Cosmic Ray and Multiwavelength Context

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MPE Garching

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

Astron. Astrophys. 66, 205—209 (1978)

ASTRONOMY AND ASTROPHYSICS

The Radio Halo of NGC 891

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Summary. Recent high resolution observations of NGC 891 made with the Westerbork array at 6, 21 and 49 cm provide information on the propagation of relativistic electrons and the distribution of magnetic fields away from the disc. Simple models of diffusive and convective transport of electrons are constructed to account for the spatial distribution of intensity and spectral index. The magnetic field must fall off rather slowly with height above the plane, with most of the intensity decrease resulting from electron propagation and energy losses.

Key words: cosmic-rays — radio haloes — magnetic fields

1. Introduction

Allen et al. (1977, hereafter referred to as ABS) have prepared high resolution maps of the edge-on Sab galaxy NGC 891, using the Westerbork aperture synthesis telescope at 6, 21 and 49 cm wavelengths. These straints on possible models for both the electron propagation and the magnetic field variation.

In this paper, simple models involving separately diffusive and convective propagation are used as a basis for the interpretation of the observations. The diffusion model has already been used (Strong, 1977) in connection with the low-frequency drift-scan observations of our Galaxy, and this makes a useful comparison with the results of the present work on NGC 891.

2. The Models

Pure diffusion and pure convection models for the electron propagation will be considered. In each case, the electrons are assumed to have their sources in the disc, and to be injected with a power-law spectrum with (differential) index γ_0, and to move either diffusively in 3-D or convectively in 1-D perpendicular to the disc with constant velocity.

a) Diffusion Model

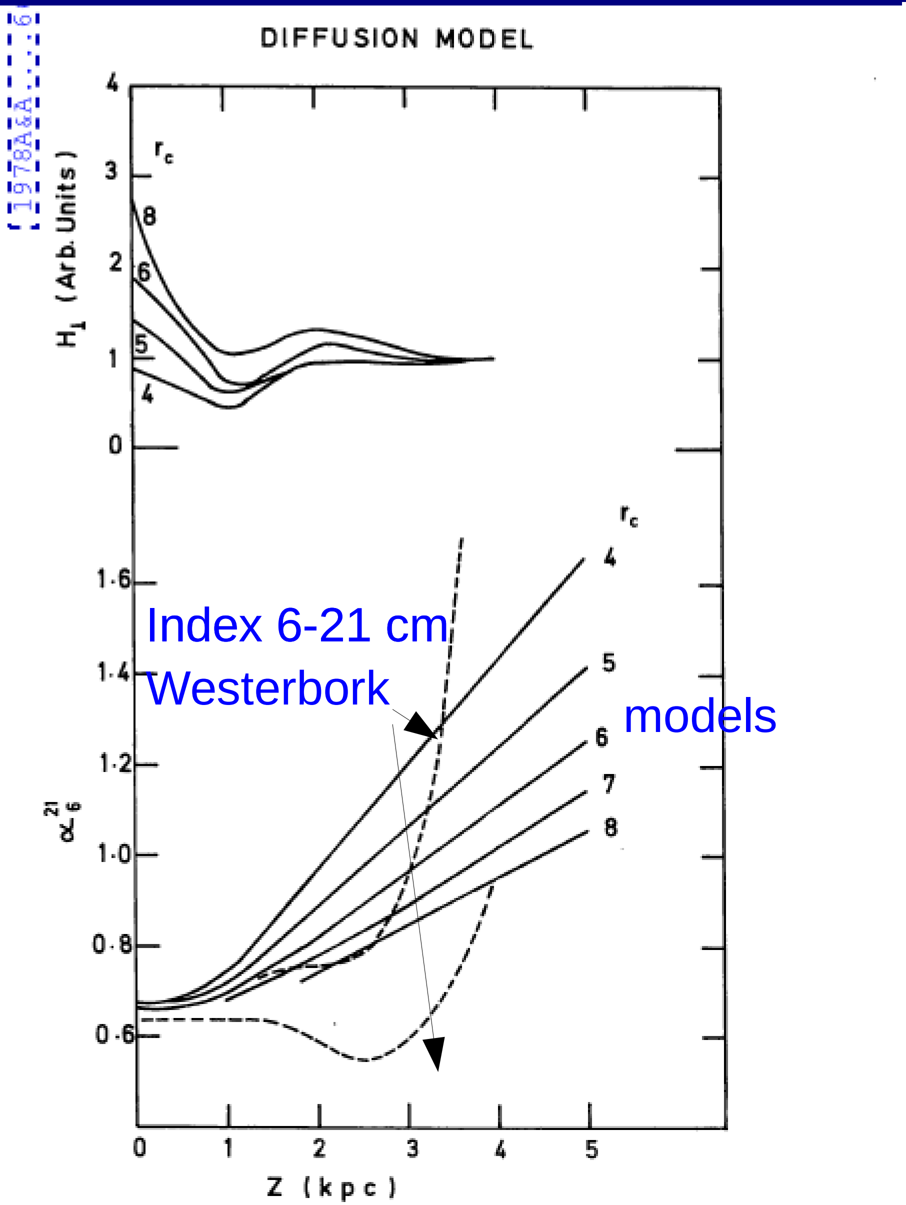

Fig. 2. Observed variation of α_6^{21} with z at 21-cm resolution (dashed lines), plotted with the predictions of diffusion models for $r_c = 4-8$ kpc. Data are from ABS, and the predictions are convolved with the appropriate beam and averaged over strips 195″ (=13 kpc) long parallel to the major axis of the galaxy. The variation of H, with z is also shown, arbitrarily normalized to 1 at $z = 4.0$ kpc

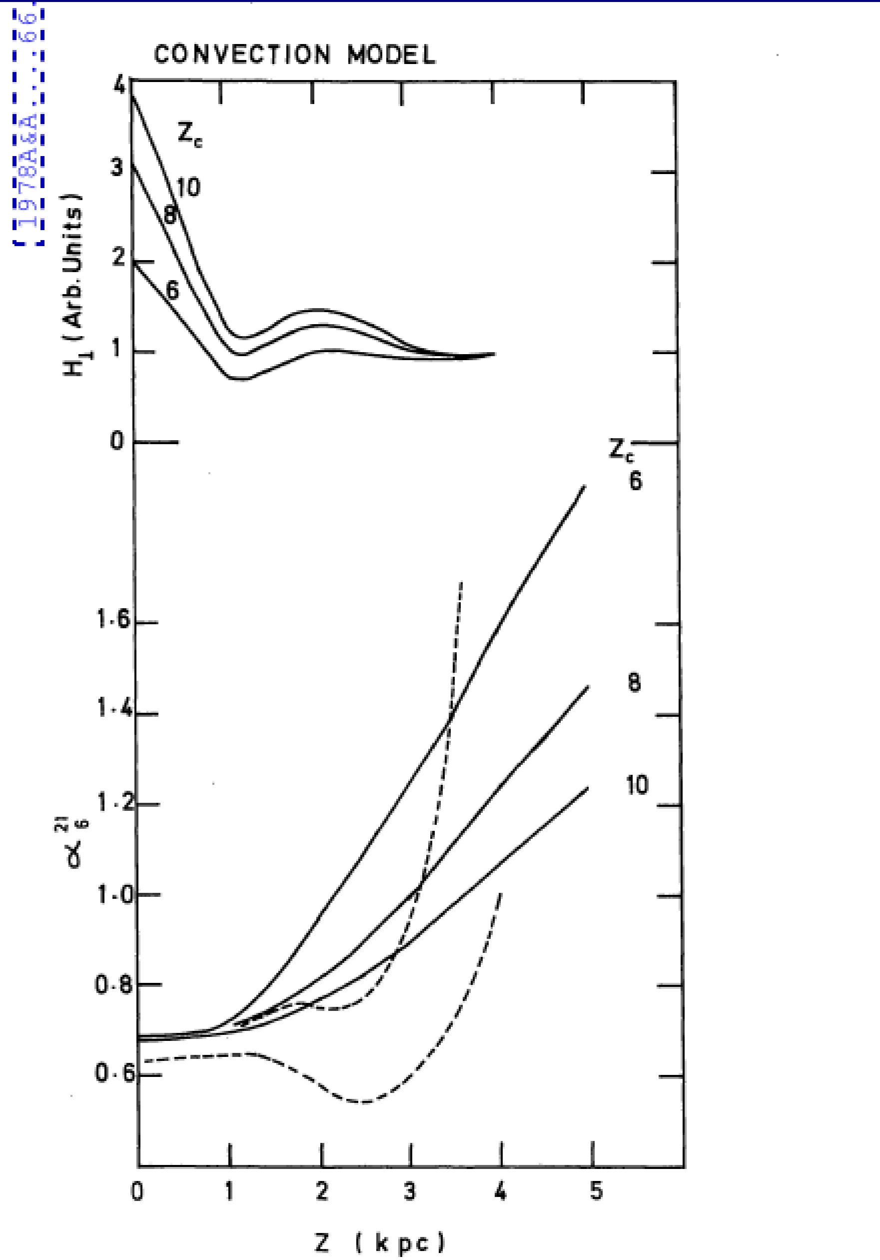

Fig. 3. As for Figure 2, but using convection models with $z_c = 6-10$ kpc

Data were not good enough to test models. Will be interesting to compare 35 years later!
(+ Beck etal. 1979, + Hummel, Dahlem, Beck... circa 1991 ++...)

Mon. Not. R. astr. Soc. (1977) **181**, 311–322

Diffusion models for the low-frequency radio emission from the Galactic halo

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Summary. The low-frequency drift-scan observations of the Galactic radio emission at high latitudes are discussed in the context of simple diffusion-plus-energy-loss models for the propagation of electrons away from the Galactic plane. It is shown that for certain parameters such models can reproduce the observations quite well. The halo emissivity in the region just outside the disc at the solar radius is ~7000 K/kpc at 17.5 MHz. The average magnetic field in the halo must be ~0.2 of that in the disc, and the diffusion mean free path about 1 pc. The full width to half-maximum of the 17.5 MHz emission is about 6 kpc.

Milky Way
Drift Scans from Bridle 1967

17.5 / 81.5 MHz
Various declinations

F= measure of spectral variation
'T-T plots' : eliminates zero-level dependence

Diffusion model:
Consistent with cosmic-ray electron propagation in halo with energy losses.

But local features,
Loop I etc?

(revisit with LOFAR?)

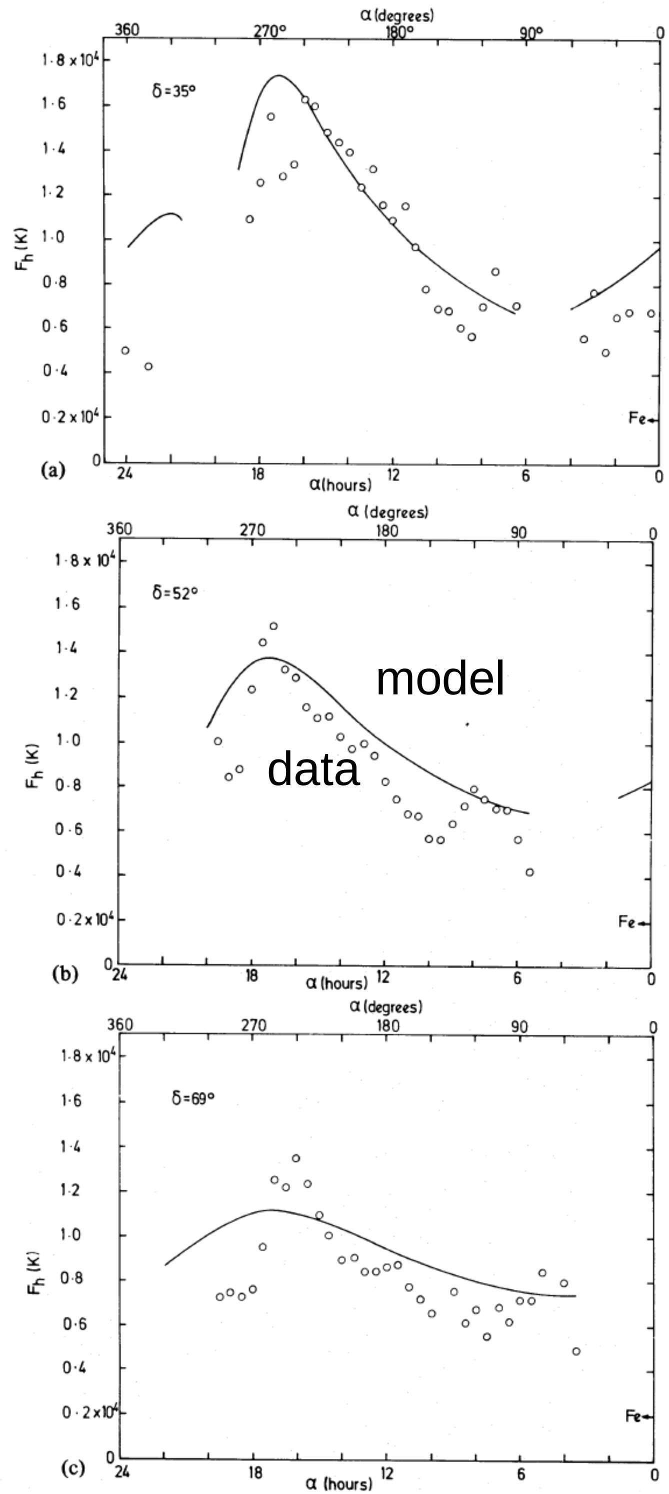


Figure 4. Predicted variation of F with α for r_c = 10 kpc, γ = 1.3, $\epsilon_{1h}(\odot)$ = 6750 K/kpc and F_e = 2000 K, for (a) δ = 35°, (b) δ = 52° and (c) δ = 69°.

Strong 1977

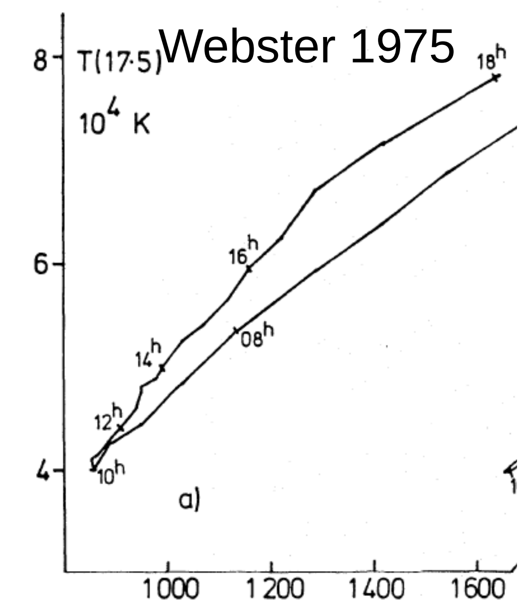


FIG. 2. *(a) The T–T plot on δ = +52° o beamwidth at 17·5 and 81·5 MHz. (b) A t on the halo model described in Sections 4 a*

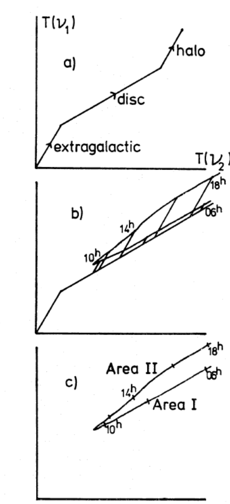


FIG. 1. *Three sketches illustrating the construction of a T–T plot. In (a) the three vectors corresponding to the extragalactic, disc and halo contributions are shown for one particular direction in the sky. The construction for several directions is shown in (b), and in (c) the locus of the resultants is drawn, shorn of all construction lines.*

All the theory that is needed for the synchrotron component??

a) Diffusion Model

This model is based on that described in Strong (1977) for the halo of the Galaxy. The electrons propagate according to the usual 3-D steady-state transport equation:

$$D\nabla^2 N + \frac{\partial}{\partial E}\left(N\frac{dE}{dt}\right) = q(E,\mathbf{r}) \qquad (1)$$

where

$N(E,\mathbf{r})$ = electron differential spectrum at $\mathbf{r}$
D = diffusion coefficient (assumed constant)
E = electron energy
$\mathbf{r}$ = electron spatial co-ordinate
$q(E,\mathbf{r})$ = electron source function, assumed to be zero outside the (infinitesimally thin) disc, and a function of the form $Q(R)\cdot AE^{-\gamma_0}$ in the disc, where R is galactocentric distance. $Q(R)$

The solution to (1) is well known (see e.g. Gratton, 1972) and is

$$N(E,\mathbf{r}) = \int \frac{q(E,\mathbf{r})}{4\pi D|\mathbf{r}-\mathbf{r}^1|}\,\phi(\gamma,s)\,d^3\mathbf{r}^1 \qquad (2)$$

where

$$\phi(\gamma,s) = \frac{e^{-s}s^{-\gamma+3/2}}{\sqrt{\pi}}\int_0^\infty e^{-x}x^{\gamma-2}\left(1+\frac{x}{s}\right)^{3/2-\gamma}dx \qquad (3)$$

and

$$s(E,\mathbf{r}) = \frac{bE\mathbf{r}^2}{4D}. \qquad (4)$$

b) Convection Model

The electrons are assumed to move in the z-direction at constant speed v, and to lose energy as in (a), so that at height z the spectrum becomes

$$N(E,z) = AE^{-\gamma}\left(1-\frac{z}{v}bE\right)^{\gamma-2}. \qquad (11)$$

8. Conclusion

Both simple diffusion and convection models for propagation of electrons away from the disc of NGC 891 can be consistent with the observed variation of spectral index and intensity perpendicular to the disc of the galaxy, with the convection model requiring rather high velocities.

In both cases, the fall off in $H_\perp$ out to $z=4$ kpc is less than a factor of two, and field in the halo region seems to be almost constant. Such an extended magnetic field may have important consequences for theories of the galactic fields.

Nearby galaxies detected in gamma rays by Fermi-LAT

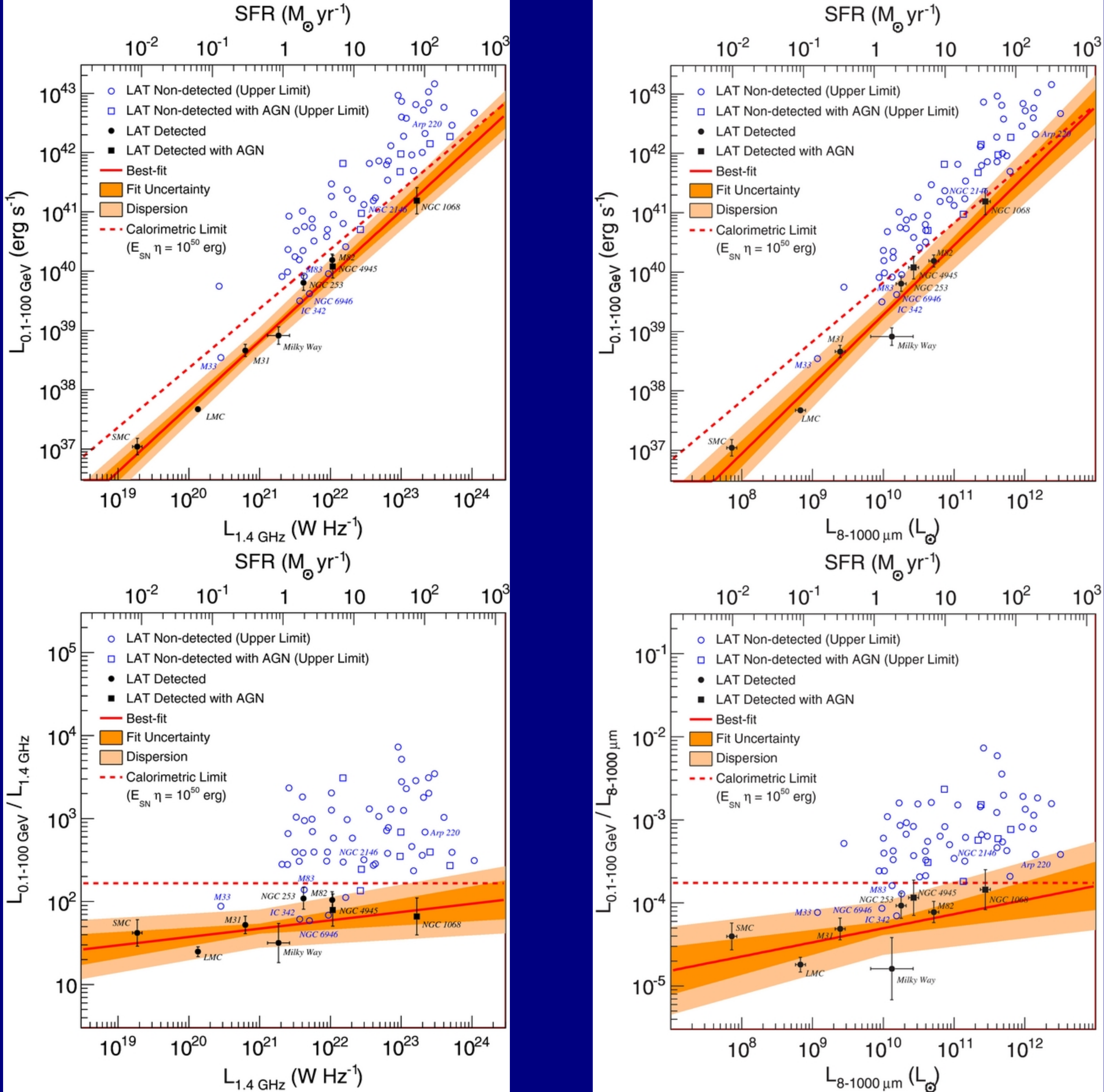
Large Magellanic Cloud
Small Magellanic Cloud
M31 Andromeda: normal Galaxy
NGC253 starburst
M82 starburst
NGC1068 starburst / Sy2
NGC4945 starburst / Sy2

Gamma rays proportional to SFR, radio.

CHANGES galaxies too weak in gamma rays even for Fermi (worth checking: exercise for this week).

Fermi collab.

ApJ 755,164 (2012)



Some questions for CHANGES galaxies from cosmic-ray viewpoint :

1. Do they support the naïve expectations of standard electron propagation?
   = injection in disk, propagation with energy losses in halo by diffusion
   and/or convection.
   The test: spectral index variations with distance from disk.

2. If YES - we can get the propagation parameters and compare with Milky Way,
   where we have much more detailed information but are inside it.

3. If NO - what revisions are required, is the 'standard model' any use at all?
   Are things just too complicated in reality?
   Back to the drawing board?

4. If SOMETIMES – where and why does it break down?

5. Is there a cosmic-ray disk and a halo, or just a halo as assumed in many models?

6. Lepton calorimeters? - FIR-radio correlation.

7. How much does thermal emission confuse things?

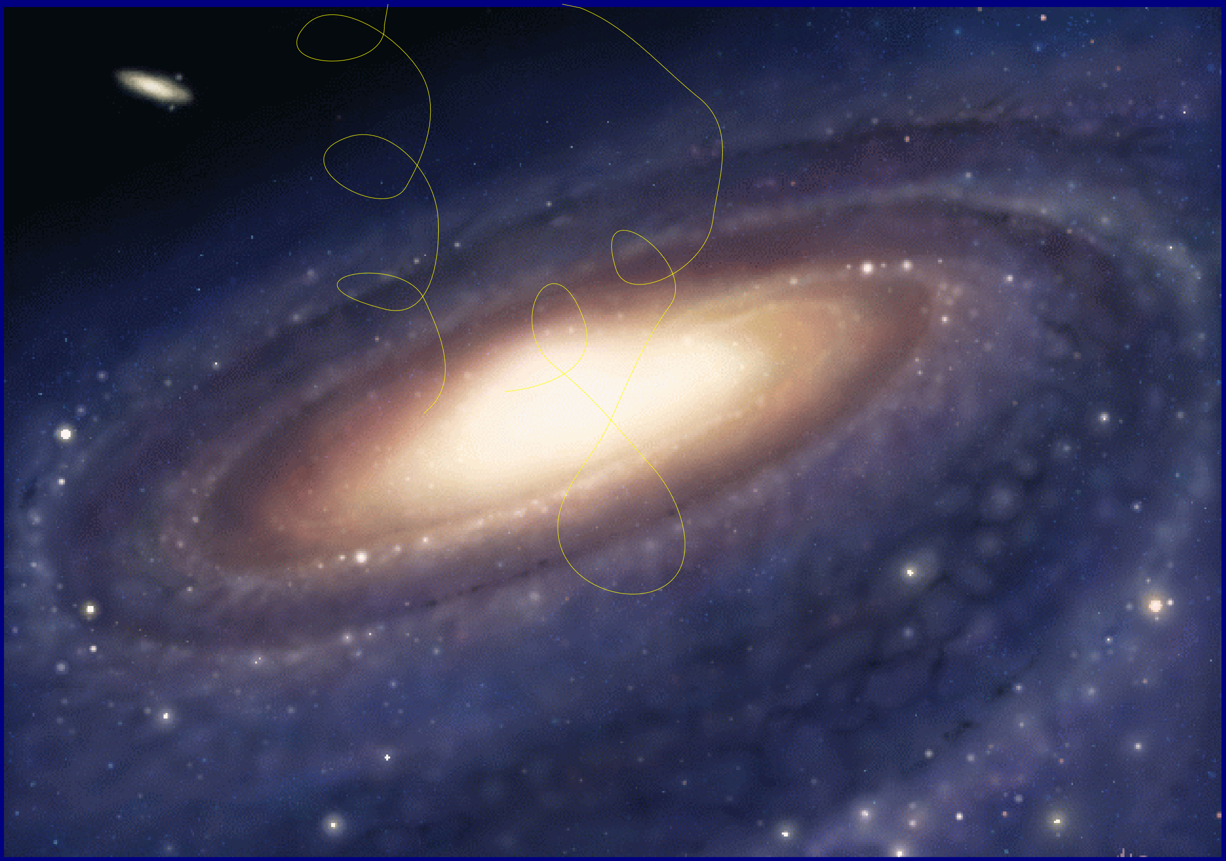
Topics

Synchrotron in high-energy context

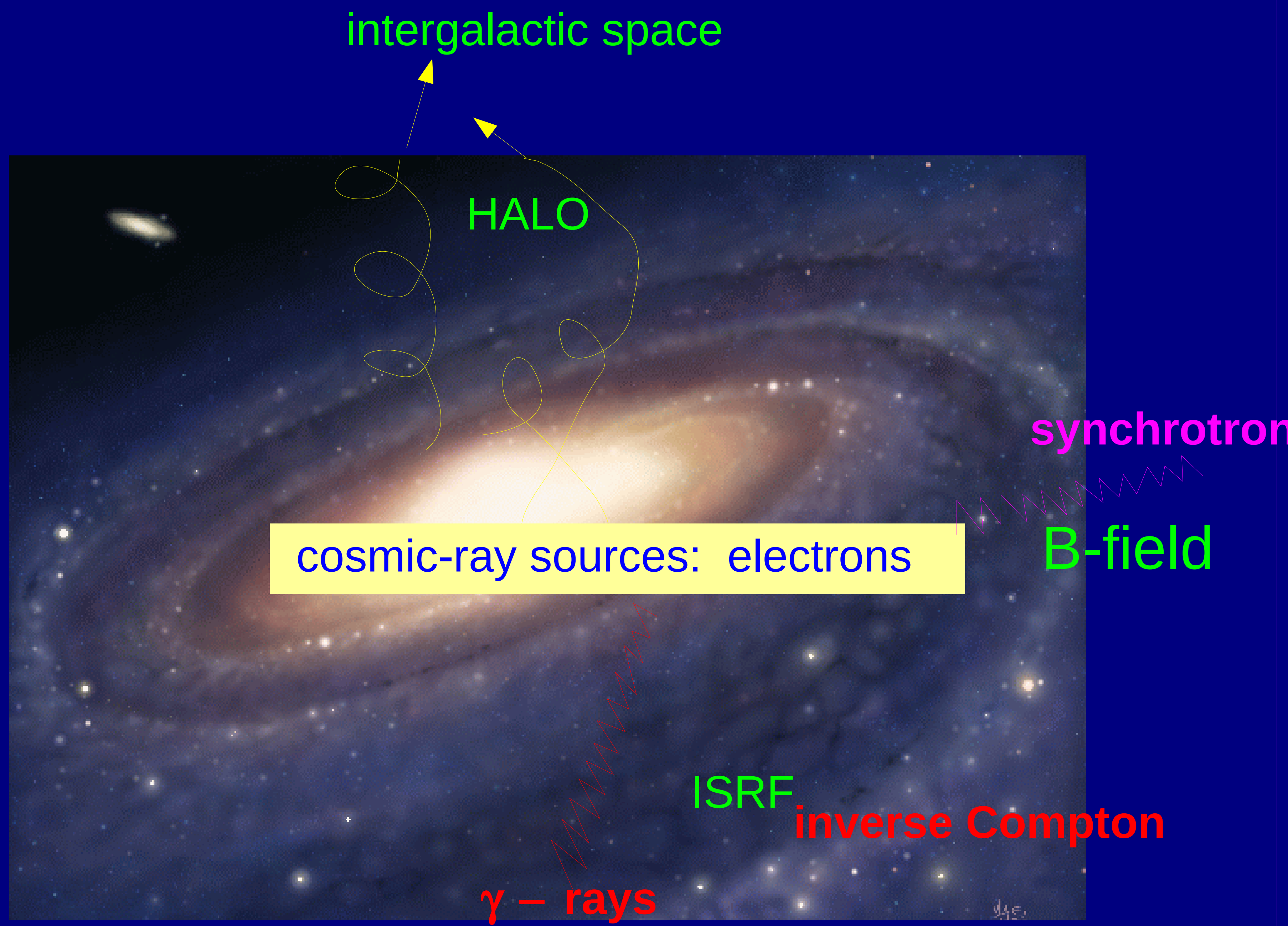
Spectral aspects

Polarization, magnetic fields

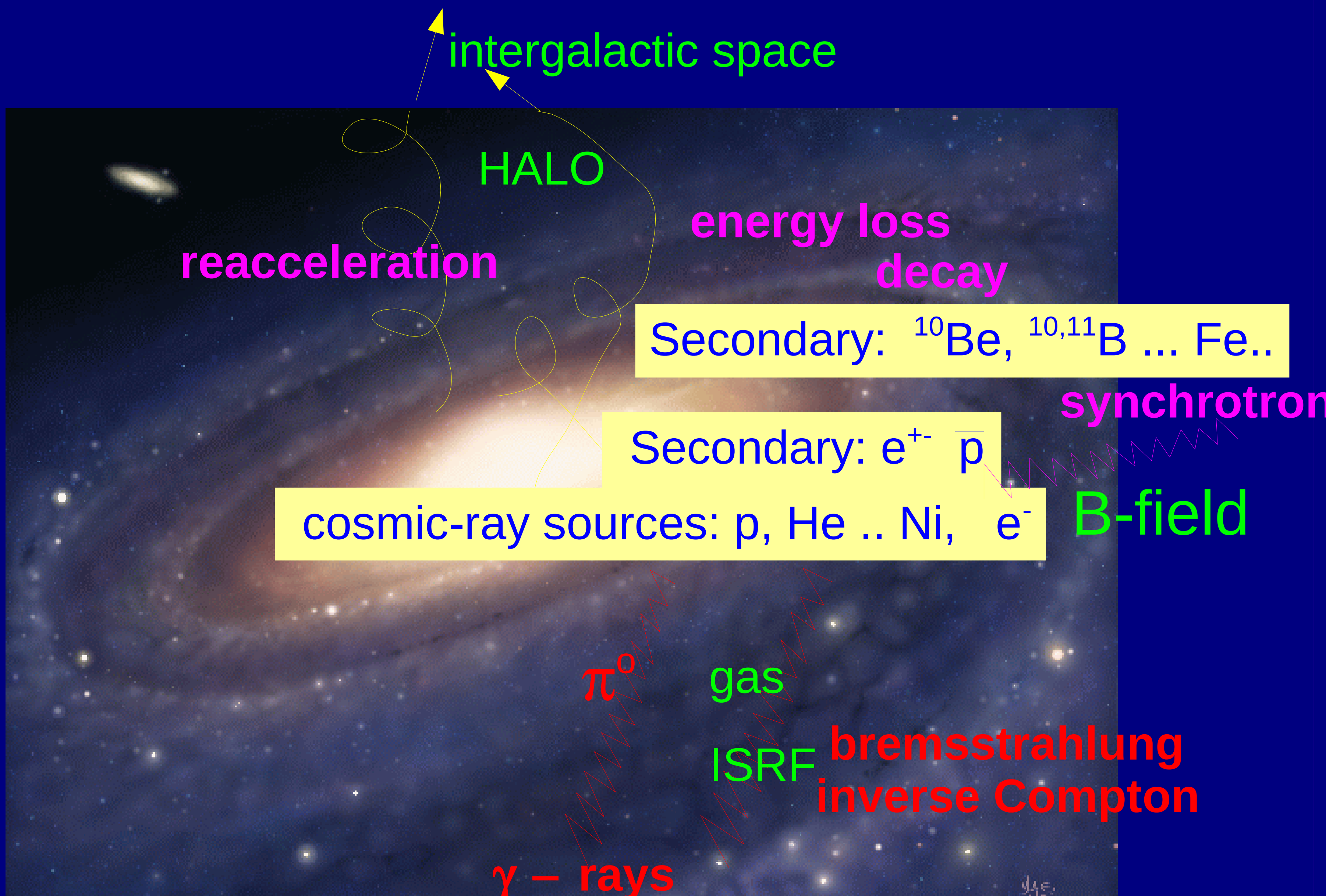
Gamma rays



High energy particles and radiation in the Galaxy

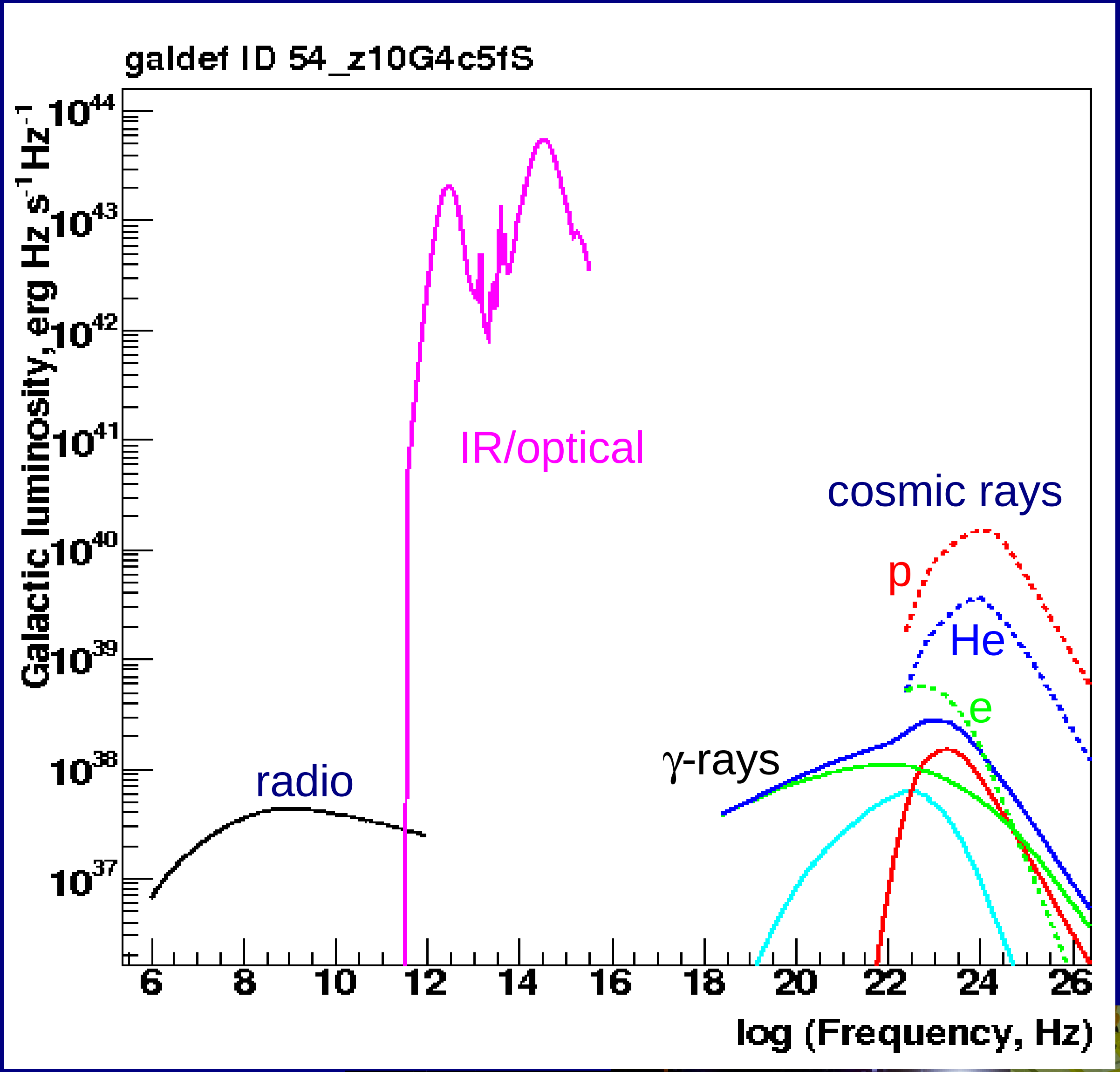

intergalactic space
HALO
synchrotron
cosmic-ray sources: electrons
B-field
ISRF
inverse Compton
γ – rays

