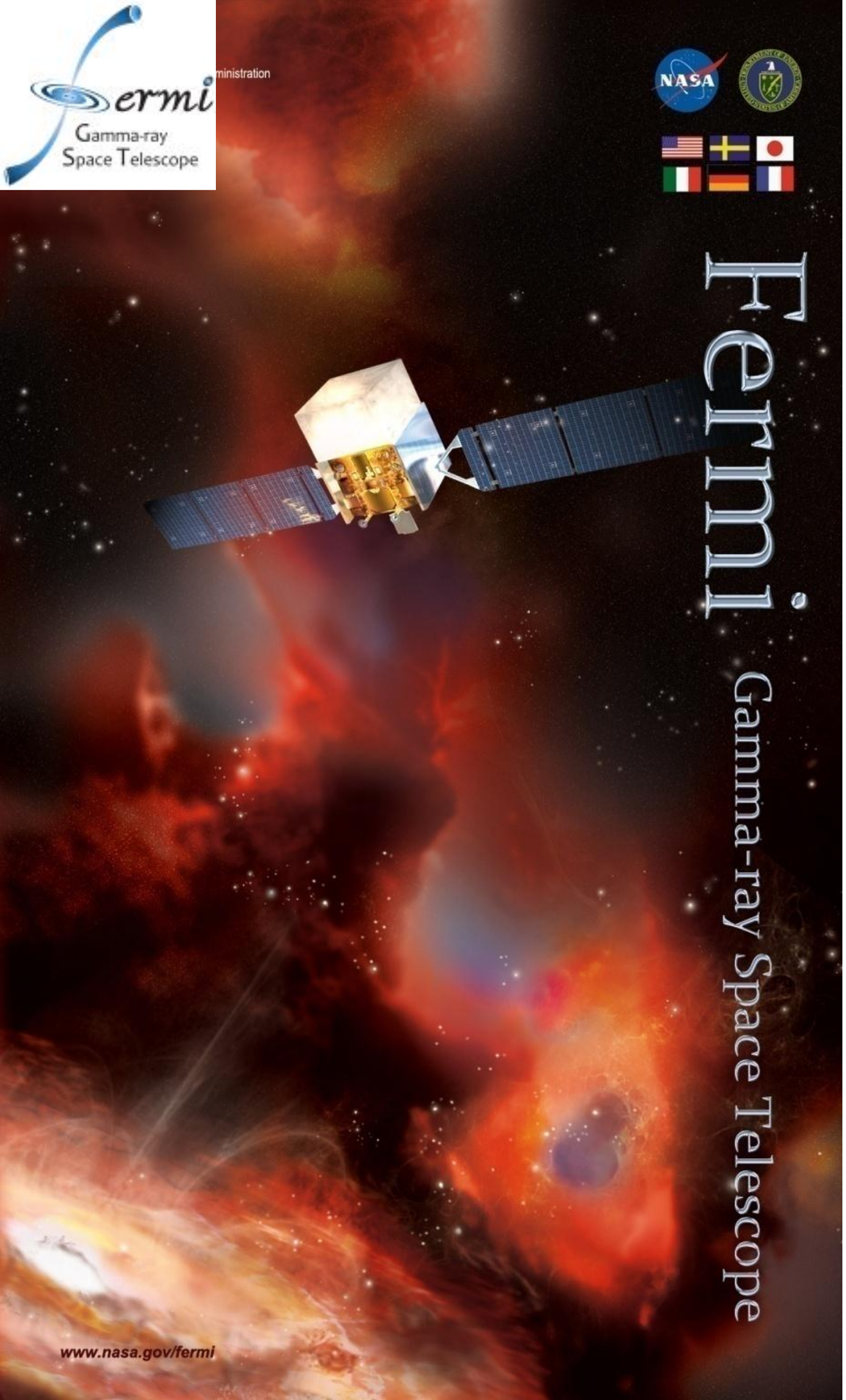
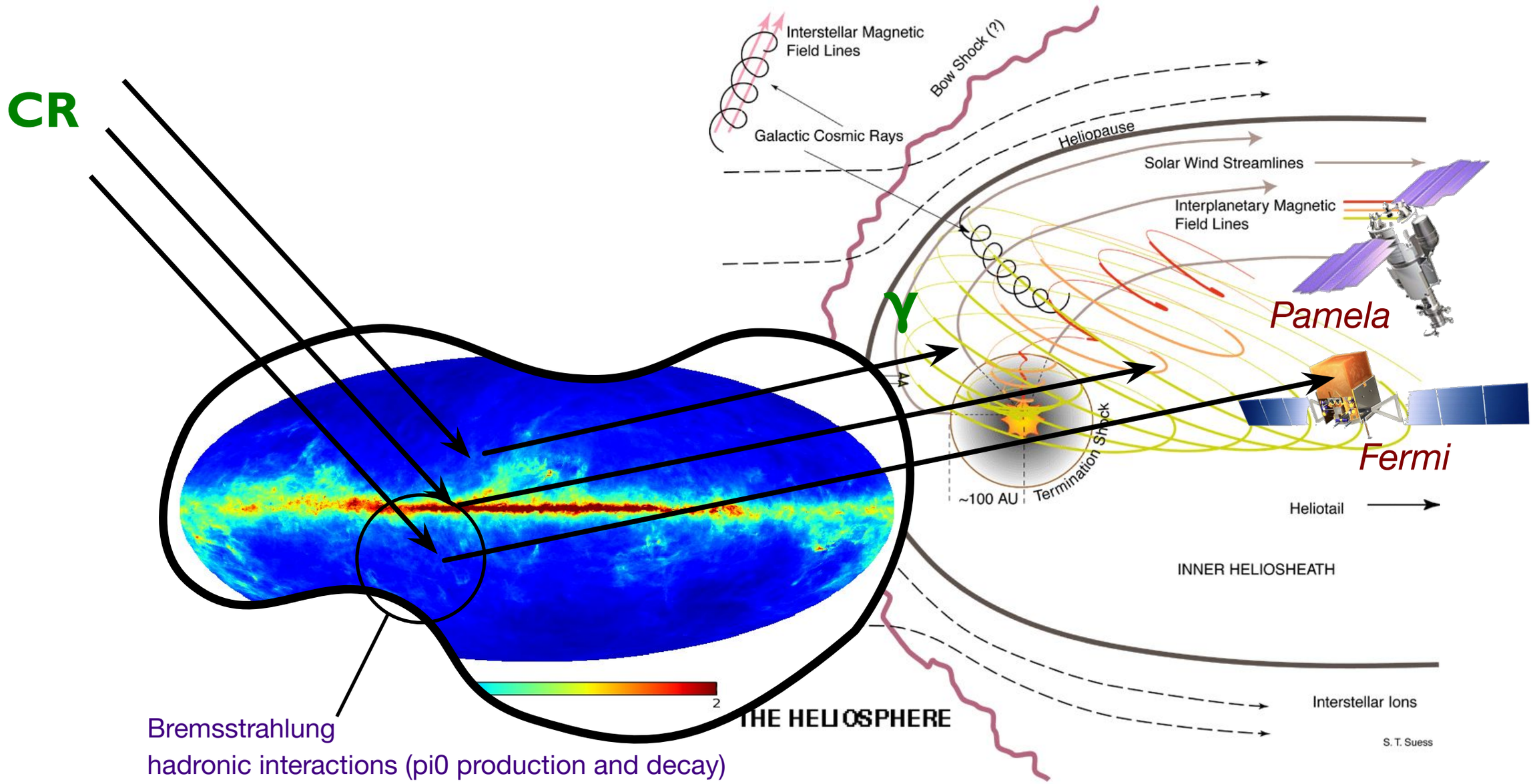


The gamma-ray sky and impact of cross-section uncertainties

Jean-Marc Casandjian
SAp, IRFU, CEA Saclay



$$N_\gamma = q \times N(H) + stuff$$

$$q \propto F_{CR} \times \sigma_{pp \to \gamma}$$

2.2 Propagation equation

$q \propto F_{CR} \times \sigma_{pp\to\gamma}$

The CR propagation equation for a particular particle species can be written in the general form:

$$\begin{aligned}\frac{\partial\psi(\vec{r},p,t)}{\partial t} &= q(\vec{r},p,t) + \vec{\nabla}\cdot(D_{xx}\vec{\nabla}\psi - \vec{V}\psi) \\ &+ \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{1}{p^2}\psi - \frac{\partial}{\partial p}\left[\dot{p}\psi - \frac{p}{3}(\vec{\nabla}\cdot\vec{V})\psi\right] - \frac{1}{\tau_f}\psi - \frac{1}{\tau_r}\psi \quad (1)\end{aligned}$$

2.2 Propagation equation

$q \propto F_{CR} \times \sigma_{pp\to\gamma}$

The CR propagation equation for a particular particle species can be written in the general form:

$$\begin{aligned}\frac{\partial\psi(\vec{r},p,t)}{\partial t} &= q(\vec{r},p,t) + \vec{\nabla}\cdot(D_{xx}\vec{\nabla}\psi - \vec{V}\psi) \\ &+ \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{1}{p^2}\psi - \frac{\partial}{\partial p}\left[\dot{p}\psi - \frac{p}{3}(\vec{\nabla}\cdot\vec{V})\psi\right] - \frac{1}{\tau_f}\psi - \frac{1}{\tau_r}\psi \quad (1)\end{aligned}$$

$$N_\gamma = q \times N(H) + stuff$$

2.2 Propagation equation

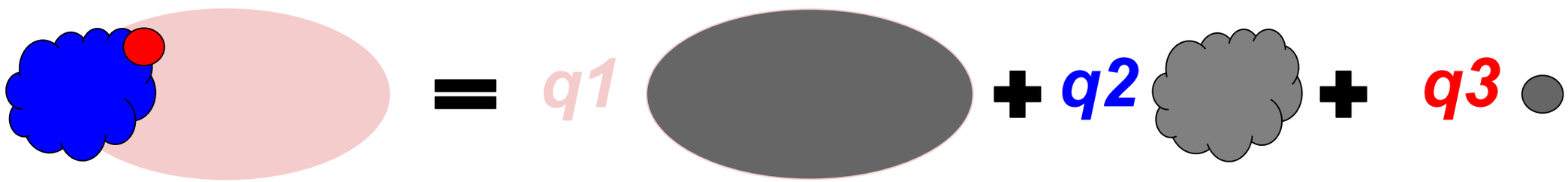
$q \propto F_{CR} \times \sigma_{pp\to\gamma}$

The CR propagation equation for a particular particle species can be written in the general form:

$$\frac{\partial\psi(\vec{r},p,t)}{\partial t} = q(\vec{r},p,t) + \vec{\nabla}\cdot(D_{xx}\vec{\nabla}\psi - \vec{V}\psi) + \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{1}{p^2}\psi - \frac{\partial}{\partial p}\left[\dot{p}\psi - \frac{p}{3}(\vec{\nabla}\cdot\vec{V})\psi\right] - \frac{1}{\tau_f}\psi - \frac{1}{\tau_r}\psi \quad (1)$$

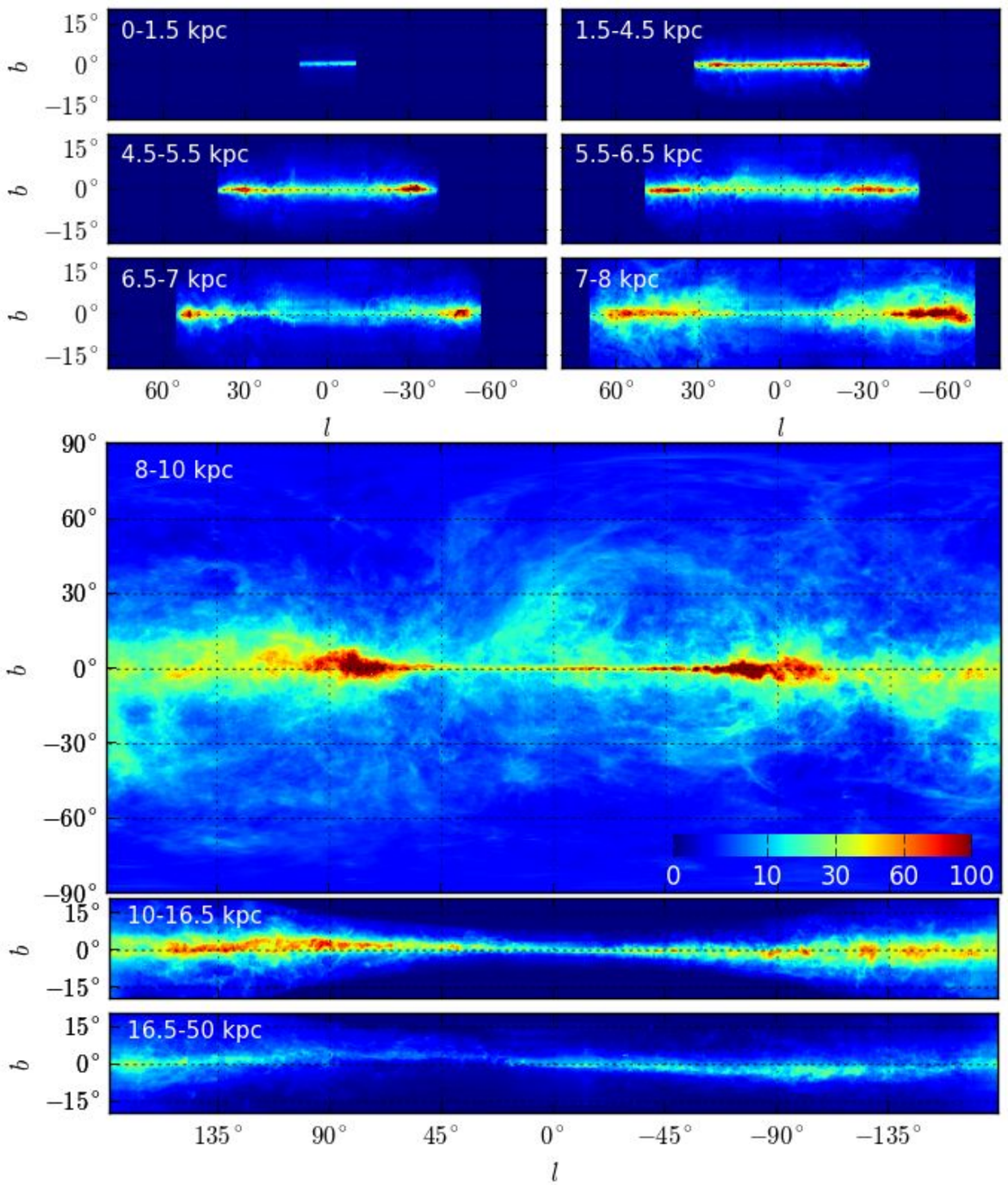
$$N_\gamma = q \times N(H) + stuff$$

Template method :

