Cosmic ray studies with GALPROP

Andy Strong
MPE Garching

Cosmic-ray backgrounds in Dark Matter Searches

Alba Nova, Stockholm
25-27 Jan 2010

Remember
Tango in Paris ?

Annual Reviews of Nuclear and Particle Science, 2007

REVIEWS IN ADVANCE

Cosmic-Ray Propagation and Interactions in the Galaxy

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Key Words

energetic particles, gamma rays, interstellar medium, magnetic fields, plasmas

Abstract

We survey the theory and experimental tests for the propagation of cosmic rays in the Galaxy up to energies of 10^{15} eV. A guide to the previous reviews and essential literature is given, followed by an exposition of basic principles. The basic ideas of cosmic-ray propagation are described, and the physical origin of its processes is explained. The various techniques for computing the observational consequences of the theory are described and contrasted. These include analytical and numerical techniques. We present the comparison of models with data, including direct and indirect—especially γ-ray—observations, and indicate what we can learn about cosmic-ray propagation. Some important topics, including electron and antiparticle propagation, are chosen for discussion.

Quote......

It is unclear whether one would wish to go much beyond the generalizations discussed here for an analytically soluble diffusion model. The added insight from any analytic solution of a purely numerical approaches is quickly cancelled by the growing complexity of the formulae. With rapidly developing computational capabilities, one could profitably employ numerical solutions....

Quote......

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----------------- J.M. Wallace, ApJ, 1981

Quote......

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----------------- J.M. Wallace, ApJ, 1981

more than ¼ century ago

' We are not alone '.

Other *numerical* propagation codes e.g.

Evoli / Maccione / Gaggero / Grasso	DRAGON code (similar to GALPROP)
Buesching/Pohl	Green's function approach
DeMarco/ Blasi/Stanev	Trajectory approach, for > 1 PeV
Hanasz, Lesch, Koturba	PIERNIK code: MHD, CR= fluid. CR-driven dynamo

They emphasize other aspects than GALPROP,

Analytical propagation code:

Putze, Derome, Maurin ..	USINE: most advanced on the market

Guiding principle:

to fit a wide range of data even approximately
is more important than
to fit a small range of data precisely

The original motivation :

- to escape from the leaky-box

into the Galaxy

but now...
precision experiments e.g.
Fermi, PAMELA, AMS, ACE ....
require correspondingly *detailed* models to do them justice.

Leaky-box, path-length distribution models
these are numerical 0-D models

not discussed here since we regard them as outdated.

But it is a well-known fact that for stable nuclei without energy losses, these methods can be designed to produce the same results as propagation models,

So OK for for cosmic-ray source composition studies.

For unstable nuclei, electrons, positrons, gamma rays.... not realistic enough to be useful

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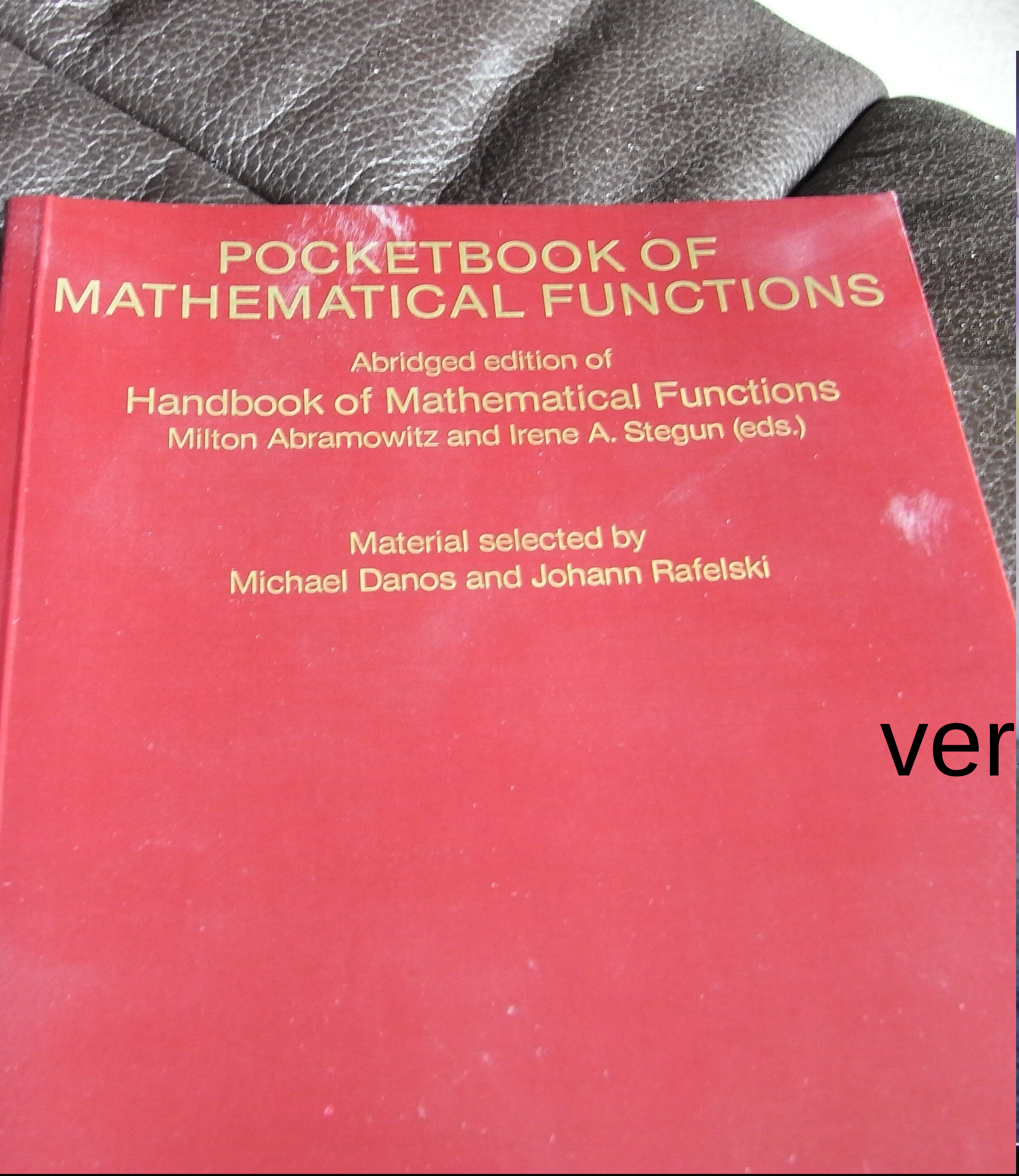
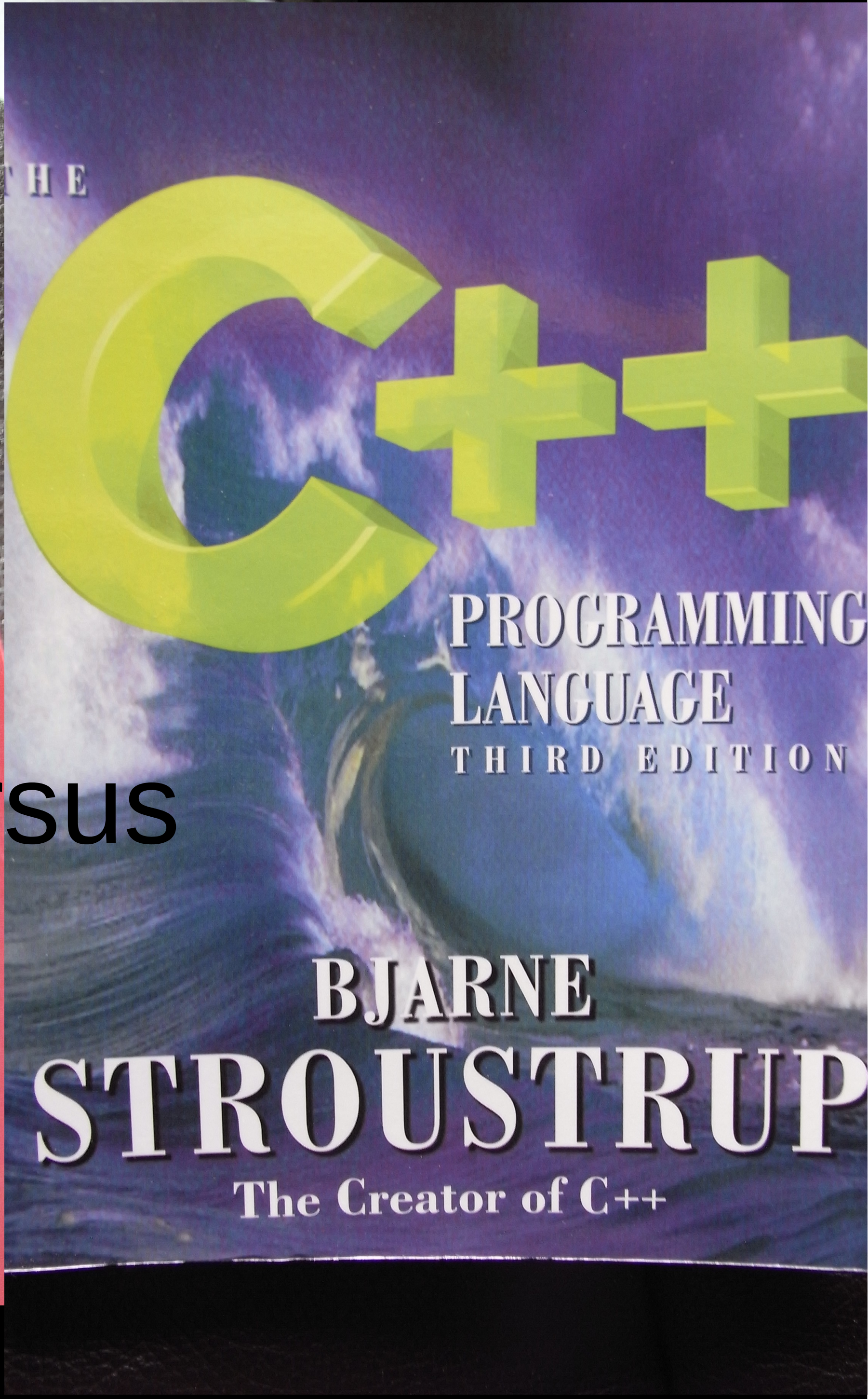
Spatial Propagation models

Advantage is the physical interpretation in terms of diffusion, convection etc.
related to the real Galaxy. Intuitive understanding of meaning of terms.

Both analytical and numerical, and hybrids, all have their proponents.


POCKETBOOK OF
MATHEMATICAL FUNCTIONS
Abridged edition of
Handbook of Mathematical Functions
Milton Abramowitz and Irene A. Stegun (eds.)
Material selected by
Michael Danos and Johann Rafelski

versus


C++
PROGRAMMING
LANGUAGE
THIRD EDITION
BJARNE
STROUSTRUP
The Creator of C++

Propagation models

A main advantage is the physical interpretation in terms of diffusion, convection etc. related to the real Galaxy. Intuitive understanding of meaning of terms.

1D, 2D, or 3D
Both analytical and numerical, and hybrids, all have their proponents.

Analytical	Numerical
Mainly 1D, some 2D	2D or 3D
complex (but impressive) formulae	simple formulae (computer does the work)
simplified energy losses	full energy losses
simplified gas distribution	gas based on HI, CO surveys in 3D
simplified magnetic field	any magnetic field model
gamma rays only in simple way	full gamma ray calculation
synchrotron only in simple way	full synchrotron calculation

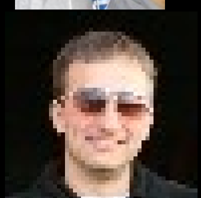
GALPROP code

Built up over more than 10 years by a small (but growing) team.

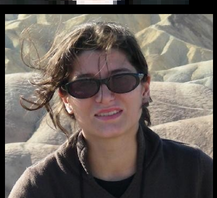
Dramatis personae:

Igor Moskalenko (Stanford) : physics processes. GALPROP website/forum

Troy Porter (UCSC): interstellar radiation field, configuration



Gulli Johannesson (Stanford): HEALPix, parallelization, gas surveys, Fermi interface



Elena Orlando (MPE) : magnetic fields and synchrotron

Seth Digel (Stanford): gas surveys specialist

Andy Strong (MPE) : project management, code hosting, and general coding

GALPROP

Public code (but new release slow in coming, sorry !)

Dedicated website *galprop.stanford.edu* for code and forum, ~90 registrations

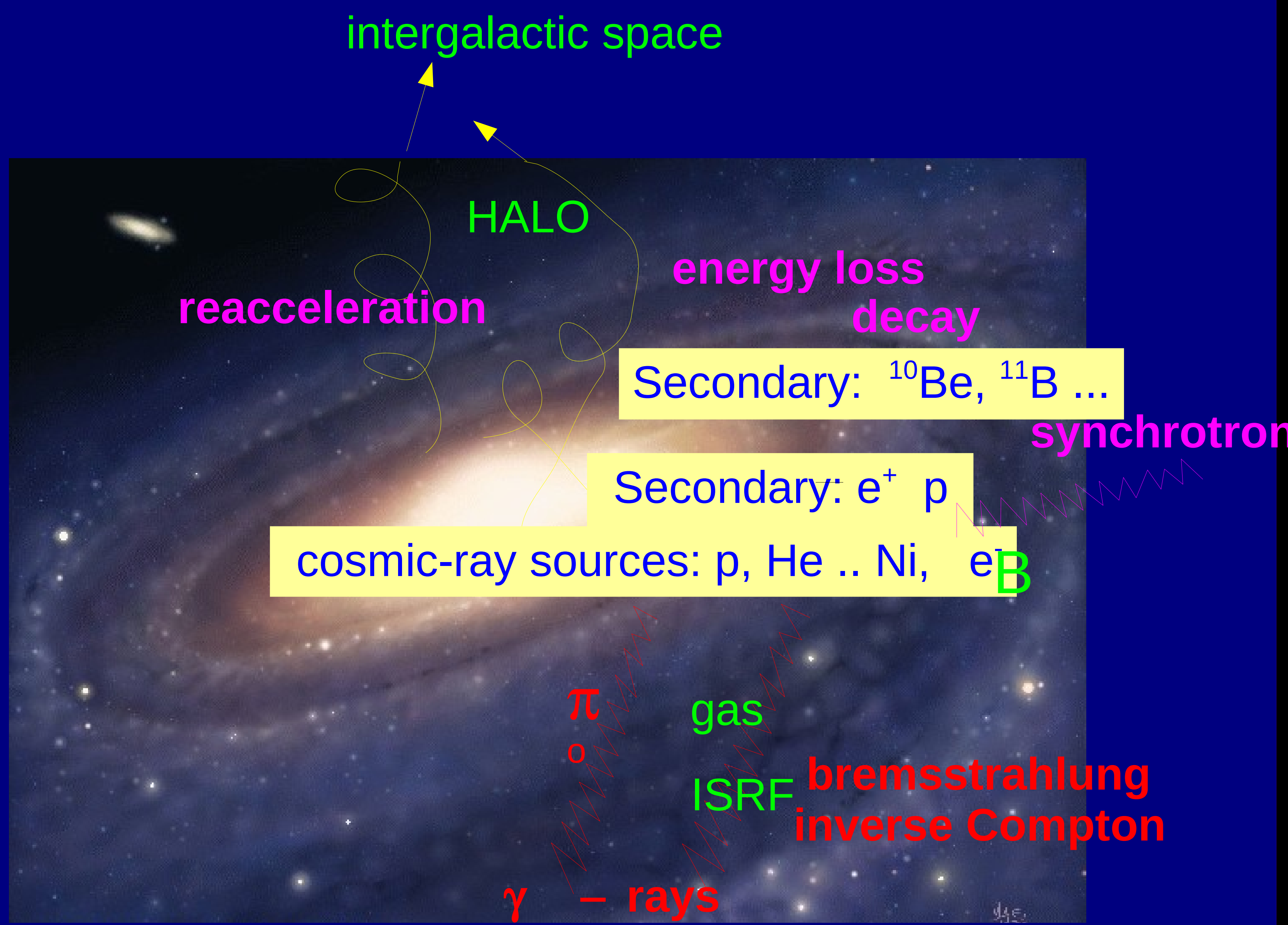
Used in many papers / year

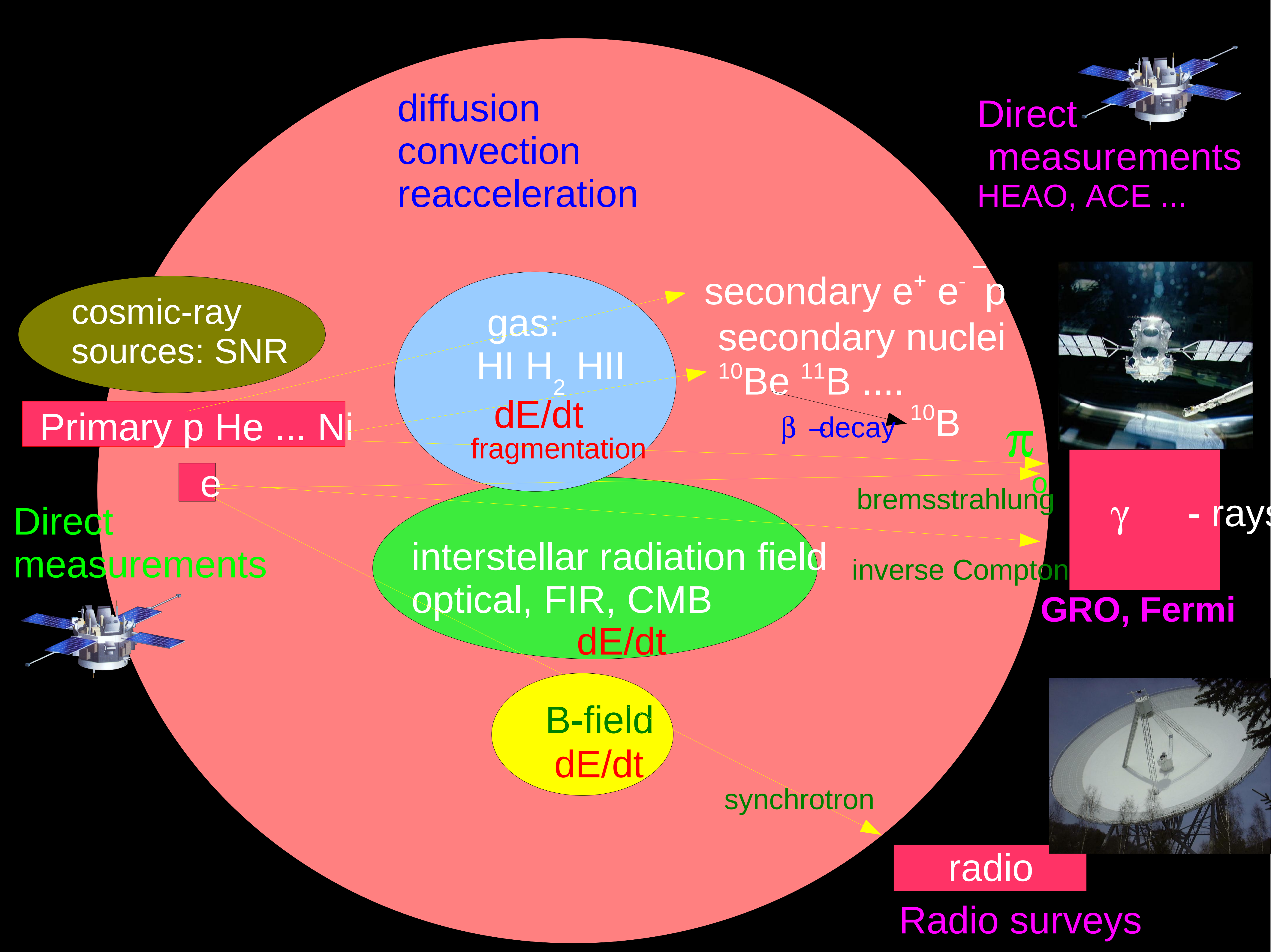
Adopted as standard model for Fermi, for both diffuse and source analysis

Need such a model to do justice to the quality of Fermi data

Other applications include contribution to Planck Galaxy model.

focus : cosmic-ray production & propagation in the Galaxy

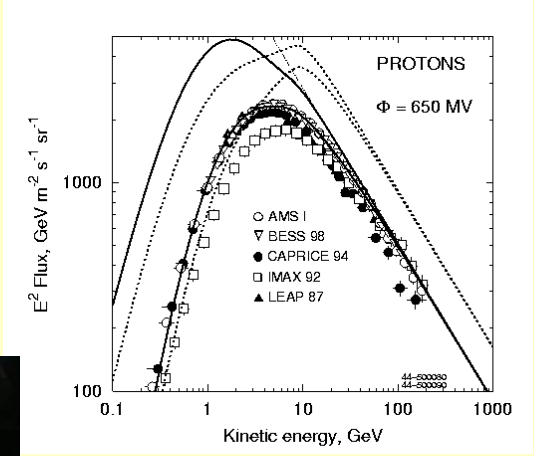

intergalactic space
HALO
reacceleration
energy loss
decay
Secondary: ^{10}Be, ^{11}B ...
synchrotron
Secondary: e^{+} p̄
cosmic-ray sources: p, He .. Ni, e^{-}
B
π^{o}
gas
ISRF
bremsstrahlung
inverse Compton
γ – rays

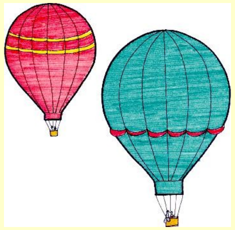

diffusion
convection
reacceleration
Direct
measurements
HEAO, ACE ...
cosmic-ray
sources: SNR
gas:
HI H2 HII
dE/dt
fragmentation
secondary e+ e- p̄
secondary nuclei
10Be 11B ....
β -decay
10B
Primary p He ... Ni
π0
e
bremsstrahlung
γ - rays
Direct
measurements
interstellar radiation field
optical, FIR, CMB
dE/dt
inverse Compton
GRO, Fermi
B-field
dE/dt
synchrotron
radio
Radio surveys

The **goal** : use *all* types of data in self-consistent way to test models of cosmic-ray propagation.

