Cosmic Rays and Magnetic Fields in a multiwavelength context

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MPE Garching

DFG FOR 1254 Workshop on Magnetic Fields in galaxies
MPIfR Bonn, 6-8 March 2013

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

WHY ?

Why consider the high-energy astrophysics connection ?

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

+ magnetic fields.

Gives insight into the synchrotron emission – spectral and spatial

Polarized synchrotron is essential part of this topic.

Topics

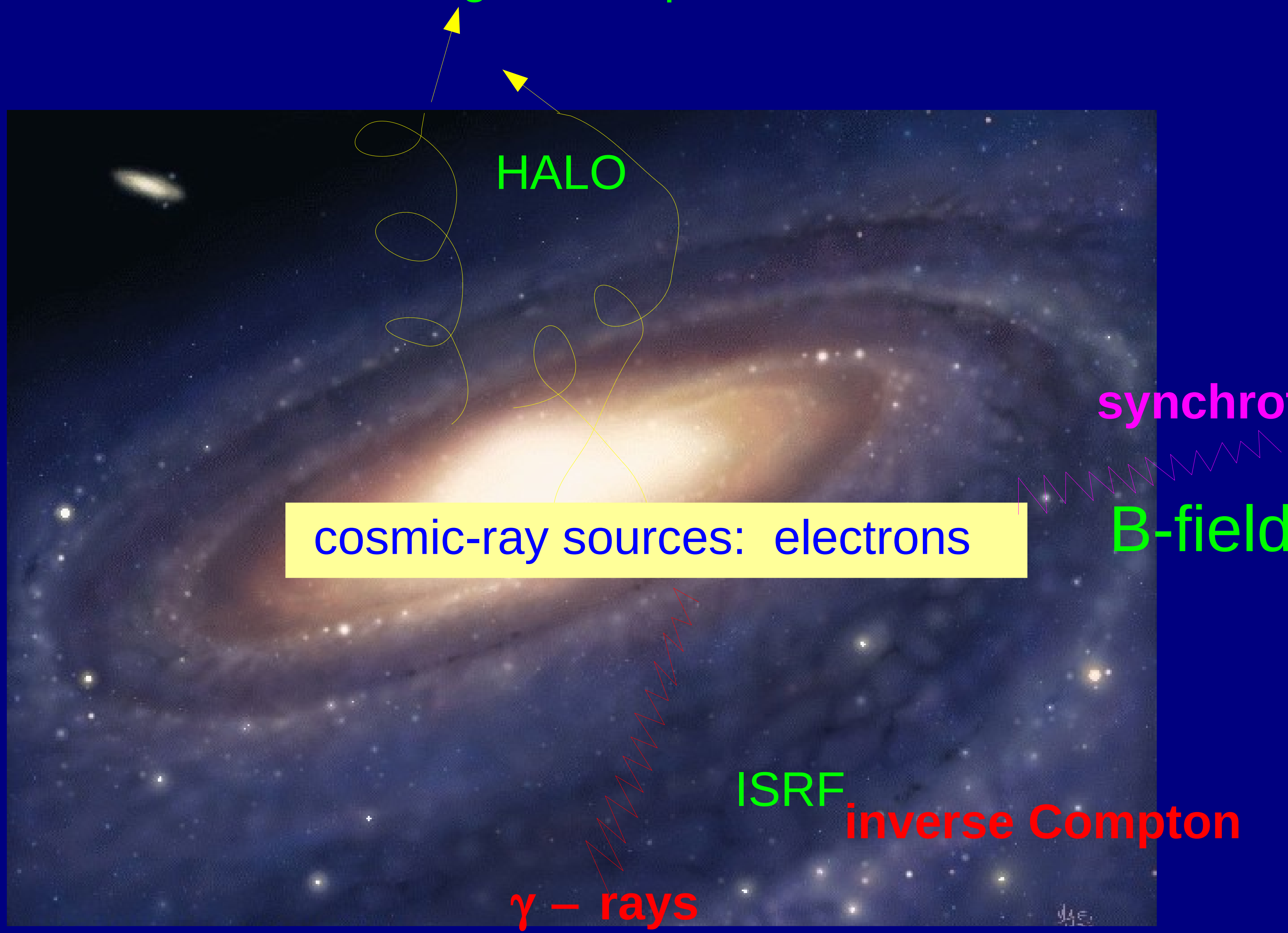
Synchrotron in high-energy context

Spectral aspects

Polarization, magnetic fields

Gamma rays

High energy particles and radiation in the Galaxy



intergalactic space

HALO

synchrotron

cosmic-ray sources: electrons

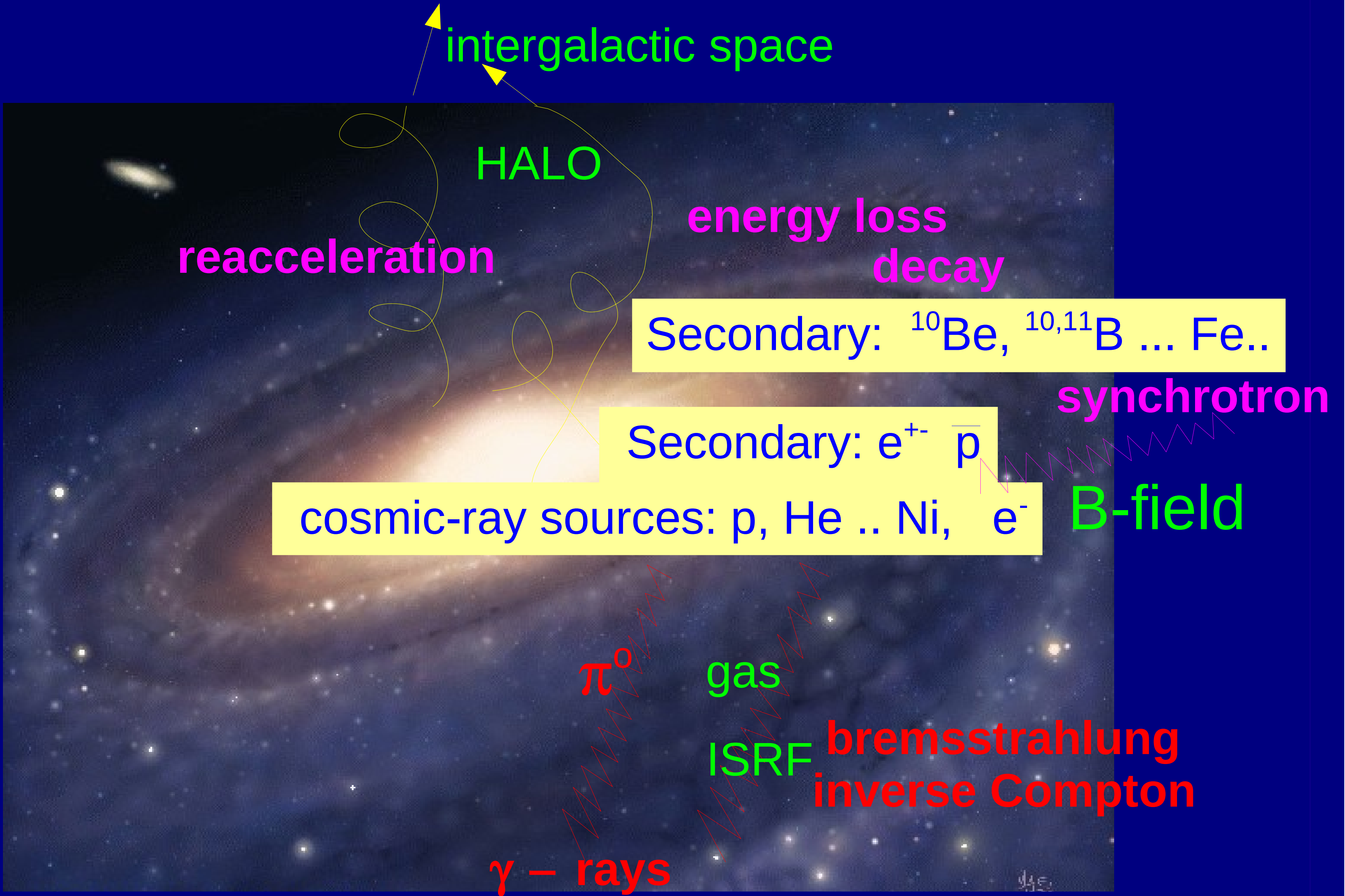
B-field

ISRF

inverse Compton

γ – rays

COSMIC RAYS produce many observables



intergalactic space

HALO

reacceleration

energy loss

decay

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

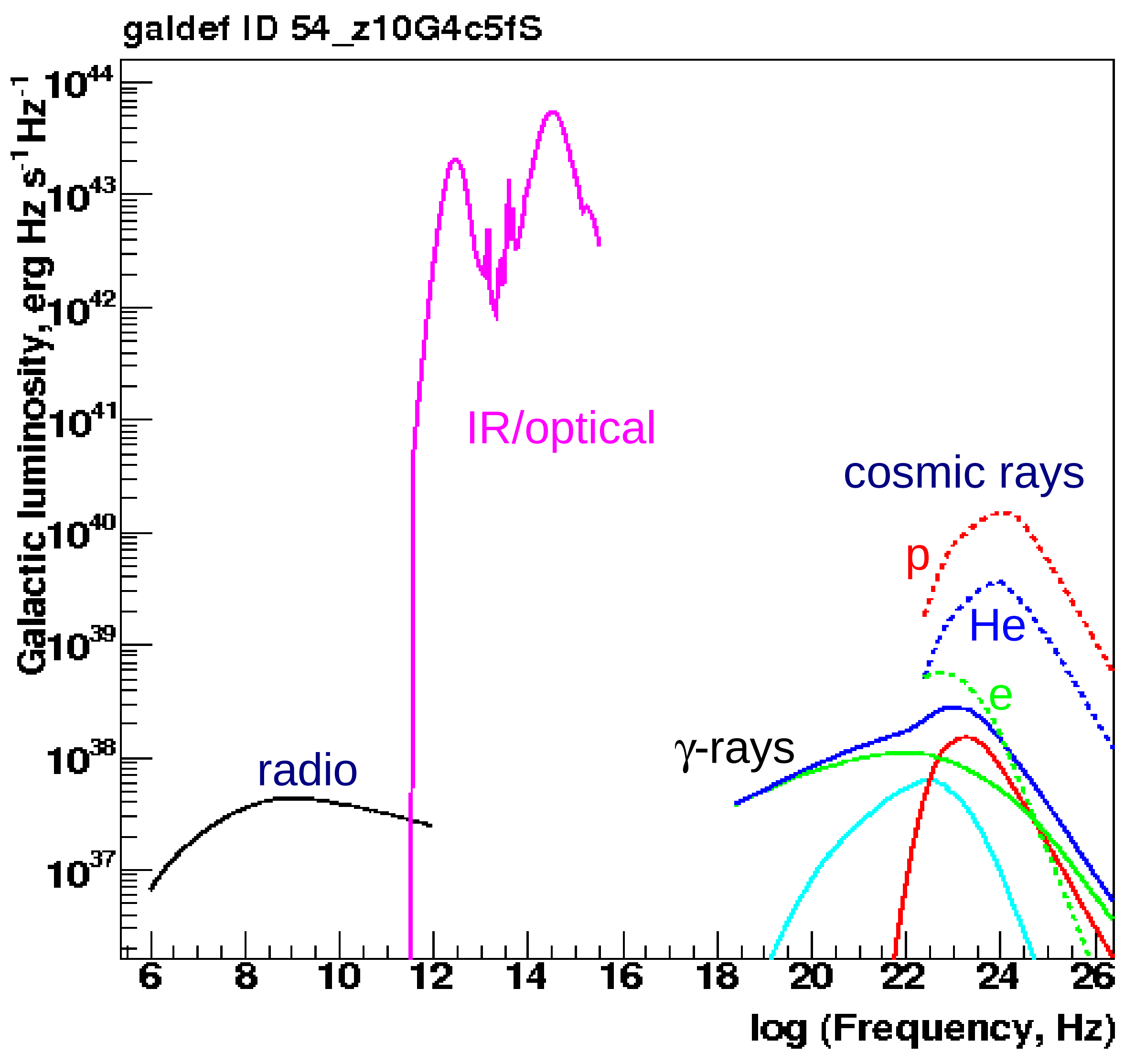
bremsstrahlung

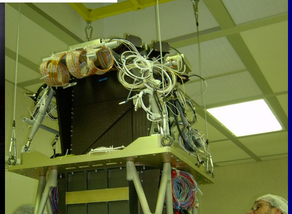
inverse Compton

γ – rays

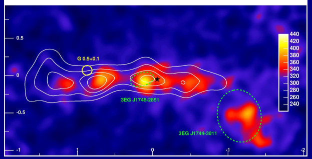
GALPROP model

Galaxy luminosity over 20 decades of energy

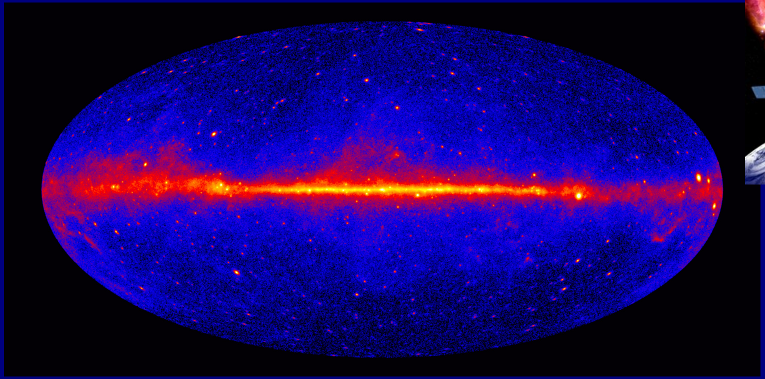




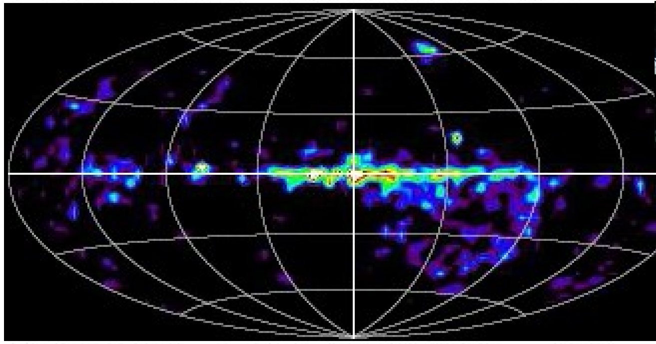
TeV

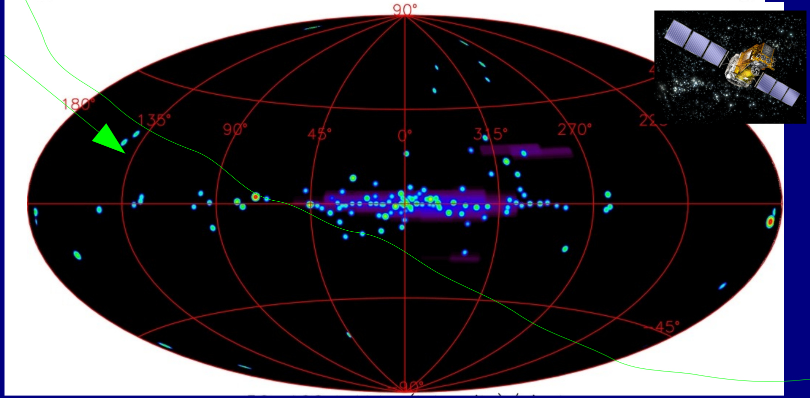


GeV

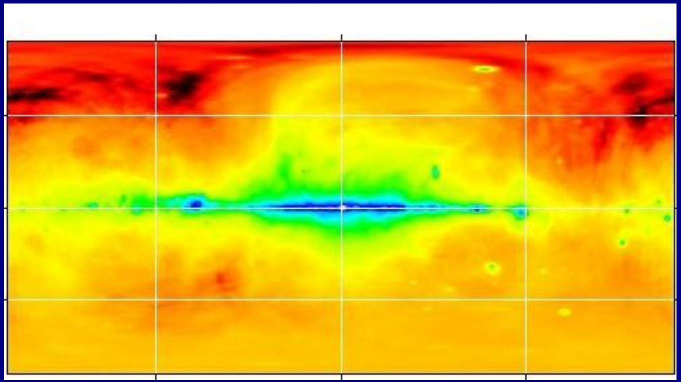


MeV





Cosmic-ray interactions
probed
by their photon emission



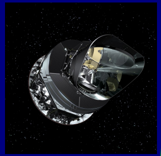
µeV

GHz

The Planck one-year all-sky survey

esa

(c) ESA, HFI and LFI consortia, July 2010



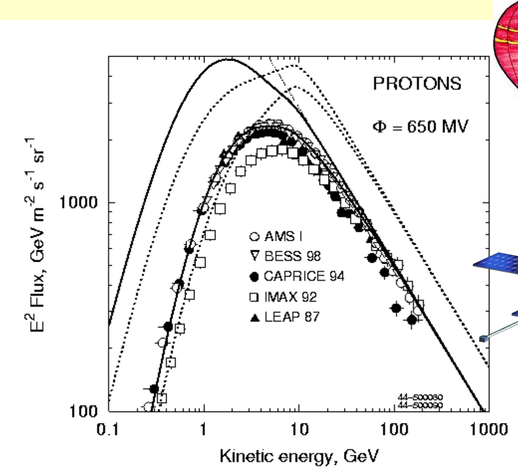
meV

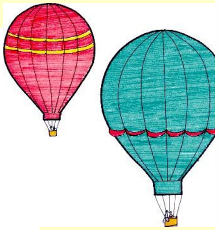
THz

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...

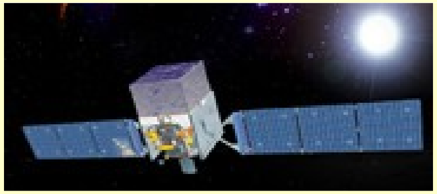


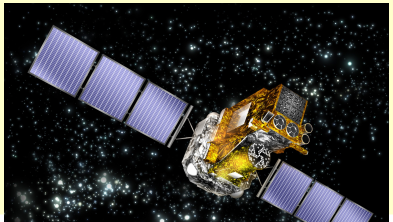


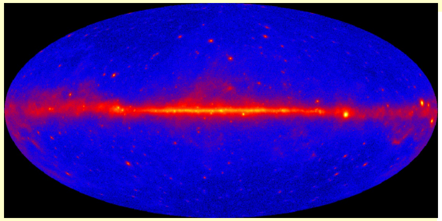
Victor Hess before his 1912 balloon
in Austria, during which he discove
cosmic rays