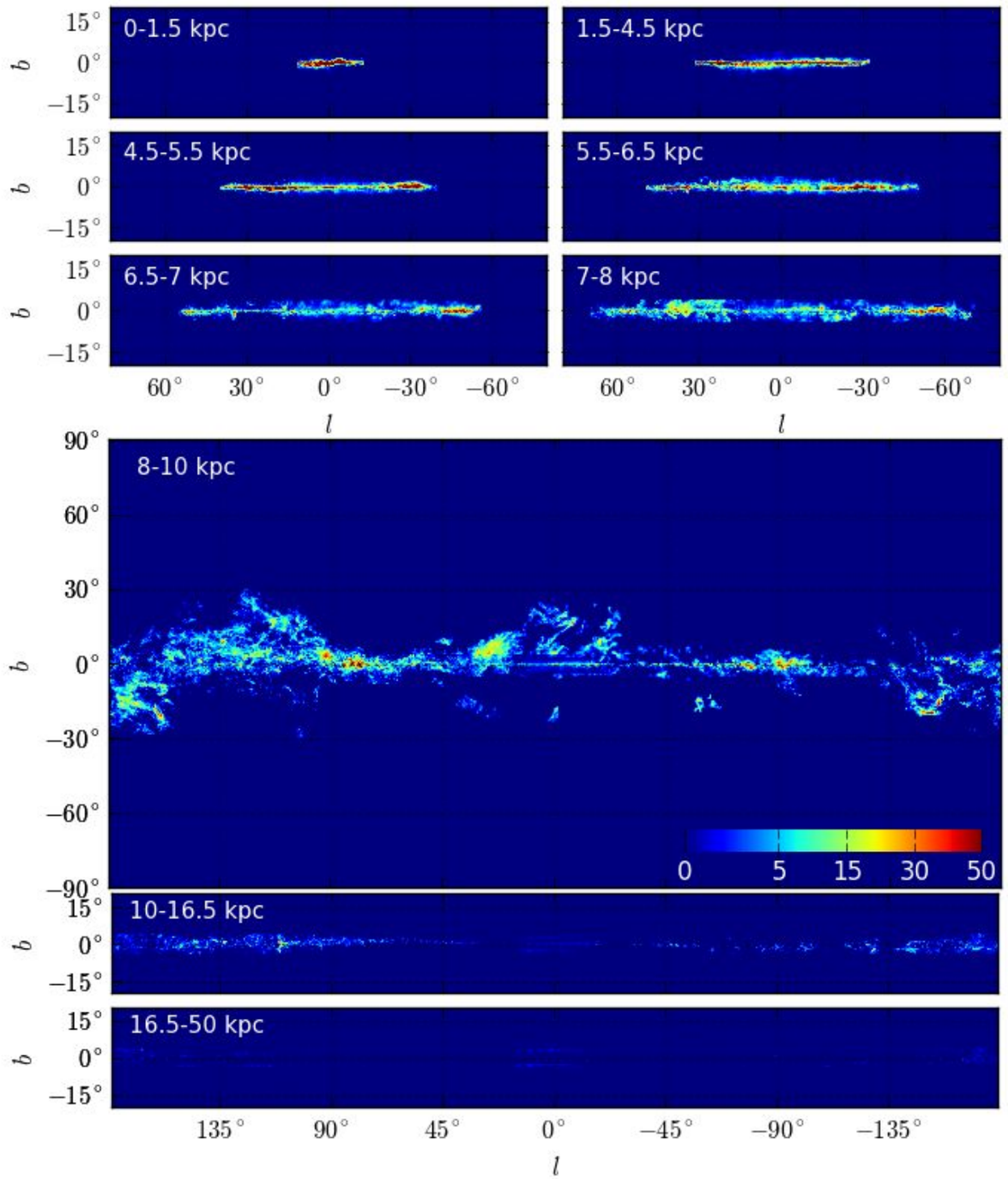


$$N_\gamma = q \times N(H) + stuff$$

$N(HI)$



CO

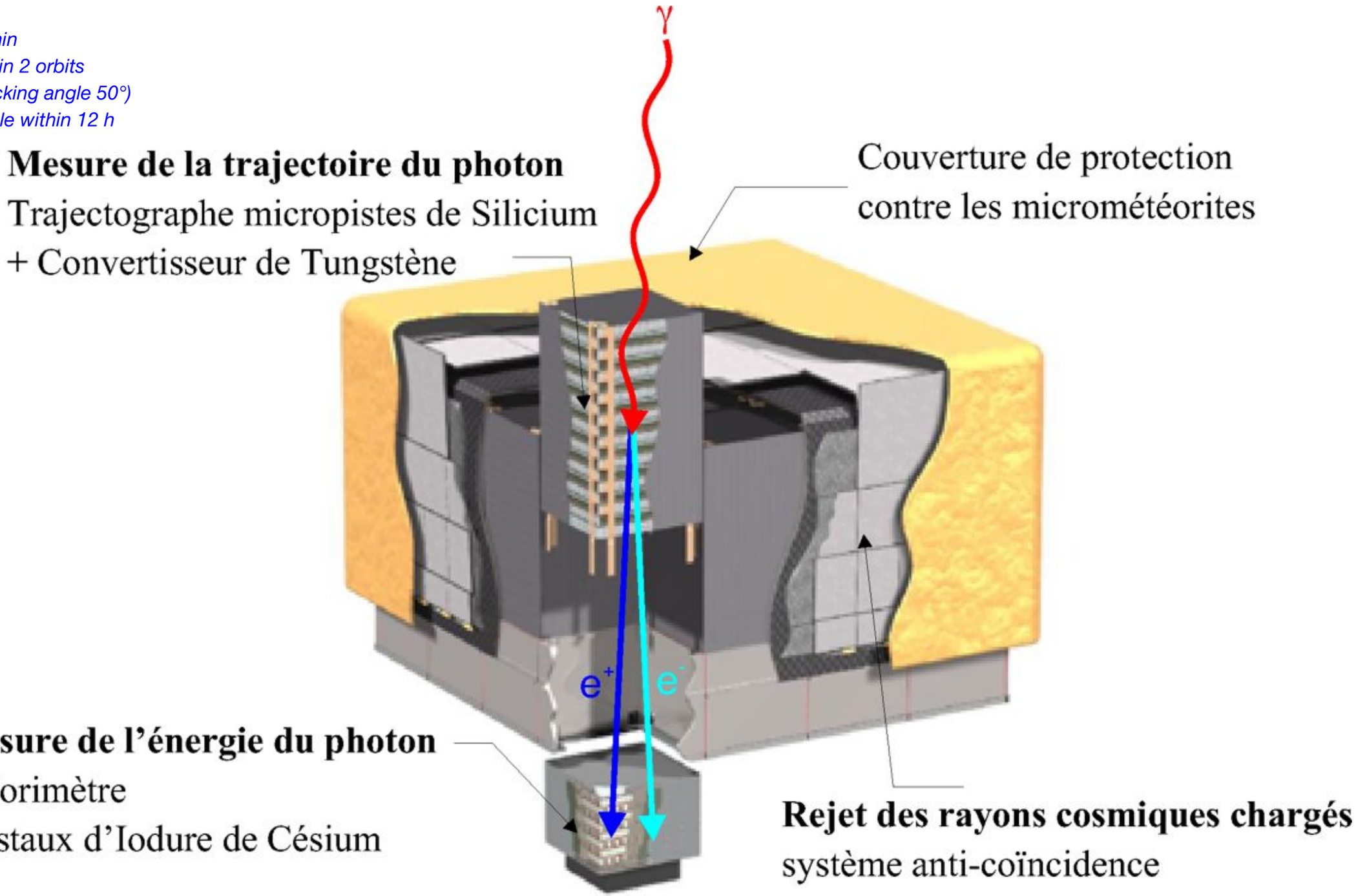



Large Area Space Telescope
GLAST
NASA

Fermi collaboration:
~600 papers
~30k citations for cat 1

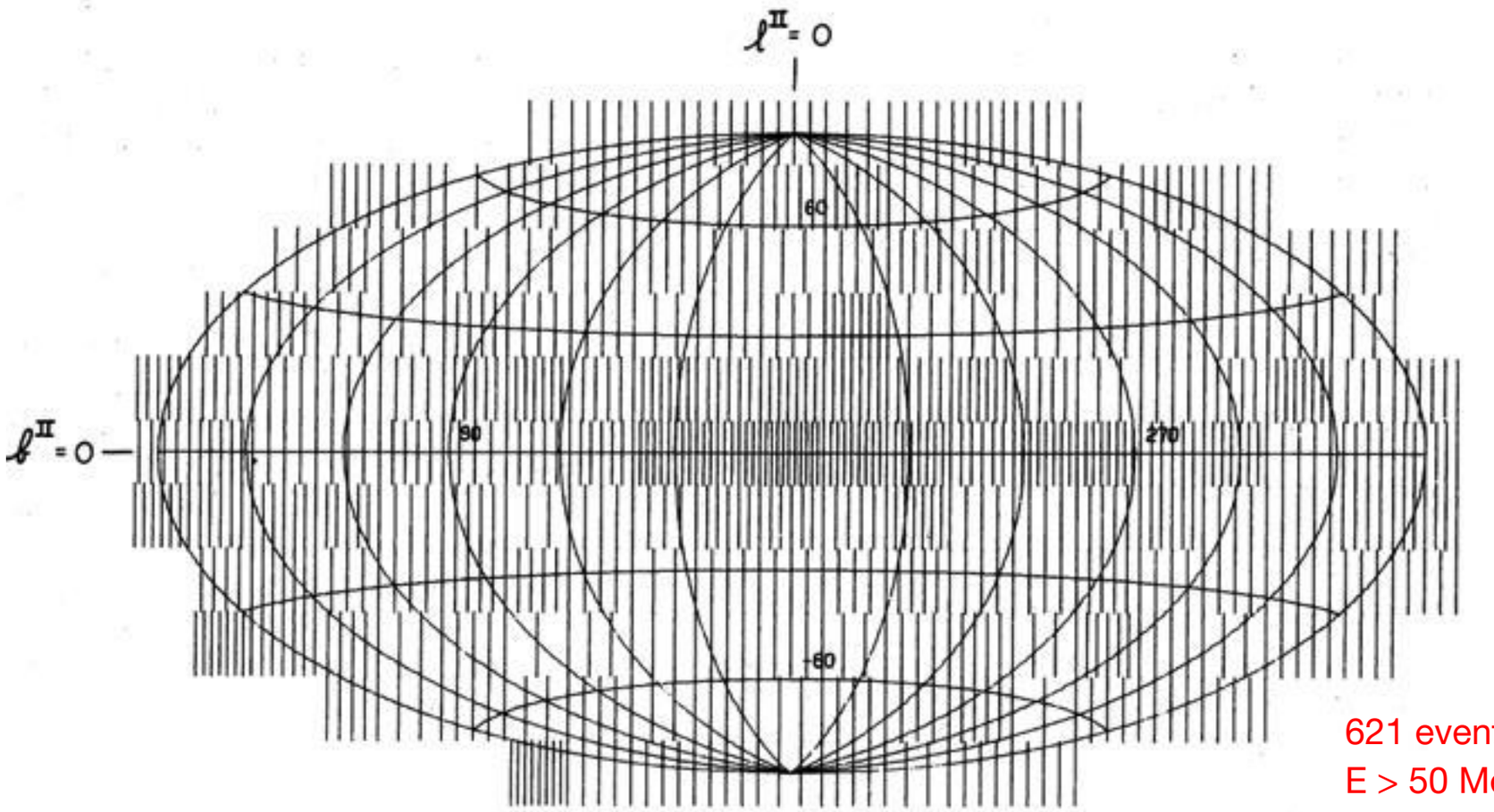
The LAT detector

Energy range: 30 MeV- 300 GeV
large FOV: 2.4 sr
A_{eff}:~8000 cm^2 at 1 GeV
PSF: $\theta_{68\%}$~0.8° at 1 GeV
altitude: 565 km
inclination: 25.6°
orbital period: 91 min
whole sky covered in 2 orbits
in survey mode (rocking angle 50°)
public data, available within 12 h



First evidence of interstellar emission

OSO-3 (Third Orbiting Solar Observatory, launched on 1967)



621 events
E > 50 MeV

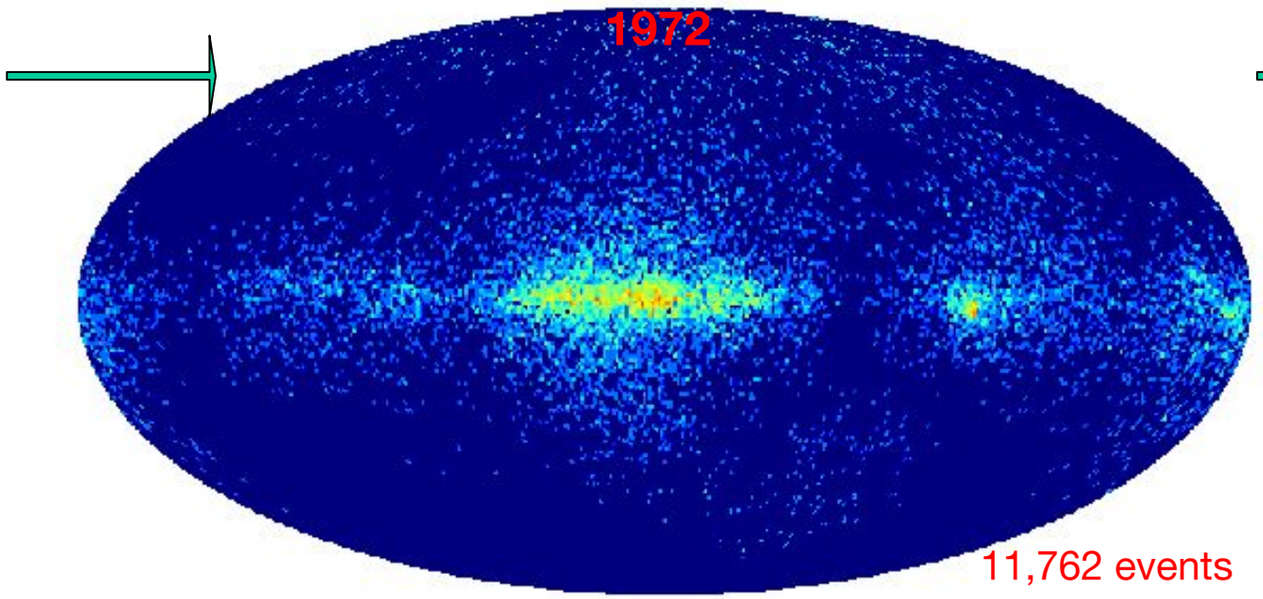
FIG. 8.—Sky map of the γ-ray intensity in galactic coordinates. The element of area on the map to which the formula given in the text applies is approximately 245 square degrees.

