GALPROP code for CR propagation and diffuse emissions

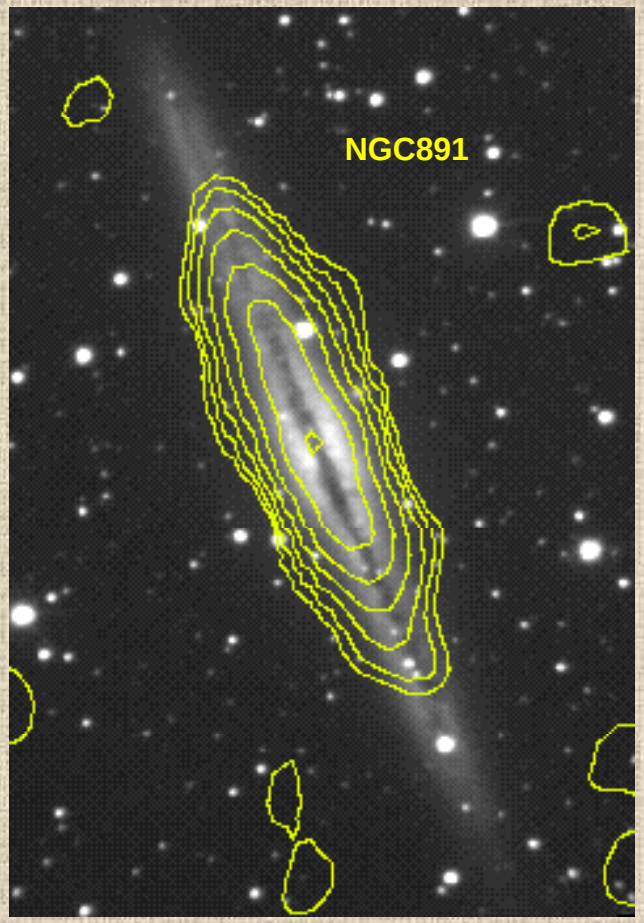
Igor V. Moskalenko
Stanford & KIPAC

Contents

- Introduction to propagation of CRs
- Building a model of the diffuse emission
- Effect of anisotropic inverse Compton scattering
- A view from far far away: multi-wavelength luminosity of the Milky Way
- Bayesian analysis of propagation parameters
- GALPROP WebRun

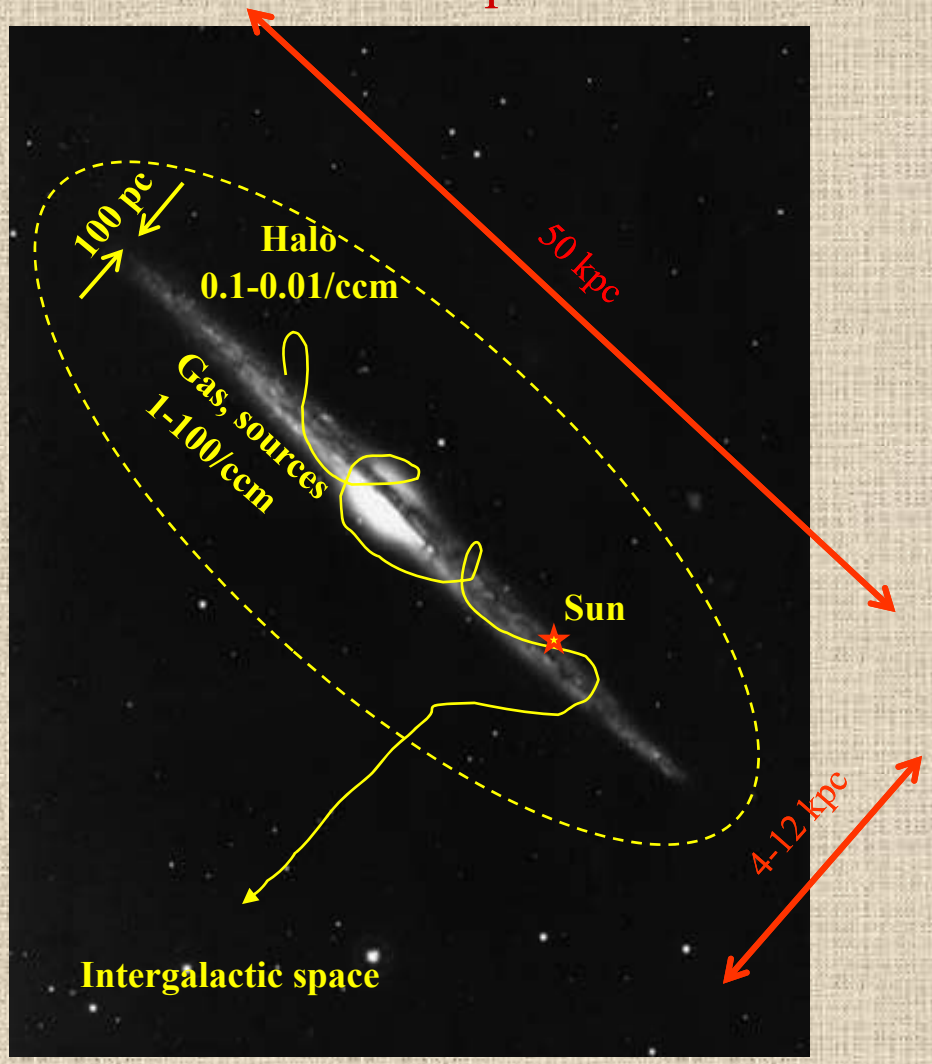
CR Propagation: Milky Way Galaxy

Optical image: Cheng et al. 1992, Brinkman et al. 1993
Radio contours: Condon et al. 1998 AJ 115, 1693



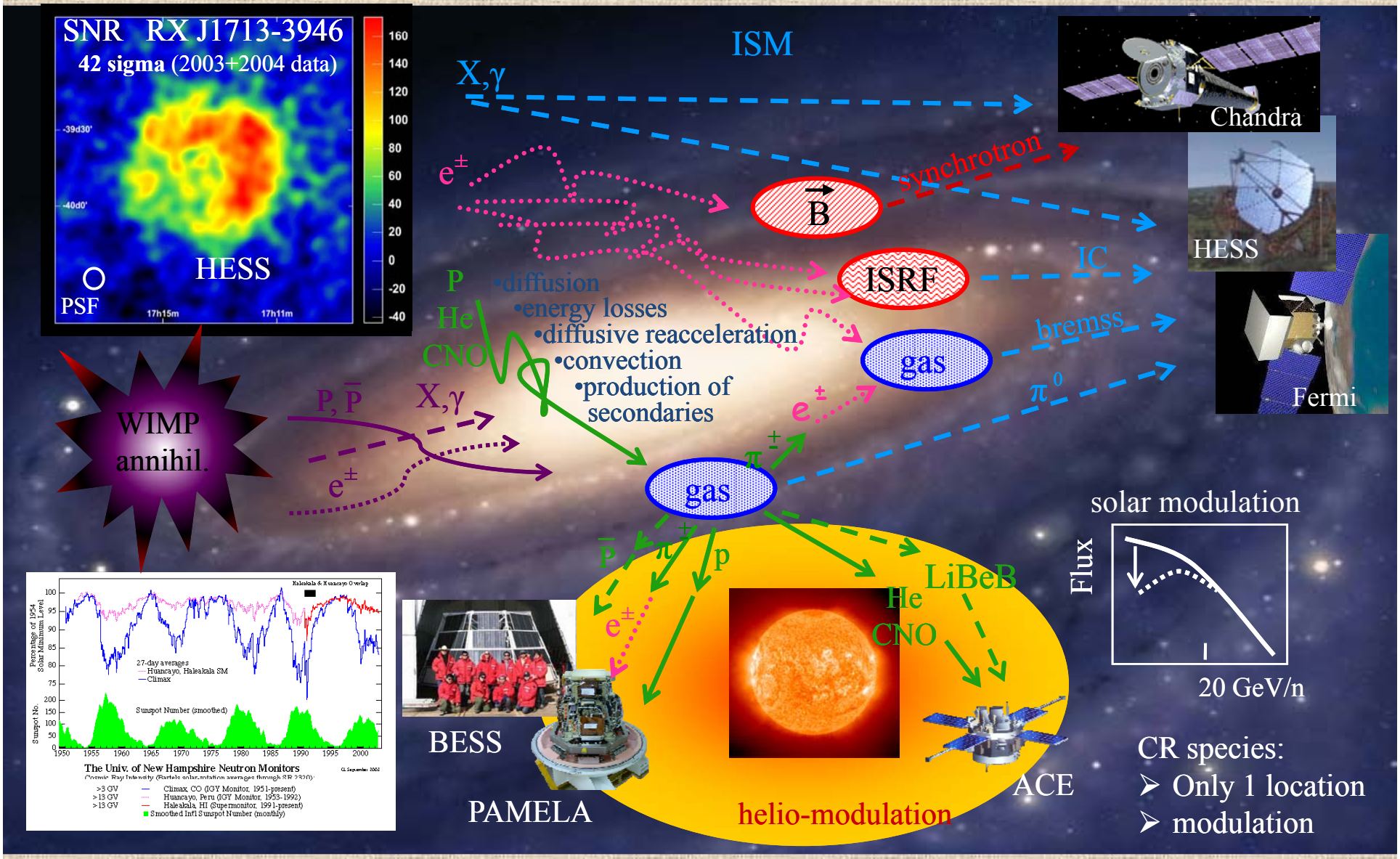
R Band image of NGC891
1.4 GHz continuum (NVSS), 1,2,…64 mJy/ beam

1 kpc ~ 3×10^{21} cm



"Flat halo" model (Ginzburg & Ptuskin 1976)

CRs in the Interstellar Medium



Components of realistic CR propagation model

- Detailed gas distribution (energy losses, π^0, bremsstrahlung)
- Interstellar radiation field (IC, $e^{\pm}$ energy losses)
- Nuclear & particle production cross sections & the reaction network
- Gamma-ray production: bremsstrahlung, IC, π^0
- Energy losses: ionization, Coulomb, brems, IC, synchrotron
- Solve transport equations for all CR species
- Derive the propagation parameters

Transport Equations ~90 (no. of CR species)

$$\frac{\partial \psi(\vec{r}, p, t)}{\partial t} = q(\vec{r}, p)$$ sources (SNR, nuclear reactions…)

diffusion $$+ \vec{\nabla} \cdot [D_{xx} \vec{\nabla} \psi - \vec{V} \psi]$$

diffusive reacceleration
(diffusion in the momentum space)
$$+ \frac{\partial}{\partial p}\left[p^2 D_{pp} \frac{\partial}{\partial p} \frac{\psi}{p^2} \right]$$

convection
(Galactic wind)

E-loss $$- \frac{\partial}{\partial p}\left[\frac{dp}{dt}\psi - \frac{1}{3} p \vec{\nabla} \cdot \vec{V} \psi \right]$$

fragmentation $$- \frac{\psi}{\tau_f} - \frac{\psi}{\tau_d}$$ radioactive decay

+ boundary conditions

$\psi(\mathbf{r},p,t)$ – density per total momentum

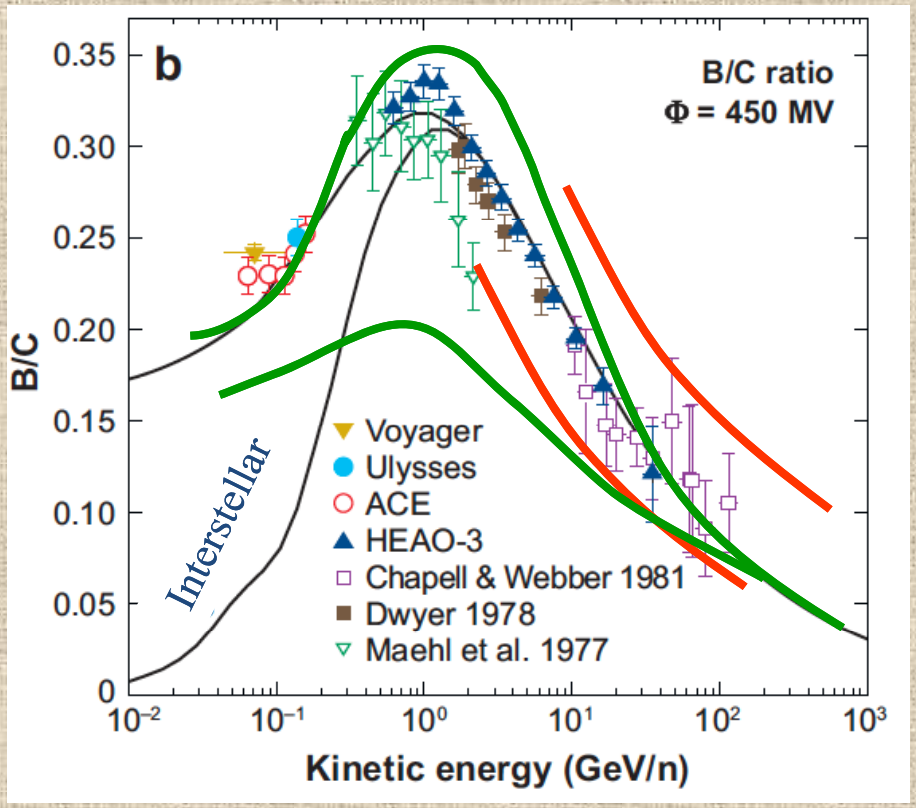
Secondary/primary nuclei ratio & CR propagation

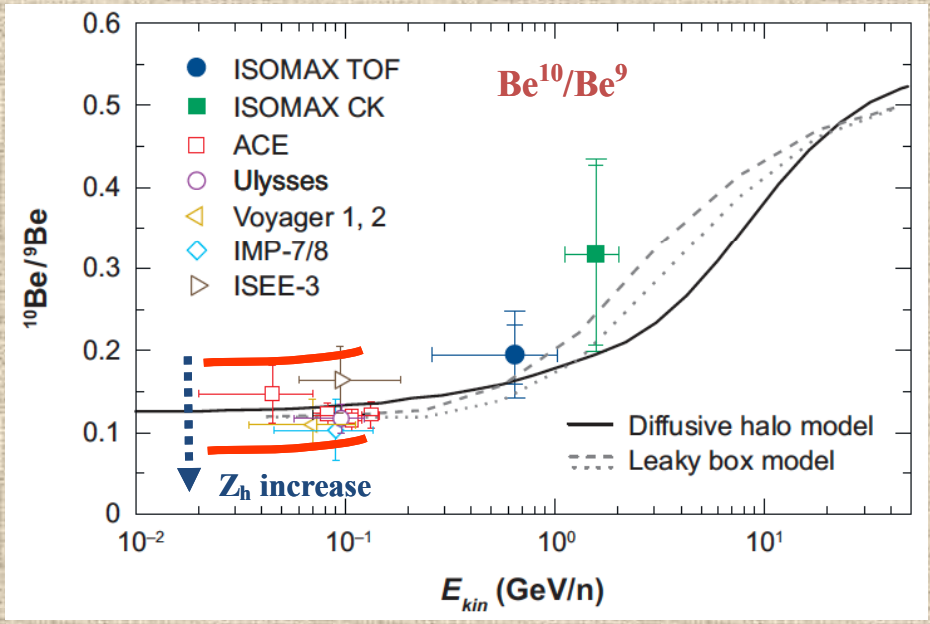
Typical parameters (model-dependent):

