GALPROP Retrospective and Outlook

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Feb 2 2016

GALPROP

Origins

Shortcomings

'Competitors'

Future desiderata

More physical approaches

Potpourri of relevant topics

The original motivation :

- to escape from the leaky-box

into the Galaxy

The original motivation :

- to escape from the leaky-box

into the Galaxy

but now...

precision experiments e.g.

Fermi, PAMELA, ACE, AMS02, Planck

and now also Voyager beyond the heliosphere

require correspondingly *detailed* – 'realistic' - models to do them justice

Annual Reviews of Nuclear and Particle Science, 2007

Cosmic-Ray Propagation and Interactions in the Galaxy

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Annu. Rev. Nucl. Part. Sci. 2007. 57:285–327

The *Annual Review of Nuclear and Particle Science* is online at http://nucl.annualreviews.org

This article's doi: 10.1146/annurev.nucl.57.090506.123011

0163-8998/07/1123-0285$20.00

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....

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

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

34 years ago!

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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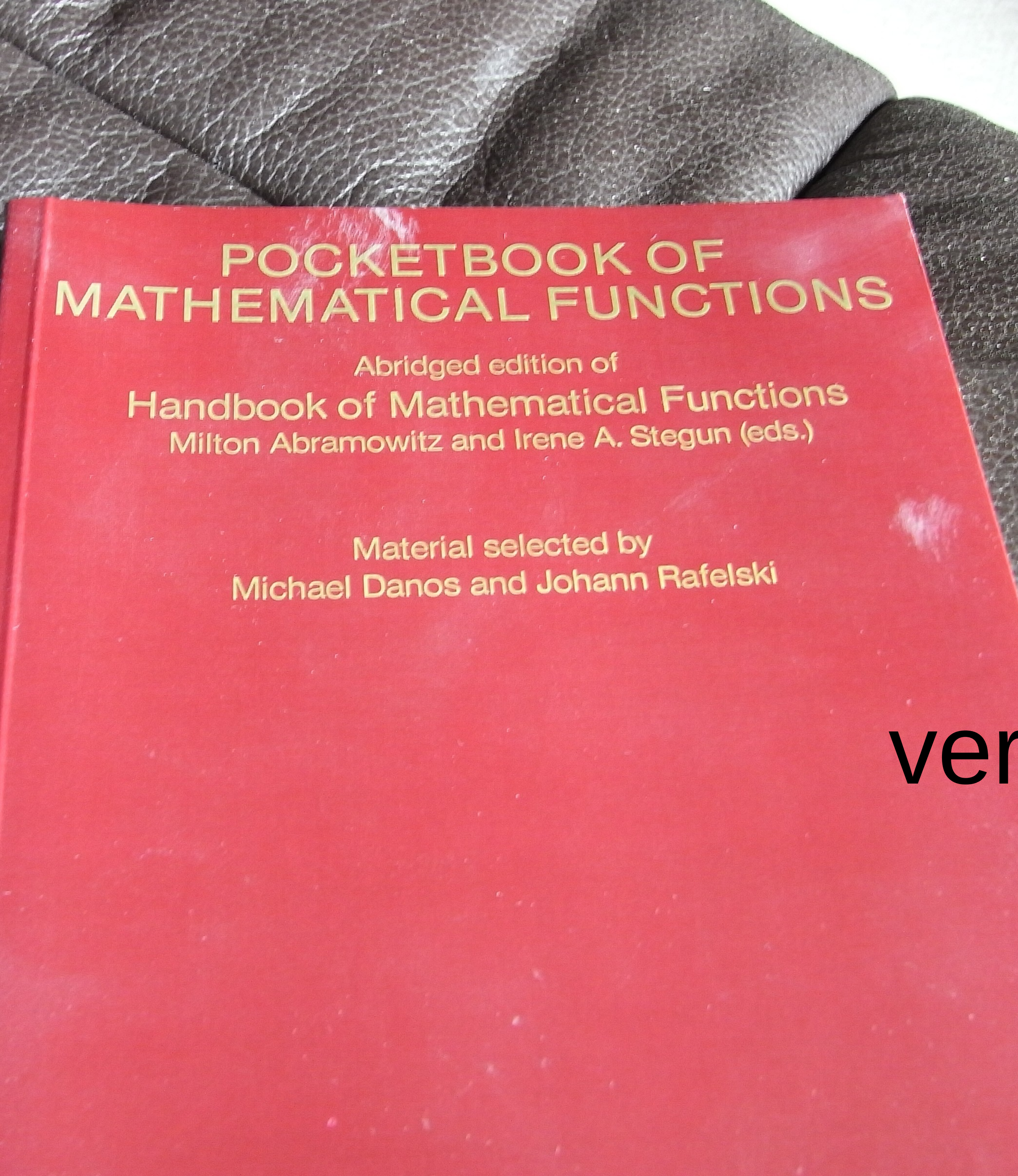
Spatial Propagation models

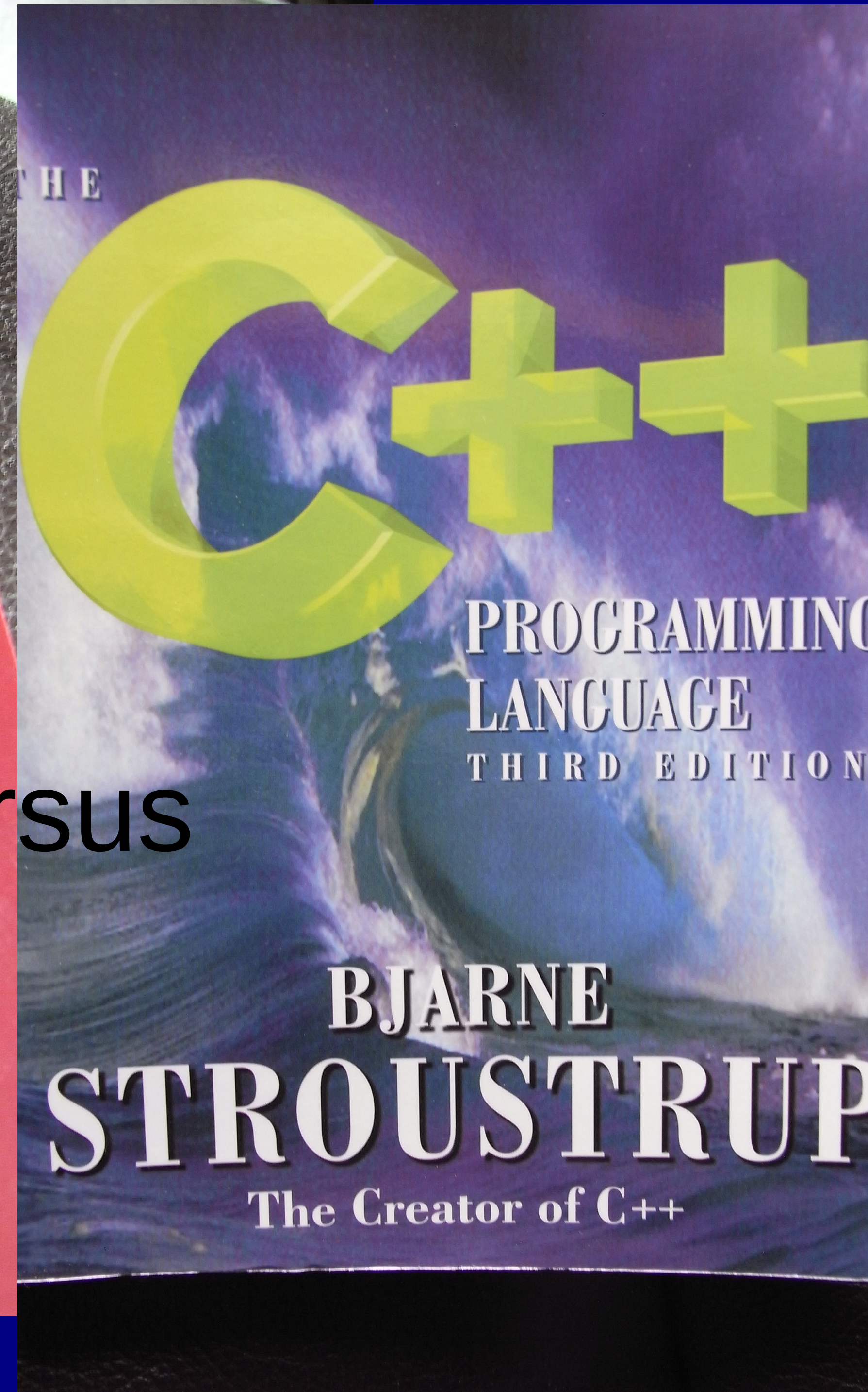
Advantage is the physical interpretation in terms of diffusion, convection etc.
related to the real Galaxy. Intuitive understanding of meaning of terms.

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

Workshop
"Tango in Paris" 2009
session
on
cosmic-ray programmes


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++

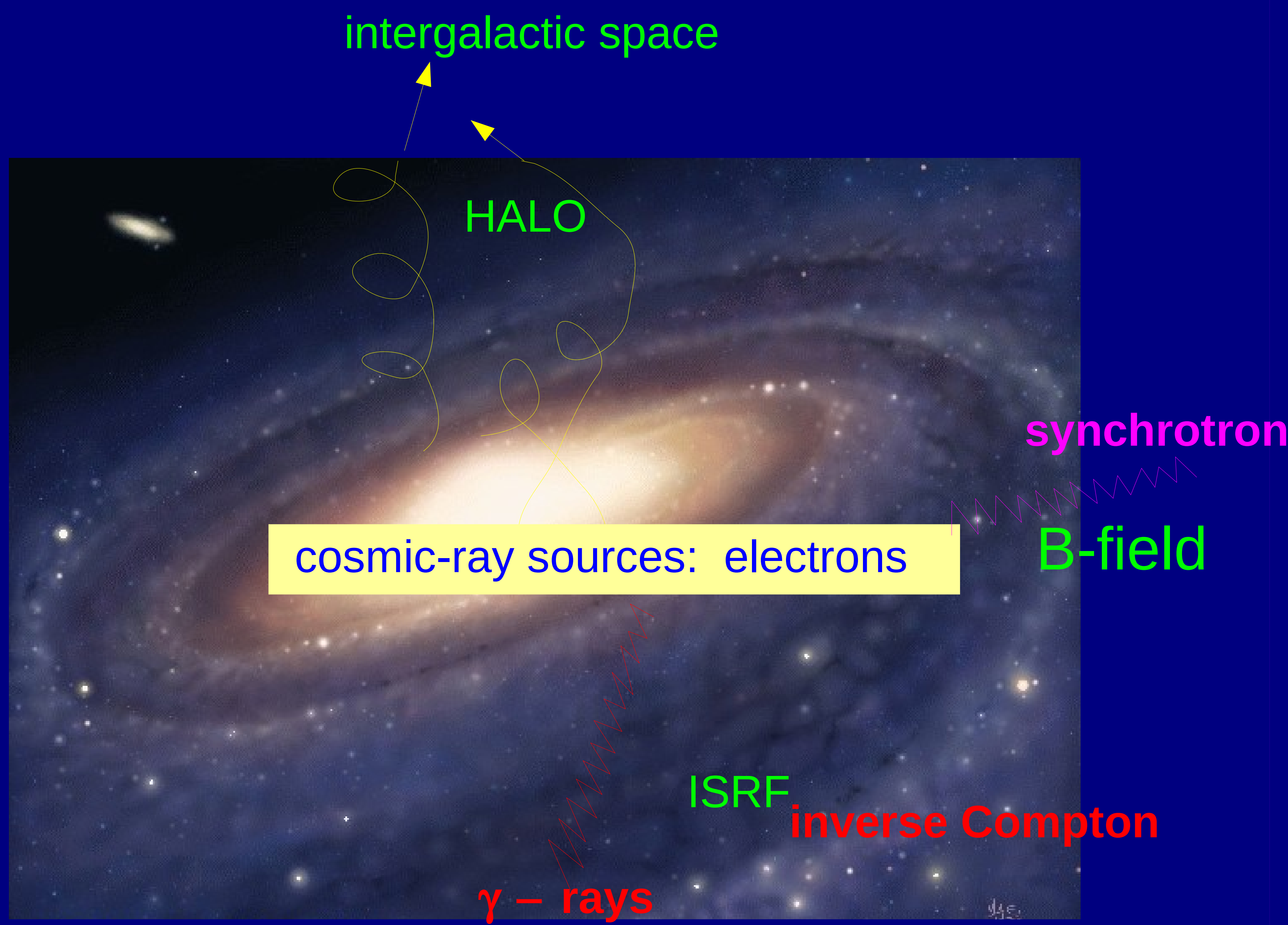
Propagation models

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.

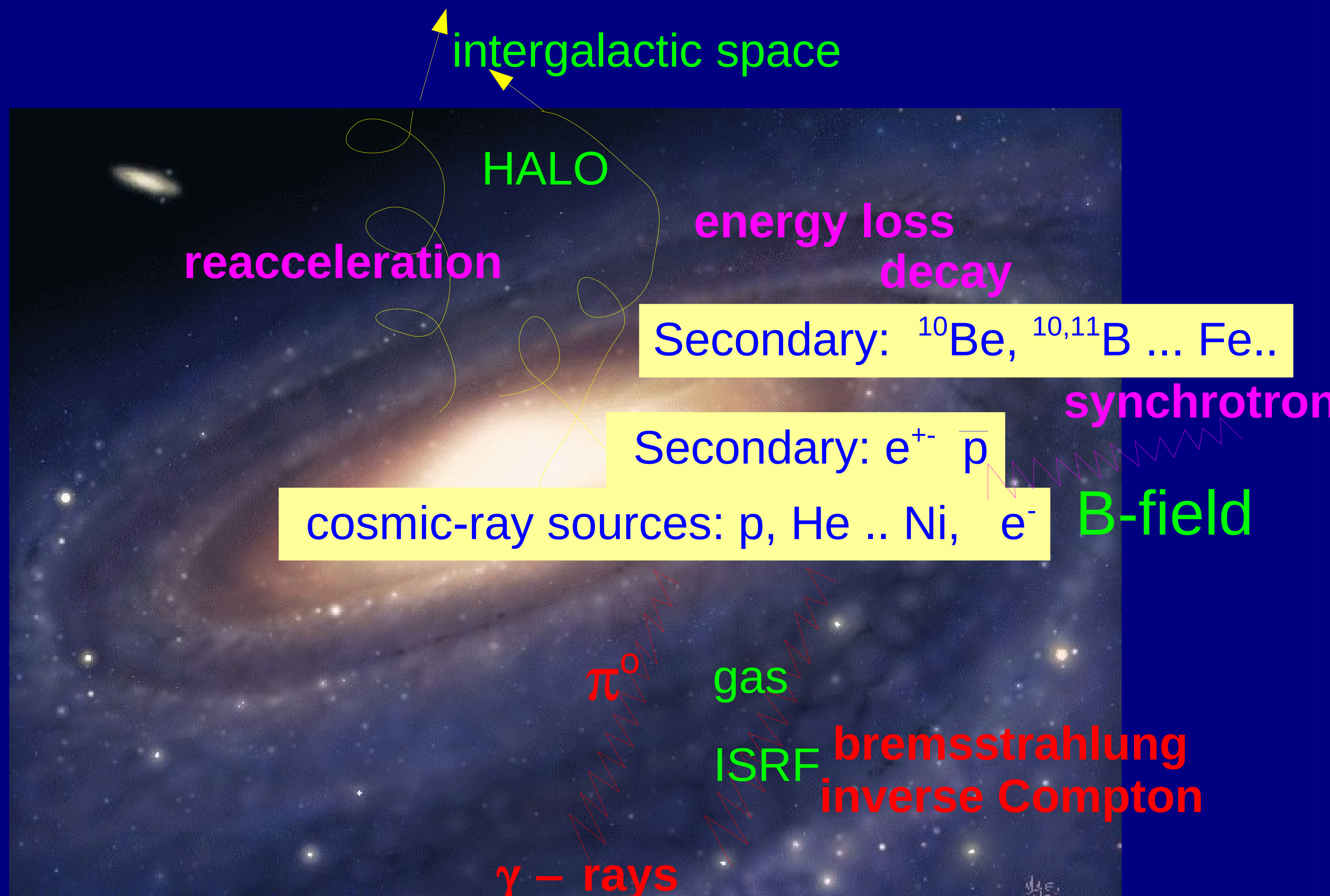
Analytical	Numerical
Mainly 1D, some 2D	2D or 3D
complex (but impressive) formulae	simple formulae (computer does the work)
simplified energy losses	full energy losses
simplified gas distribution	gas based on HI, CO surveys in 3D
simplified magnetic field	any magnetic field model
gamma rays only in simple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

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

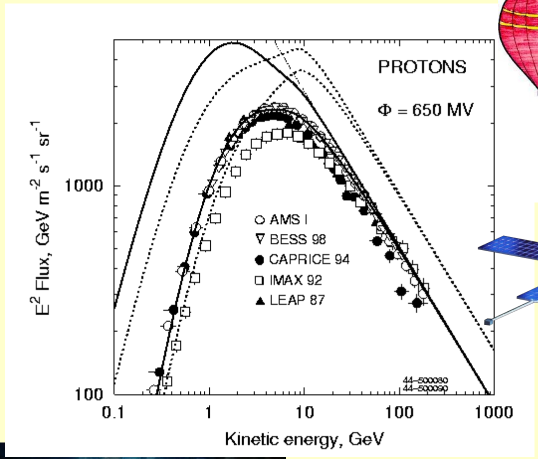


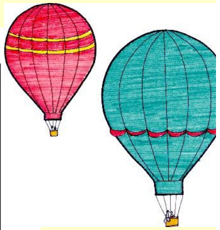
GALPROP model

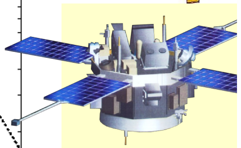
The **goal** : use *all* types of data in self-consistent way to test models of cosmic-ray propagation.

Observed *directly, near Sun:*

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

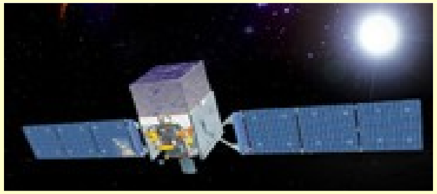


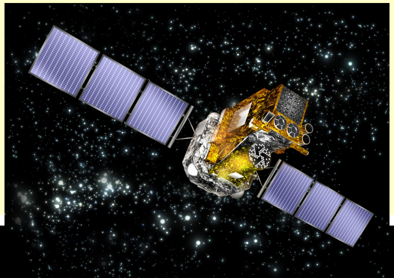


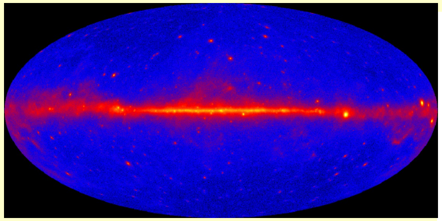


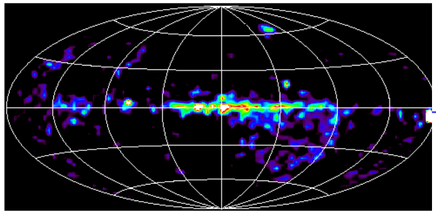
Observed *from whole Galaxy:*

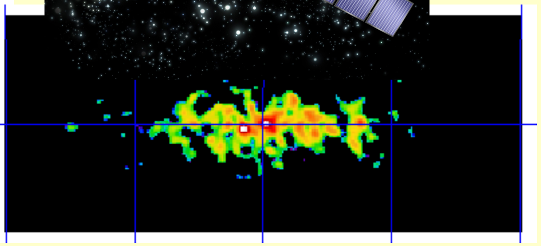
γ - rays



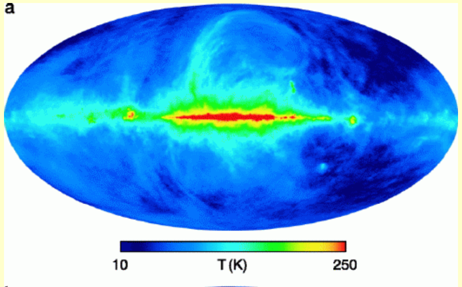




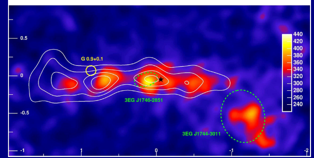




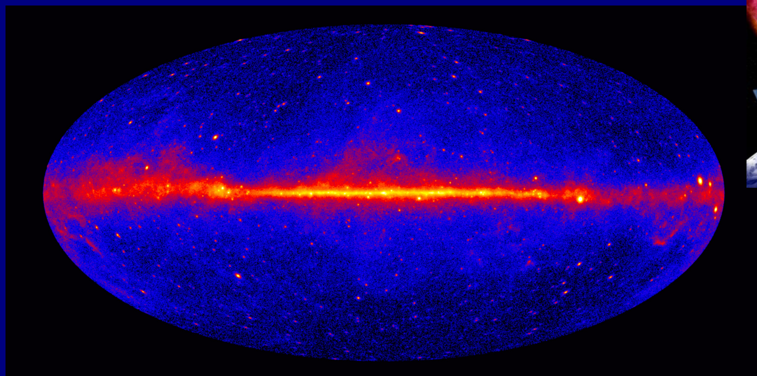
synchrotron



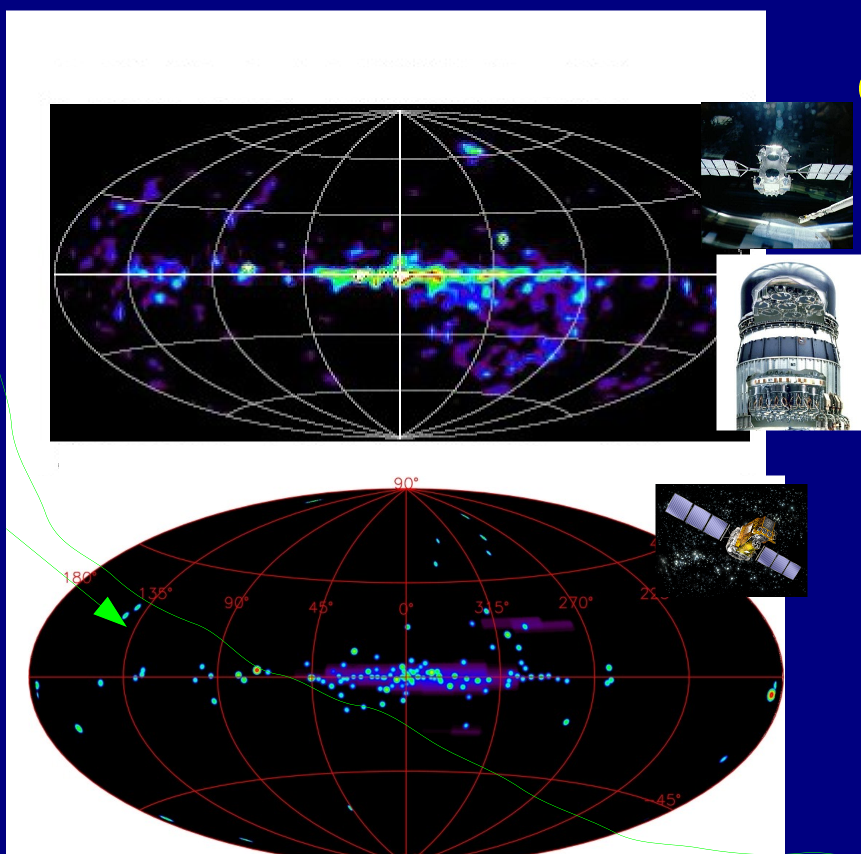
TeV



GeV



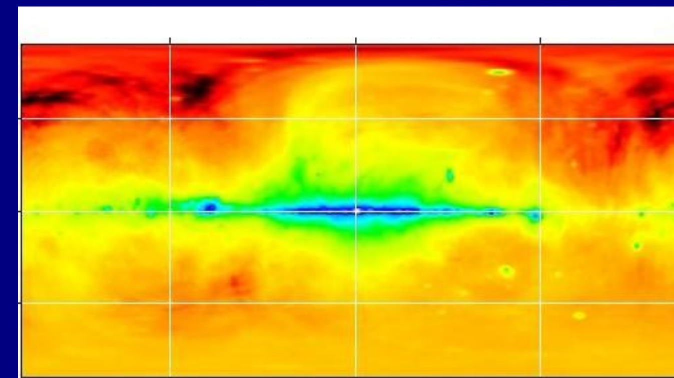
MeV

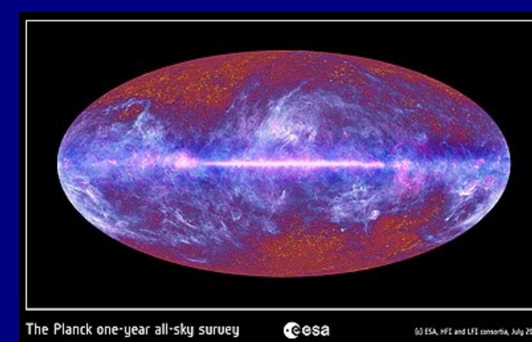


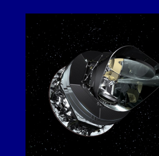
Cosmic-ray interactions
probed
by their photon emission

μeV

GHz







meV

THz

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

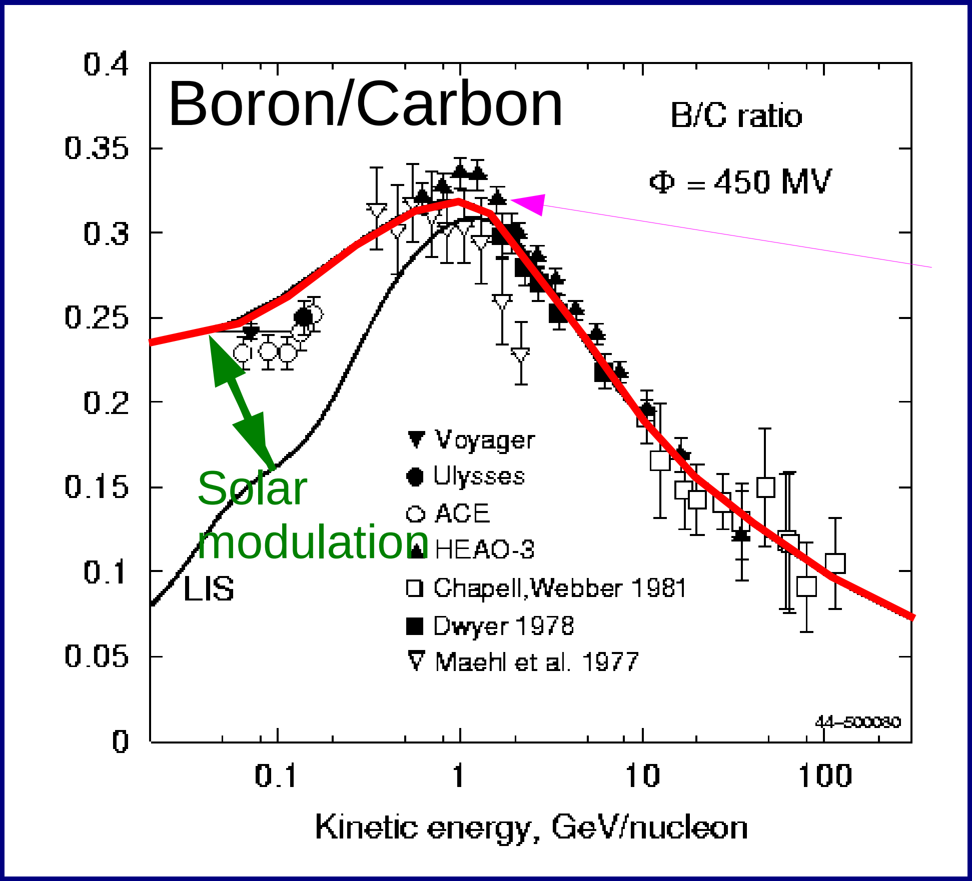
adiabatic momentum loss

$- \psi / \tau_f$ nuclear fragmentation

$- \psi / \tau_r$ radioactive decay

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

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

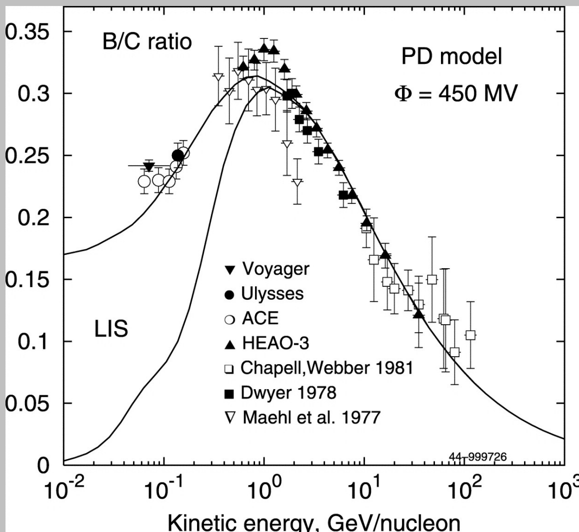
Momentum space diffusion

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

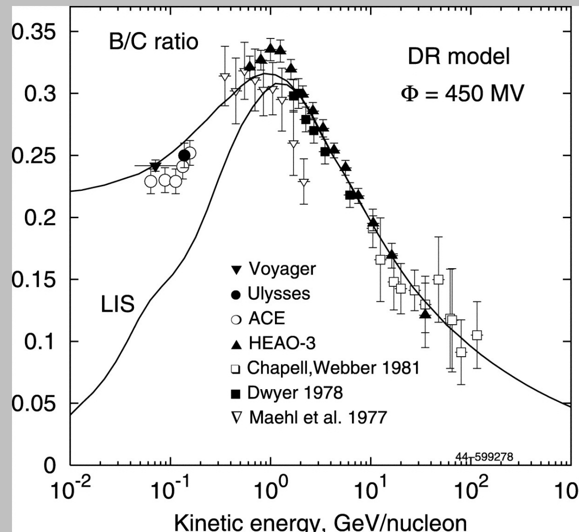
However reacceleration not proven, maybe does not happen

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

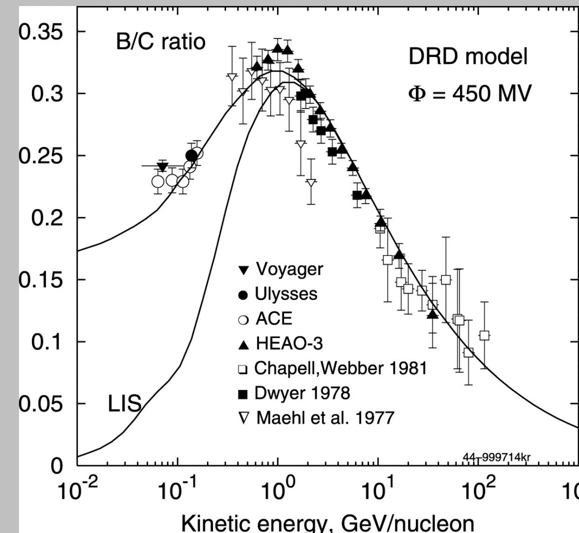
plain diffusion



diffusive reacceleration



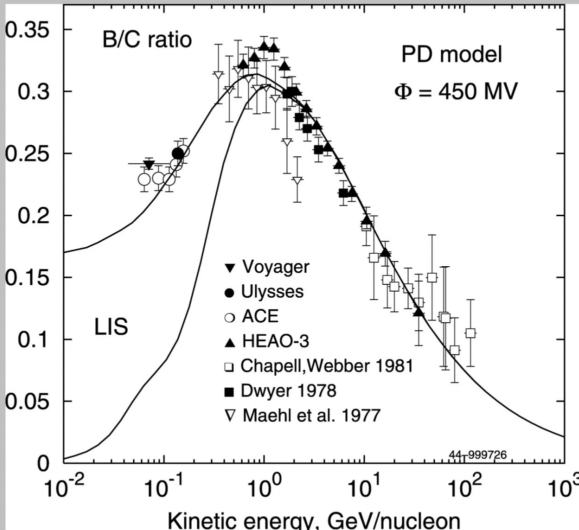
wave damping



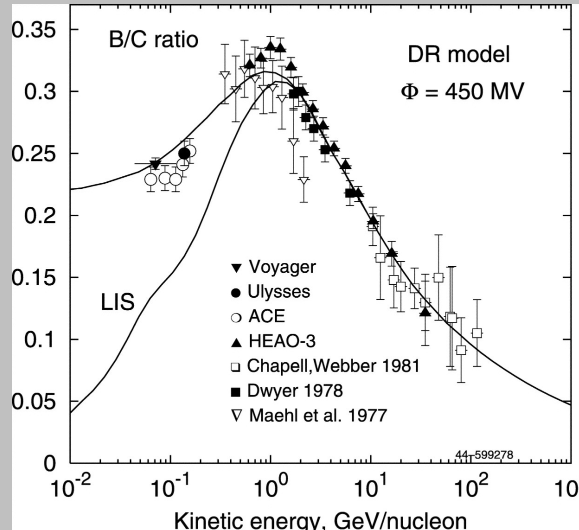
For any model, first adjust parameters to fit Boron/Carbon

Ptuskin et al. 2006 ApJ 642, 902

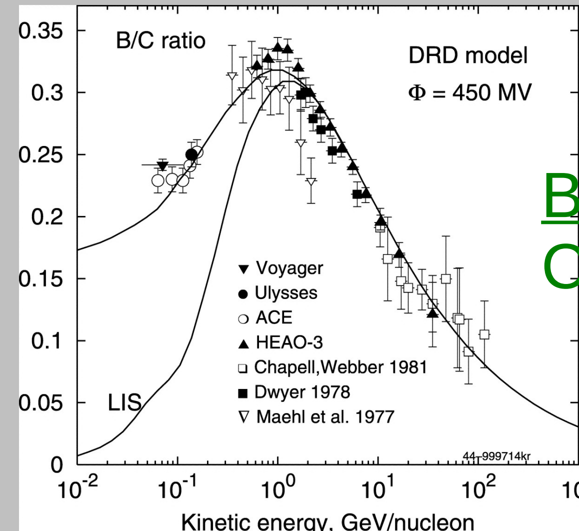
plain diffusion



diffusive reacceleration



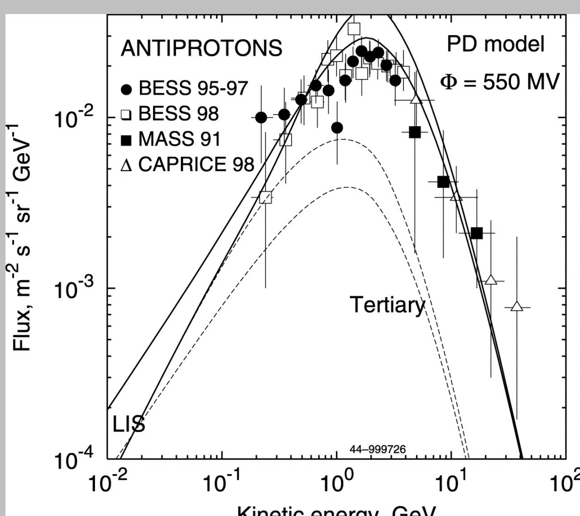
wave damping

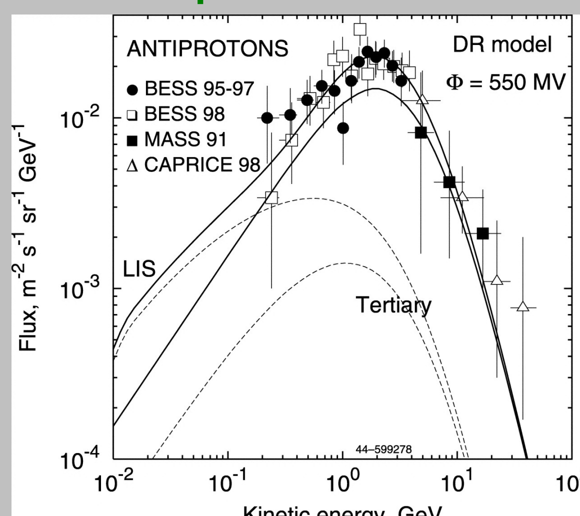


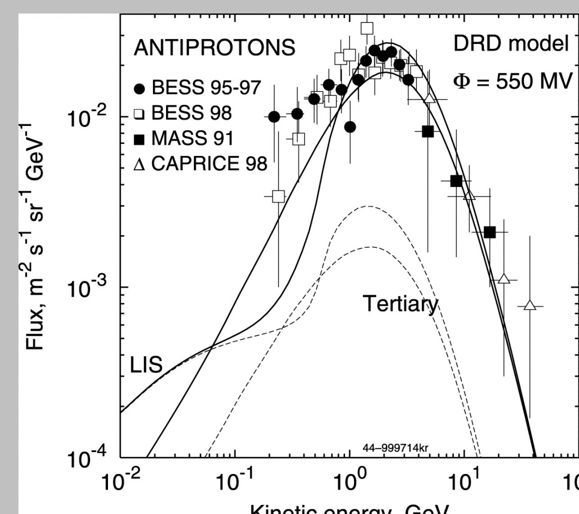
Boron/
Carbon

then predict the other cosmic-ray spectra

antiprotons

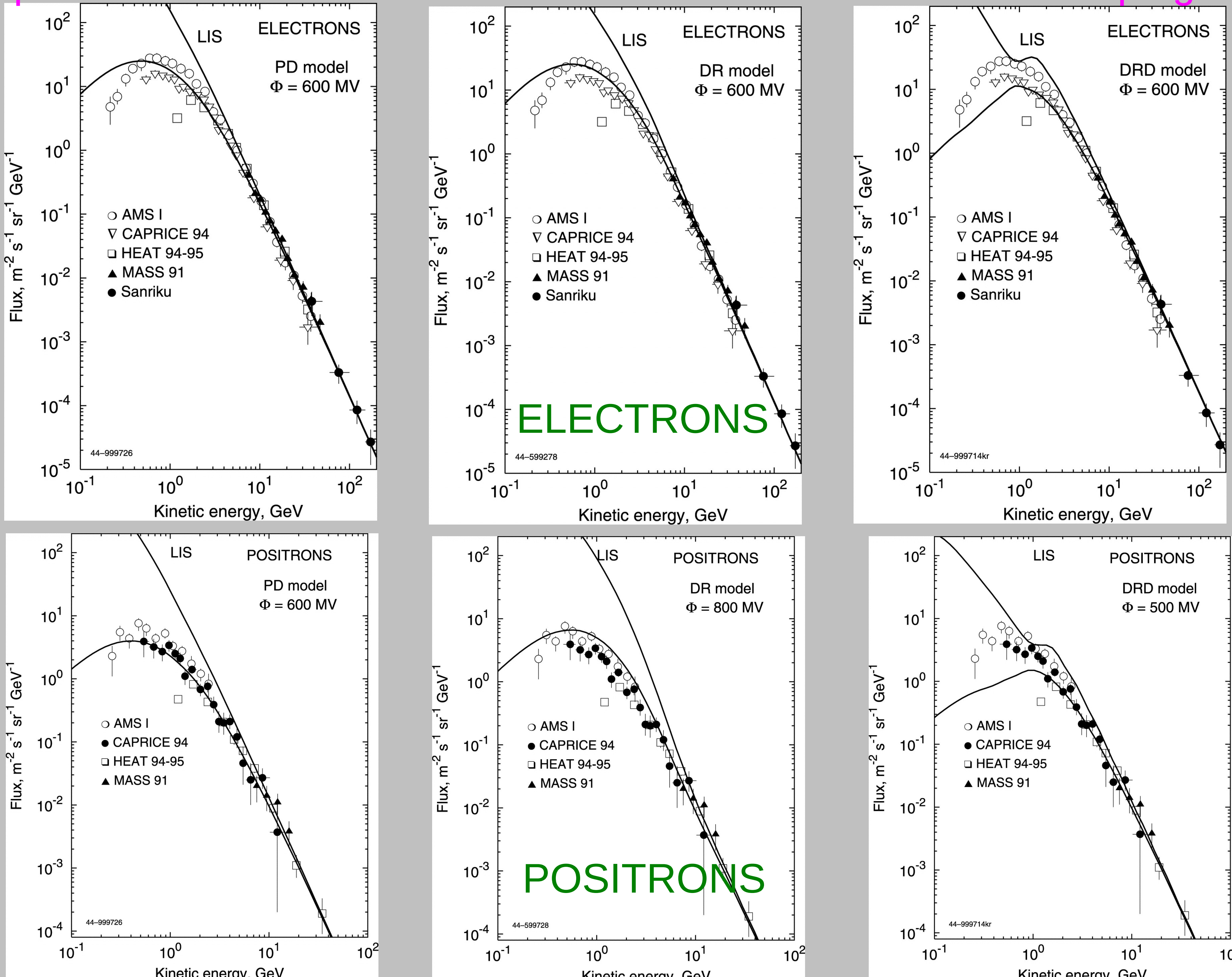






Ptuskin et al. 2006 ApJ 642, 902

plain diffusion | diffusive reacceleration | wave damping



GALPROP retrospective

1993 start with student PhD	idl
1995	fortran90 AWS + Igor Moskalenko
2000	c++ version

Troy Porter, Seth Digel, Gulli Johannesson, Elena Orlando
joined in following years

GALPROP owes part of success to long-term stable base over 20 years

Continuity is important!