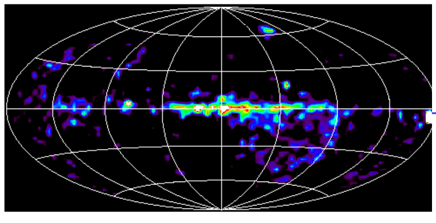
Observed *from whole Galaxy:*

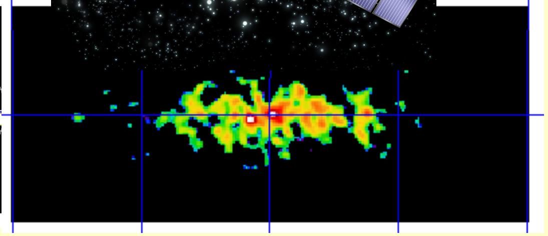
γ - rays



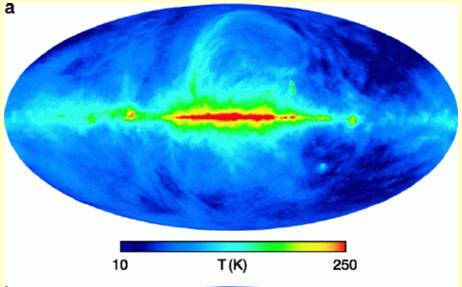








synchrotron



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

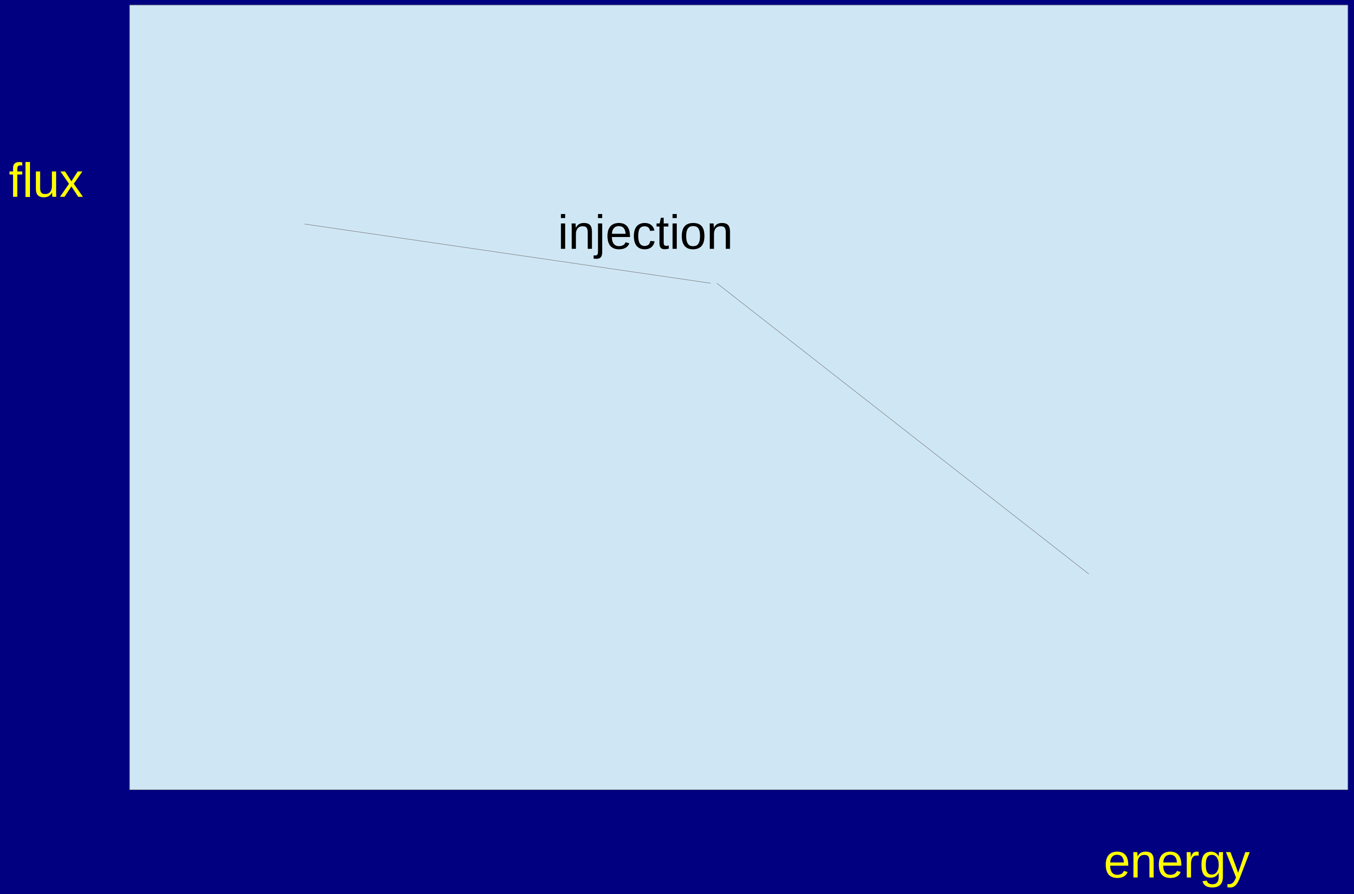
ionization, bremsstrahlung

adiabatic momentum loss

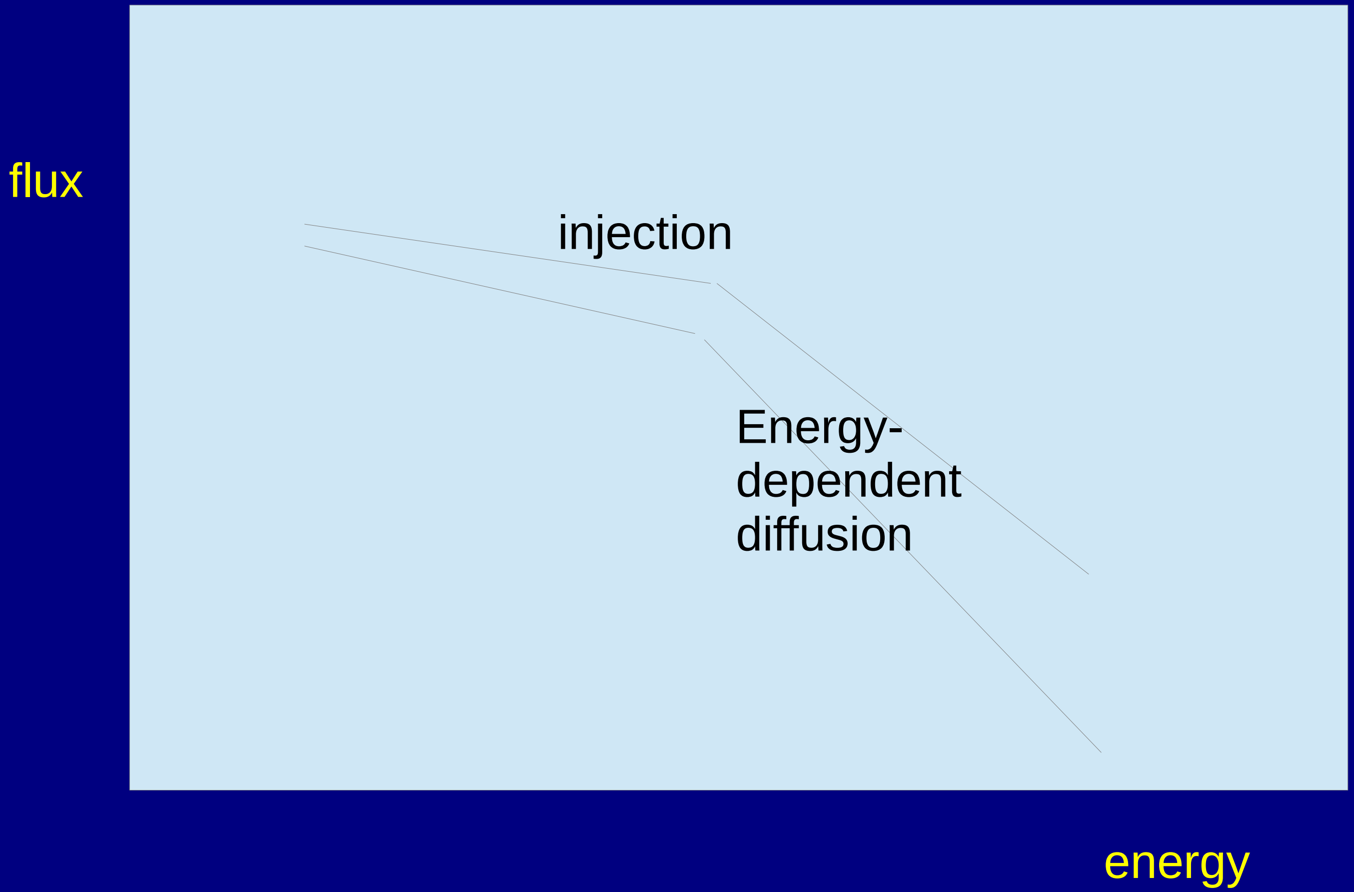
$- \psi/\tau_f$ nuclear fragmentation

$- \psi/\tau_r$ radioactive decay

Producing the cosmic-ray electron spectrum



Producing the cosmic-ray electron spectrum



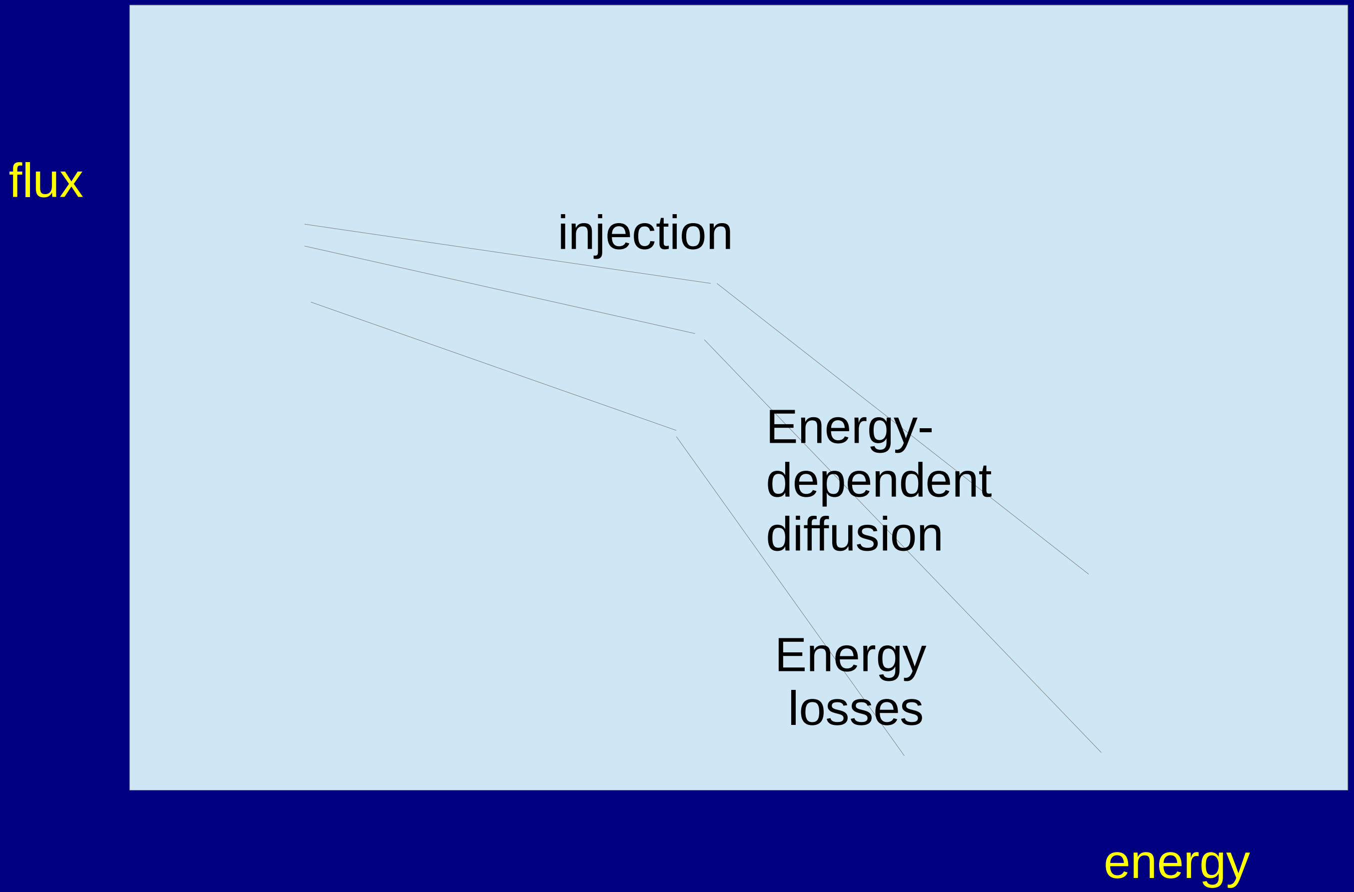
flux

injection

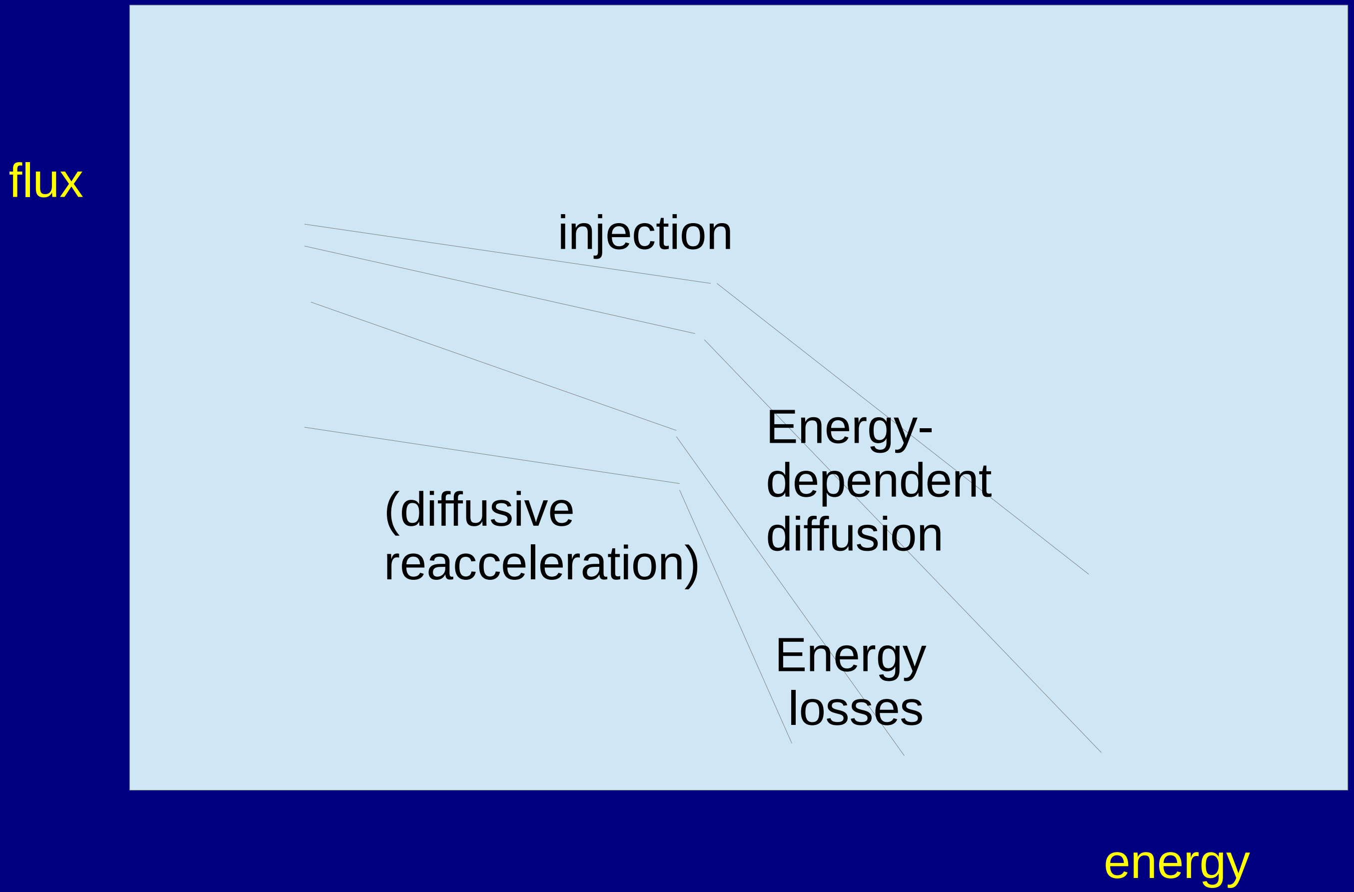
Energy-
dependent
diffusion

energy

Producing the cosmic-ray electron spectrum



Producing the cosmic-ray electron spectrum



flux

injection

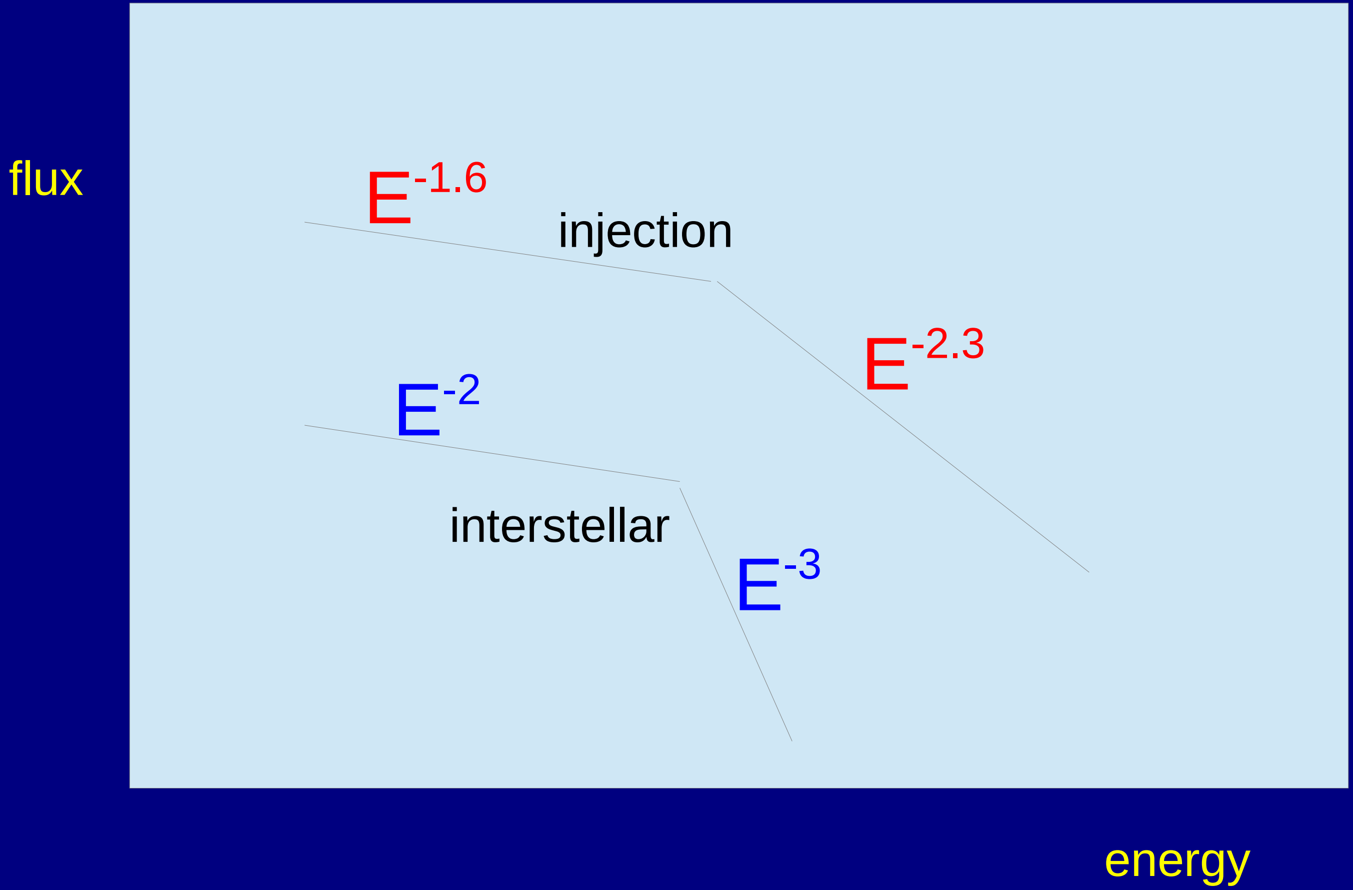
Energy-
dependent
diffusion

(diffusive
reacceleration)

Energy
losses

energy

Producing the cosmic-ray electron spectrum



flux

$E^{-1.6}$

injection

$E^{-2.3}$

E^{-2}

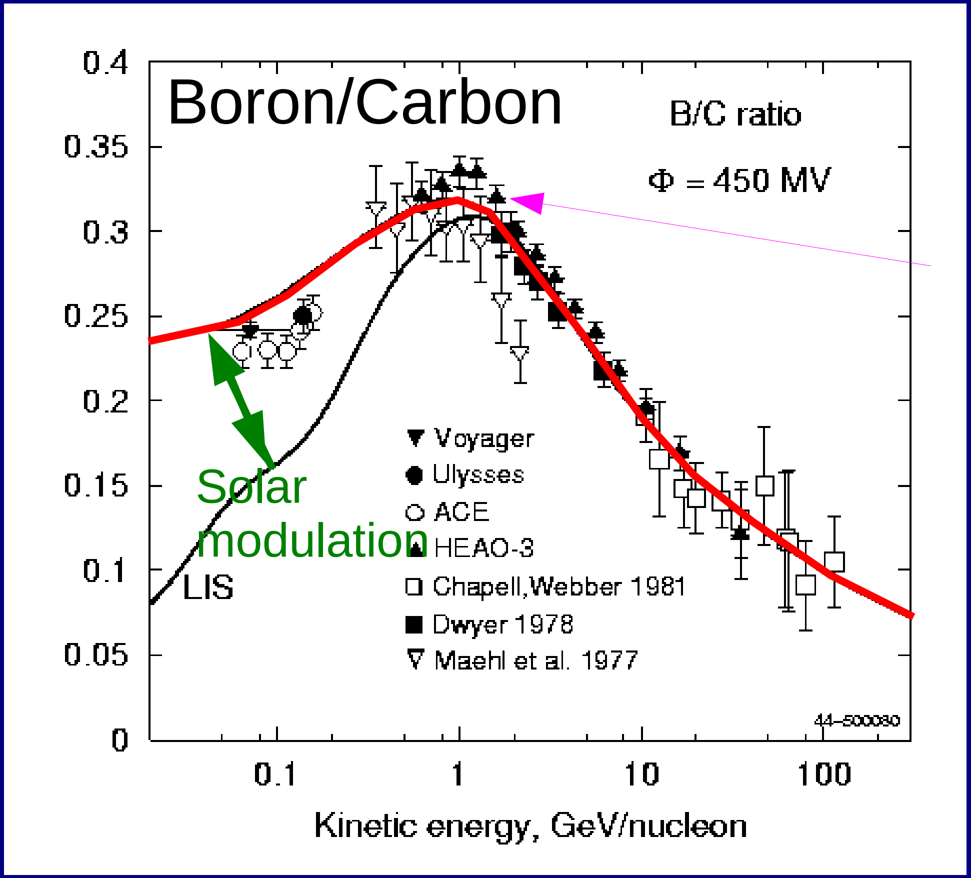
interstellar

E^{-3}

energy

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

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

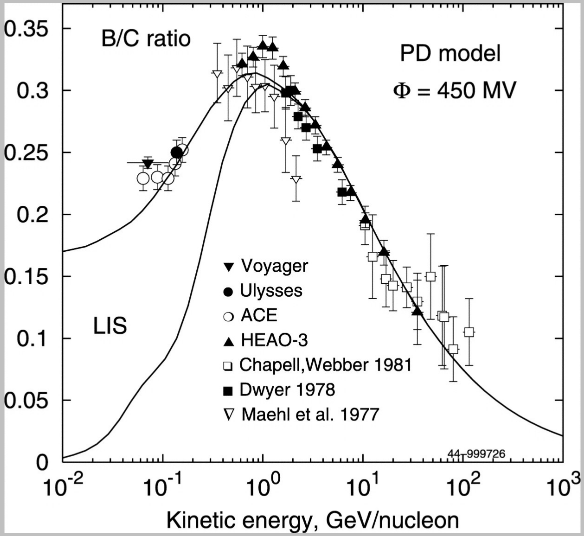
Momentum space diffusion

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

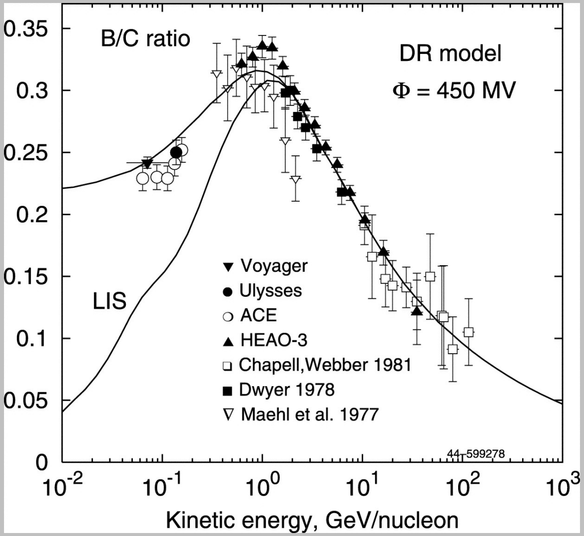
However reacceleration not proven, maybe does not happen

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

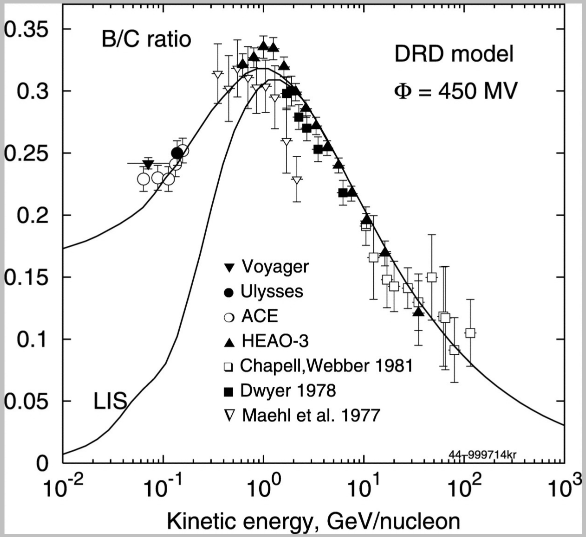
plain diffusion



diffusive reacceleration



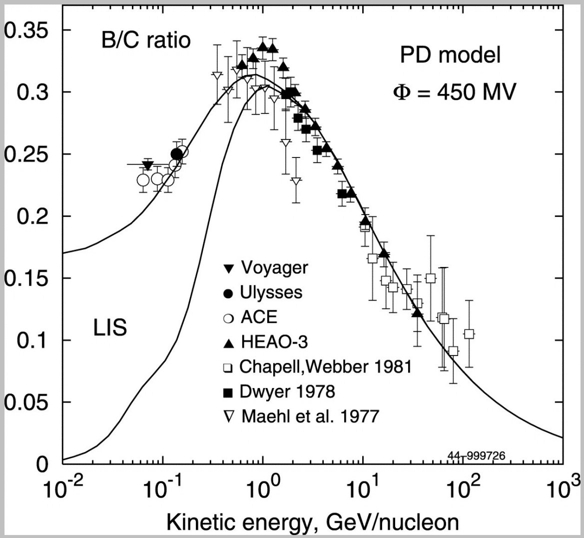
wave damping



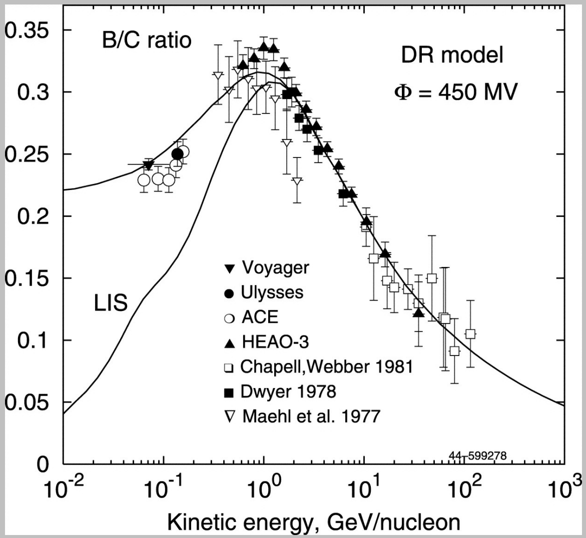
For any model, first adjust parameters to fit Boron/Carbon