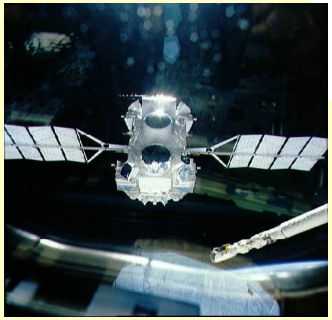
Observed *directly, near Sun:*

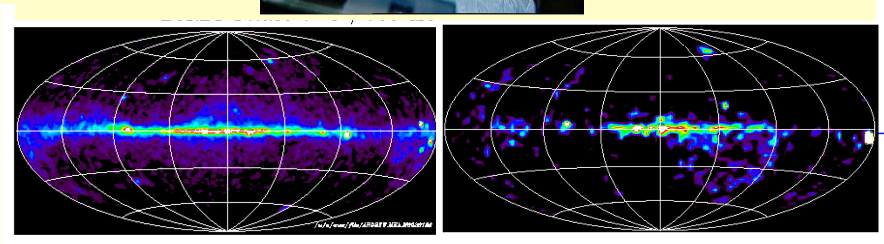
- primary spectra (p, He ... Fe; e^-)
- secondary/primary (B/C etc)
- secondary e^+ , pbar

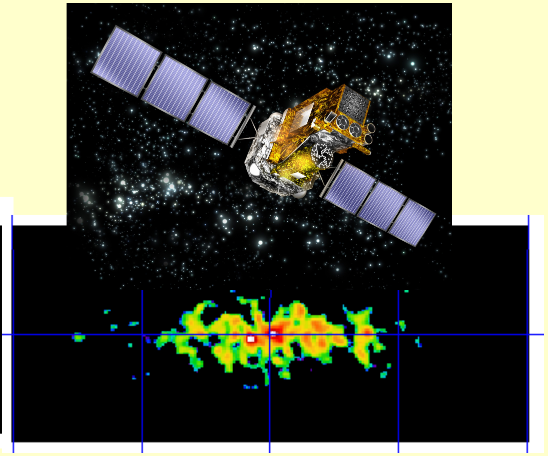




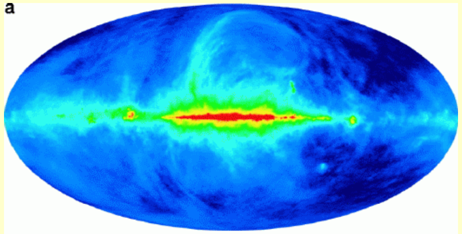
Observed *from whole Galaxy:*







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

How the propagation is computed:.

Linear equation, easy to solve.

2D or 3D grid, resolution down to 100 pc

$\Delta n = dn/dt \, \Delta t$ “

stabilized by Crank-Nicolson scheme

dn/dt = source terms + propagation terms

Δt = eg 1000 yrs

for steady-state, follow until dn / dt=0
(trick : start with large Δt and decrease Δt: finds steady-state fast)

or time-dependent solution if required eg for stochastic sources.

nuclei: start from ^{64}Ni and work down in (A, Z)
including secondary production
plus secondary positrons, electrons, pbar

primary electrons: separate species

Model for cosmic-ray propagation

3D gas model based on 21-cm (atomic H), CO (tracer of H_2) surveys

cosmic-ray sources *f* (r, E*)*

interstellar radiation field *f* (r, ν)

nuclear cross-sections database

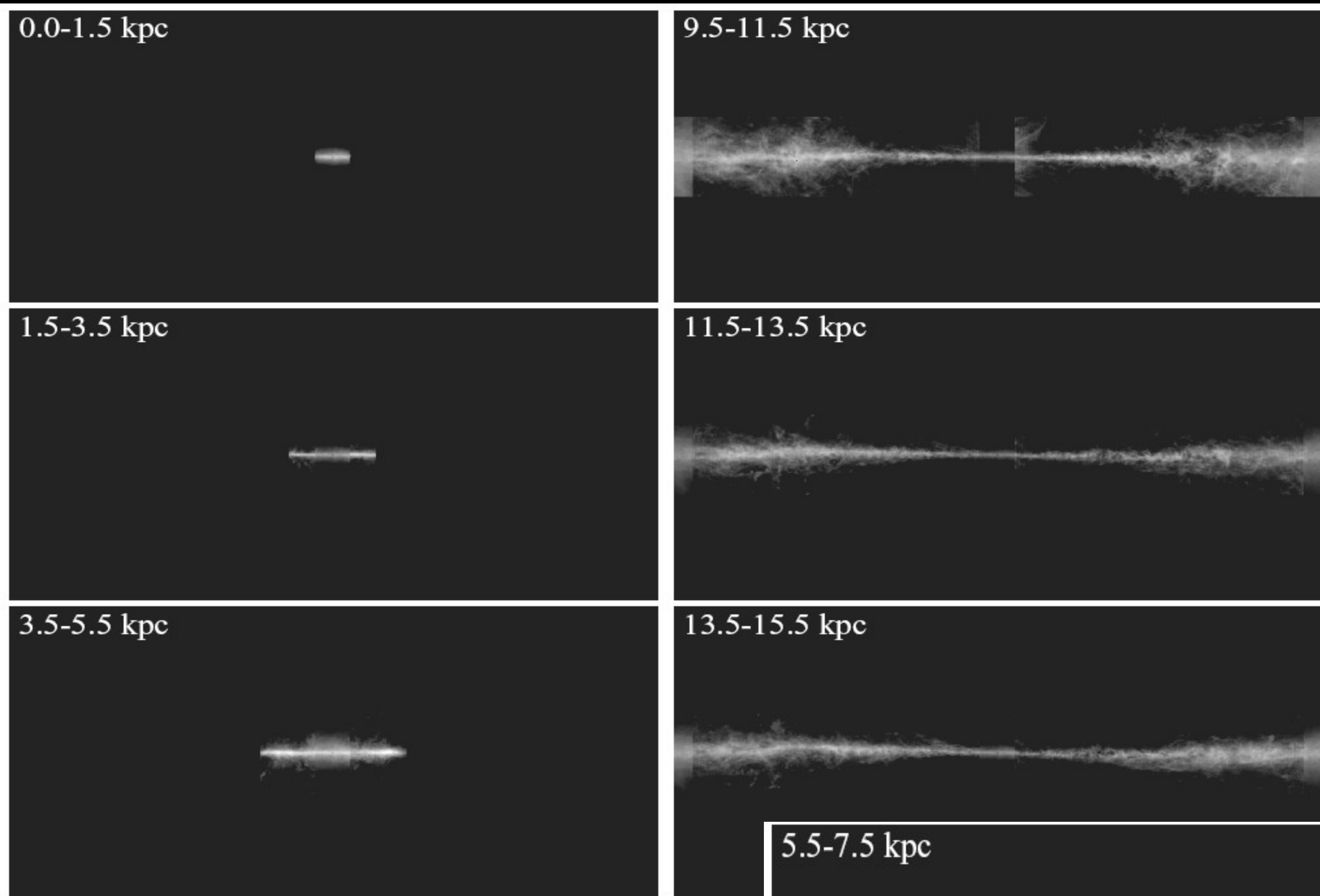
energy-loss processes

B-field model

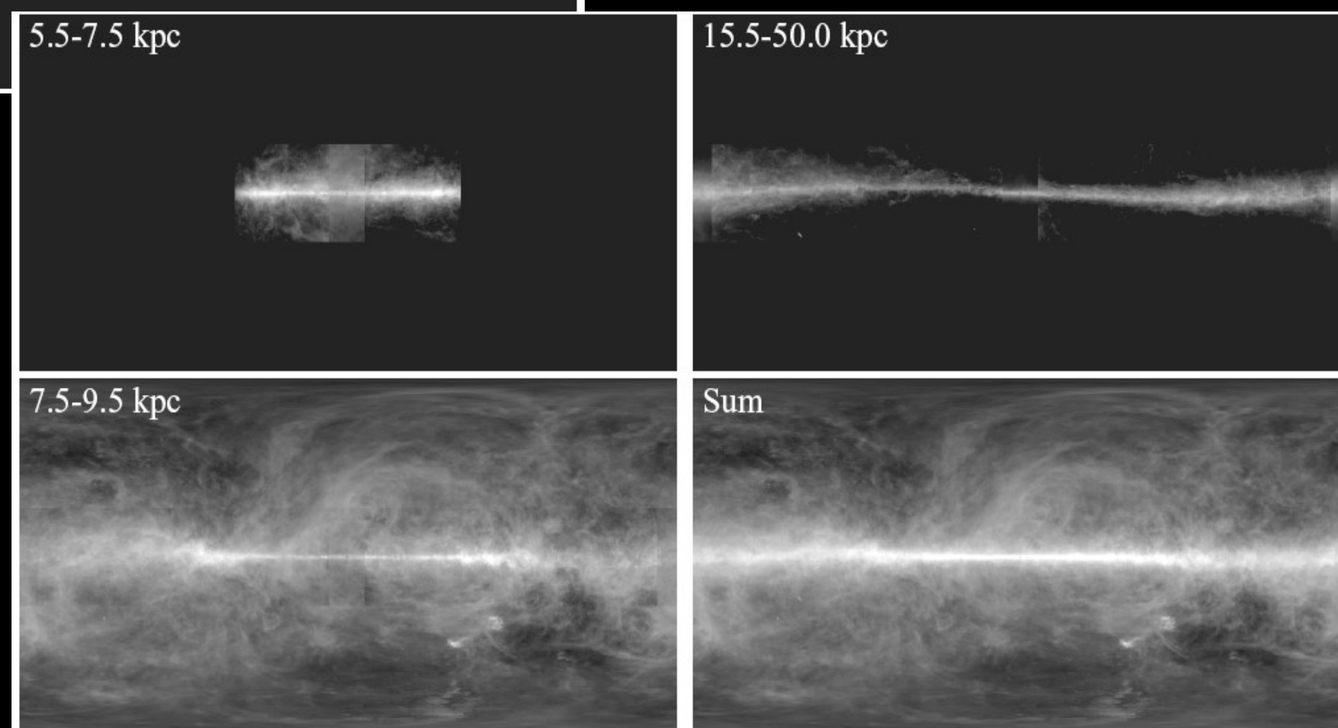
γ – ray, synchrotron

Gas Rings: HI Inner & Outer Galaxy

Seth Digel'05



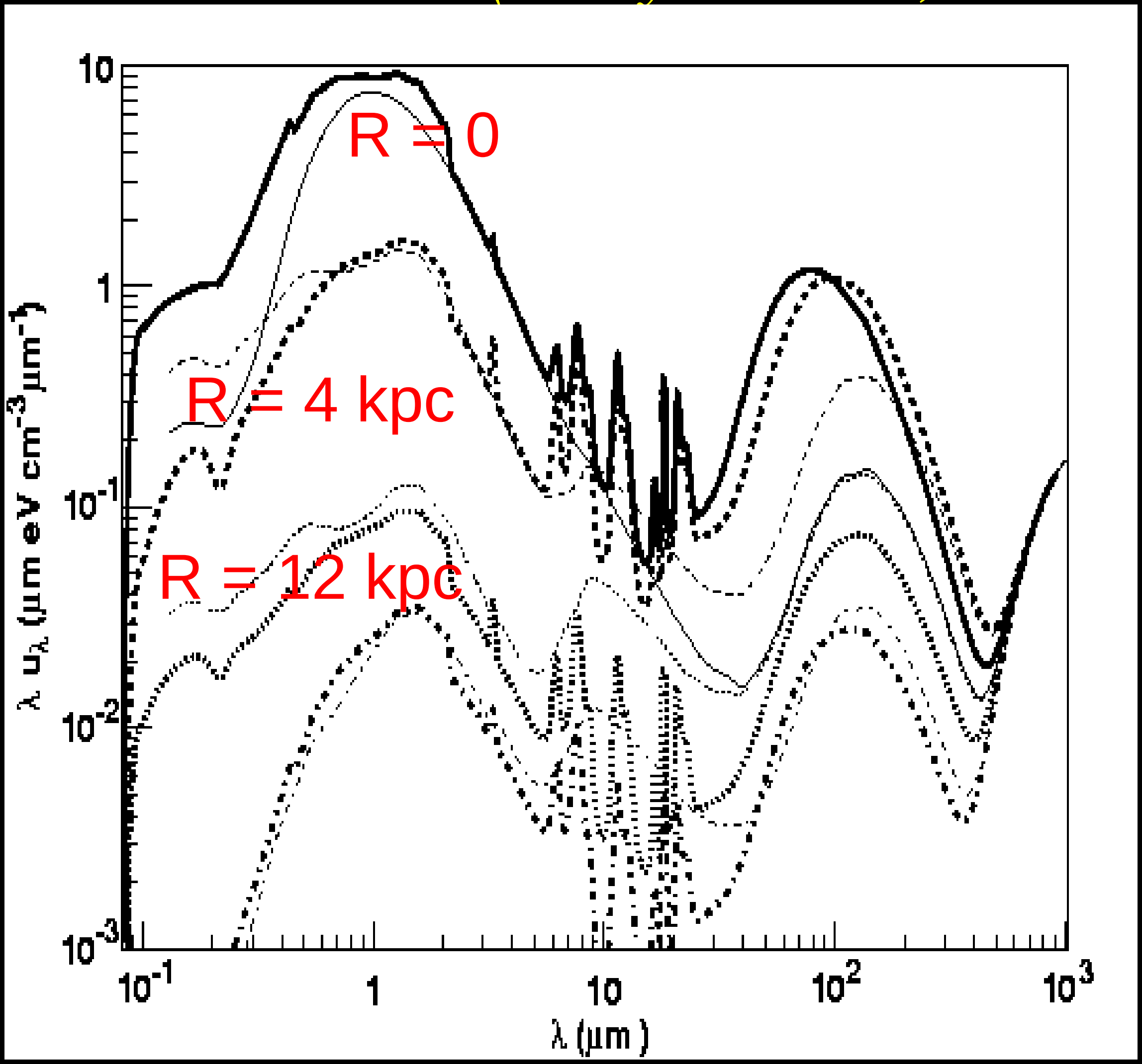
Gas Rings: HI Local Galaxy



Interstellar Radiation Field
(for electron dE/dt, inverse Compton γ -rays):
new model *(Troy Porter, UCSC)*

New *ISRF using latest information*

stellar populations, dust radiative transfer



UV optical IR FIR CMB

GALPROP computes:

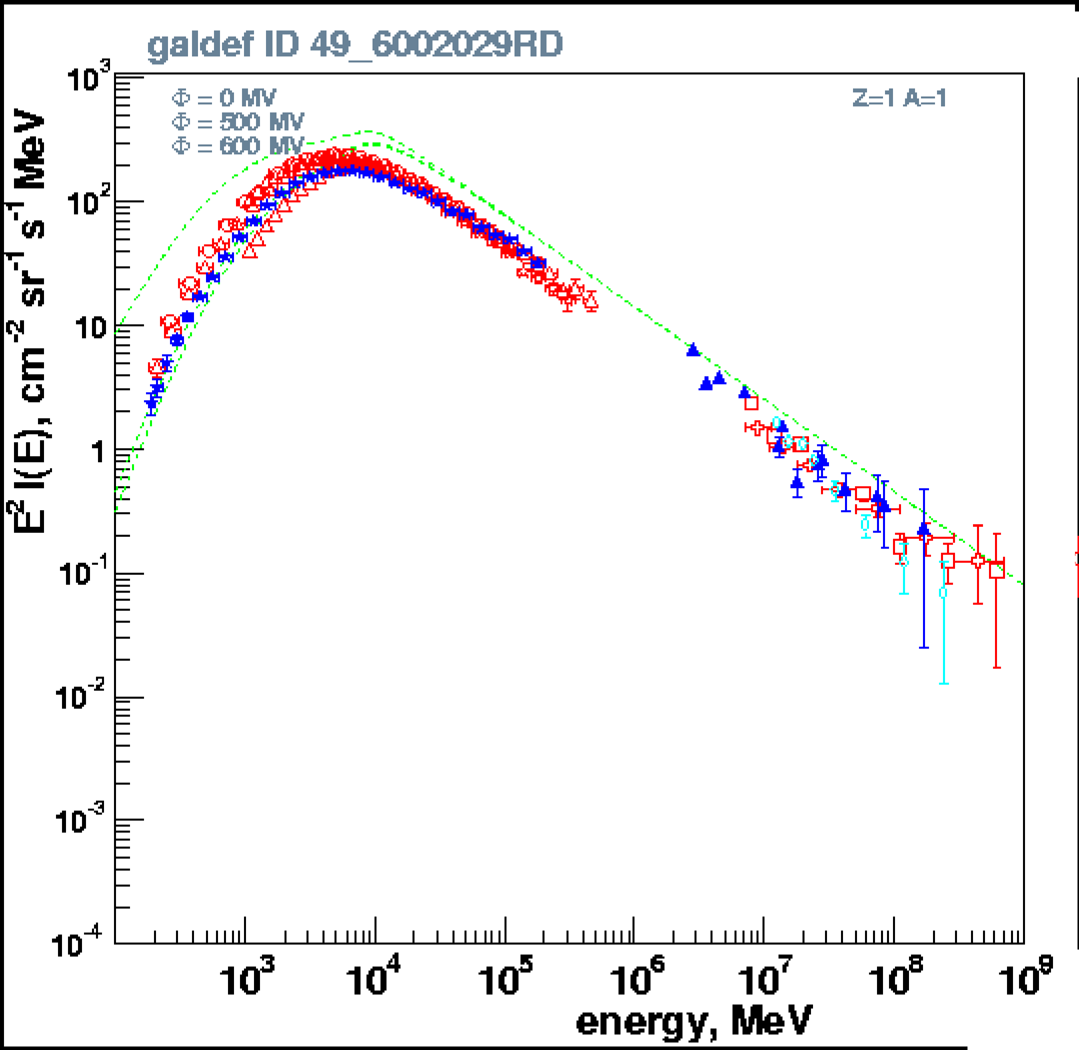
cosmic-ray fluxes f (A, Z, x, y, z , E)

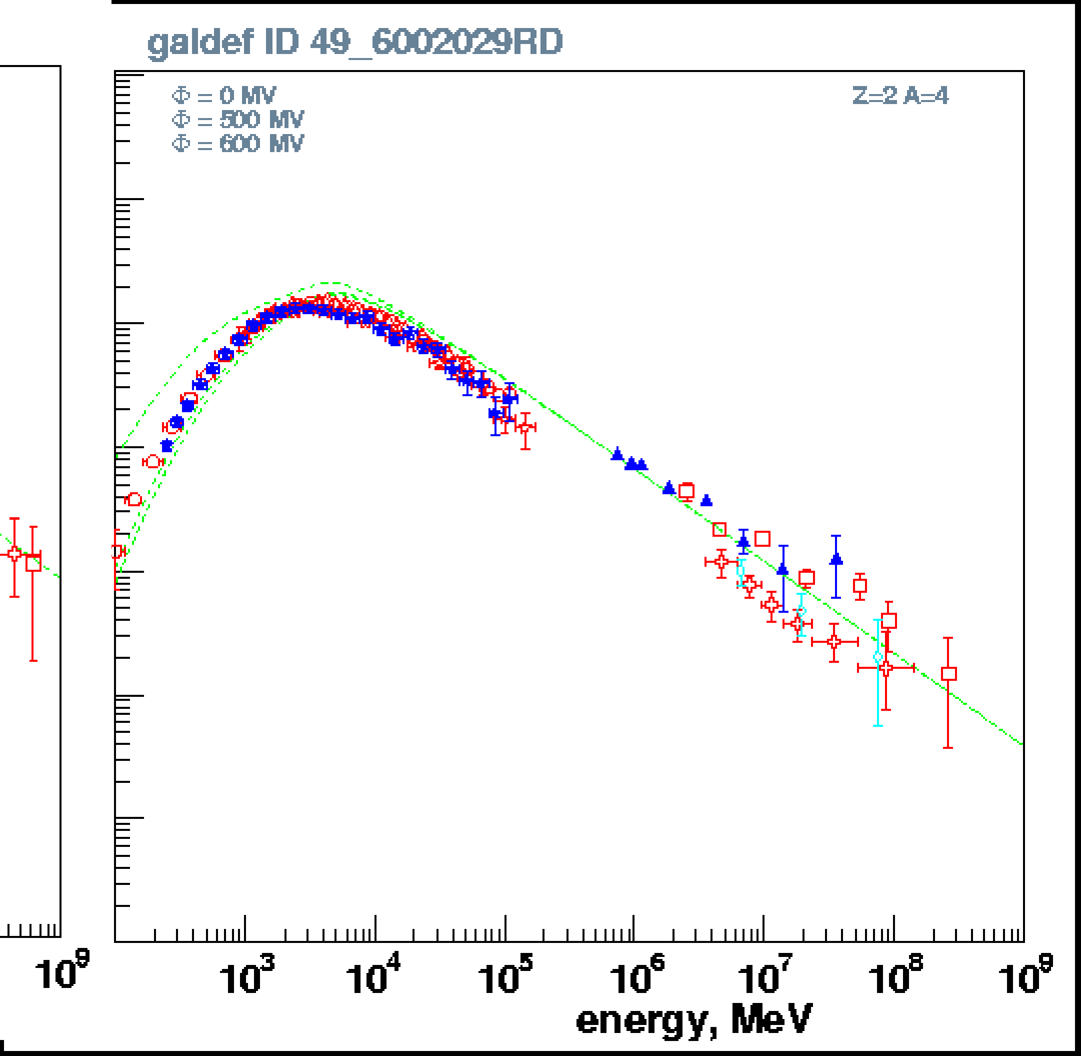
gamma ray skymaps (l , b , E)

synchrotron skymaps (l , b , ν)