$D \sim 10^{28} (\rho/1\ GV)^{\alpha}\ cm^2/s$

$\alpha \approx 0.3\text{-}0.6$

$Z_h \sim 4\text{-}6$ kpc; $V_A \sim 30$ km/s

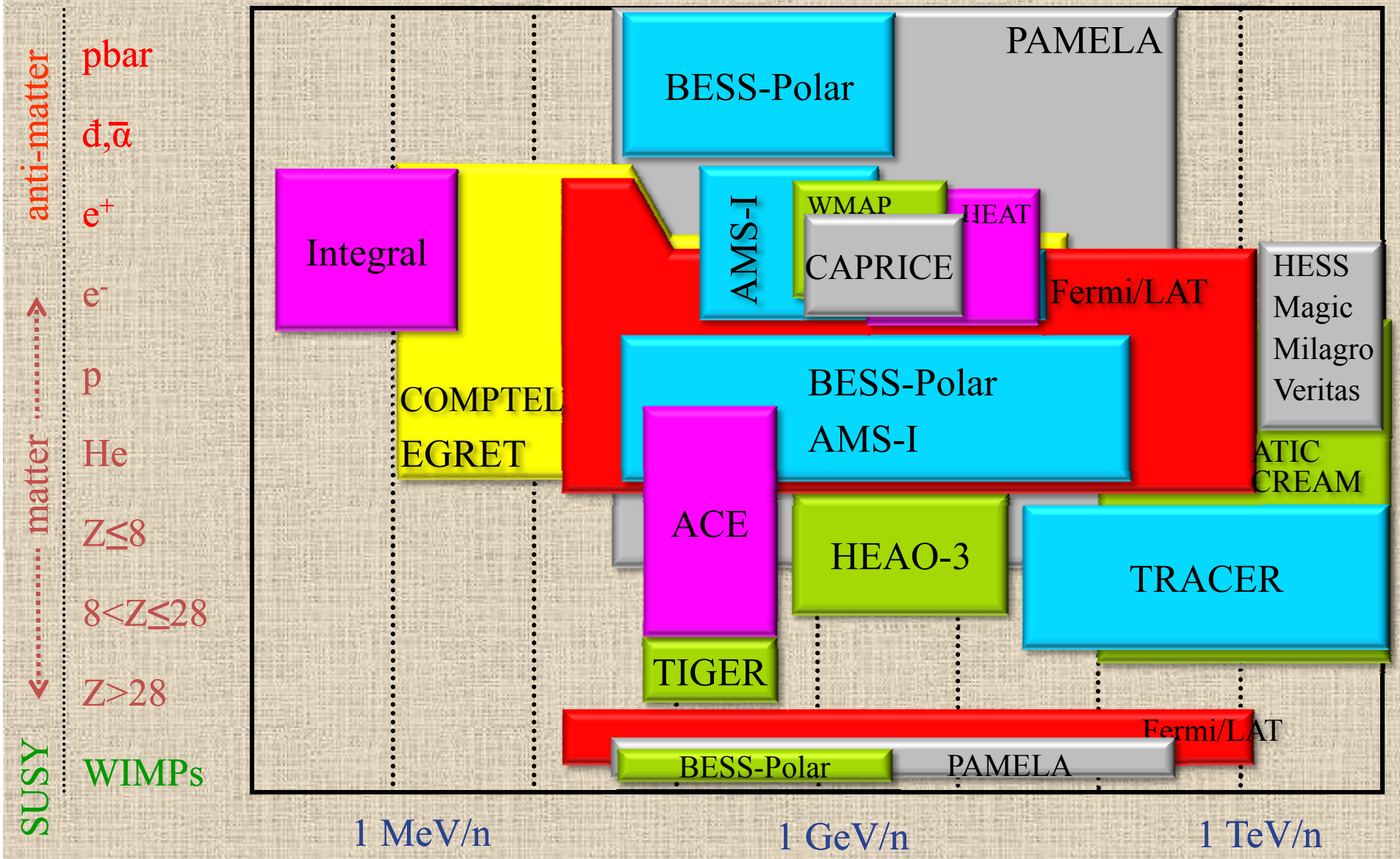




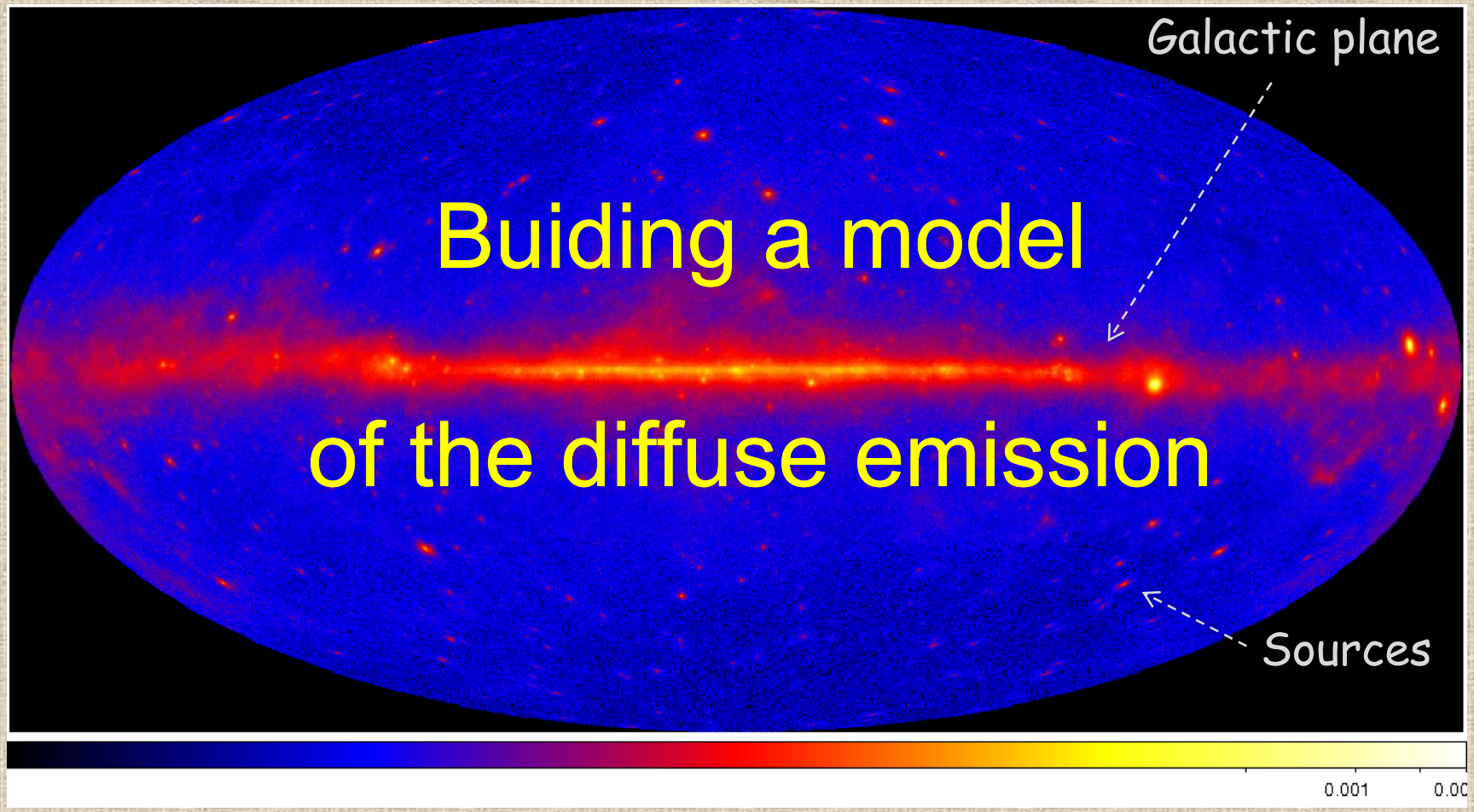
Using secondary/primary nuclei ratio (B/C) & radioactive isotopes (e.g. Be^{10}):

- Diffusion coefficient and its index
- Galactic halo size Z_h
- Propagation mode and its parameters (e.g., reacceleration V_A, convection V_z)
- Propagation parameters are model-dependent

Relevant CR and gamma-ray (also CR!) instruments



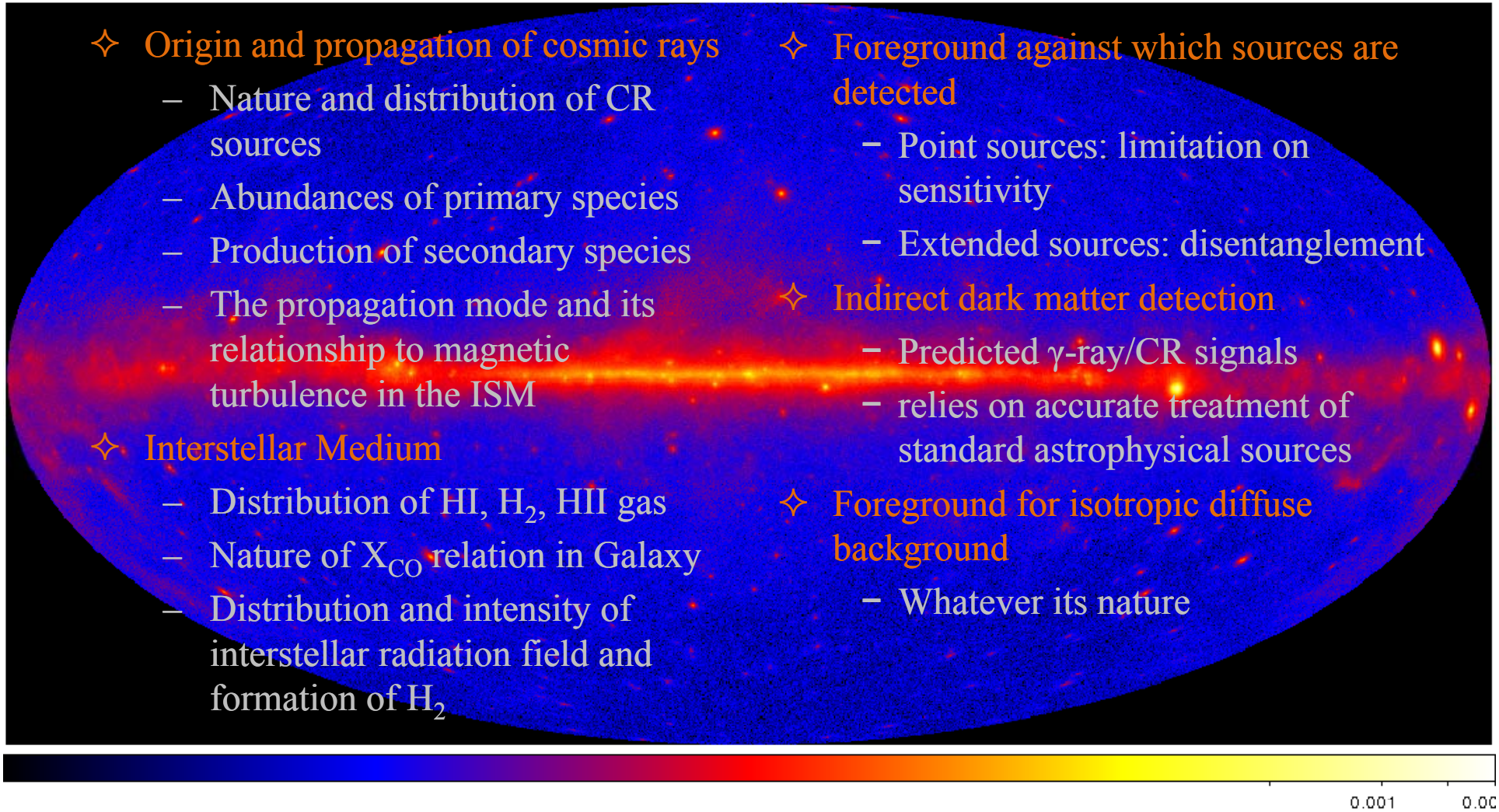
Fermi-LAT 1-year Gamma-Ray Skymap



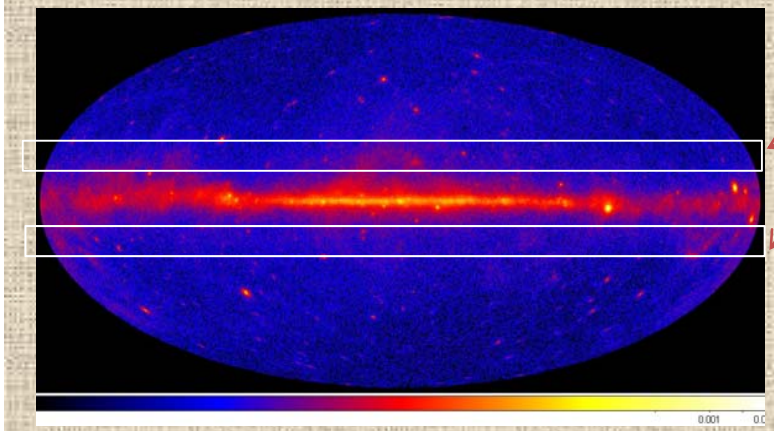
Dominating source of gamma rays on the sky. Produced by CR interactions with interstellar gas and radiation field – the so-called diffuse emission. The diffuse Galactic gamma rays are the tracers of CR proton and electron spectra throughout the Galaxy.