Ptuskin et al. 2006 ApJ 642, 902

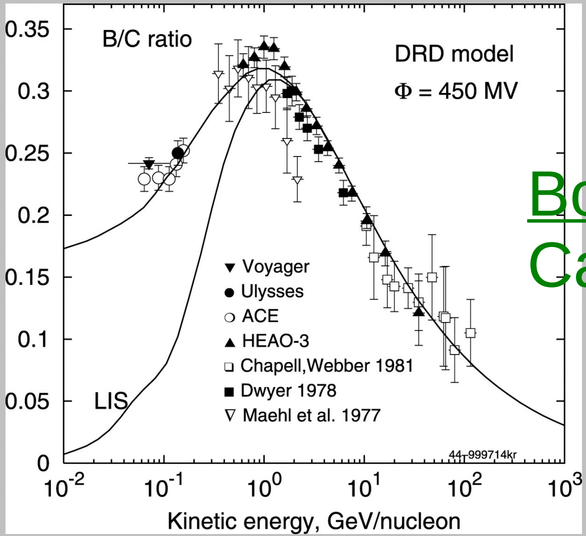
plain diffusion



diffusive reacceleration



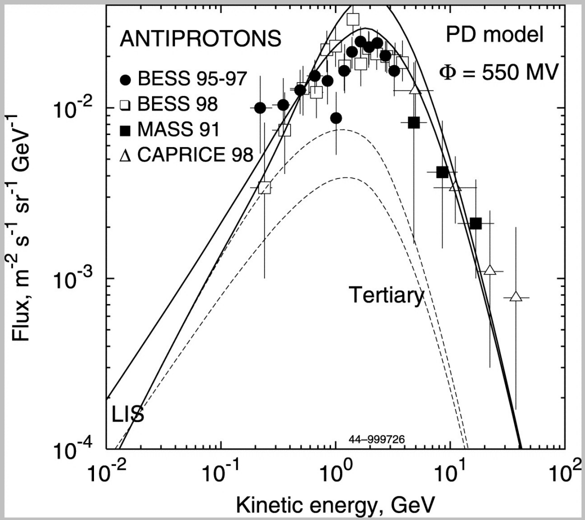
wave damping

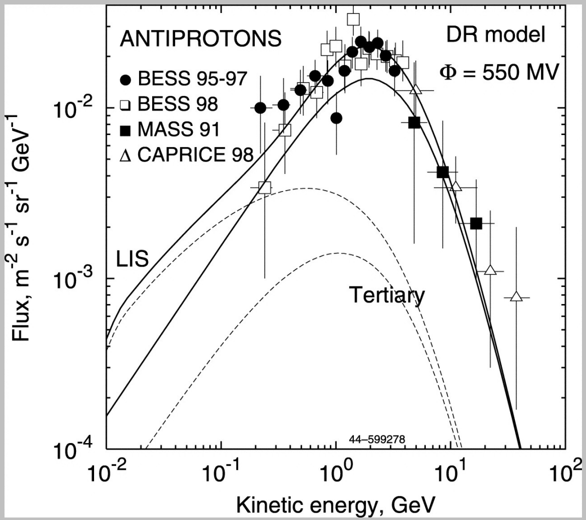


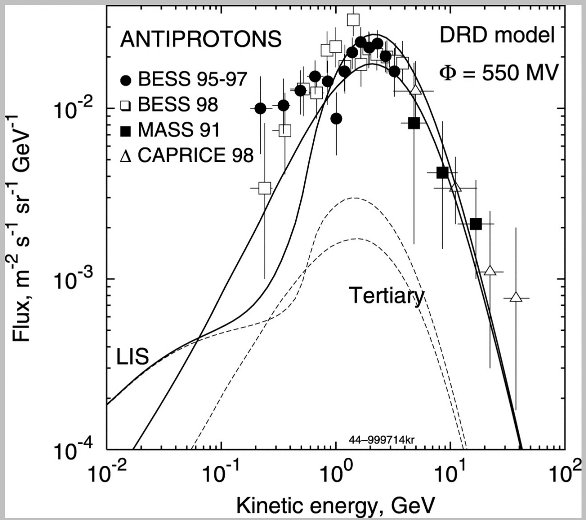
Boron/
Carbon

then predict the other cosmic-ray spectra

antiprotons

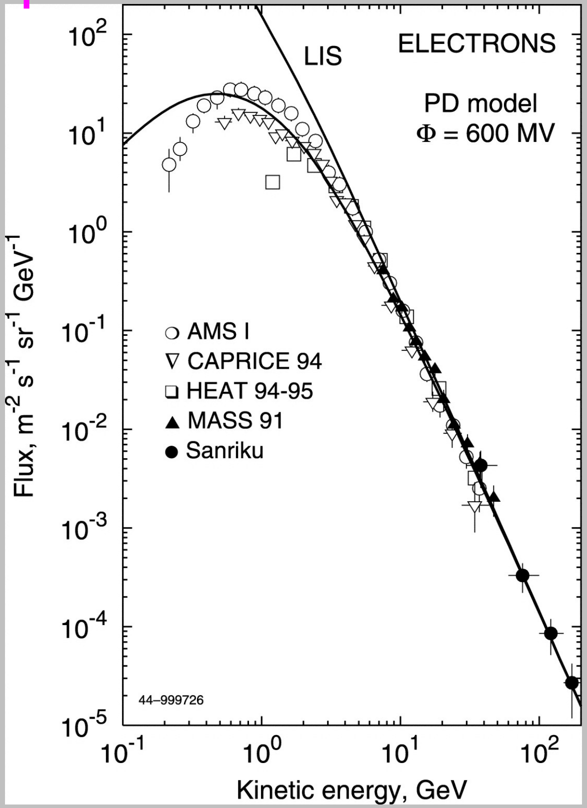


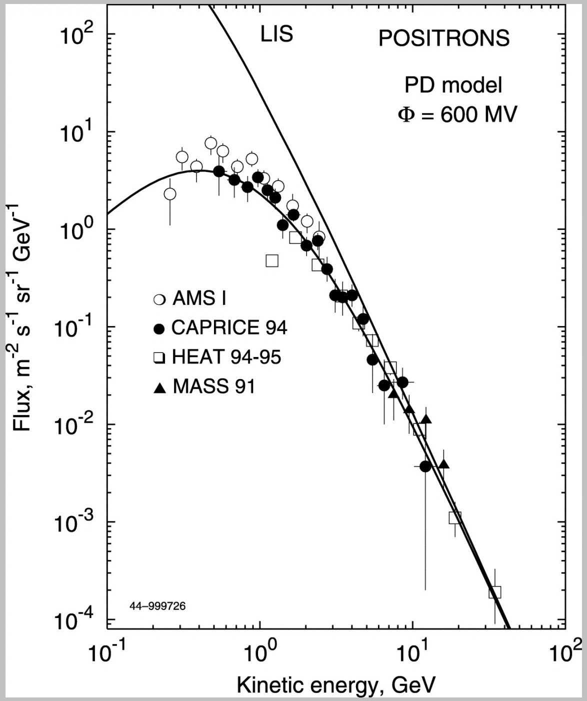




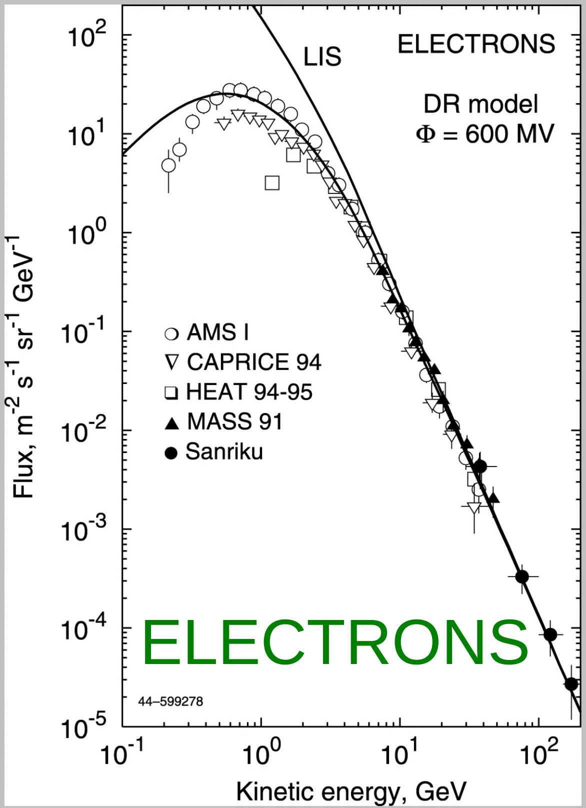
Ptuskin et al. 2006 ApJ 642, 902

plain diffusion

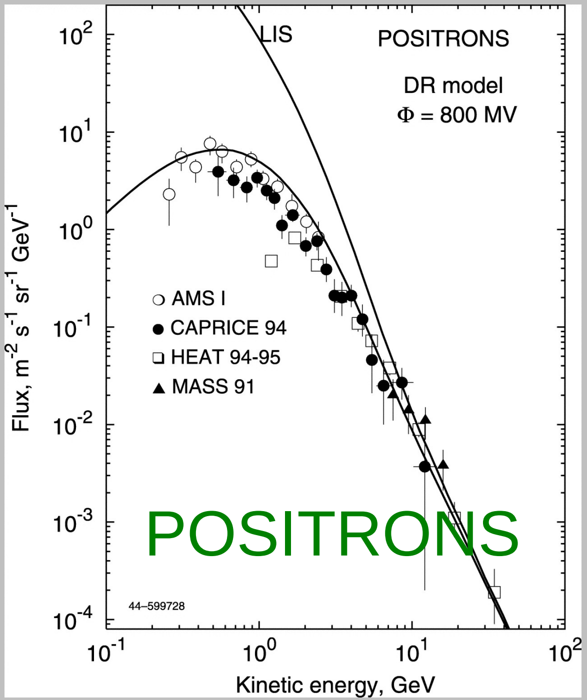




diffusive reacceleration

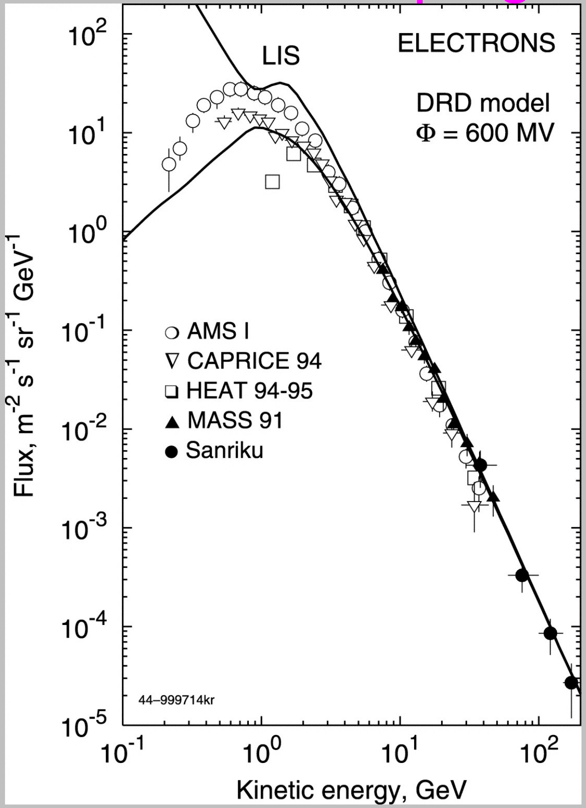


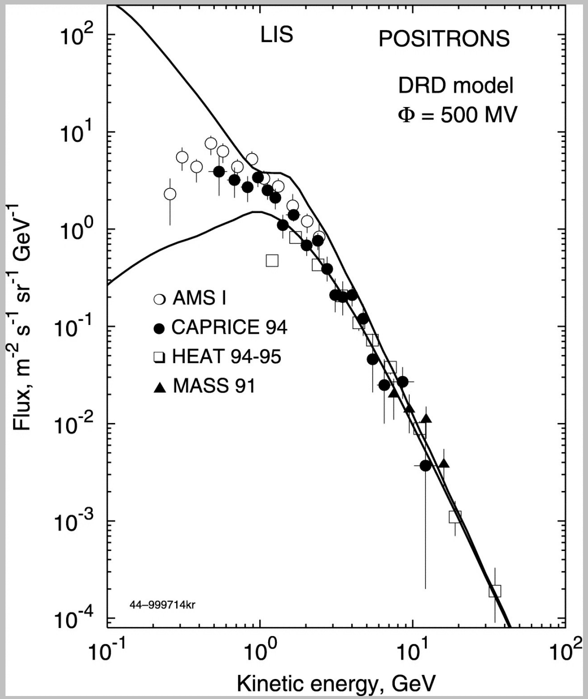
ELECTRONS

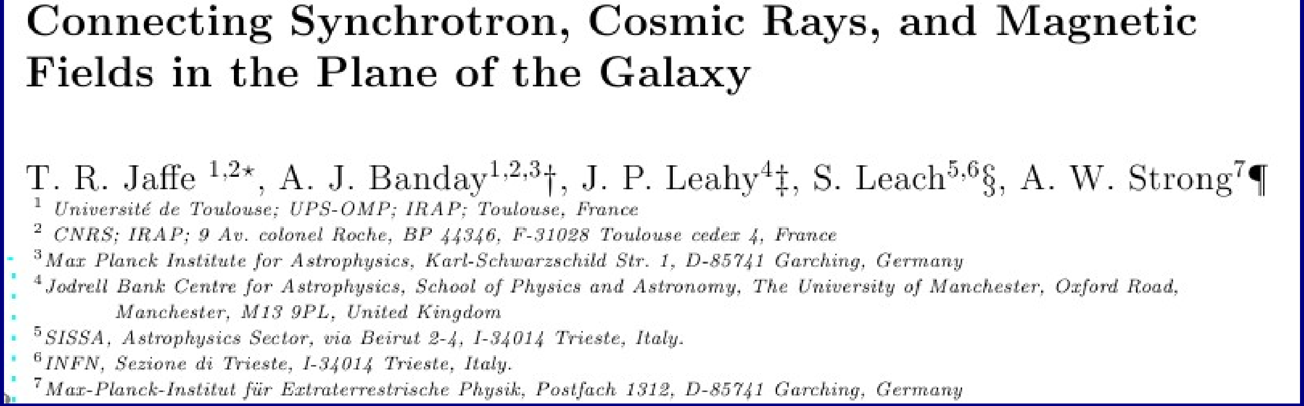


POSITRONS

wave damping







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

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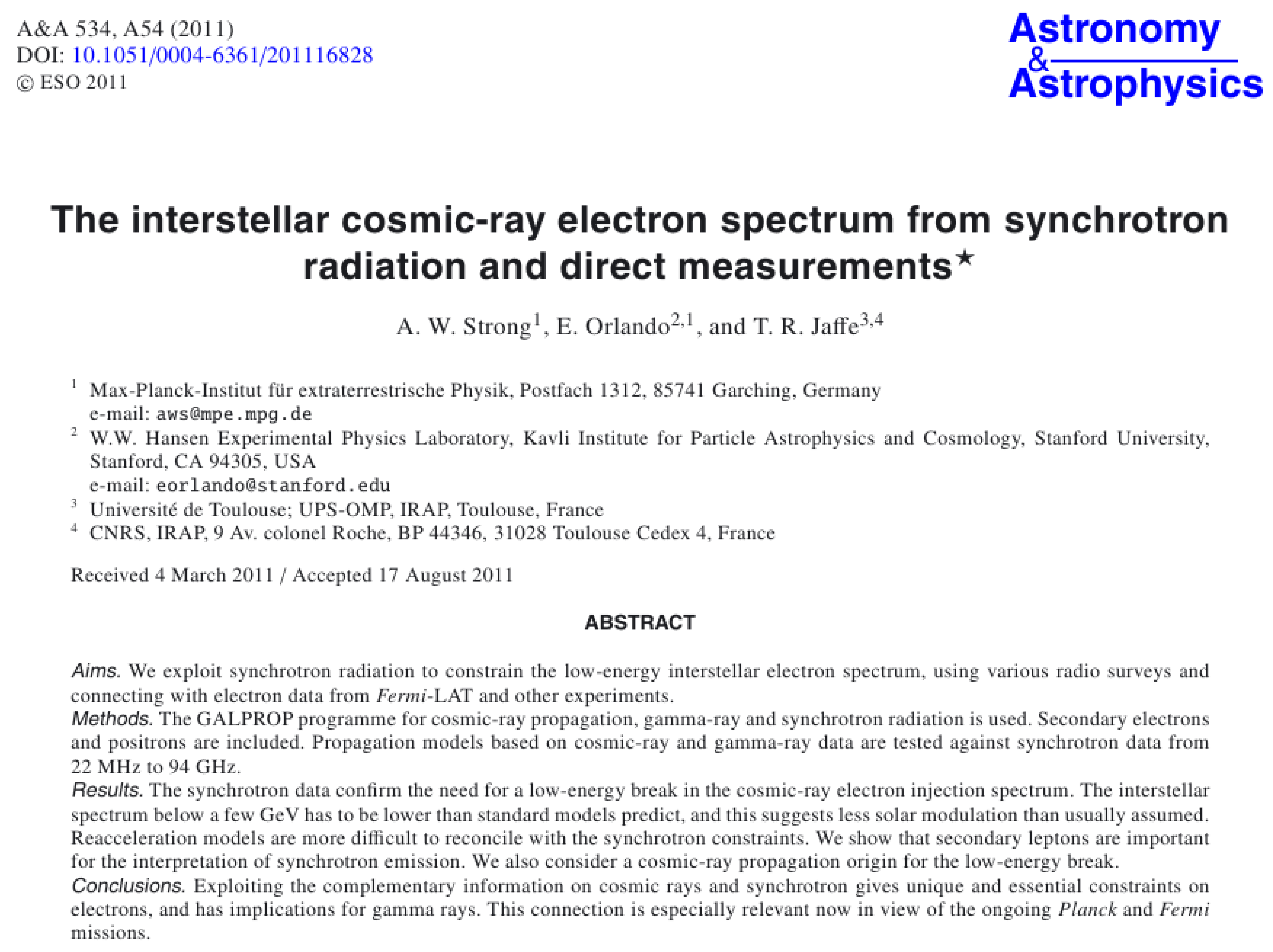
MNRAS 416, 1152 (2011)

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



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

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

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ABSTRACT

Aims. We exploit synchrotron radiation to constrain the low-energy interstellar electron spectrum, using various radio surveys and connecting with electron data from *Fermi*-LAT and other experiments.

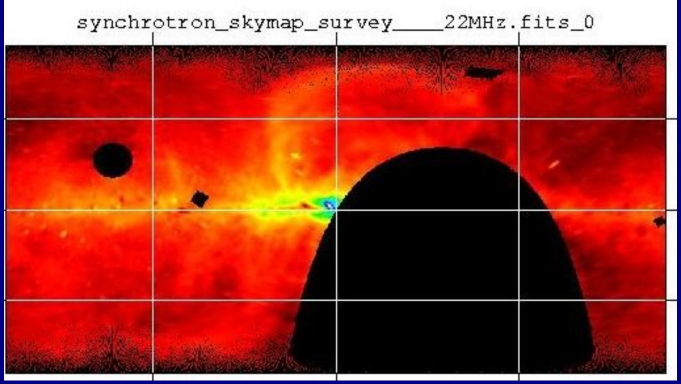
Methods. The GALPROP programme for cosmic-ray propagation, gamma-ray and synchrotron radiation is used. Secondary electrons and positrons are included. Propagation models based on cosmic-ray and gamma-ray data are tested against synchrotron data from 22 MHz to 94 GHz.

Results. The synchrotron data confirm the need for a low-energy break in the cosmic-ray electron injection spectrum. The interstellar spectrum below a few GeV has to be lower than standard models predict, and this suggests less solar modulation than usually assumed. Reacceleration models are more difficult to reconcile with the synchrotron constraints. We show that secondary leptons are important for the interpretation of synchrotron emission. We also consider a cosmic-ray propagation origin for the low-energy break.

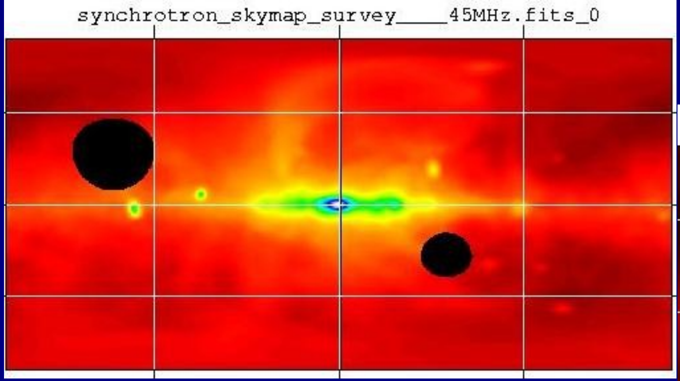
Conclusions. Exploiting the complementary information on cosmic rays and synchrotron gives unique and essential constraints on electrons, and has implications for gamma rays. This connection is especially relevant now in view of the ongoing *Planck* and *Fermi* missions.

Following results based on this paper.

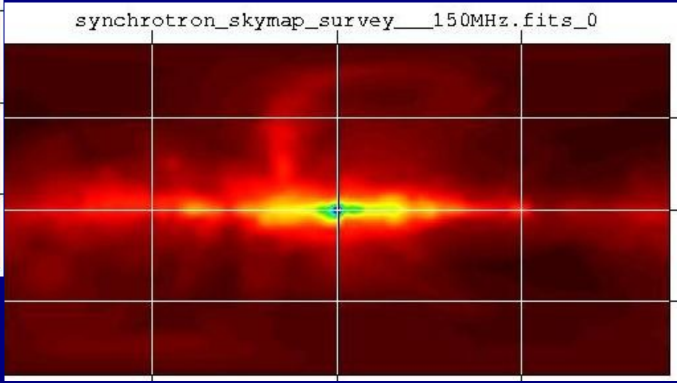
Continuum sky surveys



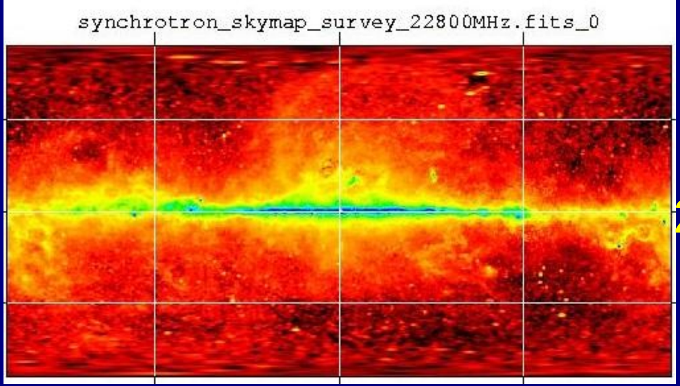
22 MHz



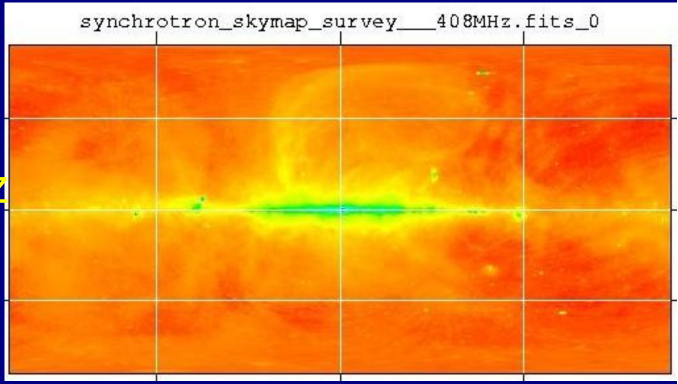
45 MHz



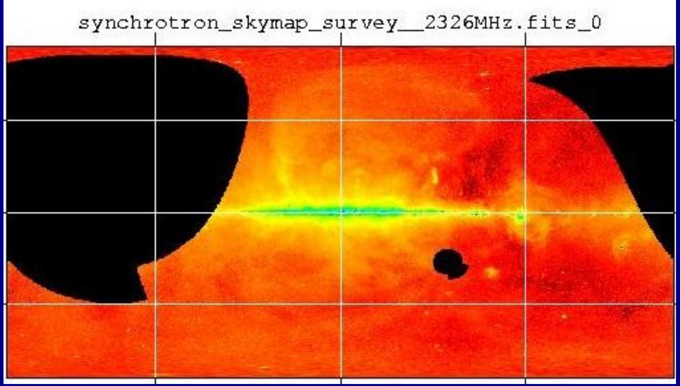
150 MHz



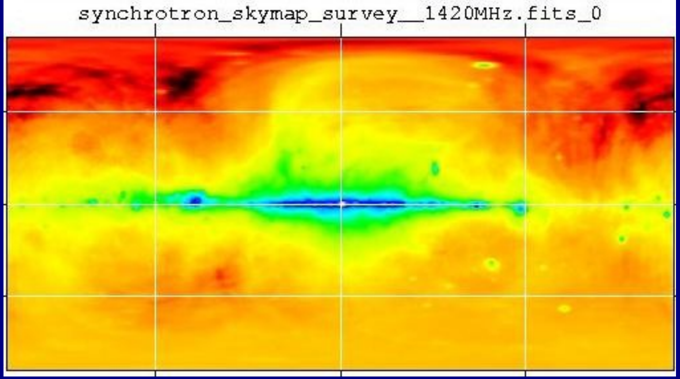
23 GHz



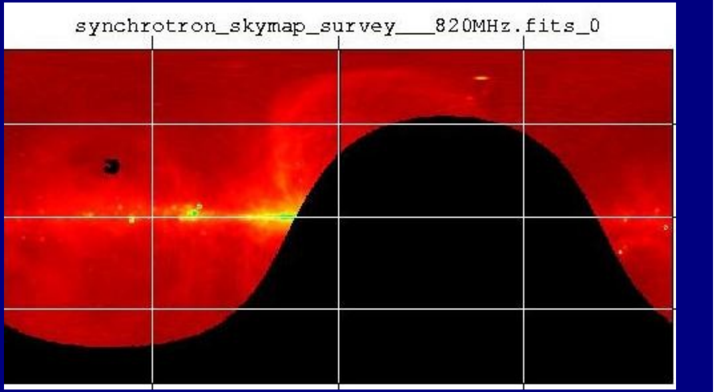
408 MHz



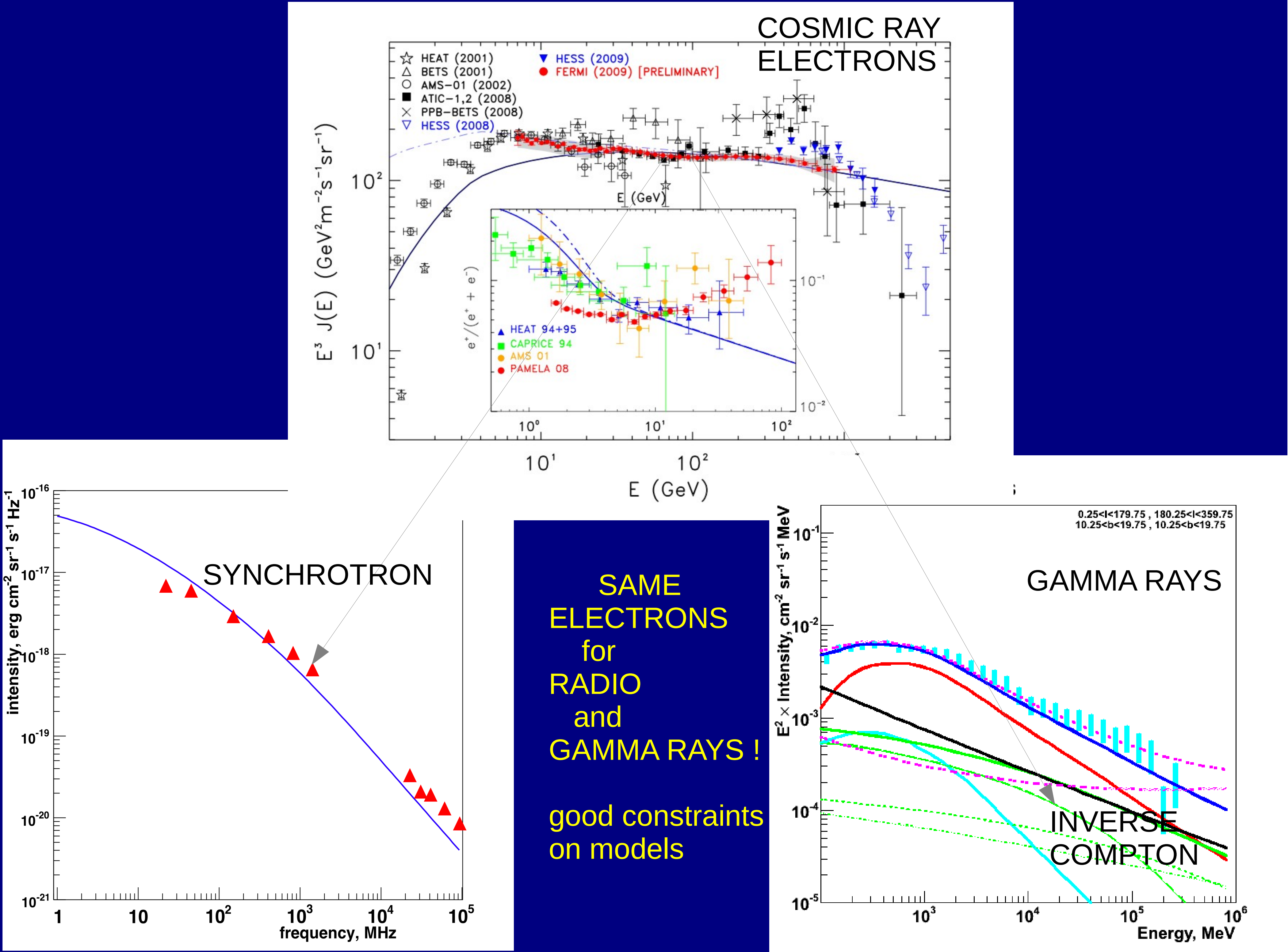
2.3 GHz



1.4 GHz

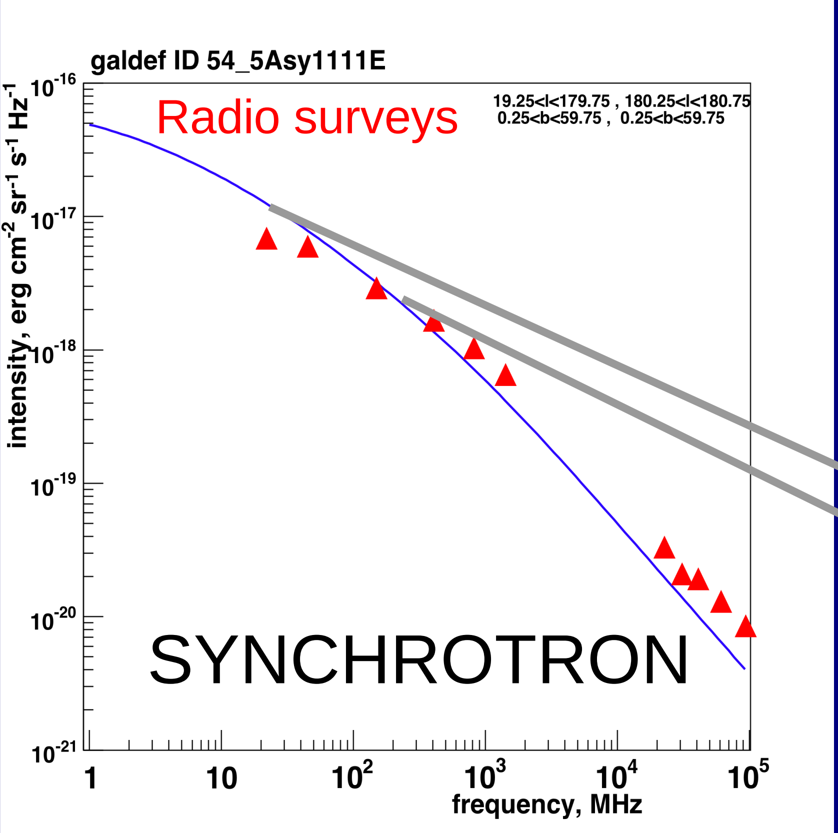


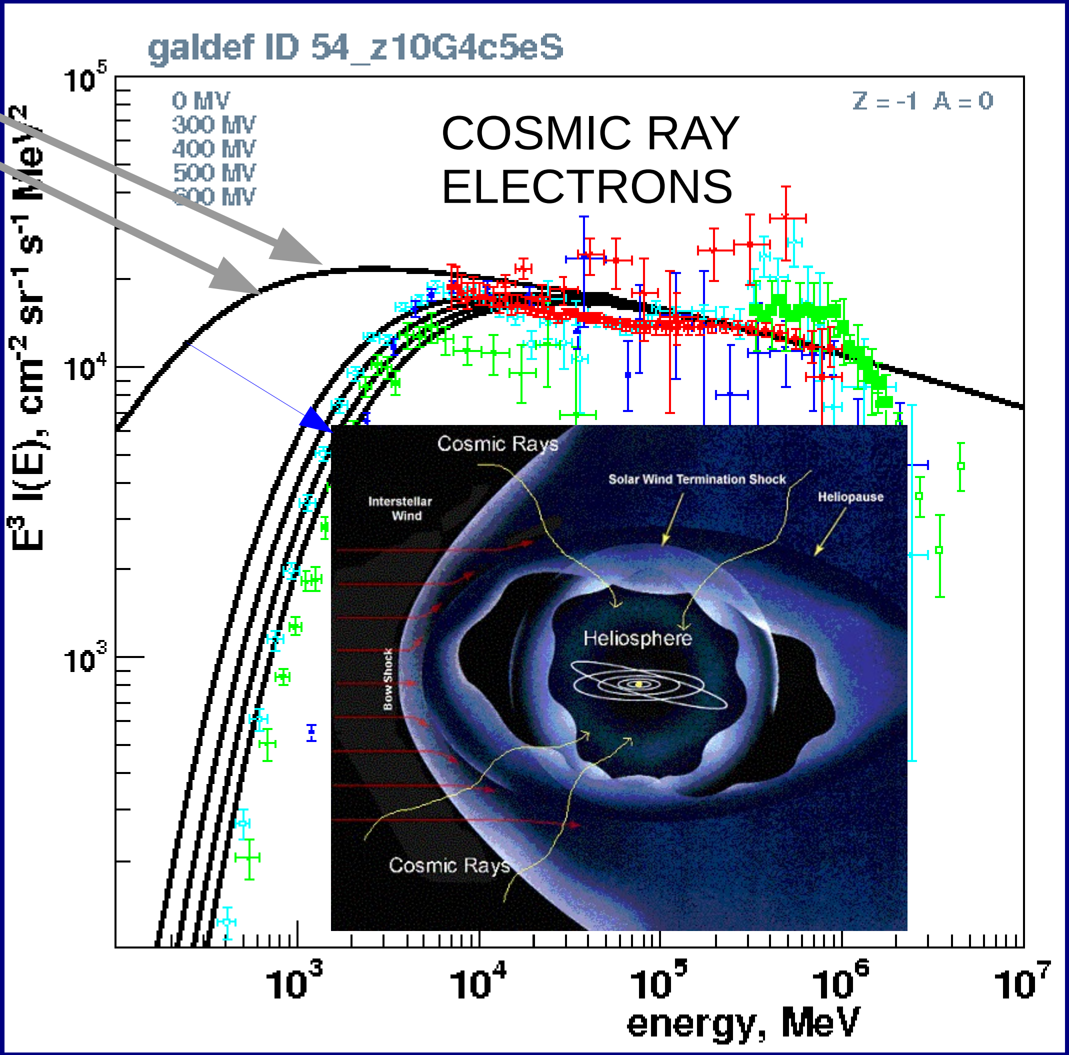
820 MHz



SAME ELECTRONS
for
RADIO
and
GAMMA RAYS !

