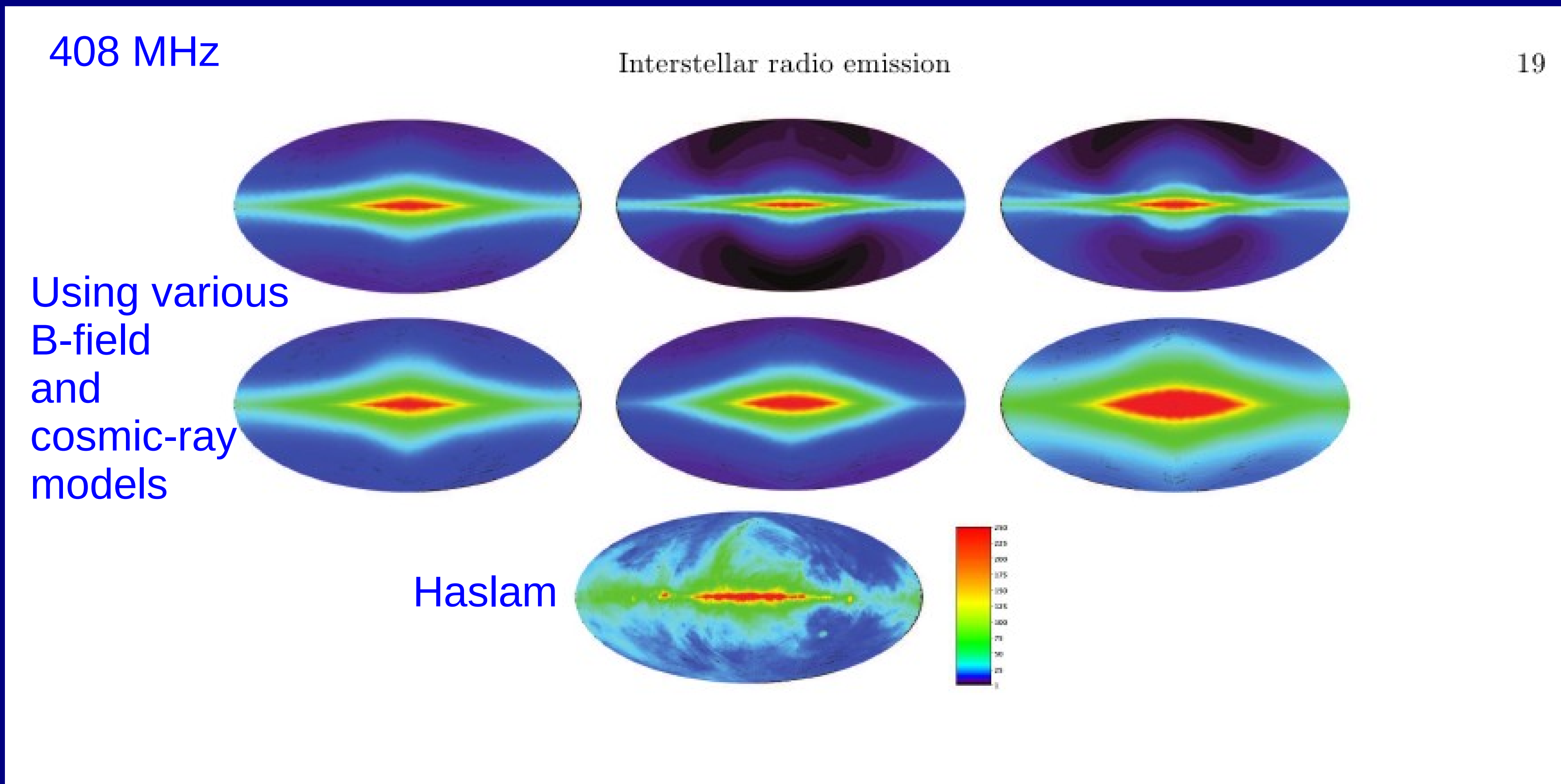








galdef ID 55_z04LMPD_SUNfitE
Stokes Q
Q
Stokes Q
Q
Stokes P
P
Stokes P
P
Stokes I
I
Stokes I
I
synch
synch
408 MHz
408 MHz
brightness temperature, K
Galactic longitude
Galactic latitude

