μeV to TeV Radiation from Cosmic Rays in the Galaxy

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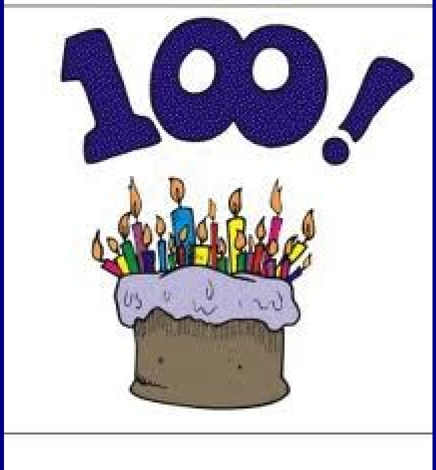
MPE Garching

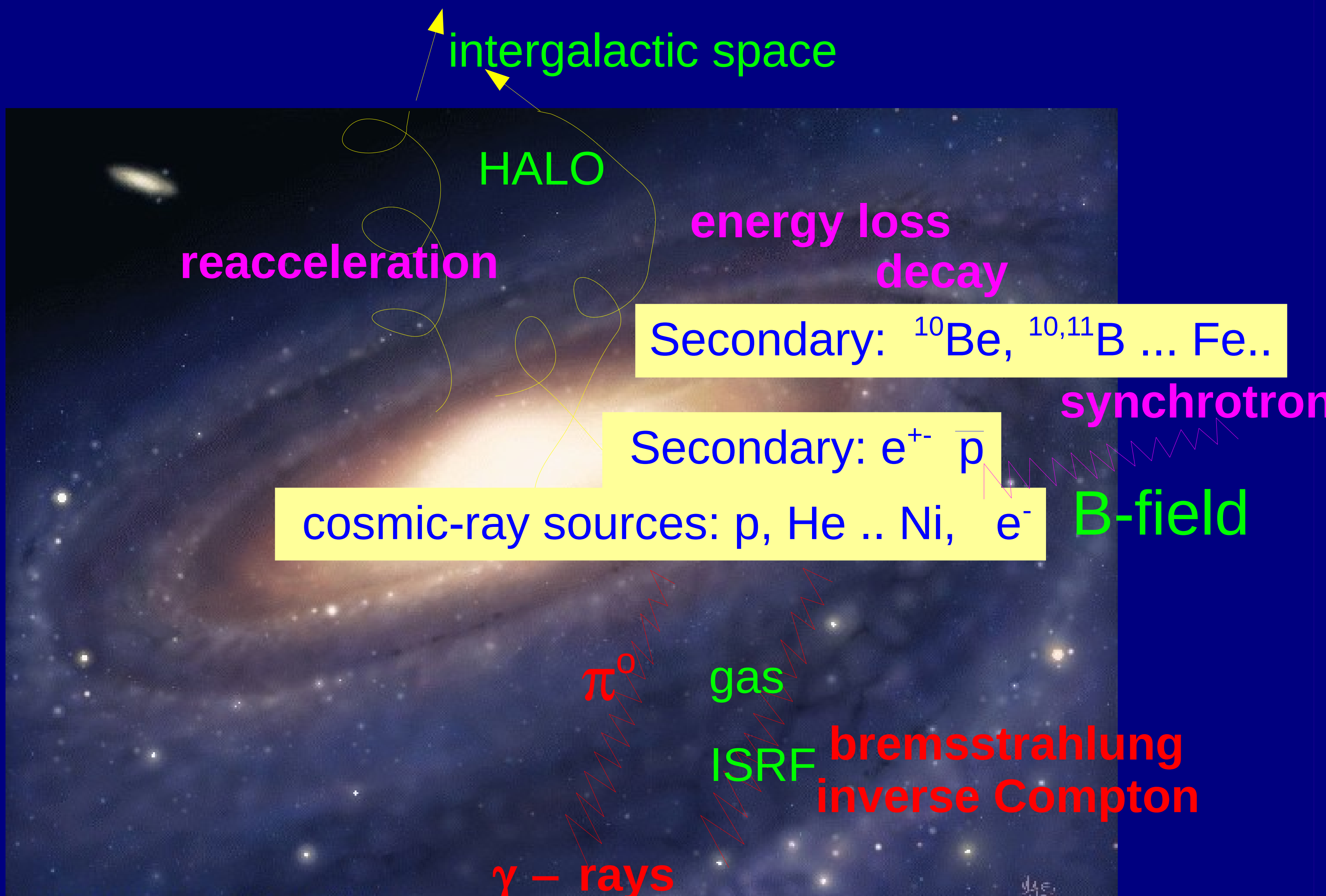
9th INTEGRAL Symposium
Paris, 15-19 October 2012

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

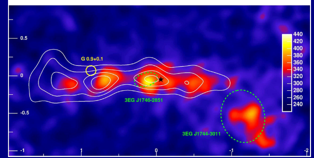


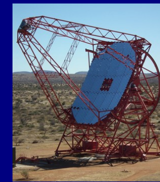
High energy particles and radiation in the Galaxy

COSMIC RAYS produce many observables

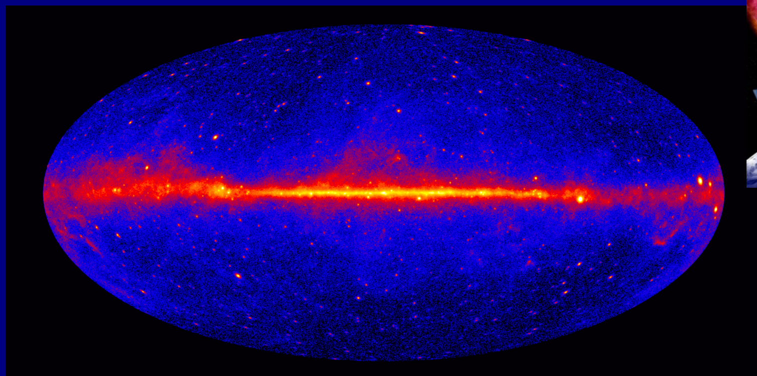


TeV

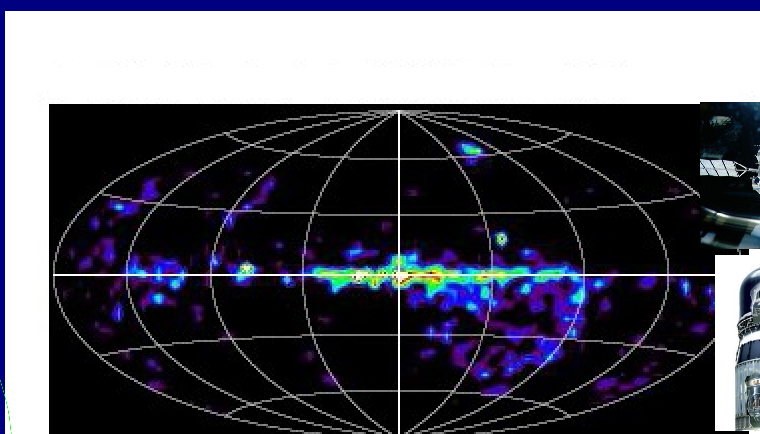


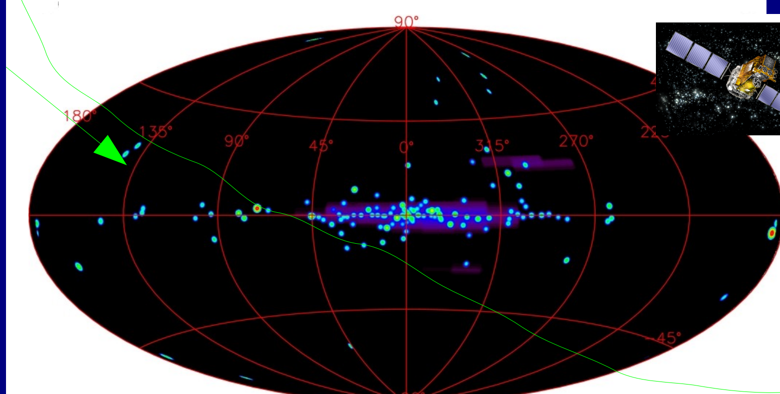


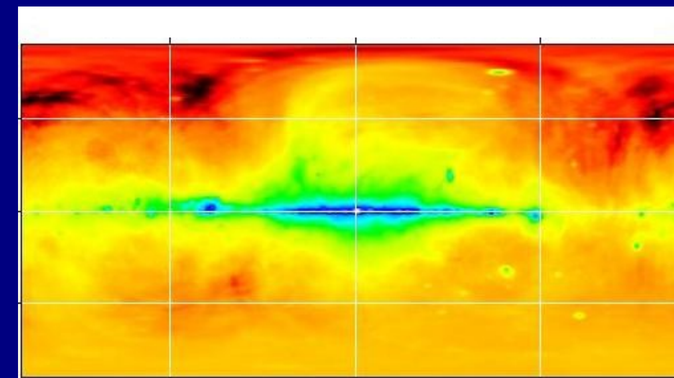
GeV



MeV



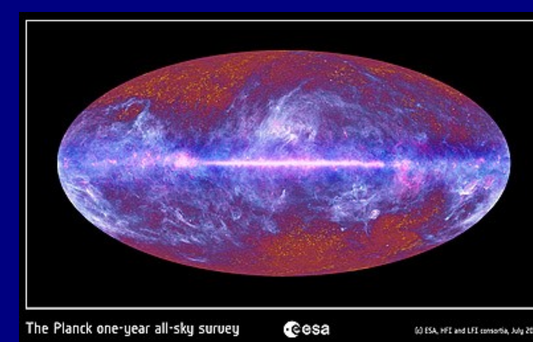


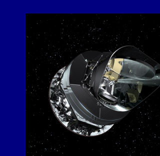


Cosmic-ray interactions probed by their photon emission

µeV

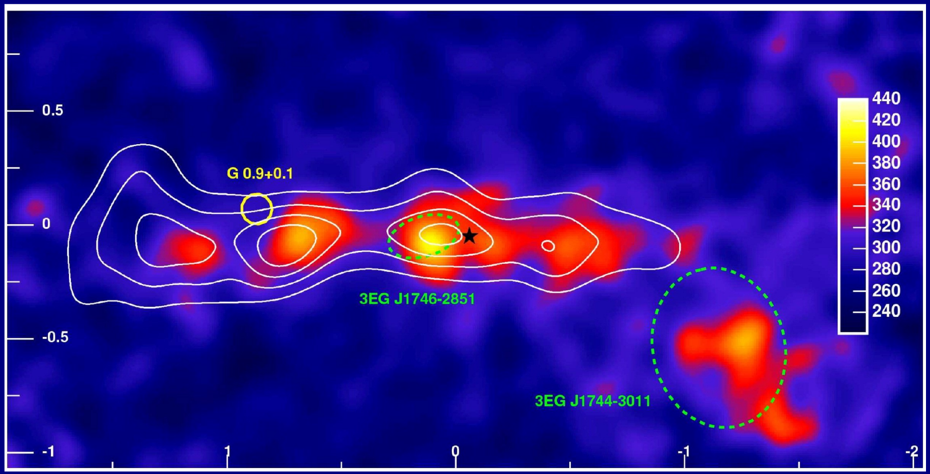
GHz





meV

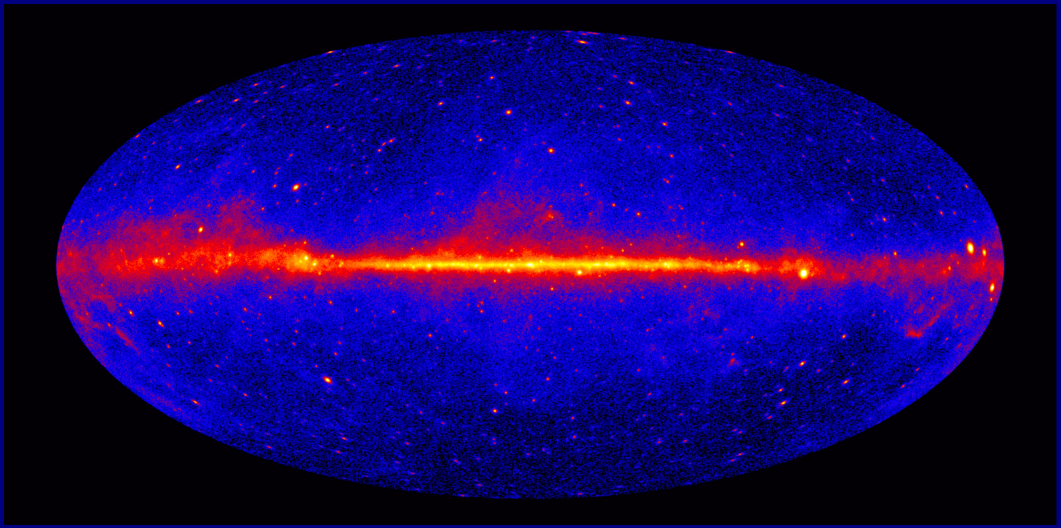
THz



H.E.S.S.
Galactic centre region

Cosmic-rays: >TeV protons interacting with gas

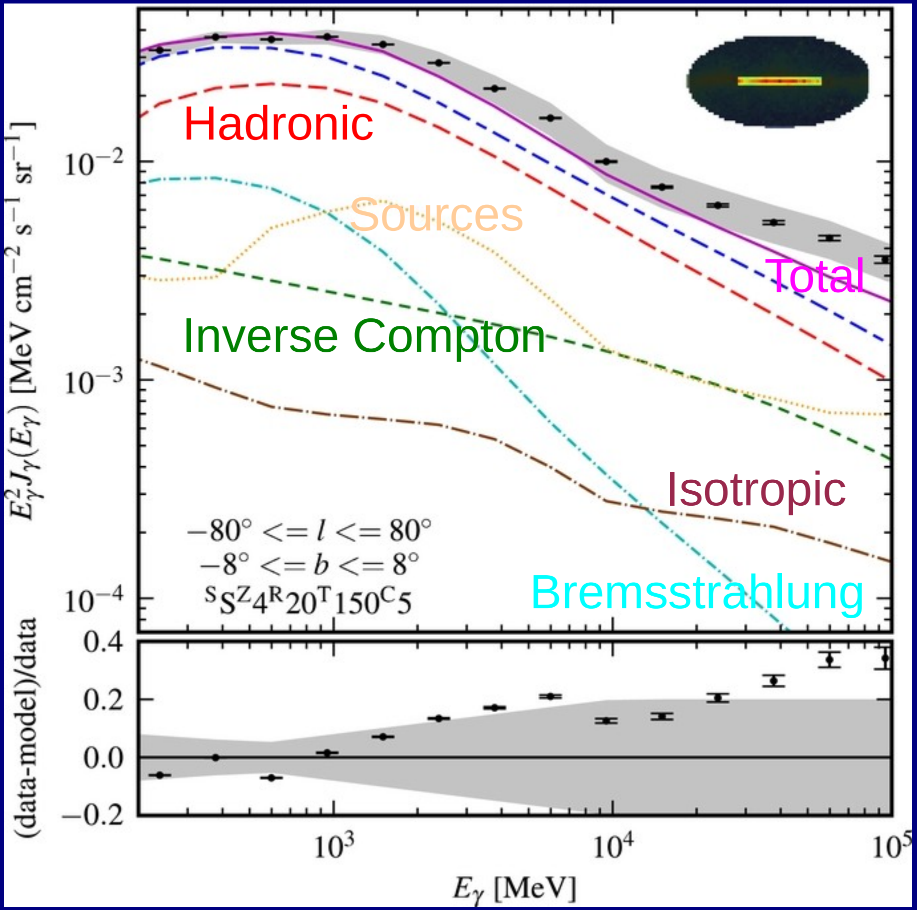
1 – 10 GeV



Cosmic-ray protons interacting with gas : hadronic

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

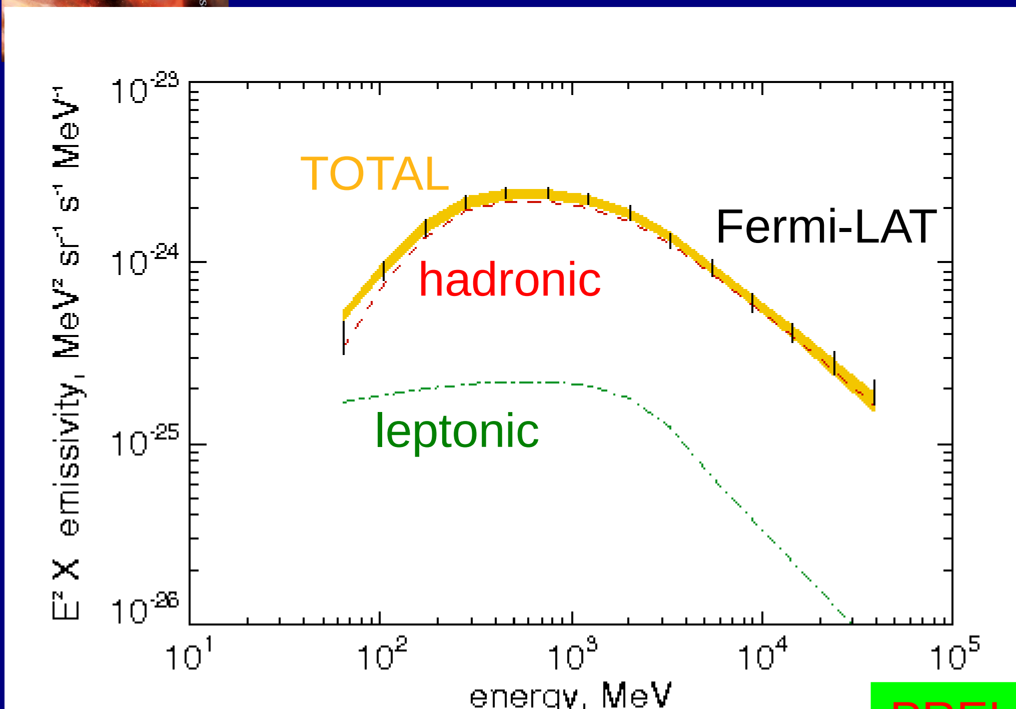
Fermi-LAT
Inner Galaxy Gamma Ray Spectrum