.... and more

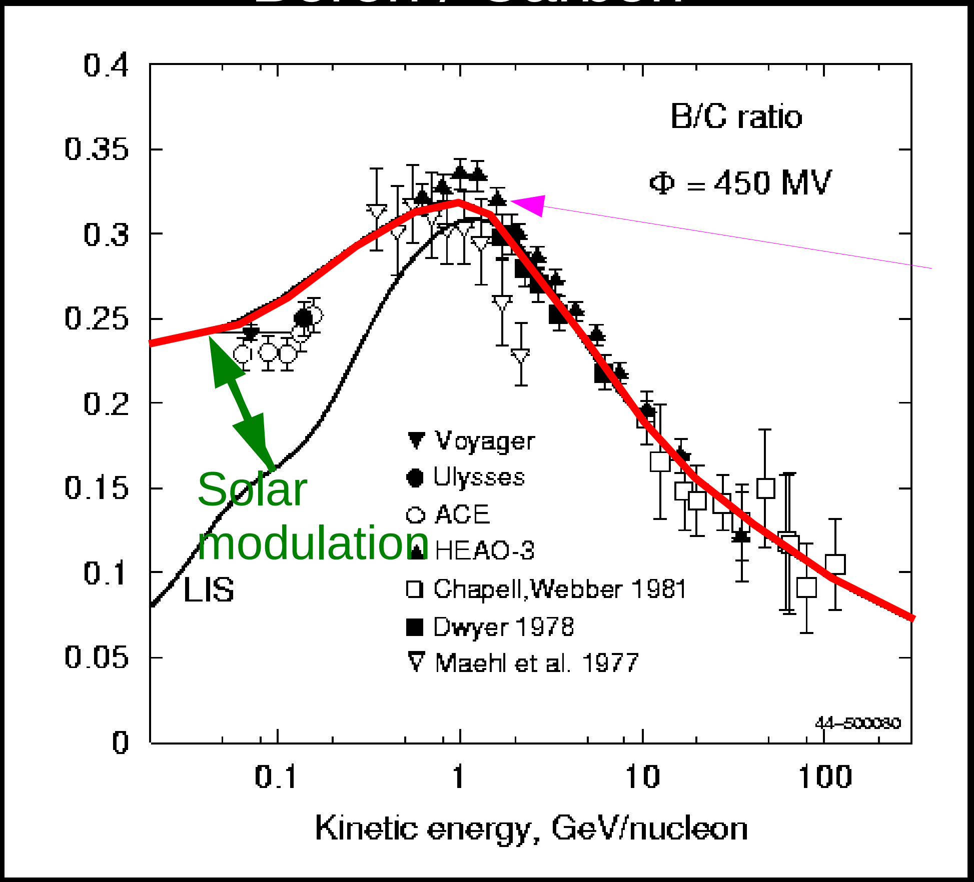
Key data : primary cosmic-ray nuclei spectra





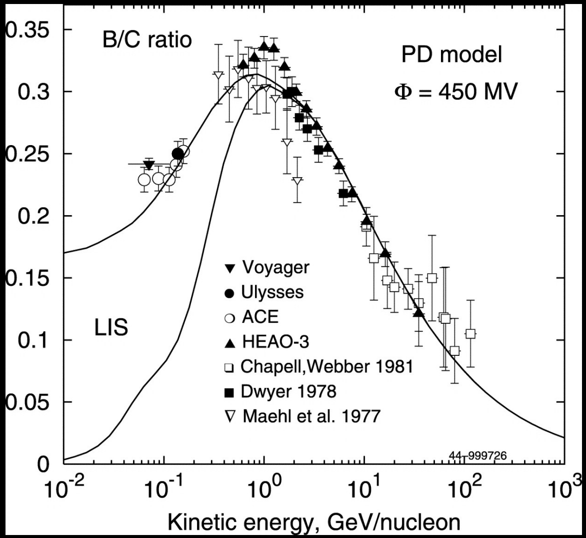
Key data II: cosmic-ray secondary/primary ratios: e.g. Boron/Carbon probes cosmic-ray propagation parameters

Boron / Carbon

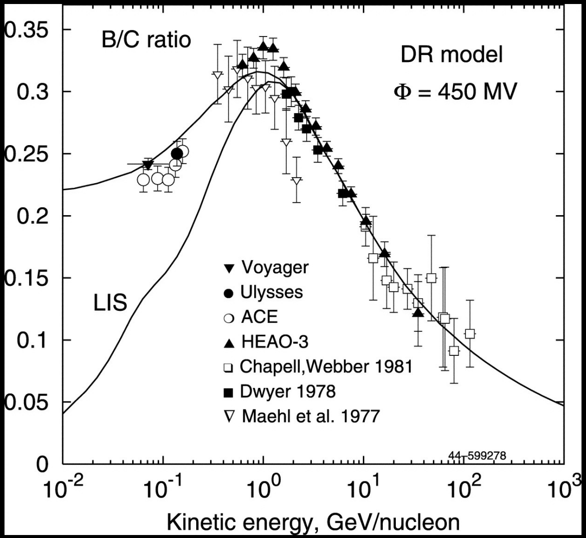


Peak in B/C can be explained by **diffusive reacceleration** with Kolmogorov $D \sim \beta p^{1/3}$

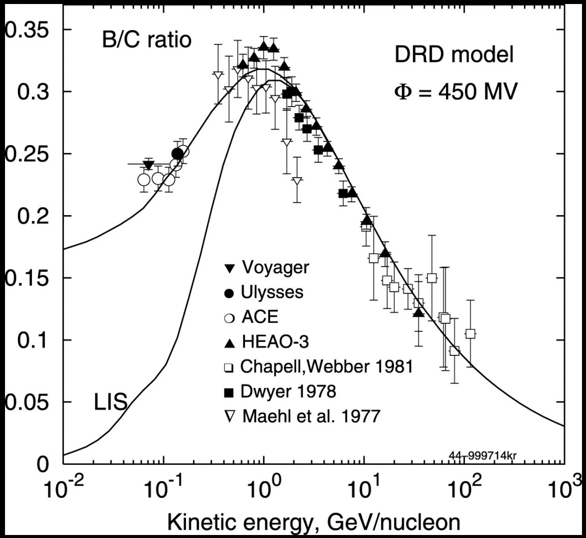
plain diffusion



diffusive reacceleration



wave damping



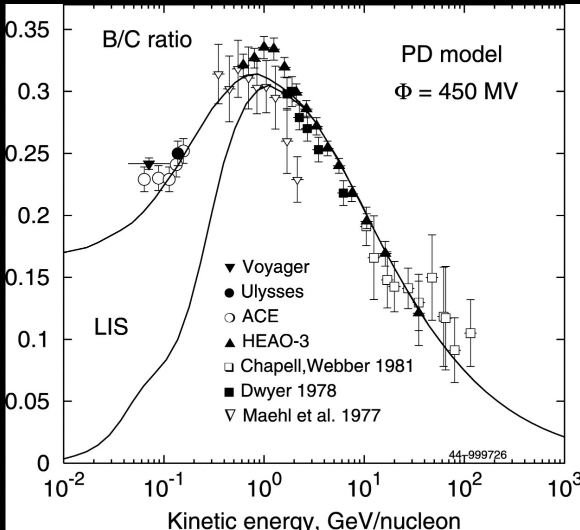
For any model, first adjust parameters to fit Boron/Carbon

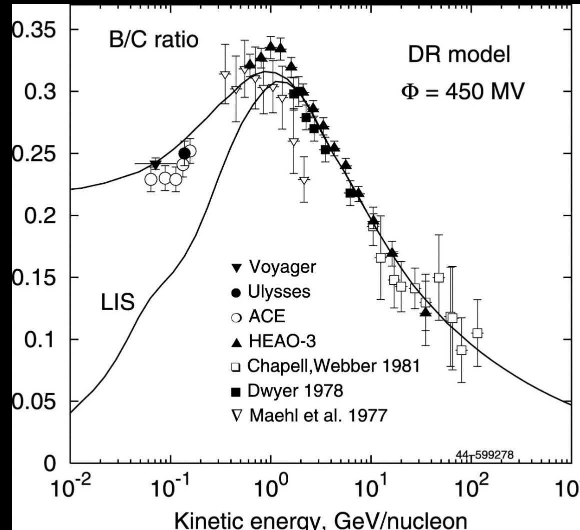
Ptuskin et al. 2006 ApJ 642, 902

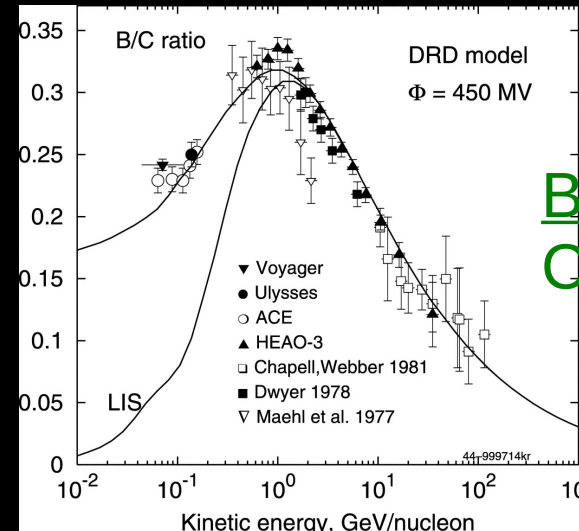
plain diffusion

diffusive reacceleration

wave damping



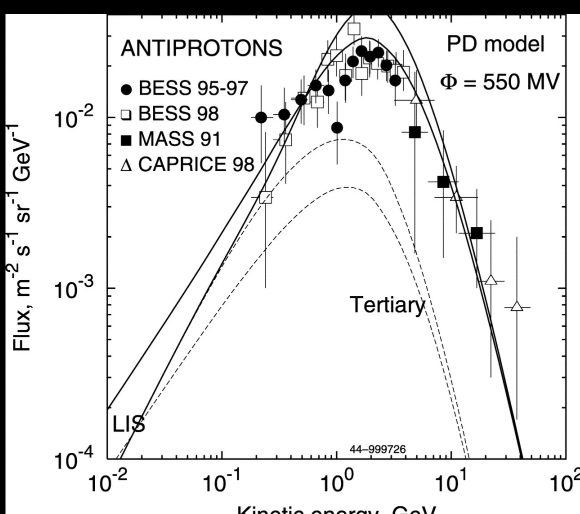


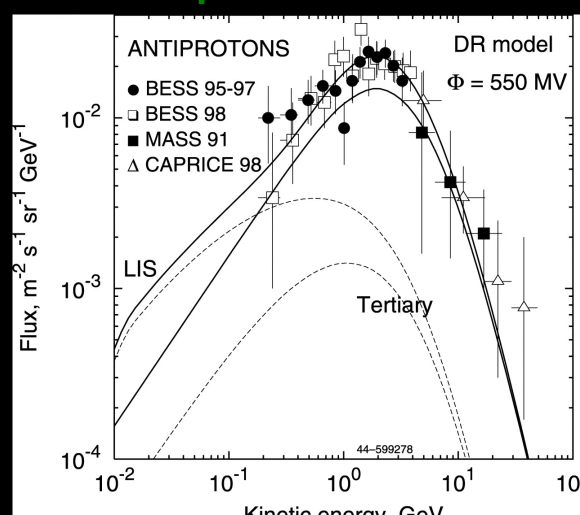


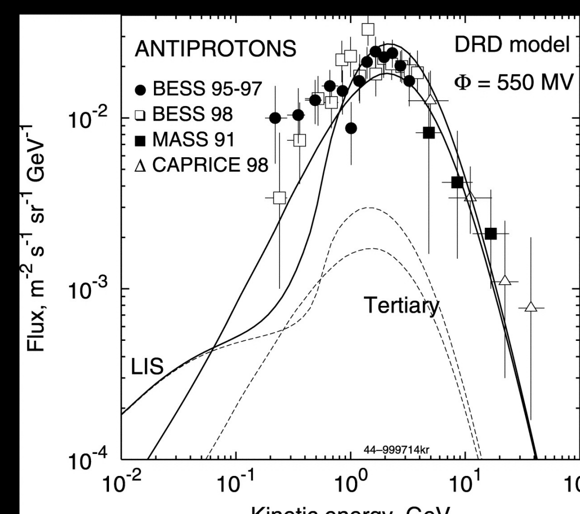
Boron/ Carbon

then predict the other cosmic-ray spectra

antiprotons

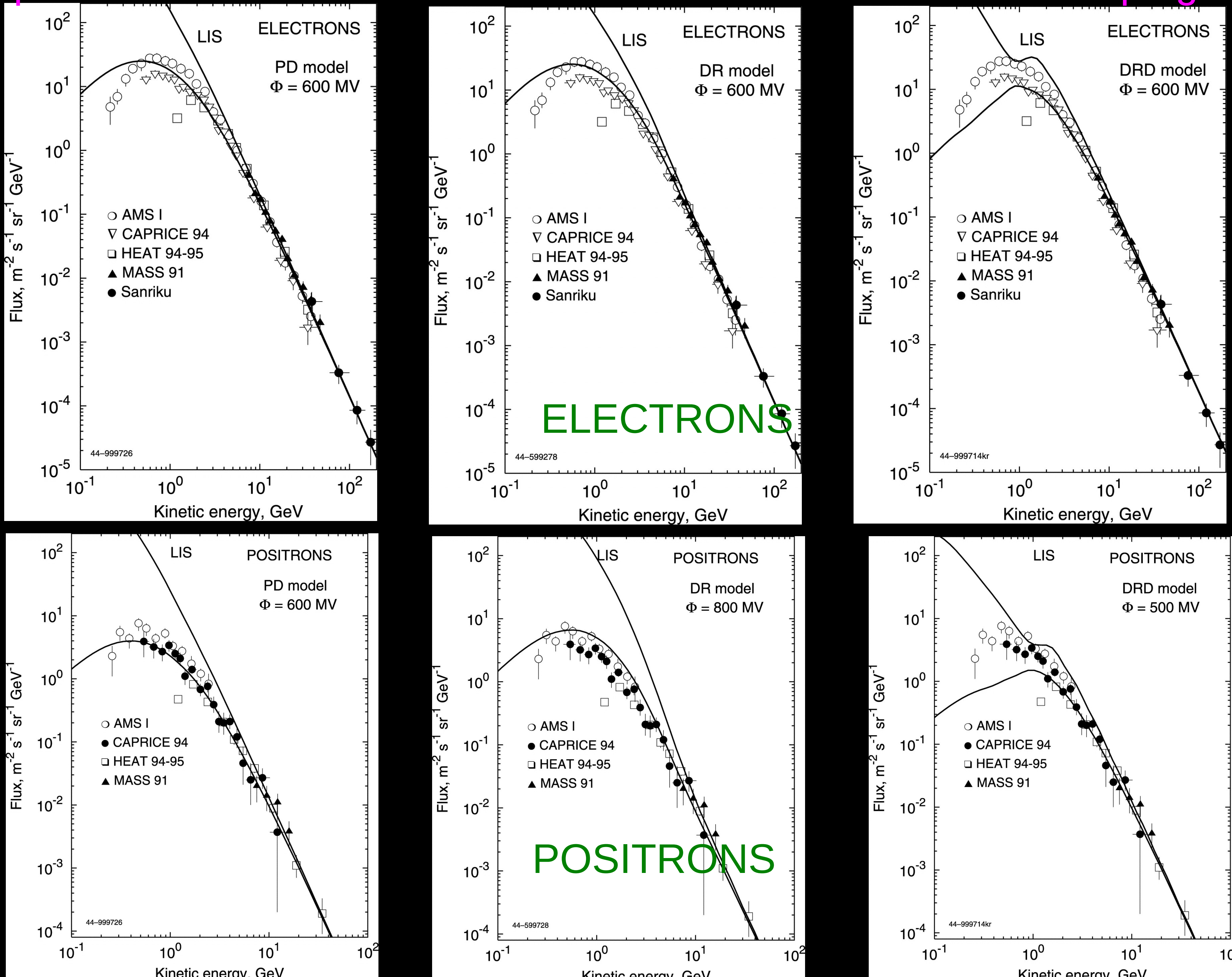






Ptuskin et al. 2006 ApJ 642, 902

plain diffusion | diffusive reacceleration | wave damping



the dangers of diffusive reacceleration

the dangers of diffusive reacceleration

$$D_{pp} D_{xx} \sim p^2 v_A^2$$

we have adopted a model with large reacceleration (v_A=30 km s^{-1})
and Dxx ~ $p^{1/3}$
as a reference for most of our GALPROP applications

since this seems the best way to reproduce the shape of B/C at low energy

this needs CR injection spectrum with a break at a few GeV to compensate the resulting *bump* from reacceleration.

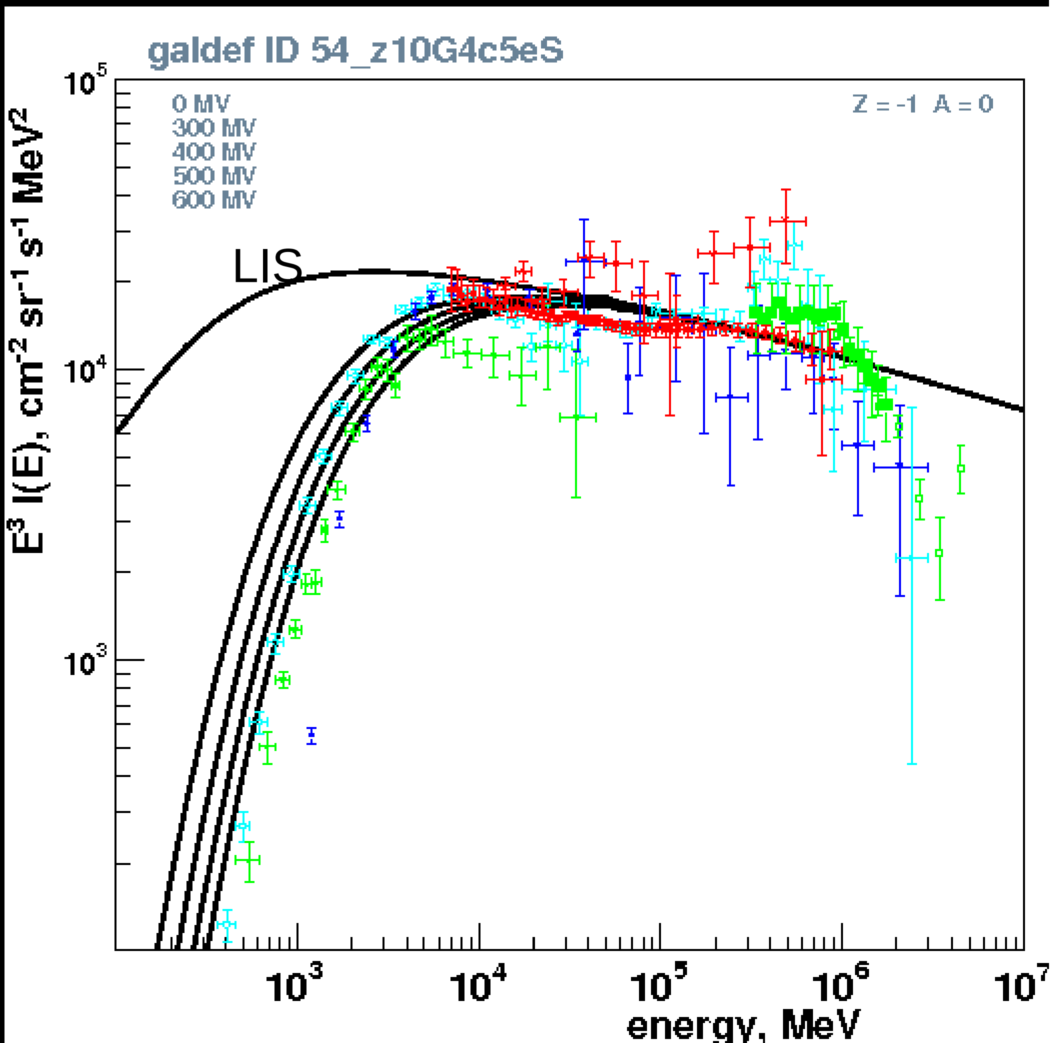
Models with less or no reacceleration and hence no injection break should be studied.

Find other ways (e.g. convection) to explain B/C.

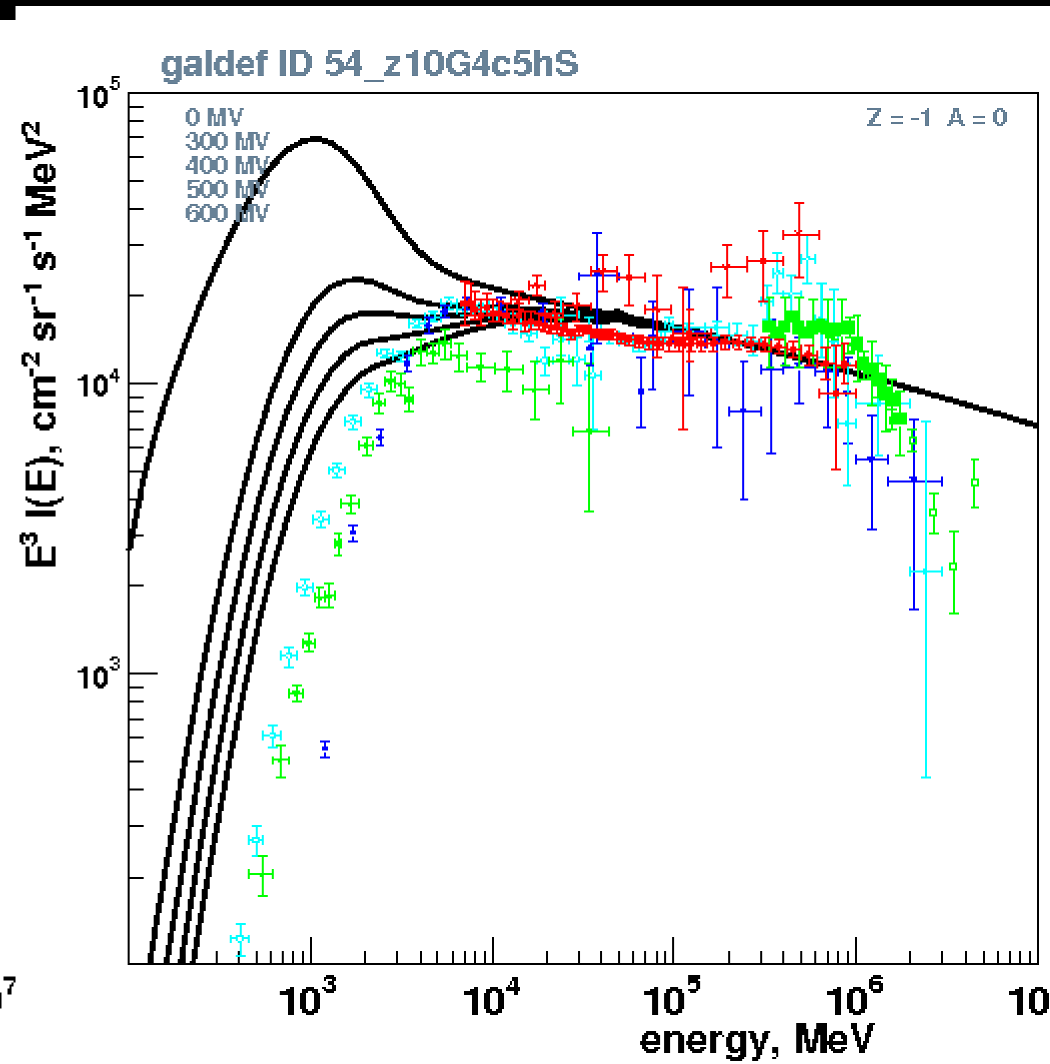
The new high-quality CR data will improve experimental tests.