COSMIC RAYS produce many observables

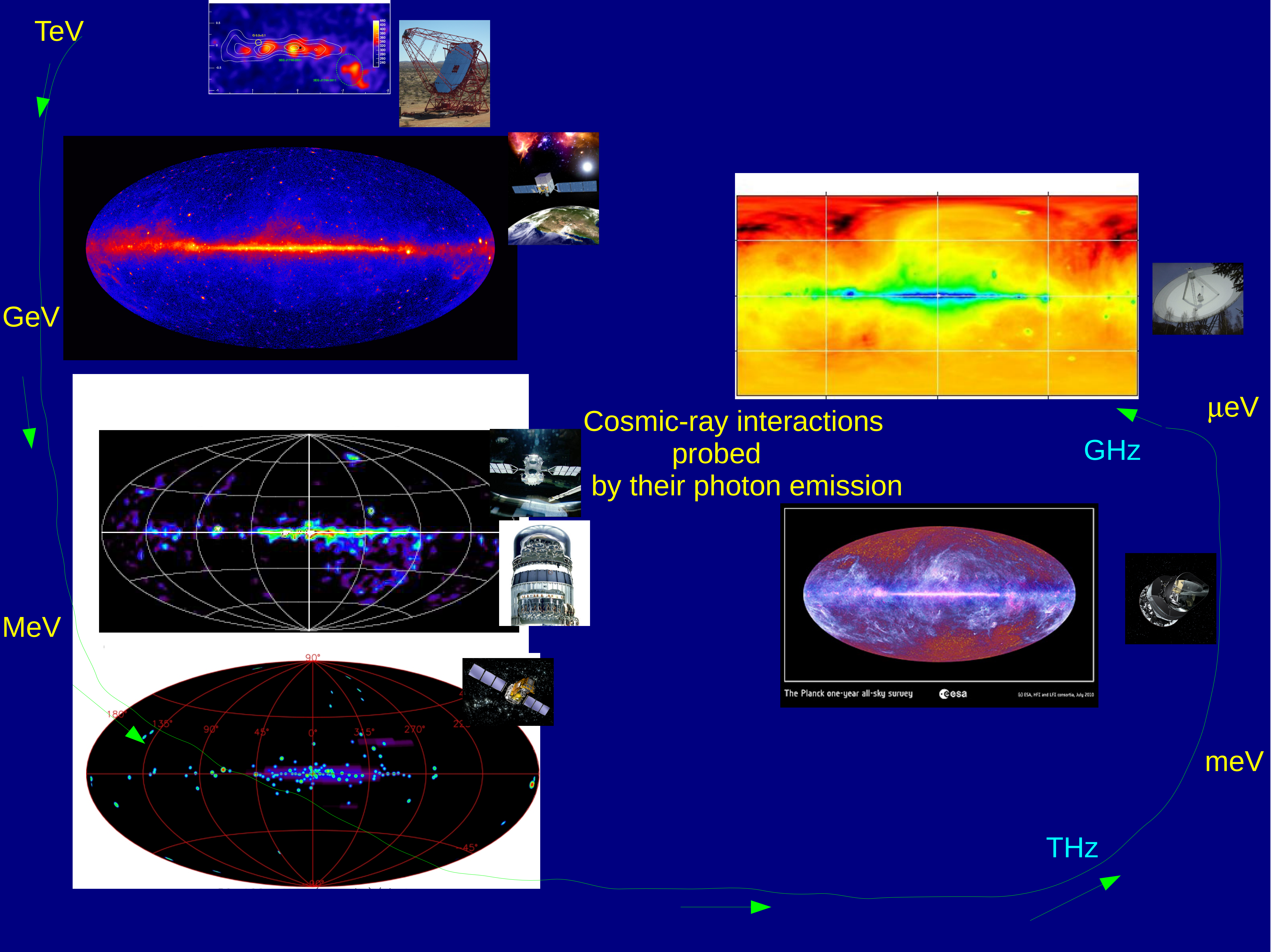


GALPROP model

Galaxy luminosity over 20 decades of energy



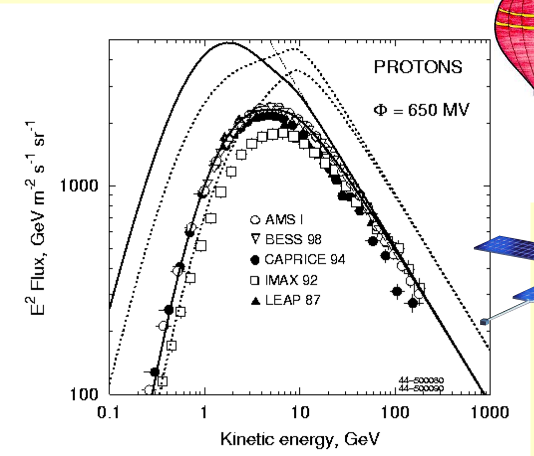
Strong et al. (2010), ApJL 722, L58

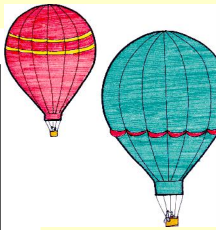

TeV
GeV
MeV
Cosmic-ray interactions
probed
by their photon emission
μeV
GHz
meV
THz
The Planck one-year all-sky survey
esa
90°
180°
135°
90°
45°
0°
315°
270°
-45°

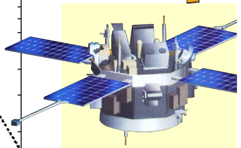
The **goal** : use *all* types of data in self-consistent way to test models of cosmic-ray propagation.

Observed *directly, near Sun:*

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

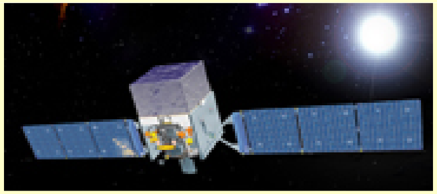


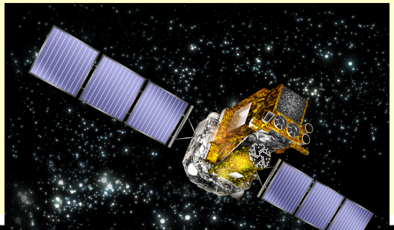


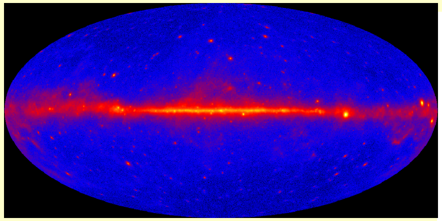


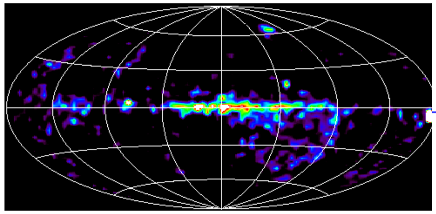
Observed *from whole Galaxy:*

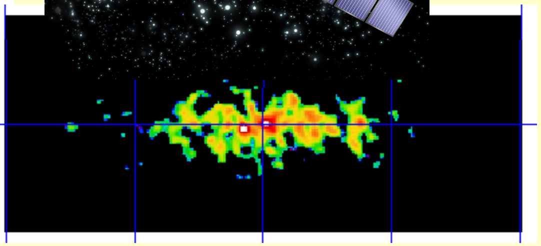
γ - rays



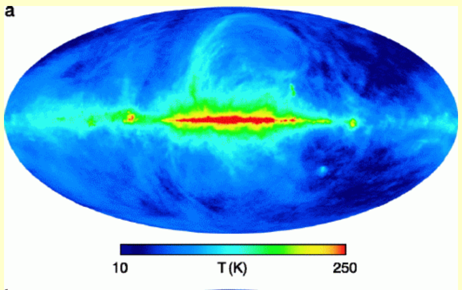








synchrotron



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)

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

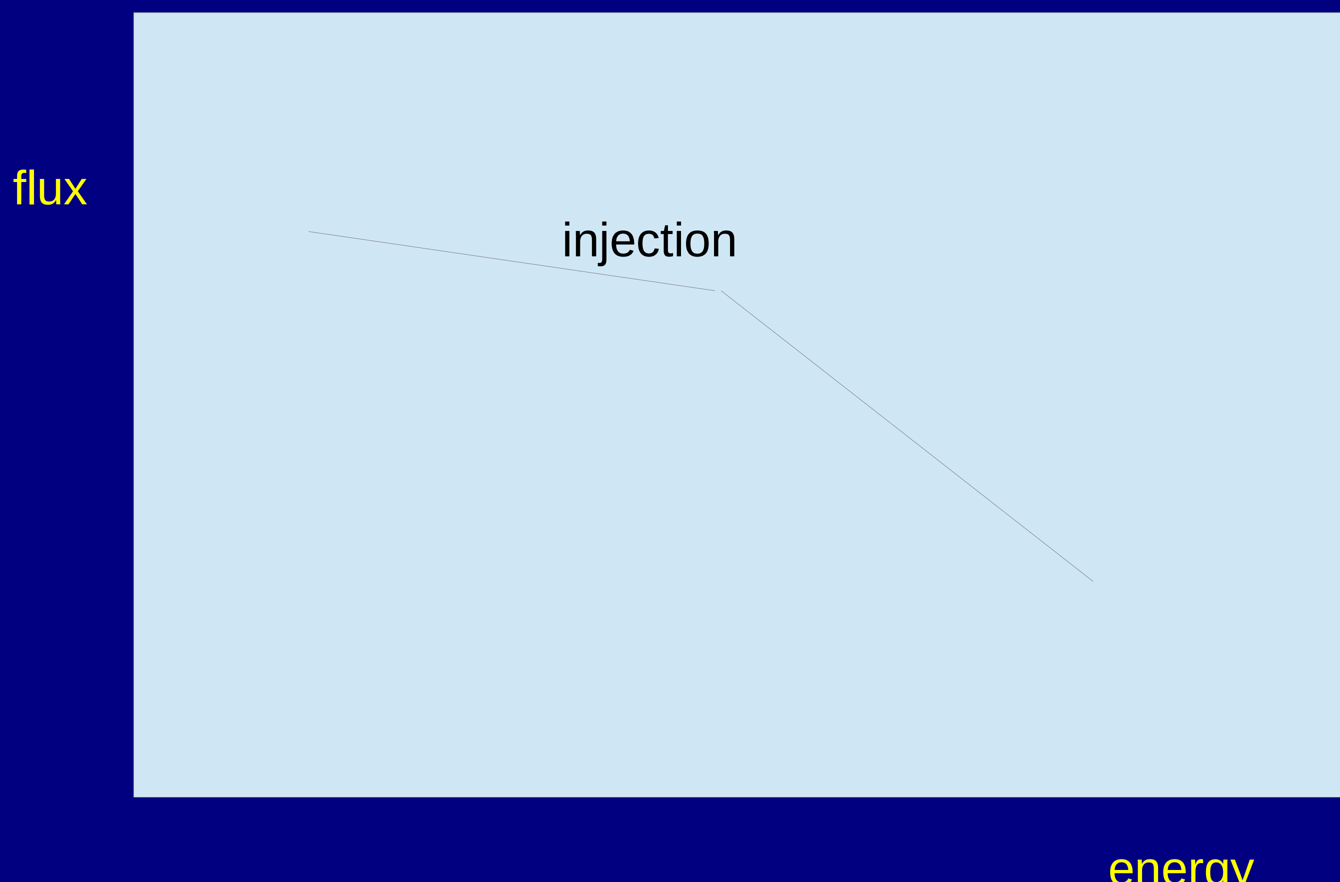
momentum loss
ionization, bremsstrahlung

adiabatic momentum loss

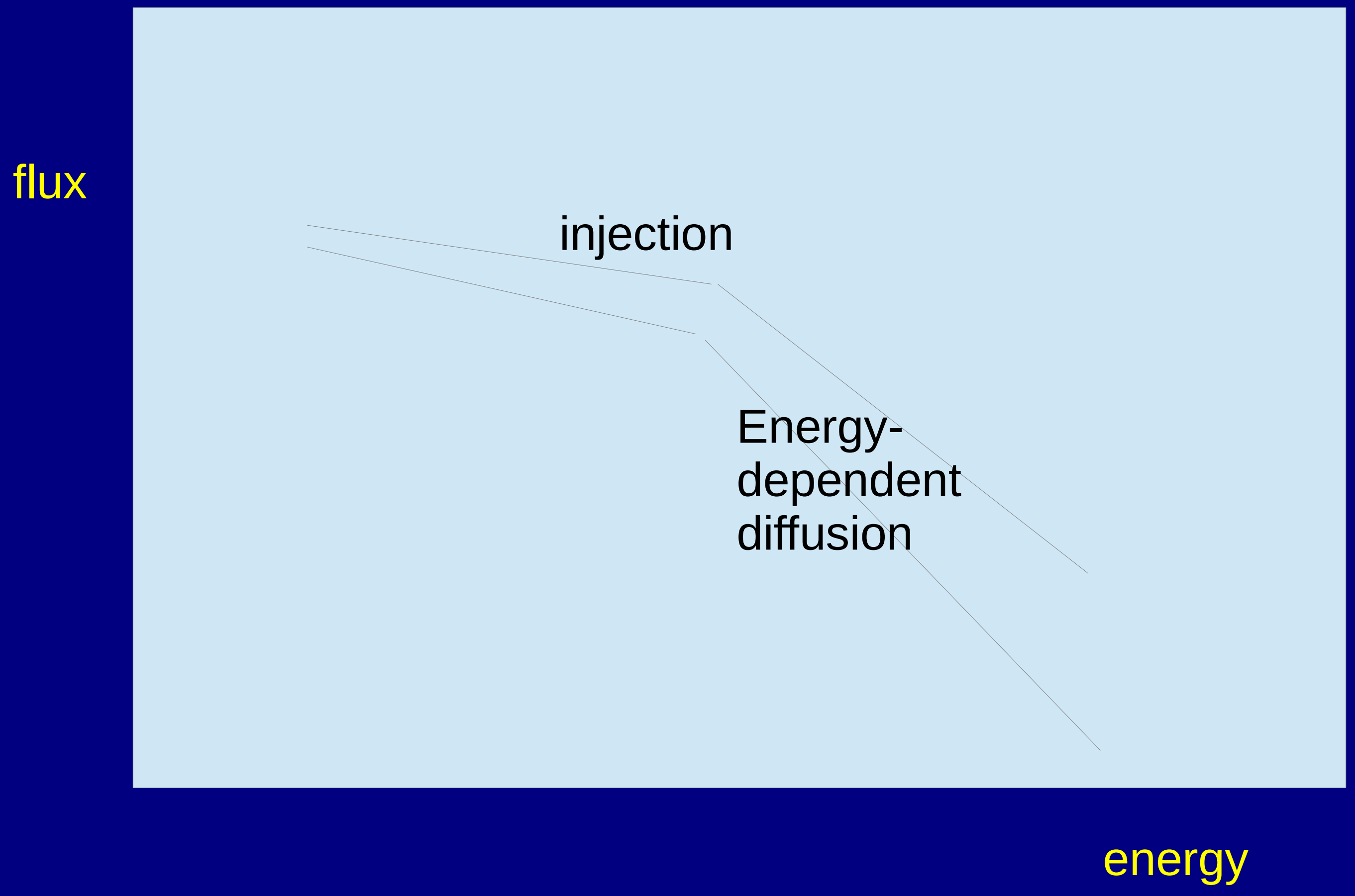
$$- \psi/\tau_f$$ nuclear fragmentation

$$- \psi/\tau_r$$ radioactive decay

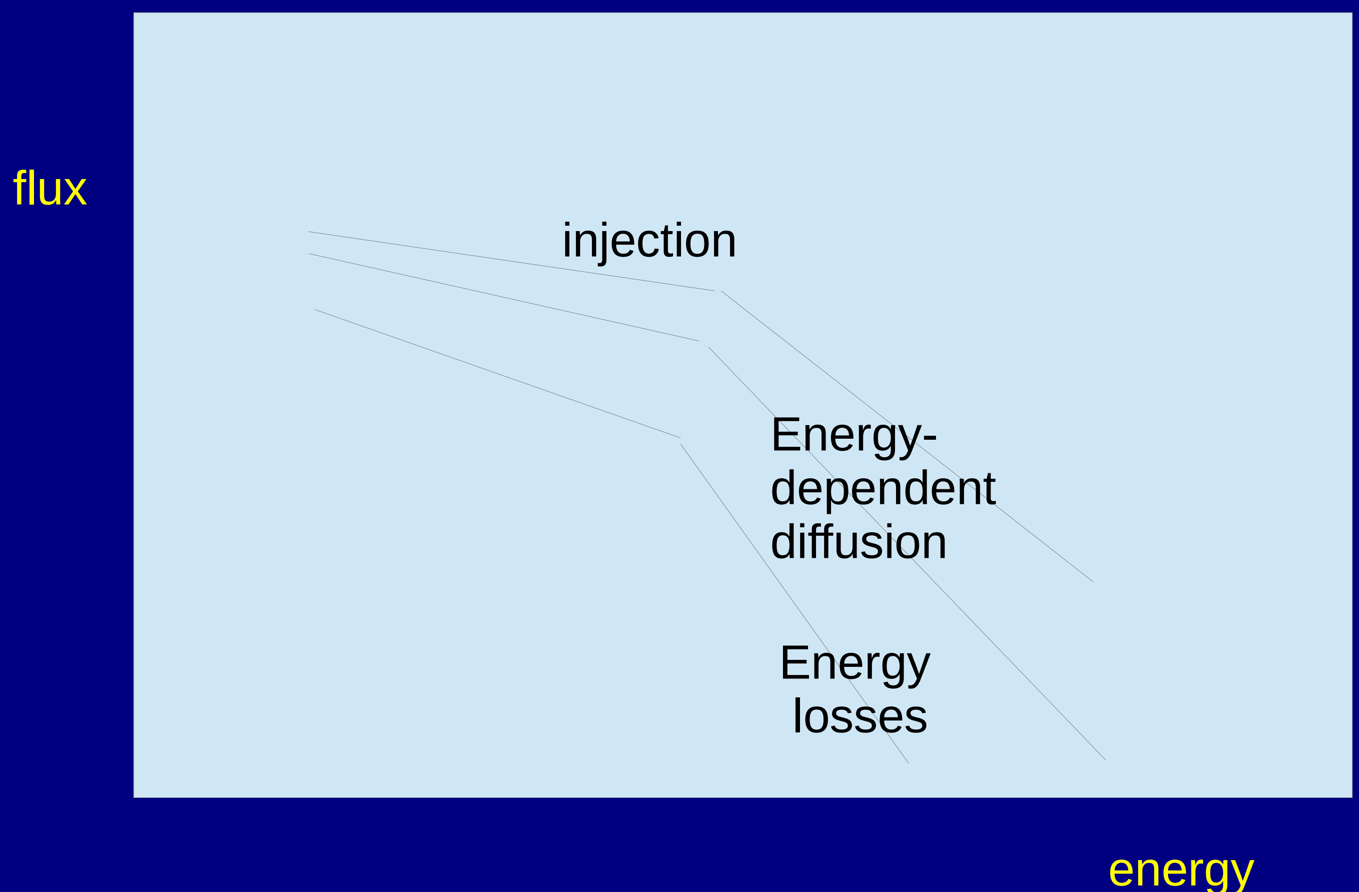
Producing the cosmic-ray electron spectrum



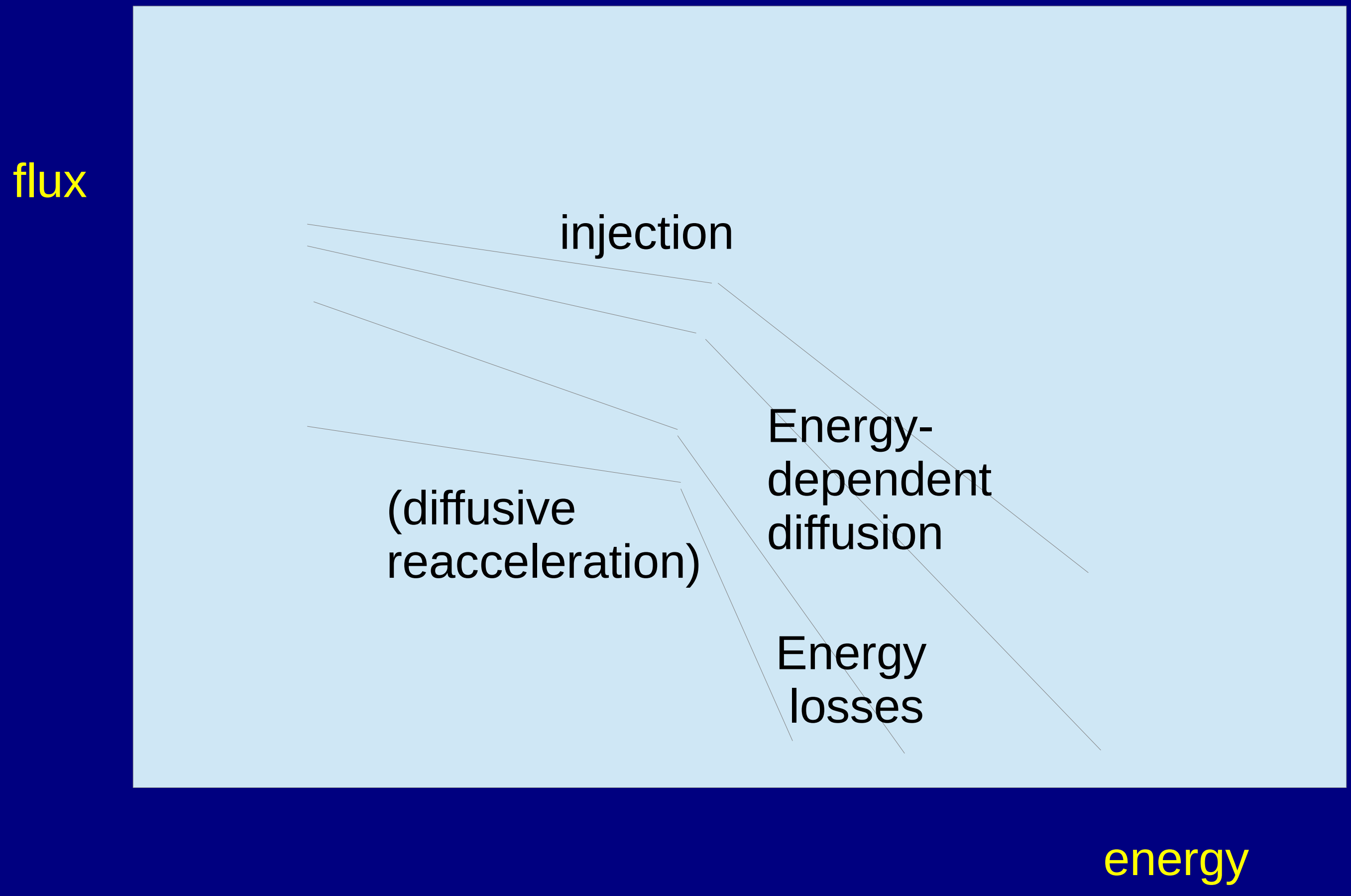
Producing the cosmic-ray electron spectrum



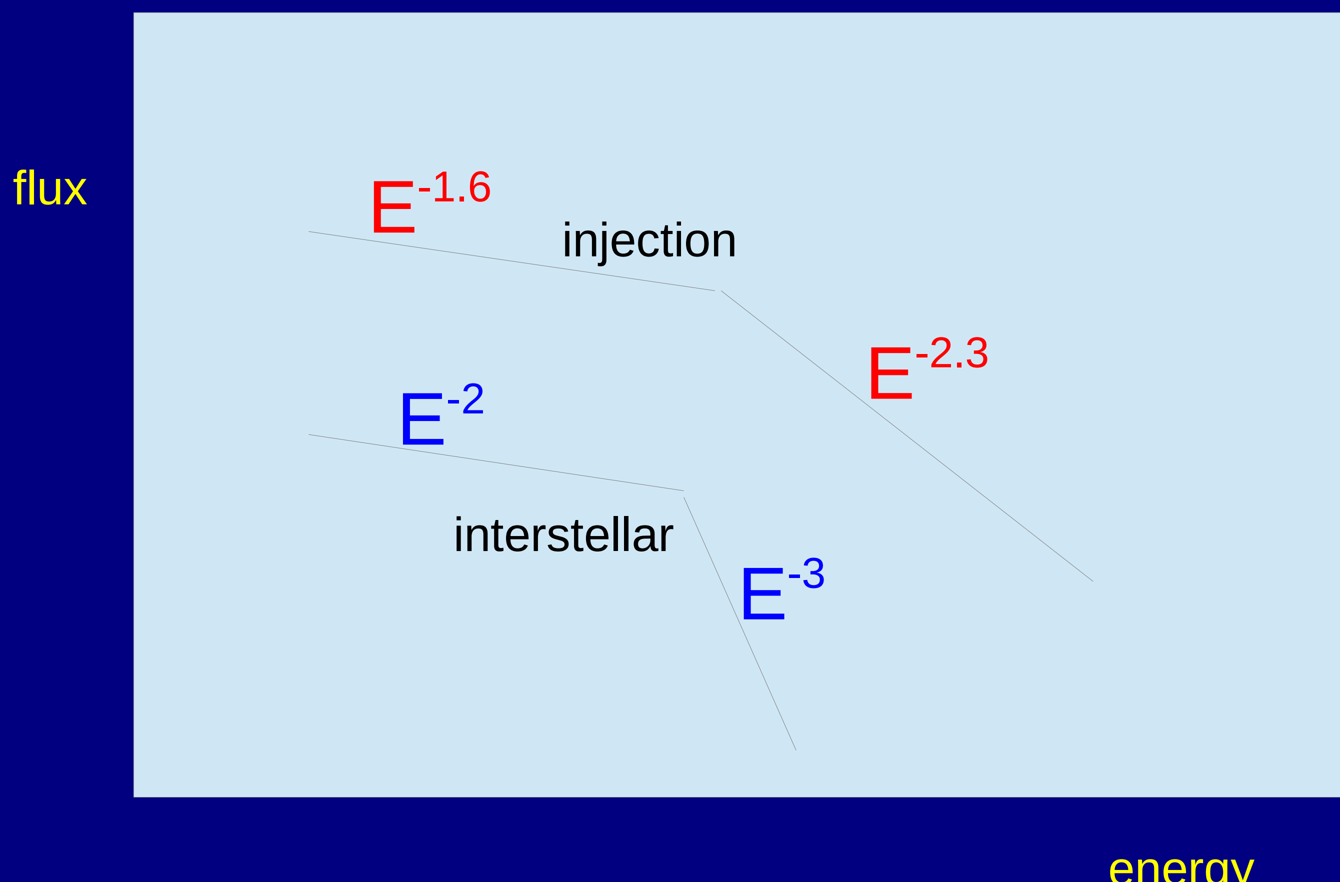
Producing the cosmic-ray electron spectrum



Producing the cosmic-ray electron spectrum

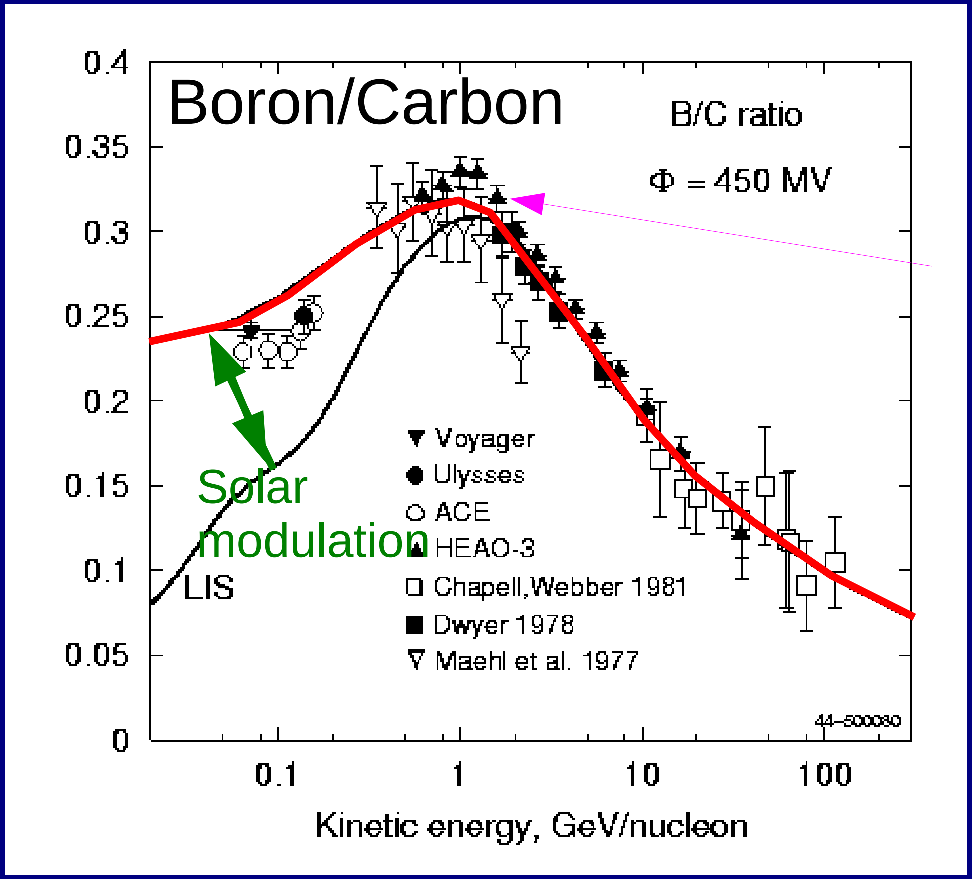


Producing the cosmic-ray electron spectrum



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

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

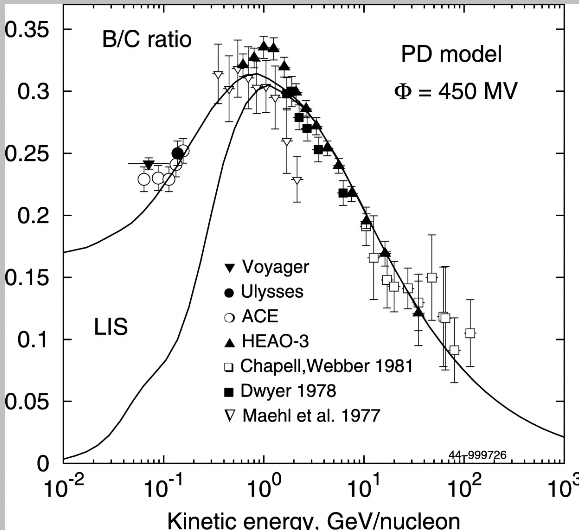
Momentum space diffusion

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

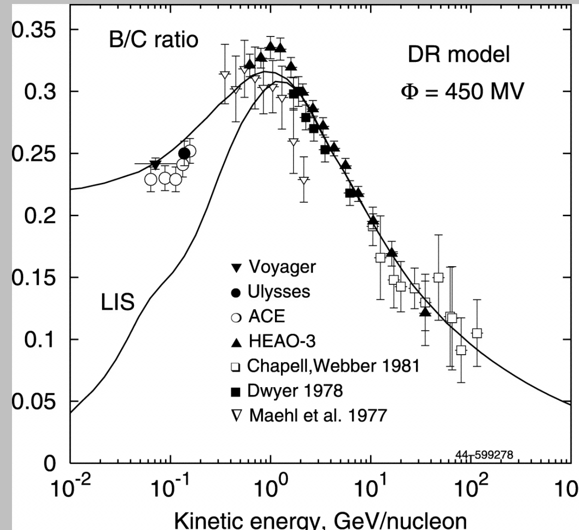
However reacceleration not proven, maybe does not happen