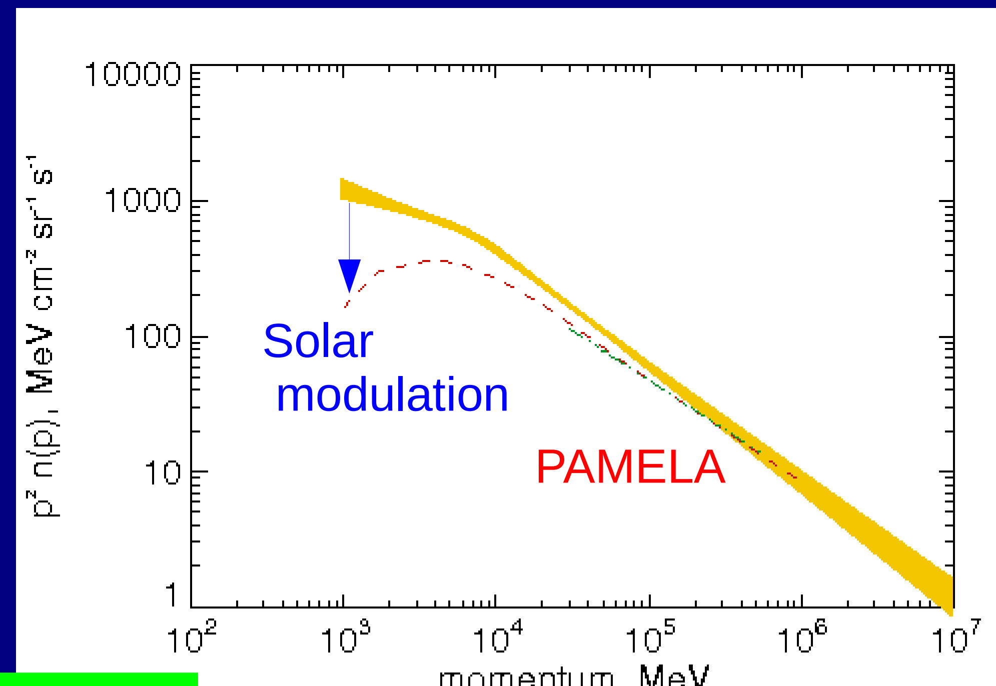


Ackermann et al. ApJ 750, 3 (2012)

Interstellar Cosmic ray spectra derived from gamma rays

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





PRELIMINARY

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

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.

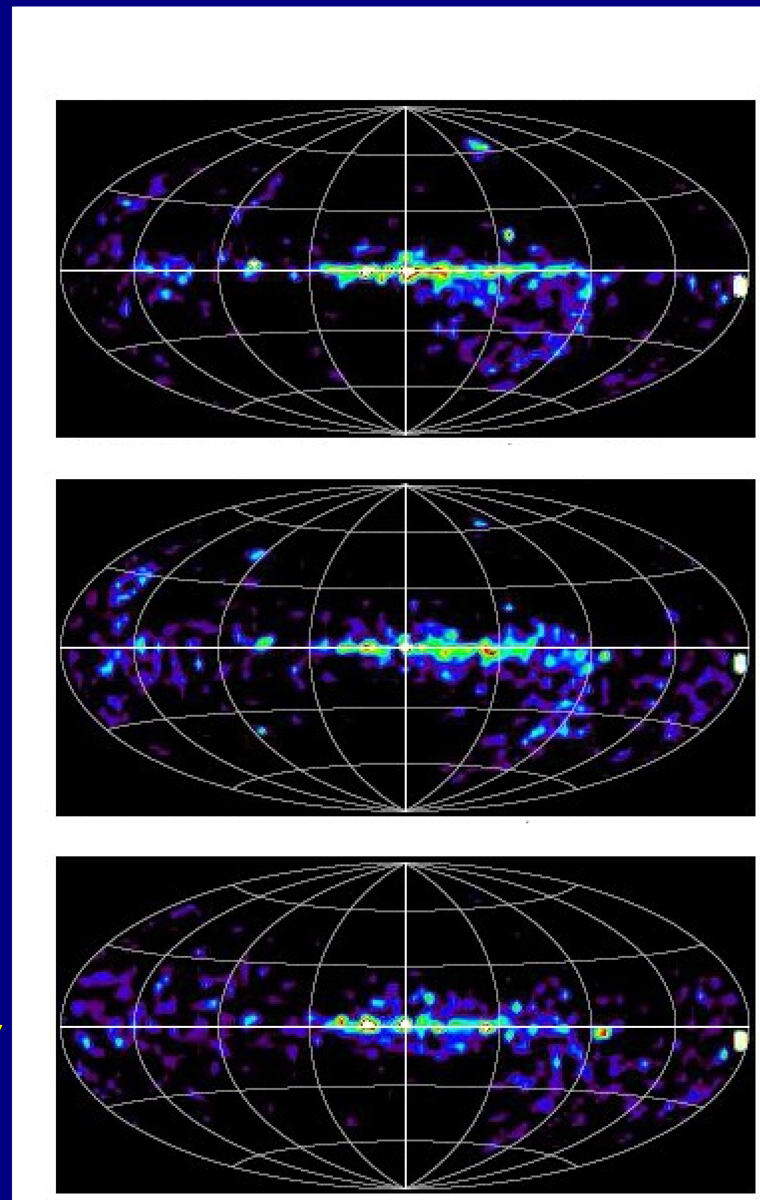
CGRO/ COMPTEL

MeV continuum

1 – 3 MeV

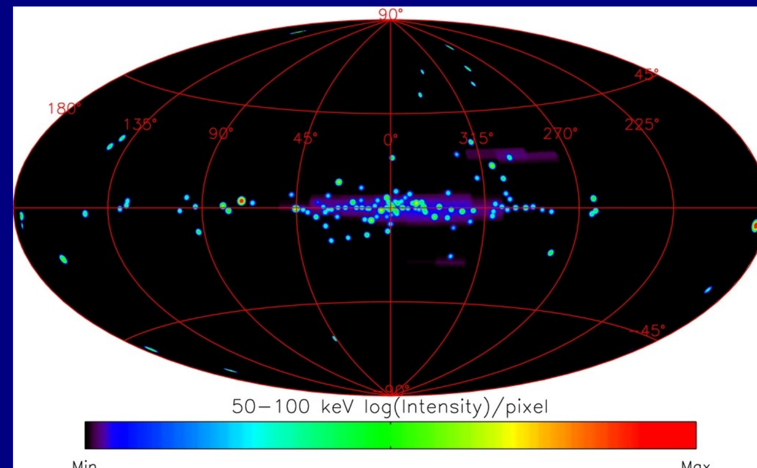
3 – 10 MeV

10 – 30 MeV



Unique heritage data:
COMPTEL analysis continues....

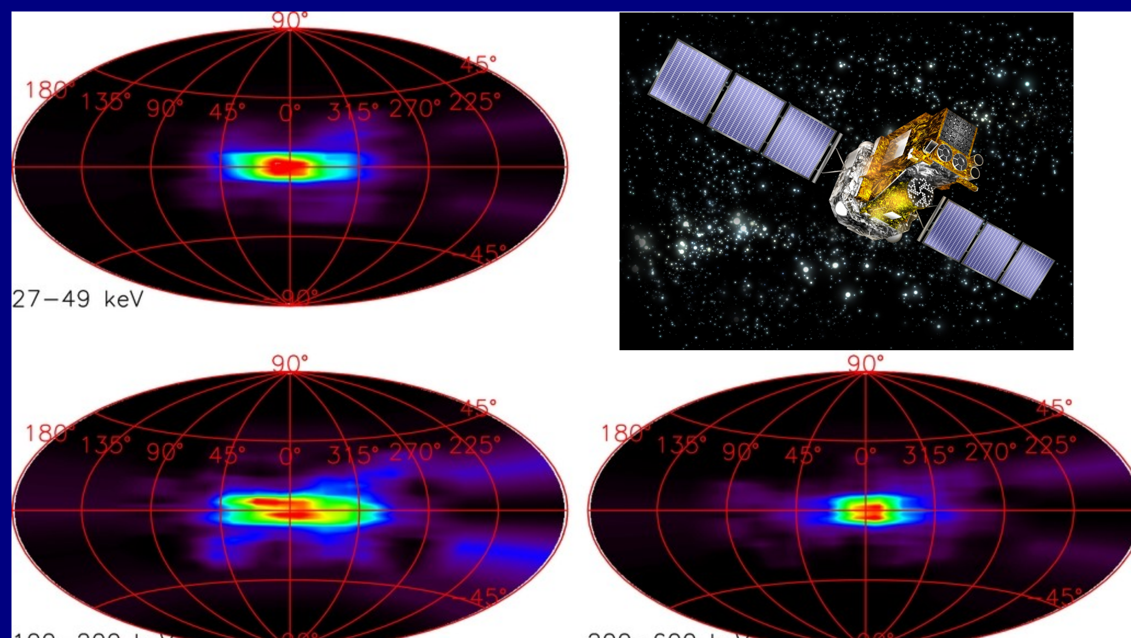
Mainly cosmic-ray electrons interacting with interstellar radiation ?
or unresolved sources ?



INTEGRAL / SPI
Continuum skymaps

Bouchet et al.
ApJ 739, 29 (2011)

See following talk
by Laurent Bouchet



A real mix of processes !

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

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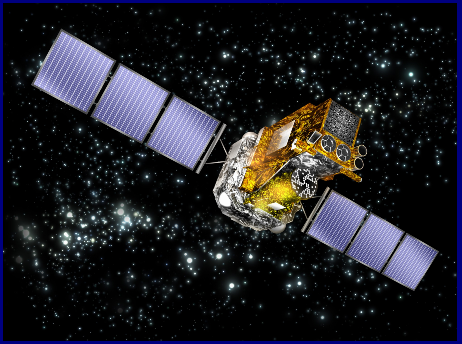

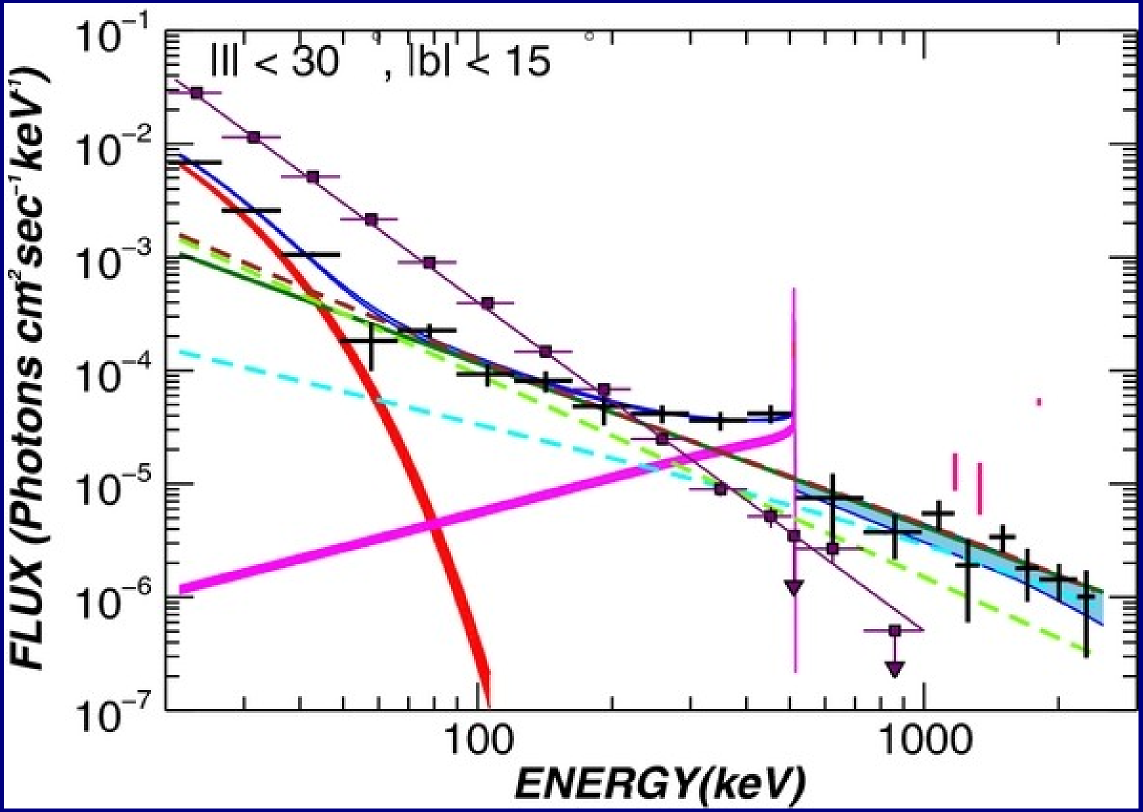

Inner Galaxy
INTEGRAL / SPI
Bouchet et al. ApJ 739, 29 (2011)

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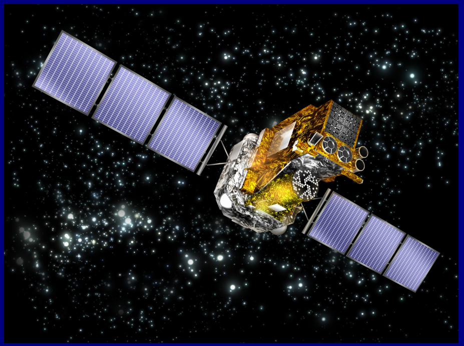
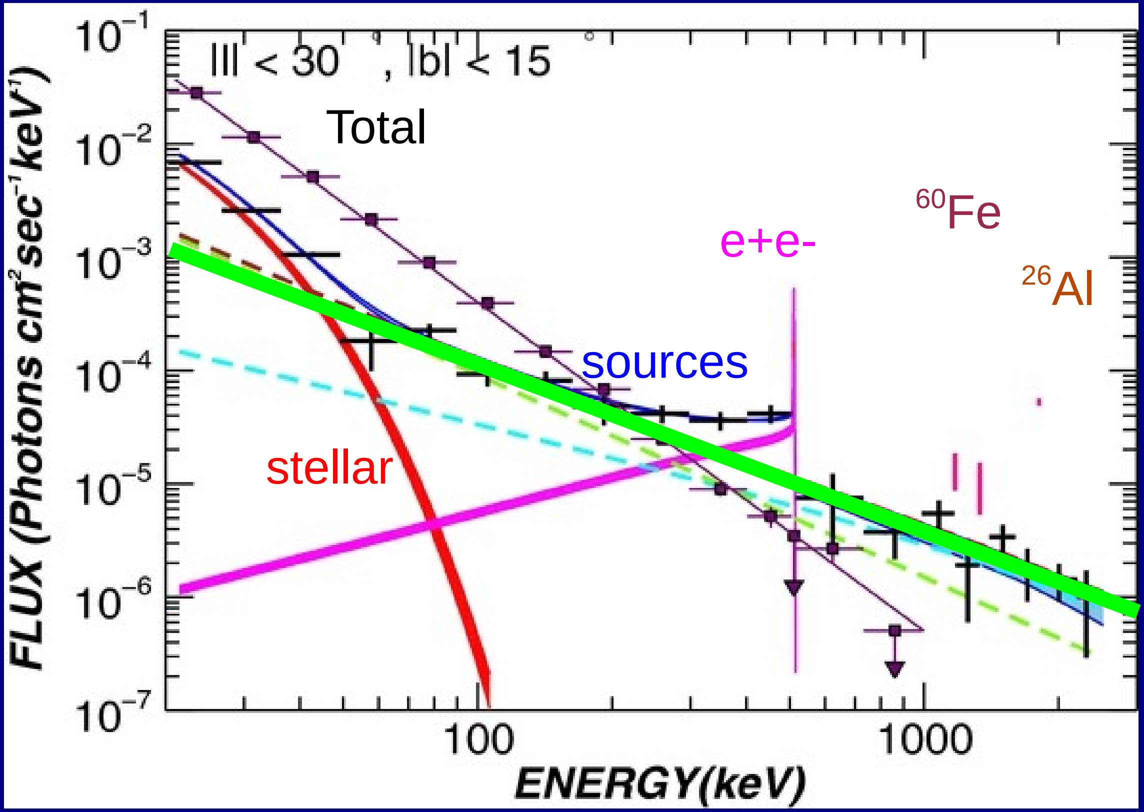
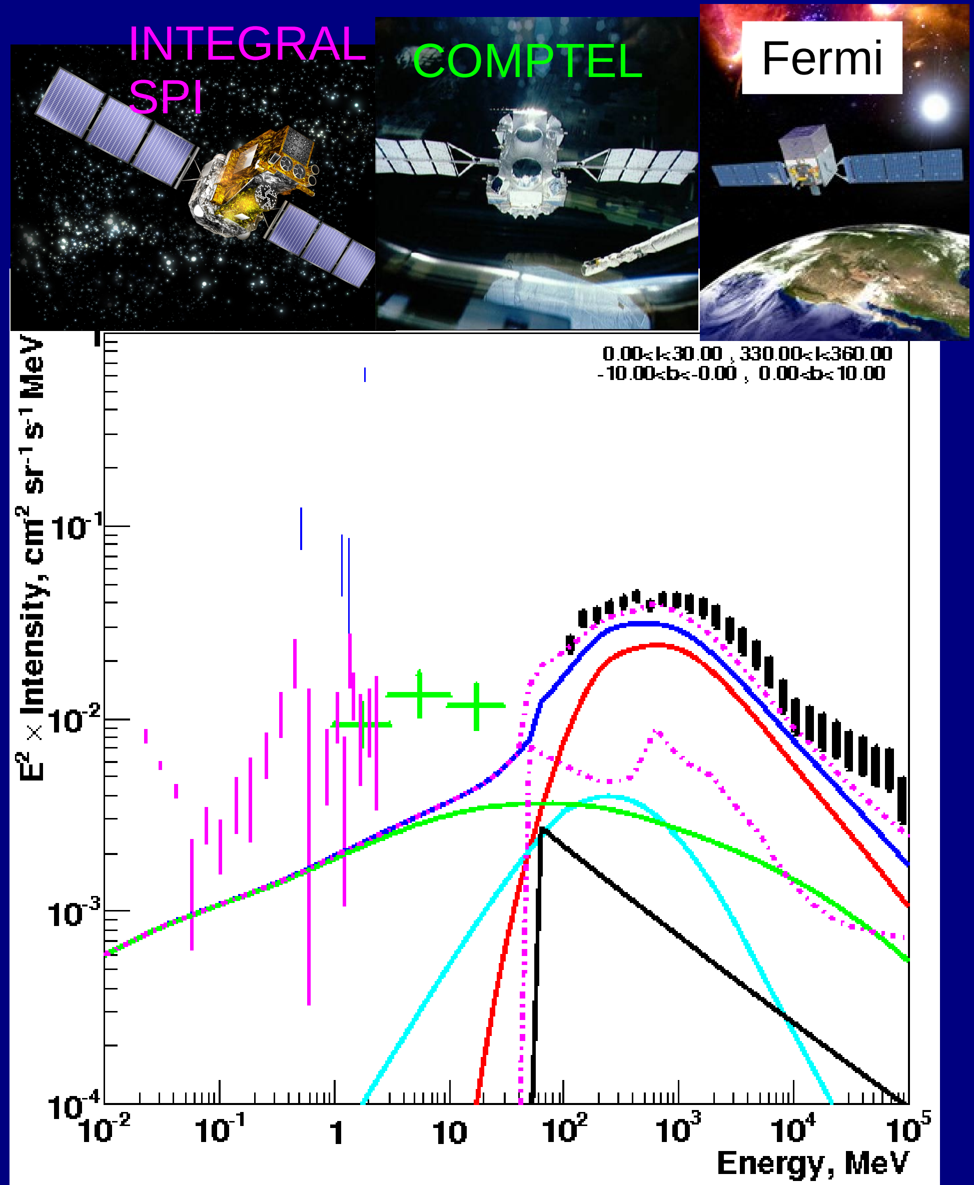