Seemed an obvious idea in retrospect, why was it not done before?
Why so long before others followed?
Surprising that it is still the most-used programme on the market.

GALPROP developments 2013-2015 by AWS

Based on the 2011 public version 54,
(which was not followed by further releases by GALPROP team)

Available from sourceforge
ICRC 2015, arXiv:1507.05020 and updated Explanatory Supplement

>500 downloads so far

Enhancements:

Physical processes

Hadronic production cross sections QGSJET; Dermer for low energies
Hadronic energy losses via pion-production (were not included!)
Deuterium production by p-p fusion
Synchrotron radiation: polarization and new magnetic field models
Free-free emission in radio
Free-free absorption (radio low frequencies)

Cosmic-ray propagation

Accurate solution option. Avoids operator splitting and time-step fix.
Advantage: demonstrably steady-state solution, disadvantage: slow!
Anisotropic diffusion – perpendicular and parallel D can differ
Convective transport – more physical variation of velocity with z
Boundary condition: avoid forcing to zero at halo boundary. Not free escape!
Primary positrons; since now experimentally required.
spectrum and distribution independent from electrons

Formats:

HealPIX skymaps with energy in columns, compatible with CDS Aladin plotting package

GALPROP desiderata:

Update spallation cross-sections (e.g. DRAGON has FLUKA-based cross-sections)
Further improve hadronic production of gammas and e+-
Spiral and other structures
Replace old Fortran routines (!)
Free-escape at boundary: implement correctly

Keep improving/updating!
More involvement of other groups?

Combine forces with MHD Galactic modellers (see later).

GALPROP updates by Eric Carlson @ UCSC
Variable grid spacing, radial winds etc
Plus many associated tools for Fermi data etc
Soon to be written up for his PhD thesis.

github.com/erccarls/galprop

Hot news:
Hammurabi new release coming soon from Tess Jaffe
With GALPROP interface!

Hammurabi = synchrotron package used for Planck etc.
Full Stokes parameters.

Additional to GALPROP features:
Faraday depolarization
Faraday rotation of radio sources
More advances B-field models

GALPROP can compute electrons + positrons
→ good combination.

In addition:

GALPLOT plotting package compatible with GALPROP
Cosmic-ray spectra, ratios, gamma rays, synchroton
Cosmic-ray database, compatible with Maurin's CRDB.
Fermi and other data, radio surveys
Publicly available

Various other tools:

Inverse Compton routines

Heliospheric and stellar inverse Compton: StellarICS package
(used by Fermi-LAT for diffuse emission model)

Synchrotron routines

Propagation programmes: ' We are not alone '.

Other *numerical* propagation programmes e.g.

Evoli / Maccione / Gaggero / Grasso	**DRAGON**	PUBLIC
Ralf Kissman (Innsbruck group)	**PICARD**	**3D, most recent, not yet public**

***Analytical* propagation programme:**

Maurin / Putze / Derome **USINE**: PUBLIC (?)

Other programmes emphasizing other aspects than GALPROP:

Büsching/Pohl	Green's function approach
Hanasz, Lesch, Koturba	PIERNIK code: MHD, CR= fluid. CR-driven dynamo
DeMarco, Blasi, Stanev	Trajectory approach, for > 1 PeV
Girichidis	MHD with CR = fluid.
Benyamin etal	Monte Carlo particle propagation

DRAGON Cosmic-ray propagation package
(Daniele Gaggero, Carmelo Evoli, Giuseppe DiBernardo, etal)

Concept same as GALPROP

Newly written, improved structure

Extras w.r.t GALPROP:

Spatial dependence of diffusion coefficient
Full anisotropic diffusion tensor
Spatial grid size variation
FLUKA spallation cross-sections (Nicola Mazziotta, Bari)
Spiral structure

Public: used for various papers apart from DRAGON team.

PICARD Cosmic-ray propagation package.

Uni Innsbruck: Ralf Kissmann, (Michael Werner), Olaf Reimer with AWS@MPE
New student now working on PICARD at Innsbruck.

Fully 3D from outset.
Modern numerical techniques for solving cosmic-ray propagation.
Accurate and fast. Full MPI parallelization.
This allows fine 3D spatial resolution with reasonable CPU resources.
Spiral structure incorporated.
Uses *hdf5* for model storage (more flexible than *FITS* for 3D models)

Werner, M. et al. 2015, Astroparticle Physics 64, 18 : CR protons, electrons and spiral arms
Kissmann, R. et al. 2015, Astroparticle Physics 70, 39 : secondary/primary ratios

Synchrotron, B-fields: not yet, but foreseen. Fits well into 3D scheme.
Will allow all components to be accurately included.

A public version is planned sometime in the future.

Probably PICARD will replace GALPROP in the long term.

Anyway good to have multiple CR propagation packages:
e.g. GALPROP, DRAGON, PICARD
for cross-checks and healthy competition.

Propagation in 3D spiral-arm cosmic-ray source distribution models and secondary particle production using PICARD

R. Kissmann [a,*], M. Werner [a], O. Reimer [a], A.W. Strong [b]

[a] Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität Innsbruck, A-6020 Innsbruck, Austria
[b] Max Planck Institut für extraterrestrische Physik, Postfach 1312, D-85741 Garching, Germany

Kissmann, R. et al. 2015, Astroparticle Physics 70, 39

Features of PICARD

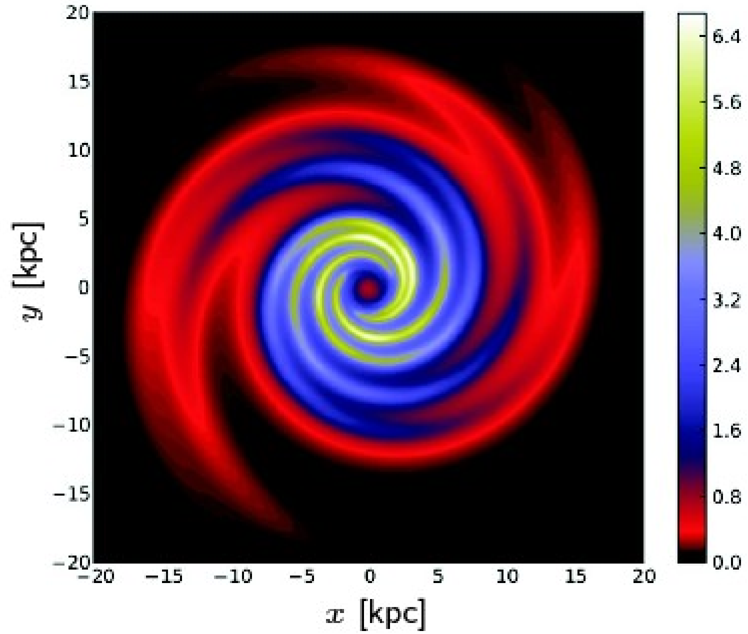
Solver

- Steady-state solution
- Explicit time integrator
- MPI-parallel
- Improved nuclear network
- Speed

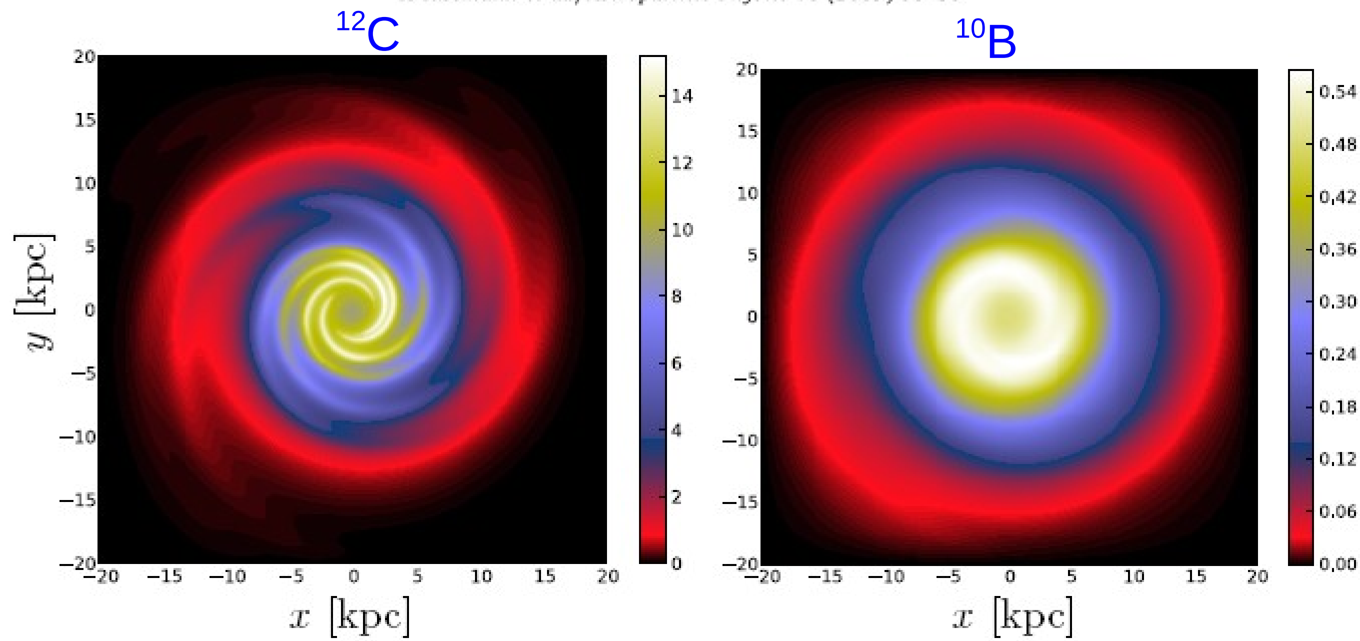
Example Resolution

- Standard CR simulation (e.g., Fermi Diffuse Paper)
  - 2D (1 kpc $\times$ 100 pc)
- PICARD
  - 3D (up to $\sim$75 pc^3)

Example Simulation Results

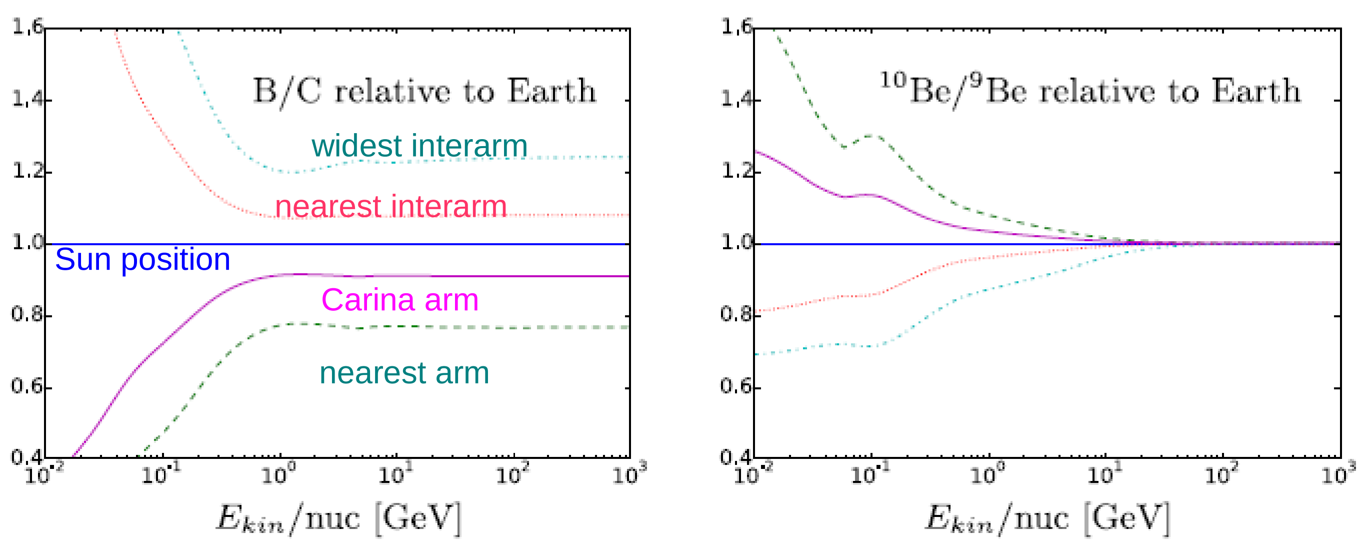


(RK et al. (2014))



secondaries smoother than primaries

Fig. 2. Cosmic-ray flux in the Galactic plane at an energy of ~10 GeV/nucleon for the Steiman source distribution in model z4R20. Data are given in units of GeV/nucleon/m^2s sr. On the left the flux for ^{12}C as a standard primary is shown and on the right the flux for ^{10}B as a standard secondary.



Deviations relative to the spectrum at the nominal position of Earth (solid blue line) are shown for the nearest spiral arm (green dashed line), the nearest inter-arm position (red dotted line), the widest inter-arm region (cyan dash-dotted line), and an intermediate position in the direction of the Carina arm (solid magenta line). (For interpretation

PICARD Cosmic-ray propagation package.

Werner, M. et al. 2015, Astroparticle Physics 64, 18 : CR and spiral arms

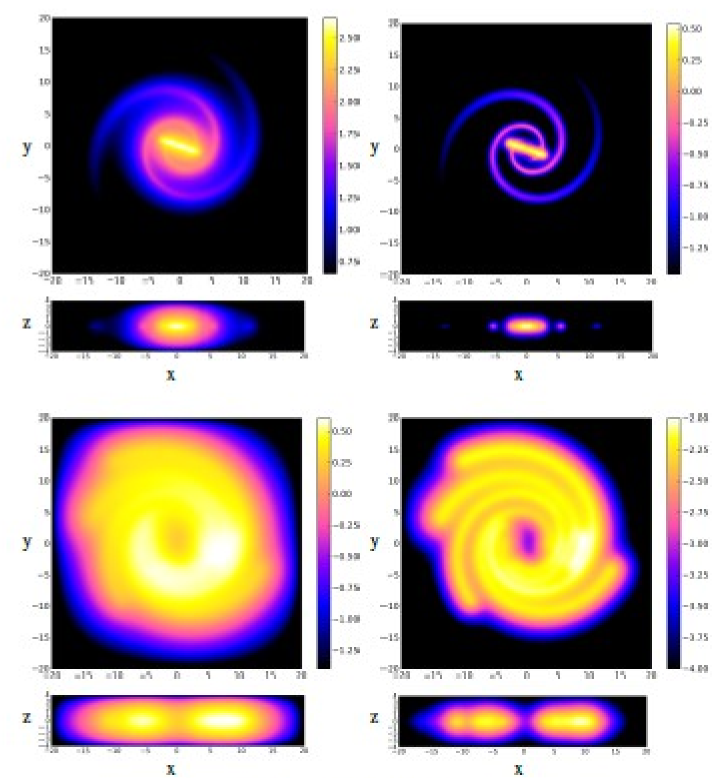


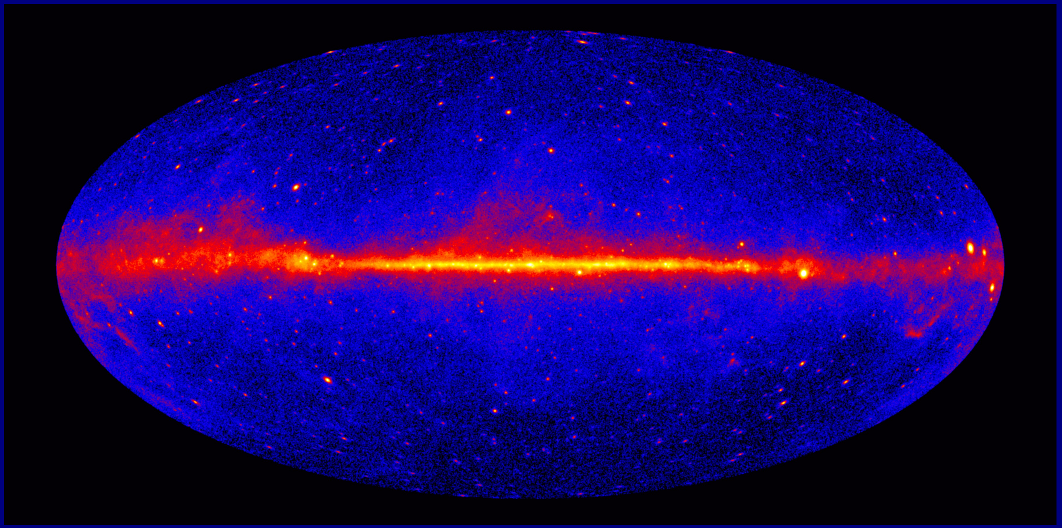
Figure 4: Same as Figure 3, but for electrons.

Cosmic-ray electrons, for 4 different spiral-arm source distributions

Fermi
Gamma-ray
Space Telescope

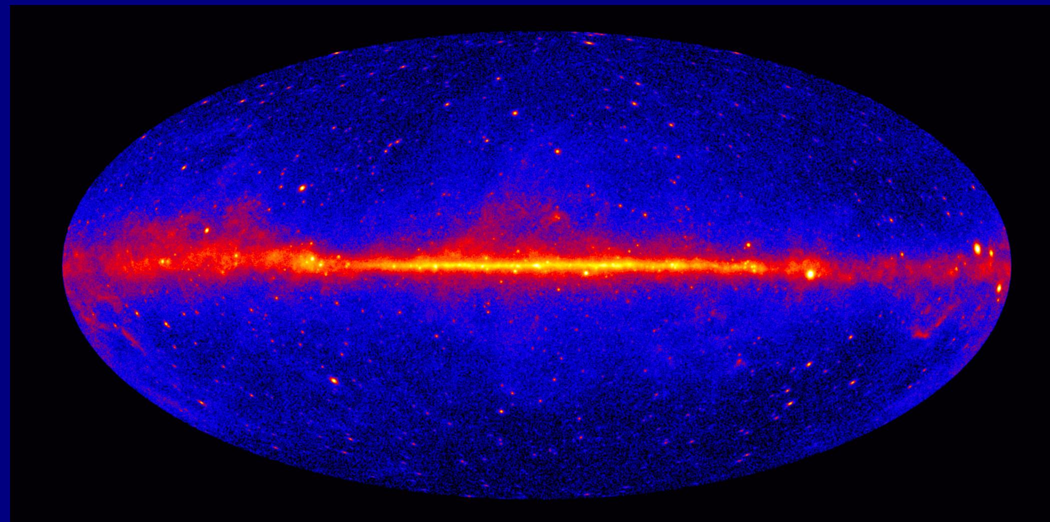
Exploiting gamma rays

1 – 10 GeV

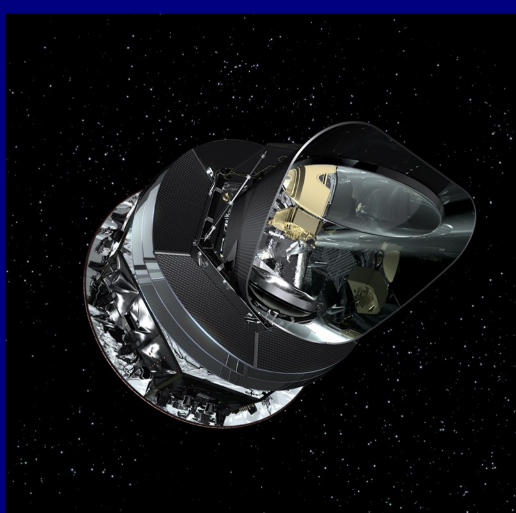


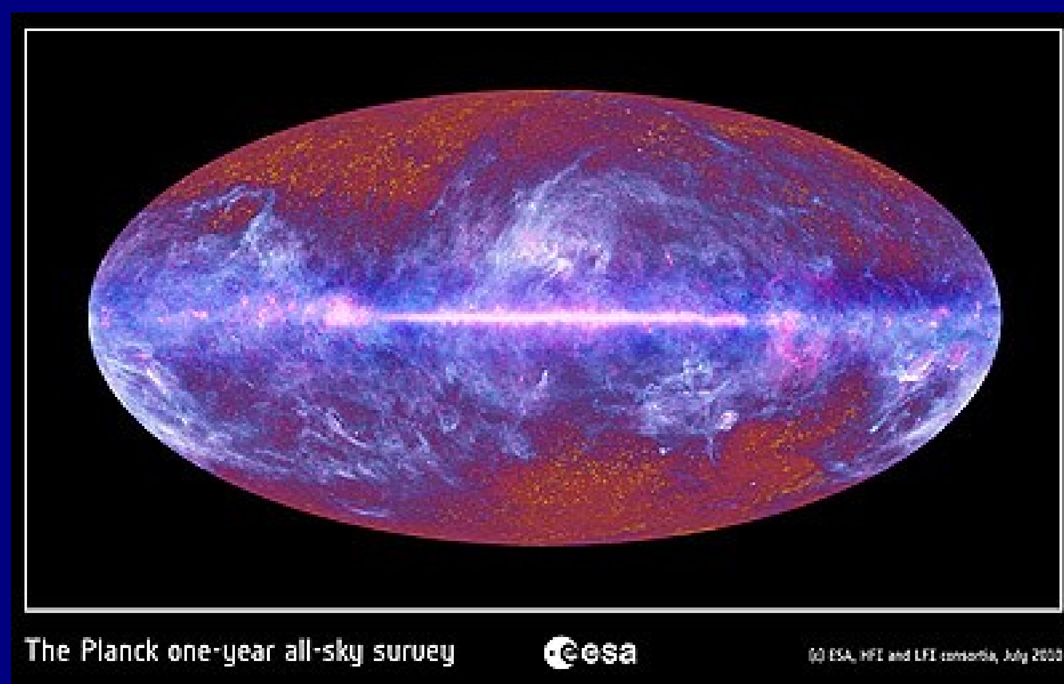
Cosmic-ray protons interacting with gas : hadronic (pion-decay)

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



2 years

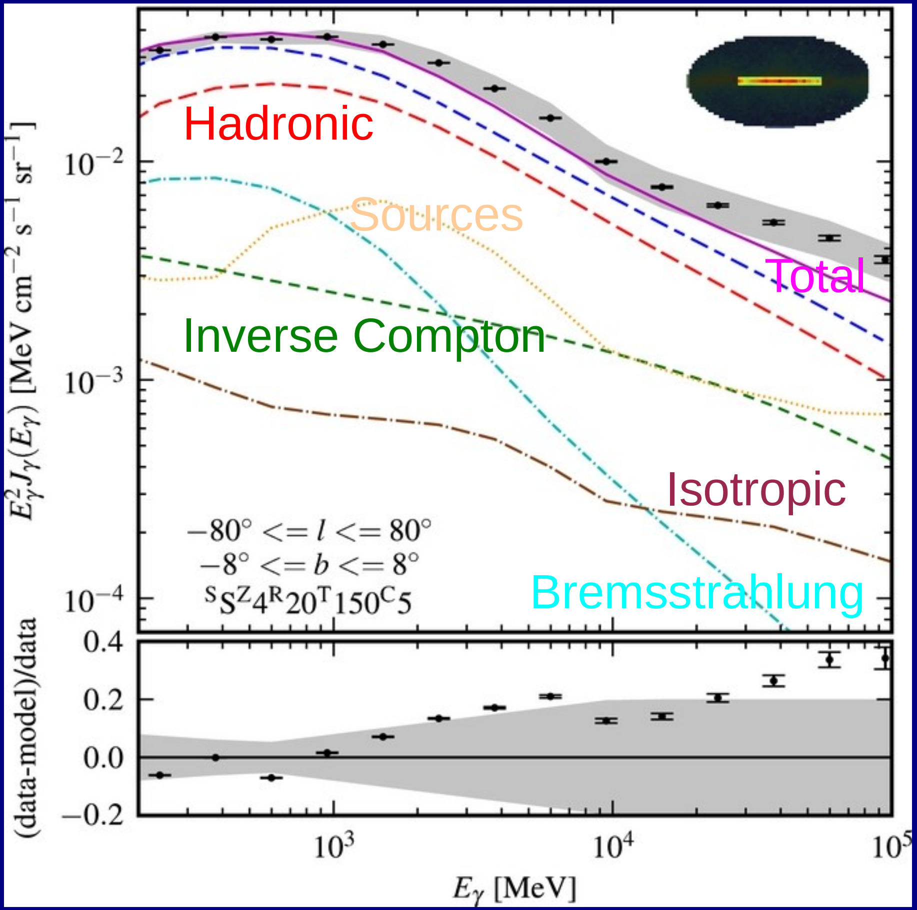




1 year

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

Fermi-LAT
Inner Galaxy Gamma Ray Spectrum



Ackermann et al. ApJ 750, 3 (2012)

Gamma-ray sky points to radial gradients in cosmic-ray transport

Daniele Gaggero,[1,2,*] Alfredo Urbano,[1,†] Mauro Valli,[1,2,‡] and Piero Ullio[1,2,§]

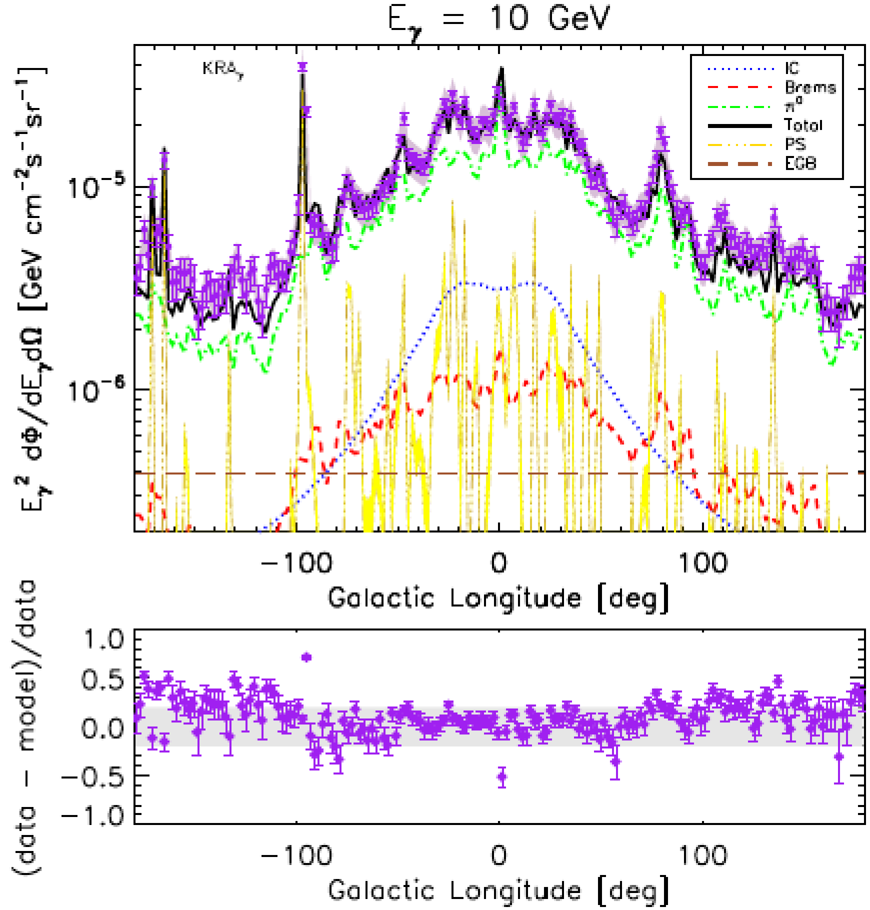


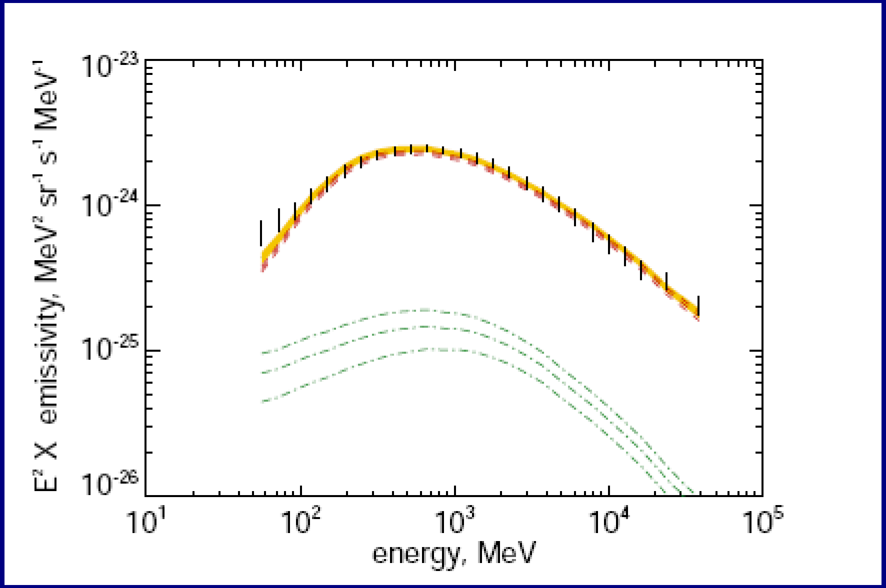
FIG. 8. *Longitudinal profile at fixed energy* $E_\gamma = 10$ *GeV. We average in latitude over the interval* $|b| < 5^\circ$.

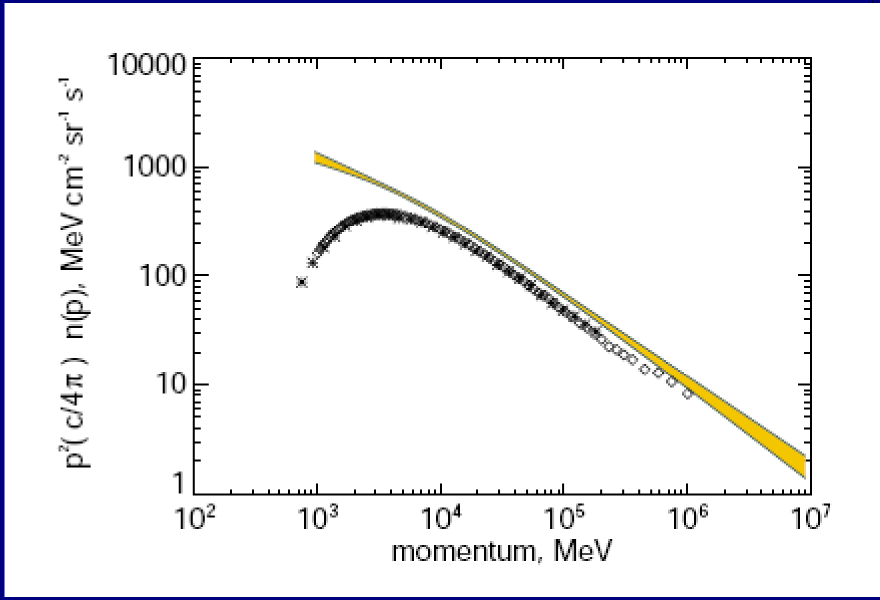
Potpourri of related topics to mention

Interstellar Cosmic ray spectra derived from gamma rays

Method : Bayesian analysis (Strong etal arXiv:1507.05006)

Gamma-ray gas emissivity *used to derive* Cosmic-ray protons via pion-decay





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).

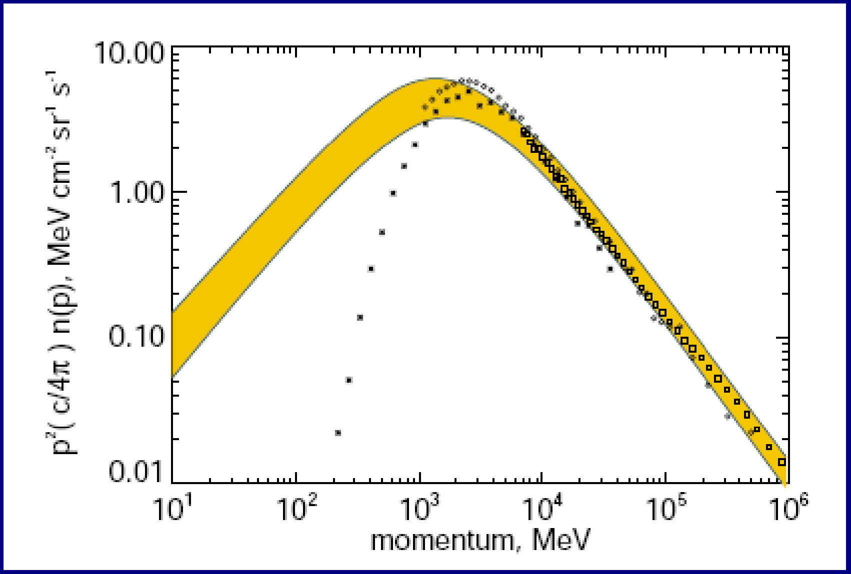
Power-law in momentum overall, but low-energy break
e.g. from power-law injection and interstellar propagation (diffusion = f(E))

Interstellar spectrum essential to test heliospheric modulation models.

CR spectrum modelled as smoothly broken power-law in momentum

$$n(p) \propto 1 \;/\; [(\frac{p}{p_{br}})^{\alpha_1/\delta} + (\frac{p}{p_{br}})^{\alpha_2/\delta}]^{\delta}$$

form used is $n(p) \propto 1 \;/\; [(\frac{p}{p_{br}})^{\alpha_1/\delta} + (\frac{p}{p_{br}})^{\alpha_2/\delta}]^{\delta}$ where α_1, α_2 are the indices below and above the break respectively for $\alpha_1 < \alpha_2$, and the spectrum breaks around a momentum centred on p_{br}; the parameter δ controls the sharpness of the break: smaller δ produces a sharper break, typical values are δ =0.5 – 1.5. It converges to the given power-laws at low and high p, with a smooth transition.



Method: Bayesian, MultiNest package implementing Nested Sampling algorithm
10 parameters
Posterior chains used to sample the resulting spectra.

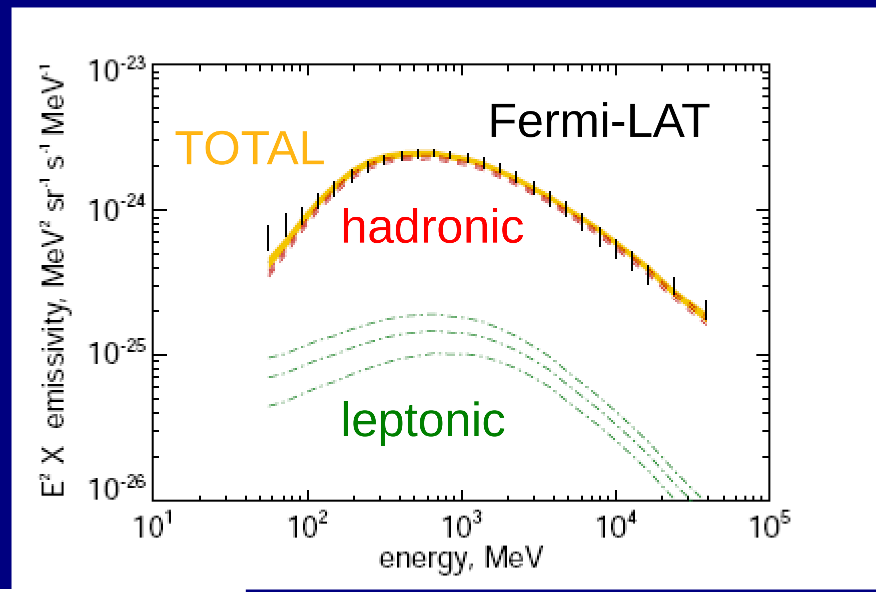
Table 1: Summary of model fits to equation 6.1. Entries are prior range, posterior mean and standard deviation. The proton parameters are constrained by the γ-ray emissivities, while the lepton parameters reflect mainly the prior from synchrotron and direct measurements. The parameters are highly correlated and degenerate, so the resulting spectrum derived from the full posterior (Fig 1) is preferred to the individual parameters. The CR density n_{ref} is multiplied by $(c/4\pi)$ to give a flux in the usual units quoted in experiments. p_{ref}= 10^5 MeV for protons, 2×10^4 MeV for leptons.

