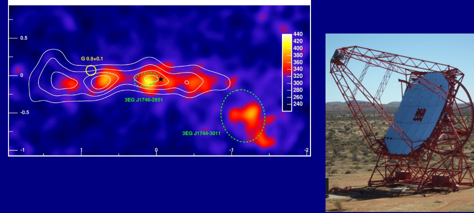
μeV to TeV Radiation from Cosmic Rays in the Galaxy

Andy Strong,

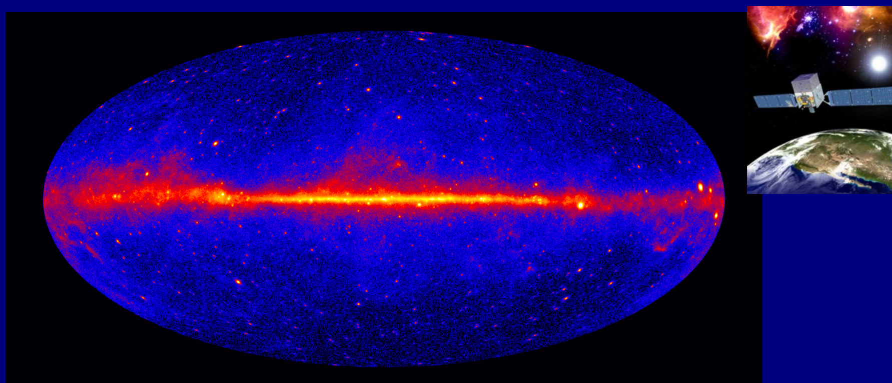
MPE Garching

Workshop: Searching for the the Sources of Galactic Cosmic Rays
APC Paris, 14-16 December 2012

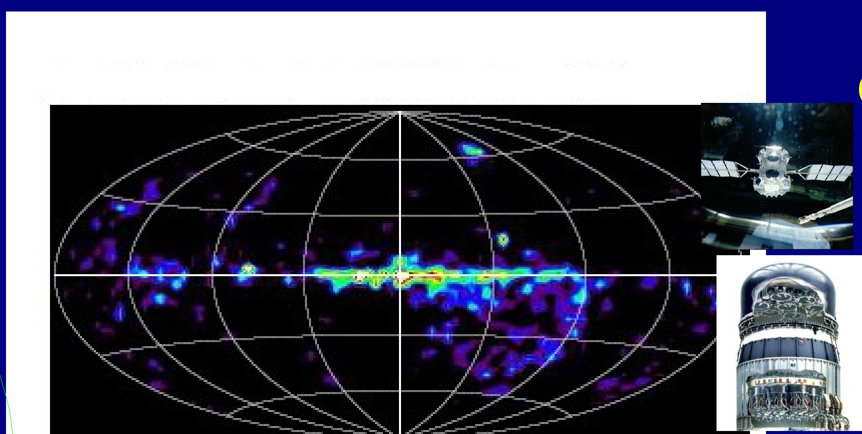
TeV

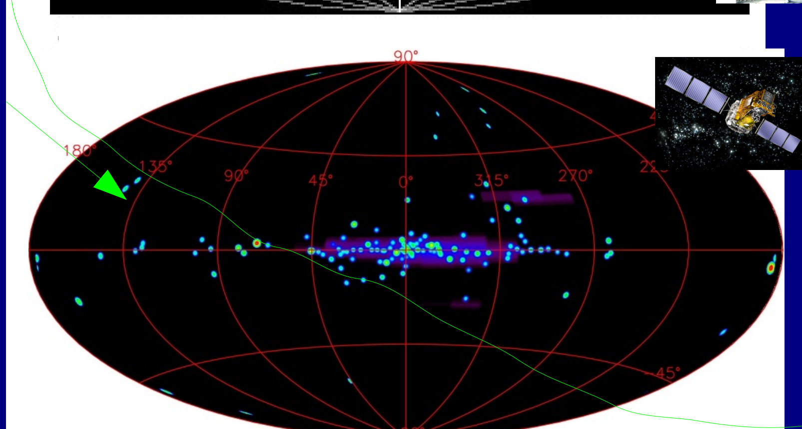


GeV

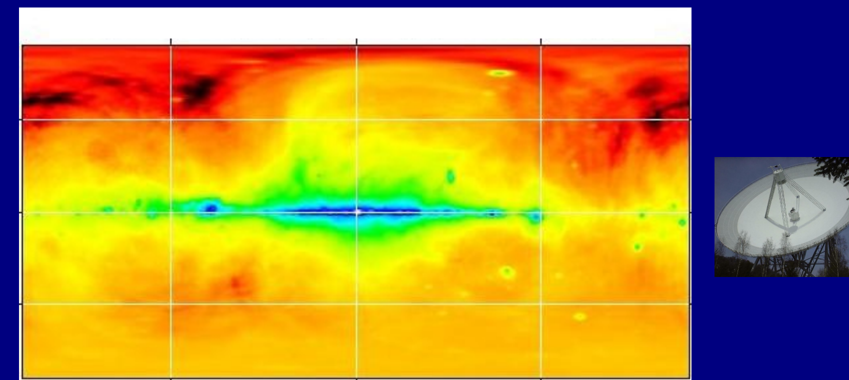


MeV



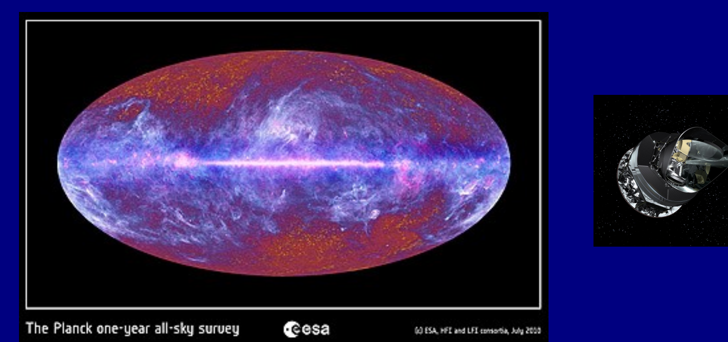


Cosmic-ray interactions
probed
by their photon emission



μeV

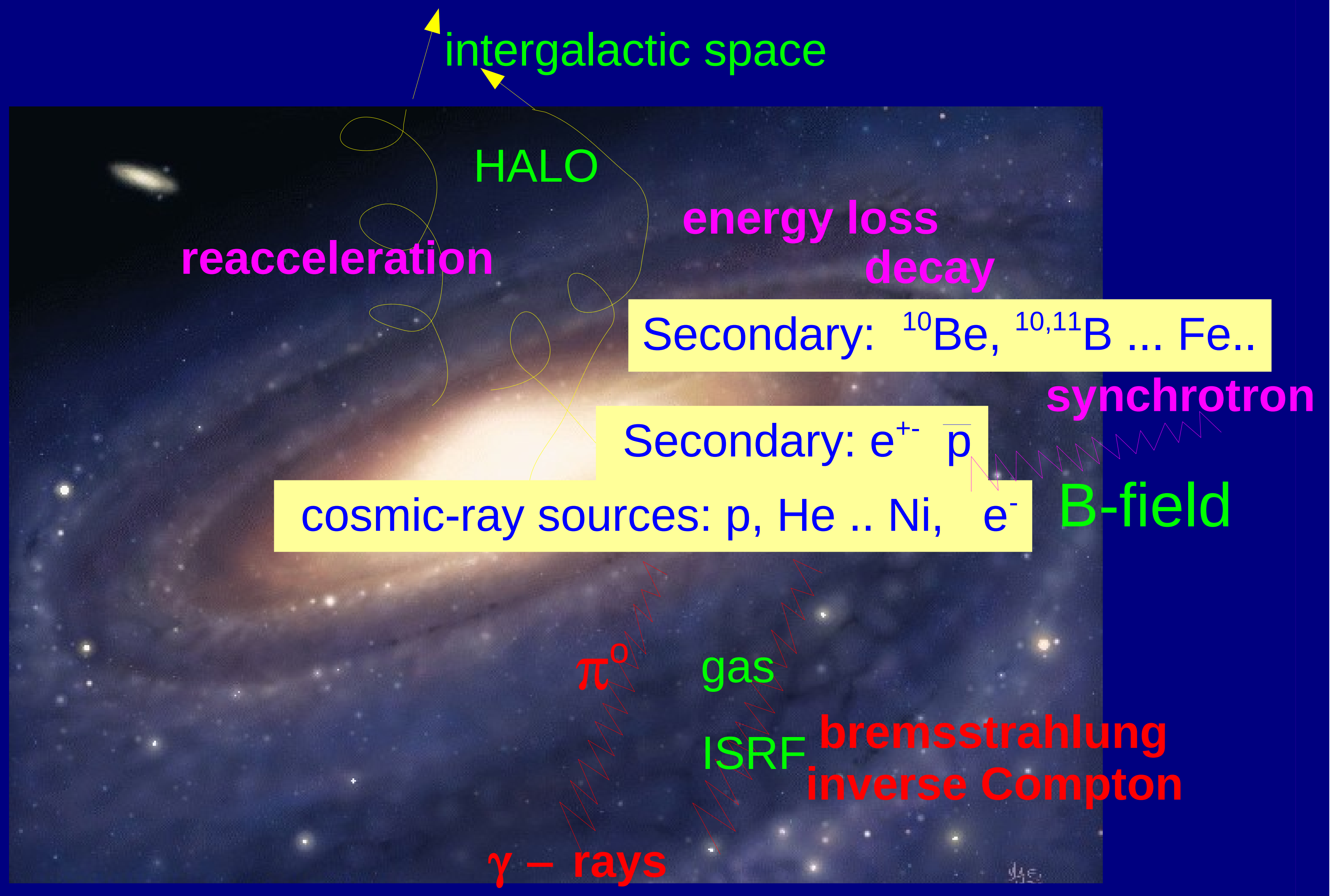
GHz

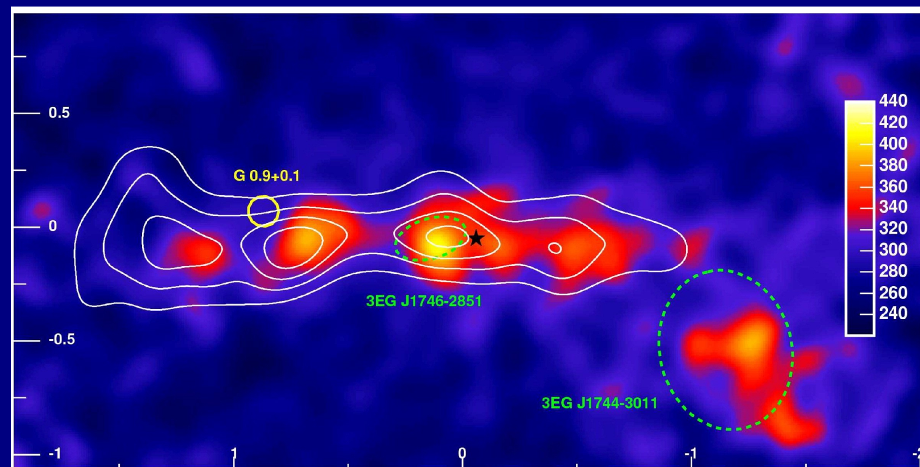


meV

THz

COSMIC RAYS produce many observables



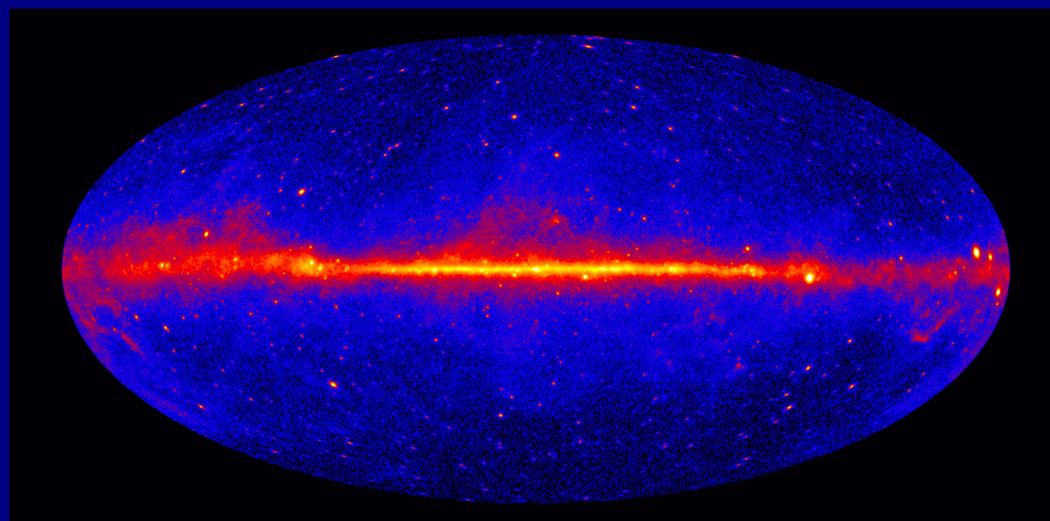


H.E.S.S.
Galactic centre region

Cosmic-rays: >TeV protons interacting with gas

Fermi
Gamma-ray
Space Telescope

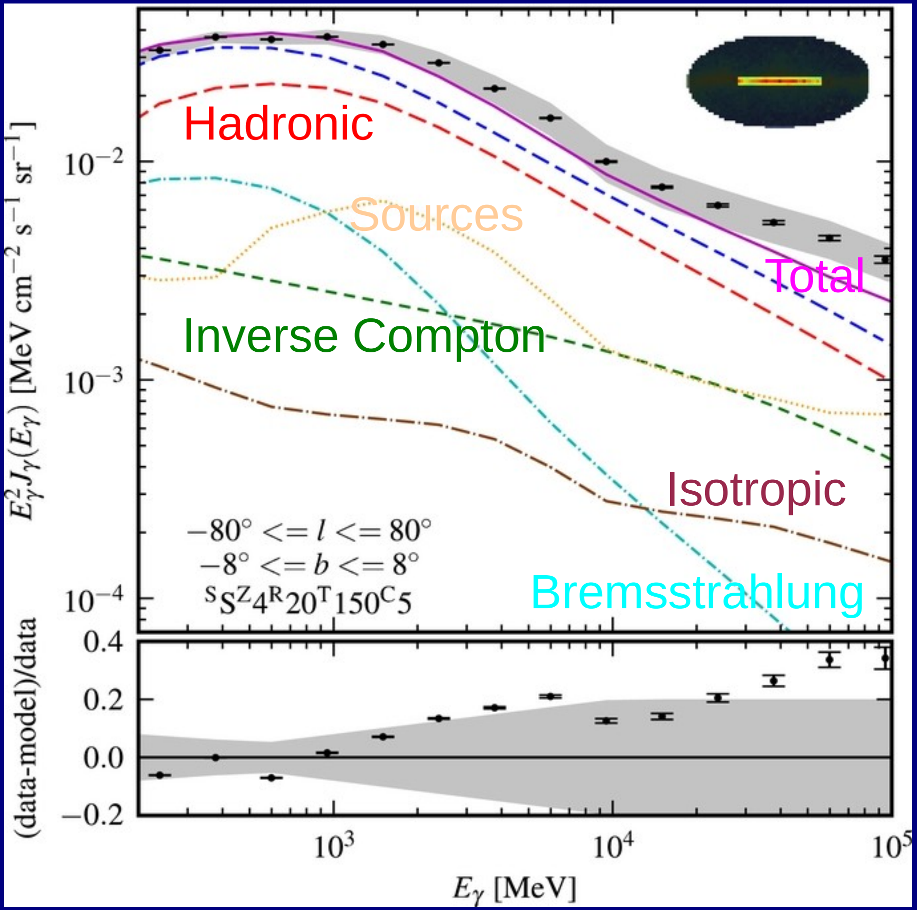
1 – 10 GeV



Cosmic-ray protons interacting with gas : hadronic

Cosmic-ray electrons and positrons interacting with interstellar radiation : inverse Compton

Fermi-LAT
Inner Galaxy Gamma Ray Spectrum



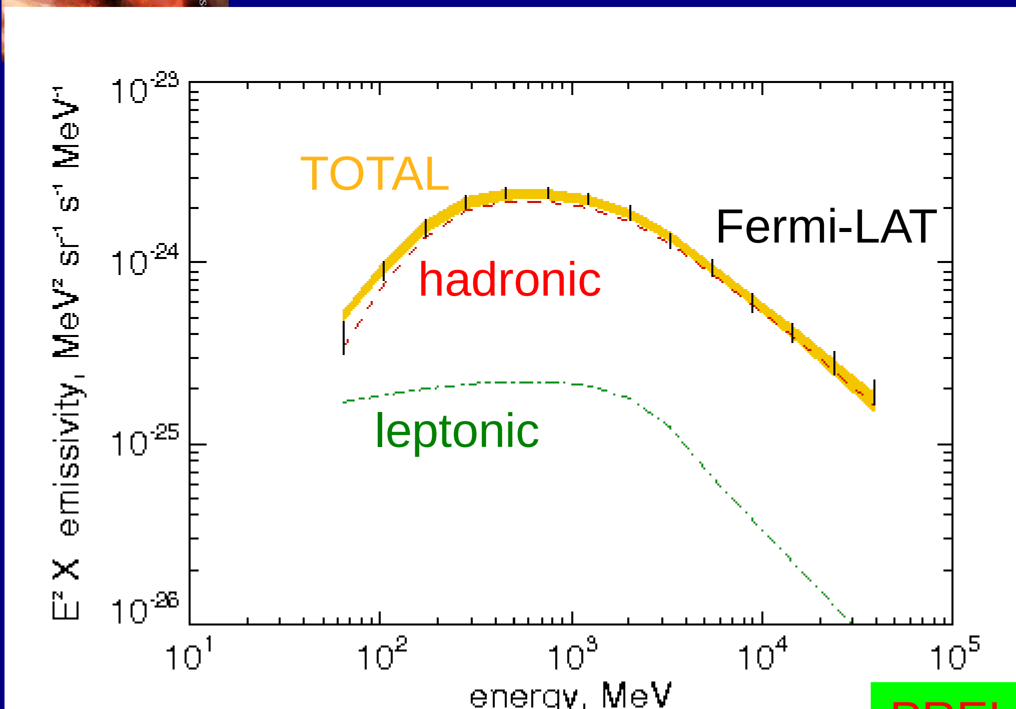
(see talk by Igor Moskalenko, this conference)

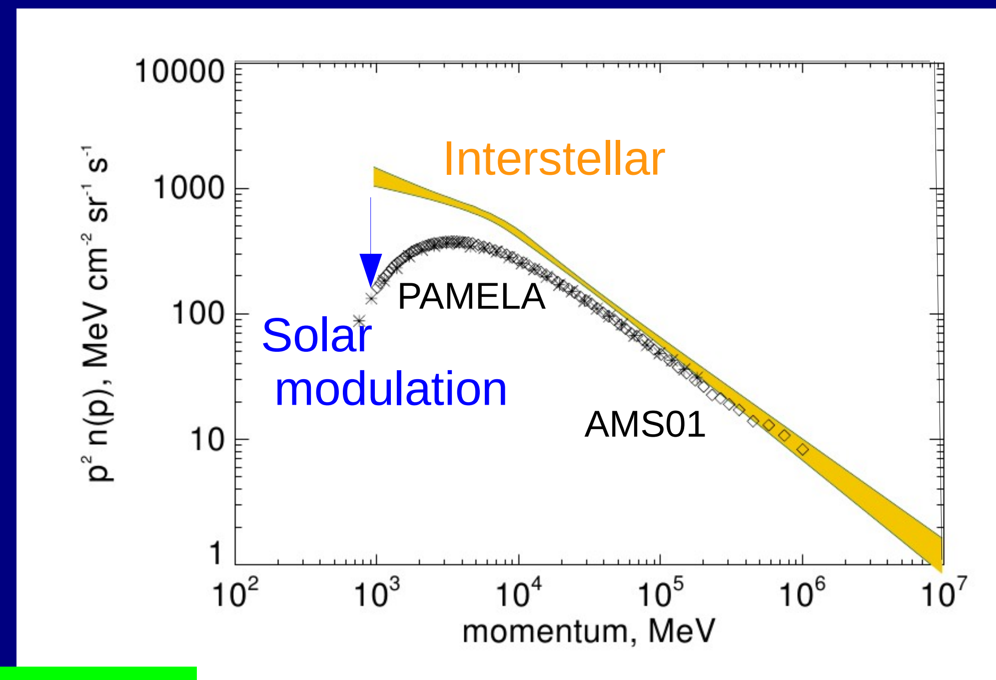
Ackermann et al. ApJ 750, 3 (2012)

Interstellar Cosmic ray spectra derived from gamma rays

Method : Bayesian analysis

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





PRELIMINARY

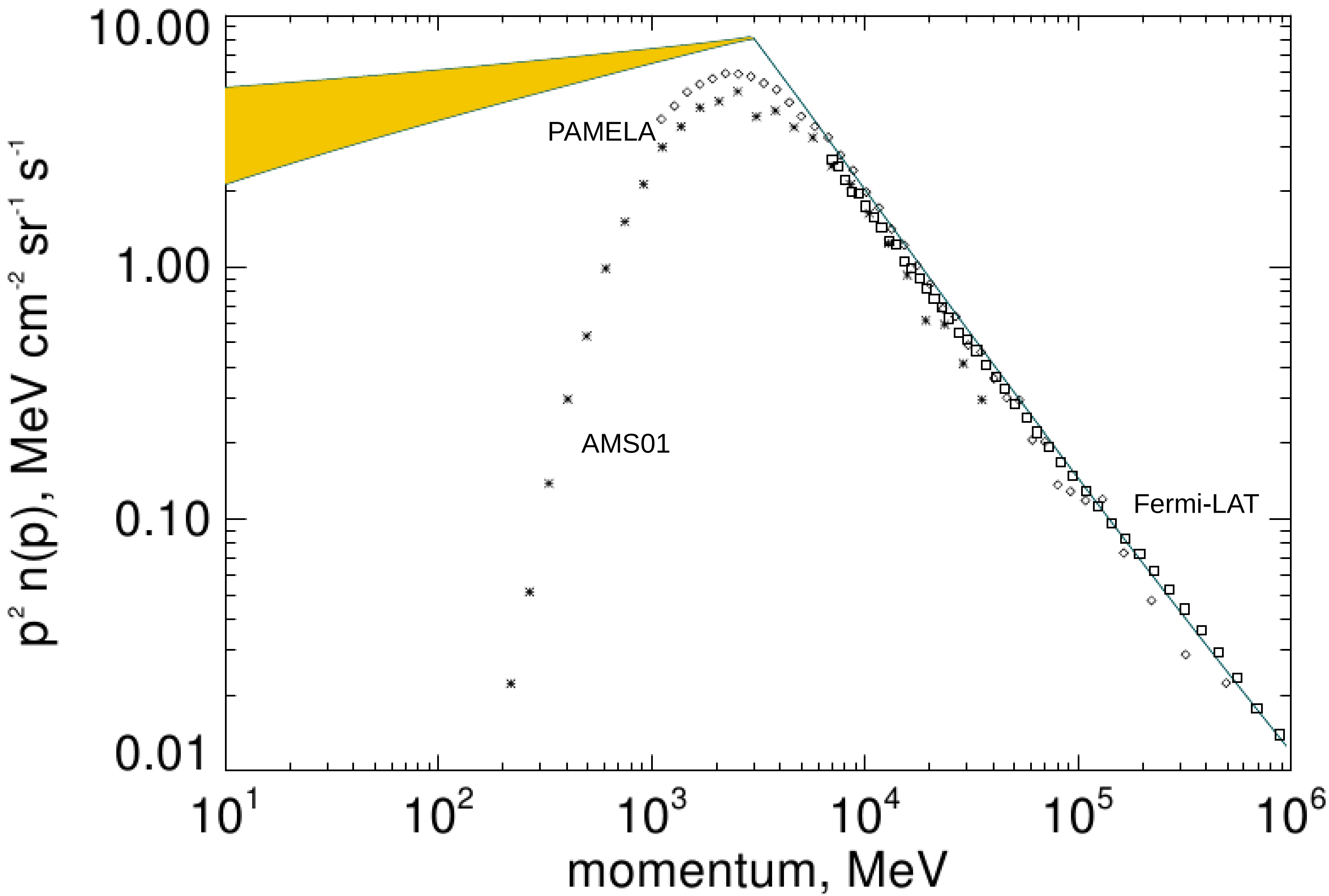
Below 10 GeV affected by solar modulation, but gamma rays probe the interstellar spectrum.

