The interstellar cosmic-ray spectra from synchrotron and gamma rays

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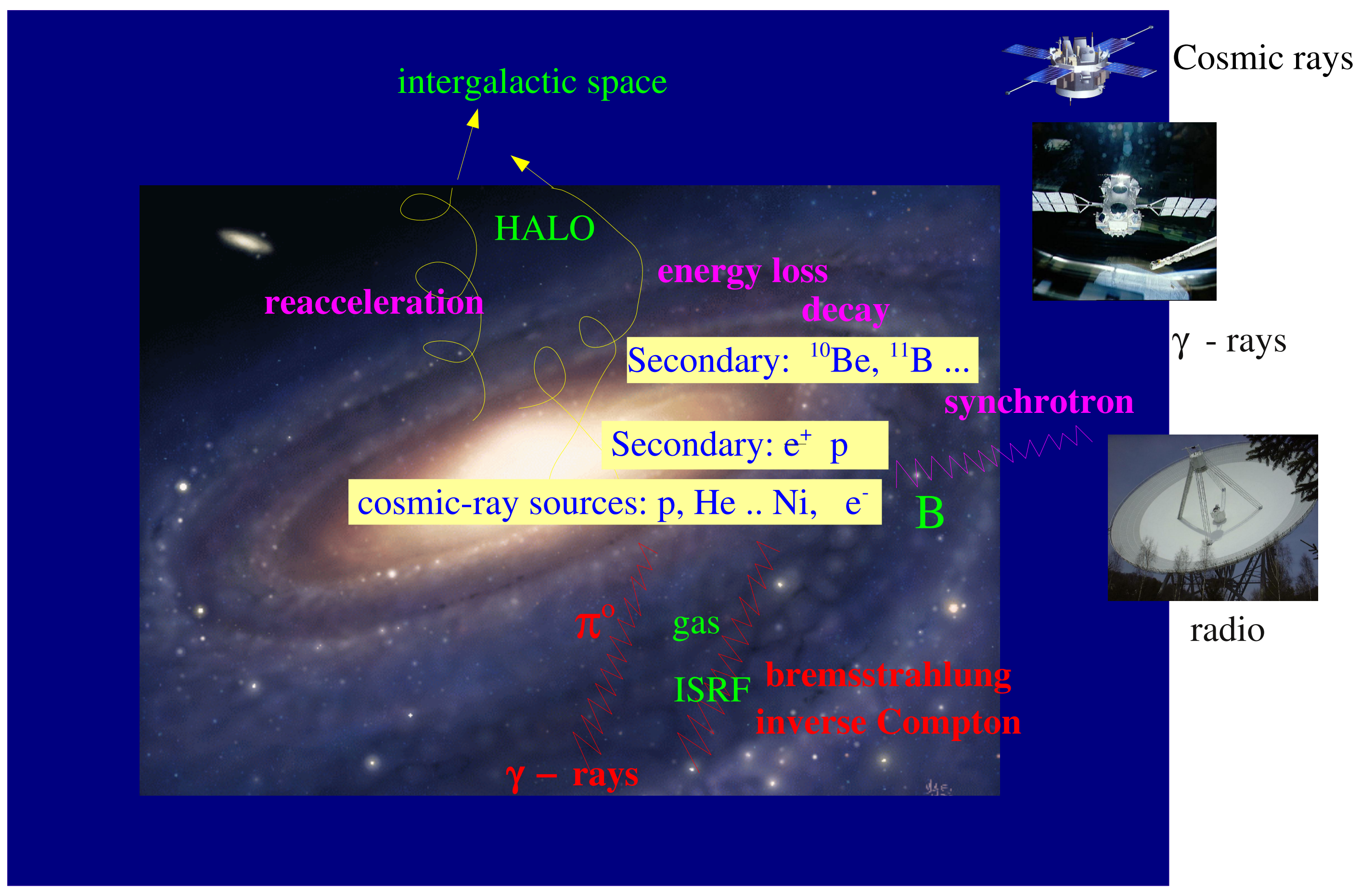
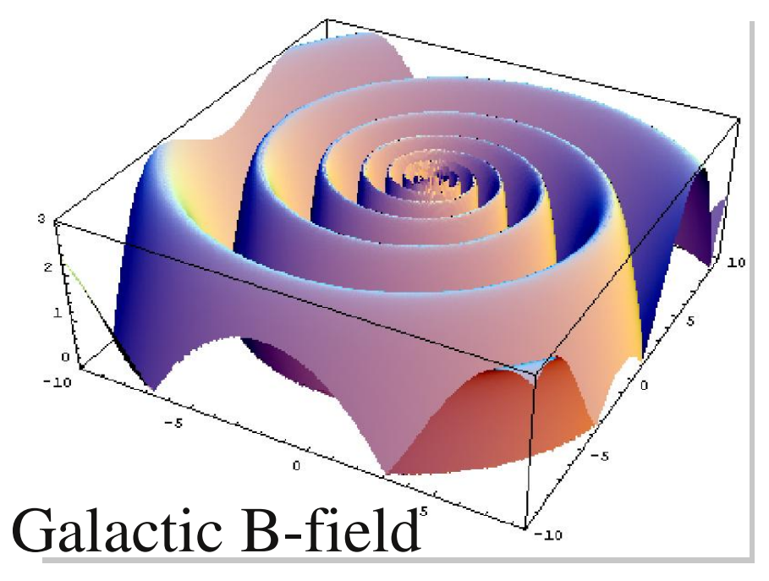
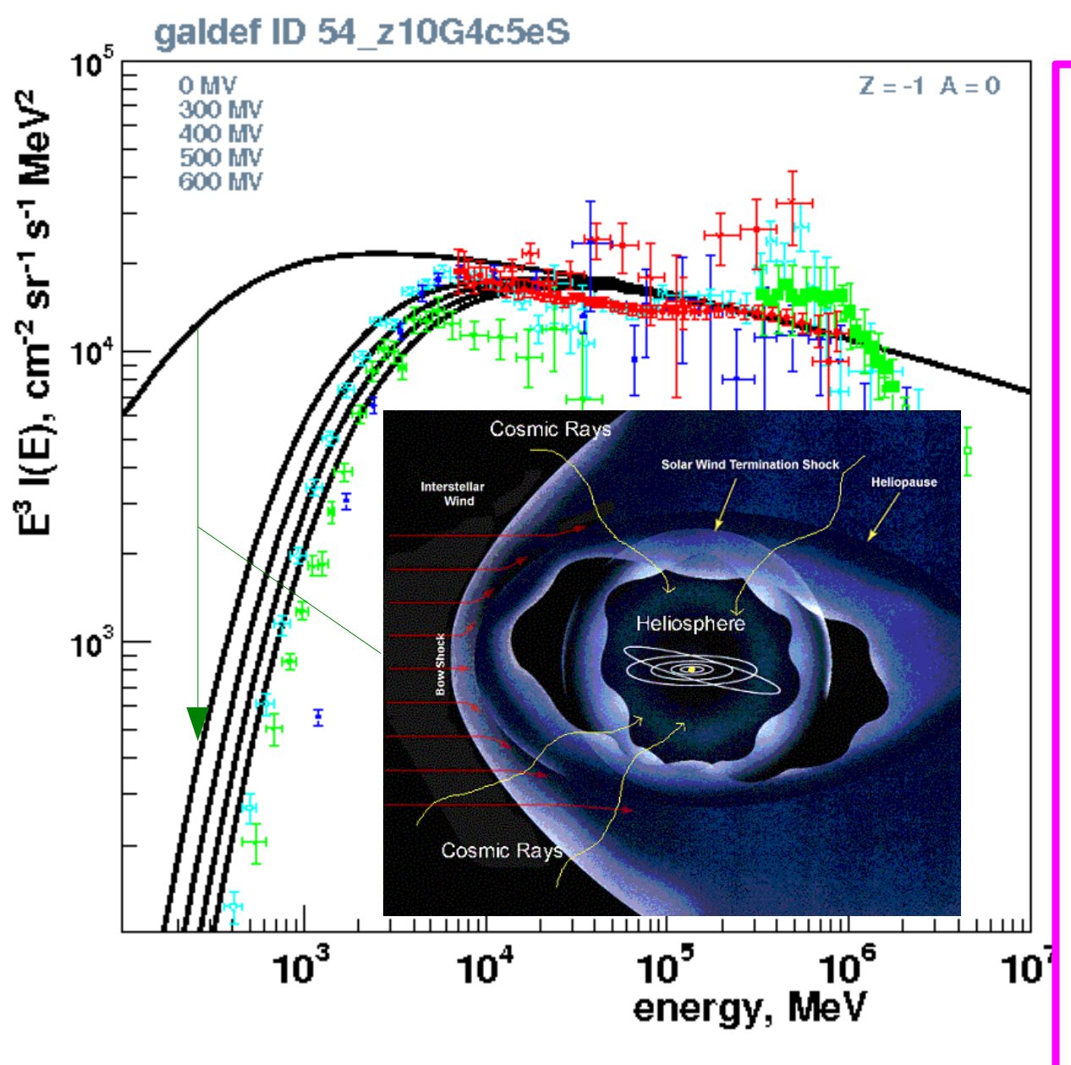
The interstellar electron (and positron) spectra are difficult to determine at low energies due to solar modulation. Synchrotron emission provides constraints which are independent of modulation, and which sample the Galaxy on the large scale. We use synchrotron surveys from 22 MHz to 94 GHz combined with direct measurements of electrons to obtain the ambient interstellar spectrum, and compare with models which relate this to the injection spectrum and cosmic-ray propagation. We also use the gamma-ray emissivity to determine the interstellar cosmic-ray proton spectrum, and compare the form in kinetic energy with that in momentum.