Parameter	range: min	max	mean	std	units
Protons					
$(c/4\pi)n_{ref}$	1×10^{-9}	20×10^{-9}	6.4×10^{-9}	0.3×10^{-9}	cm^{-2} sr^{-1} s^{-1} MeV^{-1}
α_1	2.2	2.7	2.37	0.09	
α_2	2.6	3.5	2.82	0.05	
δ	0.05	1.0	0.5	0.1	
p_{br}	1000	10000	5870	2200	MeV
Leptons					
$(c/4\pi)n_{ref}$	1×10^{-9}	3×10^{-9}	2.2×10^{-9}	0.5×10^{-9}	cm^{-2} sr^{-1} s^{-1} MeV^{-1}
α_1	1.8	2.2	2.0	0.1	
α_2	3.1	3.2	3.15	0.03	
δ	0.05	1	0.47	0.25	
p_{br}	500	2000	1130	4067	MeV

Interstellar Cosmic ray spectra derived from gamma rays

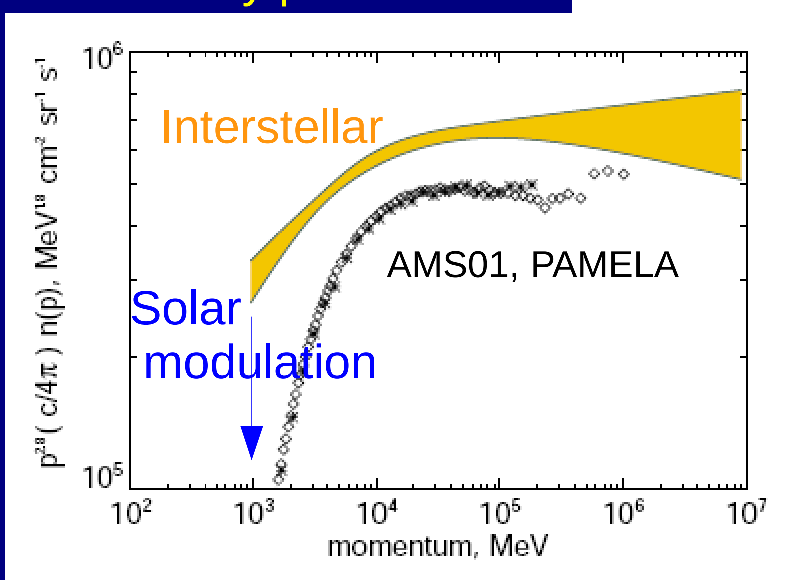
Method : Bayesian analysis

Gamma-ray gas emissivity

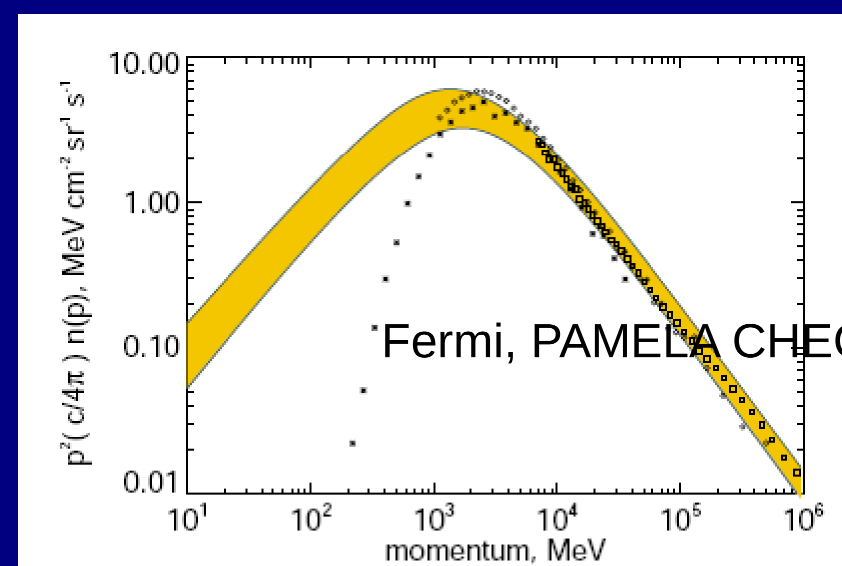


+ constraints
from synchrotron

Cosmic-ray protons



Cosmic-ray leptons



Technical note

Use momentum, not kinetic energy!
Momentum is physically appropriate for acceleration mechanisms
e.g. diffusive shock acceleration gives power-law in momentum.

Kinetic energy power-law has a break break when plotted in momentum

Originally pointed out by Chuck Dermer, see e.g. Strong etal ICRC2015

Also: use density $n(p)$ not flux $I(p)$
More physical, $n(p)$ are the units used by GALPROP etc.
We don't want the velocity!

Observers usually use $I(E_k)$ which is convenient since
$n(p) = (4\pi/c)\ I(E_k)$

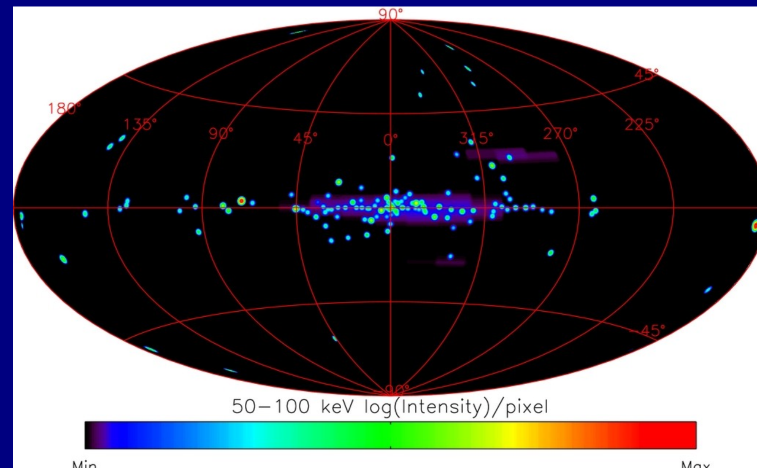
Low energy Gamma rays

Fermi low-energy extension with Pass8 event processing.
Down to 20 MeV, difficult because of broad PSF, energy dispersion and earth emission
But coming along.

COMPTEL (1-30 MeV) heritage, still only available mission in this range.
Good news: Werner Collmar (MPE Garching) still working on this (only he can!)
Example: LS5039 microquasar periodicity
New point-source catalogue, eventually all-sky maps on the horizon.

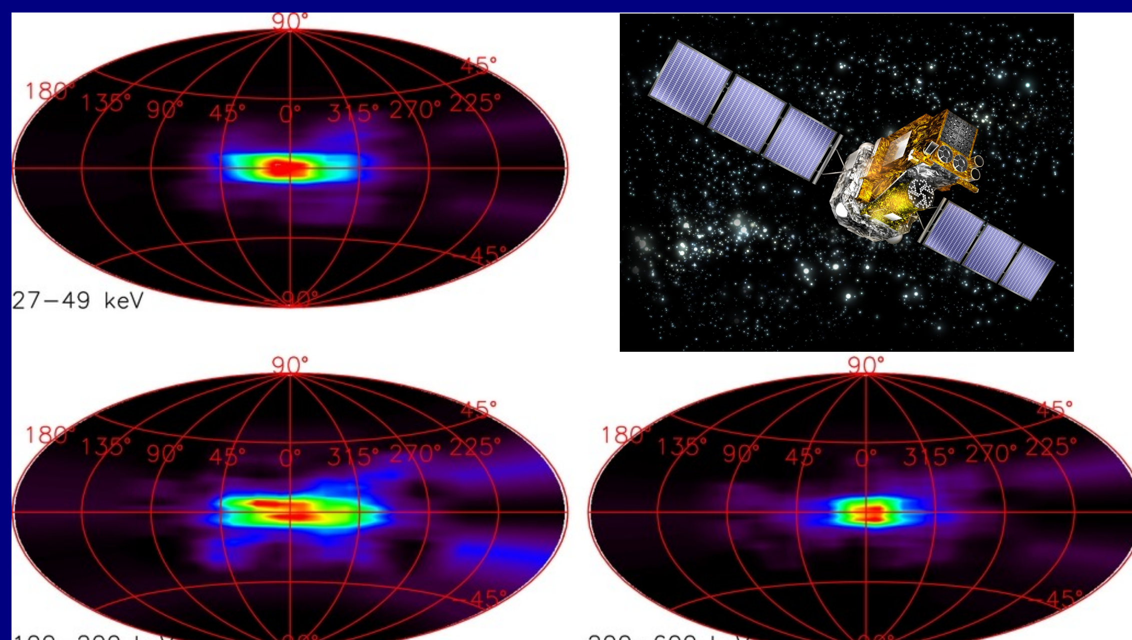
(INTEGRAL/SPI: only 20 keV - 1 MeV)

New missions unfortunately slow in coming but e.g. AstroGam initiative
Large interest in the community.



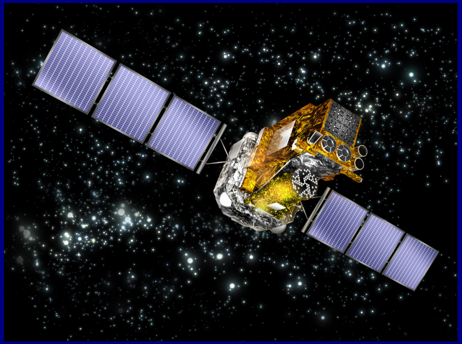
INTEGRAL / SPI
Continuum skymaps

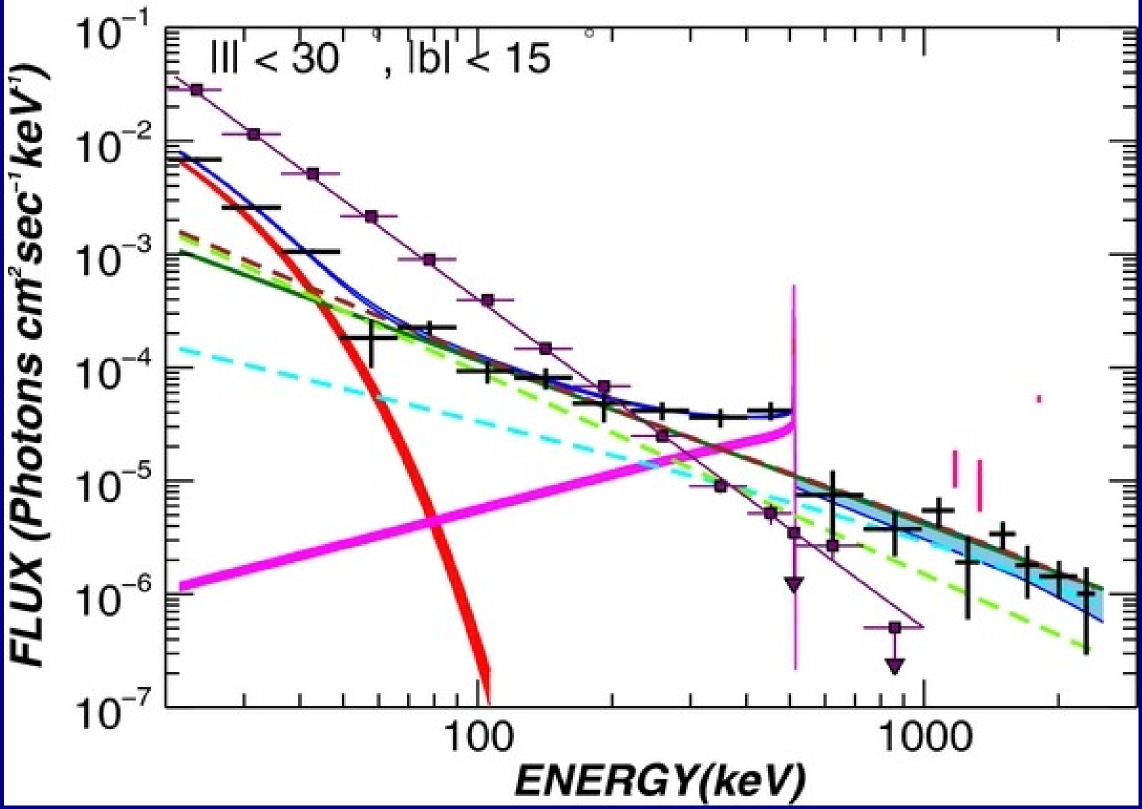
Bouchet et al.
ApJ 739, 29 (2011)



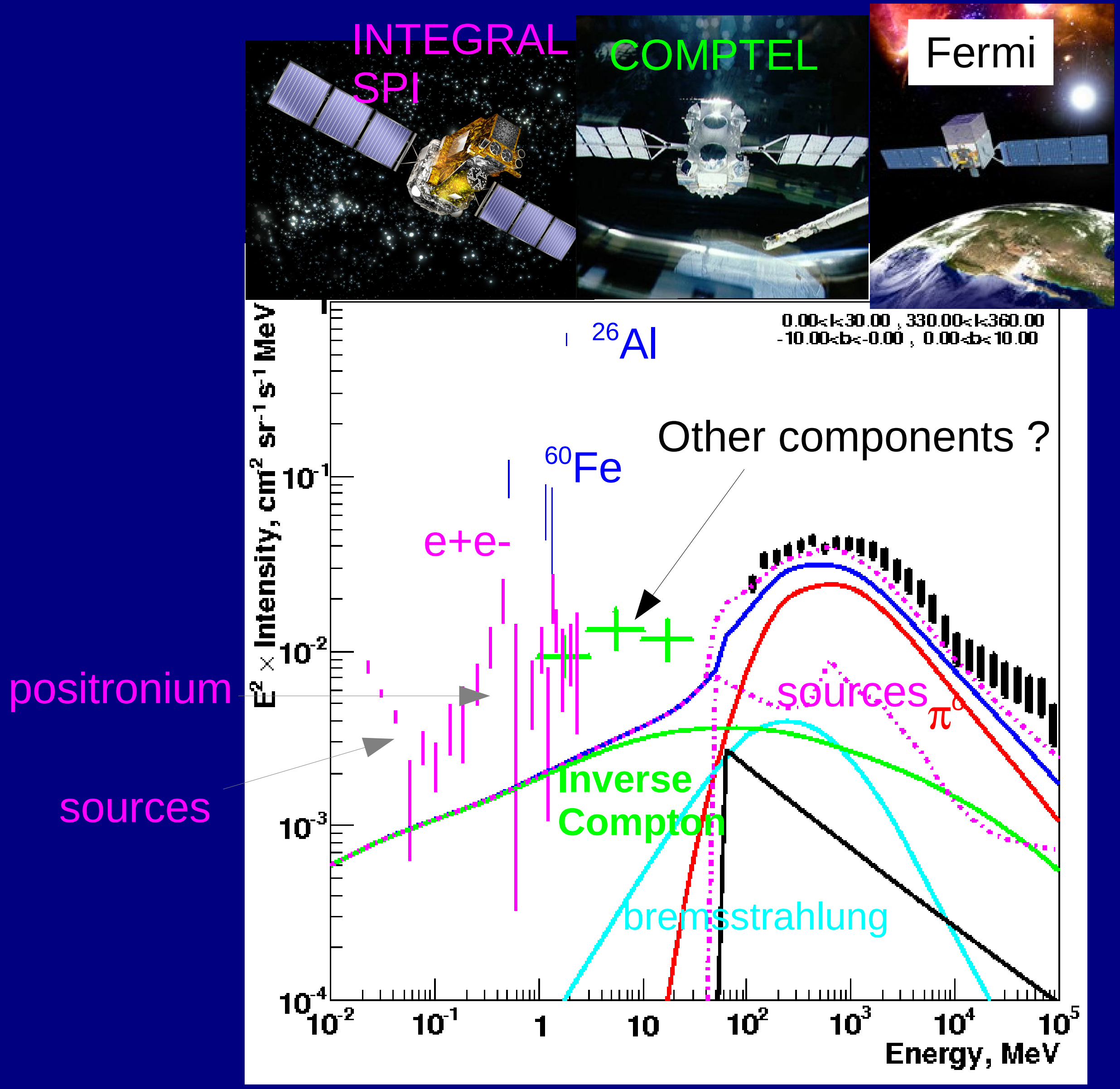
A real mix of processes !

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



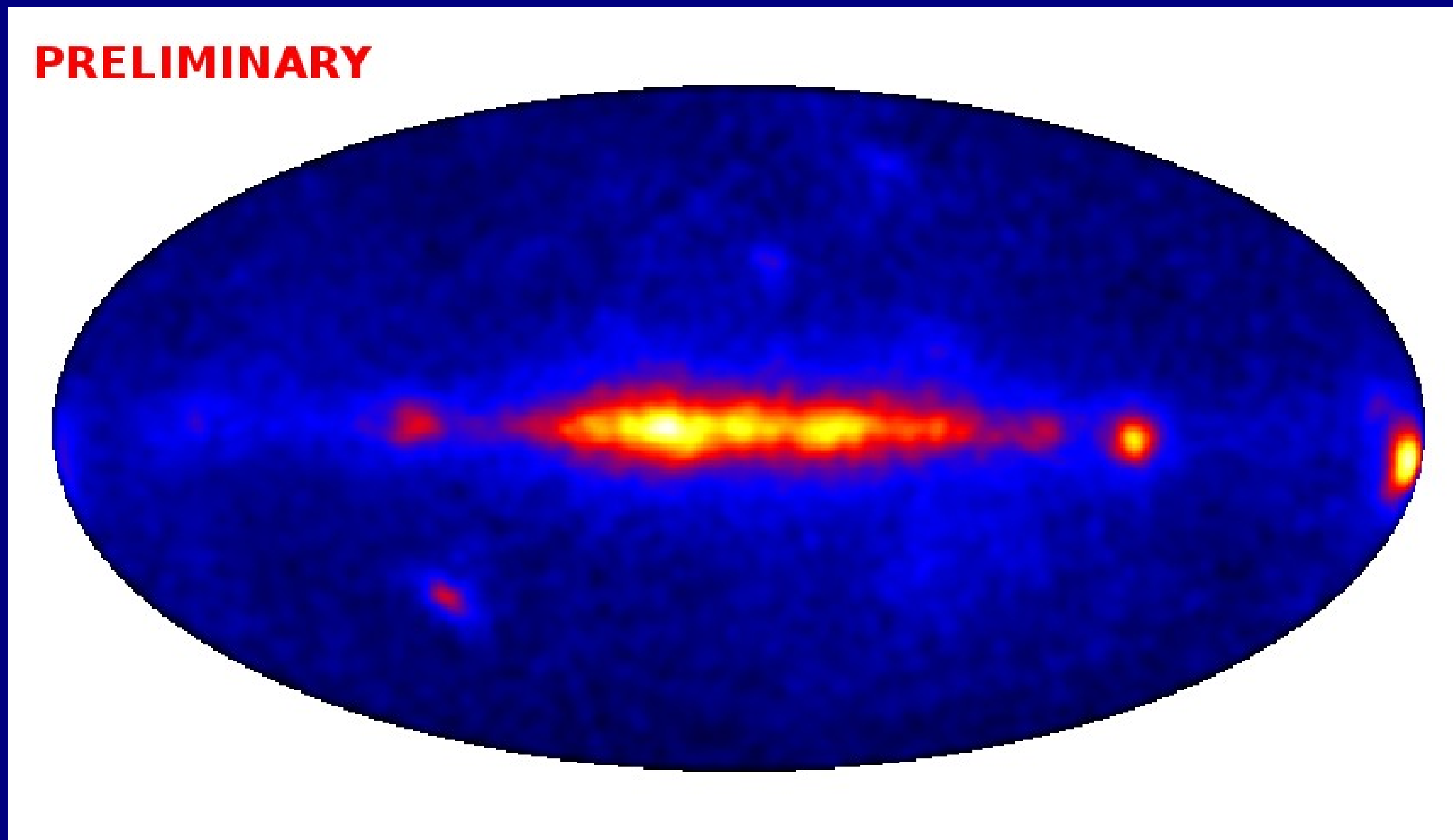


Inner Galaxy: keV to TeV



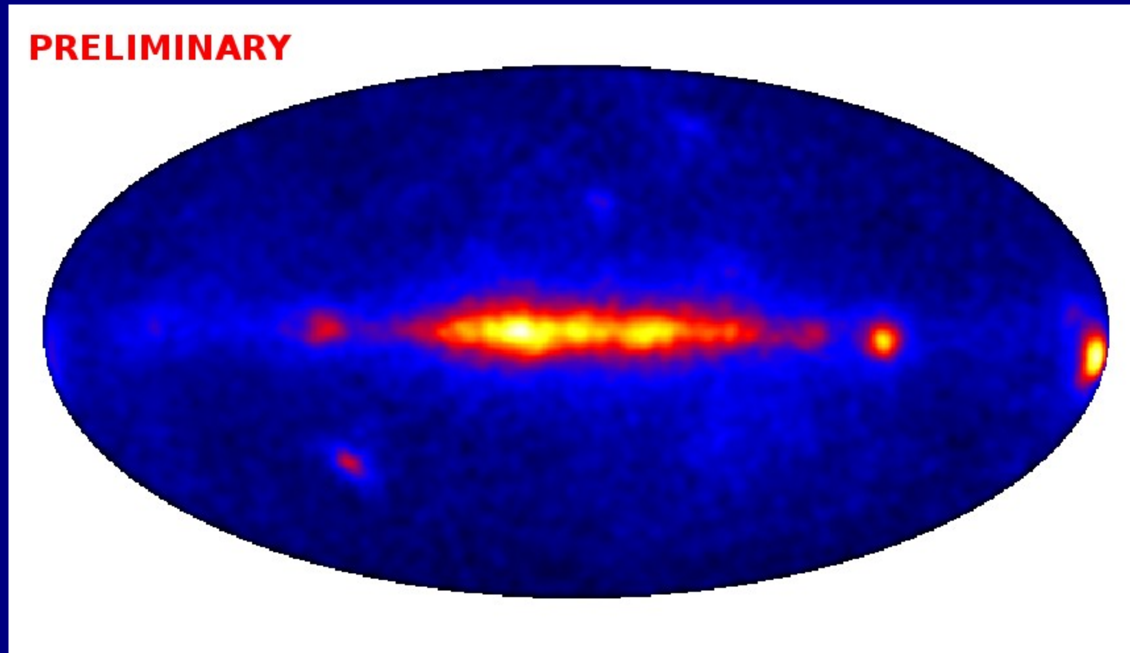
GeV electrons – inverse Compton - important for MeV gamma rays !

Fermi-LAT 25 – 40 MeV



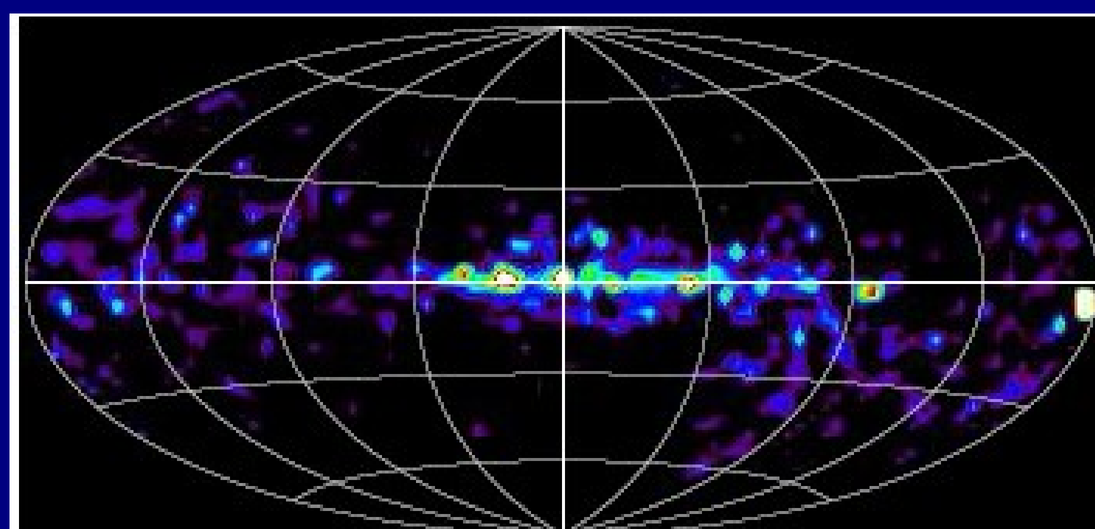
NB low angular and energy resolution !
Nominal energy range: photons may originate from range 10 to <100 MeV.
But valuable to bridge the MeV gap.

Fermi-LAT 25-40 MeV



meets

COMPTEL 10-30 MeV



The Nine Lives of Cosmic Rays in Galaxies

Isabelle A. Grenier,[1] John H. Black,[2] and Andrew W. Strong[3]

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[2]Department of Earth & Space Sciences, Chalmers University of Technology, Onsala Space Observatory, SE-439 92 Onsala, Sweden; email: john.black@chalmers.se

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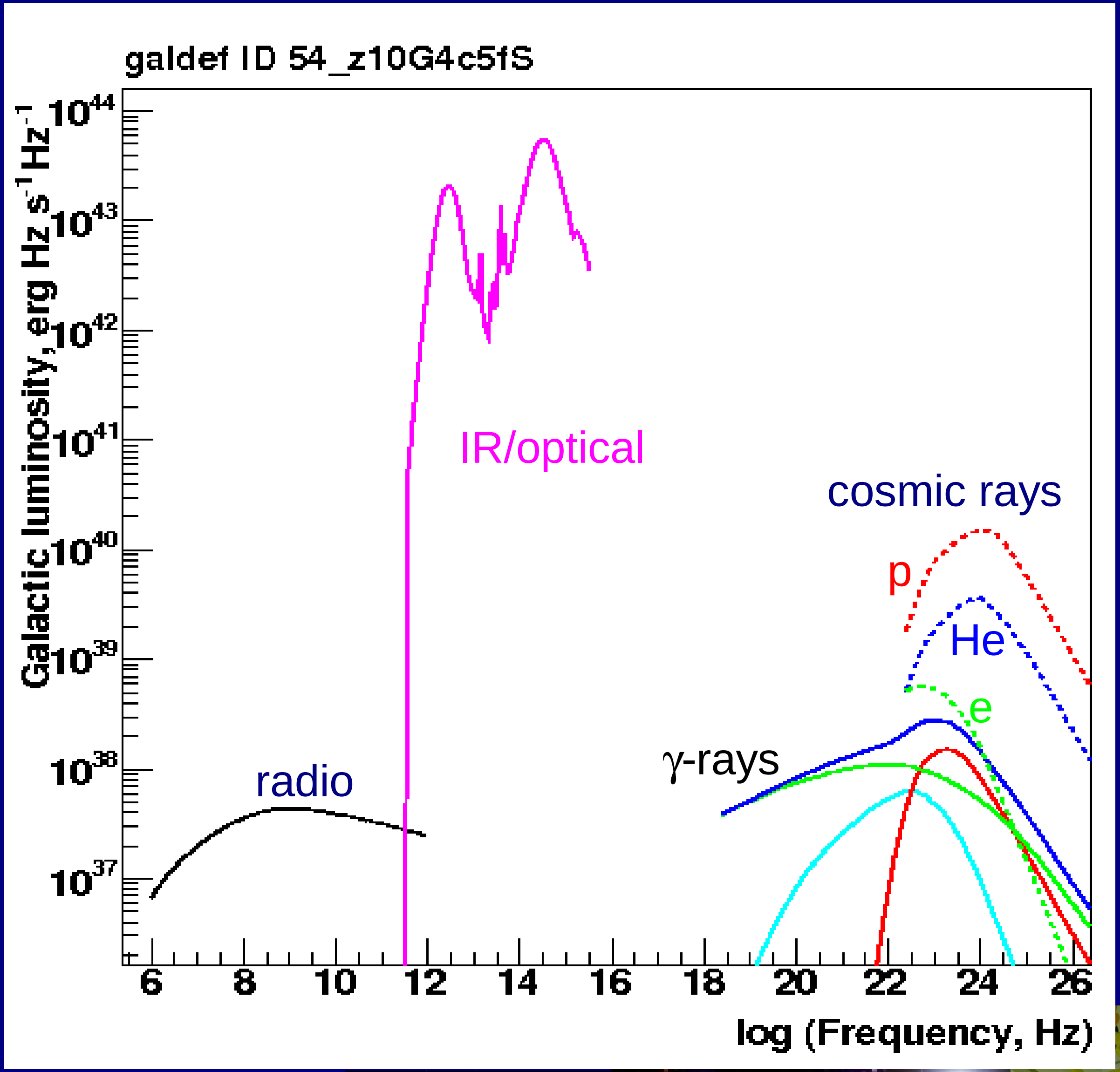
Annual Review of Astronomy and Astrophysics, Vol 53, 2015

Galaxy luminosity over 20 decades of energy



Strong et al. (2010), ApJL 722, L58

Interstellar gamma-ray spectrum

Harder gamma-ray spectrum in Galactic plane than expected from
local cosmic-ray proton spectrum via pion-decay

Gaggero etal. 2015 invoke spatially varying momentum-dependence of diffusion coeffiicient.

Gamma-ray sky points to radial gradients in cosmic-ray transport

Daniele Gaggero,[1,2,*] Alfredo Urbano,[1,†] Mauro Valli,[1,2,‡] and Piero Ullio[1,2,§]

Phys. Rev. D 91, 083012 (2015)

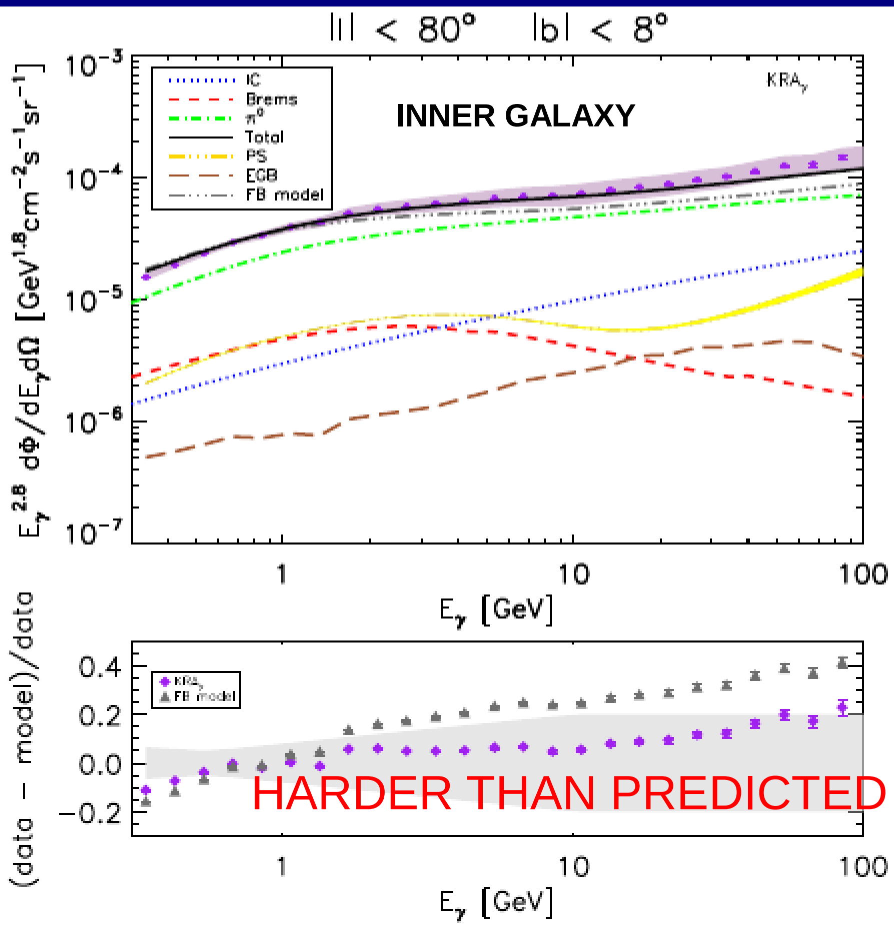


FIG. 1. *Upper panel. Comparison between the γ-ray flux computed with the CR propagation model proposed in this Letter (KRA$_\gamma$ total flux: solid black line; individual components shown) and the* Fermi-LAT *data (purple dots, including both statistic and systematic errors) in the Galactic disk. For comparison, we also show the total flux for the FB model defined in ref. [1] (double dot-dashed gray line). Lower panel. Residuals computed for the KRA$_\gamma$ and FB models.*

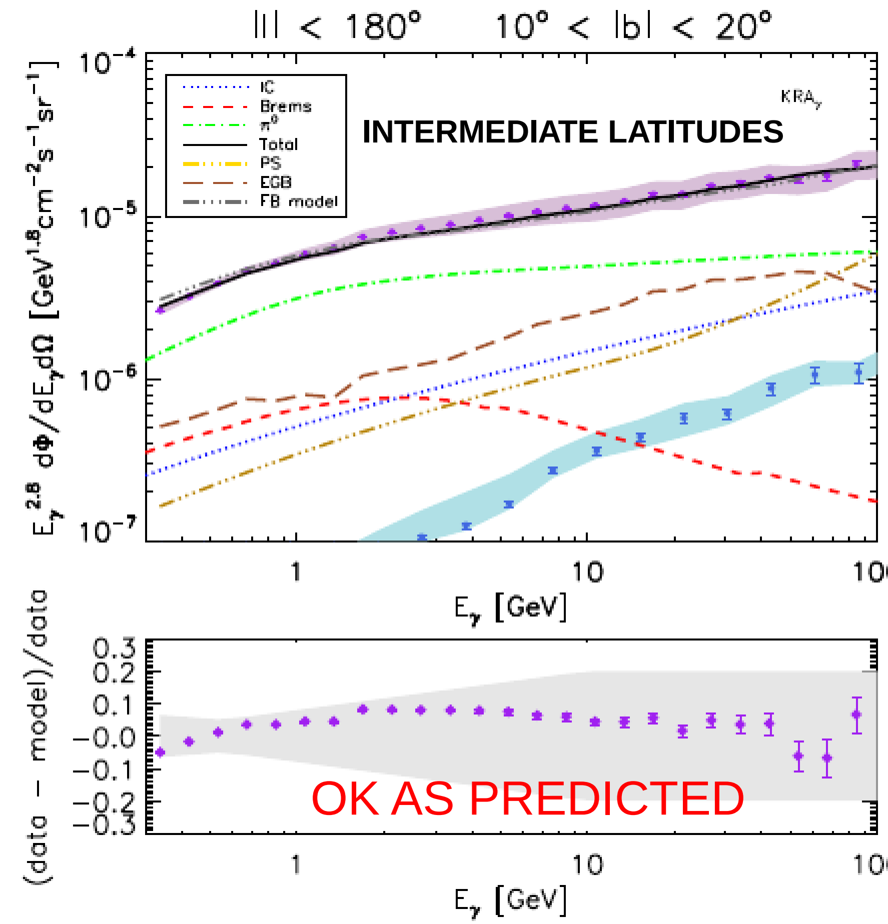


FIG. 7. *The same as in fig. [1] but considering the strip $|l| < 180°$, $10° < |b| < 20°$. The azure band represents the contribution of the Fermi bubbles according to ref. [37].*

Interstellar gamma-ray spectrum

Harder gamma-ray spectrum in Galactic plane than expected from
local cosmic-ray proton spectrum via pion-decay

Gaggero etal. 2015 invoke spatially varying momentum-dependence of diffusion coeffiicient.

But since Galactic plane spectrum is harder than local, can be just a local CR source
Different from typical Galactic case.
Then spectral index in the plane is the normal case.

THIS IS A BIG EFFECT AND DESERVES MORE ATTENTION!

Diffusive reacceleration called into question

Diffusive reacceleration = diffusion in momentum
Spatial diffusion will be accompanied by momentum diffusion if the scattering medium is moving.
Standard formula : $D_{pp} = p^2 V_A^{\ 2} / (9 D_{xx})$

Popular since explains peak in B/C energy-dependence without
ad-hoc break in $D_{xx}(p)$ and more consistent with Kolmogorov diffusion index 1/3

Avoids high-energy anisotropy problem

BUT it is not proved!
In reacceleration models,
a large fraction of the energy in cosmic rays (up to 30%) comes from reacceleration i.e.
in the interstellar medium. So SNR are not the only major source of CR!

Is this physically plausible, and where does the energy come from?

Other ways to get B/C: convection is a natural mechanism.
Needs much more work.

See Drury & Strong ICRC 2015 arXiv:1508.02675

Low energy cosmic rays: 1-100 MeV

Important for interstellar chemistry: ionization. Traced by H_3^+
Hot topic!

Voyager 1 enters interstellar space, measures MeV protons unmodulated

For cosmic-ray propagation and modulation a new era starting.

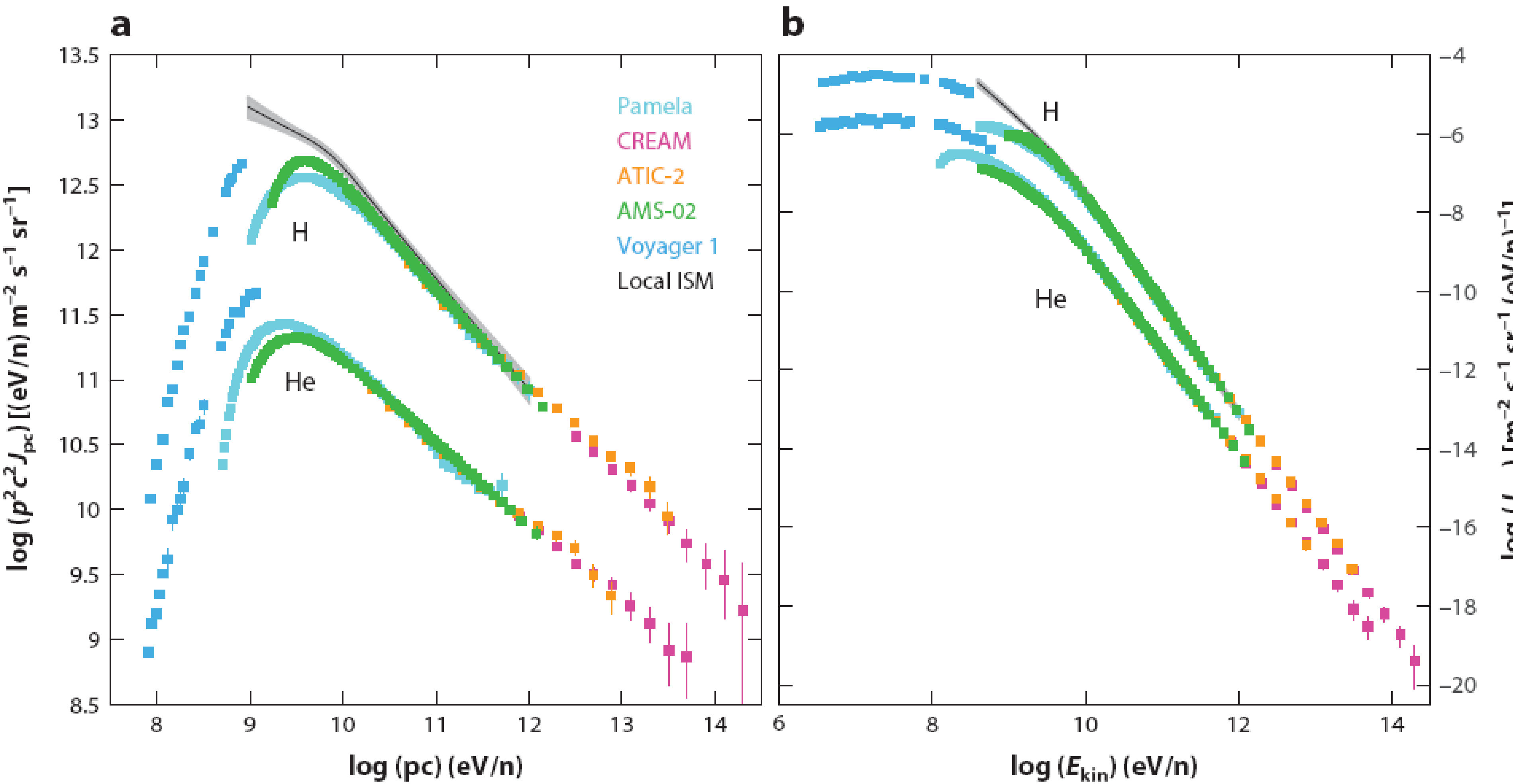


Figure 1

Local spectra of cosmic-ray protons and helium, as measured near the Earth and heliopause (Panov et al. 2009, Adriani et al. 2011, Yoon et al. 2011, Choutko et al. 2013, Stone et al. 2013, Consolandi et al. 2014), and displayed without solar demodulation (*a*) in momentum distributions and (*b*) in particle spectra in kinetic energy. They indicate proton hardening and He enrichment above a few hundred GeV. The gray band marks the range of proton spectra inferred in the local ISM from the average γ-ray emissivity of the interstellar gas, given the current uncertainties in the hadronic cross sections (data from Dermer et al. 2013b).