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 electrons from synchrotron, gamma rays and direct measurements



PRELIMINARY

Effects of Cross Sections on Fits to Emissivity

This model shown in previous two slides
||
V

CROSS-SECTIONS

	Kamae Kachelriess & Ostapchenko	Dermer, Stecker Stephens & Badhwar	
proton break momentum	6.5 (±2.1) GeV	6.7 (±2.5) GeV	
proton index below break	2.4 (0.1)	2.5 (0.1)	
proton index above break	2.9 (0.1)	2.8 (0.1)	
proton normalization	1.3 (0.1)	1.4 (0.1)	
electron break momentum	3.0	3 .0	(fixed from synchrotron)
electron index below break	1.8 (0.1)	1.9 (0.1)	

PRELIMINARY

See also talk by Chuck Dermer, this conference and Fermi Symposium 2012

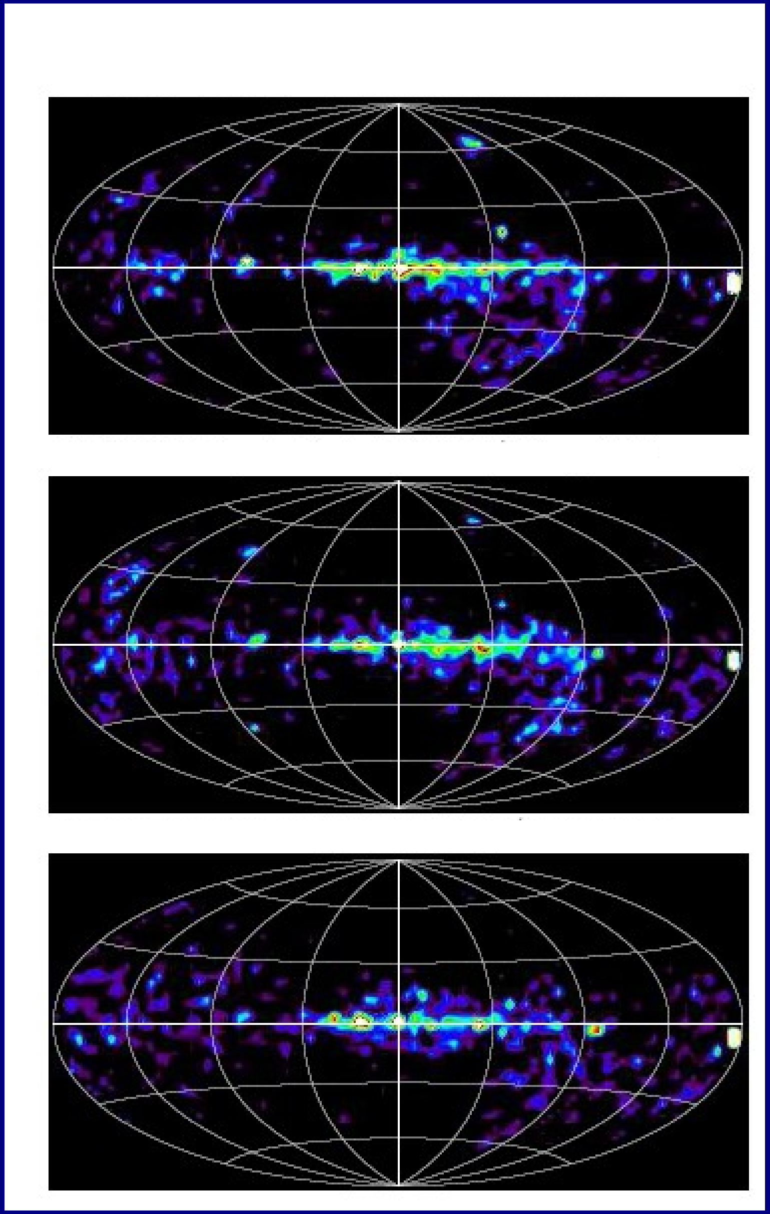
CGRO/ COMPTEL

MeV continuum

1 – 3 MeV

3 – 10 MeV

10 – 30 MeV

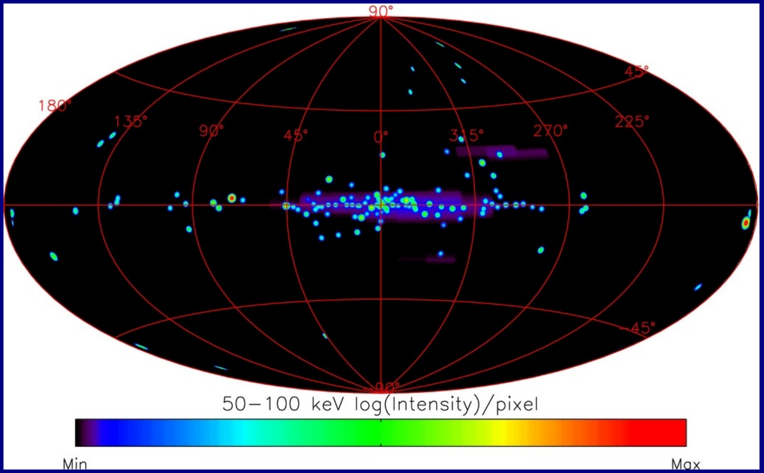


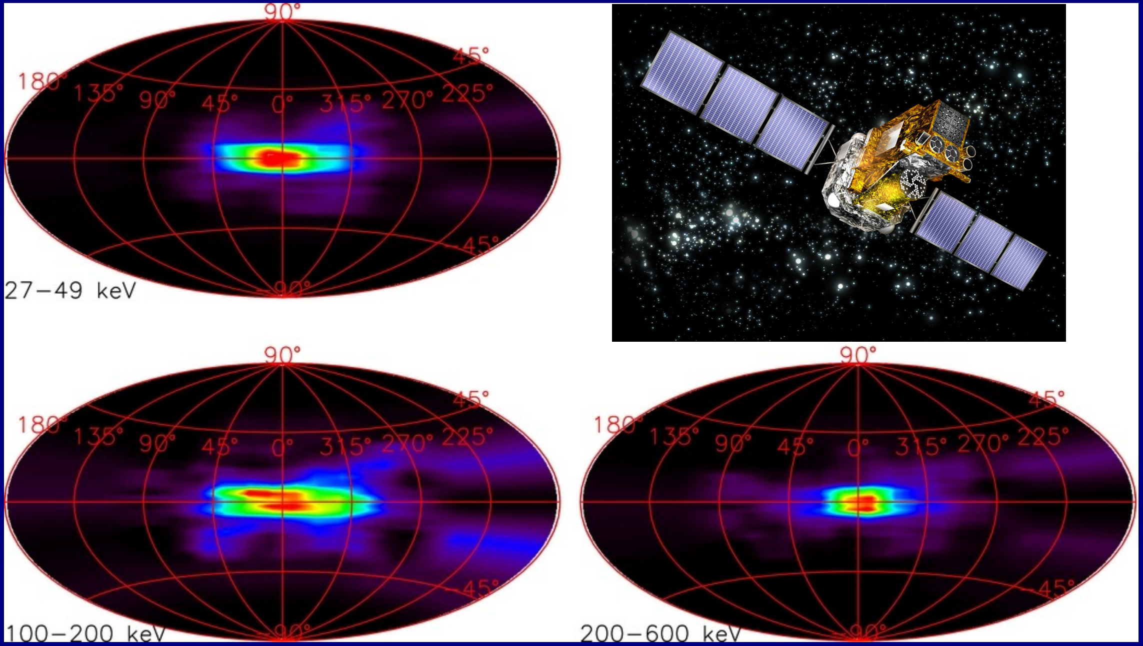
Unique heritage data:
COMPTEL analysis continues....

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

INTEGRAL / SPI
Continuum skymaps

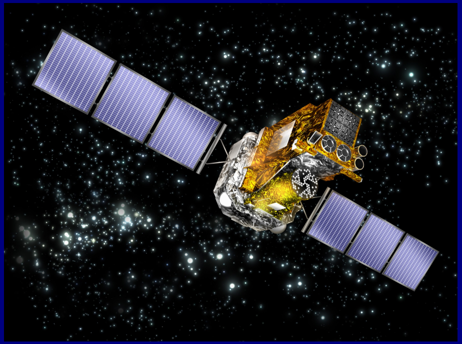
Bouchet et al.
ApJ 739, 29 (2011)

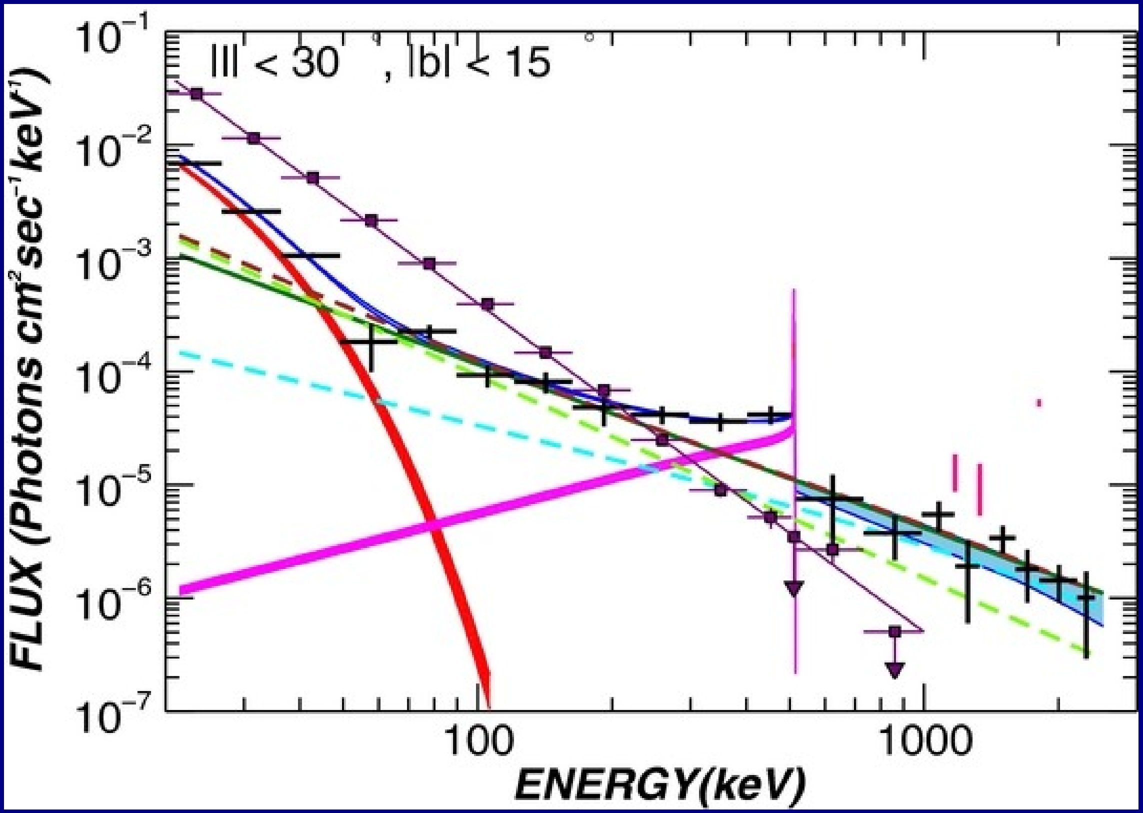




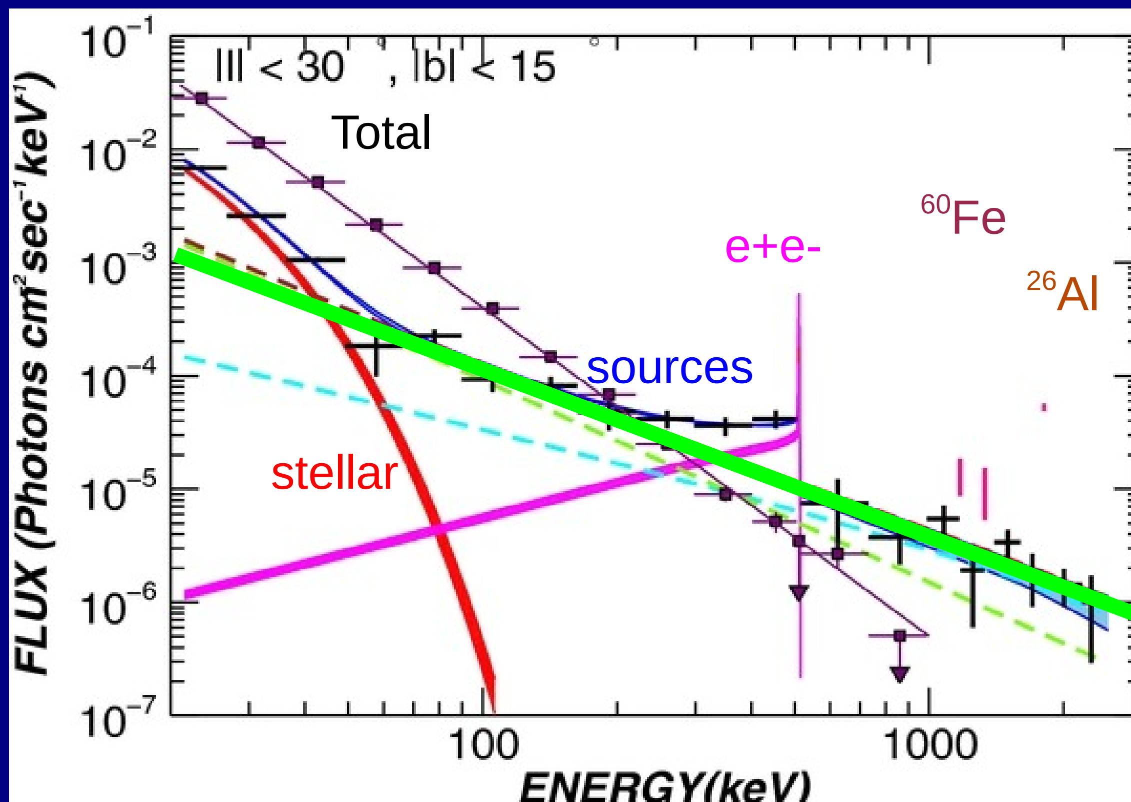
A real mix of processes !

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



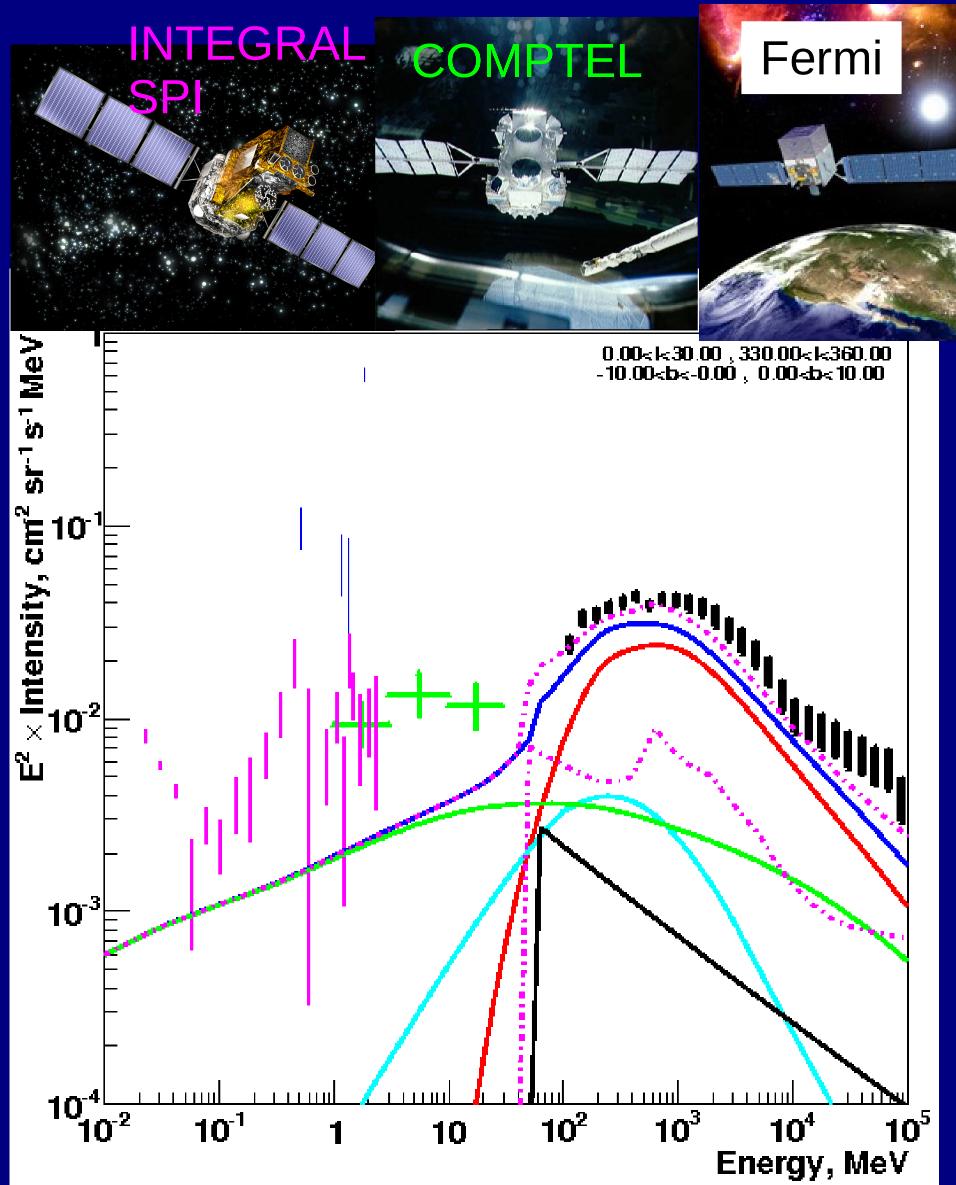


Inner Galaxy
INTEGRAL / SPI
Bouchet et al.   ApJ 739, 29 (2011)



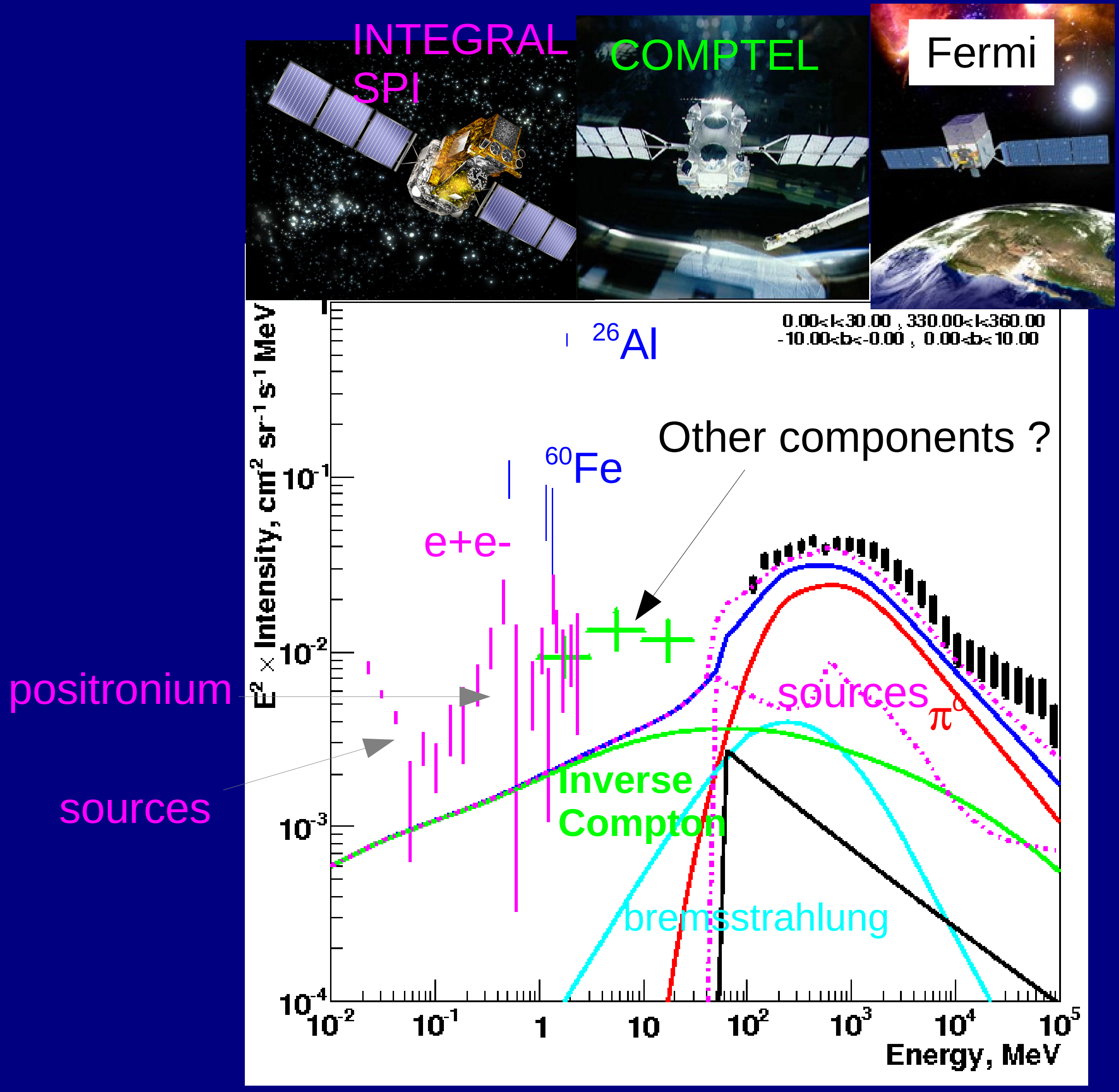
Non-thermal:
Cosmic-ray interactions

Inner Galaxy: keV to TeV



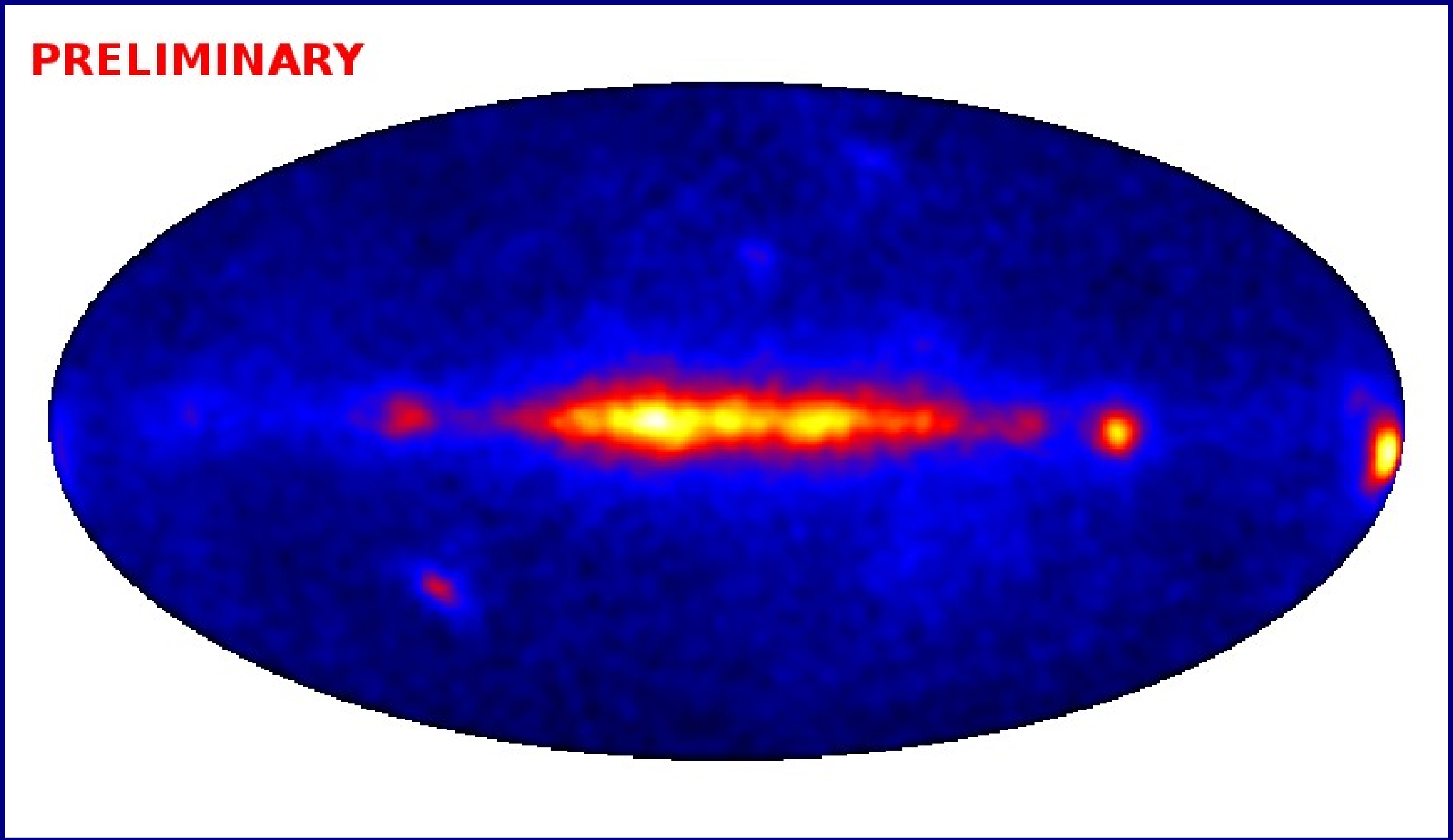
Strong 2011, Proc. 12 ICATPP Conf. arXiv:1101.1381

Inner Galaxy: keV to TeV



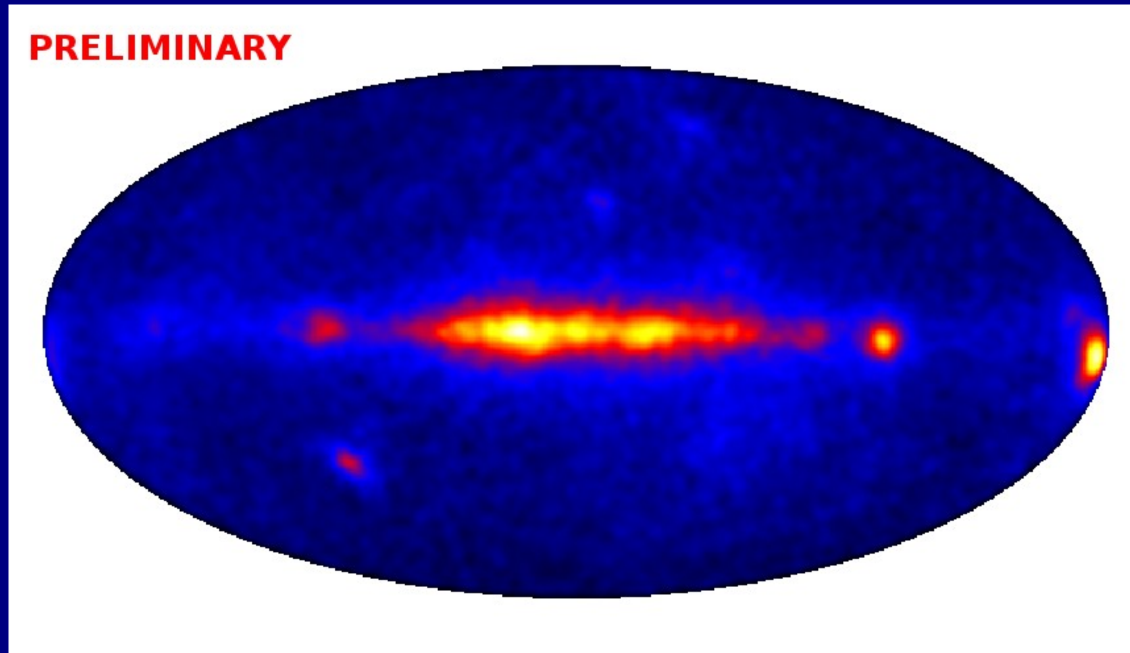
GeV electrons – inverse Compton - important for MeV gamma rays !