ELECTRONS
injection spectrum index 2.42, no break

without reacceleration



with reacceleration

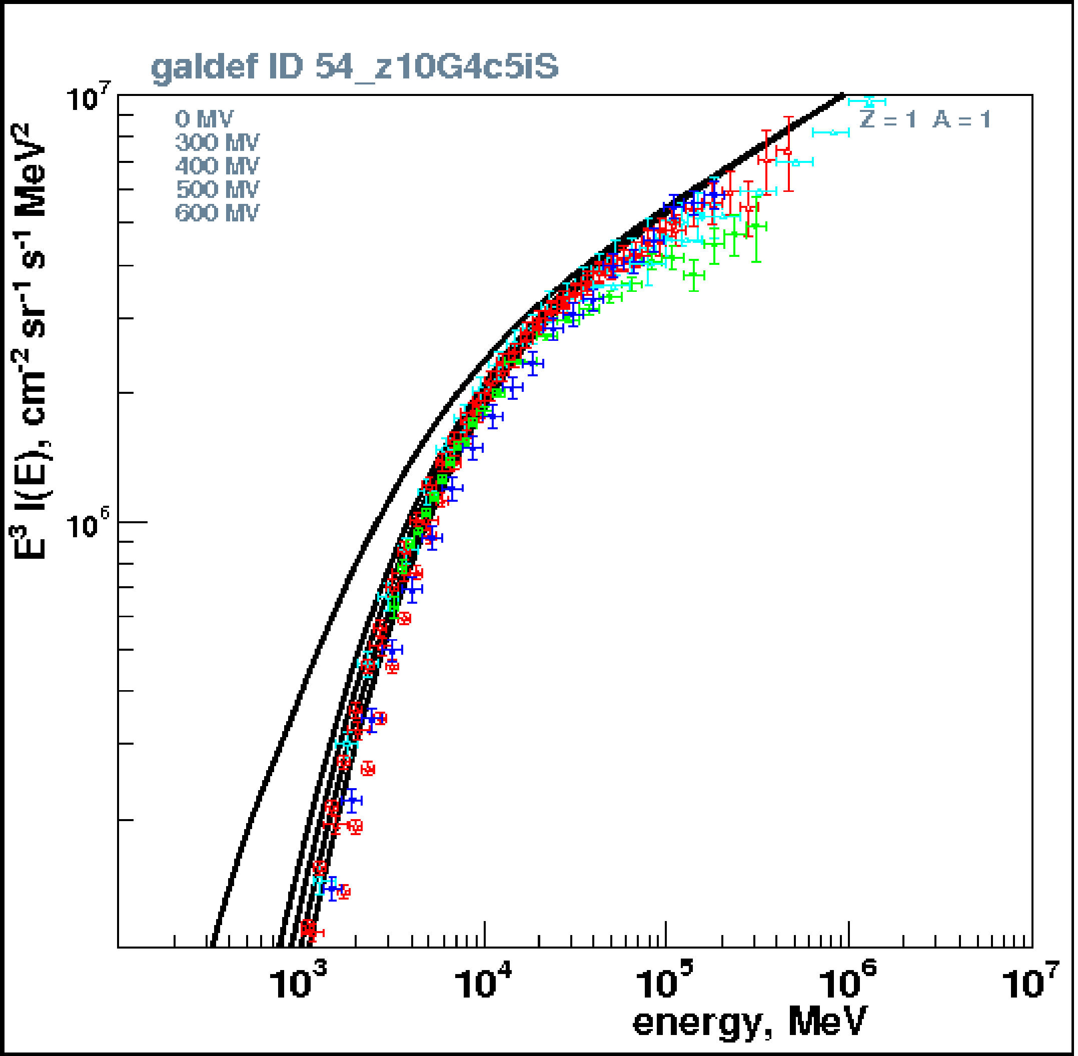


big bump ! but cannot exclude, due to modulation.
>>>>> radio data (see later)

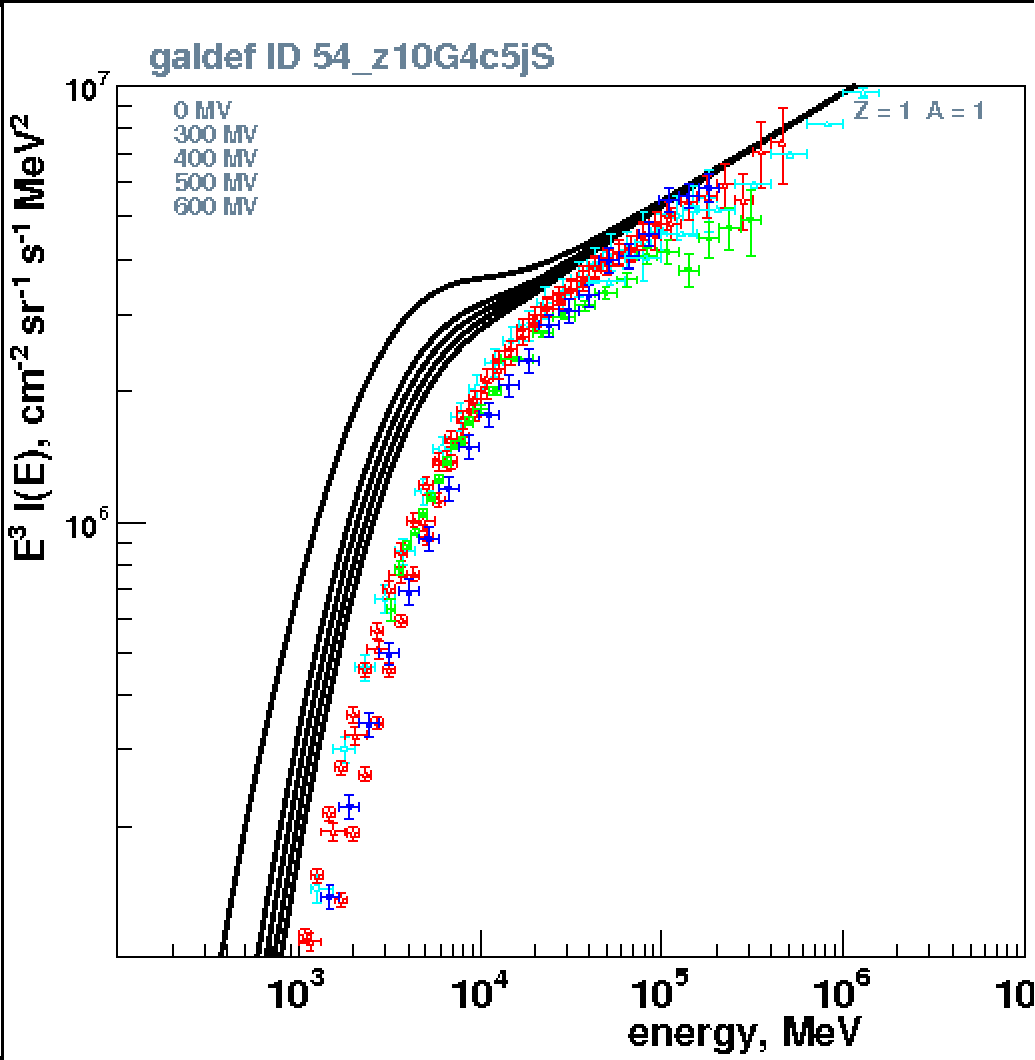
PROTONS

injection spectrum index 2.42, *without* break

without reacceleration



with reacceleration

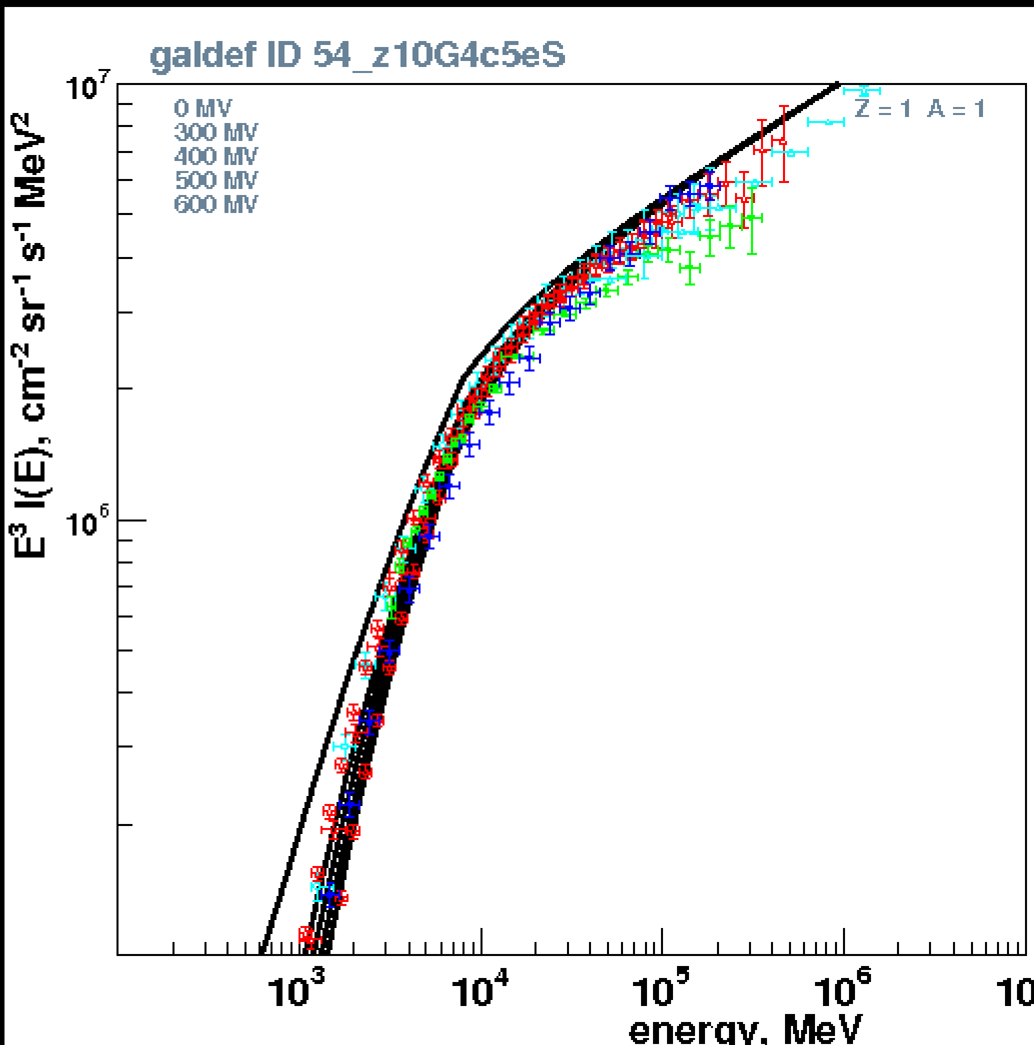


both could be consistent with data given uncertainty in modulation

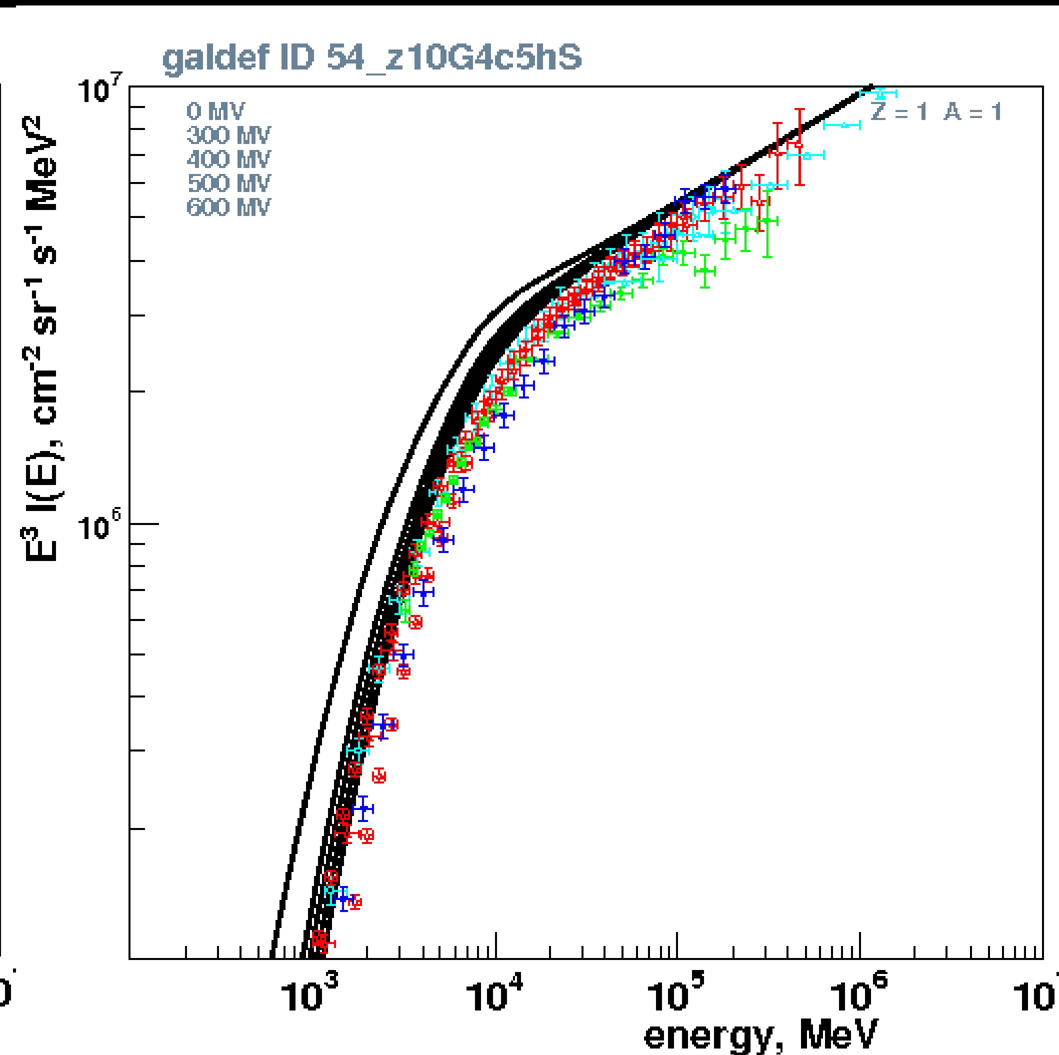
PROTONS

injection spectrum index 2.42, *with* break to 1.6 below 4 GeV

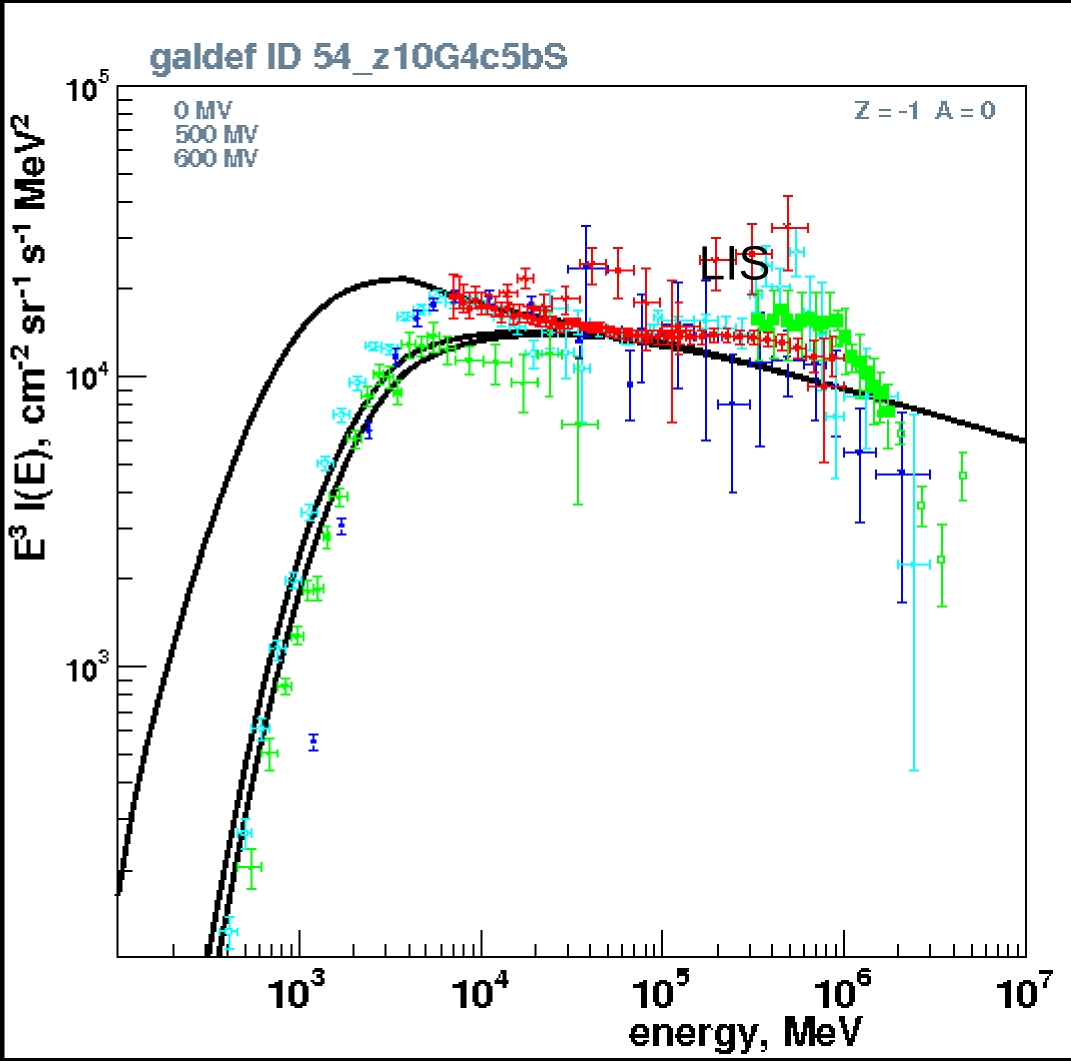
without reacceleration



with reacceleration



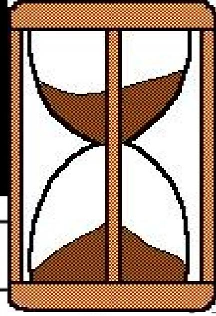
both consistent with data given uncertainty in modulation reacceleration and injection spectrum break at 4 GeV 1.6 / 2.42



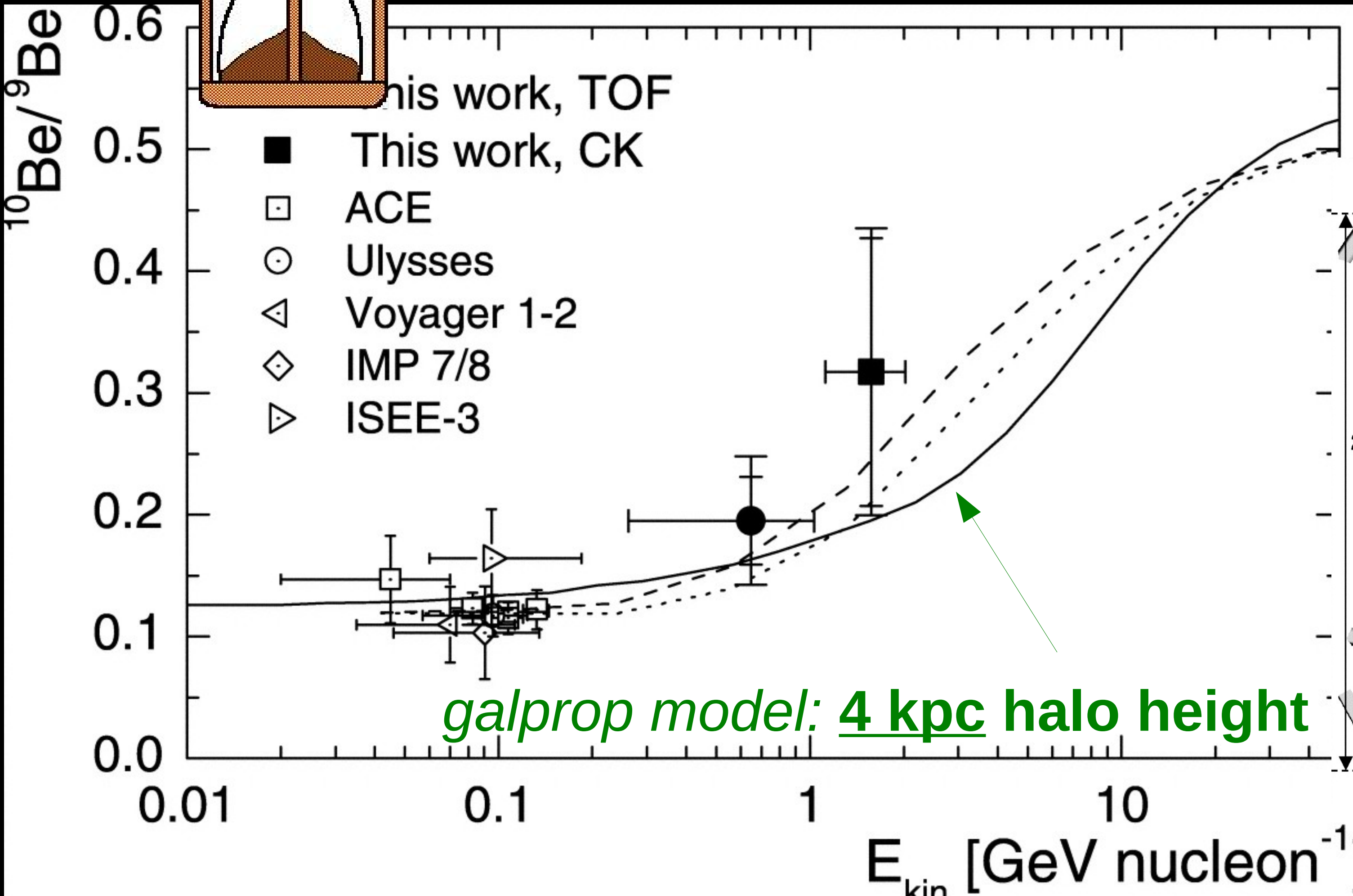
fixes the bump but at the price of a complicated model