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

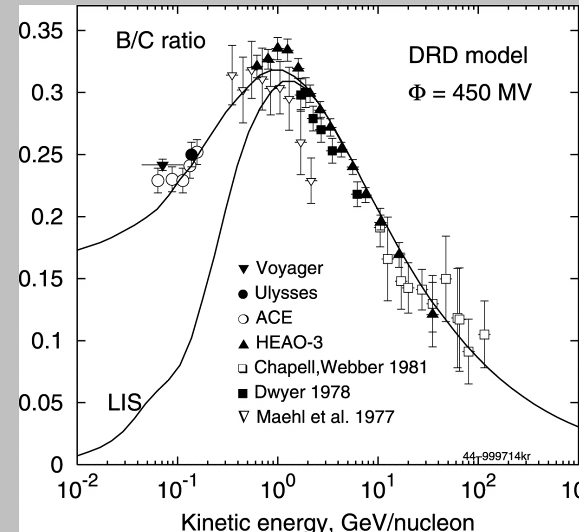
plain diffusion



diffusive reacceleration



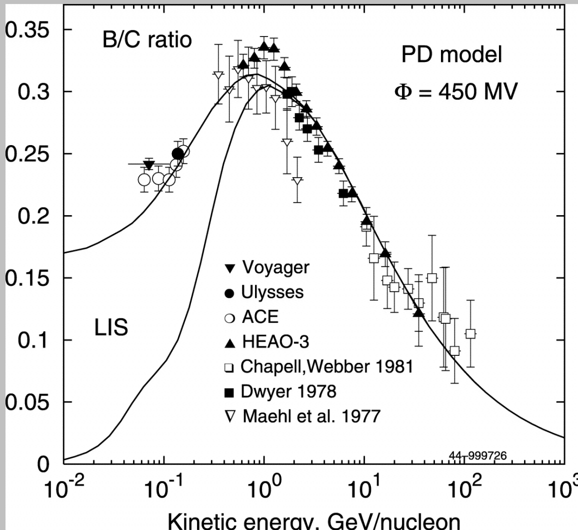
wave damping

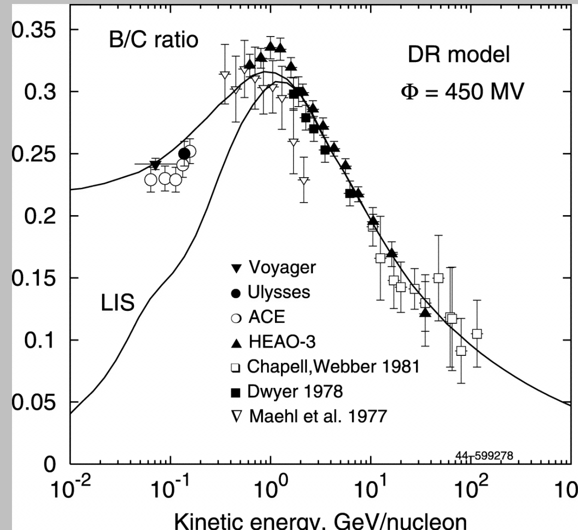


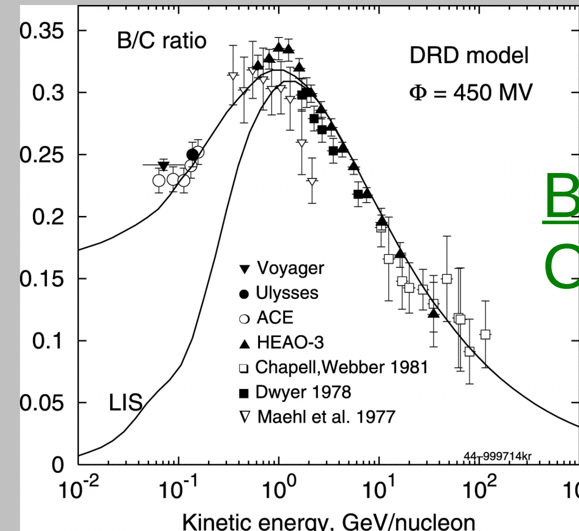
For any model, first adjust parameters to fit Boron/Carbon

Ptuskin et al. 2006 ApJ 642, 902

plain diffusion — diffusive reacceleration — wave damping



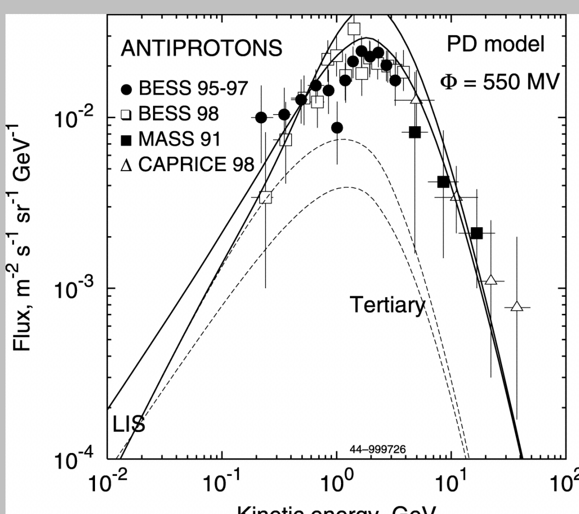


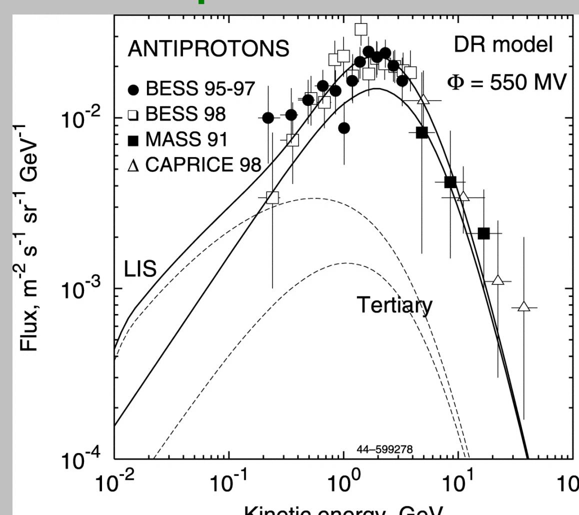


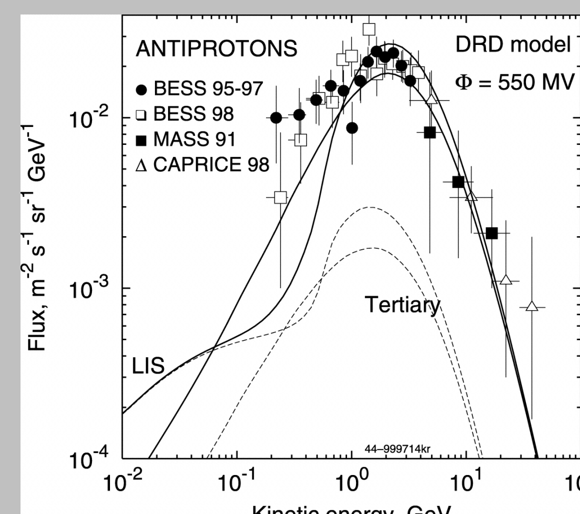
Boron/ Carbon

then predict the other cosmic-ray spectra

antiprotons

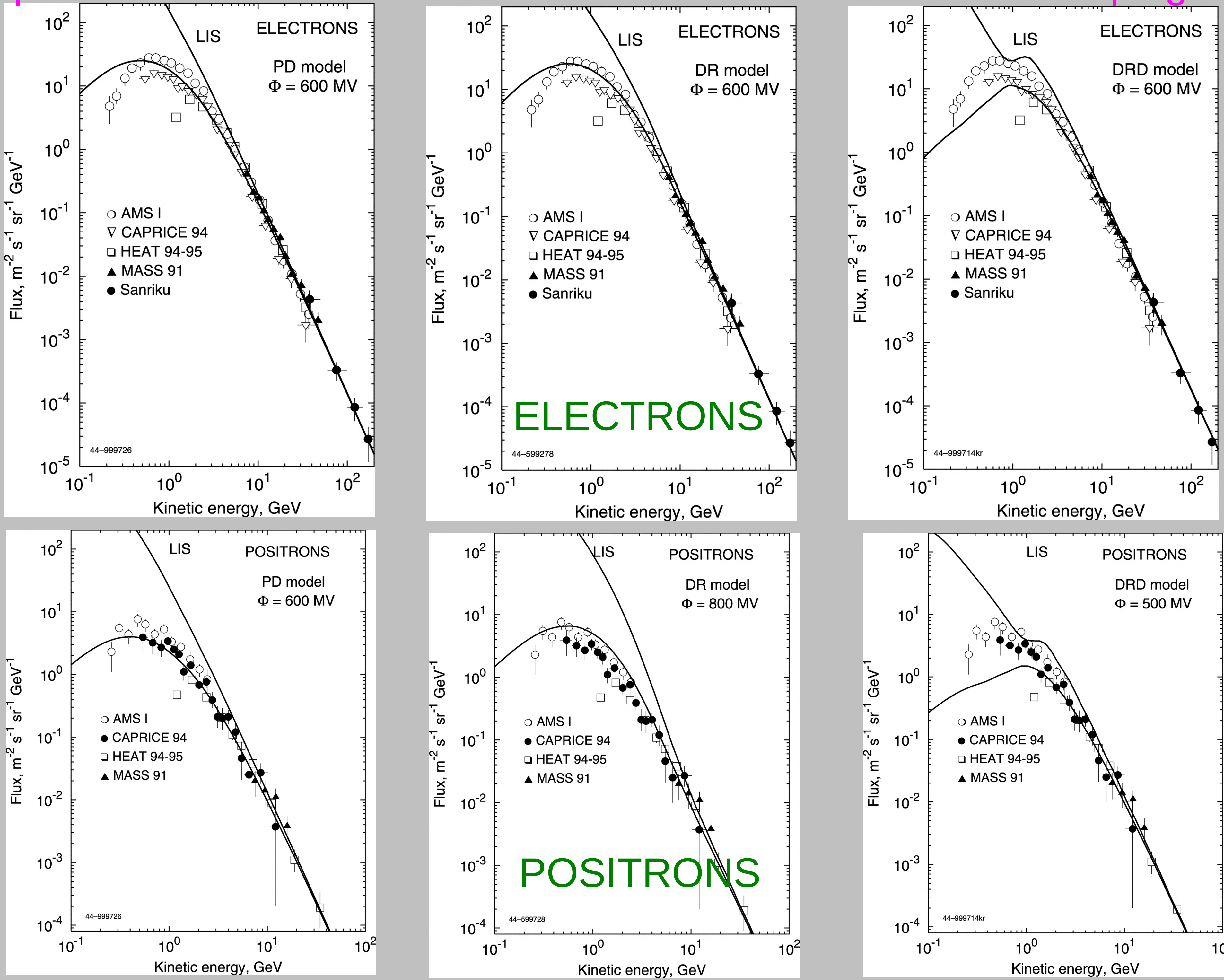






Ptuskin et al. 2006 ApJ 642, 902

plain diffusion | diffusive reacceleration | wave damping



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

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MNRAS 416, 1152 (2011)

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

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DOI: 10.1051/0004-6361/201116828

Astronomy & Astrophysics

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

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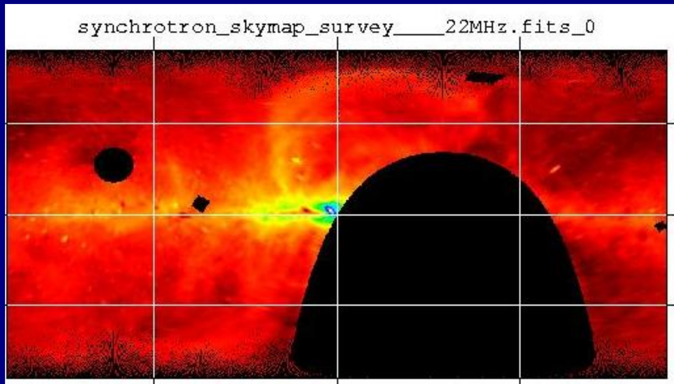
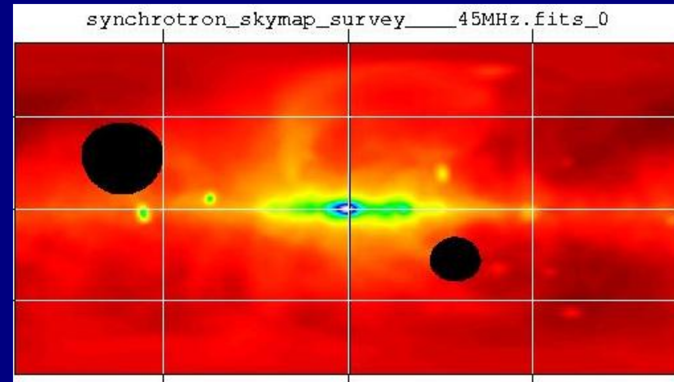
ABSTRACT

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.

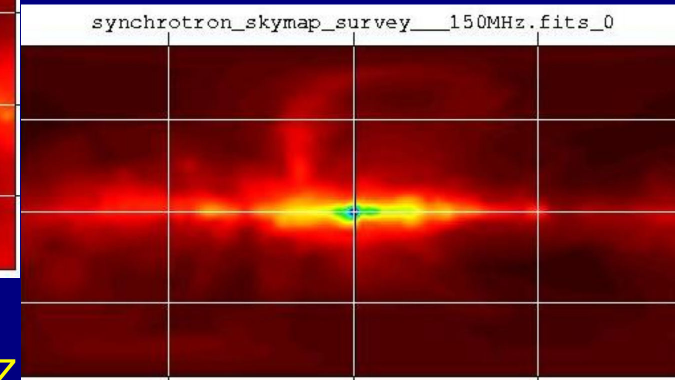
Following results based on this paper.



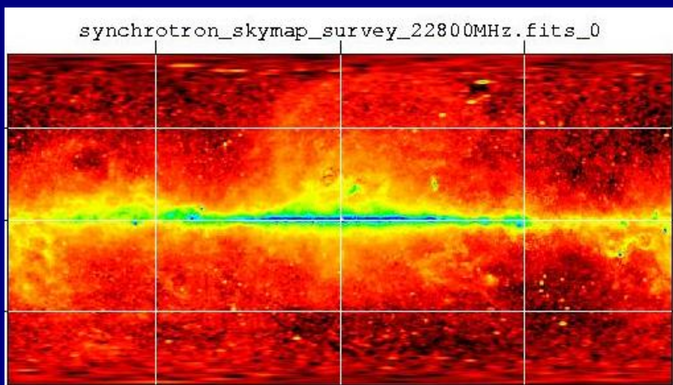
22 MHz



45 MHz



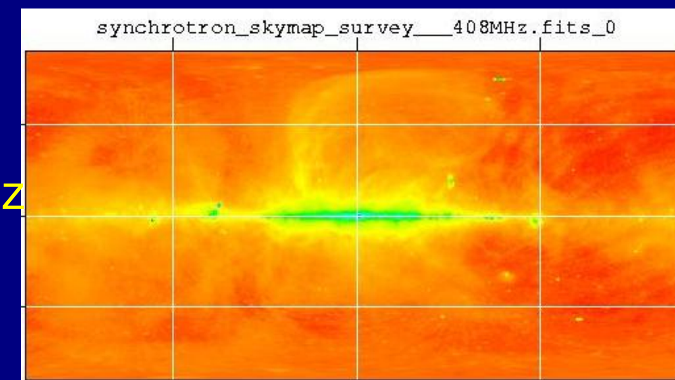
150 MHz

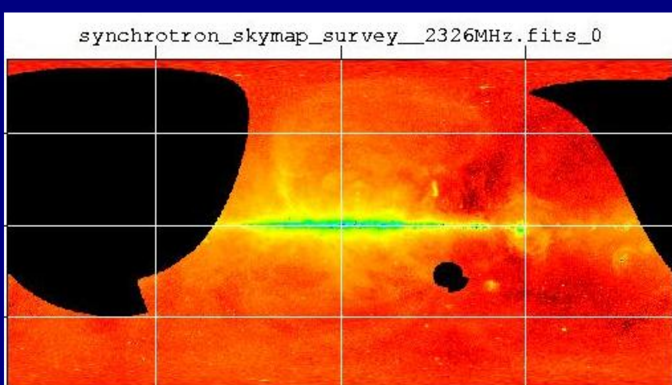


23 GHz

Continuum sky surveys

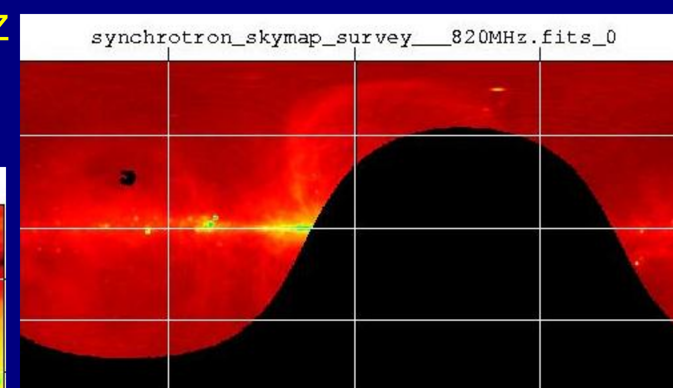
408 MHz



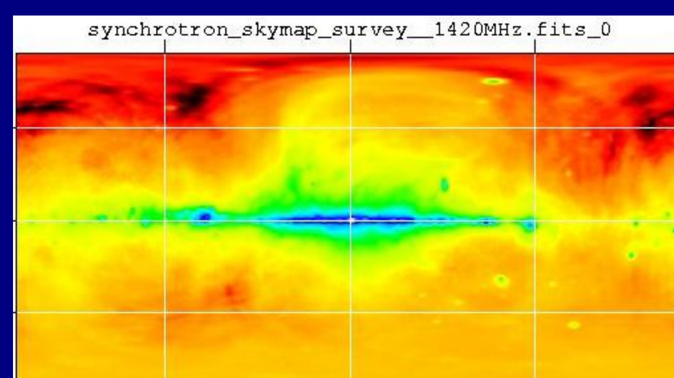


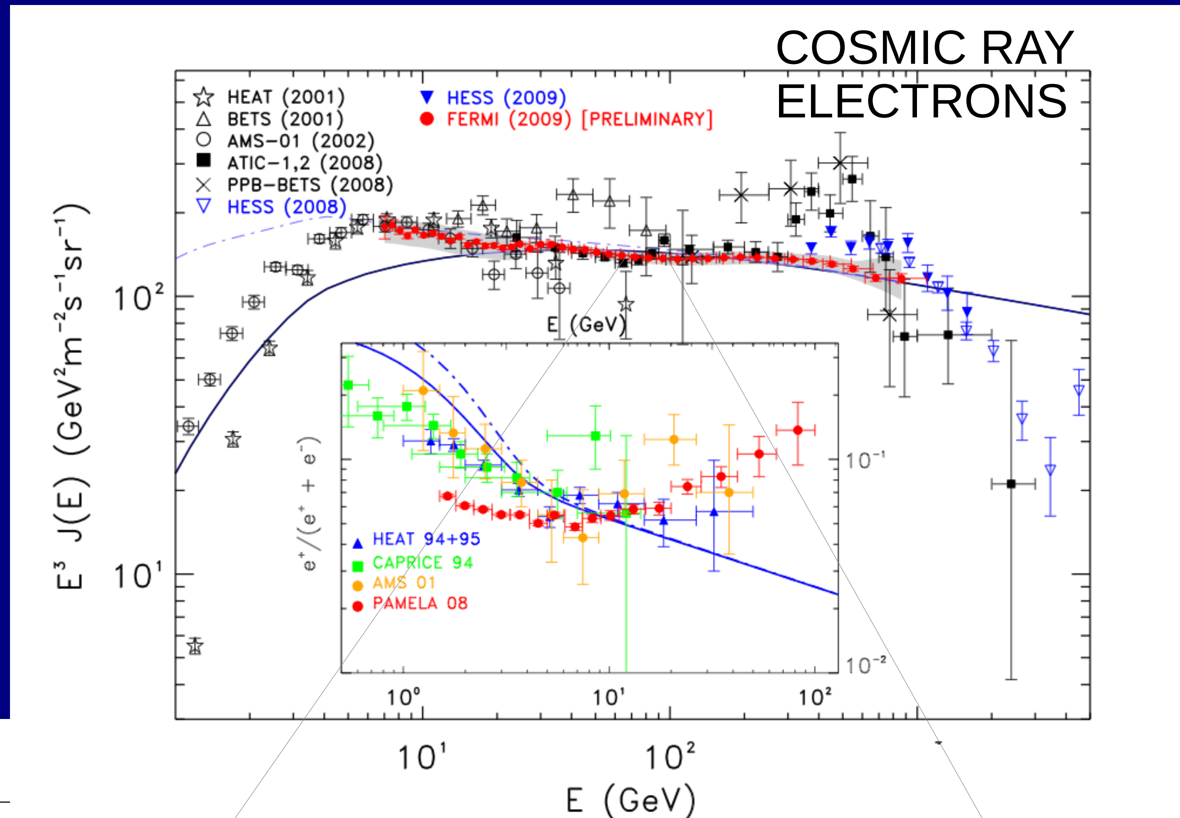
2.3 GHz

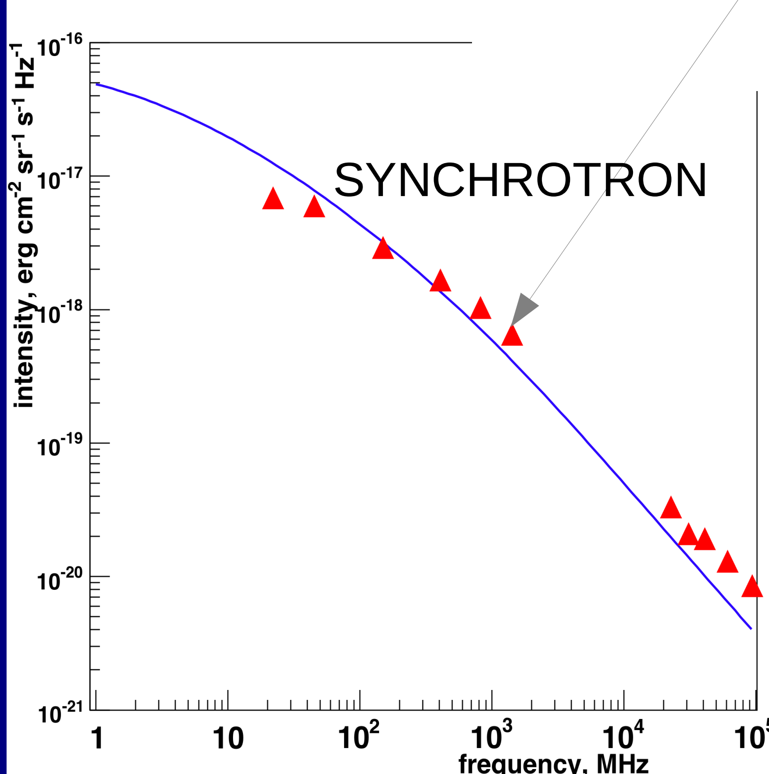
820 MHz



1.4 GHz

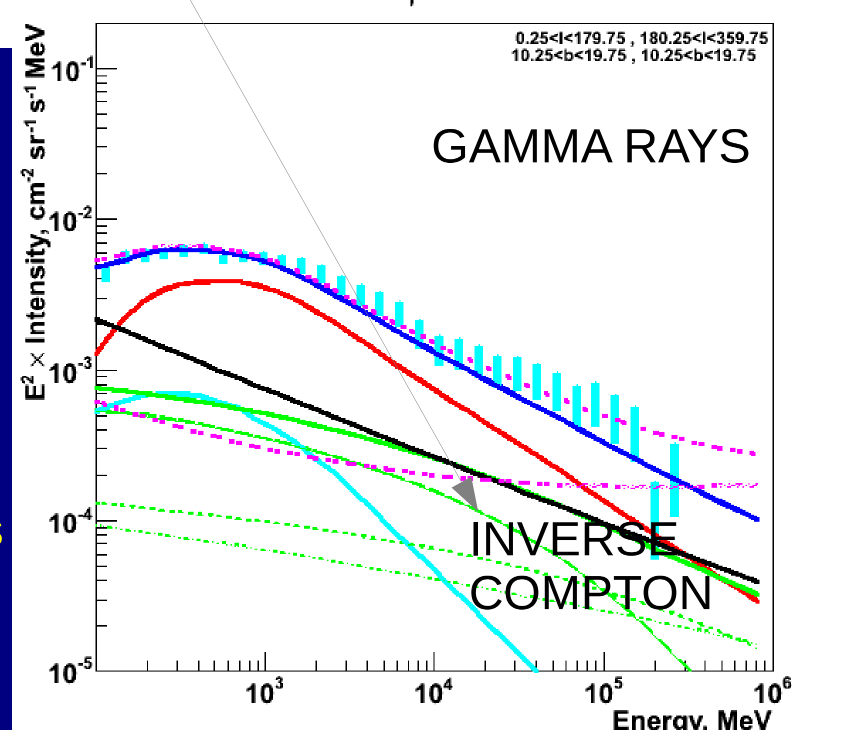


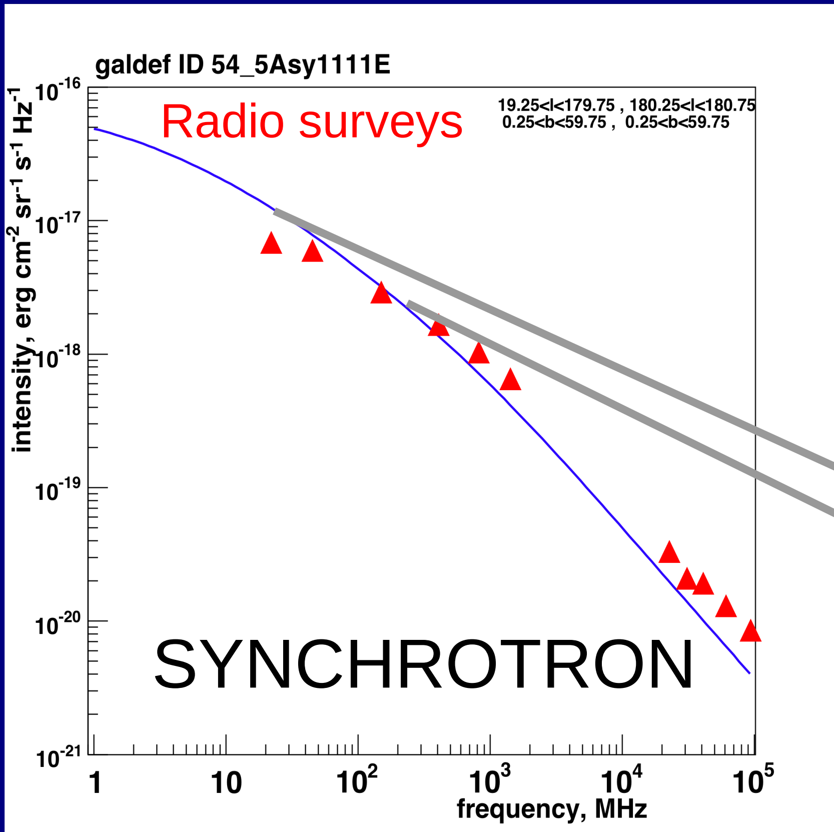


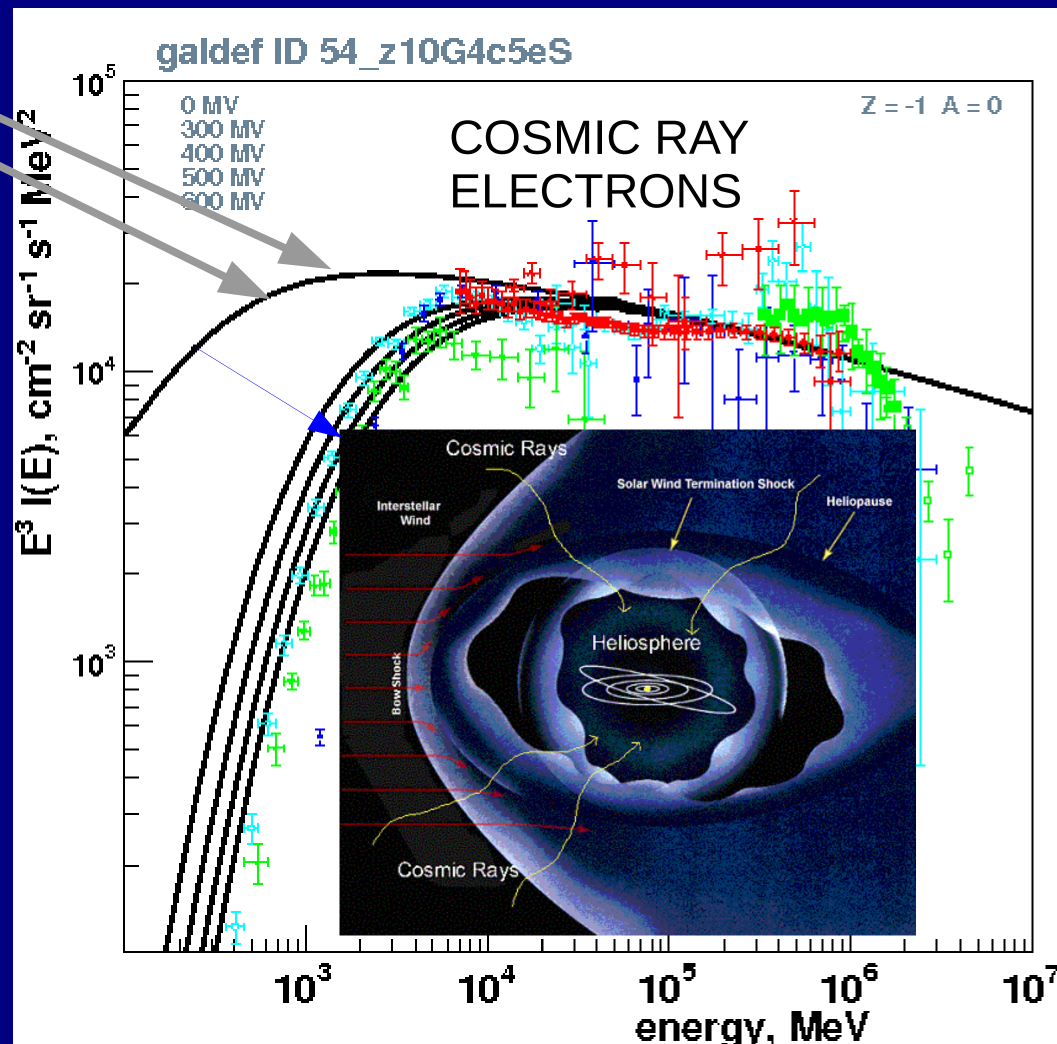


SAME
ELECTRONS
for
RADIO
and
GAMMA RAYS !