Kraushaar *et al.*, ApJ, 1972,177,341

counts per 0.25 degree pixel
sqrt color scaling

x19 second Small Astronomical Satellite E > 50 MeV

1972

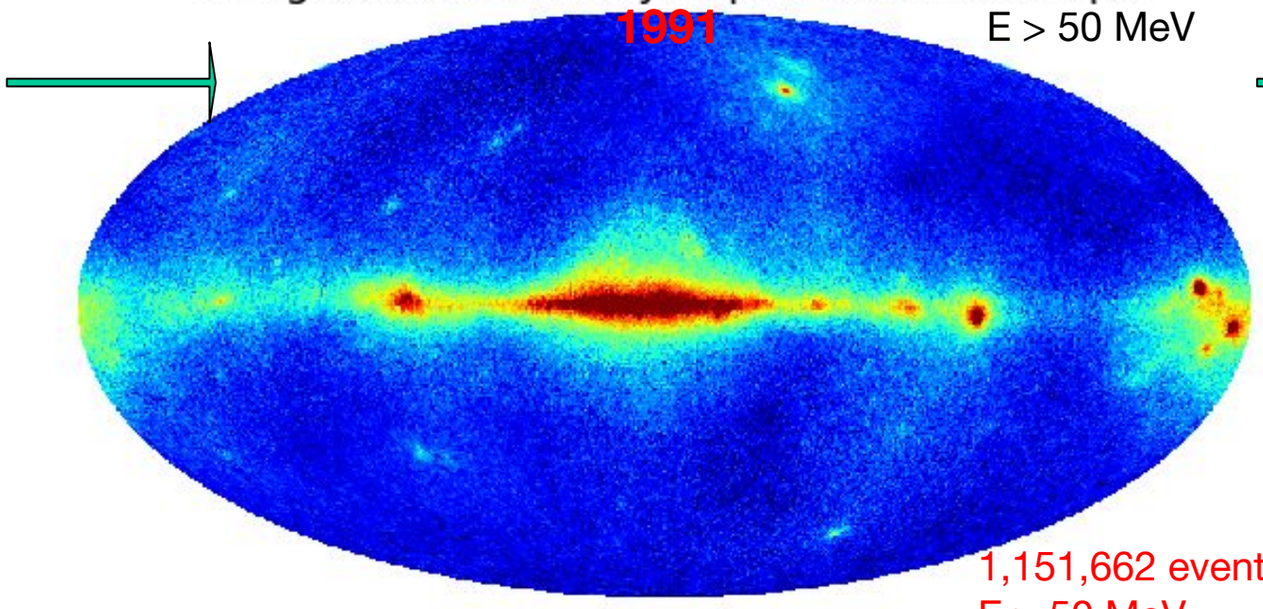


11,762 events
E > 50 MeV

0 1

x6 Energetic Gamma Ray Experiment Telescope

1991



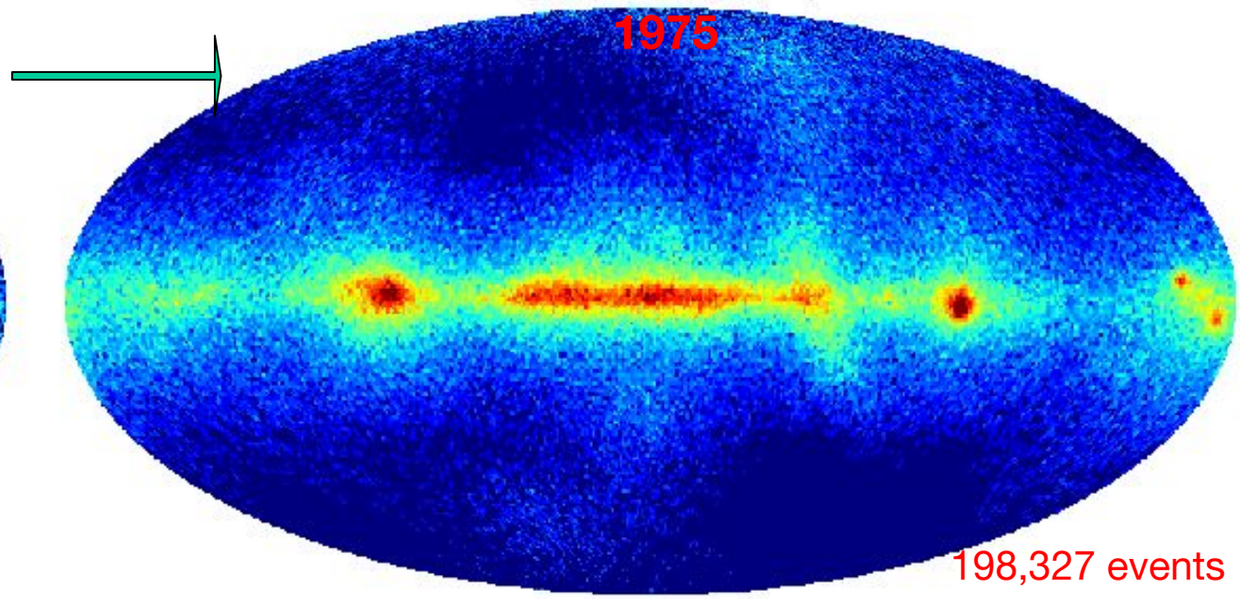
E > 50 MeV

1,151,662 events
E > 50 MeV

0 16

x17 Cosmic ray Satellite ('option B') E > 50 MeV

1975

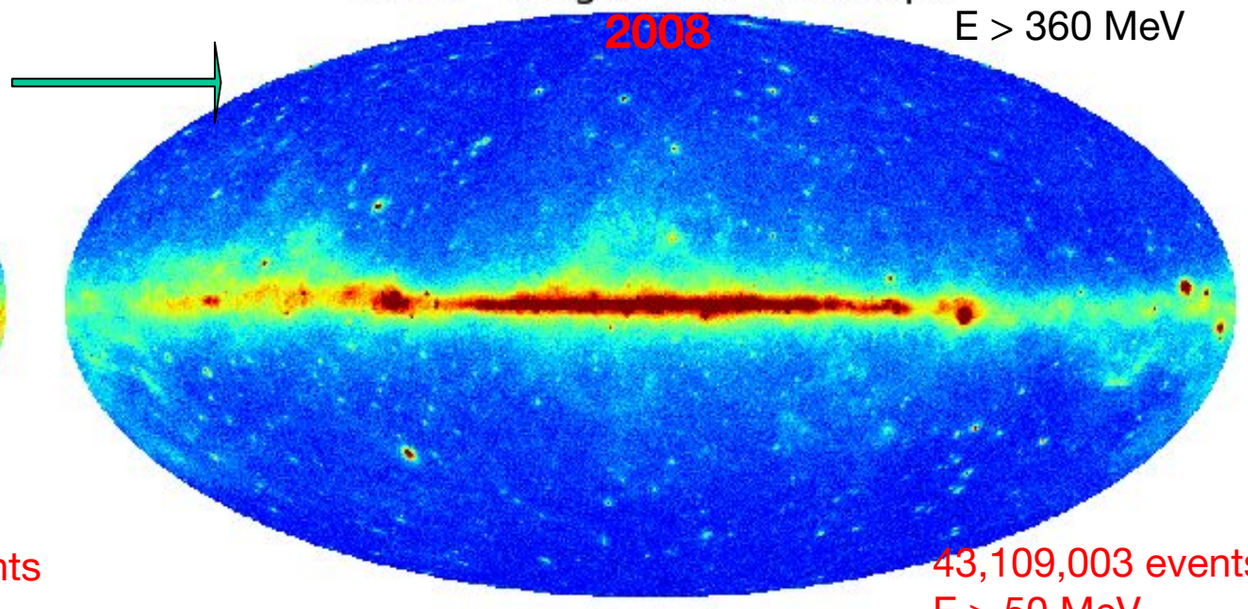


198,327 events
E > 50 MeV

0 4

x37 Fermi - Large Area Telescope

2008



E > 360 MeV

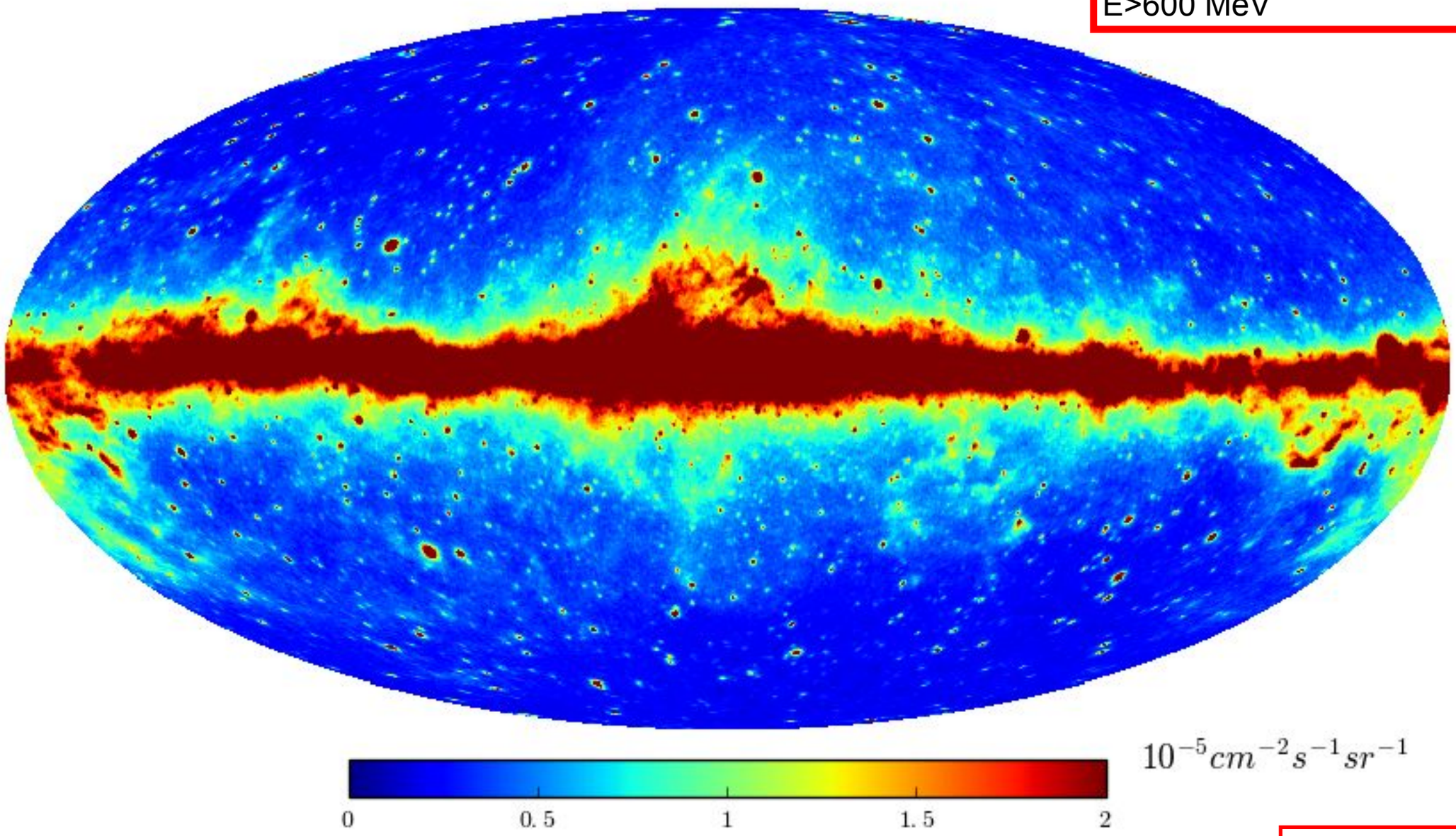
43,109,003 events
E > 50 MeV
diffuse ~60%

0 225

NASA High Energy Astrophysics Science Archive Research Center (HEASARC)

LAT with 8 years of data

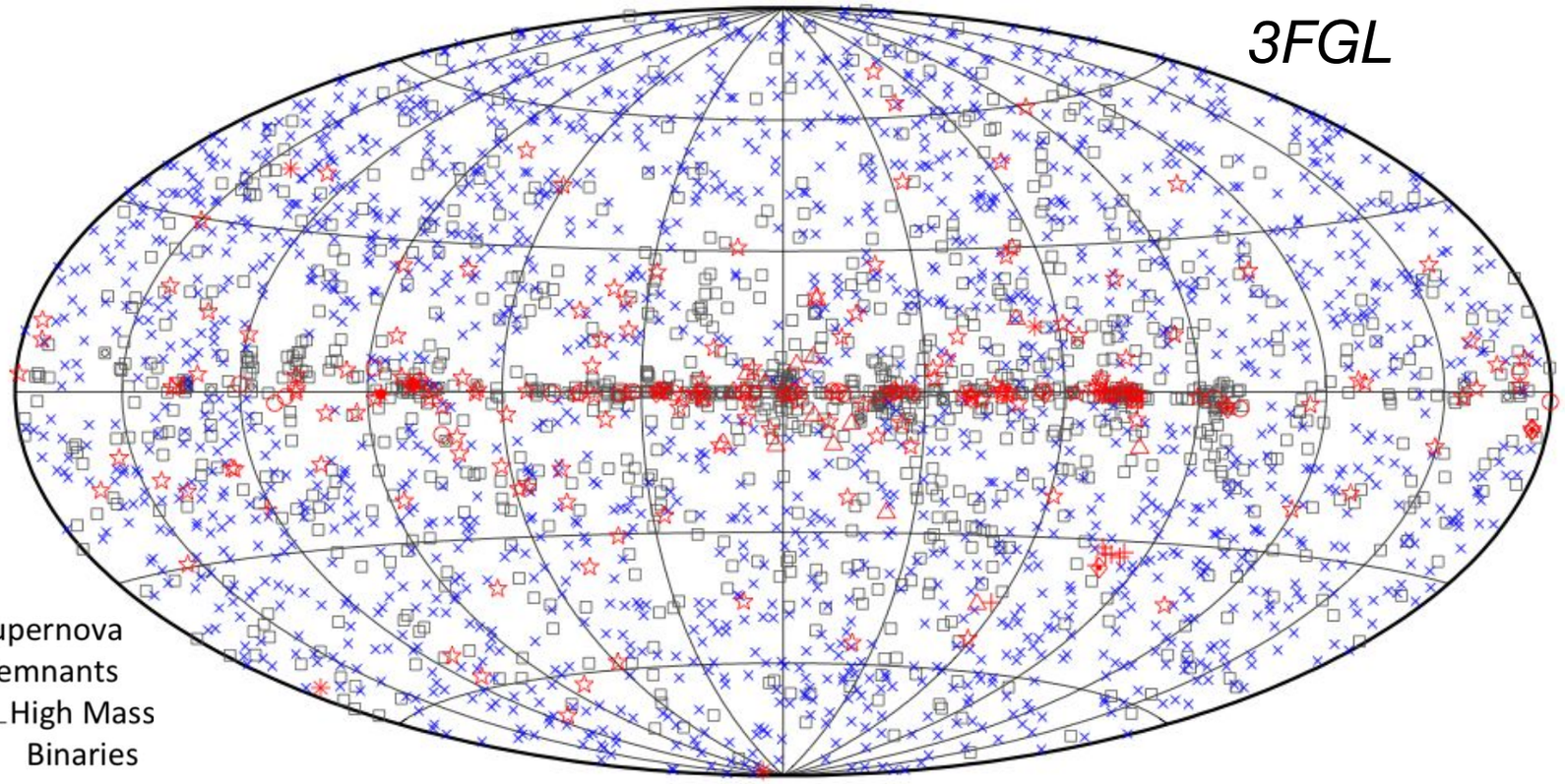
counts per 0.25 degree pixel
linear color scaling
E>600 MeV