Diffuse Galactic Gamma-ray Emission

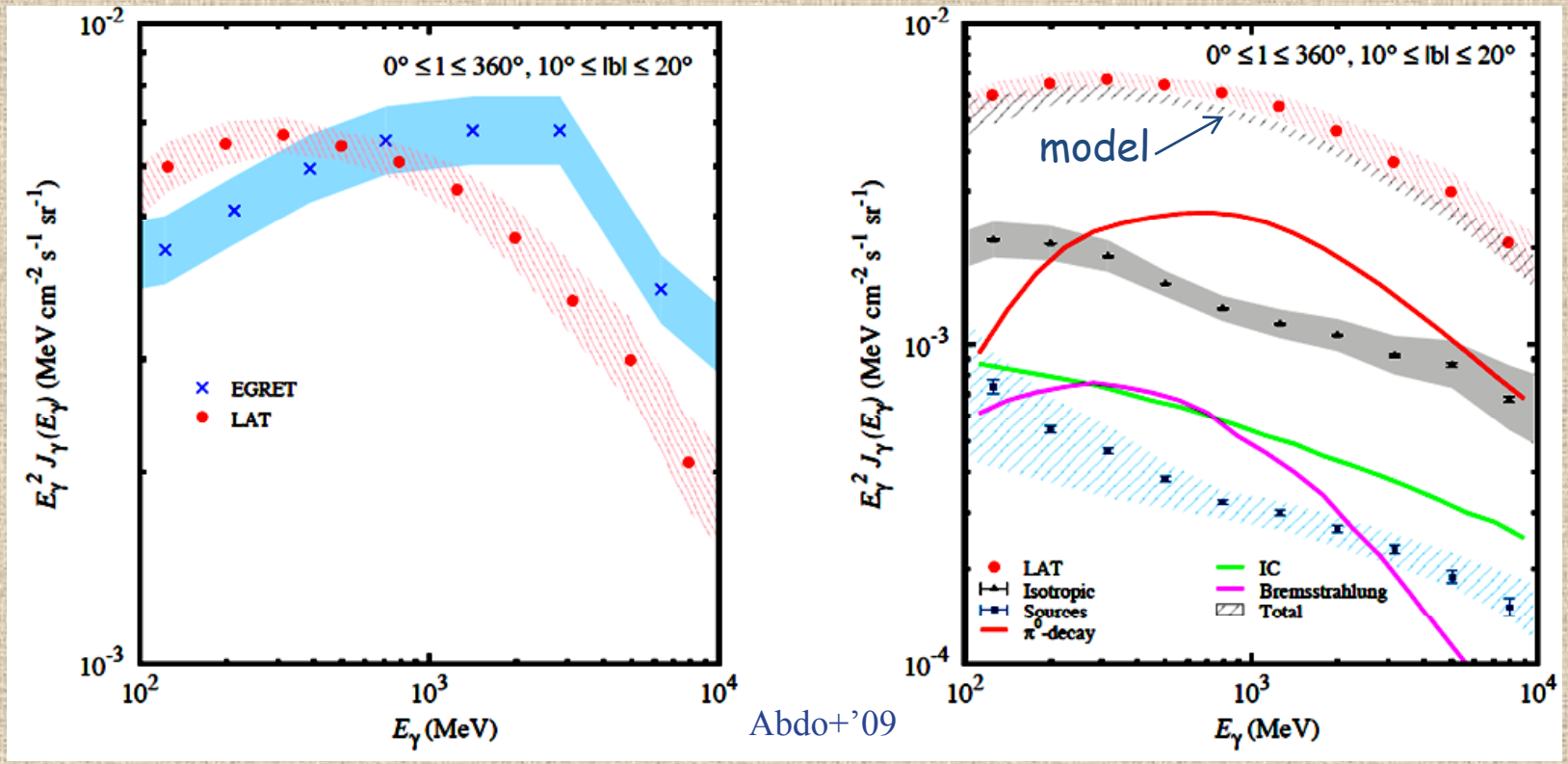
- Origin and propagation of cosmic rays
  - Nature and distribution of CR sources
  - Abundances of primary species
  - Production of secondary species
  - The propagation mode and its relationship to magnetic turbulence in the ISM
- Interstellar Medium
  - Distribution of HI, H_2, HII gas
  - Nature of X_{CO} relation in Galaxy
  - Distribution and intensity of interstellar radiation field and formation of H_2
- Foreground against which sources are detected
  - Point sources: limitation on sensitivity
  - Extended sources: disentanglement
- Indirect dark matter detection
  - Predicted γ-ray/CR signals
  - relies on accurate treatment of standard astrophysical sources
- Foreground for isotropic diffuse background
  - Whatever its nature



Fermi-LAT: diffuse gammas



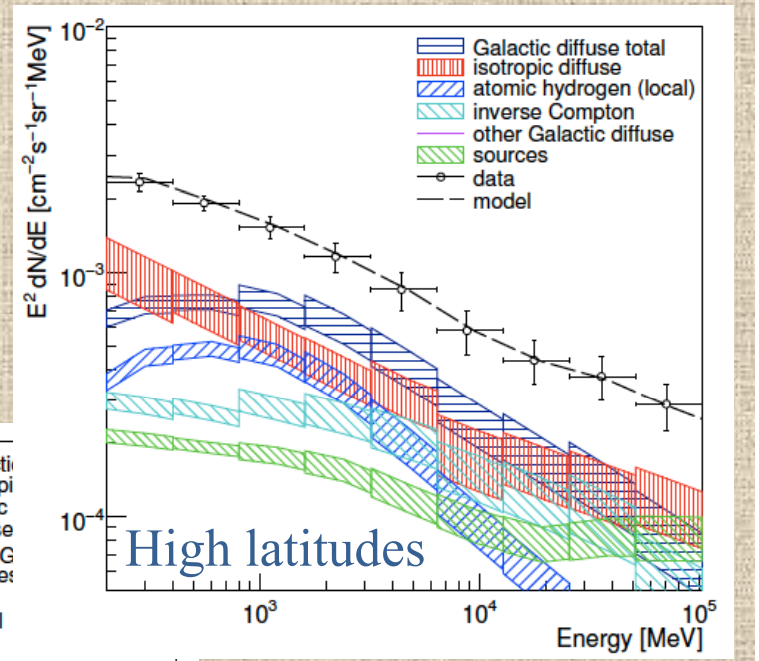
- Conventional GALPROP model is in agreement with the Fermi-LAT data at mid-latitudes (mostly local emission)
- The EGRET "GeV excess" is not confirmed
- This means that we understand the basics of cosmic ray propagation and calculate correctly interstellar gas and radiation field, at least, locally

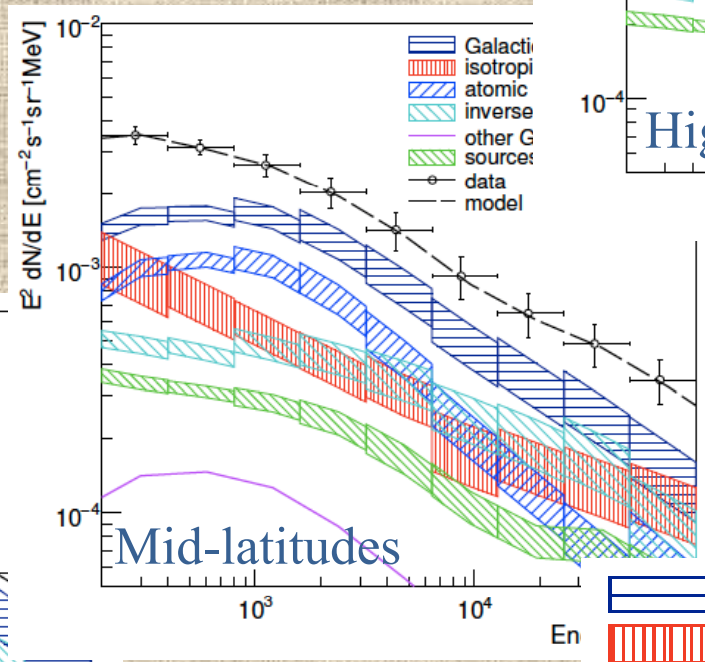


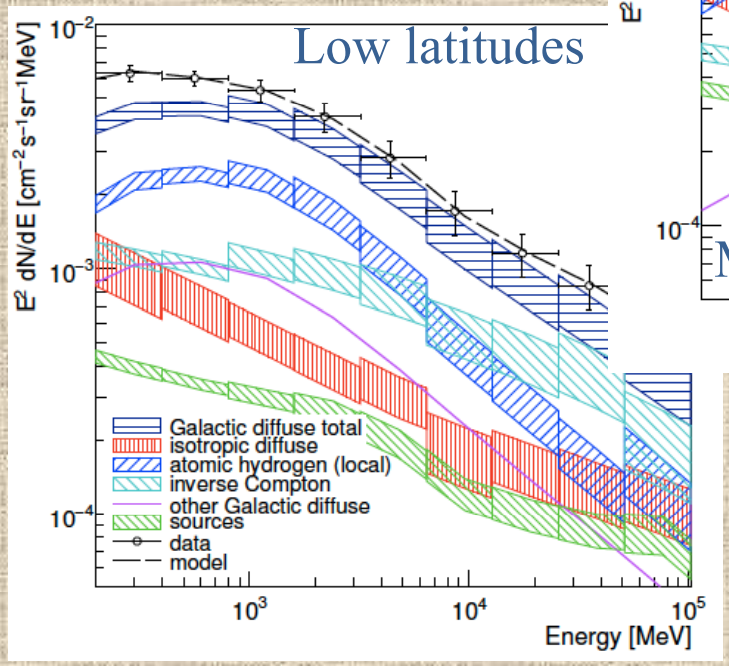
Abdo+'09

Diffuse emission at low to high Galactic latitudes

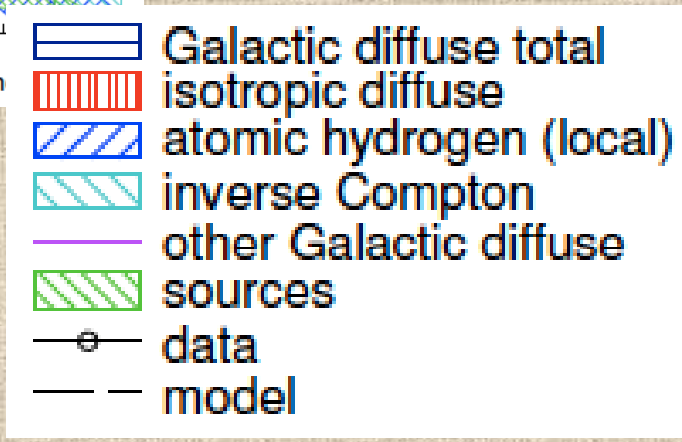
- Pion-decay and inverse Compton emission are two dominant components – allow us to probe the average CR proton and electron spectra along the line of sight
- The GALPROP predictions agree well with the LAT data