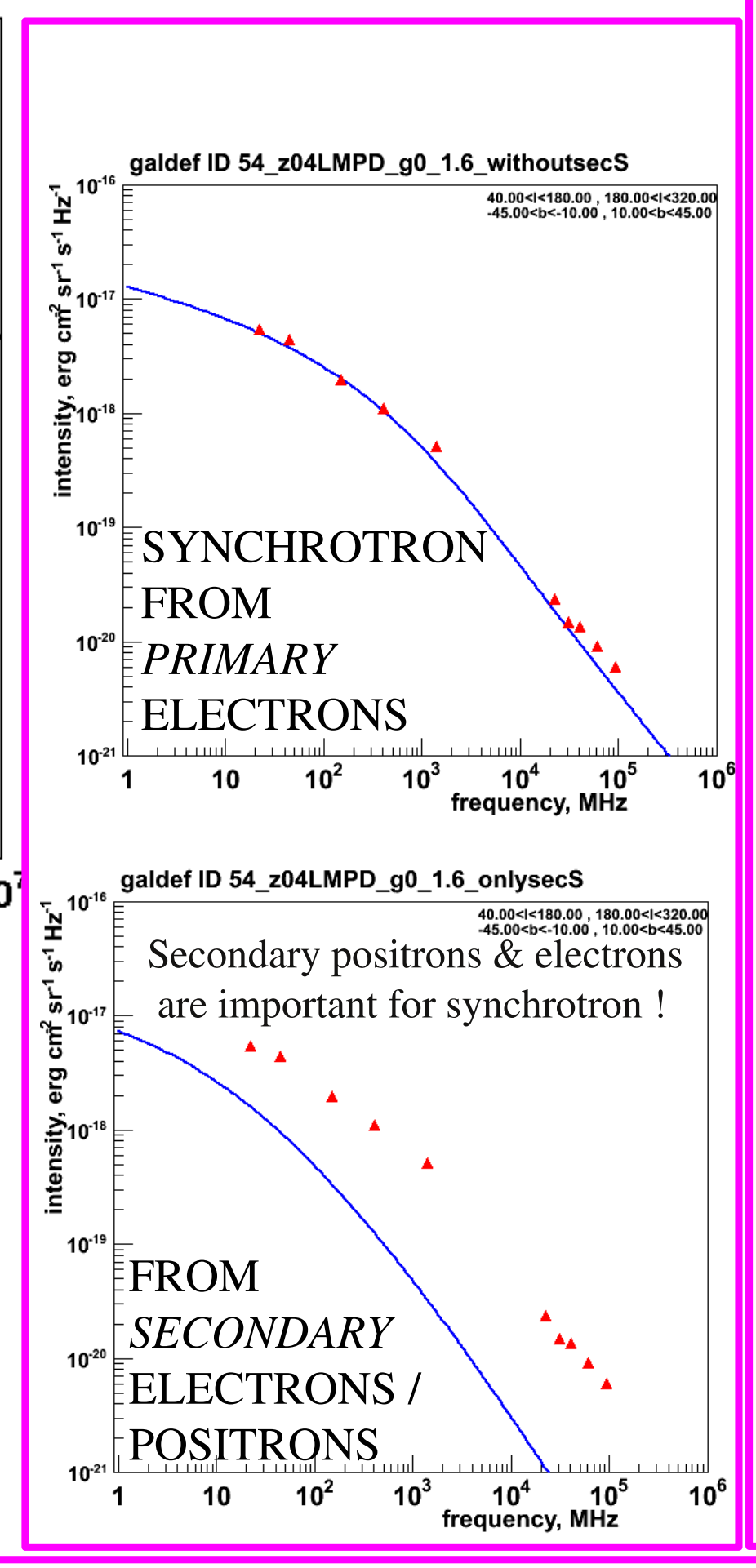
LEPTONIC COMPONENT





Galactic B-field

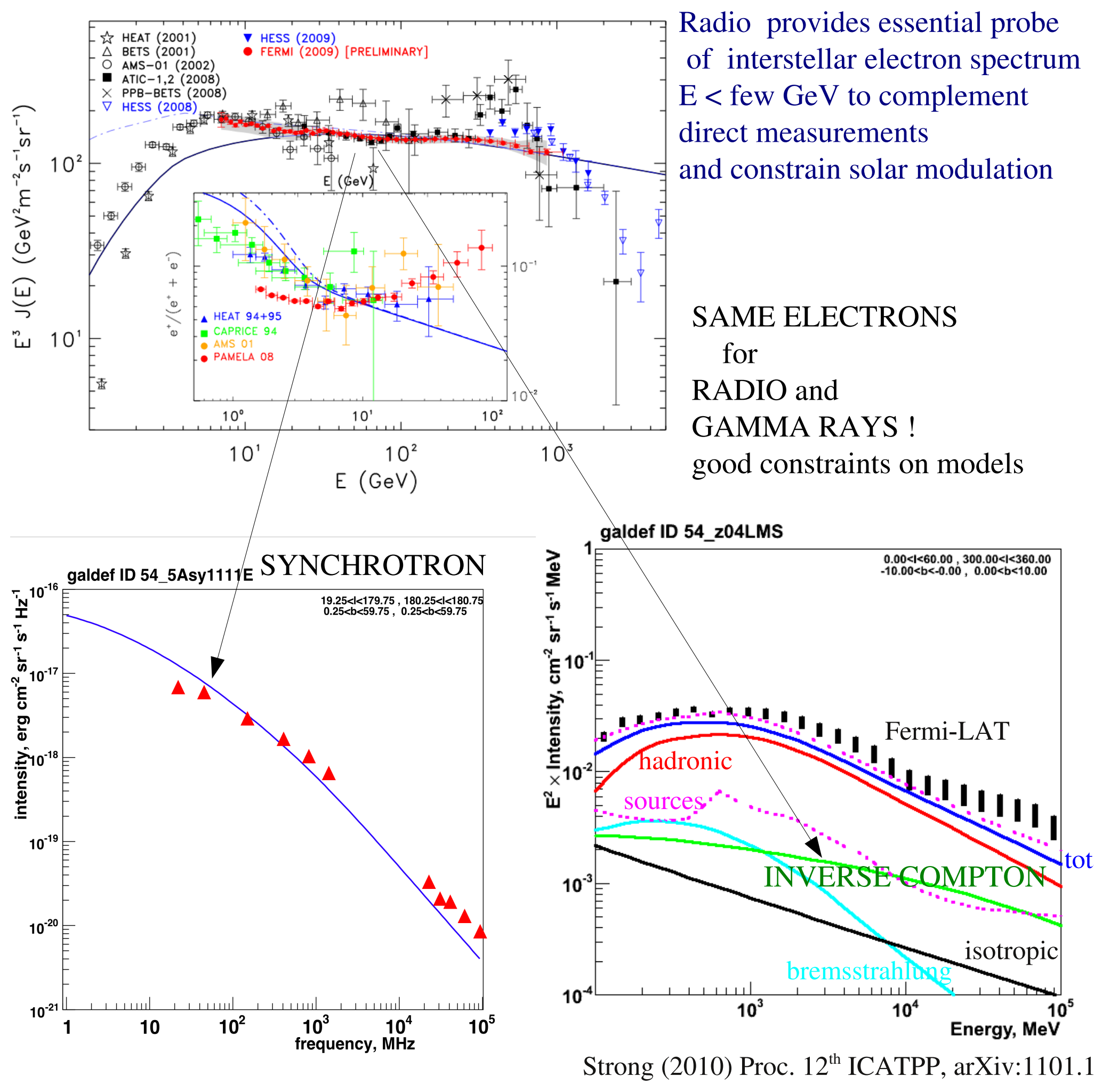




SYNCHROTRON FROM *PRIMARY* ELECTRONS

Secondary positrons & electrons are important for synchrotron !