Fermi-LAT 25 – 40 MeV



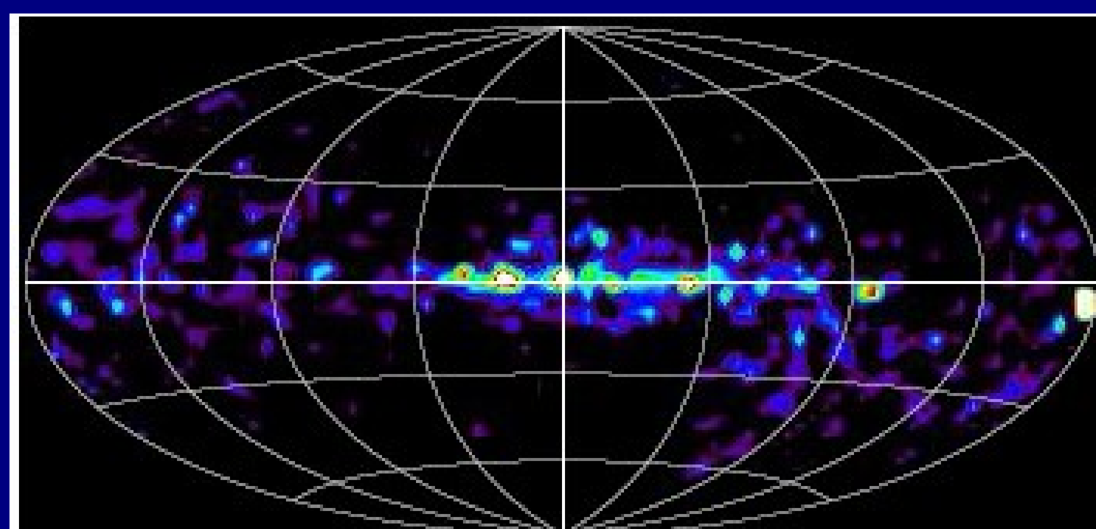
NB low angular and energy resolution !
Nominal energy range: photons may originate from range 10 to <100 MeV.
But valuable to bridge the MeV gap.

Fermi-LAT 25-40 MeV

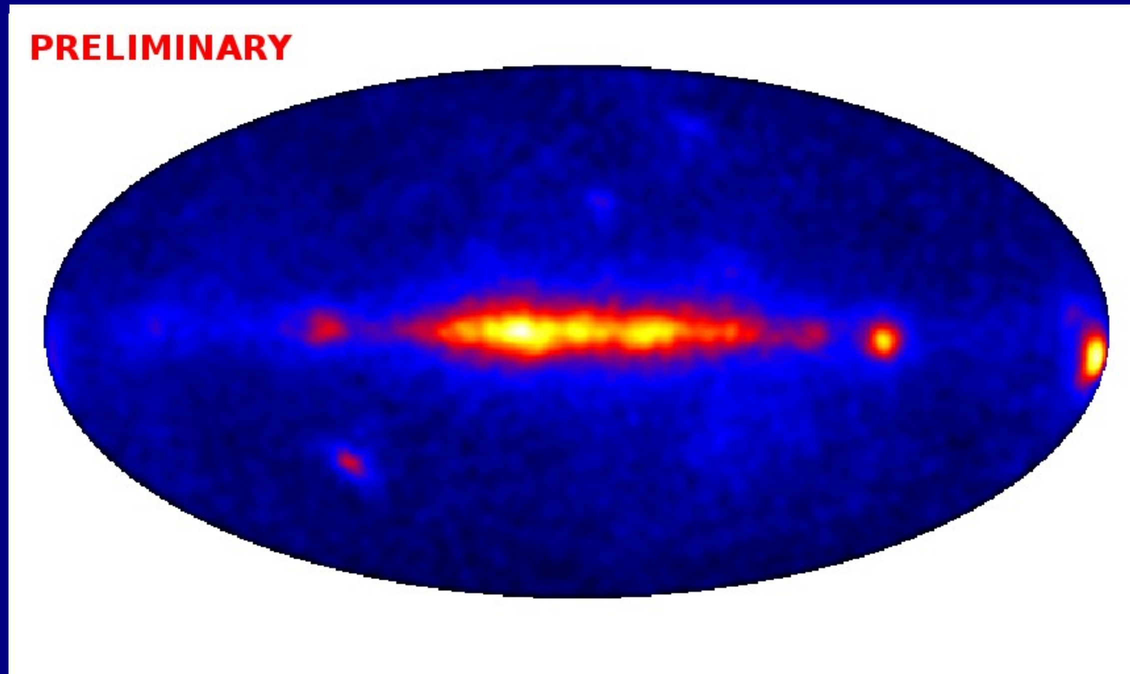


meets

COMPTEL 10-30 MeV

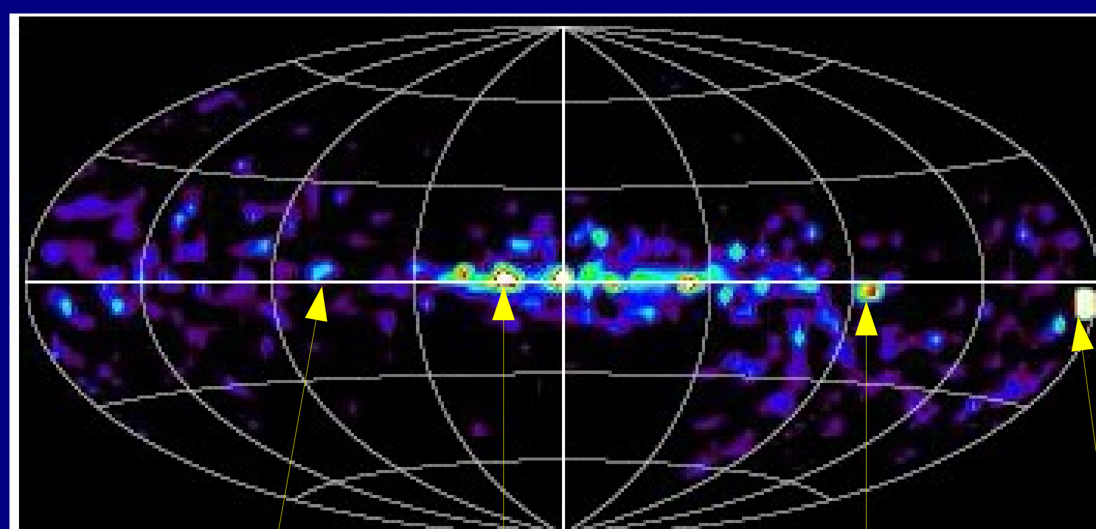


Fermi-LAT 25-40 MeV



meets

COMPTEL 10-30 MeV

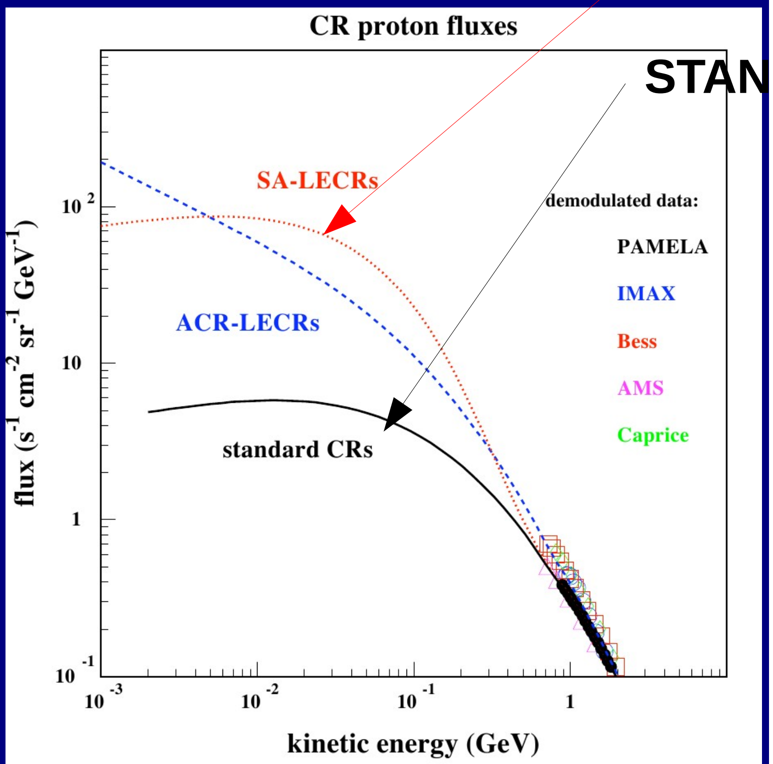


Galactic Plane

Cyg X-1 LS5039 Vela PSR Crab

Interstellar chemistry → ionization rates → cosmic rays → nuclear lines

Low energy cosmic rays



Ionization rate

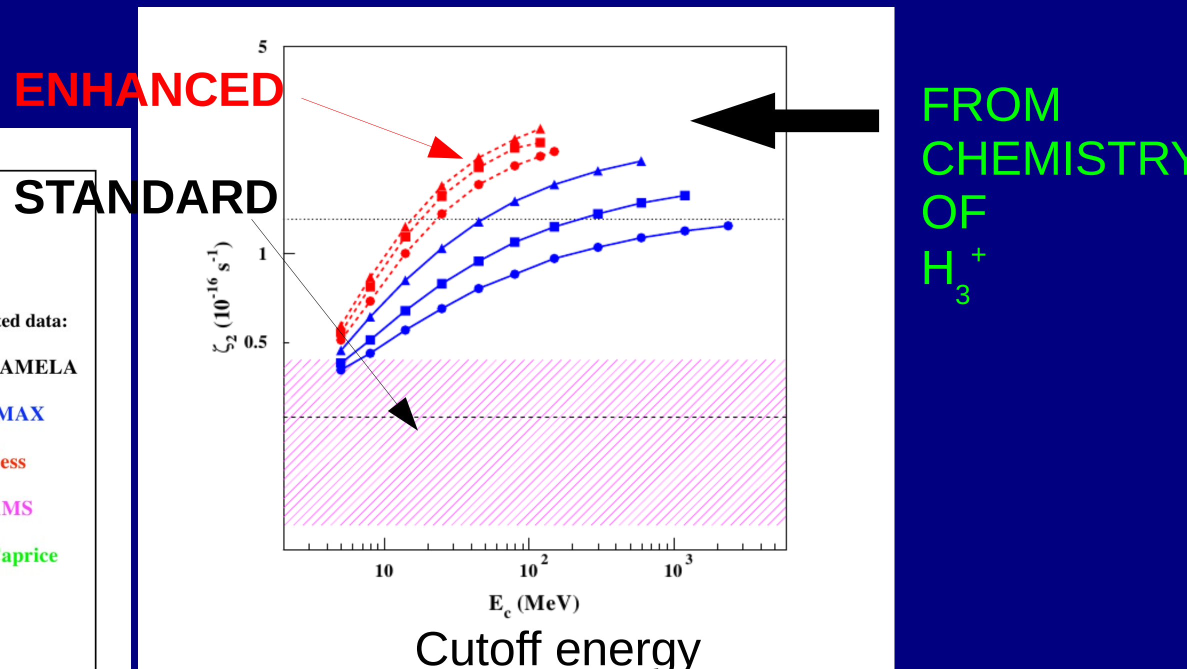


Fig. 4.— Calculated ionization rates of cosmic rays in dense molecular clouds supposing that particles with energies below 10 MeV per nucleon do not penetrate these places. Red symbols (connected by the dashed lines) show the values for SA-LECRs with spectral indices $s = 2.0$ (triangles), $s = 2.35$ (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 ($\zeta_{CR} = (0.28\pm0.14) \times 10^{-16}$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

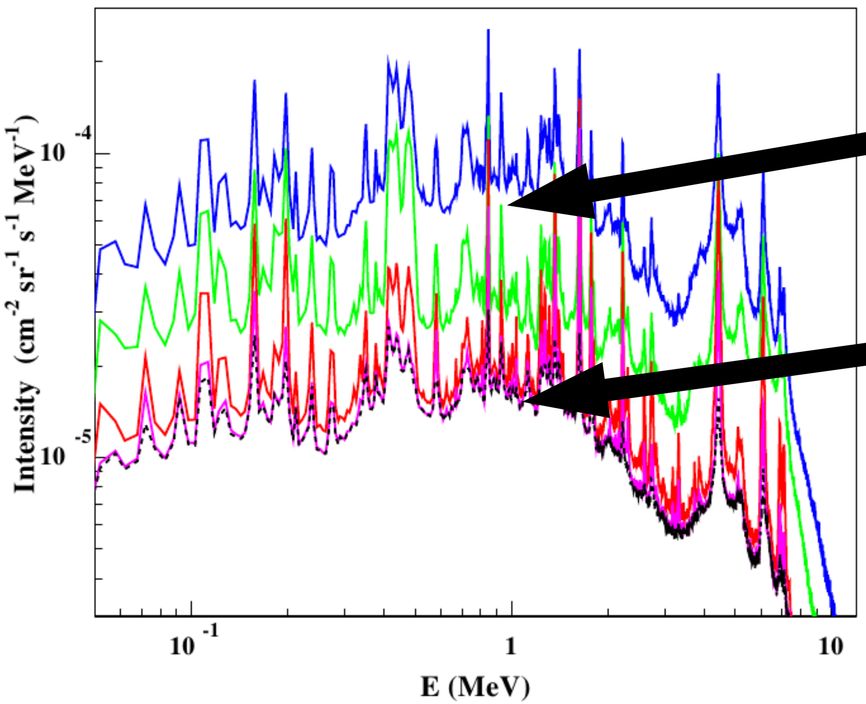
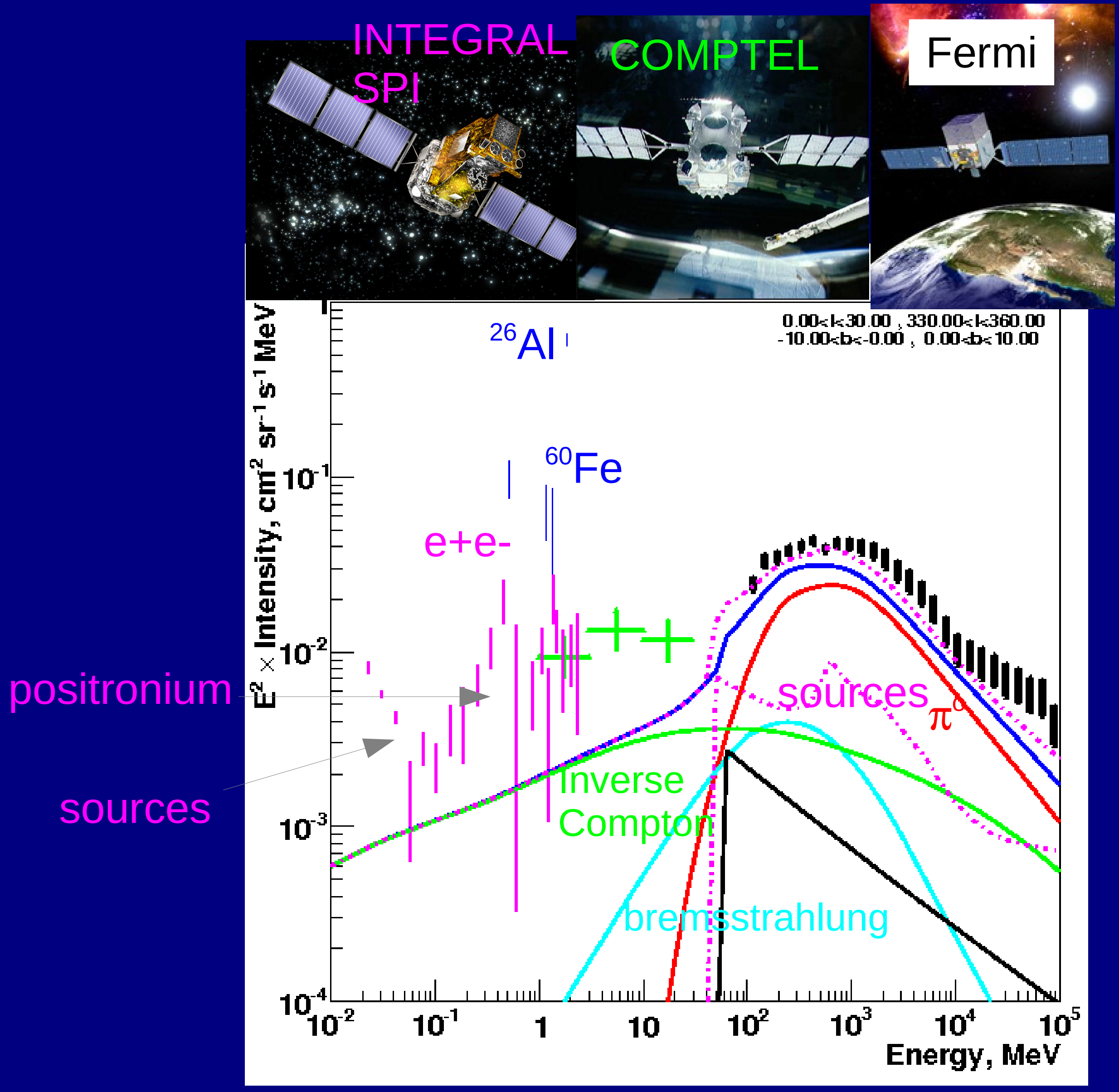


Fig. 6.— Calculated nuclear γ-ray line emissions from the inner Galaxy for CRs with ACR-LECR components following the model of Scherer et al. (2008a) with $s = 2.4$, $E_c = 5$, 25 and 1200 MeV (magenta, red and green lines, resp.) and SA-LECR with $s = 2.0$ and $E_c =$ 120 MeV (blue line). The emission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

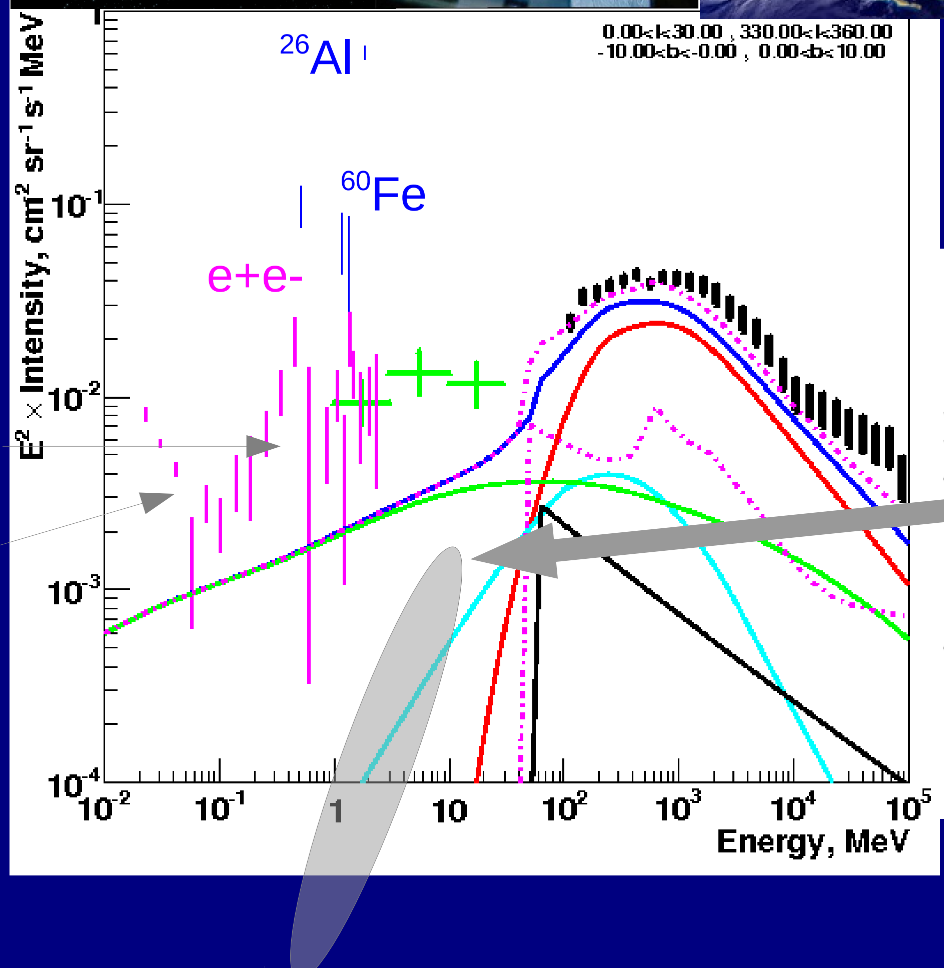
Benhabiles-Mezhoud,Kiener, Tatischeff & Strong, 2012, ApJ in press, arXiv 1212.1622

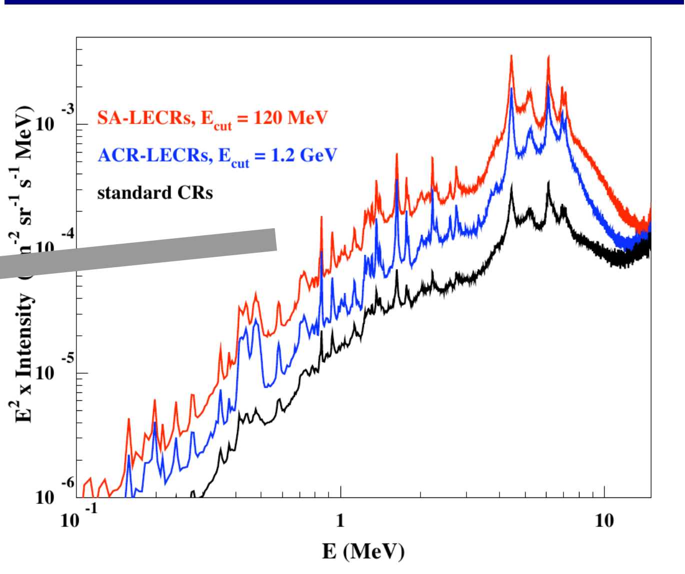
More chance to detect nuclear lines !