Grenier, Black & Strong, ARAA 53, 2015

New local interstellar spectra for protons, Helium and Carbon derived from PAMELA and Voyager 1 observations

D. Bisschoff • M.S. Potgieter

arXiv:1512.04836 Dec 2015

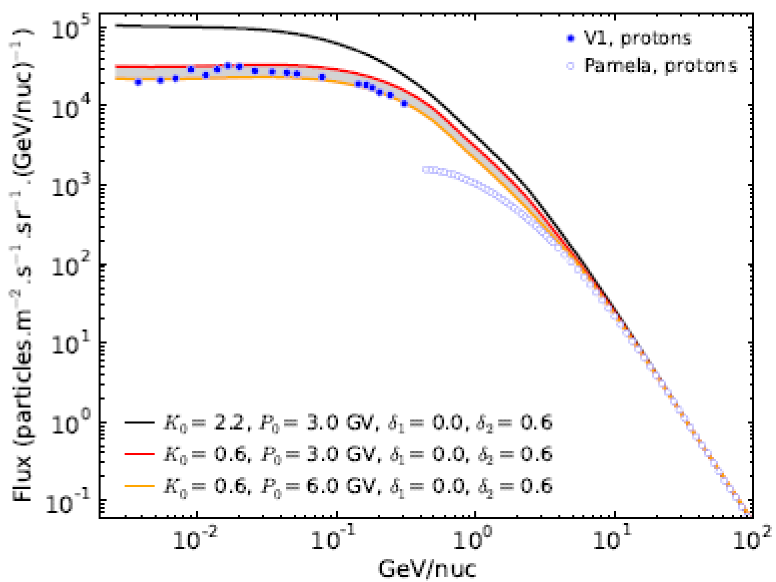


Fig. 3 The computed proton LIS band bounded by the parameters listed in Fig. 2, upper value given by the red curve and lower value by the yellow curve. These two LIS's, together with the reference LIS (black curve), are compared to the V1 and PAMELA proton data. A computed LIS reproducing the V1 data should ideally lie inside this band, given the spread in the observations. The PAMELA observations above 20 GeV are clearly reproduced well where solar modulation becomes negligible

GALPROP model
Fitted to Voyager 1

Gamma rays as gas tracer, dark gas

Gamma rays detect ALL gas independent of phase, via pion-decay.

Led to first detection of CO-dark molecular hydrogen (Grenier 2005)

Meanwhile confirmed e.g. by Planck thermal dust analyses.

Gas models for GALPROP etc have to address this.

See Strong, Black & Grenier ARAA 53 (2015) for recent review.

Also
C+ line emission (Herschel) REF
Radio recombination line survey (Jodrell Bank) HII, with kinematic info
HII is important for gammas too.

Source populations: how much of 'diffuse Galactic emission' is really sources?

Fermi-LAT 3rd Catalogue has ~3000 sources, about 300 Galactic.
The Galaxy contains perhaps 50000 sources, *most below detection threshold*.
They make a contribution to the 'diffuse' emission from the Galaxy.
Source population modelling: 5-10% contribution, energy-dependent.
Hence essential to account for this in analyses of 'diffuse' emission.

Source population synthesis in Fermi 3FGL paper.

2

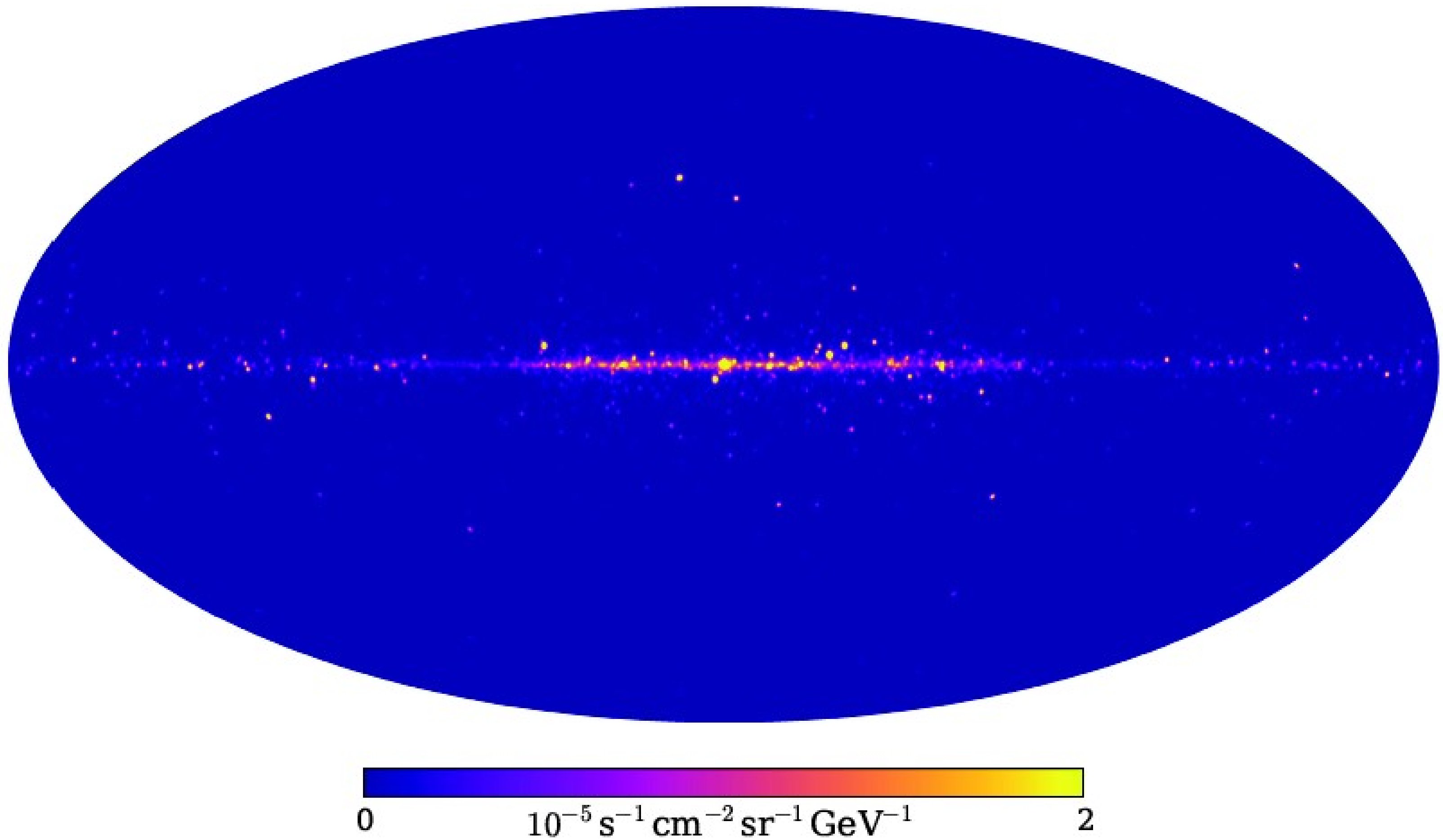


FIG. 1: All-sky model of the gamma-ray flux (dN/dE) from young pulsars in the Milky Way (MW) at 2 GeV, as discussed in § V. The bright peak in the center results from young pulsars arising in the Central Molecular Zone (CMZ) of the Galactic Center (GC). We have set the maximum flux at $2 \times 10^{-5} \mathrm{s}^{-1} \mathrm{cm}^{-2} \mathrm{sr}^{-1} \mathrm{GeV}^{-1}$ in order to enhance the visibility of the diffuse plane emission.

New paper on populations of pulsars and MSPs: O'Leary arXiv:1601.05797

Interstellar Radiation Field

Essential for leptons: energy losses, inverse Compton

New ISRF from Richard Tuffs (Bonn)
See talk at Obergurgl 2015 Workshop

Specialist for such calculations, up to now for external galaxies
Now for Milky Way
Will be public soon.

Differs from standard GALPROP ISRF.

Need to implement it in GALPROP etc
and compare with standard GALPROP ISRF


THE
END IS
NEAR

New analysis methods

Torsten Ensslin group at MPA Garching

IFT: Information Field Theory: Bayesian technique for data analysis on fields
NIFTY: package implementing IFT for general use

Example application:
D^3PO
Gamma rays: source detection with data-driven diffuse emission (no “diffuse model”)

Denoising, Deconvolving, and Decomposing Photon Observations

Selig et al. (2014)
www.mpa-garching.mpg.de/ift/d3po

D^{3}PO

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D³PO – challenges & assumptions

Selig & Enßlin
(2013)
arXiv:

signal fields

diffuse

point-like

superposition

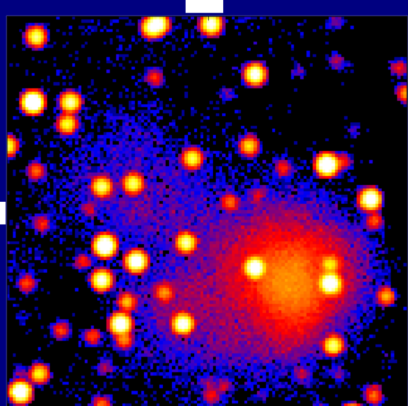
photon flux

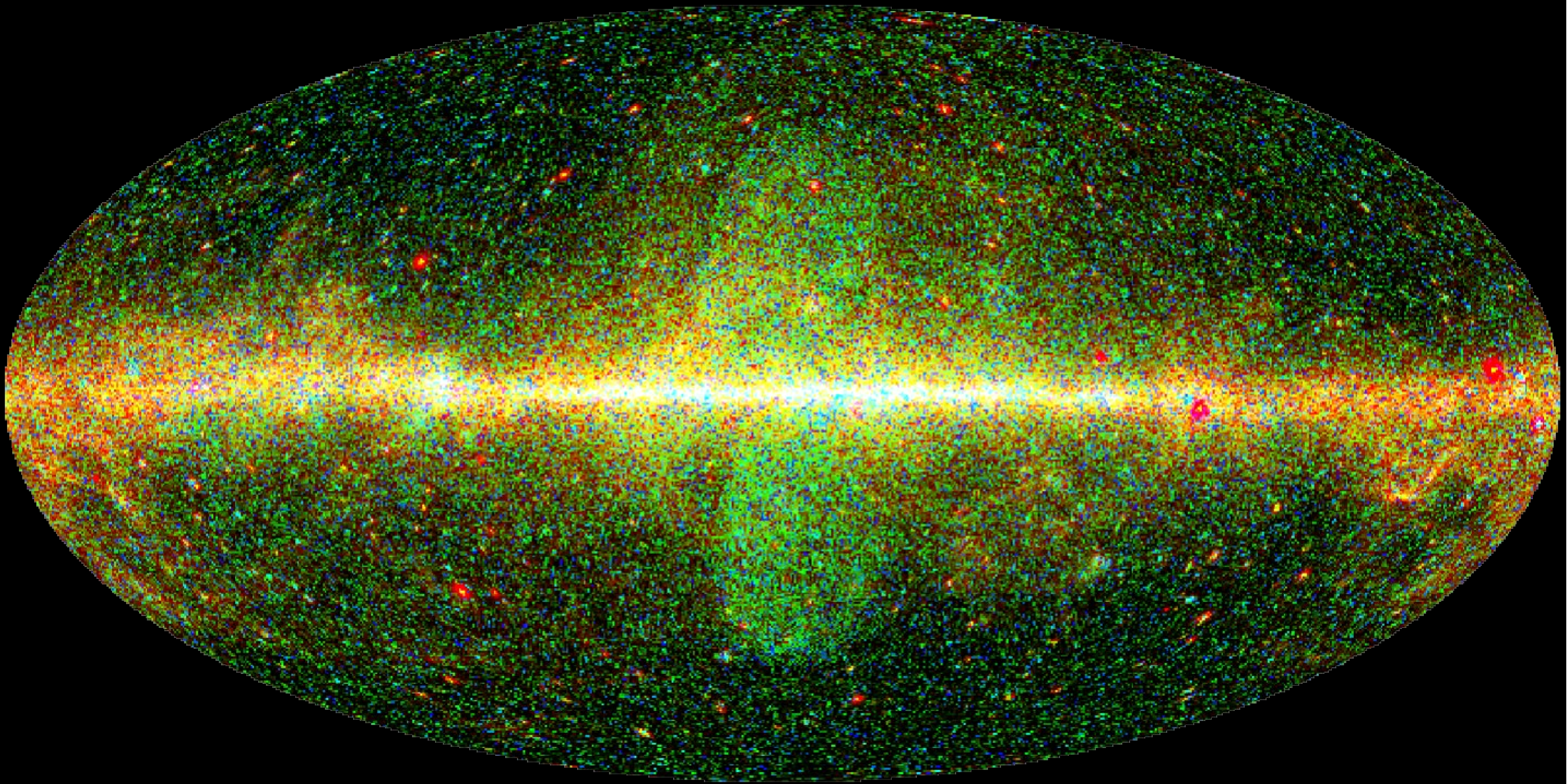
instrument response functions

photon counts

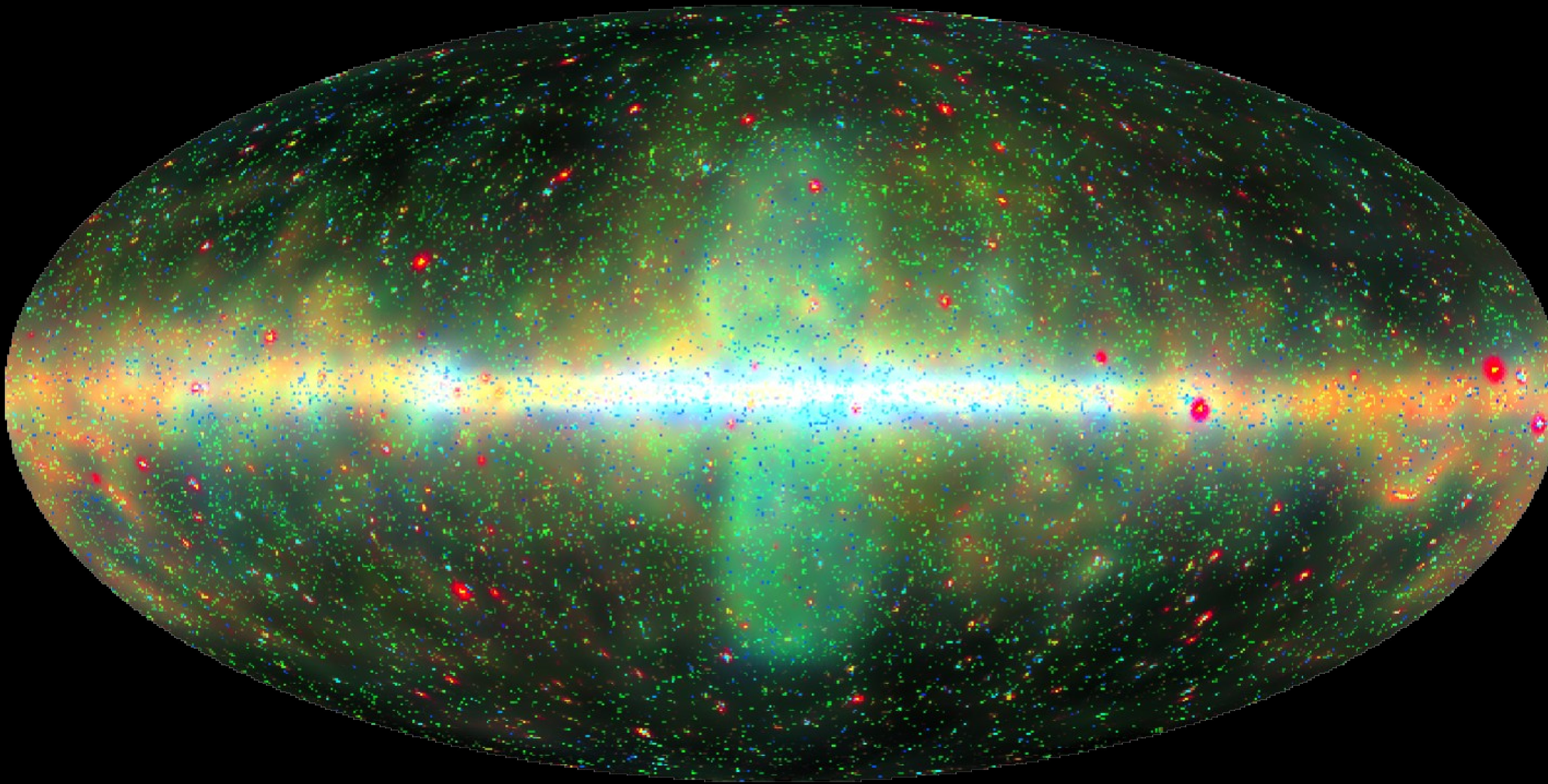
Poissonian shot noise

data

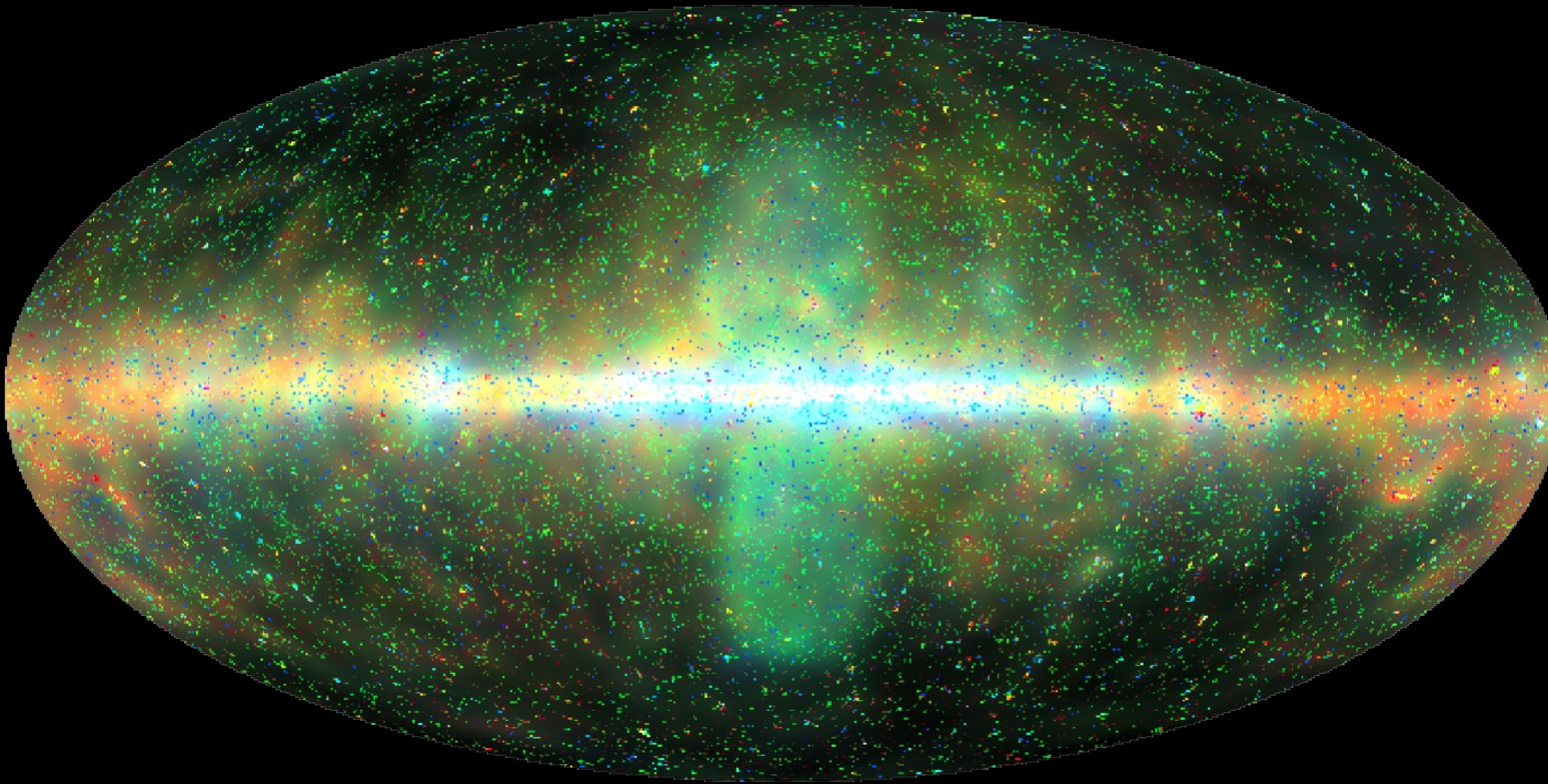




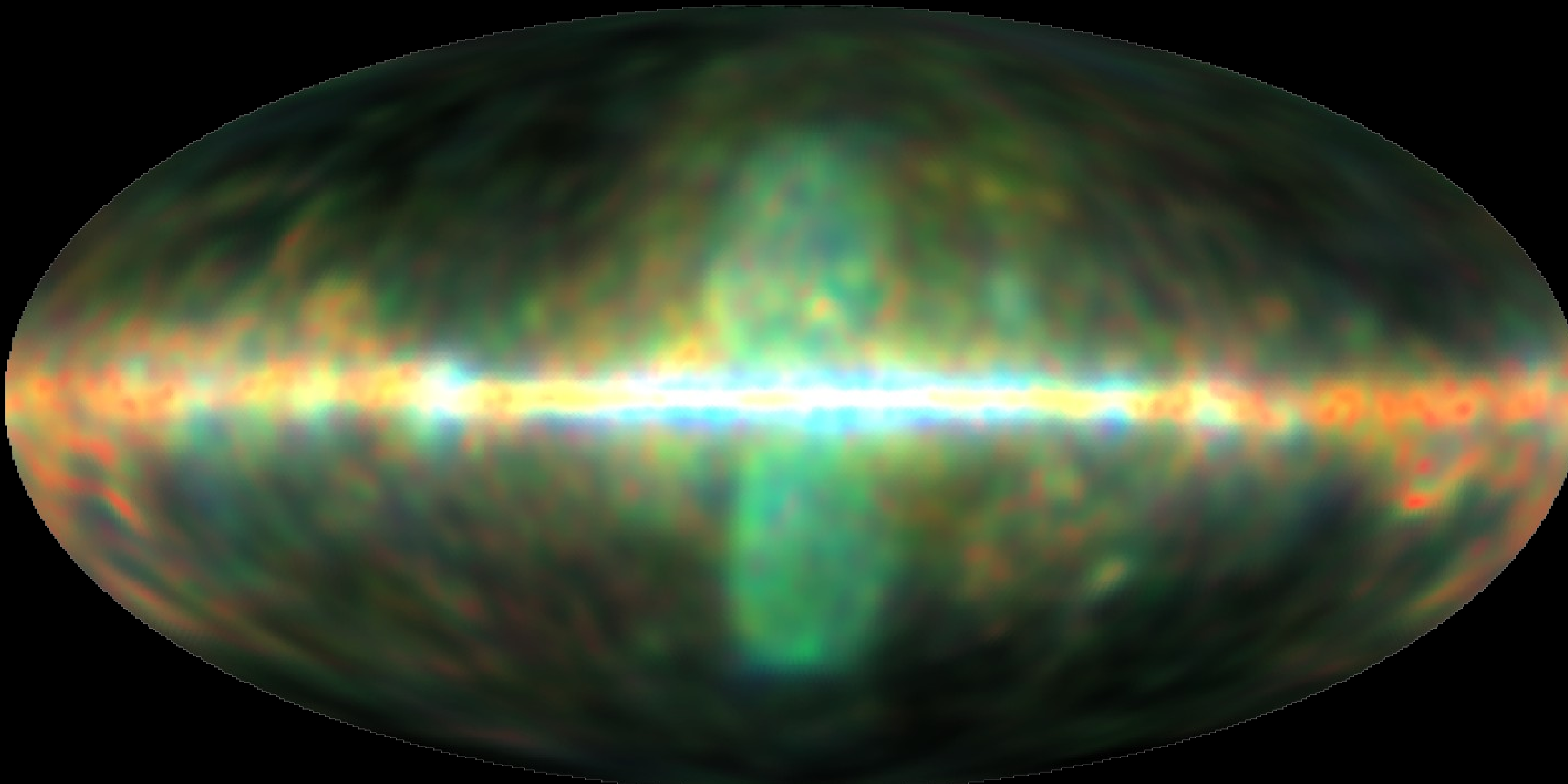
log-data



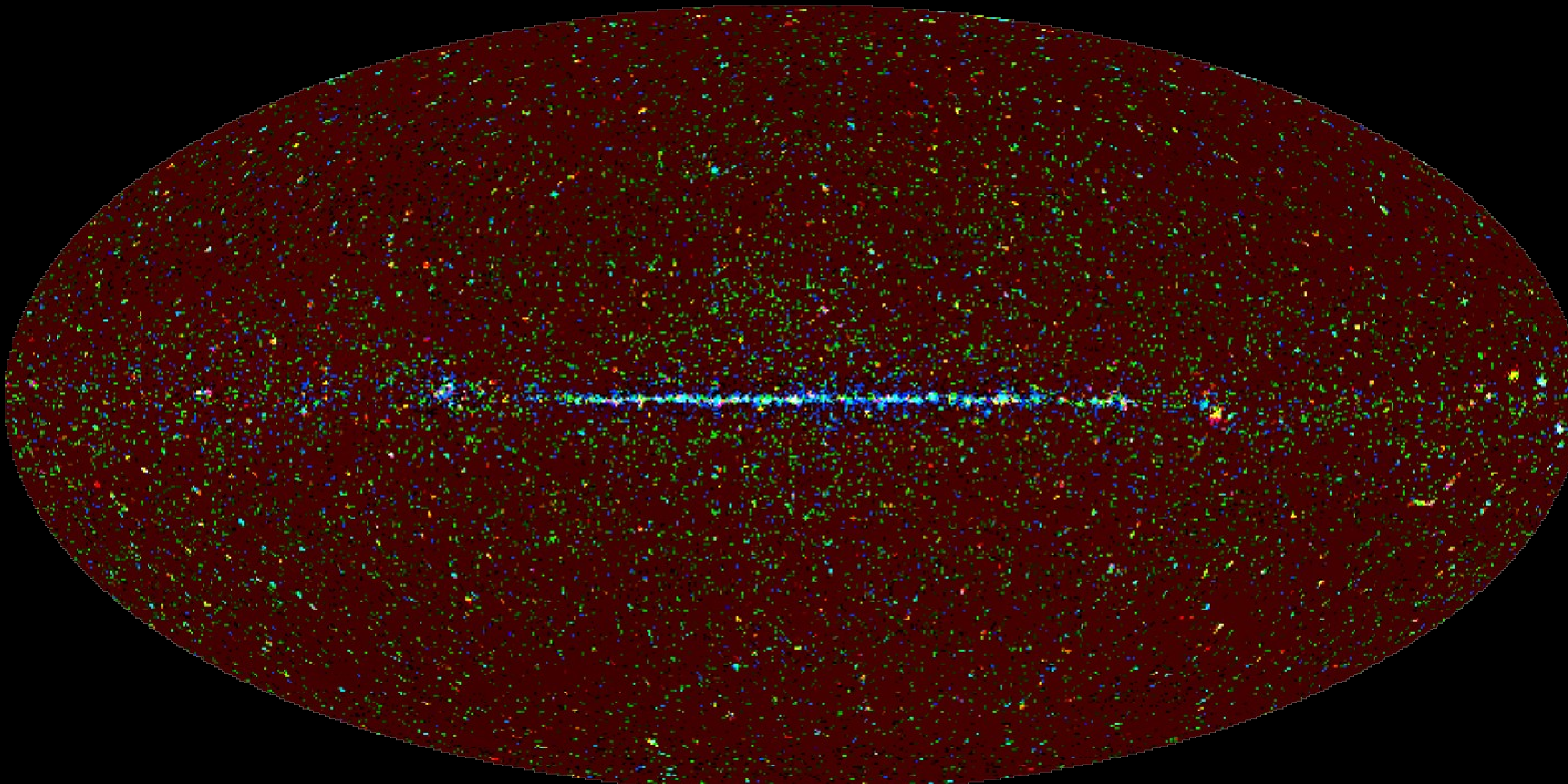
log-data … denoised



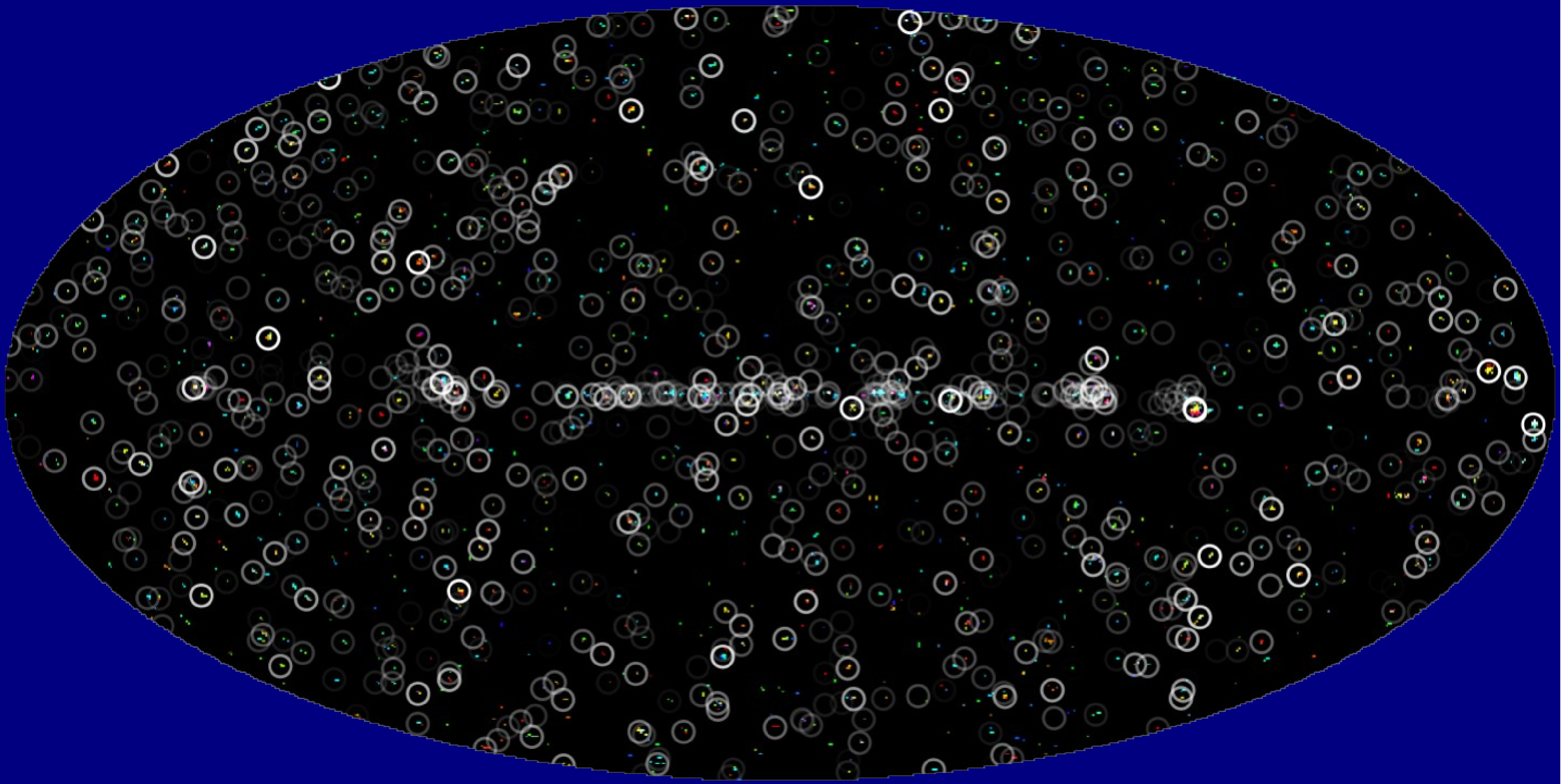
log-data … denoised … deconvolved



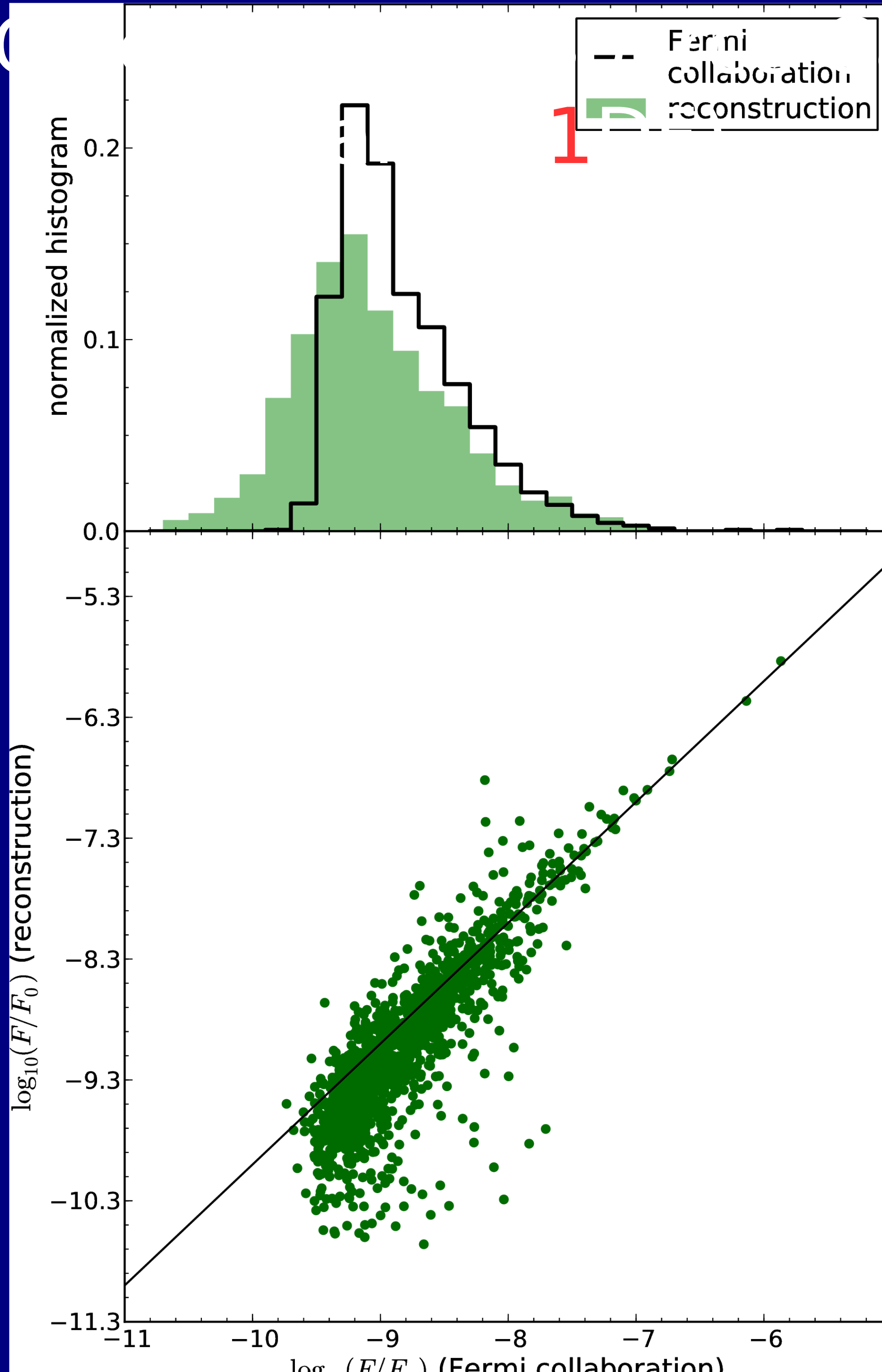
log-data … denoised … deconvolved … decomposed



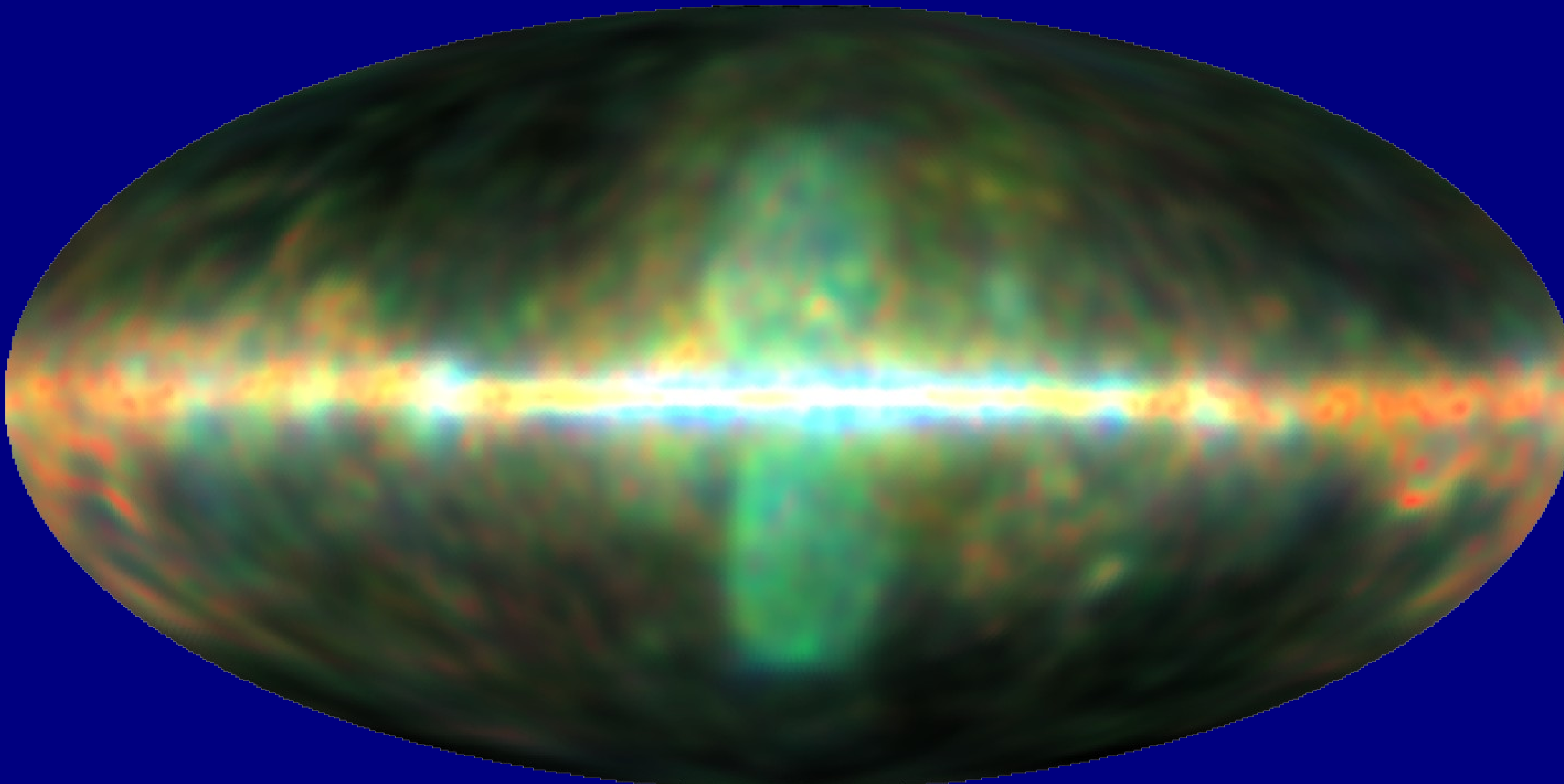
First D³PO Fermi Point Source Candidates Catalog (1DF)