FROM *SECONDARY* ELECTRONS / POSITRONS



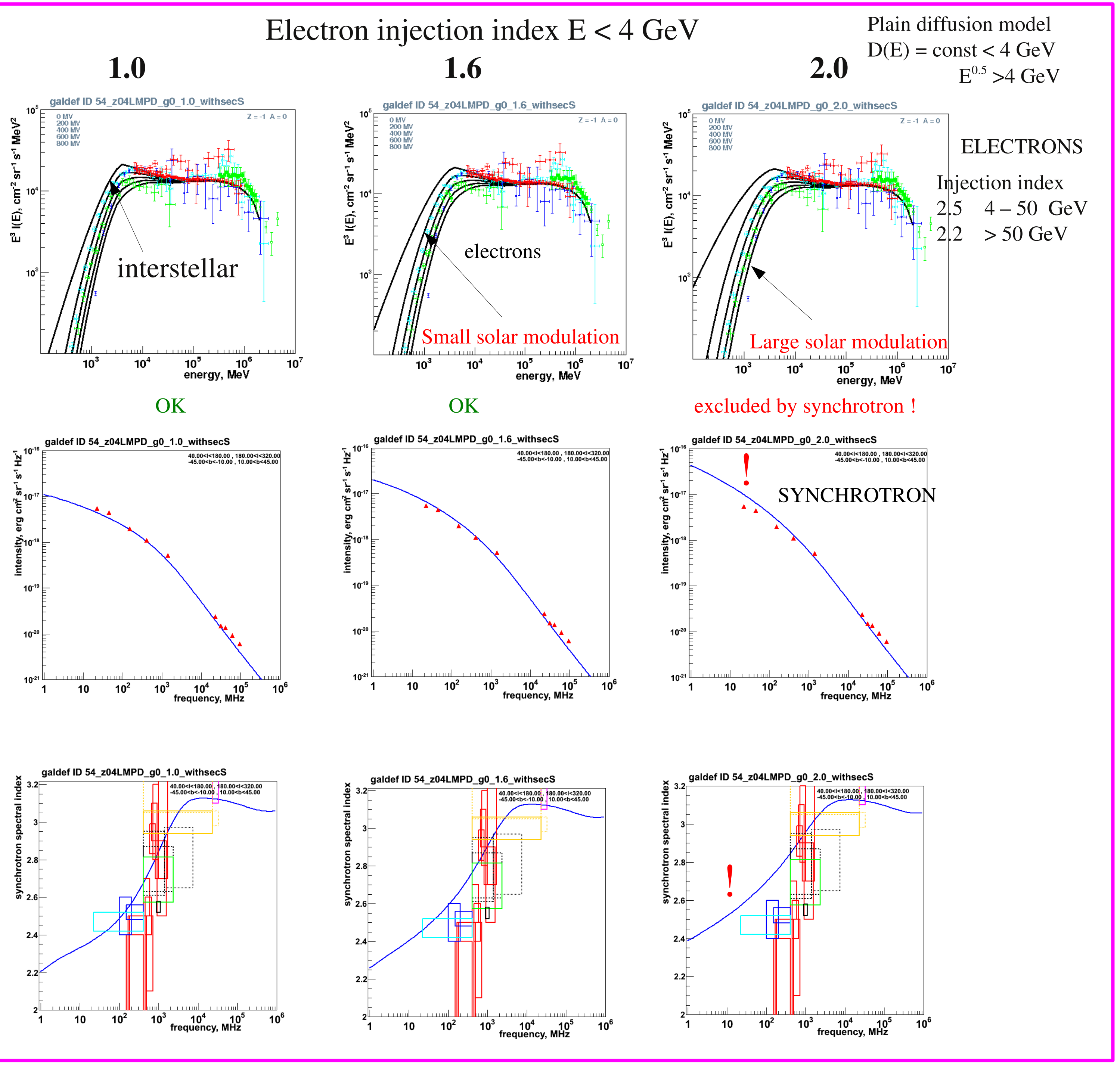
Radio provides essential probe of interstellar electron spectrum E < few GeV to complement direct measurements and constrain solar modulation