Inner Galaxy: keV to TeV

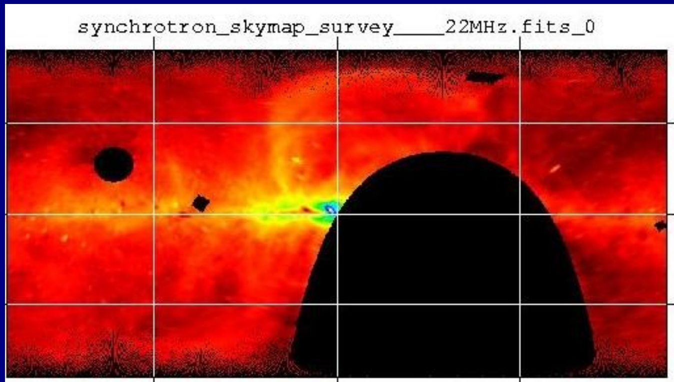


Inner Galaxy: keV to TeV

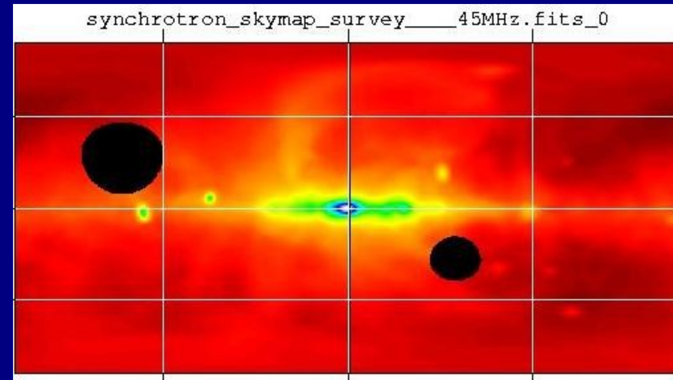




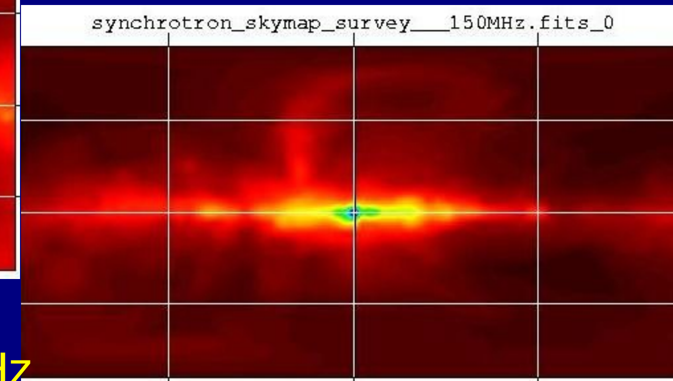
Need 10-100 times more sensitivity to study nuclear lines and line continuum
But enhance fluxes already competitive with inverse Compton at 10 MeV !



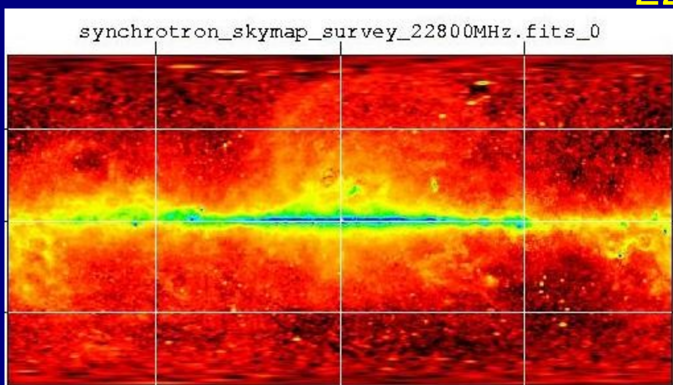
22 MHz



45 MHz

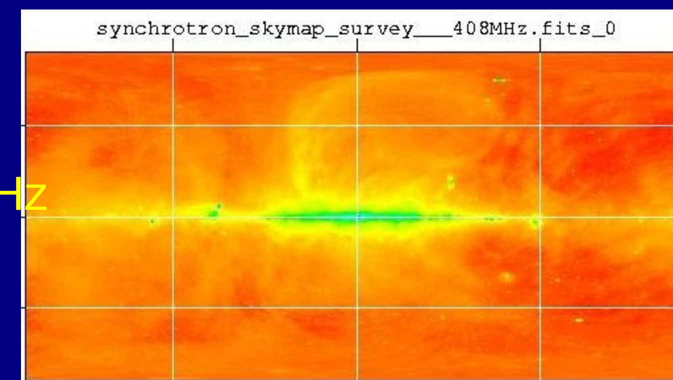


150 MHz

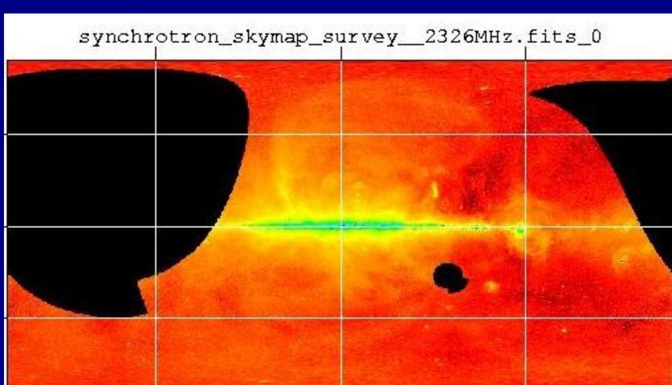


23 GHz

Continuum sky surveys

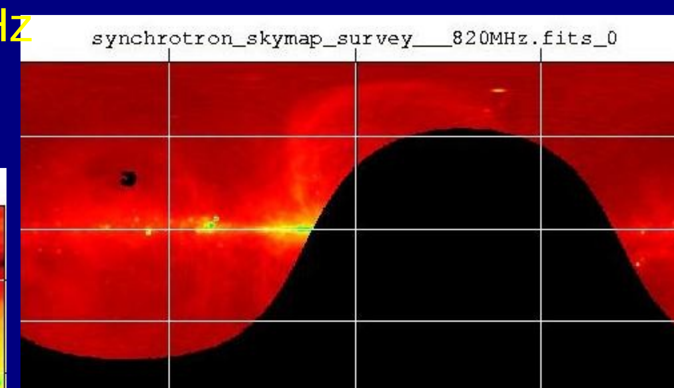


408 MHz

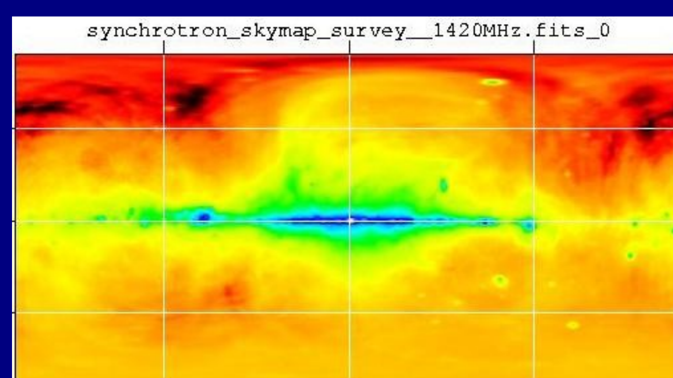


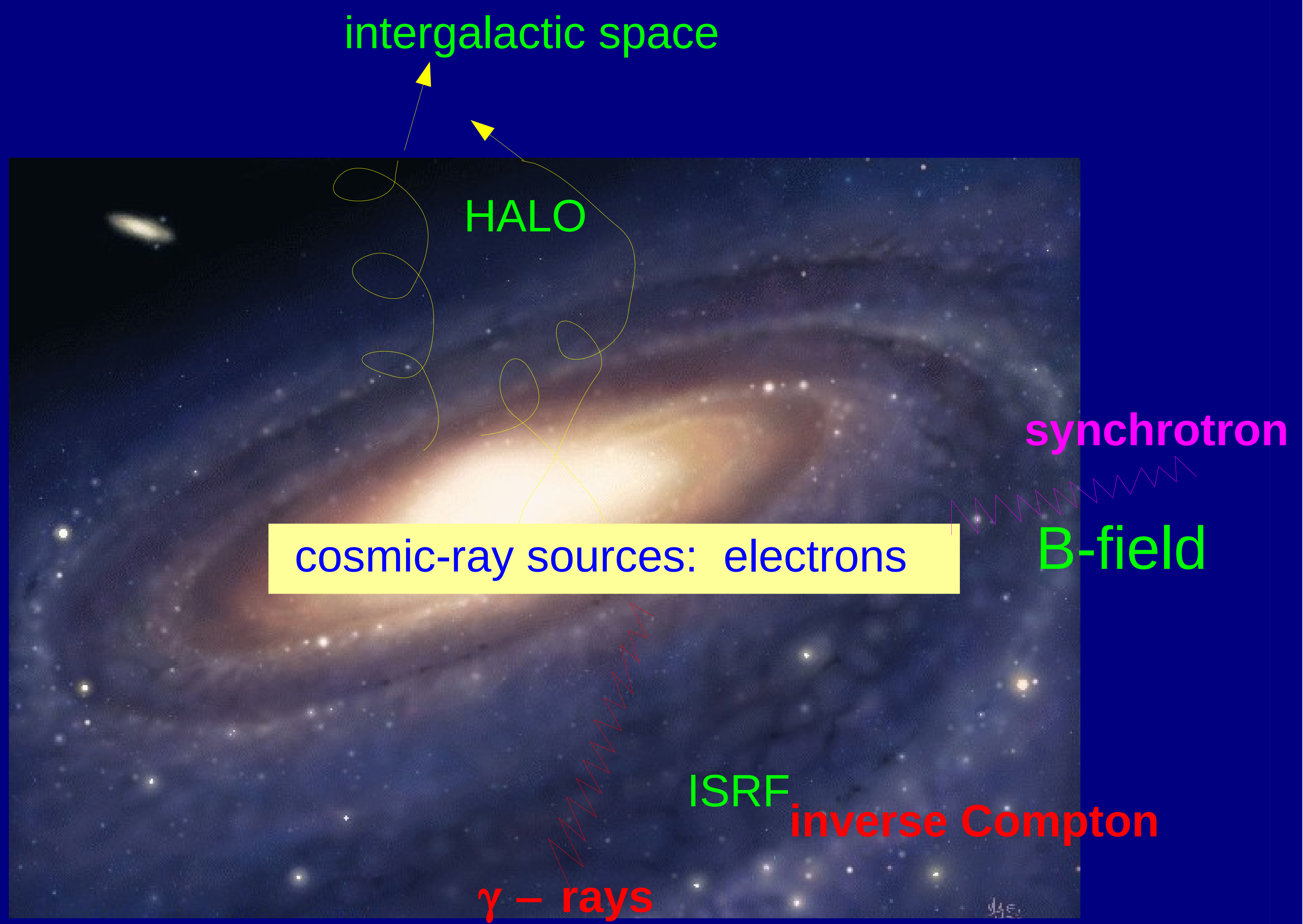
2.3 GHz

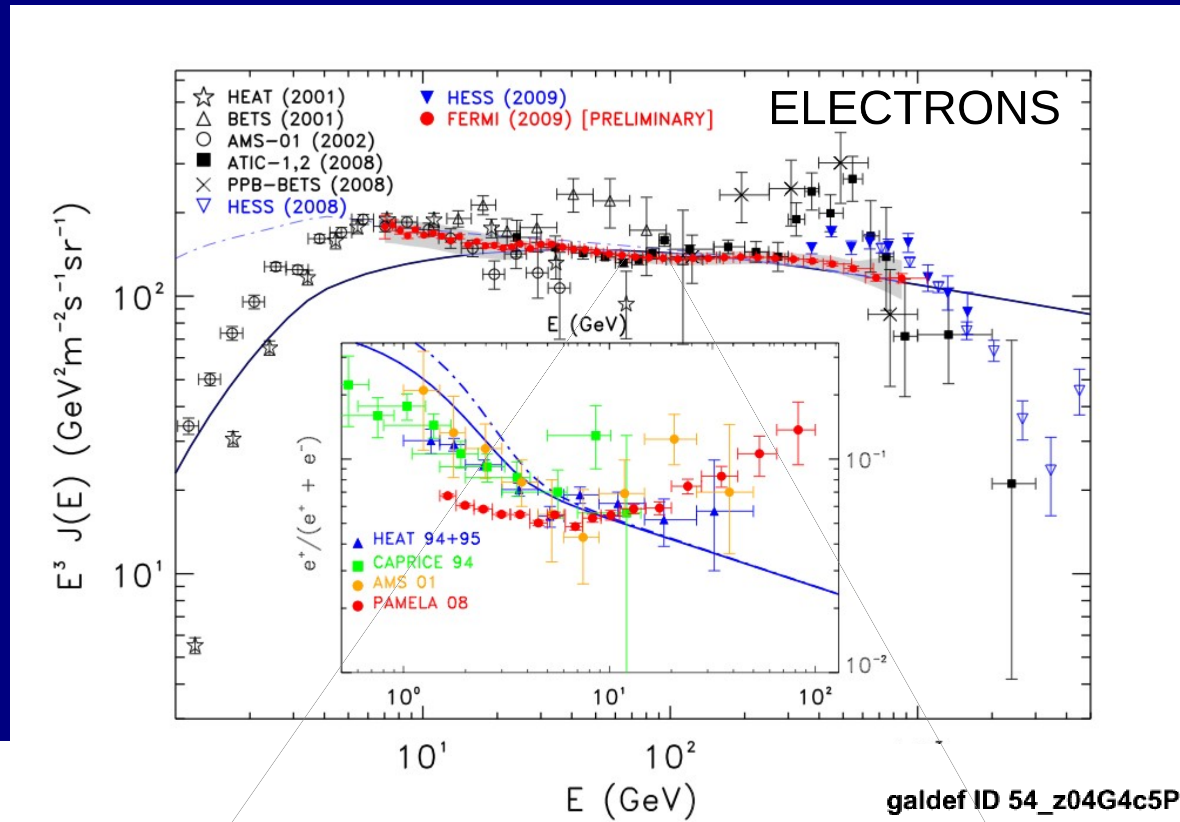
820 MHz

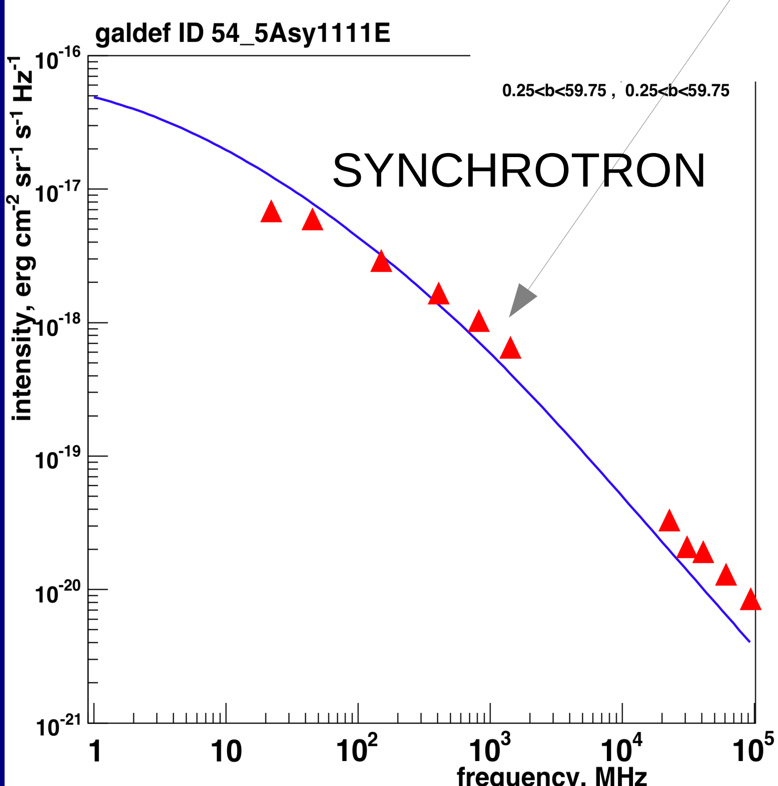


1.4 GHz



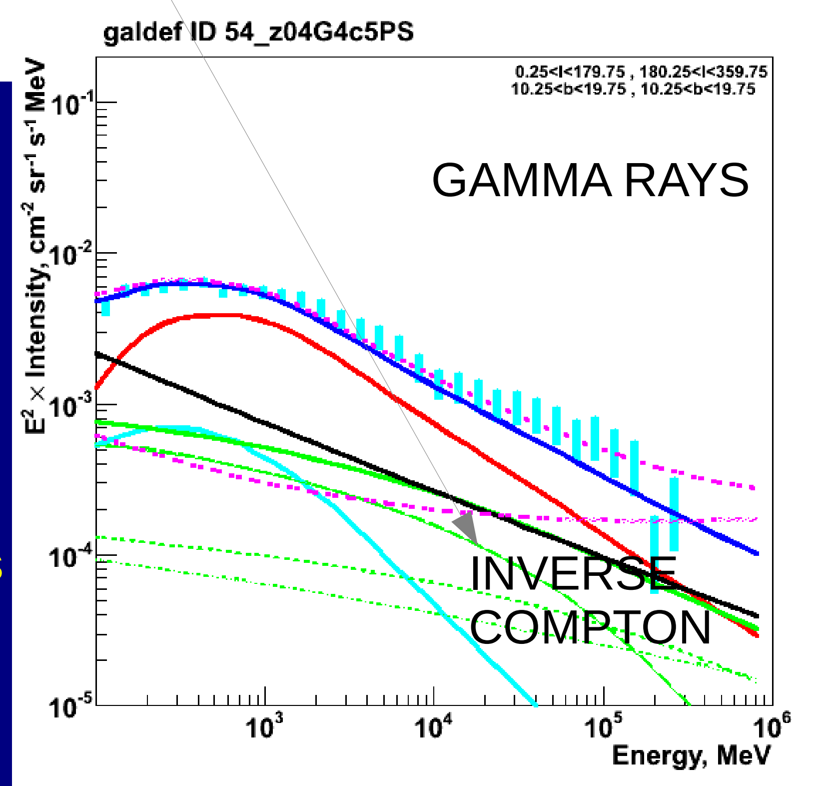

intergalactic space
HALO
synchrotron
B-field
cosmic-ray sources: electrons
ISRF
inverse Compton
γ – rays

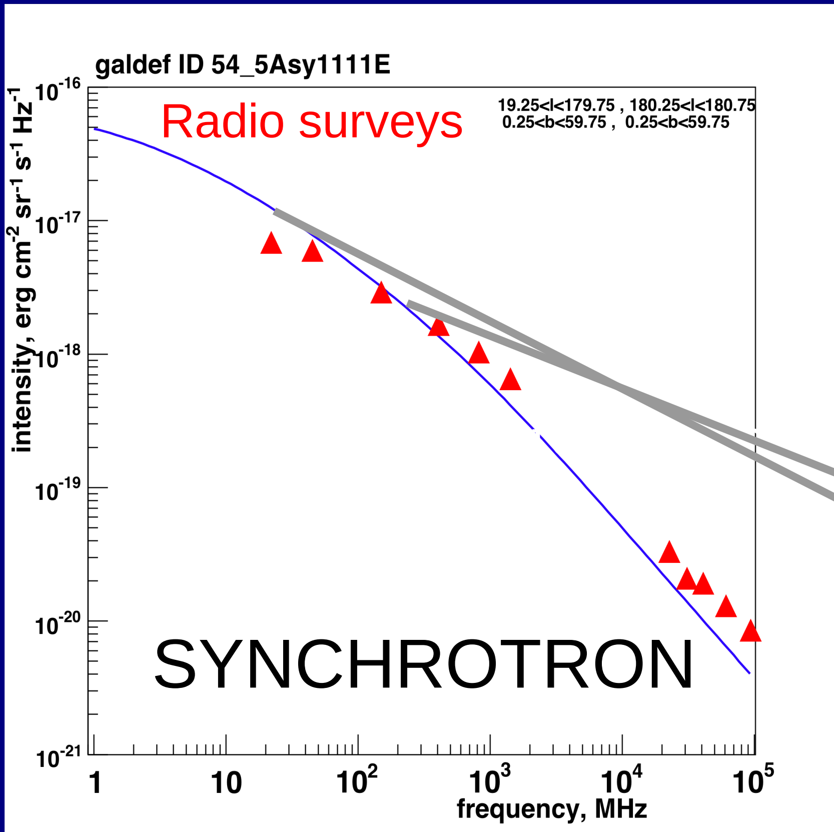


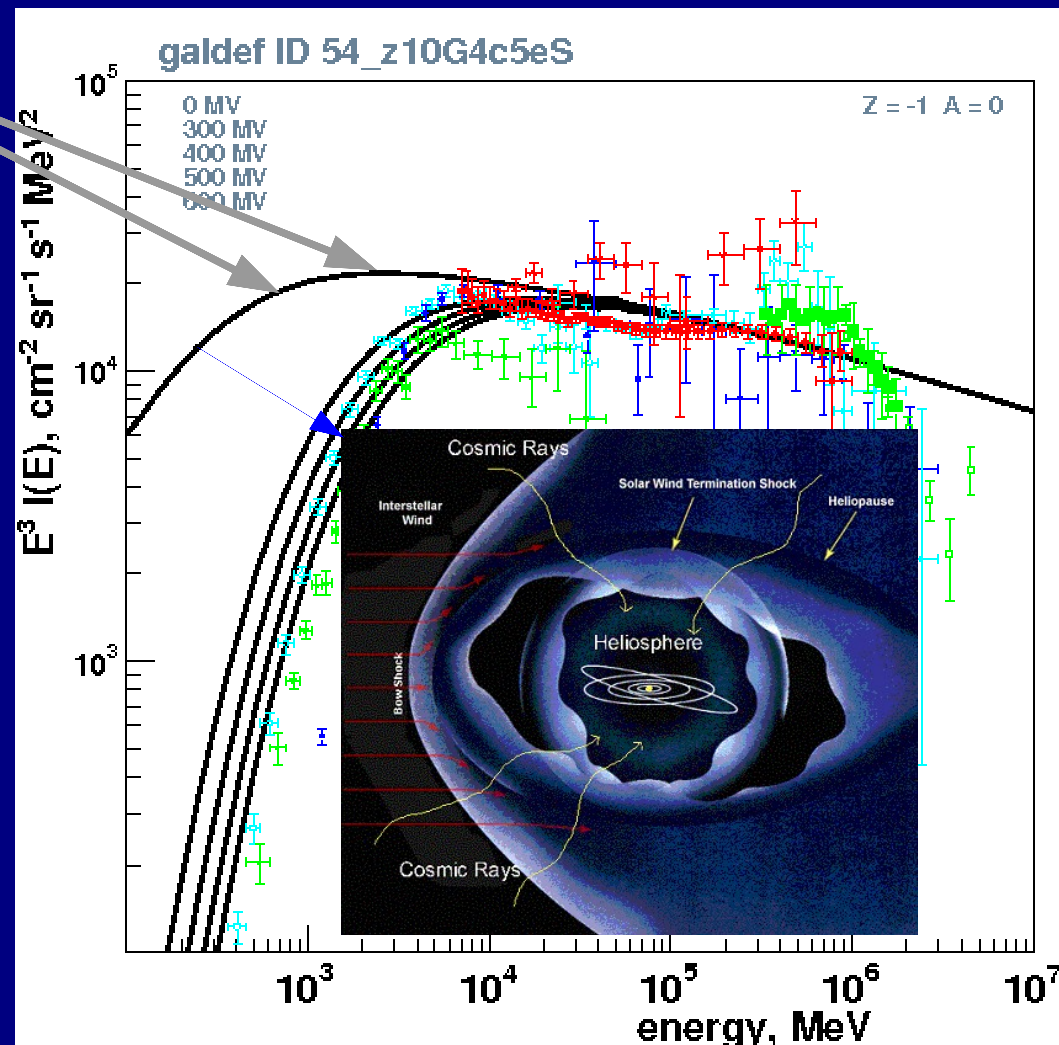


SAME
ELECTRONS
for
RADIO
and
GAMMA RAYS !

