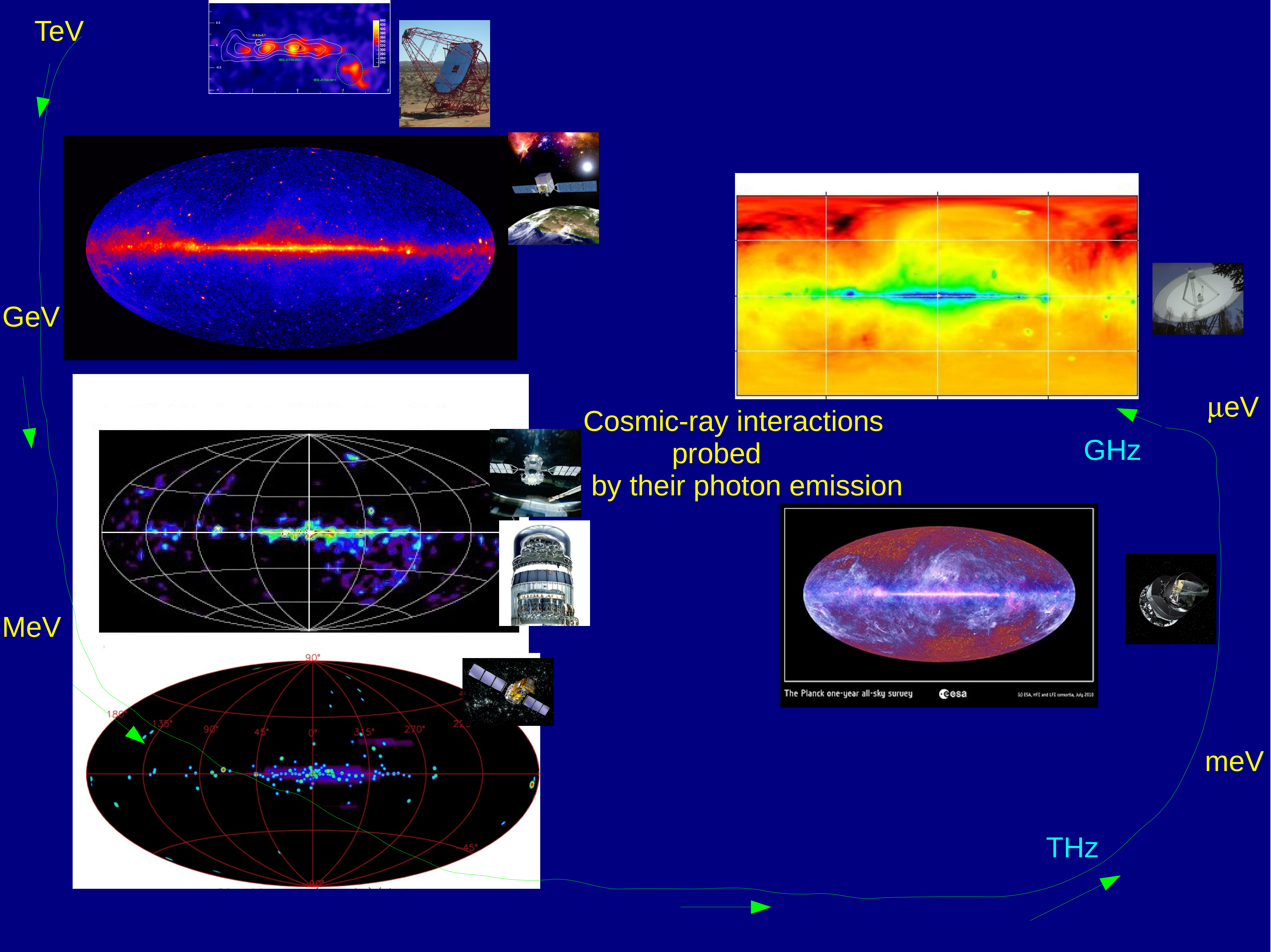
MeV astronomy of the interstellar medium

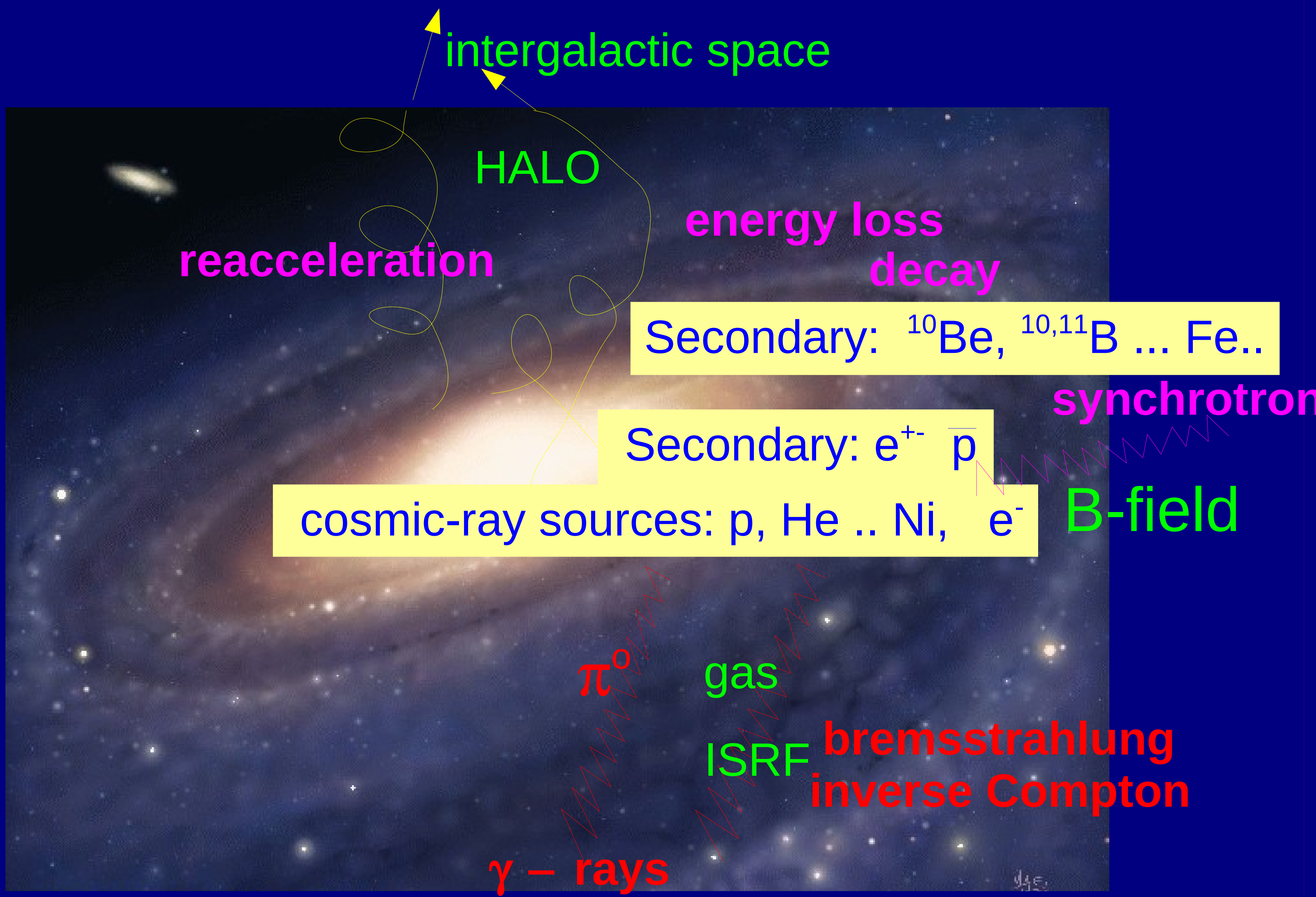
Andy Strong,

MPE Garching

Workshop: Scientific Perspectives in the MeV Domain
APC Paris, Jan 15-16 2013

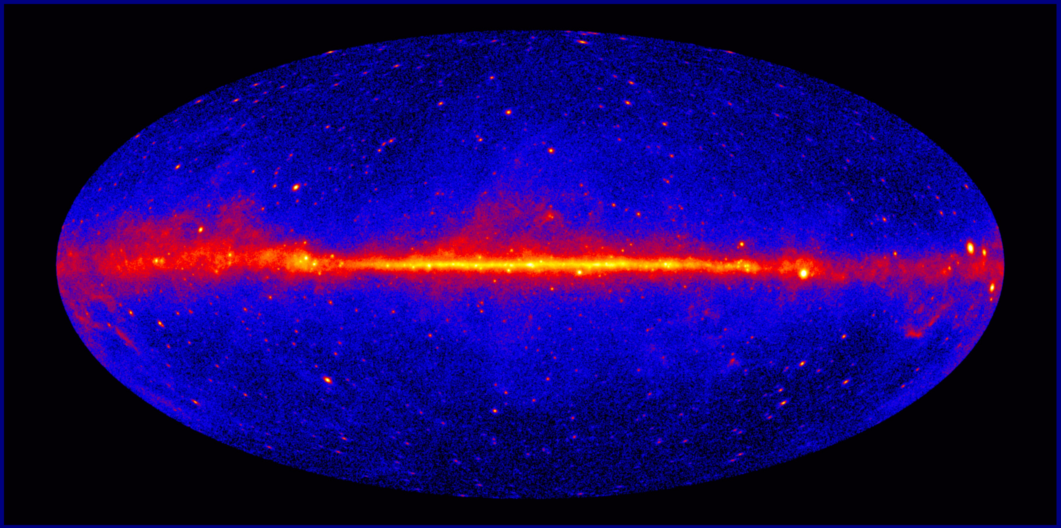

TeV
GeV
MeV
Cosmic-ray interactions
probed
by their photon emission
μeV
GHz
meV
THz
The Planck one-year all-sky survey
esa
90°
180°
135°
90°
45°
0°
315°
270°
-45°

COSMIC RAYS produce many observables



Fermi
Gamma-ray Space Telescope

1 – 10 GeV

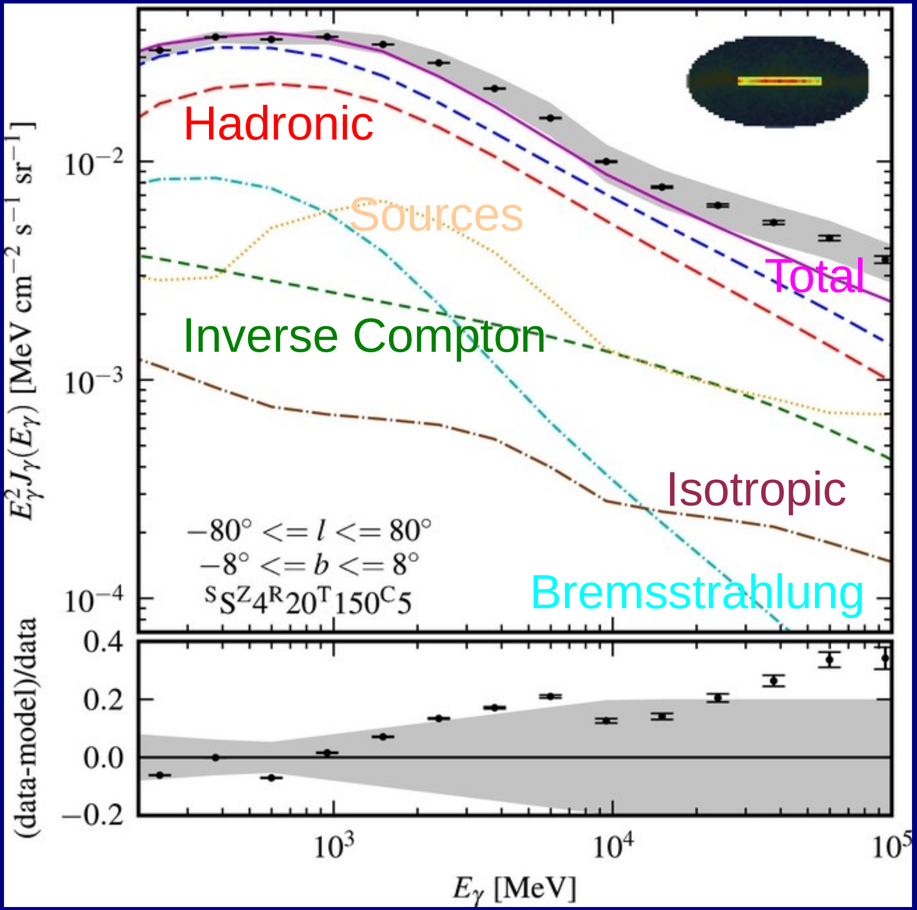


Most photons from cosmic-rays :

nuclei interacting with interstellar gas : hadronic

electrons and positrons interacting with interstellar radiation : inverse Compton
Interstellar gas : bremsstrahlung

Fermi-LAT
Inner Galaxy Gamma Ray Spectrum

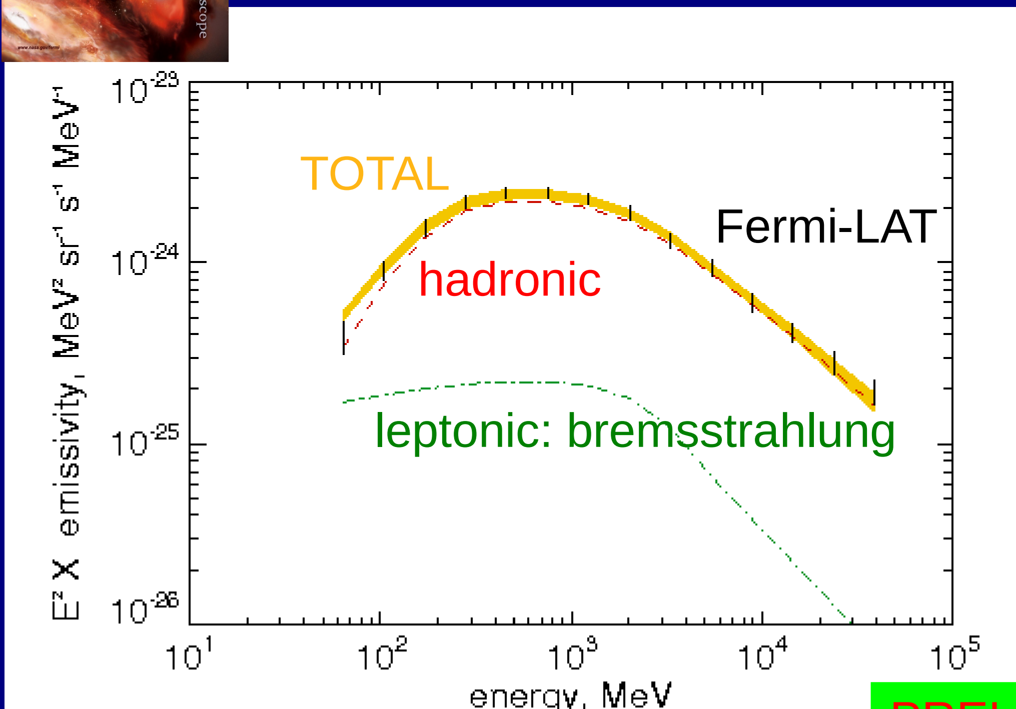


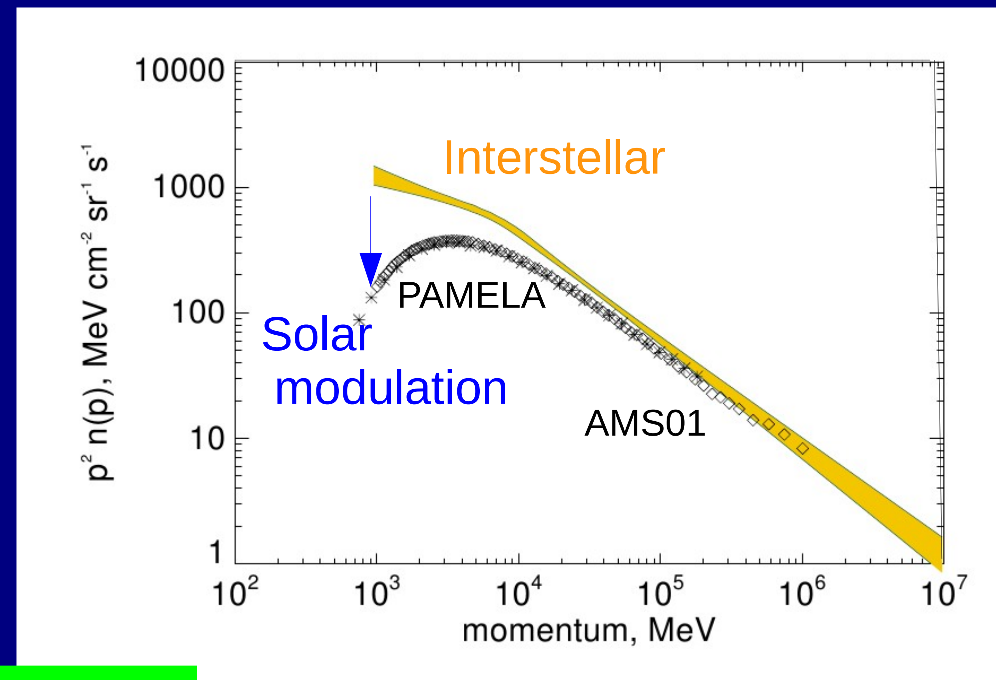
Ackermann et al. ApJ 750, 3 (2012)

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).

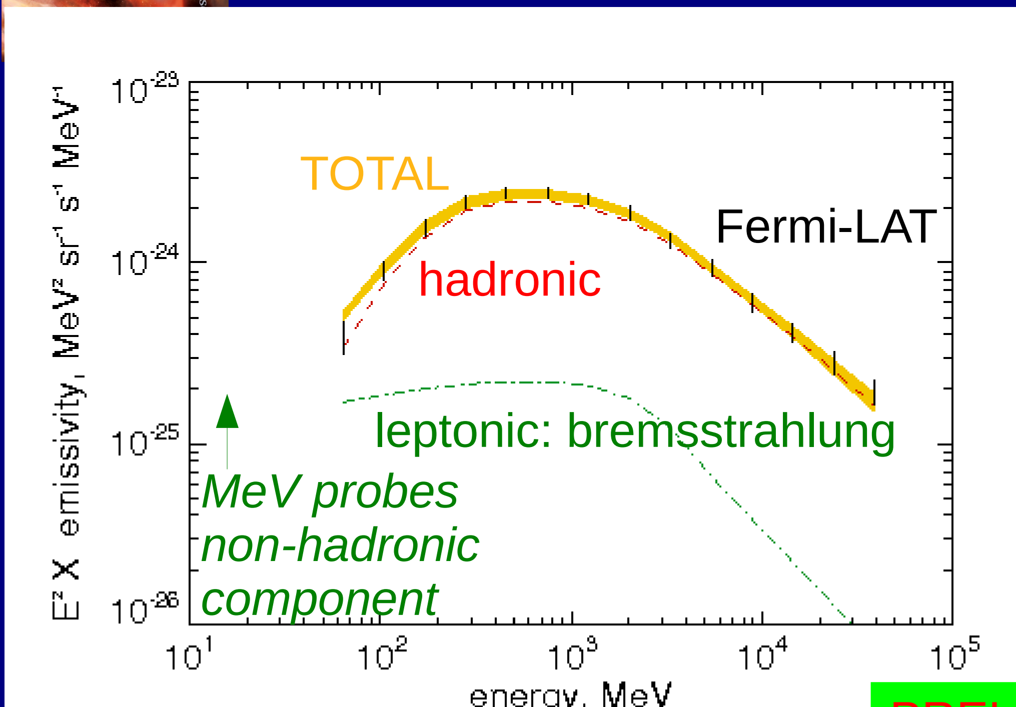
Power-law in momentum overall, but low-energy break ?
e.g. from power-law injection and interstellar propagation (diffusion = f(E))

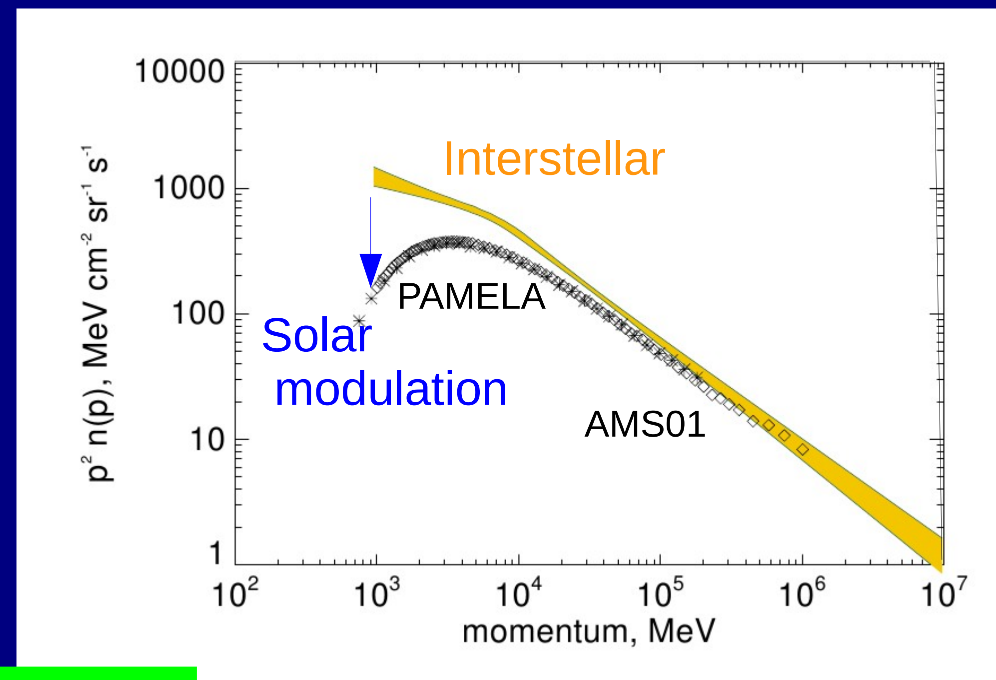
Interstellar spectrum essential to test heliospheric modulation models.