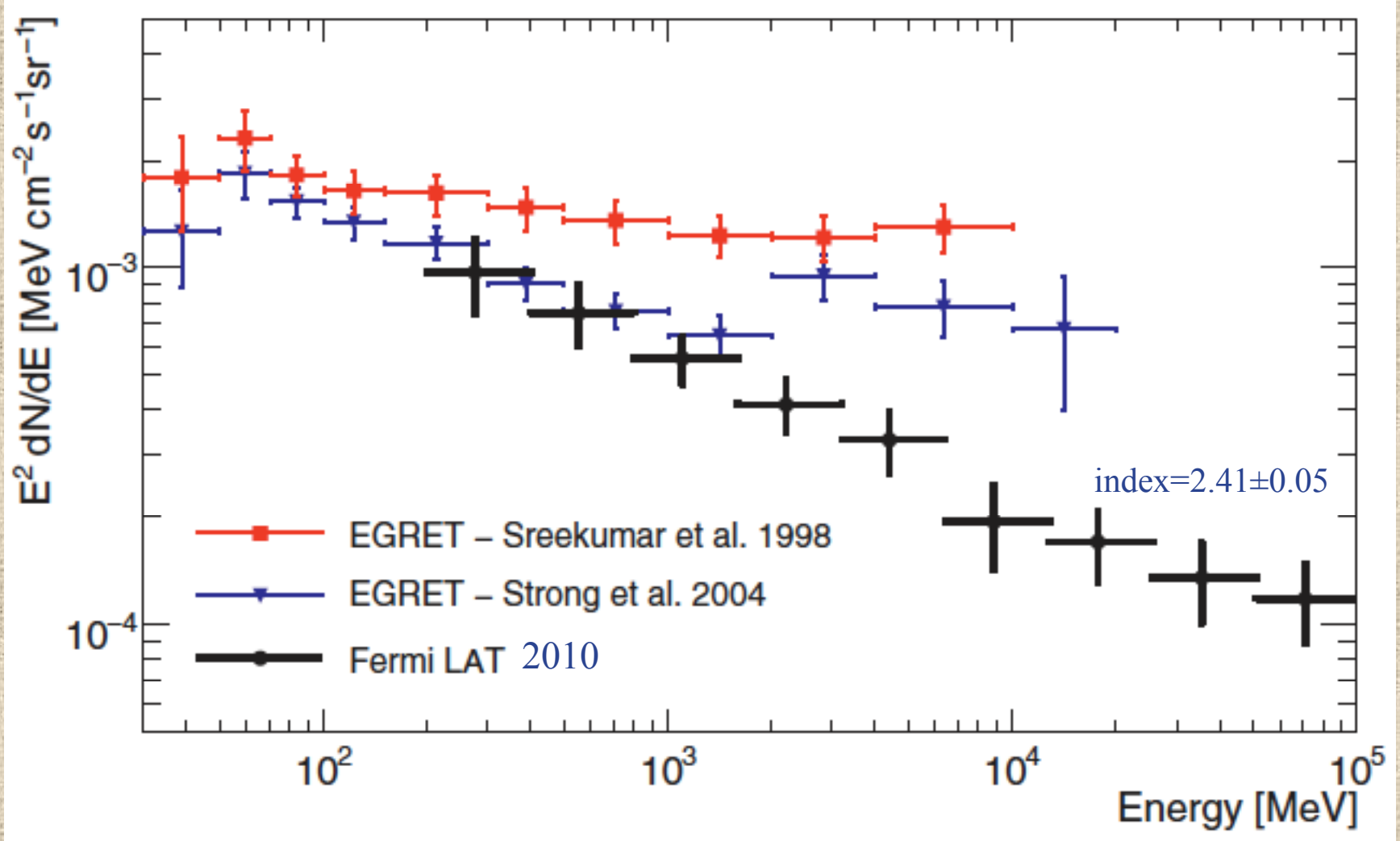




Abdo+'10

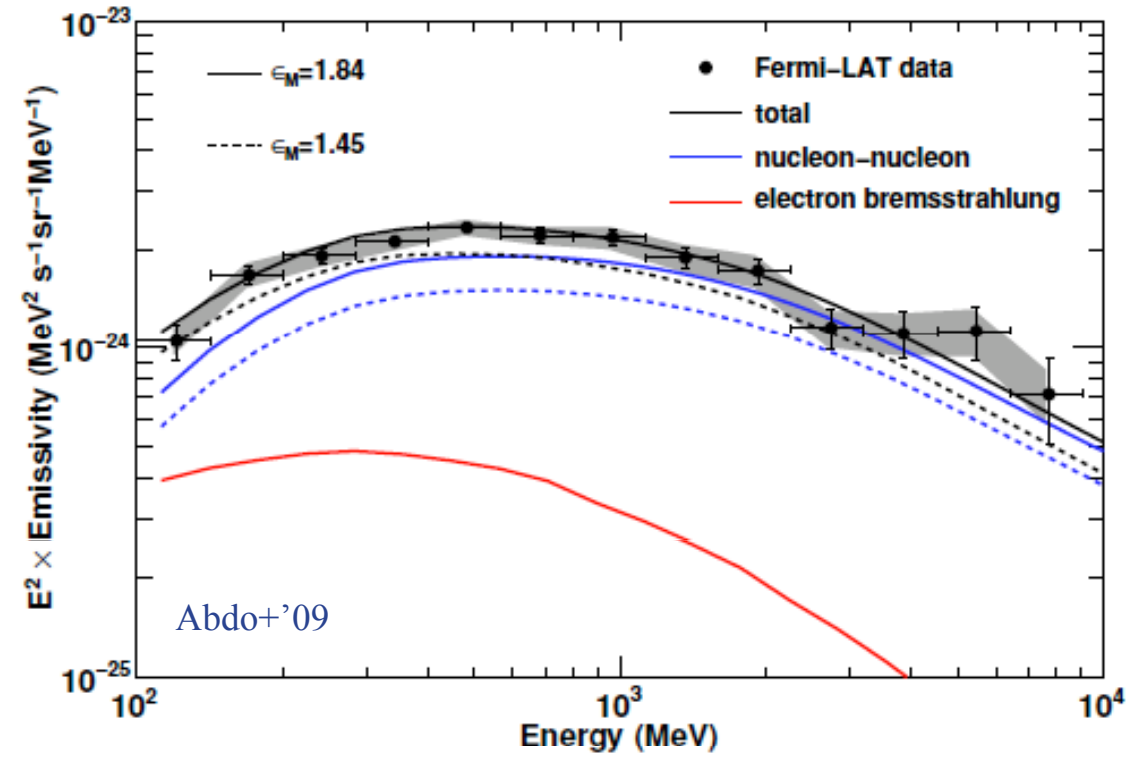


Spectrum of isotropic diffuse γ-ray emission



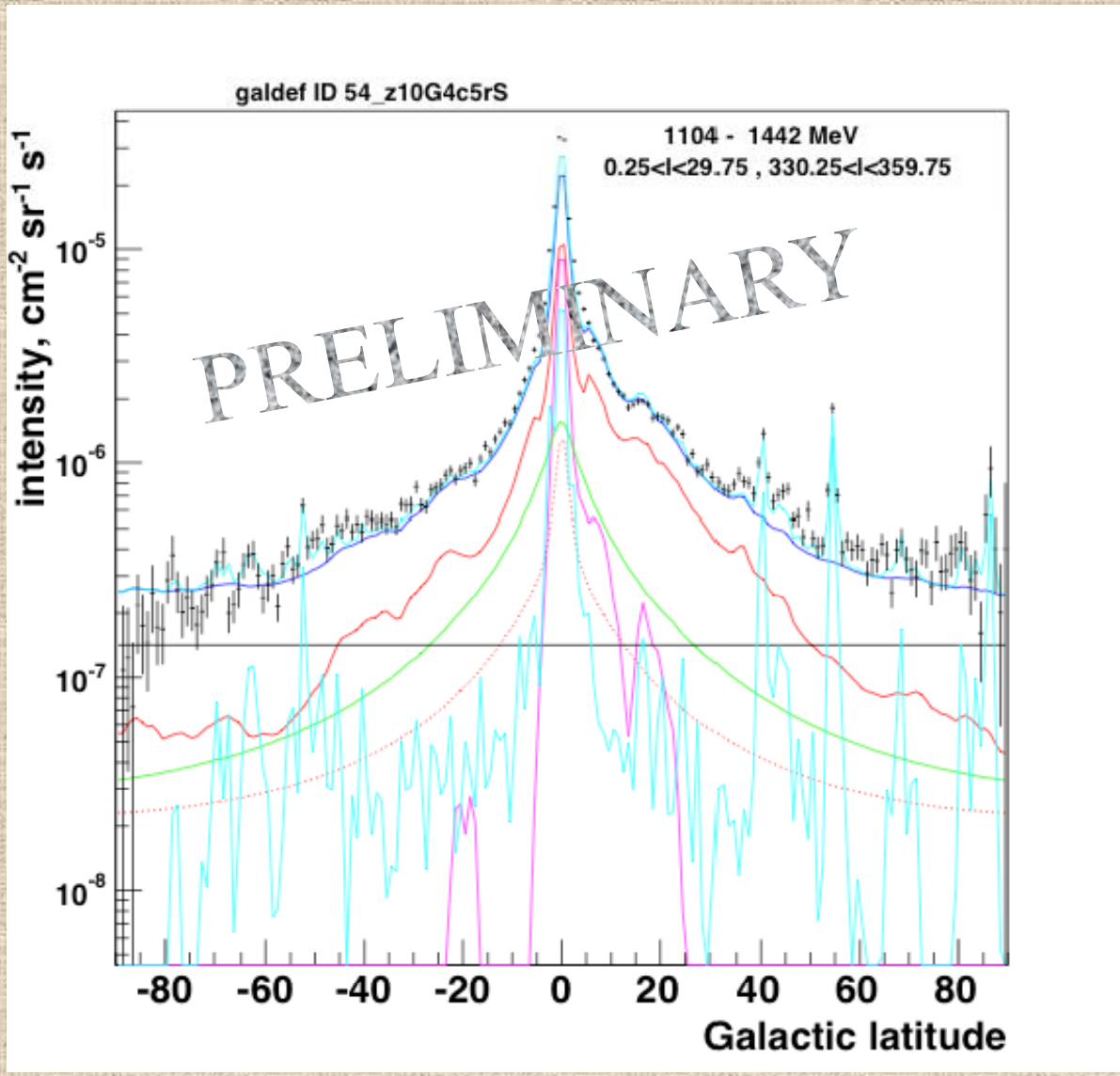
- Accessed every 6 years (1998, 2004, 2010, 2016,…)
- Time-dependent: increasingly steepens with time…

Diffuse Gammas – Local Spectrum



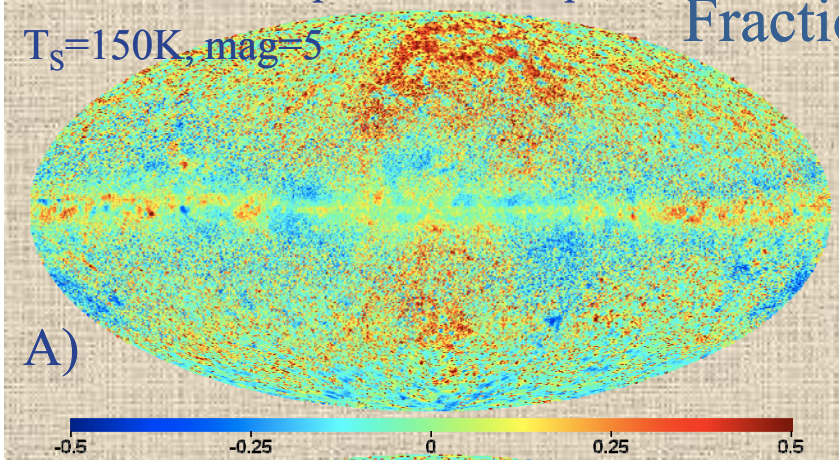
- Mid-latitudes: (200°<l<260°, 22°<b<60°)
- The spectrum of the local atomic gas emission agrees well with the GALPROP predictions
- Confirms that the local proton spectrum is similar to that derived from direct measurements

Example: latitude profile of the inner Galaxy



Fractional count residuals: (theory-data)/data

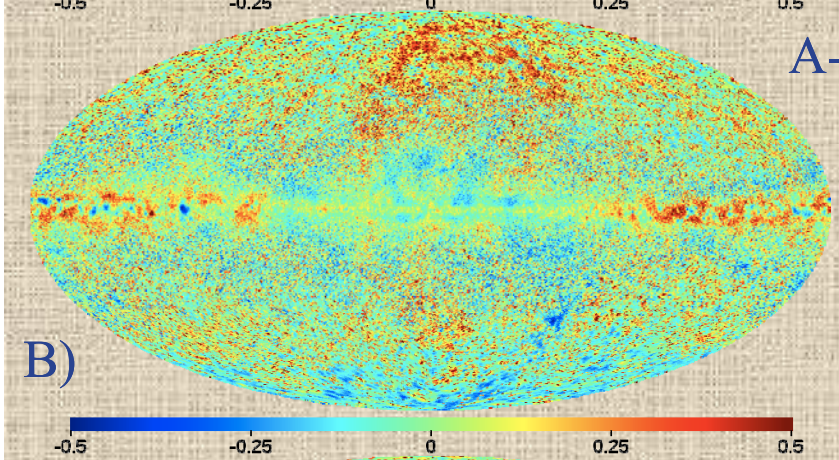
srs=SNR, Zh=4kpc, Rmax=20kpc,
T_S=150K, mag=5

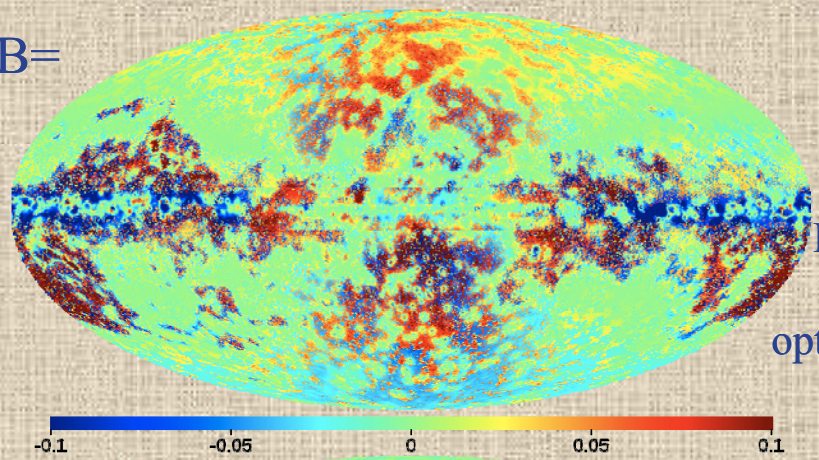


- Agreement for models is overall good but features in residuals are at ~ % level
- Difference between illustrative models due to variations of model parameters