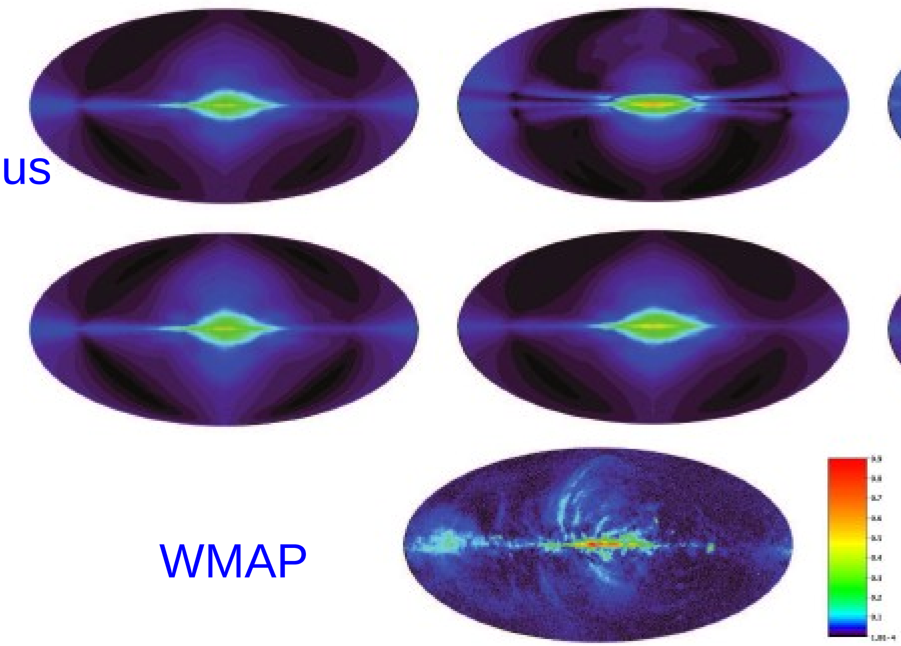


Regular B-field models from Sun etal, Pshirkov et al.
Scaling factor applied.

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.

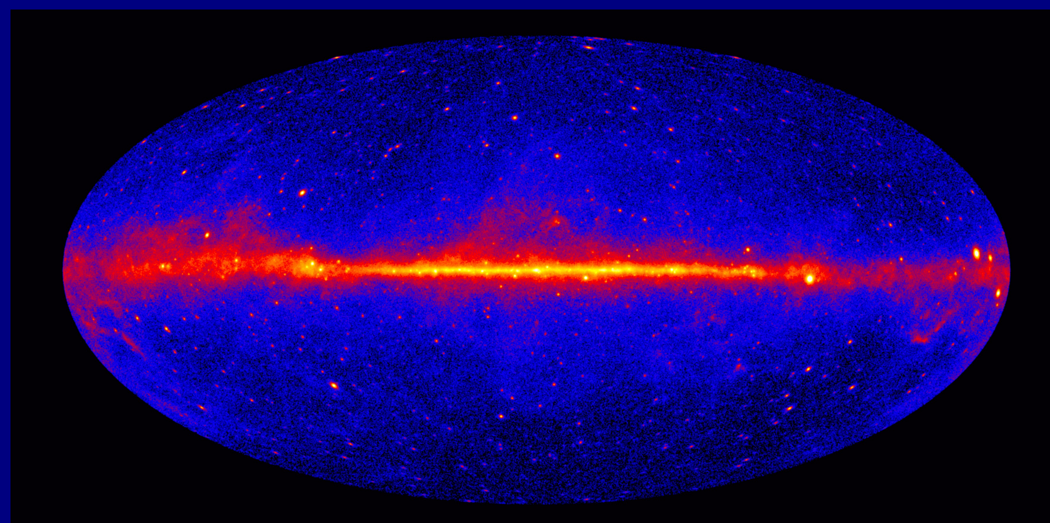
Local B- field from this paper
Using Fermi-LAT cosmic-ray electrons
408 MHz
23 GHz WMAP polarized