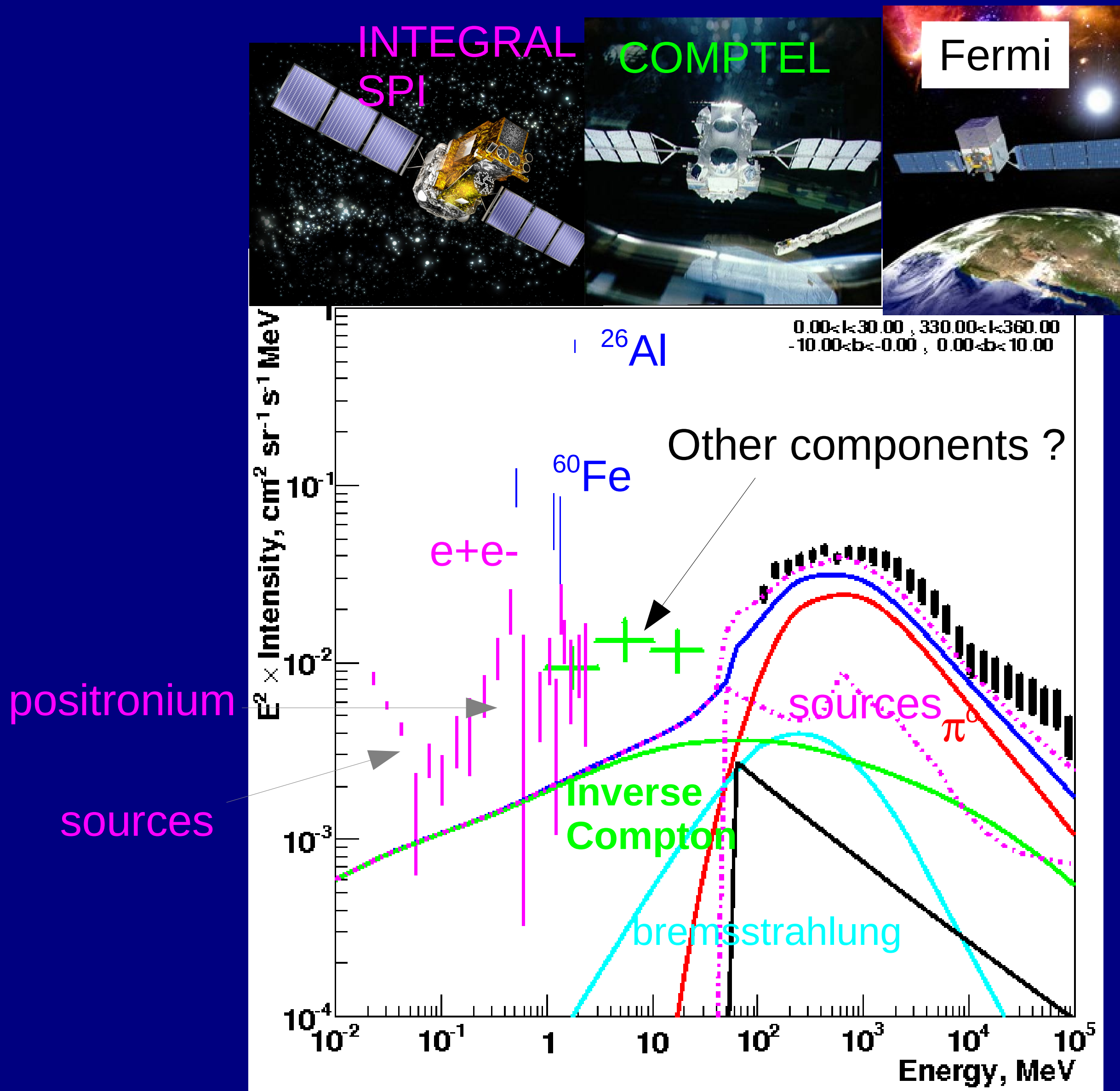
Non-thermal:
Cosmic-ray interactions

Inner Galaxy: keV to TeV



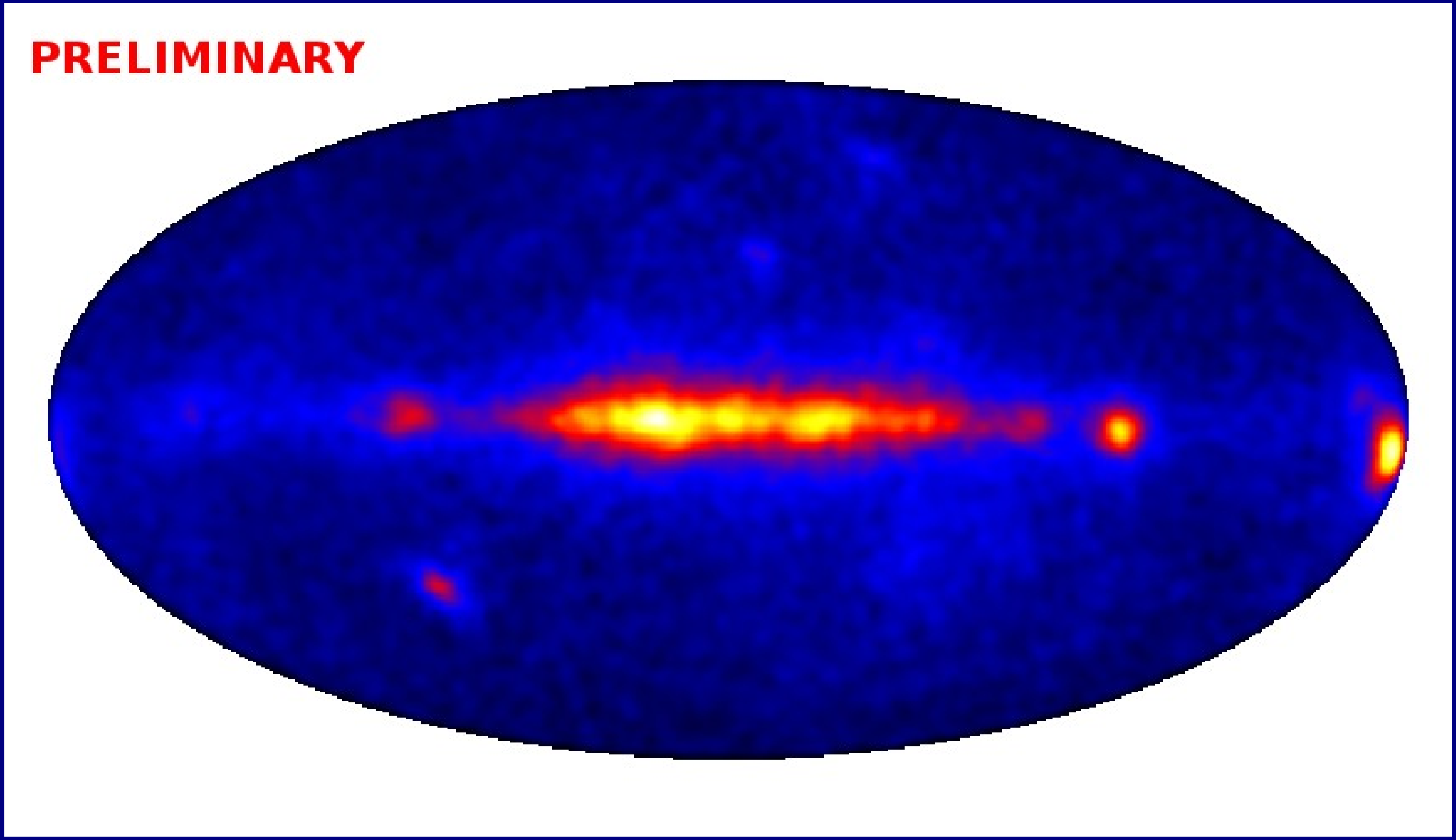
Strong 2011, Proc. 12 ICATPP Conf. arXiv:1101.1381

Inner Galaxy: keV to TeV



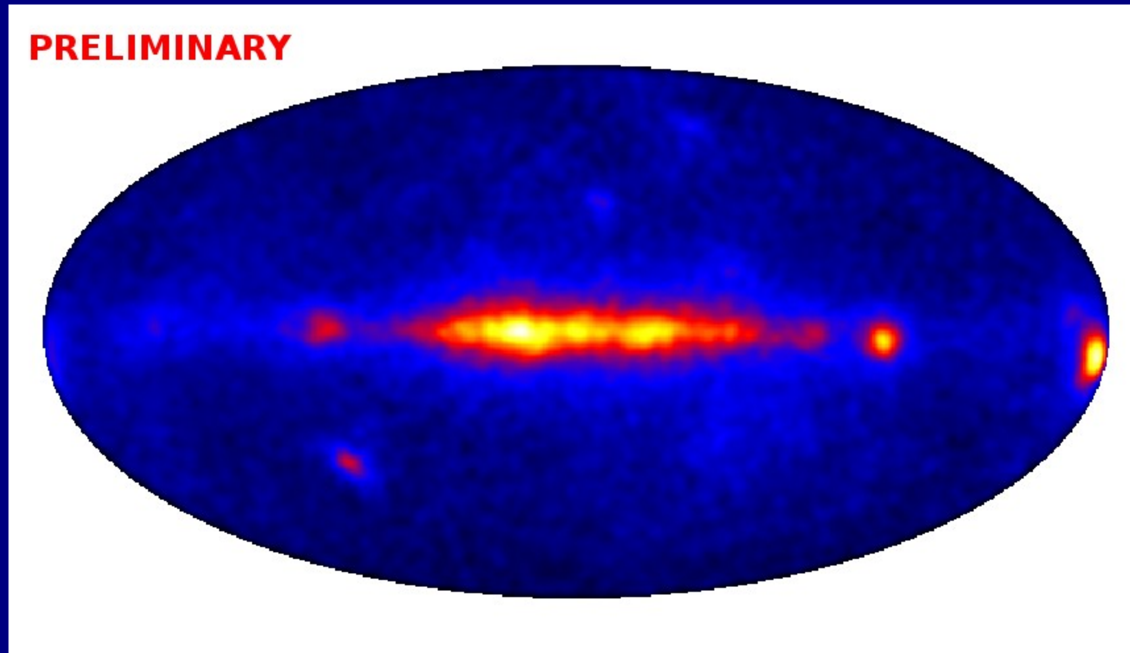
GeV electrons – inverse Compton - important for MeV gamma rays !

Fermi-LAT 25 – 40 MeV



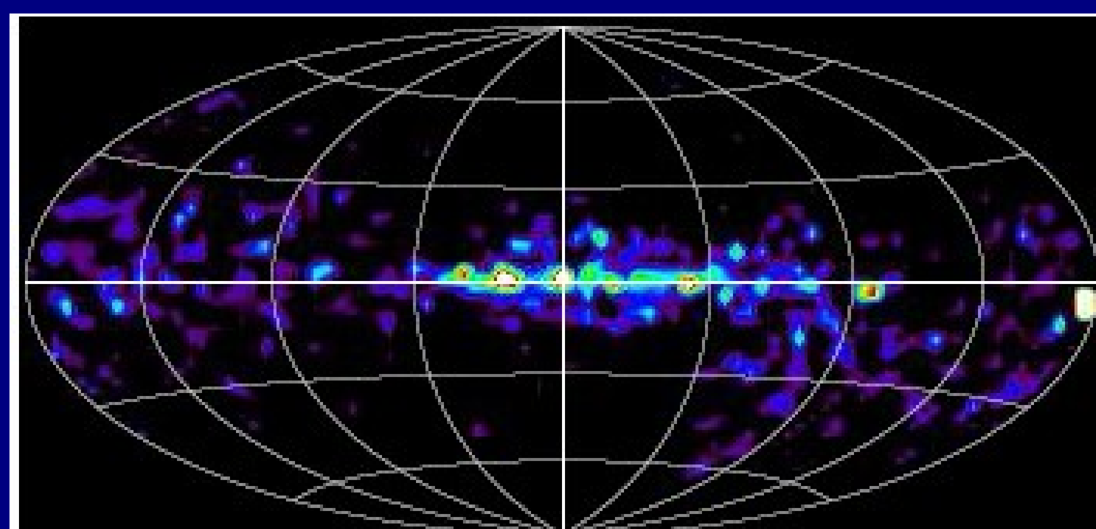
NB low angular and energy resolution !
Nominal energy range: photons may originate from range 10 to <100 MeV.
But valuable to bridge the MeV gap.