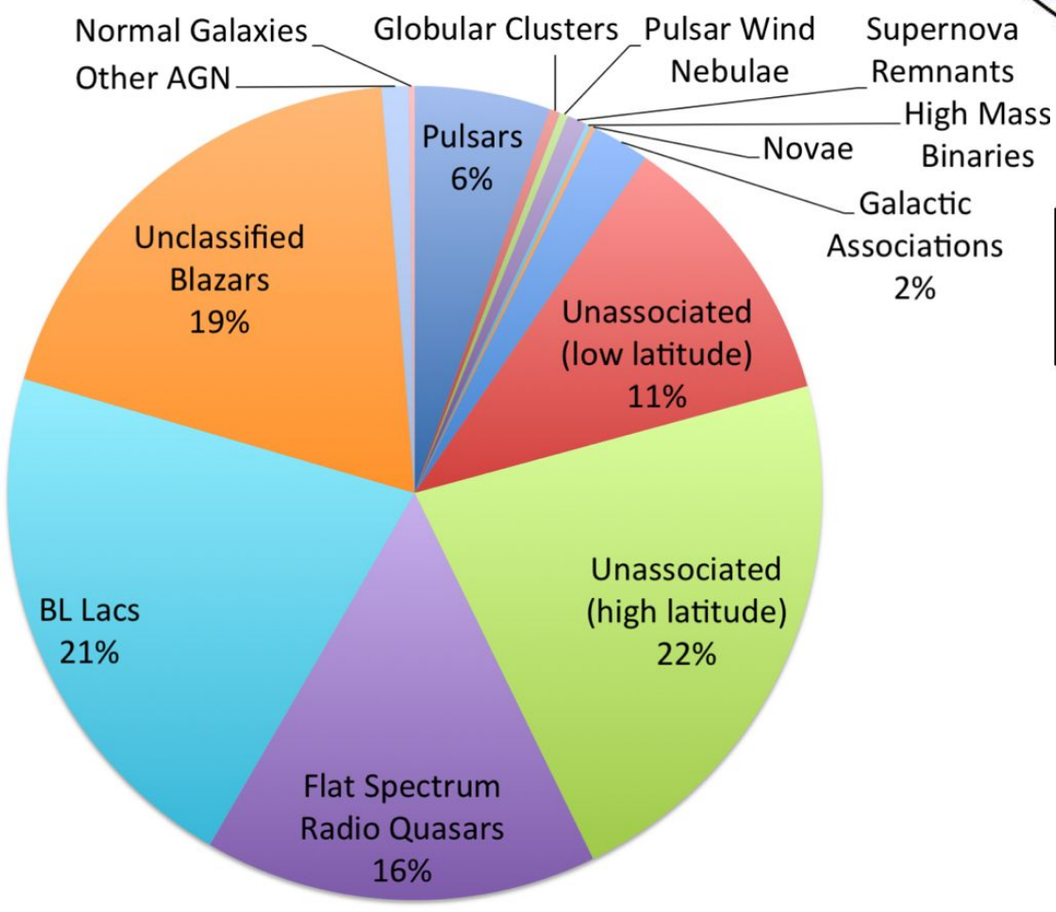


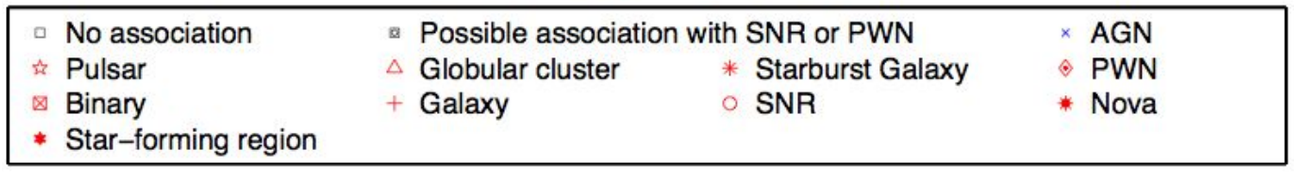
point sources

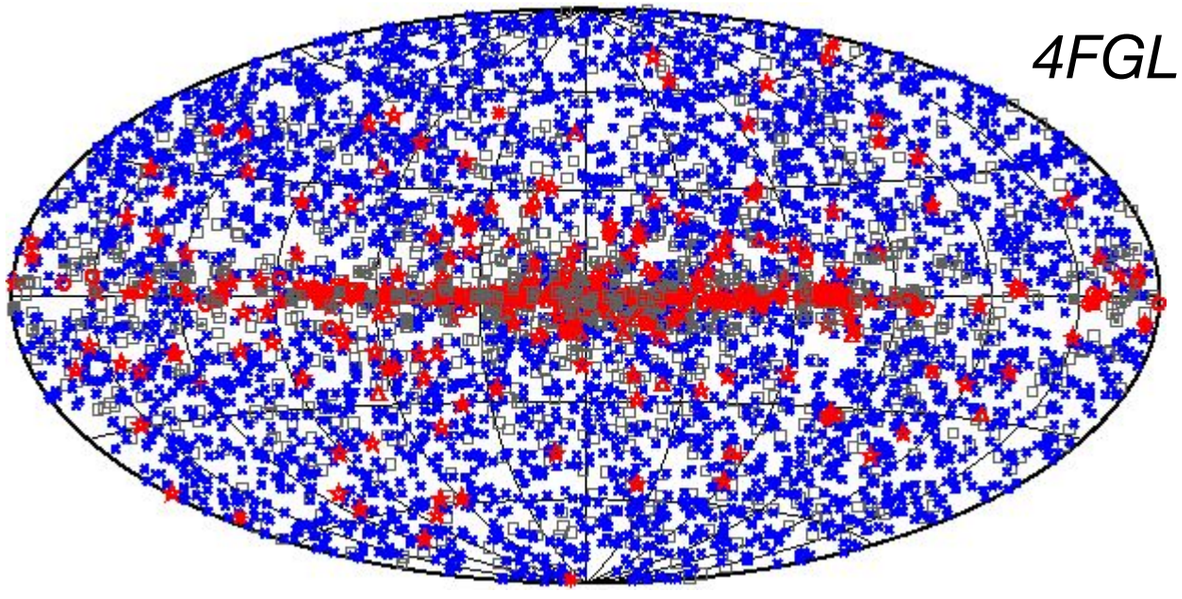
$$N_\gamma = q \times N(H) + stuff$$

3 and 4FGL Catalog: the list of point sources

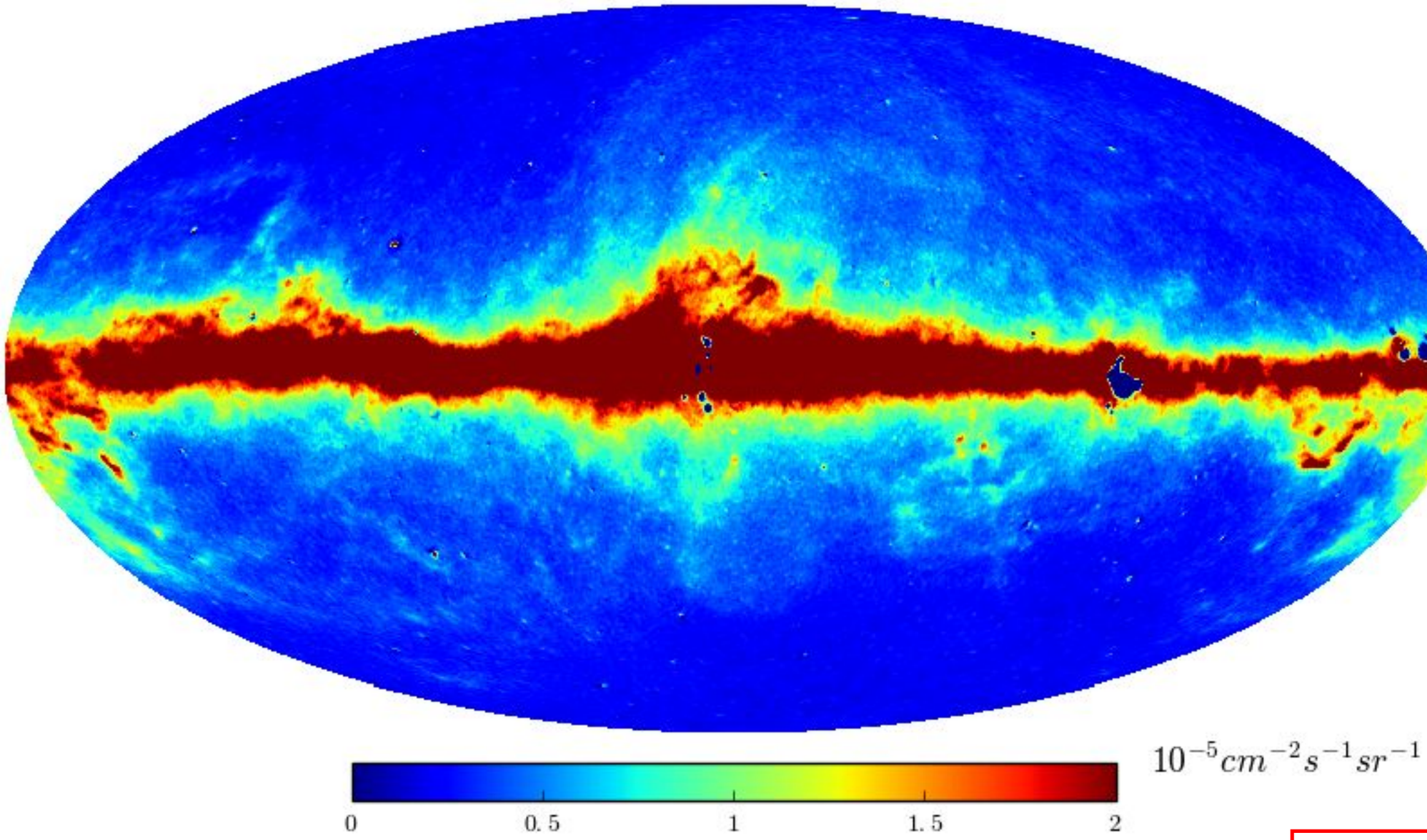








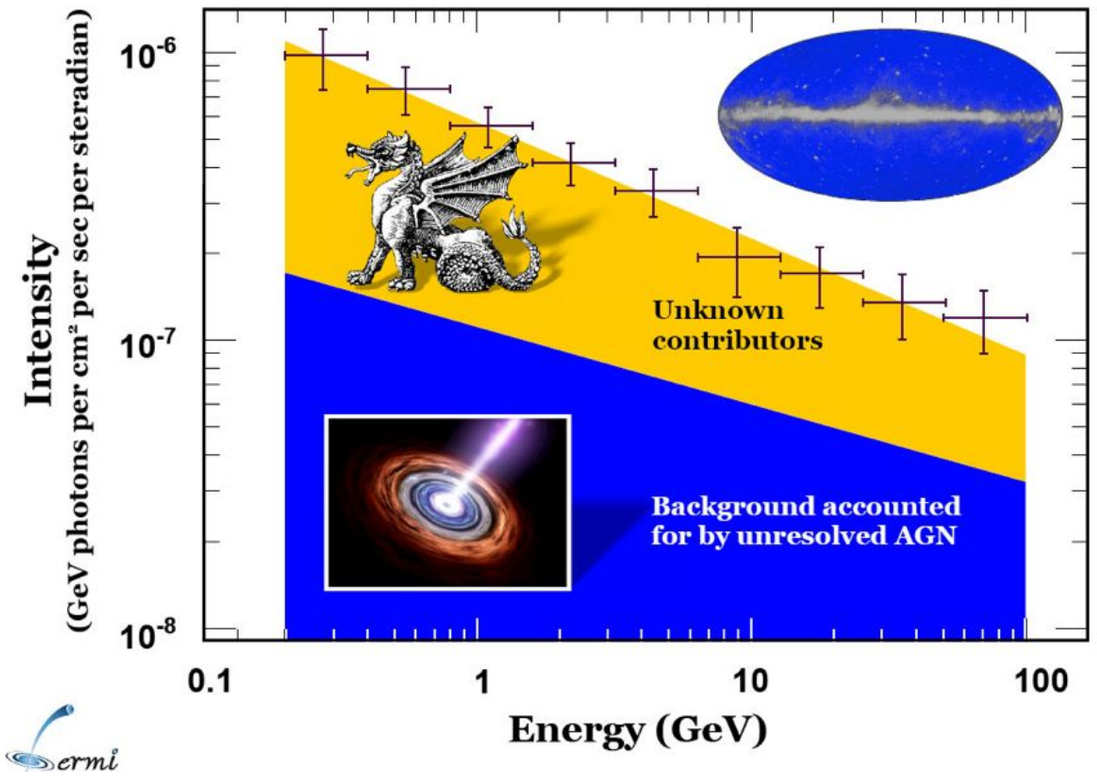
Interstellar emission ?

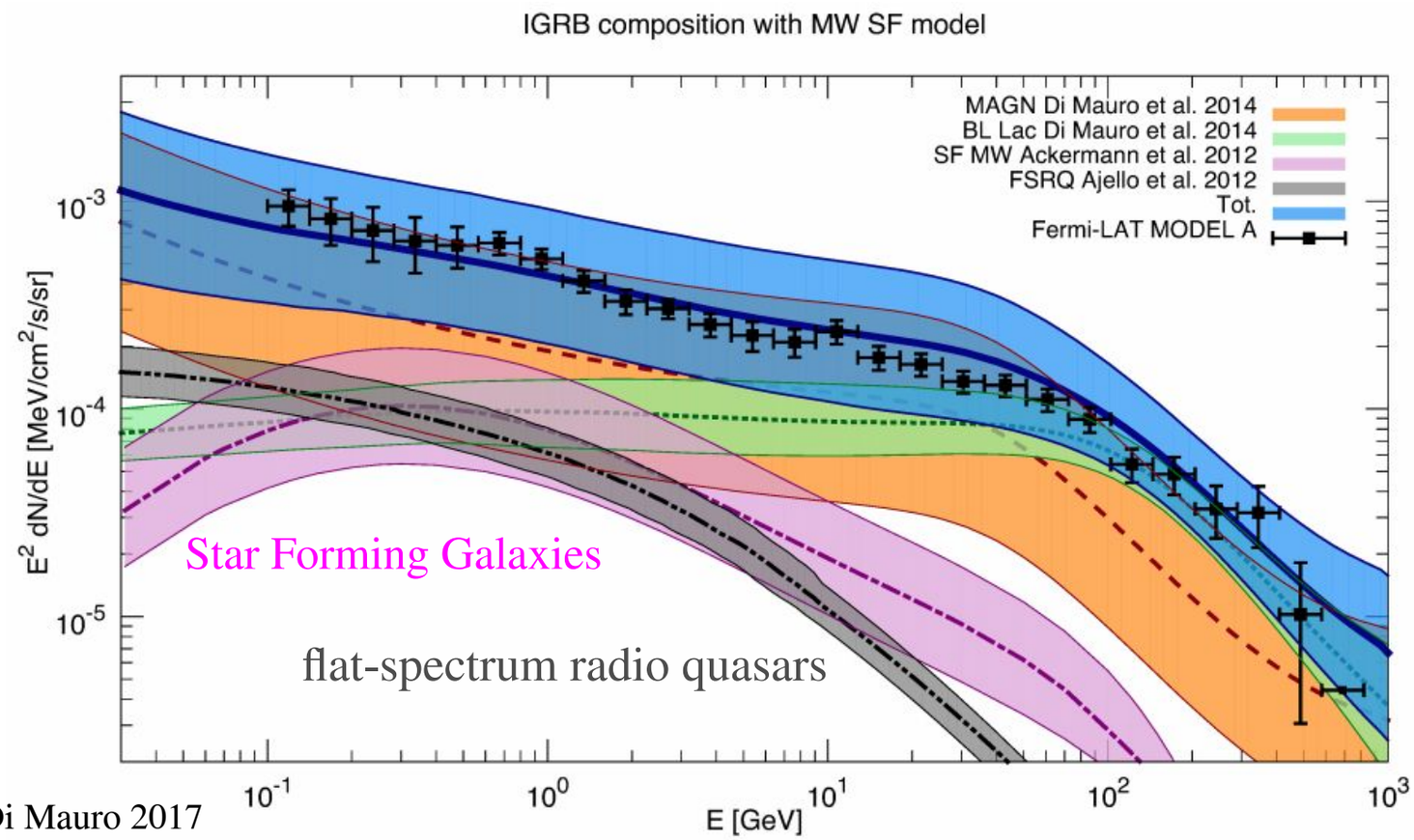


isotropic diffuse
γ-ray background

$$N_\gamma = q \times N(H) + stuff$$

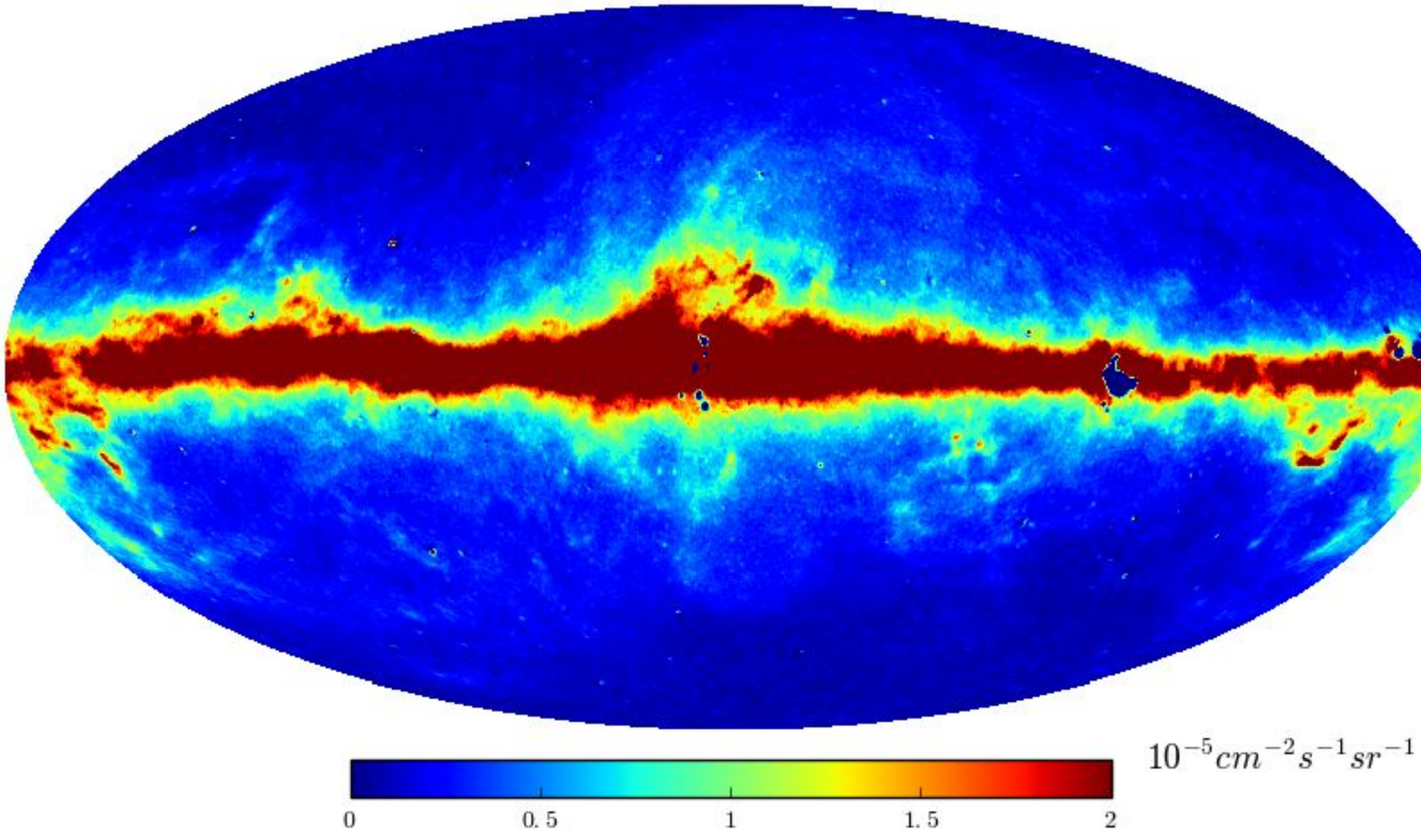
IGRB: γ-ray emission from unresolved extragalactic sources