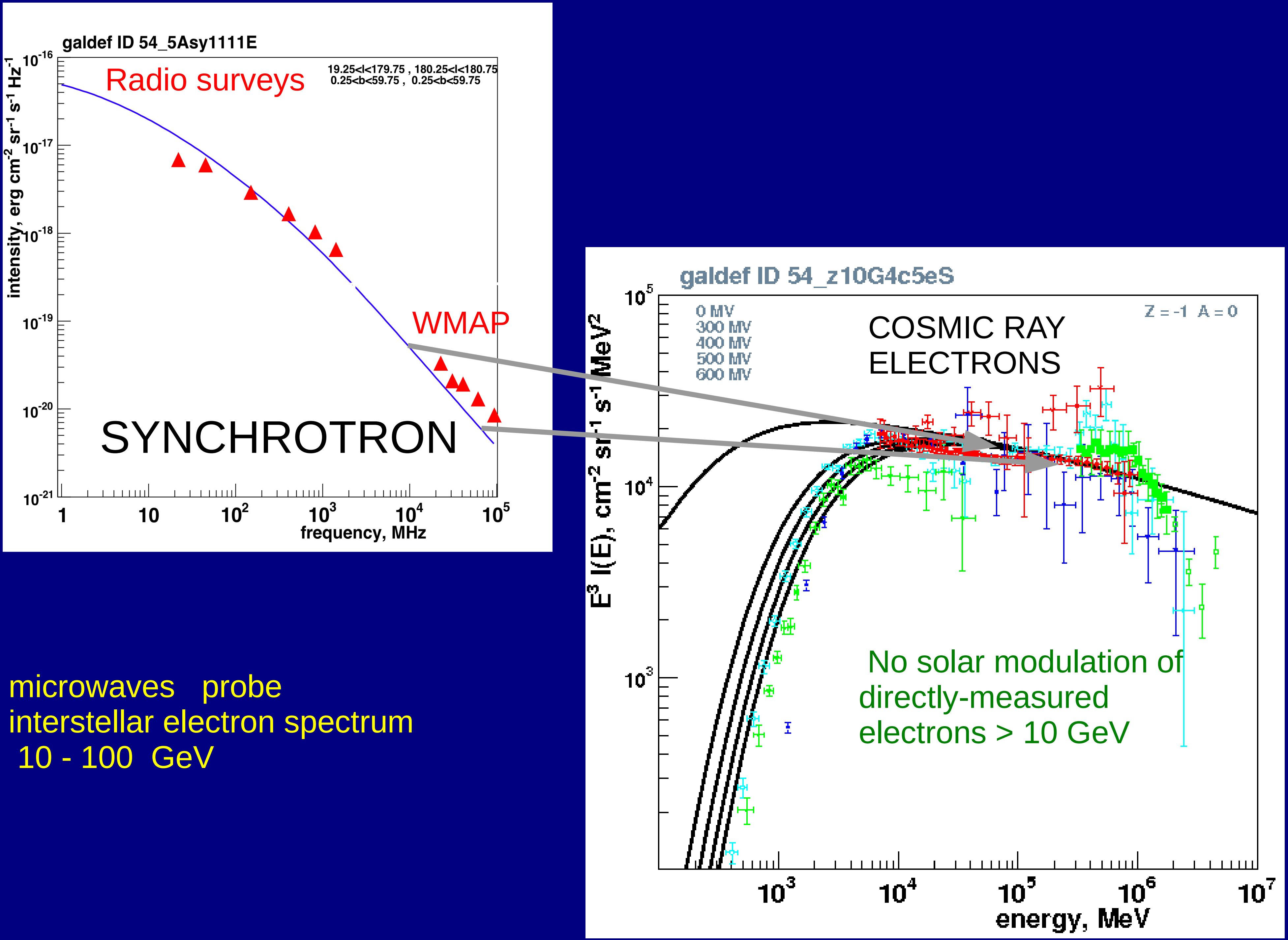
good constraints
on models





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



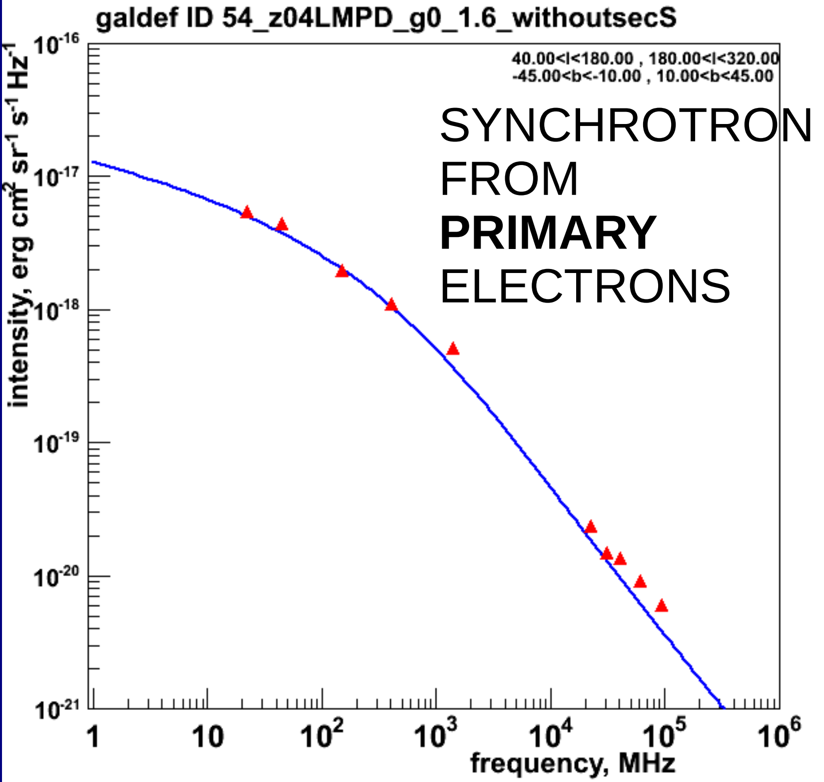
SYNCHROTRON

COSMIC RAY ELECTRONS

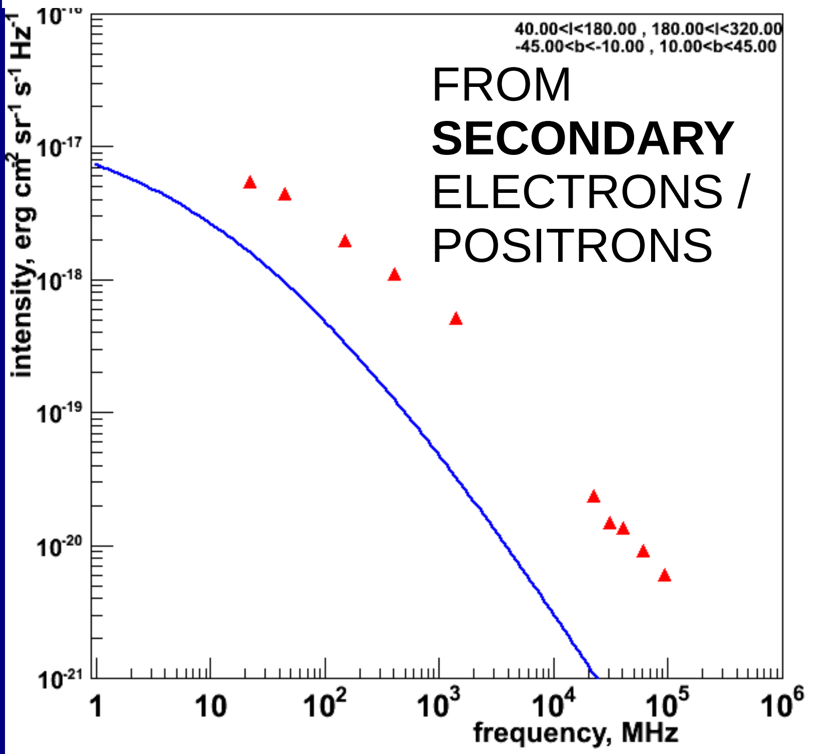
No solar modulation of directly-measured electrons > 10 GeV

microwaves probe interstellar electron spectrum 10 - 100 GeV

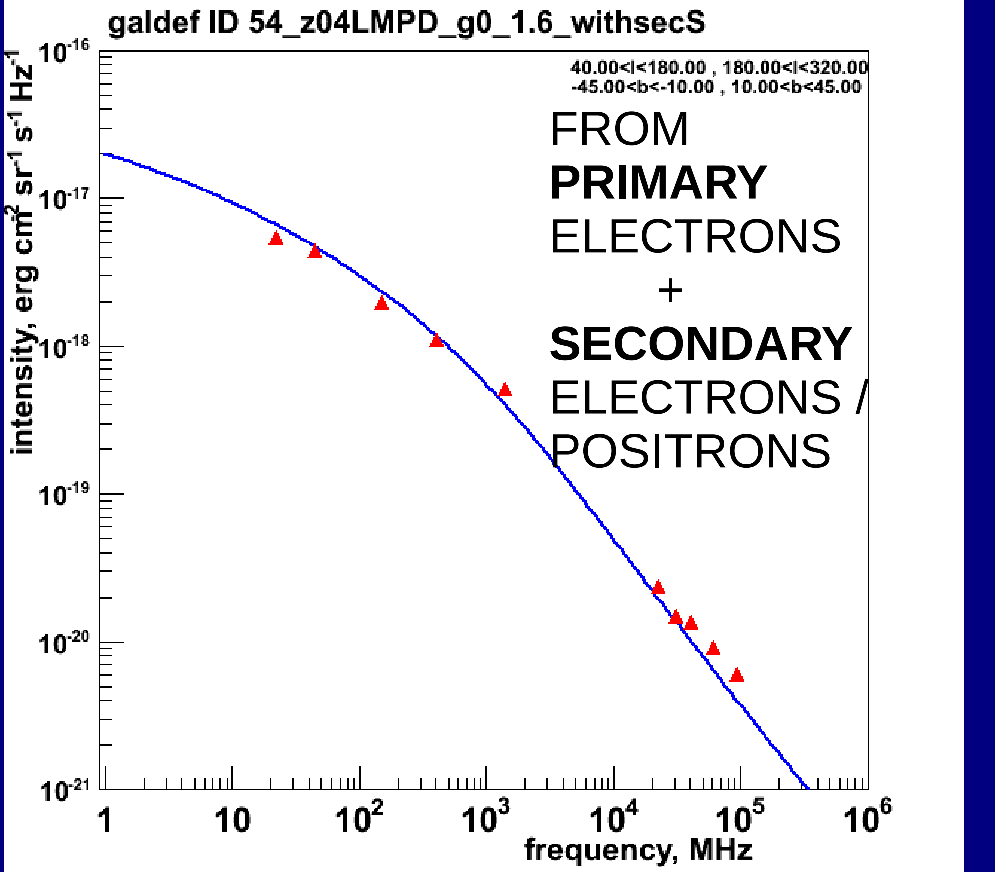
Secondary positrons
(and secondary electrons)
are important for synchrotron !



SYNCHROTRON
FROM
PRIMARY
ELECTRONS



FROM
SECONDARY
ELECTRONS /
POSITRONS



FROM
PRIMARY
ELECTRONS
+
SECONDARY
ELECTRONS /
POSITRONS

Cosmic-ray electrons

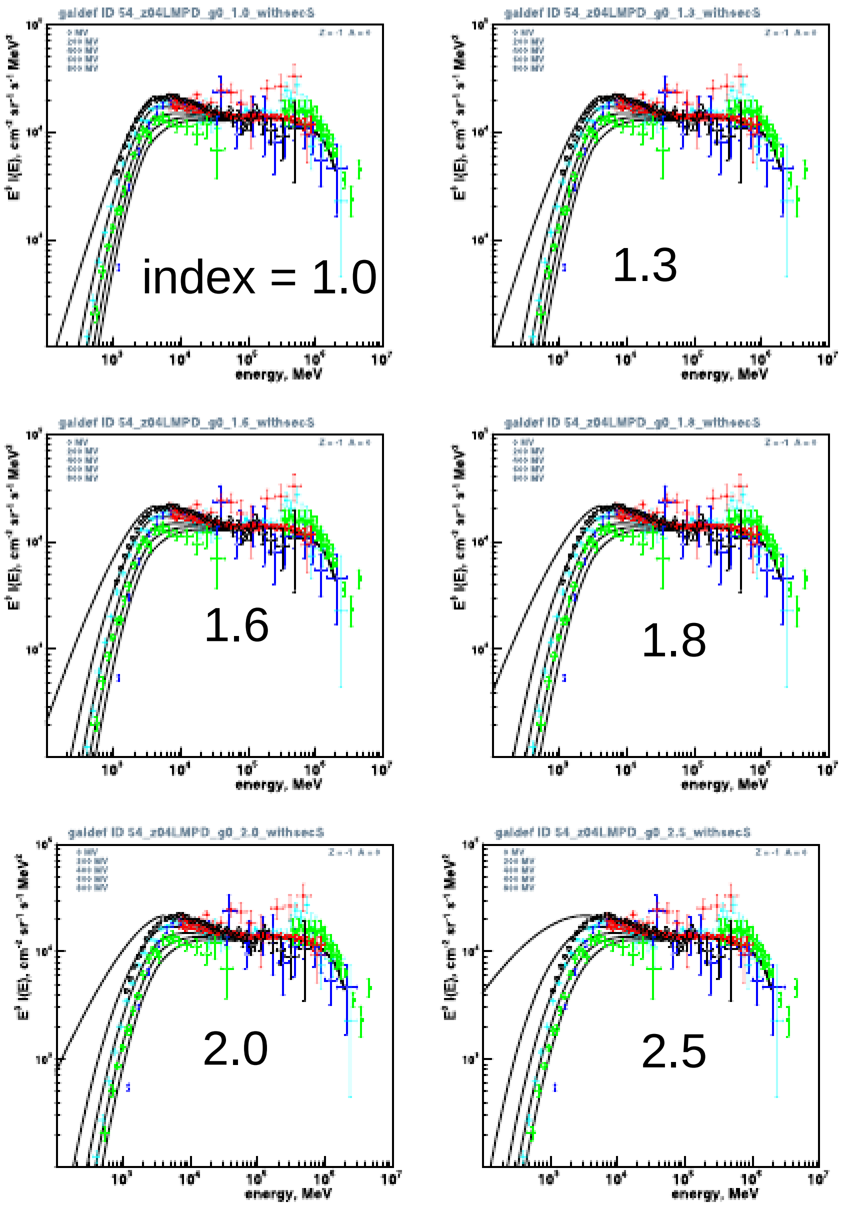


Fig. 4. Electron spectra for pure diffusion model, low-energy electron injection index 1.0, 1.3, 1.6, 1.8, 2.0, 2.5. Modulation Φ = 0, 200, 400, 600, 800 MV. Data as in Fig. 1.

Synchrotron

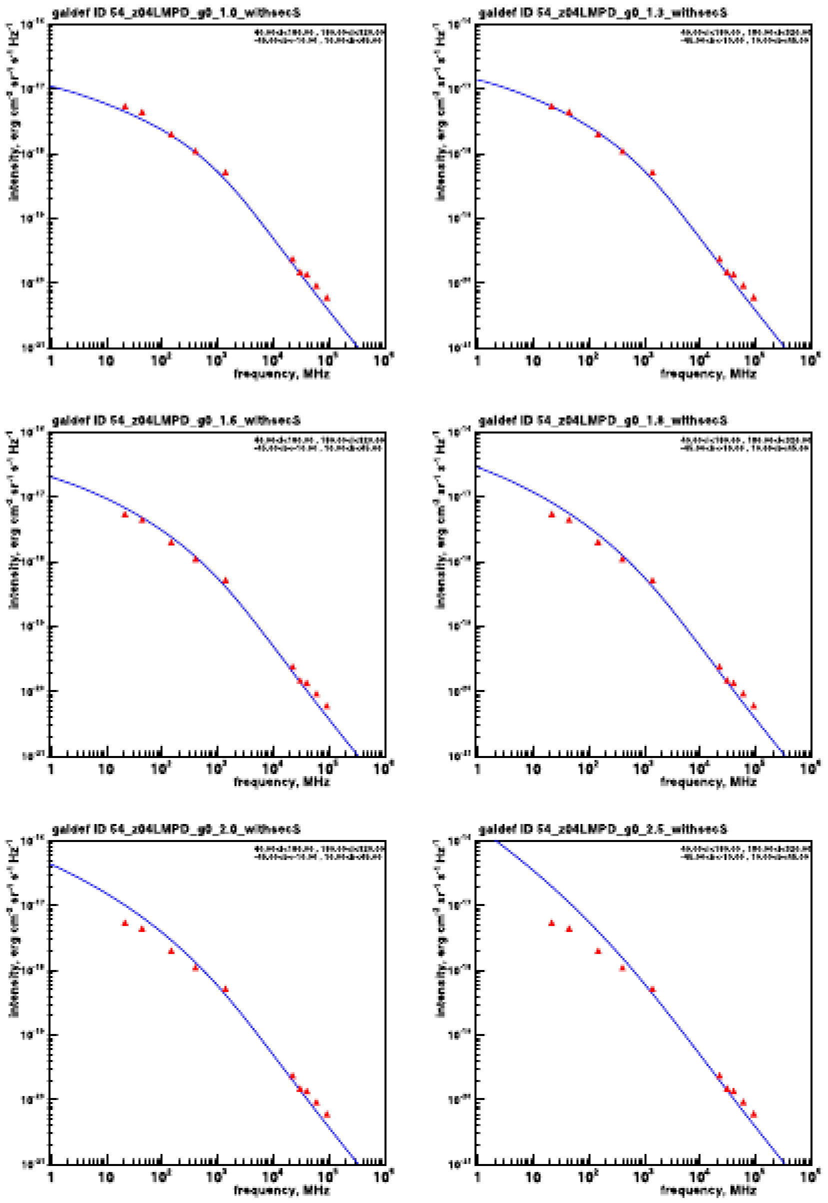


Fig. 5. Synchrotron spectra for pure diffusion model with low-energy electron injection index (*left to right, top to bottom*) 1.0, 1.3, 1.6, 1.8, 2.0, 2.5. Including secondary leptons. Data as in Fig. 2.

Effect of electron injection spectral index

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

Galactic Synchrotron Spectral Index

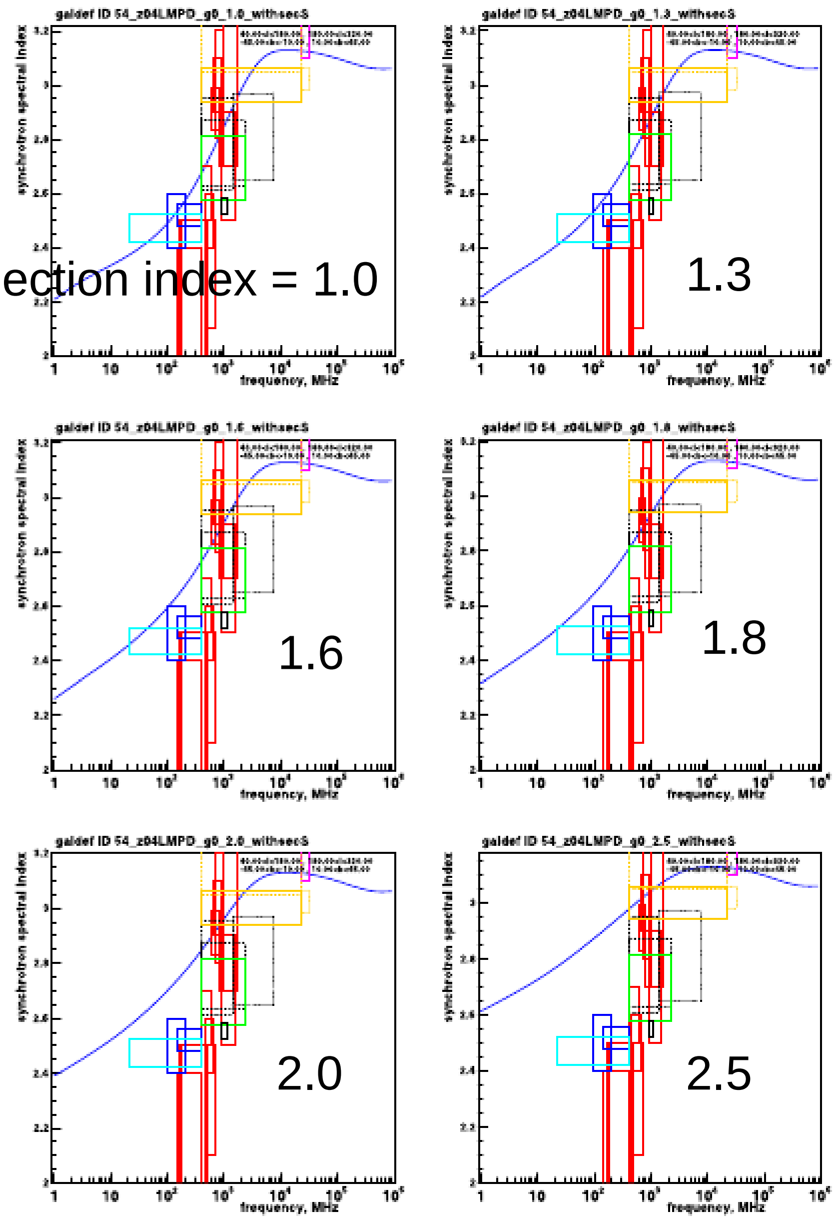


Fig. 6. Synchrotron spectral index for pure diffusion model with low-energy electron injection index (*left to right, top to bottom*) 1.0, 1.3, 1.6, 1.8, 2.0, 2.5. Including secondary leptons. Experimental ranges are based on the references reviewed in Sect. 4.1, and are intended to be representative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

Effect of electron injection spectral index

Strong, Orlando & Jaffe (2011)

Galactic
Synchrotron
Spectral
Index

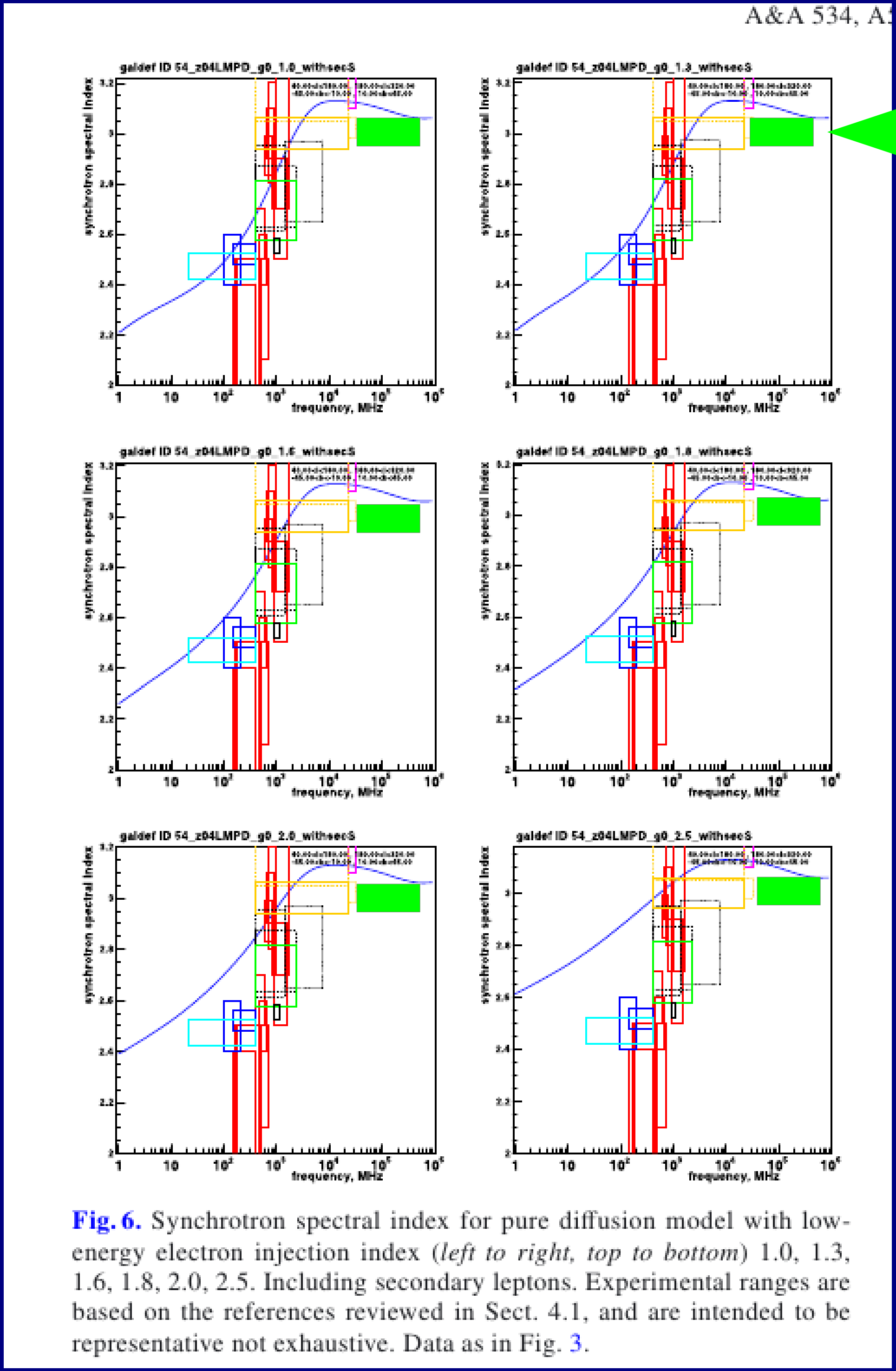

A&A 534, A

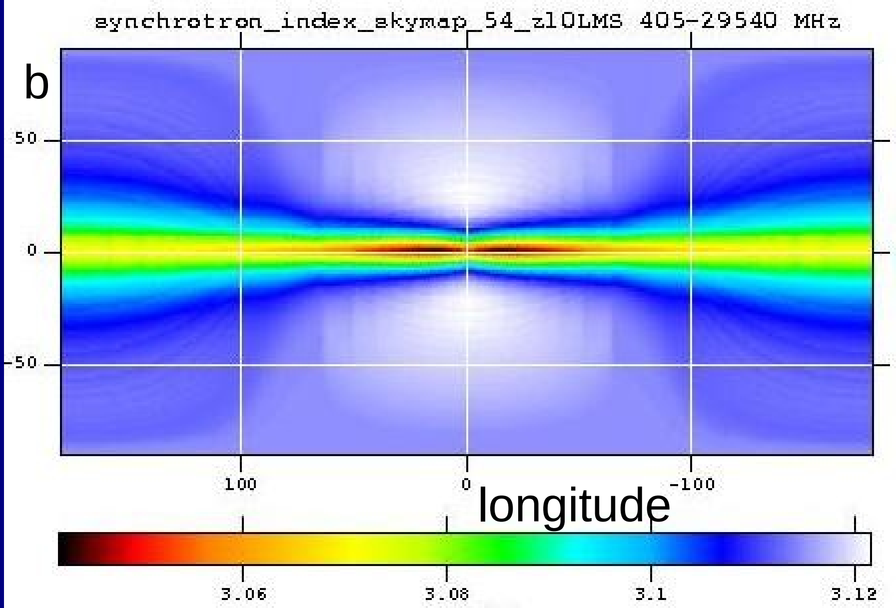
Fig. 6. Synchrotron spectral index for pure diffusion model with low-energy electron injection index (*left to right, top to bottom*) 1.0, 1.3, 1.6, 1.8, 2.0, 2.5. Including secondary leptons. Experimental ranges are based on the references reviewed in Sect. 4.1, and are intended to be representative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

Planck

A&A 536, A21 (2011)

Model Synchrotron spectral index

408 MHz – 23 GHz



Model predicts small but systematic variations due to propagation effects.

Reality is of course much more complex (Loop I etc not modelled).

The model gives a minimum underlying variation from electron propagation.

Total B (local) =7.5 μG from this analysis

Using high latitudes only, avoiding Loop I etc

Orlando and Strong 2013, submitted

What is new :

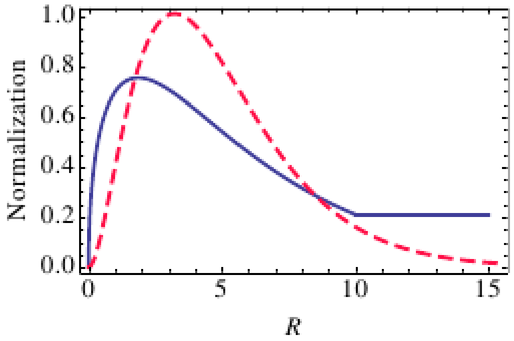
Polarized synchrotron

Separates regular from random B

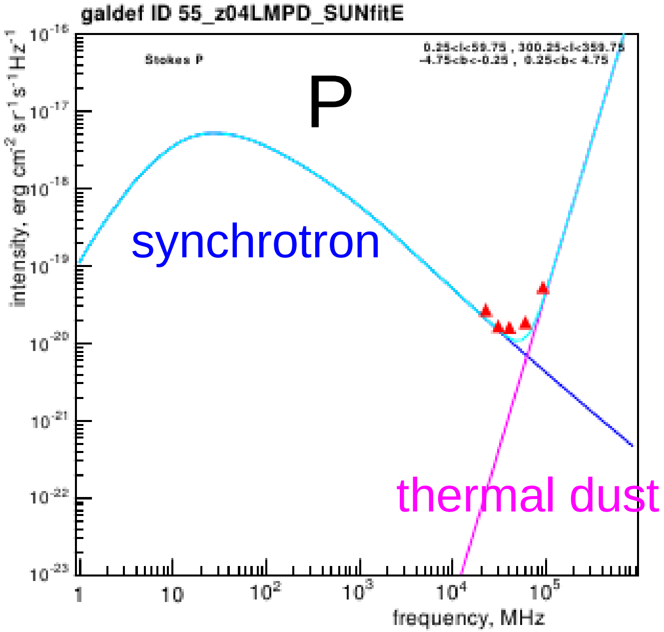
Now modelled in GALPROP

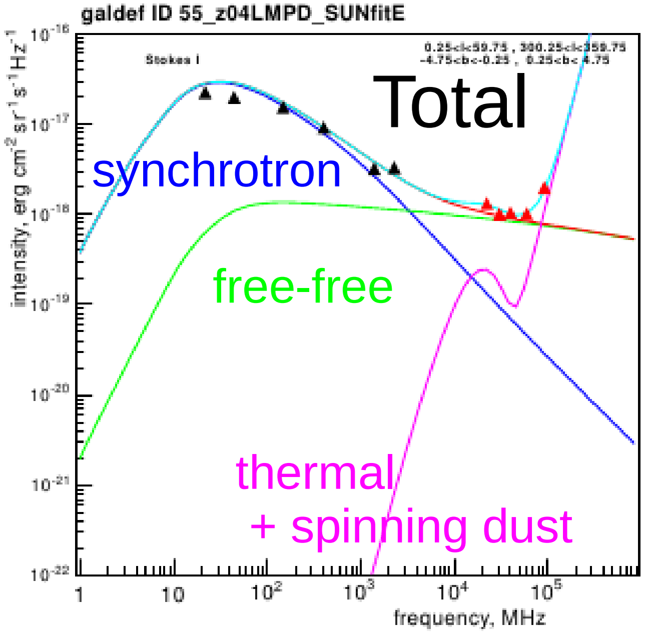
B-fields from literature, basic modifications to fit data.