Some GALPROP Applications

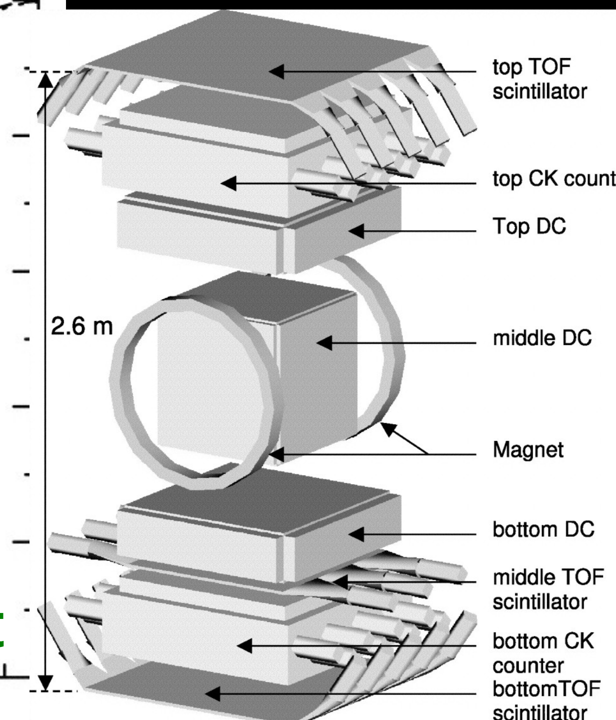
Radioactive nuclei
Electrons
Cosmic-ray source distribution
Synchrotron
Hard X-rays
Galactic SED

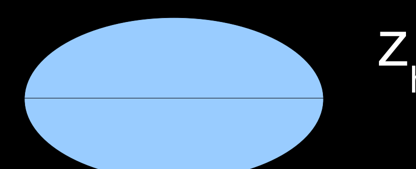


Radioactive nuclei: cosmic-ray clocks set limits on size of Galactic halo



data:
ACE, ISOMAX

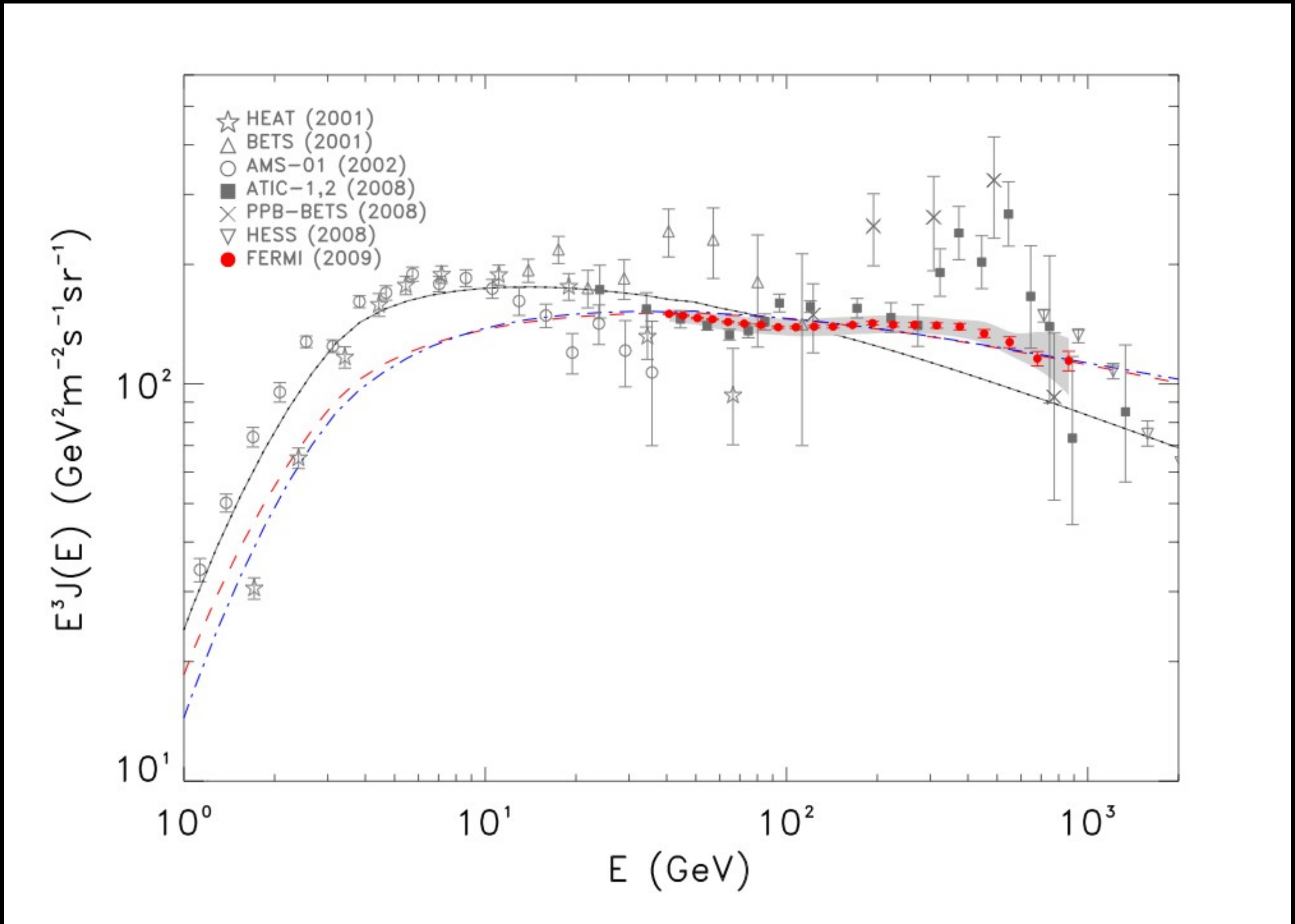




^{10}**Be** *decays* in 10^6 years, ^{9}**Be** is *stable*
so ratio sensitive to cosmic-ray confinement time, halo size

Hams et al. 2004 ApJ 611, 892

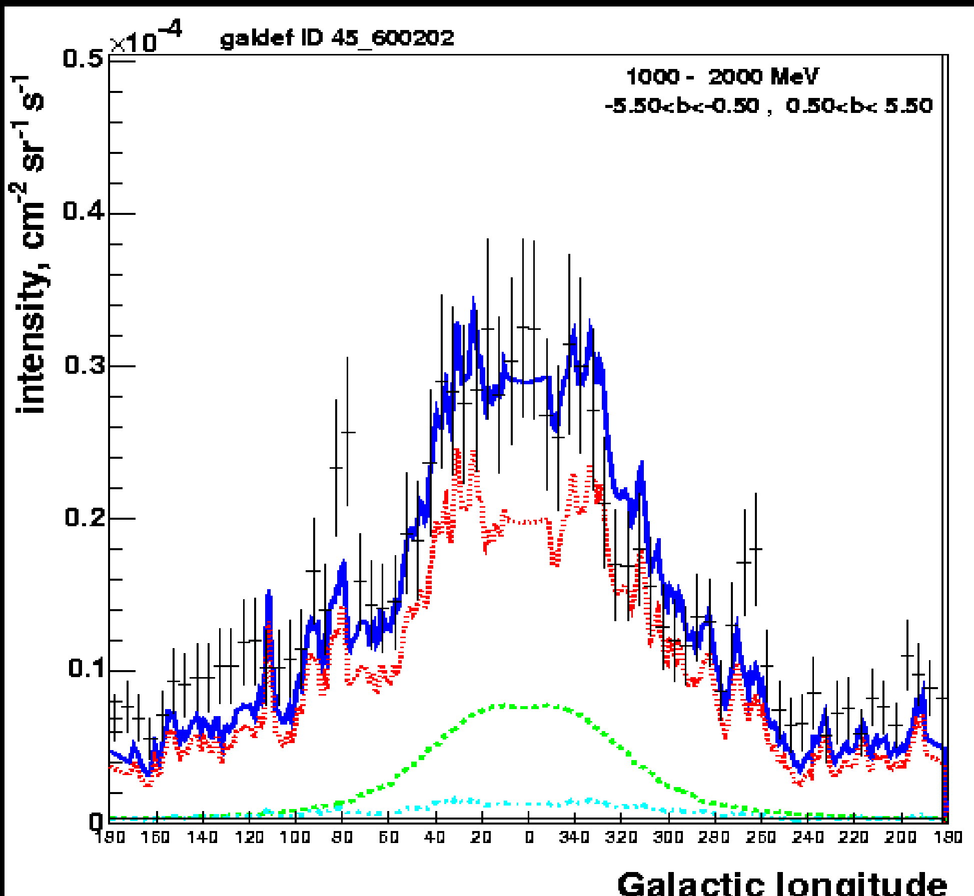
GALPROP application : models for Fermi electrons

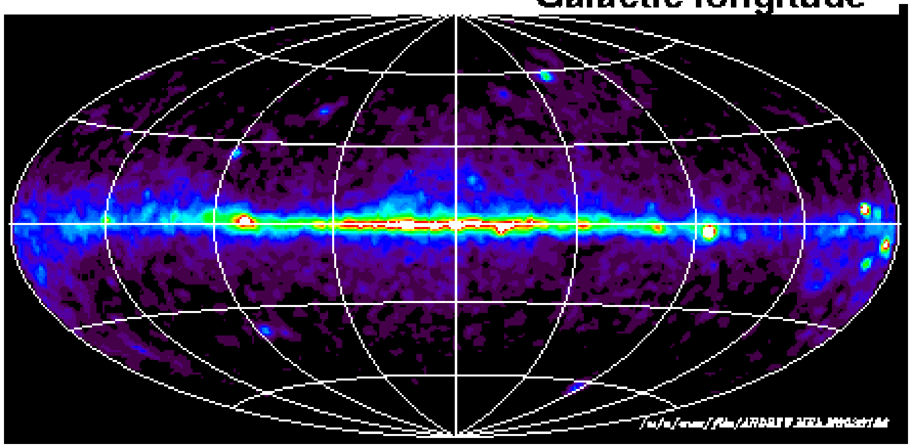


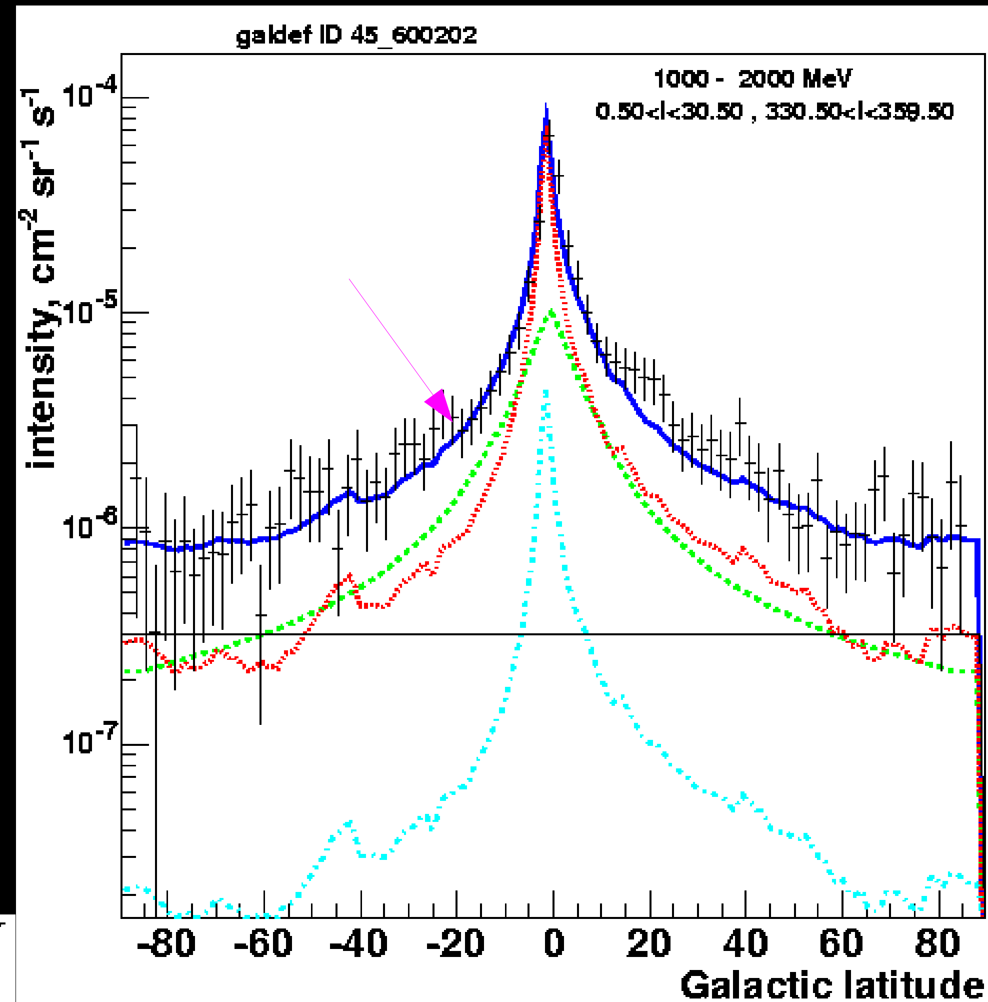
Abdo etal. 2009, Grasso etal. 2009

see Daniele Gaggero's talk for many more details !

not just spectra .... also skymaps

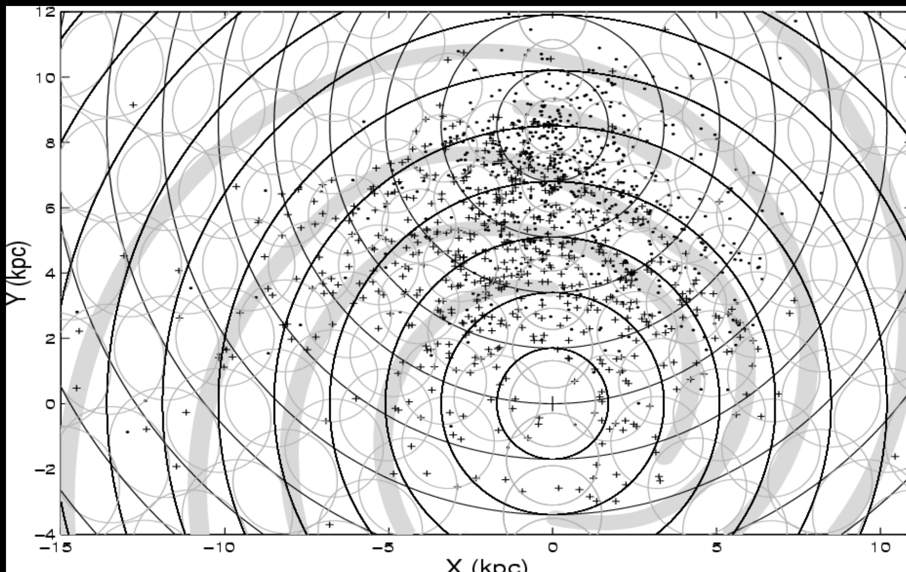






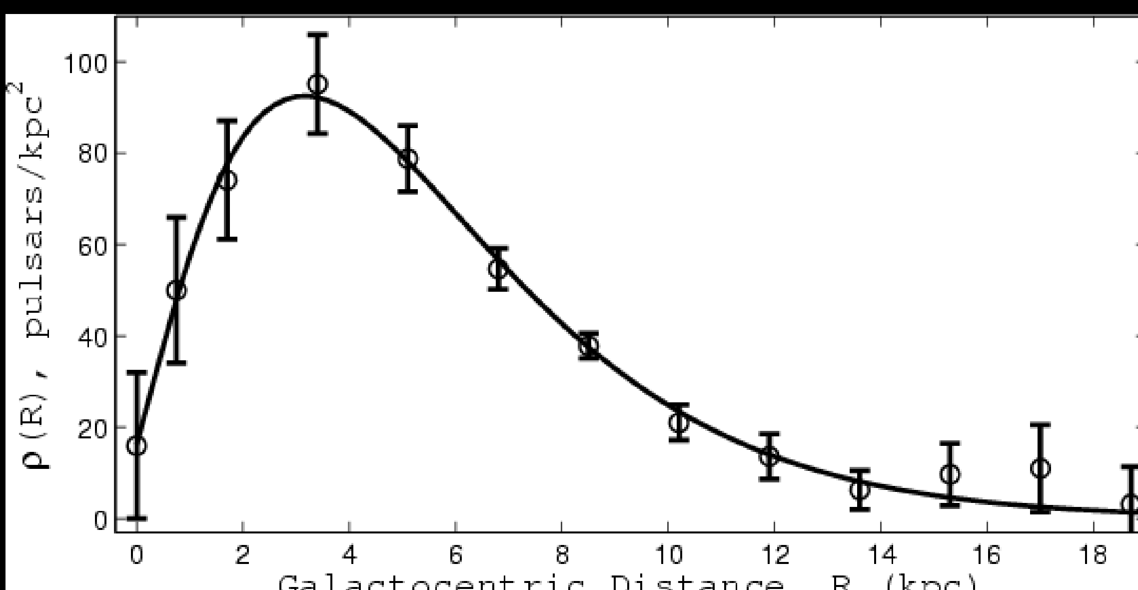
EGRET γ -ray data

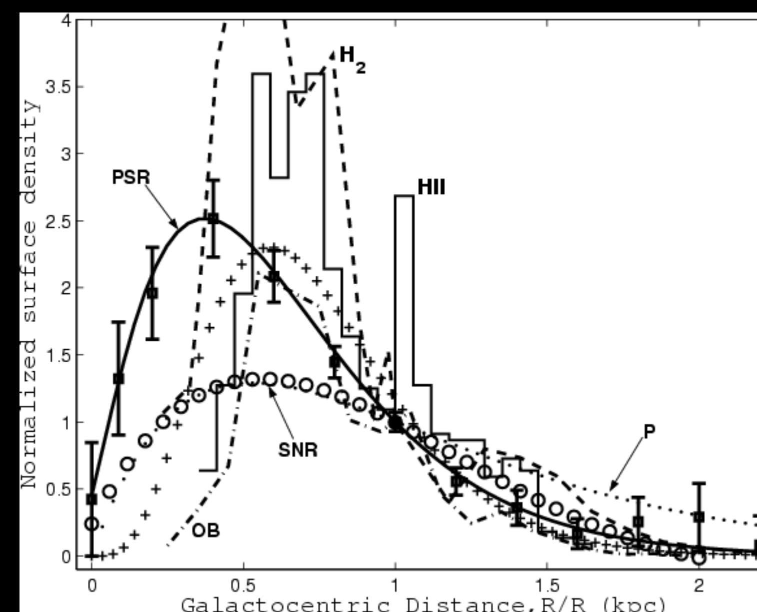
Tracer of SNR cosmic-ray sources: Pulsar distribution



Parkes Deep Survey

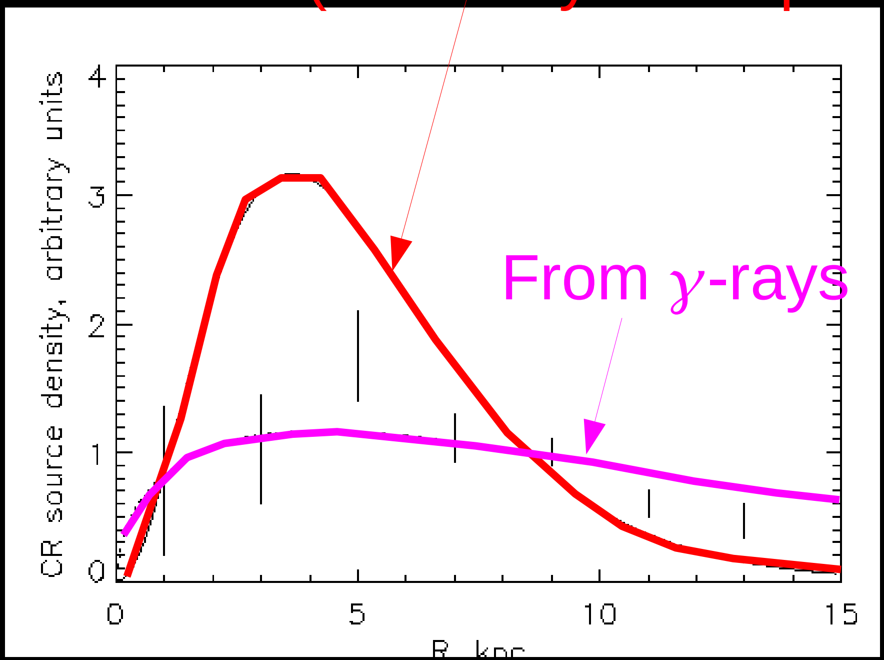
Yusifov & Kücük 2004
(Lorimer 2004: almost same result)





Old mystery of cosmic-ray gradient:
gradient based on γ-rays much smaller than SNR gradient.