Interstellar Cosmic ray spectra derived from gamma rays

Method : Bayesian analysis

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





PRELIMINARY

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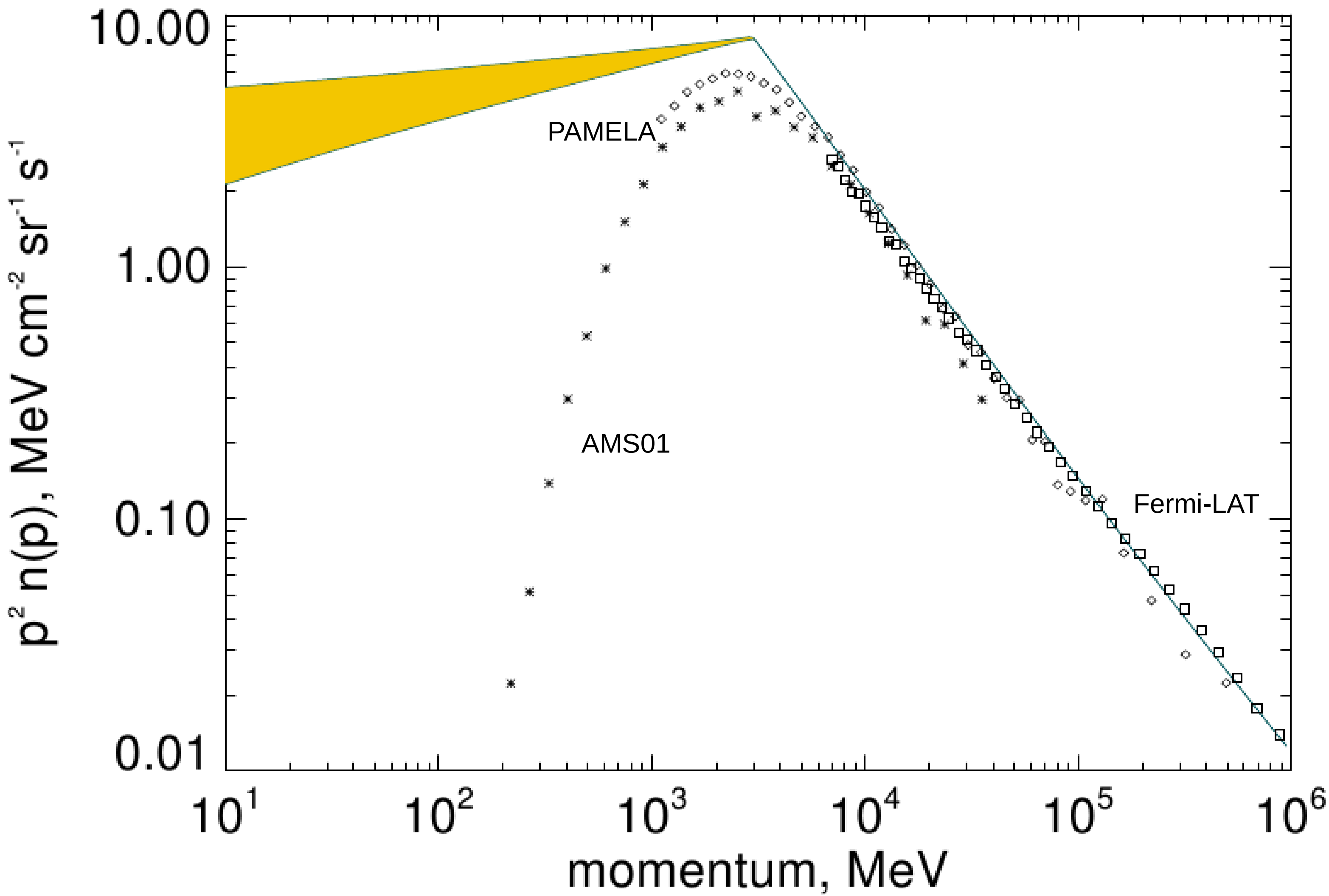
Interstellar Electrons

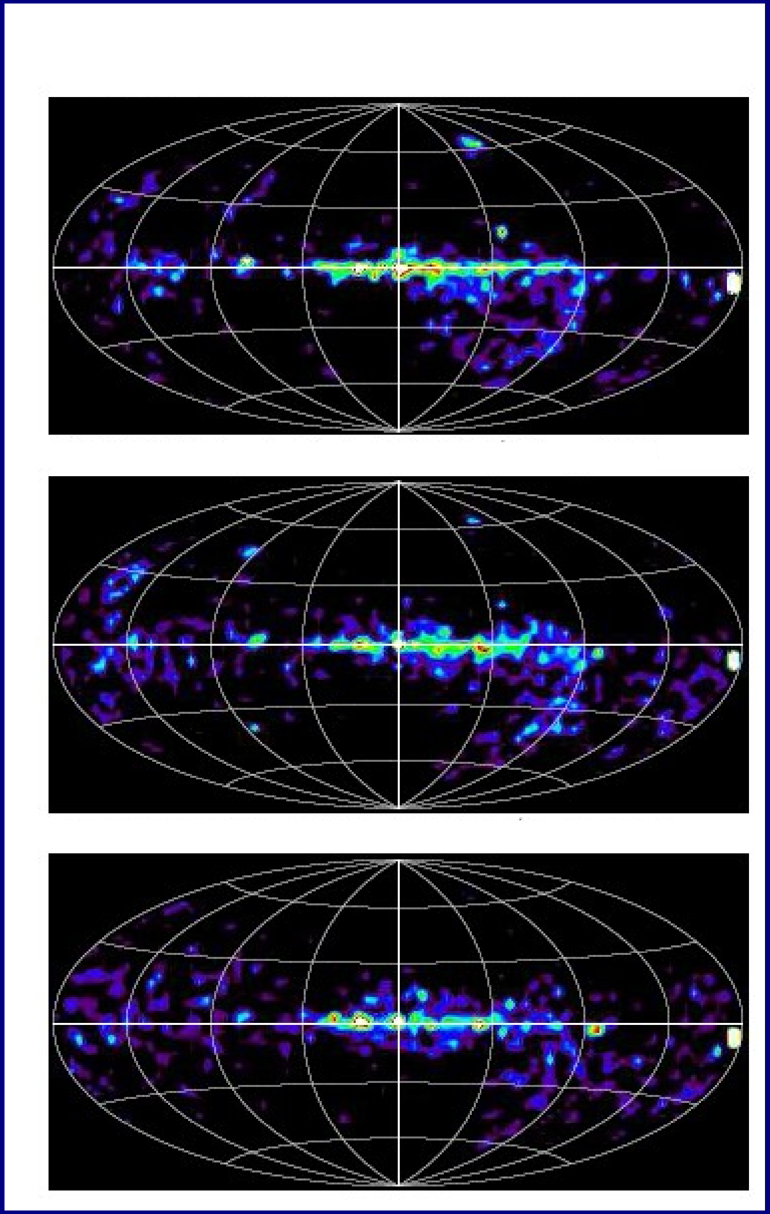
from synchrotron, gamma rays and direct measurements



PRELIMINARY

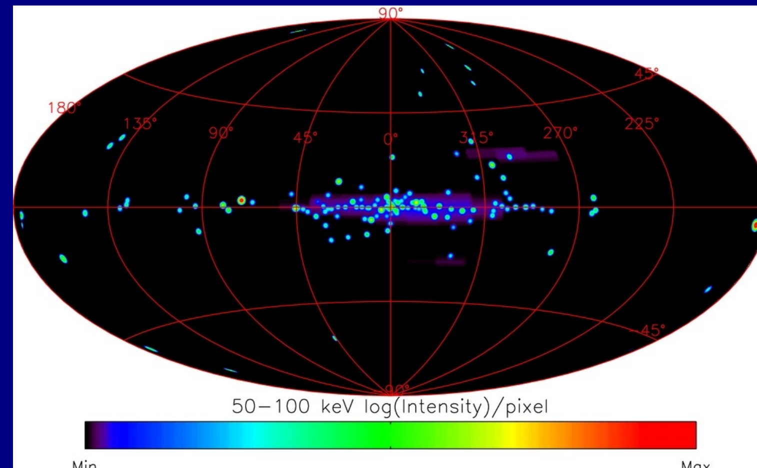
CGRO/ COMPTEL

MeV continuum



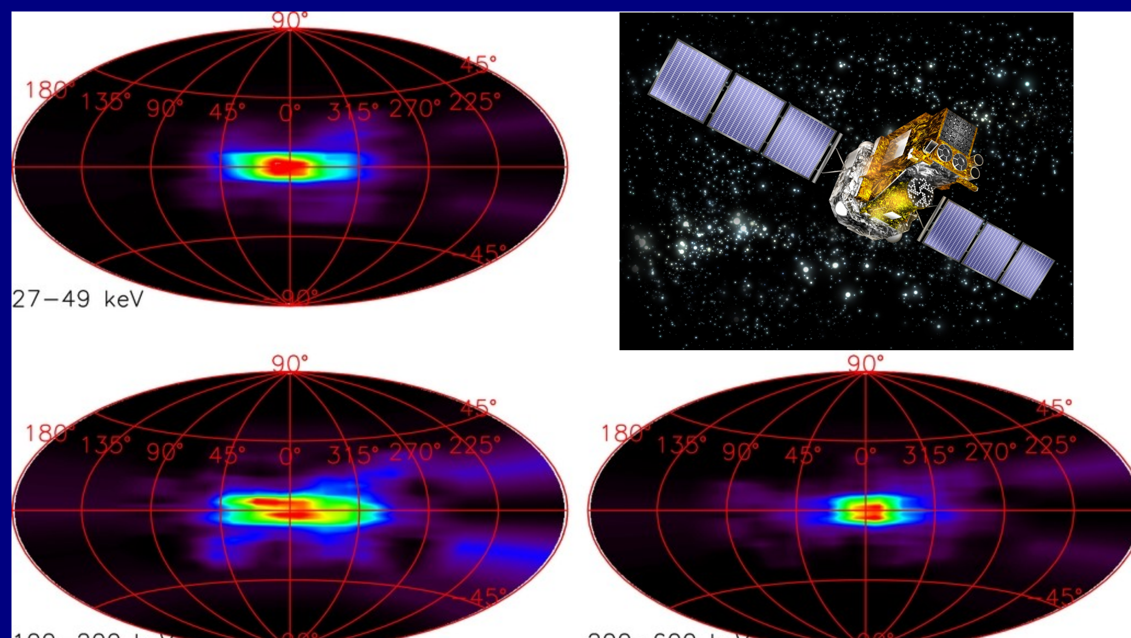
Unique heritage data:
COMPTEL analysis continues....
Talk by Werner Collmar,
this meeting

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



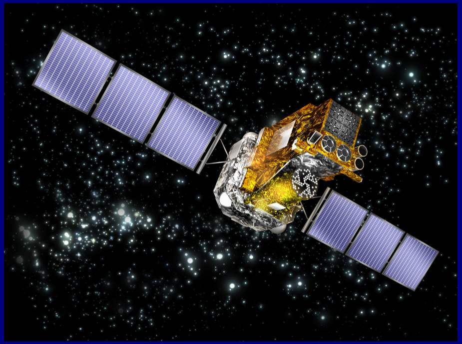
INTEGRAL / SPI
Continuum skymaps

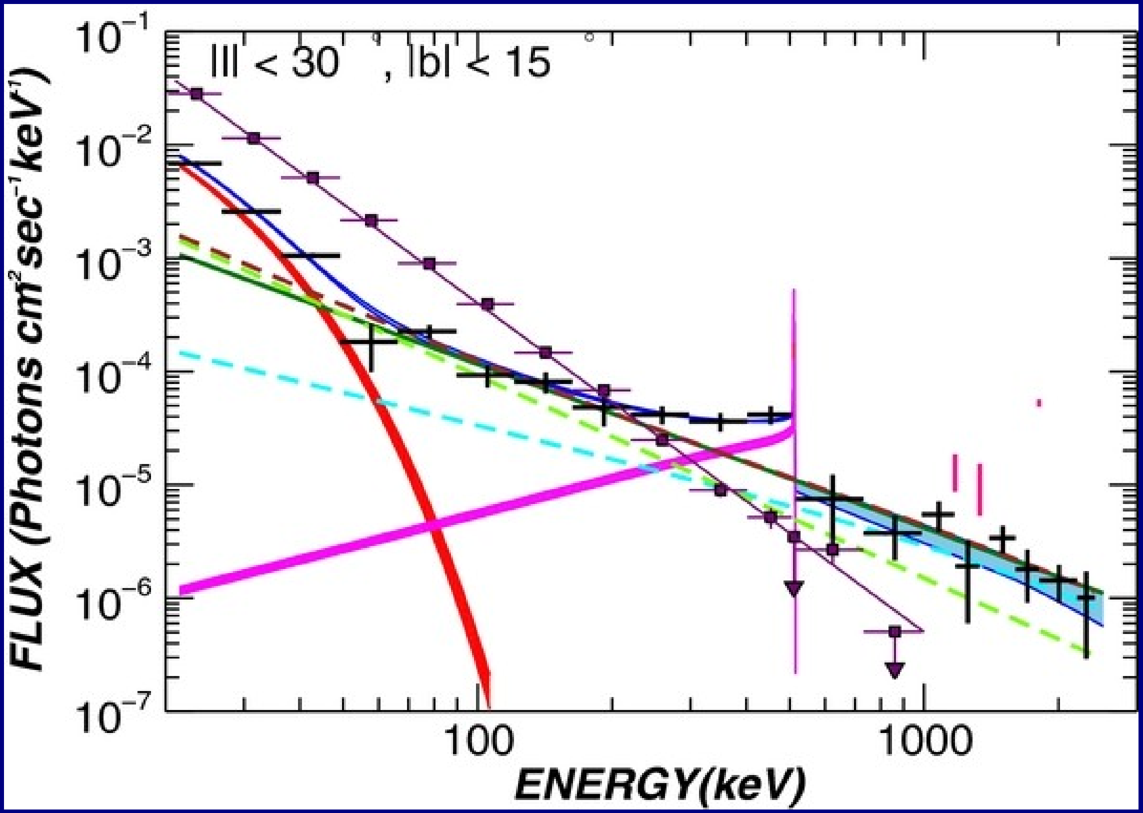
Bouchet et al.
ApJ 739, 29 (2011)



A real mix of processes !

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





Inner Galaxy
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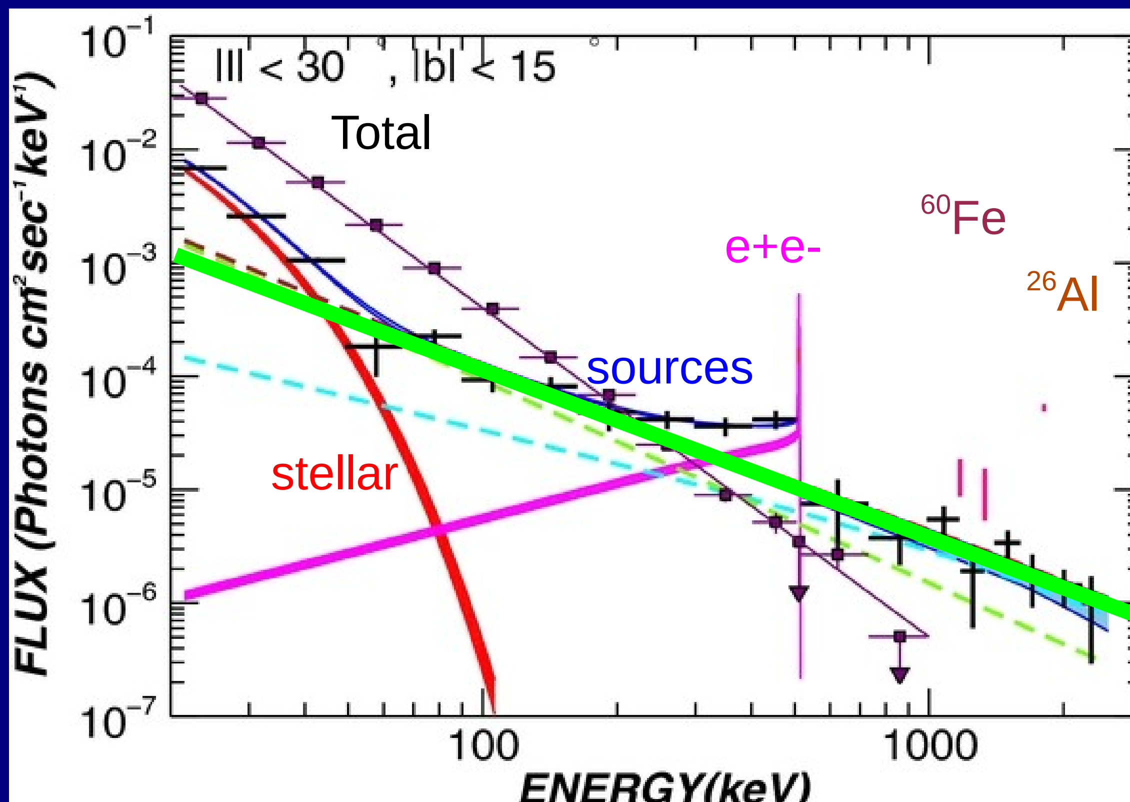
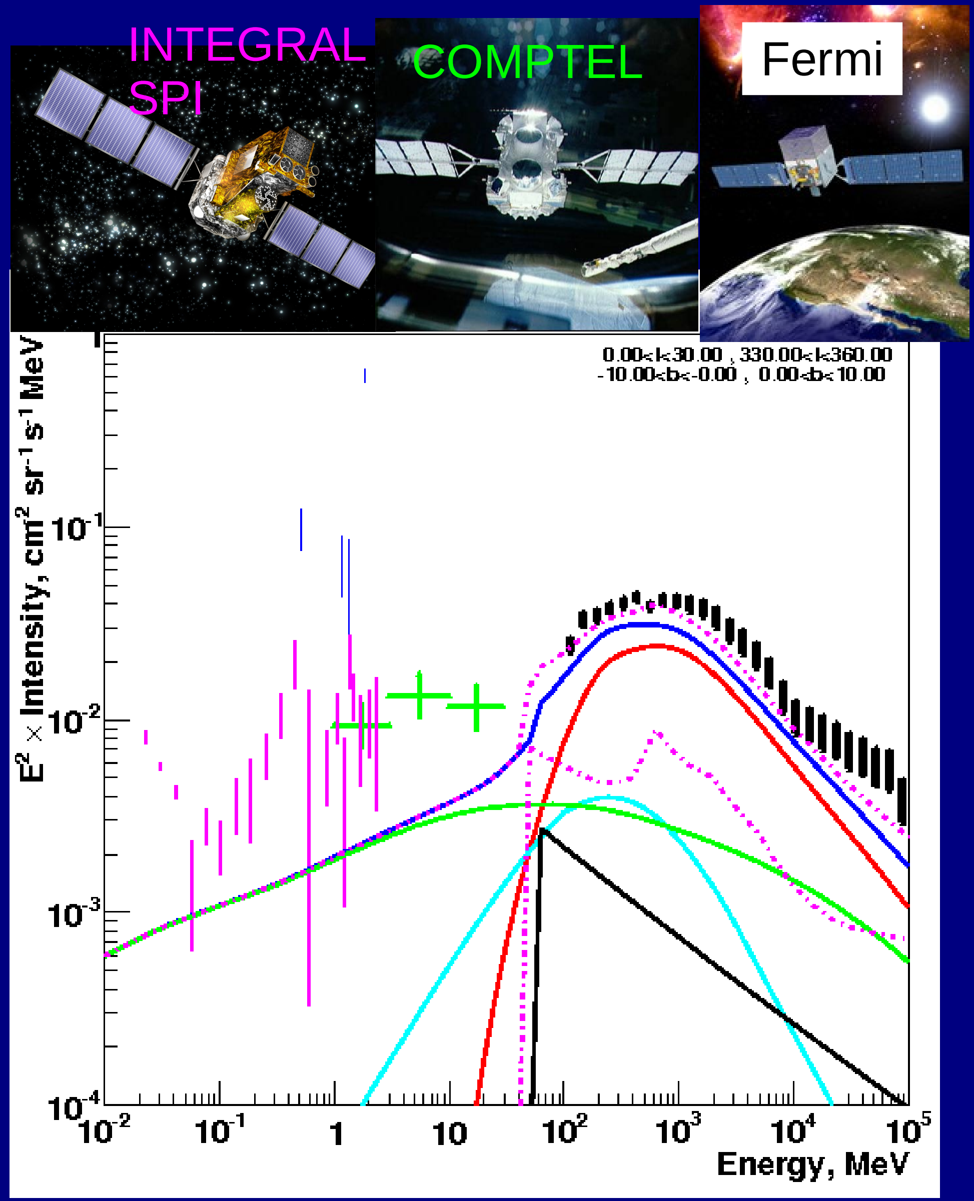