good constraints
on models

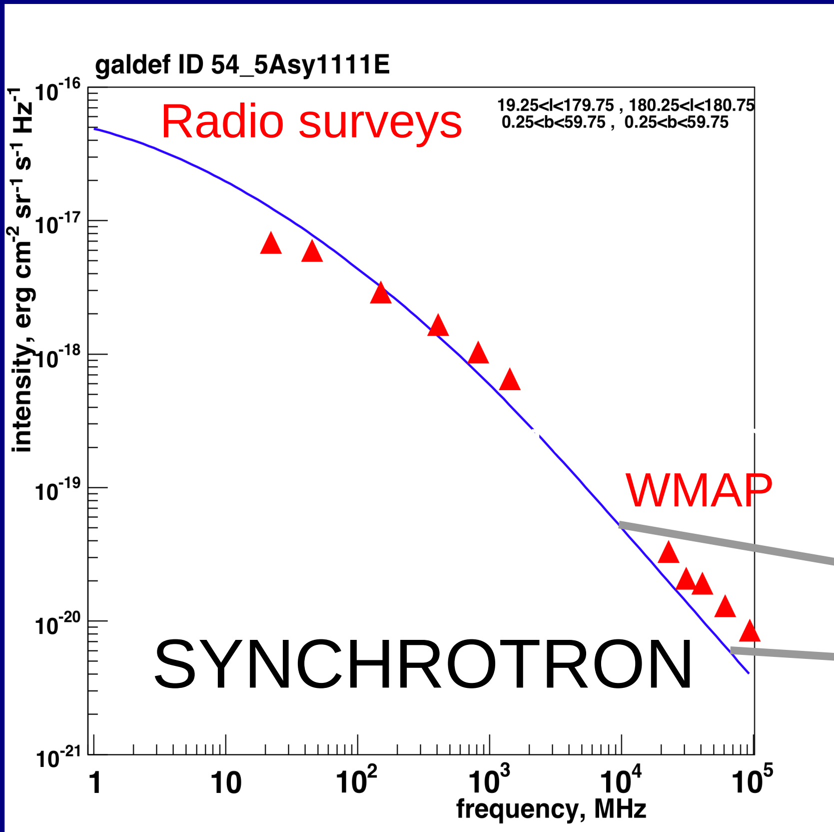


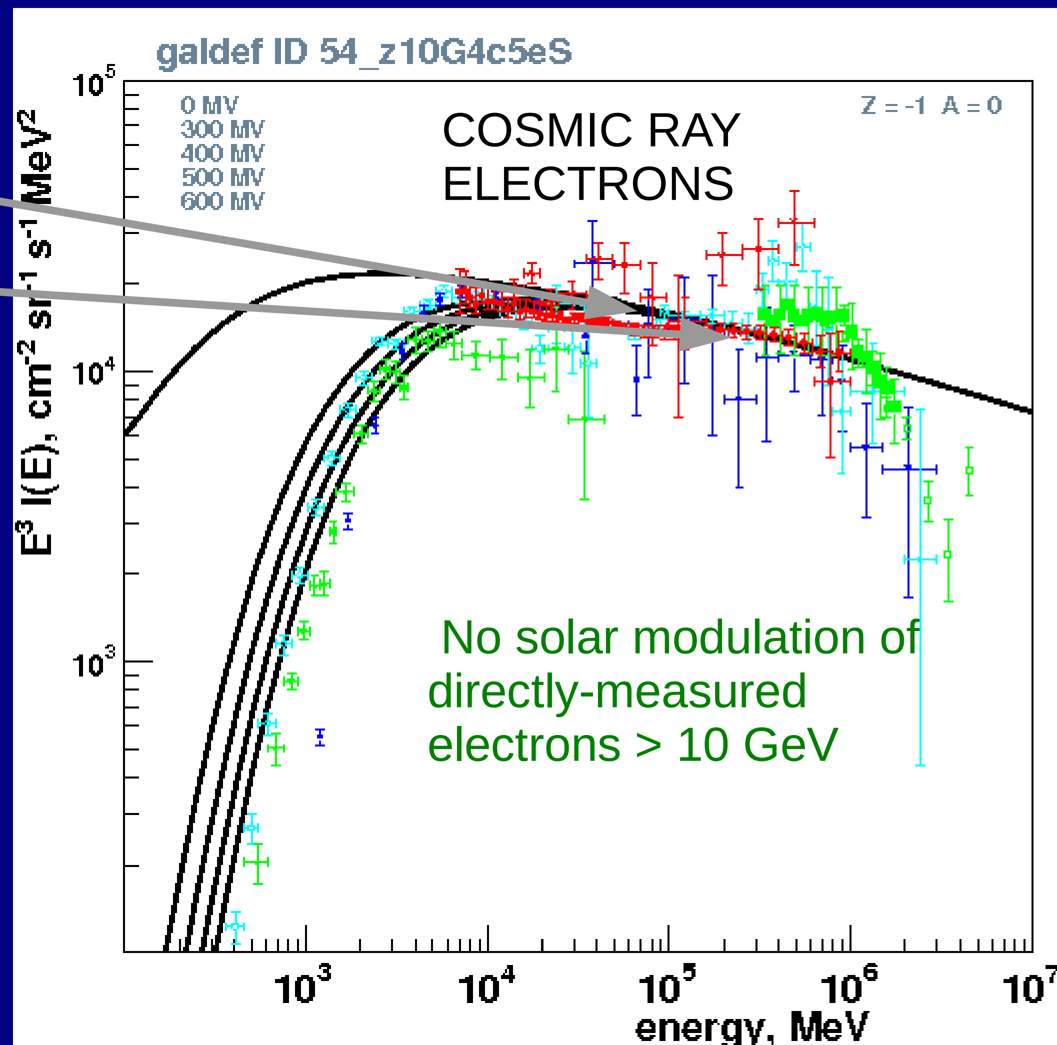




Radio provides essential probe of interstellar electron spectrum at
E < few GeV
to complement direct measurements and determine solar modulation

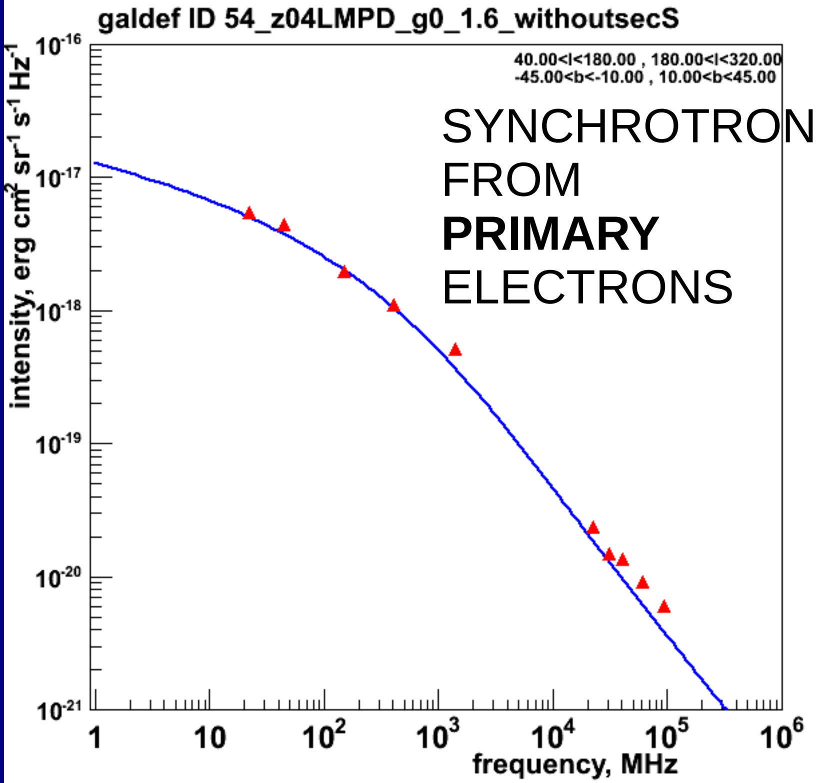
Electrons have huge uncertainty due to modulation here

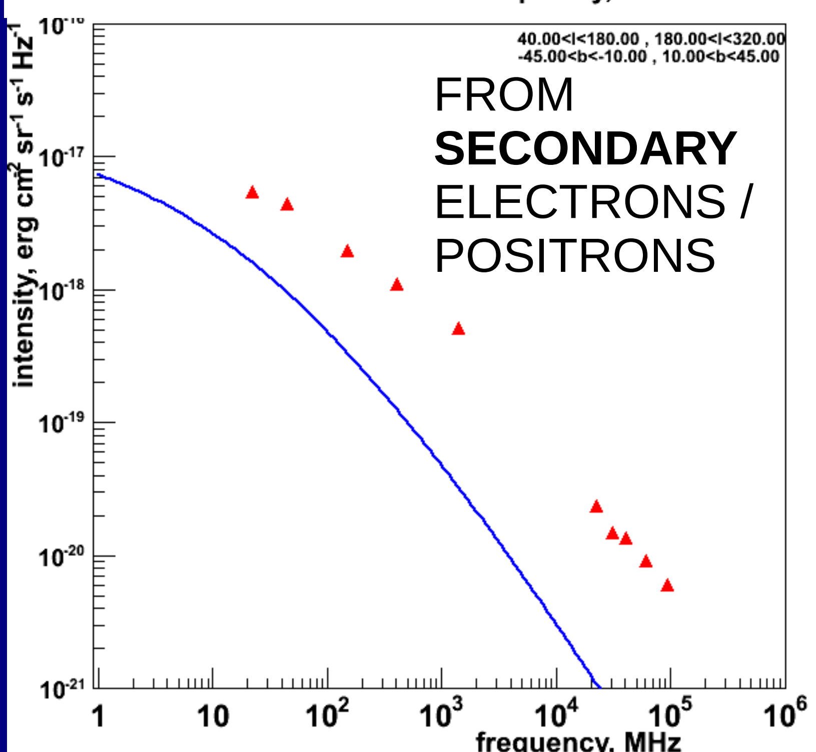


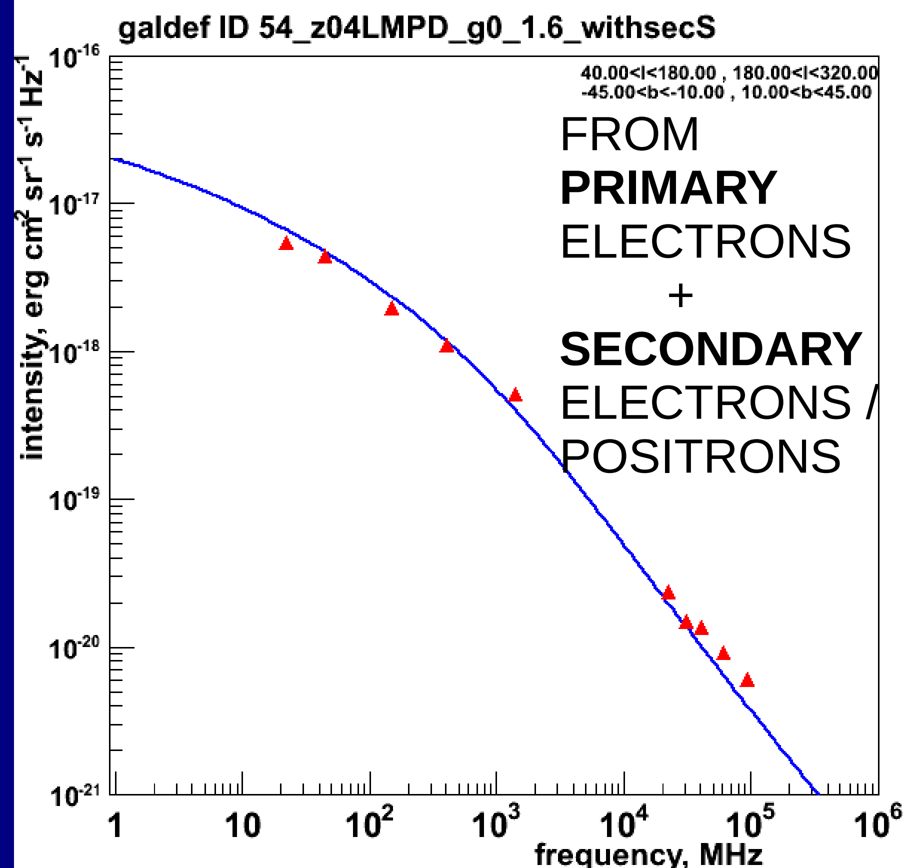


microwaves probe
interstellar electron spectrum
10 - 100 GeV

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







Cosmic-ray electrons

Synchrotron

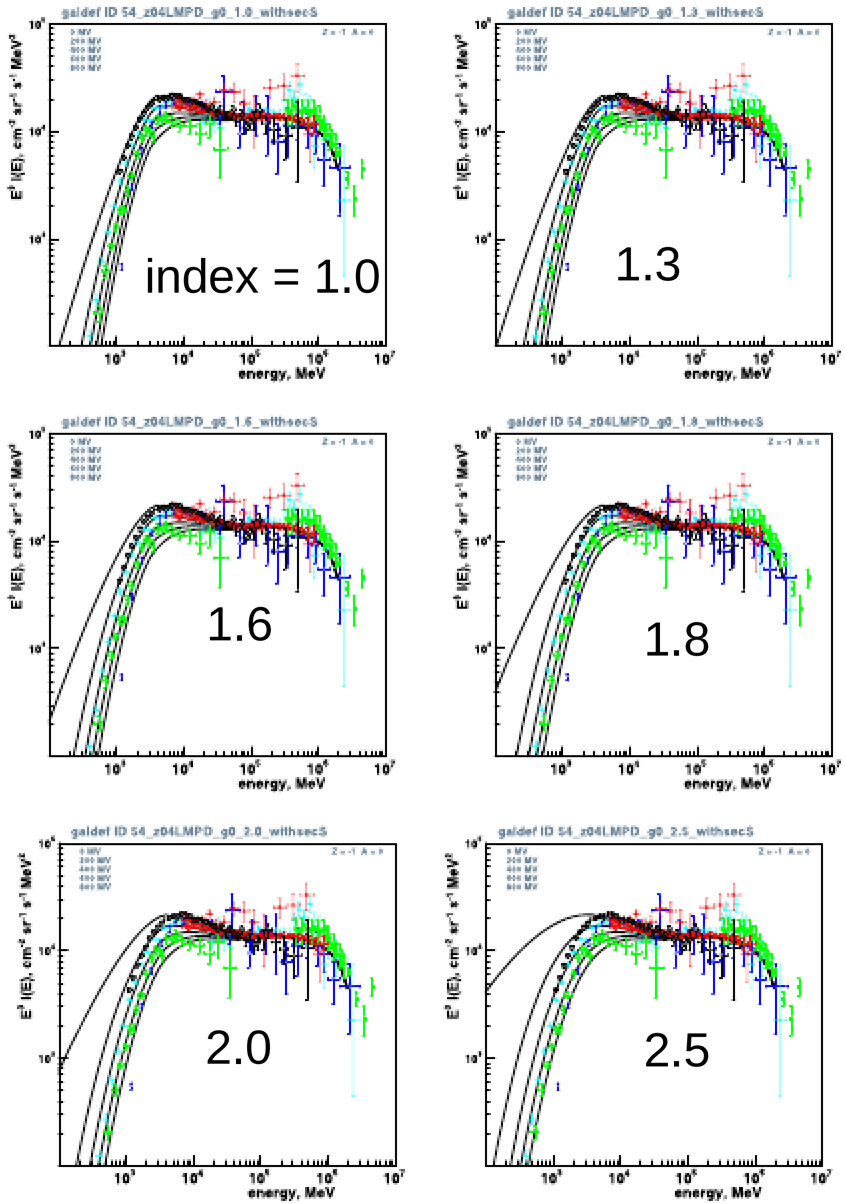


Fig. 4. Electron spectra for pure diffusion model, low-energy electron injection index 1.0, 1.3, 1.6, 1.8, 2.0, 2.5. Modulation Φ = 0, 200, 400, 600, 800 MV. Data as in Fig. 1.

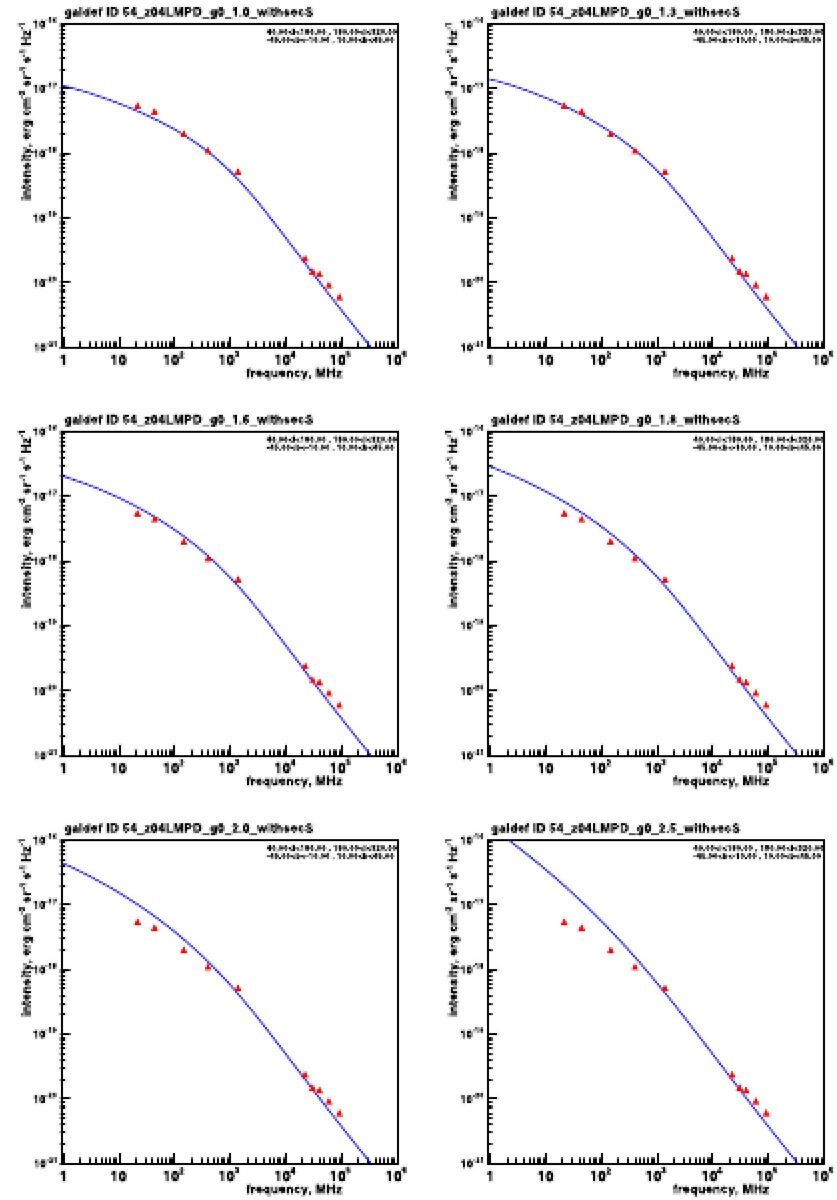


Fig. 5. Synchrotron spectra for pure diffusion model with low-energy electron injection index (*left to right, top to bottom*) 1.0, 1.3, 1.6, 1.8, 2.0, 2.5. Including secondary leptons. Data as in Fig. 2.

Effect of electron injection spectral index

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

Galactic Synchrotron Spectral Index

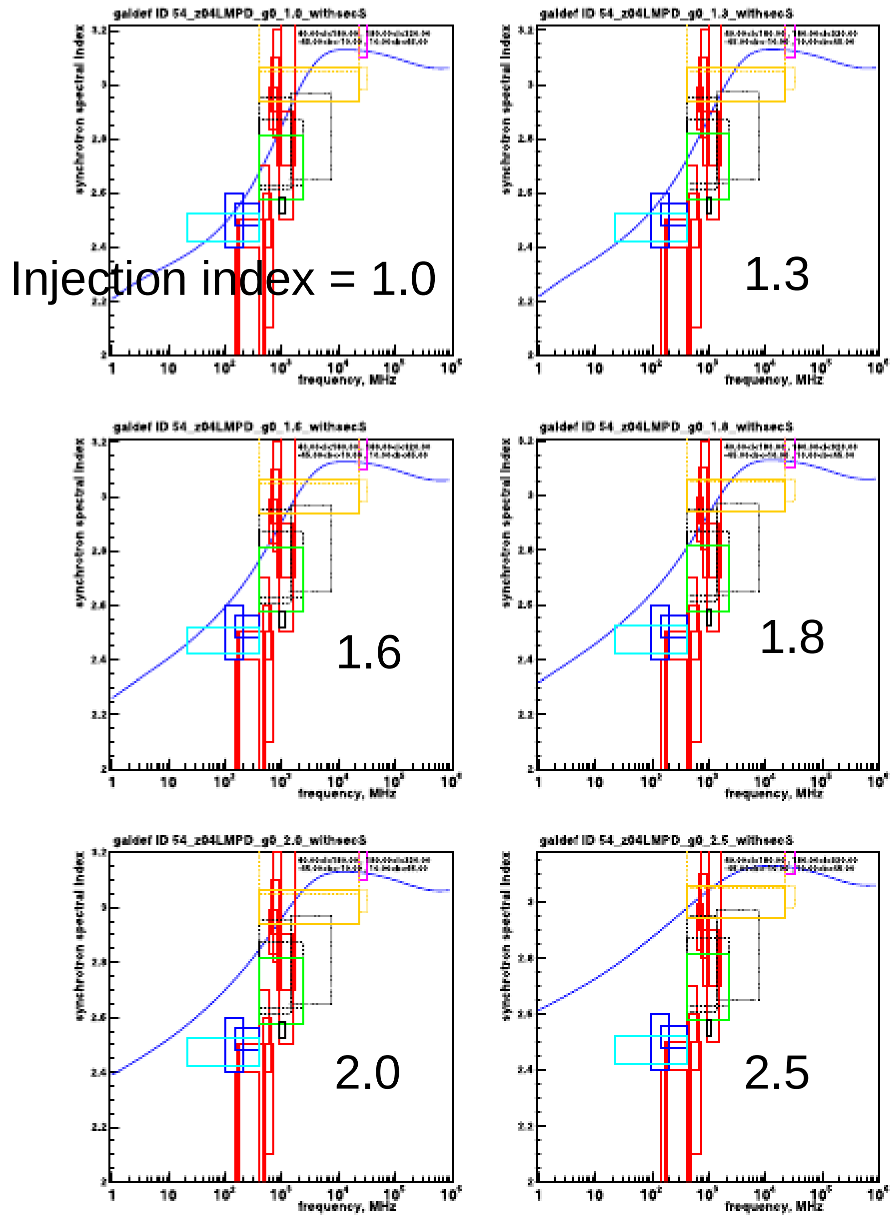
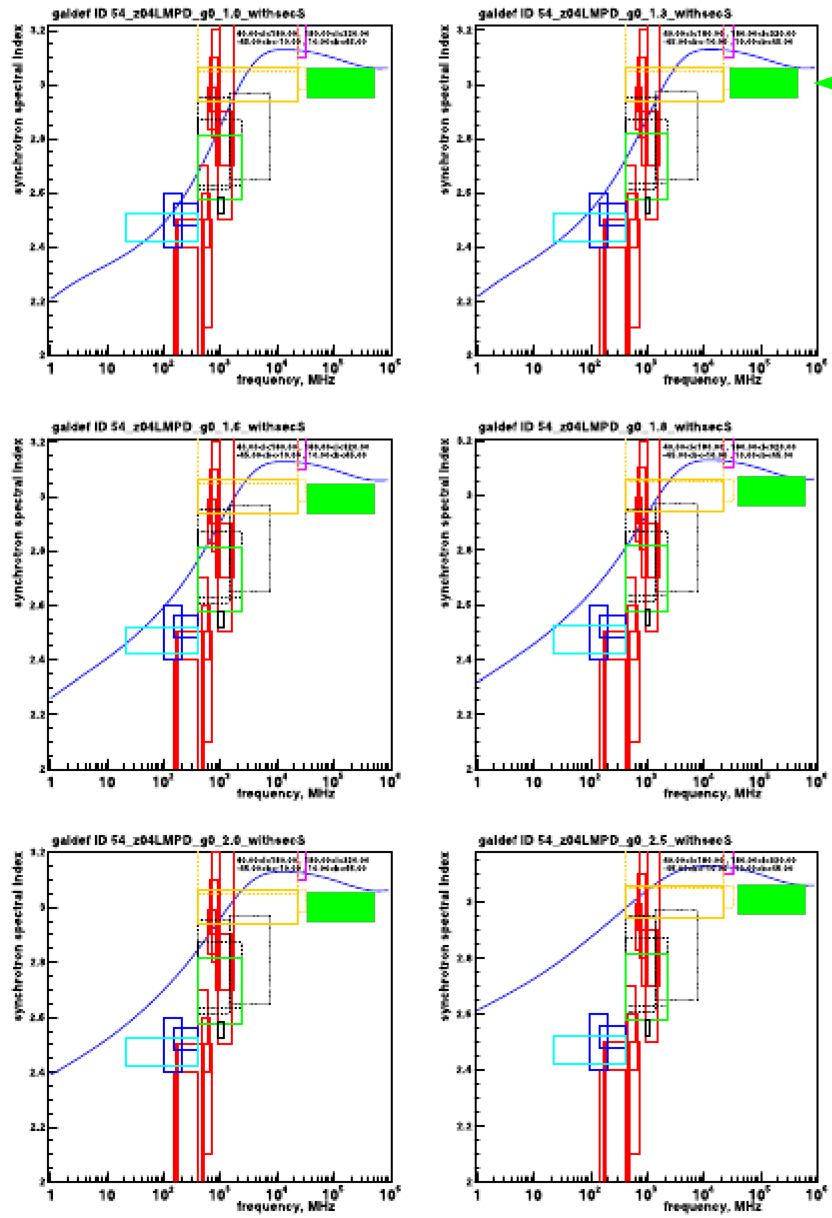


Fig. 6. Synchrotron spectral index for pure diffusion model with low-energy electron injection index (*left to right, top to bottom*) 1.0, 1.3, 1.6, 1.8, 2.0, 2.5. Including secondary leptons. Experimental ranges are based on the references reviewed in Sect. 4.1, and are intended to be representative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

Effect of electron injection spectral index

Strong, Orlando & Jaffe (2011)

Galactic Synchrotron Spectral Index



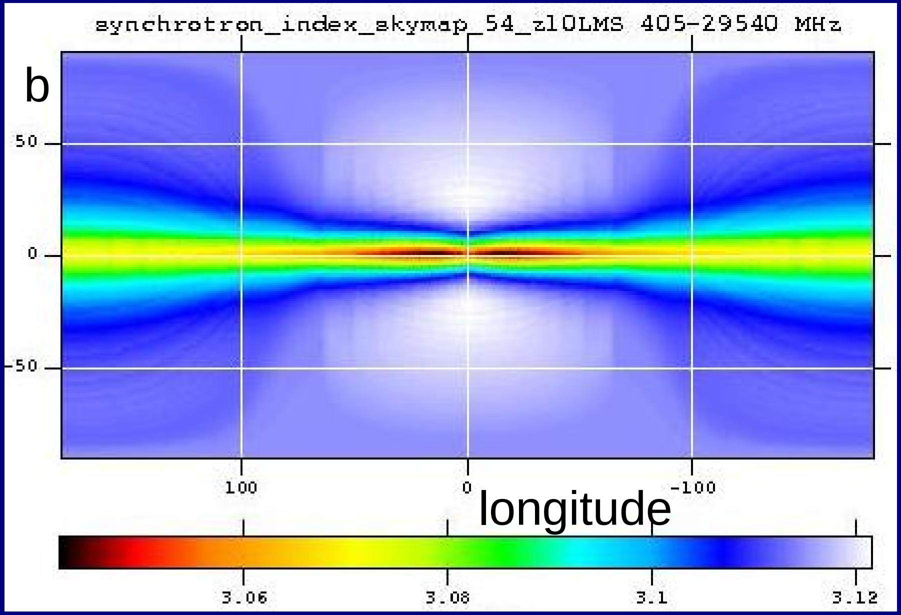
Planck

A&A 536, A21 (2011)

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 μG from this analysis

Using high latitudes only, avoiding Loop I etc

Orlando and Strong 2013

What is new :

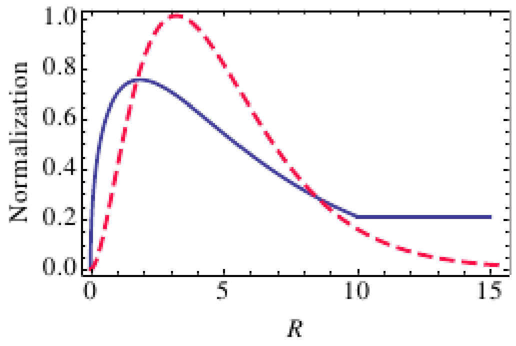
Polarized synchrotron

Separates regular from random B

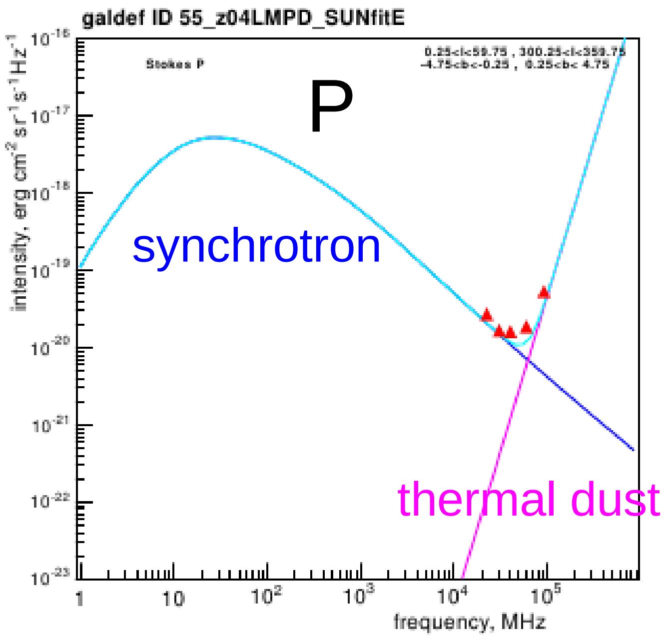
Now modelled in GALPROP

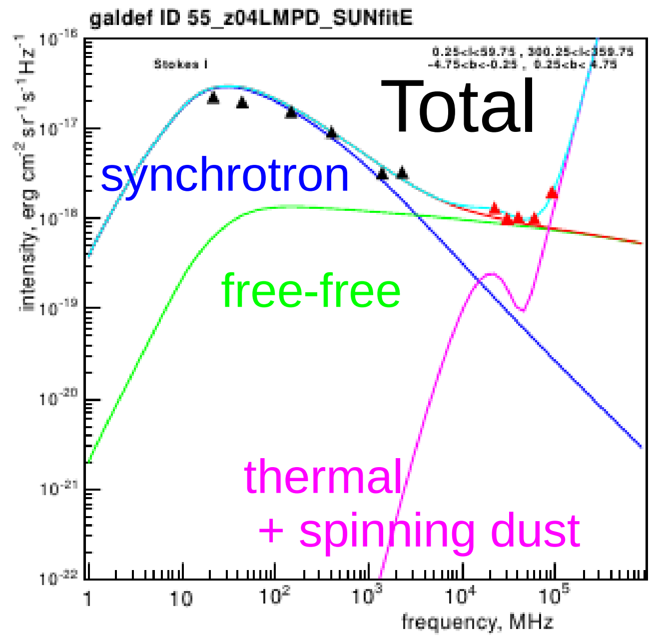
B-fields from literature, basic modifications to fit data.

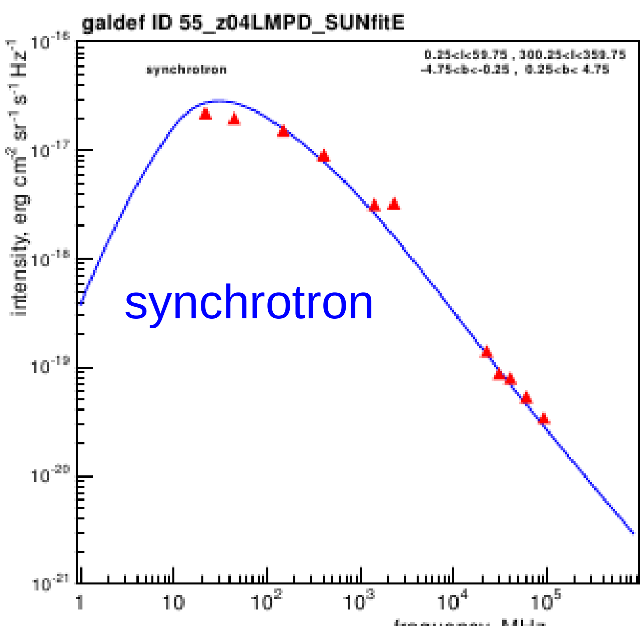
Cosmic-ray electron distribution is a main input from gamma rays.



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.