SNR (traced by latest pulsar surveys: Lorimer 2004)



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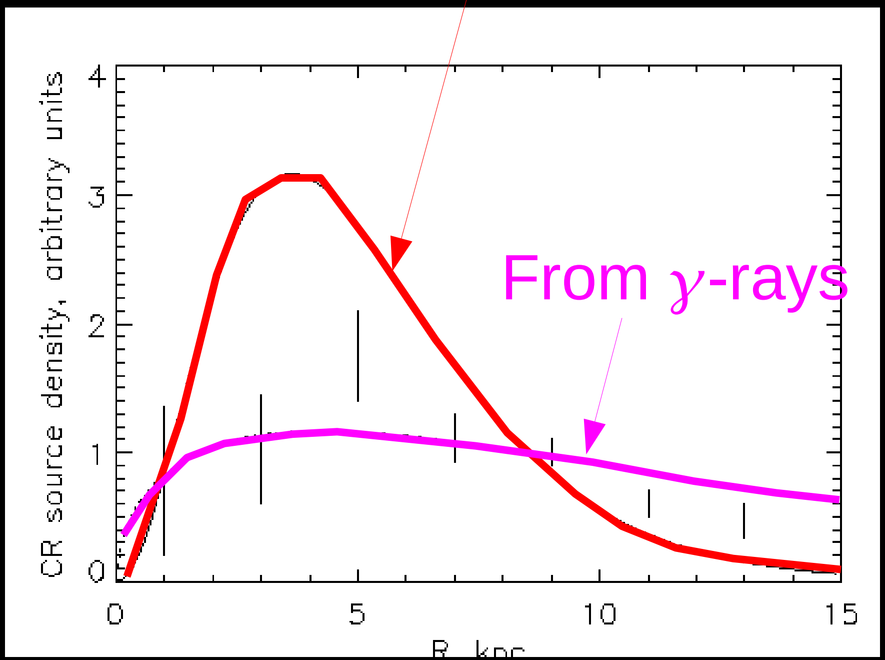
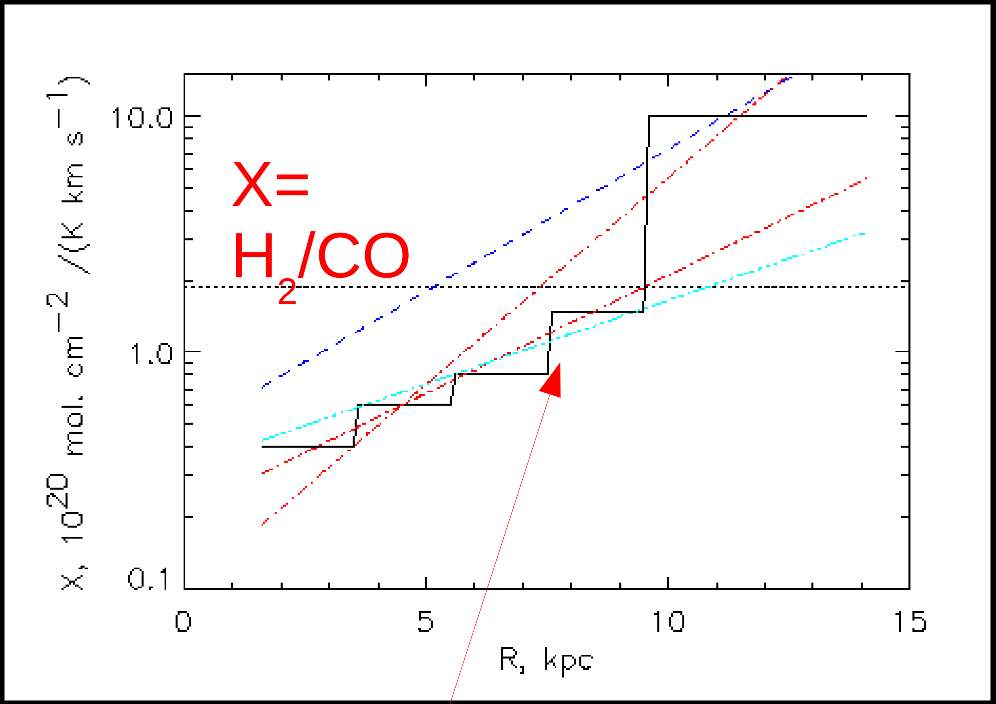




Clue: Galactic metallicity gradient e.g. [O/H]

metallicity decreases with R, X= H_2 / CO *decreases with metallicity*

>>>>>> ***X = H_2 / CO increases with radius***

γ-rays = sources(R) * X(R) *CO(R) (+ HI, inverse Compton terms)

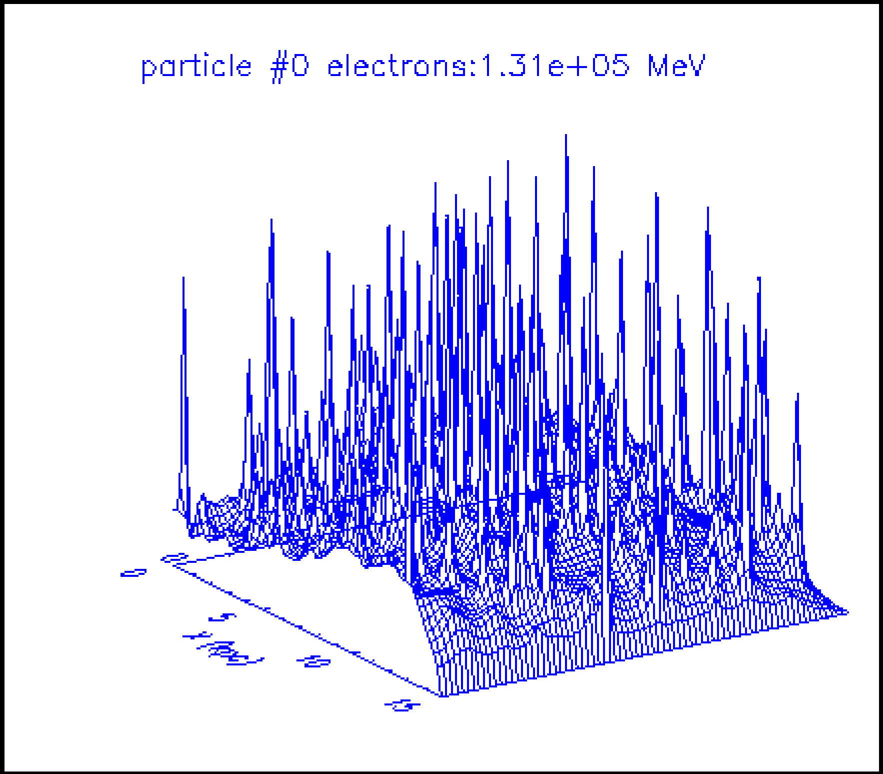
Steeper sources * flatter X = observed gamma-rays

Strong et al. 2004 *A&A 422,L47*

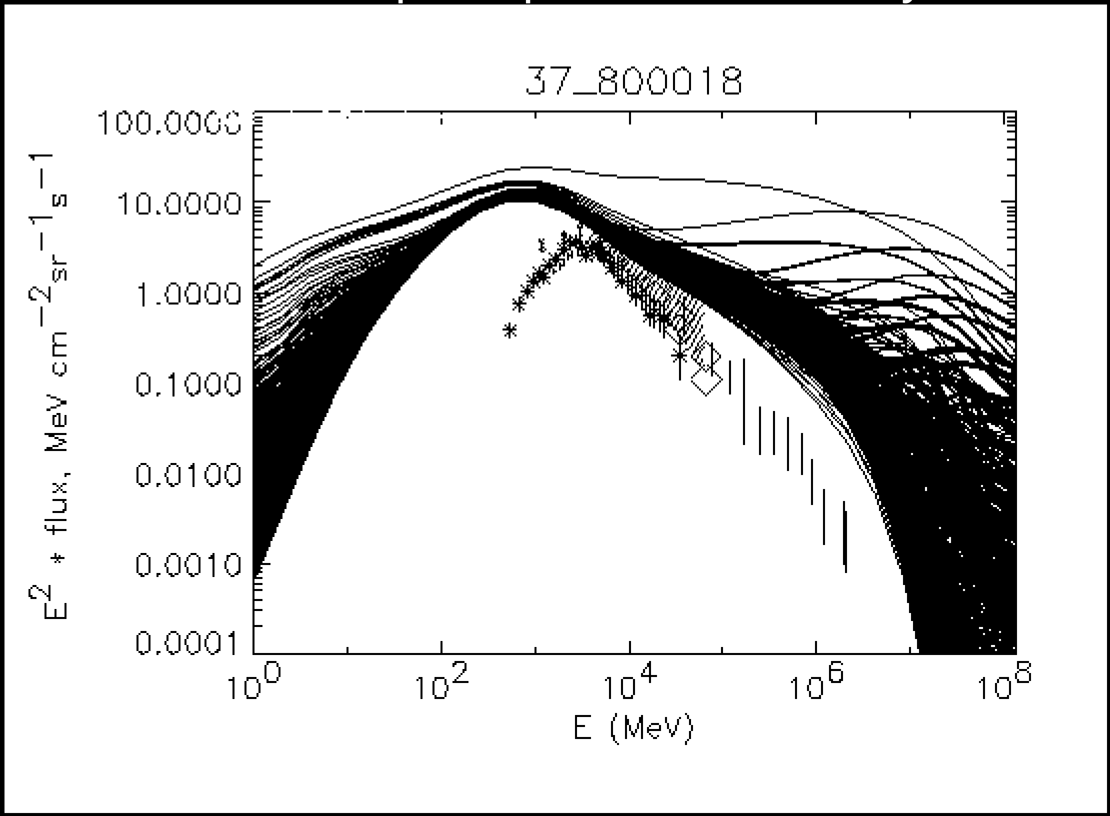
Stochastic cosmic-ray sources with GALPROP

ELECTRONS

130 GeV



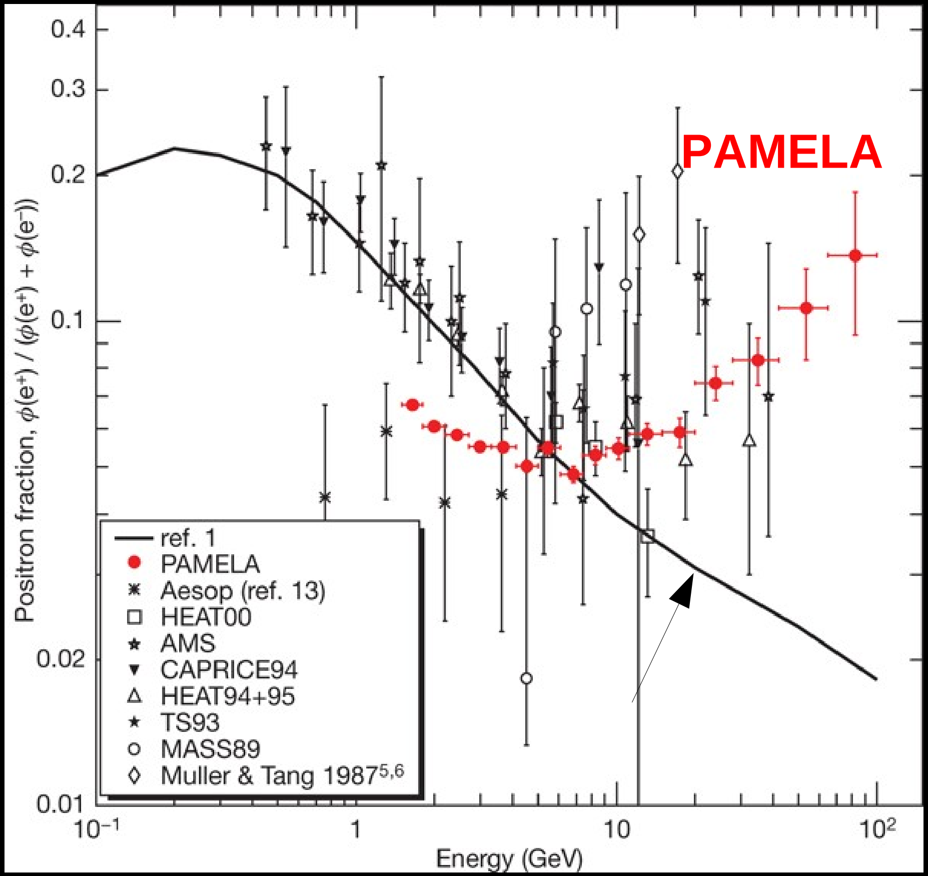
Sampled spectra over Galaxy



3D, time-dependent, several SNR/year over Galaxy

Extreme fluctations in space / time at high energies.
Strong and Moskalenko, ICRC 2001

PAMELA positron fraction with other experimental data and with secondary production model.



O Adriani *et al.* *Nature* **458**, 607-609 (2009)

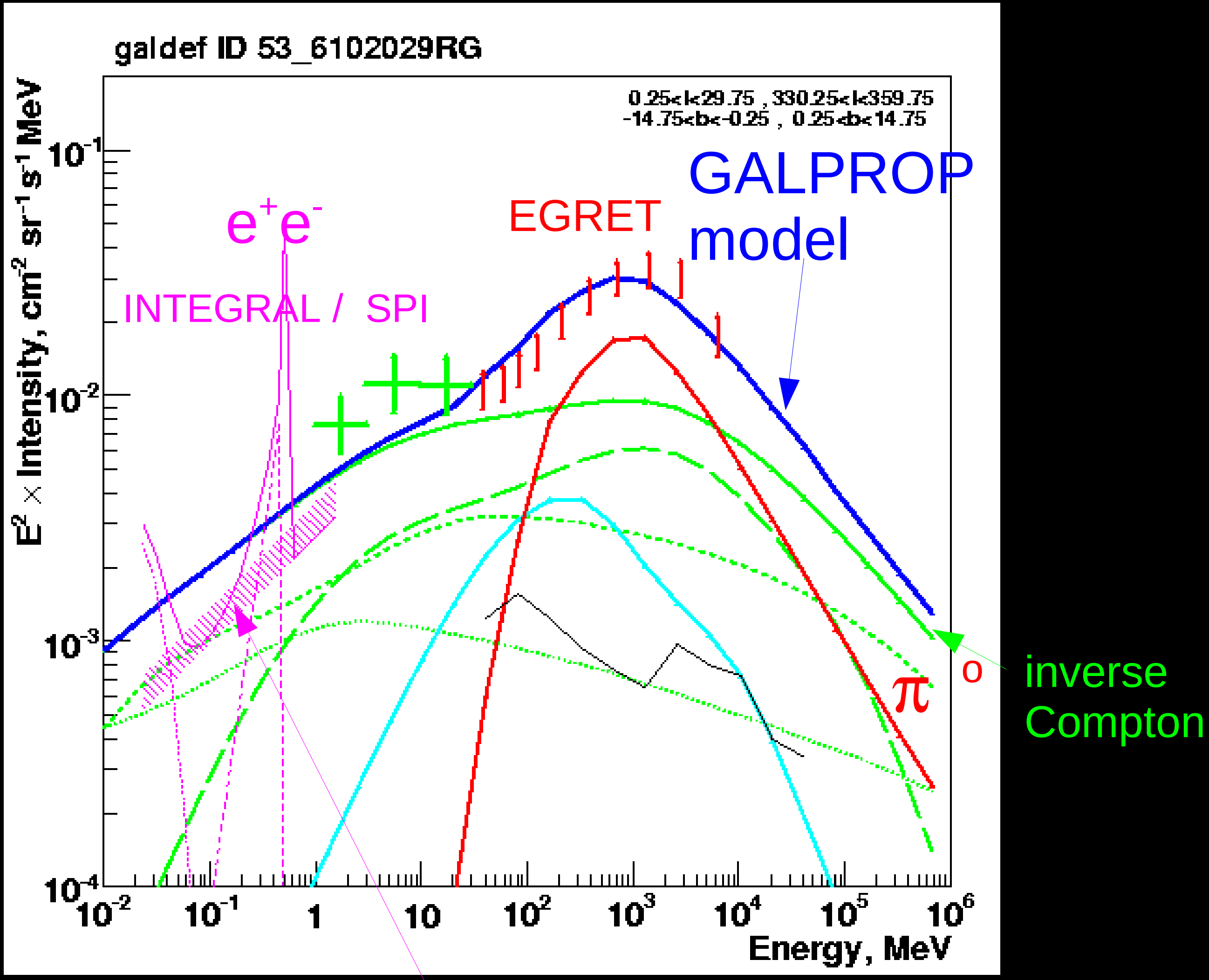
GALPROP used to calculate secondary positrons
for PAMELA
to show the excess
attributed to DM or pulsars or ....

nature

Gamma-rays, inner Galaxy

inverse Compton
from primary electrons, secondary electrons, positrons

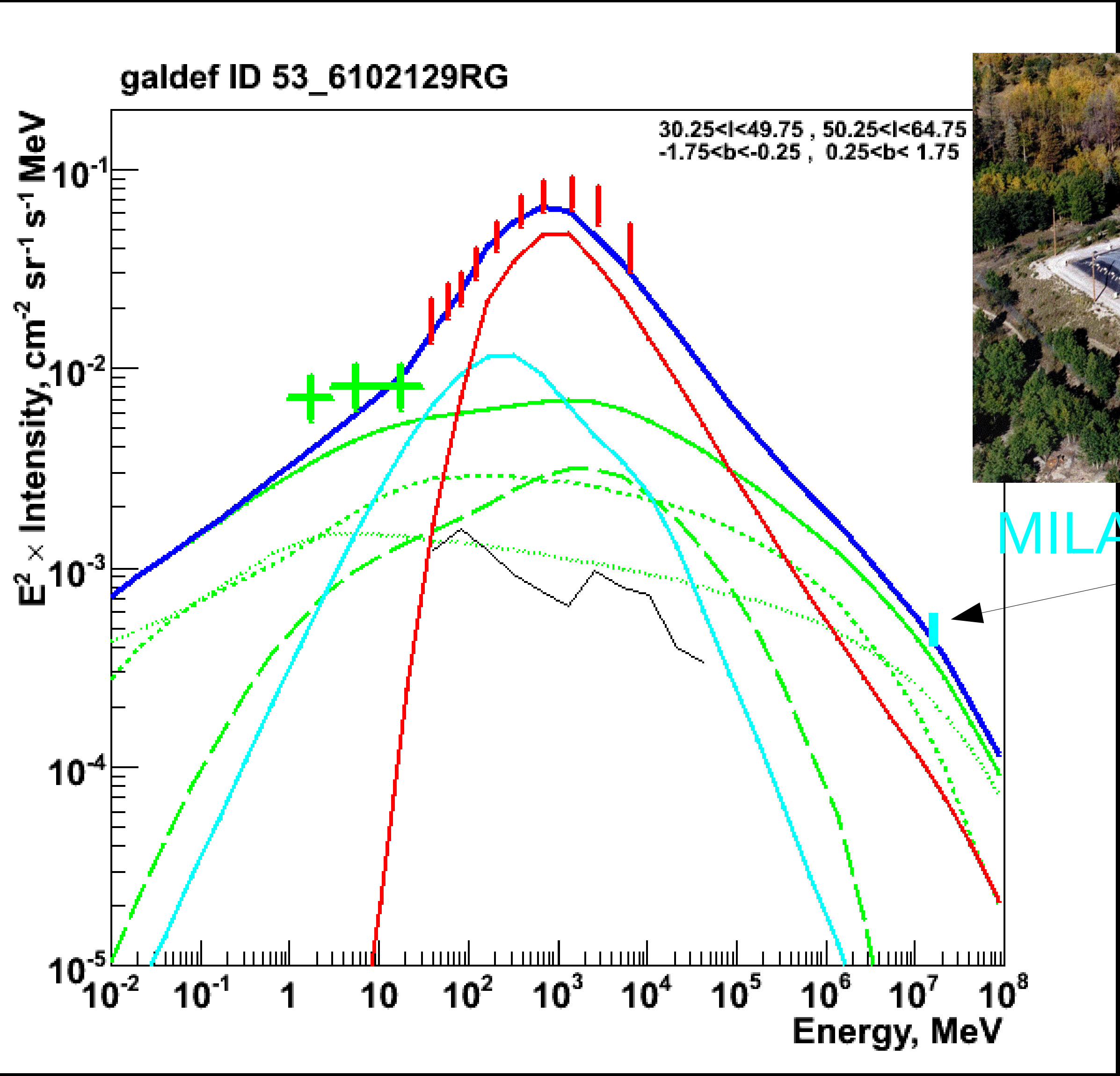
These processes are very relevant down to hard X-rays !



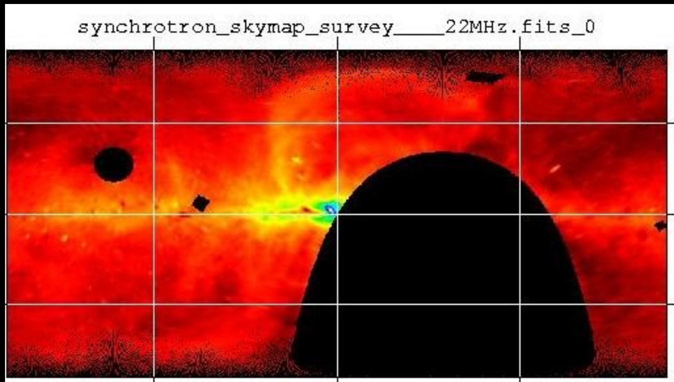
Bouchet et al power-law continuum

Porter, Moskalenko, Strong, Orlando, Bouchet ApJ 682, 400 and towards the highest energies...