good constraints
on models



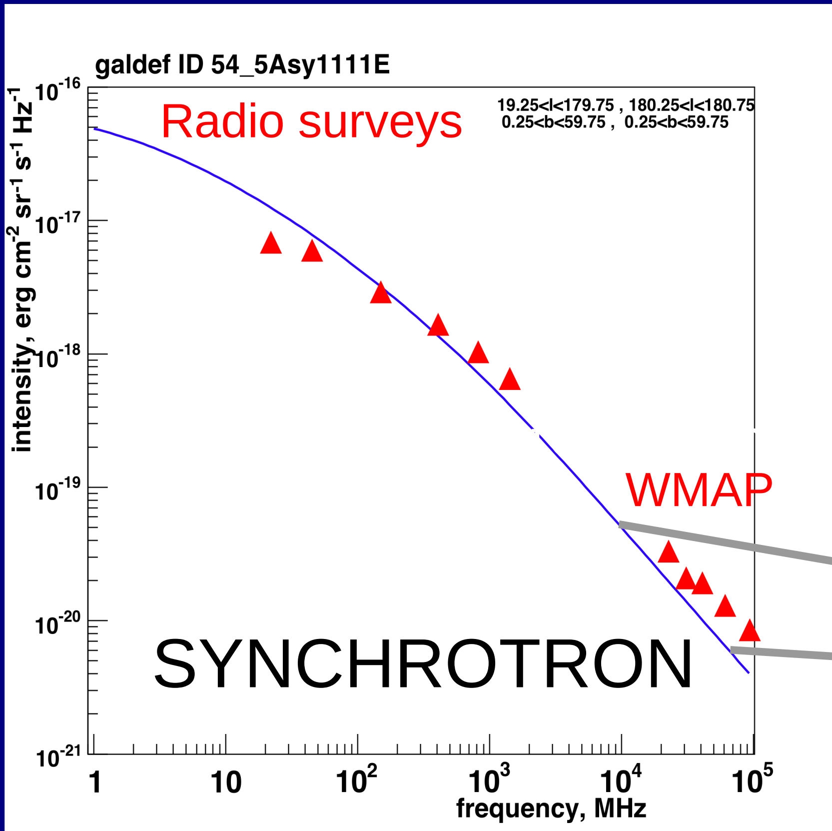


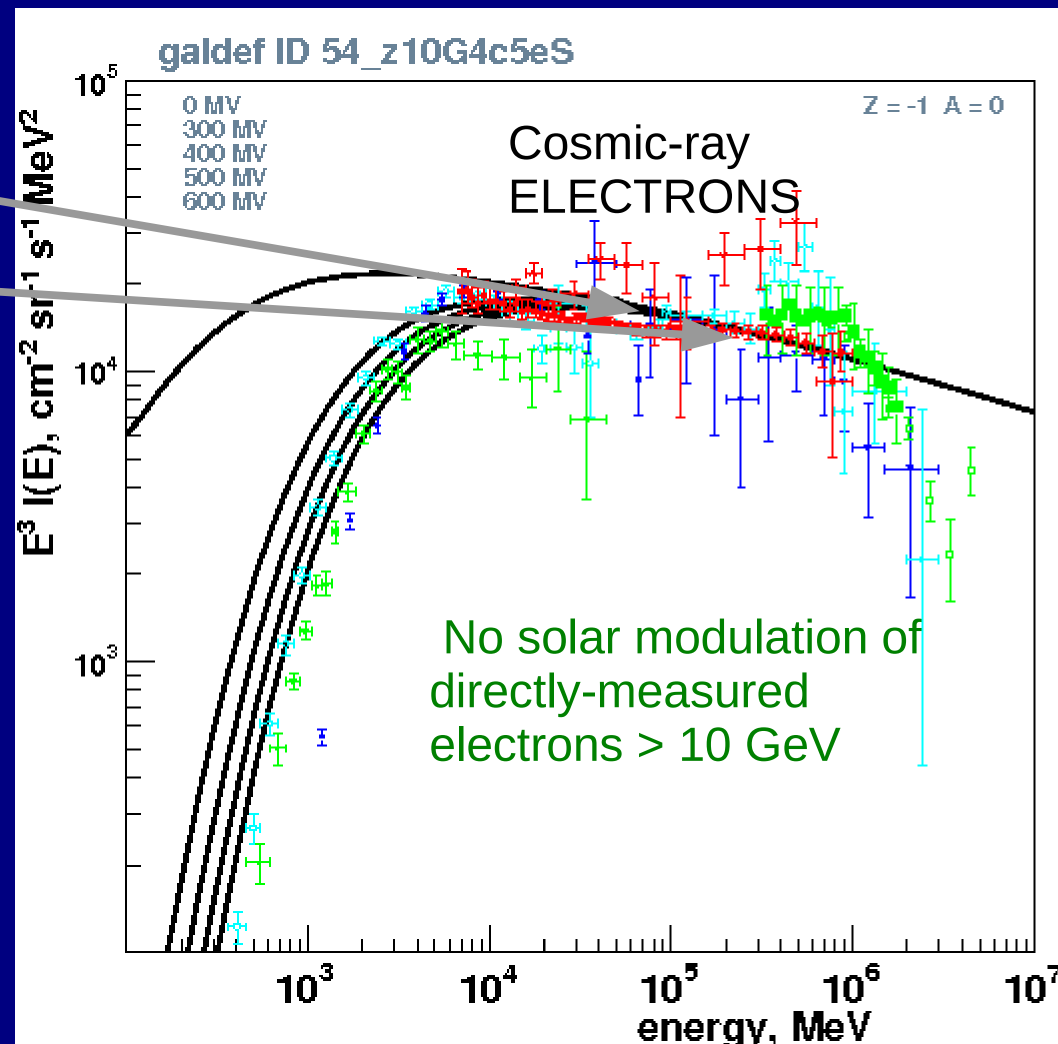


radio provides essential probe of interstellar electron spectrum at E < few GeV to complement direct measurements and determine solar modulation

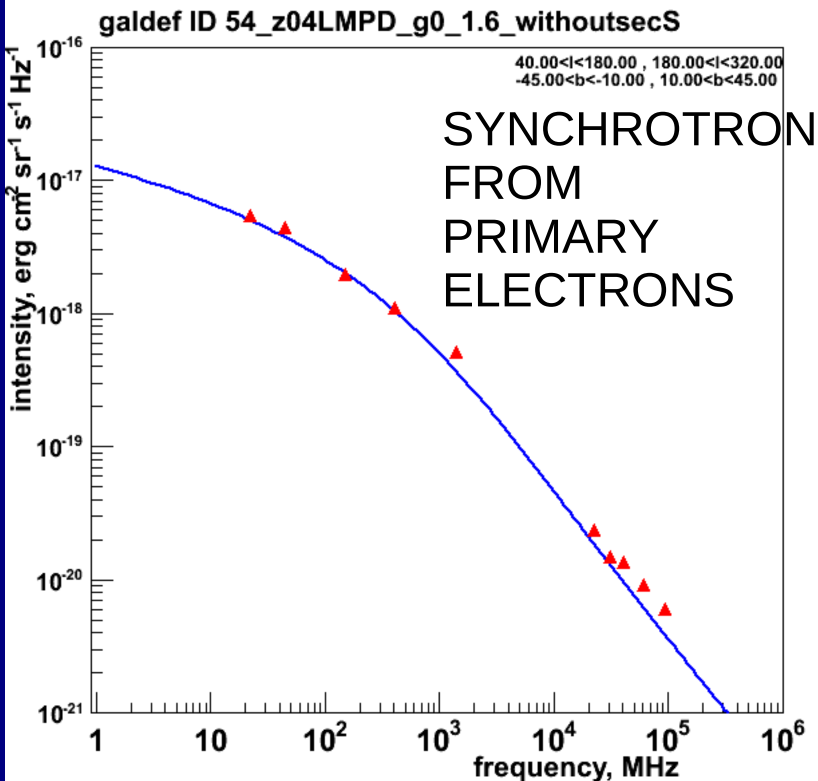
electrons have huge uncertainty due to modulation here

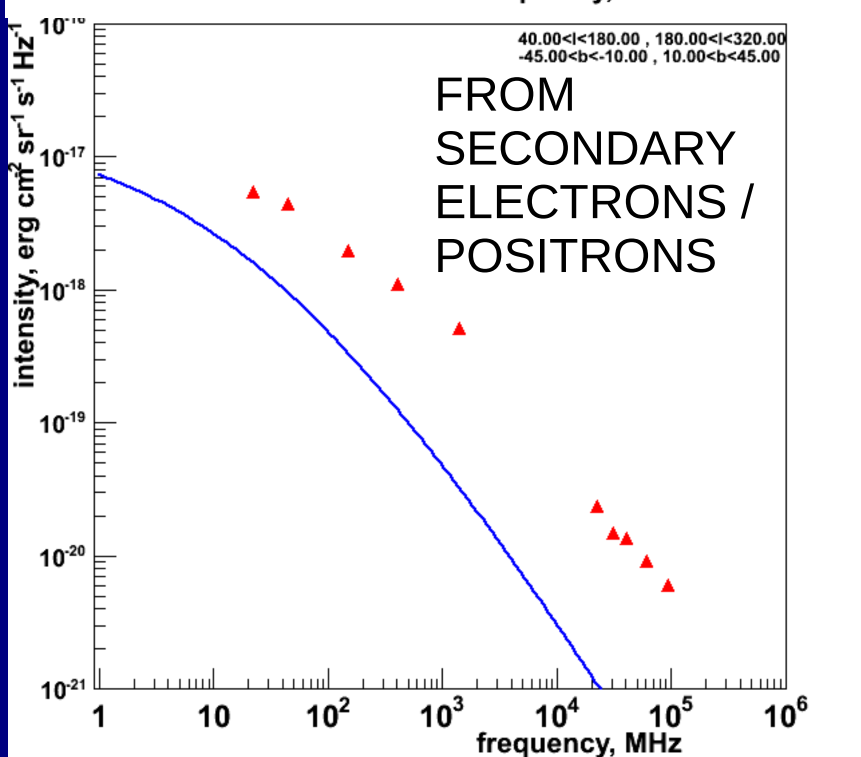
A. W. Strong, E. Orlando, T.R. Jaffe, 2011, A&A 534, A54

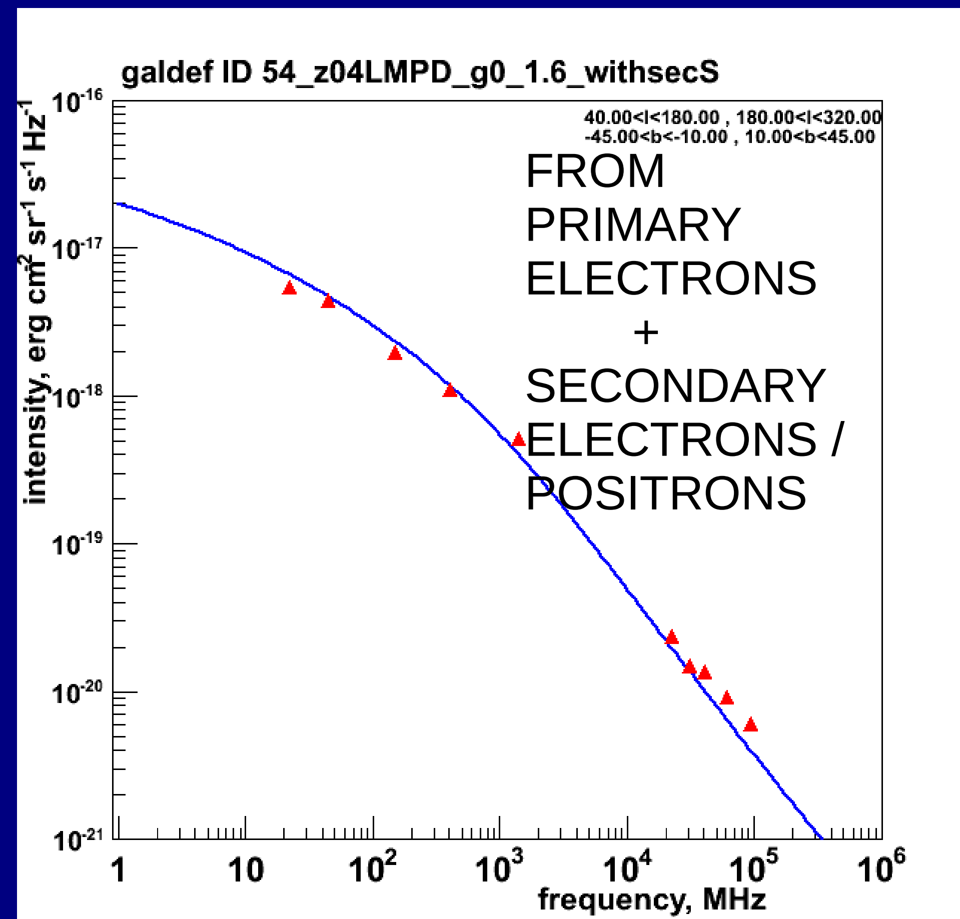




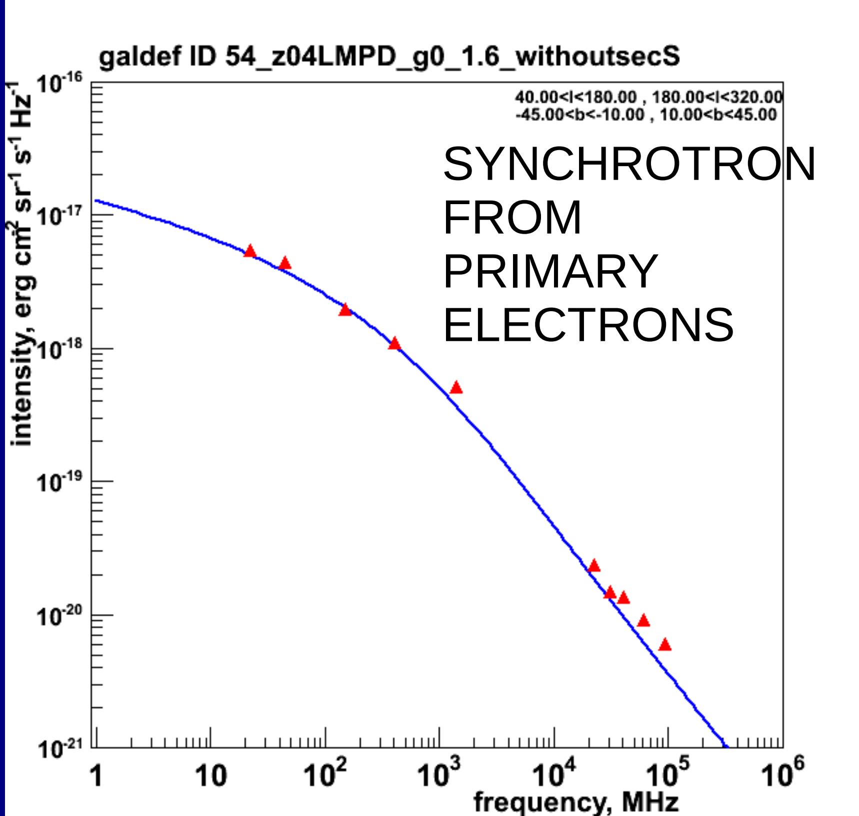
microwaves provide essential probe of interstellar electron spectrum
10 - 100 GeV

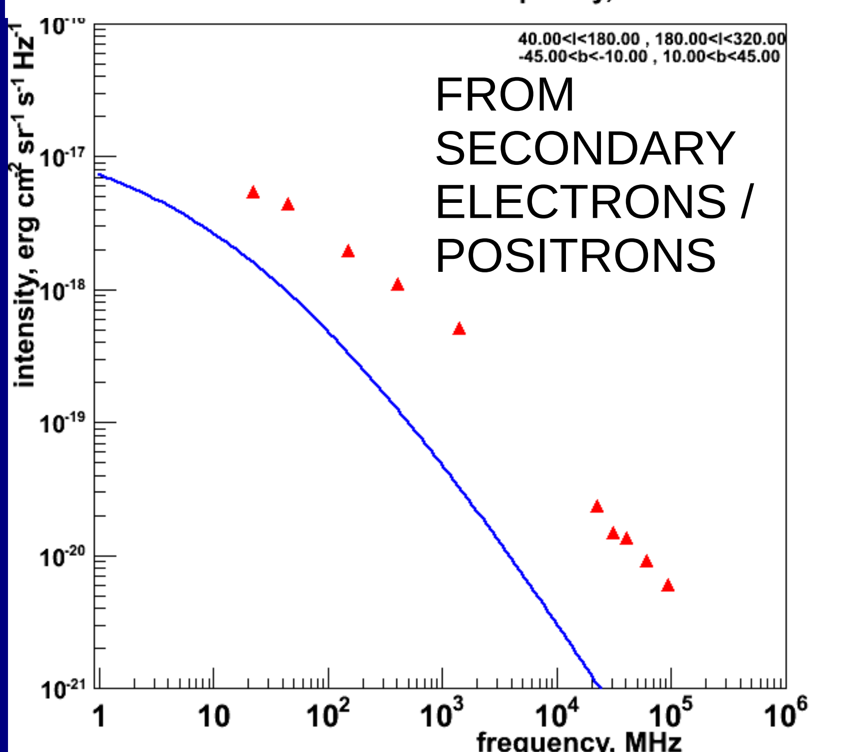




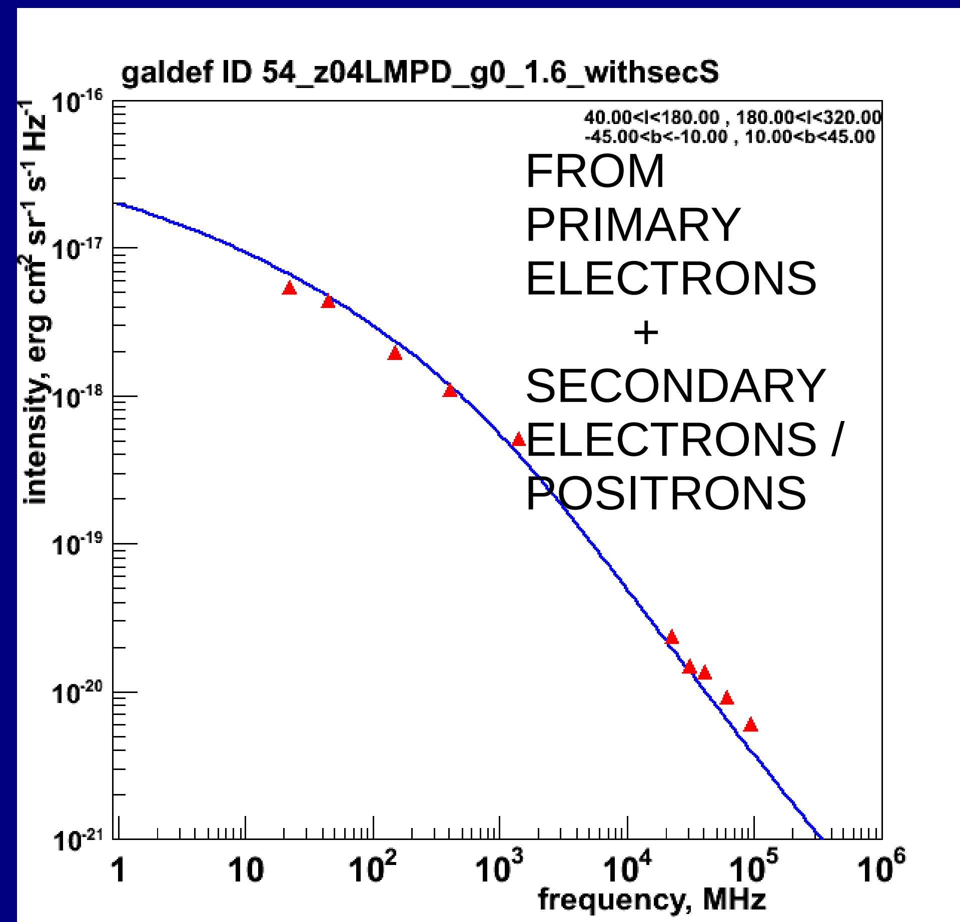


Secondary positrons
(and secondary electrons)
are important for synchrotron





See also talk by Dario Grasso, this conference



Secondary positrons (and secondary electrons) are important for synchrotron

Cosmic-ray electrons

Synchrotron

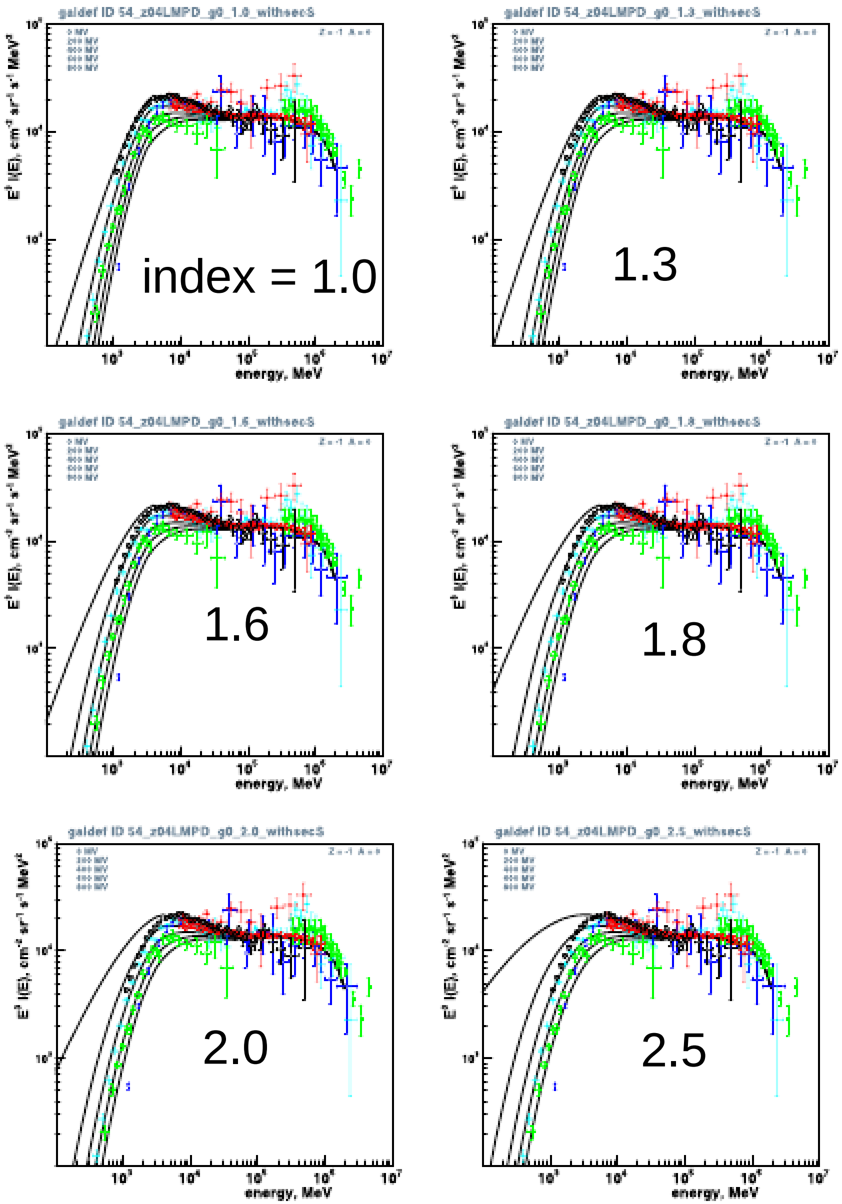


Fig. 4. Electron spectra for pure diffusion model, low-energy electron injection index 1.0, 1.3, 1.6, 1.8, 2.0, 2.5. Modulation Φ = 0, 200, 400, 600, 800 MV. Data as in Fig. 1.

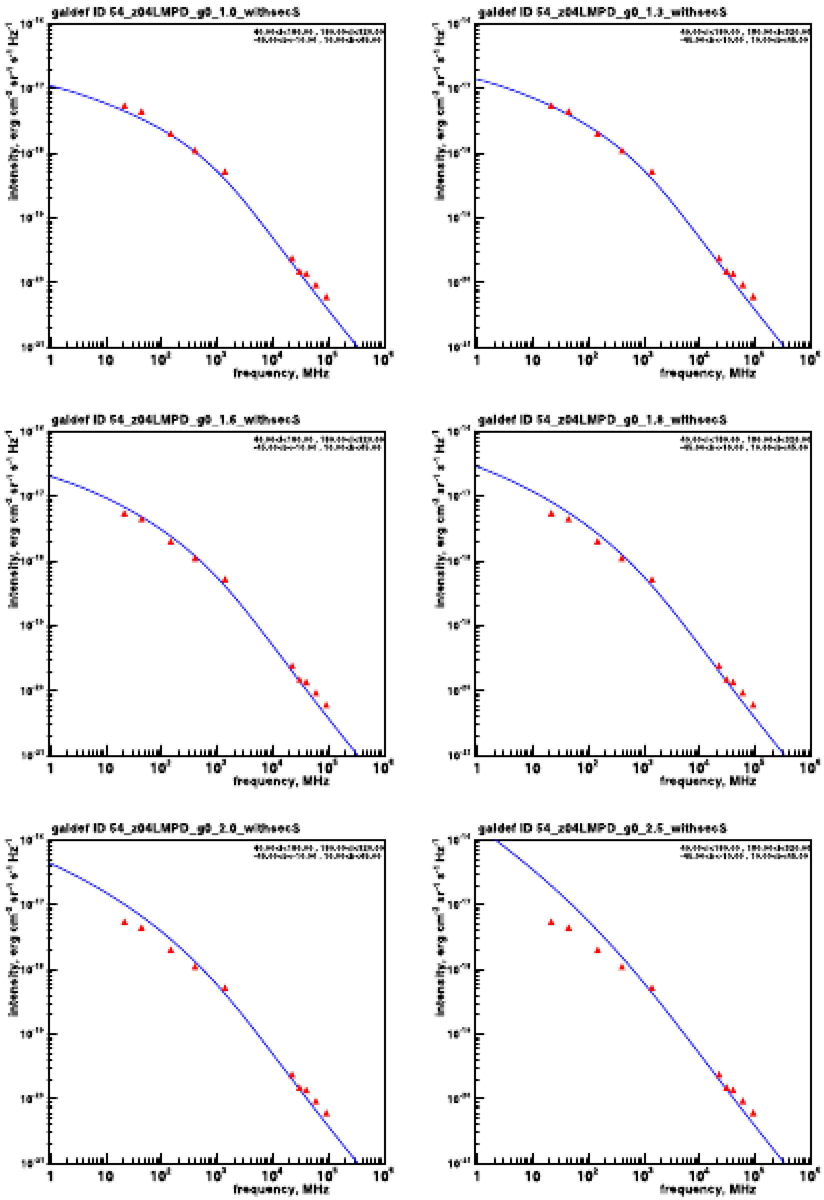


Fig. 5. Synchrotron spectra for pure diffusion model with low-energy electron injection index (*left to right, top to bottom*) 1.0, 1.3, 1.6, 1.8, 2.0, 2.5. Including secondary leptons. Data as in Fig. 2.