SAME ELECTRONS
for
RADIO and
GAMMA RAYS !
good constraints on models

Strong (2010) Proc. 12th ICATPP, arXiv:1101.1381

Electron injection index E < 4 GeV

Plain diffusion model
D(E) = const < 4 GeV
$E^{0.5}$ >4 GeV

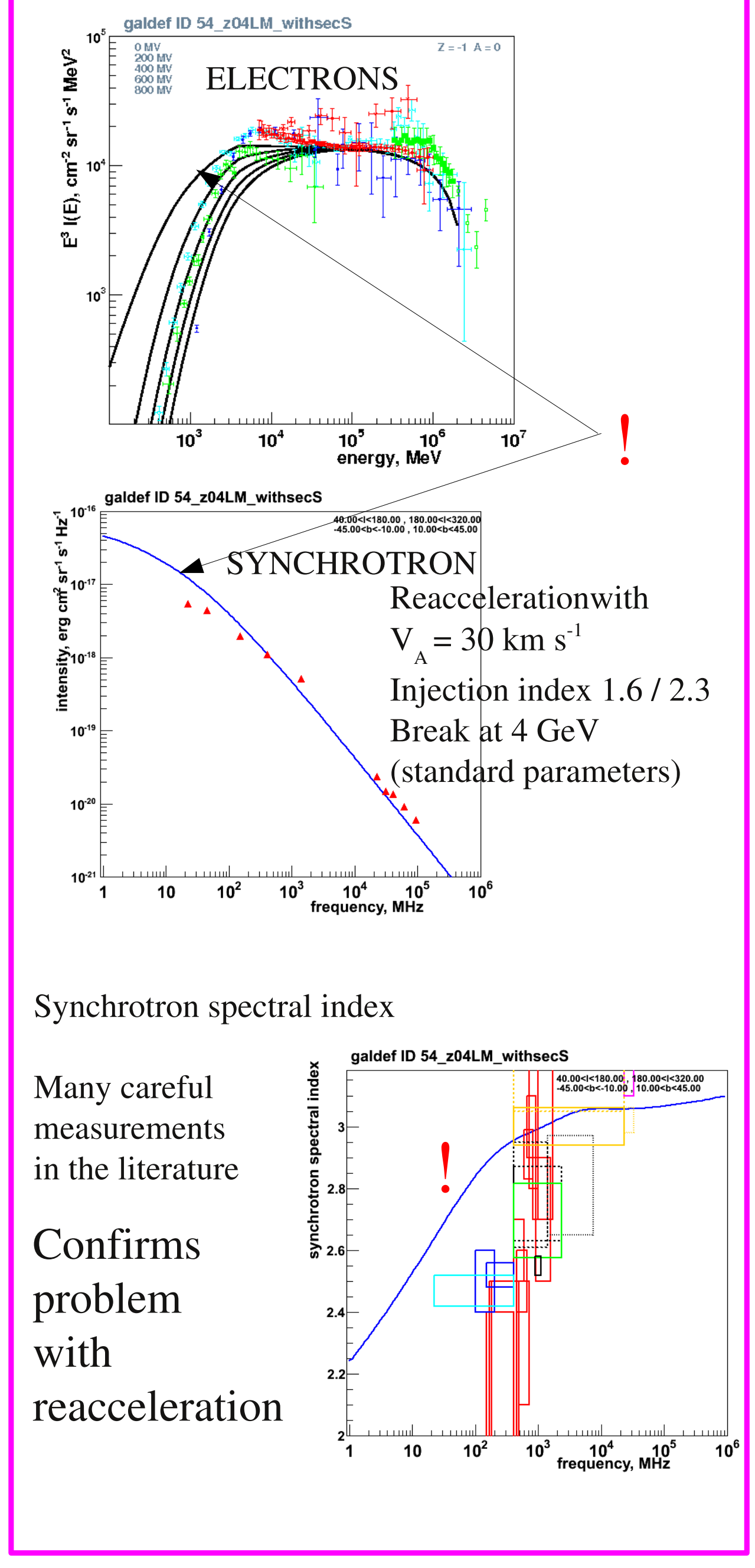


ELECTRONS

Injection index
2.5 4 – 50 GeV
2.2 > 50 GeV

OK OK excluded by synchrotron !

Diffusive reacceleration model – in trouble with synchrotron ?



Reaccelerationwith
V_A = 30 km s^{-1}
Injection index 1.6 / 2.3
Break at 4 GeV
(standard parameters)

Synchrotron spectral index

Many careful measurements in the literature

Confirms problem with reacceleration

Synchrotron provides an essential constraint on interstellar electrons which had not been fully exploited. By combining surveys over a wide frequency range with direct electron measurements, we can :

1. Obtain the interstellar electron spectrum independent of solar modulation
2. Use this to test models of propagation and injection

Main results :

1. The *ambient* interstellar electron spectrum has a break from index ~2 to ~3 around a few GeV
2. This requires *less* solar modulation than usually adopted for direct measurements.
3. The injection spectrum below a few GeV is 1.3 - 1.6 in pure diffusion models with D(E) = constant
4. Standard reacceleration models are *hard to reconcile* with the interstellar spectrum.
5. Secondary e$^+$ e$^-$ important for - and constrained by - radio emission

REFERENCE

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

HADRONIC COMPONENT

p-p, p-He, He-p, He-He + heavier nuclei → gamma rays via pions and direct production

Gamma-ray emissivity per H atom:
from Fermi-LAT, Abdo et al. (2009), ApJ 703, 1249 .
(E = 100 MeV – 10 GeV).
(For more recent Fermi results, see talk by Jean-Marc Casandjian, this conference.)

This allows the *interstellar proton spectrum* to be deduced.

The interstellar spectrum can then be compared with models of injection and propagation.
Below a few GeV: solar modulation important, can be used to test heliospheric models.

Hadronic production cross-sections still have uncertainties. Fermi-LAT accuracy is becoming limited by our knowledge of the basic physics. Here we use the Huang et al. (2007, APh. 27, 429) gamma-ray production matrices, using ISM composition and direct production at high energies (uses Kamae et al. (2006, ApJ 647, 692) at low energies, DPMJET-III at high energies).
Bremsstrahlung from electrons and positrons complicates the analysis, contributes for E < 1 GeV.