difference between residuals

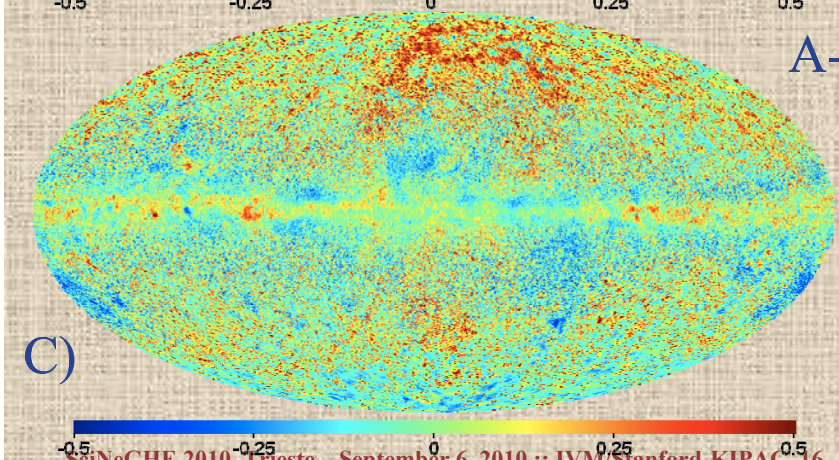
A-B=

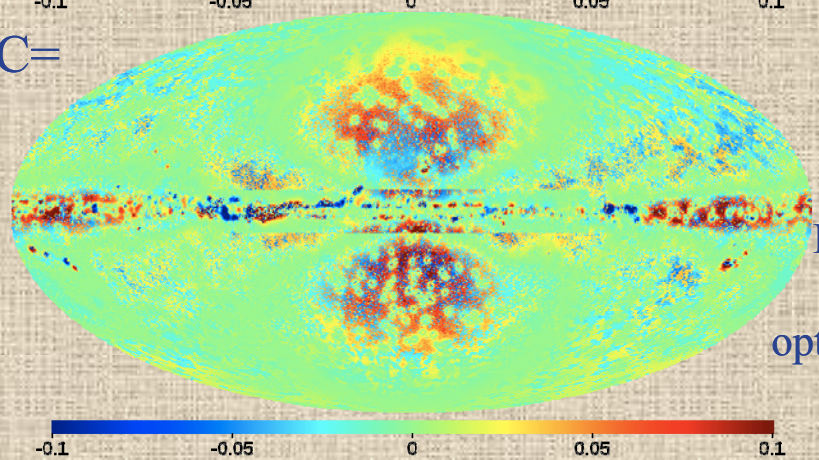




srs=Lorimer,
Zh=6kpc,
Rmax=20kpc,
mag=5,
optically thin HI

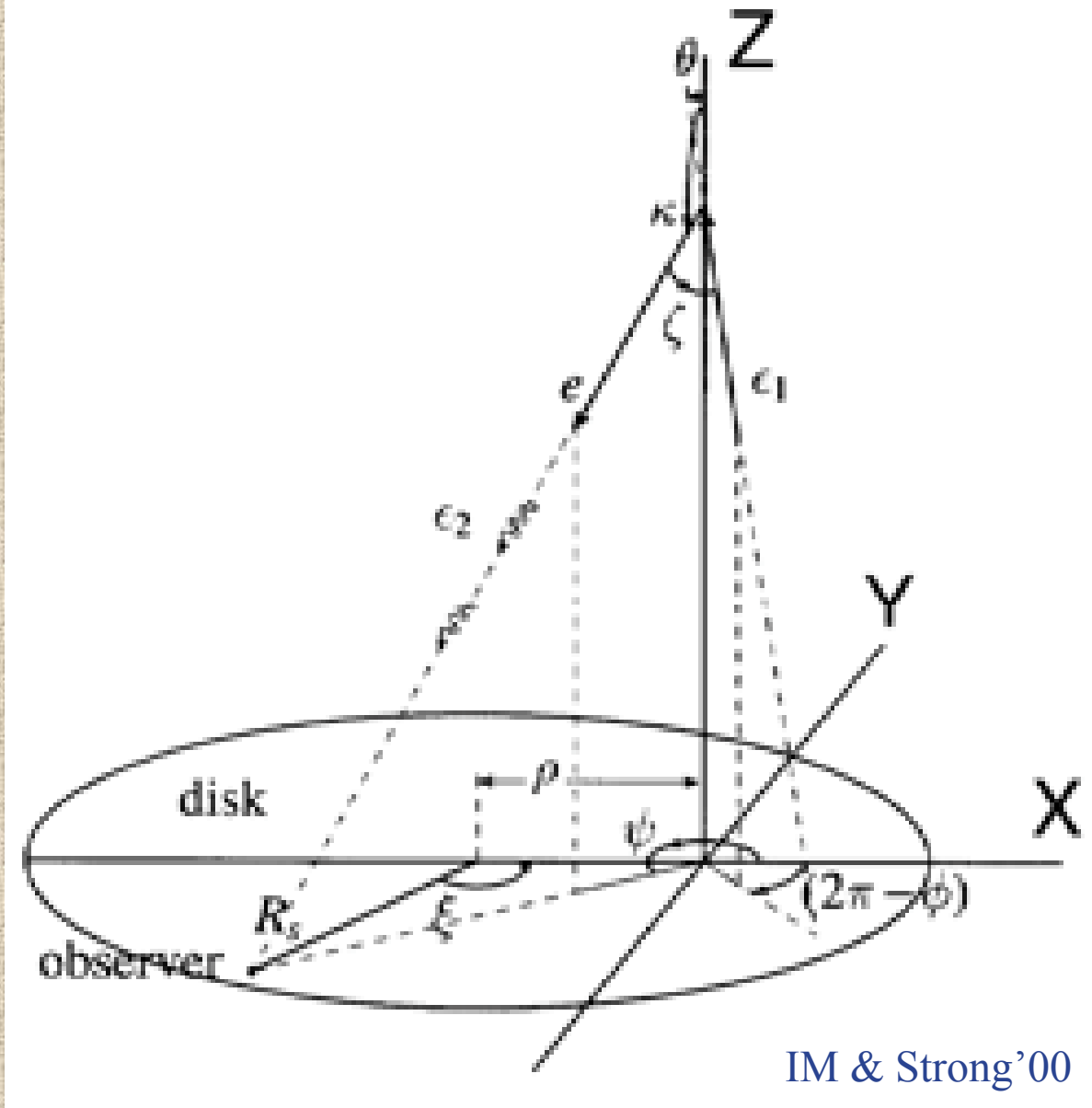
A-C=





srs=OB,
Zh=8kpc,
Rmax=30kpc,
mag=2,
optically thin HI

Anisotropic IC scattering in the Galaxy

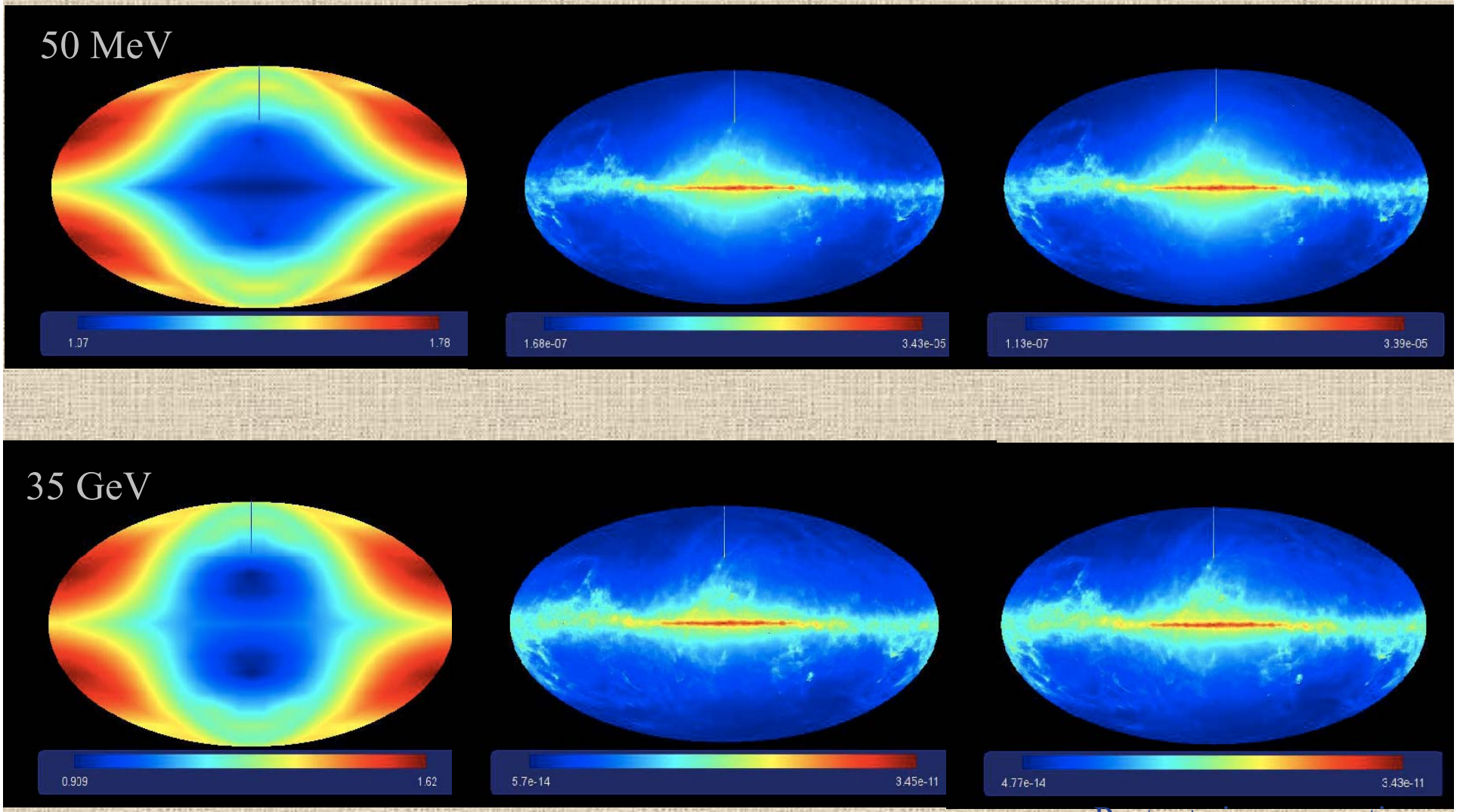


IM & Strong'00

- The formalism and effect of anisotropic IC scattering in the Galaxy: IM & Strong'00
- Varies over the sky
- Gives ×(0.7-2) more gammas vs isotropic approximation
- Has to be taken into account when modeling the diffuse emission

Standard ISRF (10 kpc halo)

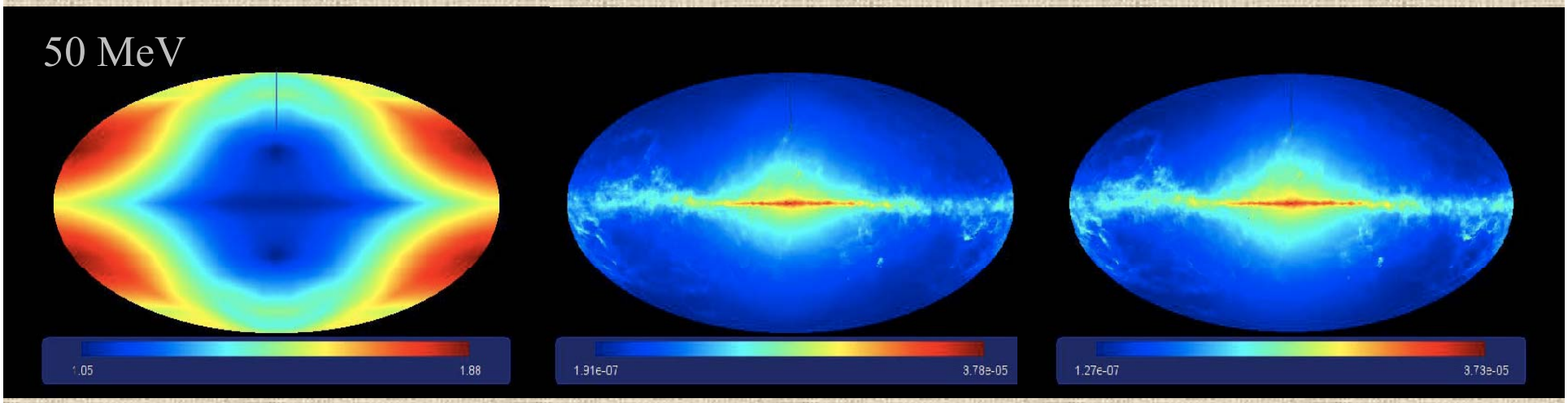
anisotropic/isotropic | aniso sum | iso sum

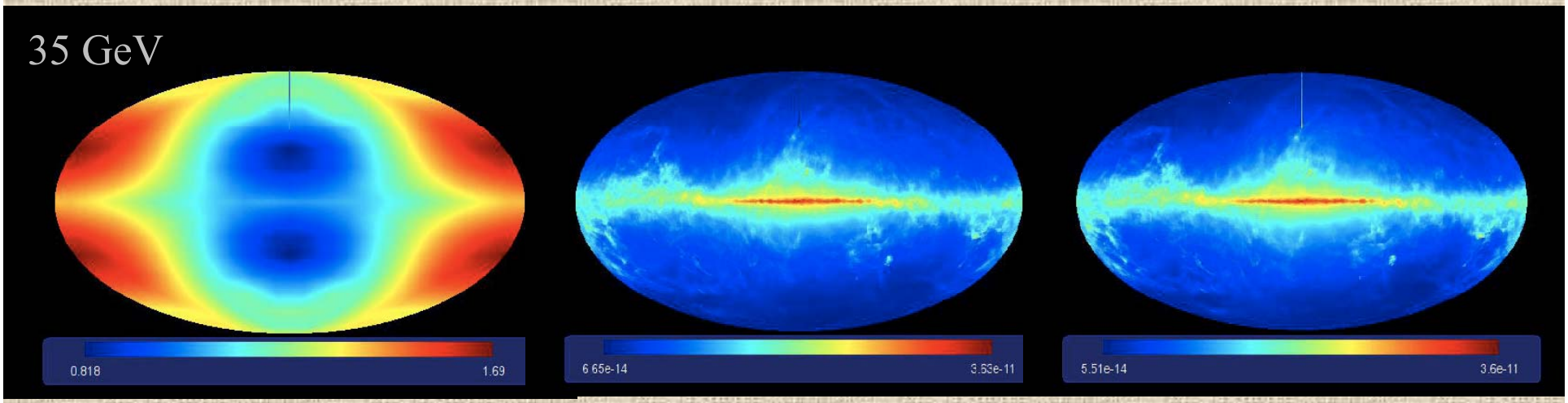


Porter+, in preparation

Bulge×10 model (10 kpc halo)

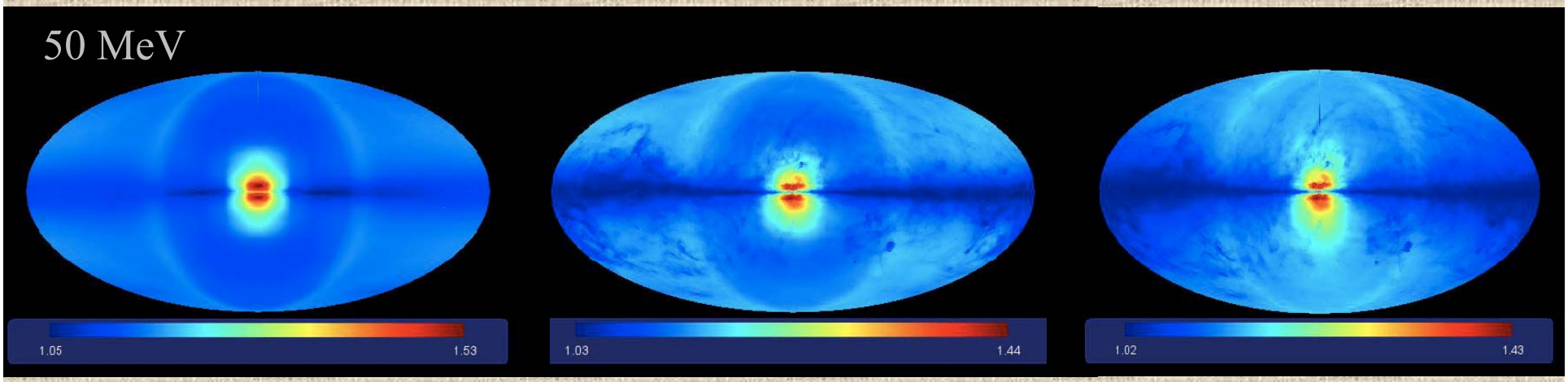
anisotropic/isotropic | aniso sum | iso sum