Regular : 3-4 μG
Random : 6 μG

Fermi
Gamma-ray Space Telescope

Exploiting gamma rays

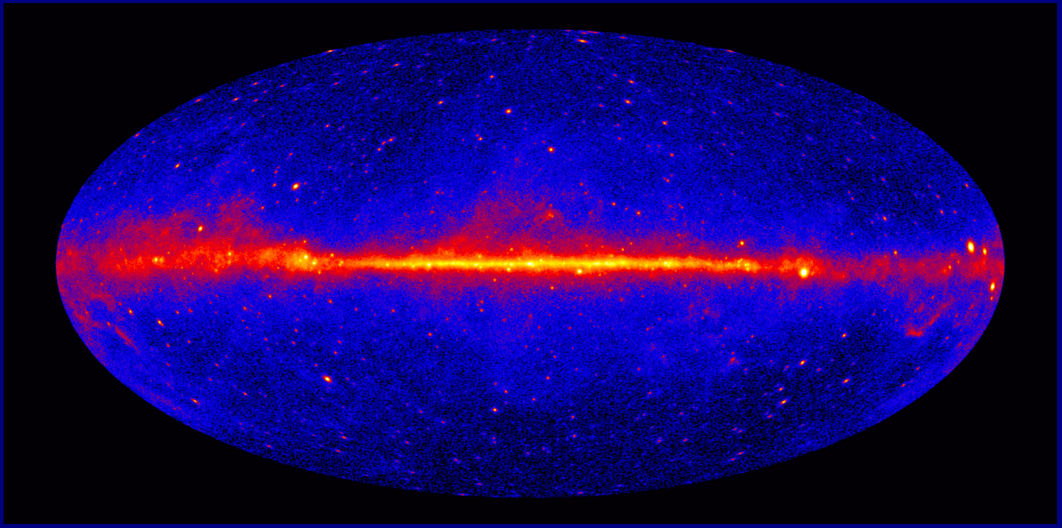
1 – 10 GeV



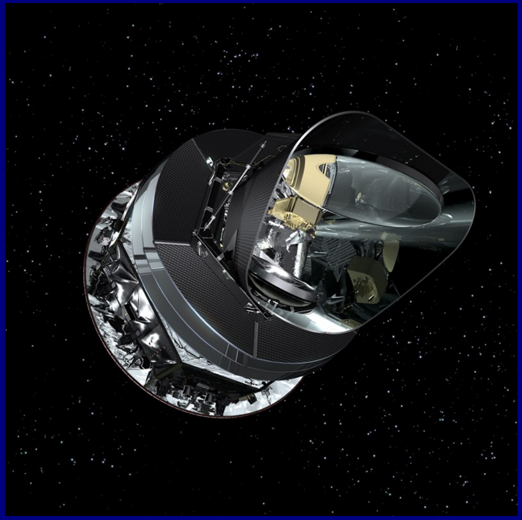
Cosmic-ray protons interacting with gas : hadronic (pion-decay)