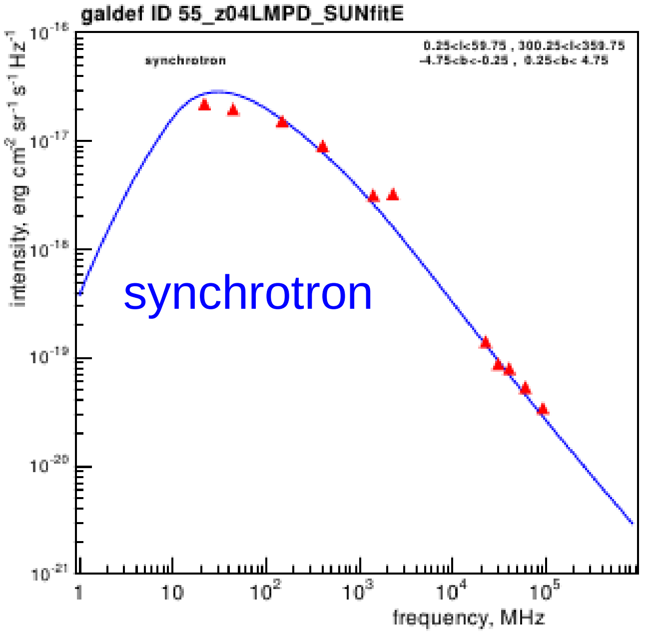
Cosmic-ray electron distribution is a main input from gamma rays.



CR source distributions from Strong et al. (2010) (blue line) and pulsar-based Lorimer et al. (2006) (red dashed line). R is the Galactocentric radius in kpc.The distributions are normalized at R= 8.5 kpc.

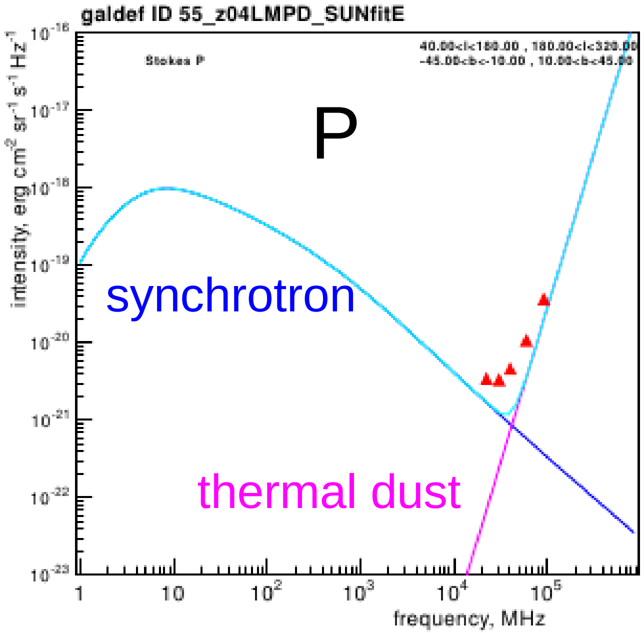


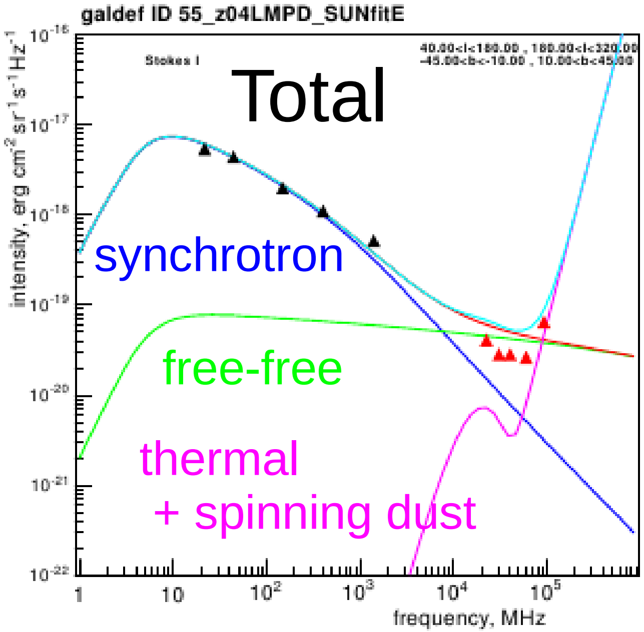


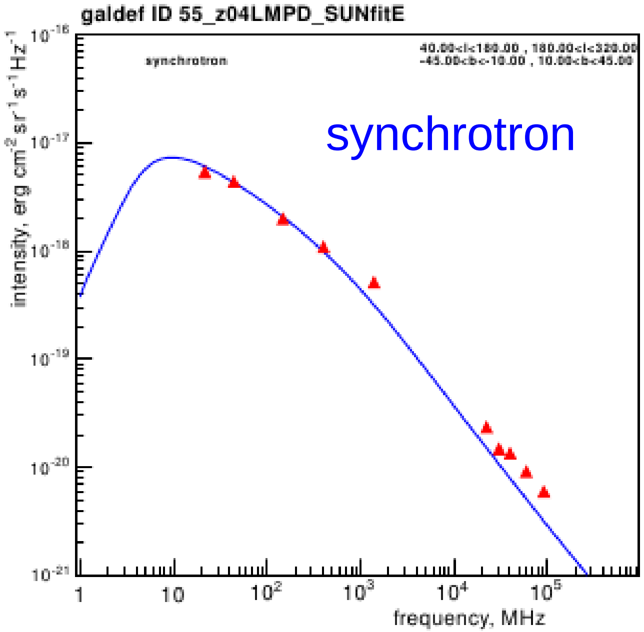


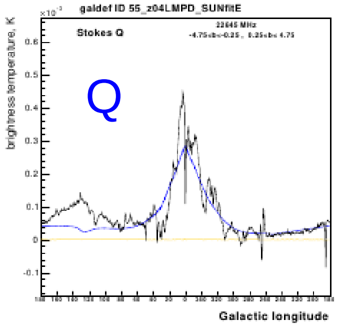
INNER GALAXY

HIGH LATITUDES





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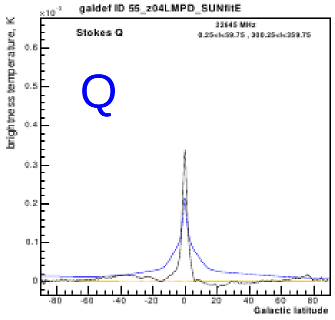
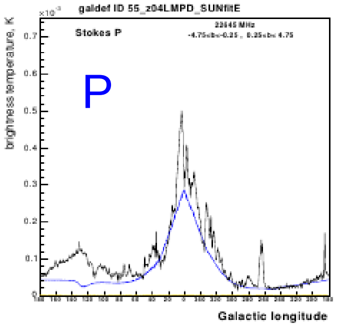
Stokes Q
22645 MHz
-4.75<b<-0.25 , 0.25<b< 4.75
Q
brightness temperature, K
×10⁻³
Galactic longitude


galdef ID 55_z04LMPD_SUNfitE
Stokes Q
22645 MHz
0.25<l<59.75 , 300.25<l<359.75
Q
brightness temperature, K
×10⁻³
Galactic latitude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22645 MHz
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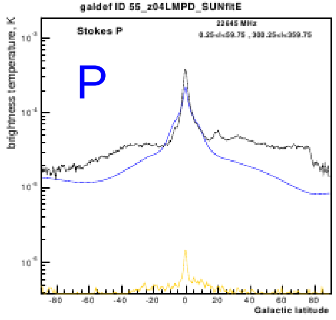
P
brightness temperature, K
×10⁻³
Galactic longitude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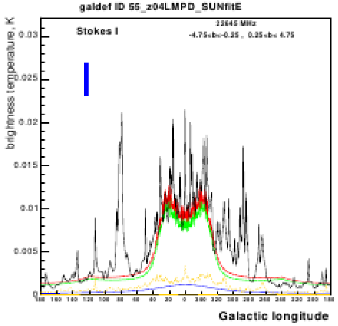
P
brightness temperature, K
Galactic latitude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Stokes I
22645 MHz
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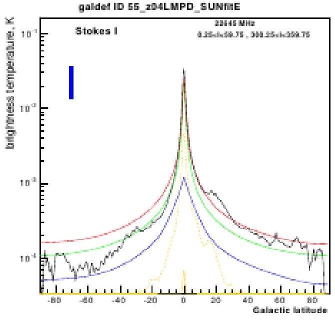
I
brightness temperature, K
Galactic longitude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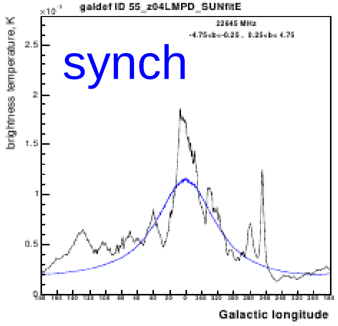
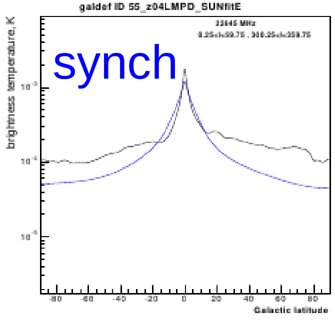
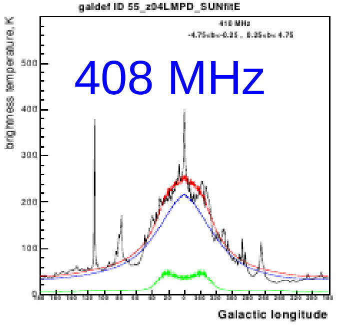
Stokes I
22645 MHz
0.25<l<59.75 , 300.25<l<359.75
I
brightness temperature, K
Galactic latitude


galdef ID 55_z04LMPD_SUNfitE
22645 MHz
-4.75<b<-0.25 , 0.25<b< 4.75
synch
brightness temperature, K
×10⁻³
Galactic longitude


galdef ID 55_z04LMPD_SUNfitE
22645 MHz
0.25<l<59.75 , 300.25<l<359.75
synch
brightness temperature, K
Galactic latitude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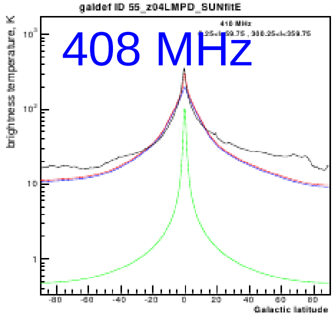
408 MHz
-4.75<b<-0.25 , 0.25<b< 4.75
408 MHz
brightness temperature, K
Galactic longitude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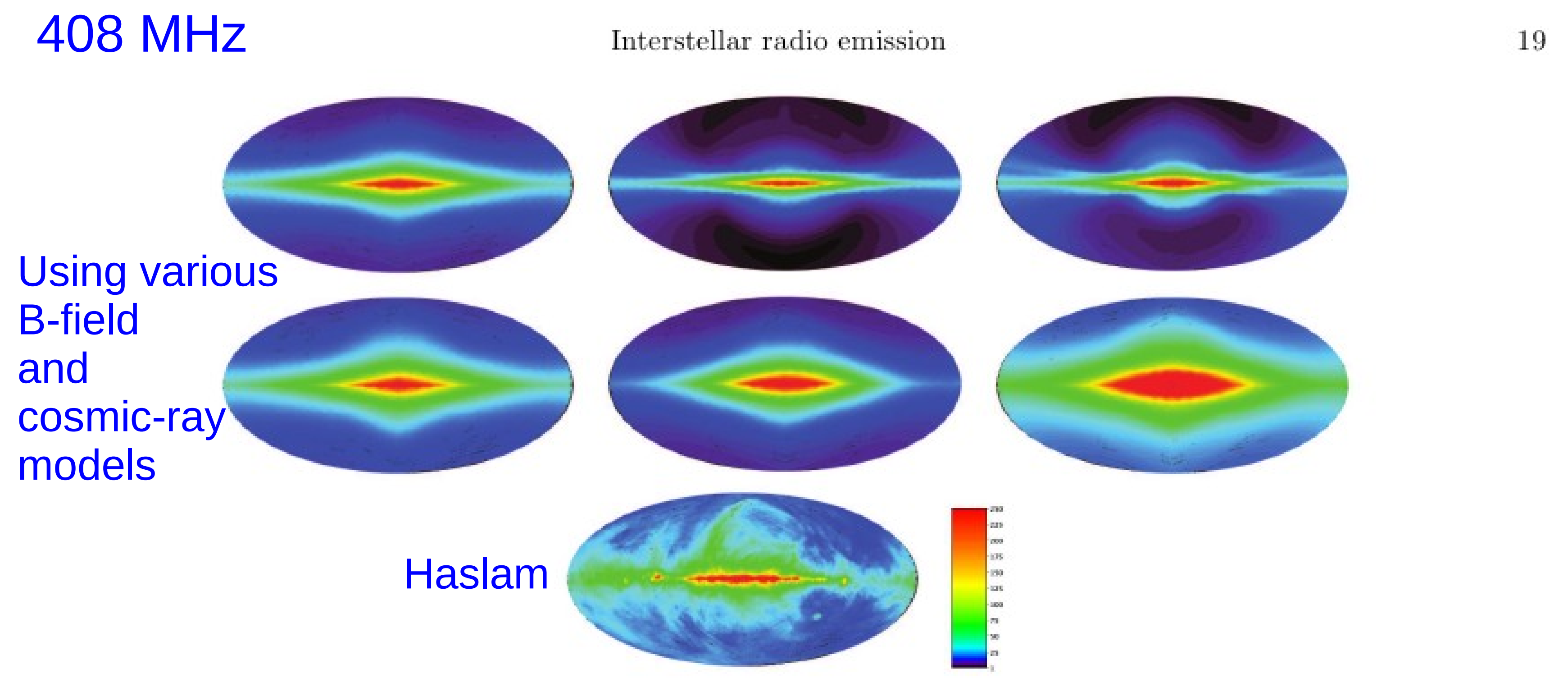
408 MHz
0.25<l<59.75 , 300.25<l<359.75
408 MHz
brightness temperature, K
Galactic latitude

408 MHz



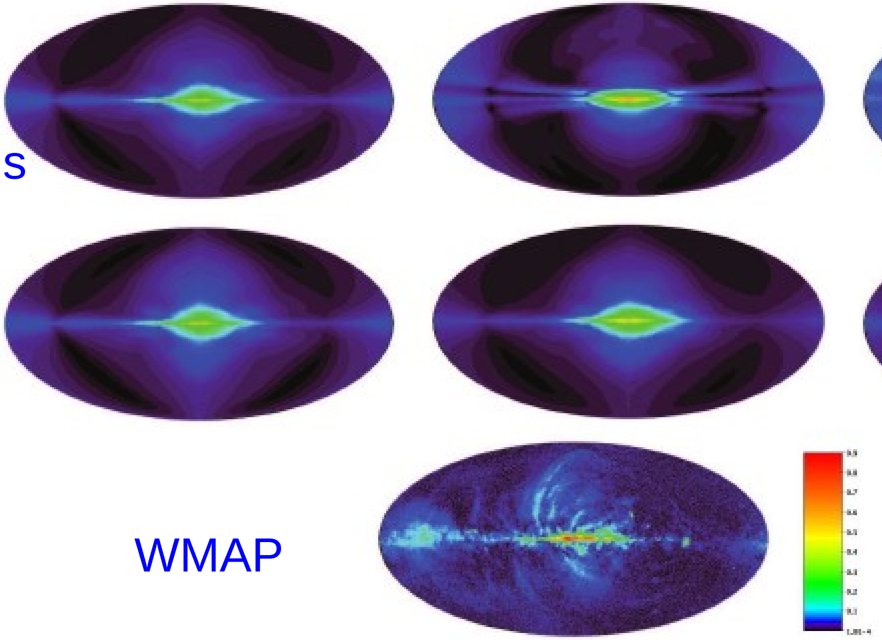
Interstellar radio emission 19

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 Strong & Orlando 2013

Using :
  Fermi-LAT cosmic-ray electrons
  408 MHz
  23 GHz WMAP polarized

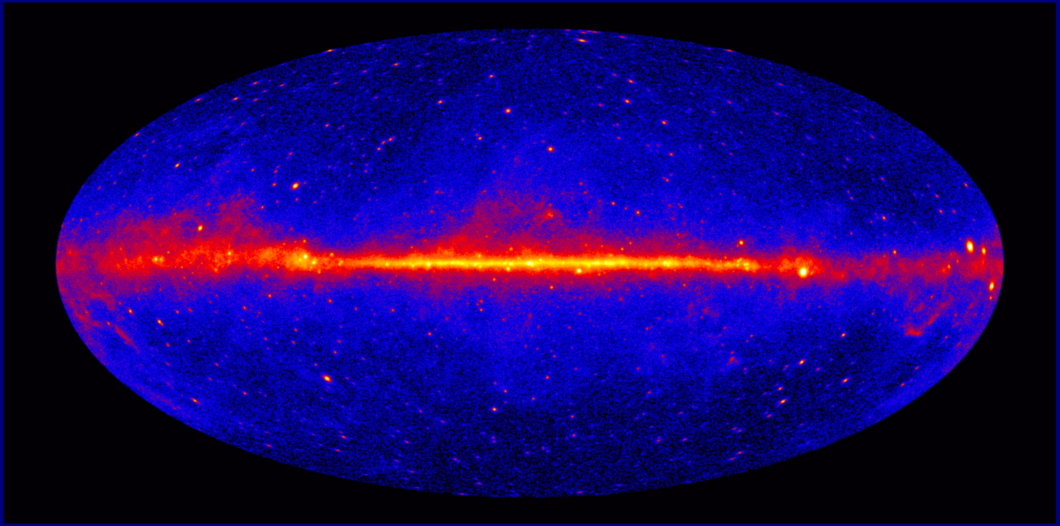
Local B-field:

Regular : 3-4 μG :
factor 1.5-2 higher than original models of Sun, Pshirkov

Random : 6 μG

Exploiting gamma rays

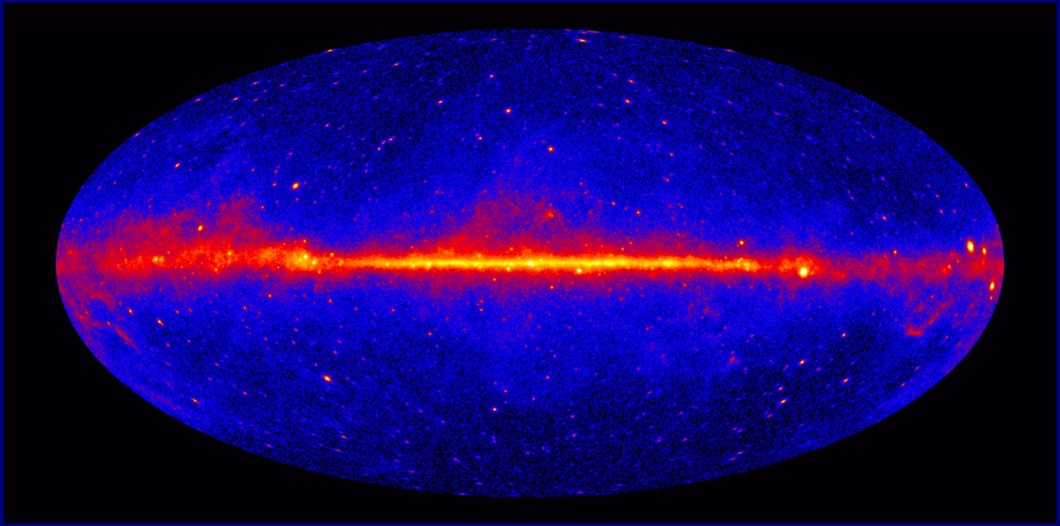
1 – 10 GeV



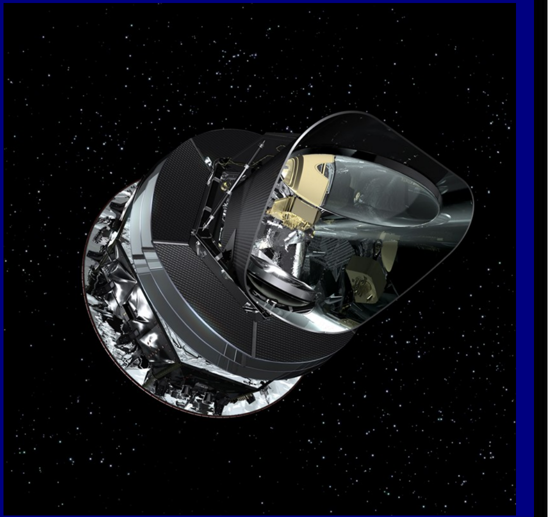
Cosmic-ray protons interacting with gas : hadronic (pion-decay)

Cosmic-ray electrons and positrons interacting with gas : bremsstrahlung

interacting with interstellar radiation : inverse Compton



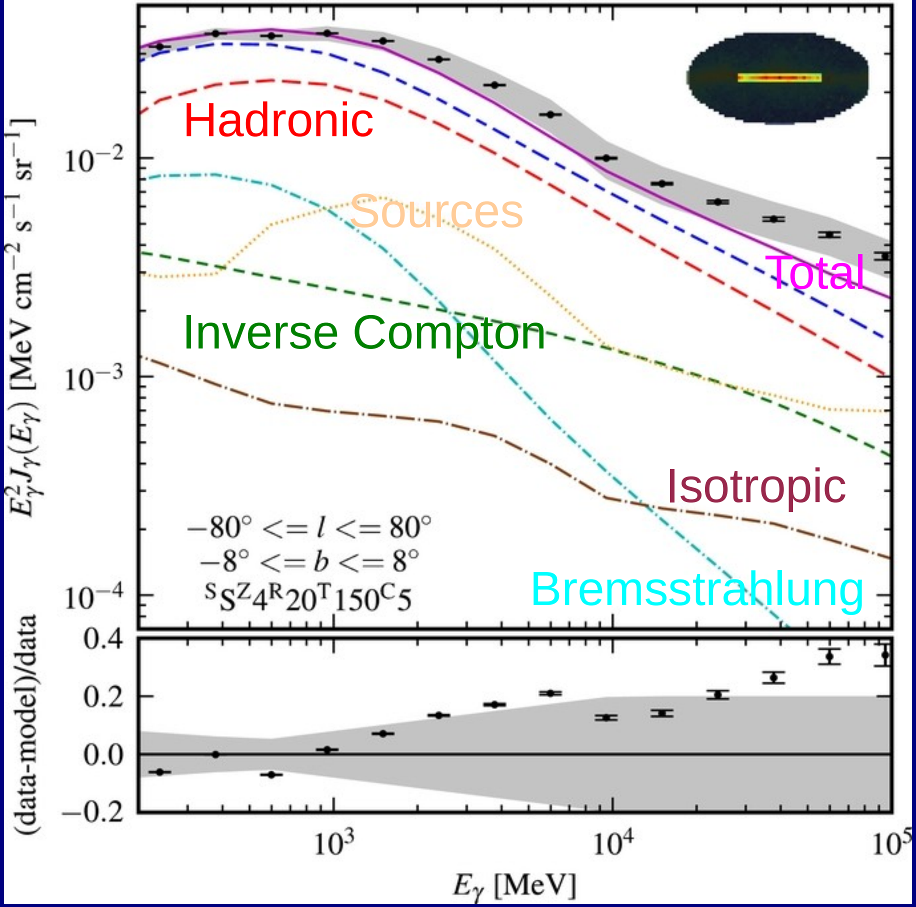
2 years



1 year

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

Fermi-LAT
Inner Galaxy Gamma Ray Spectrum

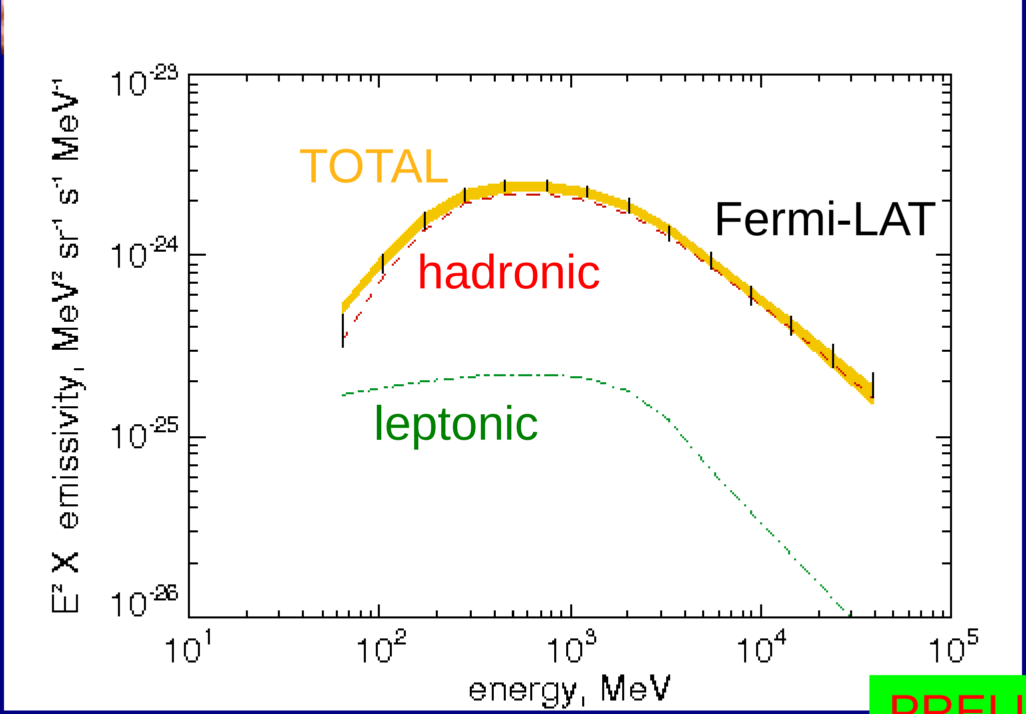


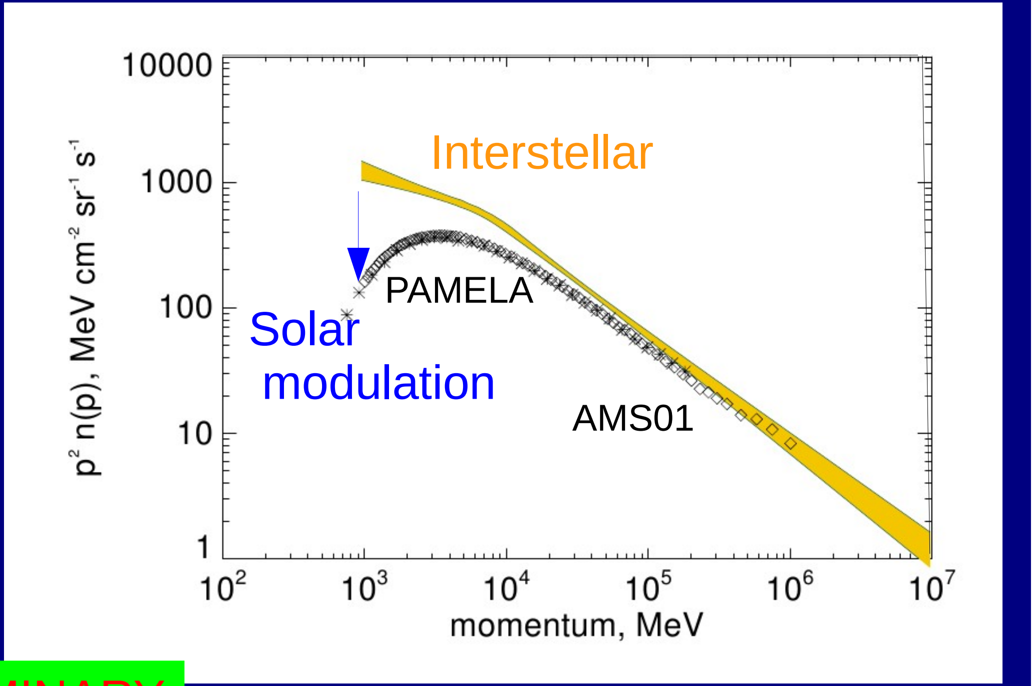
Ackermann et al. ApJ 750, 3 (2012)