Fermi-LAT 25-40 MeV

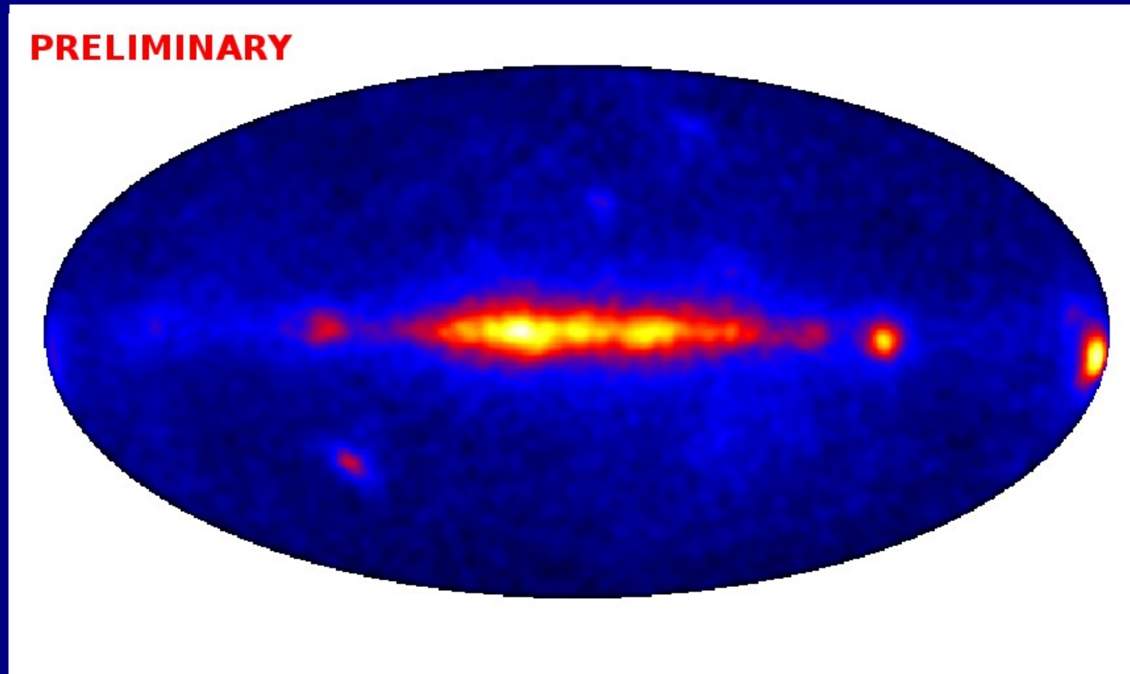


meets

COMPTEL 10-30 MeV

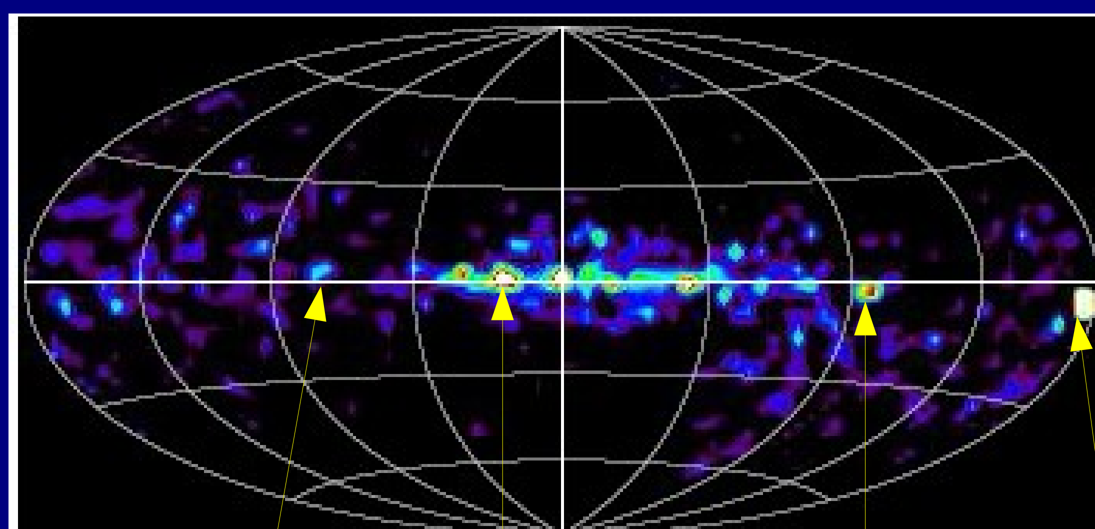


Fermi-LAT 25-40 MeV



meets

COMPTEL 10-30 MeV

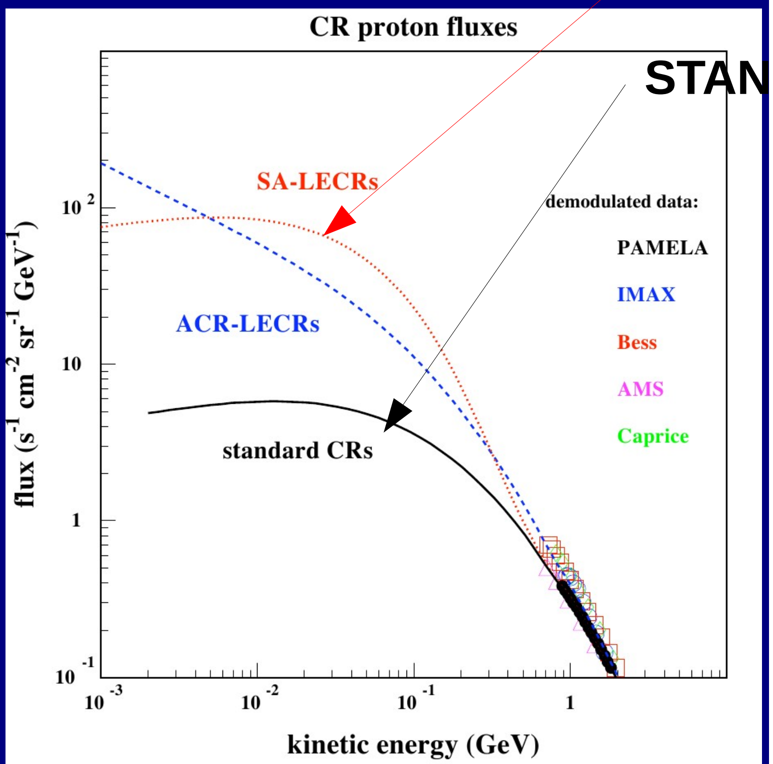


Galactic Plane

Cyg X-1 LS5039 Vela PSR Crab

Interstellar chemistry → ionization rates → cosmic rays → nuclear lines

Low energy cosmic rays



Ionization rate

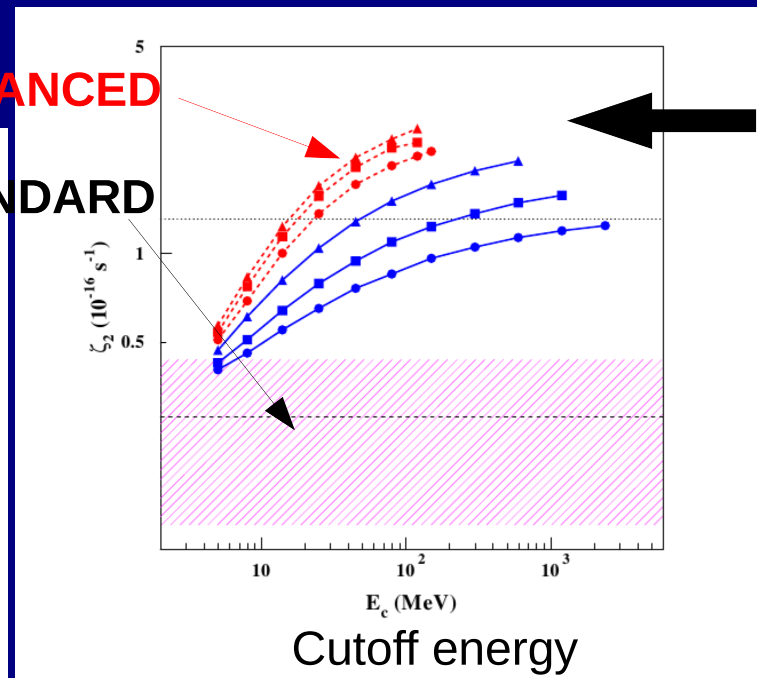


Fig. 4.— Calculated ionization rates of cosmic rays in dense molecular clouds supposing that particles with energies below 10 MeV per nucleon do not penetrate these places. Red symbols (connected by the dashed lines) show the values for SA-LECRs with spectral indices $s = 2.0$ (triangles), $s = 2.35$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

FROM CHEMISTRY OF H_3^+

Benhabiles-Mezhoud,Kiener, Tatischeff & Strong, 2012

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

Low-energy Cosmic rays

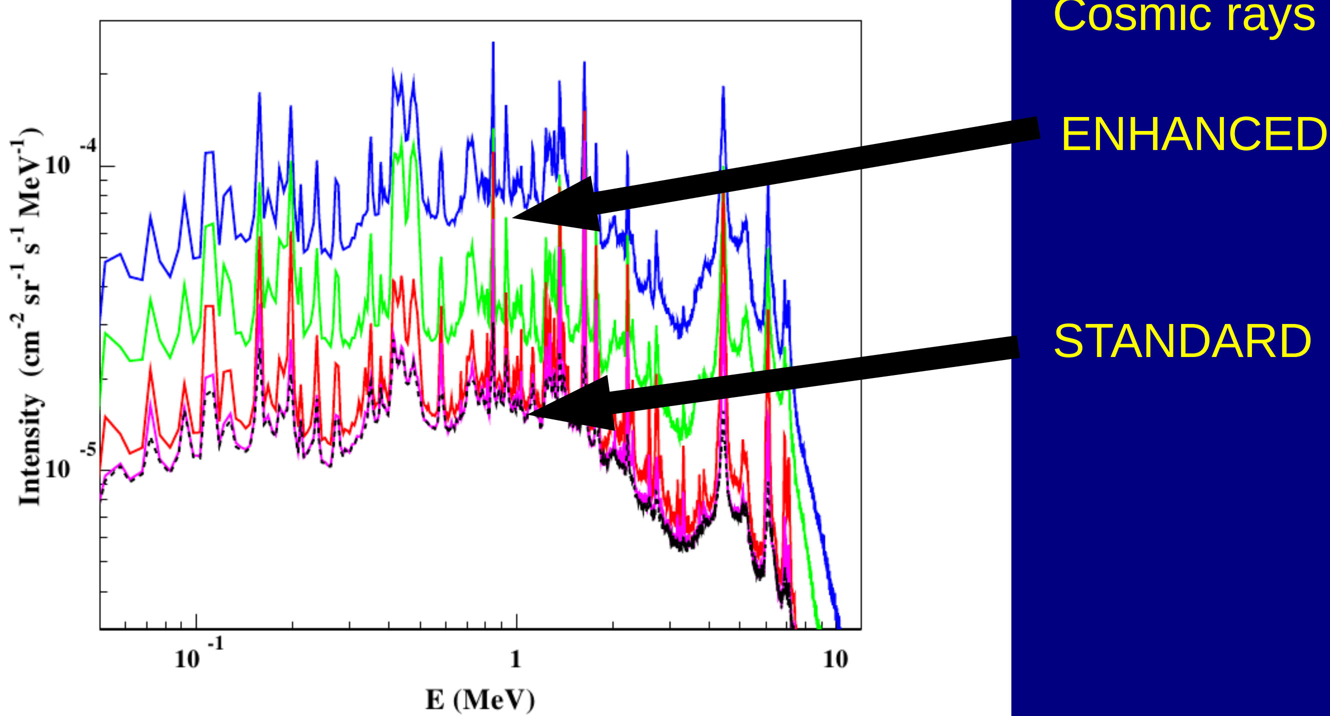
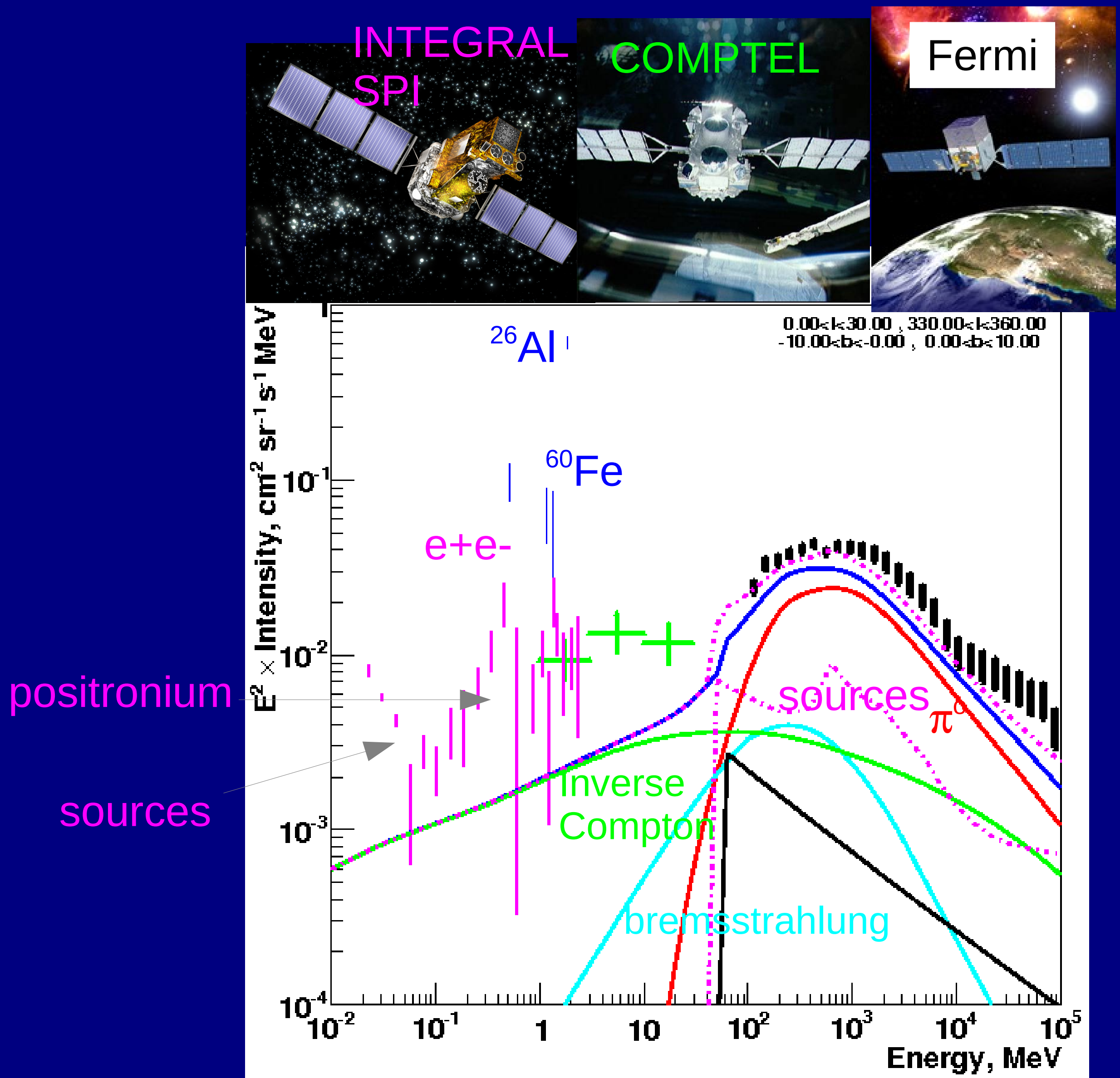


Fig. 6.— Calculated nuclear γ-ray line emissions from the inner Galaxy for CRs with ACR-LECR components following the model of Scherer et al. (2008a) with $s = 2.4$, $E_c = 5$, 25 and 1200 MeV (magenta, red and green lines, resp.) and SA-LECR with $s = 2.0$ and $E_c =$ 120 MeV (blue line). The emission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

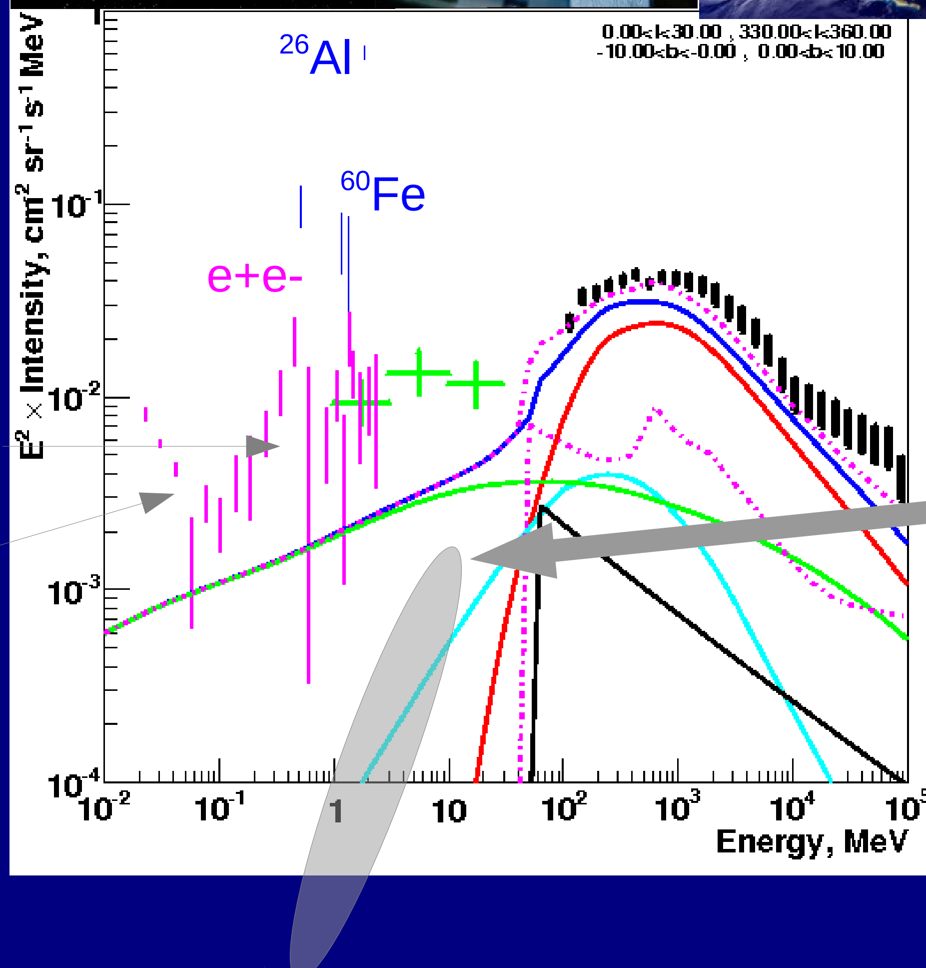
Benhabiles-Mezhoud,Kiener, Tatischeff & Strong, 2012

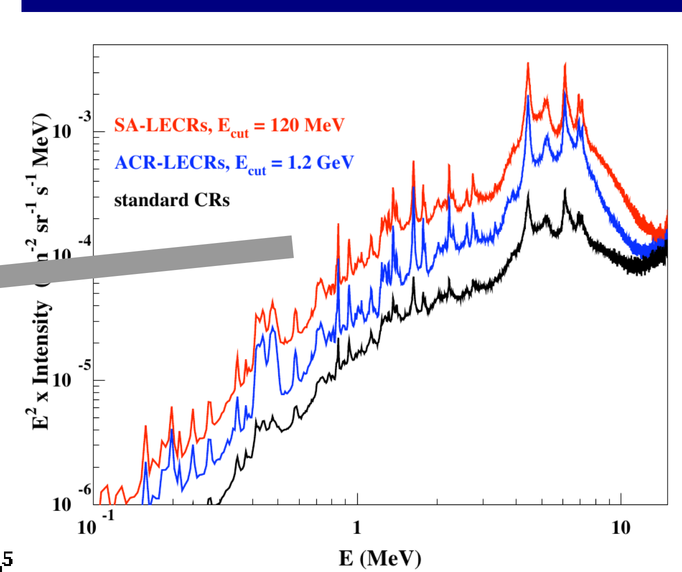
More chance to detect nuclear lines !