Cosmic-ray electrons and positrons interacting with gas : bremsstrahlung

interacting with interstellar radiation : inverse Compton



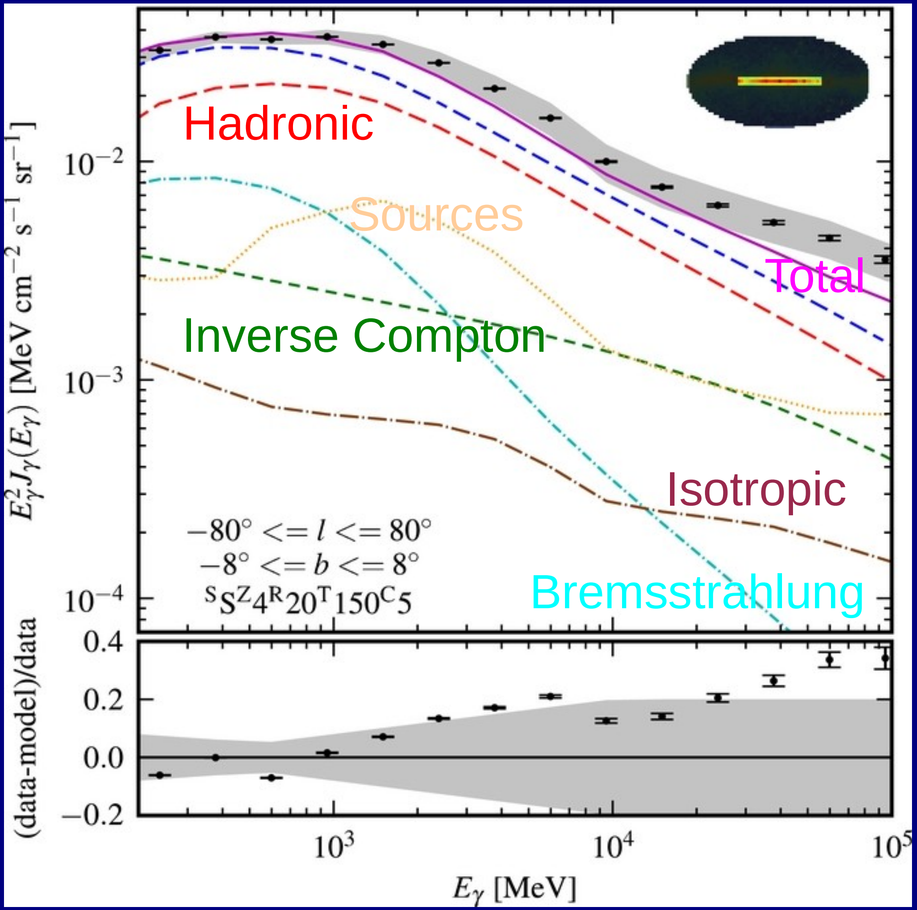
2 years



1 year

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

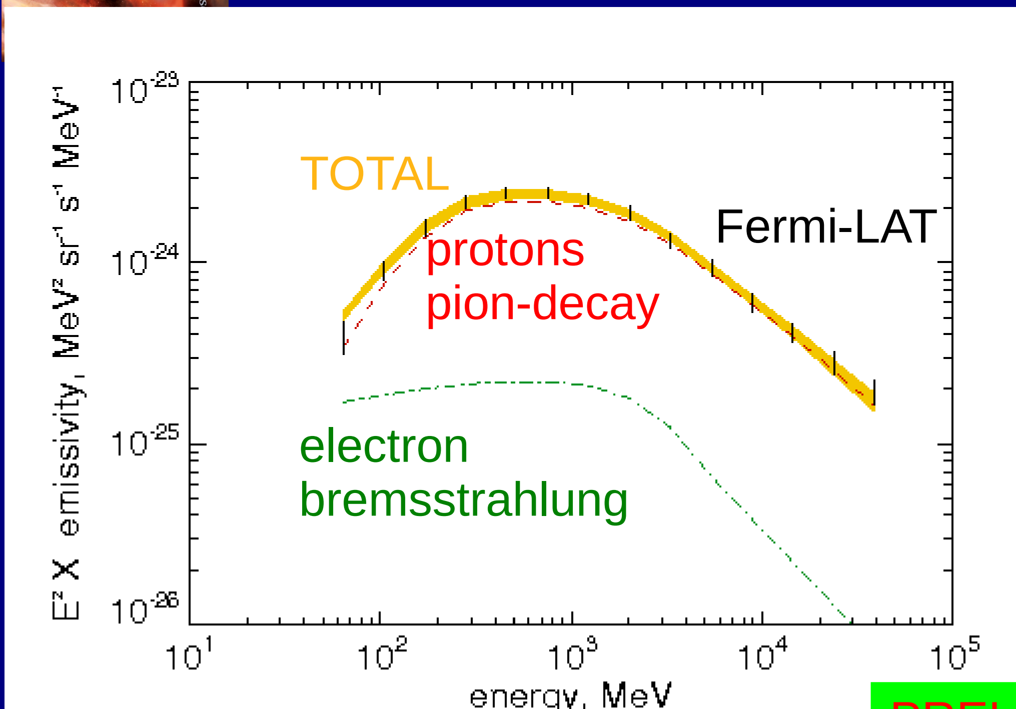
Fermi-LAT
Inner Galaxy Gamma Ray Spectrum