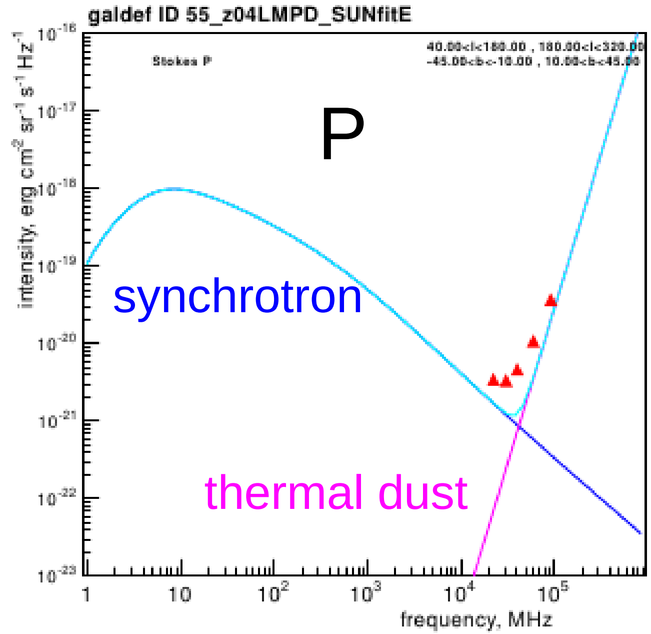


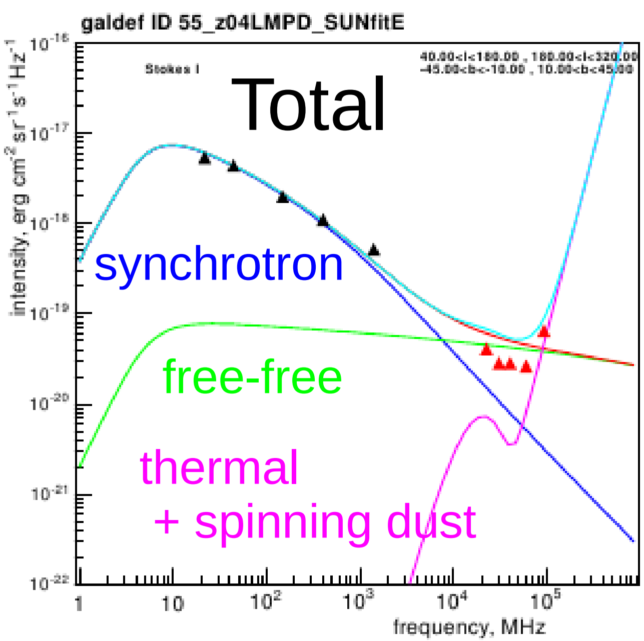


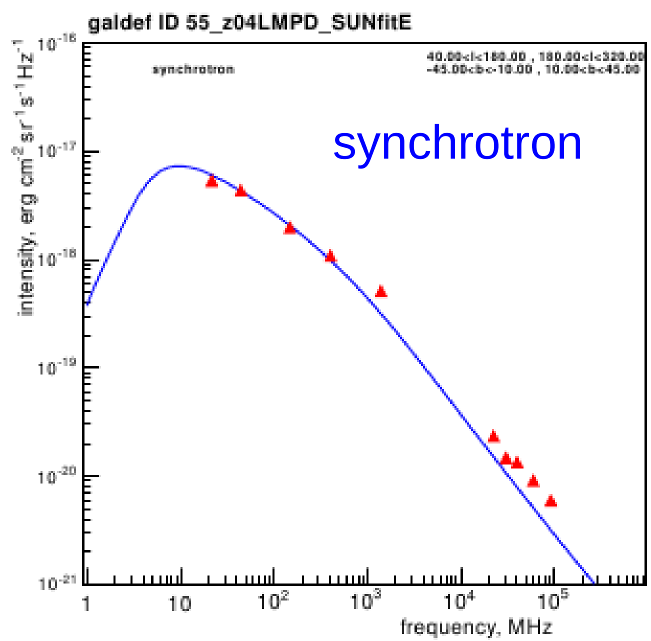


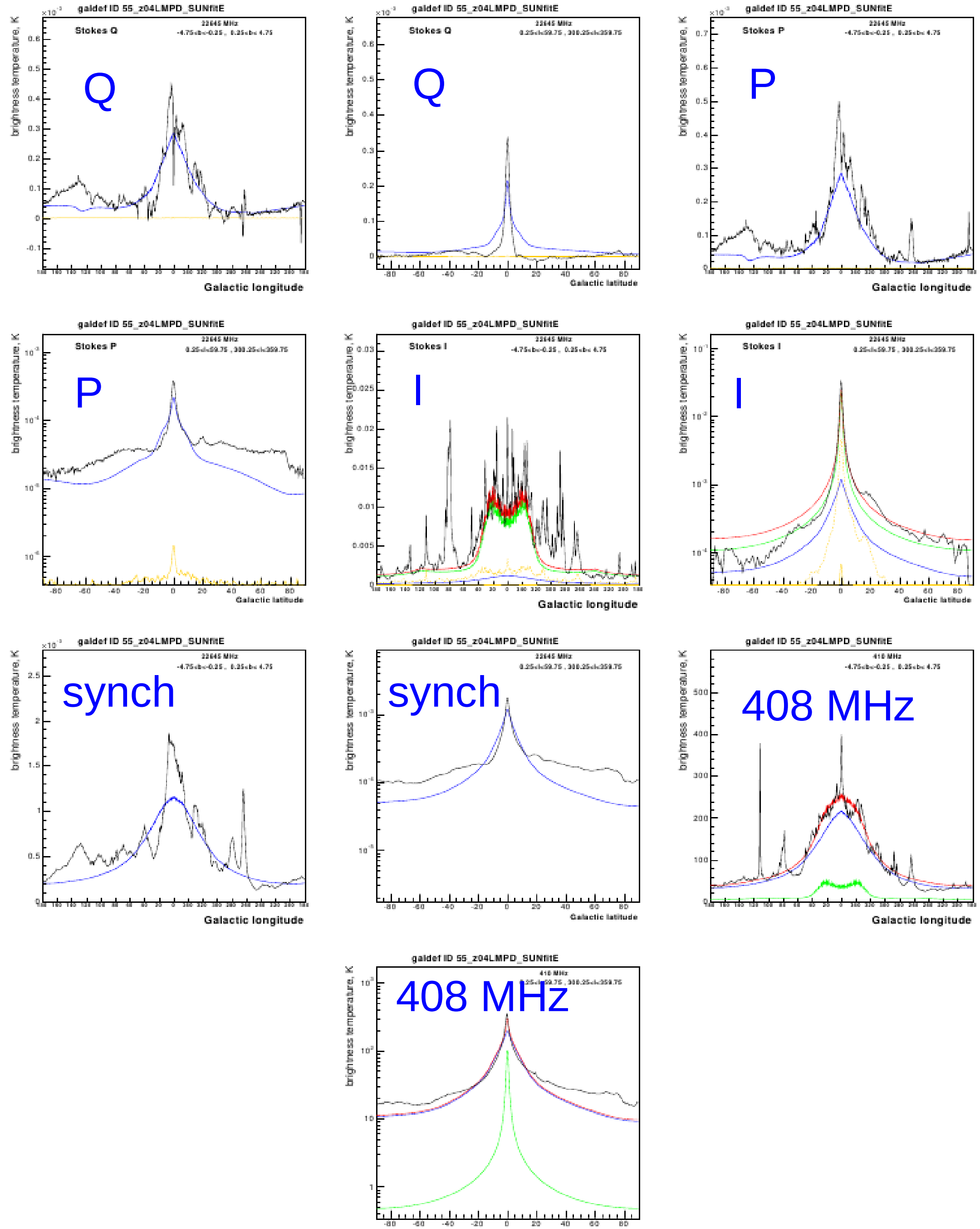
INNER GALAXY

HIGH LATITUDES





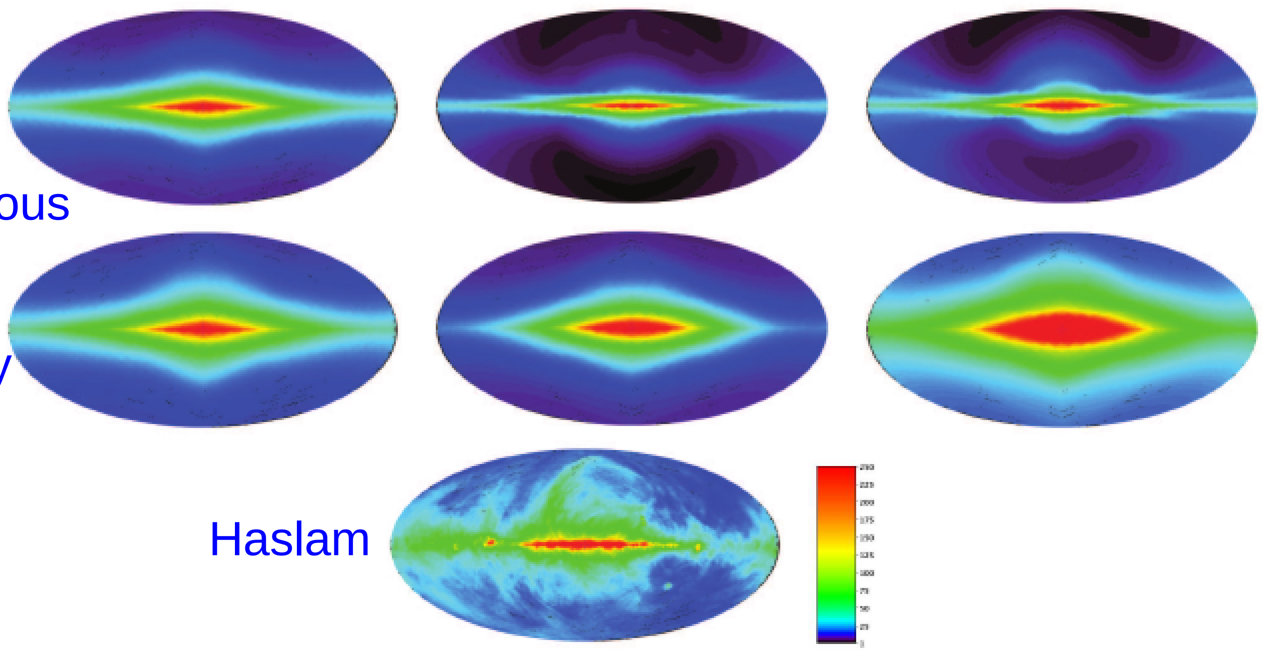



galdef ID 55_z04LMPD_SUNfitE
Stokes Q
Q
Q
Stokes P
P
P
Stokes I
I
I
synch
synch
408 MHz
408 MHz
brightness temperature, K
Galactic longitude
Galactic latitude
22645 MHz
408 MHz

408 MHz

Using various B-field and cosmic-ray models

Haslam

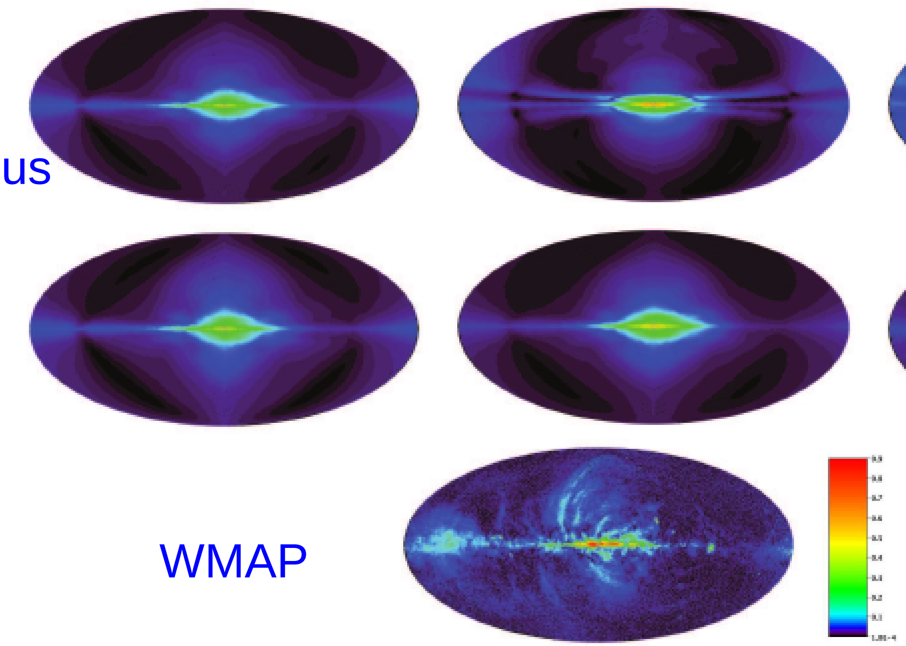


Regular B-field models from Sun etal, Pshirkov et al.
Scaling factor applied.

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.

B- field from Orlando & Strong 2013

Using :

Fermi-LAT cosmic-ray electrons

408 MHz

23 GHz WMAP polarized

Local B-field:

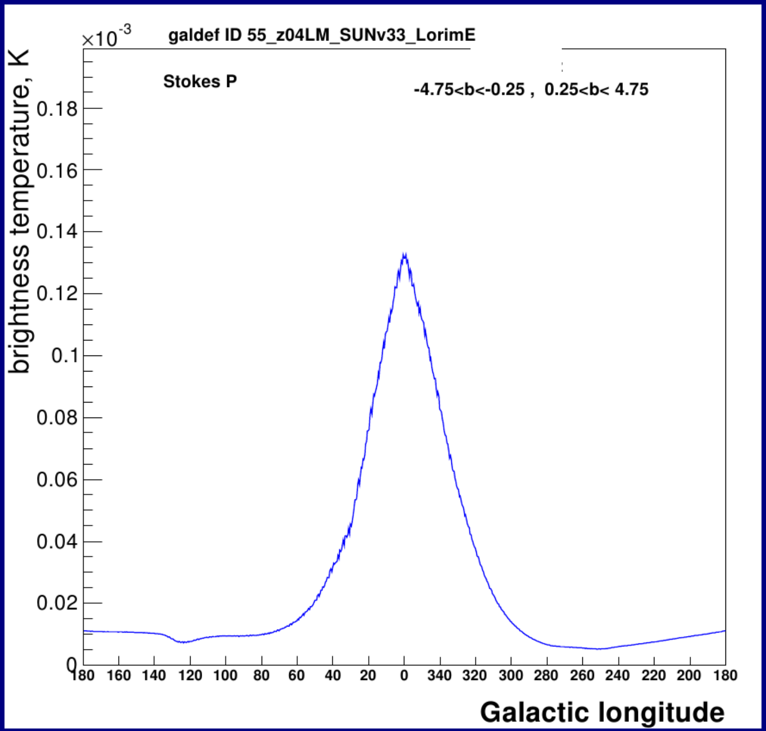
Regular : 3-4 μG :

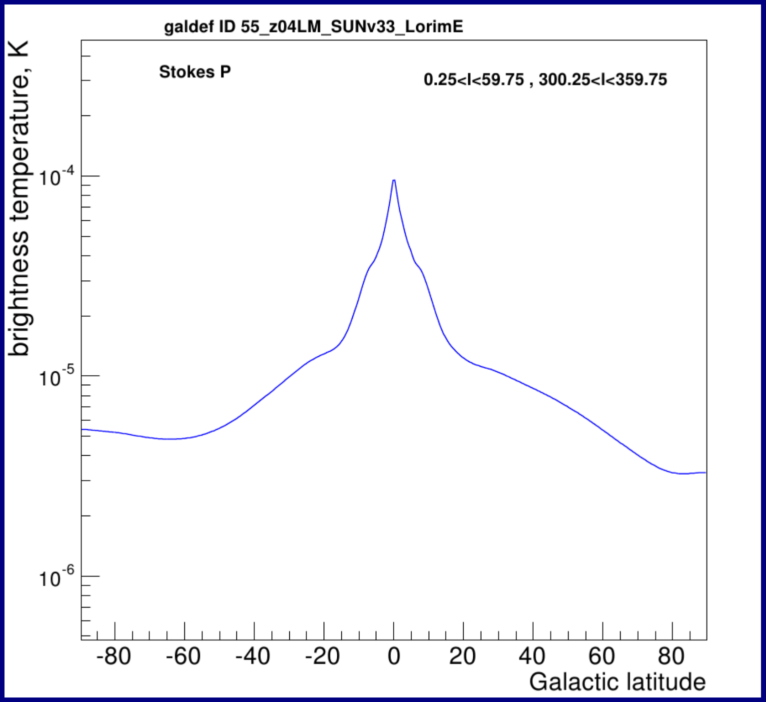
factor 1.5-2 higher than original models of Sun, Pshirkov

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

Random : 6 μG

Illustrative model for 30 GHz Stokes P

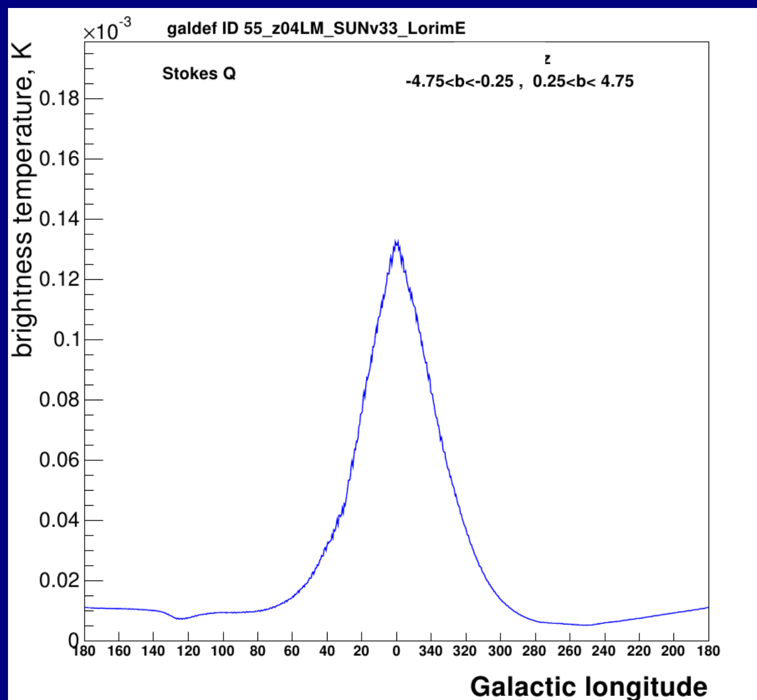


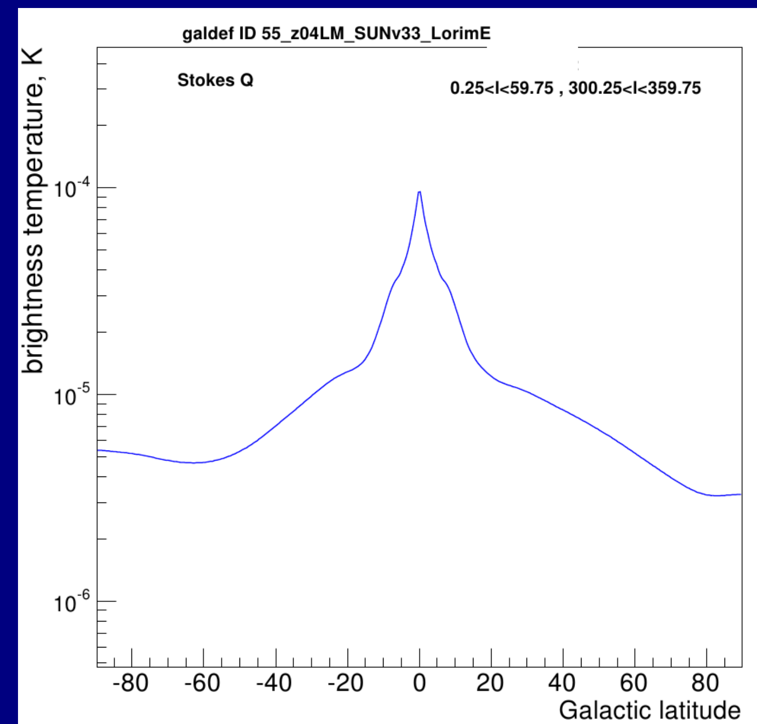


B_reg : Sun et al., scaled
B_rand : double exponential

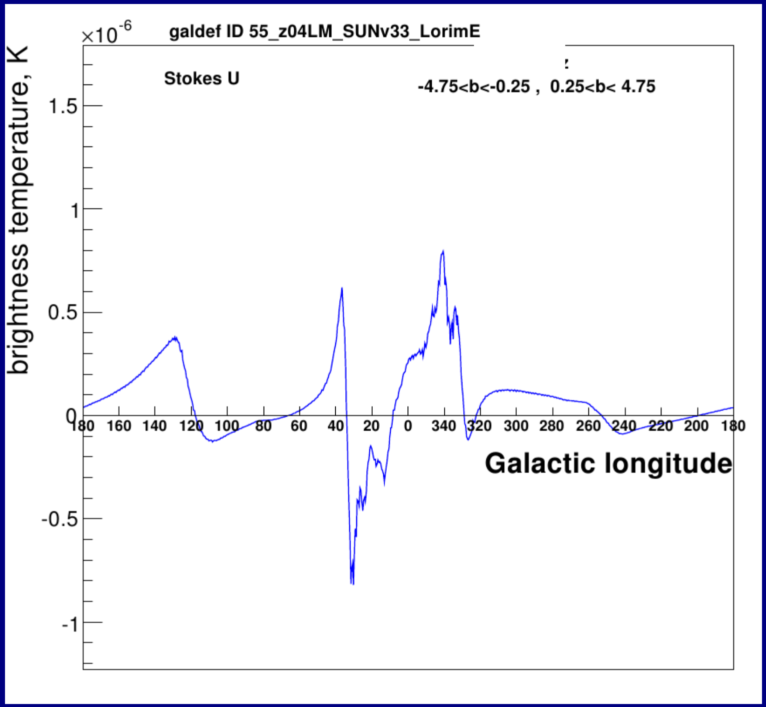
Cosmic-ray electrons based on gamma rays and locally measured spectrum

Illustrative model for 30 GHz Stokes Q

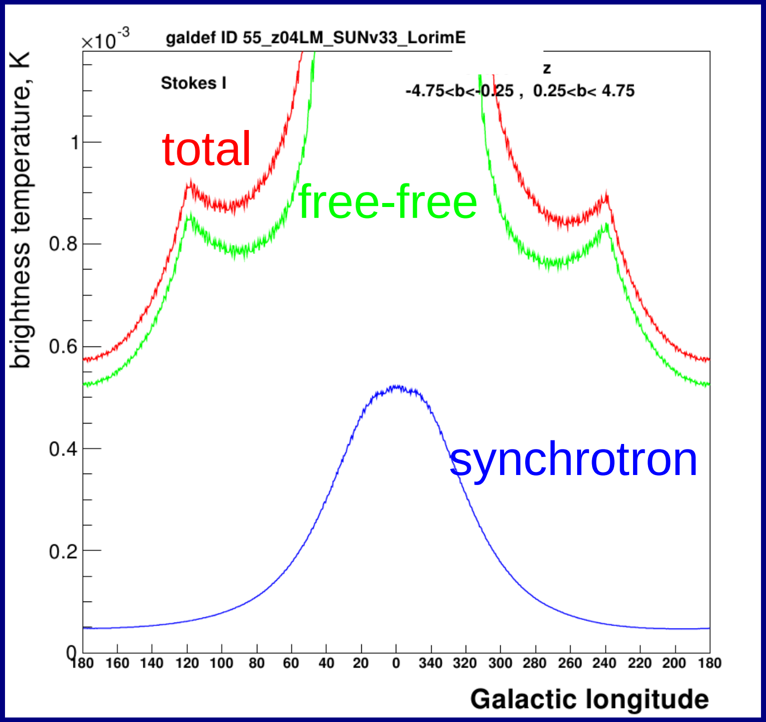


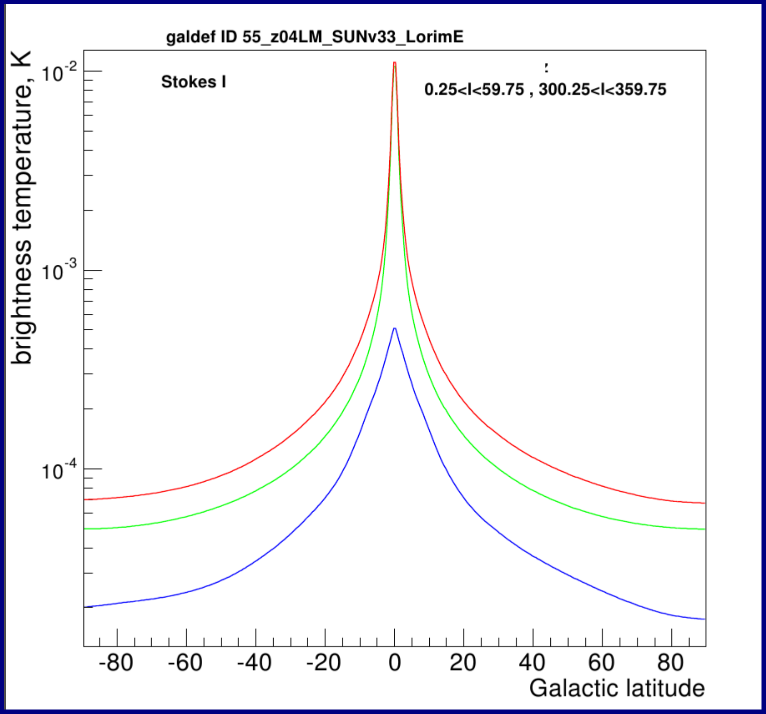


Illustrative model for 30 GHz Stokes U



Illustrative model for 30 GHz Stokes I

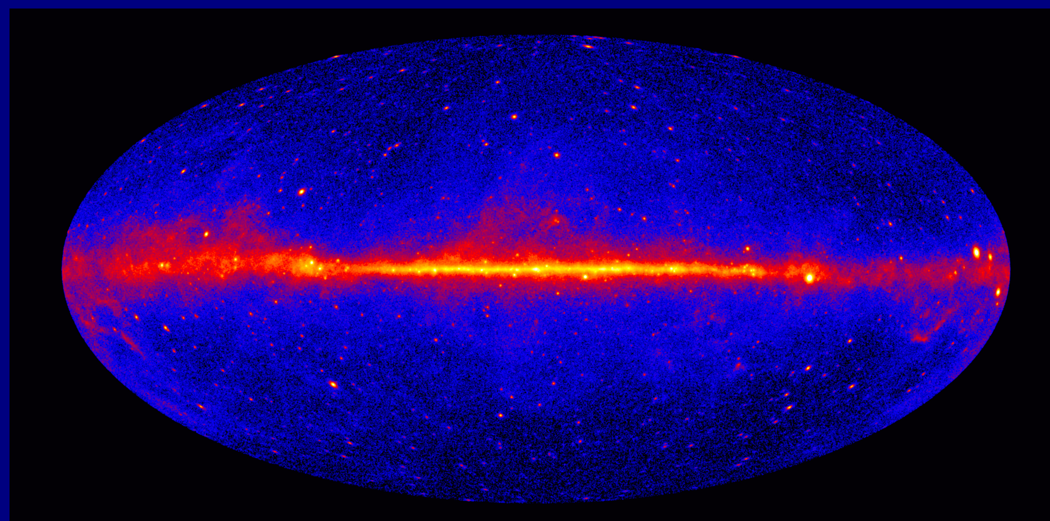




Free-free from NE2001, illustrative

Exploiting gamma rays

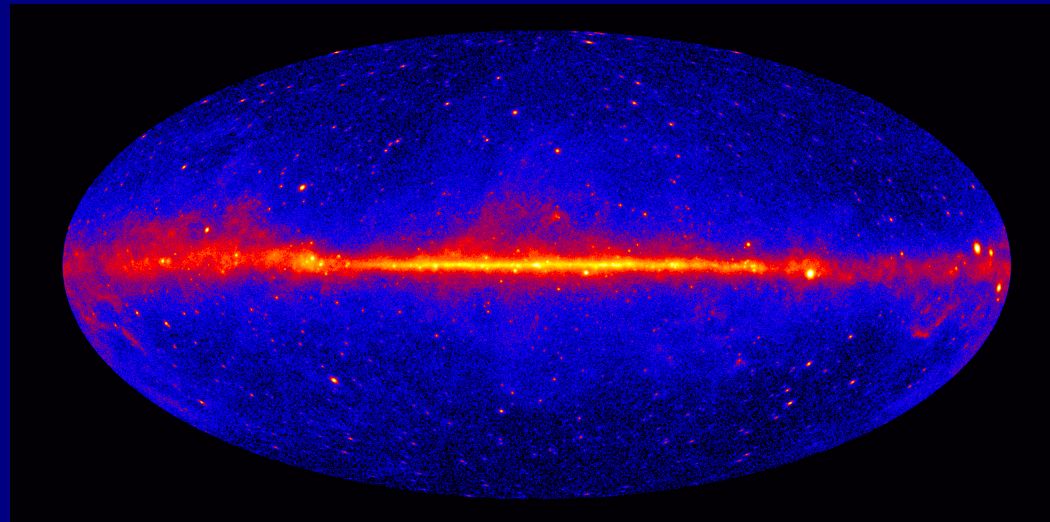
1 – 10 GeV



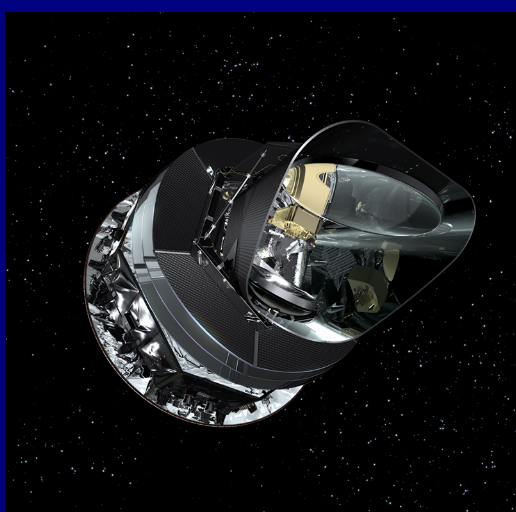
Cosmic-ray protons interacting with gas : hadronic (pion-decay)

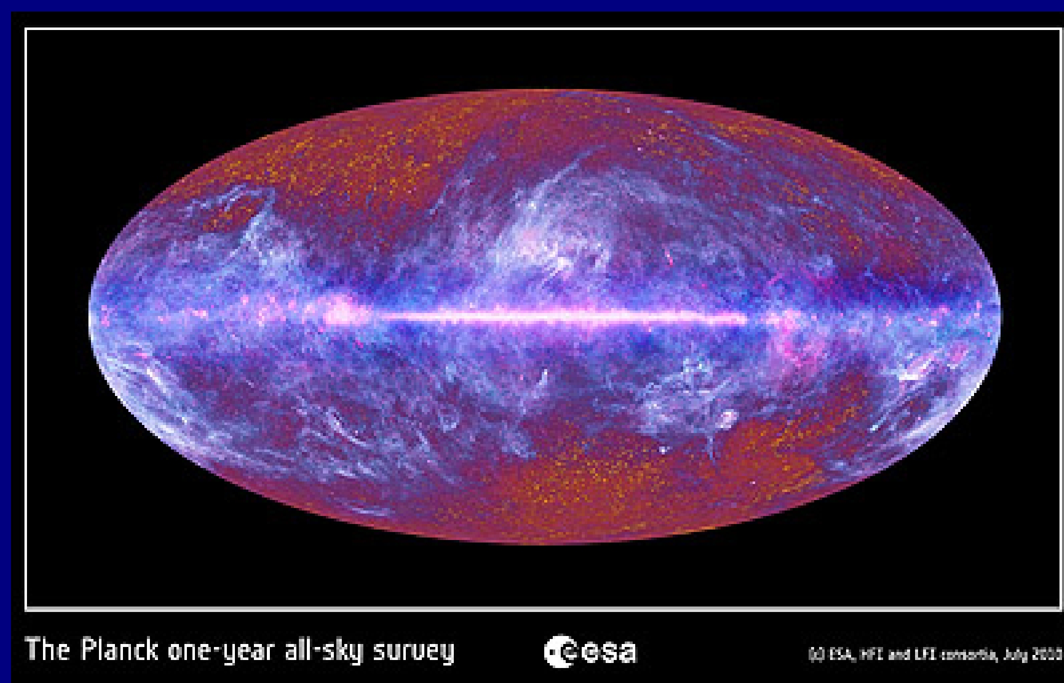
Cosmic-ray electrons and positrons interacting with gas : bremsstrahlung

interacting with interstellar radiation : inverse Compton



2 years

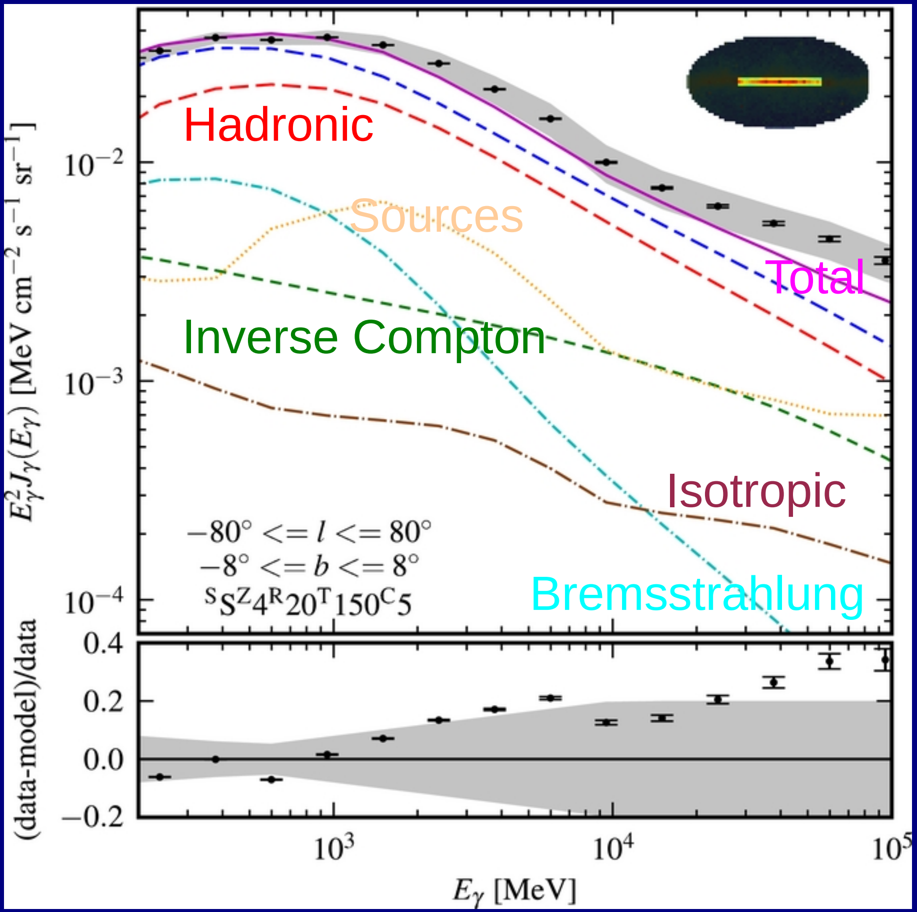




1 year

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

Fermi-LAT
Inner Galaxy Gamma Ray Spectrum

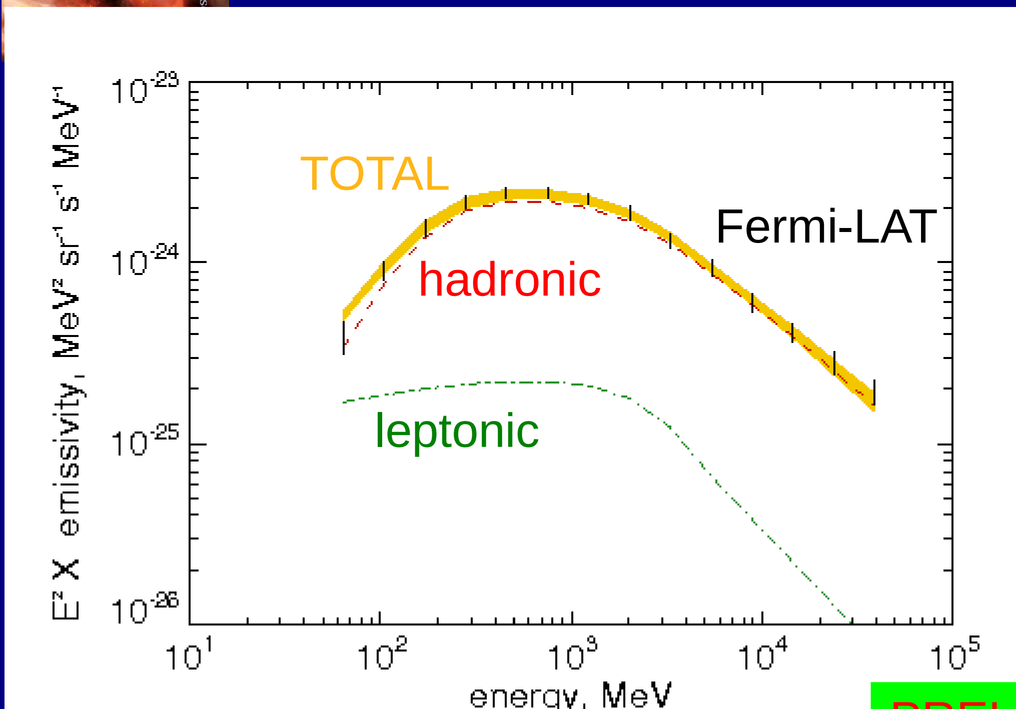


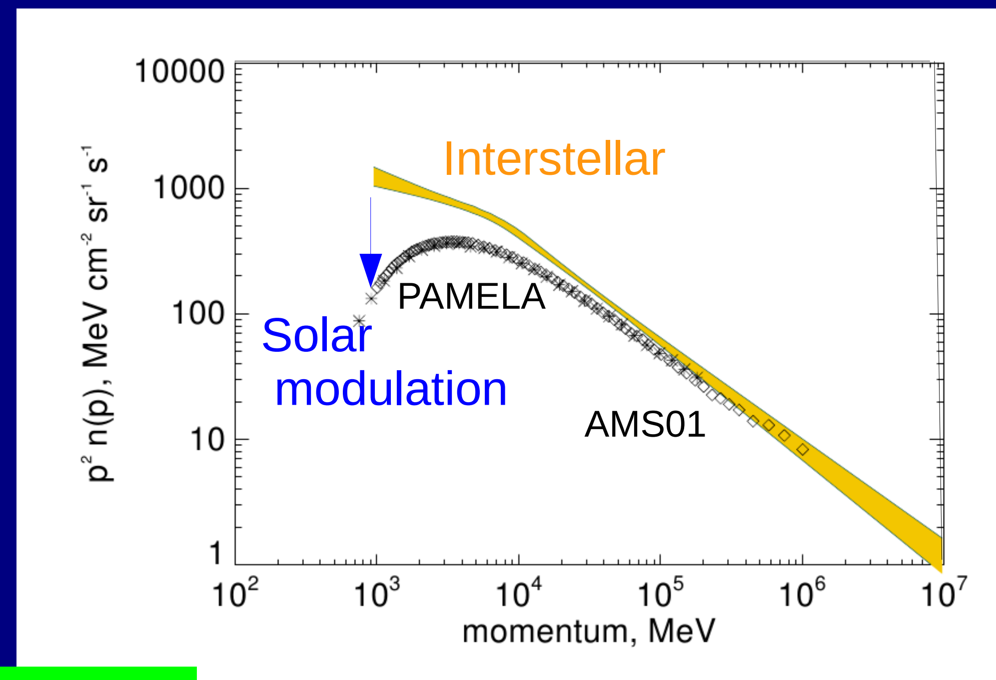
Ackermann et al. ApJ 750, 3 (2012)

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.