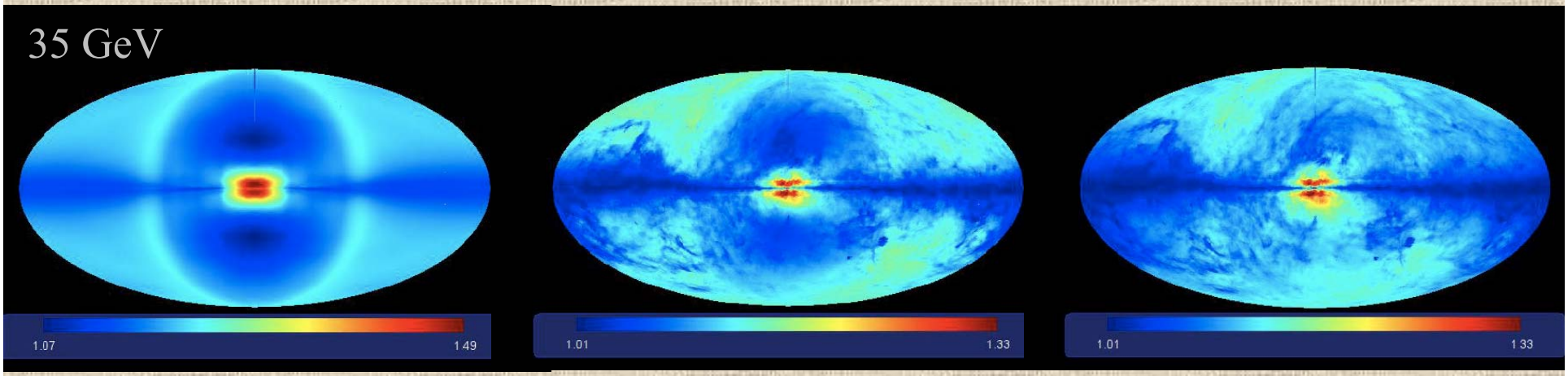


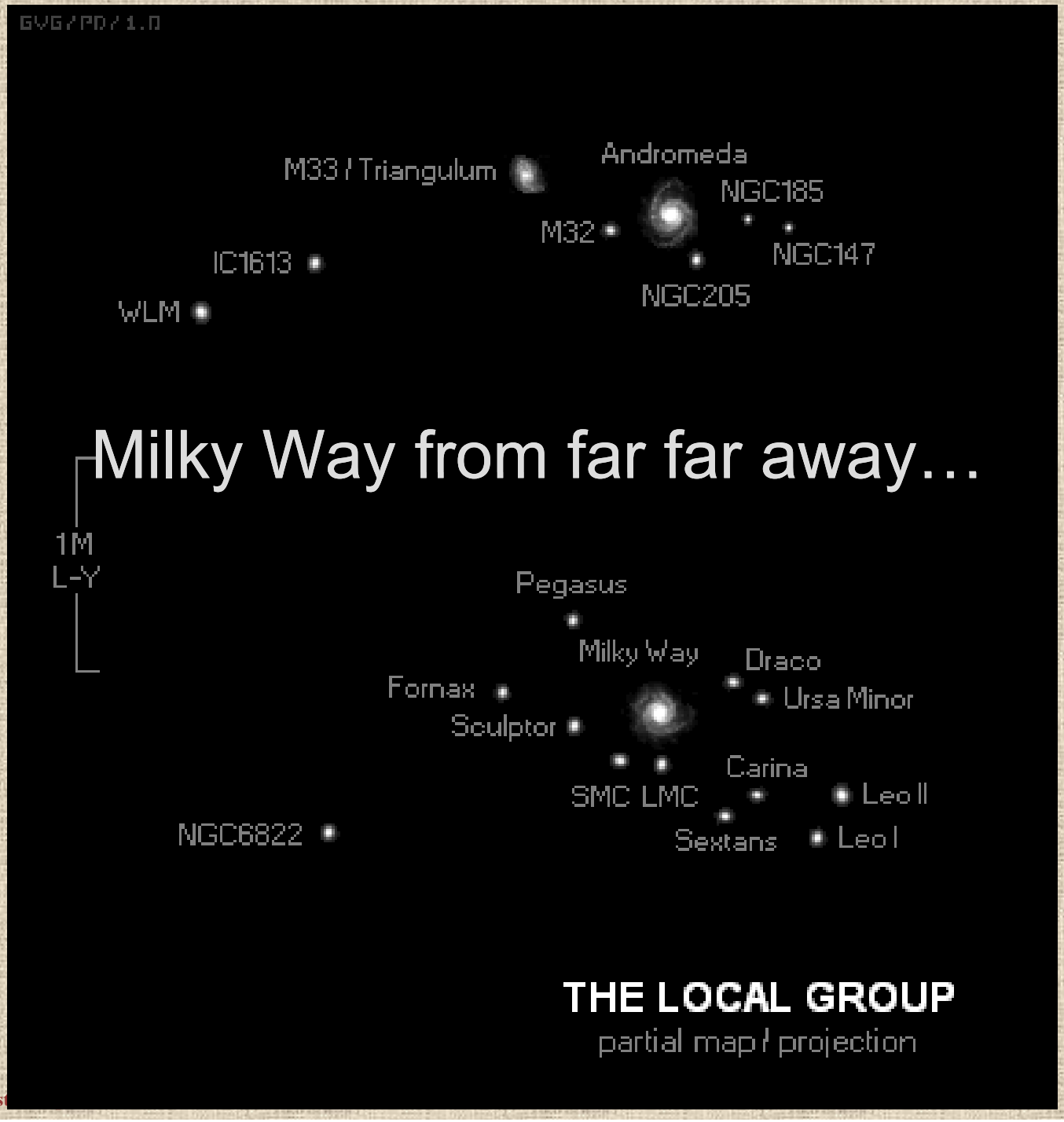


Ratio Bulge×10/Standard (10 kpc halo)

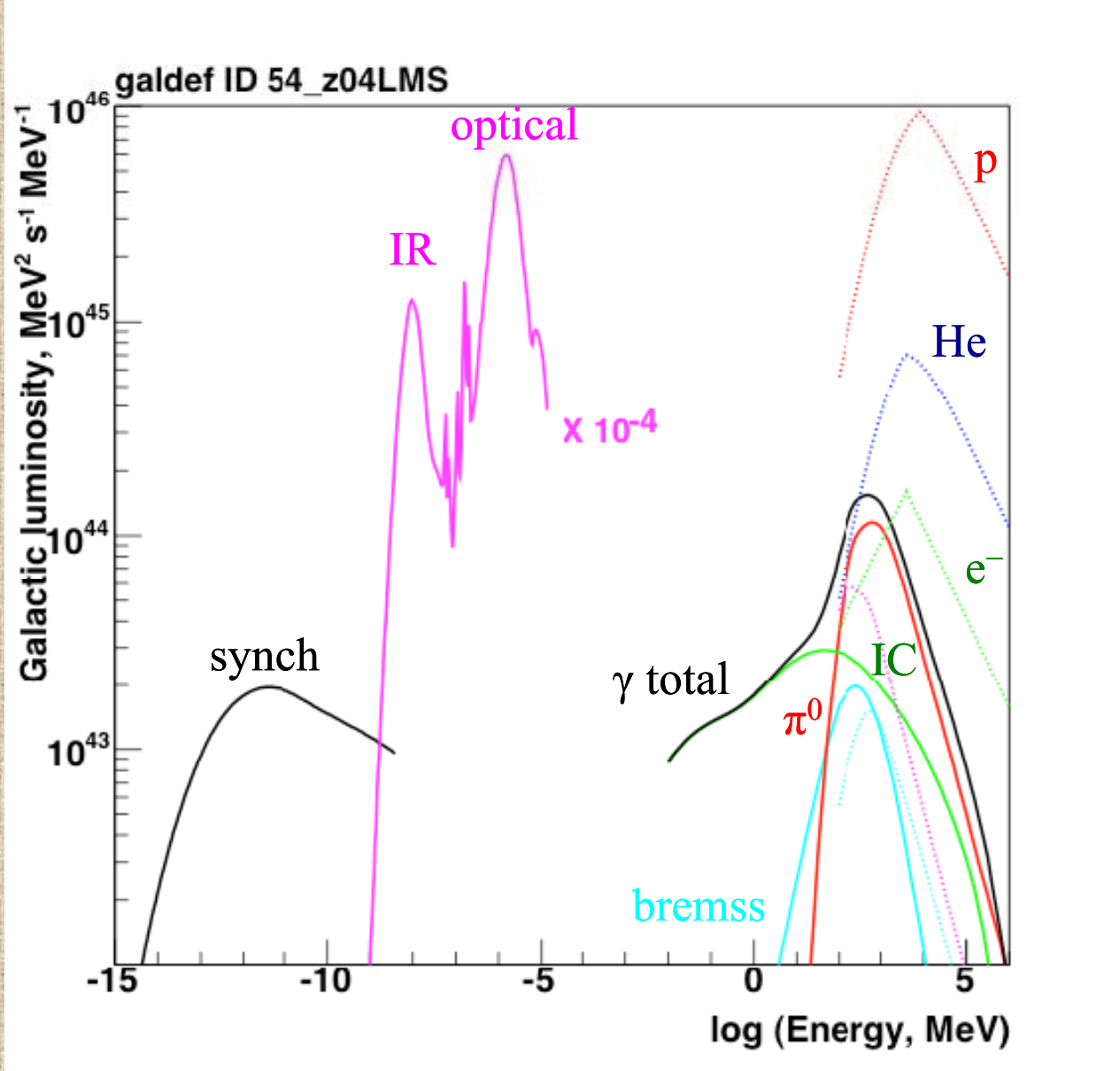
anisotropic skymap | aniso sum | iso sum






GVG/PD/1.0
M33 / Triangulum
Andromeda
NGC185
M32
NGC147
IC1613
NGC205
WLM
Milky Way from far far away…
1M
L-Y
Pegasus
Milky Way
Draco
Fornax
Ursa Minor
Sculptor
Carina
SMC LMC
Leo II
NGC6822
Sextans
Leo I
THE LOCAL GROUP
partial map / projection

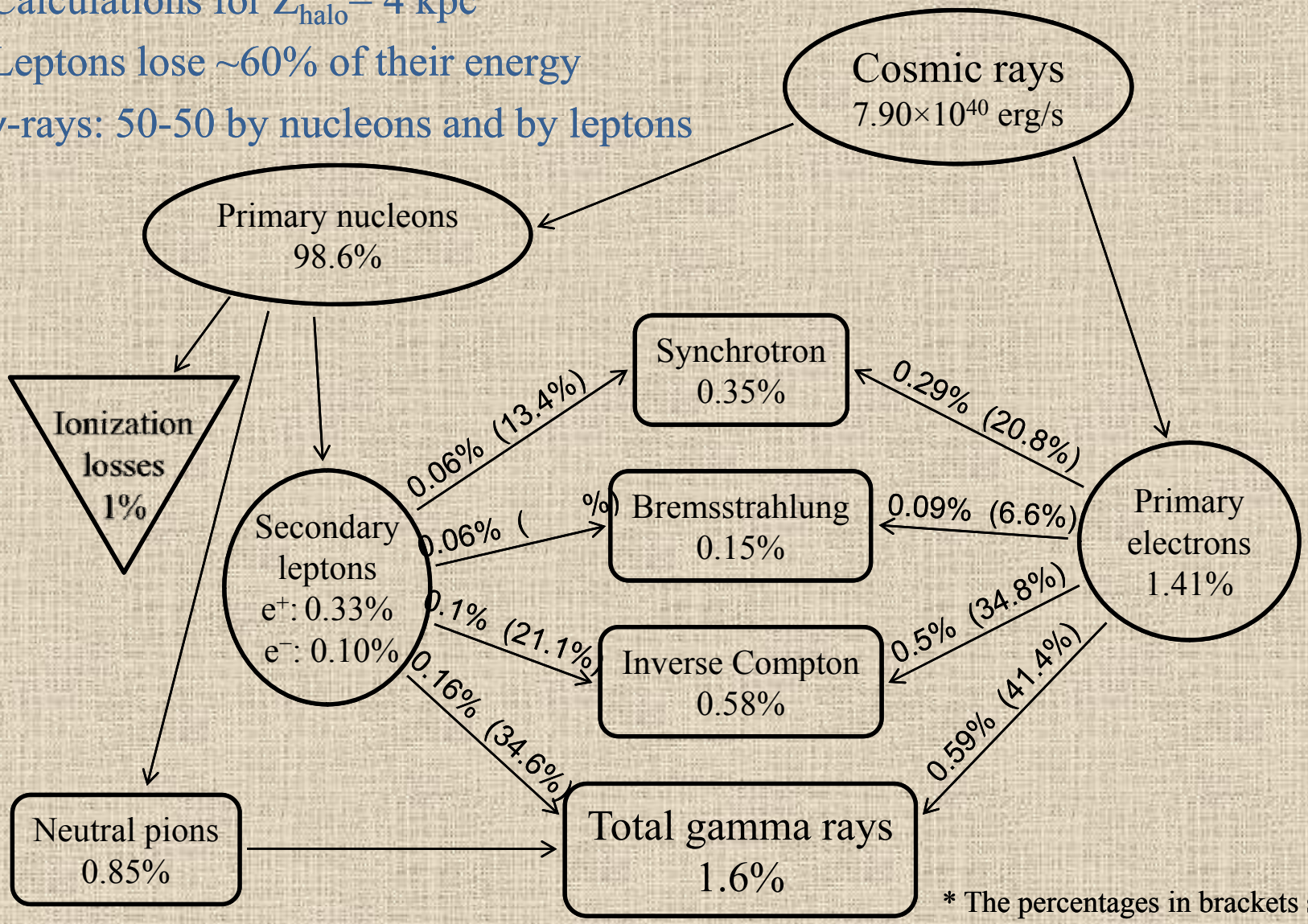
Multi-wavelength luminosity of the Milky Way



- "Proximity" of the MW plus direct measurements allow us to construct its detailed "microscopic" model (GALPROP)
- Integral properties of the MW – a useful template for studies of the normal galaxies
- Strong et al. 2010, ApJL in press

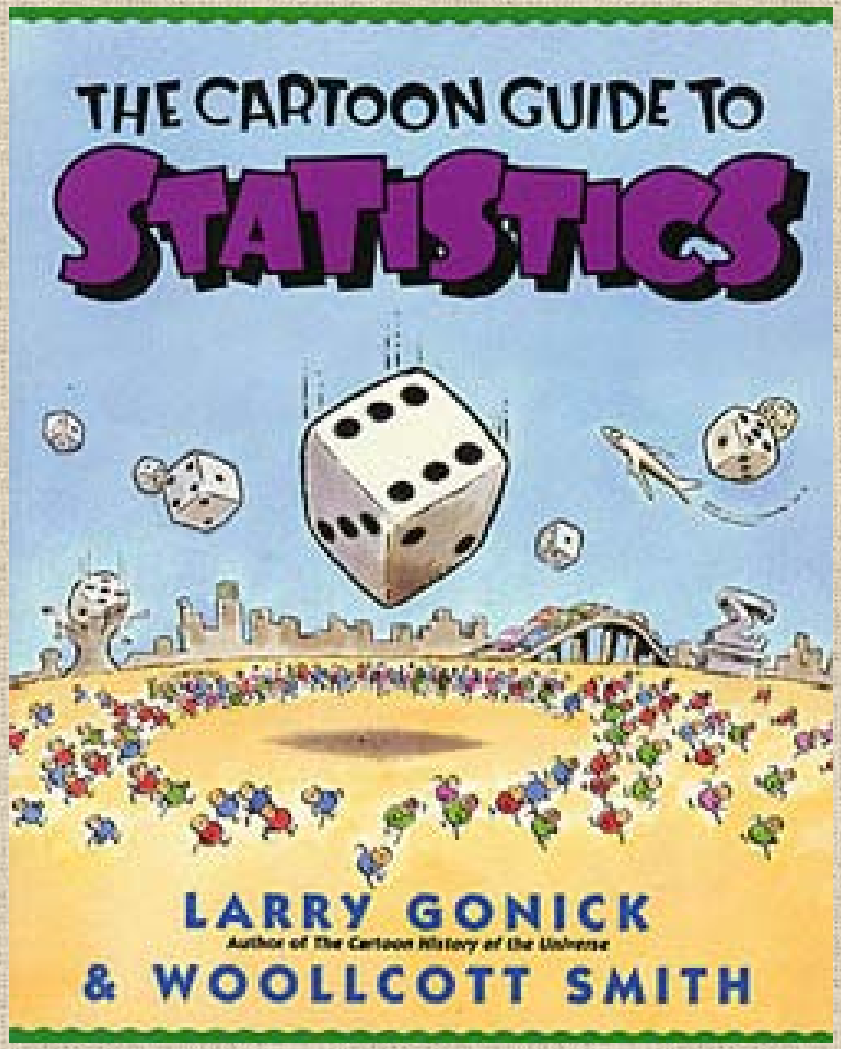
Milky Way as electron calorimeter

- Calculations for Z_{halo}= 4 kpc
- Leptons lose ~60% of their energy
- γ-rays: 50-50 by nucleons and by leptons



* The percentages in brackets show the values relative to the luminosity of their respective lepton populations

Constrains on CR propagation models from global scans



Methodology

- Bayesian approach (Θ – vector of parameters, D – available observations):

$$P(\Theta \mid D) = \frac{P(D \mid \Theta) P(\Theta)}{P(D)}$$

  P(Θ|D) – posterior distribution of parameters

  P(D|Θ) – likelihood function (for fixed D)