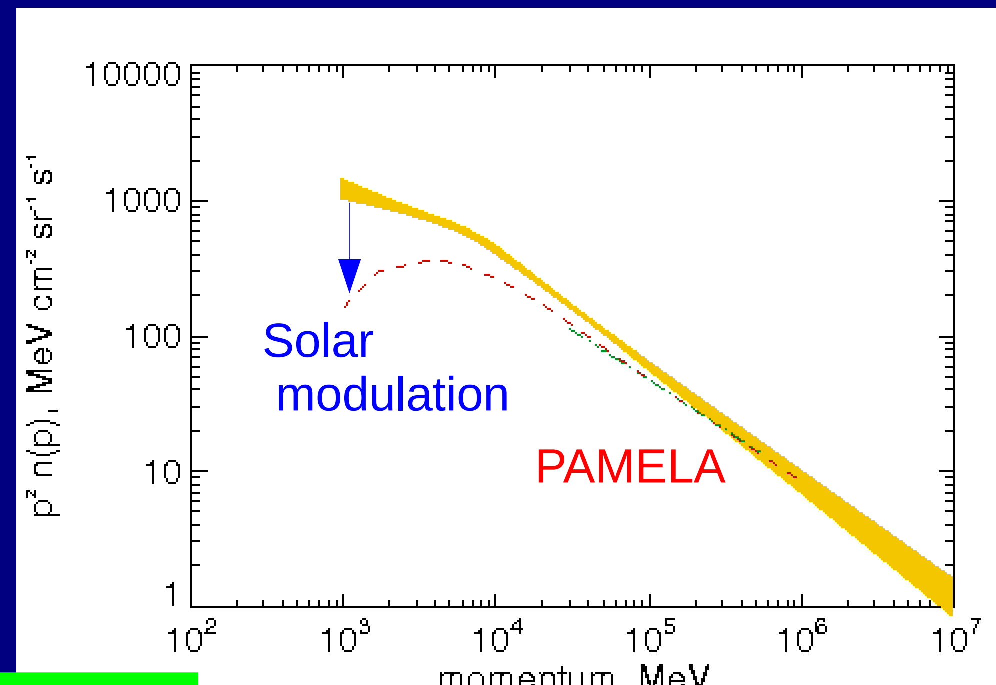


Ackermann et al. ApJ 750, 3 (2012)