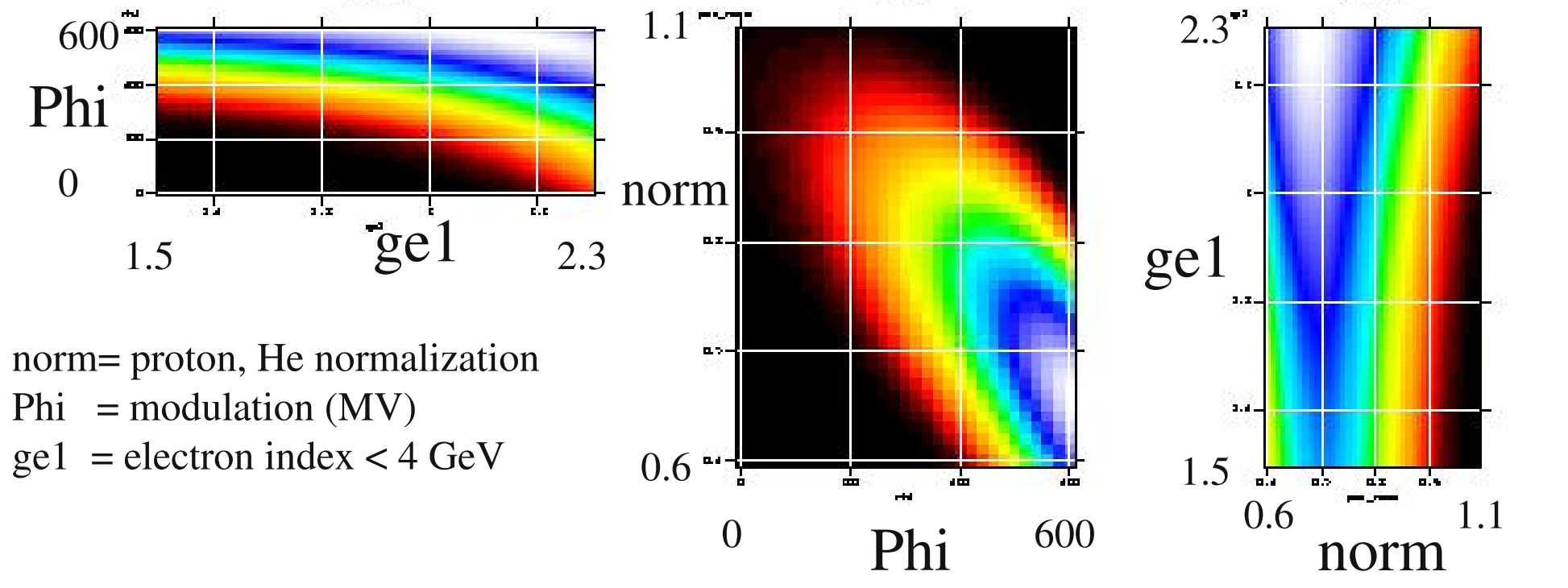
Method

Parameterize the *proton interstellar spectrum* by scaling factor and modulation parameter. As a basis we use the Shikaze et al. (2007, APh 28, 154) general formulation $f(\beta, p)$ used for BESS data.

Parameterize the *electron interstellar spectrum* using broken power-law, fixed to Fermi-LAT electron measurements > 7GeV, with a parameter for the spectral index below 4 GeV.
Compute prob(q(E) | protons, Helium, electrons) = prob (q(E)| **x**)
where q(E) = gamma-ray emissivity spectrum per H atom
x = vector of parameters for proton and electron spectra.
With only 3 parameters it is easy to cover explicitly the full parameter space, and perfom the required integrations.
Uniform prior within reasonable limits → posterior prob (**x** | q(E)).
Compute posterior proton spectrum = $\int$prob (I(E_k(**x**)) d^N**x** at each E_k.

The resulting spectrum is thus averaged over the parameterization so robust against the particular form chosen (i.e. it is not a best-fit but a weighted average of models). The method can be extended to any parameterization or even use a free-form spectrum.