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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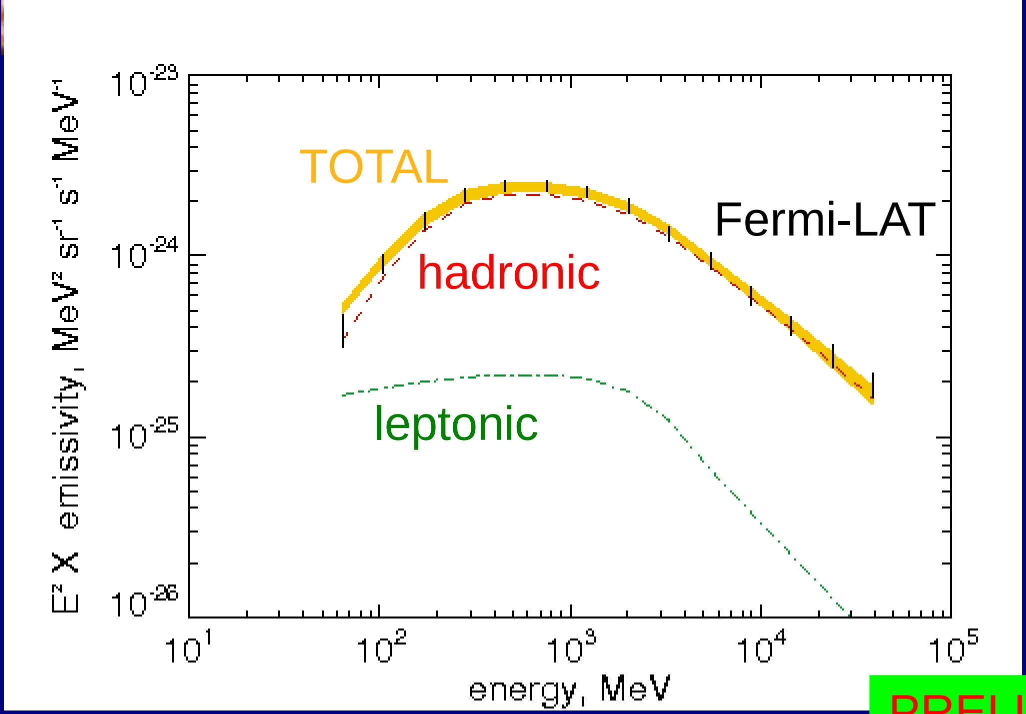

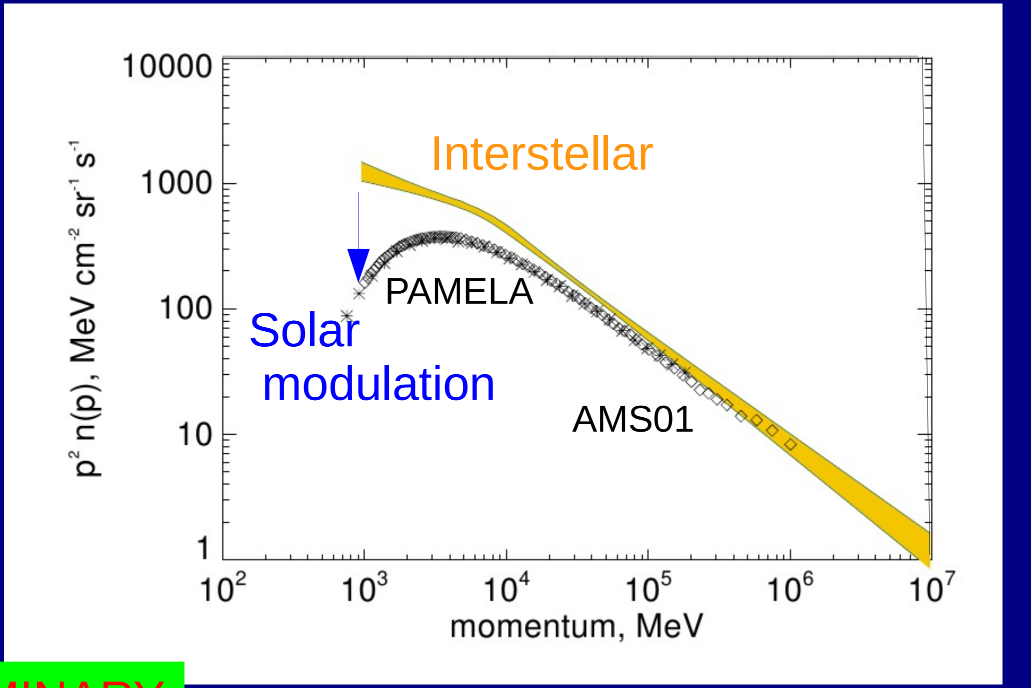

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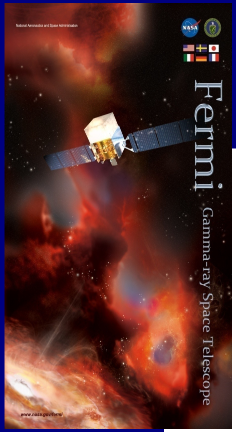
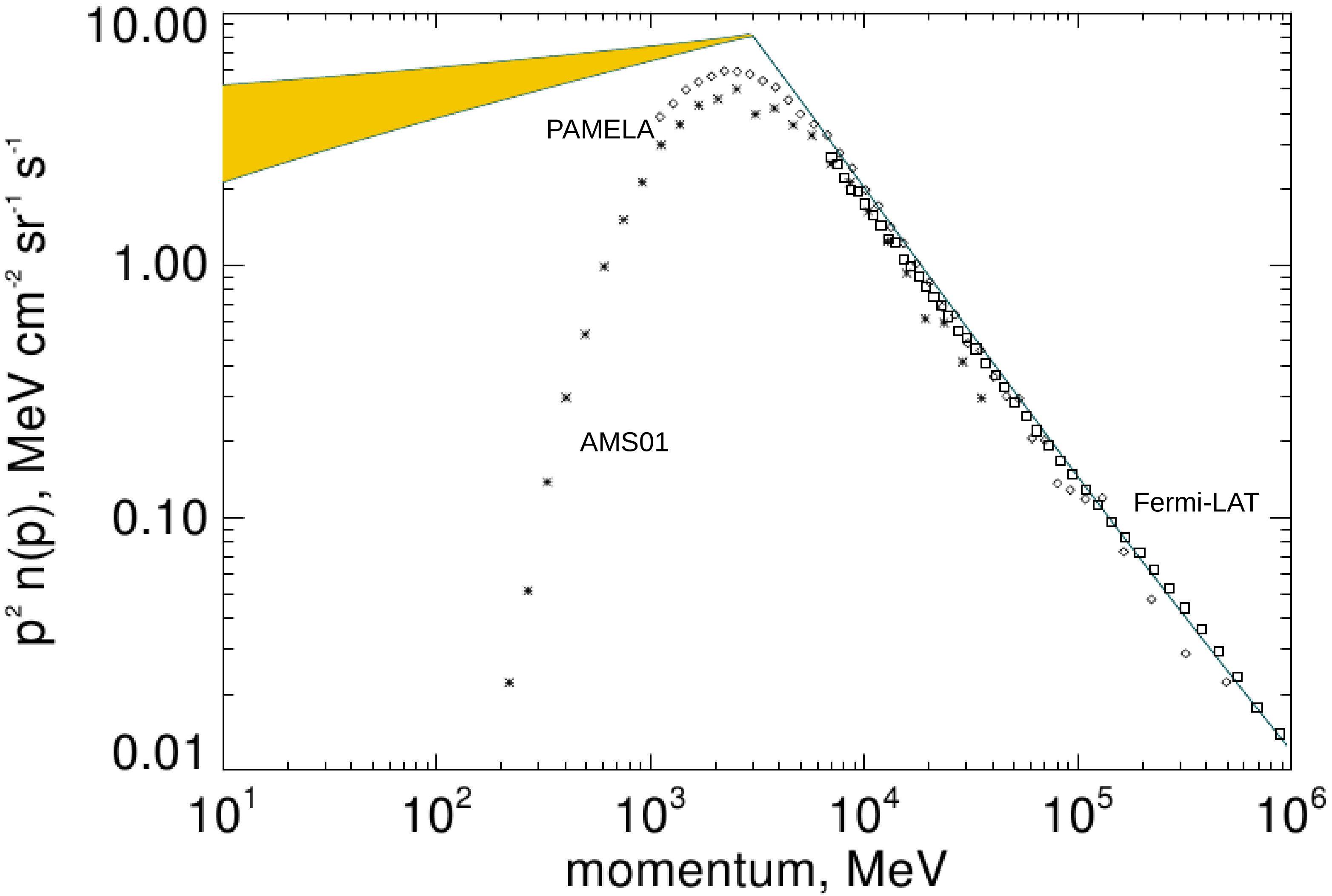


Interstellar electrons from synchrotron, gamma rays and direct measurements



PRELIMINARY

Effects of Cross Sections on Fits to Emissivity

This model shown in previous two slides
||
V

CROSS-SECTIONS

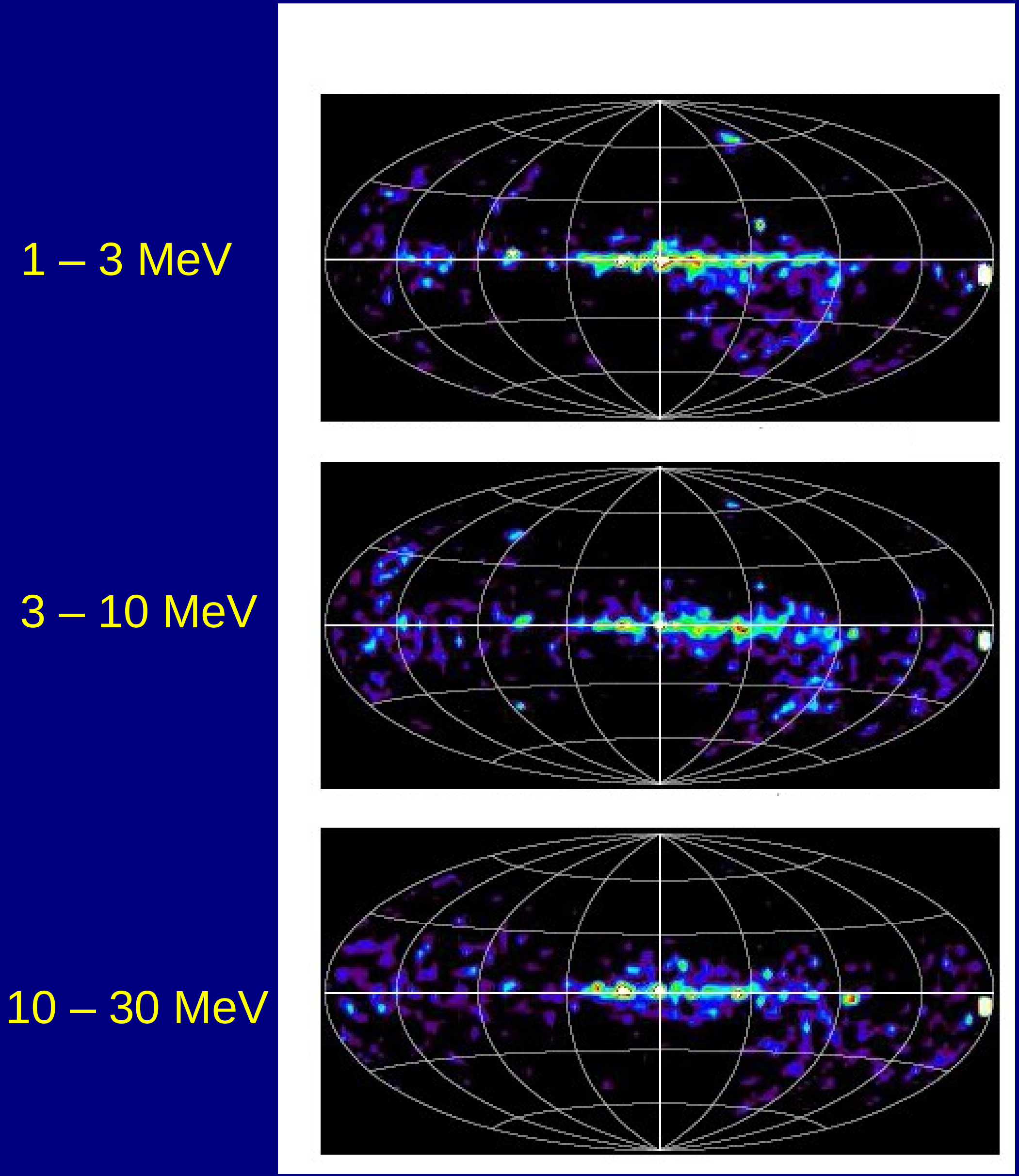
	Kamae Kachelriess & Ostapchenko	Dermer, Stecker Stephens & Badhwar
proton break momentum	6.5 (±2.1) GeV	6.7 (±2.5) GeV
proton index below break	2.4 (0.1)	2.5 (0.1)
proton index above break	2.9 (0.1)	2.8 (0.1)
proton normalization	1.3 (0.1)	1.4 (0.1)
electron break momentum	3.0	3 .0 (fixed from synchrotron)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

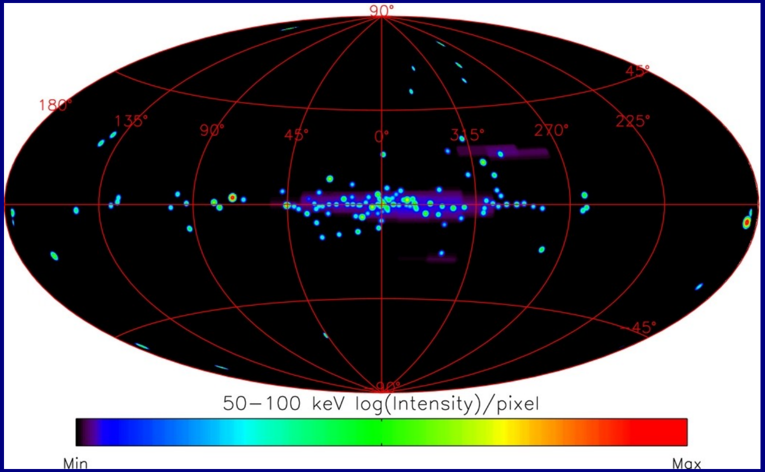


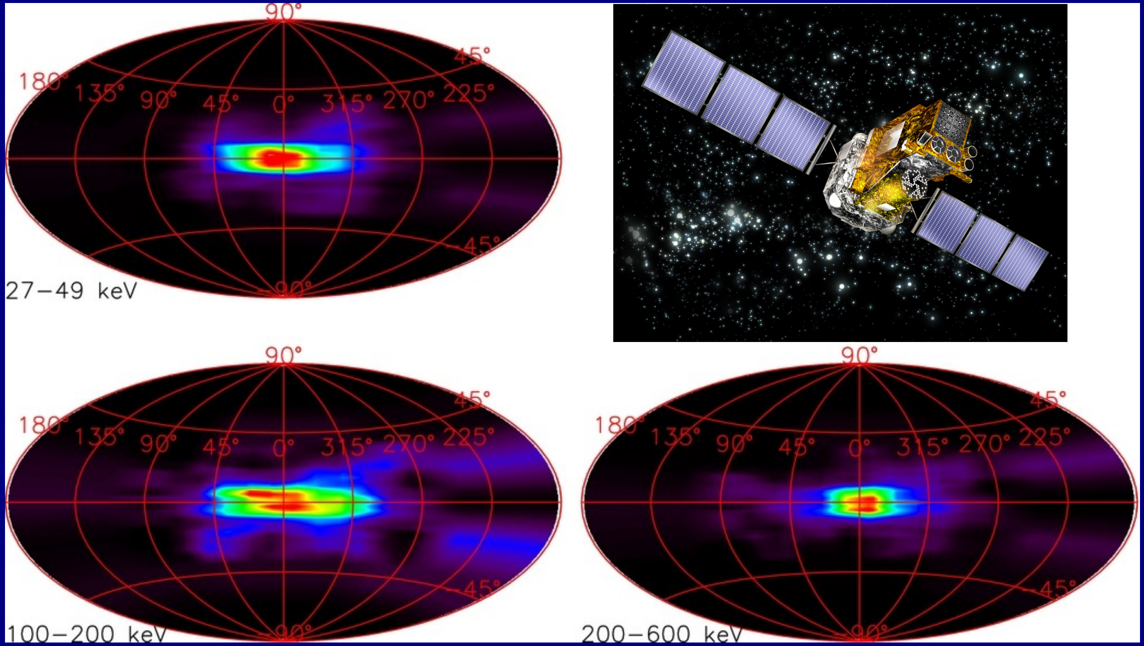
Unique heritage data:
COMPTEL analysis continues....

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

INTEGRAL / SPI
Continuum skymaps

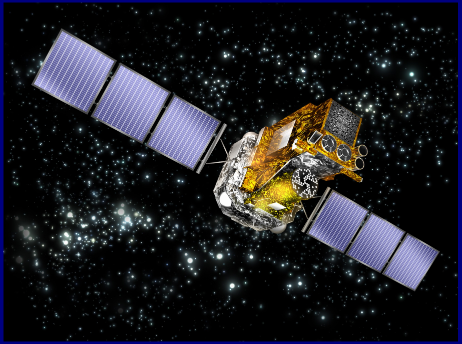
Bouchet et al.
ApJ 739, 29 (2011)

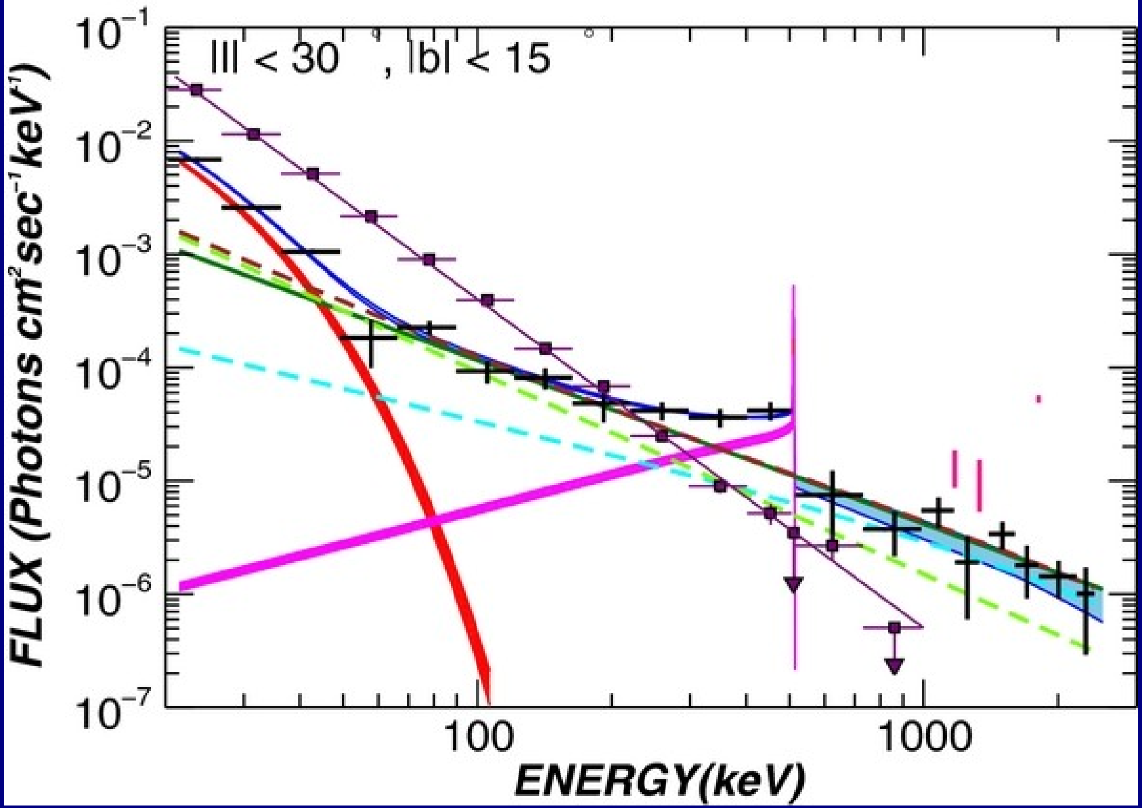




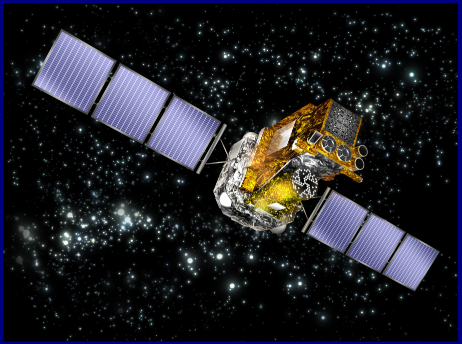
A real mix of processes !

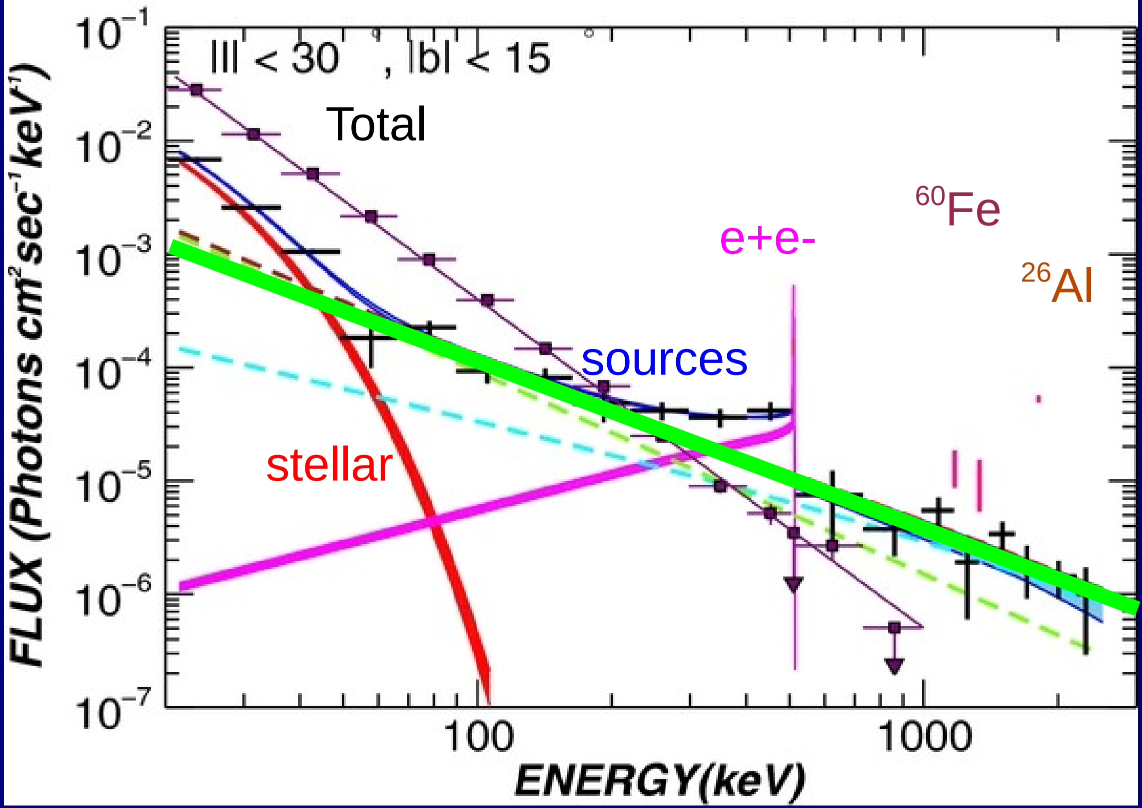
Inner Galaxy
INTEGRAL / SPI
Bouchet et al.   ApJ 739, 29 (2011)





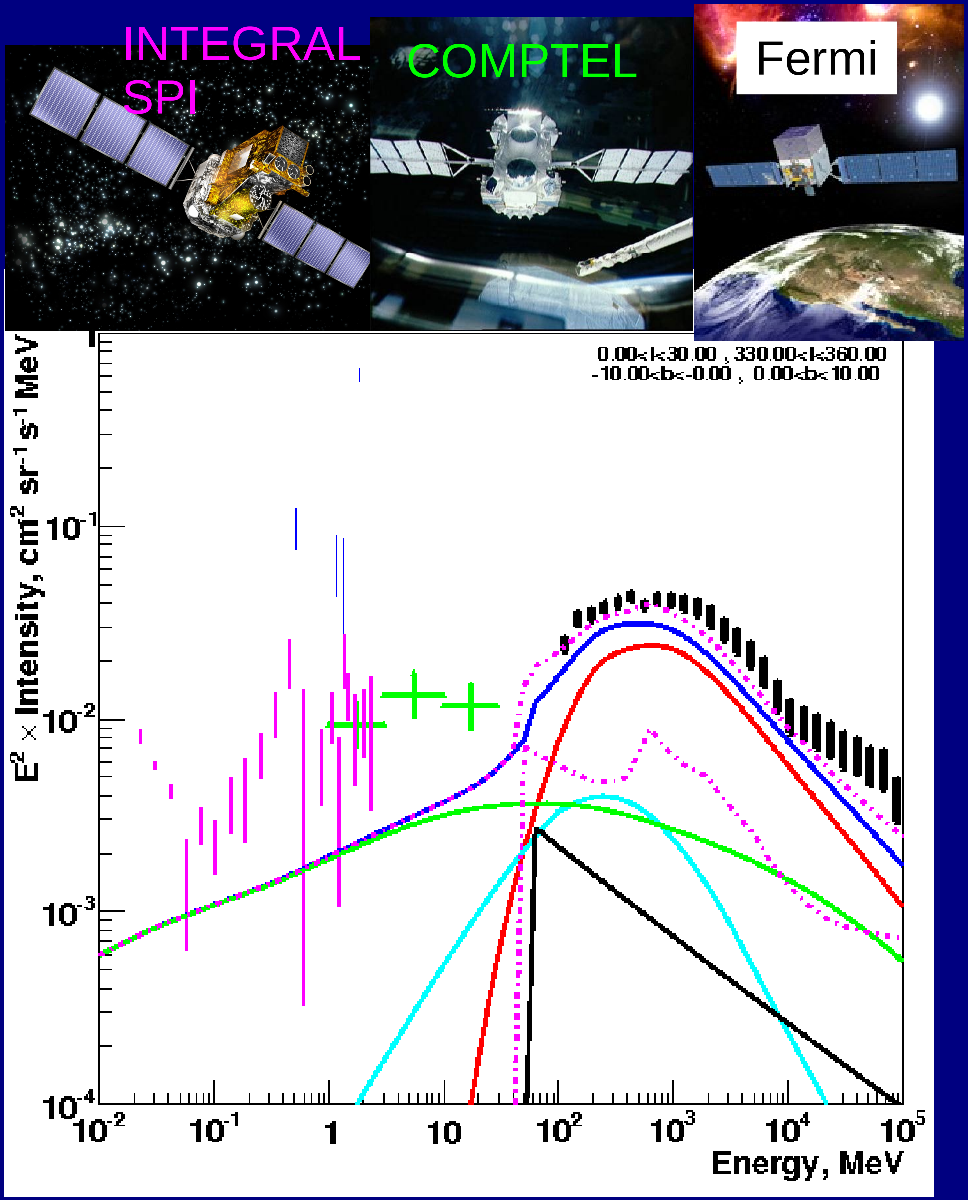
Inner Galaxy
INTEGRAL / SPI
Bouchet et al.   ApJ 739, 29 (2011)