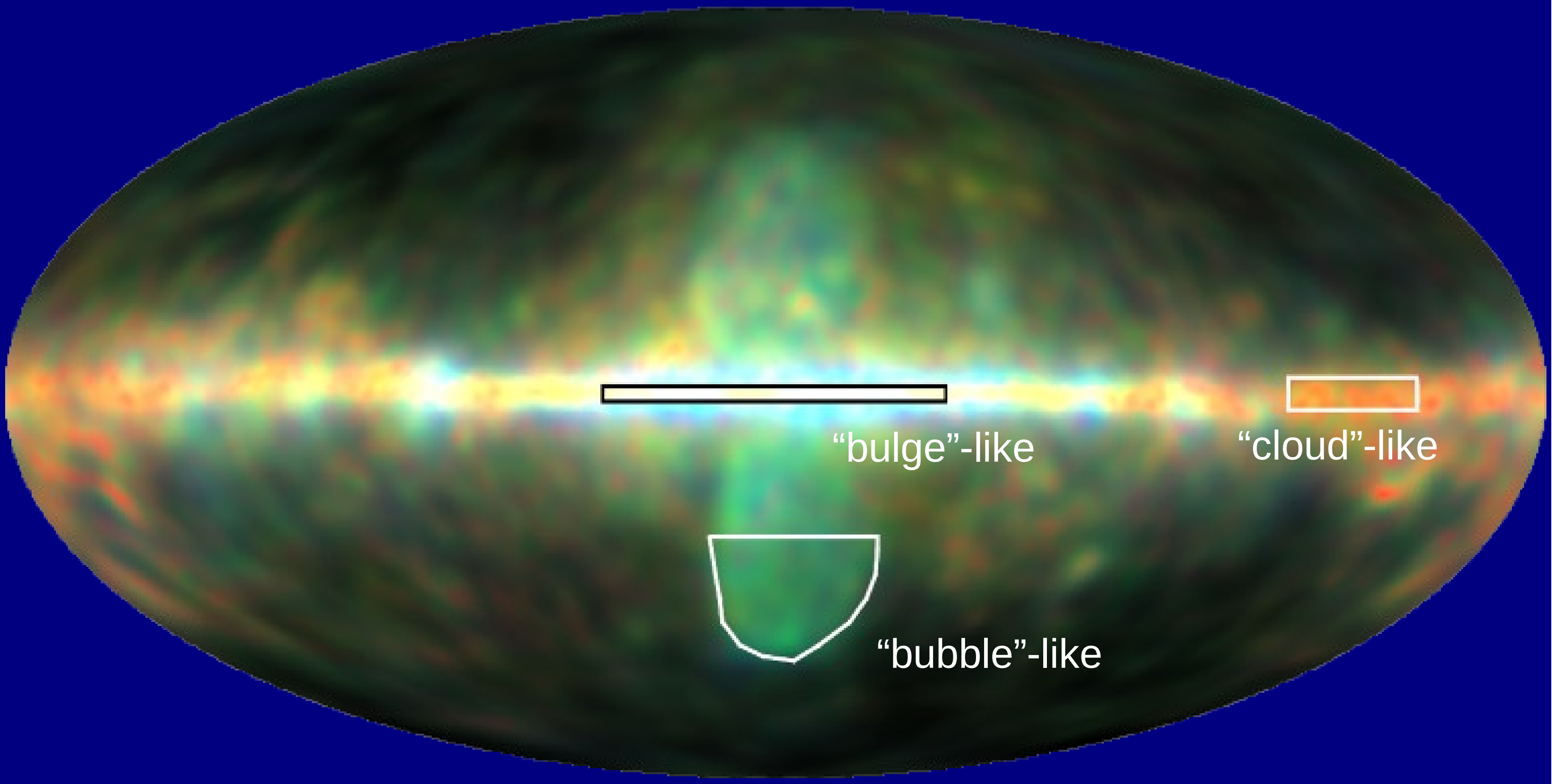
First D^{3}P… andidates



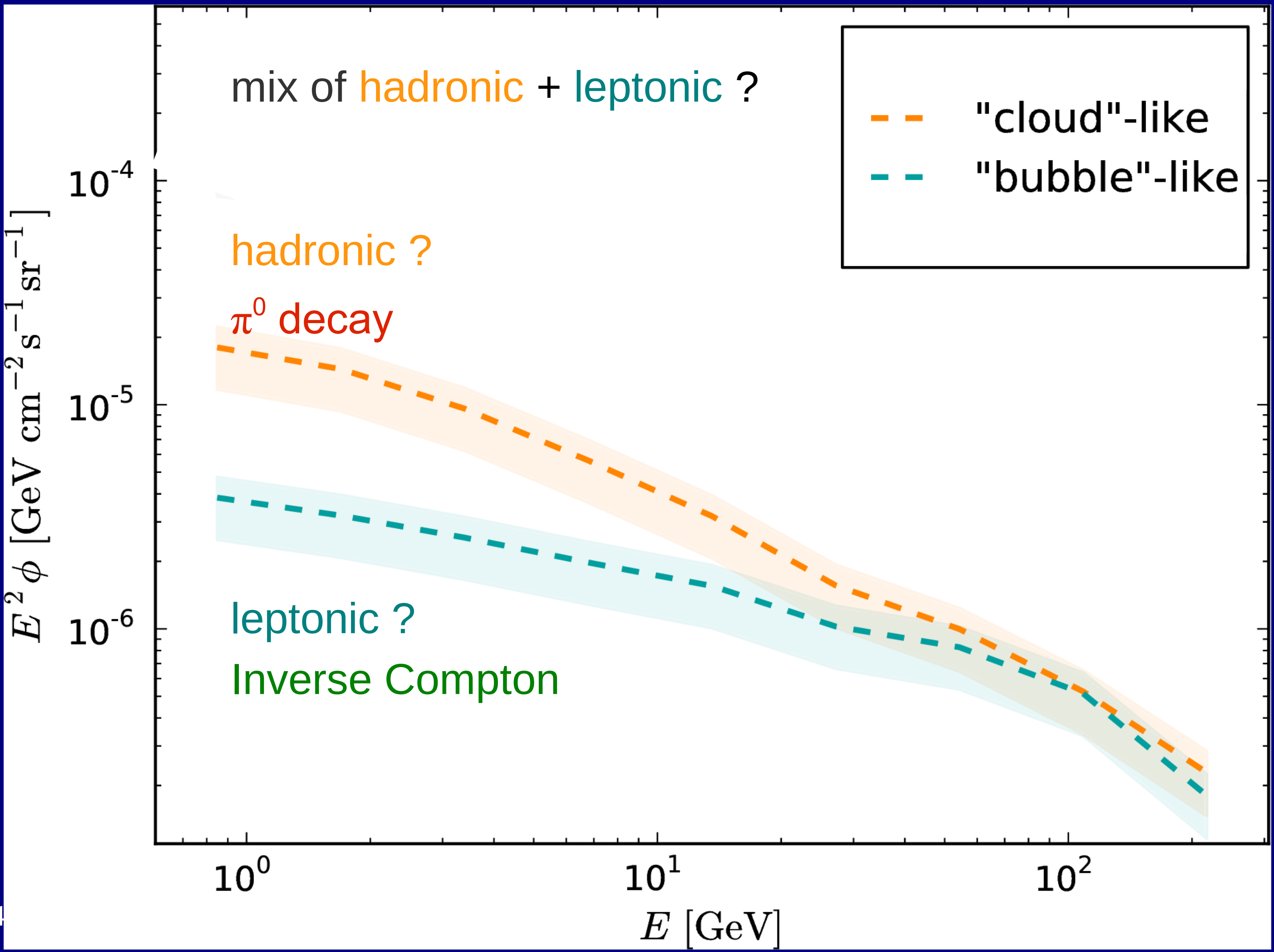
Diffuse gamma-ray sky



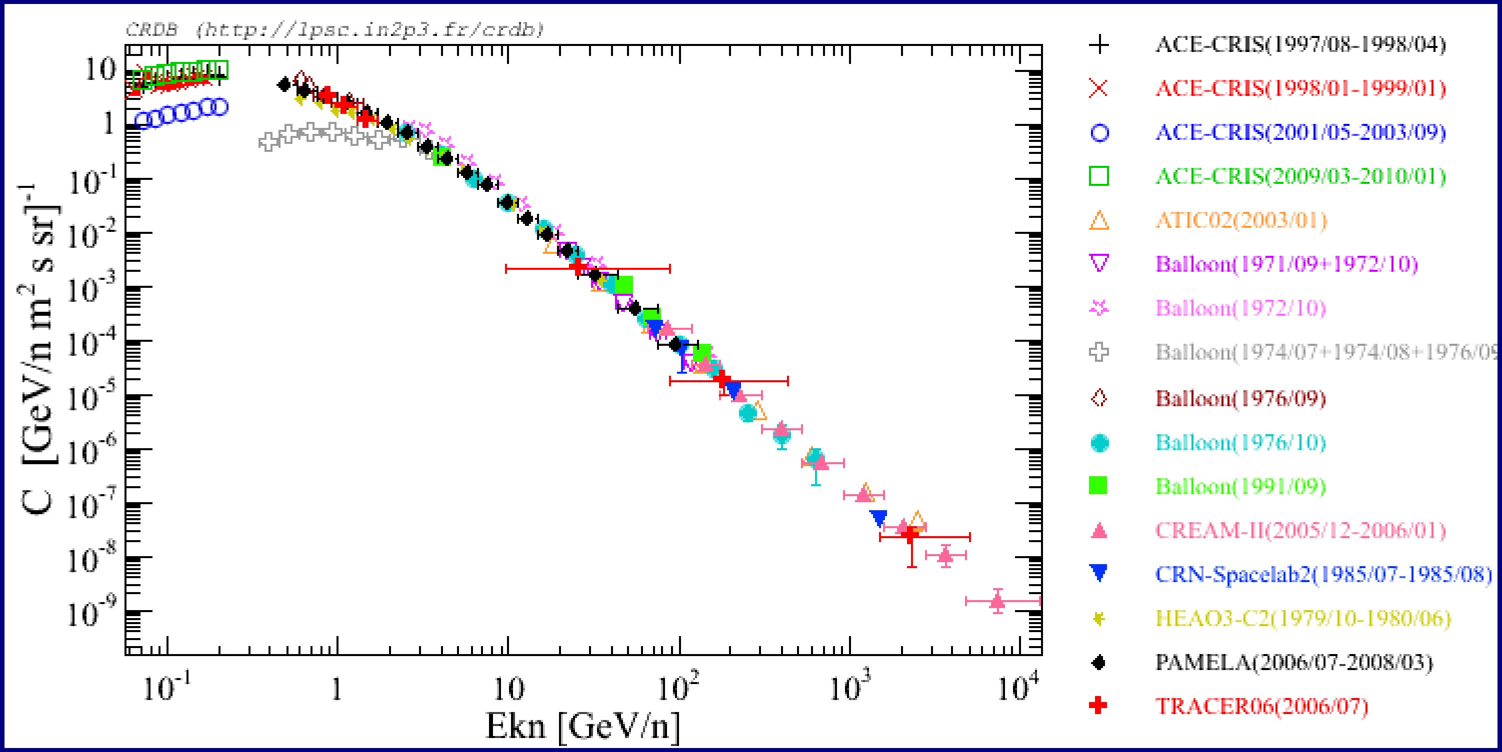
Diffuse gamma-ray sky



Spectra of diffuse components



David Maurin etal CR database: wonderful facility!
CRDB lpsc.in2p3.fr/cosmic-rays-db
Sample plot: Carbon



Enhances value of experiments, surprising little attention devoted to this before.
Replaces earlier compilation by Strong & Moskalenko.

Gamma-ray emitting supernova remnants as the origin of Galactic cosmic rays?

Julia Becker Tjus[a,*], Björn Eichmann[a], Mike Kroll[a], Nils Nierstenhöfer[a]

[a] *Theoretische Physik IV: Plasma-Astroteilchenphysik*
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Ruhr-Universität Bochum
44780 Bochum
Germany

(actually triggered my visit here !)

Use 21 Fermi-LAT SNRs to model proton spectrum.
These are 10% of total active SNRs, assume they are typical.
GALPROP 3D point-source injection mode.
Study proton spectral variations over Galaxy

Not yet secondaries?

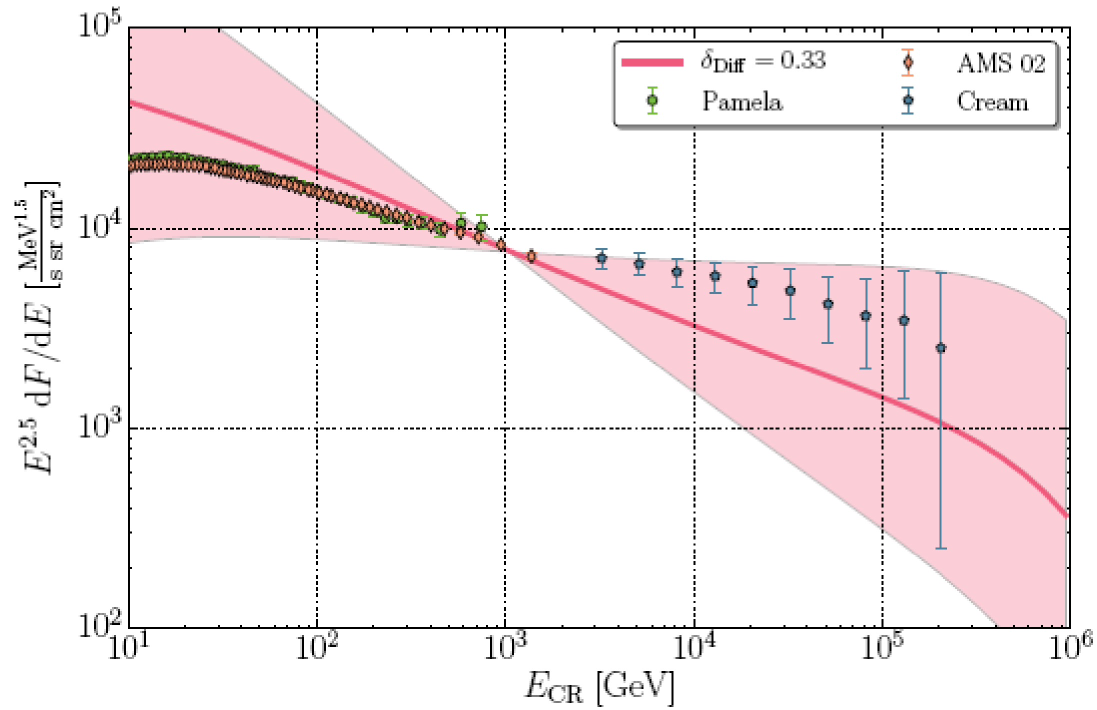


Figure 5: The CR flux in the large galaxy for simulated 20,000 SNRs, with the individual injection parameters taken from [17], considering a 1σ error in the spectral index. The diffusion coefficient has been set to a Kolmogorov-type diffusion, i.e. $D \propto E^{0.33}$. Experimental data taken from CREAM [69], PAMELA [70] and AMS-01 [71].

SNRs : several with claimed 'pion-peak'

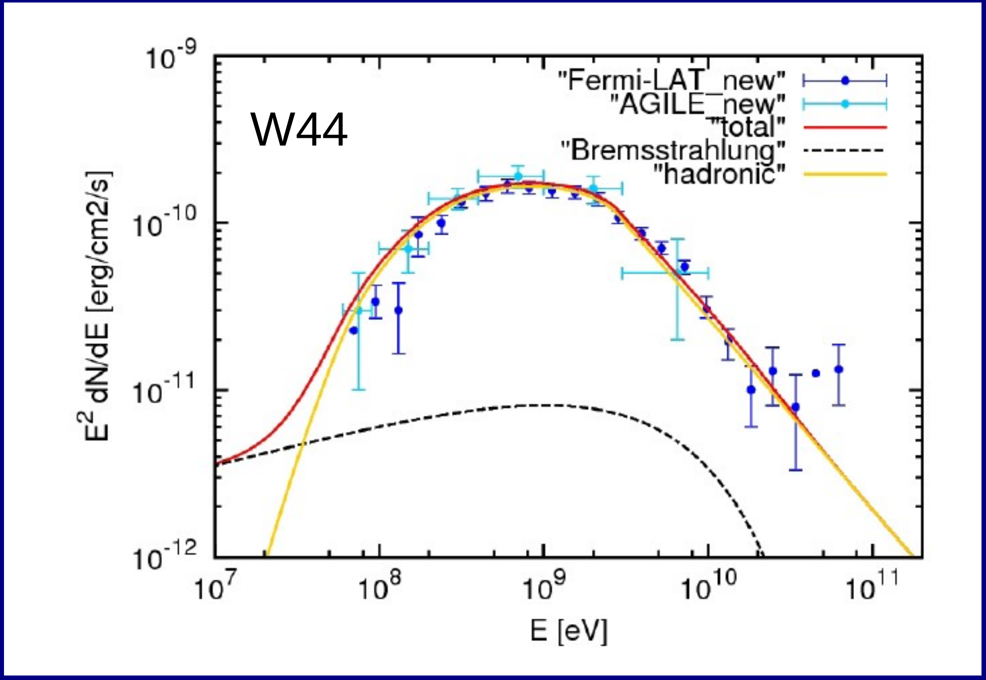
But beware, this is at $m(\pi^{o})$ /2 = 67.5 MeV, so Fermi hardly covers it.

NB multiplying by E^2 is good but shifts the peak to higher energies, do not see the 'bump'

May be instead an indication for break in proton spectrum.

Need Fermi extension to lower energies, coming with Pass 8.

Sample spectrum: W44, Cardillo etal 2014. Model proton spectrum has break at 20 GeV.



New 25 Jan: Fermi paper on **RCW86**: arXiv:1601.06534
Latest Pass 8 data. Favours a leptonic model

More physical models of cosmic rays.

GALPROP & co are phenomelogical i.e. just propagation equation
with given parameters.

e.g. halo is just region with ad-hoc boundary, no physics.

But cosmic rays have dynamical effects.
Example Philipp Girichidis (MPA Garching) et al.
Cosmic-ray driven wind from SN, includes chemistry.
Cosmic rays treated as relativistic gas, no energy spectrum.
Future: put in energy-dependence, secondary production etc.
To test against cosmic-ray, gamma-ray data.

The Astrophysical Journal Letters, 816:L19 (6pp), 2016 January 10 doi:10.3847/2041-8205/816/2/L19

LAUNCHING COSMIC-RAY-DRIVEN OUTFLOWS FROM THE MAGNETIZED INTERSTELLAR MEDIUM

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$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = 0$$

$$\frac{\partial \rho \boldsymbol{v}}{\partial t} + \nabla \cdot \left(\rho \boldsymbol{v} \boldsymbol{v}^{\mathrm{T}} - \frac{\boldsymbol{B}\boldsymbol{B}^{\mathrm{T}}}{4\pi} \right) + \nabla p_{\mathrm{tot}} = \rho \boldsymbol{g}$$

$$\frac{\partial e}{\partial t} + \nabla \cdot \left[(e + p_{\mathrm{tot}}) \boldsymbol{v} - \frac{\boldsymbol{B}(\boldsymbol{B} \cdot \boldsymbol{v})}{4\pi} \right] = \rho \boldsymbol{v} \cdot \boldsymbol{g} + \nabla \cdot \mathsf{K} \nabla e_{\mathrm{CR}} + \dot{u}_{\mathrm{chem}} + \dot{u}_{\mathrm{inj}}$$

$$\frac{\partial \boldsymbol{B}}{\partial t} - \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) = 0$$

$$\frac{\partial e_{\mathrm{CR}}}{\partial t} + \nabla \cdot (e_{\mathrm{CR}} \boldsymbol{v}) = -p_{\mathrm{CR}} \nabla \cdot \boldsymbol{v} + \nabla \cdot (\mathsf{K} \nabla e_{\mathrm{CR}}) + Q_{\mathrm{CR}}.$$

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CrossMark

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Modified FLASH code

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$$\frac{\partial e}{\partial t} + \nabla \cdot \left[(e + p_{\mathrm{tot}})\boldsymbol{v} - \frac{\boldsymbol{B}(\boldsymbol{B}\cdot\boldsymbol{v})}{4\pi}\right] = \rho \boldsymbol{v}\cdot\boldsymbol{g} + \dot{u}_{\mathrm{chem}} + \dot{u}_{\mathrm{inj}}$$

$$\frac{\partial \boldsymbol{B}}{\partial t} - \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) = 0$$

$$p_{\mathrm{tot}} = p_{\mathrm{th}} + p_{\mathrm{mag}}$$

$$e = \rho v^2/2 + e_{\mathrm{th}} + B^2/8\pi$$

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$$\frac{\partial \boldsymbol{B}}{\partial t} - \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) = 0$$

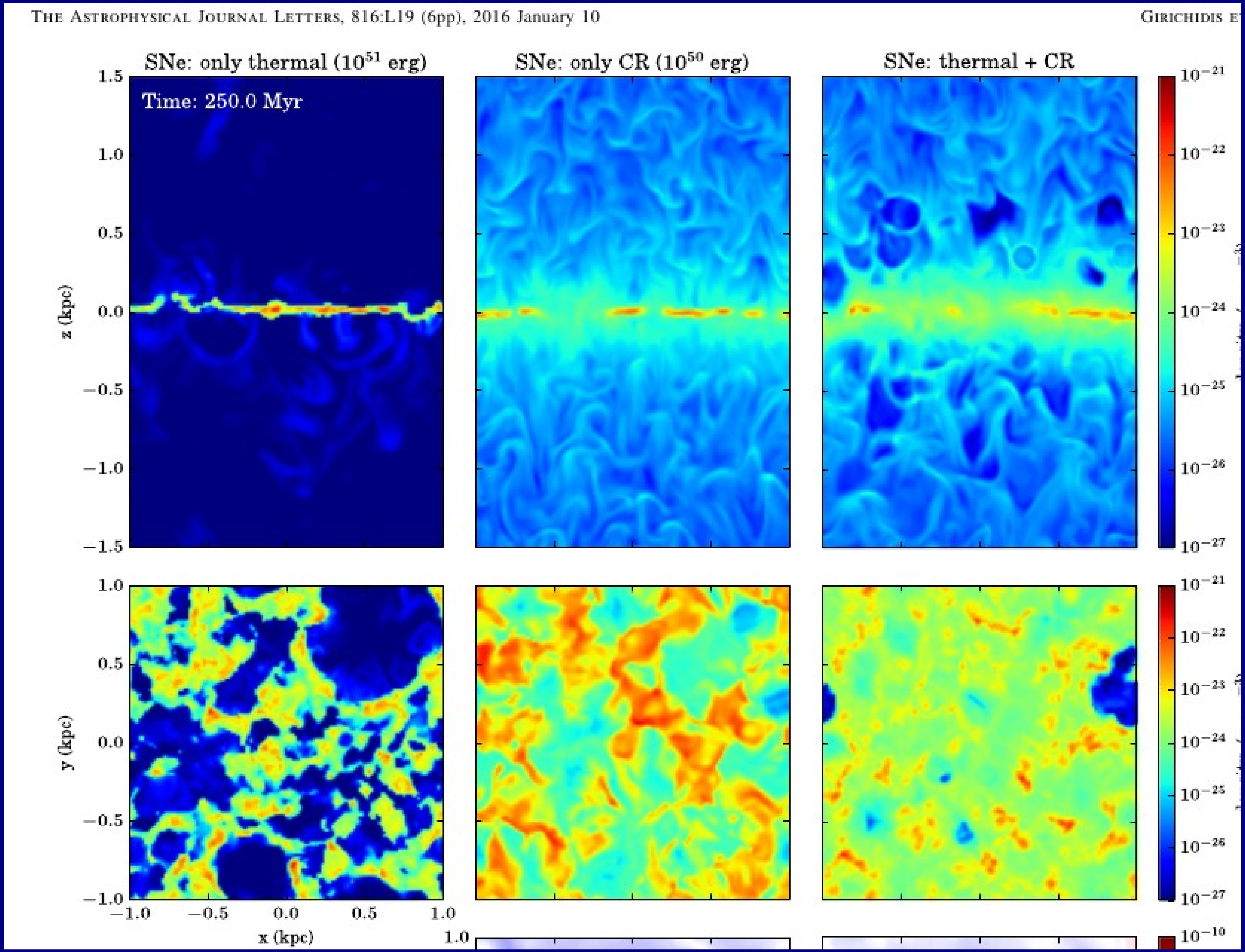
$$\boxed{\frac{\partial e_{\mathrm{CR}}}{\partial t} + \nabla \cdot (e_{\mathrm{CR}}\boldsymbol{v}) = -p_{\mathrm{CR}} \nabla \cdot \boldsymbol{v} + \nabla \cdot (\mathsf{K}\nabla e_{\mathrm{CR}}) + Q_{\mathrm{CR}}.}$$

$$p_{\mathrm{tot}} = p_{\mathrm{th}} + \boxed{p_{\mathrm{CR}}} + p_{\mathrm{mag}}$$

$$e = \rho v^2/2 + e_{\mathrm{th}} + \boxed{e_{\mathrm{CR}}} + B^2/8\pi$$

Supernovae energy input

only thermal only cosmic rays both



Time-dependent simulations avaiable for download

Cosmic rays increase vertical gas scale

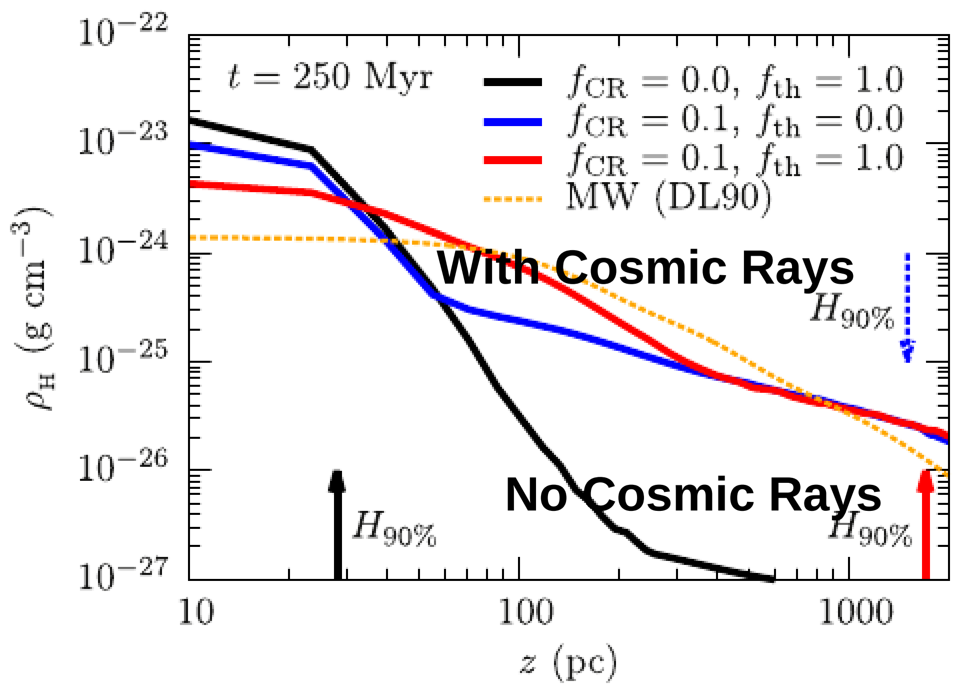


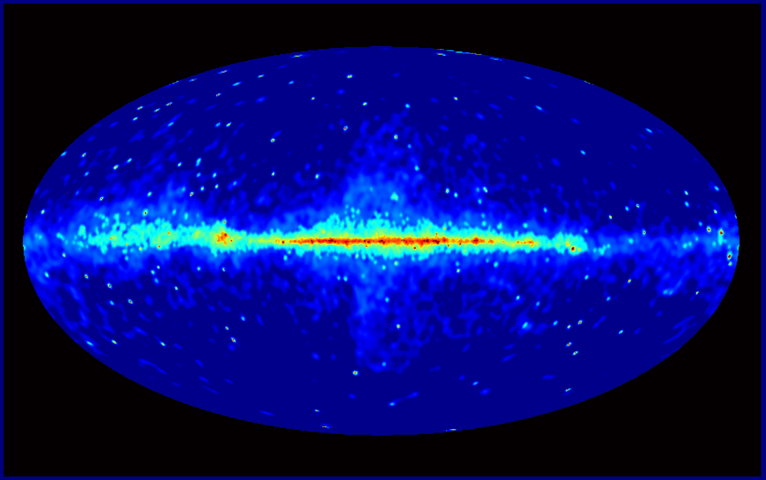
Figure 2. Vertical profiles of the total gas density for all simulations. The arrows indicate the height of 90% enclosed mass. A fit to the observed density profile of the solar neighborhood (Dickey & Lockman 1990) are shown in yellow. Thermal energy injection alone leads to a compact atomic gas distribution. Including CR feedback results in very extended distributions, which are much closer to the observed extent of the gas. The profiles indicate that CRs have their main impact at larger altitudes.

1. Including CRs thickens the galactic disk. The height of 90% enclosed total mass is found to be $\sim$1.5 kpc in the case of 10% CR energy injection per SN after 250 Myr and to increase continuously. Comparison with the vertical density distribution in the MW indicates good agreement.
2. We find that CRs quickly lead to the formation of a warm and neutral galactic atmosphere providing a mass reservoir for galactic winds and outflows. Whereas the thermal contribution of the SNe mainly shapes the disk close to the midplane, the additional CR energy shows the strongest impact above the disk and in the halo.
3. All simulations drive gas out of the midplane with little variation over time. For purely thermal SN feedback, the outflows are hot and composed of mainly ionized hydrogen with rates below the star formation rate. They are fast (up to $\sim$ a few 100 km s^{-1}) with low densities ($\rho \lesssim 10^{-27}$ g cm^{-3}). CRs alone can drive outflows with mass loading factors of order unity, which are warm (10^4 K) and mainly composed of atomic hydrogen. They are a factor of a few slower ($\sim$10–50 km s^{-1}) and 1–2 orders of magnitude denser ($\rho \sim 10^{-26}$–10^{-25} g cm^{-3}) compare to their thermally driven counterparts.

Future work in context of cosmic-ray physics:

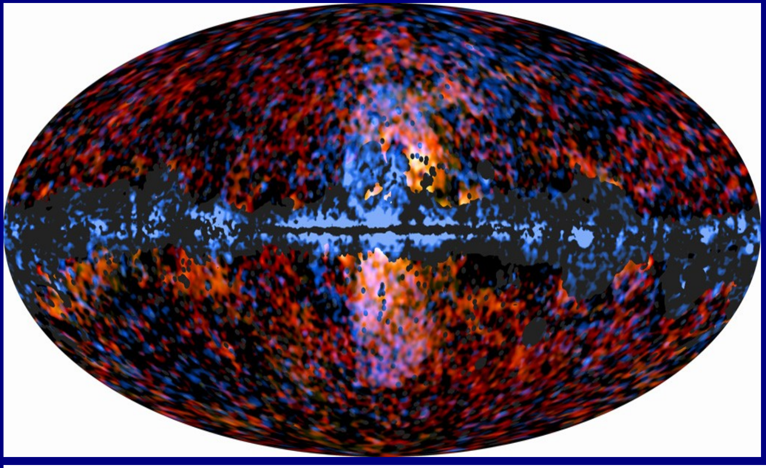
* Test such cosmic-ray-driven wind models against cosmic-ray and gamma-ray data.
* Extend models to include energy spectrum of cosmic rays (at present just a single fluid)
* Use to make GALPROP-like approaches more physical for convection and halo structure instead of simple pre-defined forms.

Fermi Bubbles

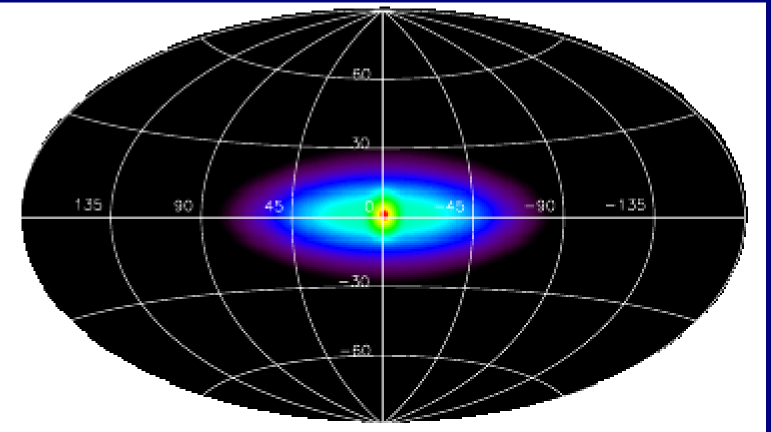


(related to WMAP Haze ?)

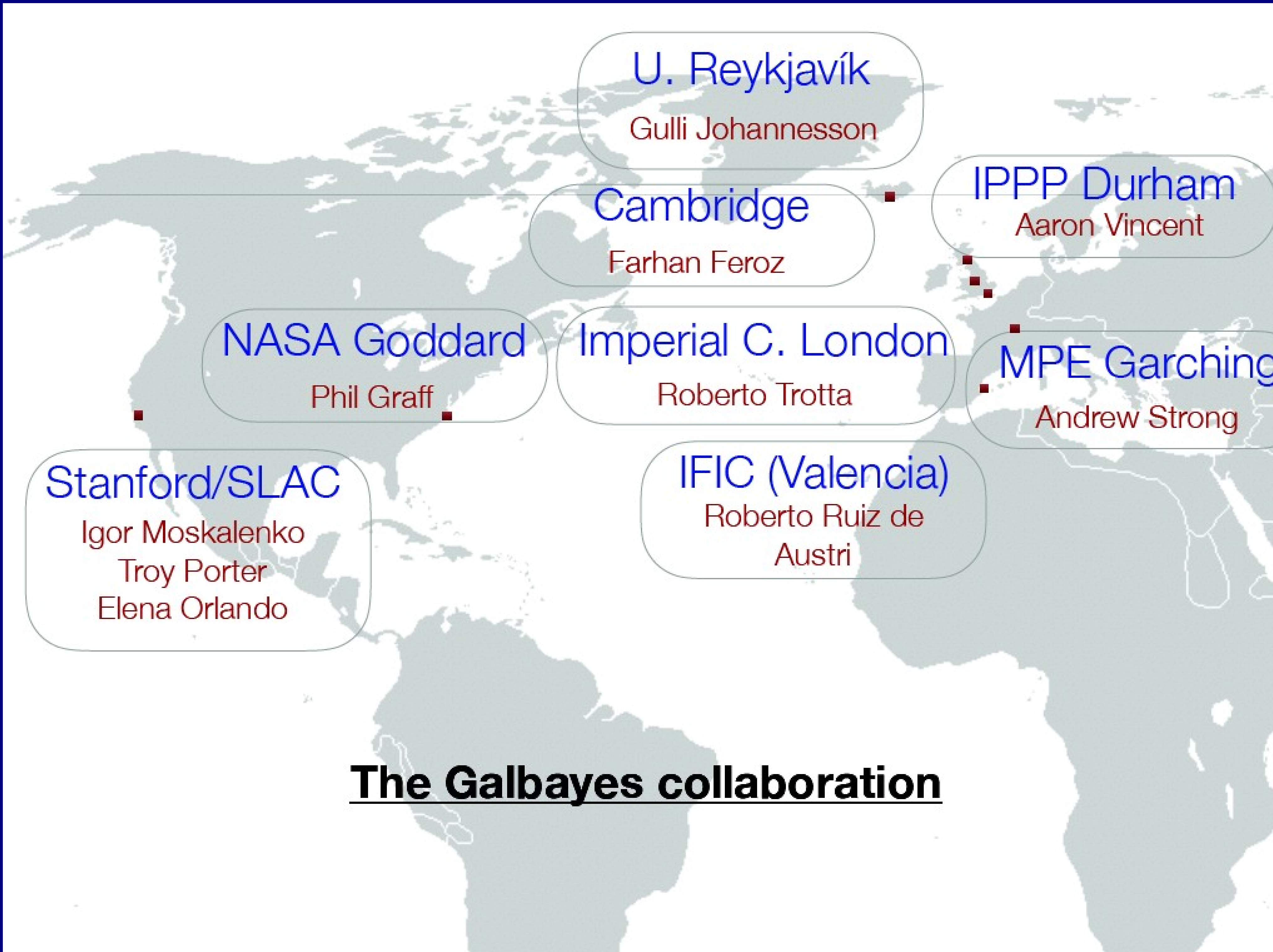
Planck haze (arXiv:1208.5483)
Overlaid on Fermi Bubbles



connection to 511 keV line ?