Marginalized posterior probability



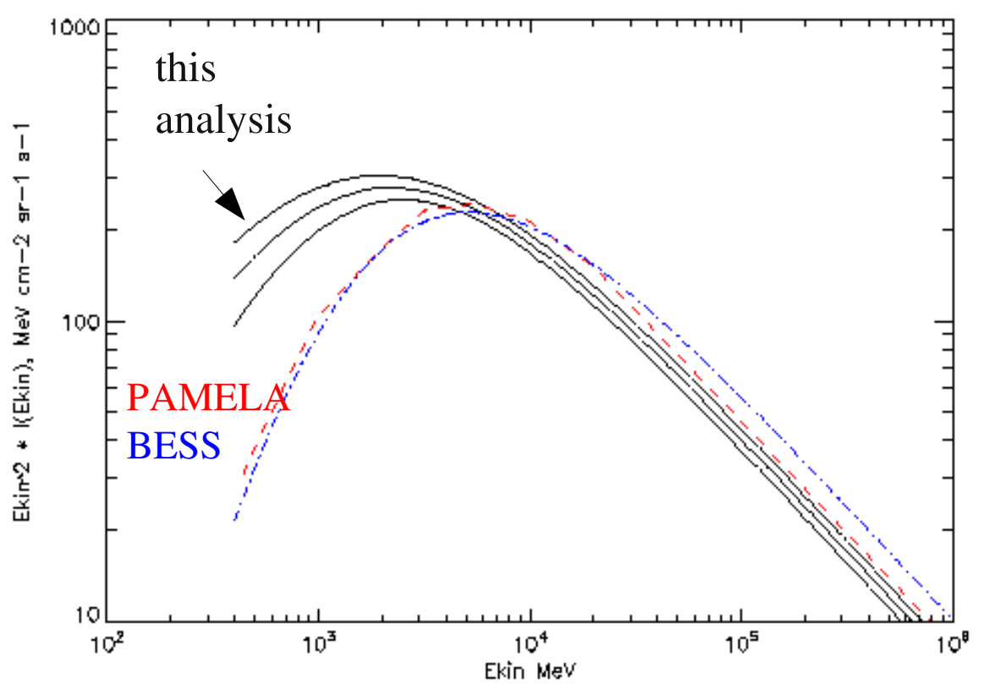
norm= proton, He normalization
Phi = modulation (MV)
ge1 = electron index < 4 GeV

The correlation between the parameters is evident. The normalization and the electron index are orthogonal since the high energies determine the normalization. The normalization and Phi are highly correlated, Phi and electron index are less correlated.

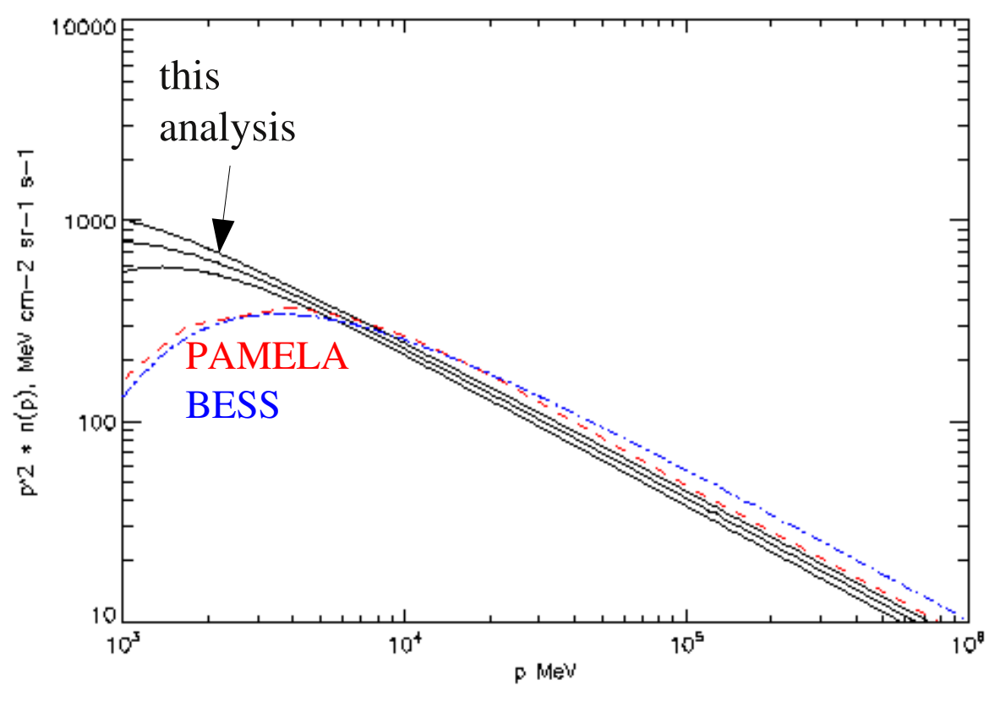
Protons

flux as function of kinetic energy E_k
with standard deviation range.
Exhibits large break in flux(E_k).
At high energies it is slighly lower than BESS,
But agrees better with PAMELA,

At low energies the modulation of the interstellar spectrum is manifest.



density as function of momentum *p*.
$n(p) = (4\pi/c)\, I(E_k(p))$
the spectrum is much less structured when represented as density spectrum in momentum (cf. Dermer arXiv:1206.2899 :
power law expected from shock acceleration).
The spectrum does not show any sign of the bump which would be expected from propagation with large reacceleration
(see also electrons analysis on the left panel).



Outlook

Emissivities from Fermi-LAT will allow accurate determination of interstellar protons for comparison with models.

Interpreting the Fermi-LAT data requires improvements in the accuracy of physics production cross-sections !

Combining these constraints with those from synchrotron emission is the obvious next step to remove the remaining degeneracy in separating the hadronic from the leptonic emission.