Effect of electron injection spectral index

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

Galactic Synchrotron T_B Spectral Index

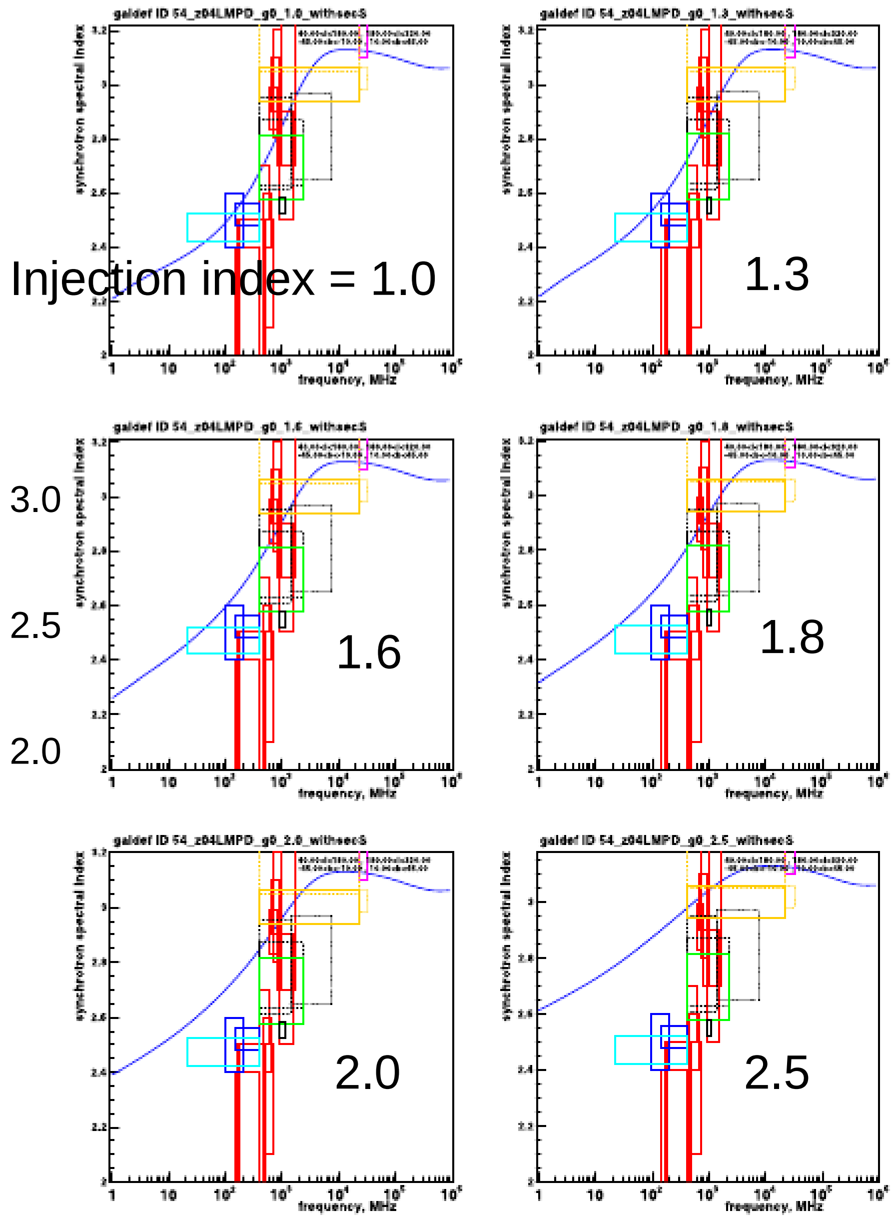


Fig. 6. Synchrotron spectral index for pure diffusion model with low-energy electron injection index (*left to right, top to bottom*) 1.0, 1.3, 1.6, 1.8, 2.0, 2.5. Including secondary leptons. Experimental ranges are based on the references reviewed in Sect. 4.1, and are intended to be representative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

Effect of electron injection spectral index

Strong, Orlando & Jaffe (2011)

Galactic Synchrotron T_B Spectral Index

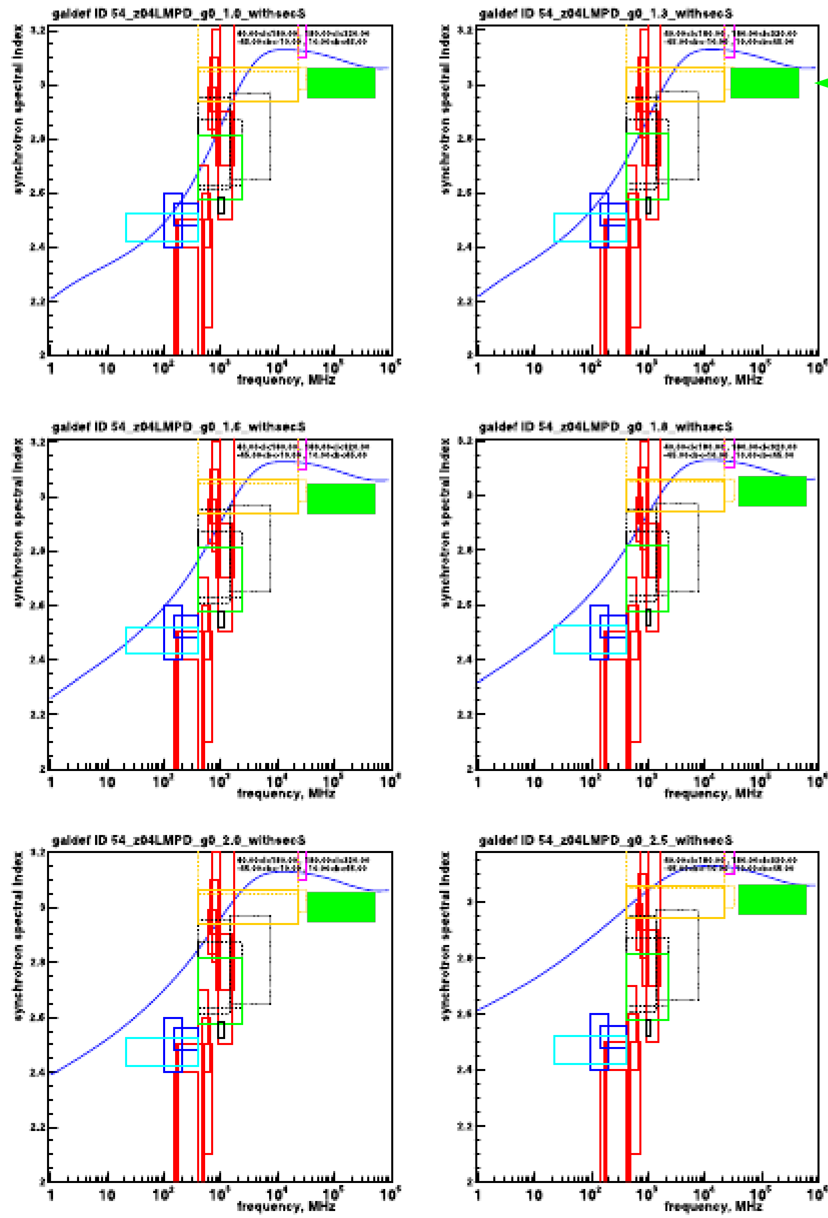


Fig. 6. Synchrotron spectral index for pure diffusion model with low-energy electron injection index (*left to right, top to bottom*) 1.0, 1.3, 1.6, 1.8, 2.0, 2.5. Including secondary leptons. Experimental ranges are based on the references reviewed in Sect. 4.1, and are intended to be representative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

A&A 536, A21 (2011)

Luca Maccione. ArXiv 1211.6905

PAMELA, charge and polarity dependence of e+/e-

DRAGON interstellar spectrum, solar modulation model

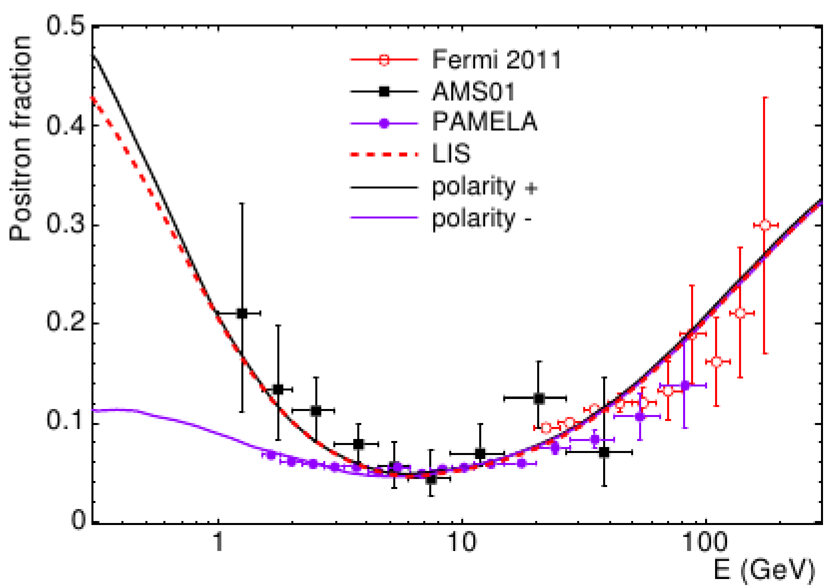


FIG. 1. The positron fraction measured by Fermi, PAMELA and AMS-01 is shown. The LIS is shown as the red dashed curve. Solid curves show the Earth positron fraction computed evolving the LIS for $\alpha = 30^\circ$ and positive polarity (black) or negative polarity (violet).

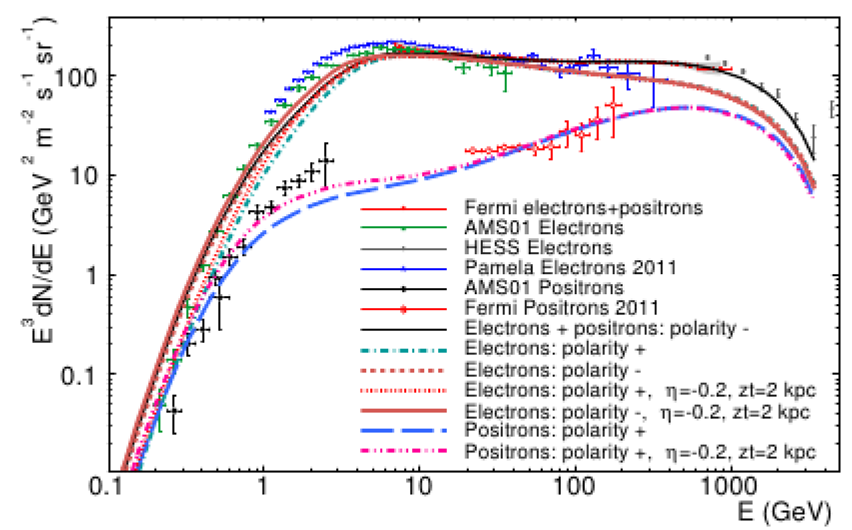
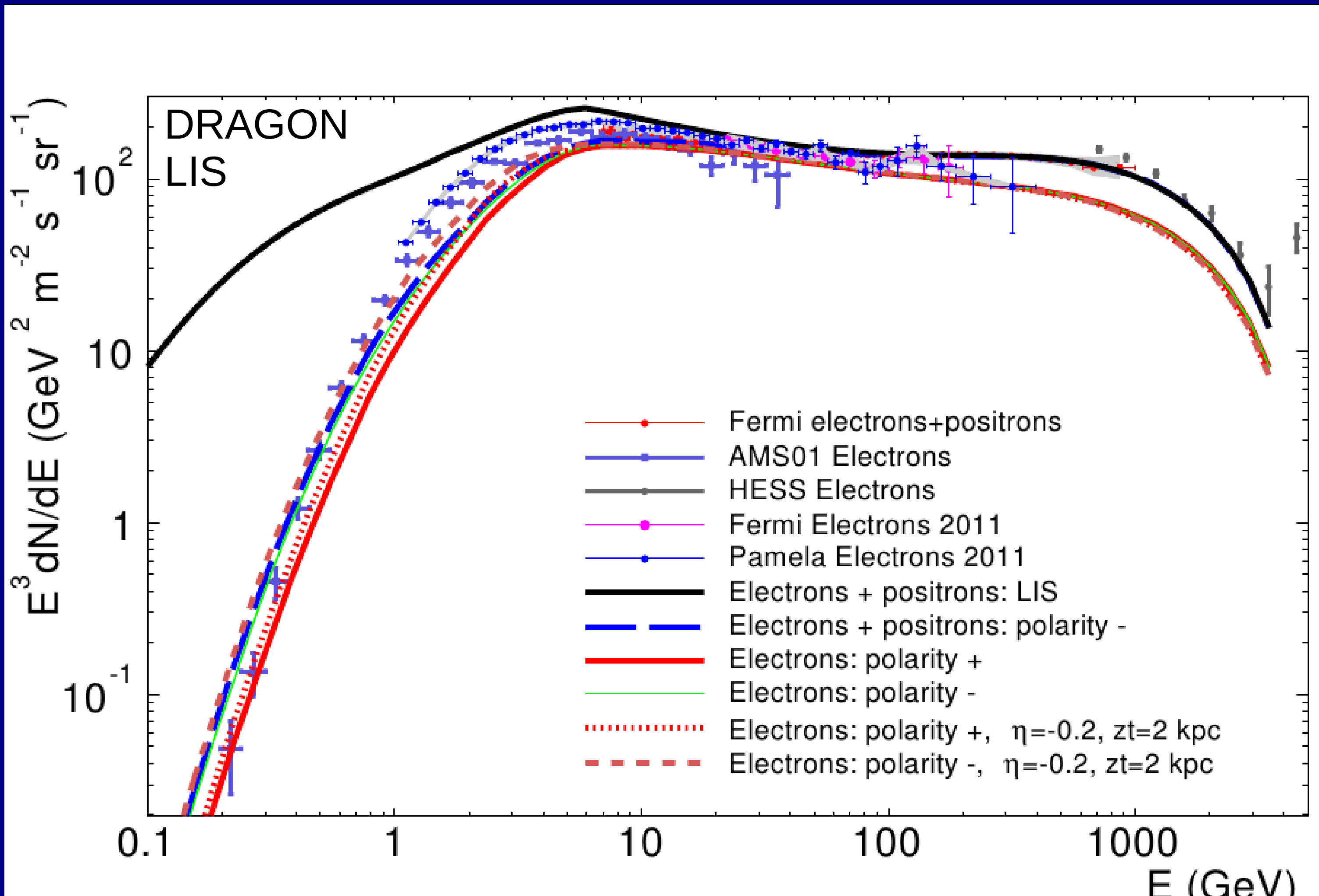


FIG. 6. The absolute e^- and e^+ spectra measured by different experiments are compared with our calculations for $\alpha = 30^\circ$ and both polarities.

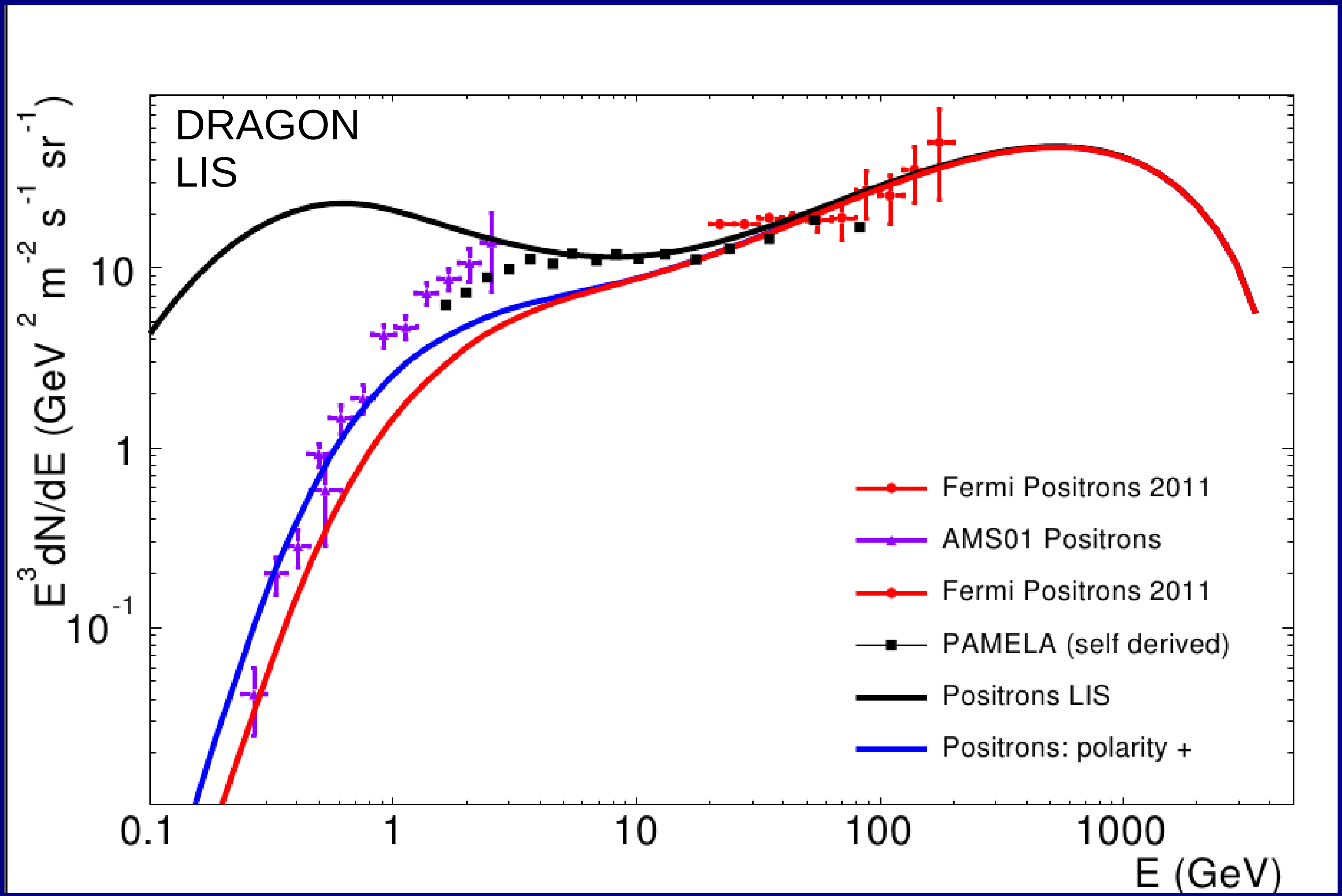
From Luca Maccione, see also arXiv 1211.6905

PAMELA, charge and polarity dependence of e+/e-



PRELIMINARY

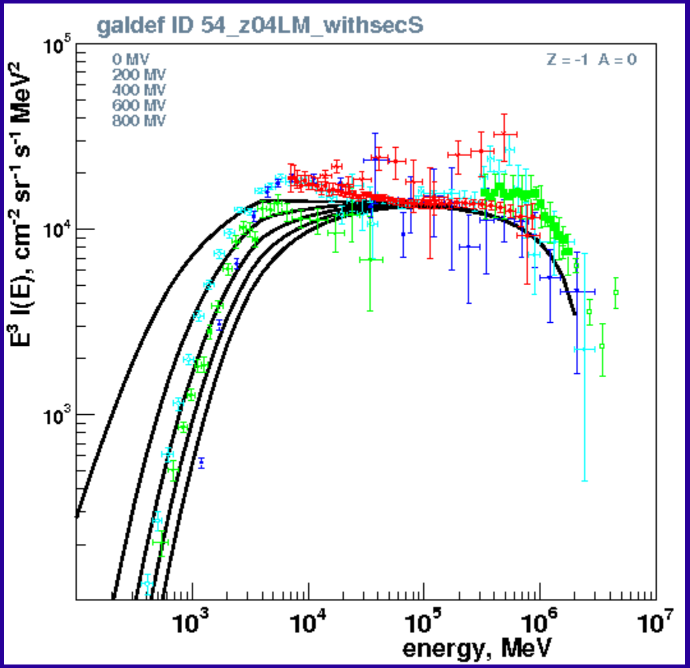
From Luca Maccione, see also arXiv 1211.6905



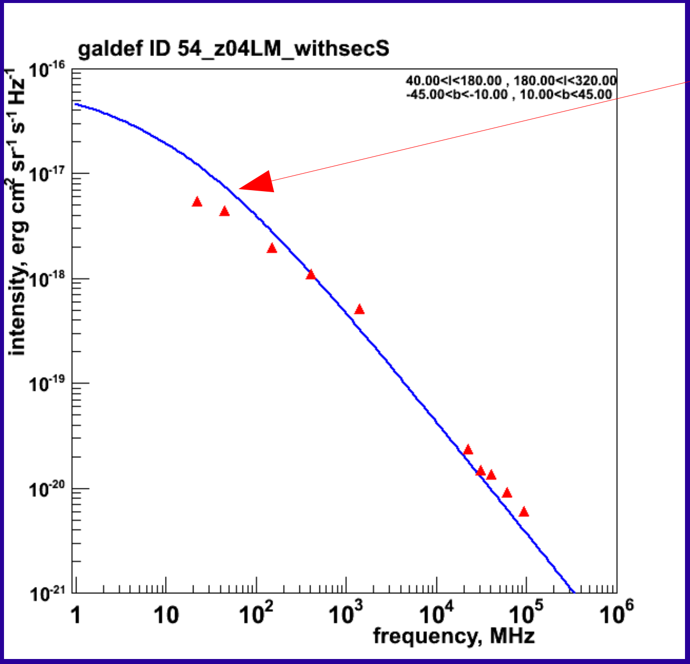
PRELIMINARY

Reacceleration models – in trouble with synchrotron

Model with large reacceleration (v_A ~35 km s^{-1}) as often used for B/C

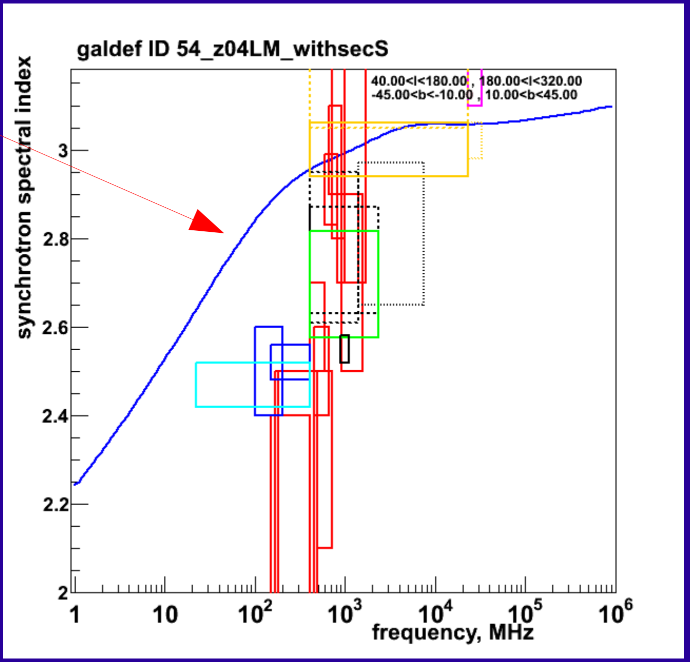


ELECTRONS



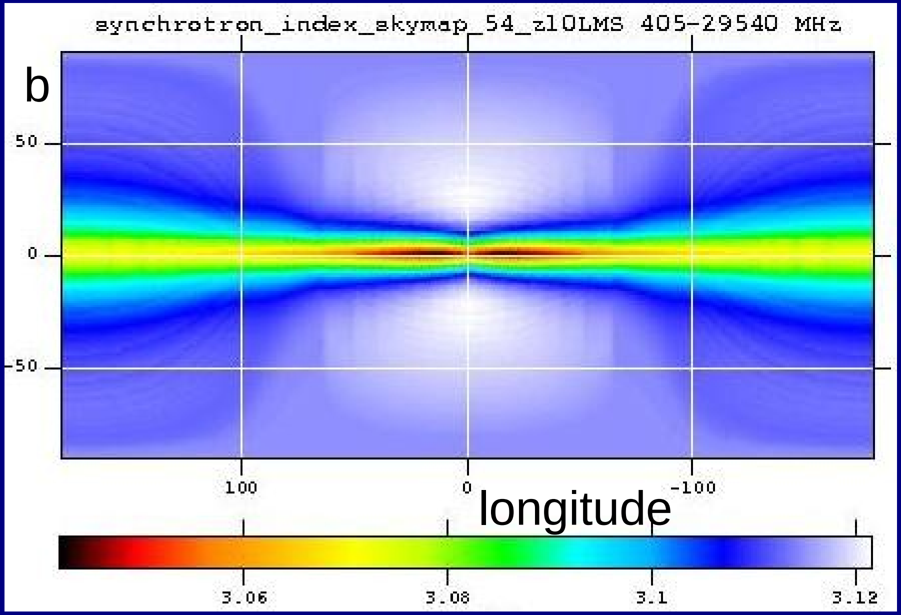
!