All are -
 centred on Galactic Centre
 leptonic
 unknown origin



The Galbayes collaboration

Free parameters

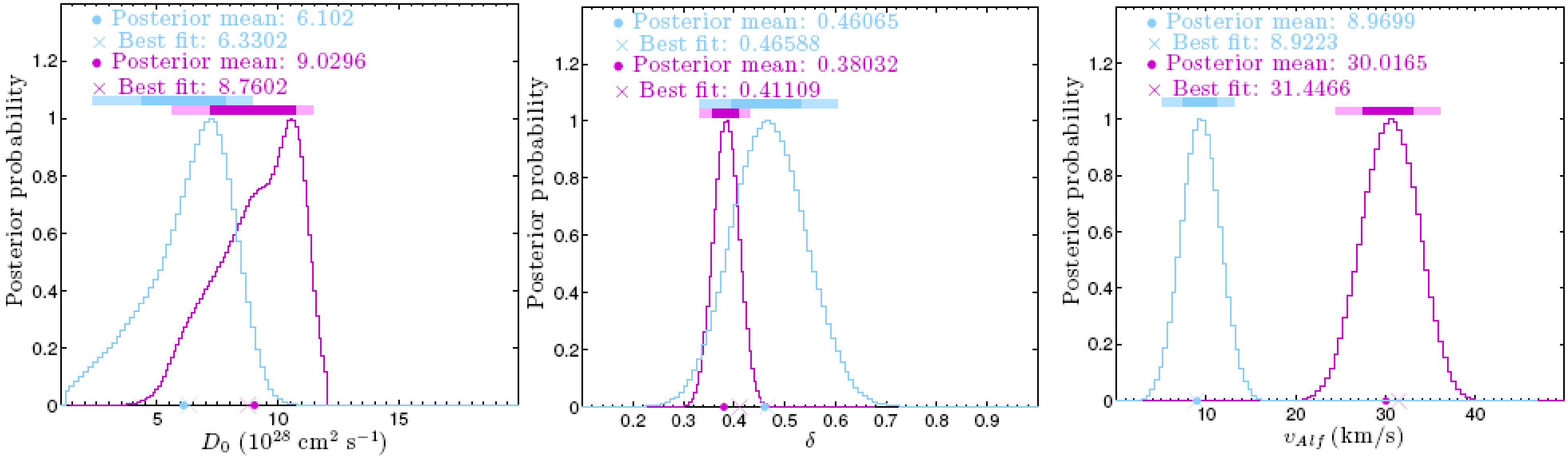
Propagation

Proton normalization (10^{-9} cm^2 sr^{-1}s^{-1}MeV^{-1})	N_p
Diffusion coefficient[a] (10^{28} cm^2 s^{-1})	D_0
Rigidity power law index	δ
Alfvén speed (km s^{-1})	$v_{\rm Alf}$
Diffusion zone half-height (kpc)	z_h
Rigidity of first injection break (10^4 MV)	ρ_{br}
Nucleus injection index below ρ_{br}	ν_0
Nucleus injection index above ρ_{br}	ν_1
Nucleus injection index above 220 GV	ν_2
Difference between p and heavier inj. indices	δ_ν

Abundances: H, He, C, N, O, Ne, Na, Mg, Al, Si

20 Free parameters!

Results: propagation parameters



Light (B … Si) elements

$p, \bar{p}, \mathrm{He}$

Electrons, synchrotron and magnetic fields

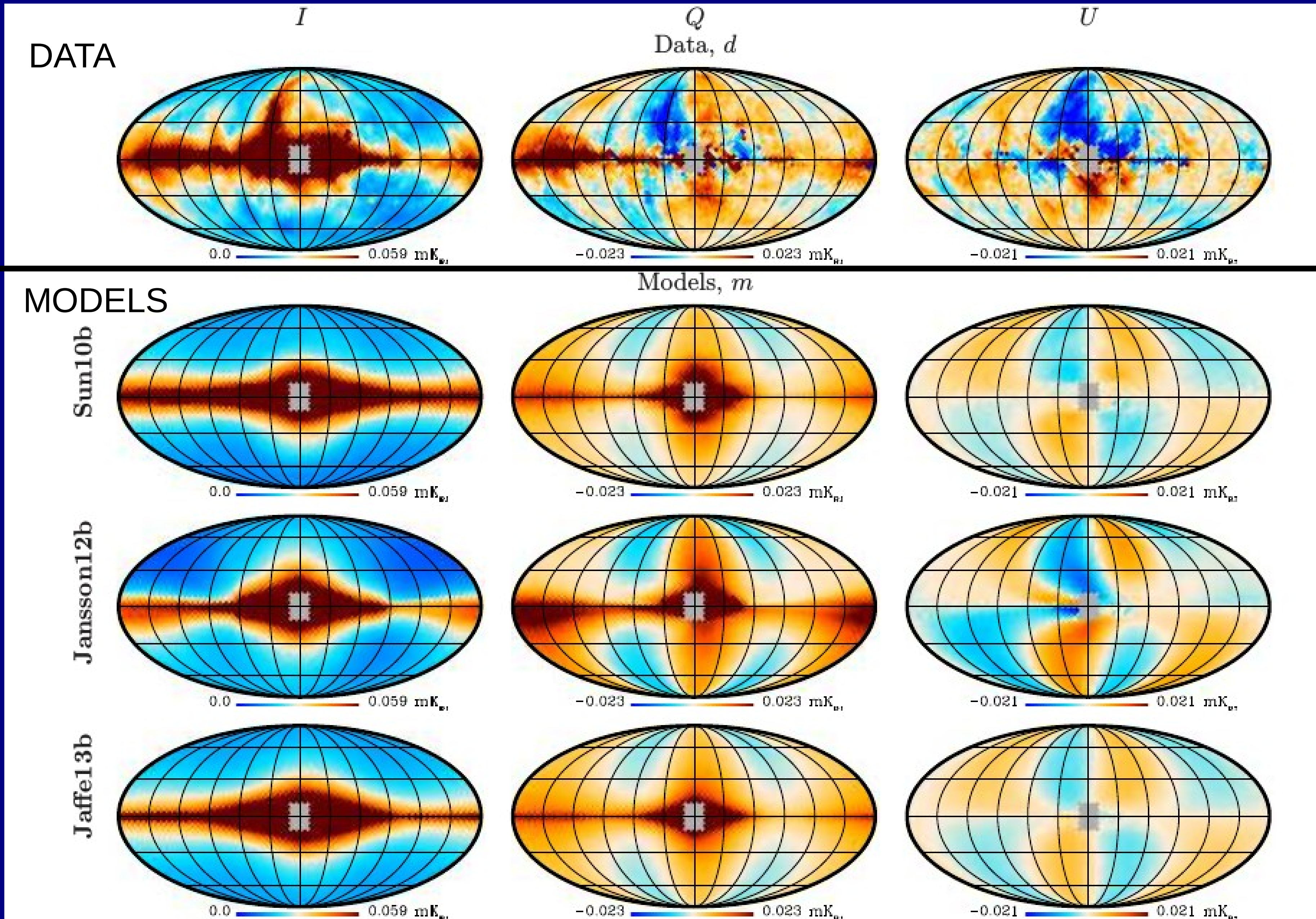
Planck : Tess Jaffe lead author arXiv:1601:00546

Planck intermediate results. XLII. Large-scale Galactic magnetic fields

Planck Collaboration: R. Adam[64], P. A. R. Ade[76], M. I. R. Alves[84, 8], M. Ashdown[58, 4], J. Aumont[49], C. Baccigalupi[74], A. J. Banday[84, 8], R. B. Barreiro[54], N. Bartolo[25, 55], E. Battaner[86, 87], K. Benabed[50, 83], A. Benoit-Lévy[20, 50, 83], J.-P. Bernard[84, 8], M. Bersanelli[28, 41], P. Bielewicz[70, 8, 74], L. Bonavera[54], J. R. Bond[7], J. Borrill[11, 79], F. R. Bouchet[50, 77], F. Boulanger[49], M. Bucher[1], C. Burigana[40, 26, 42], R. C. Butler[40], E. Calabrese[81], J.-F. Cardoso[63, 1, 50], A. Catalano[64, 61], H. C. Chiang[22, 5], P. R. Christensen[71, 31], L. P. L. Colombo[19, 56], C. Combet[64], F. Couchot[60], B. P. Crill[56, 9], A. Curto[54, 4, 58], F. Cuttaia[40], L. Danese[74], R. J. Davis[57], P. de Bernardis[27], A. de Rosa[40], G. de Zotti[37, 74], J. Delabrouille[1], C. Dickinson[57], J. M. Diego[54], K. Dolag[85, 67], O. Doré[56, 9], A. Ducout[50, 47], X. Dupac[33], F. Elsner[20, 50, 83], T. A. Enßlin[67], H. K. Eriksen[52], K. Ferrière[84, 8], F. Finelli[40, 42], O. Forni[84, 8], M. Frailis[39], A. A. Fraisse[22], E. Franceschi[40], S. Galeotta[39], K. Ganga[1], T. Ghosh[49], M. Giard[84, 8], E. Gjerløw[52], J. González-Nuevo[16, 54], K. M. Górski[56, 89], A. Gregorio[29, 39, 45], A. Gruppuso[40], J. E. Gudmundsson[82, 73, 22], F. K. Hansen[52], D. L. Harrison[51, 58], C. Hernández-Monteagudo[10, 67], D. Herranz[54], S. R. Hildebrandt[56, 9], M. Hobson[4], A. Hornstrup[13], G. Hurier[49], A. H. Jaffe[47], T. R. Jaffe[84, 8*], W. C. Jones[22], M. Juvela[21], E. Keihänen[21], R. Keskitalo[11], T. S. Kisner[66], J. Knoche[67], M. Kunz[14, 49, 2], H. Kurki-Suonio[21, 36], J.-M. Lamarre[61], A. Lasenby[4, 58], M. Lattanzi[26], C. R. Lawrence[56], J. P. Leahy[57], R. Leonardi[6], F. Levrier[61], P. B. Lilje[52], M. Linden-Vørnle[13], M. López-Caniego[33, 54], P. M. Lubin[23], J. F. Macías-Pérez[64], G. Maggio[39], D. Maino[28, 41], N. Mandolesi[40, 26], A. Mangilli[49, 60], M. Maris[39], P. G. Martin[7], S. Masi[27], A. Melchiorri[27, 43], A. Mennella[28, 41], M. Migliaccio[51, 58], M.-A. Miville-Deschênes[49, 7], A. Moneti[50], L. Montier[84, 8], G. Morgante[40], D. Munshi[76], J. A. Murphy[69], P. Naselsky[72, 32], F. Nati[22], P. Natoli[26, 3, 40], H. U. Nørgaard-Nielsen[13], N. Oppermann[7], E. Orlando[88], L. Pagano[27, 43], F. Pajot[49], R. Paladini[48], D. Paoletti[40, 42], F. Pasian[39], L. Perotto[64], V. Pettorino[35], F. Piacentini[27], M. Piat[1], E. Pierpaoli[19], S. Plaszczynski[60], E. Pointecouteau[84, 8], G. Polenta[3, 38], N. Ponthieu[49, 46], G. W. Pratt[62], S. Prunet[50, 83], J.-L. Puget[49], J. P. Rachen[17, 67], M. Reinecke[67], M. Remazeilles[57, 49, 1], C. Renault[64], A. Renzi[30, 44], I. Ristorcelli[84, 8], G. Rocha[56, 9], M. Rossetti[28, 41], G. Roudier[1, 61, 56], J. A. Rubiño-Martín[53, 15], B. Rusholme[48], M. Sandri[40], D. Santos[64], M. Savelainen[21, 36], D. Scott[18], L. D. Spencer[76], V. Stolyarov[4, 80, 59], R. Stompor[1], A. W. Strong[68], R. Sudiwala[76], R. Sunyaev[67, 78], A.-S. Suur-Uski[21, 36], J.-F. Sygnet[50], J. A. Tauber[34], L. Terenzi[75, 40], L. Toffolatti[16, 54, 40], M. Tomasi[28, 41], M. Tristram[60], M. Tucci[14], L. Valenziano[40], J. Valiviita[21, 36], B. Van Tent[65], P. Vielva[54], F. Villa[40], L. A. Wade[56], B. D. Wandelt[50, 83, 24], I. K. Wehus[56, 52], D. Yvon[12], A. Zacchei[39], and A. Zonca[23]

GALPROP Cosmic-ray electrons used for synchrotron emission

Planck comparison with B-field models, Jaffe etal 2015



TOTAL	Polarized: Stokes Q	Stokes U

CHANG-ES Project

JVLA 35 nearby edge-on galaxies
Including familiar ones NGC891, 4631 etc
21 and 6 cm, polarization

Synchrotron halos
Spectral variation, cosmic-ray propagation

Data now public, on-going analysis by collaboration
Followup with GBT, Alma etc

CHANG-ES IV: Radio continuum emission of 35 edge-on galaxies observed with the Karl G. Jansky Very Large Array in D-configuration – Data Release 1

Theresa Wiegert[1], Judith Irwin[2], Arpad Miskolczi[3], Philip Schmidt[4], Silvia Carolina Mora[5], Ancor Damas-Segovia[6], Yelena Stein[7], Jayanne English[8], Richard J. Rand[9], Isaiah Santistevan[10], Rene Walterbos[11], Marita Krause[12], Rainer Beck[13], Ralf-Jürgen Dettmar[14], Amanda Kepley[15], Marek Wezgowiec[16], Q. Daniel Wang[17], George Heald[18], Jiangtao Li[19], Stephen MacGregor[20], Megan Johnson[21], A. W. Strong[22], Amanda DeSouza[23], Troy A. Porter[24]

Composite image of 30 galaxies

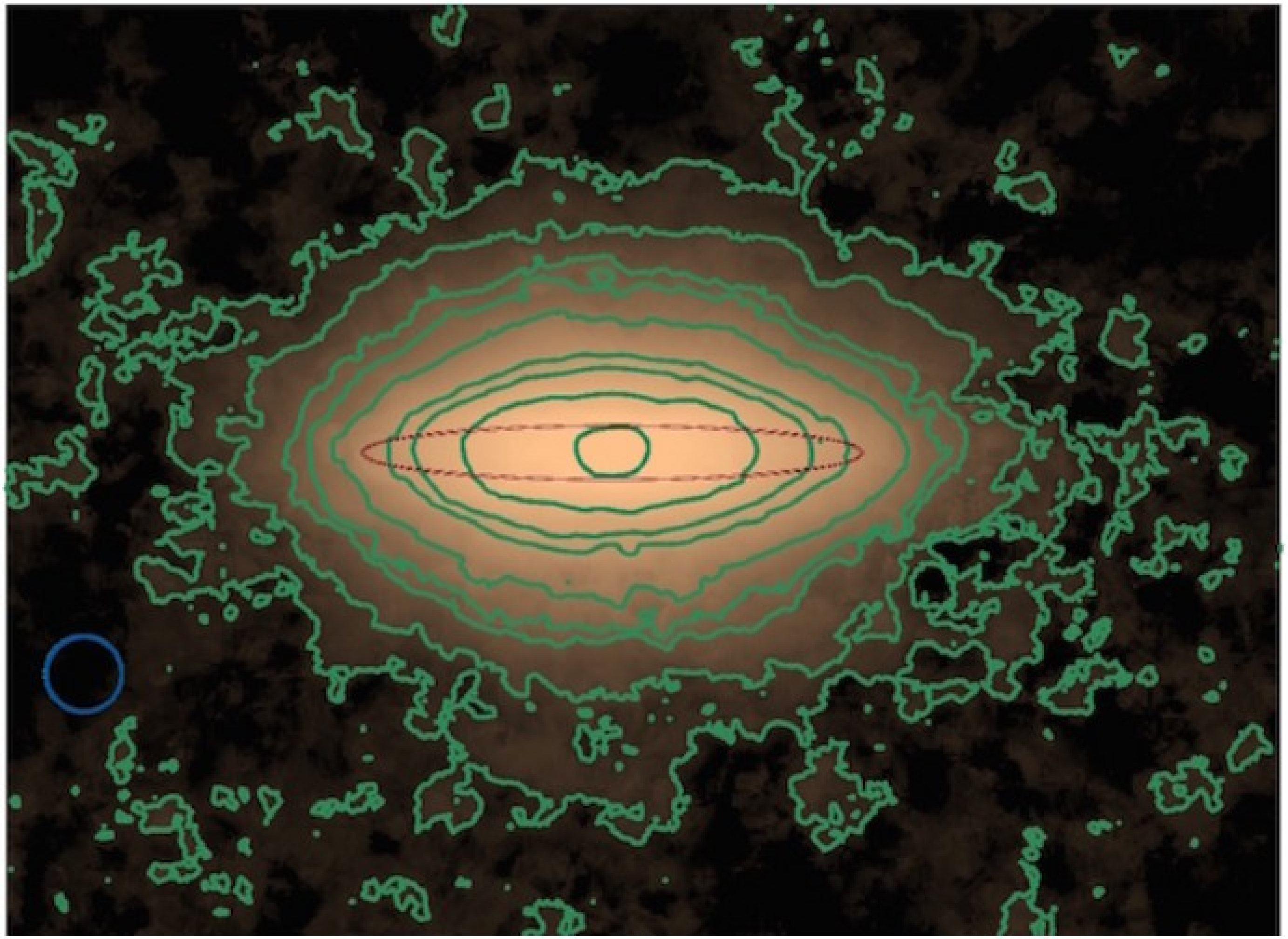
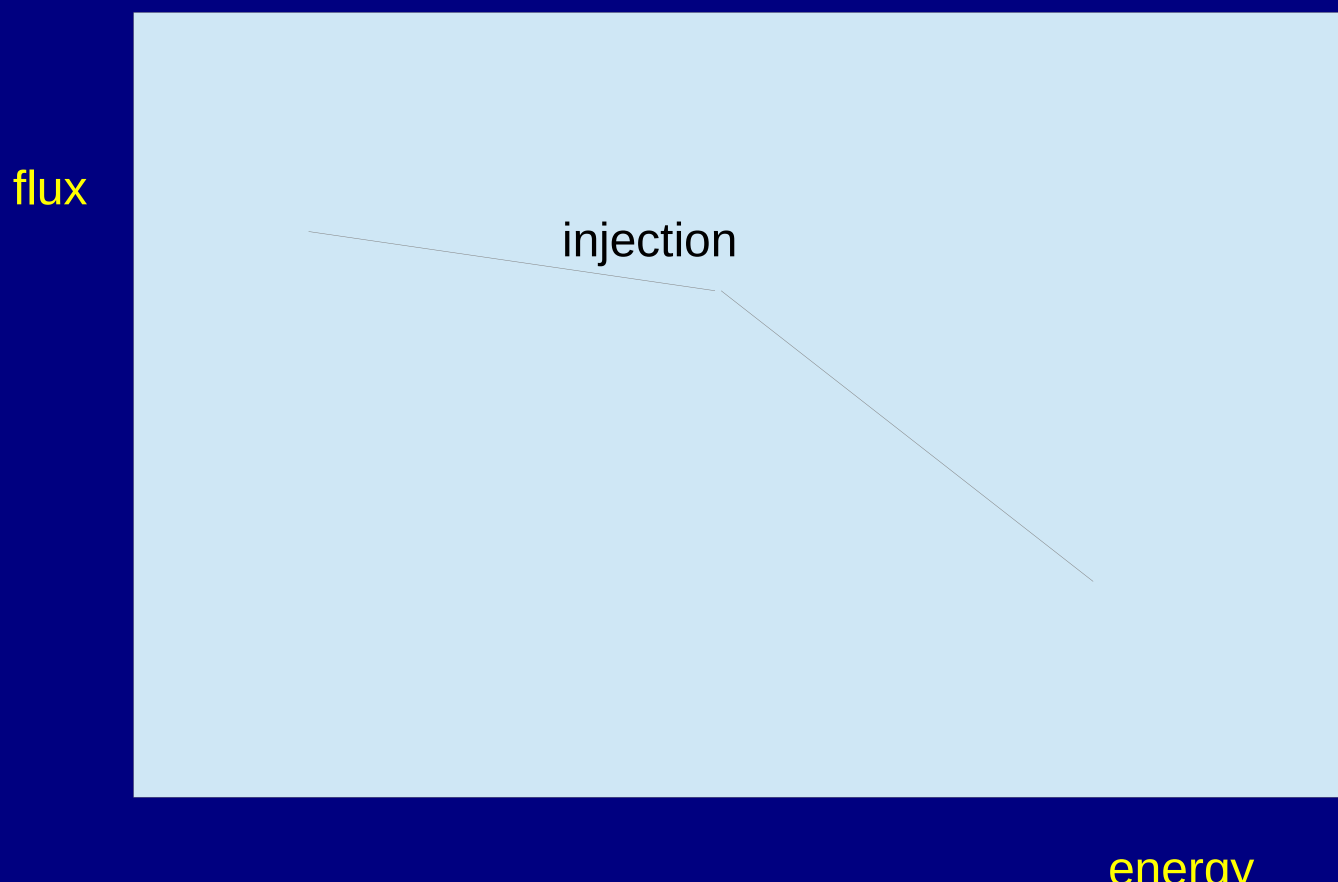


Fig. 6.— The median edge-on spiral galaxy in L-band, made from stacking 30 of the galaxies in Fig. 5. The red ellipse is a sample 22μm contour that corresponds to the scaling of the radio data and thus represents the disk radial extent. The beam shown is the *average* beam of the 30 galaxies.

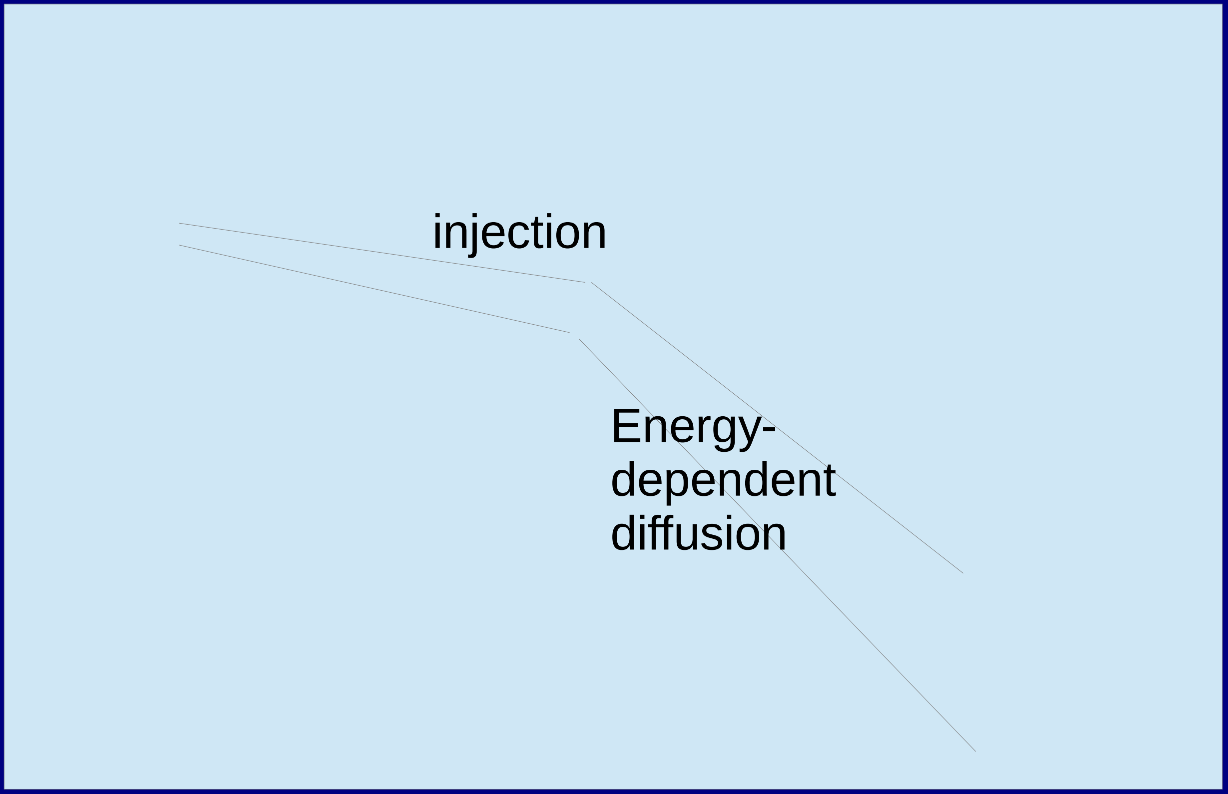

That's all Folks!

Producing the cosmic-ray electron spectrum



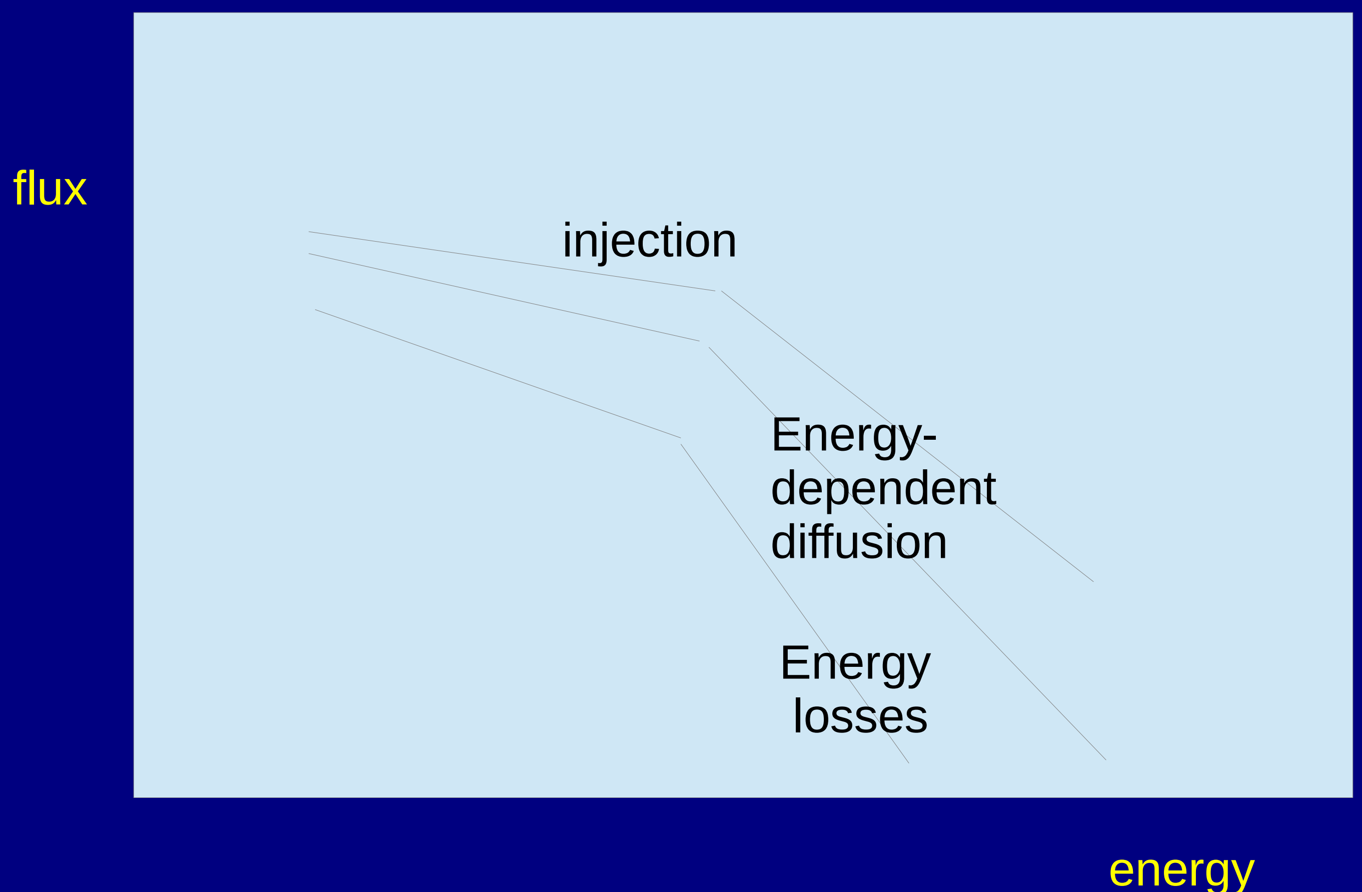
Producing the cosmic-ray electron spectrum

flux

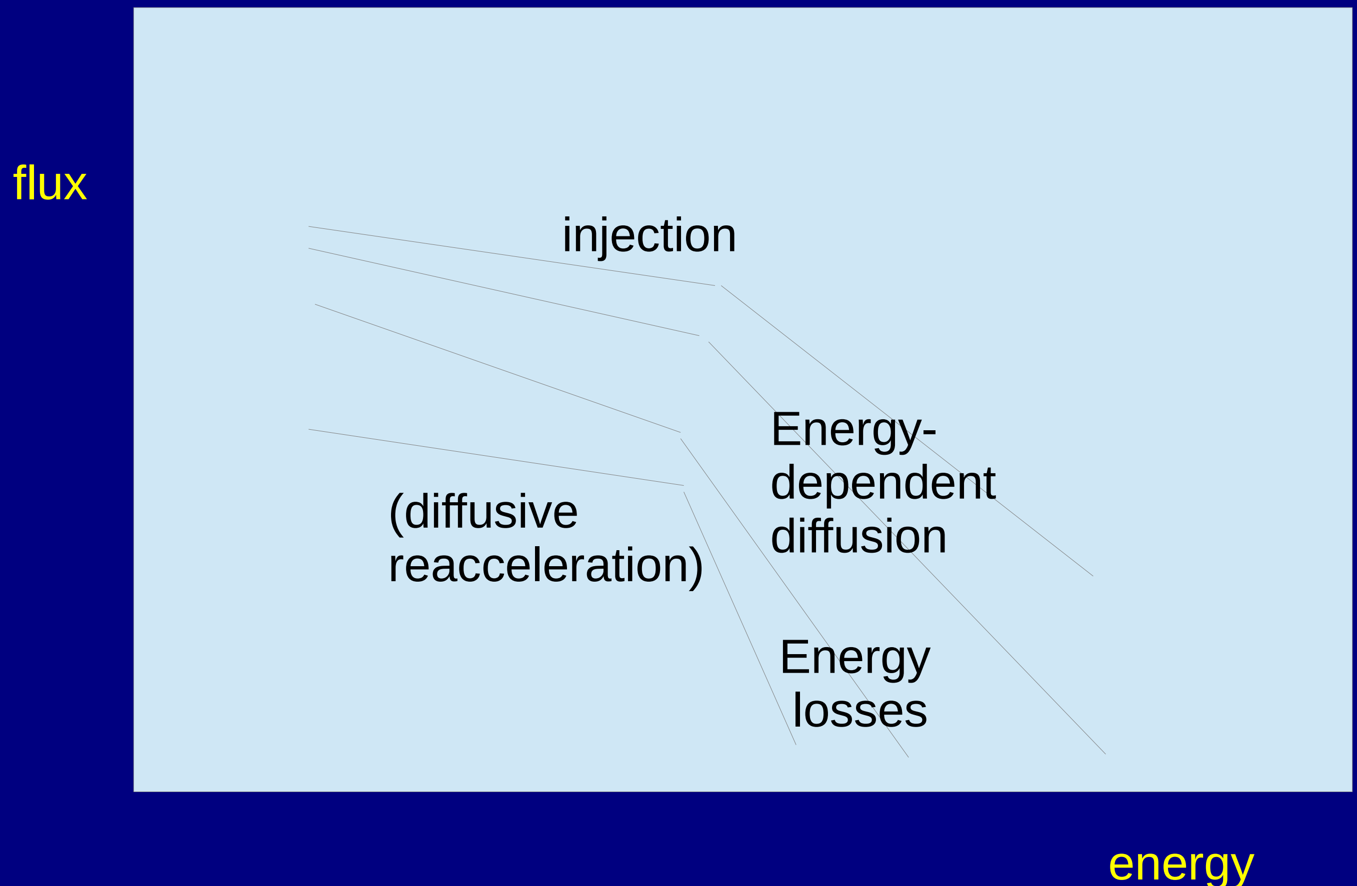


energy

Producing the cosmic-ray electron spectrum

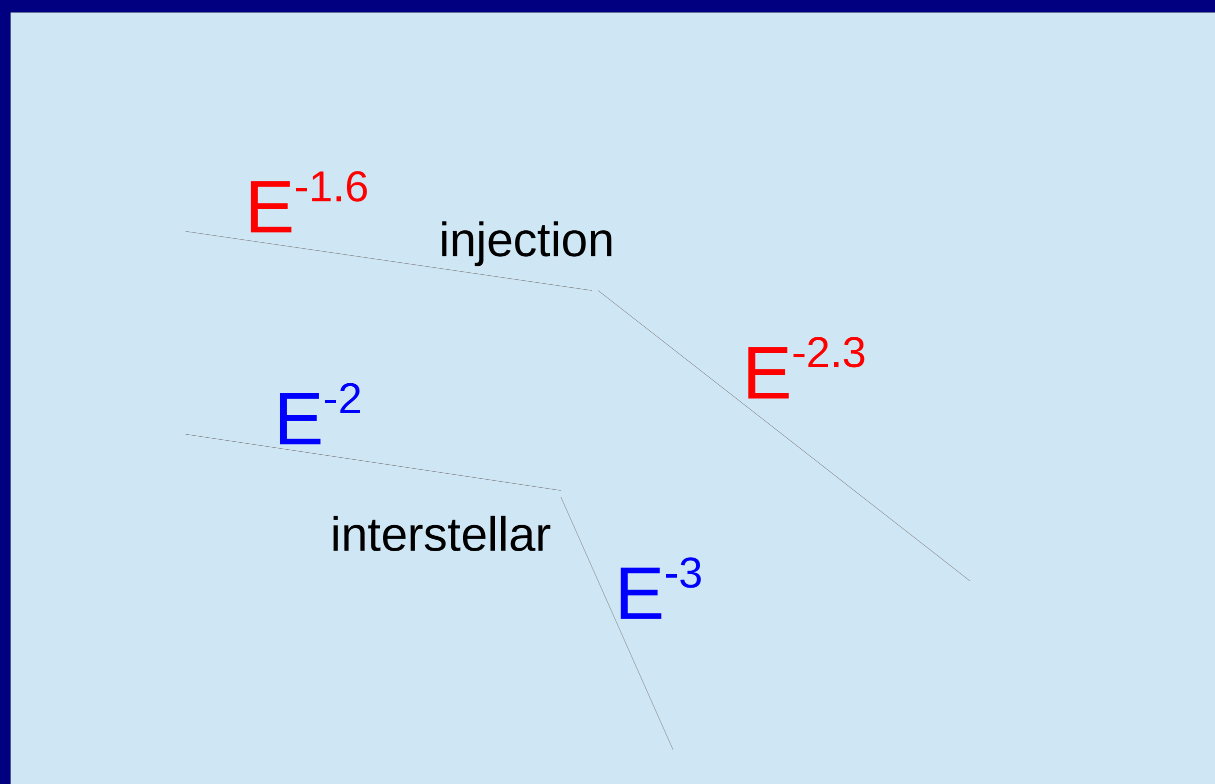


Producing the cosmic-ray electron spectrum



Producing the cosmic-ray electron spectrum

flux



energy

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

T. R. Jaffe [1,2]⋆, A. J. Banday[1,2,3]†, J. P. Leahy[4]‡, S. Leach[5,6]§, A. W. Strong[7]¶

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MNRAS 416, 1152 (2011)

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

A&A 534, A54 (2011)
DOI: 10.1051/0004-6361/201116828

Astronomy & Astrophysics

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

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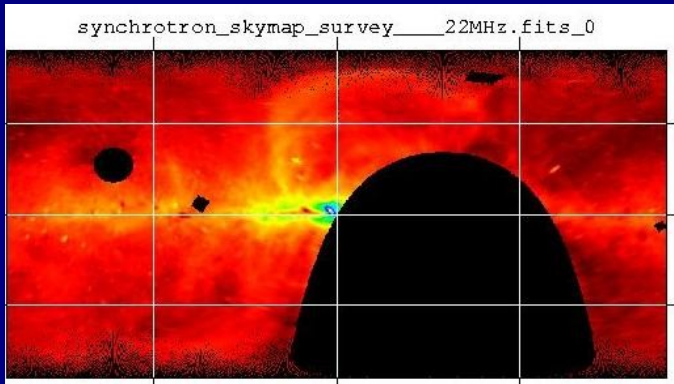
Received 4 March 2011 / Accepted 17 August 2011

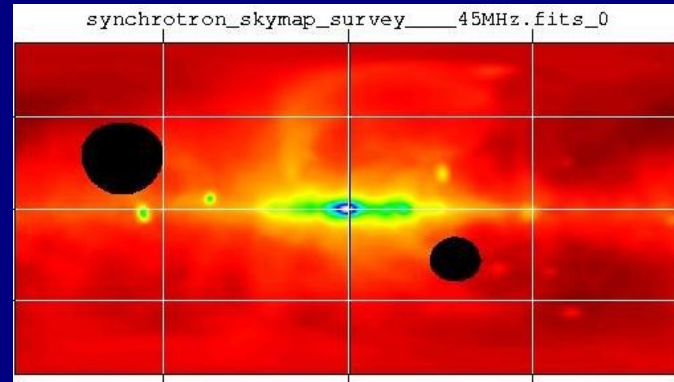
ABSTRACT

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.

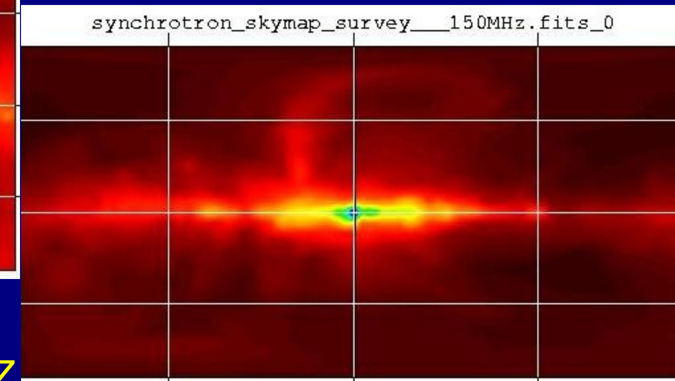
Following results based on this paper.