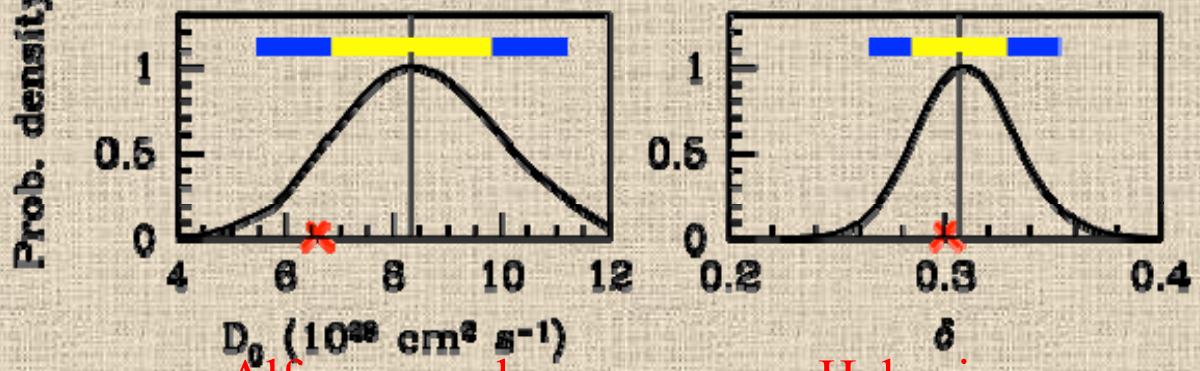
  P(Θ) – prior distribution

  P(D) – Bayesian evidence

- Bayesian approach allows for a more sophisticated treatment of systematics
- Nested sampling algorithm by John Skilling'04,06 and MultiNest by Feroz&Hobson'08 (SuperBayeS code by Ruiz de Austri+'06, Trotta+'08)
- Total 1.4×10^5 samples, ~13 CPU years
- The posterior distribution is in excellent agreement with one from MCMC
- Representative data from ACE, ISOMAX, HEAO-3, ATIC-2, CREAM
- Fit a total of 17 parameters, best fit chi-squared/dof ~ 1
- More details in the paper (to be submitted in a few days)

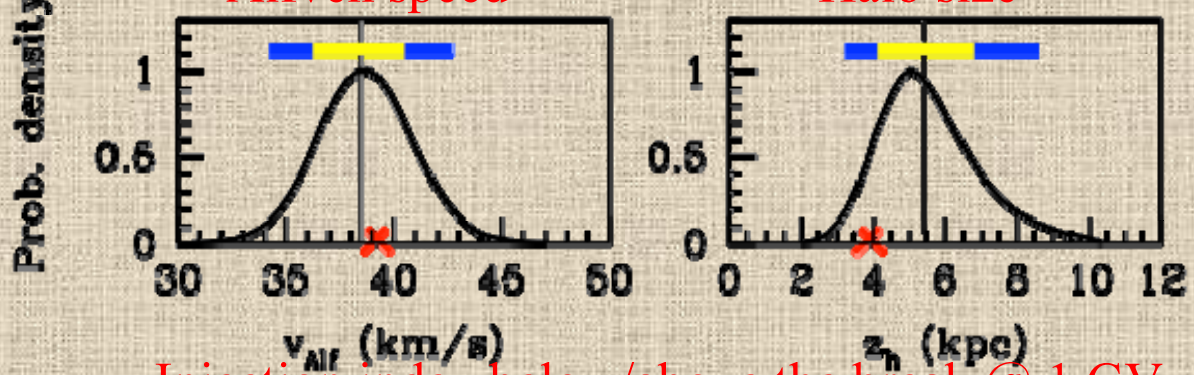
Posterior probability distributions

Normalization of the diffusion coeff. and its index

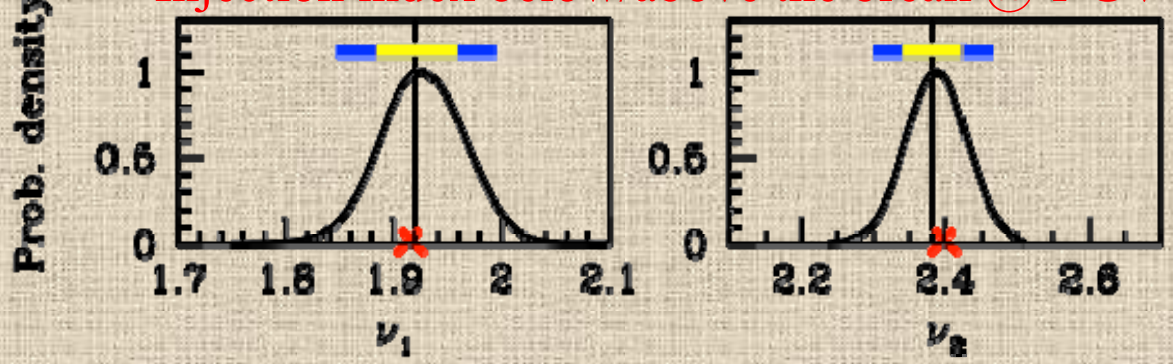


Alfven speed

Halo size



Injection index below/above the break @ 1 GV



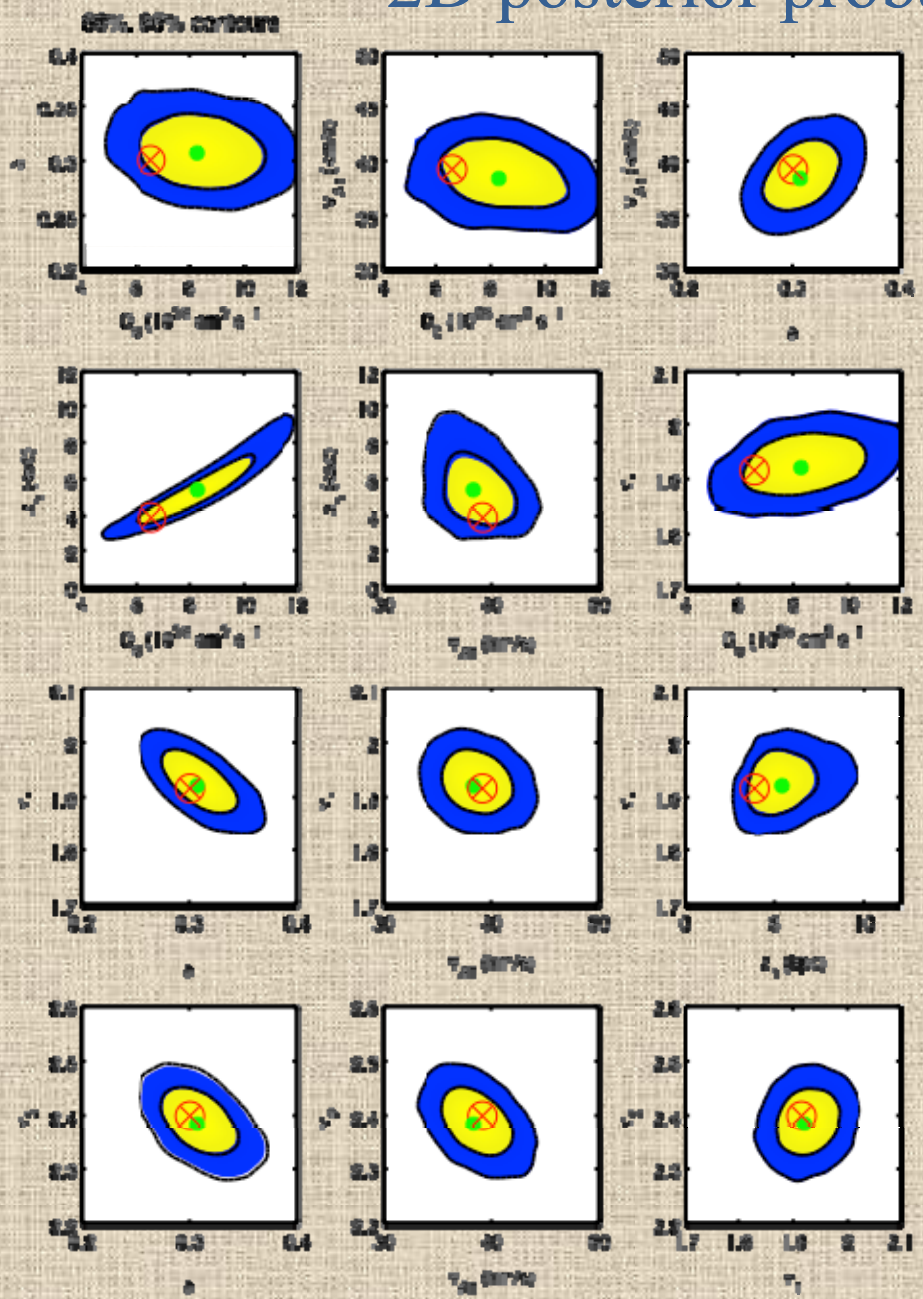
- the best fit

vertical line – posterior mean

color bar – 68%, 95% error ranges

- Reacceleration model
- Parameters are very close to those derived by the eye-fitting method

2D posterior probability distributions

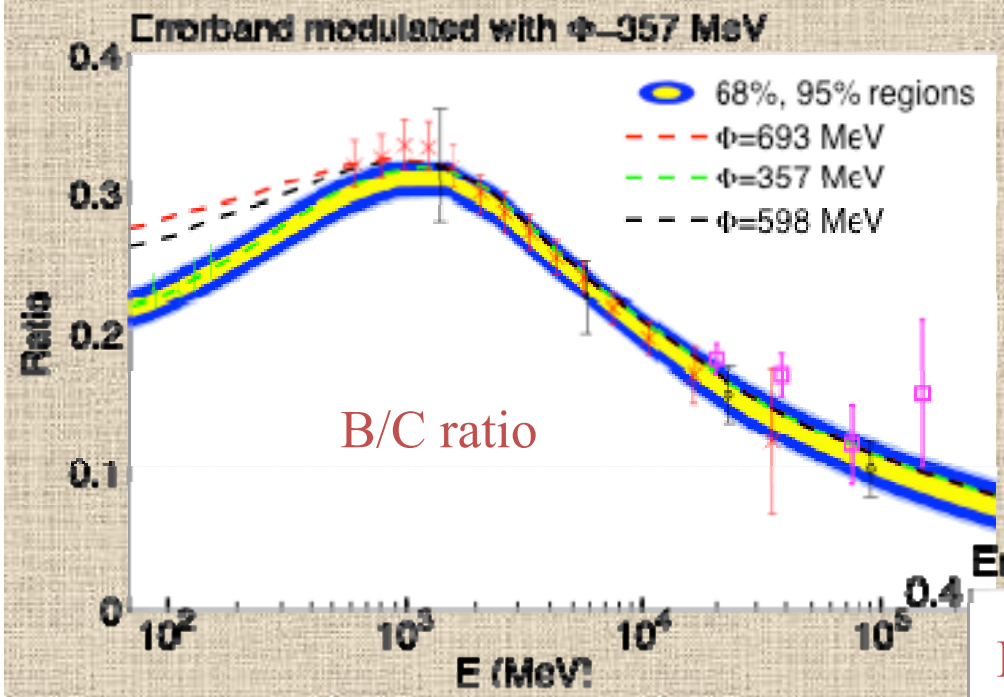


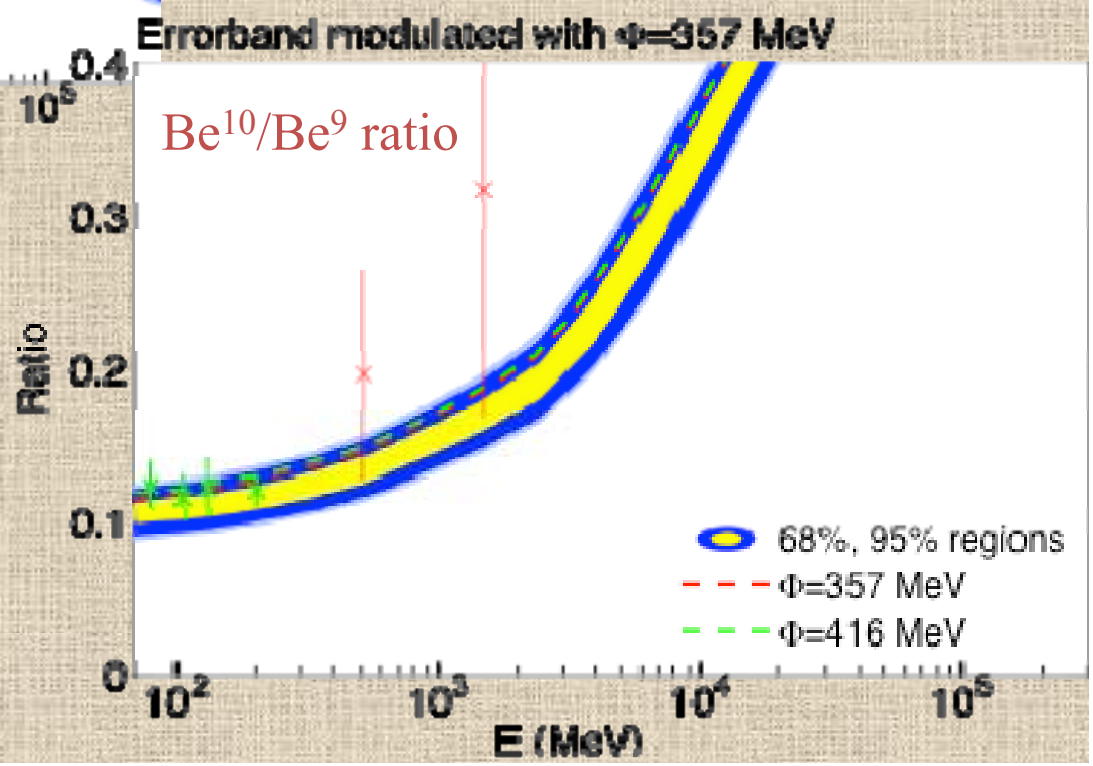
- Contours enclose 68% and 95% probability regions