Interstellar Cosmic ray spectra derived from gamma rays

Method : Bayesian analysis

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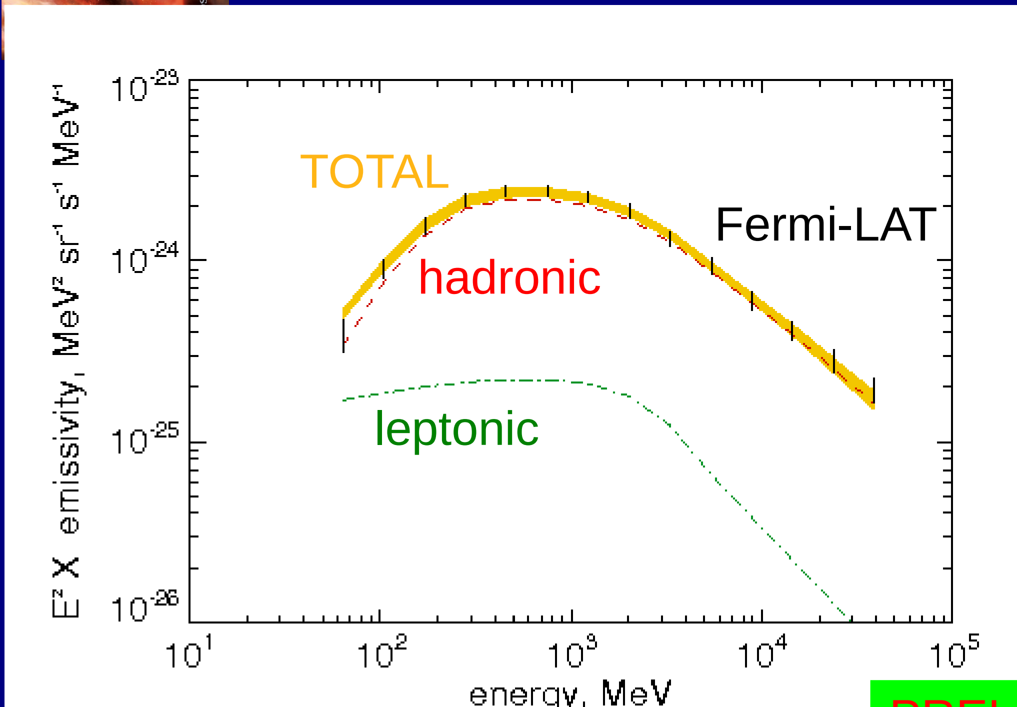

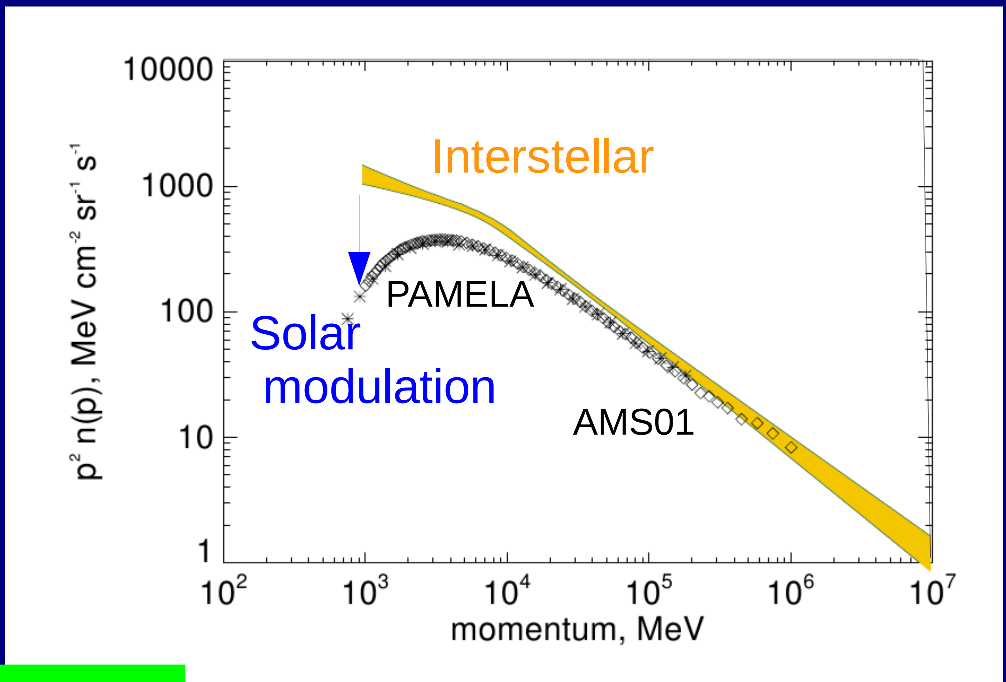

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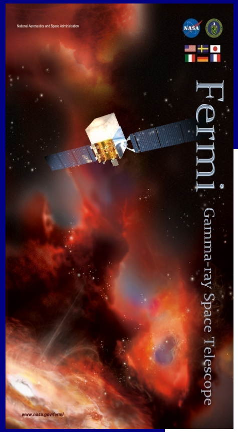
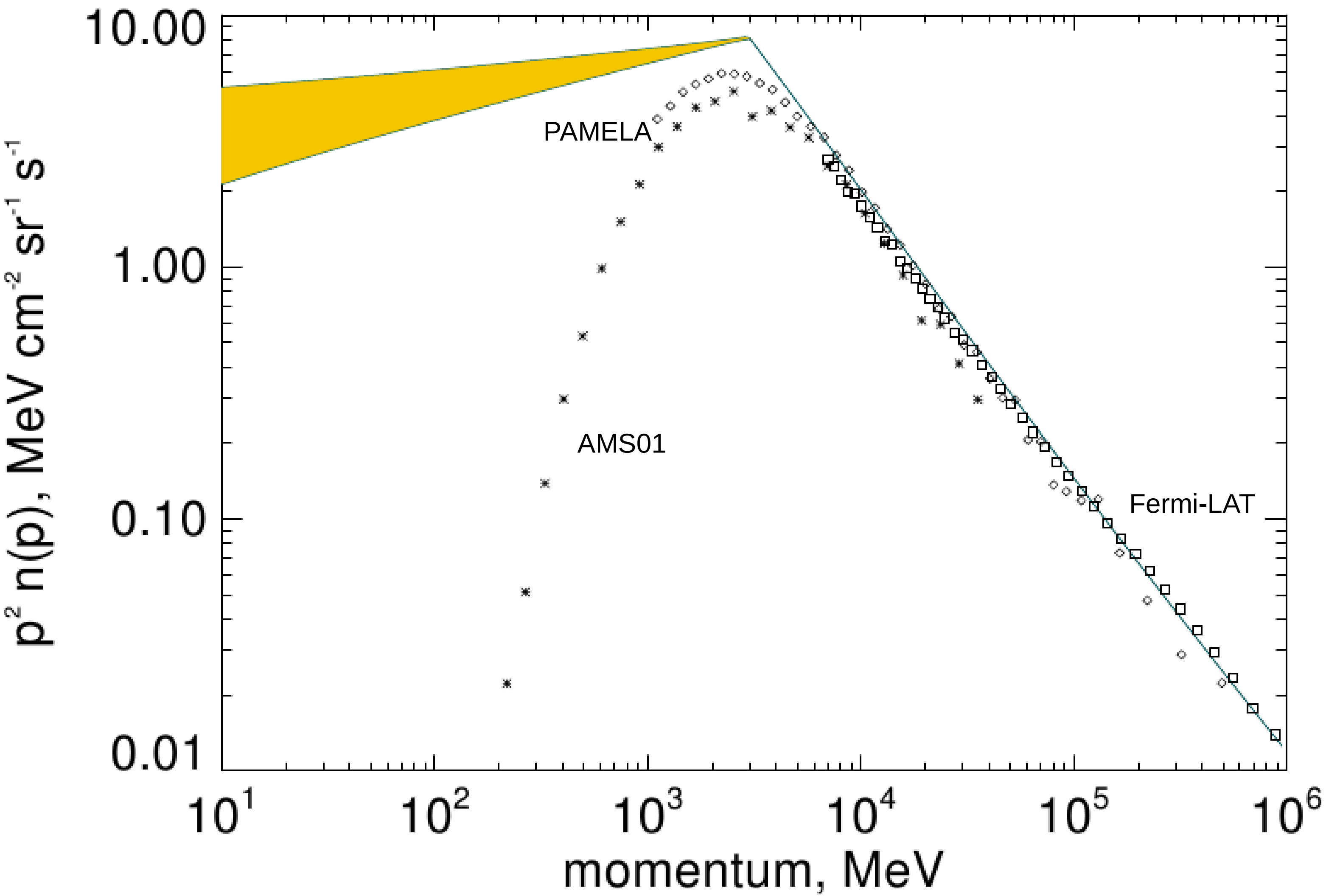


Interstellar electrons from synchrotron, gamma rays and direct measurements



PRELIMINARY

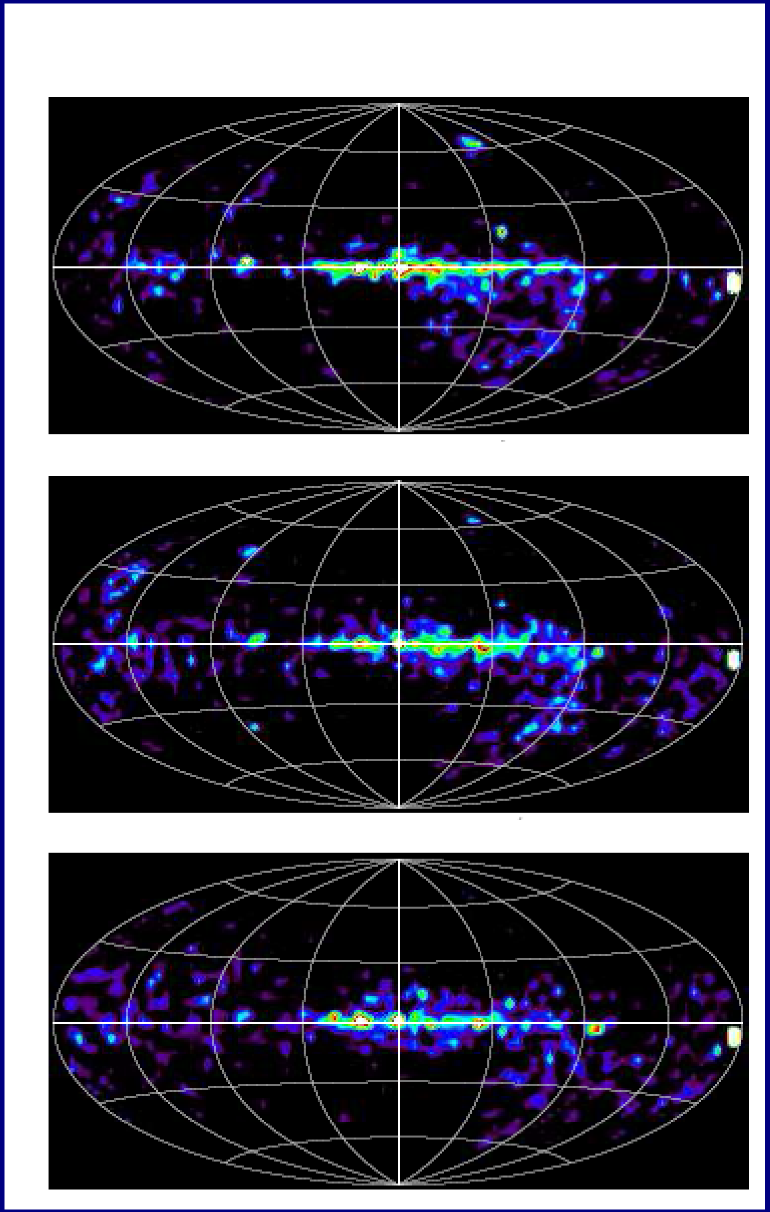
CGRO/ COMPTEL

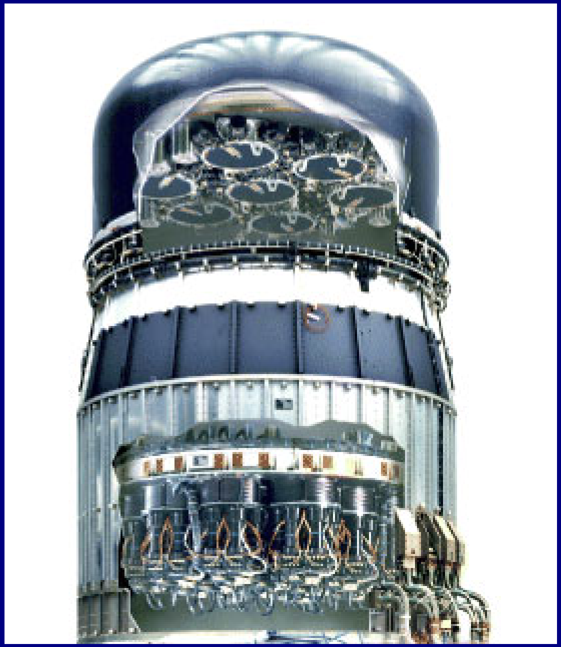
MeV continuum

1 – 3 MeV

3 – 10 MeV

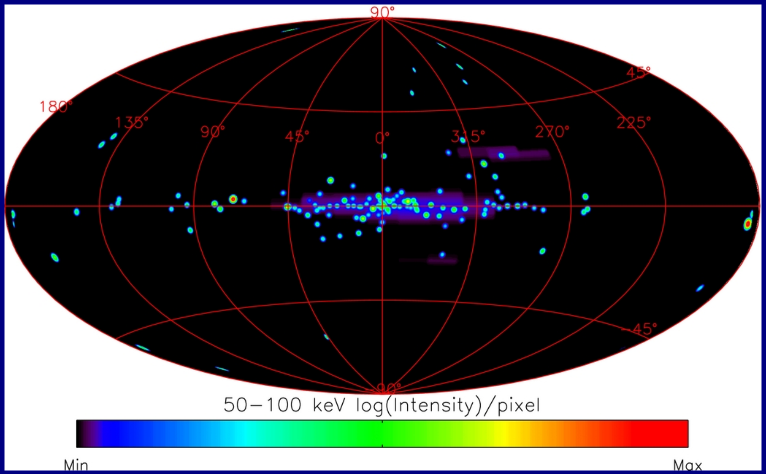
10 – 30 MeV





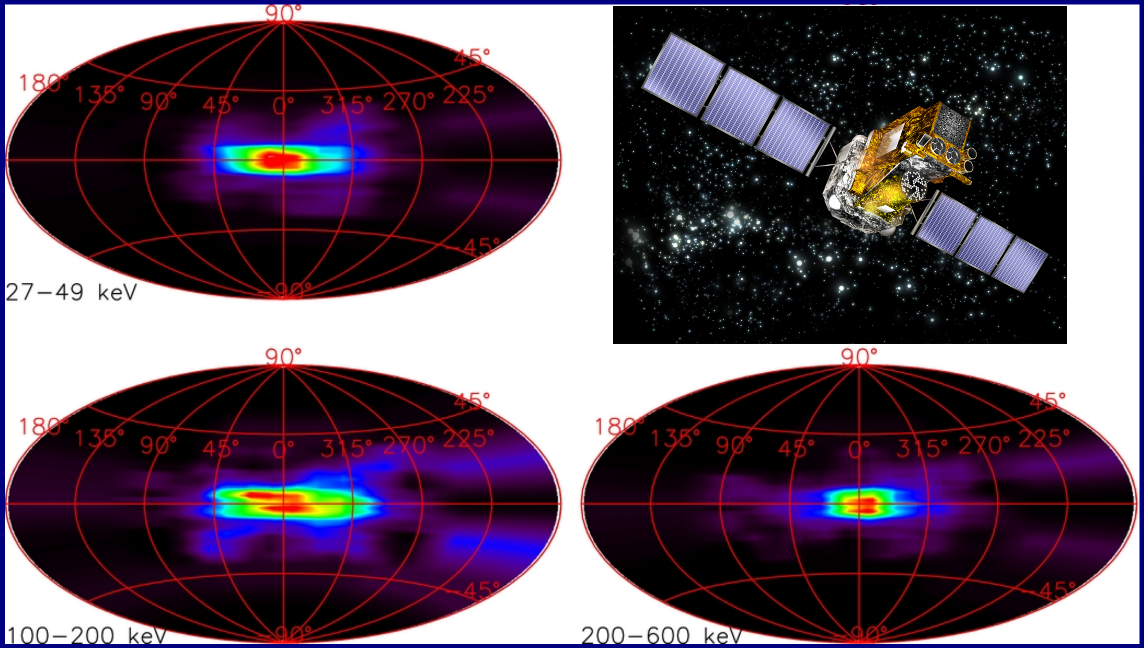
Unique heritage data:
COMPTEL analysis continues....

Mainly cosmic-ray electrons interacting with interstellar radiation and matter ?
or glow from many unresolved sources ?



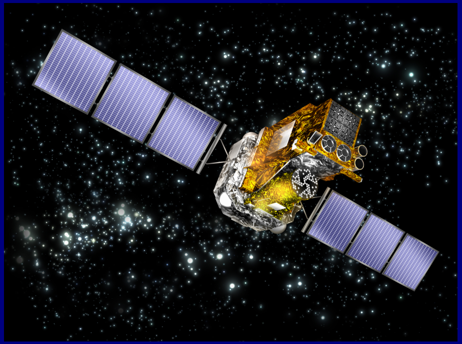
INTEGRAL / SPI
Continuum skymaps

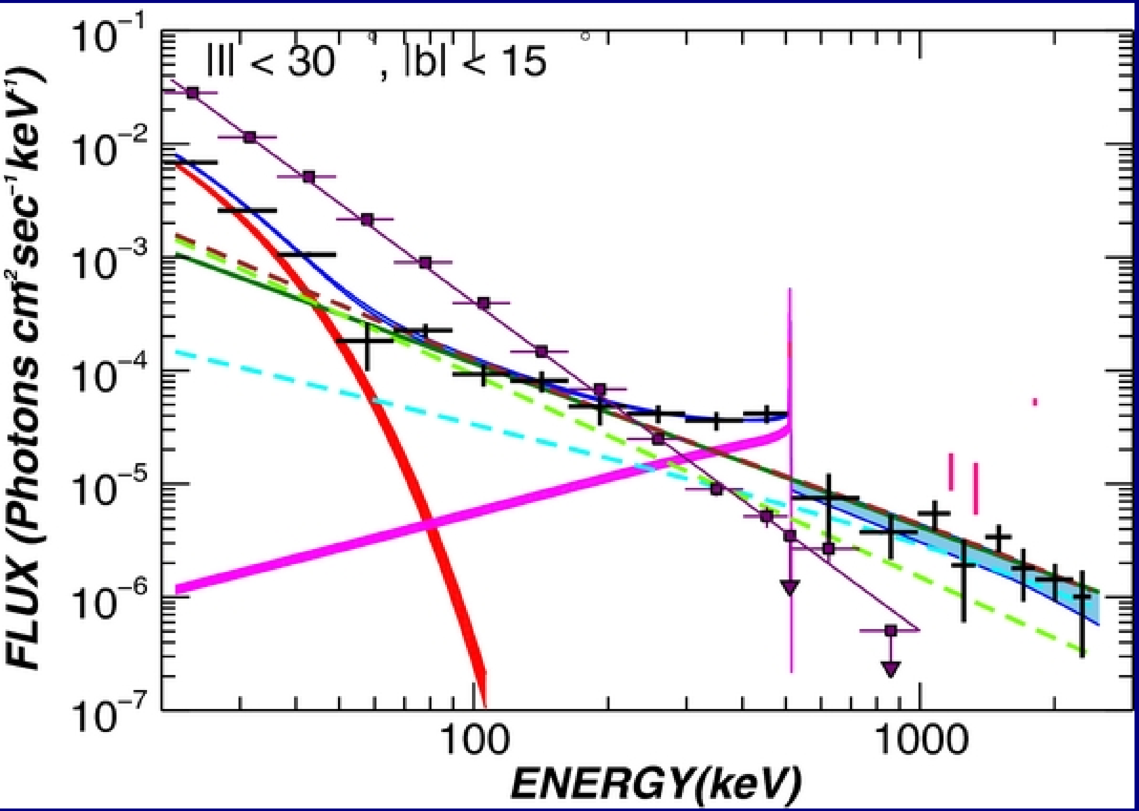
Bouchet et al.
ApJ 739, 29 (2011)



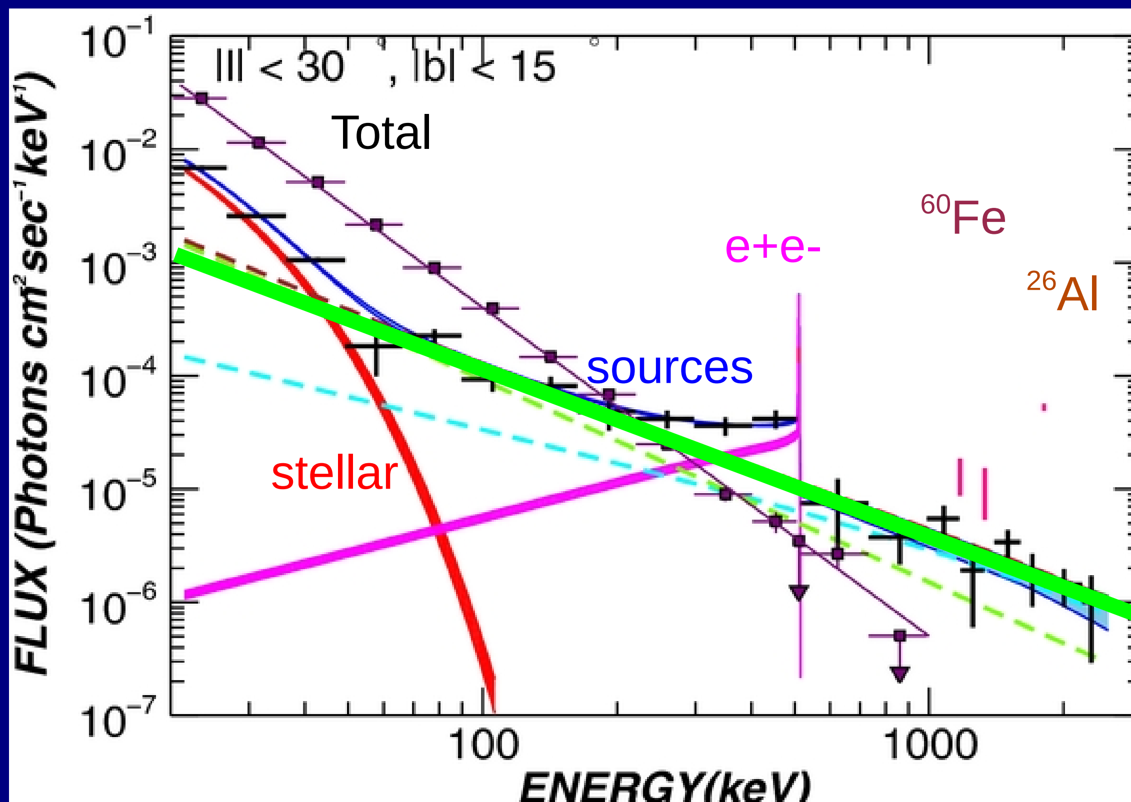
A real mix of processes !

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



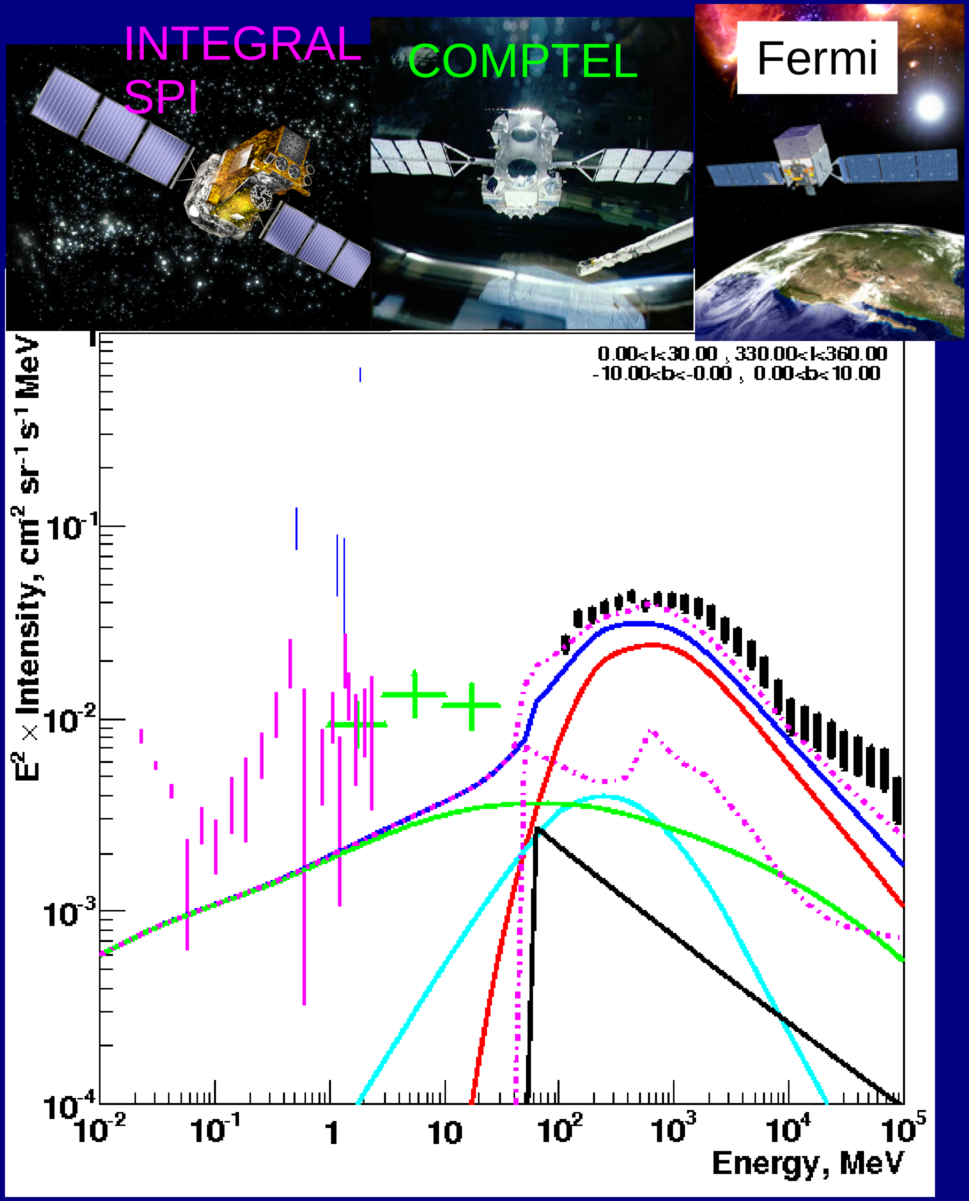


Inner Galaxy
INTEGRAL / SPI
Bouchet et al. ApJ 739, 29 (2011)



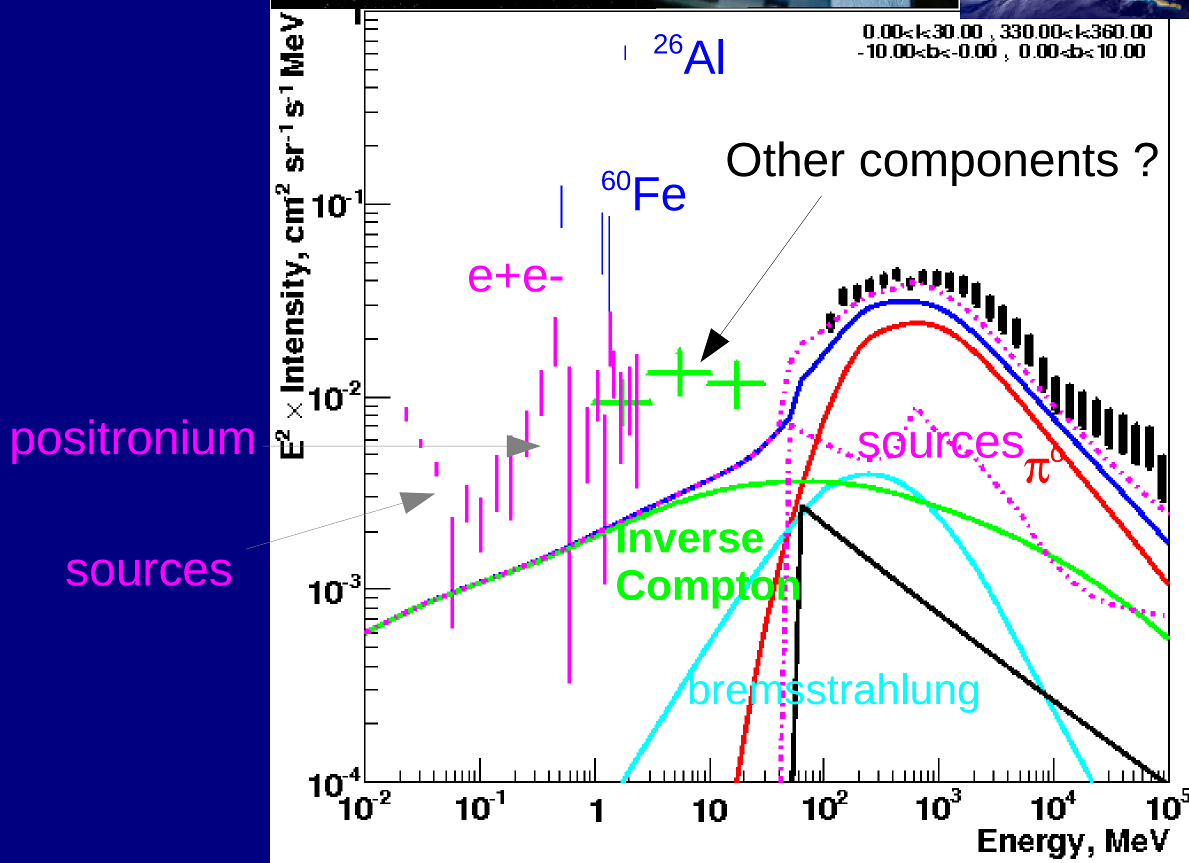
Non-thermal:
Cosmic-ray interactions

Inner Galaxy: keV to TeV



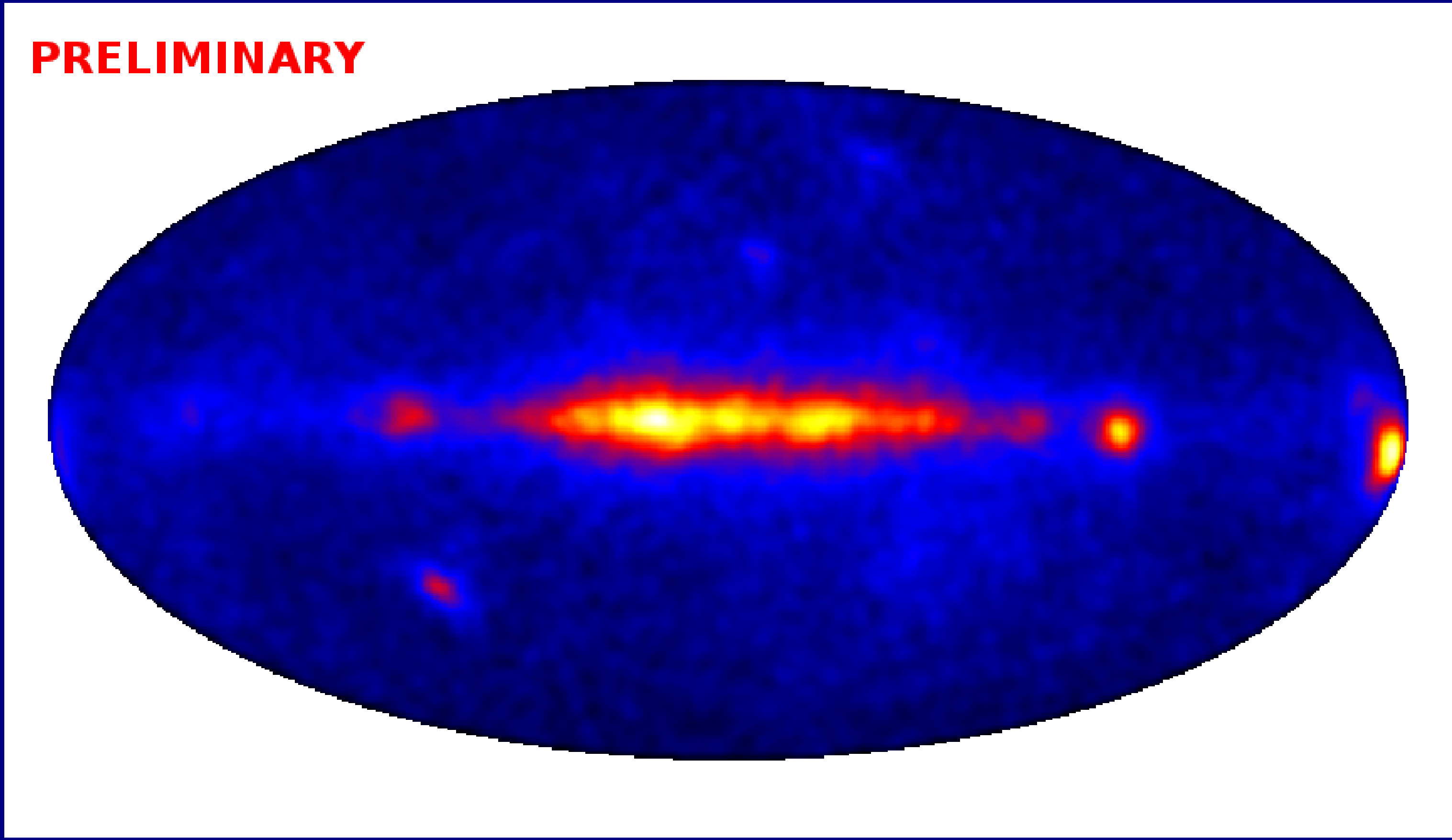
Strong 2011, Proc. 12 ICATPP Conf. arXiv:1101.1381

Inner Galaxy: keV to TeV



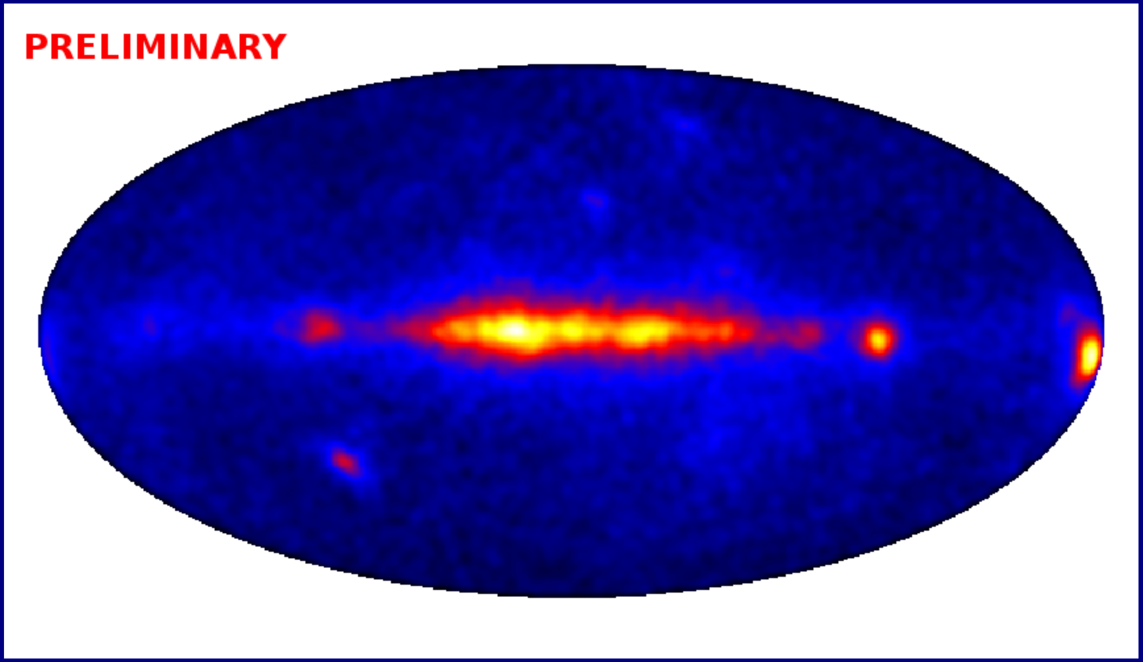
GeV electrons – inverse Compton - important for MeV gamma rays !