Di Mauro 2017

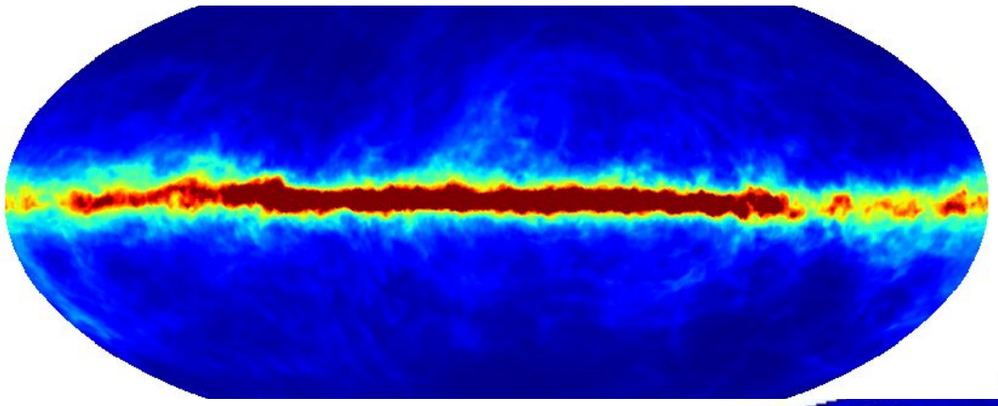
Interstellar emission !

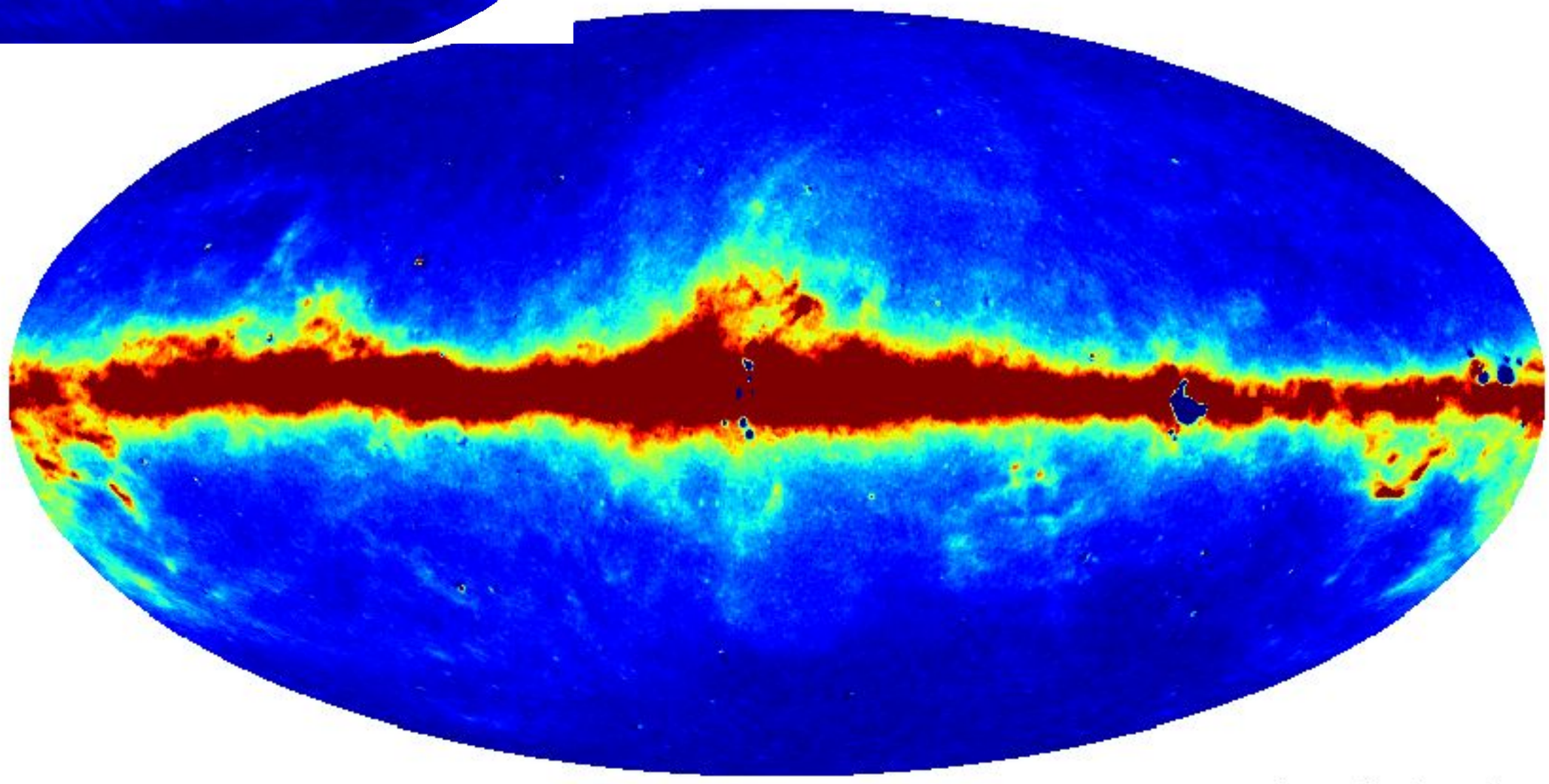


$$N_\gamma = q \times N(H) + stuff$$

Predicted LAT counts derived from LAB radio survey.

Interstellar emission: case of the interaction between CR protons and atomic hydrogen

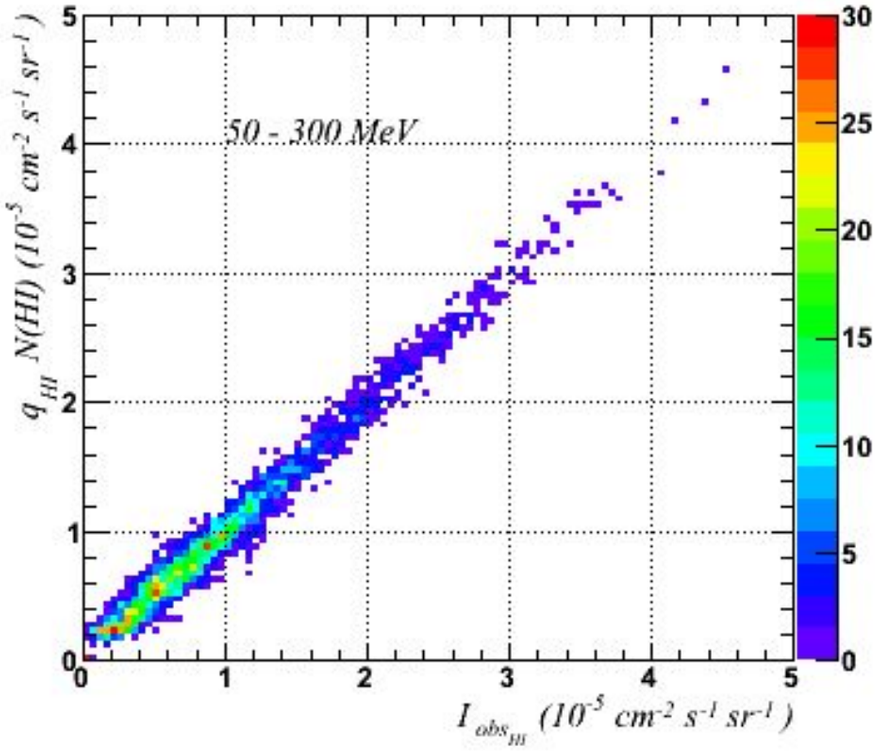


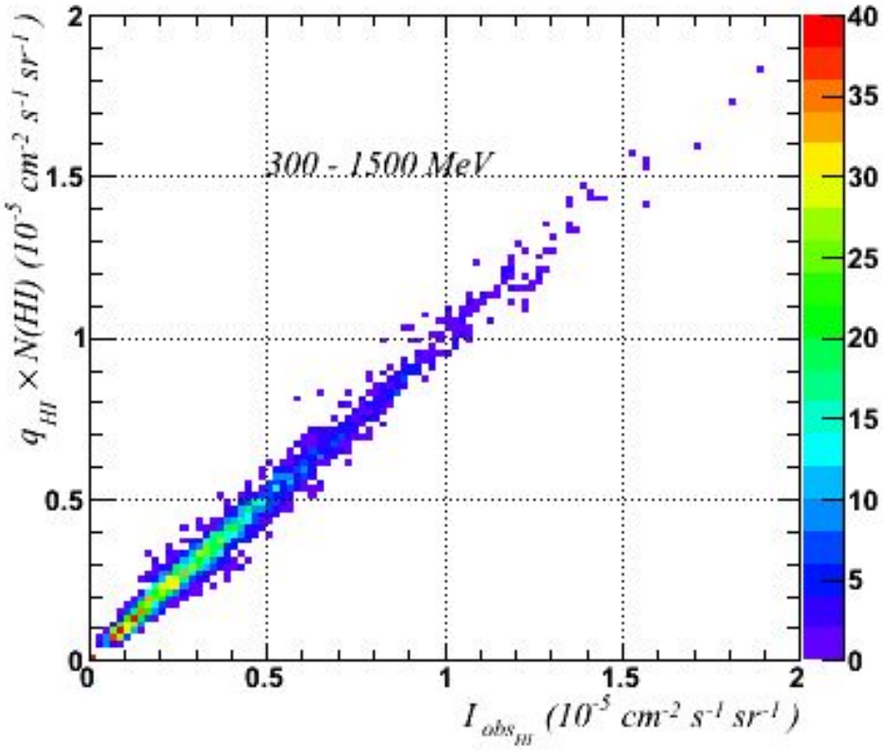


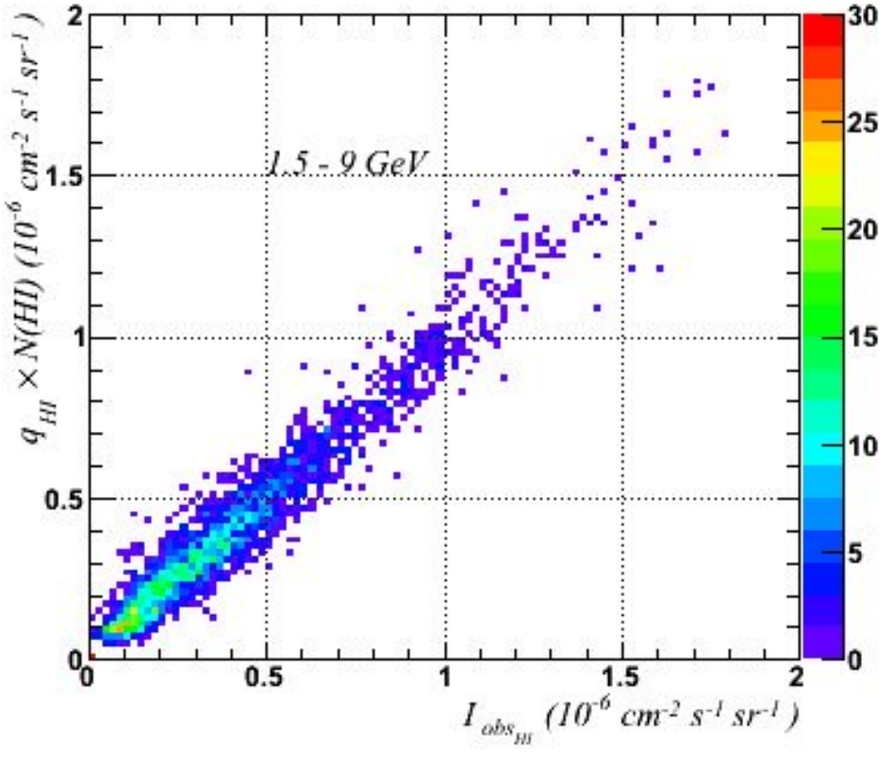
$$N_\gamma = q \times N(H) + stuff$$

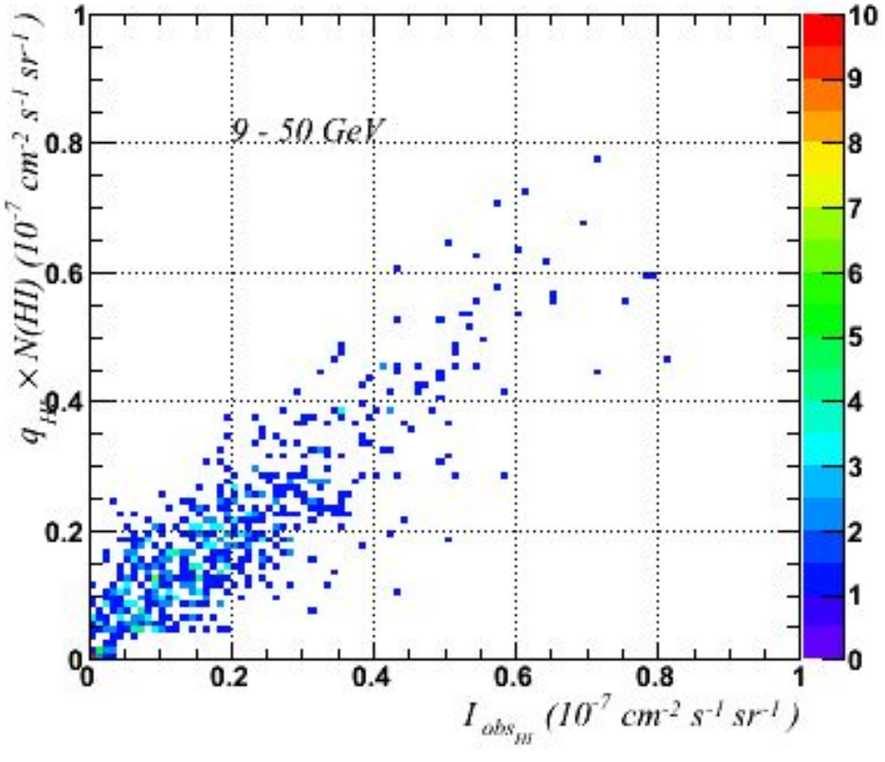
$$q \propto F_{CR} \times \sigma_{pp \to \gamma}$$