SYNCHROTRON



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.

Worth looking for with Planck etc.

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

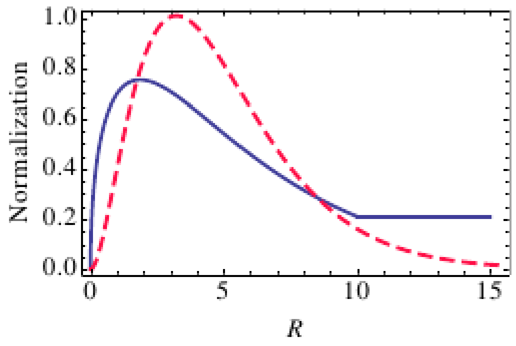
* Separates regular from random B

* Separates synchrotron from spinning dust and free-free emission

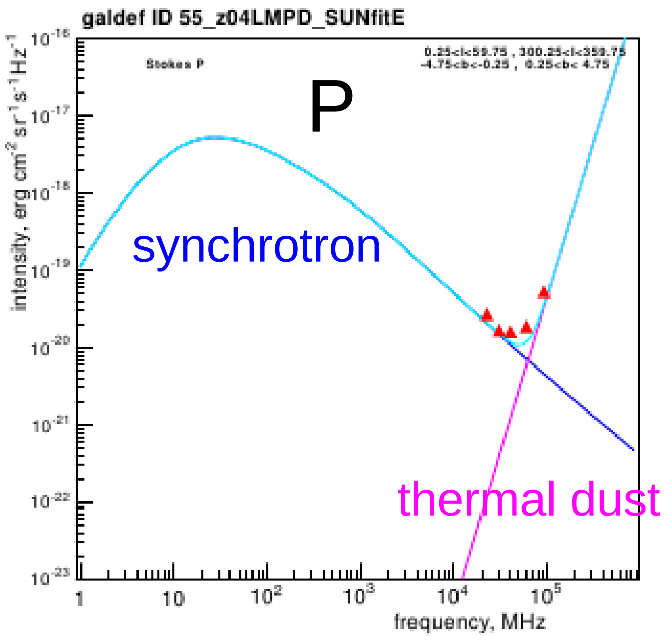
Now modelled in GALPROP

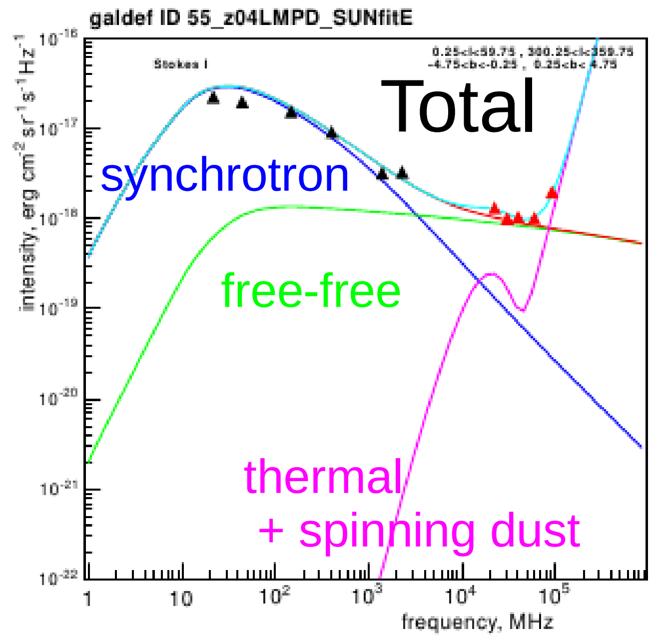
B-fields from literature, basic modifications to fit data.

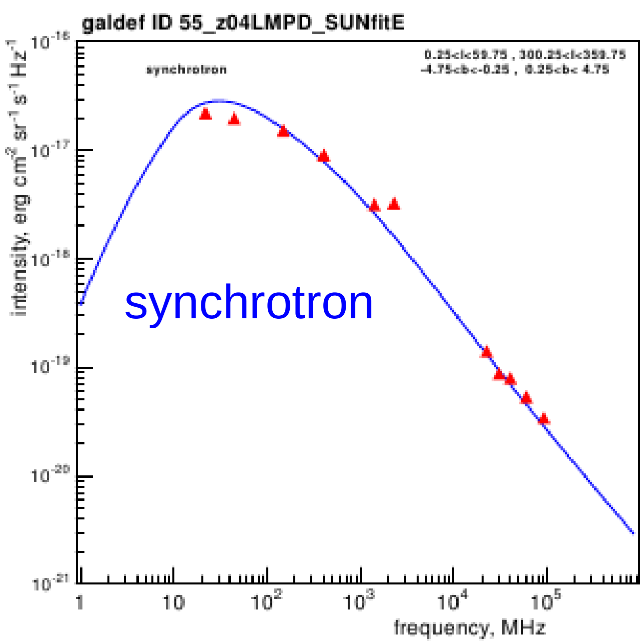
Cosmic-ray electron distribution is a main input from gamma rays.



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.

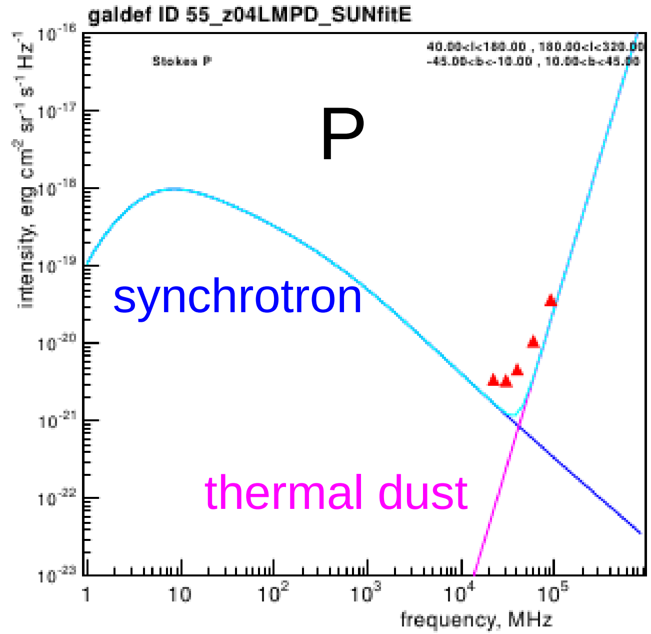


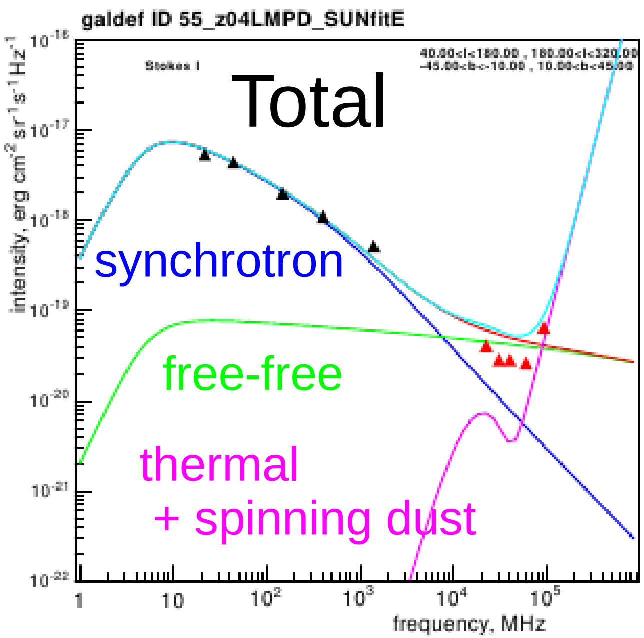


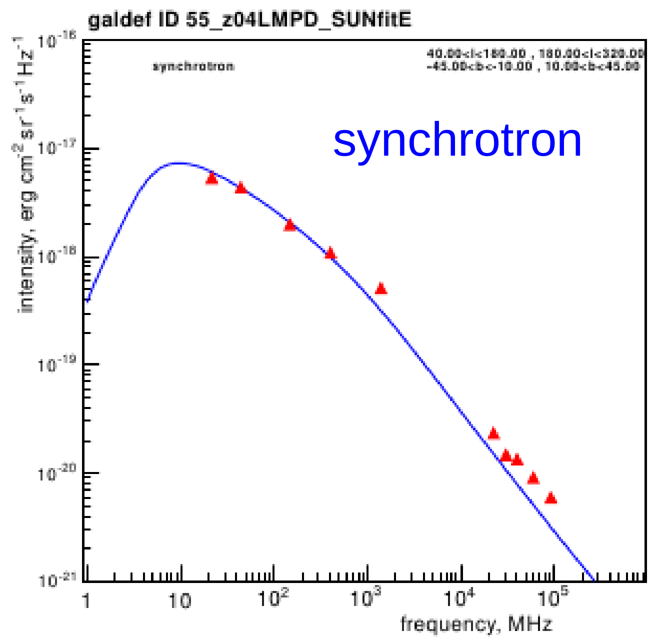


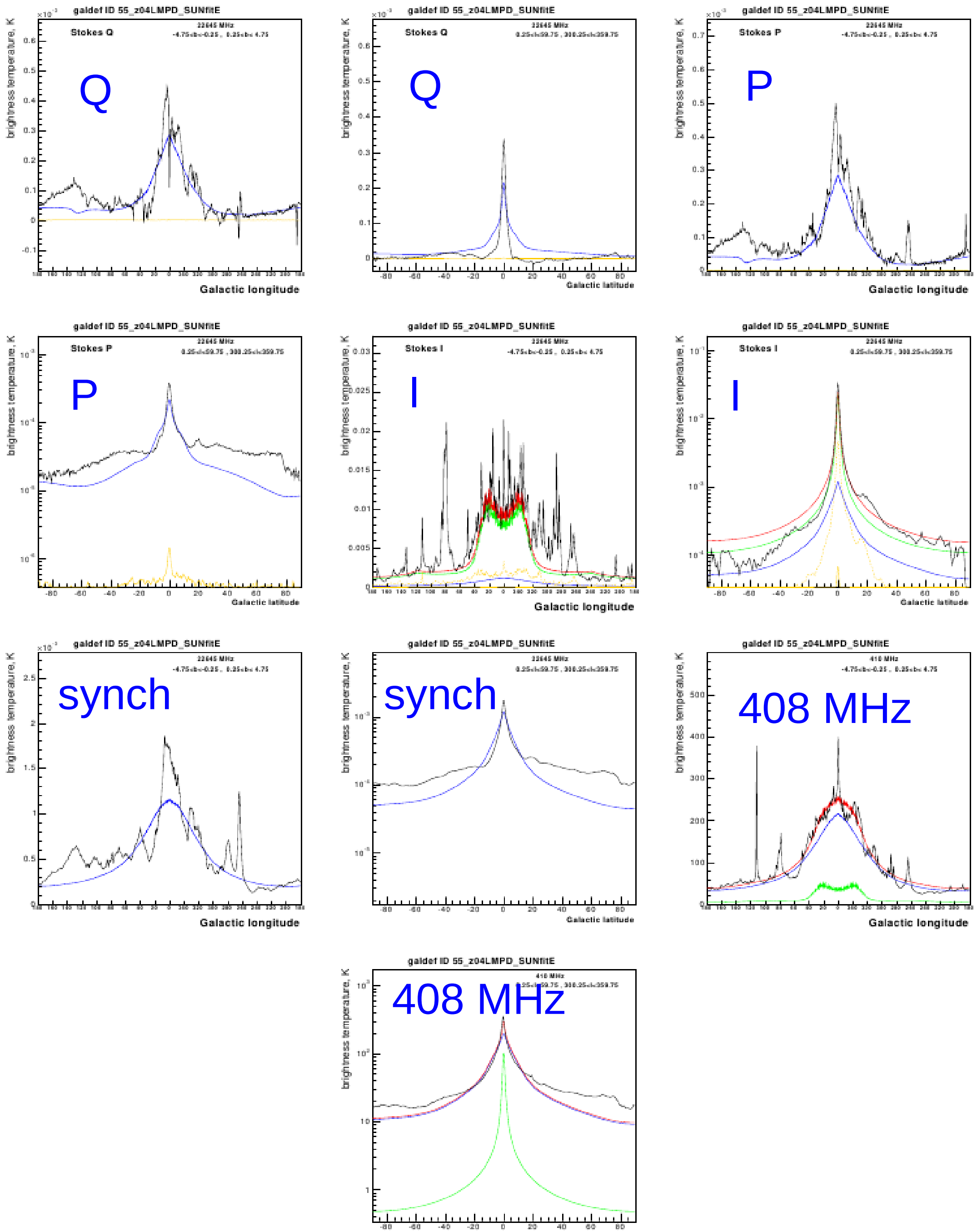
INNER GALAXY

HIGH LATITUDES

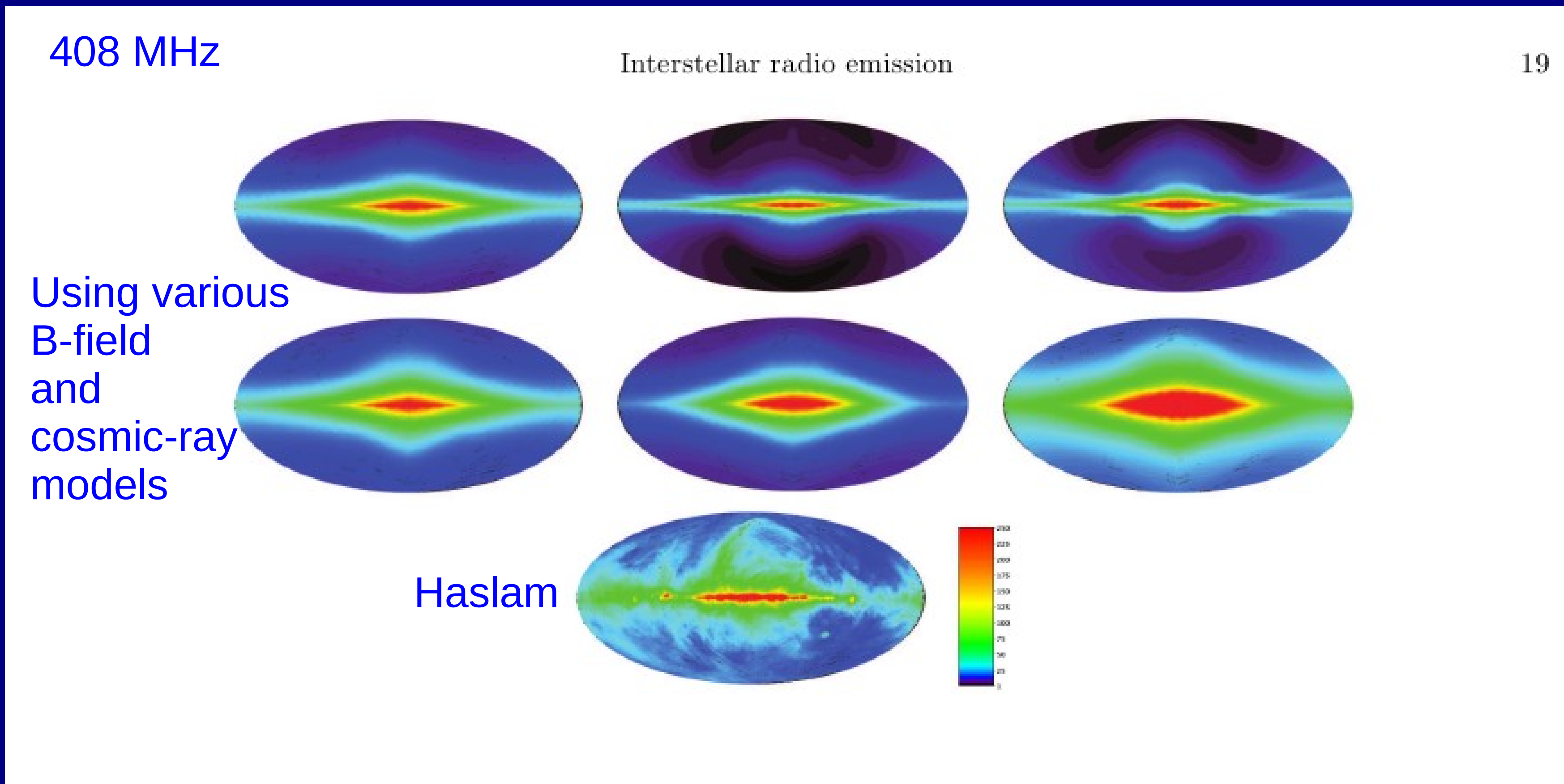








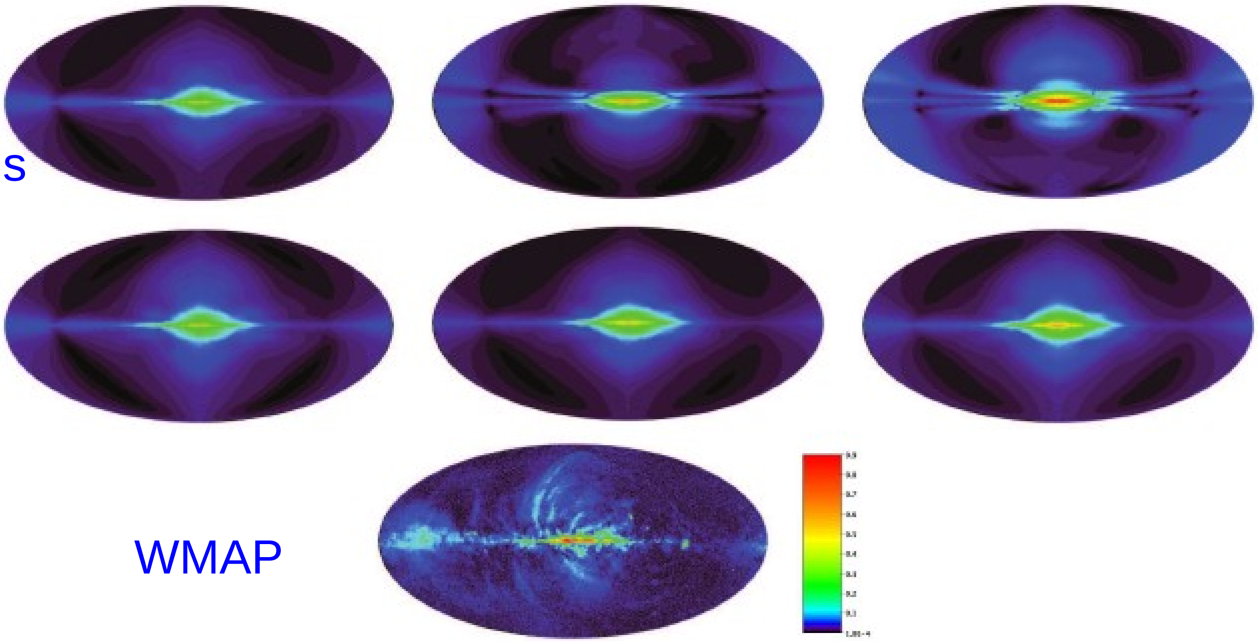
galdef ID 55_z04LMPD_SUNfitE
Stokes Q
Q
Stokes Q
Q
Stokes P
P
Stokes P
P
Stokes I
I
Stokes I
I
synch
synch
408 MHz
408 MHz
brightness temperature, K
Galactic longitude
Galactic latitude



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

23 GHz
P

Using various
B-field
and
cosmic-ray
models



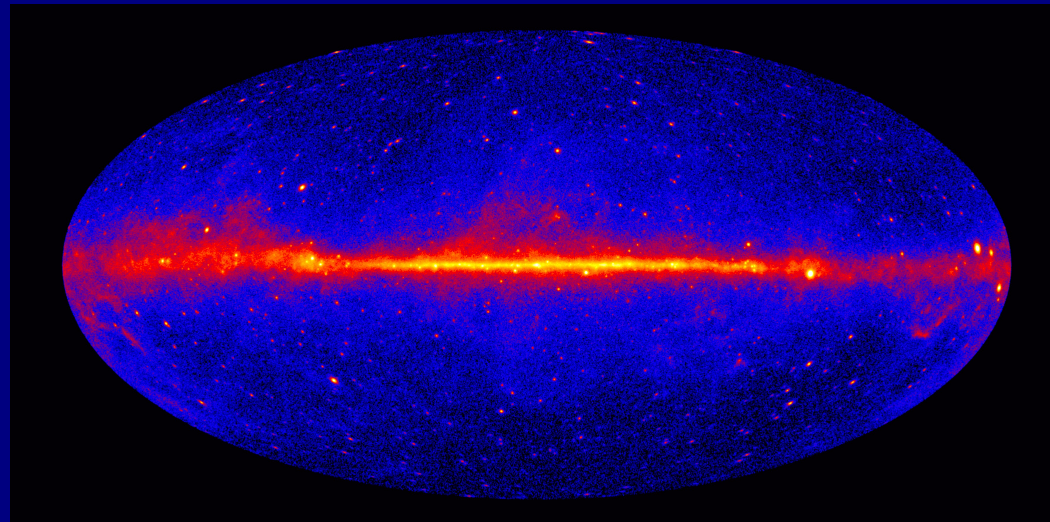
WMAP

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

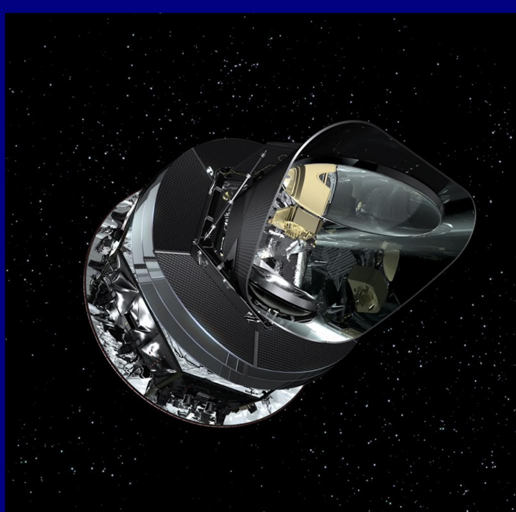
Local B- field from this paper
Using Fermi-LAT cosmic-ray electrons
408 MHz
23 GHz WMAP polarized

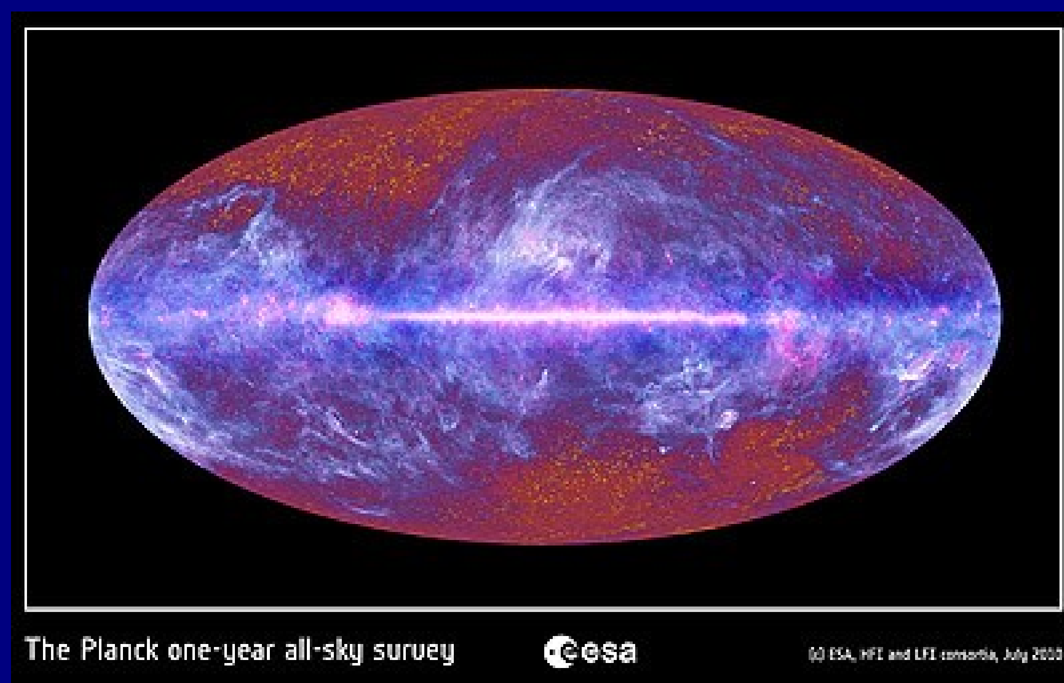
Regular : 3-4 μG
Random : 6 μG

(more on this topic: Workshop on Polarized CMB Foregrounds, MPA Garching, Nov 2012)



2 years

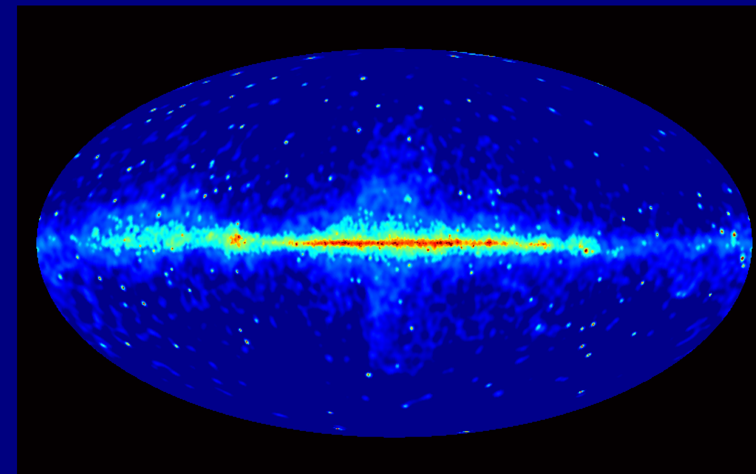




1 year

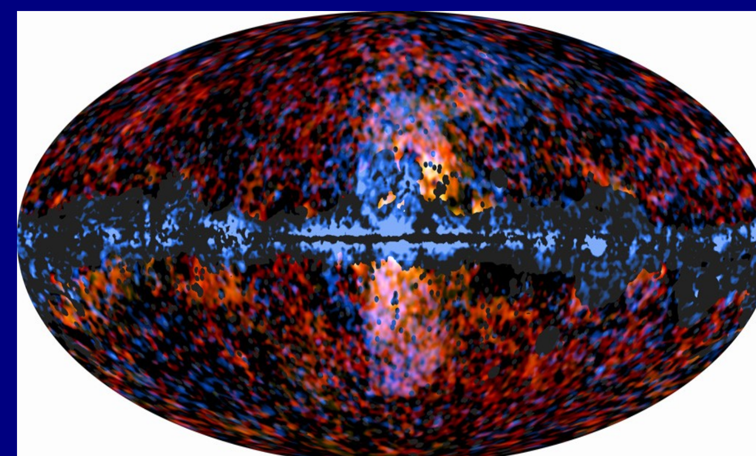
A lot of common astrophysics, cosmic rays, gas, magnetic fields !