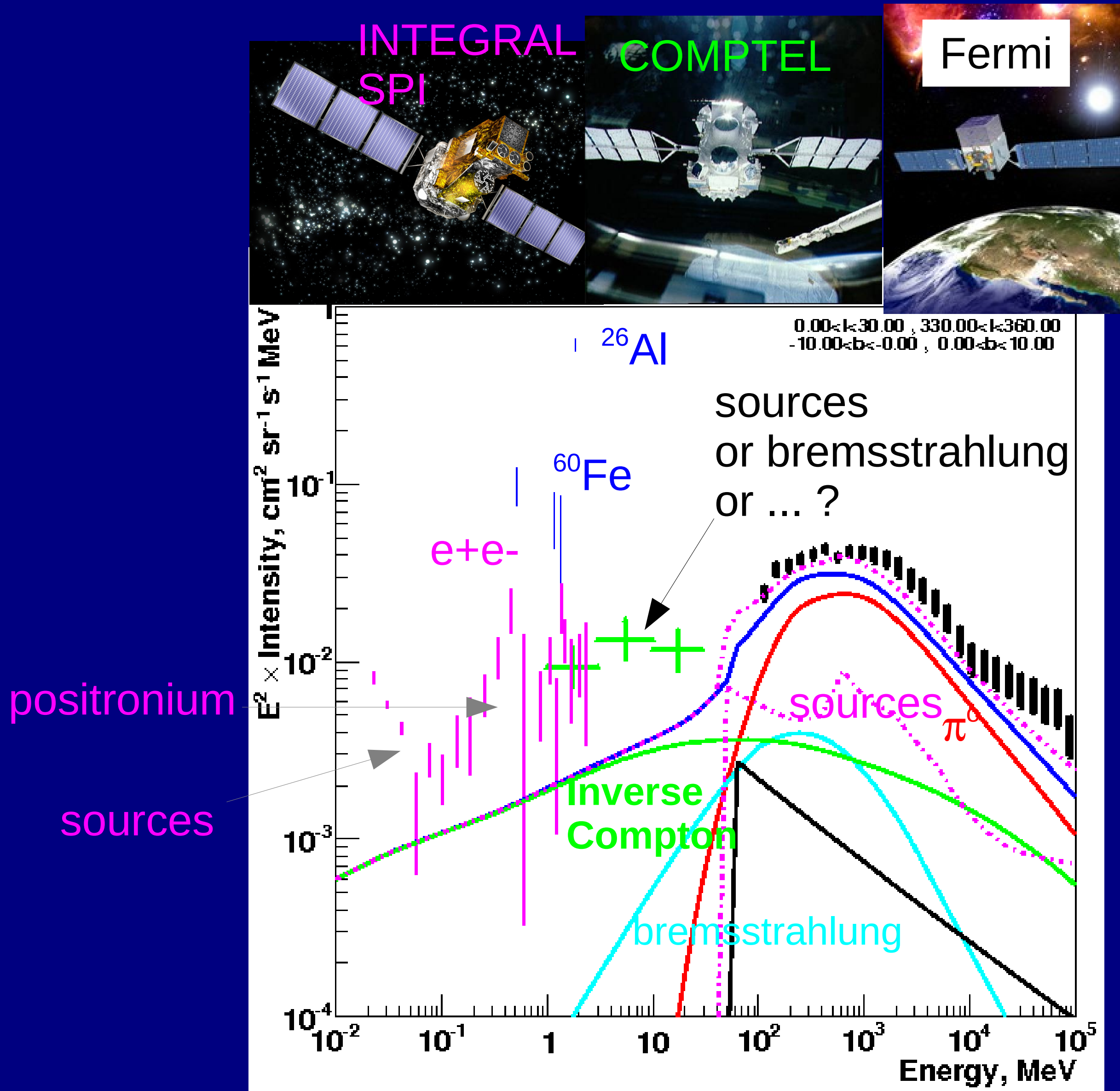
Non-thermal:
Cosmic-ray interactions

Inner Galaxy: keV to TeV



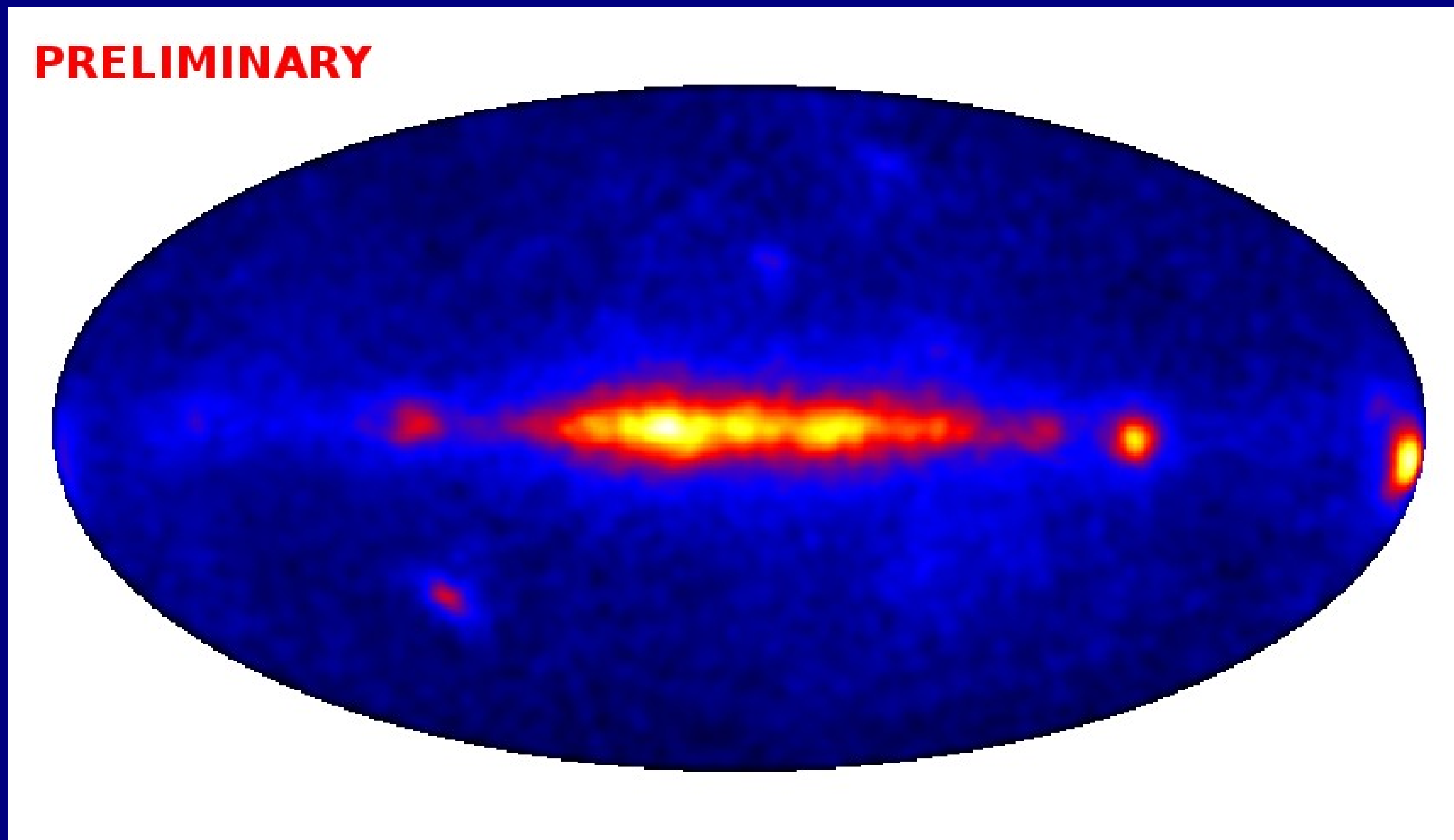
Strong 2011, Proc. 12 ICATPP Conf. arXiv:1101.1381

Inner Galaxy: keV to TeV



GeV electrons – inverse Compton - important for MeV gamma rays !
Bremsstrahlung from MeV electrons – only from theory, perhaps much larger.

Fermi-LAT 25 – 40 MeV

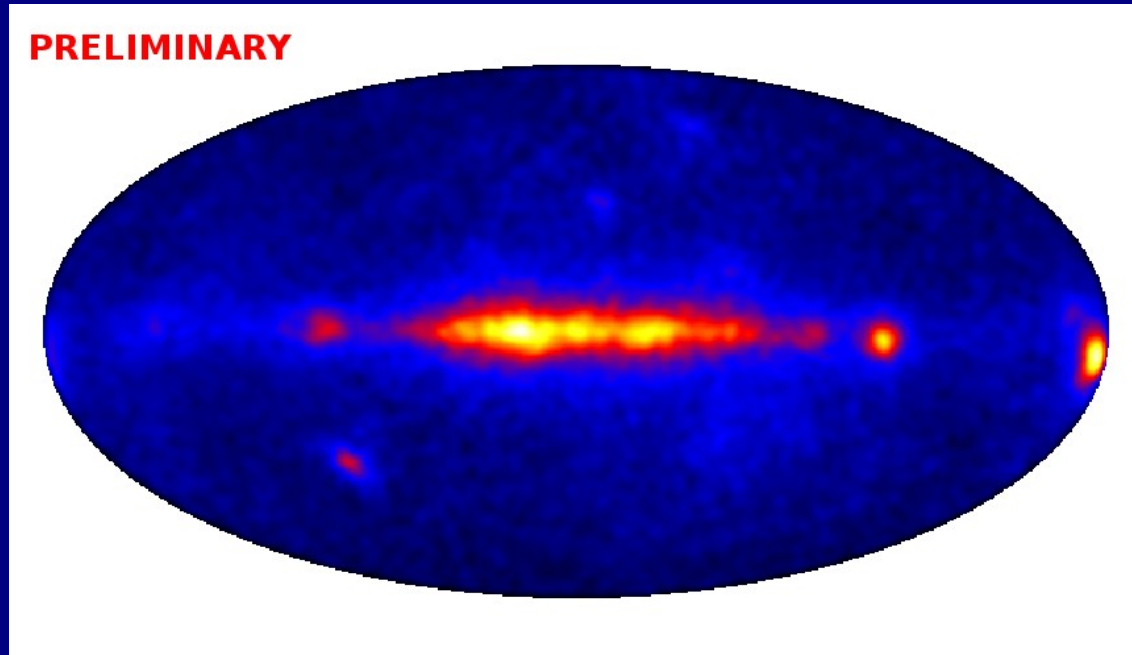


NB low angular and energy resolution !

Nominal energy range: photons may originate from range 10 to <100 MeV.

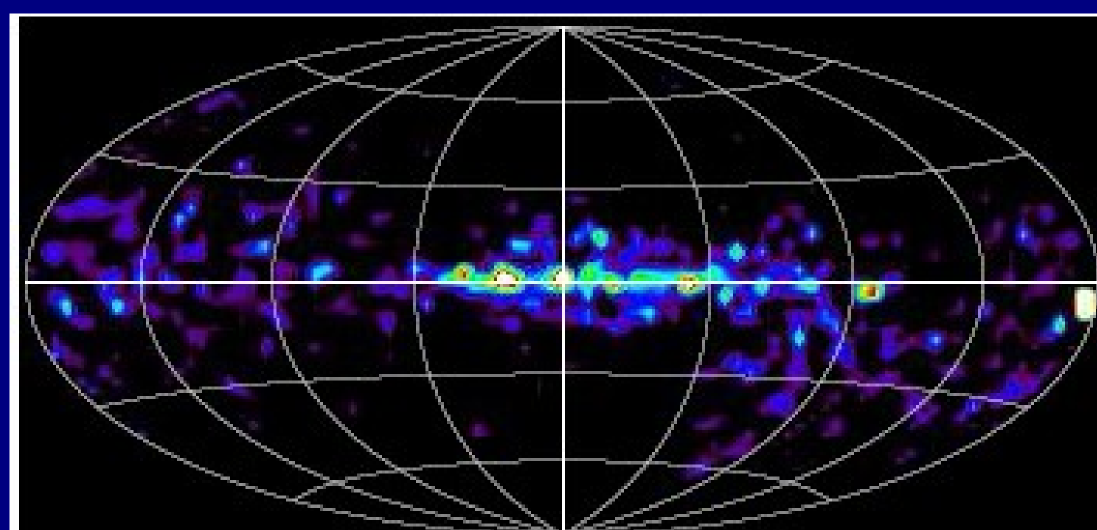
But valuable to bridge the MeV gap.