Correlation between gammas and H column density





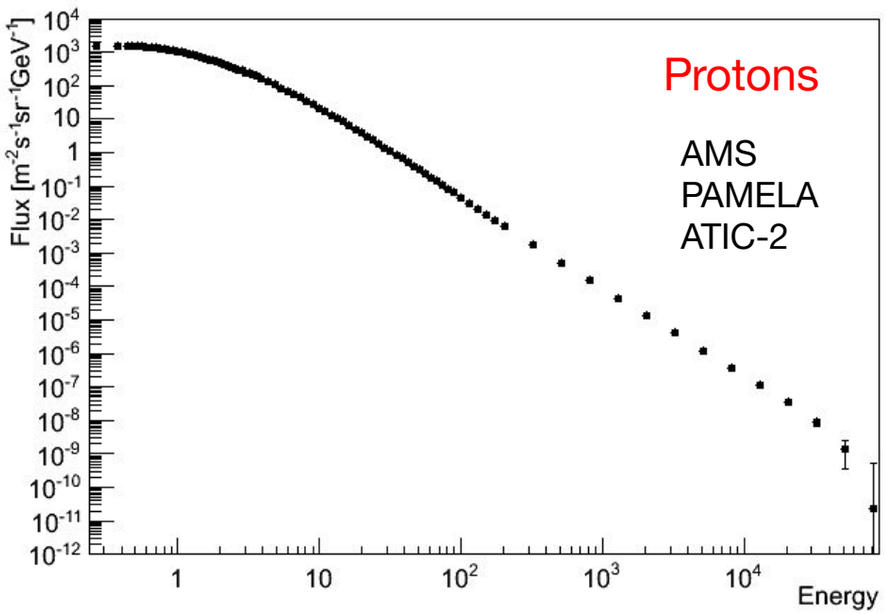


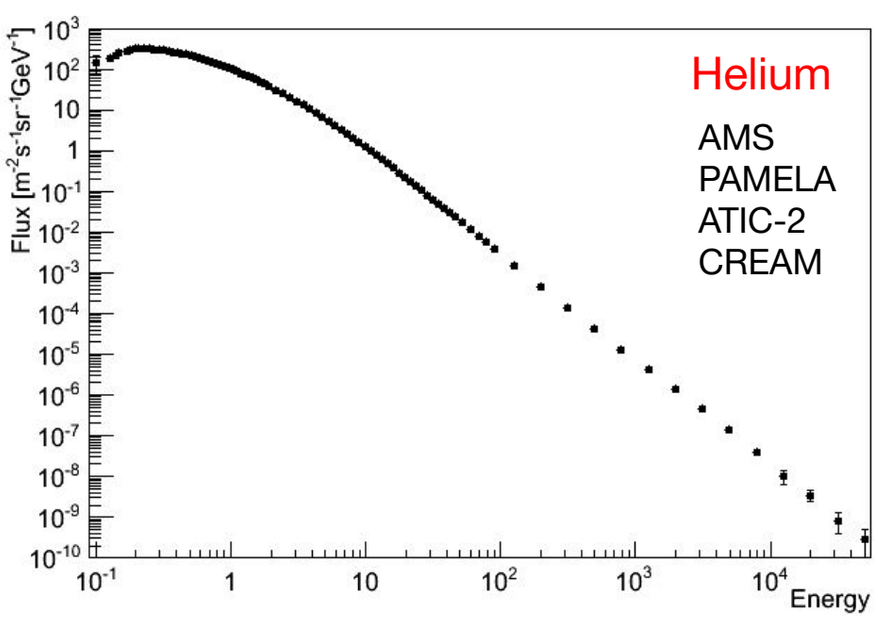


$$q_{HI} \propto F_{CR} \times \sigma_{pp \to \gamma}$$

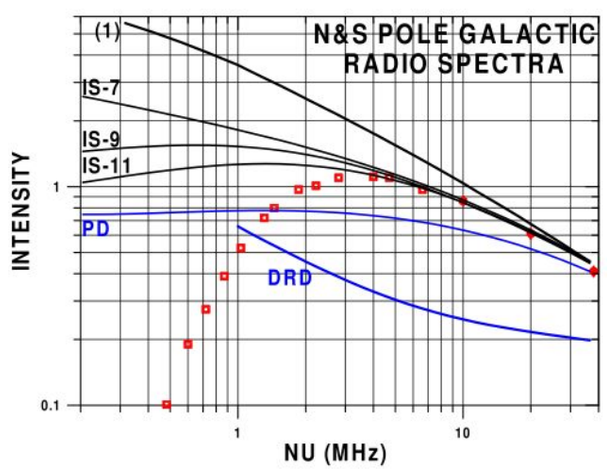
Emissivity calculated from heliospheric fluxes

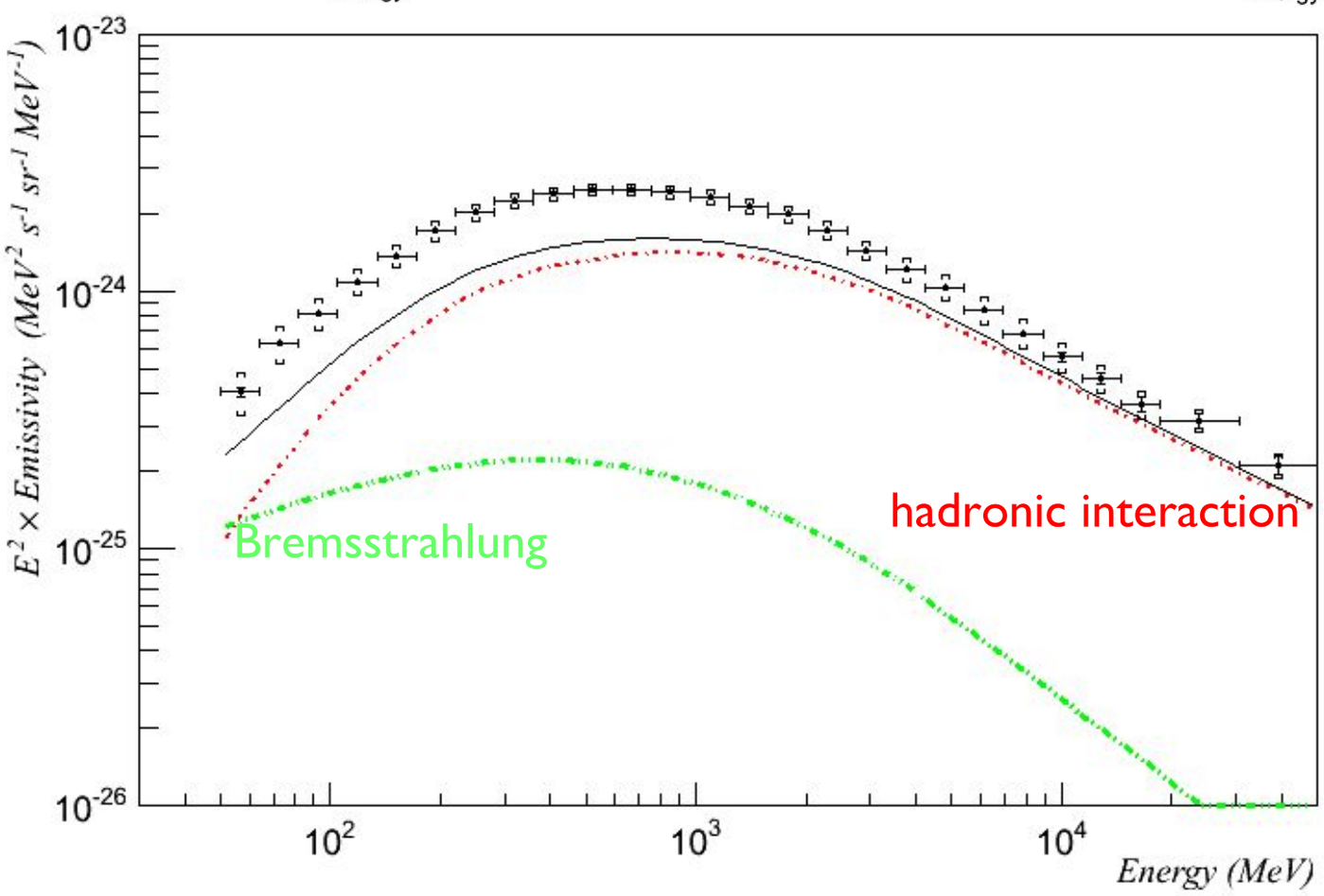
Kamae *et al.*, 2006
Mori *et al.*, 2009





Electron spectrum from synchrotron:



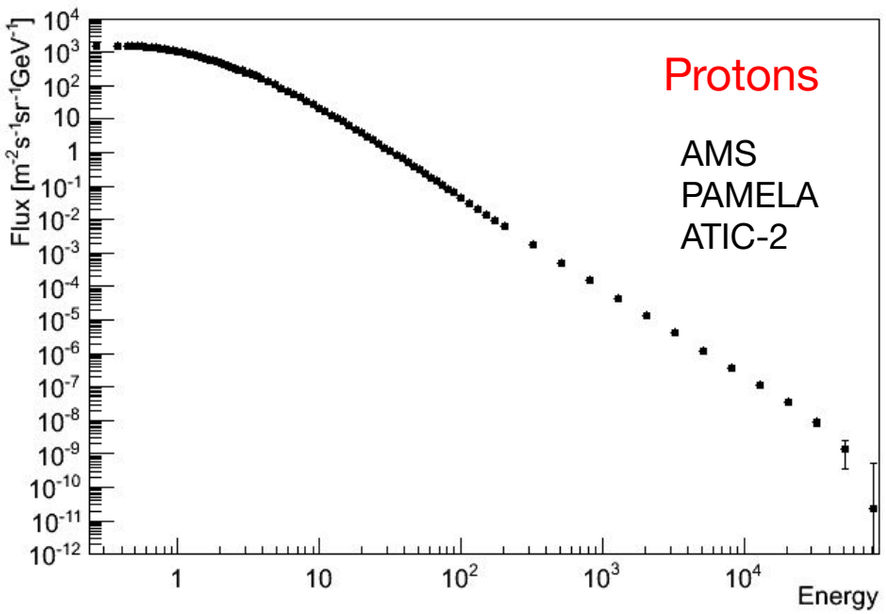


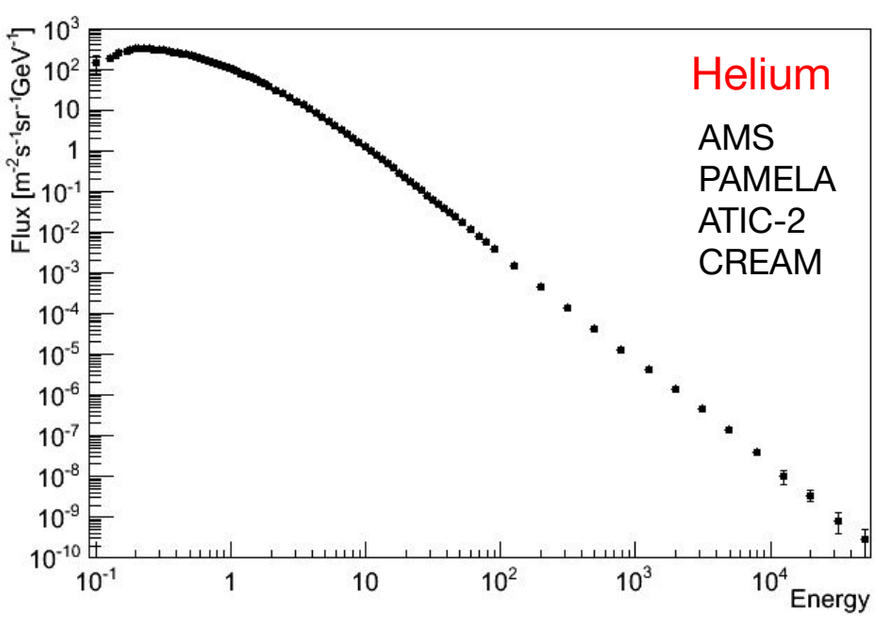
Webber & Higbie 2008, JGR, 113, 11106

$$q_{HI} \propto F_{CR} \times \sigma_{pp \to \gamma}$$

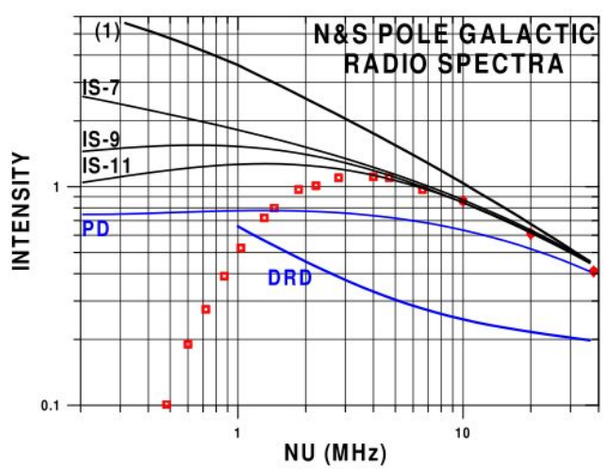
Emissivity calculated from heliospheric fluxes

Kamae *et al.*, 2006
Mori *et al.*, 2009

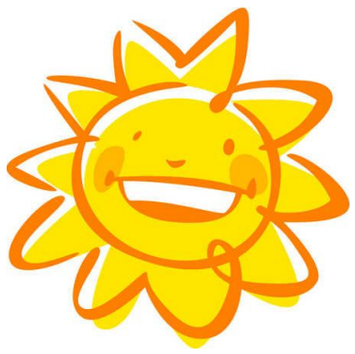


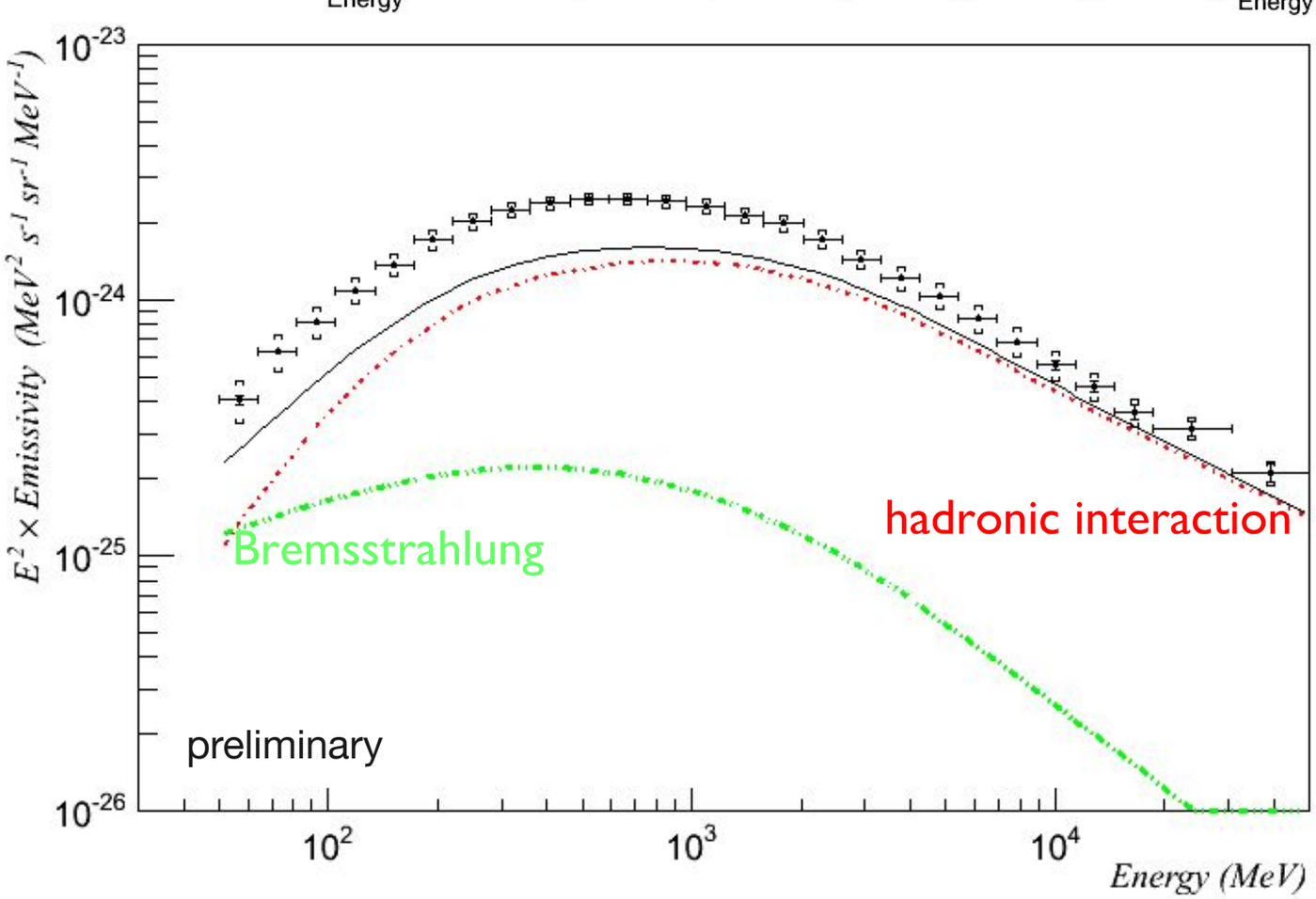


Electron spectrum from synchrotron:



Solar modulation !