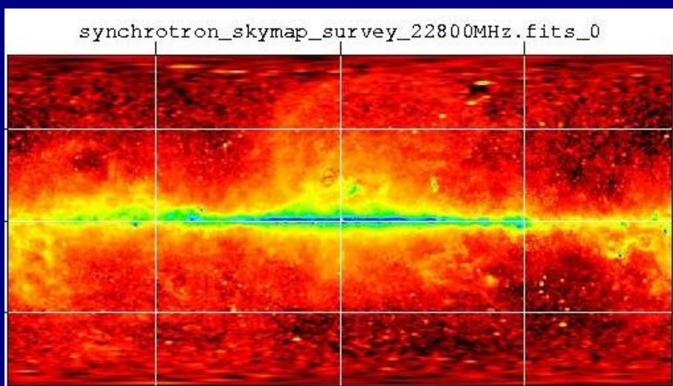
22 MHz



45 MHz



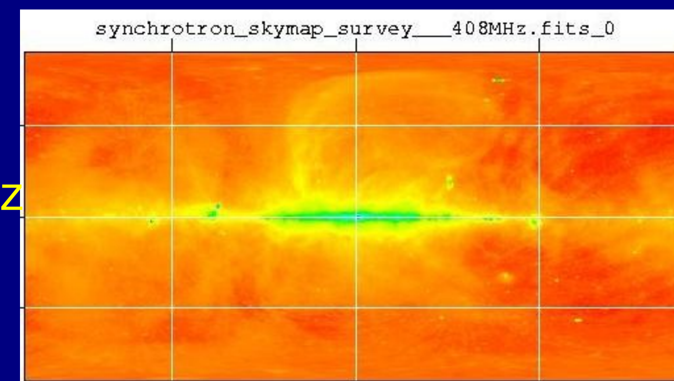
150 MHz

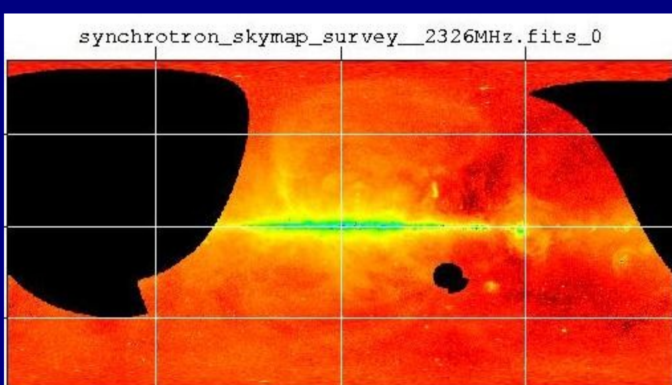


23 GHz

Continuum
sky surveys

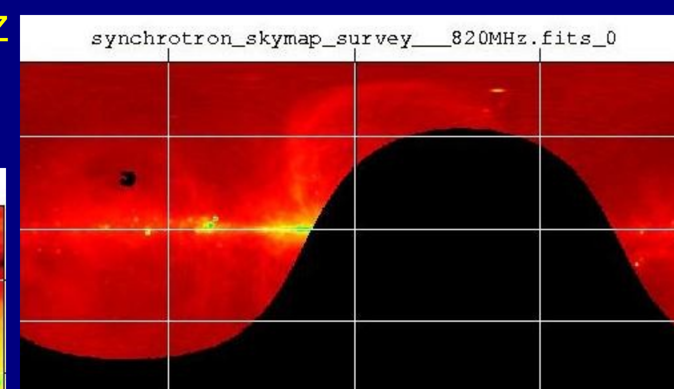
408 MHz



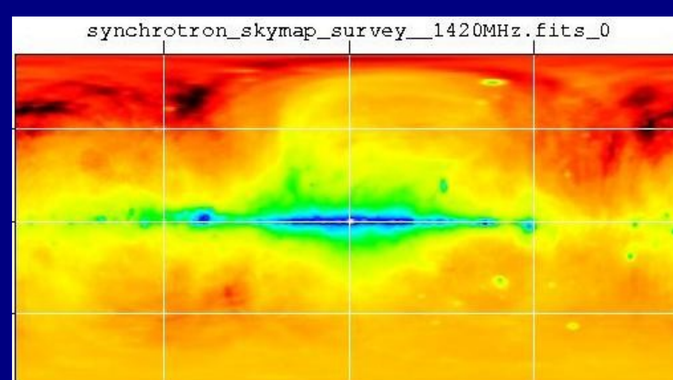


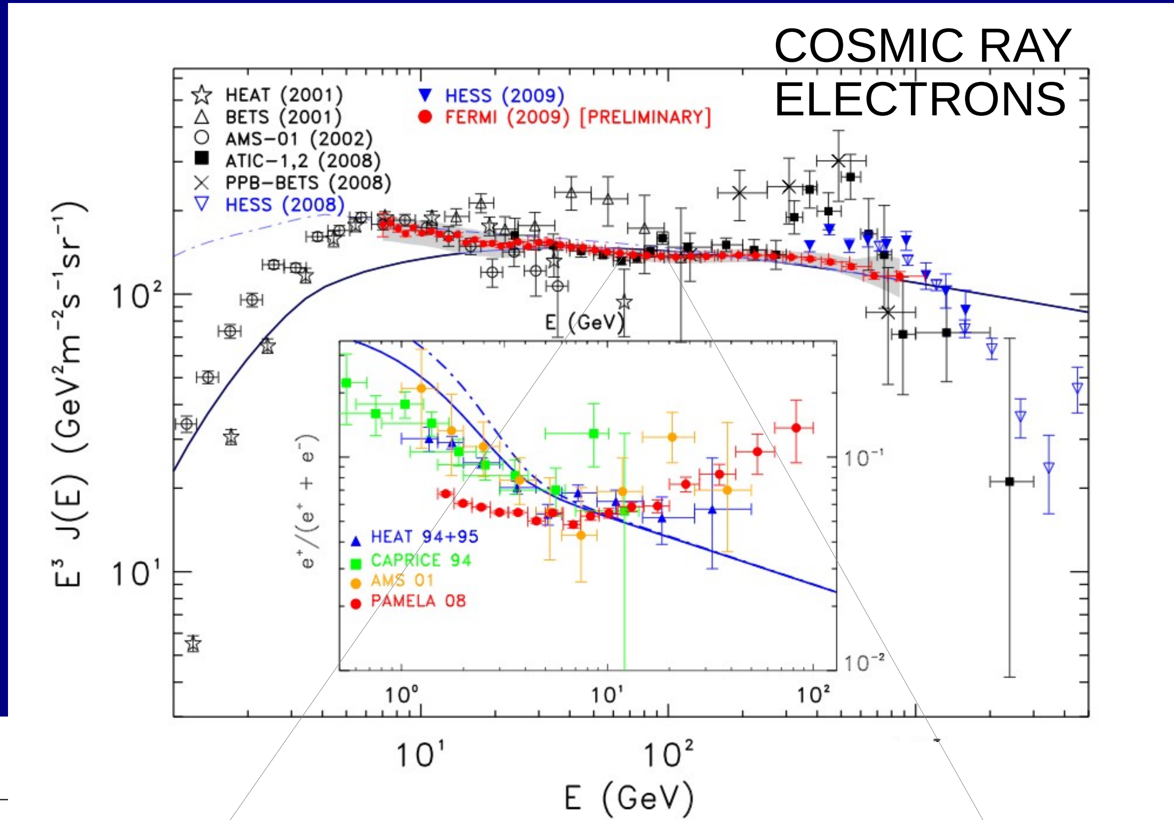
2.3 GHz

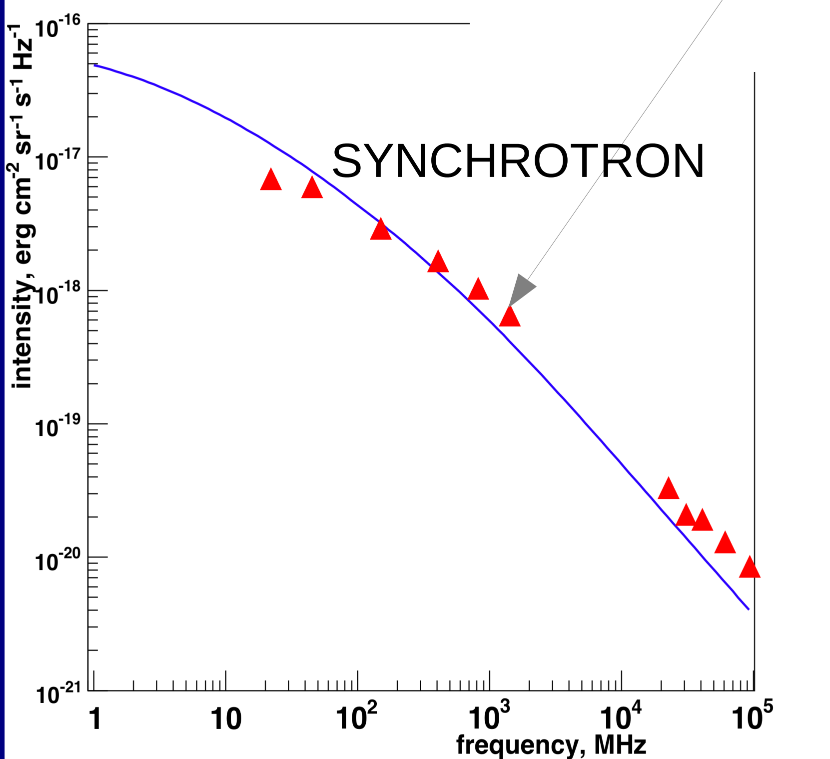
820 MHz



1.4 GHz

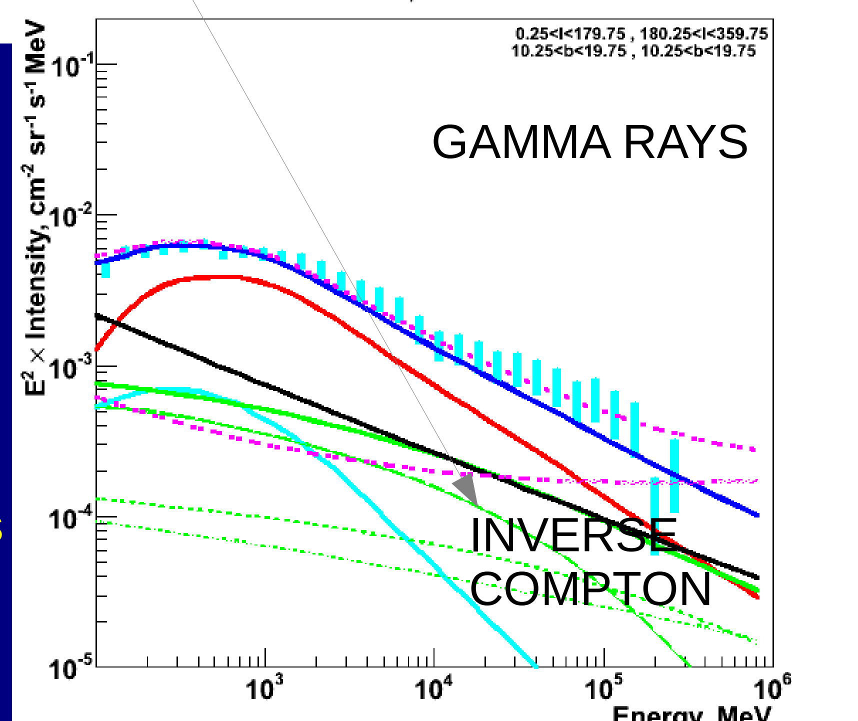


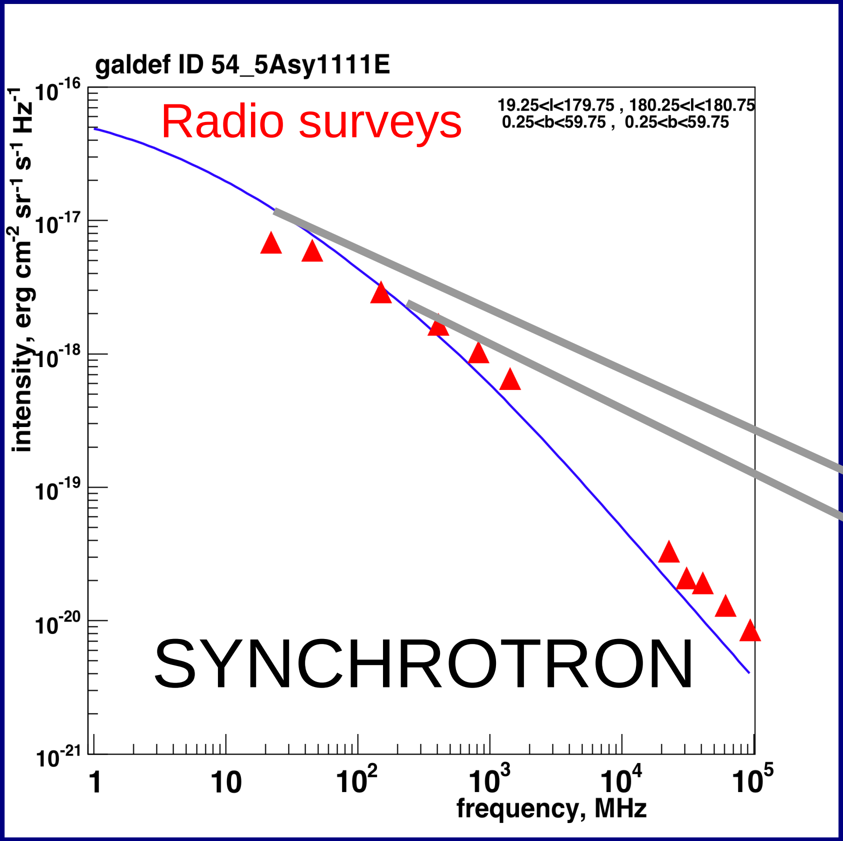


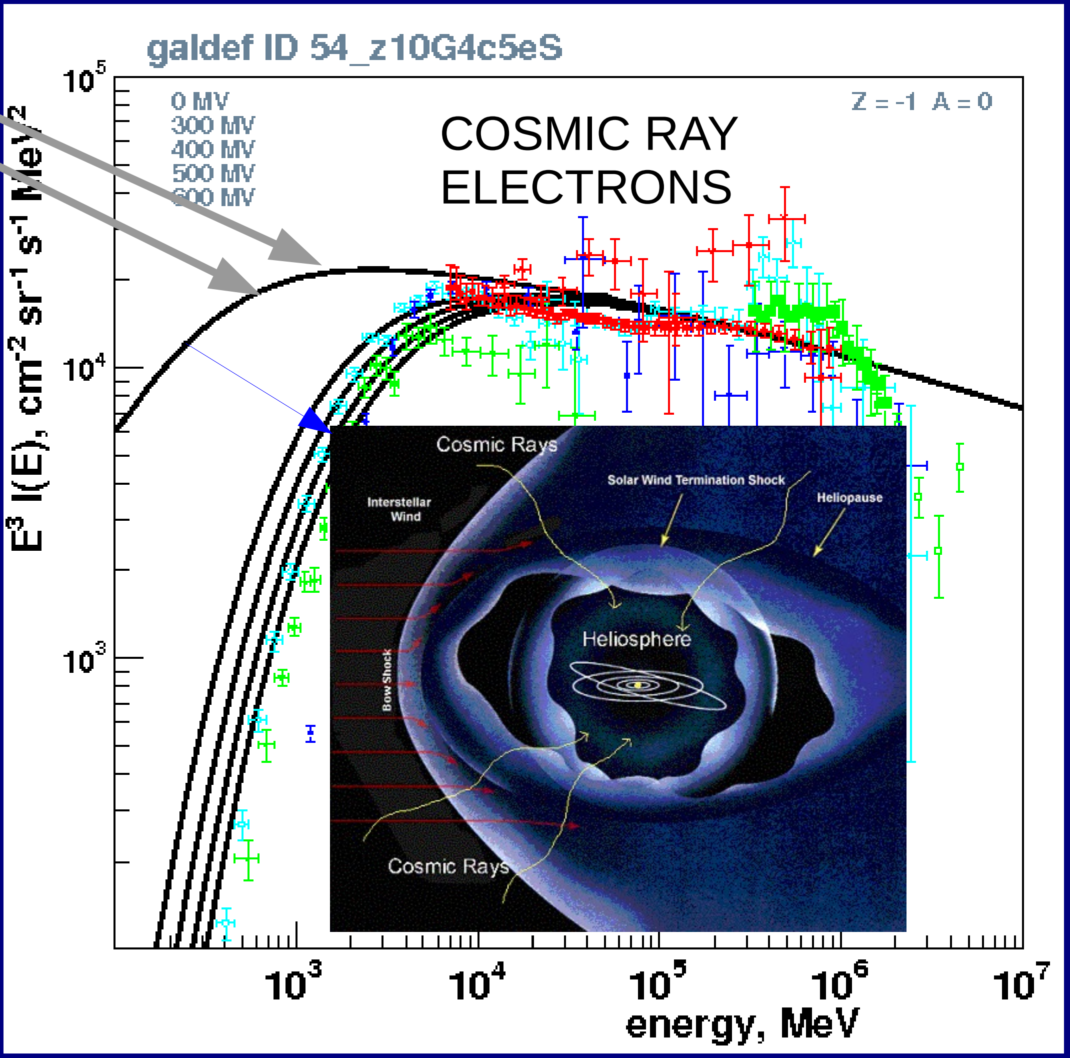


SAME
ELECTRONS
for
RADIO
and
GAMMA RAYS !

good constraints
on models

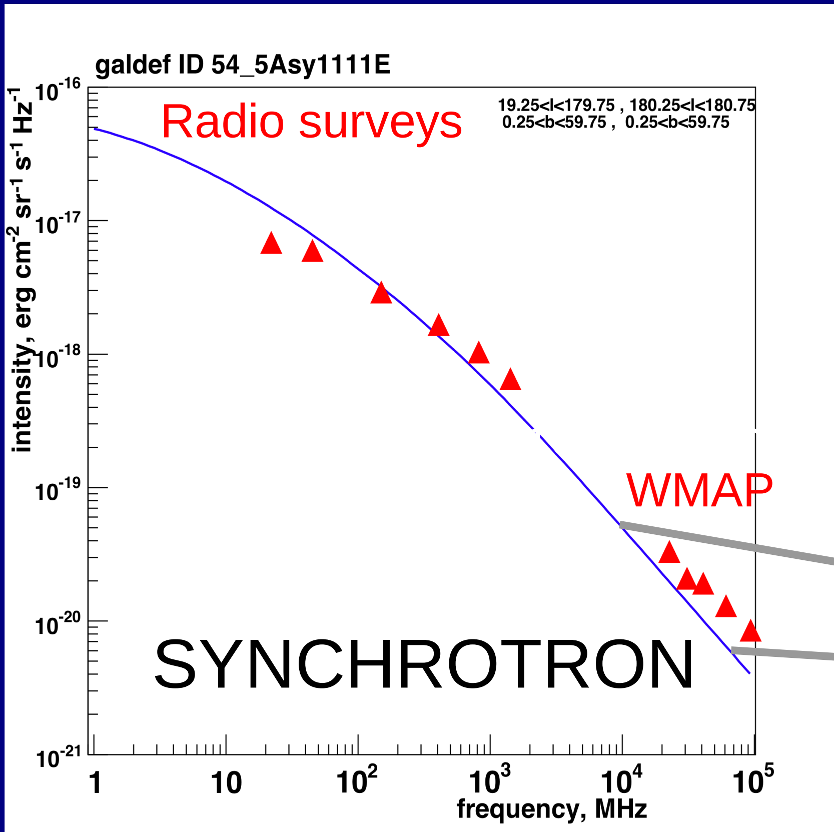


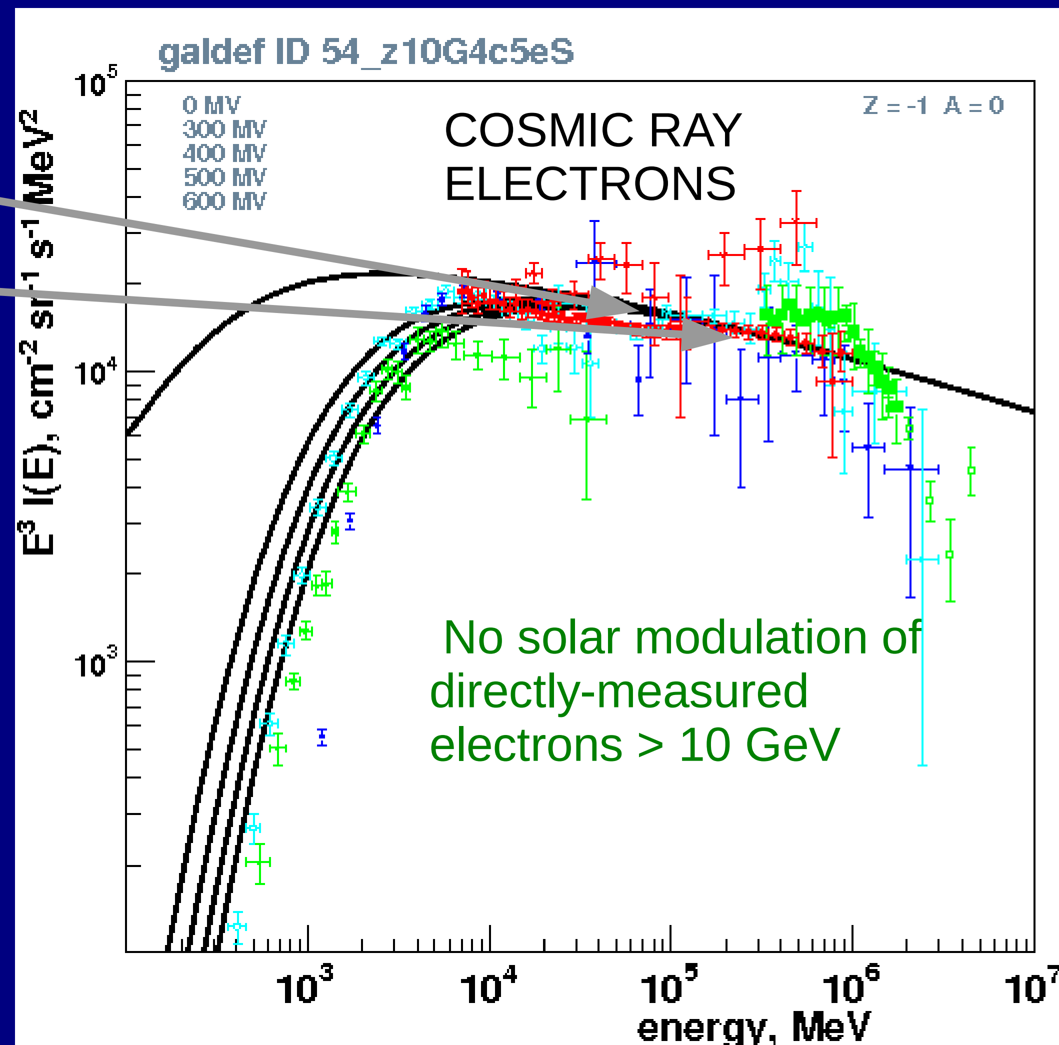




Radio provides essential probe of interstellar electron spectrum at E < few GeV to complement direct measurements and determine solar modulation

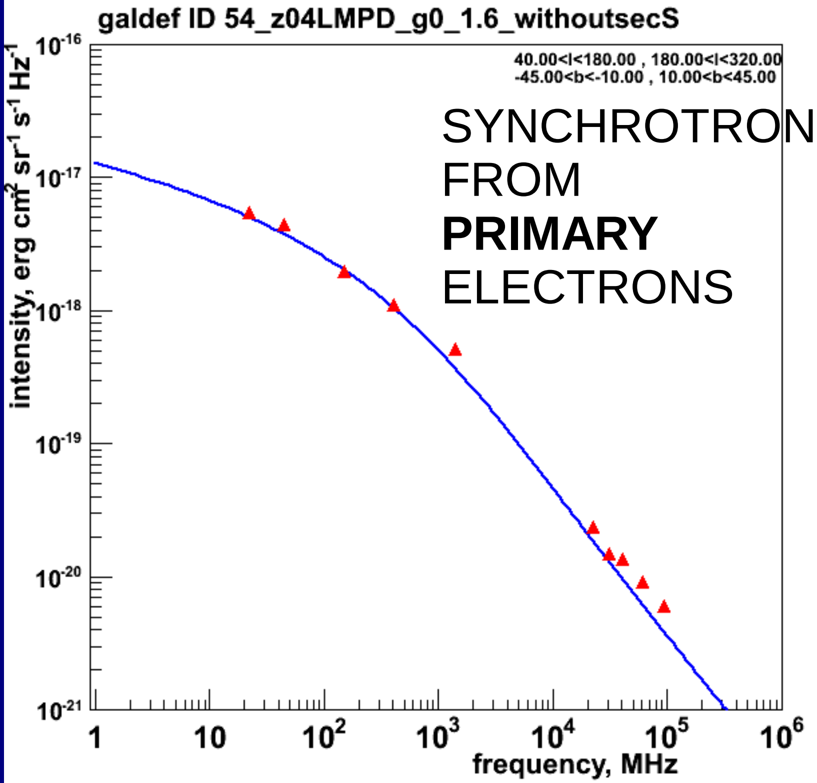
Electrons have huge uncertainty due to modulation here

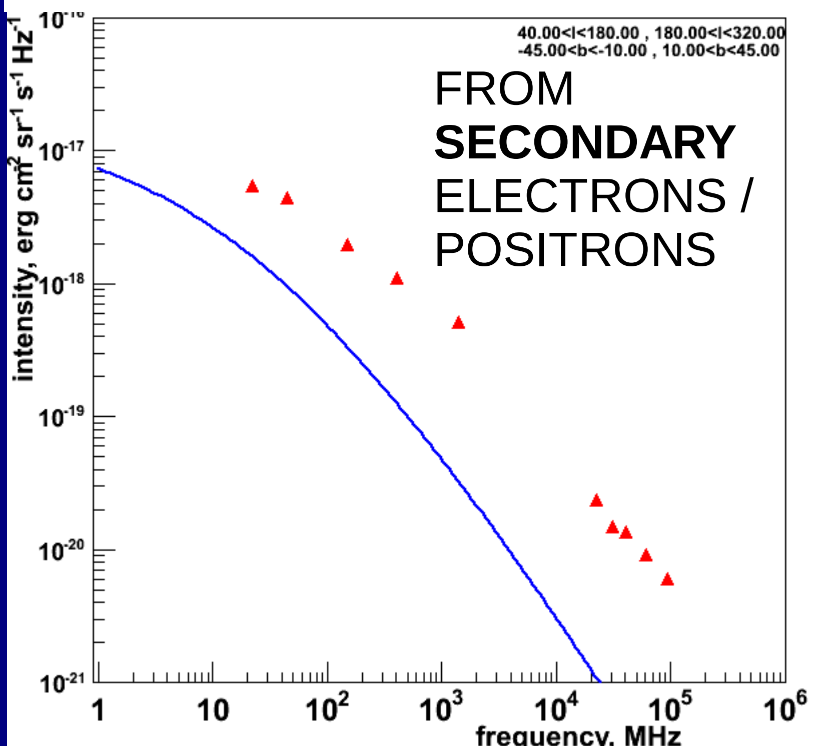


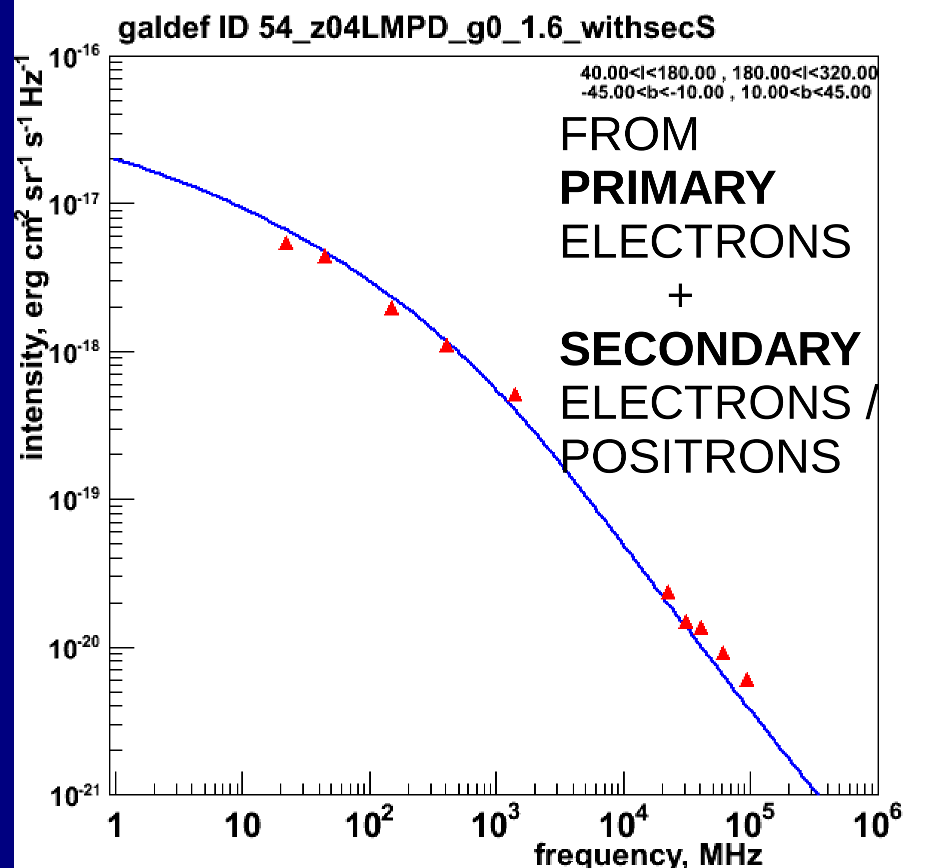


microwaves probe
interstellar electron spectrum
10 - 100 GeV

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







Cosmic-ray electrons

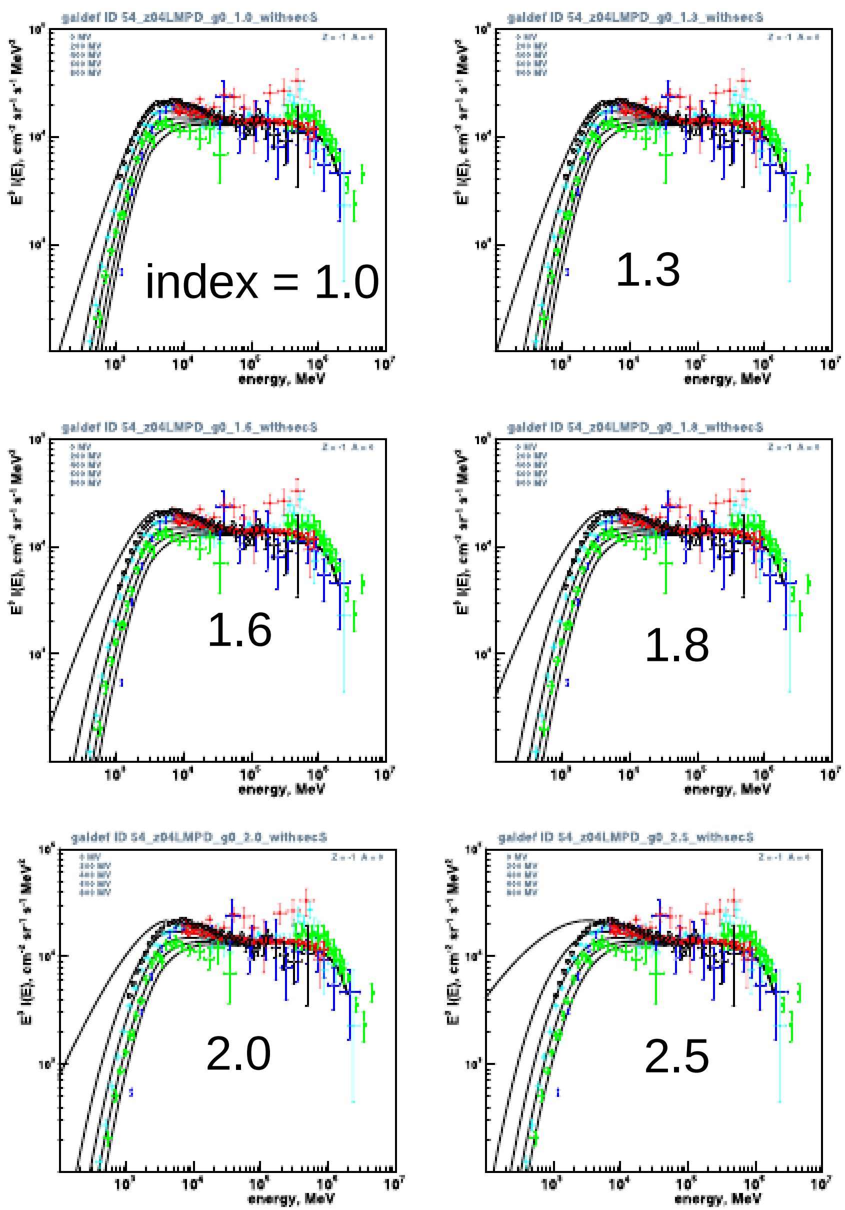


Fig. 4. Electron spectra for pure diffusion model, low-energy electron injection index 1.0, 1.3, 1.6, 1.8, 2.0, 2.5. Modulation Φ = 0, 200, 400, 600, 800 MV. Data as in Fig. 1.

Synchrotron

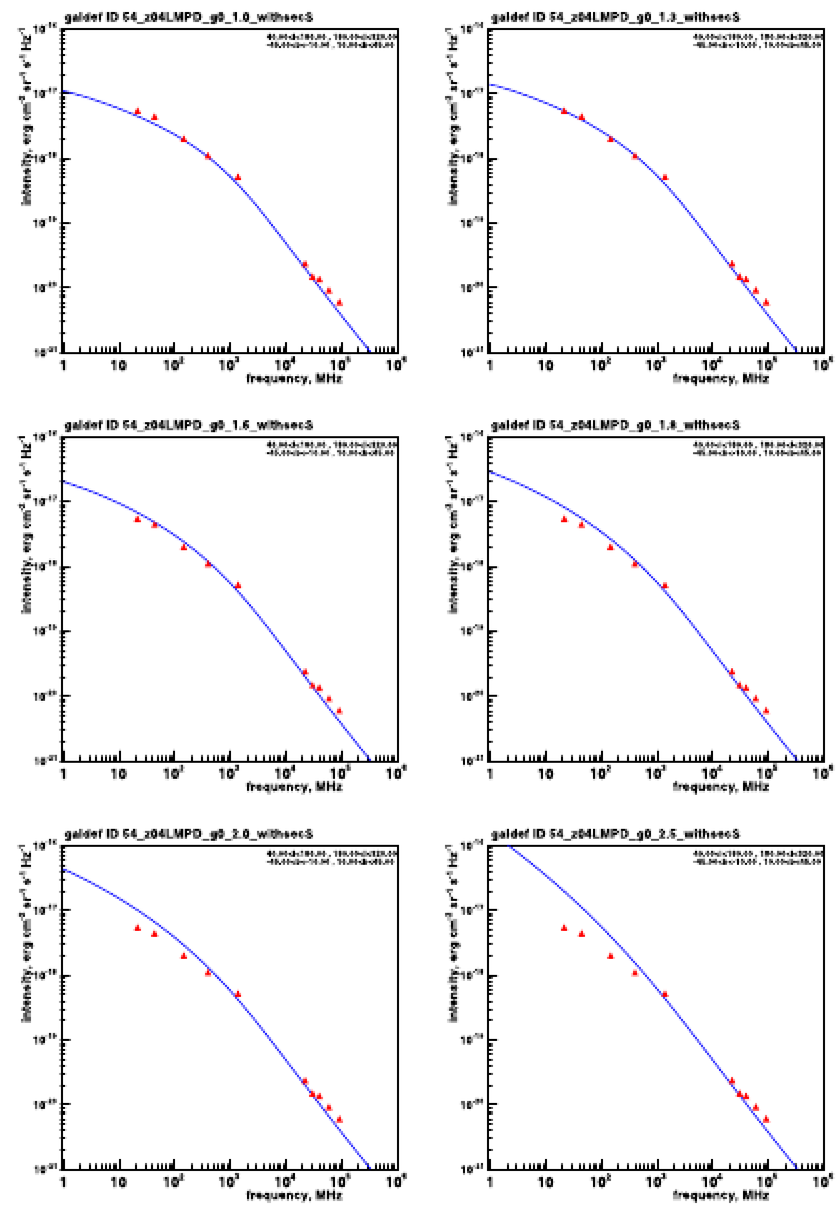


Fig. 5. Synchrotron spectra for pure diffusion model with low-energy electron injection index (*left to right, top to bottom*) 1.0, 1.3, 1.6, 1.8, 2.0, 2.5. Including secondary leptons. Data as in Fig. 2.