Fermi-LAT 25-40 MeV

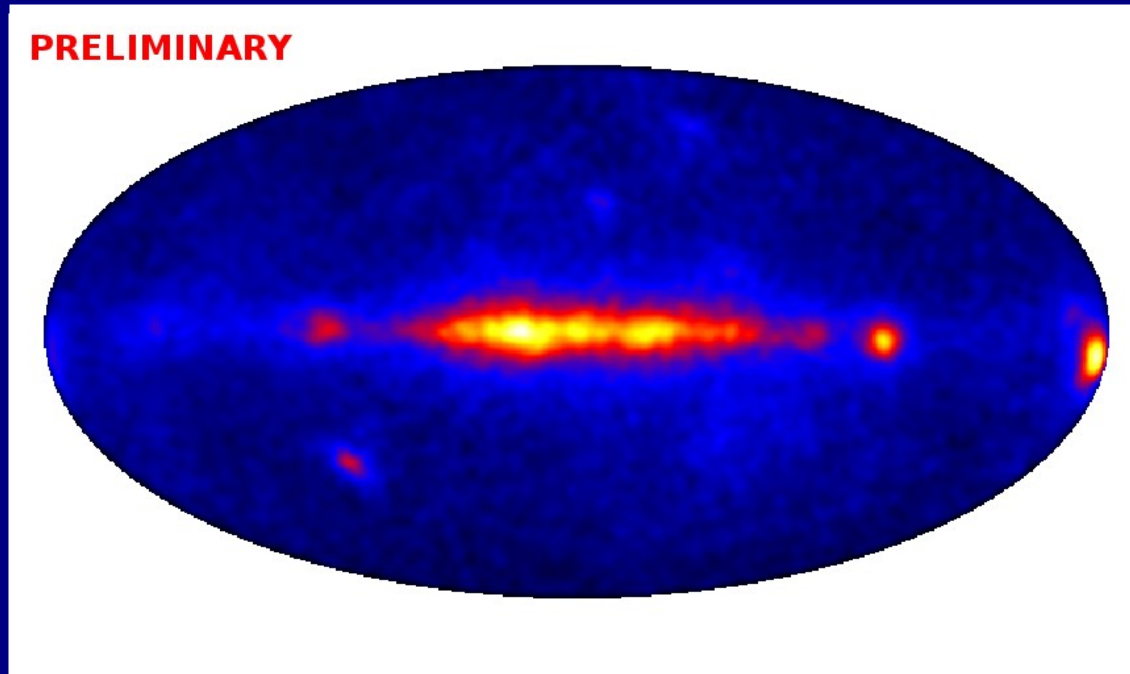


meets

COMPTEL 10-30 MeV

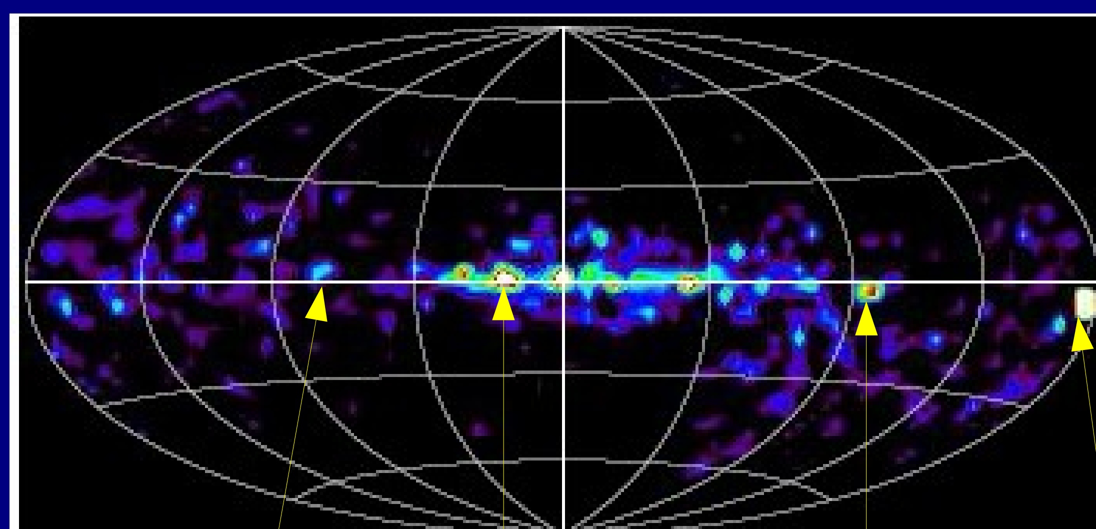


Fermi-LAT 25-40 MeV



meets

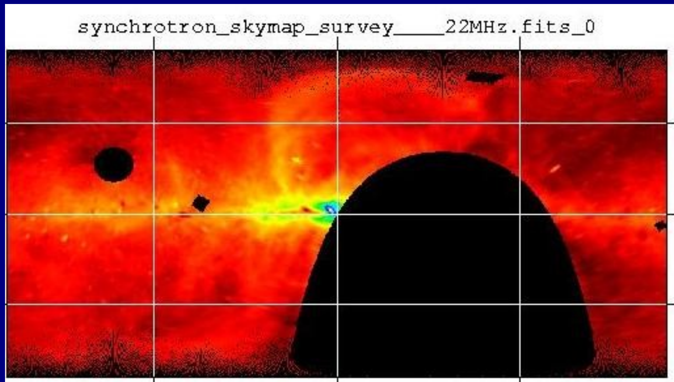
COMPTEL 10-30 MeV



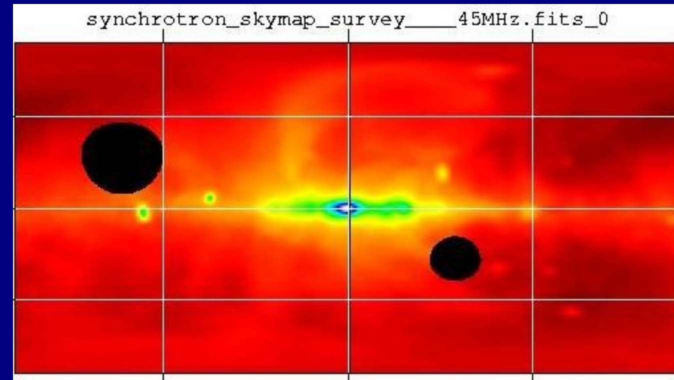
Galactic Plane

Cyg X-1 LS5039 Vela PSR Crab

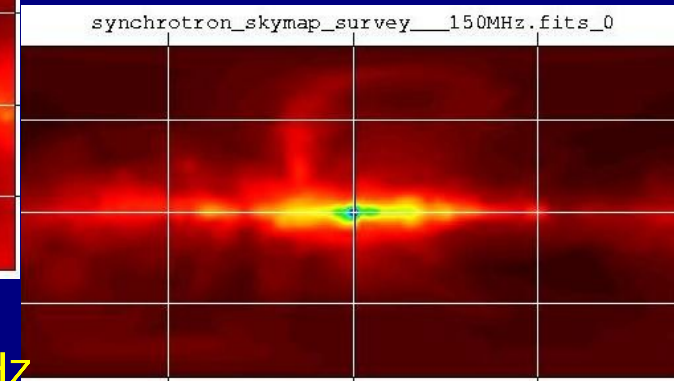
Continuum sky surveys



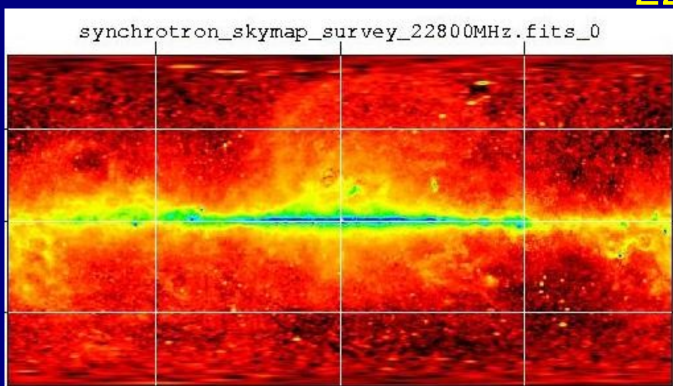
22 MHz



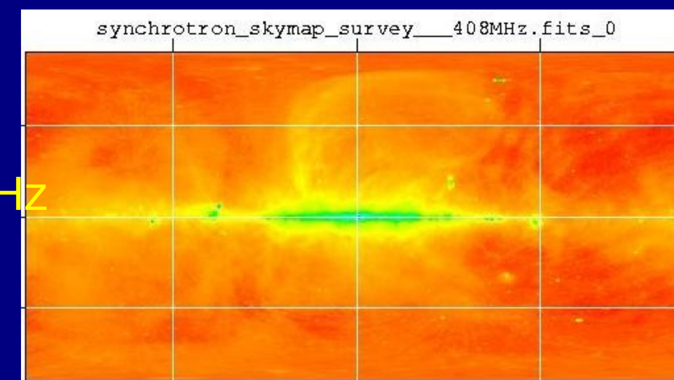
45 MHz



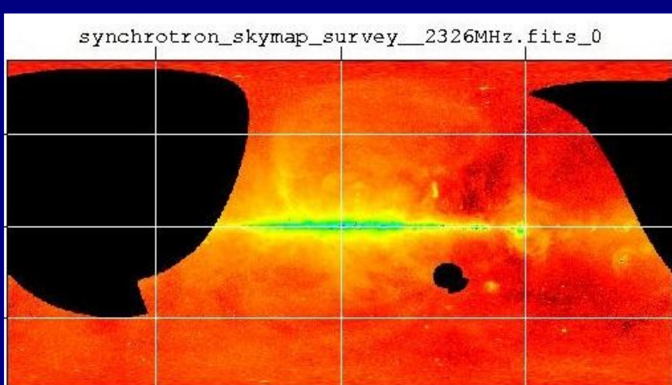
150 MHz



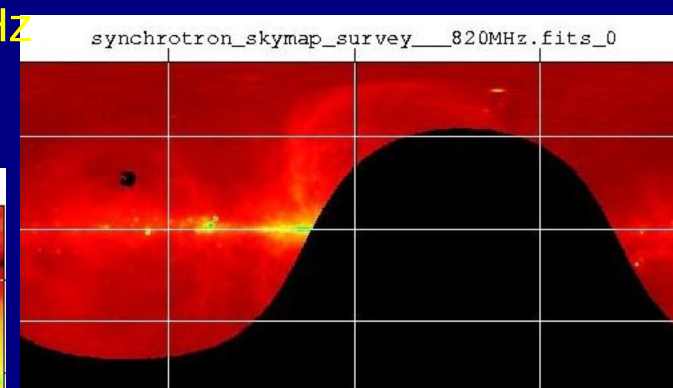
23 GHz



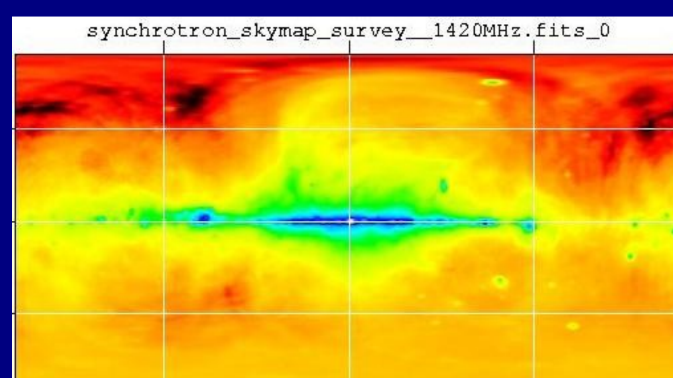
408 MHz



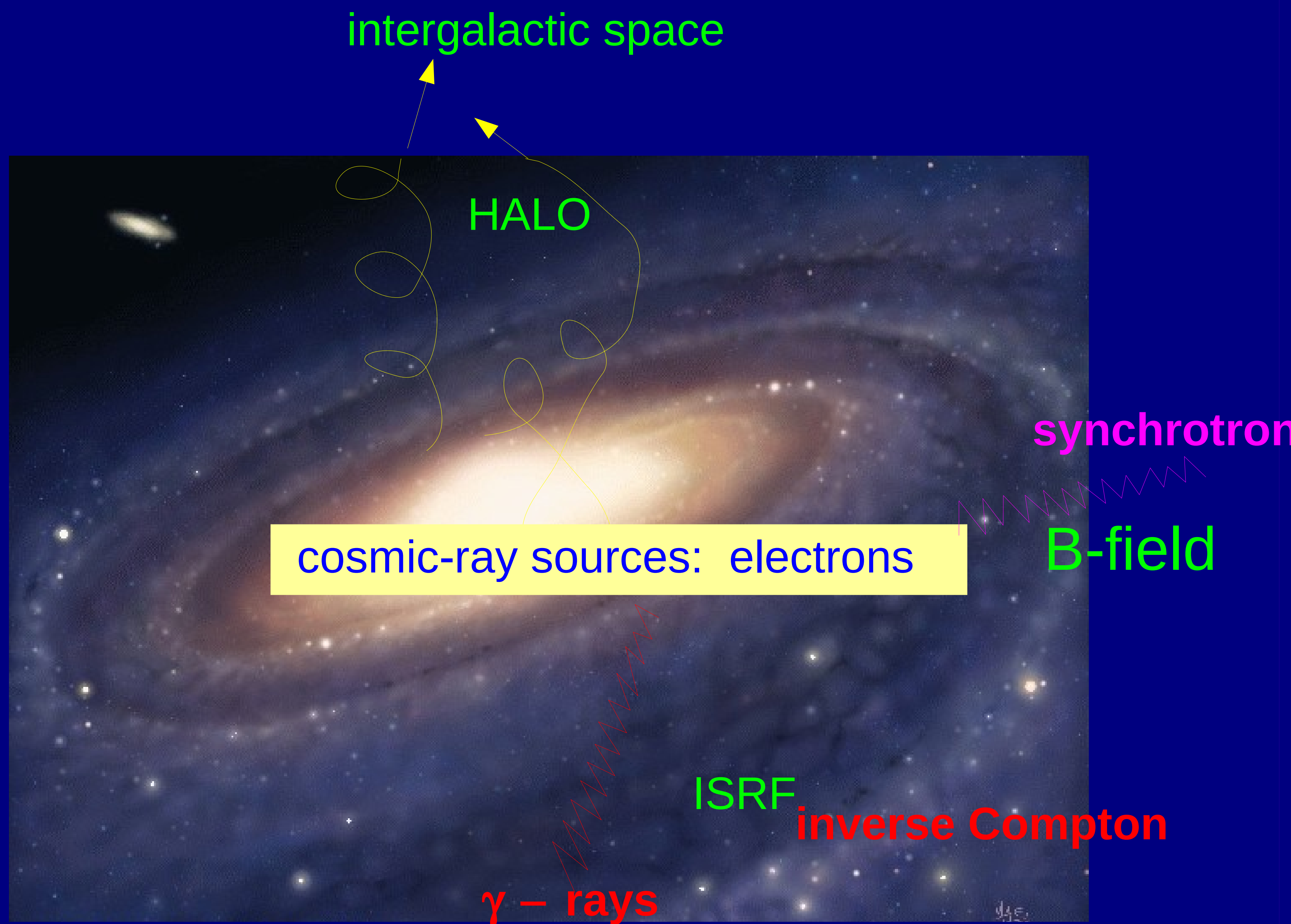
2.3 GHz

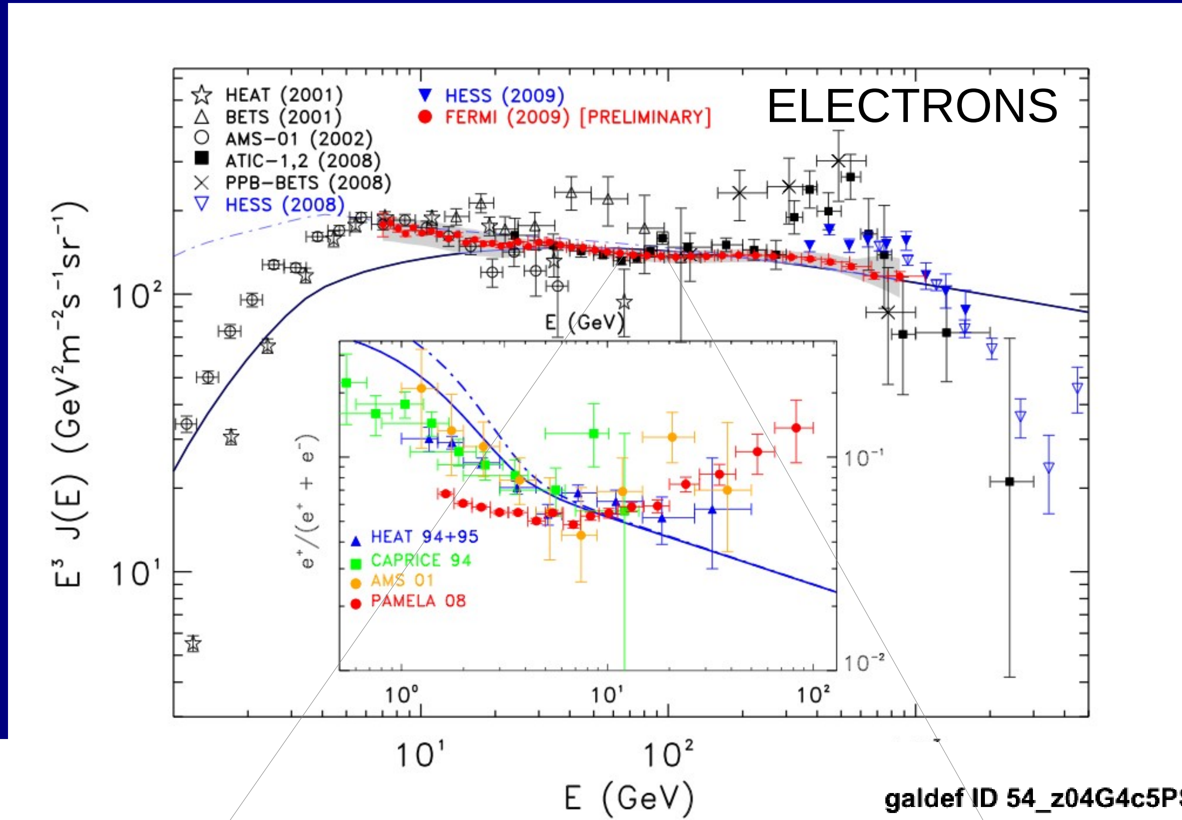


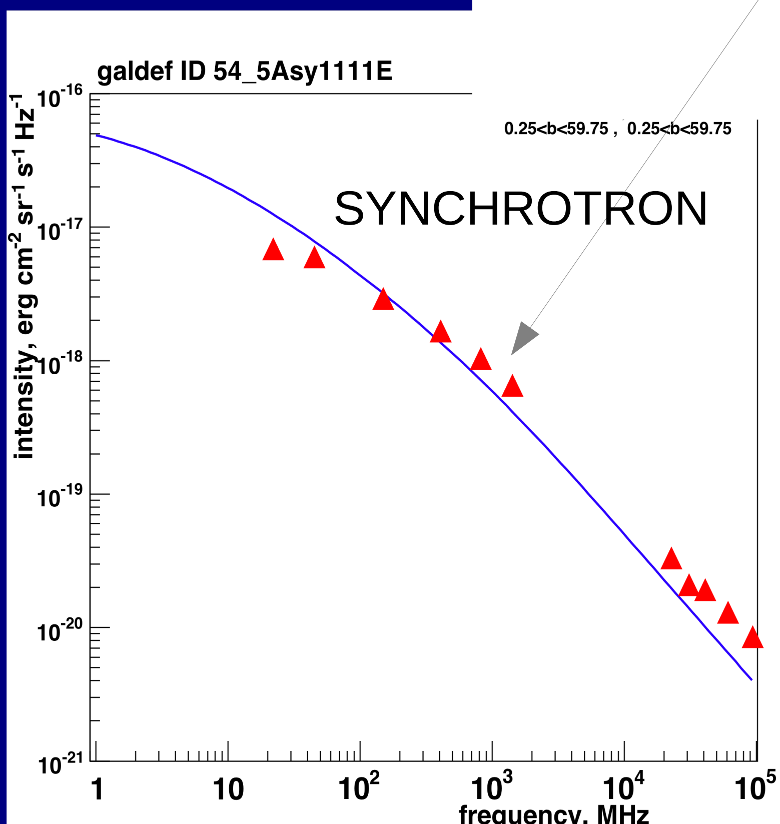
820 MHz



1.4 GHz

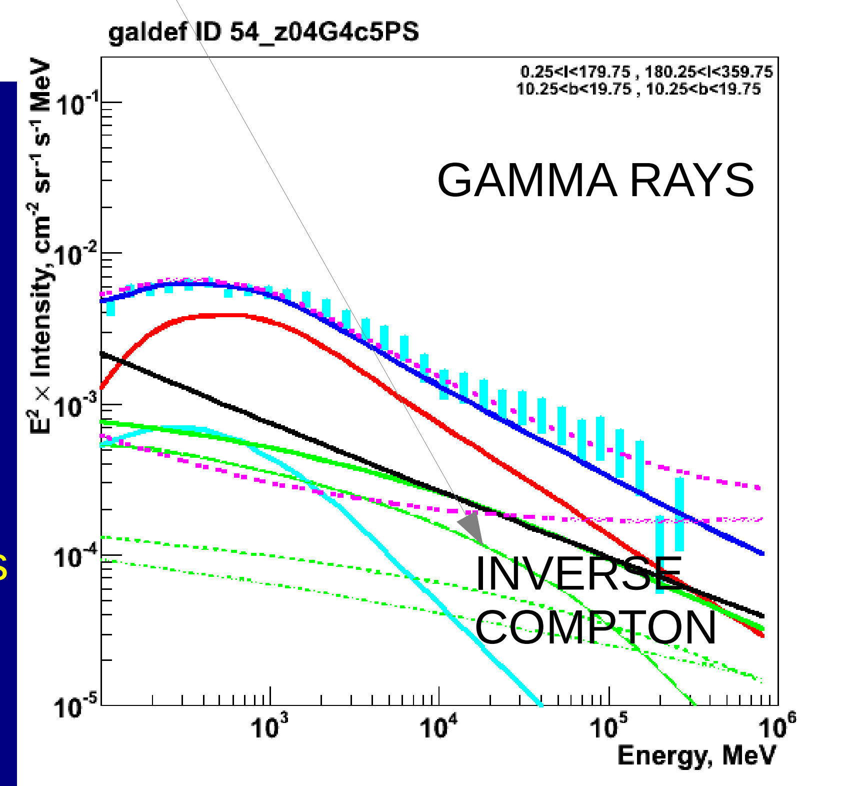

intergalactic space
HALO
synchrotron
cosmic-ray sources: electrons
B-field
ISRF
inverse Compton
γ – rays

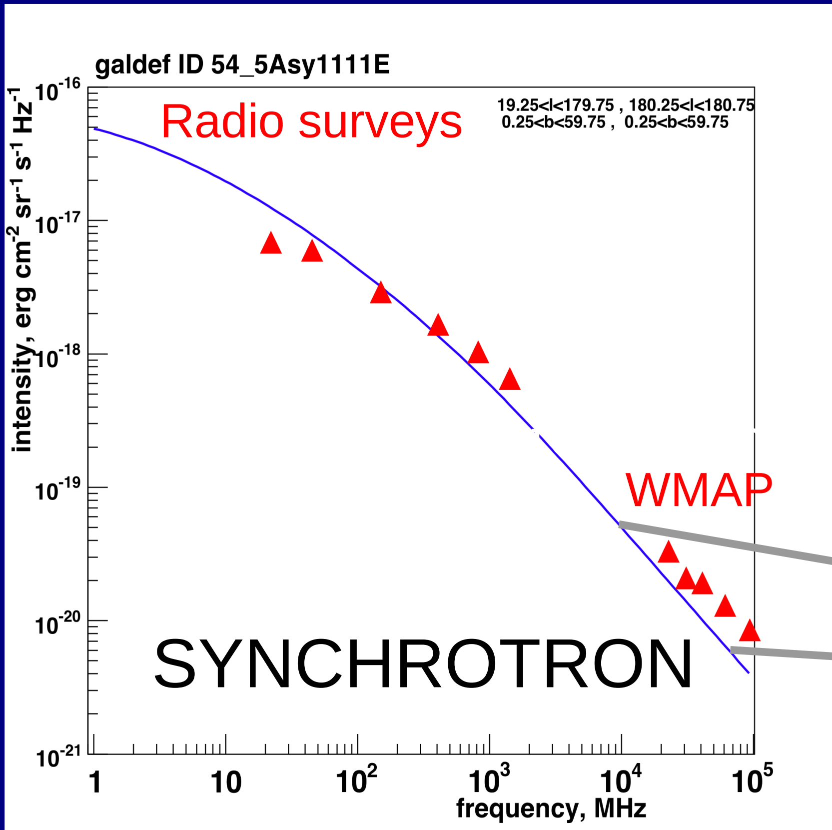


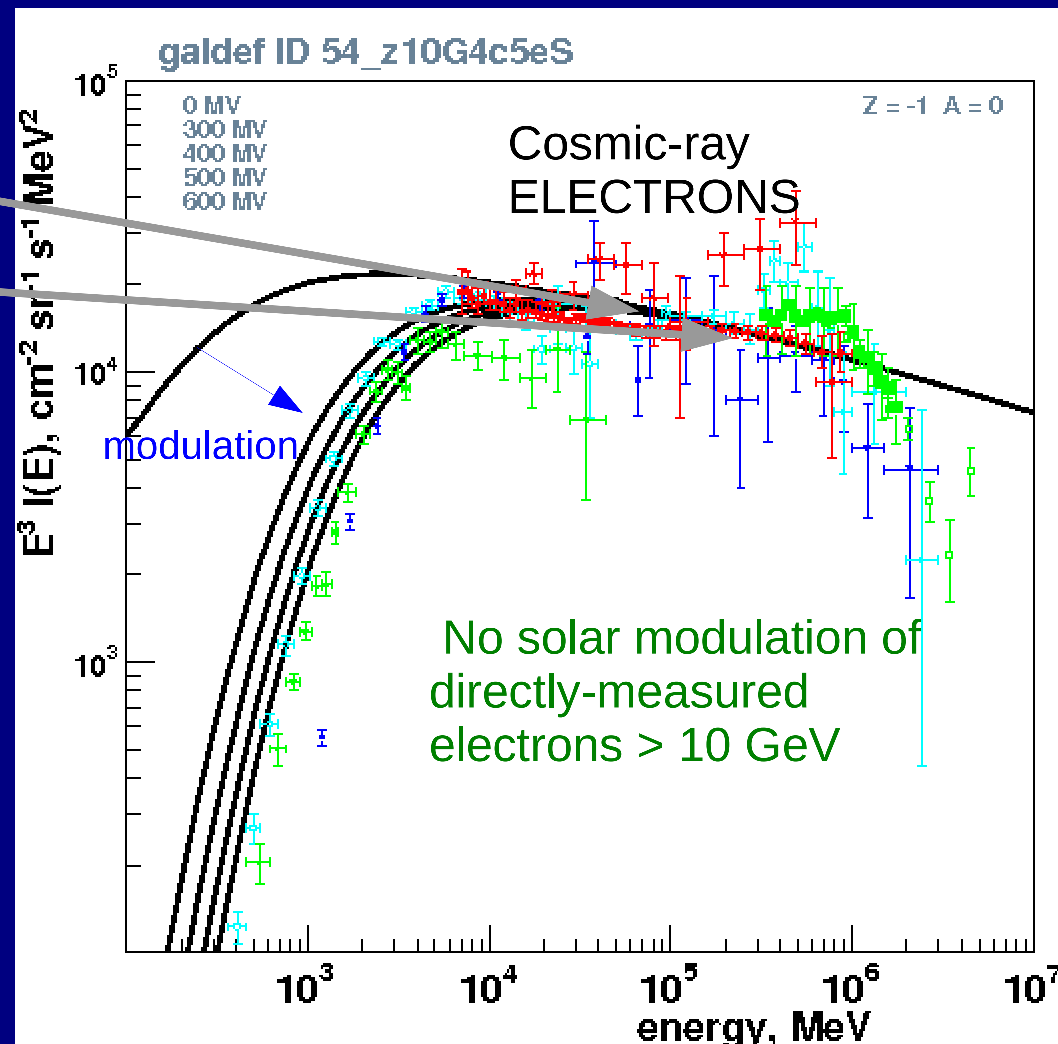


SAME ELECTRONS for RADIO and GAMMA RAYS !