Inner Galaxy: keV to TeV



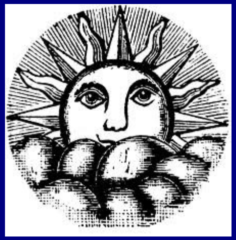
Inner Galaxy: keV to TeV





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

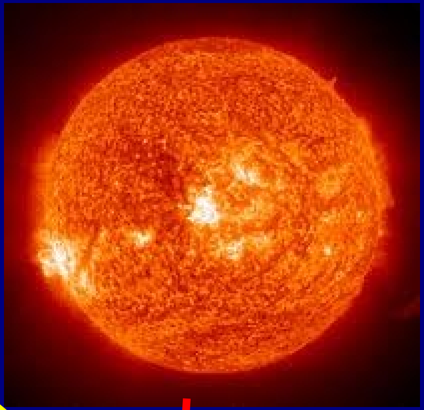
INTERLUDE



Nearer home the Sun is a large diffuse source of gamma rays !
Inverse Compton of cosmic-ray electrons on solar radiation.

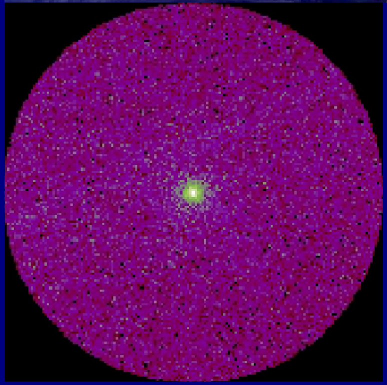
→ Inner heliosphere physics

Galactic cosmic-ray electrons
In heliosphere



Solar photon

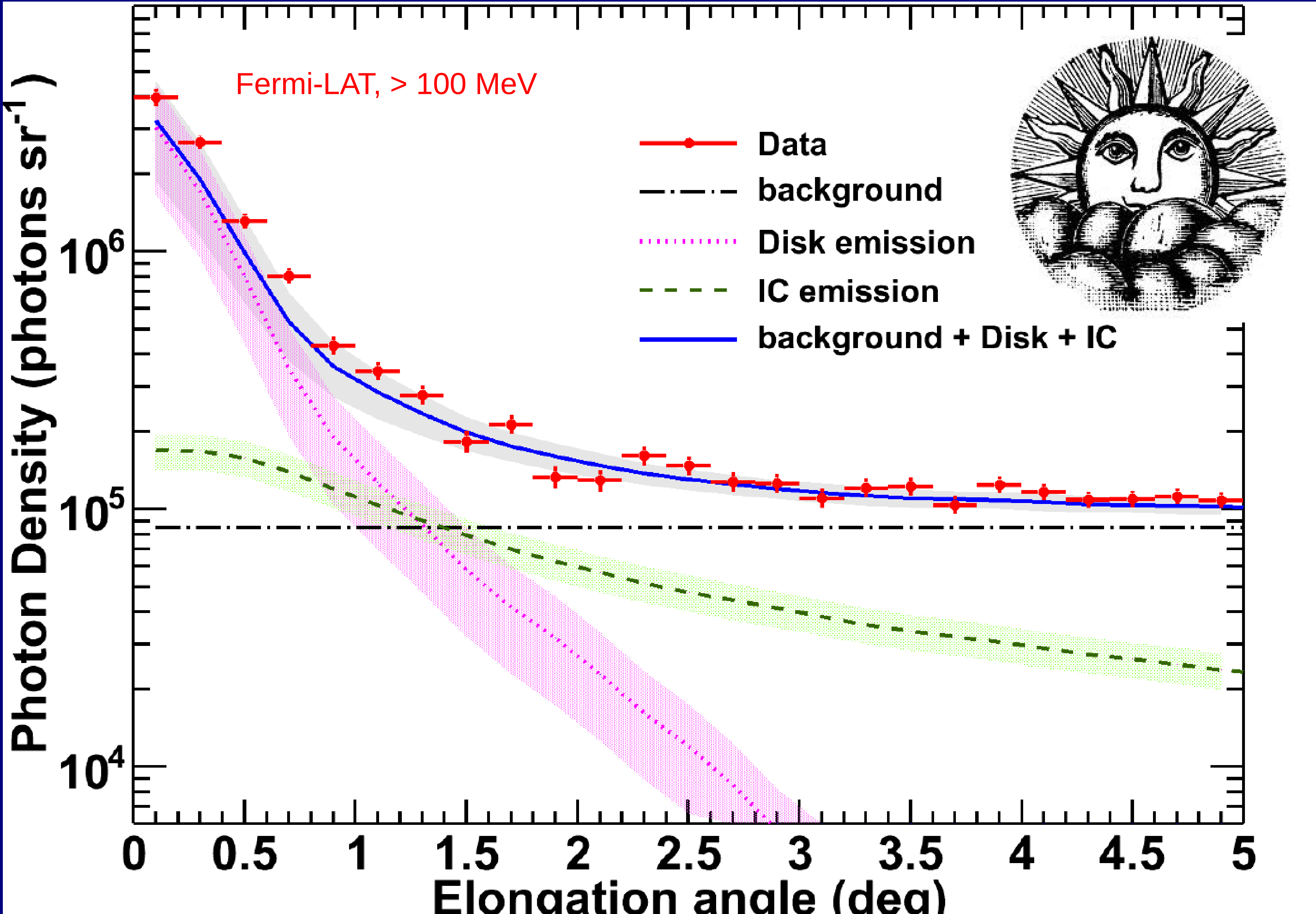
Gamma rays



Inverse Compton scattering

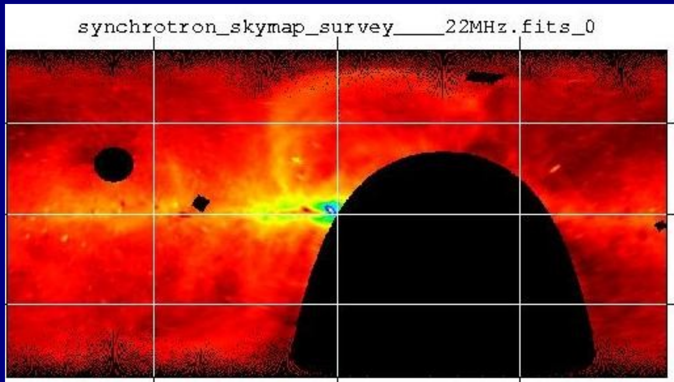
$$E_\gamma \sim \gamma^2 E_{phot}$$

Solar photons ~ 1 eV, cosmic-ray electrons ~ GeV → GeV gamma rays

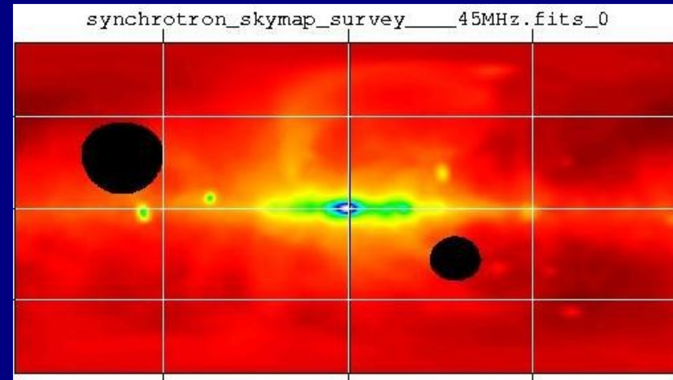


Fermi-LAT, > 100 MeV
Data
background
Disk emission
IC emission
background + Disk + IC
Photon Density (photons sr^{-1})
10^6
10^5
10^4
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Elongation angle (deg)