⊗ - best fit

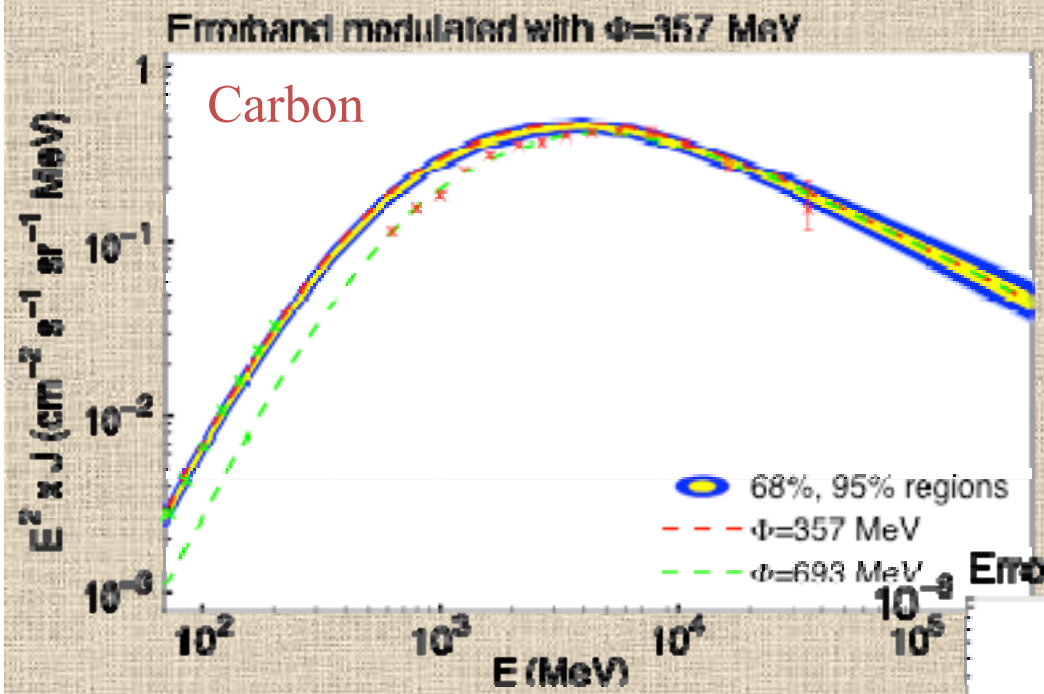
● - posterior mean

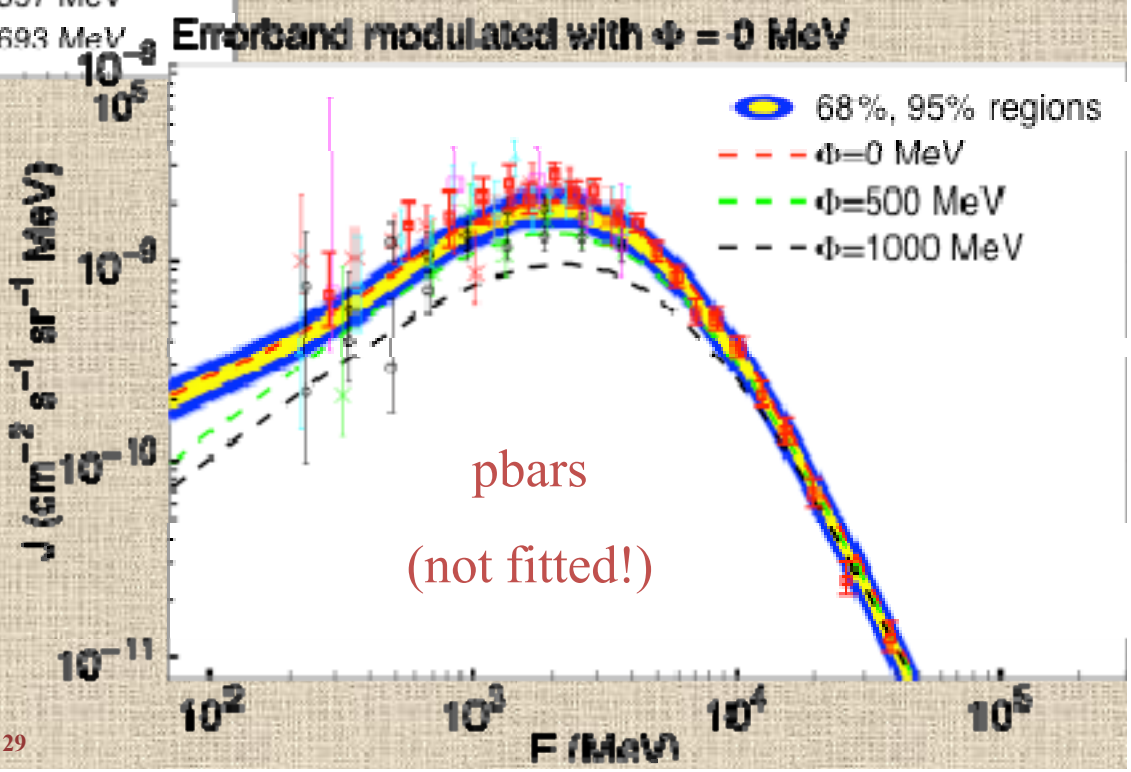
Examples of the fits: B/C and Be ratios





Examples: Carbon and pbars





GALPROP WebRun

galprop.stanford.edu

Igor Moskalenko

for the GALPROP development team

GALPROP WebRun

- GALPROP WebRun is a service that allows to run GALPROP via the WWW
- No local installation of the code or related libraries is necessary, only a web browser is required
- Available at http://galprop.stanford.edu/webrun
- Calculations can be performed on a new cluster at Stanford University, using the most recent GALPROP v54, older versions are also available
- The service is free and open to the community. Registration is required
- Acknowledge by citing the web-page and the introduction paper http://arxiv.org/abs/1008.3642 (submitted to Computer Physics Communications)

Configuring GALPROP via WebRun

GALPROP: webrun

http://galprop.stanford.edu/webrun/

galprop.stanford.edu
studies of cosmic rays and galactic diffuse gamma-ray emission

CODE | WEBRUN | FORUM | RESOURCES | PUBLICATIONS | CONTACTS | BUGS?

Search GALPROP web site | Search | Logout [avladim]

GALPROP version: 54 click to change

Enter the desired GALPROP v. 54 parameters and click 'Submit' at the bottom of the form ⇓

Common | Grids | Propagation | Gas | Sources | Emission | Abundances

WebRun Help

Configure & Submit

Help: Configure & Submit

First-time User Mode

Advanced User Mode

Monitor Queue

Download Results

Import configuration from: you can use an example or retrieve your old run

Common Parameters

Name	Value	Description
Title	Plain diffusion moc	Descriptive title used to identify the run.
n_spatial_dimensions	2	Specifies whether 2 or 3 spatial dimensions.

Energetic and Spatial Grids

Name	Value	Description
r_min	00.0	Minimum galactocentric radius (R) for 2D case, in kpc. Ignored for 3D.
r_max	20.00	Maximum galactocentric radius (R) for 2D case, in kpc. Ignored for 3D.
dr	1.0	Cell size in galactocentric radius (R) for 2D case, in kpc.
z_min	-4.0	Minimum height for 2D and 3D case, in kpc.
z_max	+4.0	Maximum height for 2D and 3D case, in kpc.
dz	0.1	Cell size in z for 2D and 3D case, in kpc

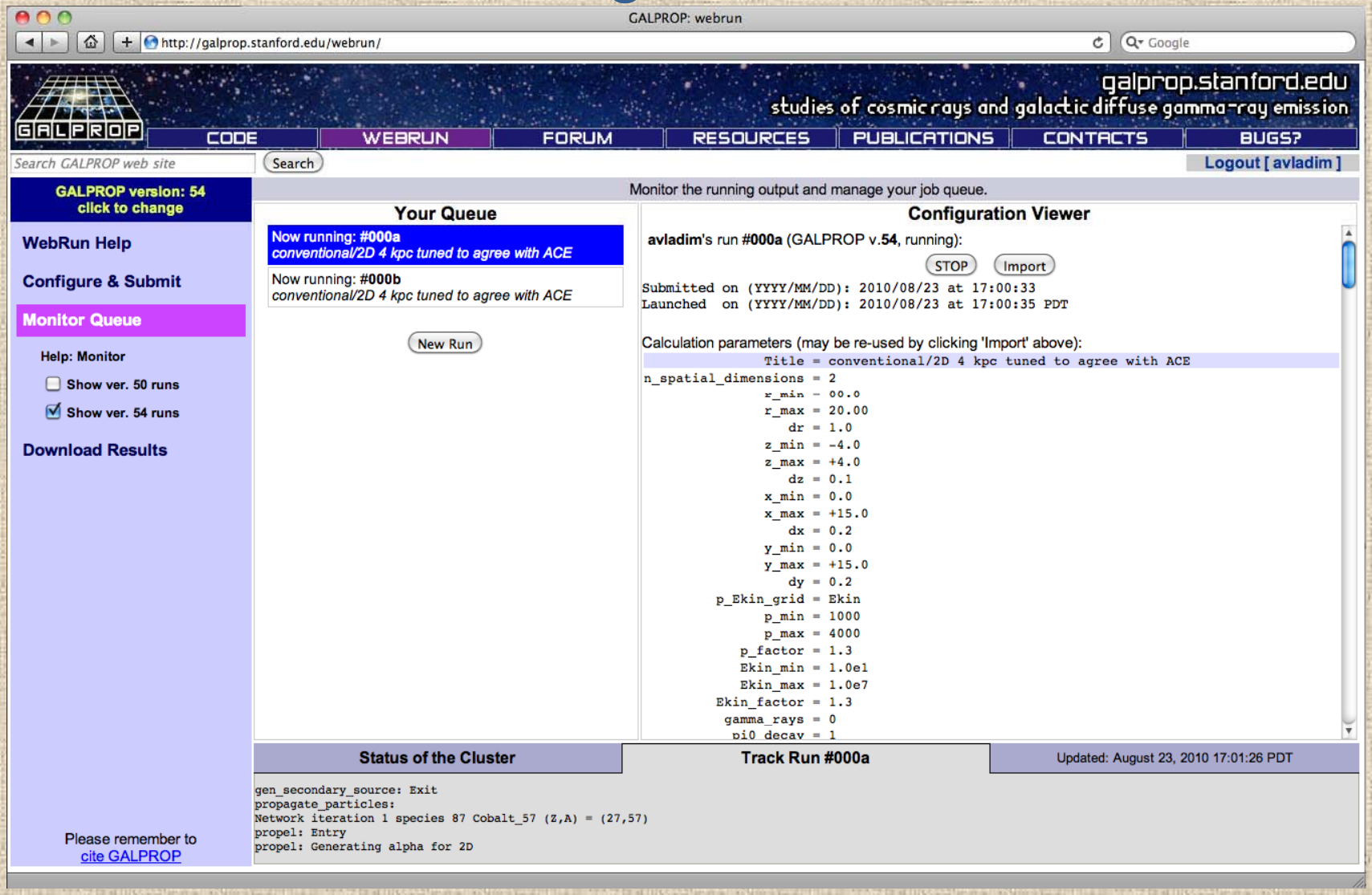
CR Propagation

Name	Value	Description
D0_xx	2.2e28	The spatial diffusion coefficient divided by beta=v/c at rigidity D_rigid_br. The value at other rigidities is determined via the formula D=beta D_0xx (rho / D_rigid_br)^D_g, where D_g=D_g_1 for rigidity less than D_rigid_br, and D_g=D_g_2 for rigidity greater than D_rigid_br.
D_rigid_br	3.0e3	Rigidity for D0_xx formula, and also break point in case D_g_1 != D_g_2.
D_g_1	0.	Diffusion coefficient index below reference rigidity. See formula for D0_xx. Kolmogorov turbulence corresponds to a value 1/3.
D_g_2	0.60	Diffusion coefficient index below reference rigidity. See formula for D0_xx. Kolmogorov turbulence corresponds to a value 1/3.

Please remember to cite GALPROP

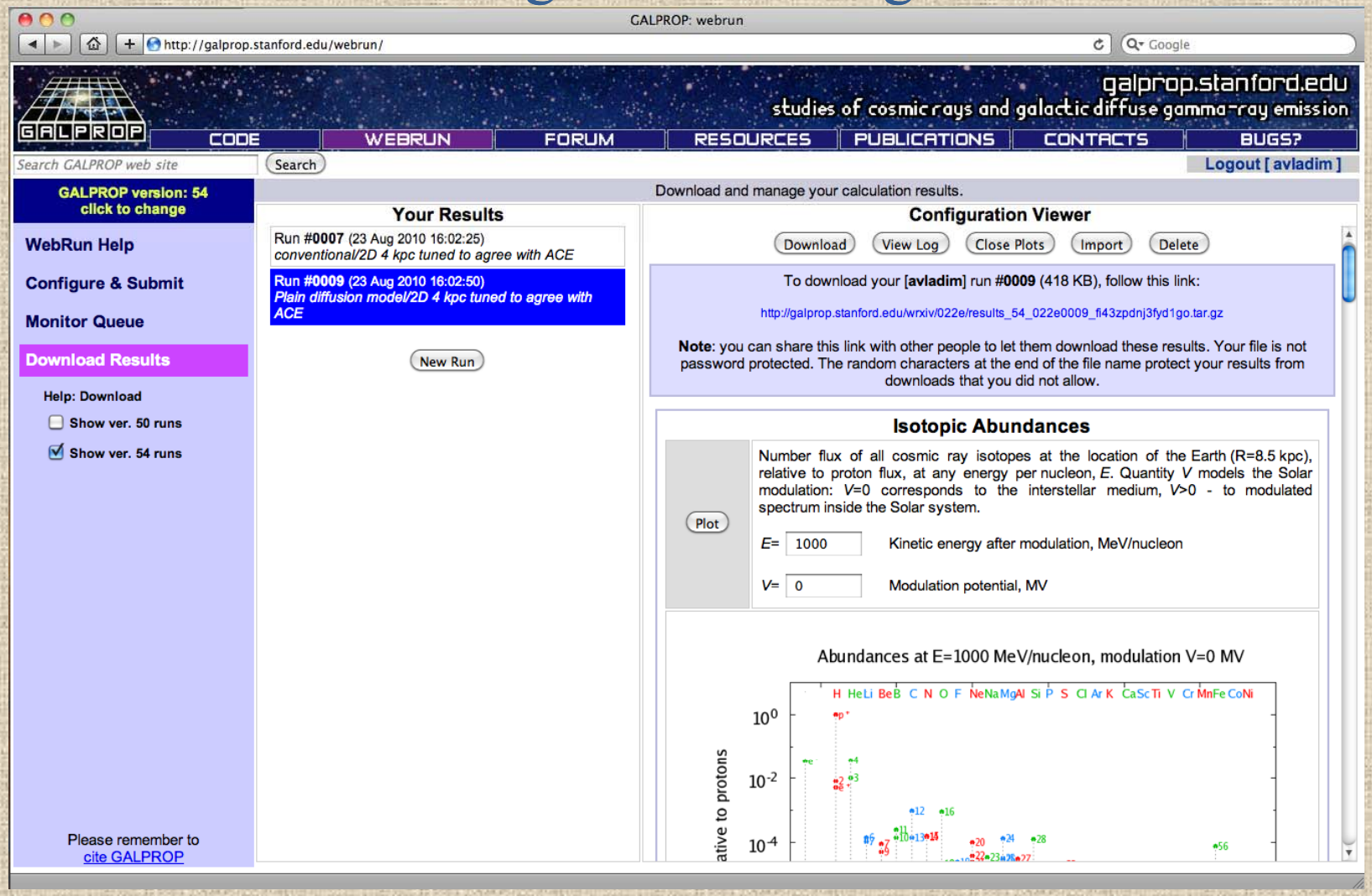
- Interactive interface for parameter entry
- Parameters are validated to avoid misconfgured runs

Running calculations



- Multiple simultaneous runs are allowed
- Sharing resources fairly between users

Evaluating and obtaining results



- Archive with FITS files (output) available to the owner
- URL to the archive may be shared with anyone
- Quick peek possible with built-in plot templates

Computing cluster (galprop.stanford.edu)

Head node:
- web server
- data storage (12TB RAID0)

Infiniband link (10 Gbit/s)

Compute nodes. On each node:
- 4 x 12-core processors (6174 AMD Opteron)
- 128 GB shared memory
- small fast hard drives.

Total: 196 cores.

Easily extendable.

Thank you !

You are here