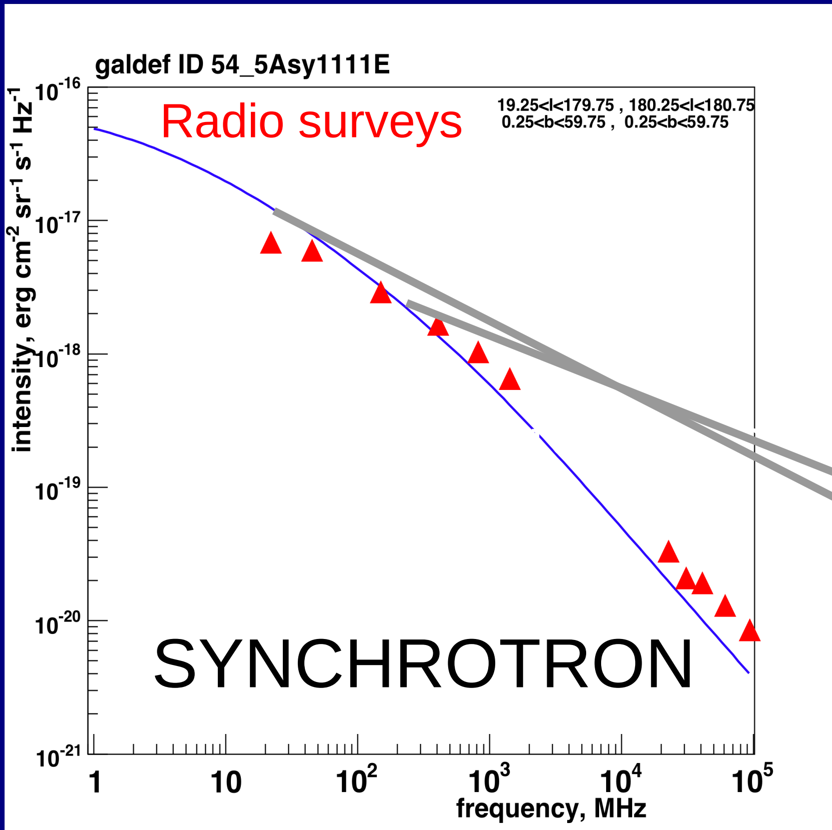
good constraints on models

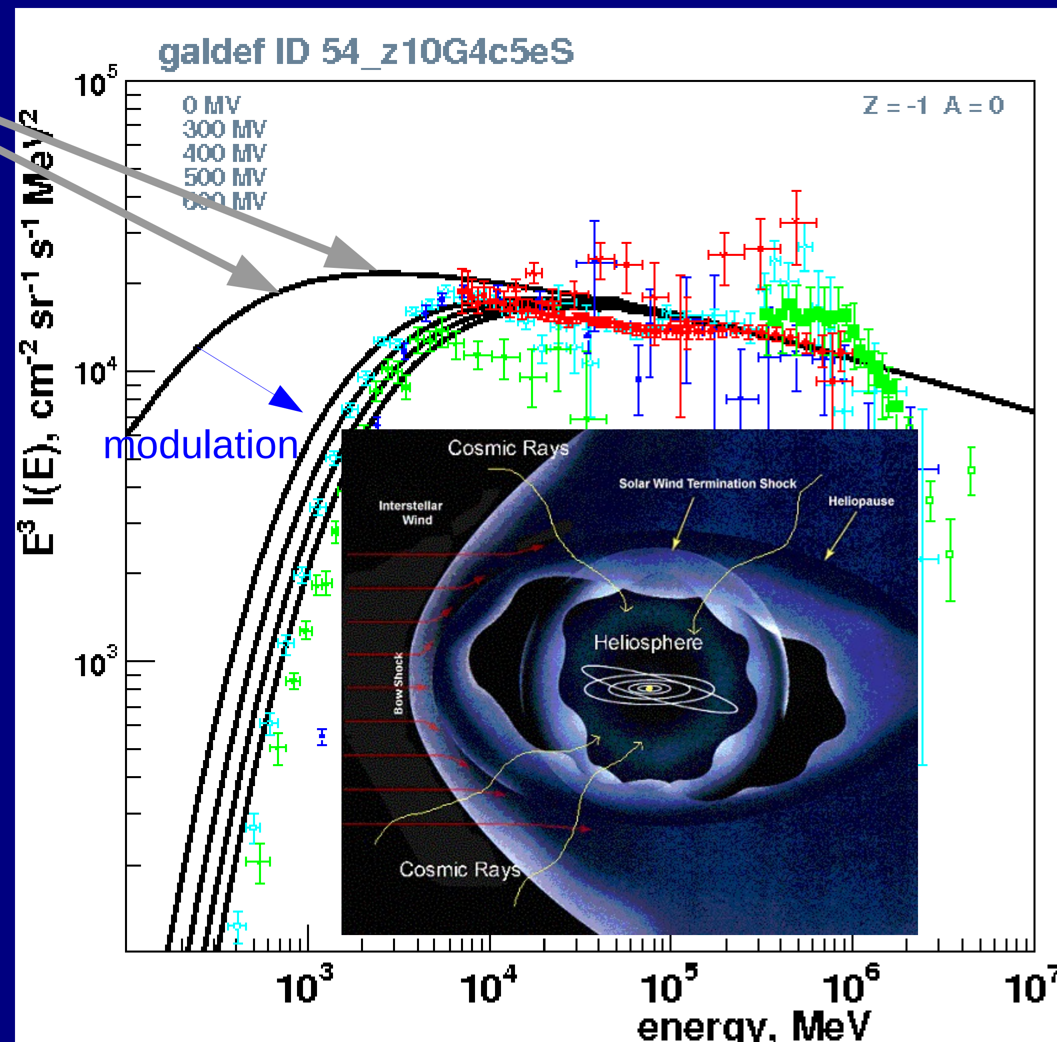






microwaves probe
interstellar electron spectrum
10 - 100 GeV





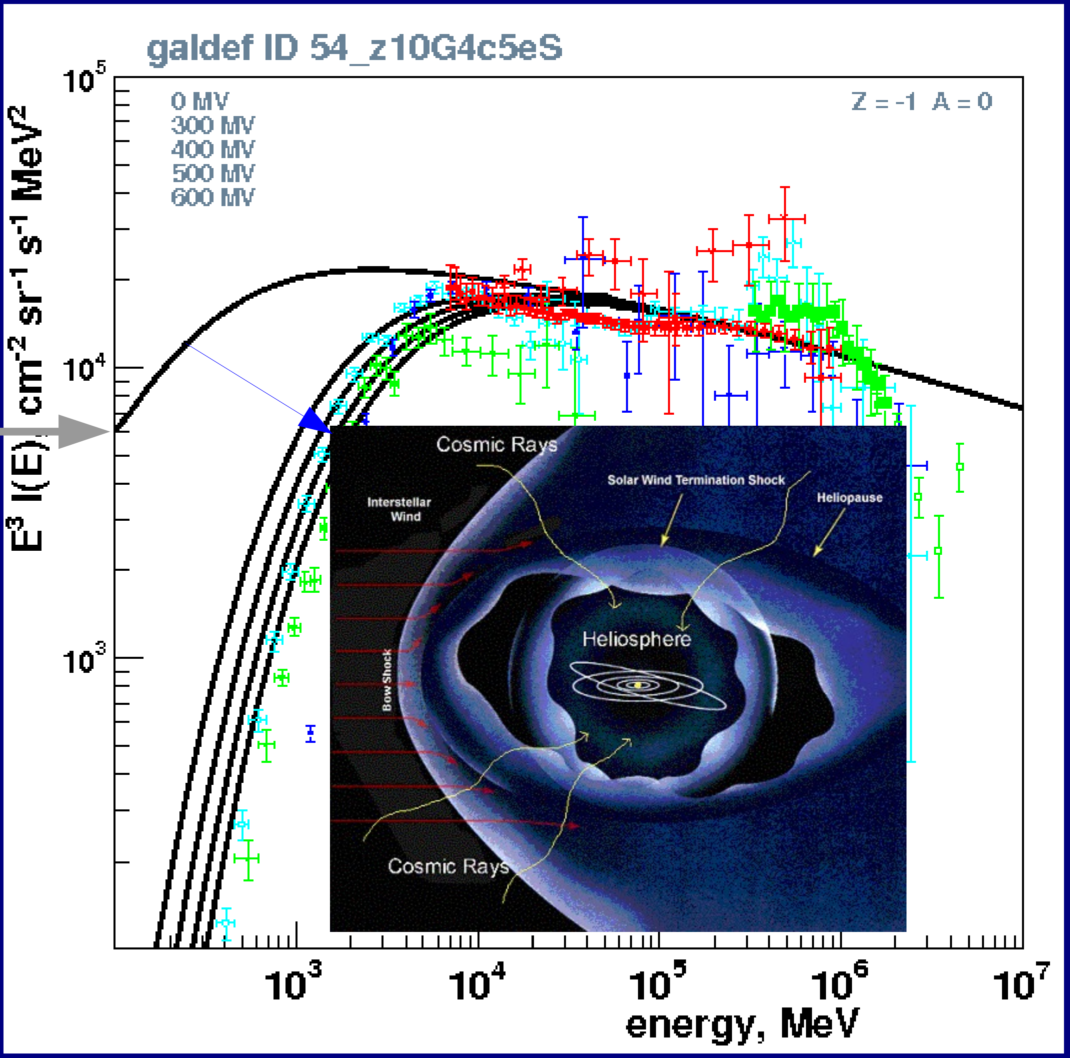
radio probes
interstellar electron spectrum at
E ~ 1 GeV
to complement direct measurements
and determine solar modulation

electrons have huge uncertainty
due to modulation here

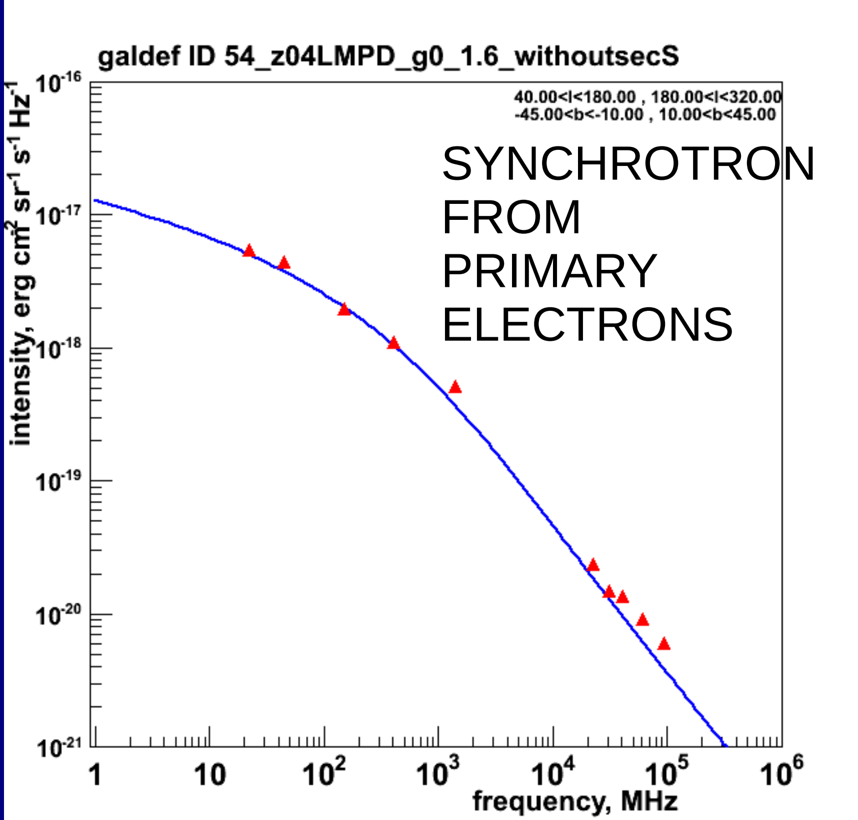
A. W. Strong, E. Orlando, T.R. Jaffe, 2011, A&A 534, A54

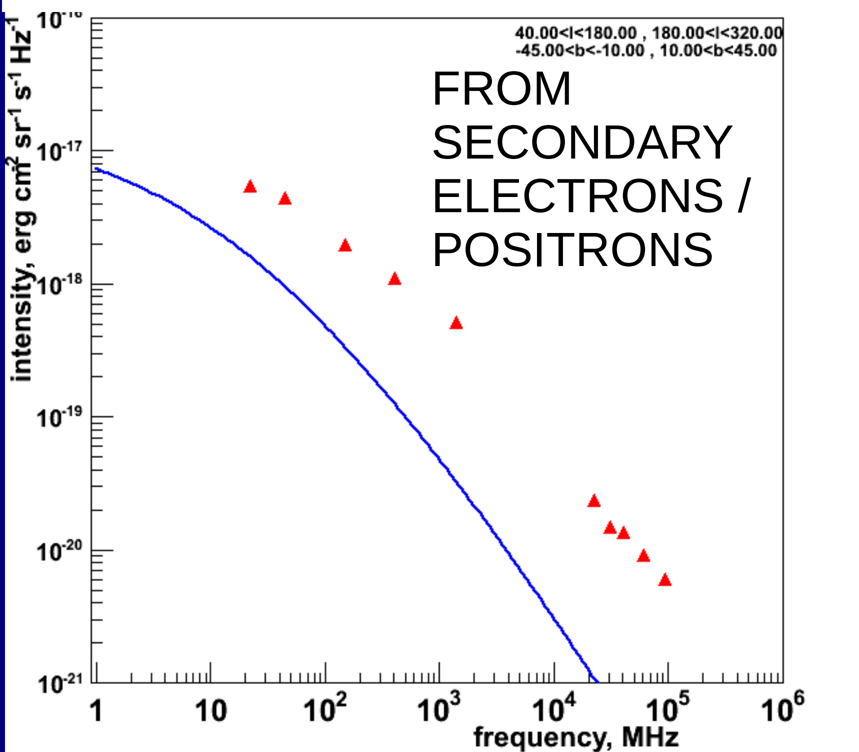
Only *MeV gammas* can
probe electrons below 100 MeV
via bremsstrahlung !

(Q: Voyager direct measurements
Now approaching interstellar ?).

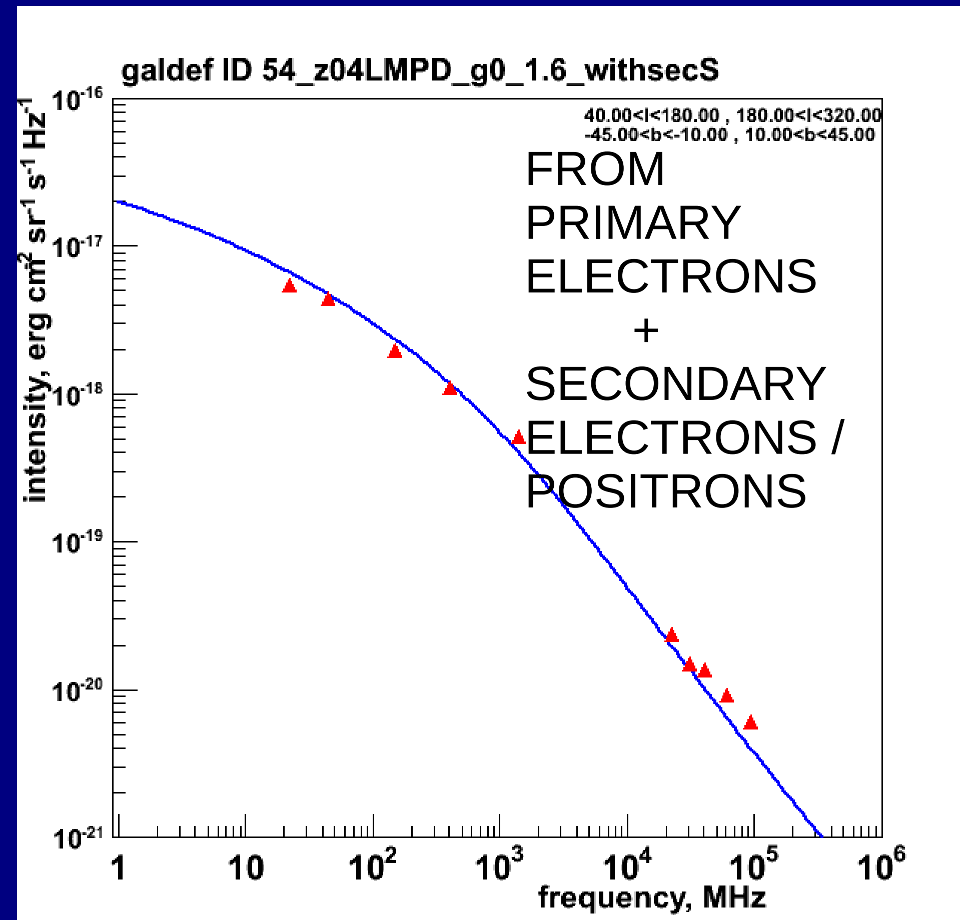


A. W. Strong, E. Orlando, T.R. Jaffe, 2011, A&A 534, A54





See also Dario Grasso,
Talk at APC CR meeting 2012



Secondary positrons
(and secondary electrons)
are important for synchrotron

Cosmic-ray electrons

Synchrotron

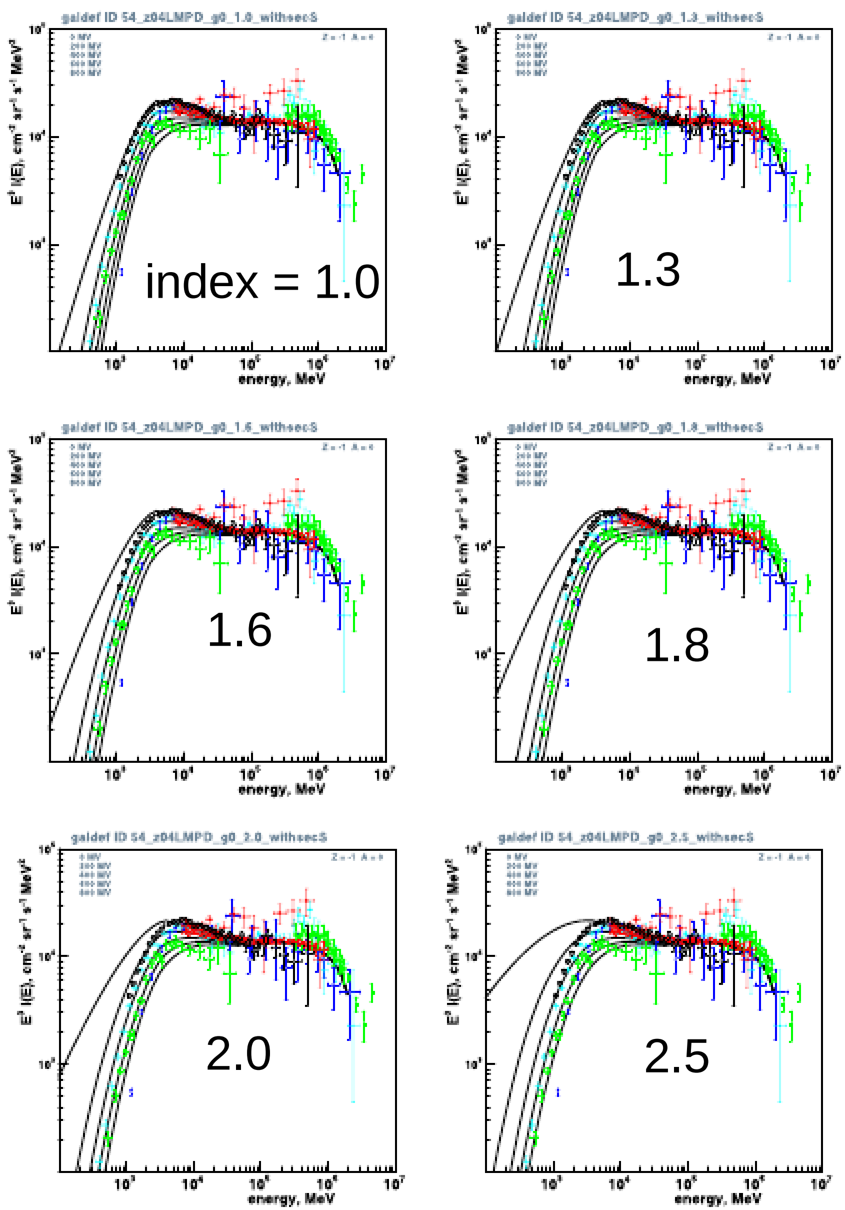


Fig. 4. Electron spectra for pure diffusion model, low-energy electron injection index 1.0, 1.3, 1.6, 1.8, 2.0, 2.5. Modulation Φ = 0, 200, 400, 600, 800 MV. Data as in Fig. 1.