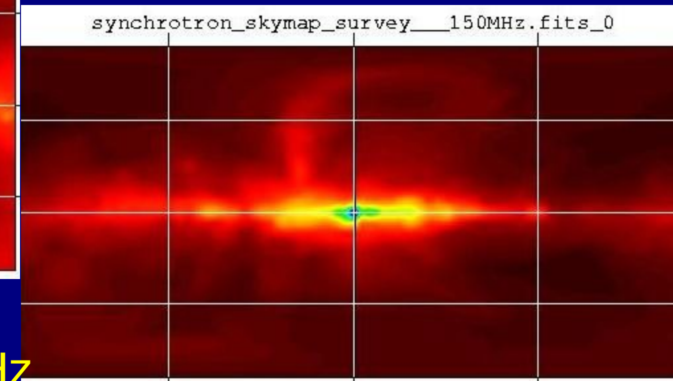
Continuum sky surveys



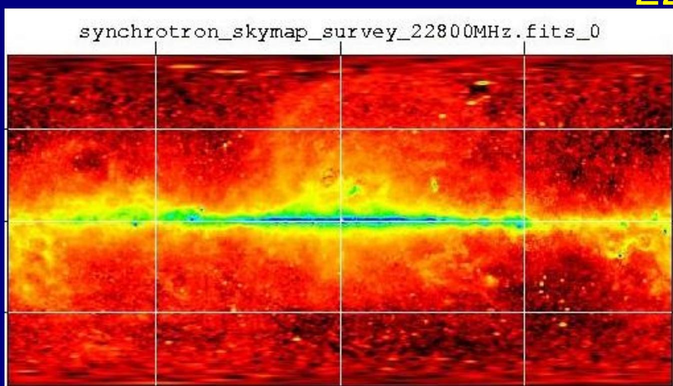
22 MHz



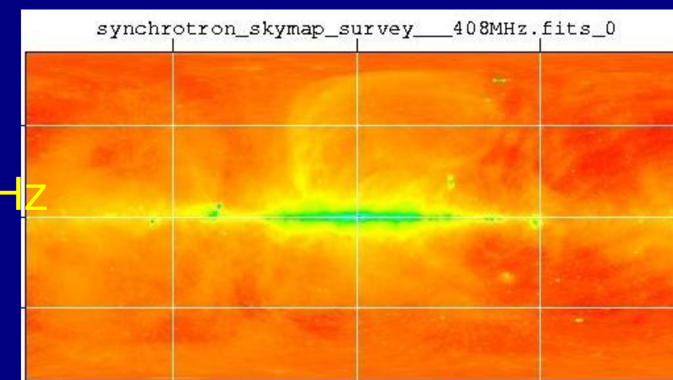
45 MHz



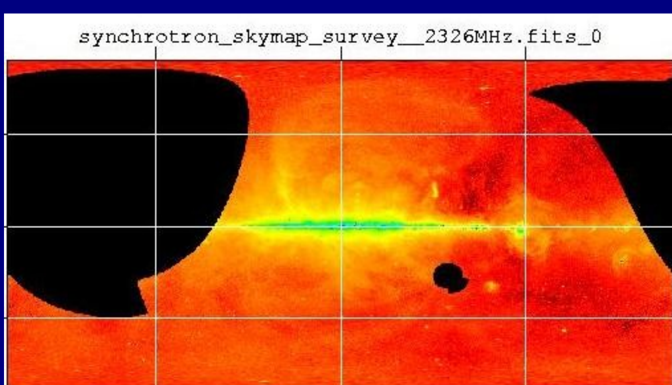
150 MHz



23 GHz

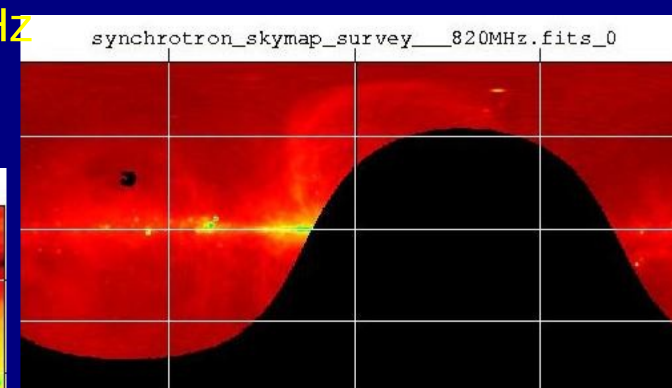


408 MHz

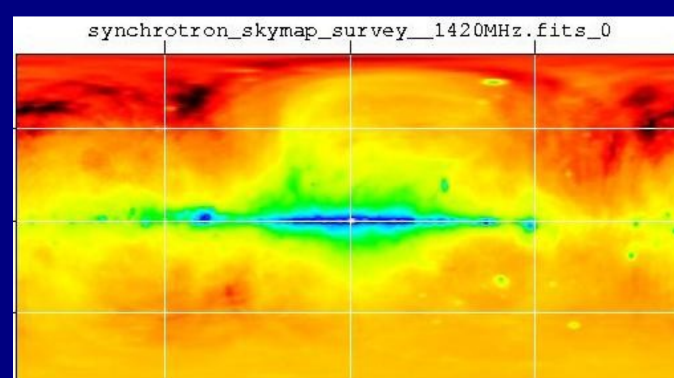


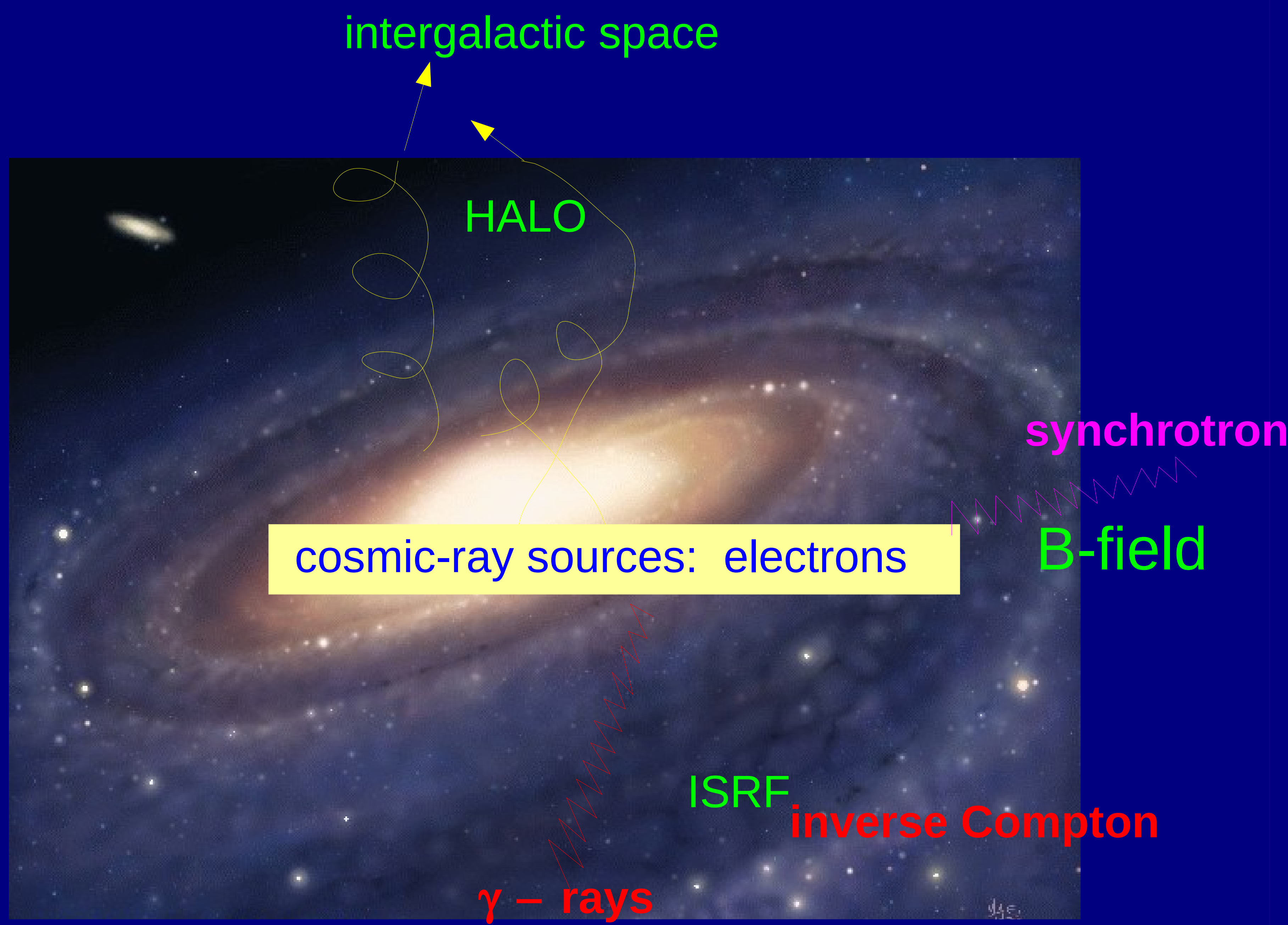
2.3 GHz

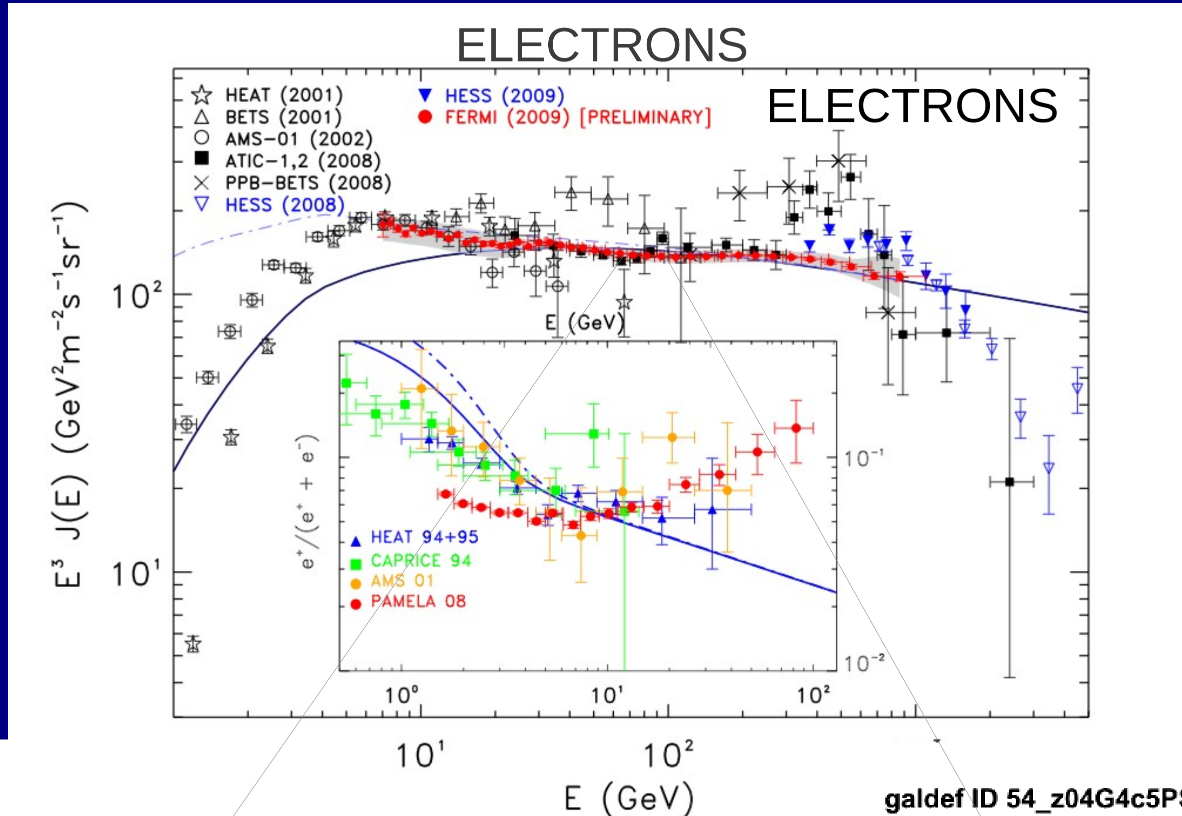
820 MHz

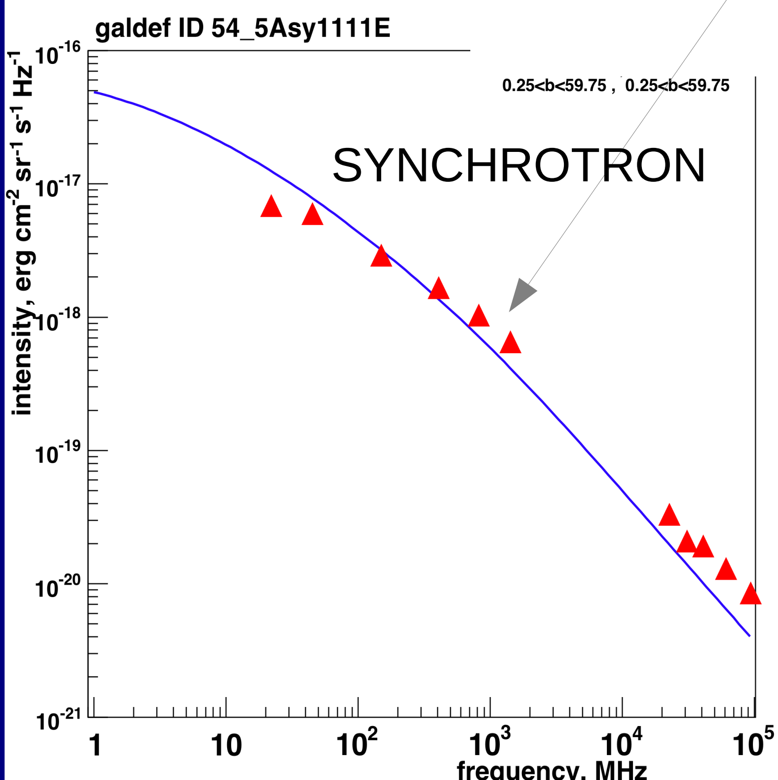


1.4 GHz



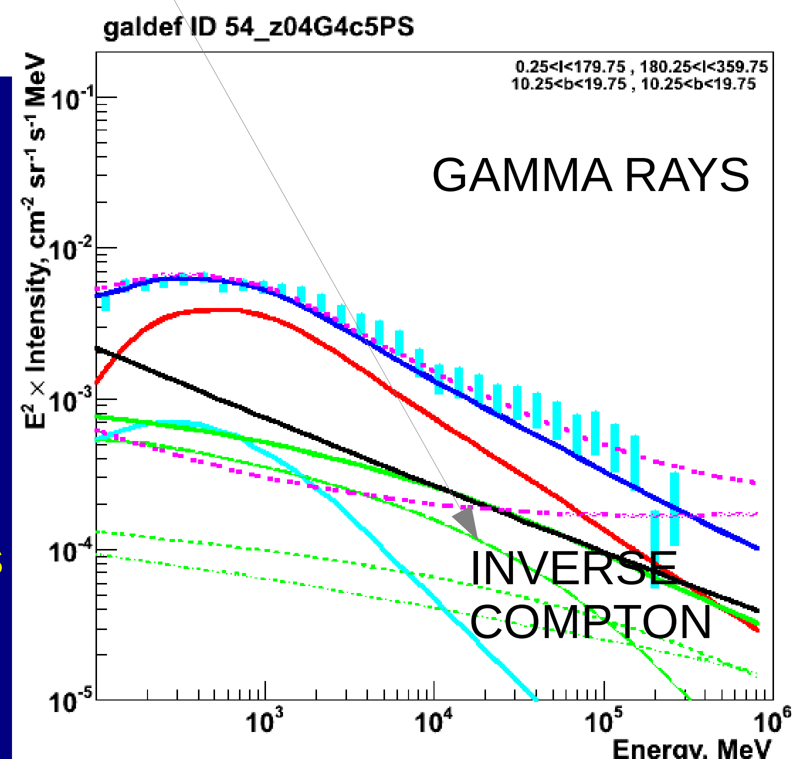

intergalactic space
HALO
synchrotron
cosmic-ray sources: electrons
B-field
ISRF
inverse Compton
γ – rays

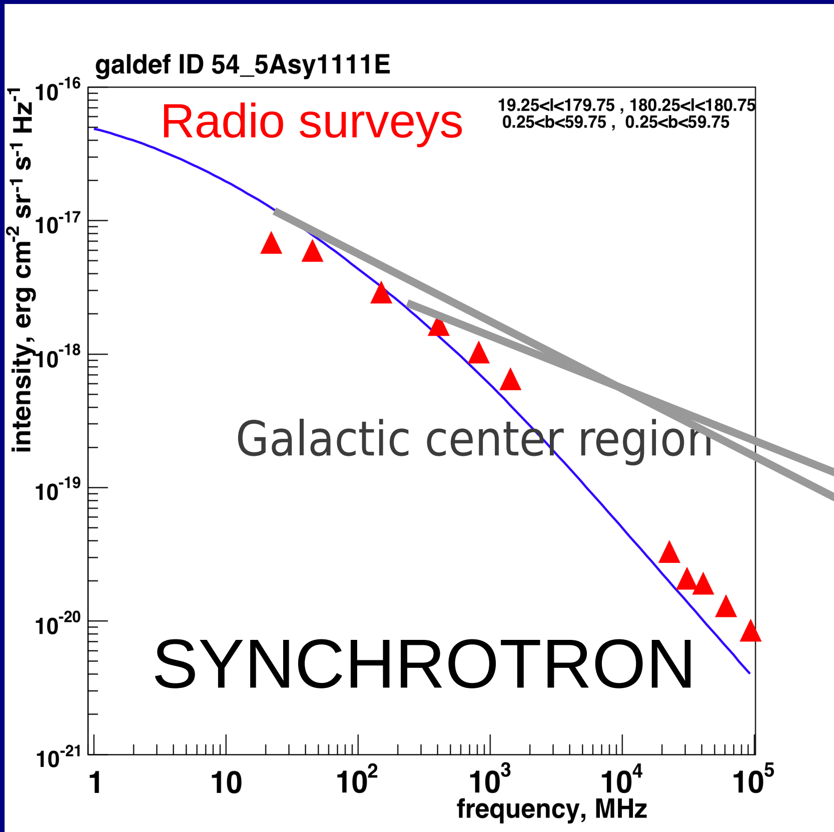


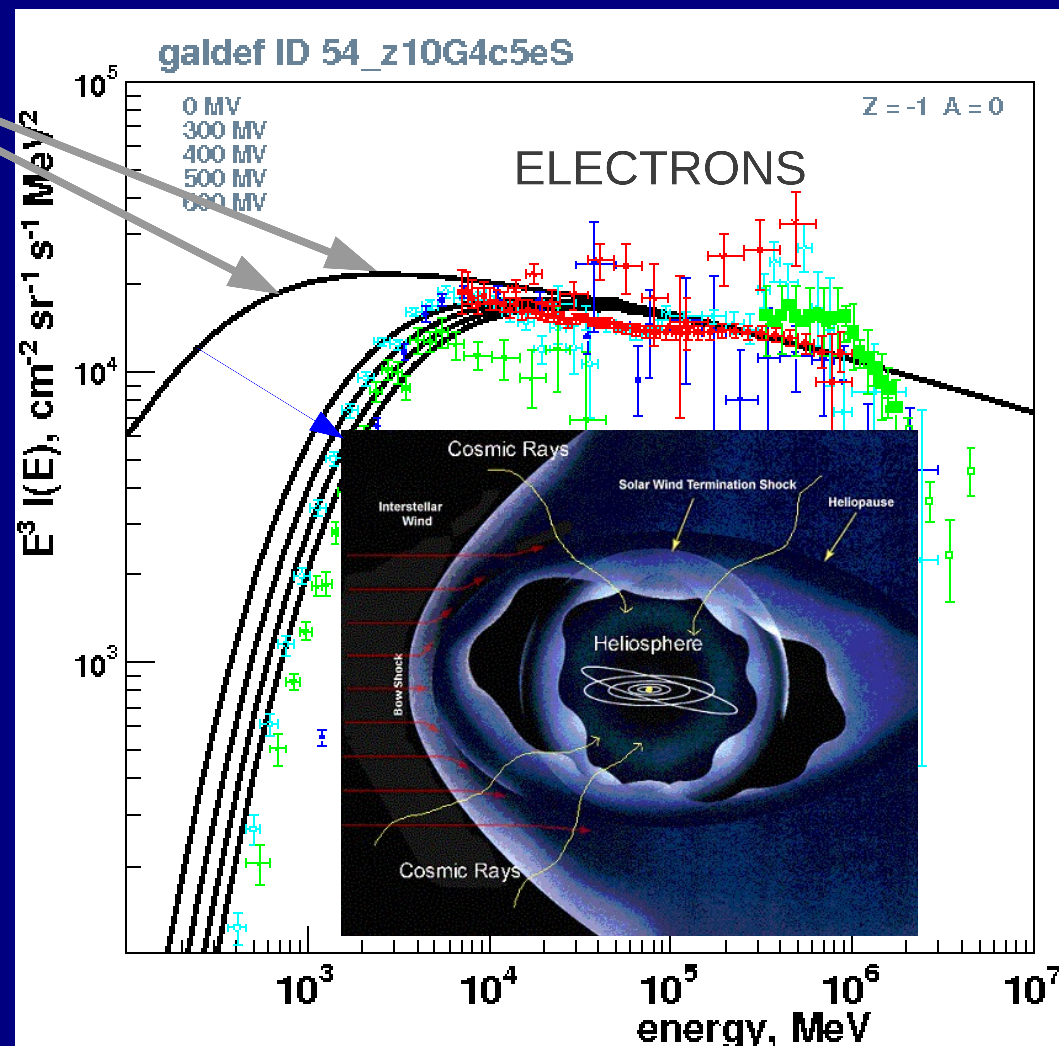


SAME ELECTRONS for RADIO and GAMMA RAYS !

good constraints on models



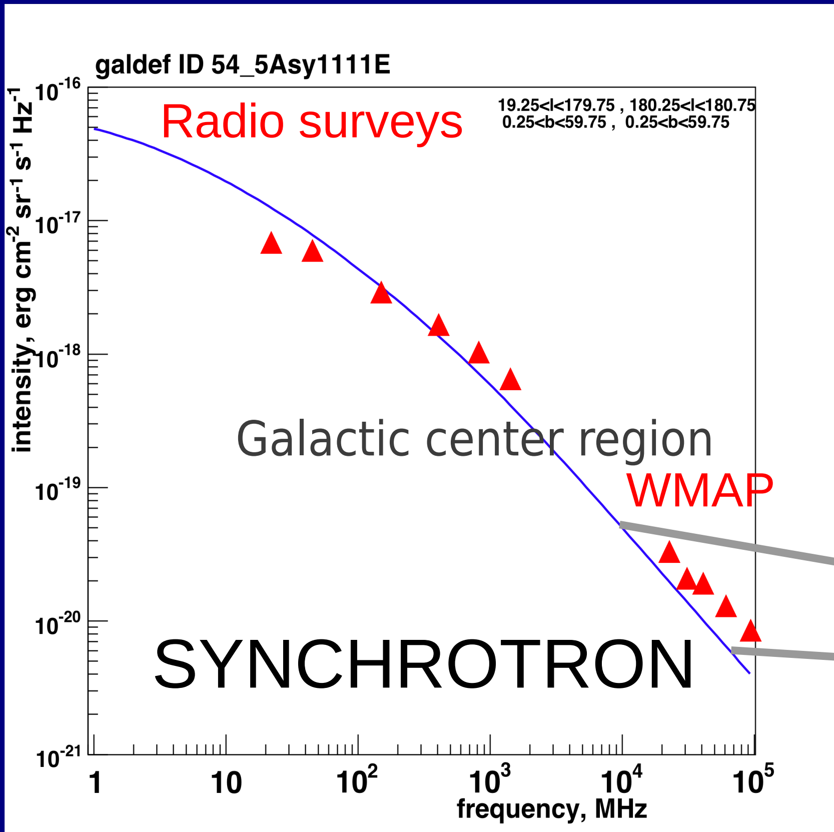


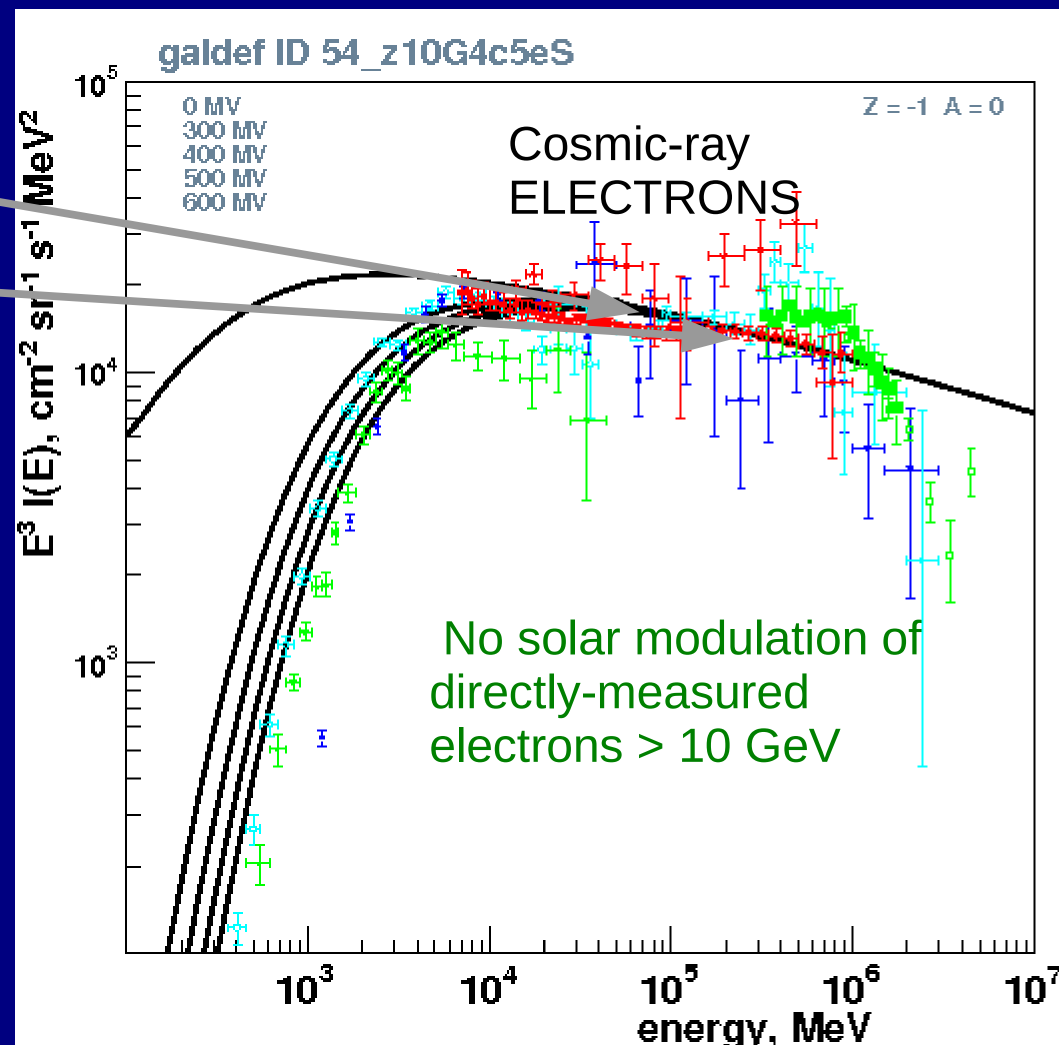


radio provides essential probe of interstellar electron spectrum at E < few GeV to complement direct measurements and determine solar modulation