Fermi-LAT 25 – 40 MeV



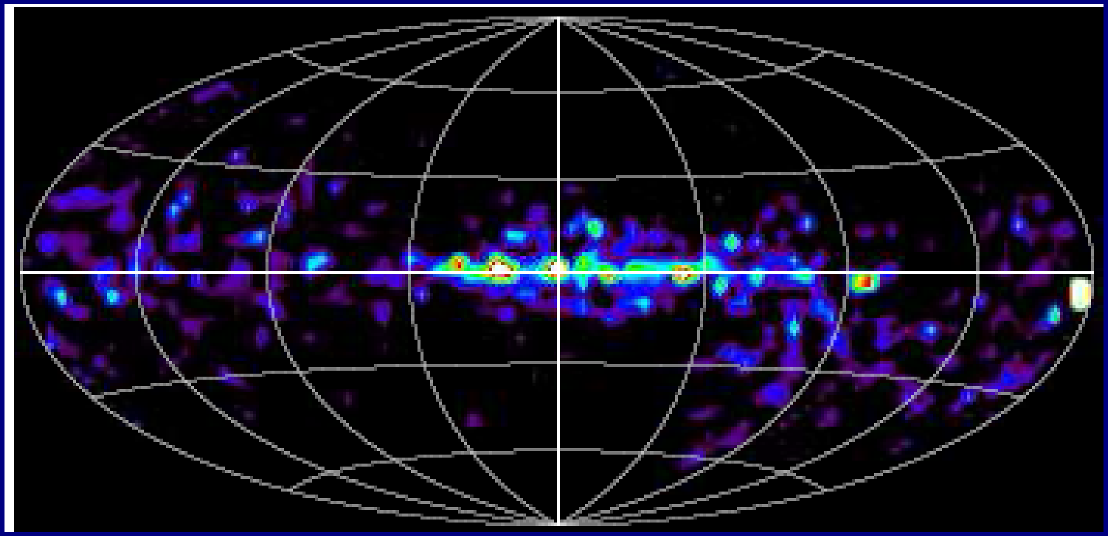
NB low angular and energy resolution !
Nominal energy range: photons may originate from range 10 to <100 MeV.
But valuable to bridge the MeV gap.

Fermi-LAT 25-40 MeV

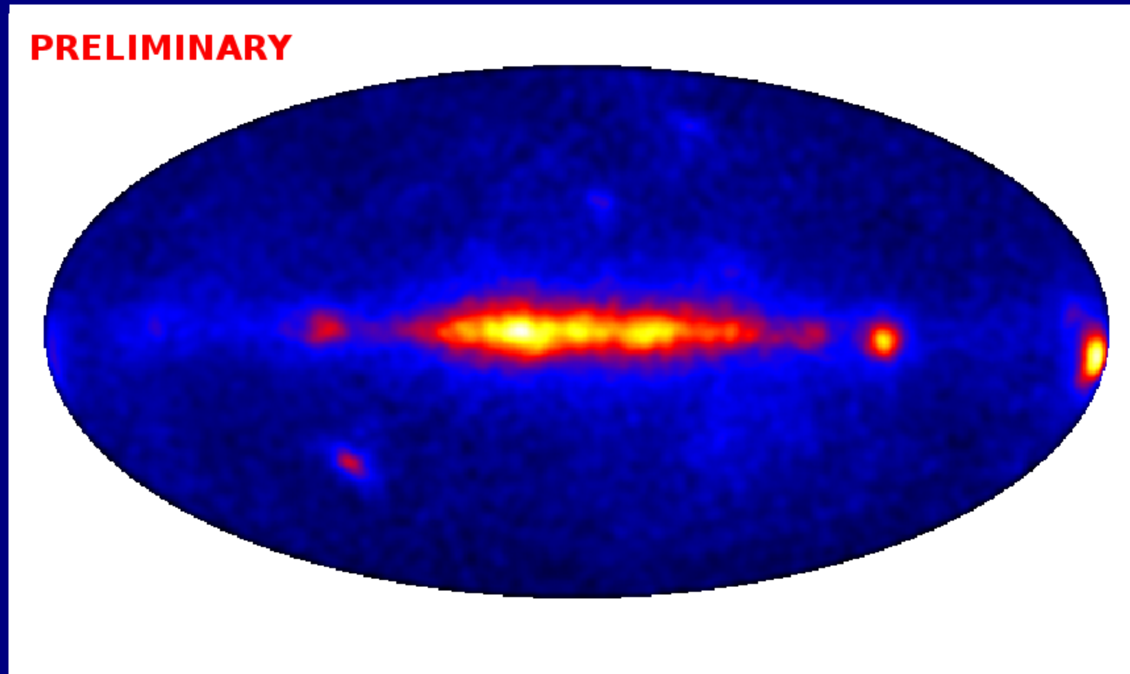


meets

COMPTEL 10-30 MeV

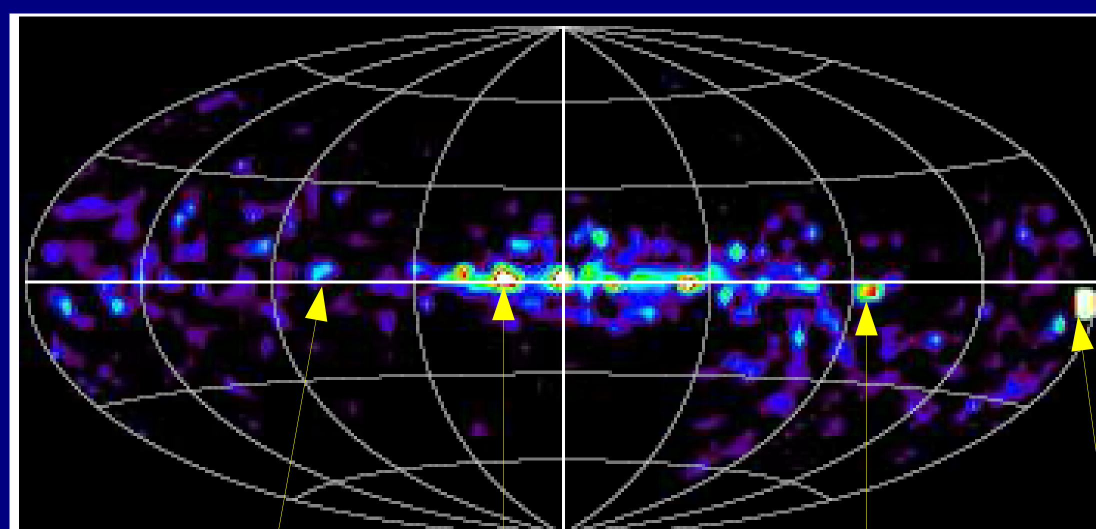


Fermi-LAT 25-40 MeV



meets

COMPTEL 10-30 MeV



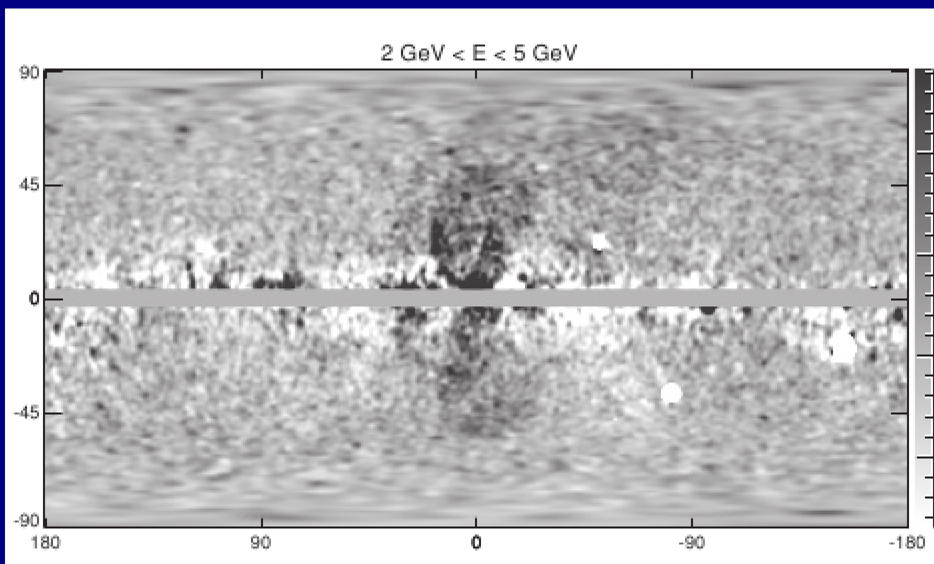
Galactic Plane

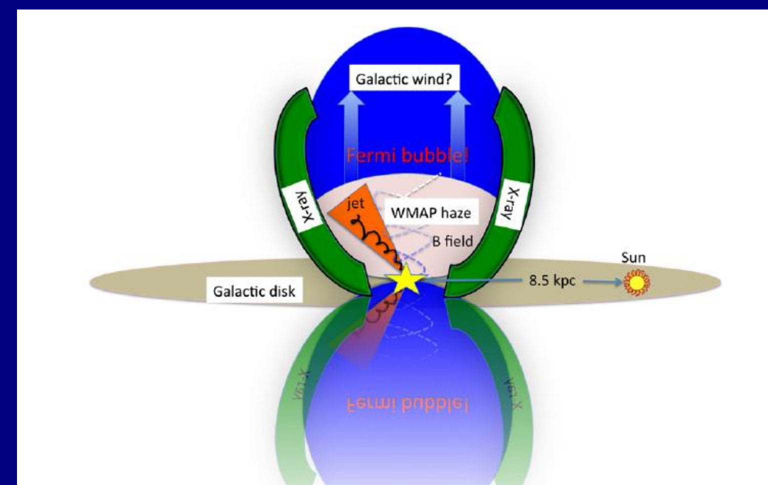
Cyg X-1 LS5039 Vela PSR Crab

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?

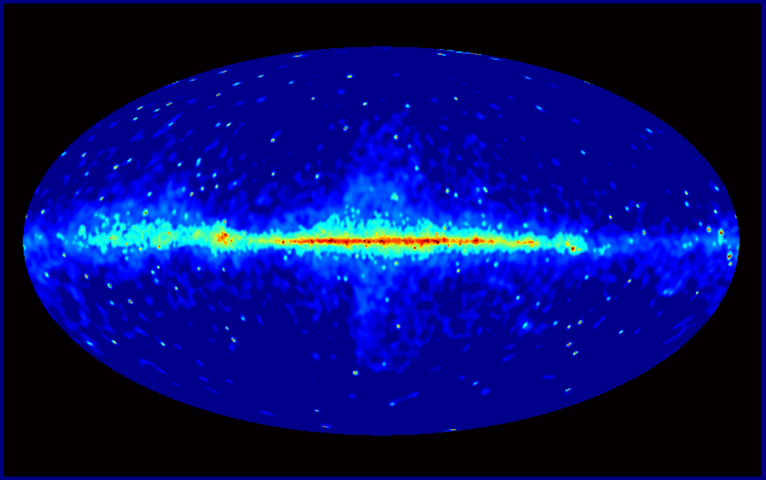
Meng Su[1], Tracy R. Slatyer[1,2], and Douglas P. Finkbeiner[1,2]





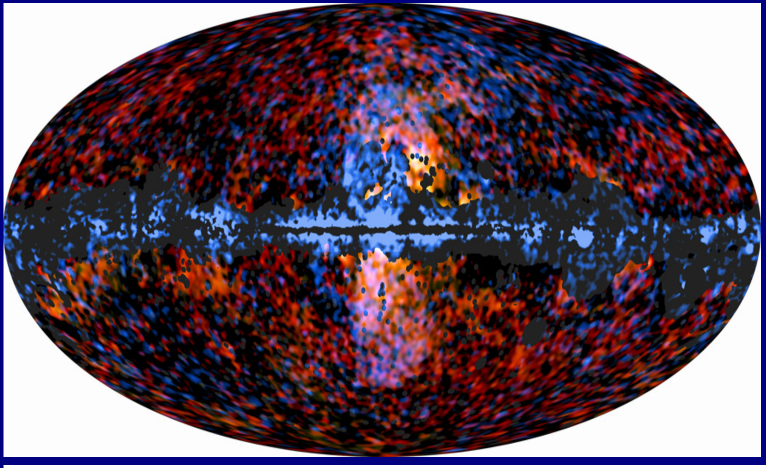
kpc-scale features centred on GC
Details depend on foreground model used (features ~ 10% of total intensity) !
Presumably inverse Compton – electrons -> radio
.

Fermi Bubbles

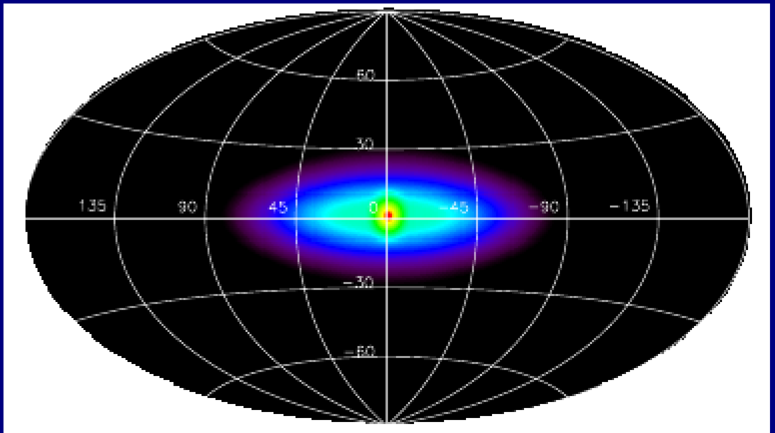


(related to WMAP Haze ?)

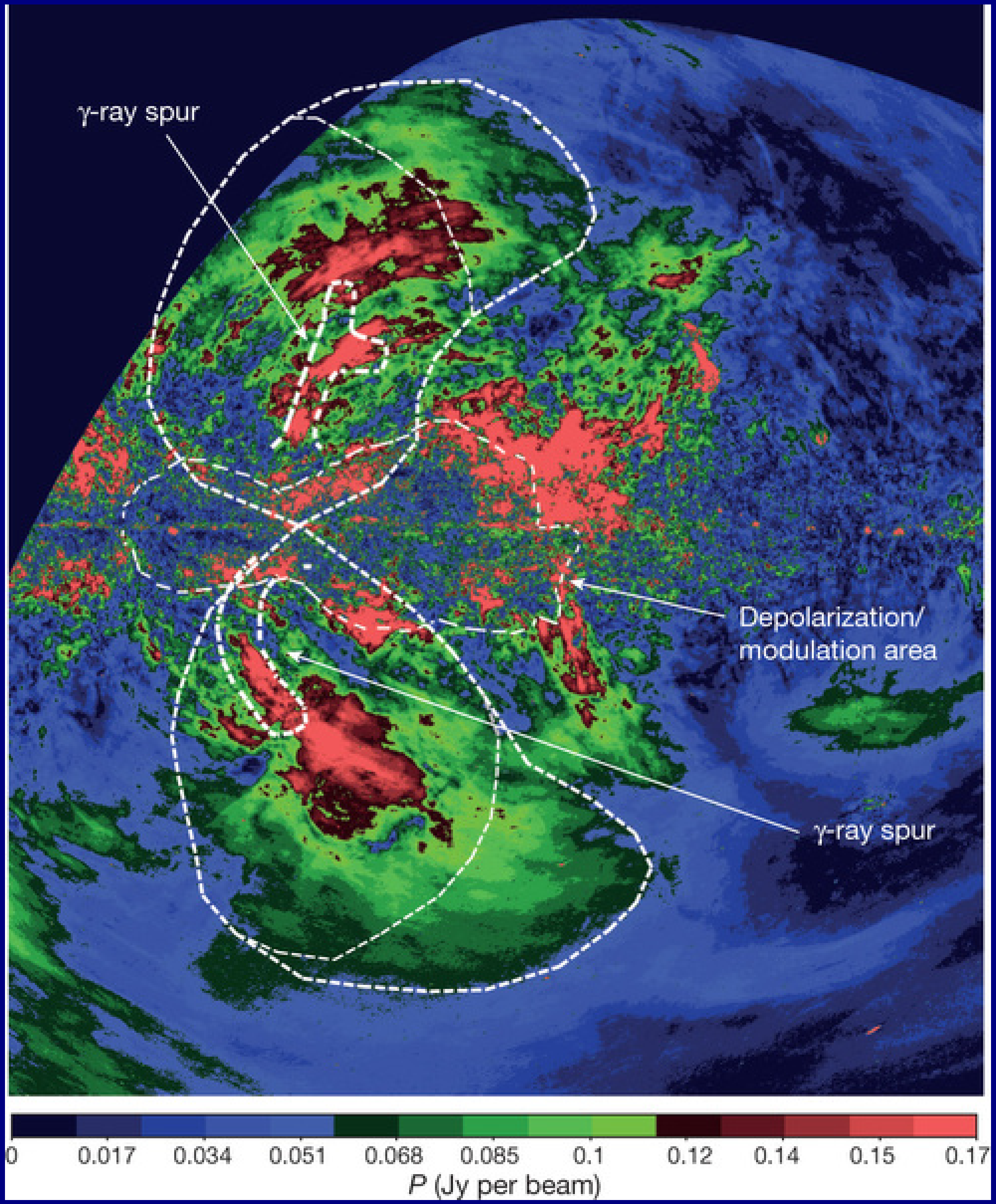
Planck haze (arXiv:1208.5483)
Overlaid on Fermi Bubbles



connection to 511 keV line ?



All are -
centred on Galactic Centre
leptonic
unknown origin

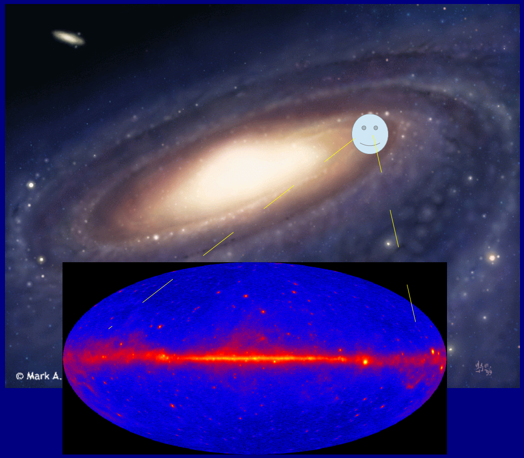


S-PASS
Southern Sky
Parkes Telescope
2.3 GHz
Polarized intensity

Carretti et al.
Nature 493, 66
(2 Jan 2013)

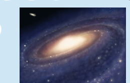
“Giant magnetized outflows from the centre of the Milky Way”
Correlates with Fermi Bubbles.
Produced by repeated episodes of star-formation at Galactic Centre?
Look for similar features in CHANGES galaxies? Visibility?

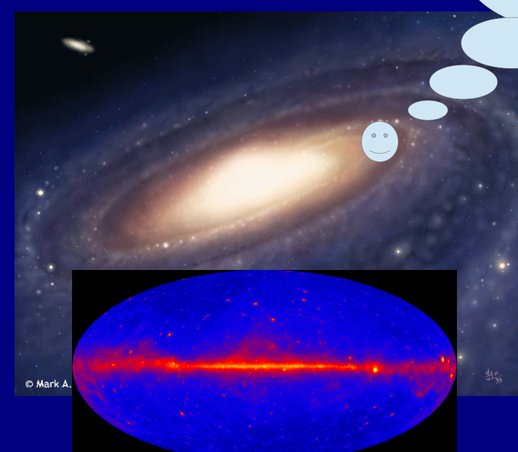
Since we live inside the Galaxy, global properties like multiwavelength luminosity (SED) are not easy to deduce.



SEDs of AGN etc are common, but not Milky Way

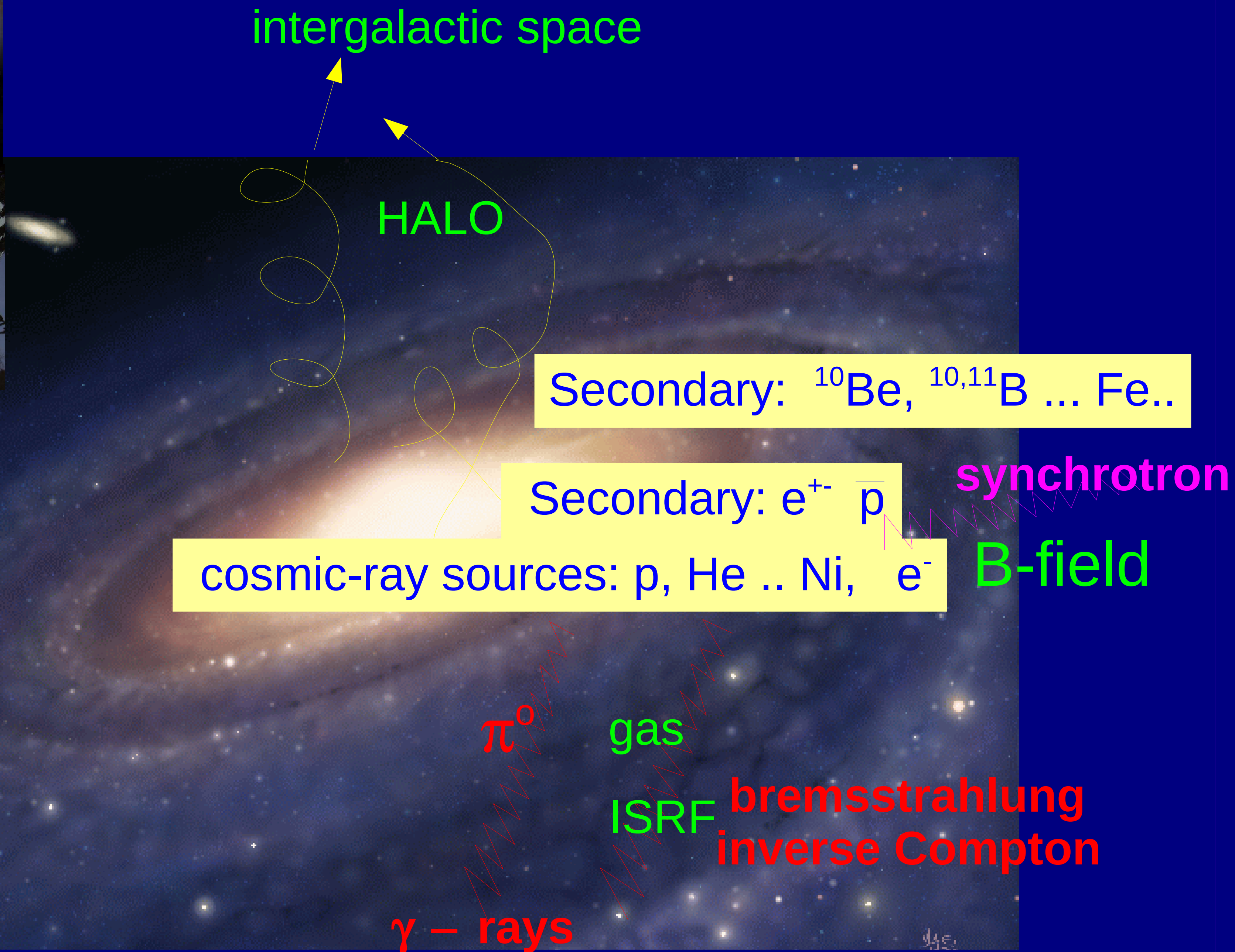
what does it
look from out
there ?