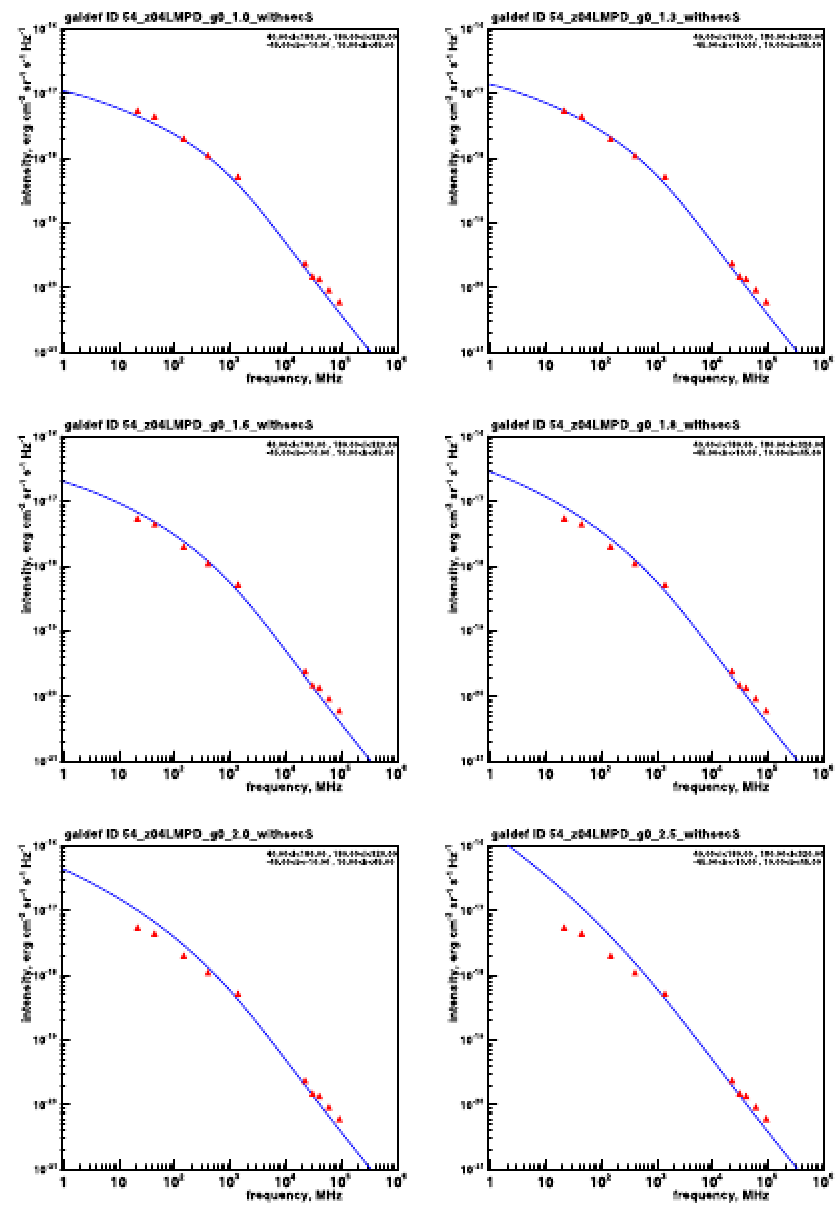


Fig. 5. Synchrotron spectra for pure diffusion model with low-energy electron injection index (*left to right, top to bottom*) 1.0, 1.3, 1.6, 1.8, 2.0, 2.5. Including secondary leptons. Data as in Fig. 2.

Effect of electron injection spectral index

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

Galactic Synchrotron T_B Spectral Index

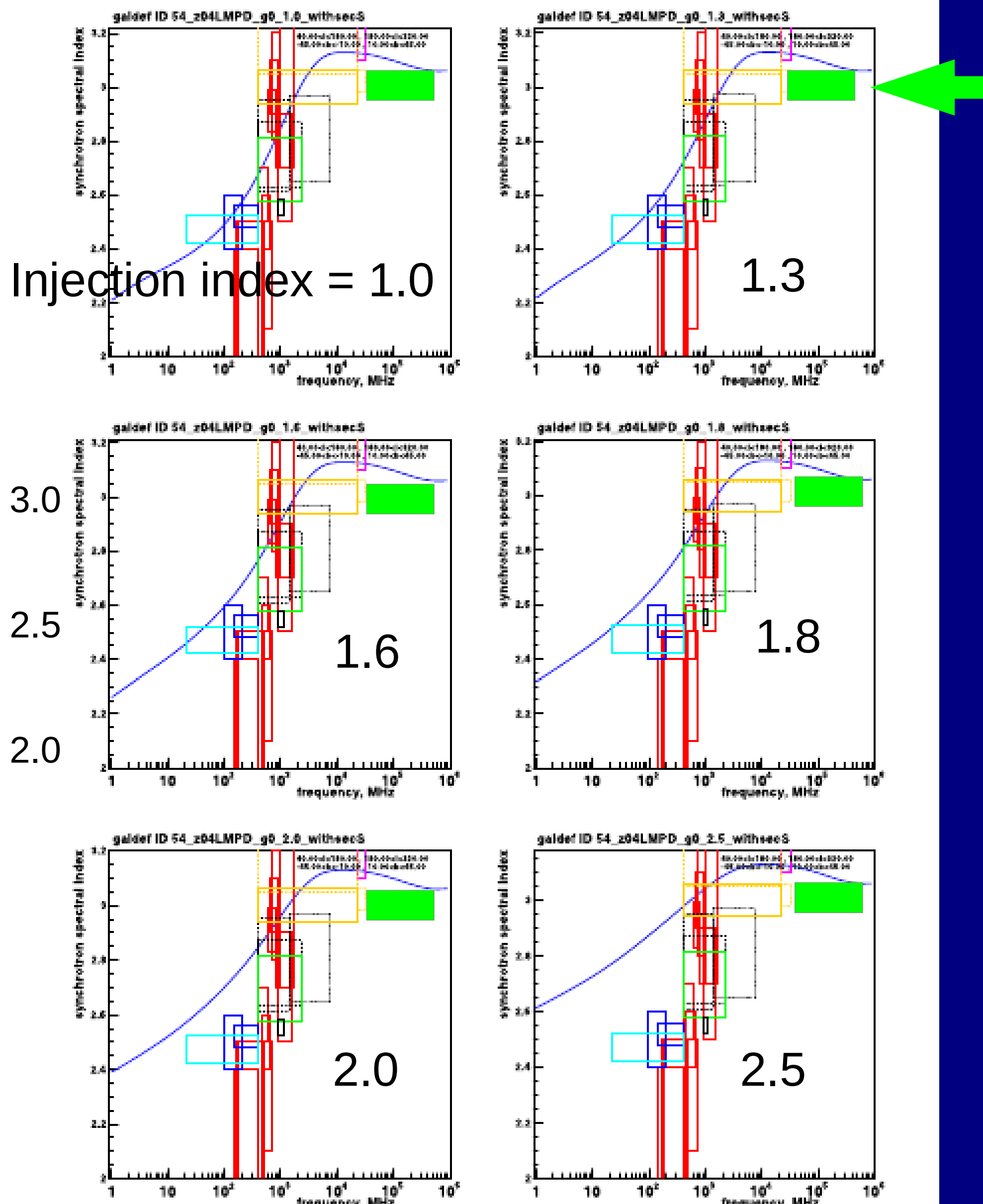


Fig. 6. Synchrotron spectral index for pure diffusion model with low-energy electron injection index (*left to right, top to bottom*) 1.0, 1.3, 1.6, 1.8, 2.0, 2.5. Including secondary leptons. Experimental ranges are based on the references reviewed in Sect. 4.1, and are intended to be representative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

A&A 536, A21 (2011)

Effect of electron injection spectral index

Strong, Orlando & Jaffe (2011)

Luca Maccione. ArXiv 1211.6905

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

DRAGON propagation model, interstellar spectrum, solar modulation model

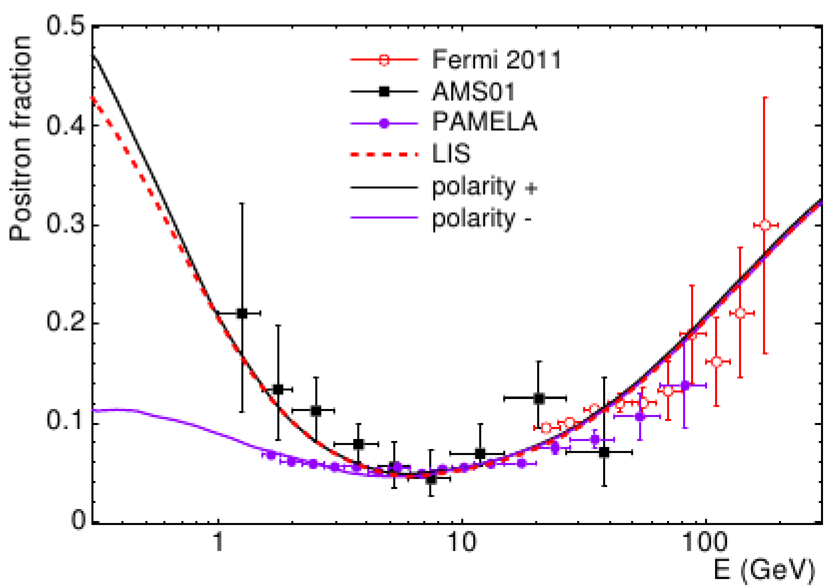


FIG. 1. The positron fraction measured by Fermi, PAMELA and AMS-01 is shown. The LIS is shown as the red dashed curve. Solid curves show the Earth positron fraction computed evolving the LIS for $\alpha = 30^\circ$ and positive polarity (black) or negative polarity (violet).

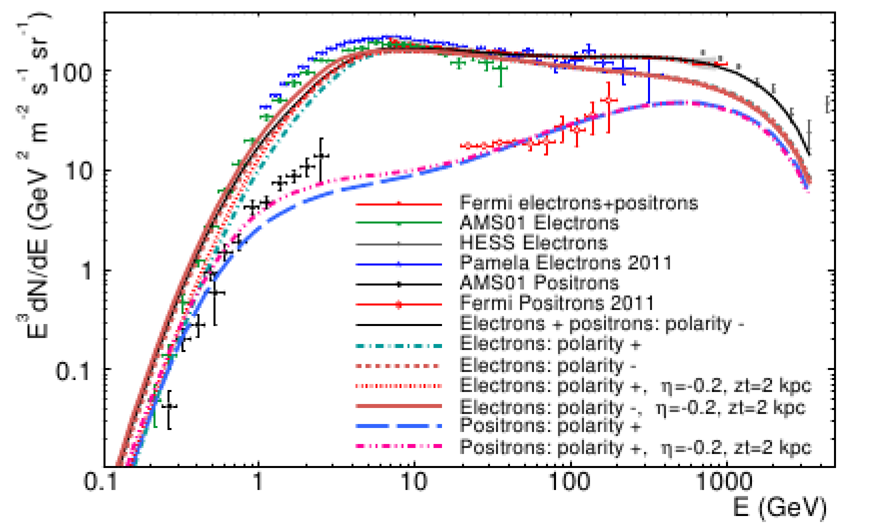
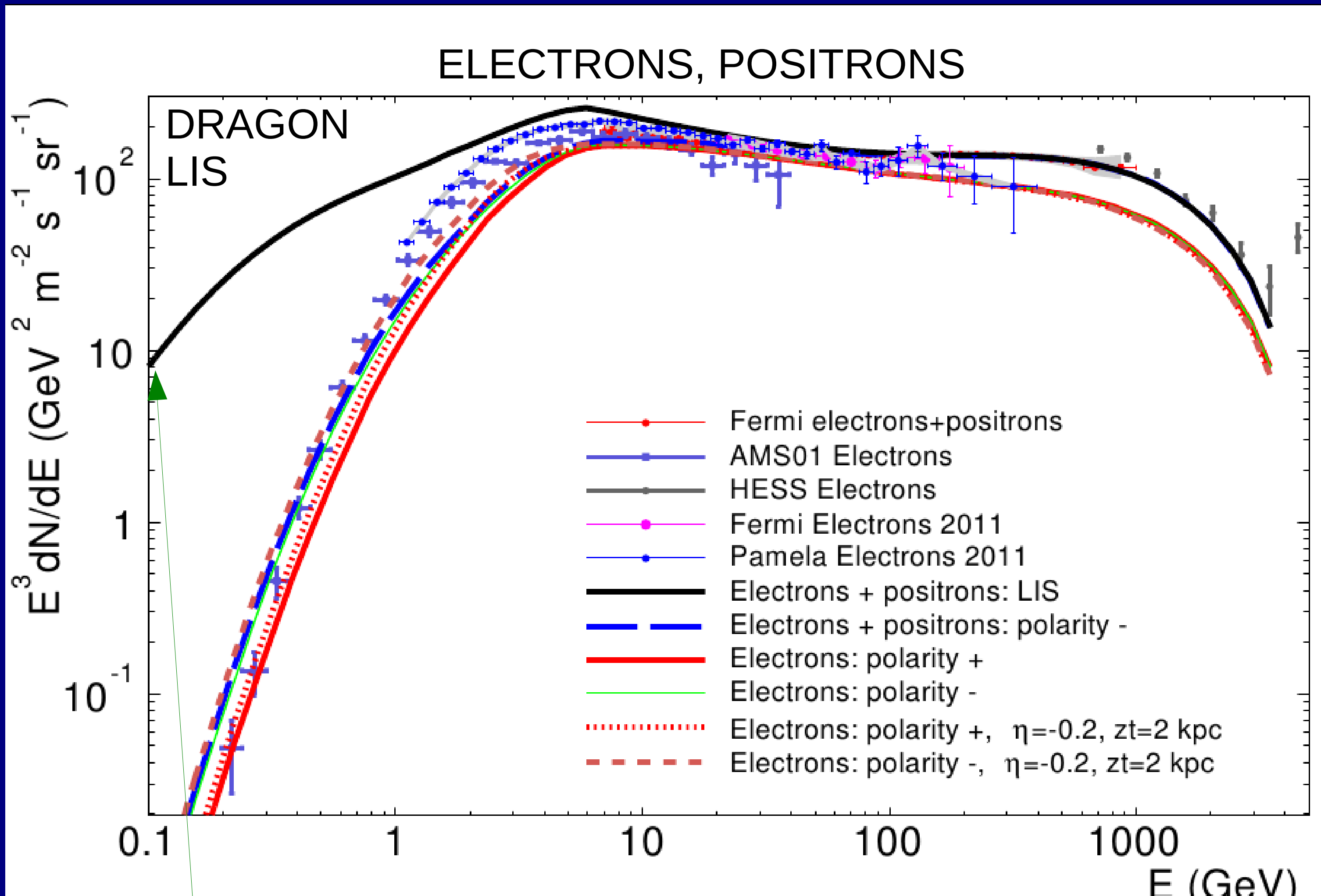


FIG. 6. The absolute e^- and e^+ spectra measured by different experiments are compared with our calculations for $\alpha = 30^\circ$ and both polarities.

From Luca Maccione, see also arXiv 1211.6905

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



MeV gammas
probe this region
via bremsstrahlung
(neither synchrotron nor direct measurements useful)

PRELIMINARY

Polarized synchrotron

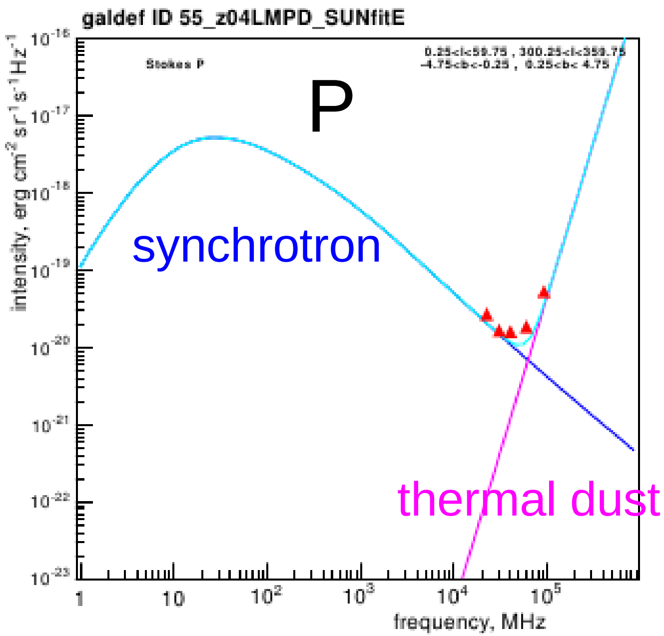
* Separates regular from random B

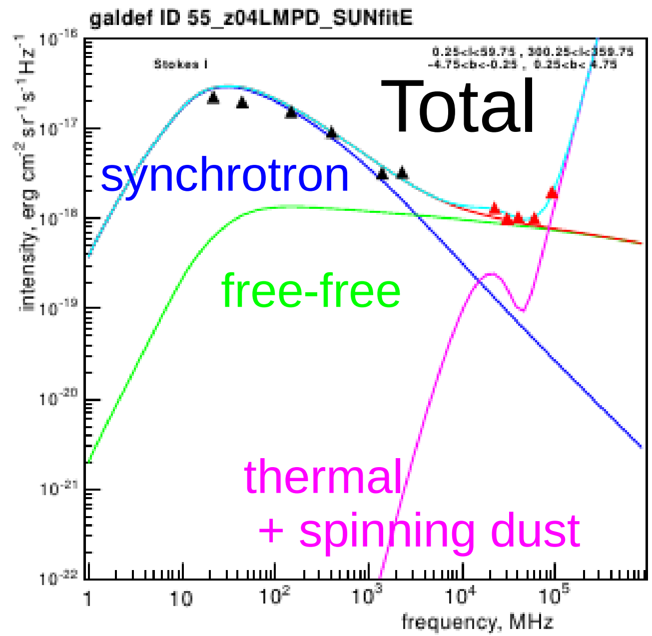
* Separates synchrotron from spinning dust and free-free emission