electrons have huge uncertainty due to modulation here

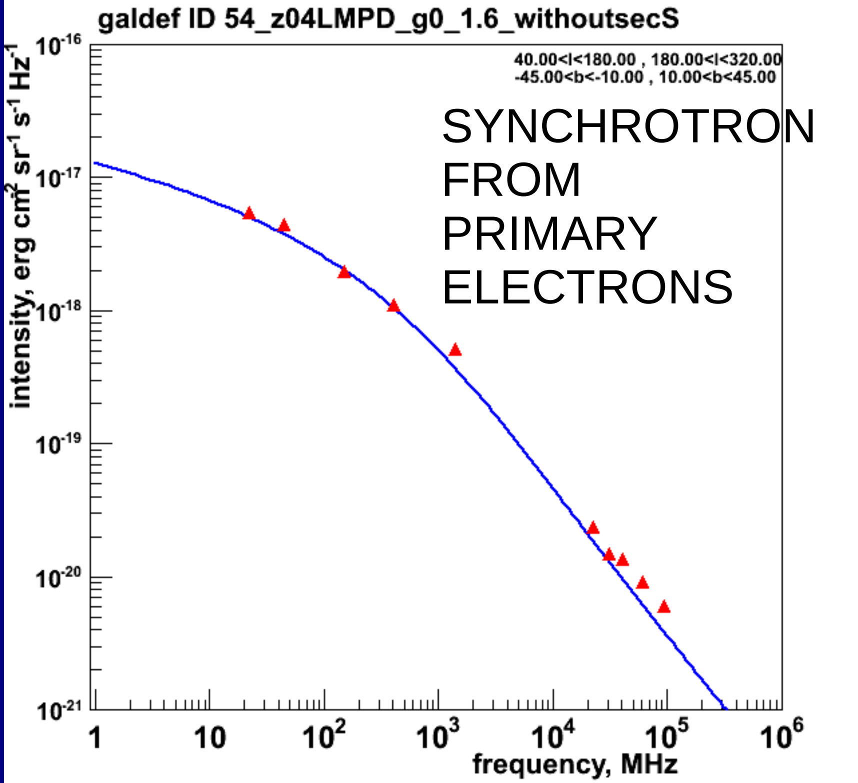
A. W. Strong, E. Orlando, T.R. Jaffe, 2011, A&A 534, A54

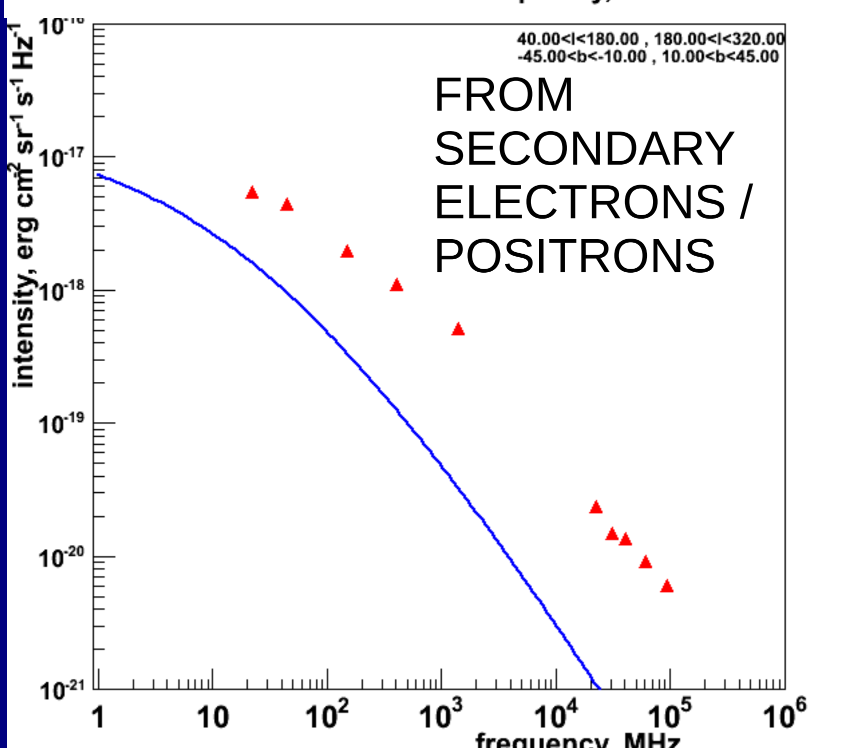


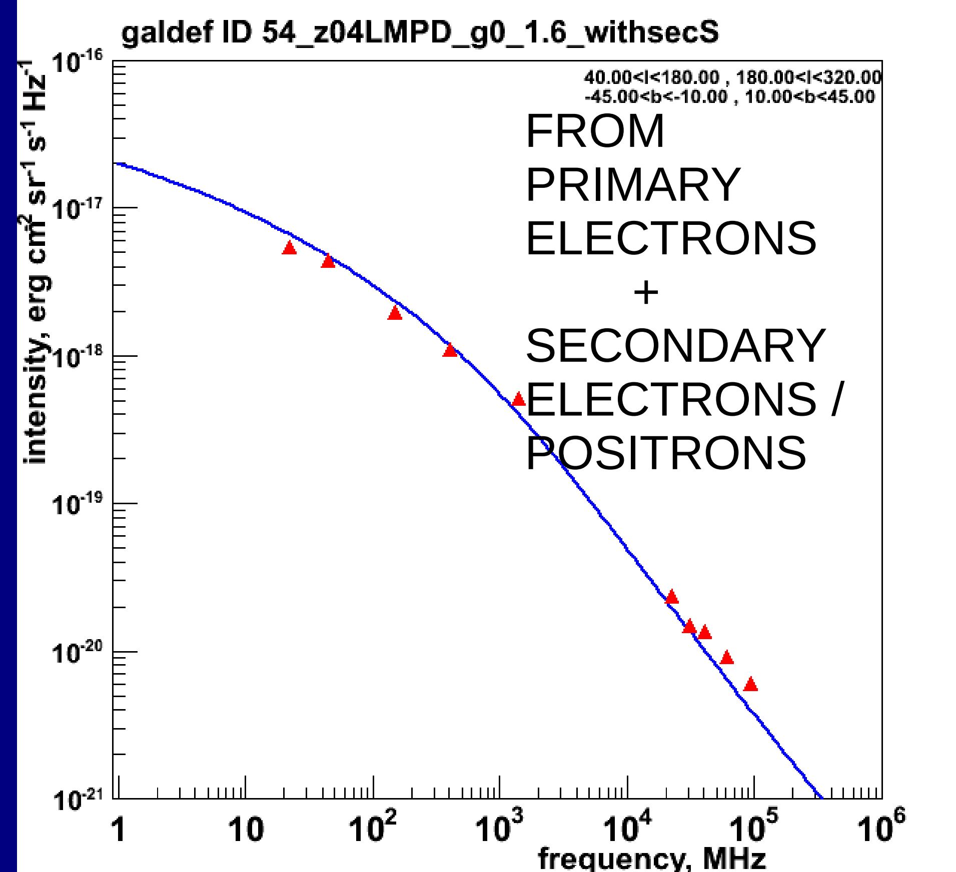


microwaves provide essential probe of interstellar electron spectrum

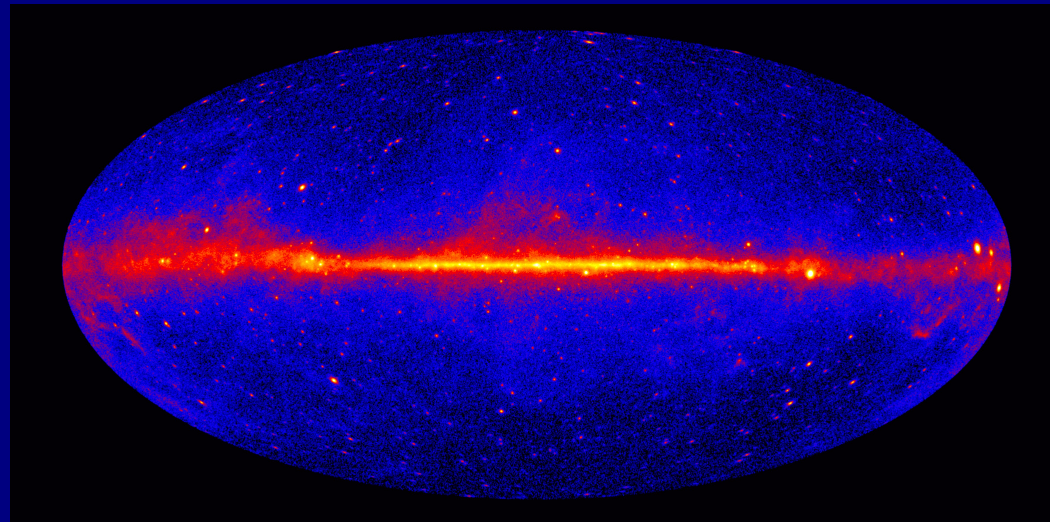
10 - 100 GeV



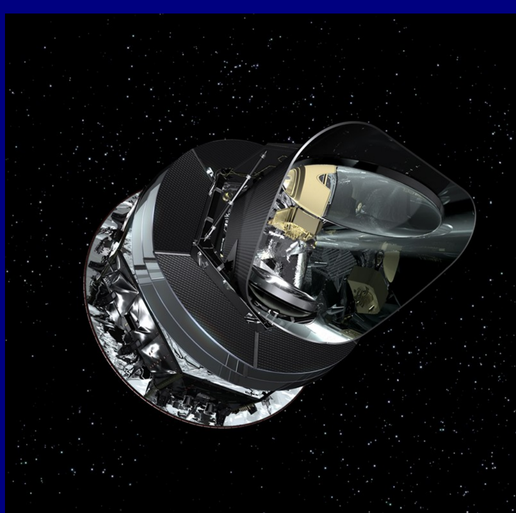


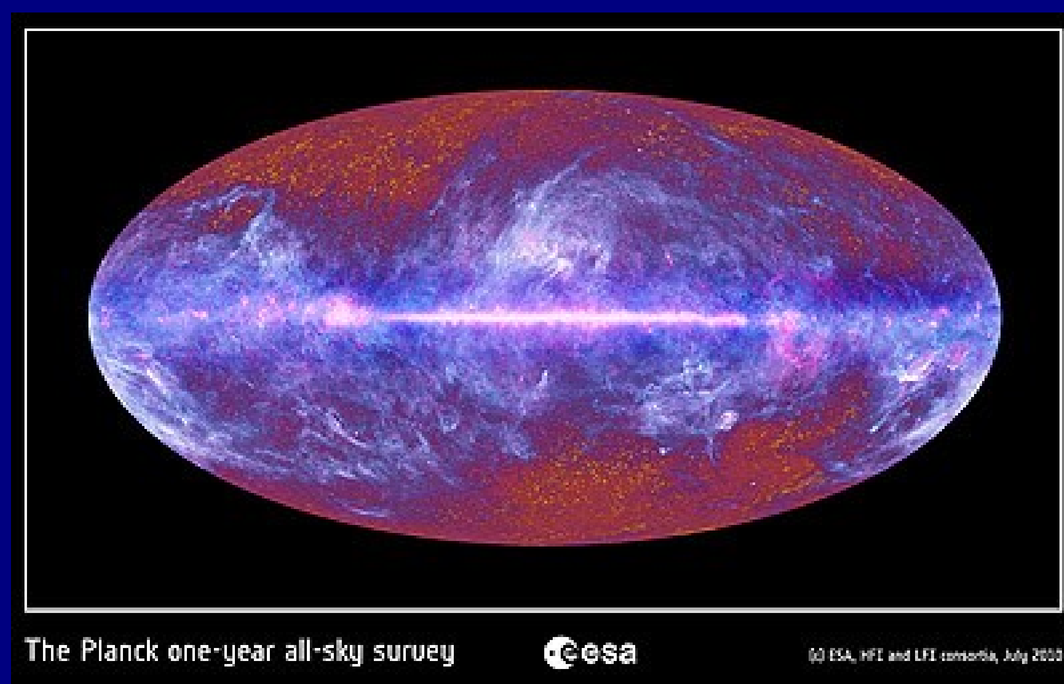


Secondary positrons
(and secondary electrons)
are important for synchrotron



2 years

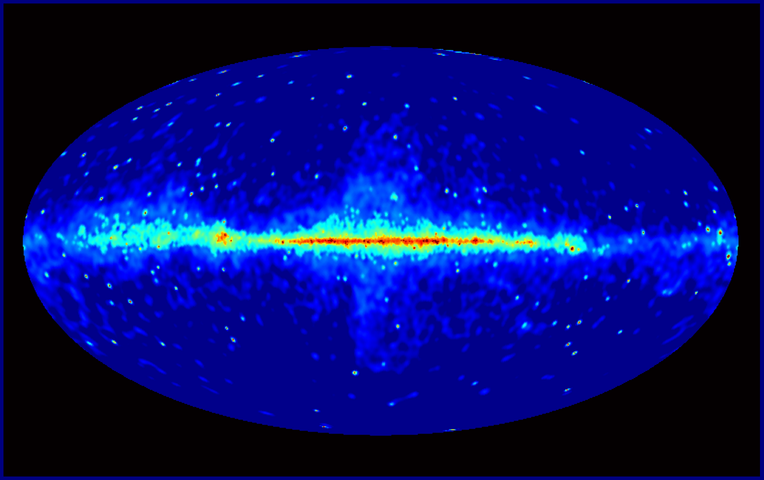




1 year

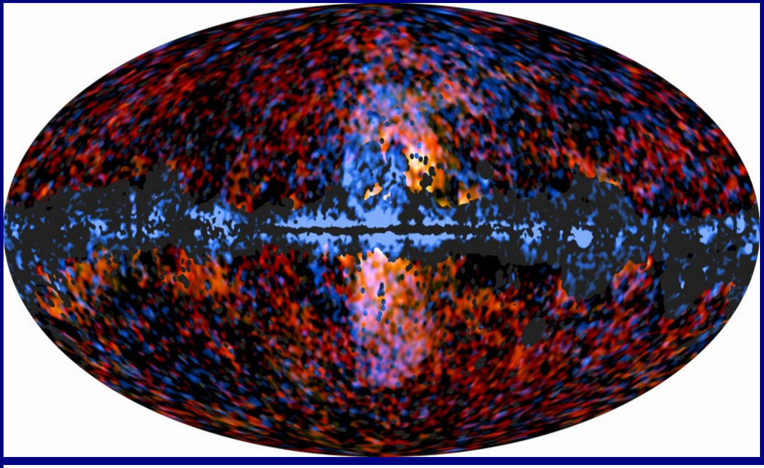
A lot of common astrophysics, cosmic rays, gas, magnetic fields !

Fermi Bubbles

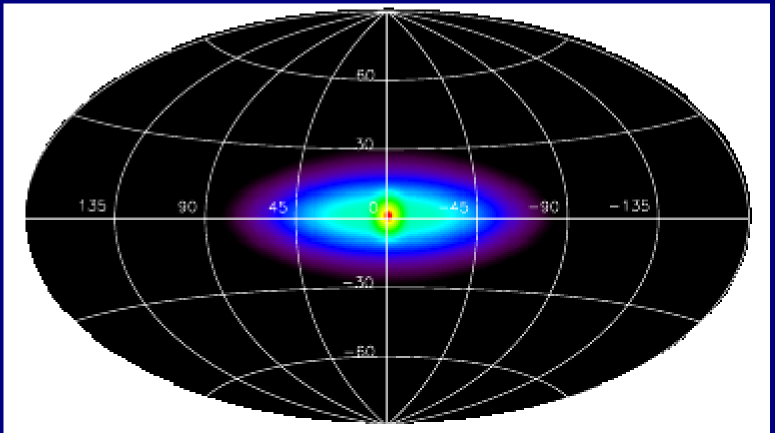


(related to WMAP Haze ?)