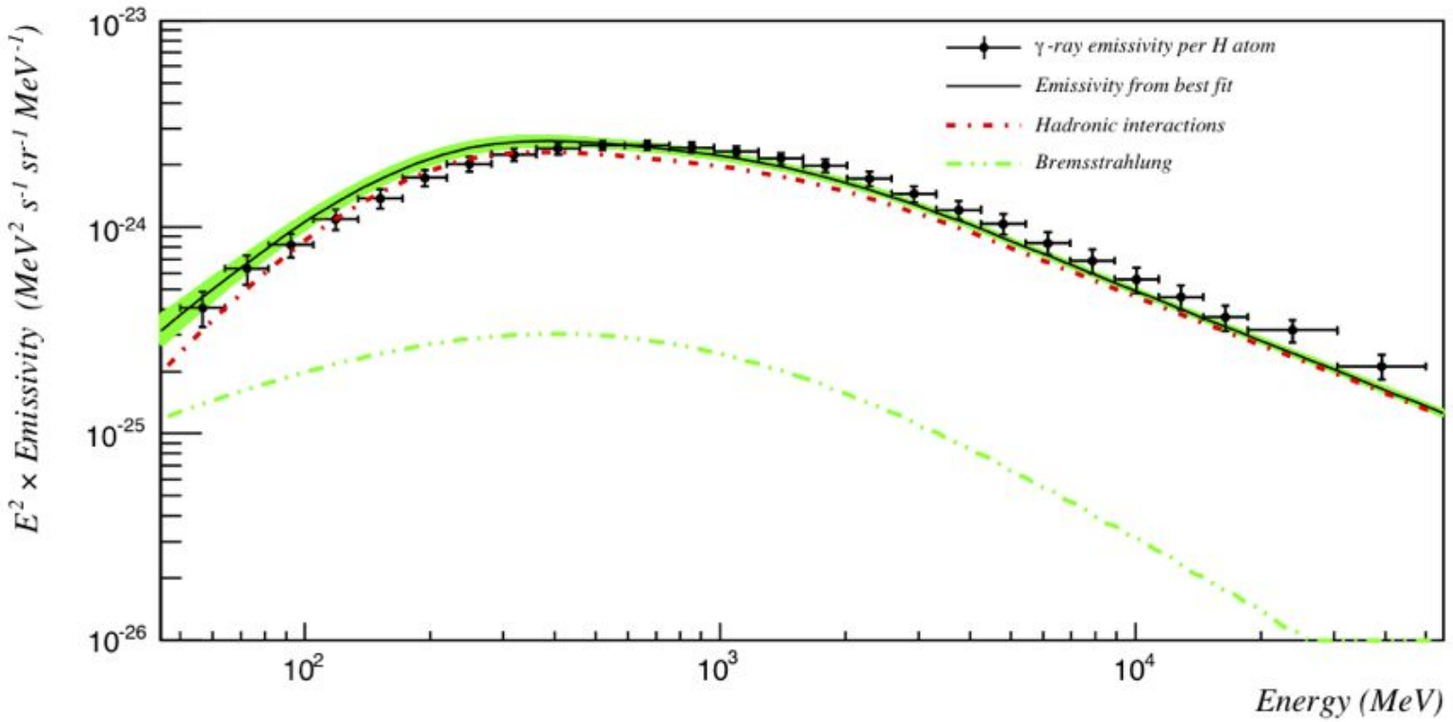


Webber & Higbie 2008, JGR, 113, 11106

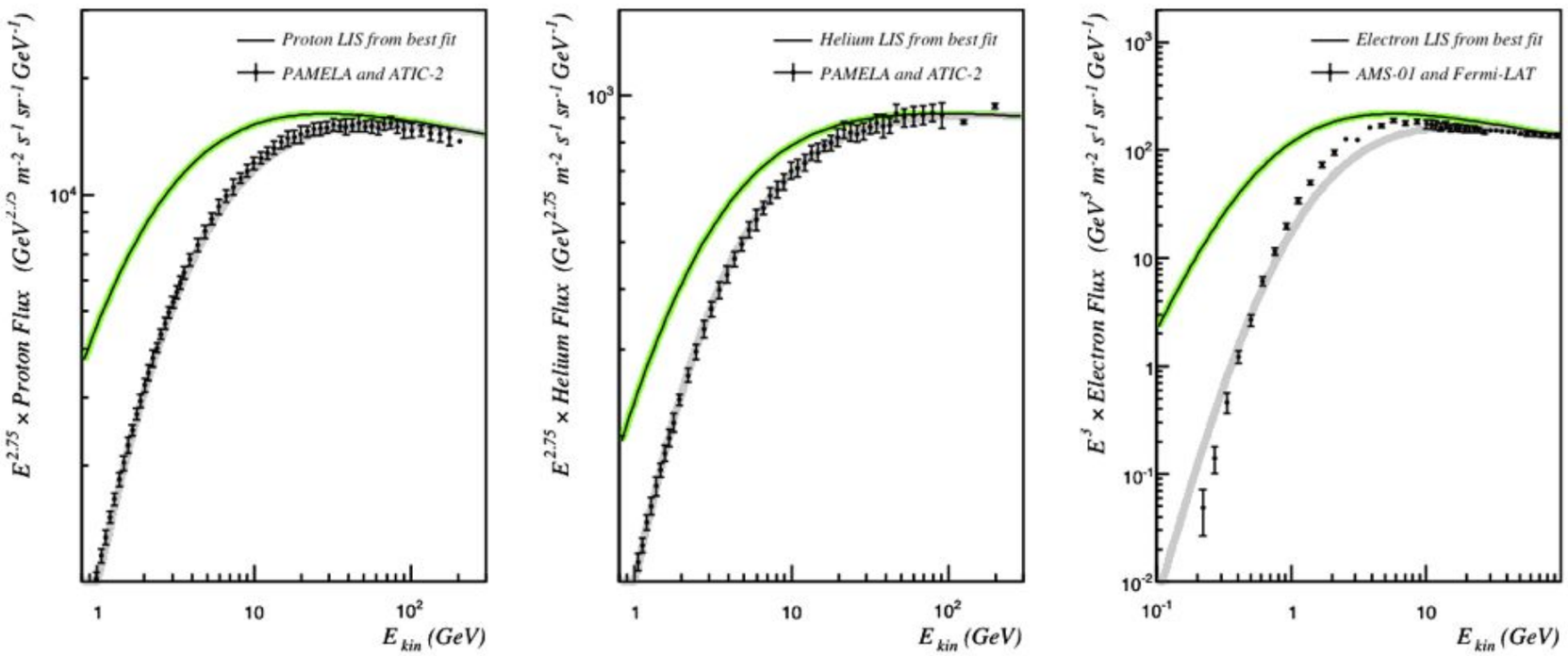
$$\frac{J(r,\mathfrak{E},t)}{\mathfrak{E}^2 - \mathfrak{E}_0^2} = \frac{J(\infty,\mathfrak{E}+\Phi)}{(\mathfrak{E}+\Phi)^2 - \mathfrak{E}_0^2}$$