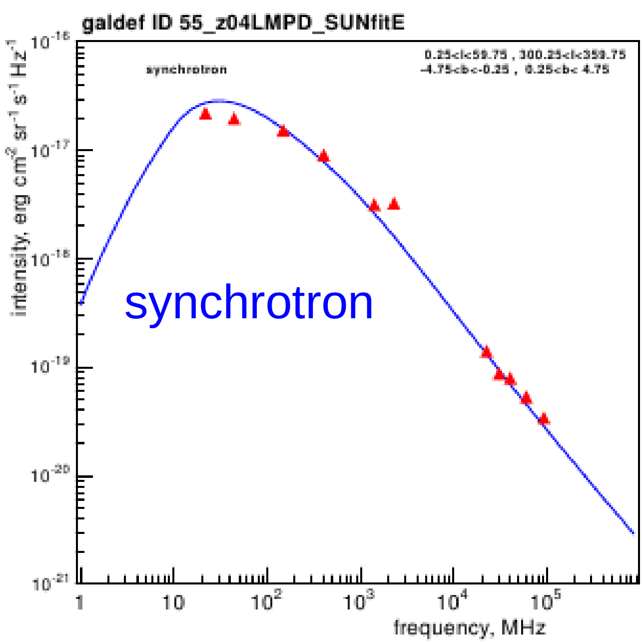
Now modelled in GALPROP

B-field models implemented

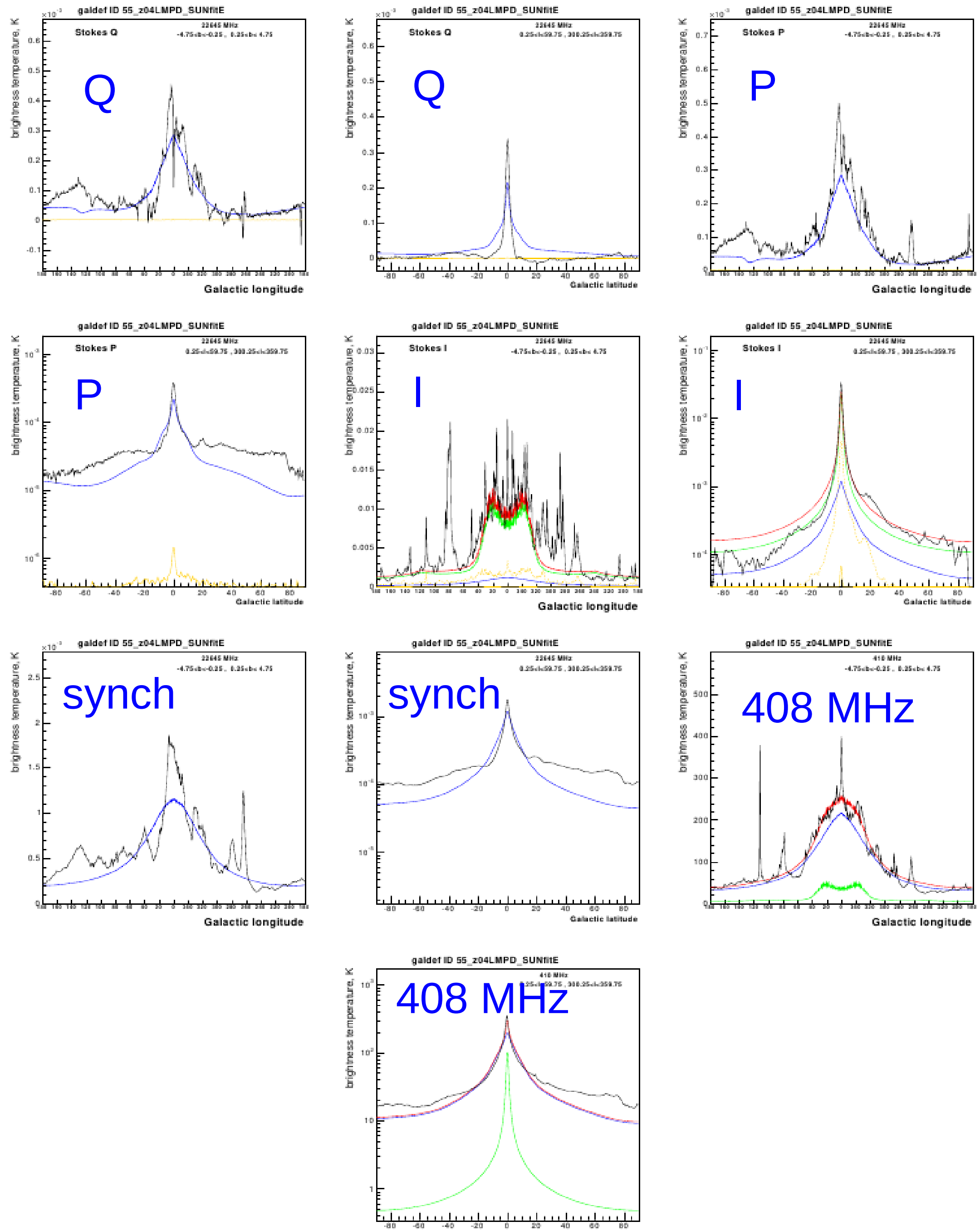
Orlando and Strong 2013



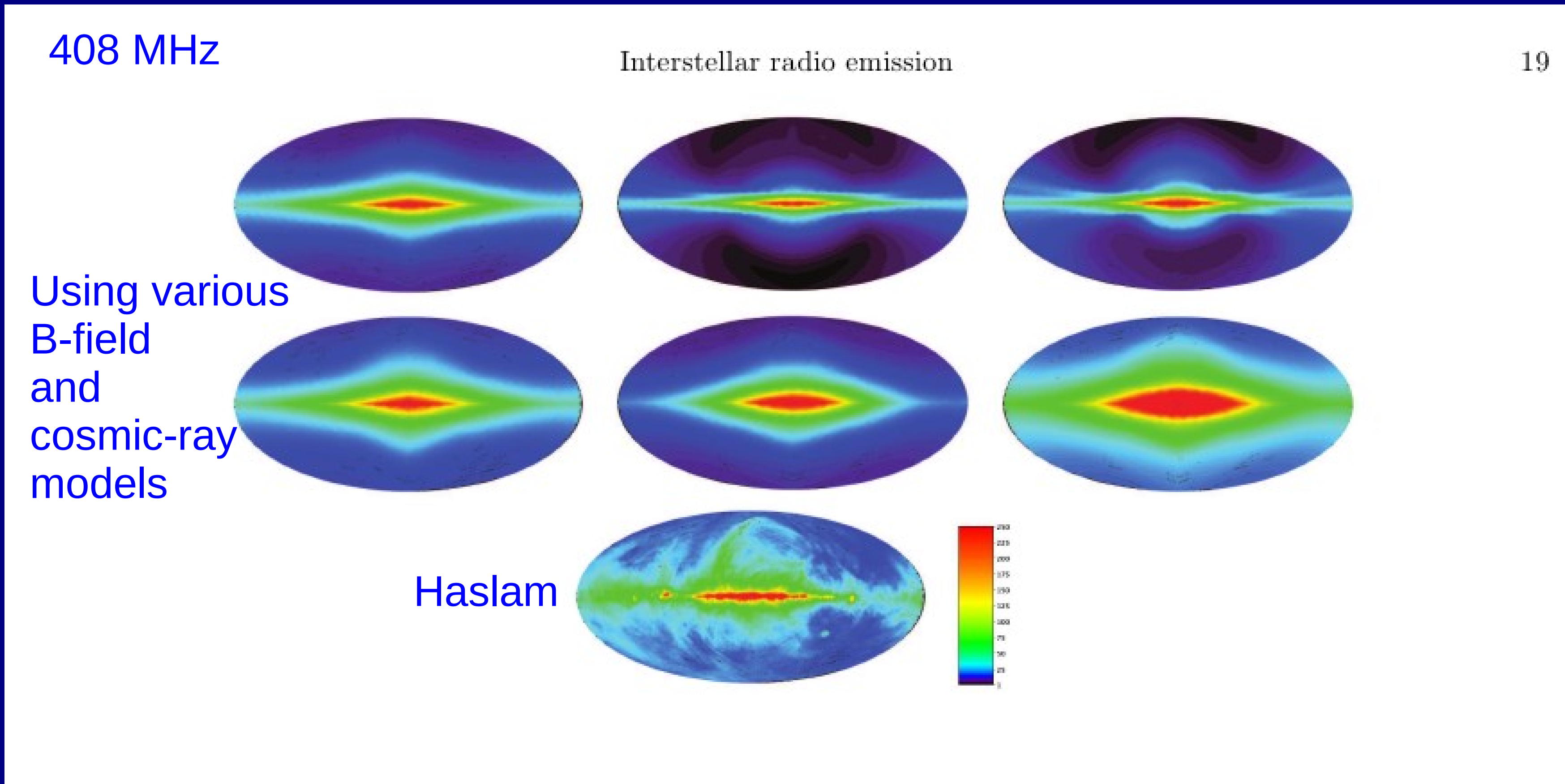




INNER GALAXY

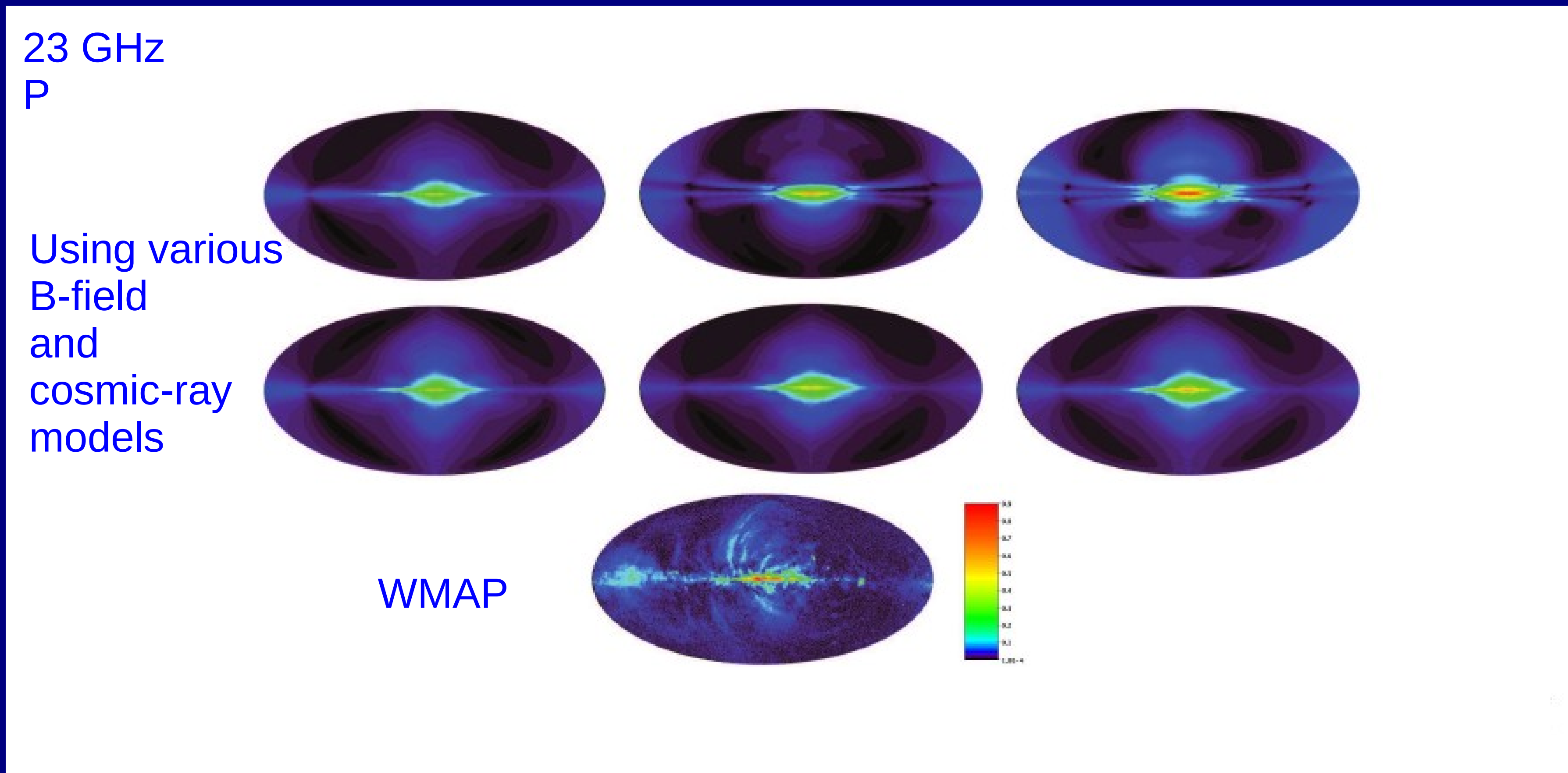

galdef ID 55_z04LMPD_SUNfitE
Stokes Q
Q
Stokes Q
Q
Stokes P
P
Stokes P
P
Stokes I
I
Stokes I
I
synch
synch
408 MHz
408 MHz
brightness temperature, K
Galactic longitude
Galactic latitude

Synchrotron from GeV electrons

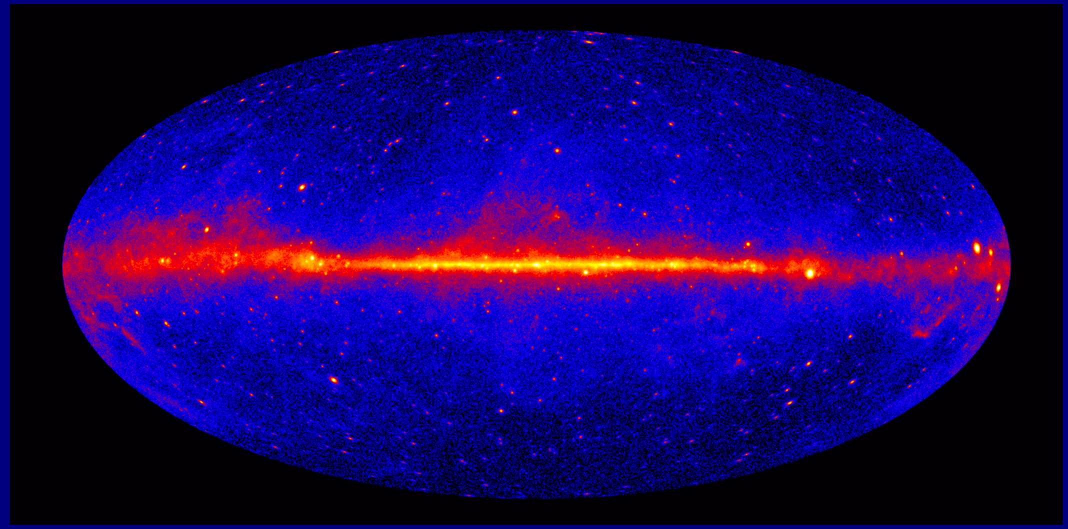


Regular B-field models from Sun etal, Pshirkov et al.
Scaling factor applied.

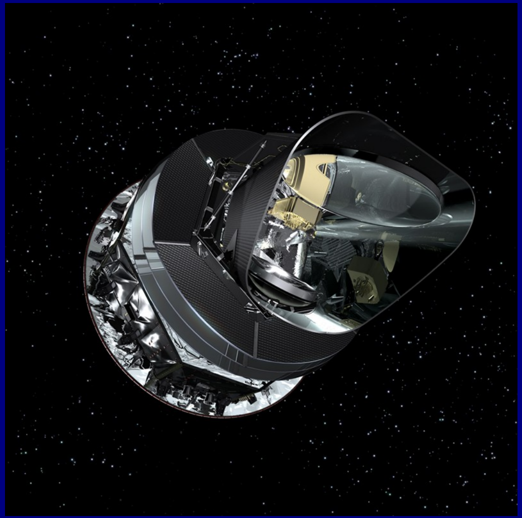
Synchrotron from 10 GeV electrons



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



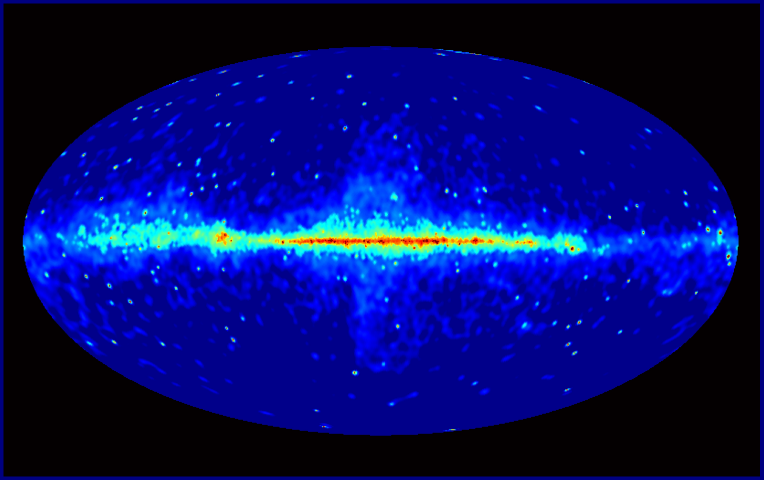
2 years



1 year

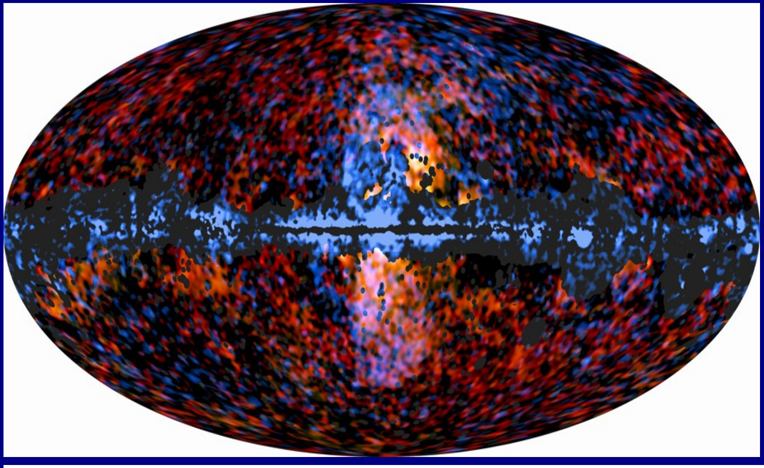
A lot of common astrophysics, cosmic rays, gas, magnetic fields ! *Will be also the case at MeV.*

Fermi Bubbles



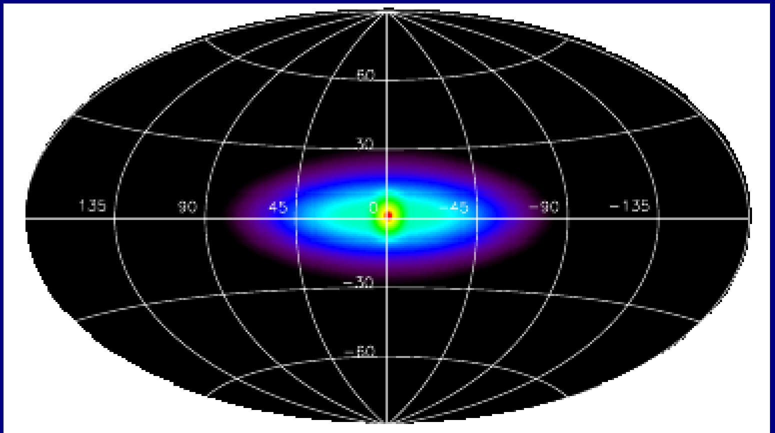
(related to WMAP Haze ?)

Planck haze (arXiv:1208.5483)
Overlaid on Fermi Bubbles

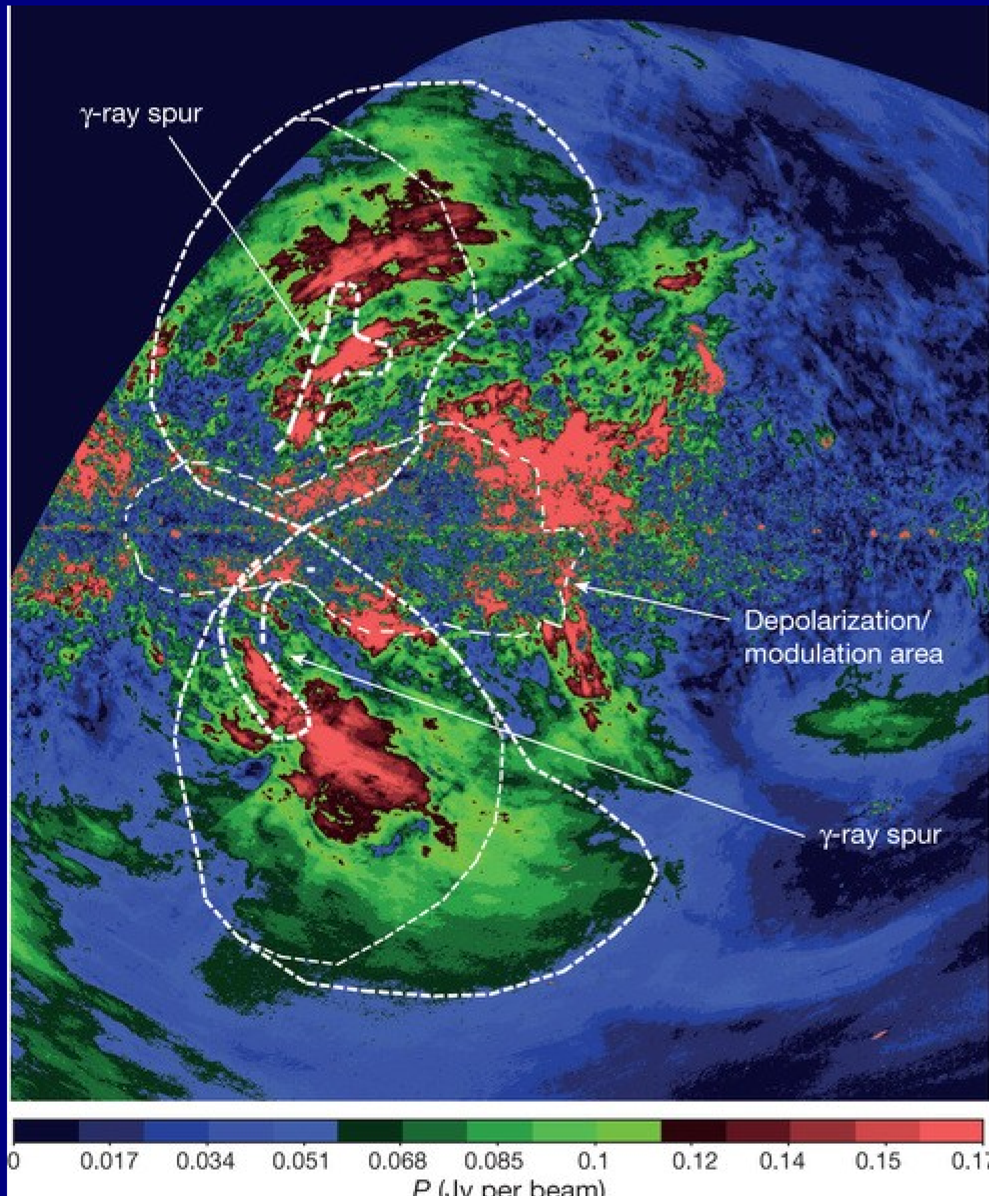


What about MeV ?

connection to 511 keV line ?