Planck haze (arXiv:1208.5483)
Overlaid on Fermi Bubbles

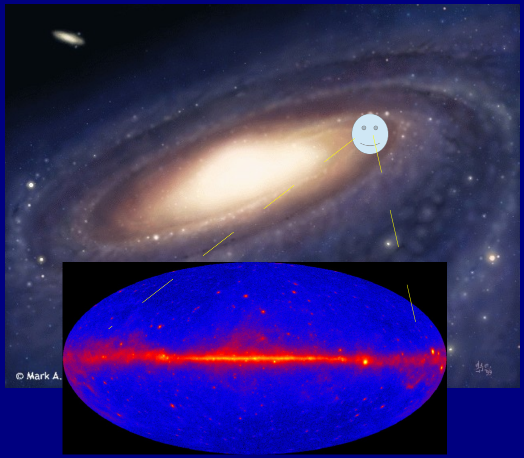


connection to 511 keV line ?



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.

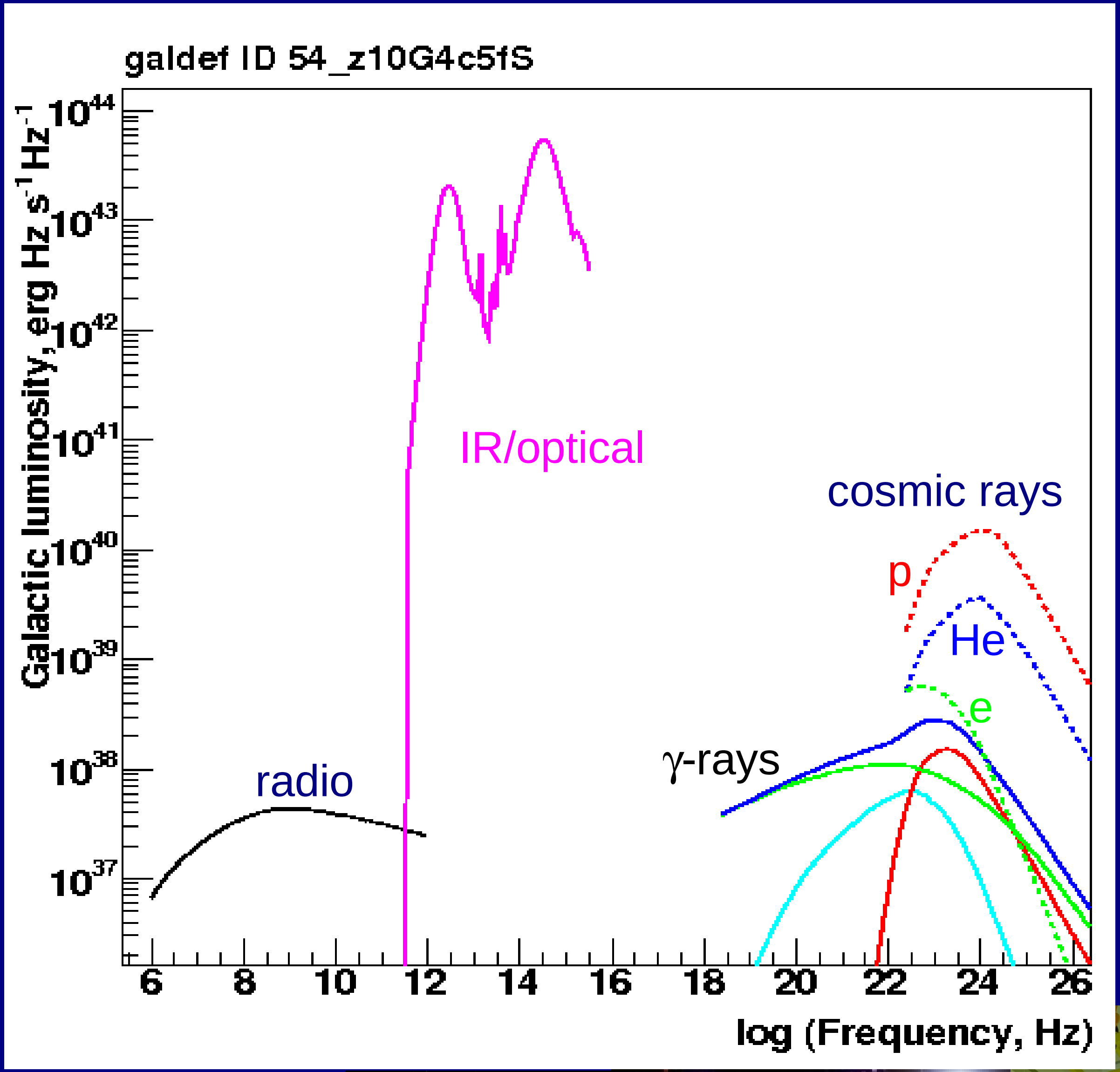


SEDs of AGN etc are common, but not Milky Way

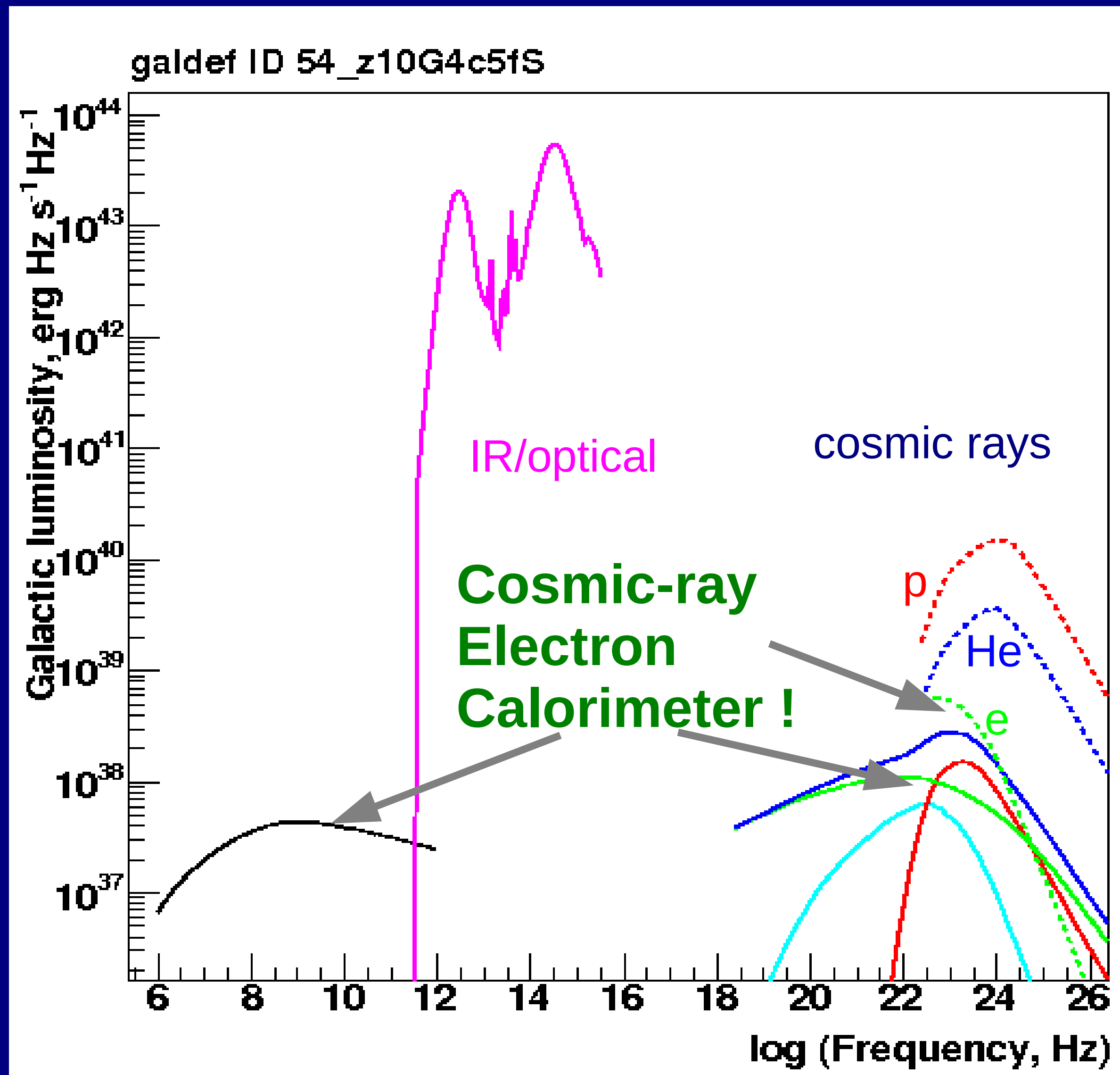

what does it look from out there ?

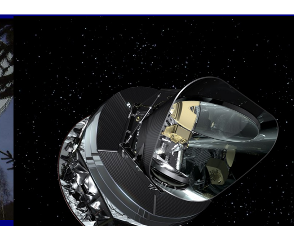

EXPERIMENTS
THEORY
intergalactic space
HALO
Secondary: ^{10}Be, ^{10,11}B ... Fe..
Secondary: e^{+-} $\bar{p}$
cosmic-ray sources: p, He .. Ni, e^-
synchrotron
B-field
π^o
gas
ISRF
bremsstrahlung
inverse Compton
γ – rays

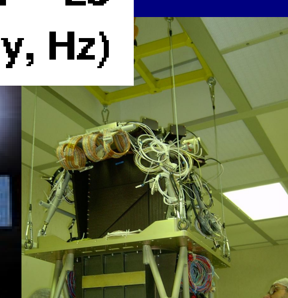
Galaxy luminosity over 20 decades of energy

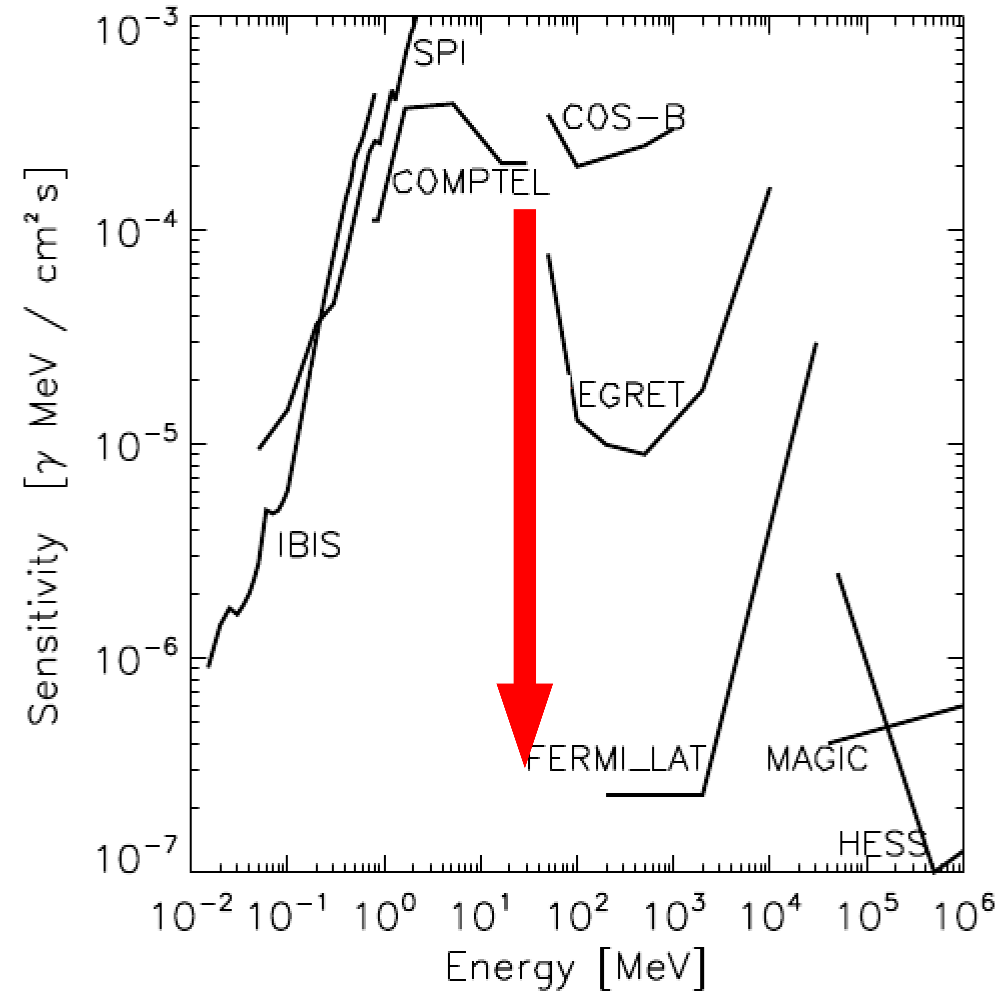


Galaxy luminosity over 20 decades of energy

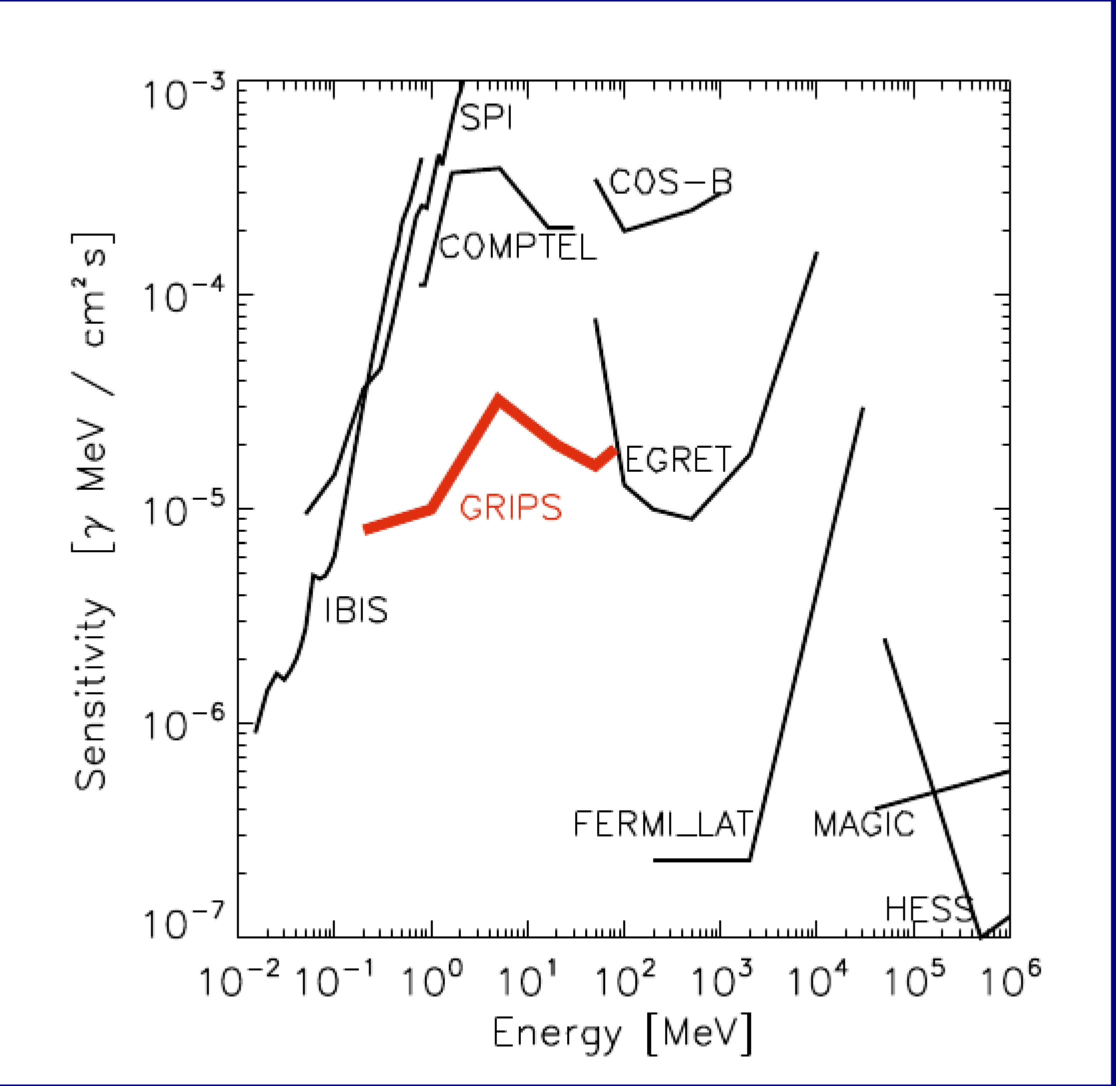








SPI
COS−B
COMPTEL
EGRET
IBIS
FERMI_LAT
MAGIC
HESS
Sensitivity [γ MeV / cm² s]
Energy [MeV]
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10⁻² 10⁻¹ 10⁰ 10¹ 10² 10³ 10⁴ 10⁵ 10⁶



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


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