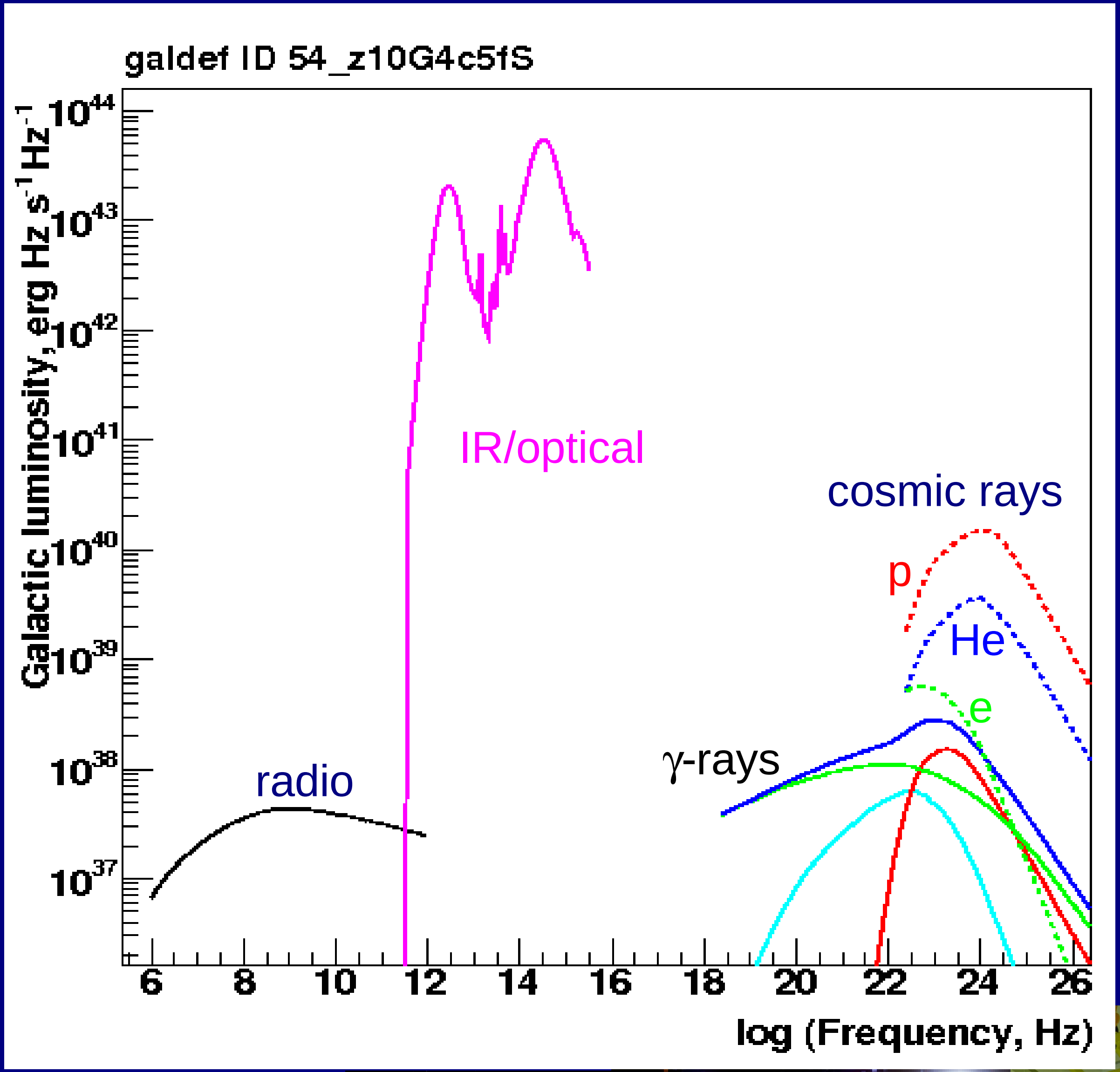


EXPERIMENTS

THEORY

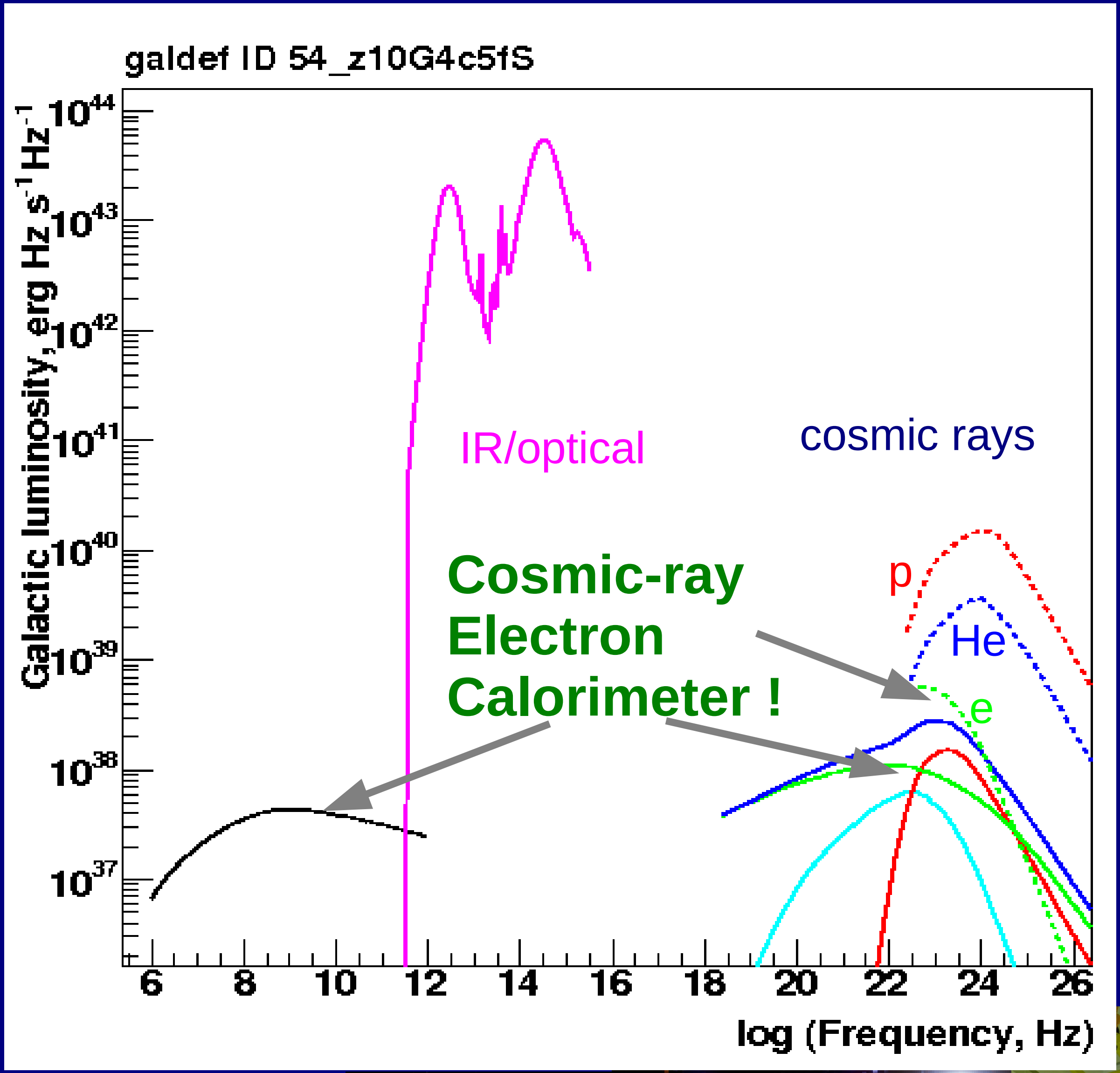


Galaxy luminosity over 20 decades of energy



Strong et al. (2010), ApJL 722, L58

Galaxy luminosity over 20 decades of energy

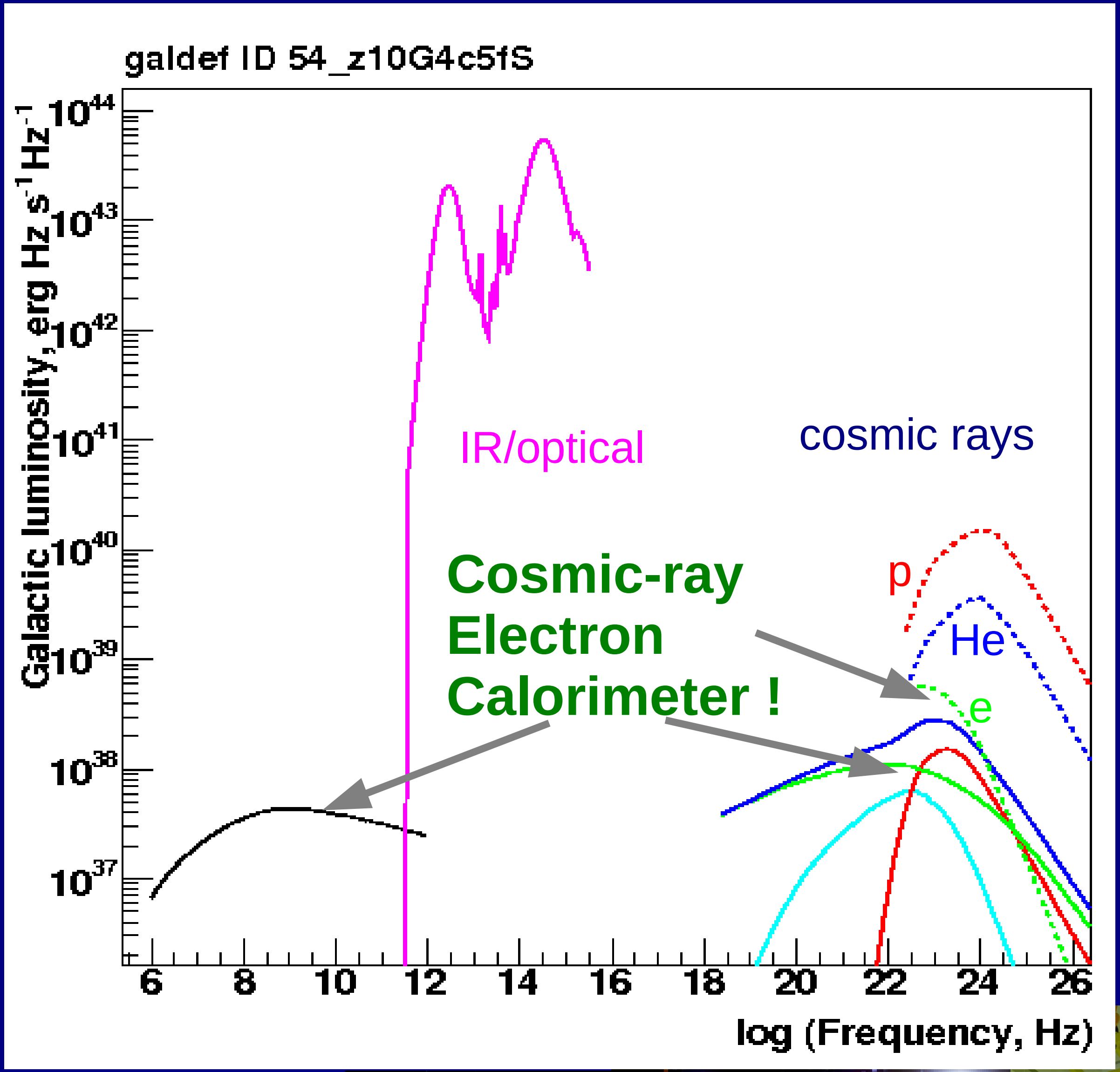


Strong et al. (2010), ApJL 722, L58

Galaxy luminosity over 20 decades of energy

Unfortunately gamma rays too weak for CHANGES galaxies!

But the rest is still interesting.



Strong et al. (2010), ApJL 722, L58

Galaxy luminosities

based on GALPROP model

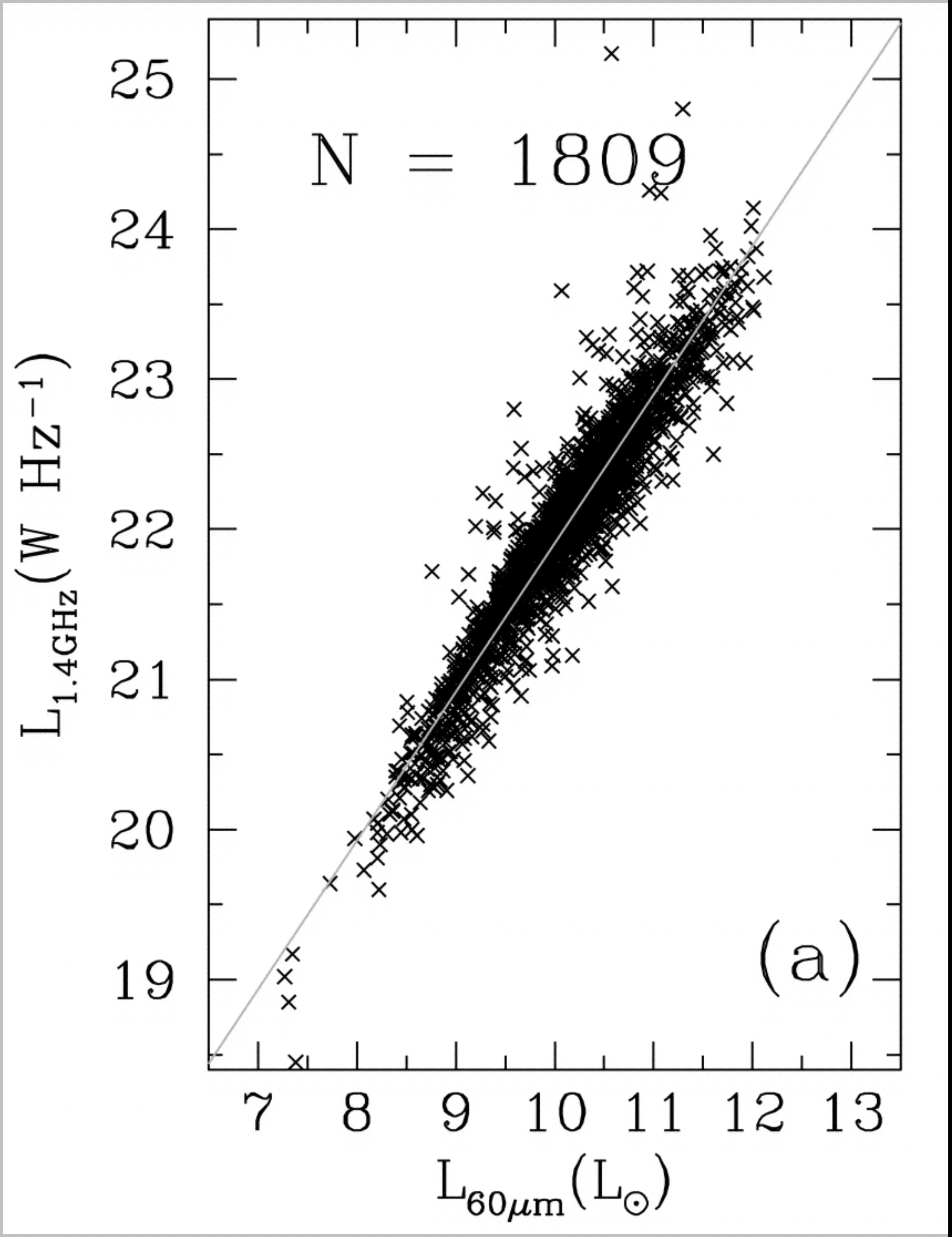
Fermi gamma rays and electrons

Cosmic-ray nuclei	10^{41}	
Cosmic-ray electrons	$1.6\ 10^{39}$	
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}	

erg s^{-1}

1% of nuclei energy converts to gamma rays
75% of electron energy converts to inverse Compton gamma rays
25% of electron energy converts to synchrotron radiation
Galaxy is electron calorimeter ! - but only if inverse Compton is included, not just synchrotron

FIR / radio correlation



Cosmic ray electron Calorimetry

Star-formation

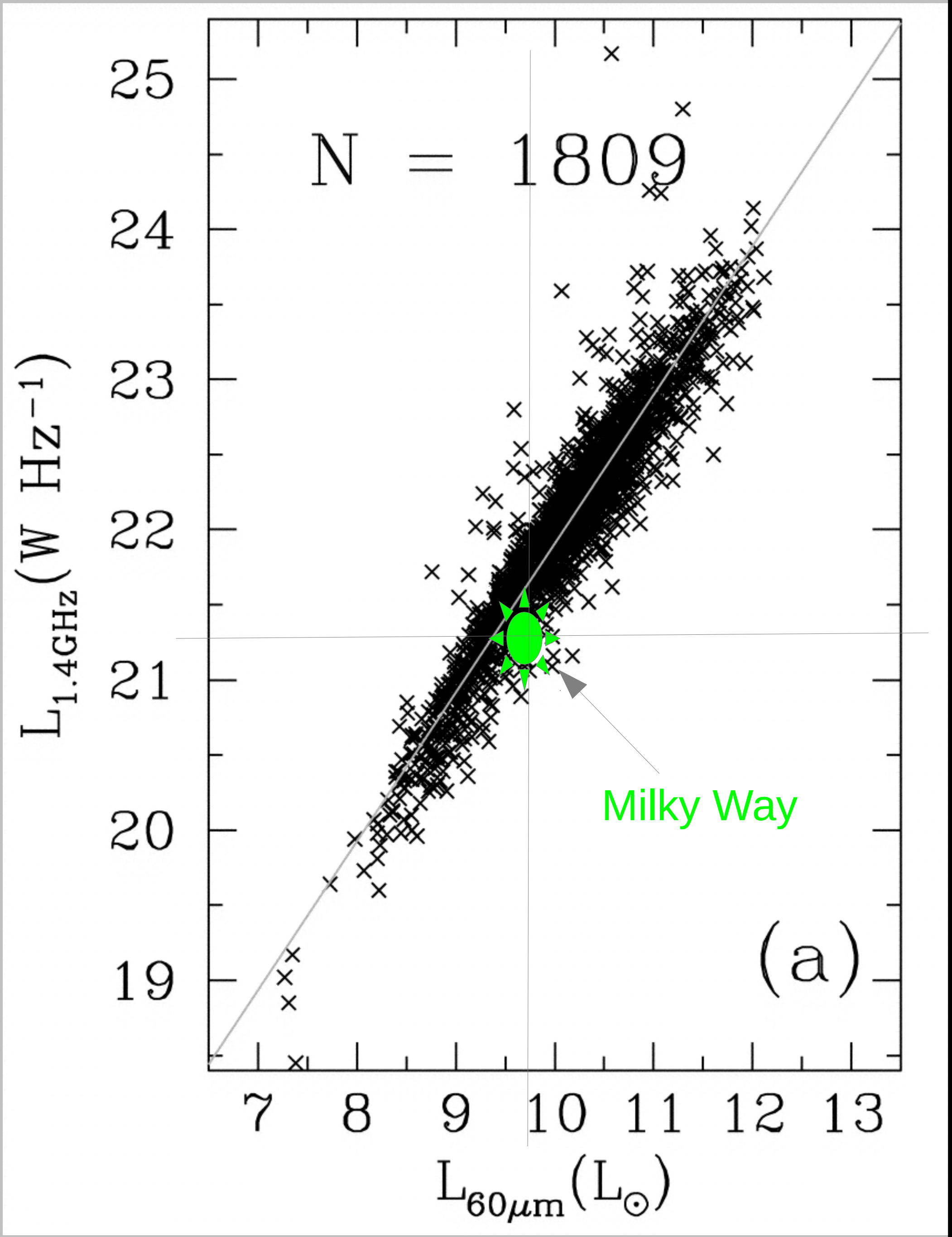
V

Cosmic rays

V

Synchrotron

FIR / radio correlation



Cosmic ray electron Calorimetry

Star-formation

V

Cosmic rays

V

Synchrotron

(Again) Some questions for CHANGES galaxies from cosmic-ray viewpoint :

1. Do they support the naïve expectations of standard electron propagation?
   = injection in disk, propagation with energy losses in halo by diffusion
   and/or convection.
   The test: spectral index variations with distance from disk.

2. If YES - we can get the propagation parameters and compare with Milky Way, where we have much more detailed information but are inside it.

3. If NO - what revisions are required, is the standard model any use at all?
   Are things just too complicated in reality?
   Back to the drawing board?

4. If SOMETIMES – where and why does it break down?

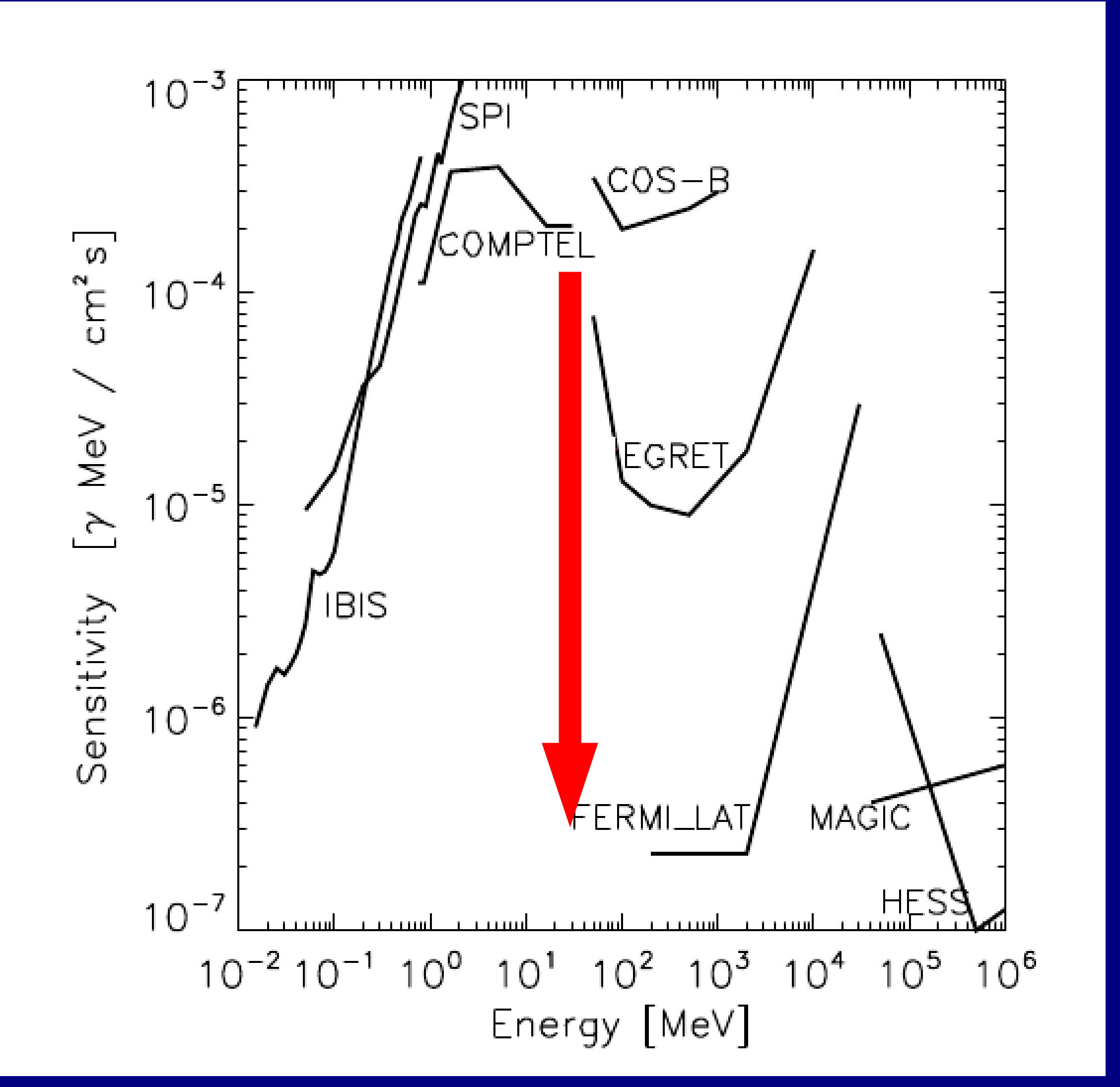
5. Is there a cosmic-ray disk and a halo, or just a halo as assumed in many models?

6. Lepton calorimeters? - FIR-radio correlation.

7. How much does thermal emission confuse things?

Hopefully at this meeting we make progress on some of these questions!

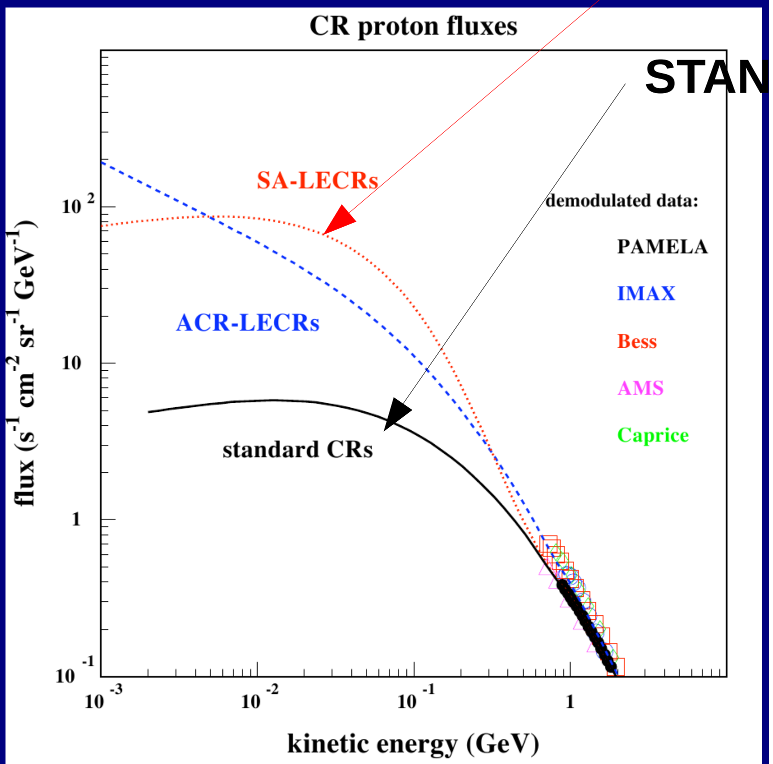
Additional stuff for reference



SPI
COS−B
COMPTEL
EGRET
IBIS
FERMI_LAT
MAGIC
HESS
Sensitivity [γ MeV / cm² s]
Energy [MeV]
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10⁻² 10⁻¹ 10⁰ 10¹ 10² 10³ 10⁴ 10⁵ 10⁶

Interstellar chemistry → ionization rates → cosmic rays → nuclear lines

Low energy cosmic rays

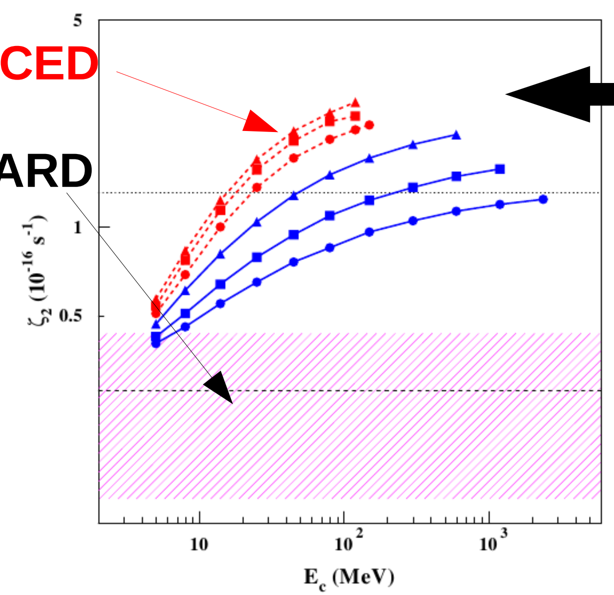


Ionization rate

ENHANCED

STANDARD

FROM CHEMISTRY OF H_3^+



Cutoff energy

Fig. 4.— Calculated ionization rates of cosmic rays in dense molecular clouds supposing that particles with energies below 10 MeV per nucleon do not penetrate these places. Red symbols (connected by the dashed lines) show the values for SA-LECRs with spectral indices $s = 2.0$ (triangles), $s = 2.35$ (squares) and $s = 2.7$ (circles), blue symbols (connected by the full lines) the values for ACR-LECRs, $s = 2.0$ (triangles), $s = 2.4$ (squares) and $s = 2.7$ (circles). The ionization rate of standard CRs (0.35×10^{-16} s^{-1}) is added. The dashed line and the hatched area show the recommended value of van der Tak & van Dishoeck (2000) for the cosmic-ray ionization rate and its uncertainty in dense molecular cloud cores (ζ_{CR} = (0.28 ± 0.14) $\times$ 10^{-16}s^{-1}). The dotted line represents their upper limit ($\sim1.3\times10^{-16}$ s^{-1}).

Benhabiles-Mezhoud,Kiener, Tatischeff & Strong, 2012, ApJ in press, arXiv 1212.1622.

Nuclear lines and line quasi-continuum using low-energy cosmic rays based on ionization rates from interstellar cloud chemistry

Low-energy Cosmic rays

ENHANCED

STANDARD

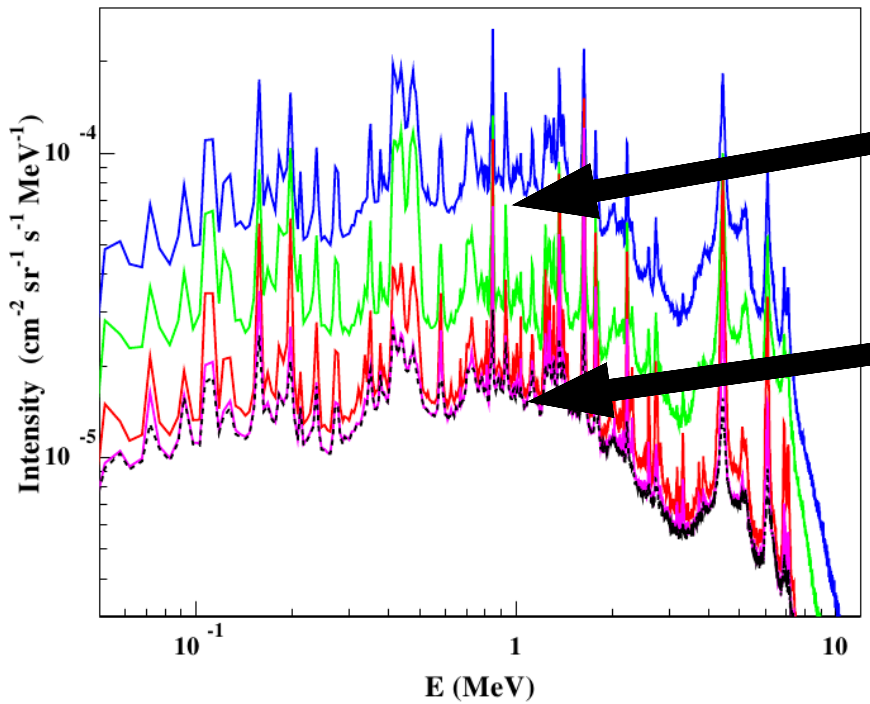
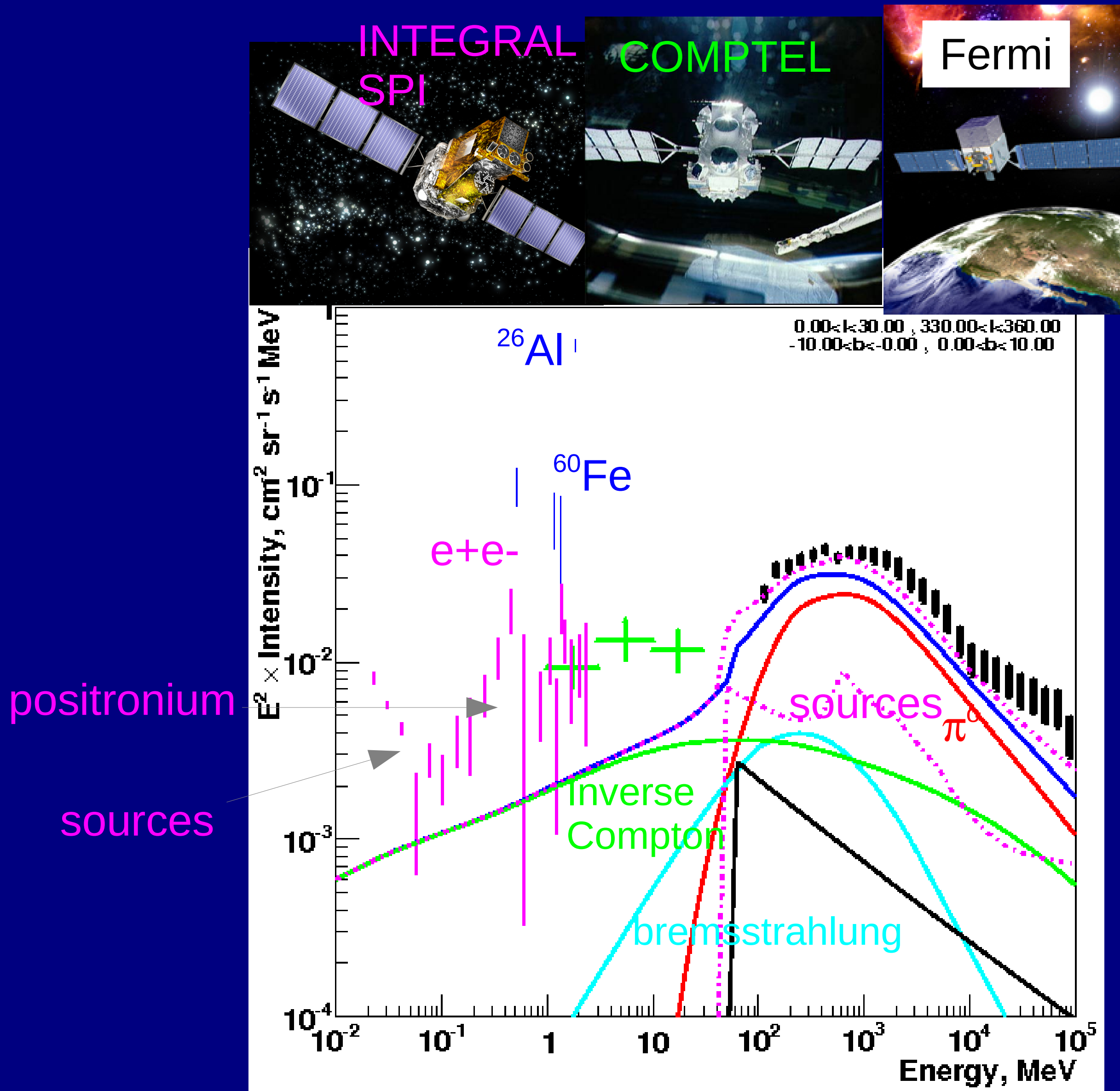


Fig. 6.— Calculated nuclear γ-ray line emissions from the inner Galaxy for CRs with ACR-LECR components following the model of Scherer et al. (2008a) with $s = 2.4$, $E_c = 5$, 25 and 1200 MeV (magenta, red and green lines, resp.) and SA-LECR with $s = 2.0$ and $E_c =$ 120 MeV (blue line). The emission due to the standard CR component alone is shown by the dashed black line.

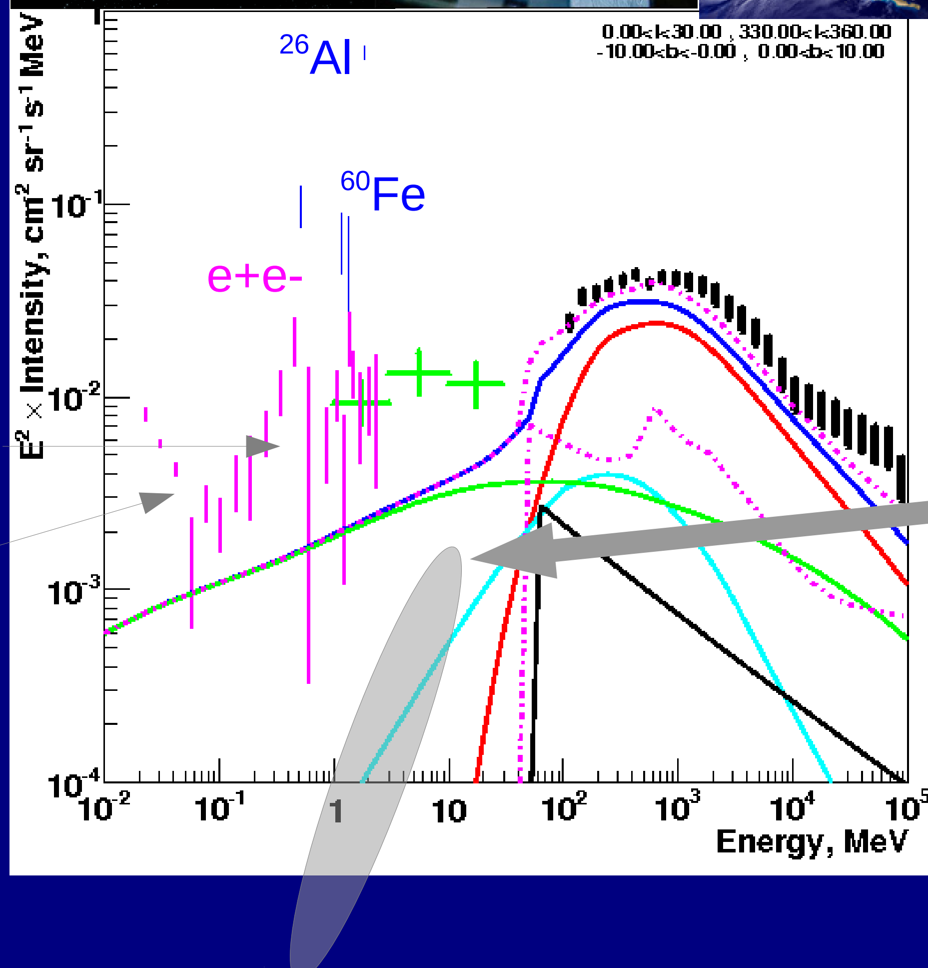
Benhabiles-Mezhoud,Kiener, Tatischeff & Strong, 2012, ApJ in press, arXiv 1212.1622

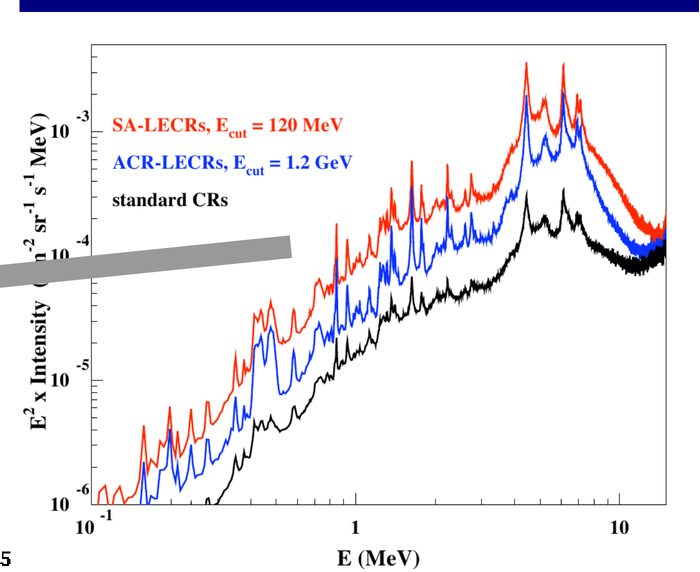
More chance to detect nuclear lines !

Inner Galaxy: keV to TeV



Inner Galaxy: keV to TeV





Need 10-100 times more sensitivity to study nuclear lines and line continuum
But enhance fluxes already competitive with inverse Compton at 10 MeV !

END