All are -
centred on Galactic Centre
leptonic
unknown origin

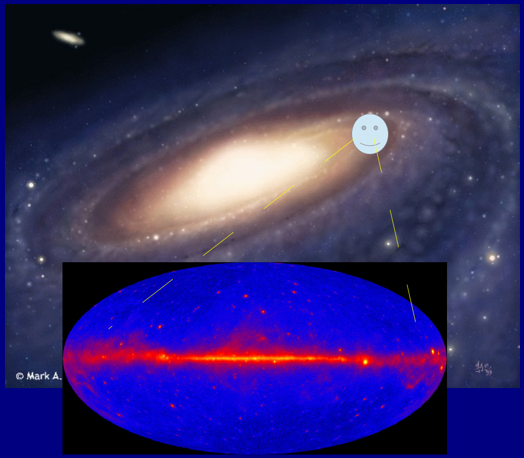


S-PASS
Southern Sky
Parkes Telescope
2.3 GHz
Polarized intensity

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

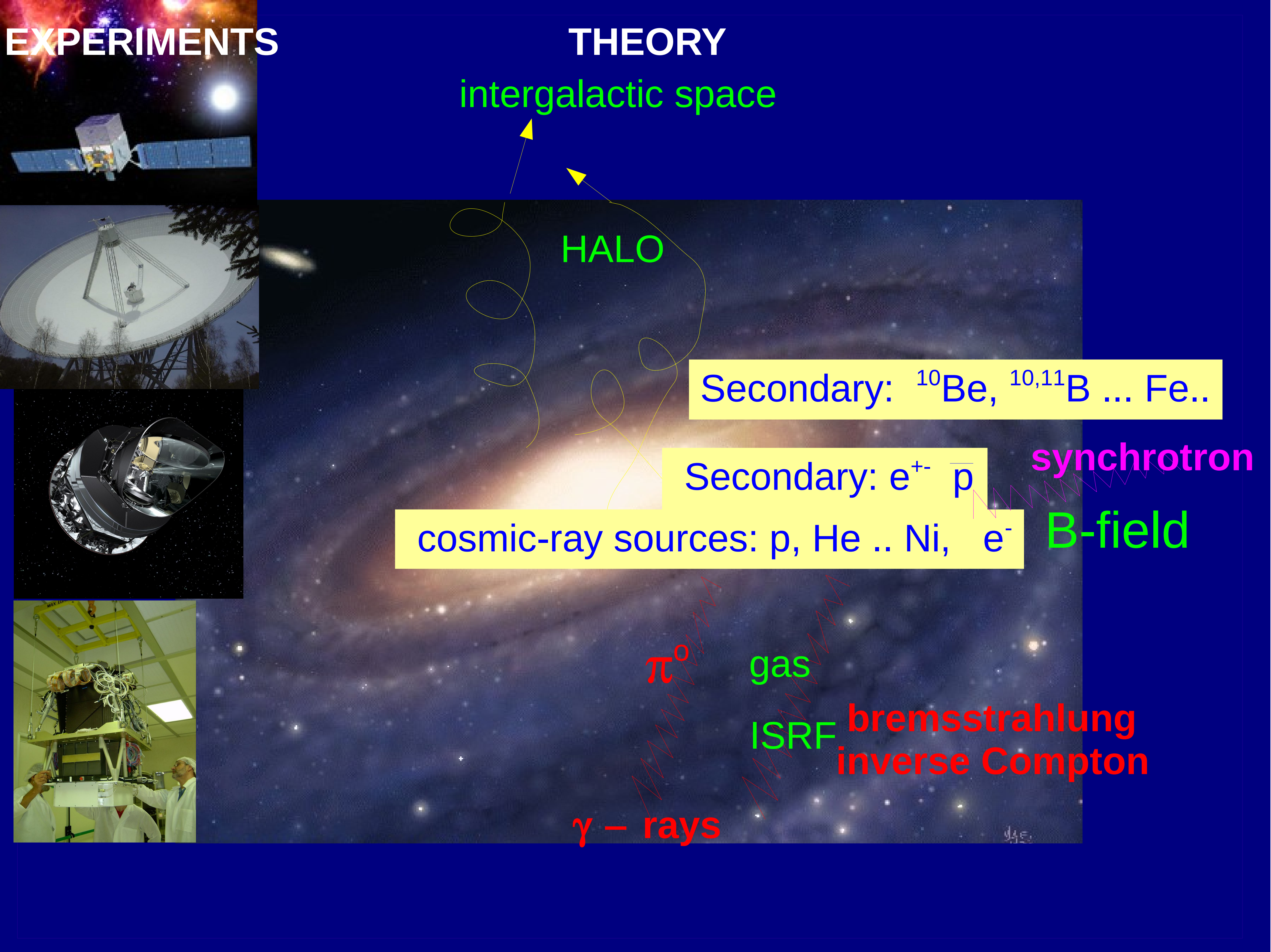
“Giant magnetized outflows from the centre of the Milky Way”
Correlates with Fermi Bubbles.
Produced by repeated episodes of star-formation at Galactic Centre ?

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

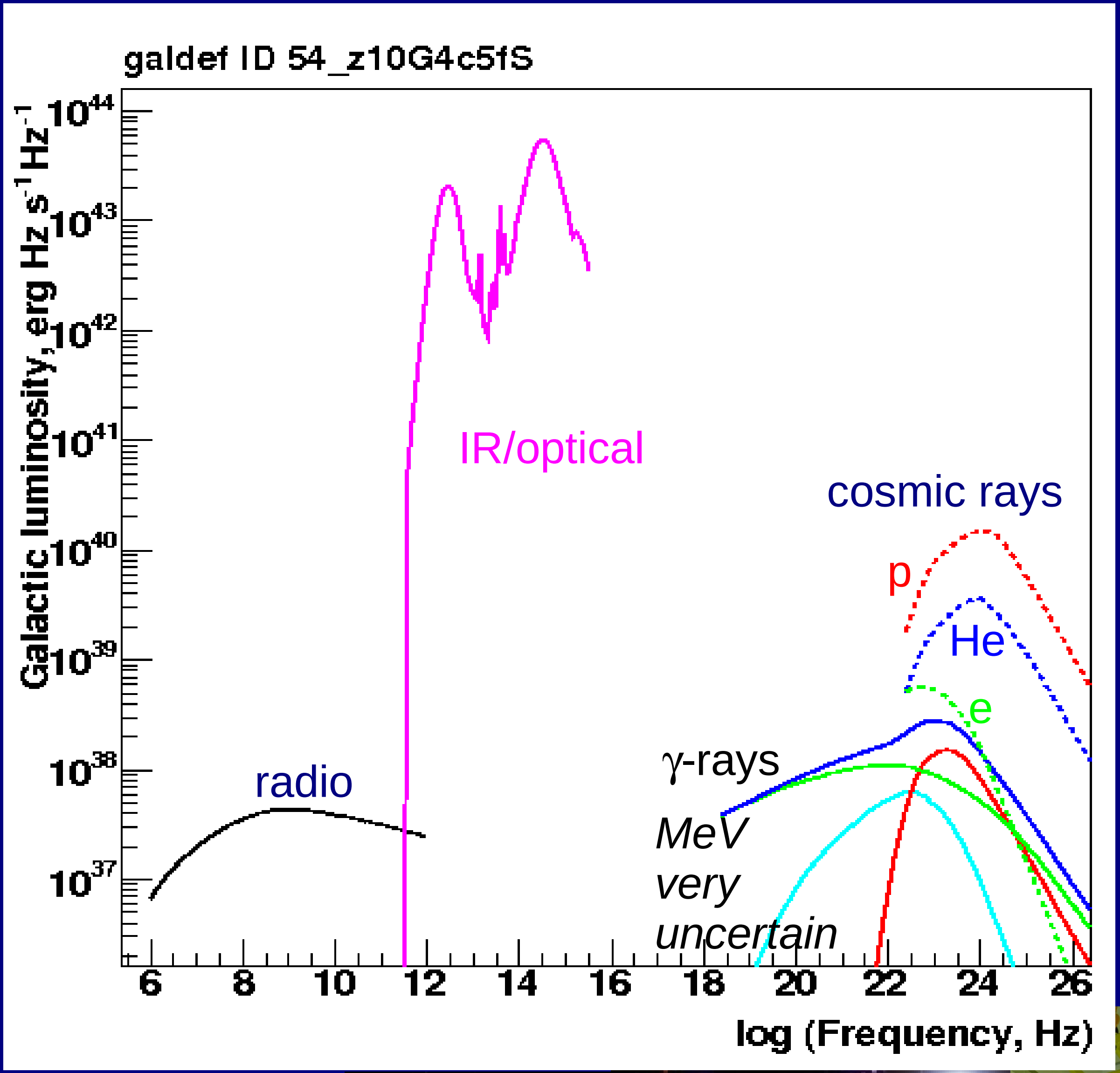


SEDs of AGN etc are common, but not Milky Way


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


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

Galaxy luminosity over 20 decades of energy



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

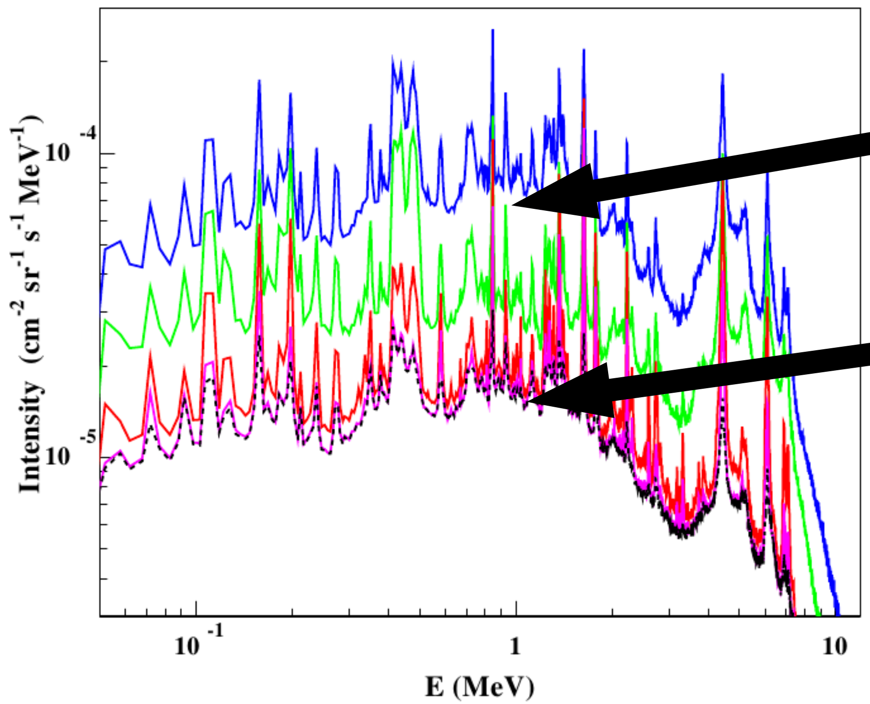


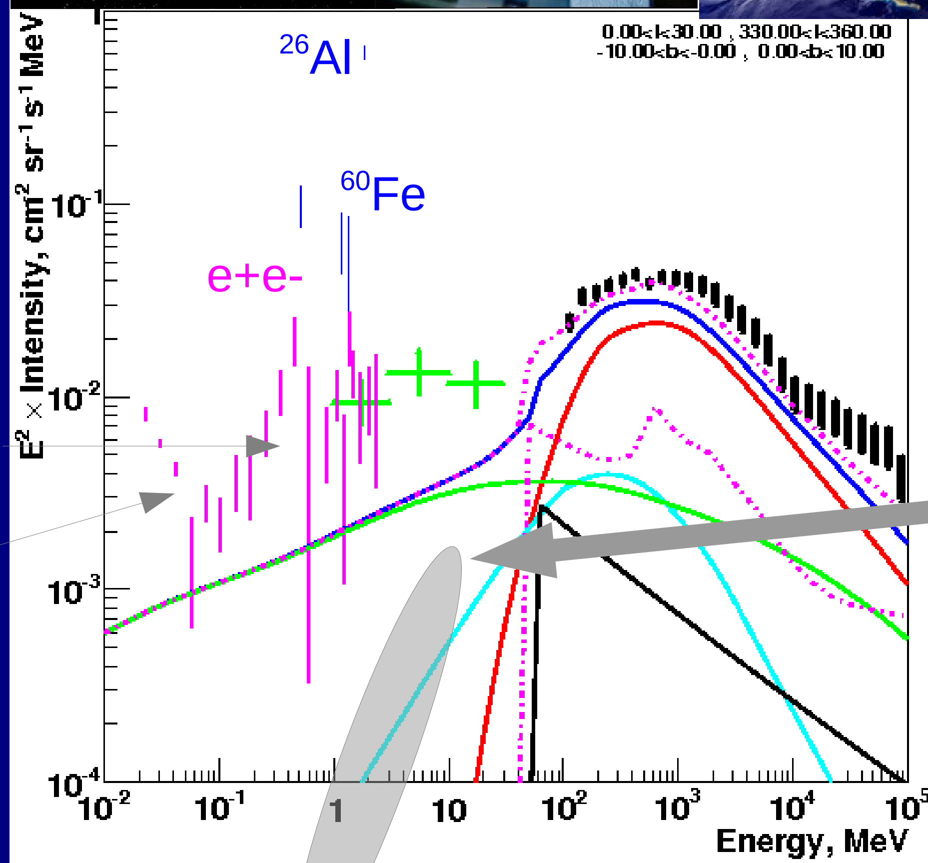
Fig. 6.— Calculated nuclear γ-ray line emissions from the inner Galaxy for CRs with ACR-LECR components following the model of Scherer et al. (2008a) with $s = 2.4$, $E_c = 5$, 25 and 1200 MeV (magenta, red and green lines, resp.) and SA-LECR with $s = 2.0$ and $E_c = 120$ MeV (blue line). The emission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

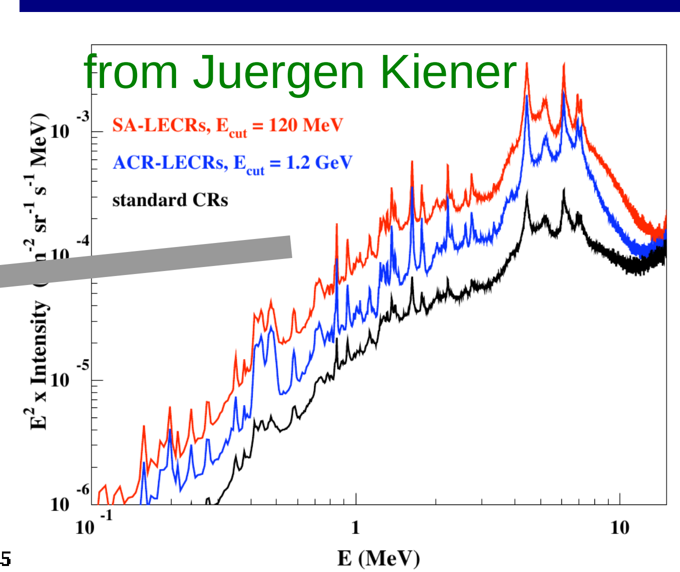
Benhabiles-Mezhoud,Kiener, Tatischeff & Strong, 2012, ApJ in press, arXiv 1212.1622

More chance to detect nuclear lines !

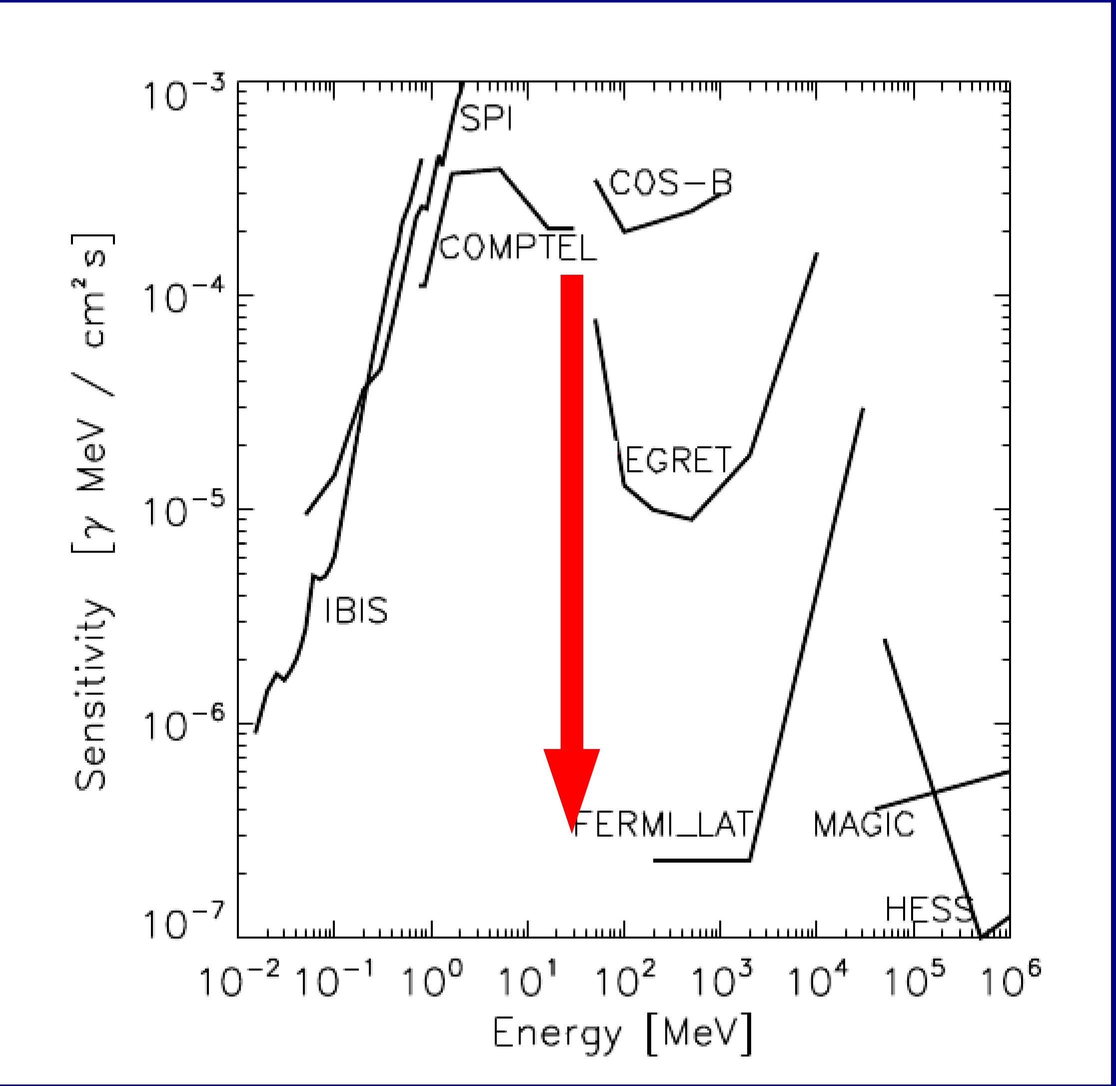
See talk by Juergen Kiener, this meeting

Inner Galaxy: keV to TeV





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


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

SUMMARY

MeV astronomy of interstellar medium provides:

Essential region below Fermi-LAT range for astrophysical interpretation
Enormous added value from complementarity.

Probe of electrons (and positrons) below 100 MeV (bremsstrahlung)
and below 1 GeV (inverse Compton)

MeV view of Fermi Bubbles / WMAP-Planck haze: changing our view of the Galaxy.

Probe of source populations in the Galaxy (cf COMPTEL excess)

+ Who knows what else ?
The last great unexplored region of the electromagnetic spectrum !
Enormous discovery potential !


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