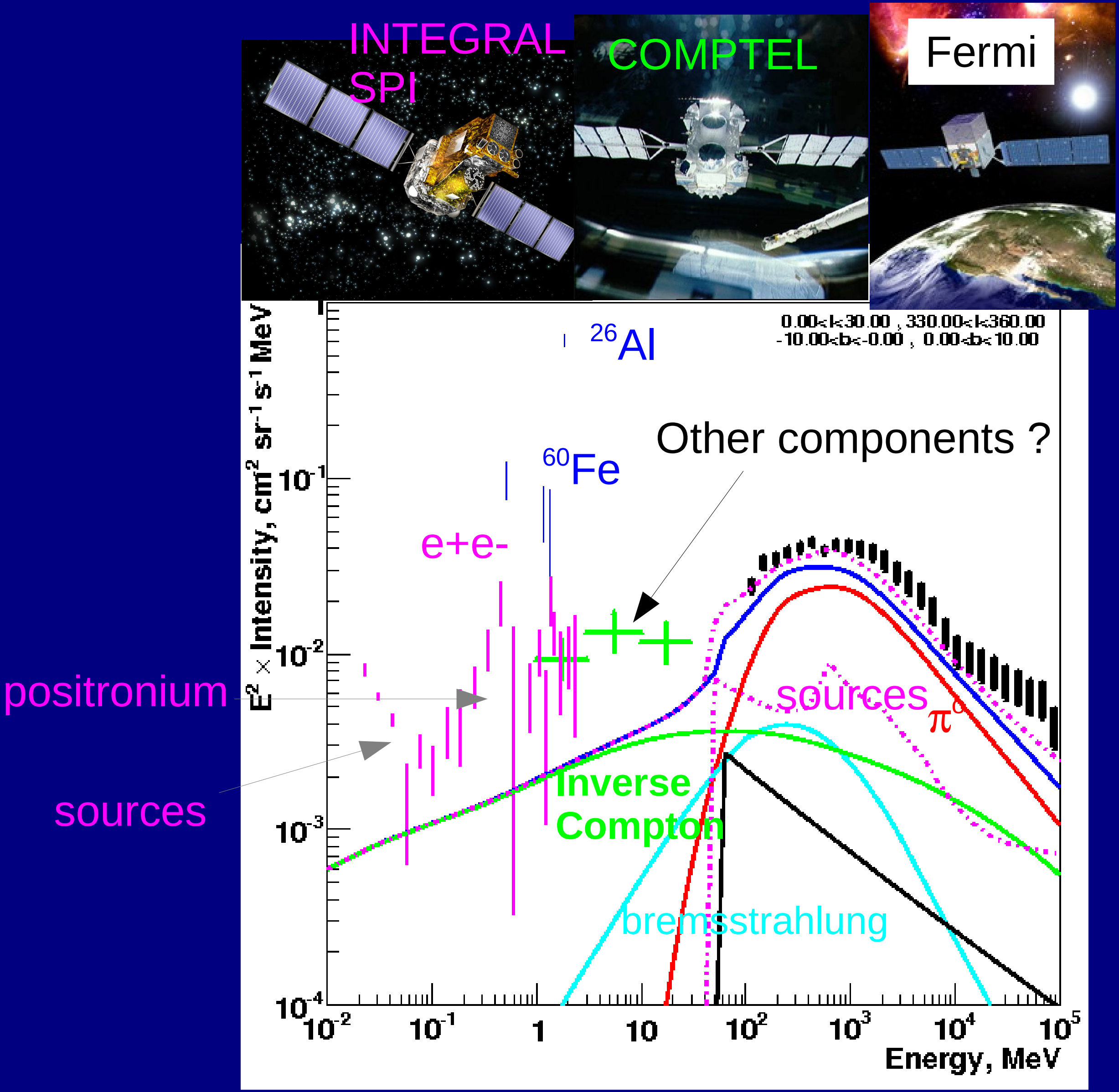
Non-thermal:
Cosmic-ray interactions

Inner Galaxy: keV to TeV



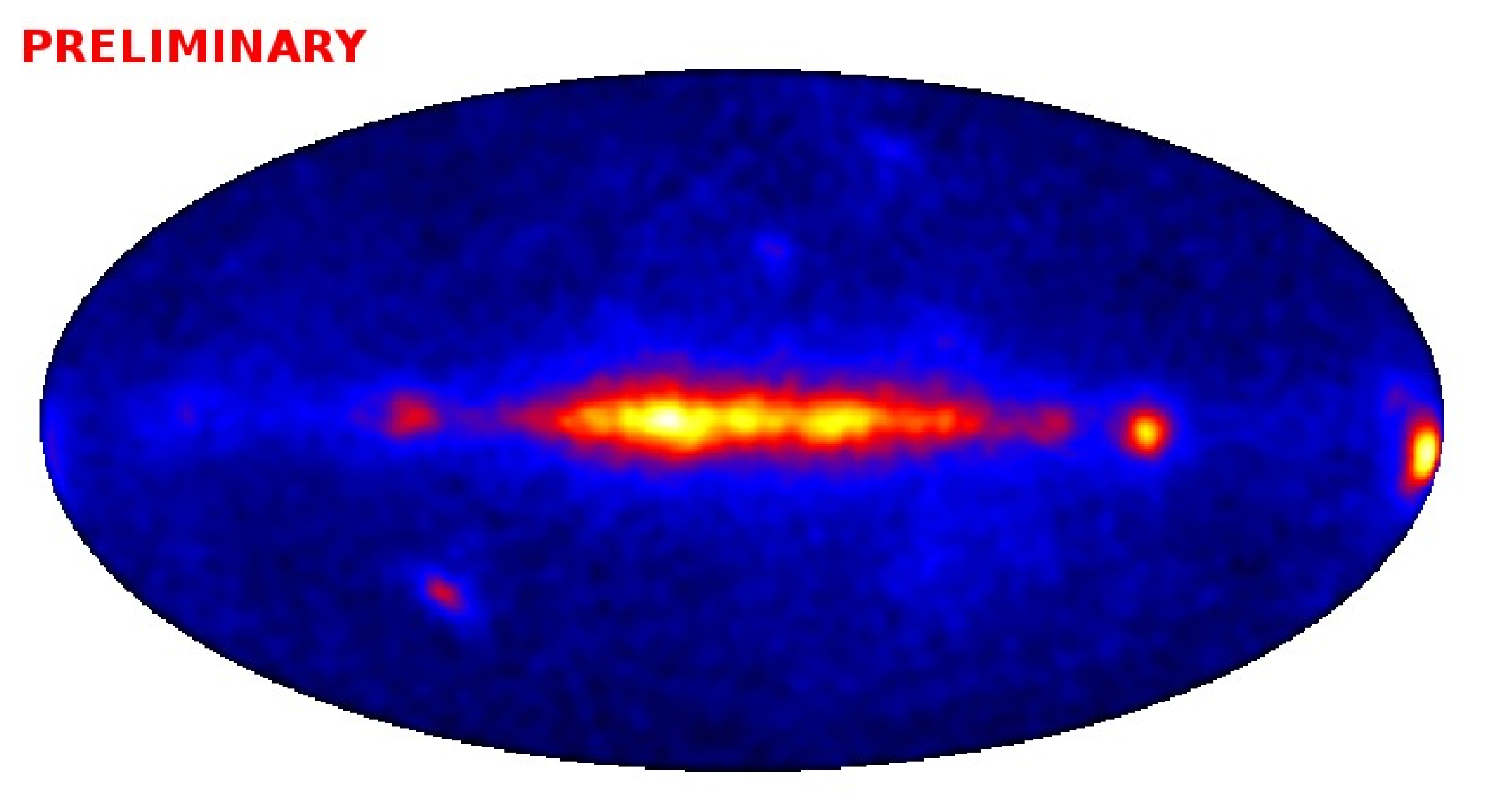
Strong 2011, Proc. 12 ICATPP Conf. arXiv:1101.1381

Inner Galaxy: keV to TeV



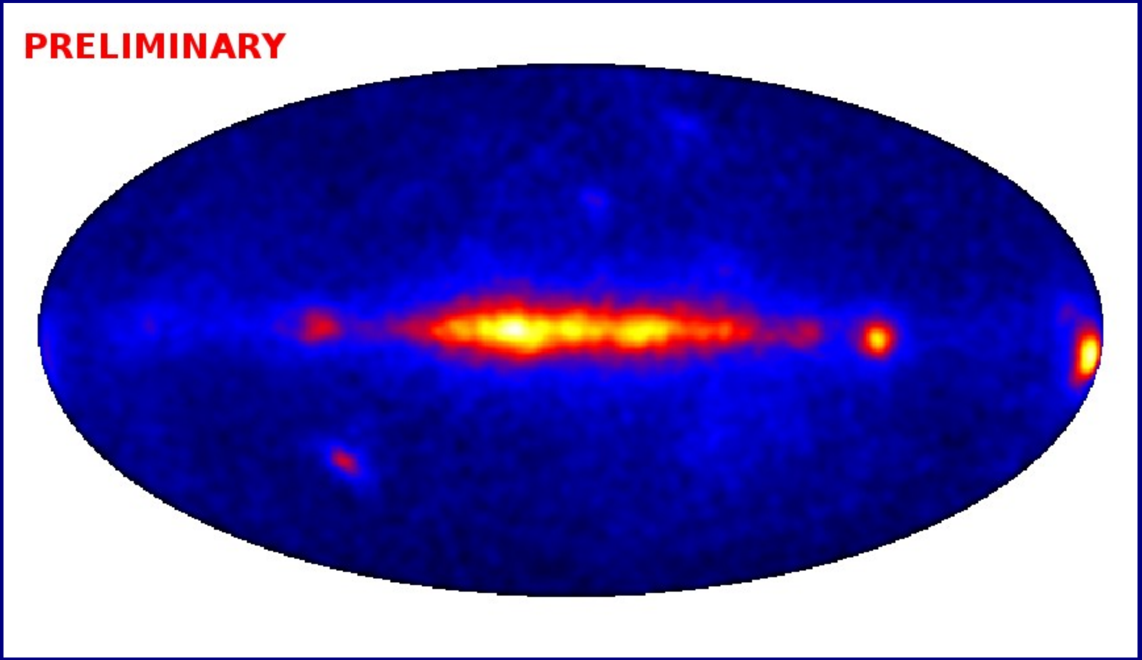
GeV electrons – inverse Compton - important for MeV gamma rays !

Fermi-LAT 25 – 40 MeV



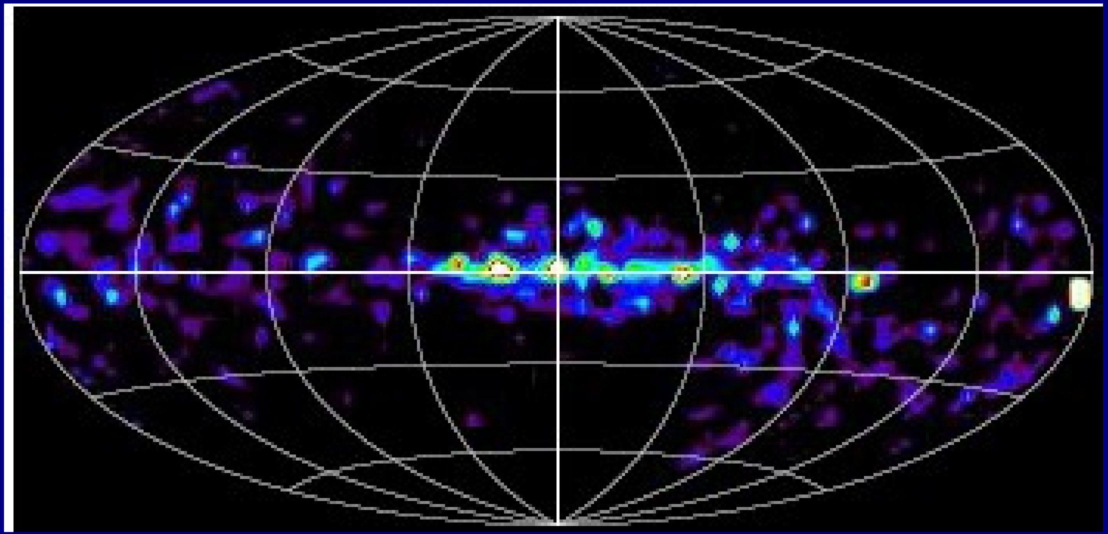
NB low angular and energy resolution !
Nominal energy range: photons may originate from range 10 to <100 MeV.
But valuable to bridge the MeV gap.

Fermi-LAT 25-40 MeV

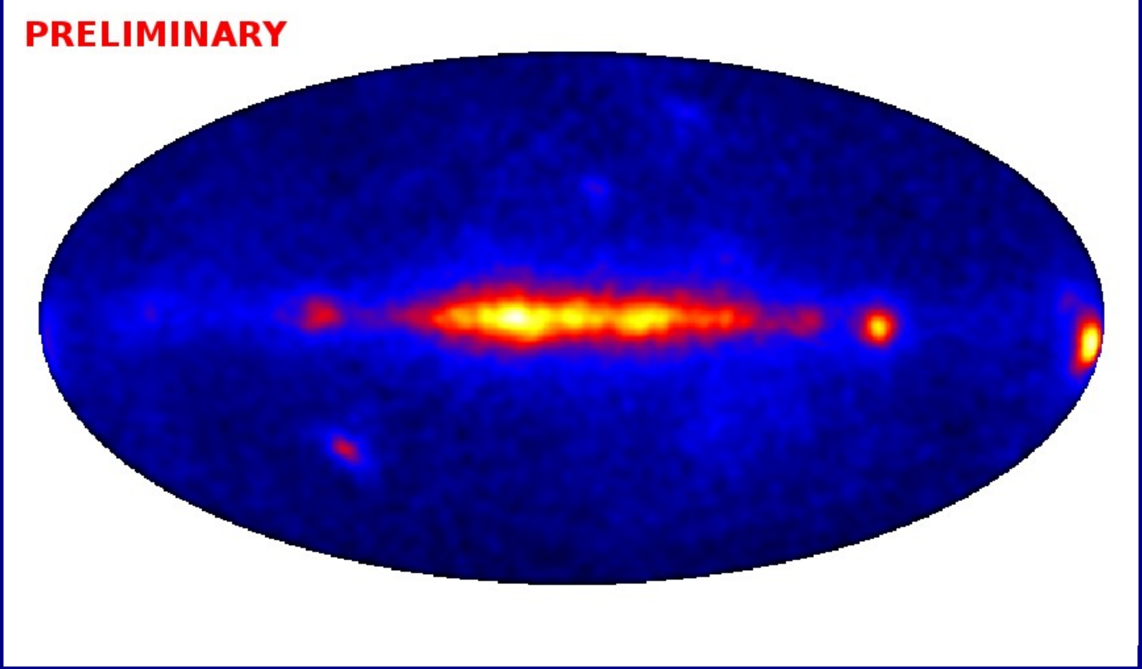


meets

COMPTEL 10-30 MeV

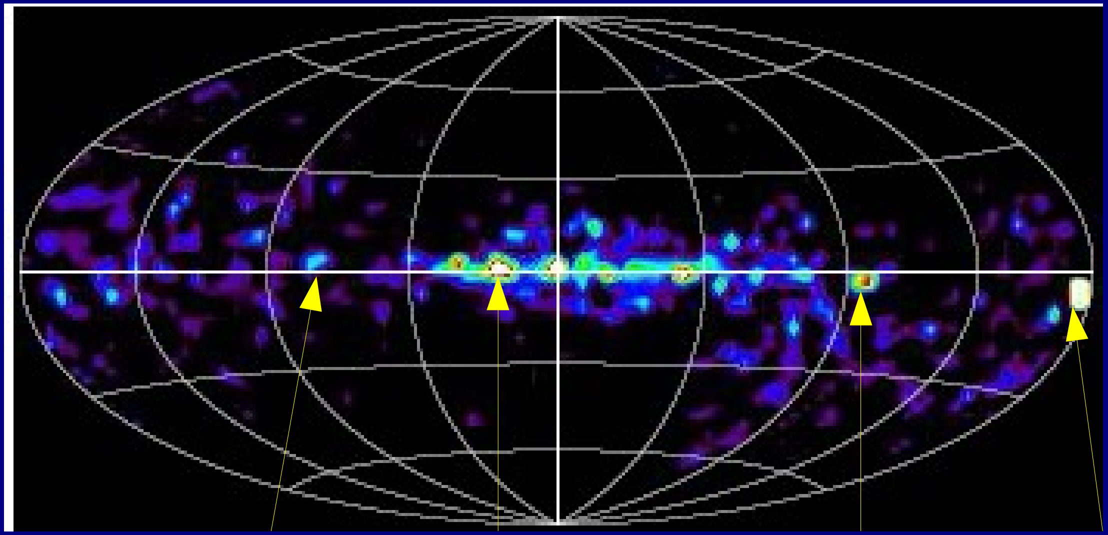


Fermi-LAT 25-40 MeV



meets

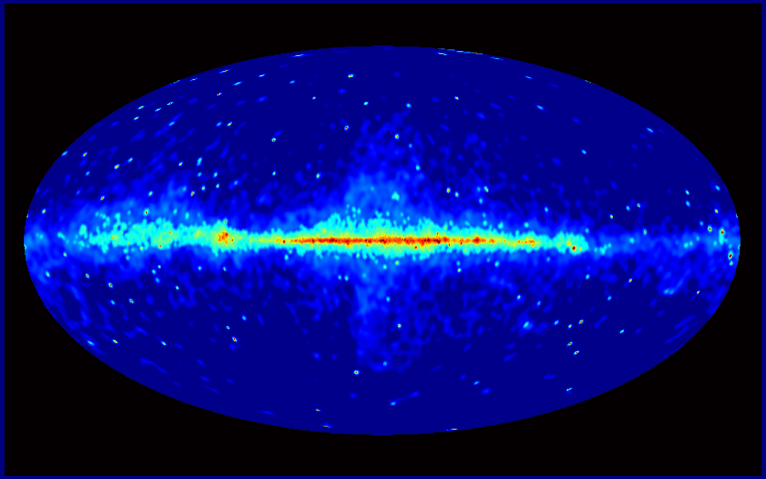
COMPTEL 10-30 MeV



Galactic Plane

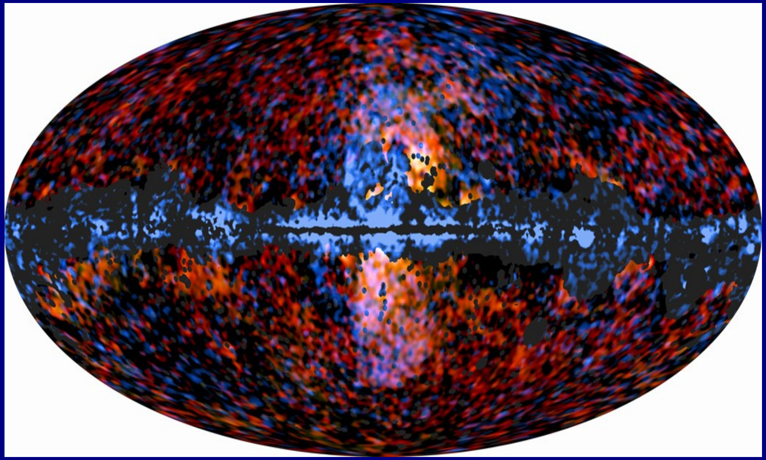
Cyg X-1 LS5039 Vela PSR Crab

Fermi Bubbles

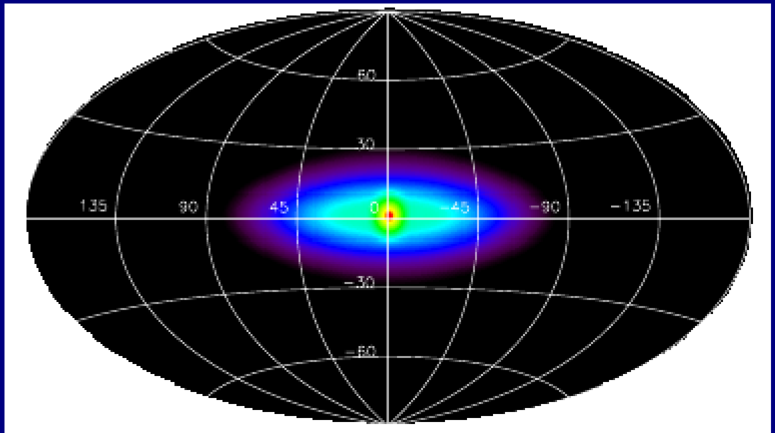


(related to WMAP Haze ?)

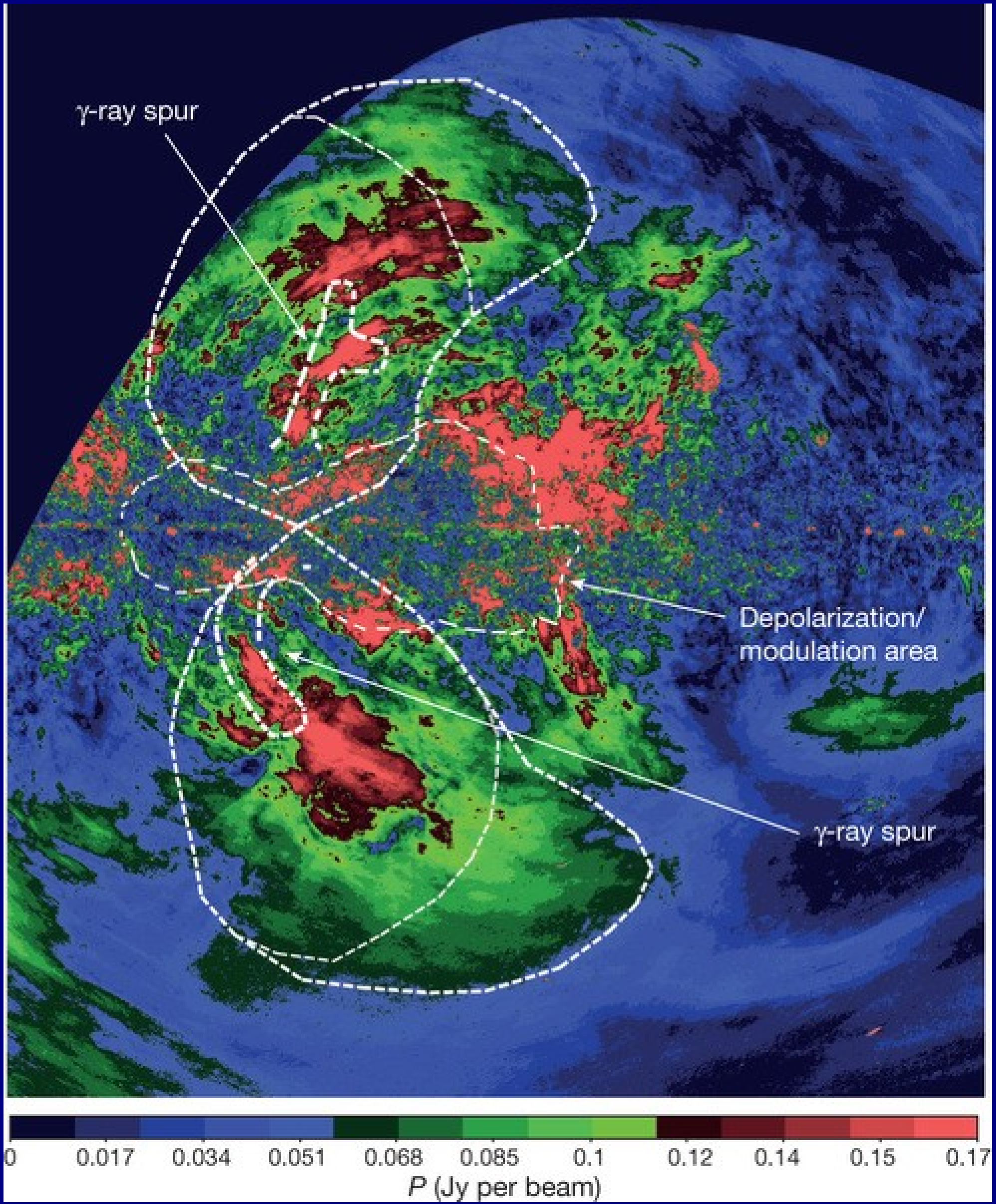
Planck haze (arXiv:1208.5483)
Overlaid on Fermi Bubbles



connection to 511 keV line ?



All are -
centred on Galactic Centre
leptonic
unknown origin

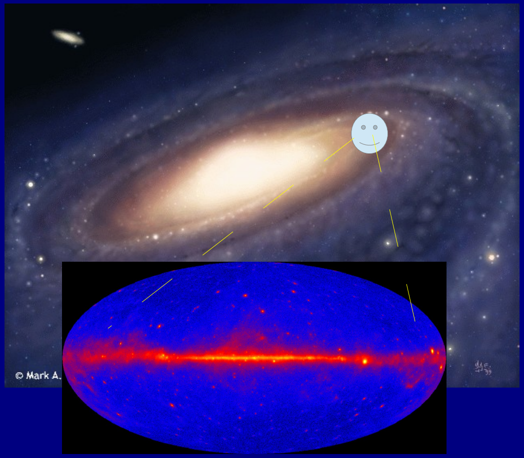


S-PASS
Southern Sky
Parkes Telescope
2.3 GHz
Polarized intensity

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

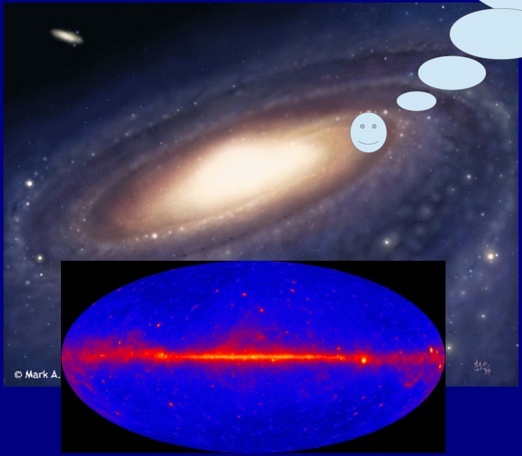
“Giant magnetized outflows from the centre of the Milky Way”
Correlates with Fermi Bubbles.
Produced by repeated episodes of star-formation at Galactic Centre ?

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



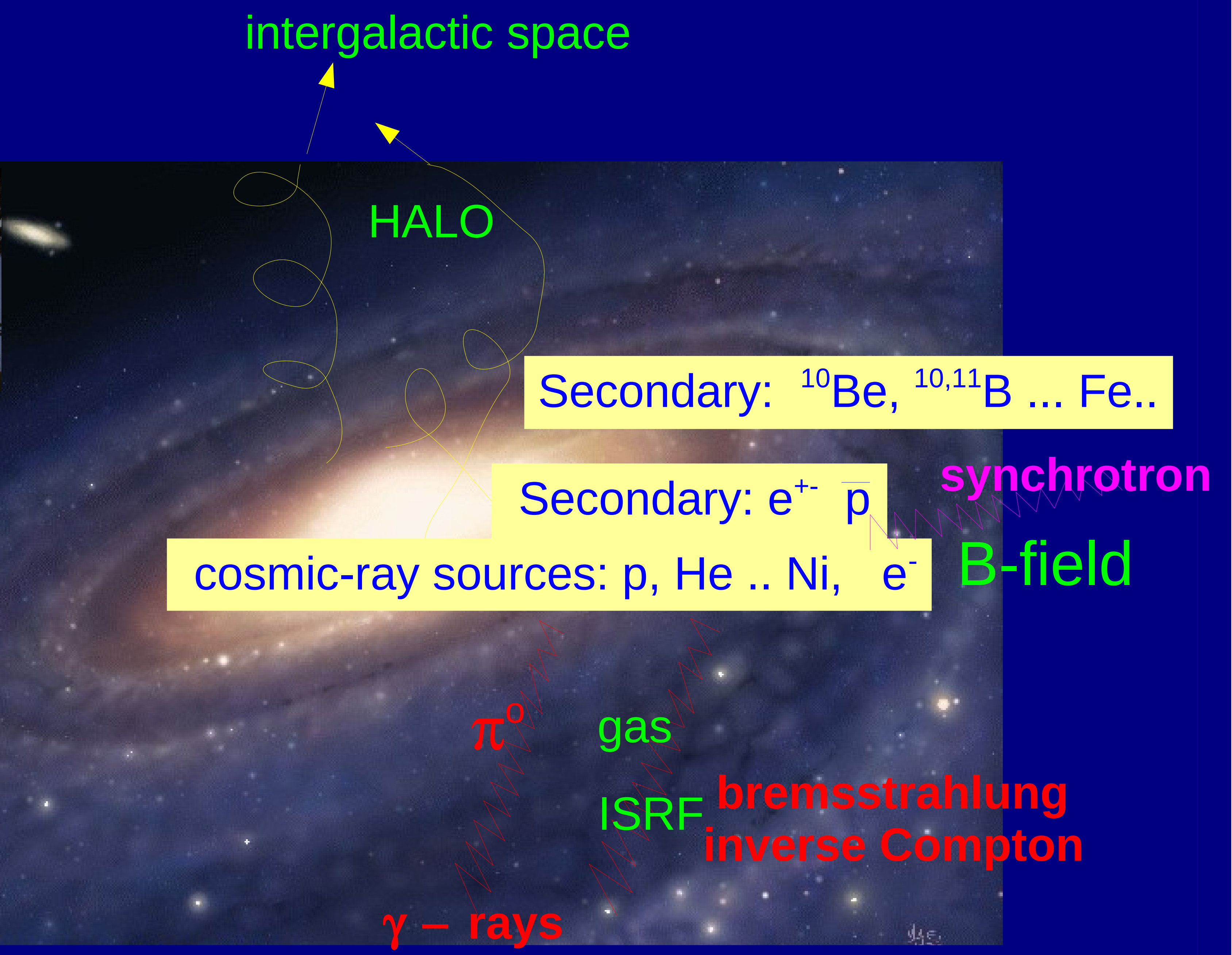
SEDs of AGN etc are common, but not Milky Way

what does it look from out there ?