Fermi Bubbles

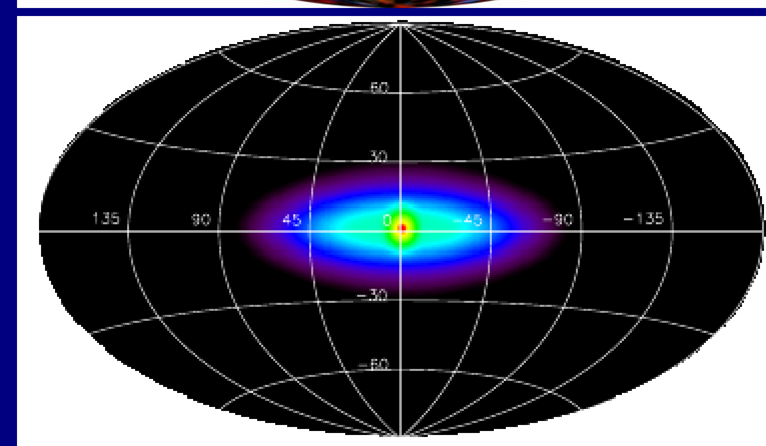


(related to WMAP Haze ?)

Planck haze (arXiv:1208.5483)
Overlaid on Fermi Bubbles



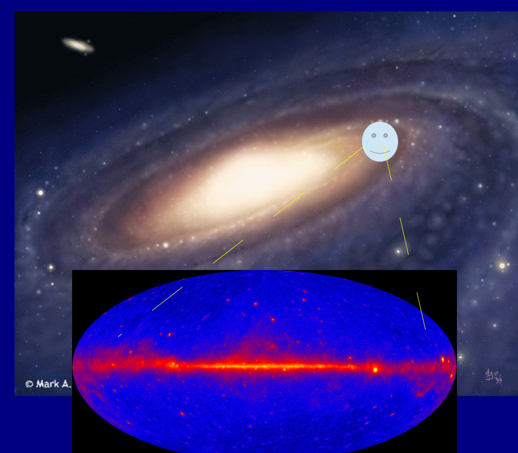
connection to 511 keV line ?



All are -

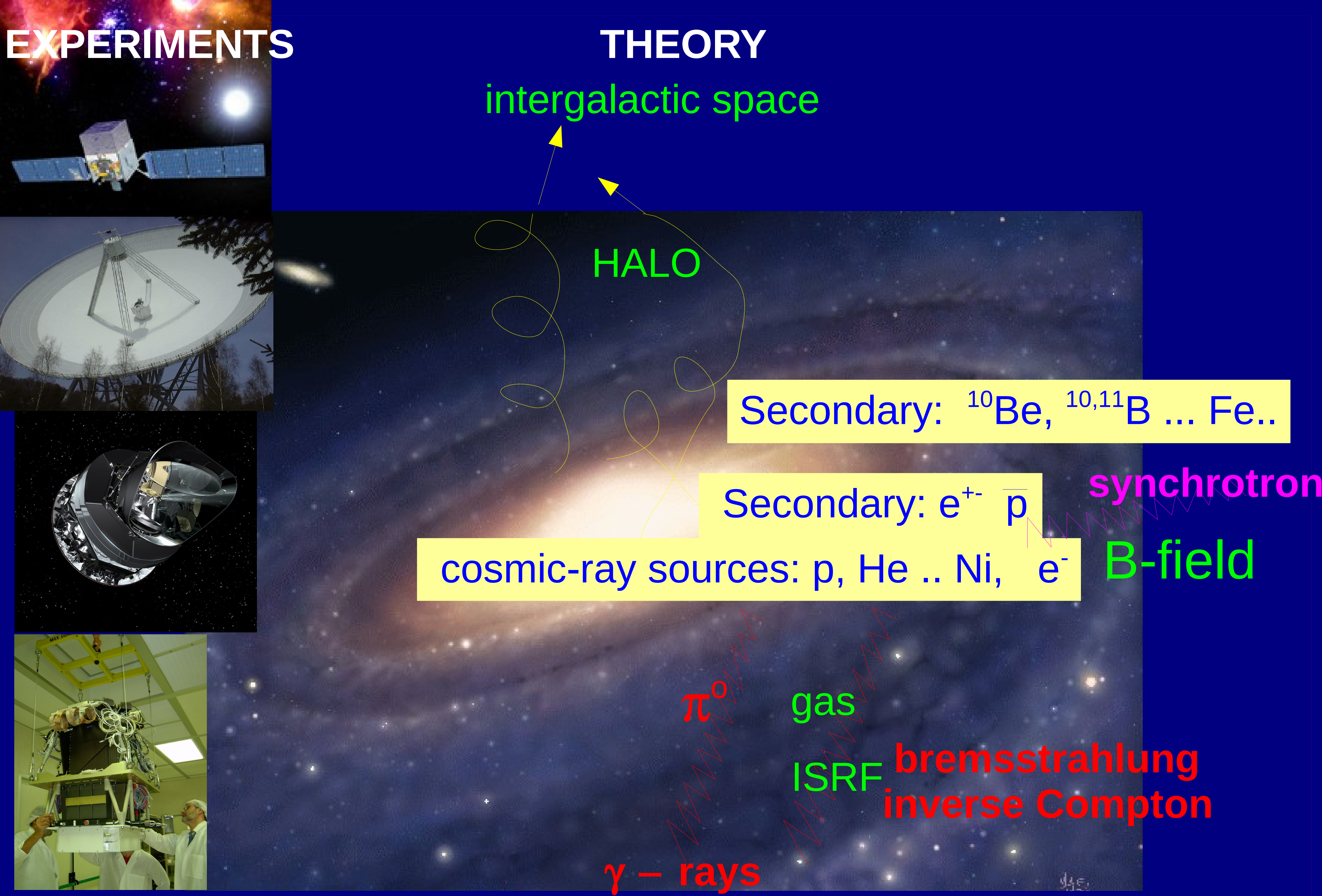
centred on Galactic Centre
leptonic
unknown origin

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

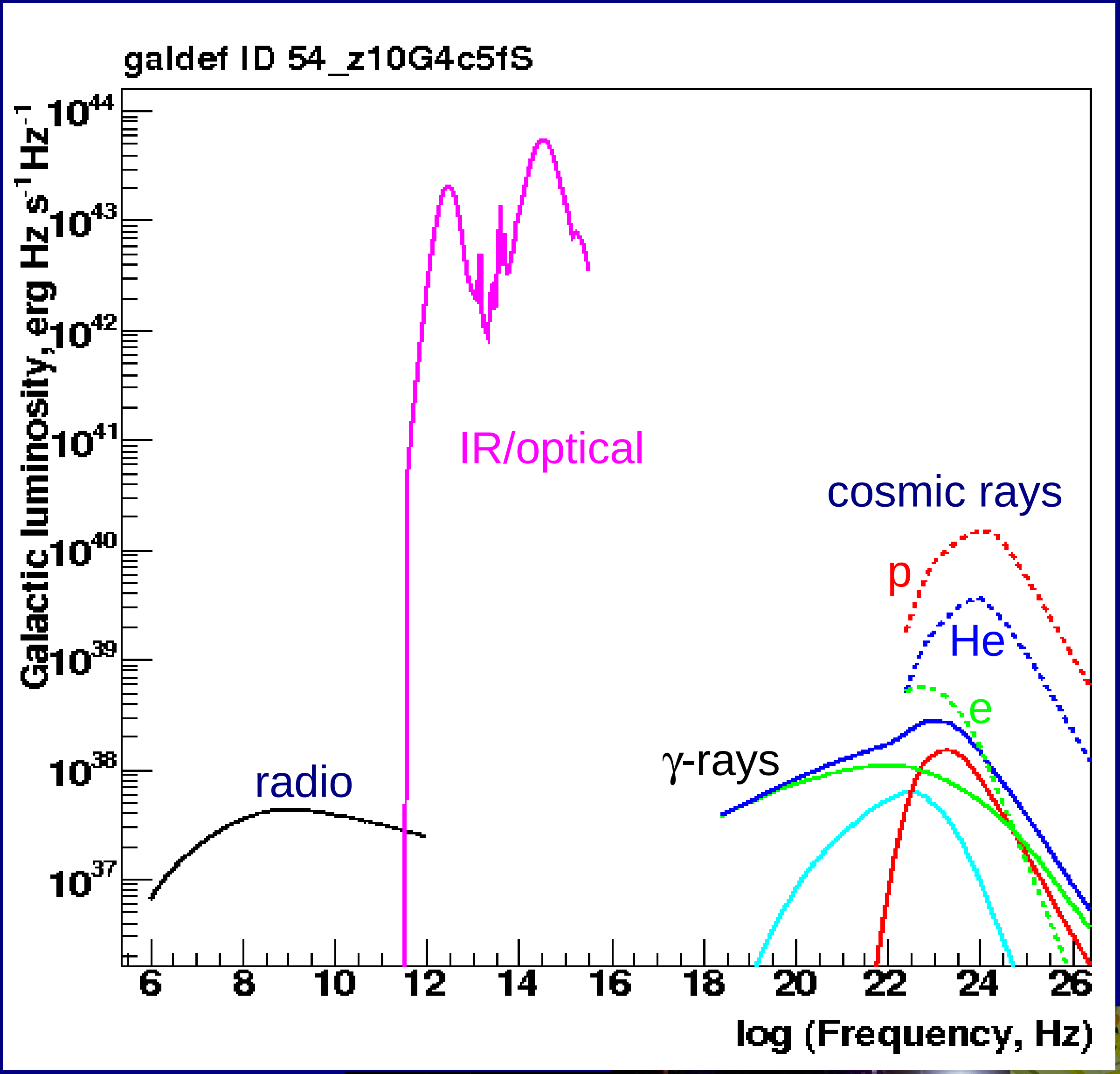


SEDs of AGN etc are common, but not Milky Way

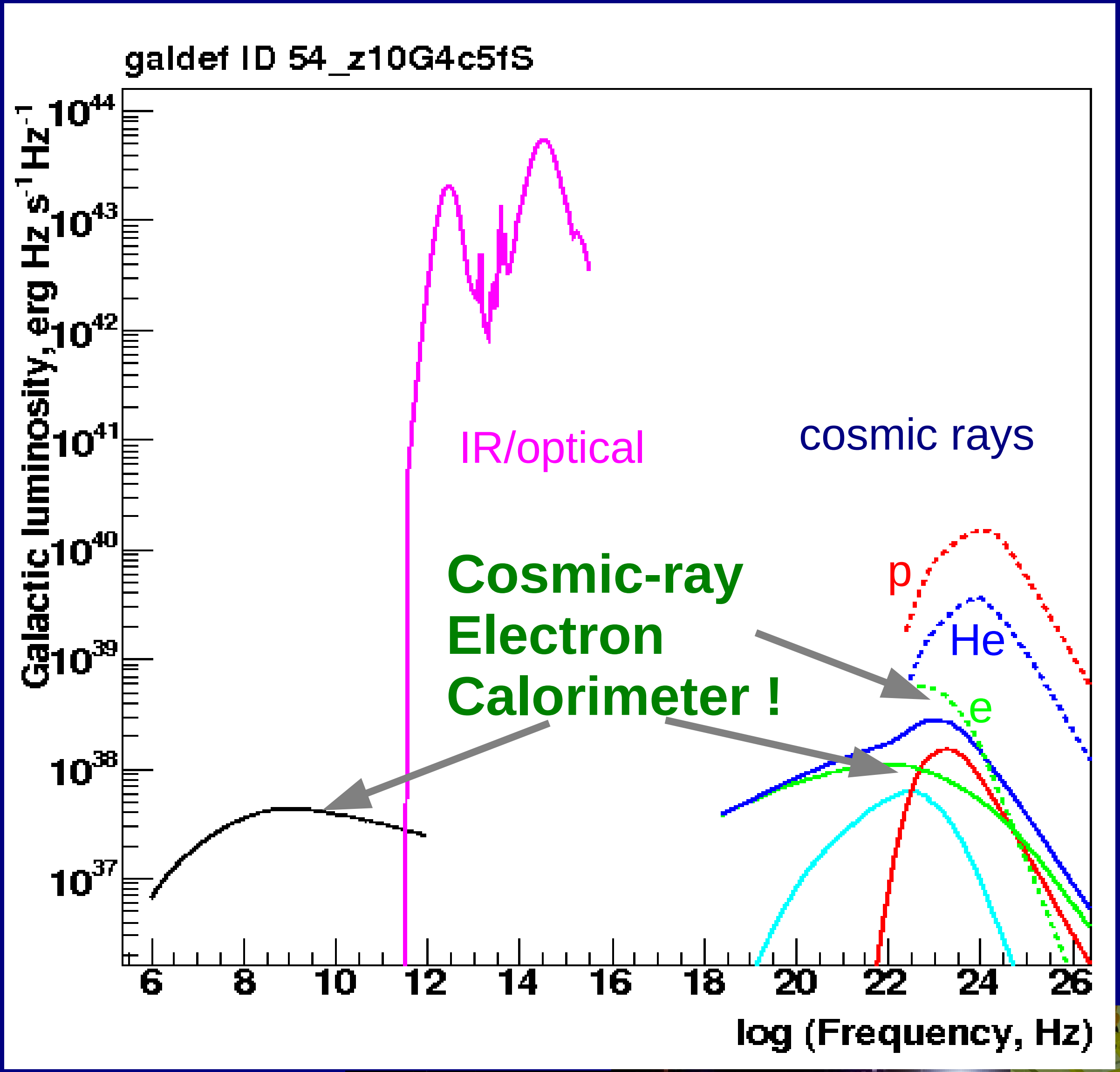

what does it look from out there ?
© Mark A.

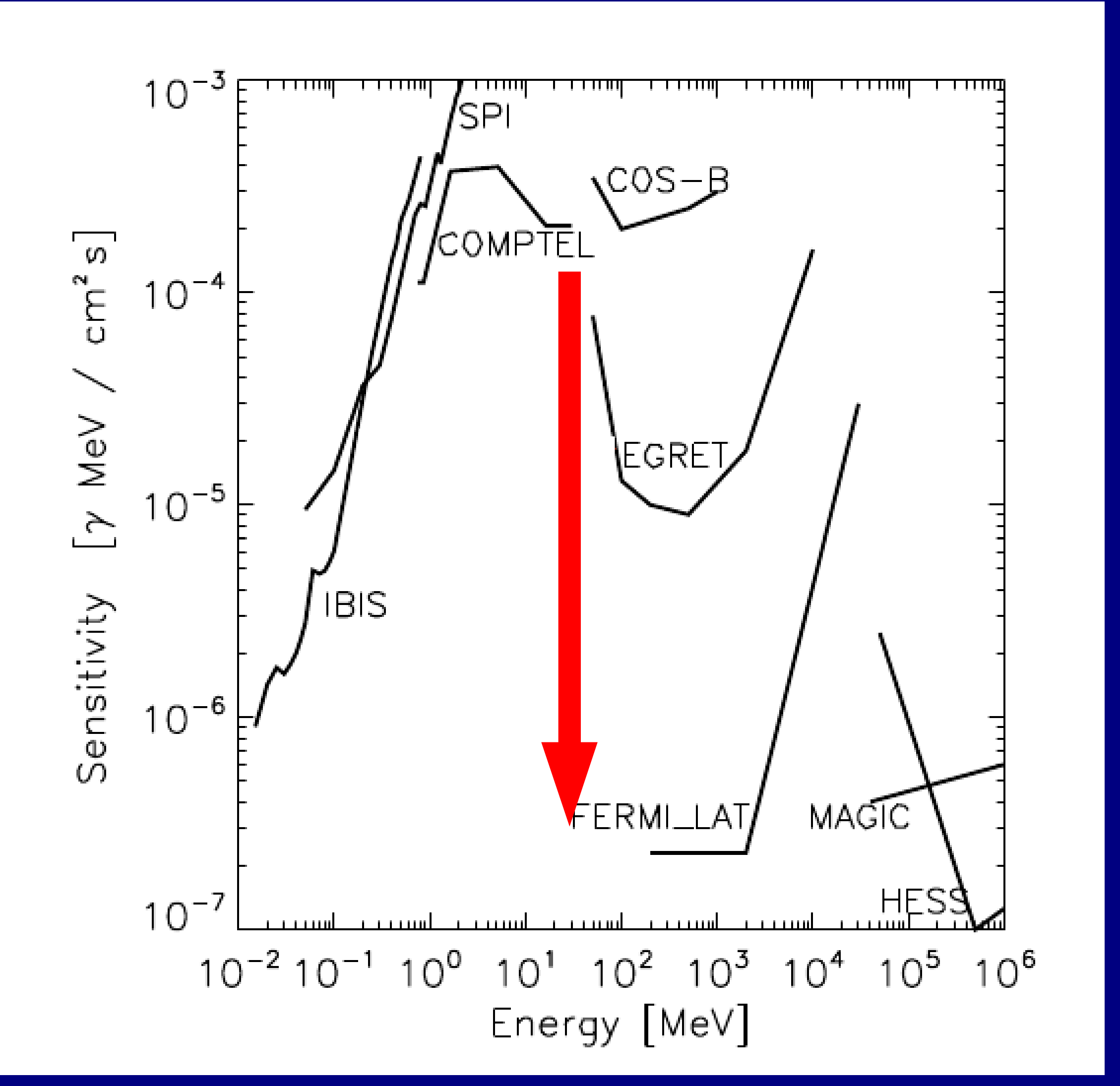

EXPERIMENTS
THEORY
intergalactic space
HALO
Secondary: ^{10}Be, $^{10,11}B$ ... Fe..
Secondary: e^{+-} $\bar{p}$
cosmic-ray sources: p, He .. Ni, e^{-}
synchrotron
B-field
π^{o}
gas
ISRF
bremsstrahlung
inverse Compton
γ – rays

Galaxy luminosity over 20 decades of energy

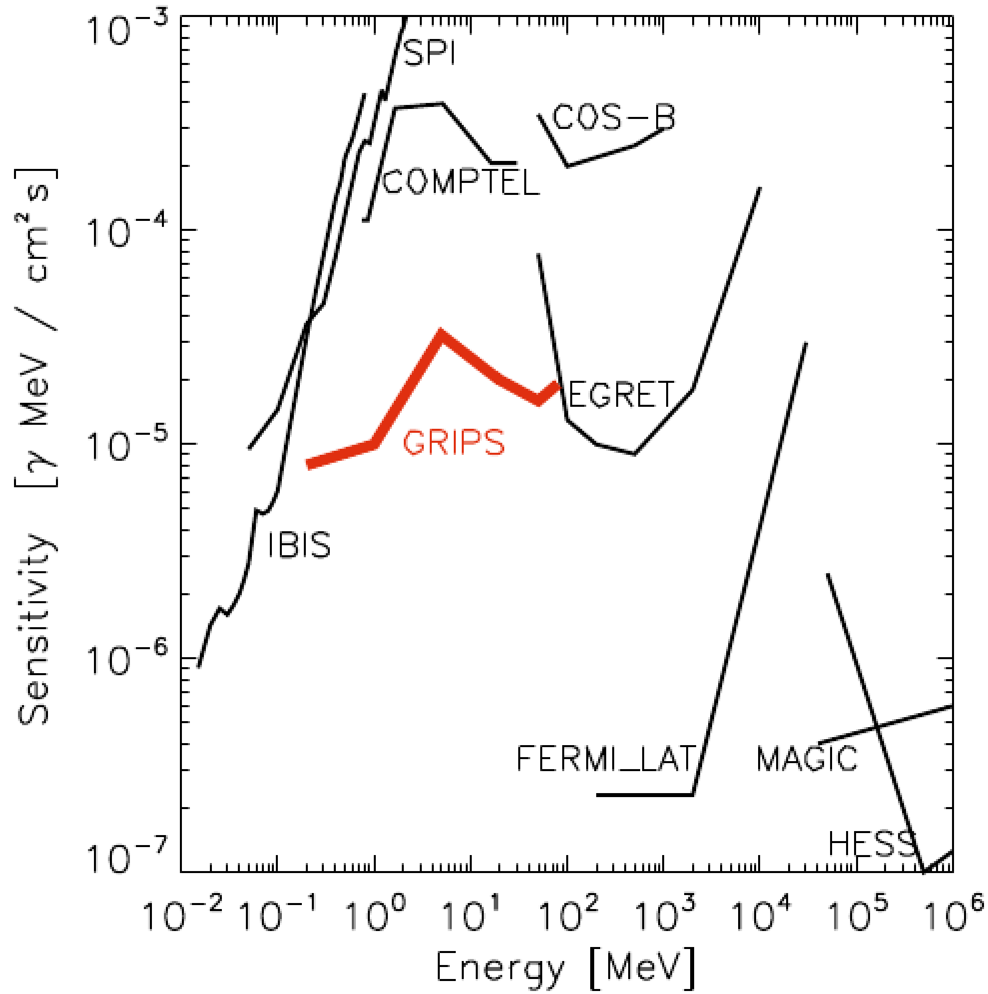


Galaxy luminosity over 20 decades of energy





SPI
COS−B
COMPTEL
EGRET
IBIS
FERMI_LAT
MAGIC
HESS
Sensitivity [γ MeV / cm² s]
Energy [MeV]



SPI
COS−B
COMPTEL
EGRET
GRIPS
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


µeV-meV
0.5-10 keV
6- 79 keV
0.02-2 MeV
0.1 GeV – 100 TeV
1-30 MeV
50 m
TAKE
AWAY
http://www.wisconsinhistory.org/whi
"Leaping the Chasm", Image ID 2101