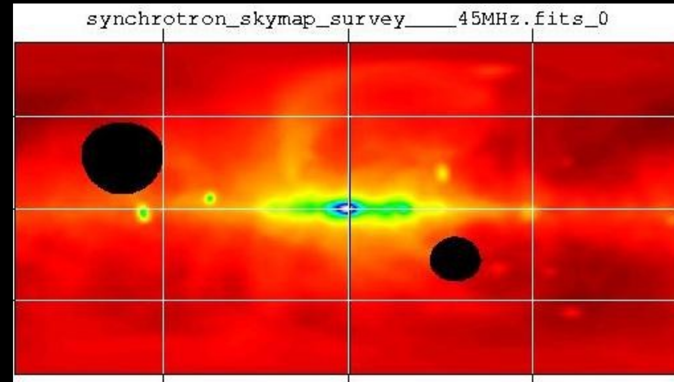
Diffuse Galactic Emission



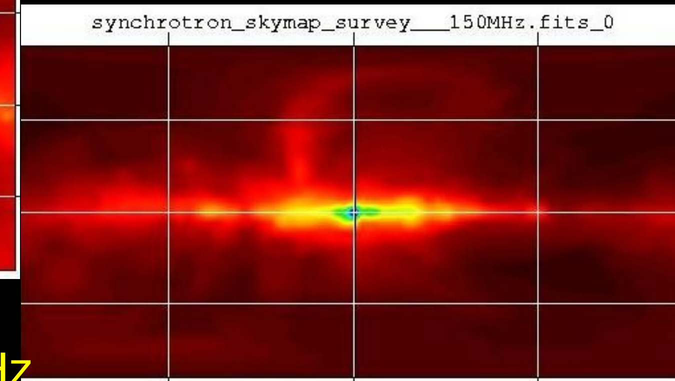
MILAGRO : 15 TeV



22 MHz

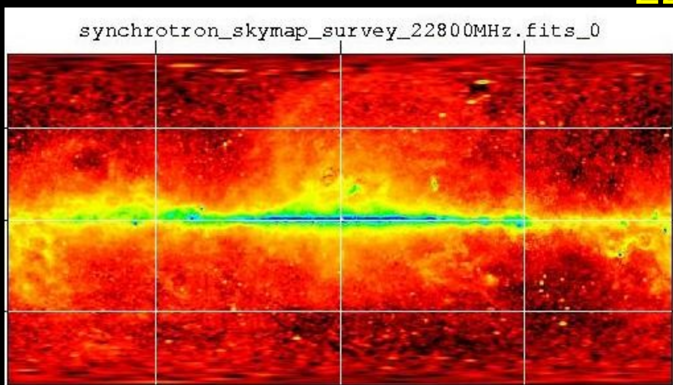


45 MHz

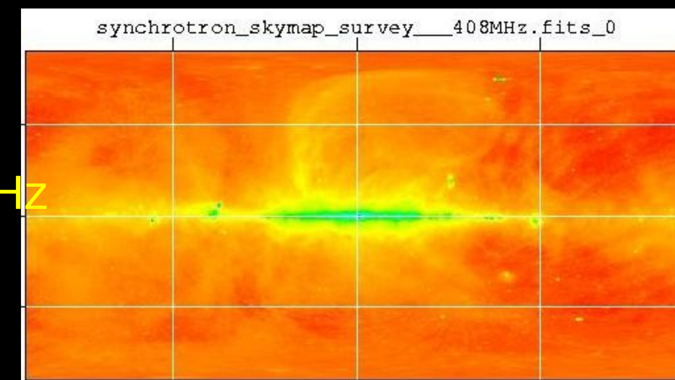


150 MHz

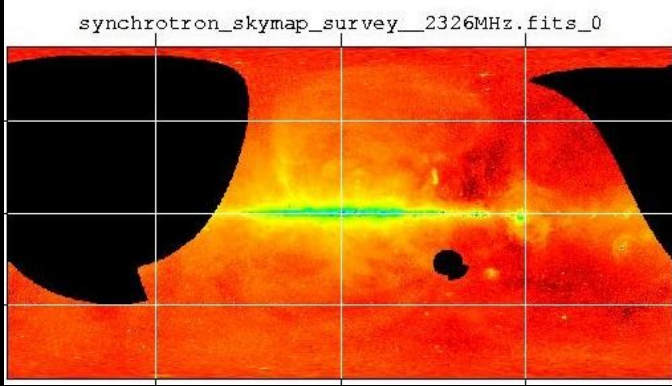
Continuum
sky surveys



23 GHz

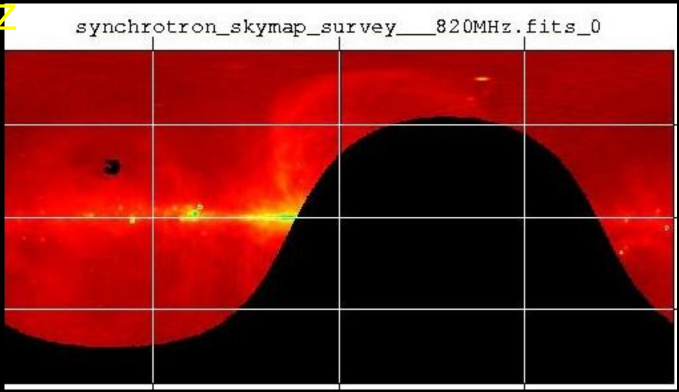


408 MHz

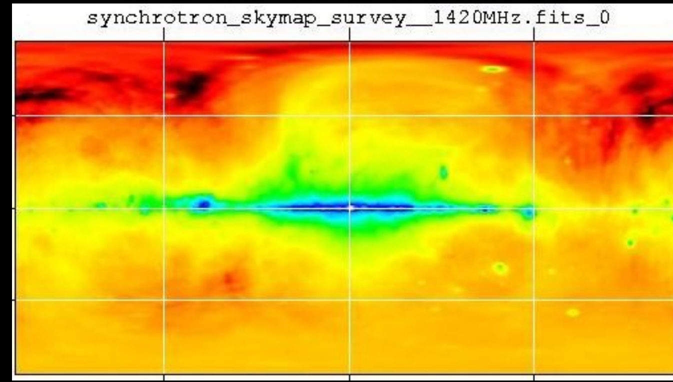


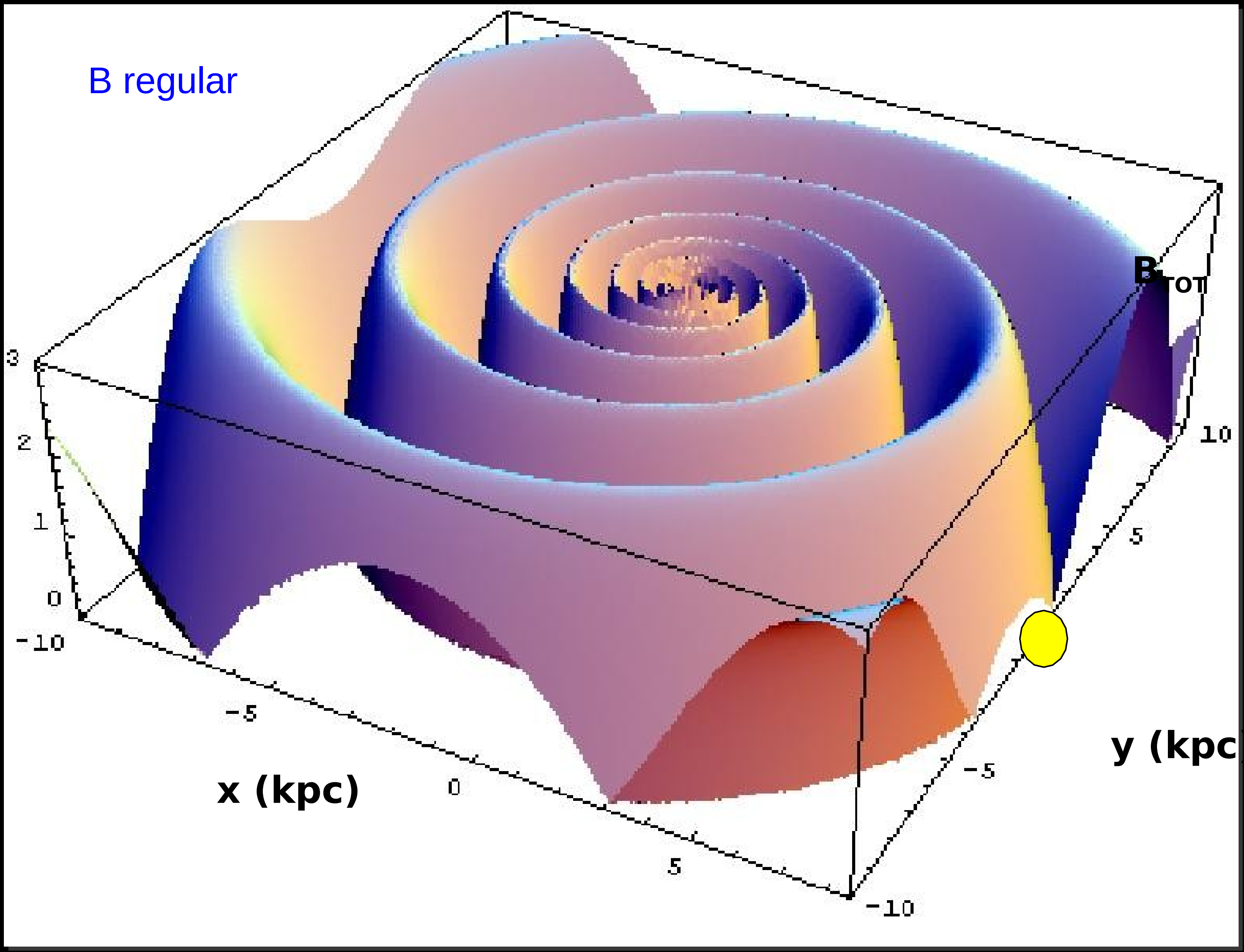
2.3 GHz

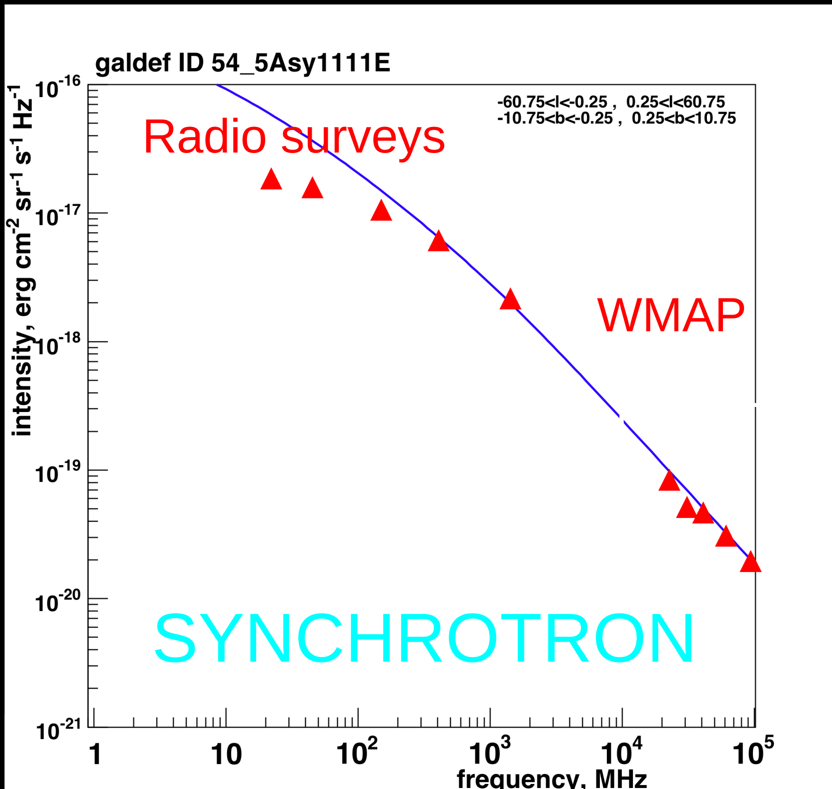
820 MHz



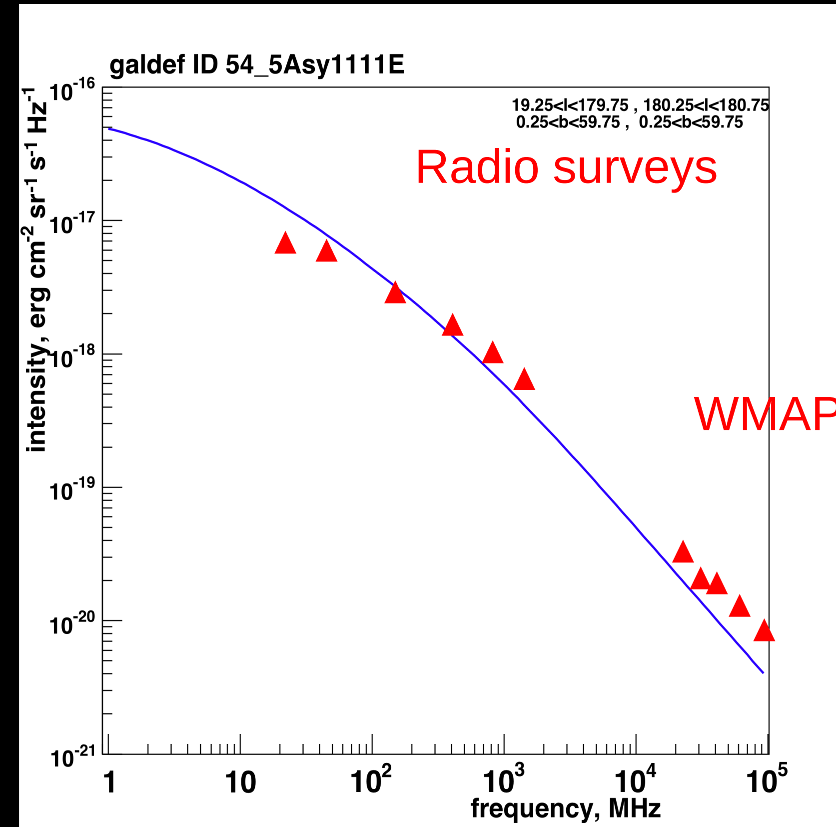
1.4 GHz

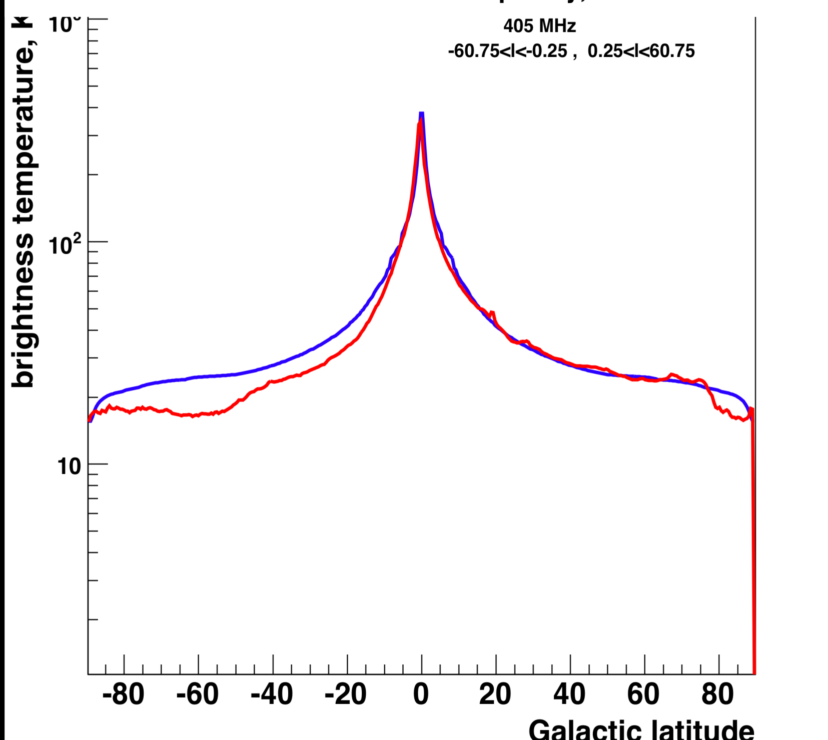



B regular
B_TOT
x (kpc)
y (kpc)
3
2
1
0
-10
-5
0
5
10
-5
-10

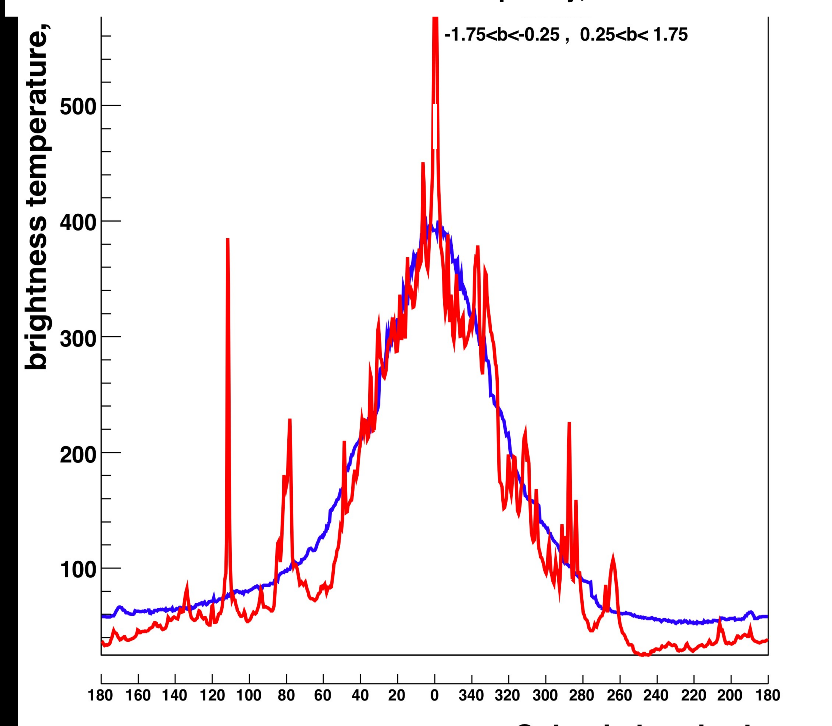


GALPROP model

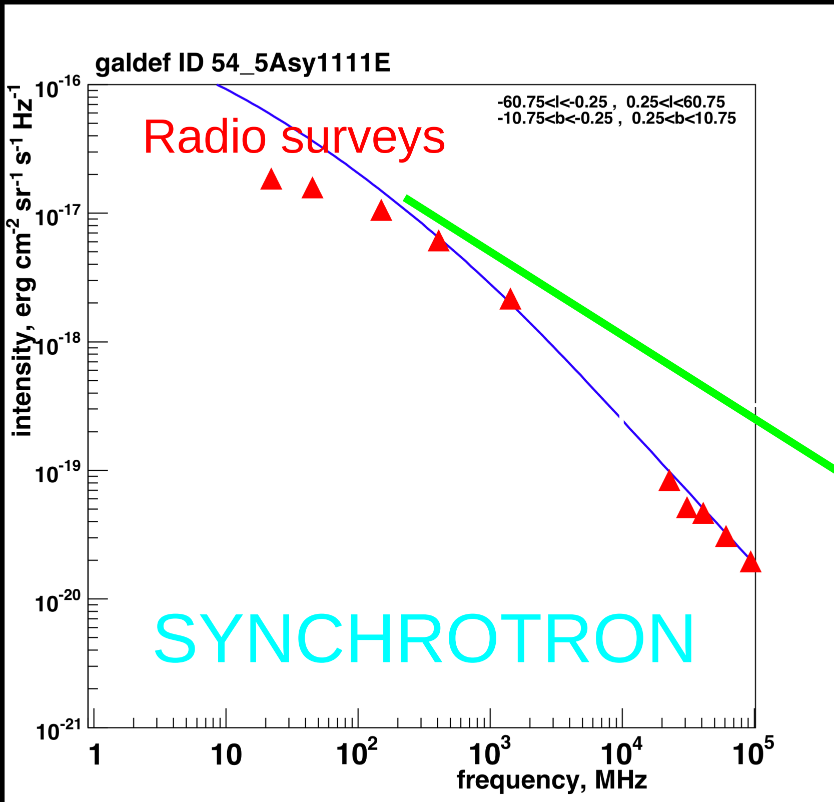




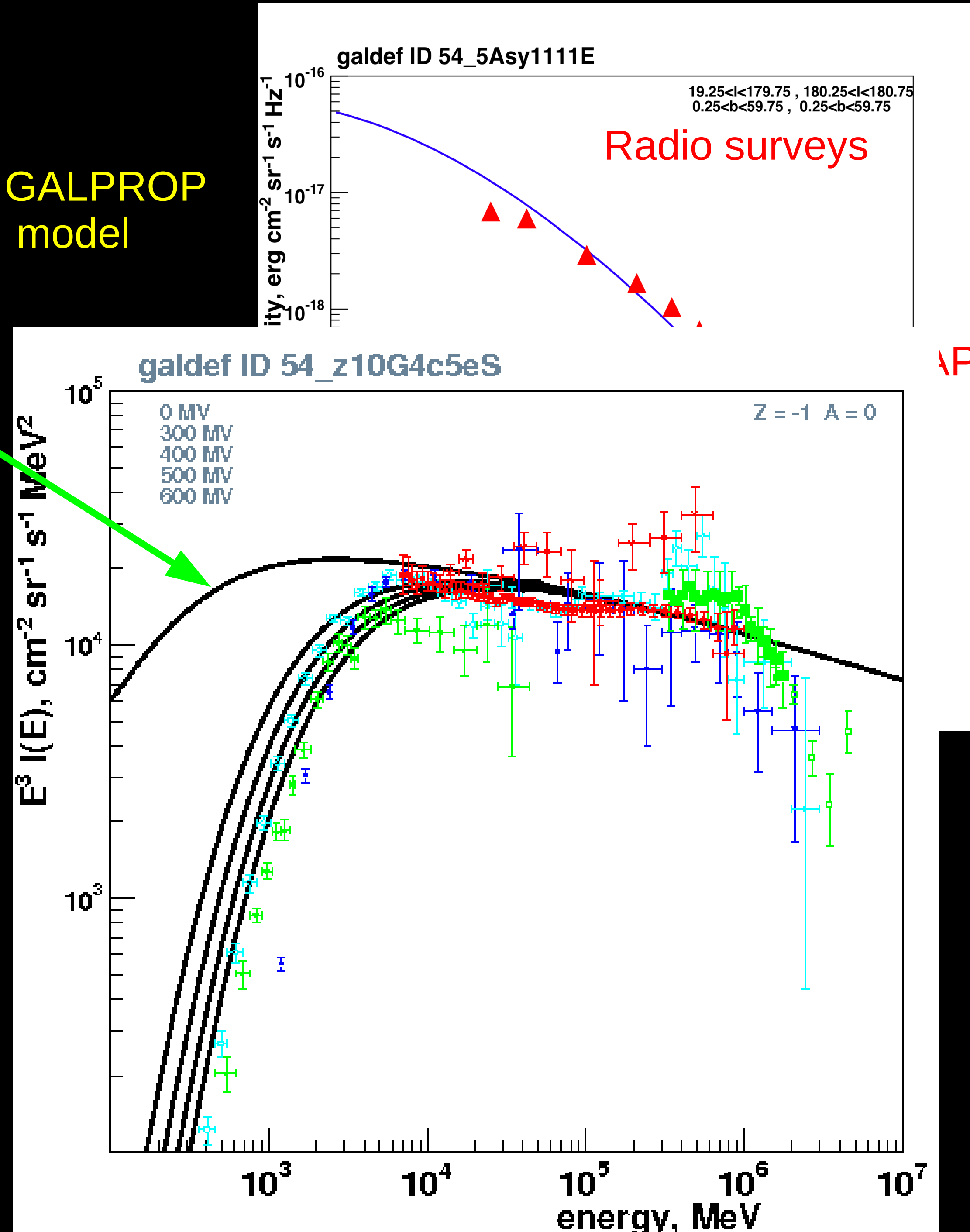
408 MHz



Elena Orlando



GALPROP model

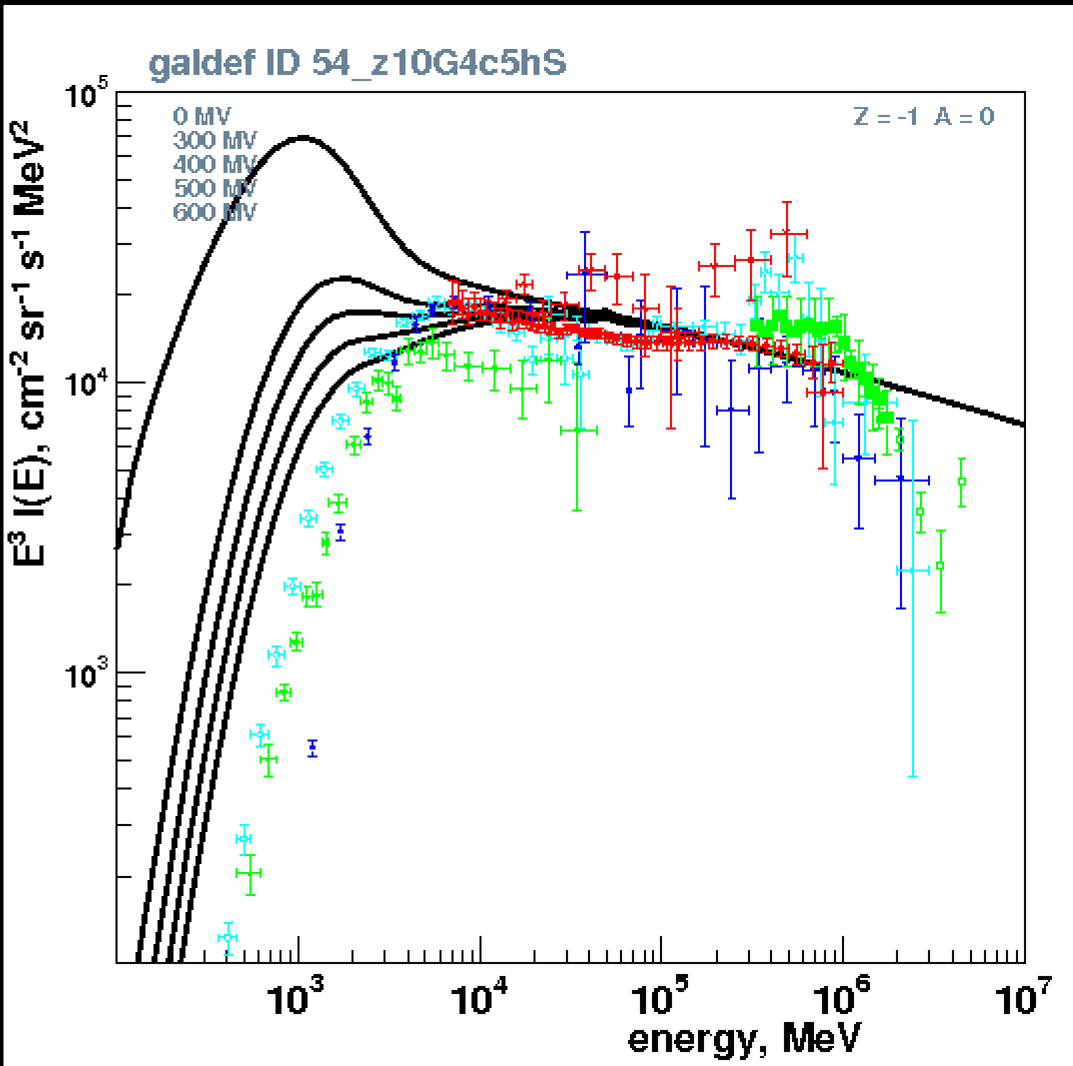


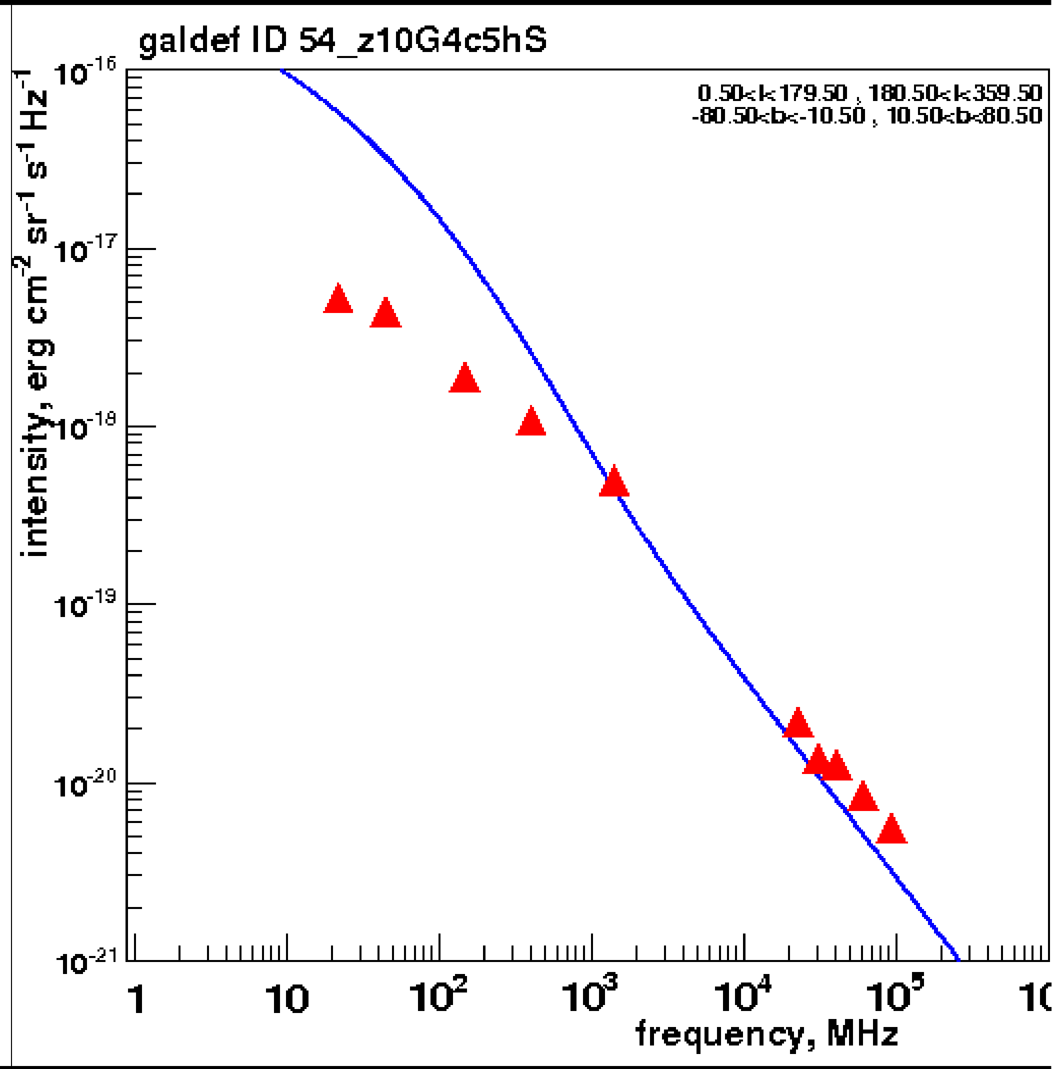
radio provides essential probe of interstellar electron spectrum at
E < few GeV
to complement direct measurments and determine solar modulation

electrons have huge uncertainty in modulation here

(can do for electrons but not nuclei !)

reacceleration, NO break in injection spectrum
clearly ruled out by radio data, although it could have
been allowed with enough solar modulation





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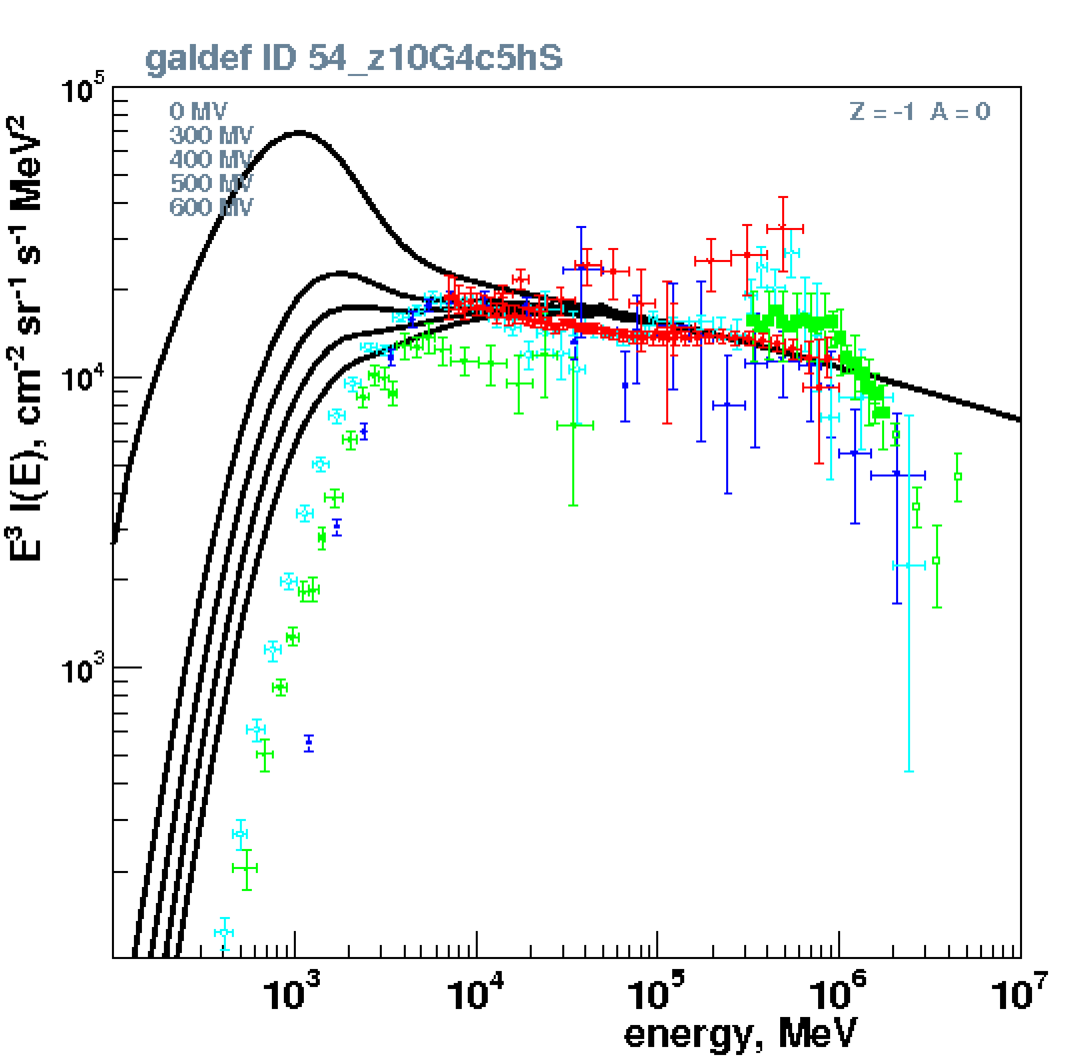
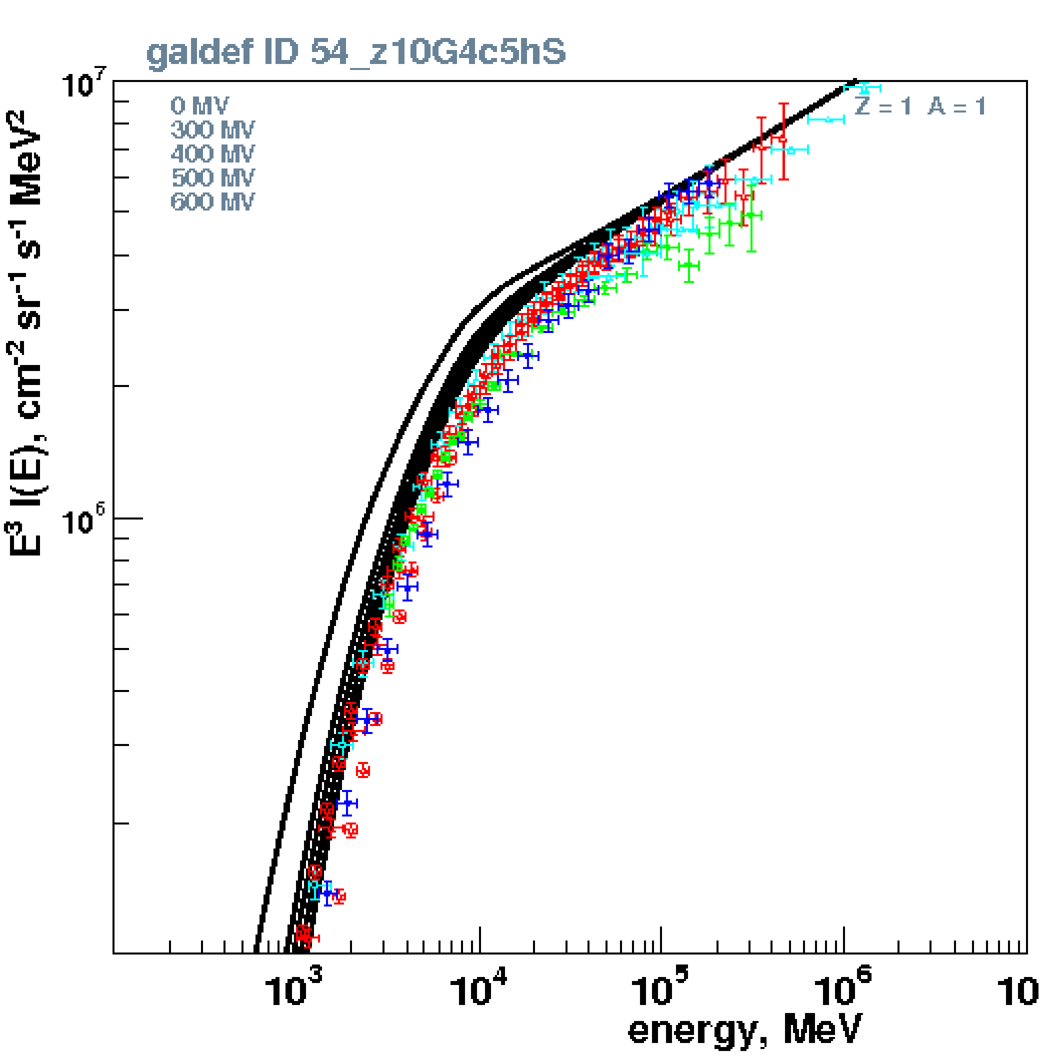




for protons no such check possible

remark on modulation:

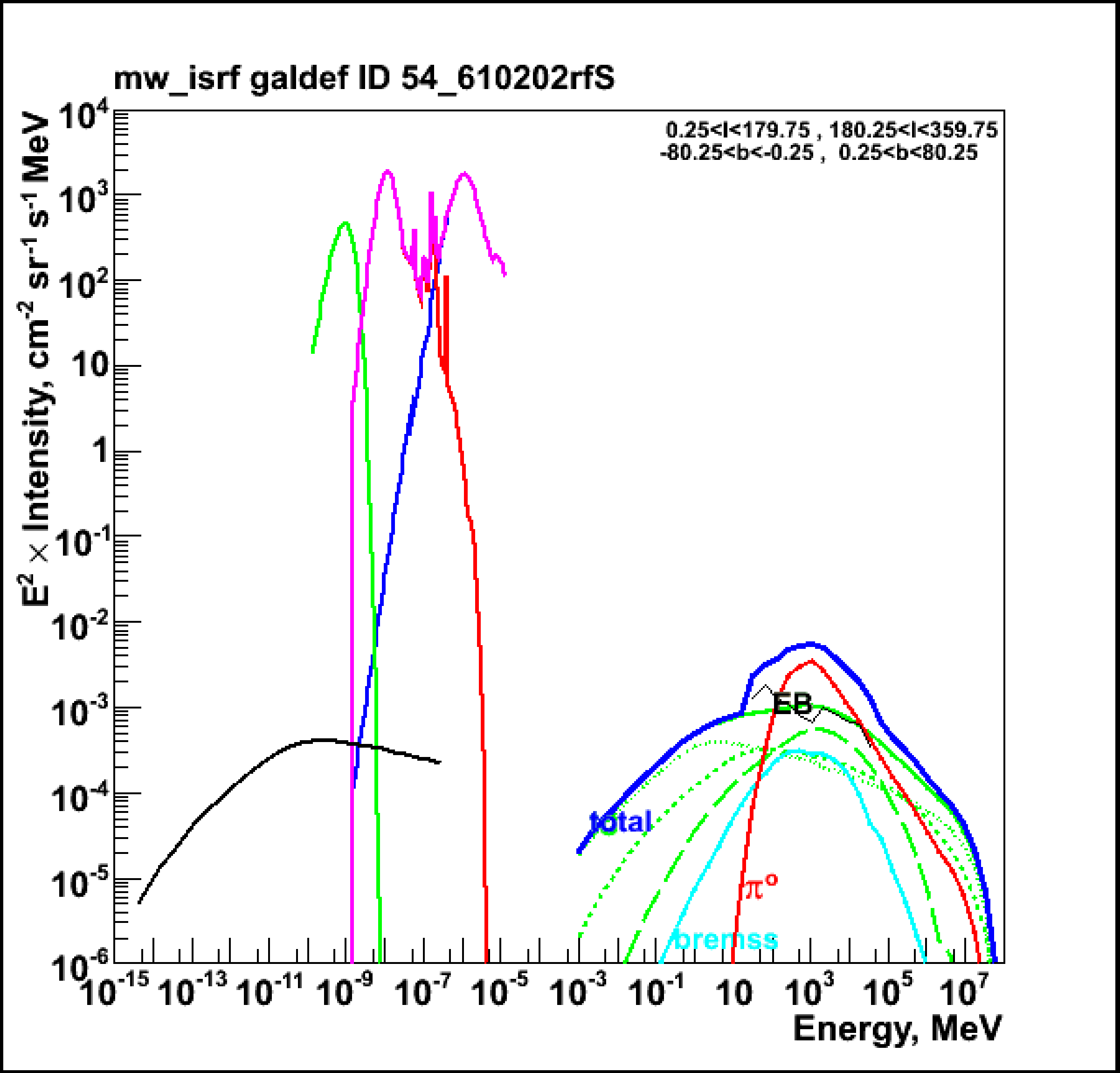
often LIS is used to get the modulation parameter (e.g. BESS paper)

and then modulation parameter used to get the LIS

way out of this circle ?

maybe gamma rays via pion-decay ?

Interstellar radiation over 20 decades of energy



radio CMB IR optical X γ

Having described some of what GALPROP can do

now...

Having described some of what GALPROP can do (more later)

now...

Some things GALPROP can't do (yet)

spatially-varying / anisotropic diffusion (but trivial to implement)

local effects: local bubble
enhancements in / exclusion from molecular clouds
.
Trajectory-type calculations – but B-field is there, so easy

MC instead of D.E. to allow more general models

more realistic Galactic winds (e.g. CR-driven)

rapid parameter scans (MCMC) but this is coming.