Effect of electron injection spectral index

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

Galactic
Synchrotron
Spectral
Index

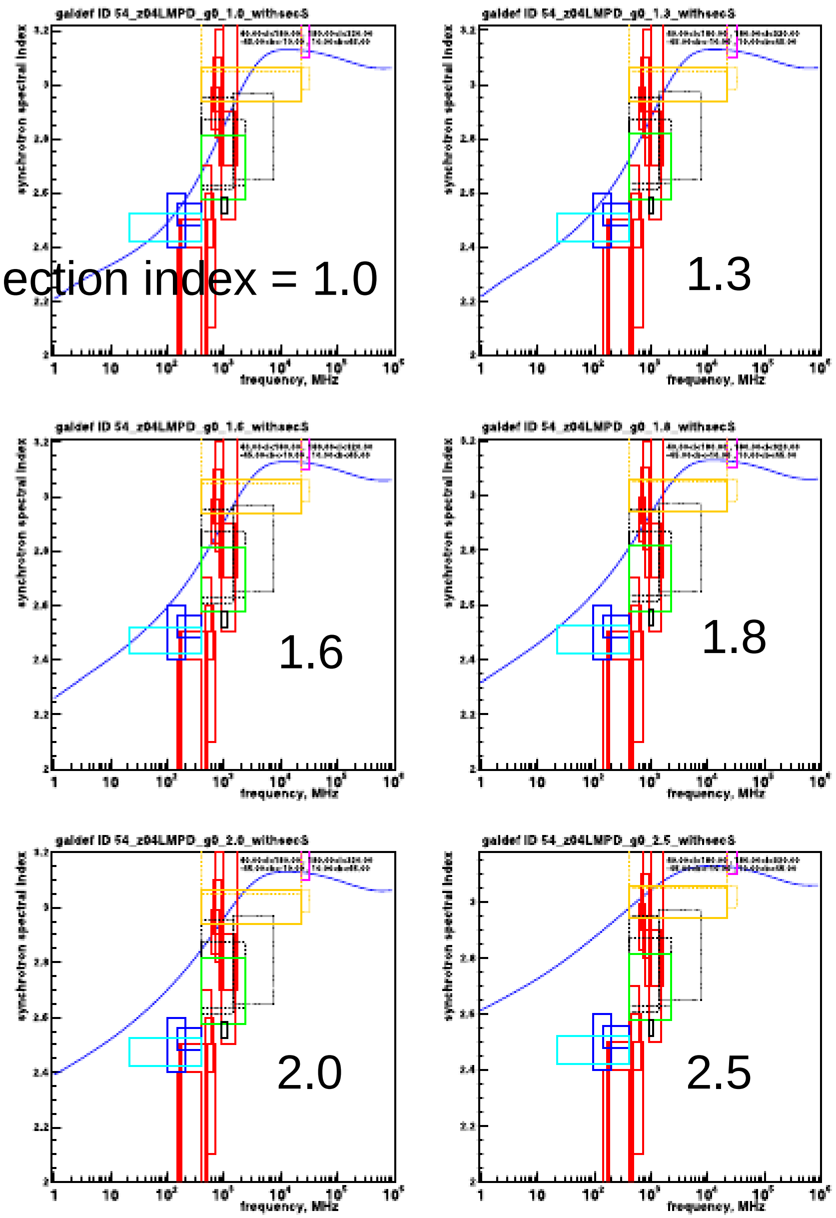


Fig. 6. Synchrotron spectral index for pure diffusion model with low-energy electron injection index (*left to right, top to bottom*) 1.0, 1.3, 1.6, 1.8, 2.0, 2.5. Including secondary leptons. Experimental ranges are based on the references reviewed in Sect. 4.1, and are intended to be representative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

Effect of electron injection spectral index

Strong, Orlando & Jaffe (2011)

Galactic Synchrotron Spectral Index

Planck

A&A 536, A21 (2011)

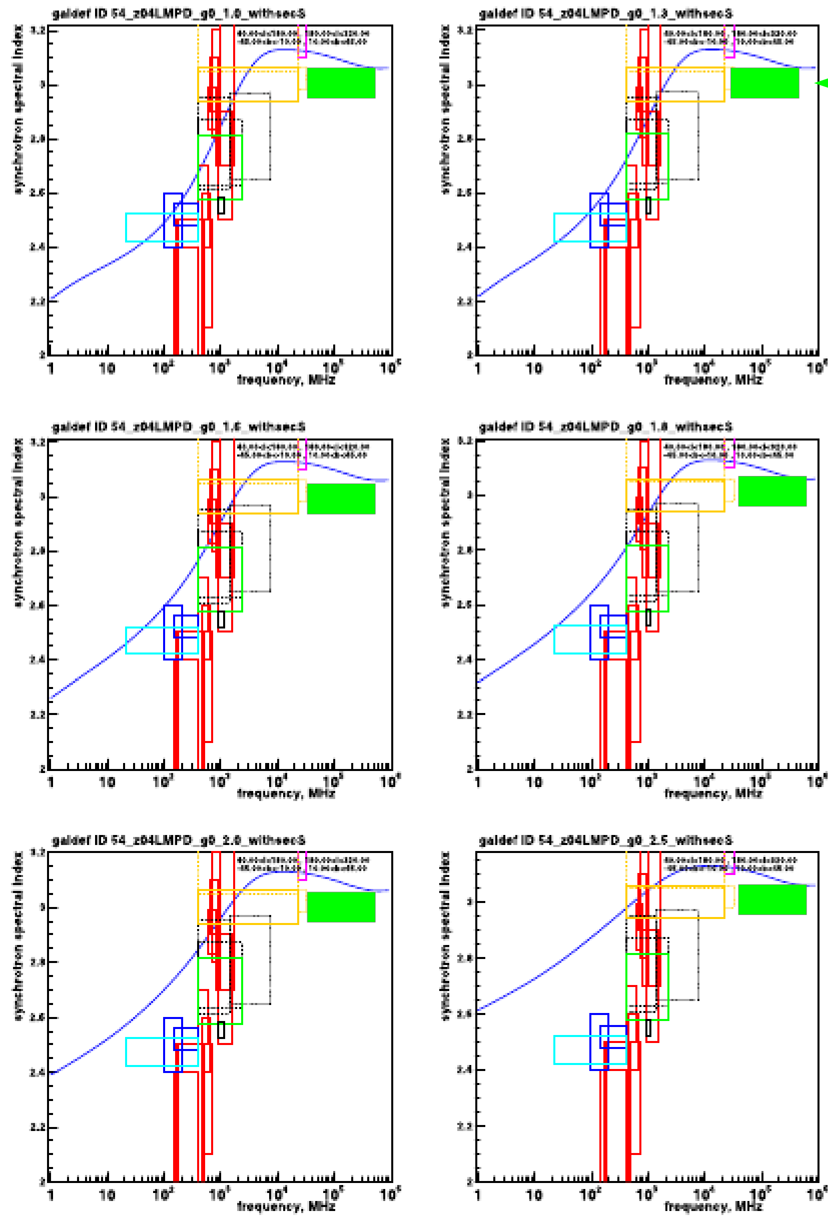
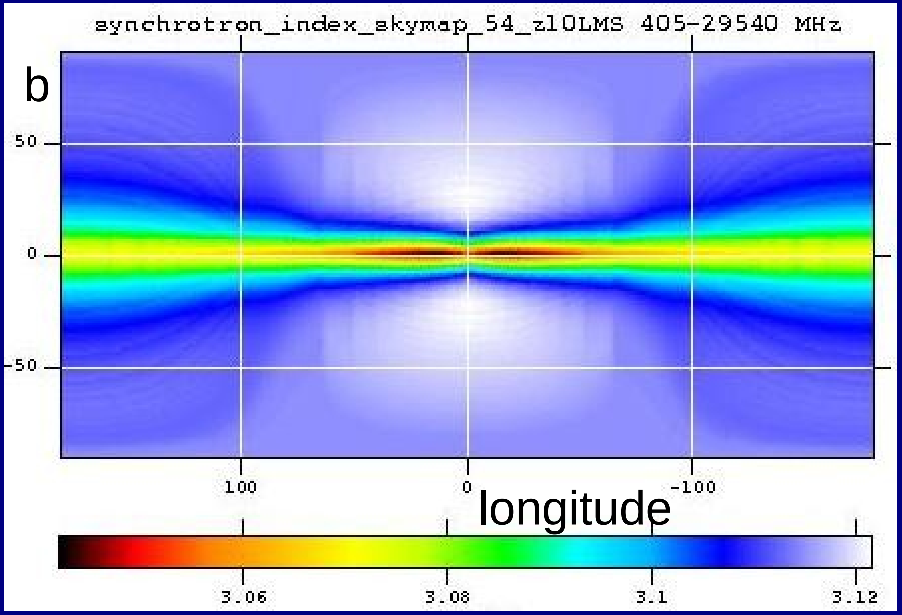


Fig. 6. Synchrotron spectral index for pure diffusion model with low-energy electron injection index (*left to right, top to bottom*) 1.0, 1.3, 1.6, 1.8, 2.0, 2.5. Including secondary leptons. Experimental ranges are based on the references reviewed in Sect. 4.1, and are intended to be representative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

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 (A&A 436, 2127)

What is new :

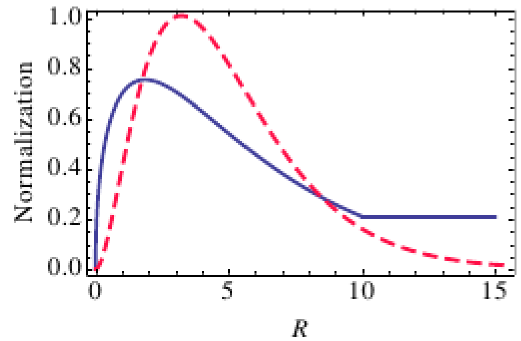
Polarized synchrotron

Separates regular from random B

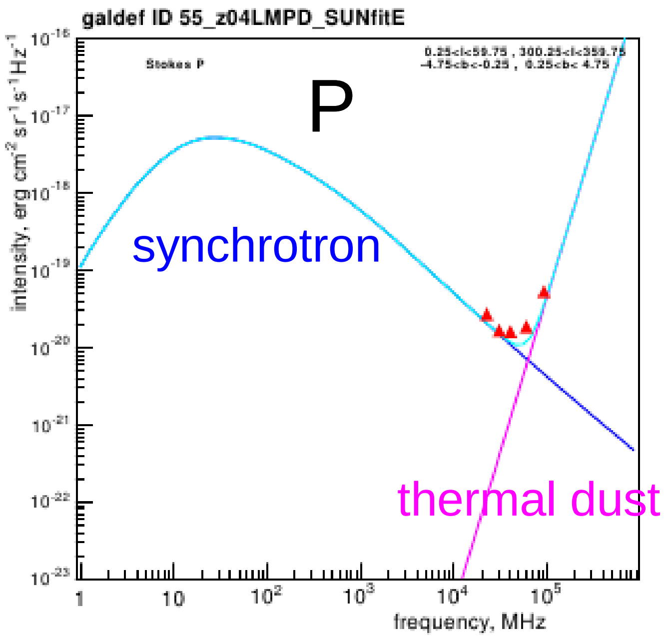
Now modelled in GALPROP

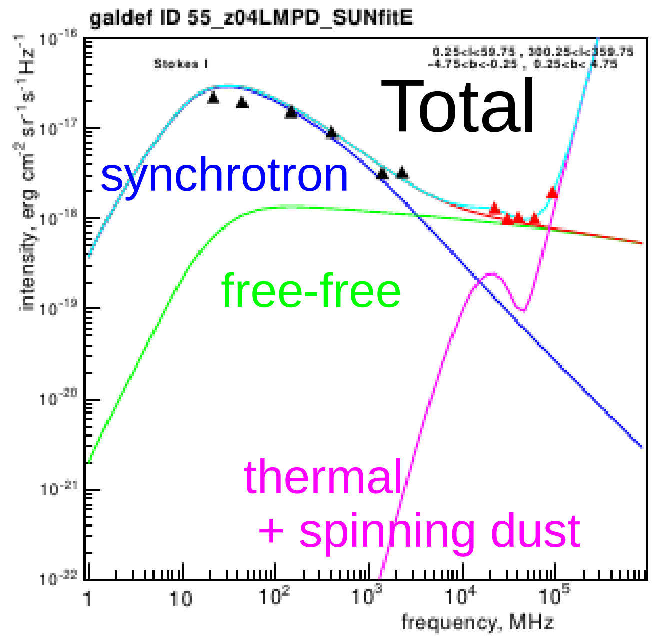
B-fields from literature, basic modifications to fit data.

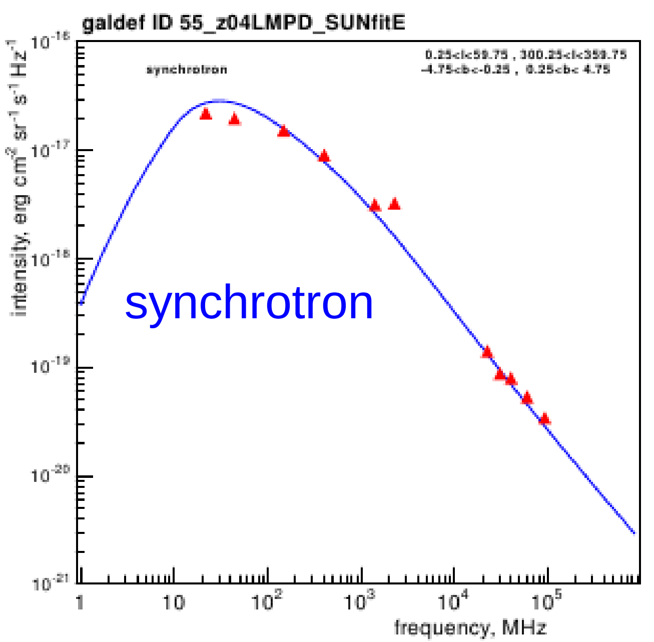
Cosmic-ray electron distribution is a main input from gamma rays.



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.

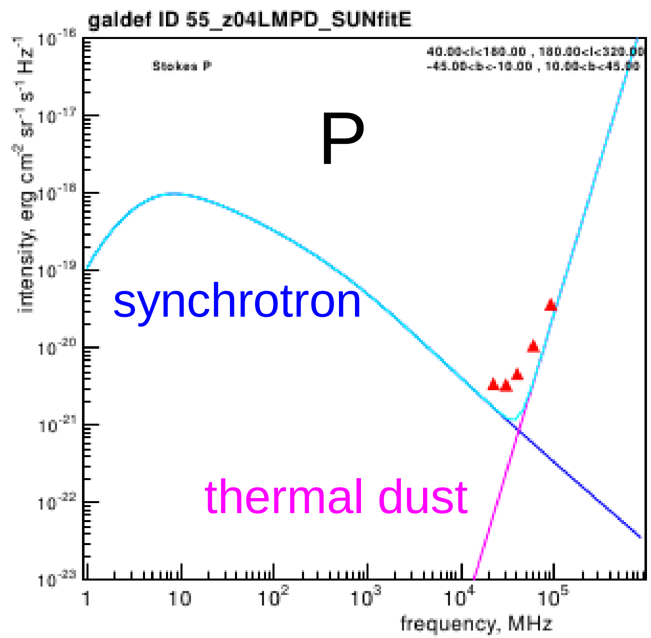


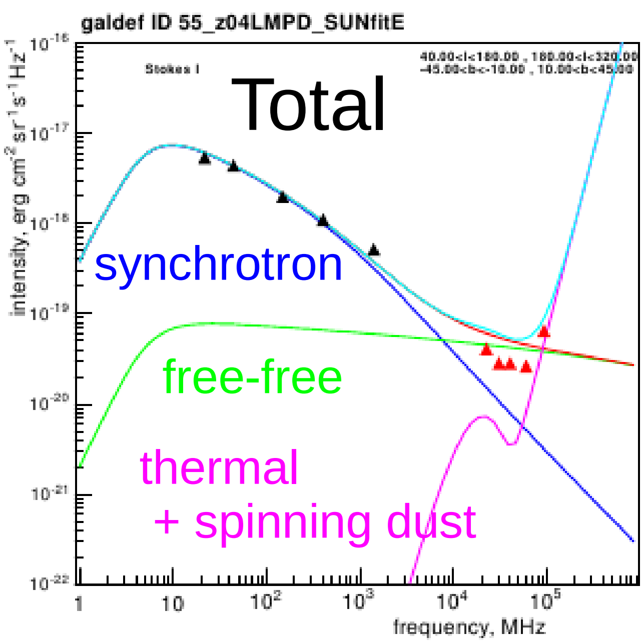


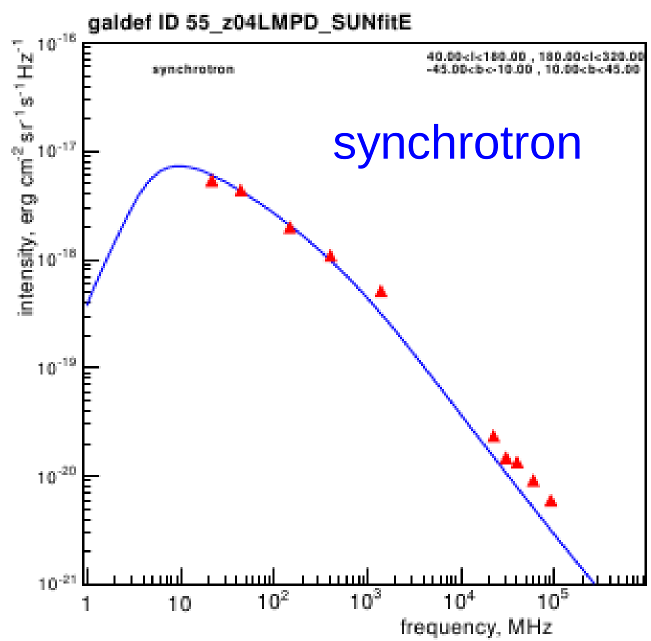


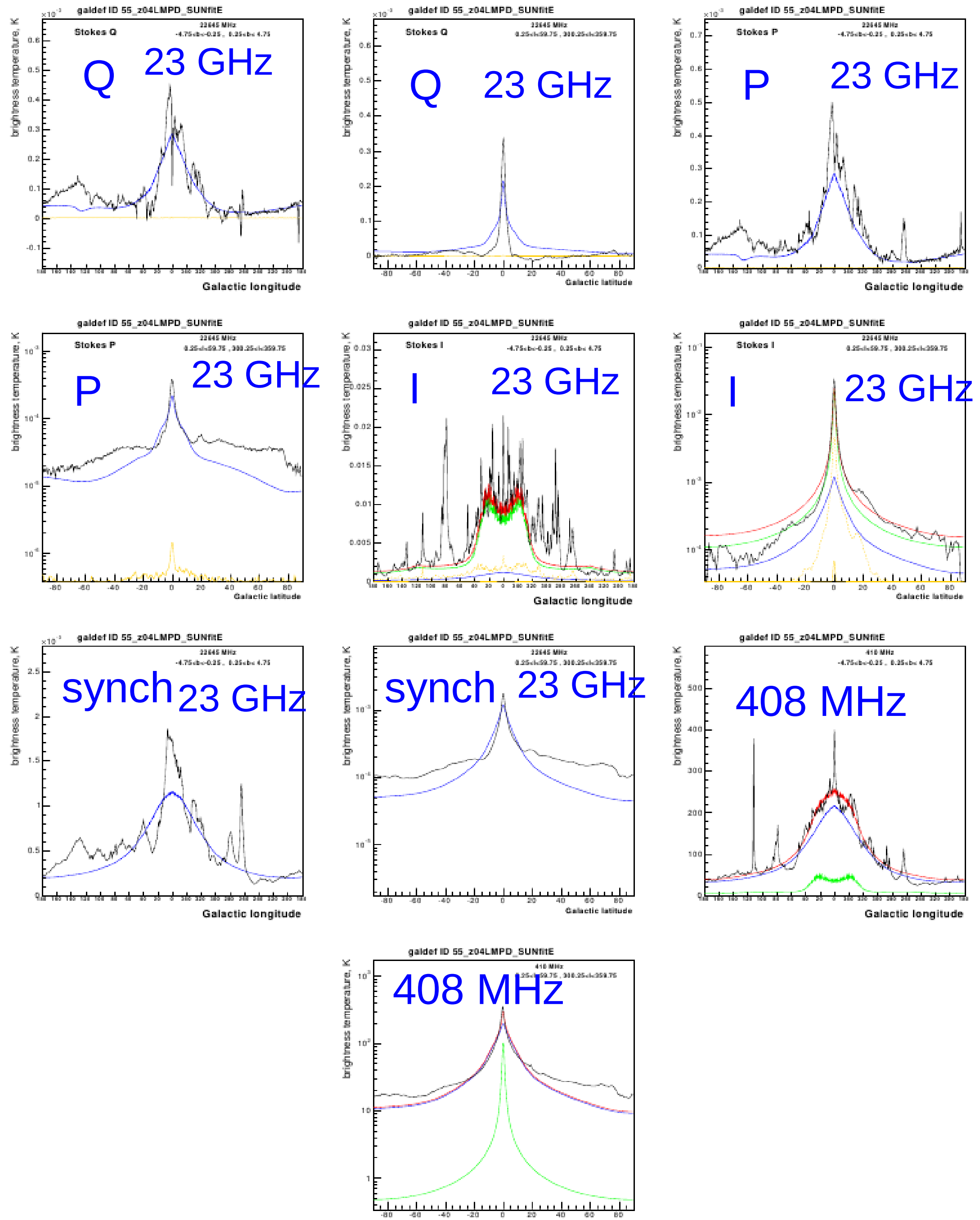
INNER GALAXY

HIGH LATITUDES



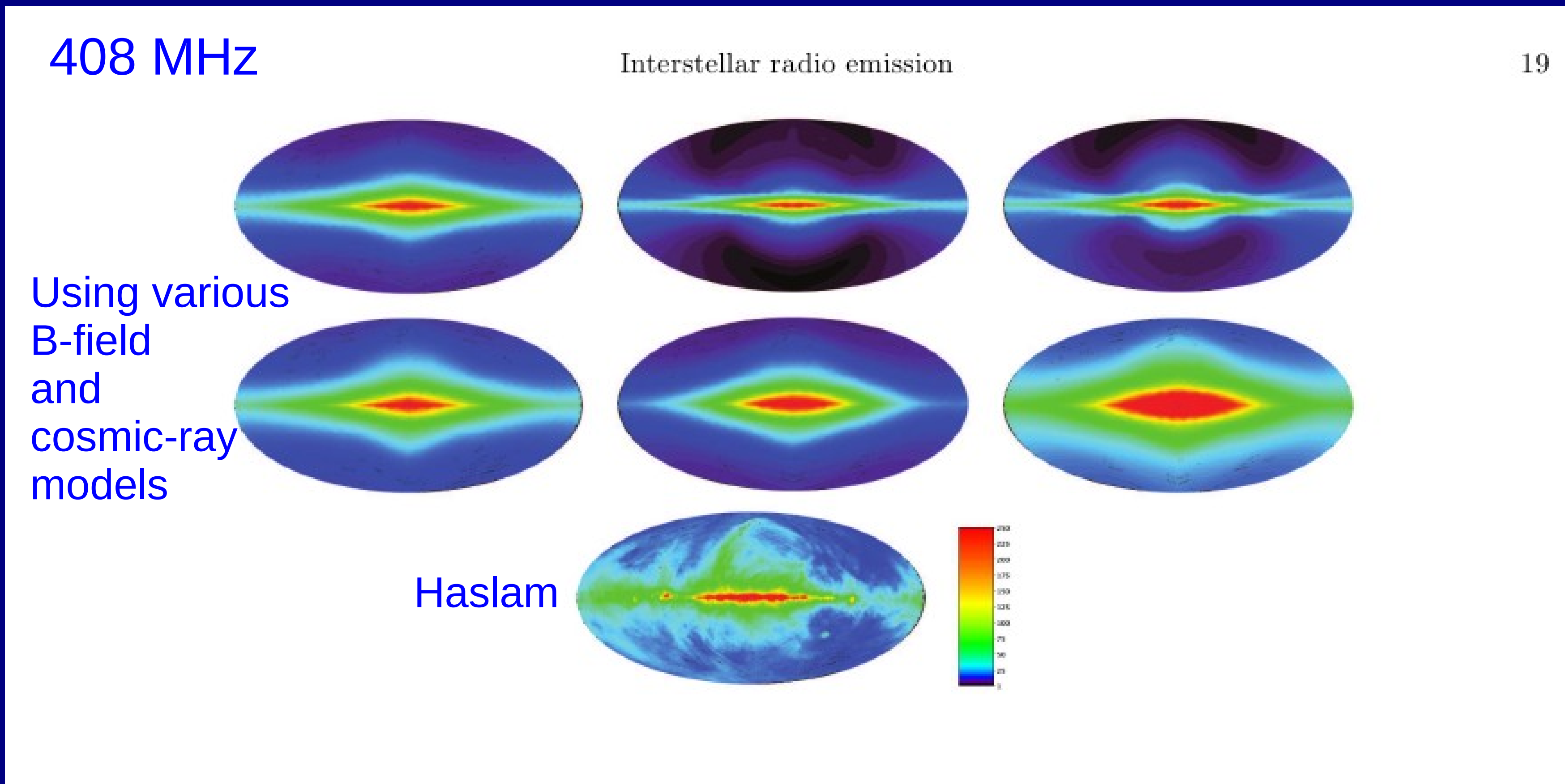






Data: WMAP

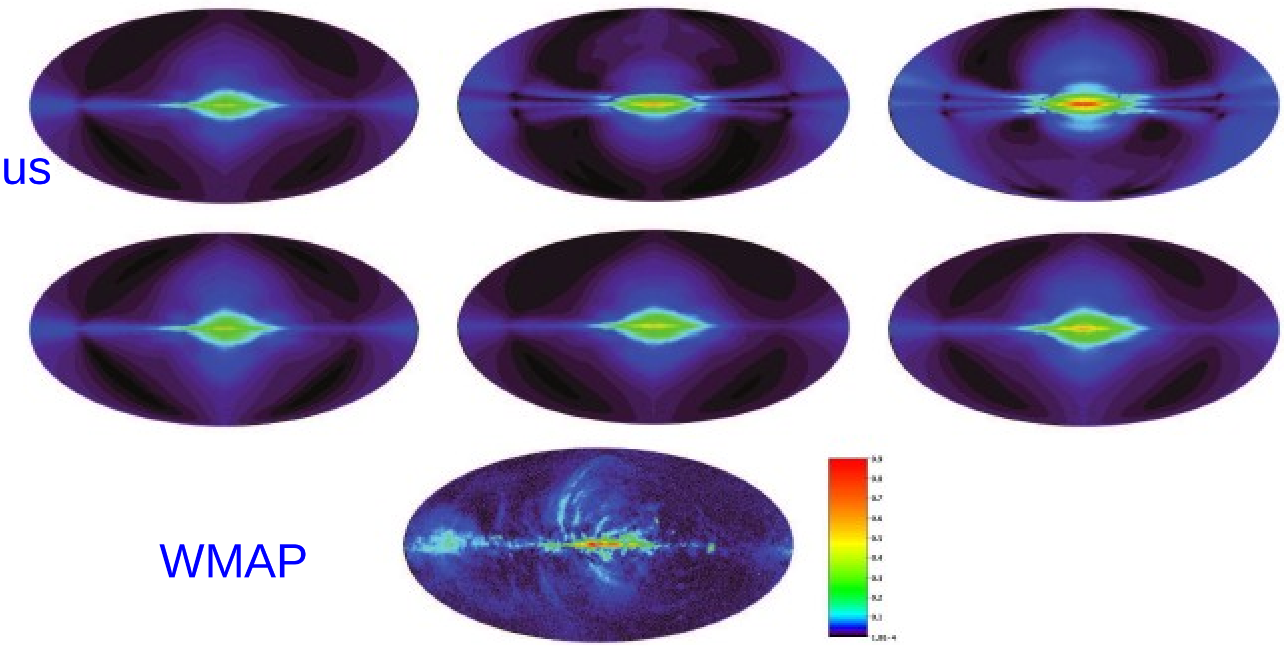
Data: Haslam



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

23 GHz
P

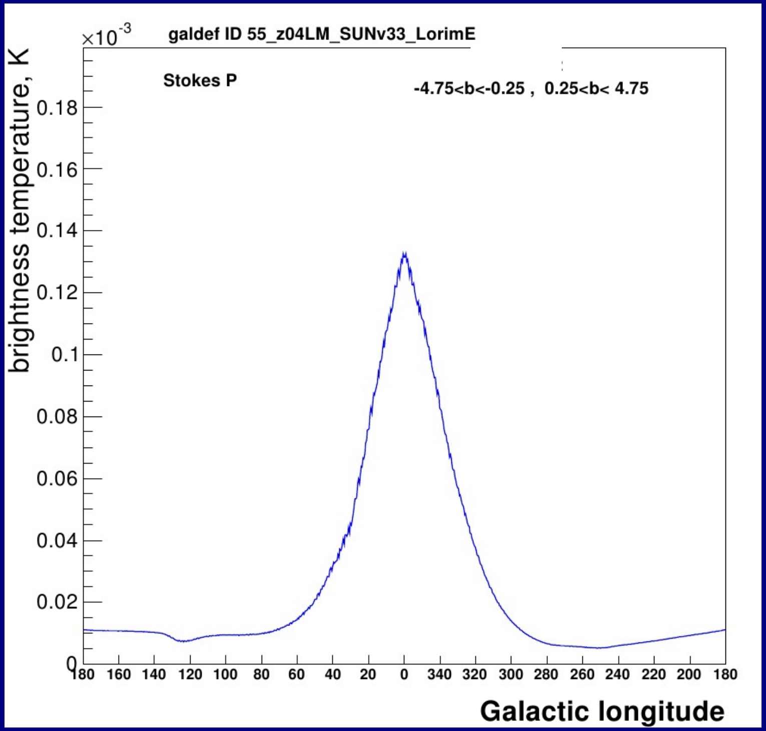
Using various
B-field
and
cosmic-ray
models

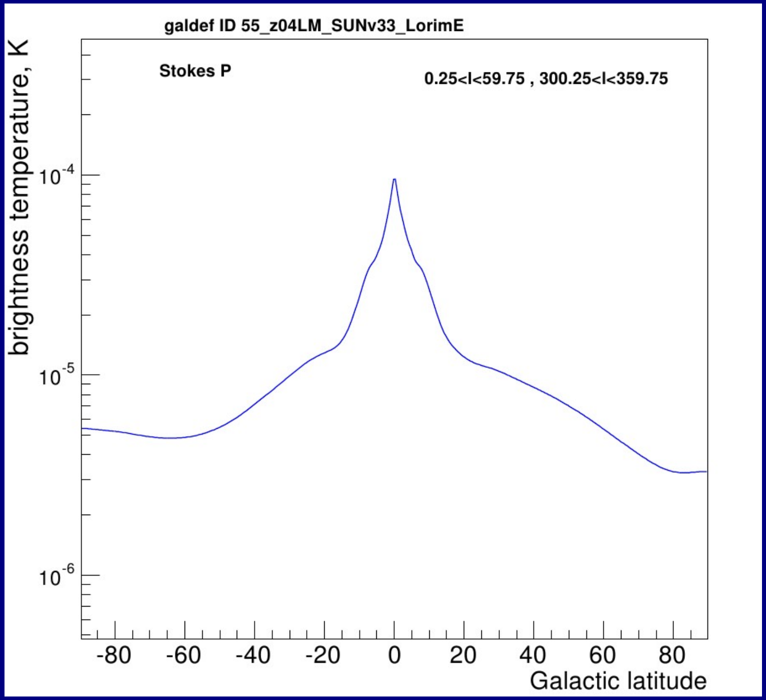


WMAP

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

Illustrative model for 30 GHz Stokes P

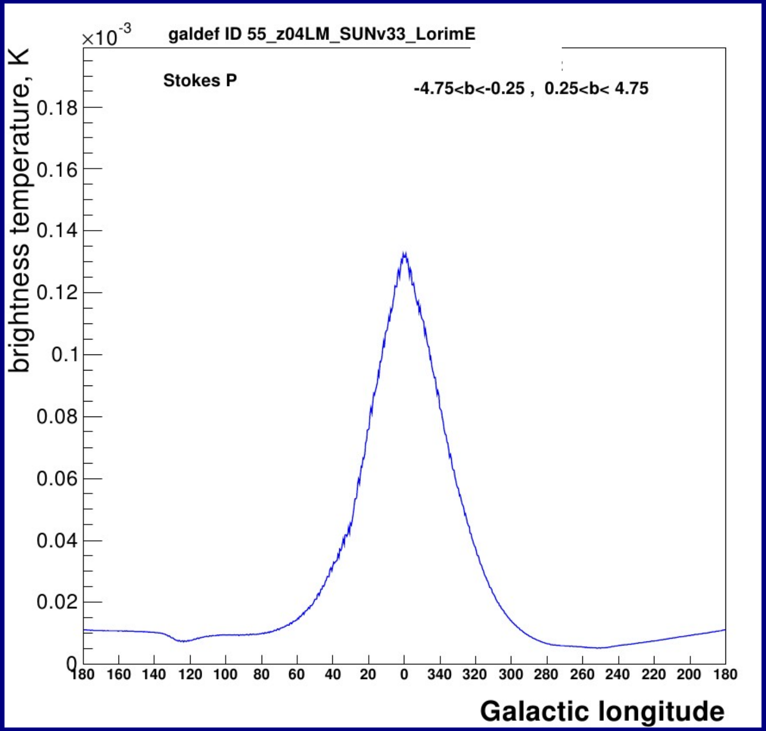


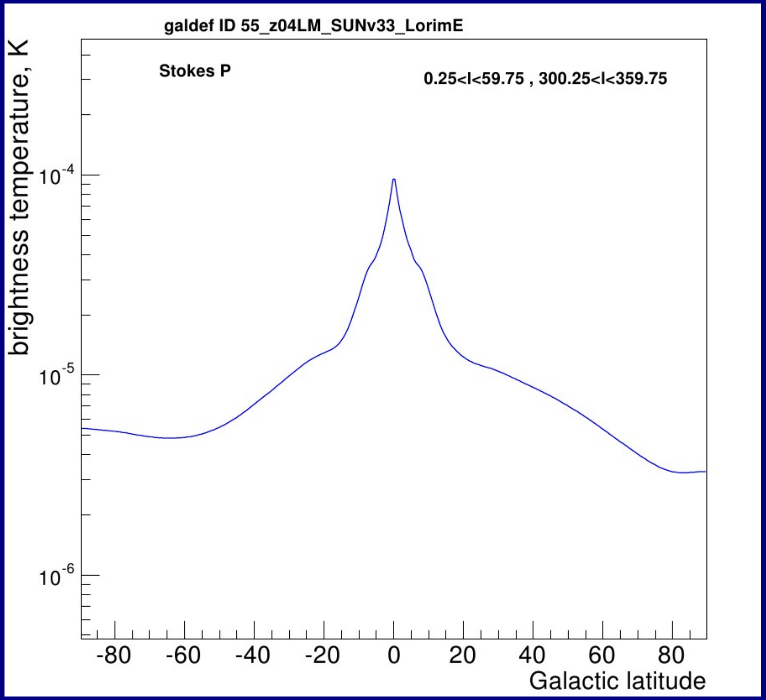


B_reg : Sun et al., scaled
B_rand : double exponential

Cosmic-ray electrons based on gamma rays and locally measured spectrum

Illustrative model for 30 GHz Stokes P

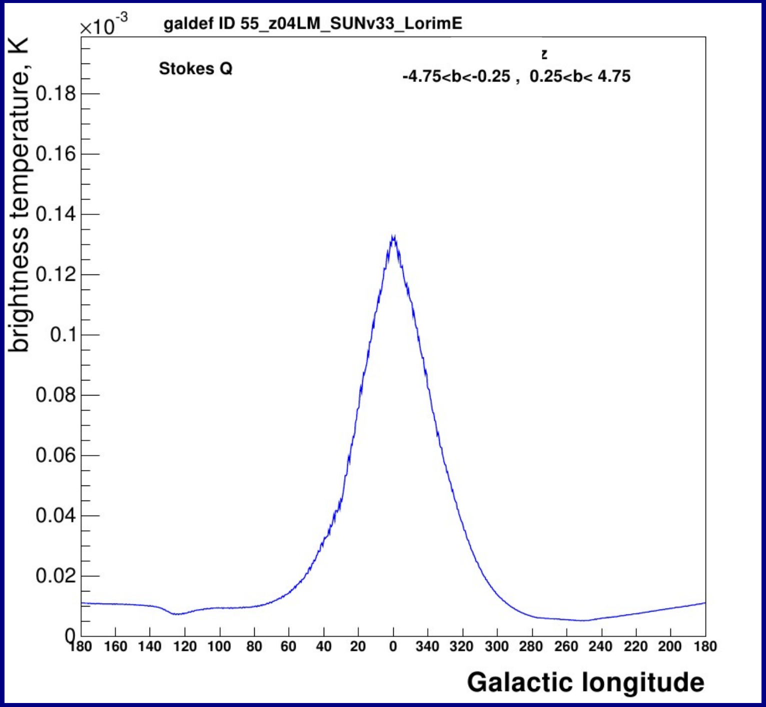


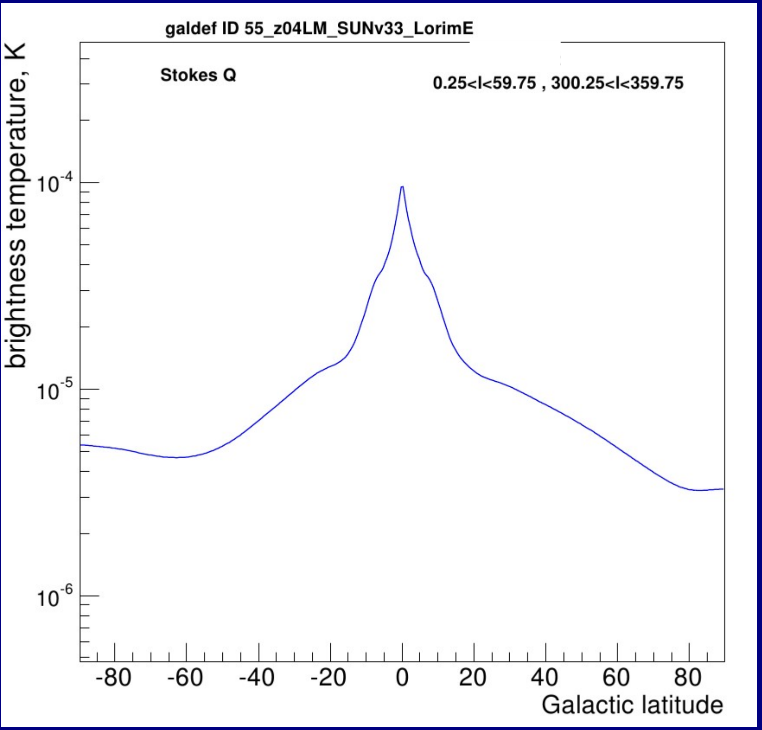


B_reg : Sun et al., scaled
B_rand : double exponential

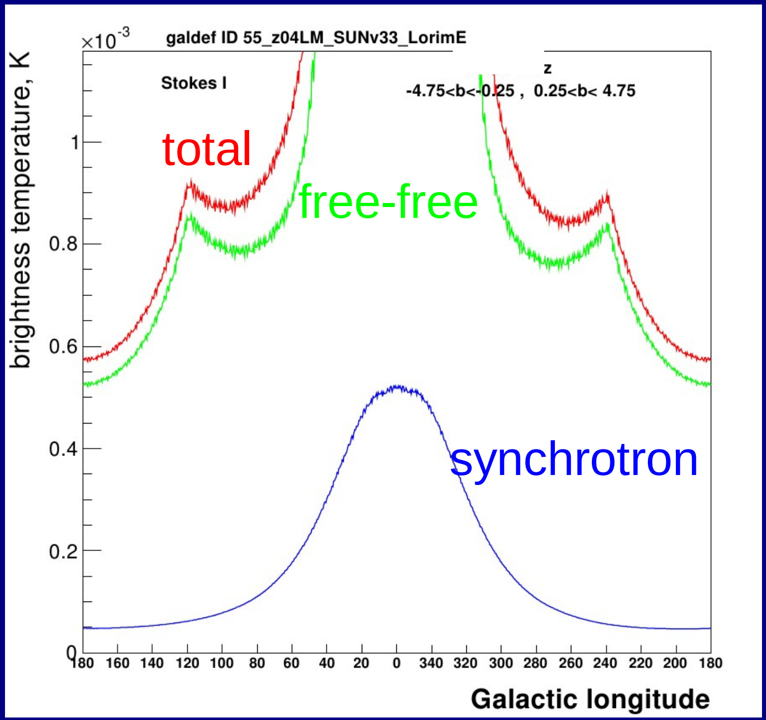
Cosmic-ray electrons based on gamma rays and locally measured spectrum

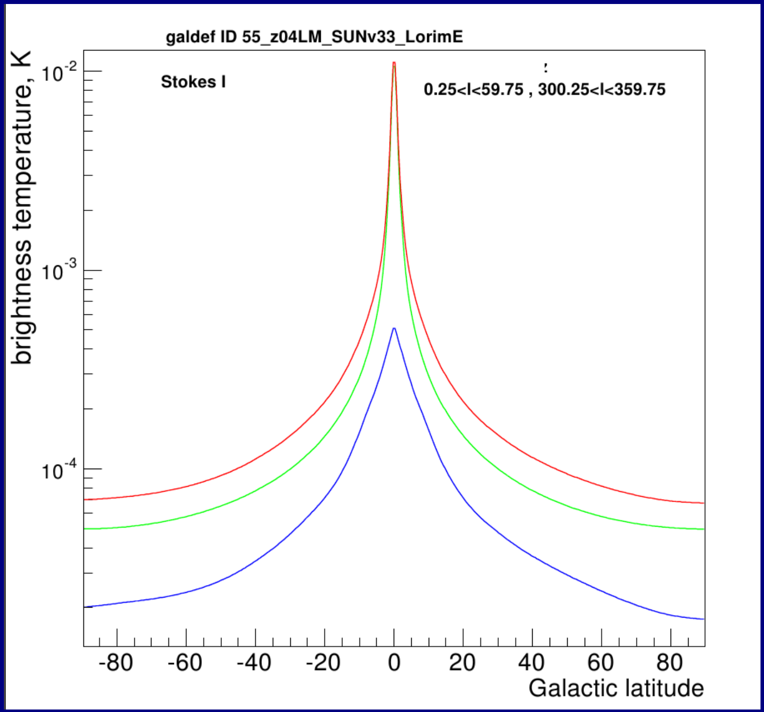
Illustrative model for 30 GHz Stokes Q





Illustrative model for 30 GHz Stokes I





Free-free from NE2001, illustrative

B- field from Orlando & Strong 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
 Attribute to anisotropic field which contributes to synchrotron
 but not to rotation measures.

Random : 6 μG

NOTES on use of GALPROP for synchrotron calculations

1. Computes synchrotron using full formulae and electron + positron spectra.
   no power law or p=-3 approximations (unlike Hammurabi).

2. 3D mode used for B-field and synchrotron.

3. Any B-field model can be incorporated, latest is Jansson & Farrar 2012.

4. Random and regular fields, Stokes Q, U, P, I for any frequencies.

5. No Faraday depolarization (unlike Hammurabi).

6. Only large-scale B, does not attempt Loops and other details.
   No pc-scale random structures (unlike Hammurabi).

7. Electron and positron spectra based on cosmic-ray propagation and locally
   measured spectra, and synchrotron data, also gamma ray constraints.

8. Updated in public domain, http://sourceforge.net/projects/galprop
   (>500 downloads since start in October 2013).

Positrons: excess above secondary production, probably pulsars.
Need to account for in synchrotron! e.g. for spectral variations measured by Planck and accurate future measurements.
Not yet done.

Synchrotron from molecular clouds

Gamma rays from the heliosphere