EXPERIMENTS

THEORY



intergalactic space

HALO

Secondary: ^{10}Be, ^{10,11}B ... Fe..

synchrotron

Secondary: e^{+-} $\bar{p}$

B-field

cosmic-ray sources: p, He .. Ni, e^{-}

π^{o}

gas

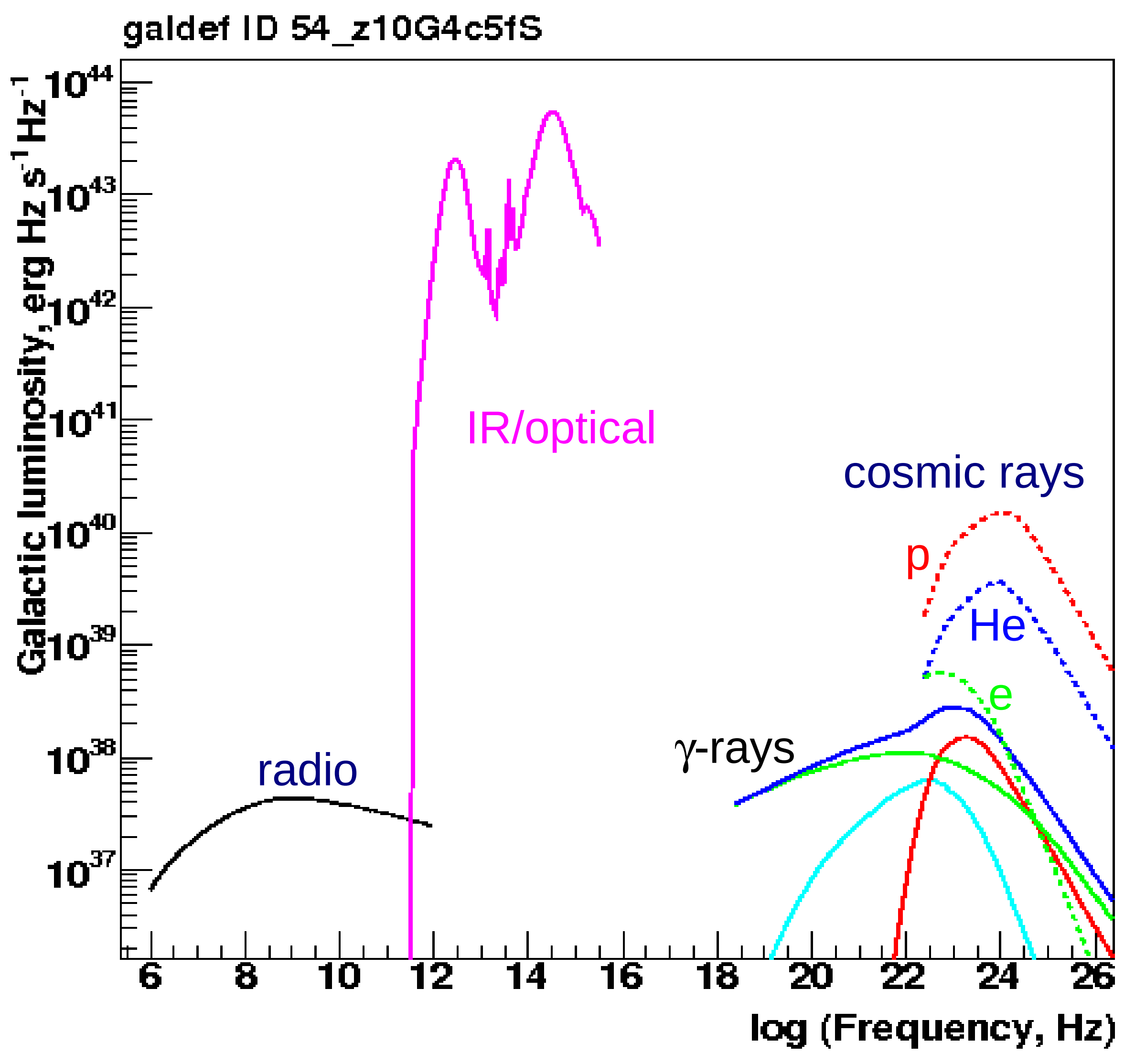
ISRF

bremsstrahlung

inverse Compton

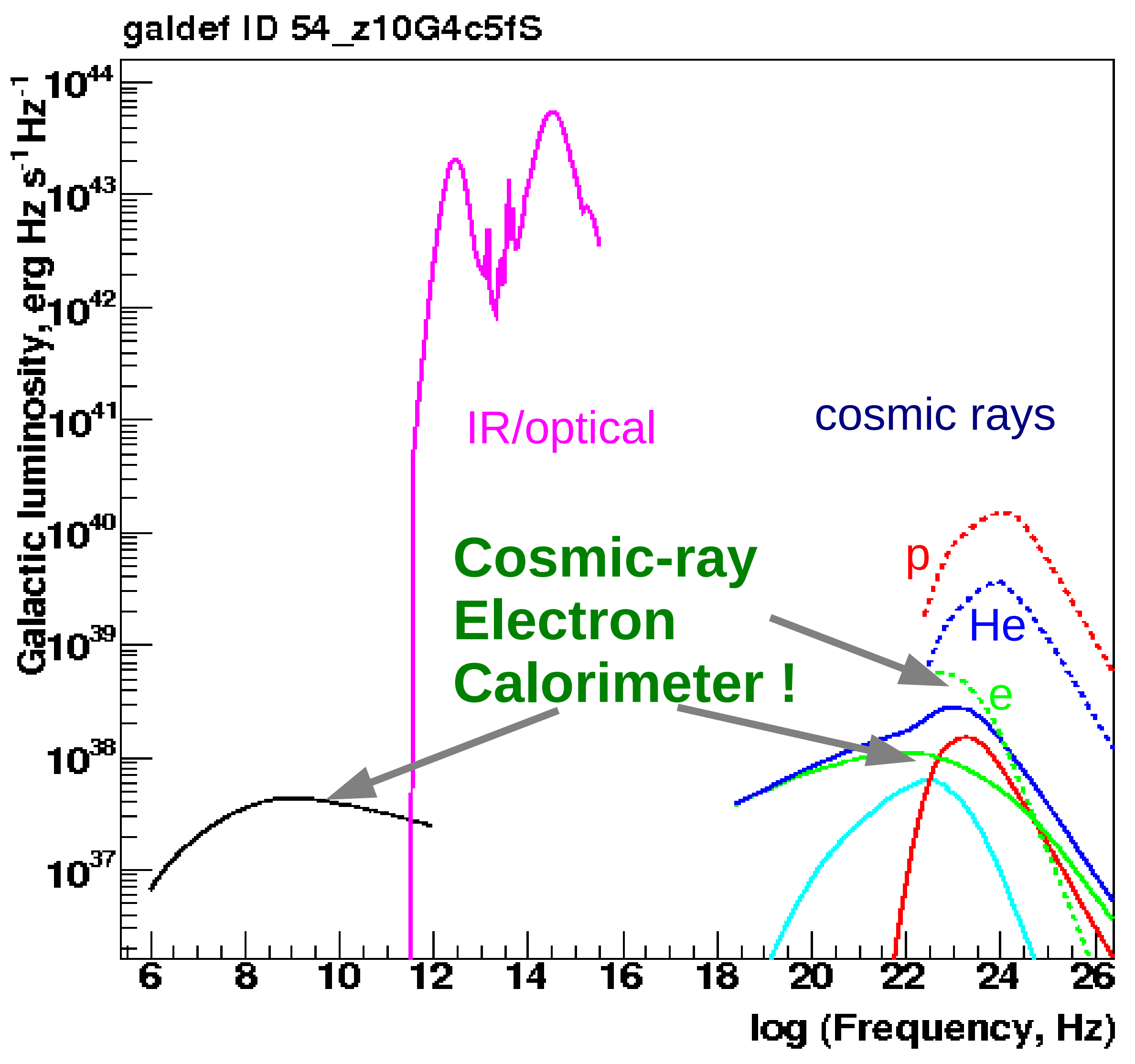
γ – rays

Galaxy luminosity over 20 decades of energy

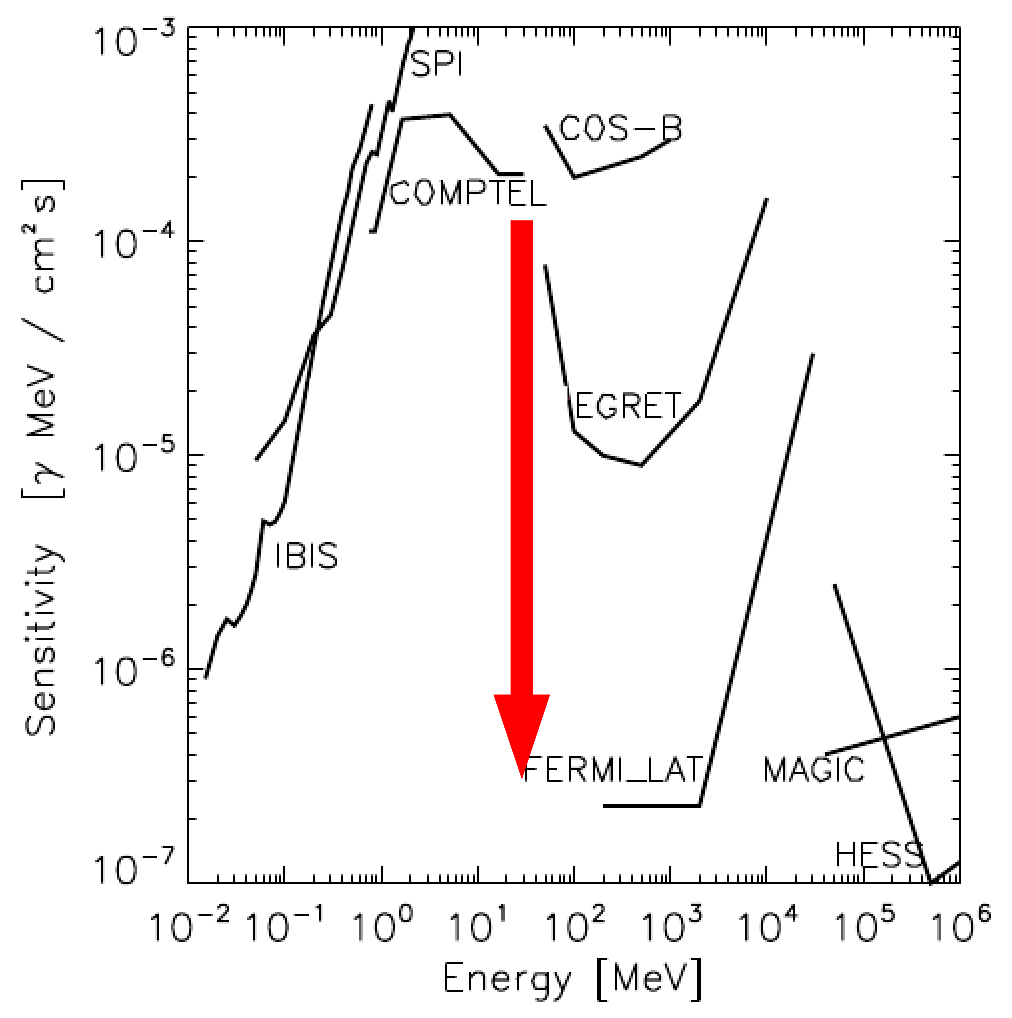




Galaxy luminosity over 20 decades of energy

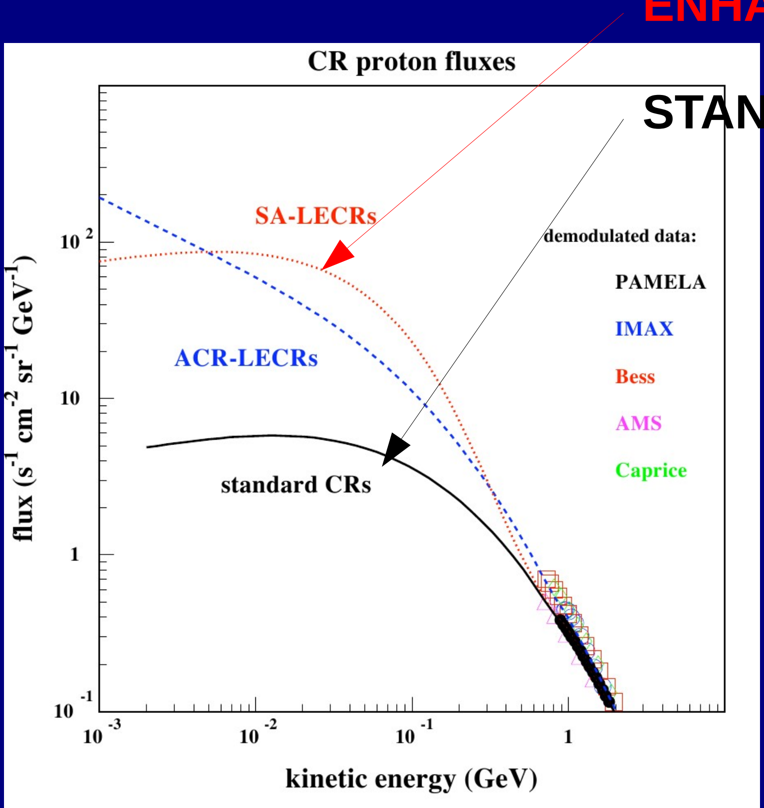


Cosmic-ray Electron Calorimeter !


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
IBIS
FERMI_LAT
MAGIC
HESS

Interstellar chemistry → ionization rates → cosmic rays → nuclear lines

Low energy cosmic rays



Ionization rate

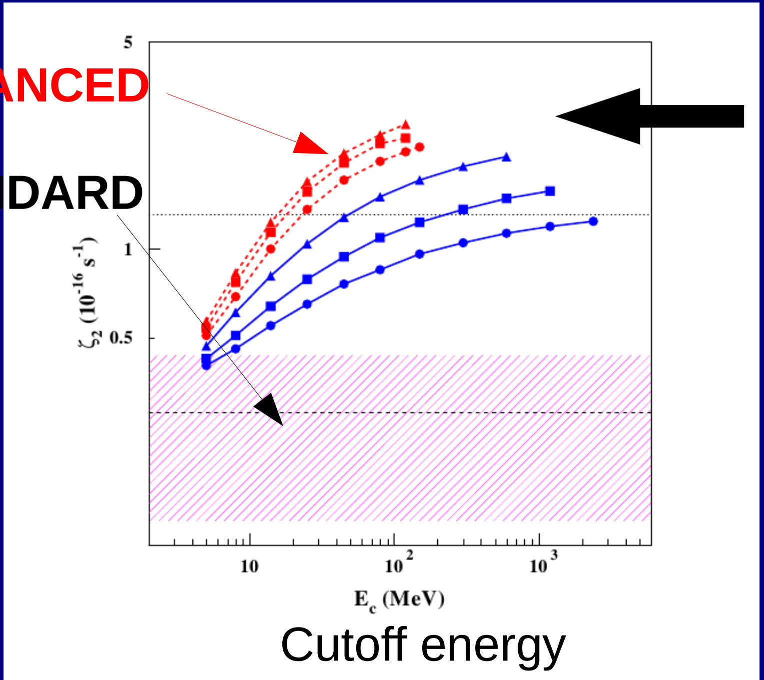


Fig. 4.— Calculated ionization rates of cosmic rays in dense molecular clouds supposing that particles with energies below 10 MeV per nucleon do not penetrate these places. Red symbols (connected by the dashed lines) show the values for SA-LECRs with spectral indices $s = 2.0$ (triangles), $s = 2.35$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

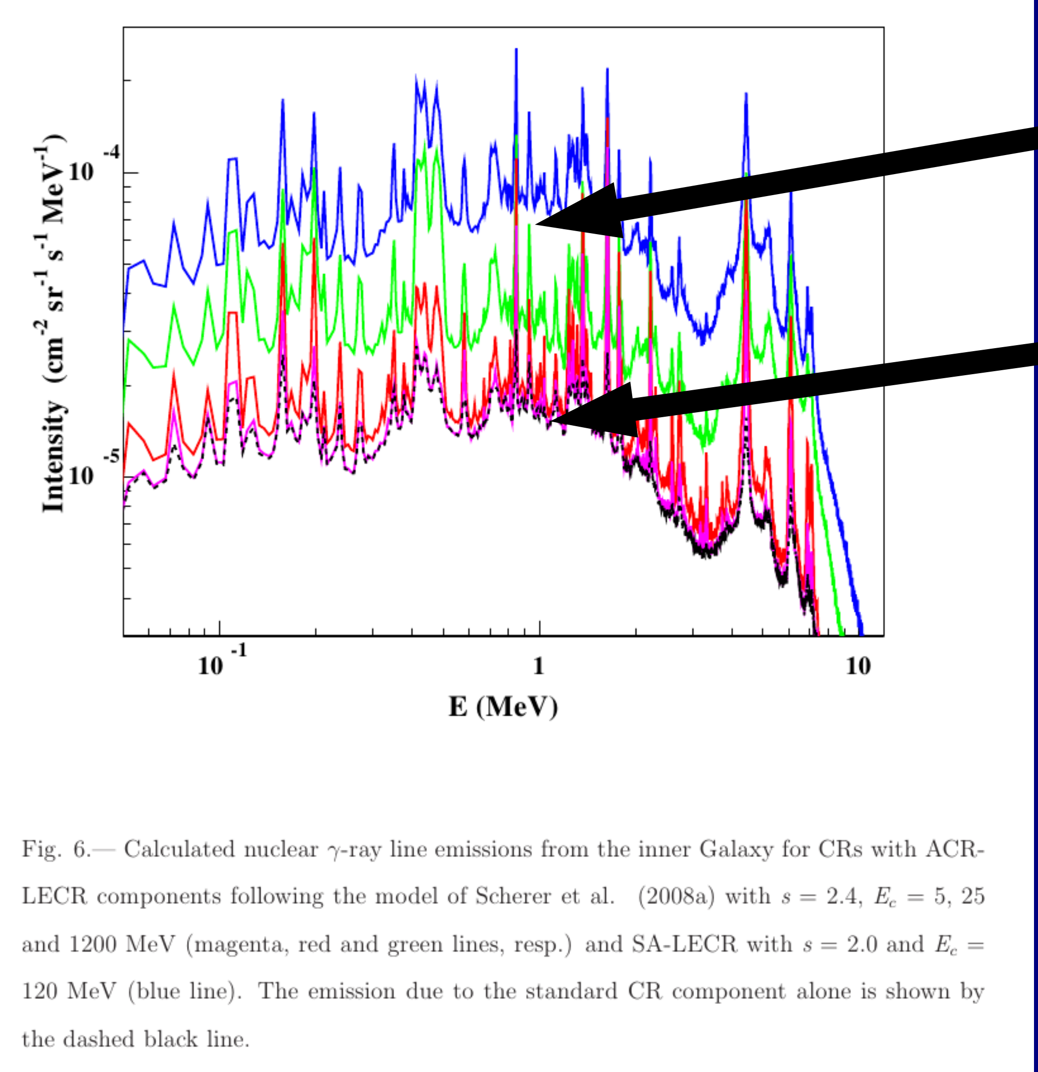


Fig. 6.— Calculated nuclear γ-ray line emissions from the inner Galaxy for CRs with ACR-LECR components following the model of Scherer et al. (2008a) with $s = 2.4$, $E_c = 5$, 25 and 1200 MeV (magenta, red and green lines, resp.) and SA-LECR with $s = 2.0$ and $E_c = 120$ MeV (blue line). The emission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

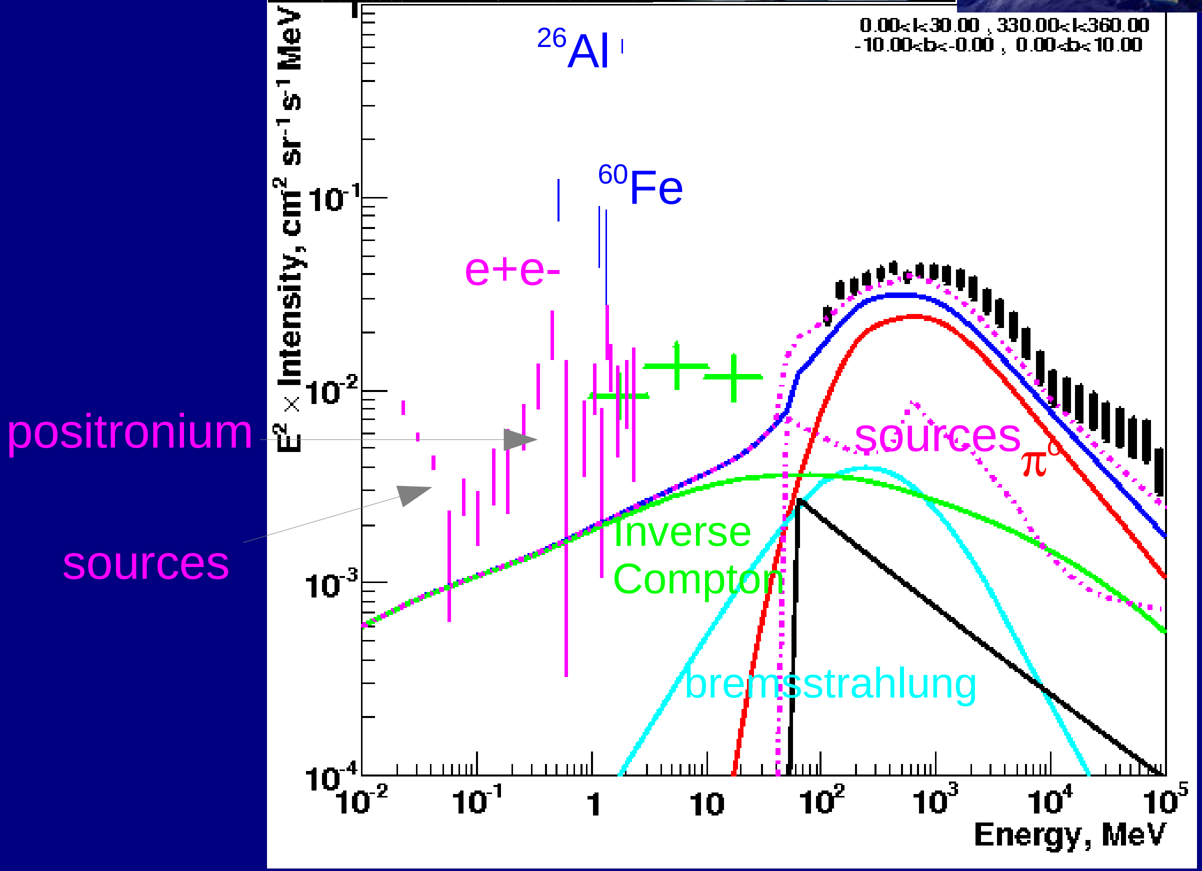
ENHANCED

STANDARD

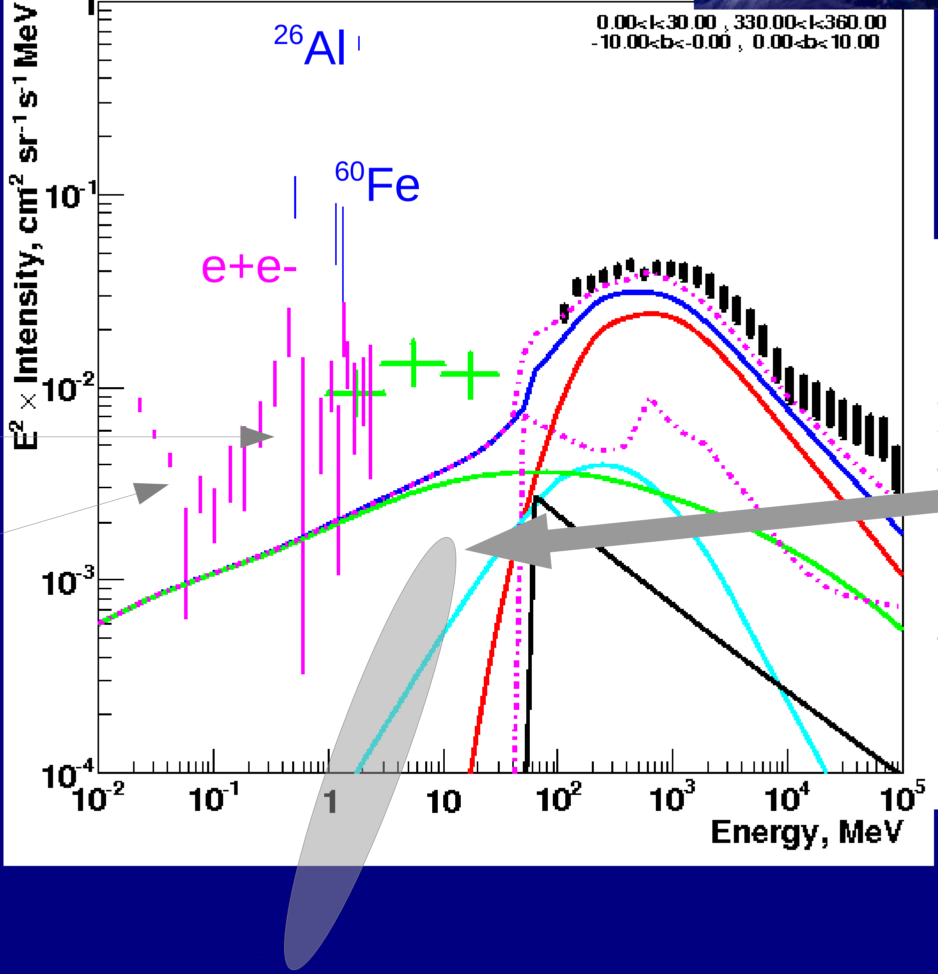
Benhabiles-Mezhoud,Kiener, Tatischeff & Strong, 2012, ApJ in press, arXiv 1212.1622

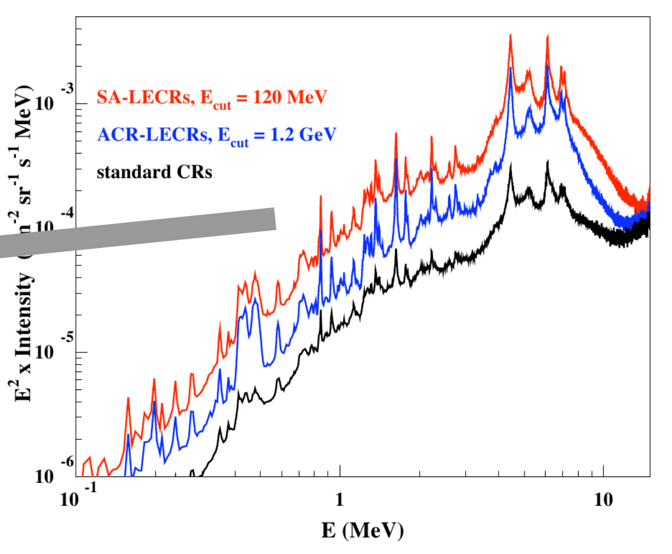
More chance to detect nuclear lines !

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