Interstellar Cosmic ray spectra derived from gamma rays

Gamma-ray gas emissivity *used to derive* Cosmic-ray protons





PRELIMINARY

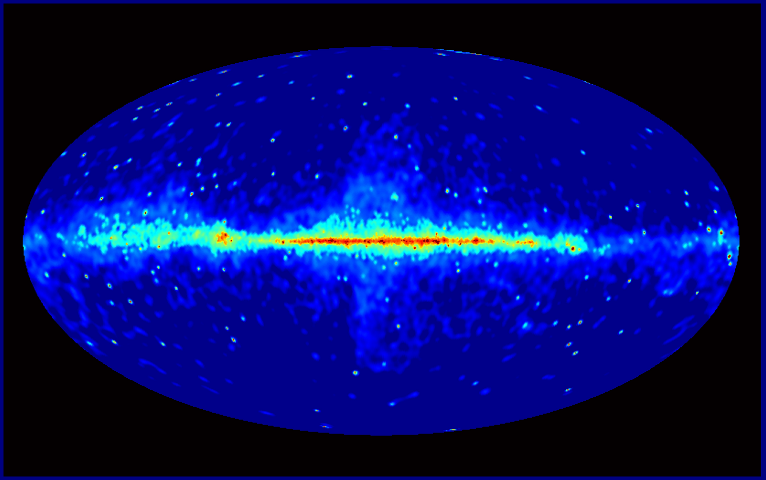
Below 10 GeV affected by solar modulation, but gamma rays probe the interstellar spectrum.

Gamma-ray emissivity of local interstellar gas – Fermi-LAT Collab.

Power-law in momentum overall, but low-energy break
e.g. from power-law injection and interstellar propagation (diffusion = f(E))

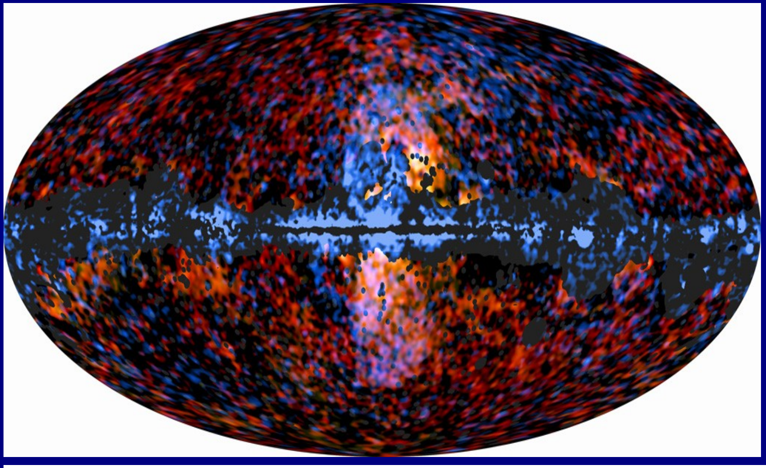
Interstellar spectrum essential to test heliospheric modulation models.

Fermi Bubbles

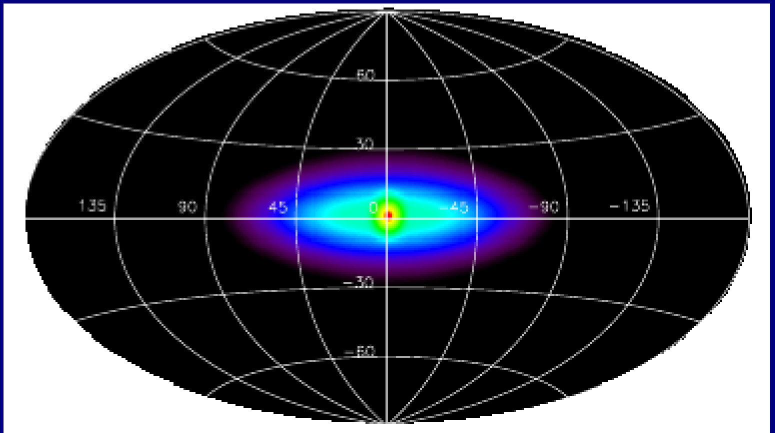


(related to WMAP Haze ?)

Planck haze (arXiv:1208.5483)
Overlaid on Fermi Bubbles



connection to 511 keV line ?



All are -
 centred on Galactic Centre
 leptonic
 unknown origin

CONCLUSION

Exploiting high-energy connection for synchrotron makes sense