Development continues, some of these are foreseen

GALPROP realistic ?

you gotta be kidding

the Galaxy and all its processes are much more complex than we know or can ever know

but it is a step in the right direction we believe.

The Astrophysical Journal, 706:L155–L159, 2009 November 20 doi:10.1088/0004-637X/706/1/L155

GLOBAL GALACTIC DYNAMO DRIVEN BY COSMIC RAYS AND EXPLODING MAGNETIZED STARS

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ABSTRACT

We report the first results of the first global galactic-scale cosmic ray (CR)–MHD simulations of CR-driven dynamo. We investigate the dynamics of magnetized interstellar medium (ISM), which is dynamically coupled with CR gas. We assume that exploding stars deposit small-scale, randomly oriented, dipolar magnetic fields into the differentially rotating ISM, together with a portion of CRs, accelerated in supernova shocks. We conduct numerical simulations with the aid of a new parallel MHD code PIERNIK. We find that the initial magnetization of galactic disks by exploding magnetized stars forms favorable conditions for the CR-driven dynamo. We demonstrate that dipolar magnetic fields supplied on small supernova remnant scales can be amplified exponentially by the CR-driven dynamo, to the present equipartition values, and transformed simultaneously to large galactic scales. The resulting magnetic field structure in an evolved galaxy appears spiral in the face-on view and reveals the so-called X-shaped structure in the edge-on view.

Key words: cosmic rays – galaxies: ISM – galaxies: magnetic fields – ISM: magnetic fields – MHD

galprop is linear, just takes D_{xx}, convection, halo boundary etc as given.

more physical models:
e.g. PIERNICK code (Hanasz et al.)

galaxy evolution, starting from no CR and no B-field, they grow with time

CR as part of MHD model of Galaxy

treated as fluid but progress towards including particle spectrum

initiative to implement CR propagation, secondary production etc in PIERNICK code to enable testing such models against CR data.

Is this the future of the subject ?

now Fermi gamma rays......

Outlook

Fermi operational , results coming out fast
Try to keep the models up to the data challenges

Continue to use GALPROP to exploit synergy between
cosmic-rays - gammas – microwave - radio