Force field approximation
Gleeson, Axford, 1968

Emissivity: a way to derive the CR fluxes

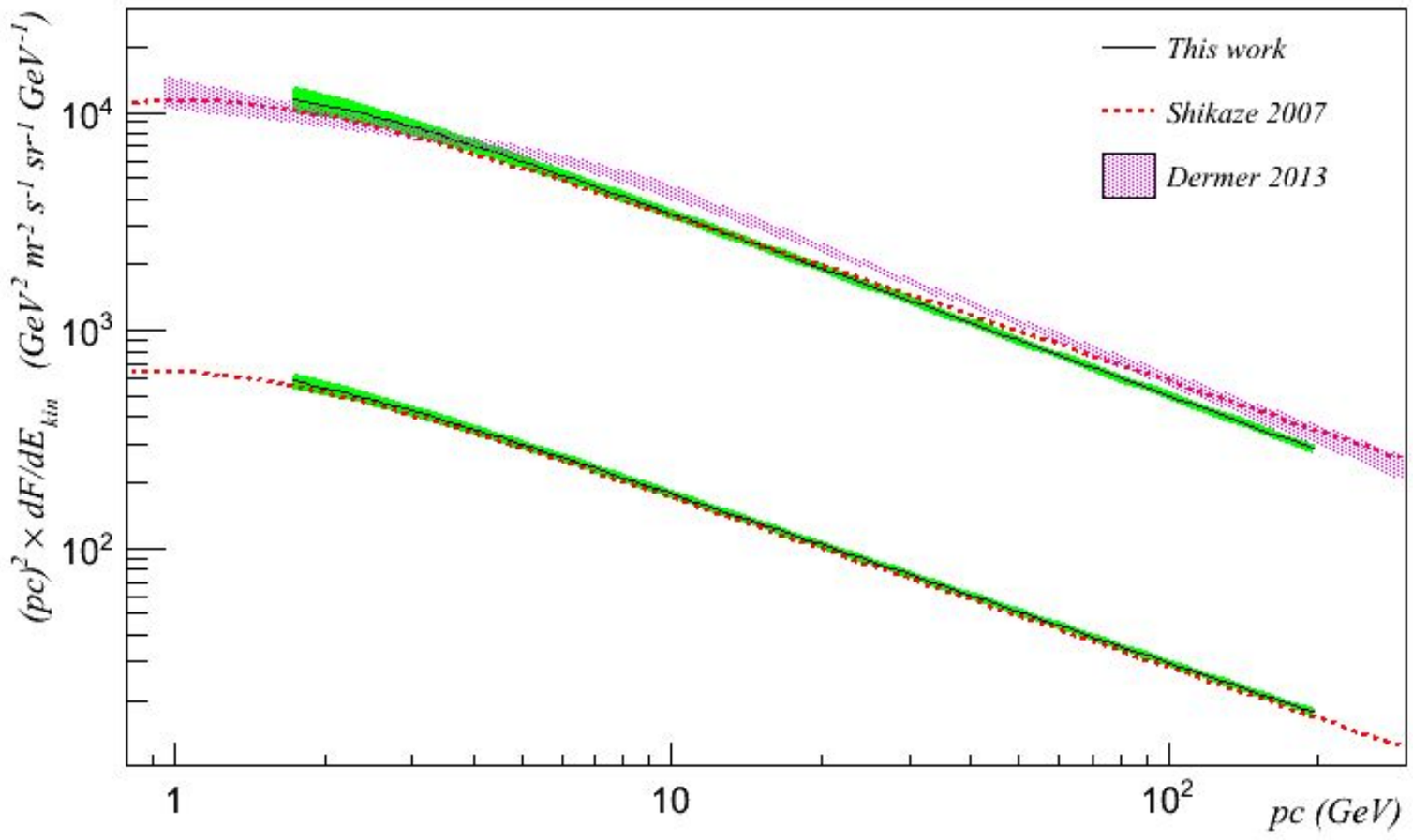


casandjian 2015



Emissivity: a way to derive the CR fluxes

p and He flux from a fit to the LAT and PAMELA

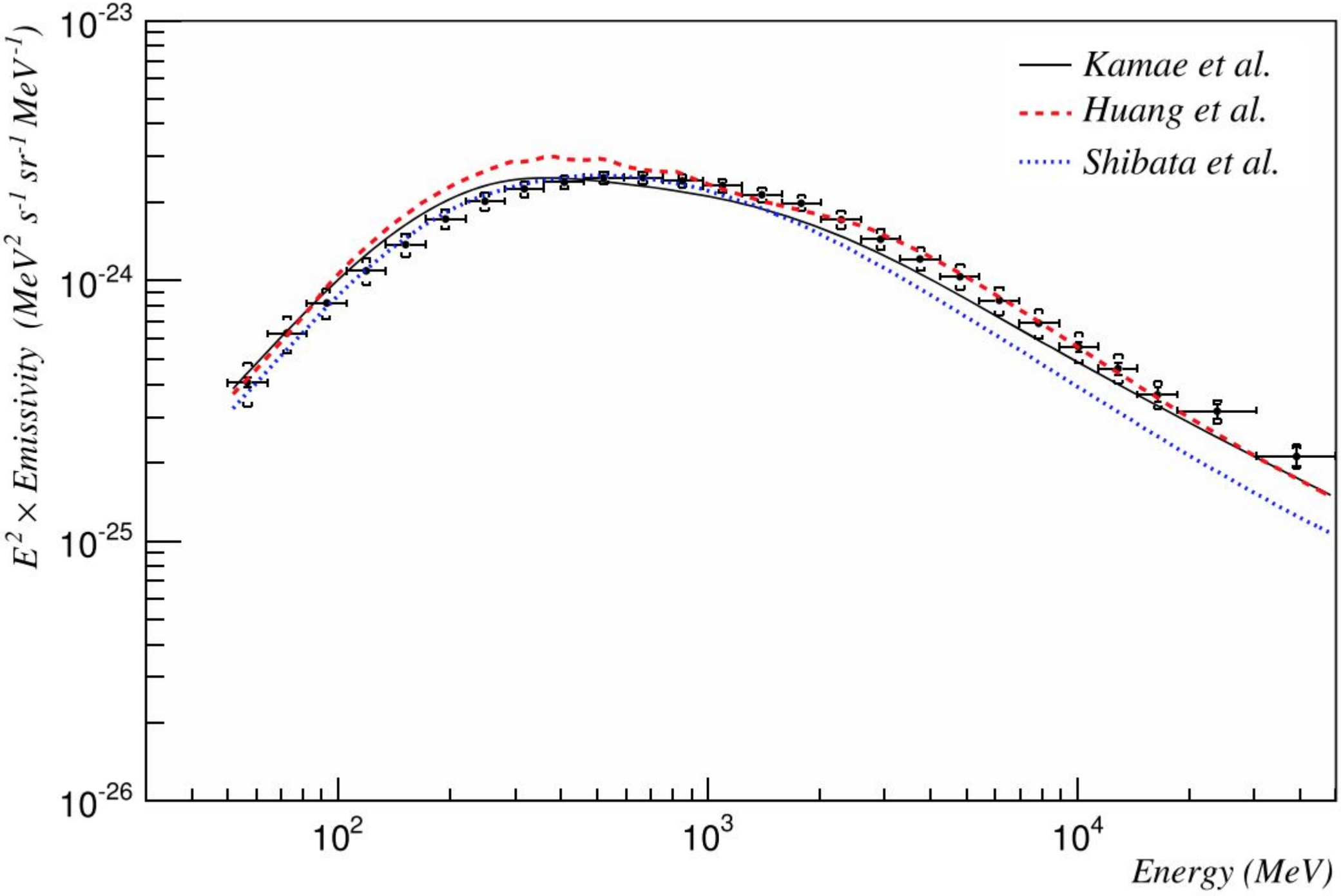


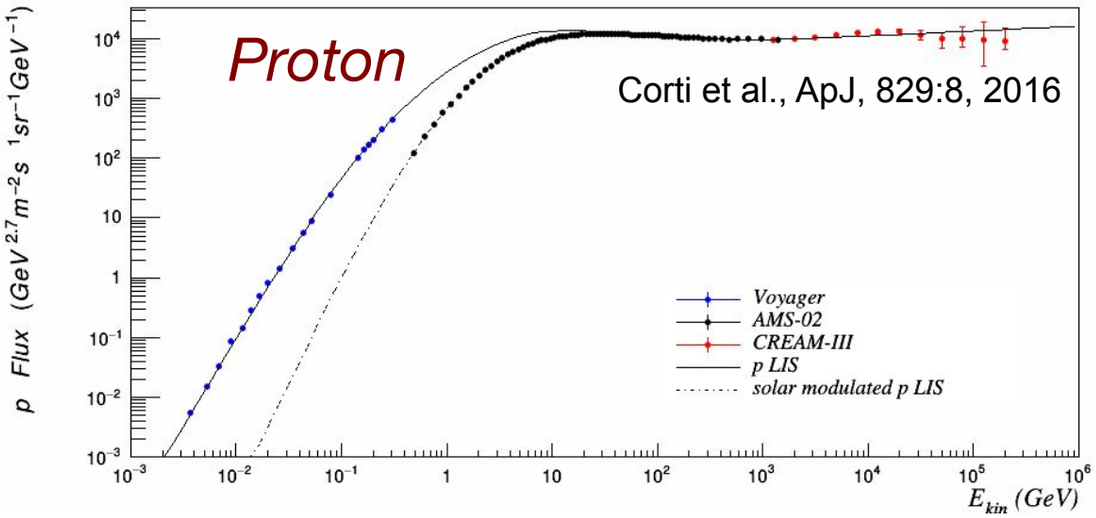
casandjian 2015

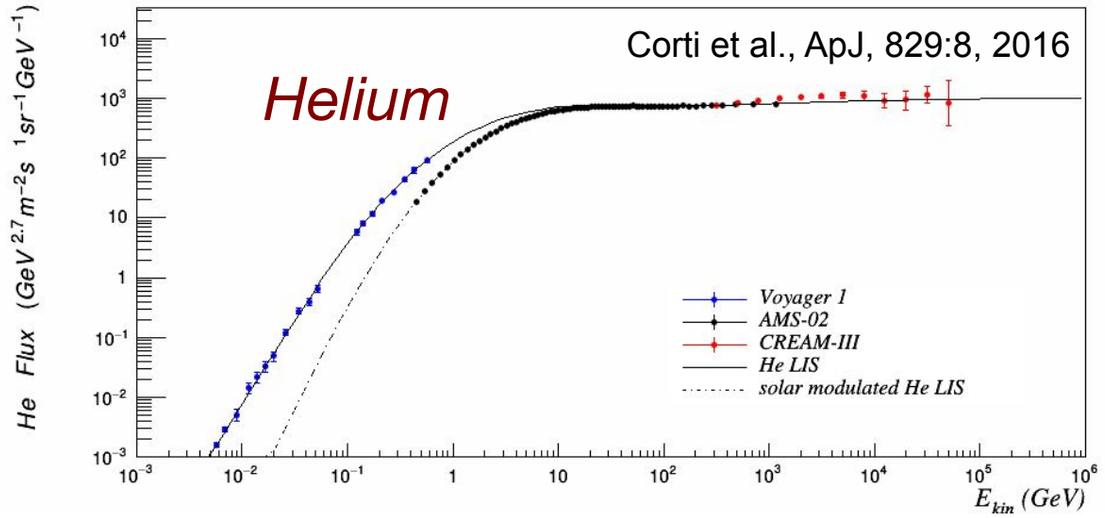
Galactocentric distance (kpc)

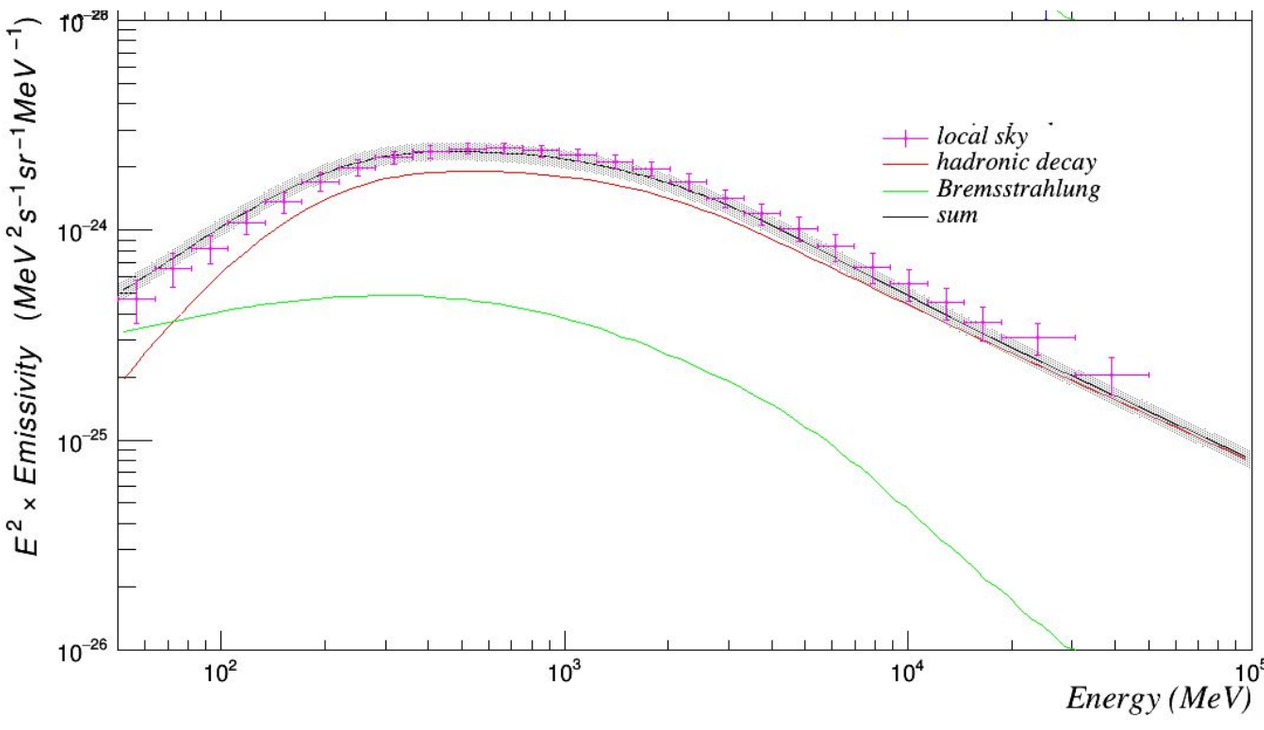
Power-law, as predicted by the diffusive shock acceleration

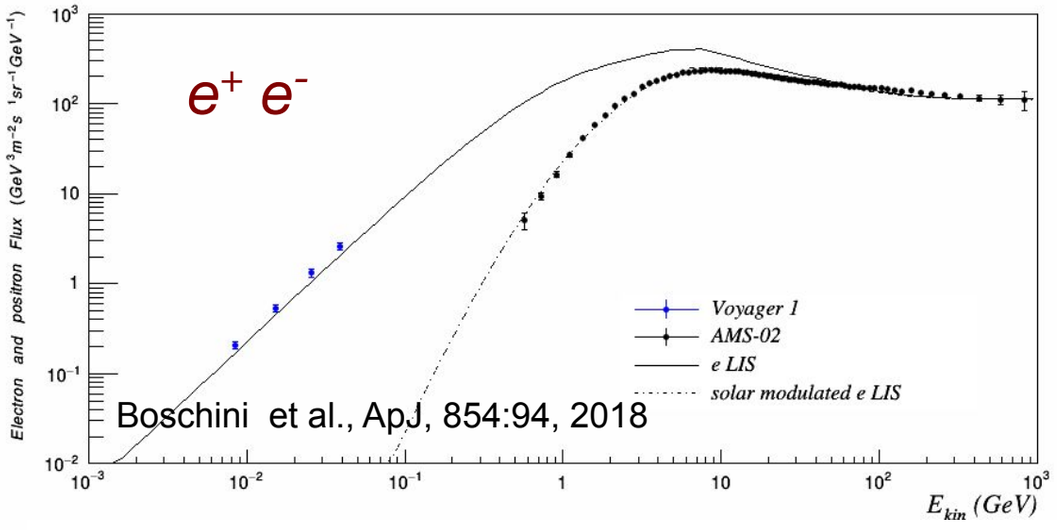
Emissivity prediction for different cross-sections











Here cross-section with heavy nuclei was scaled from p-p cross-section.

Production of secondary particles and nuclei in cosmic rays collisions with the interstellar gas using the FLUKA code

Mazziotta et al. , 2016

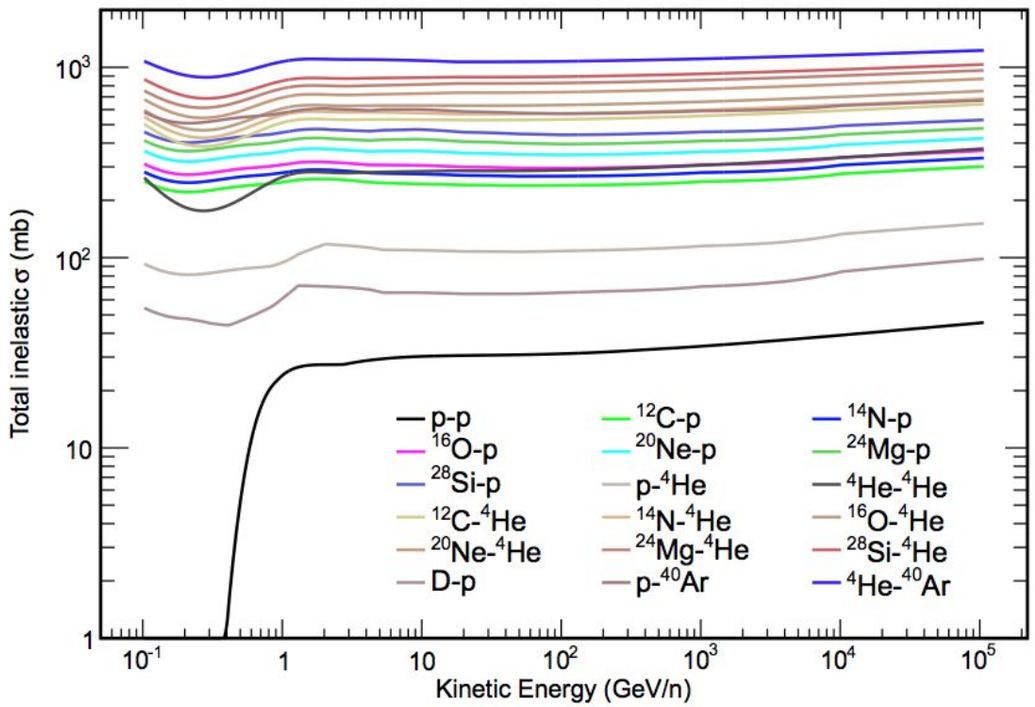


Figure 1: Total inelastic cross sections as a function of the energy per nucleon of the incoming projectile. The plot shows the cross sections for all the projectile-target pairs studied in the present work.

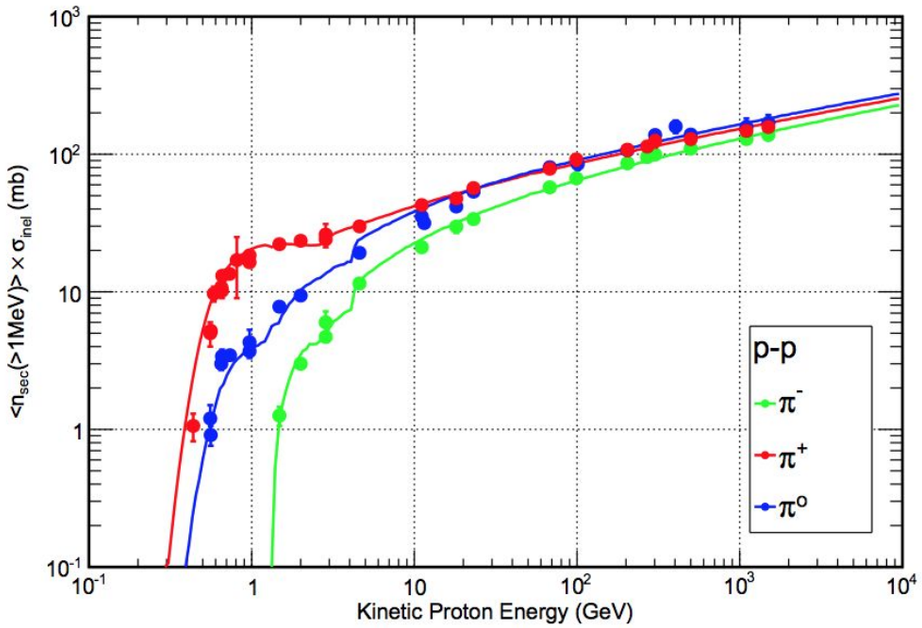
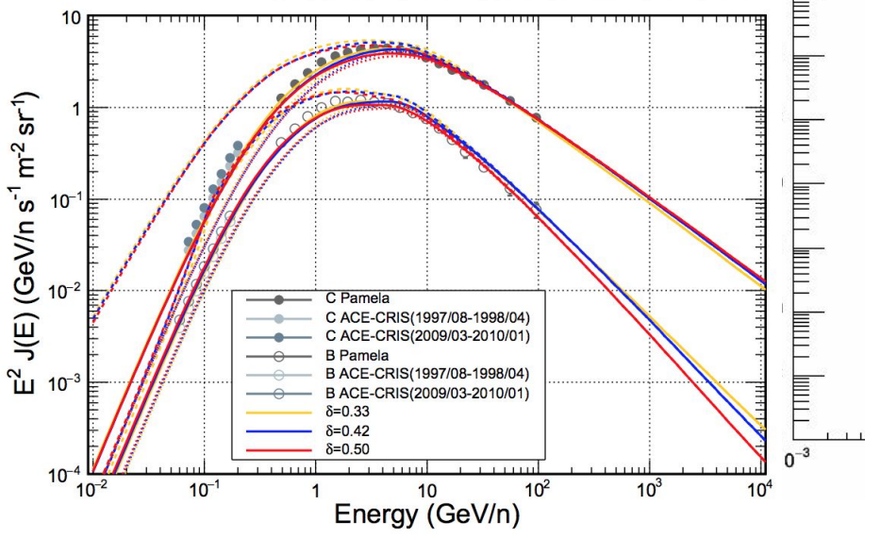
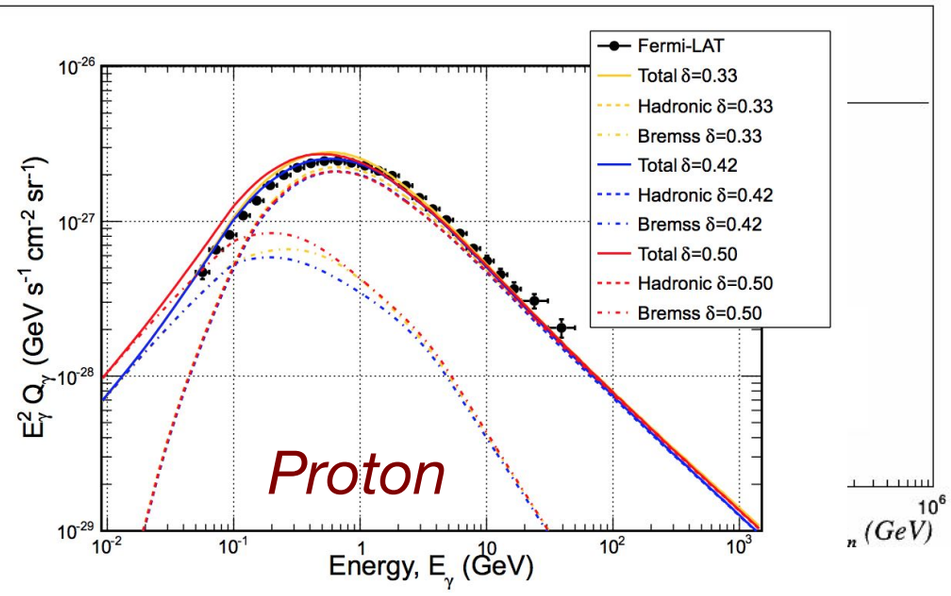
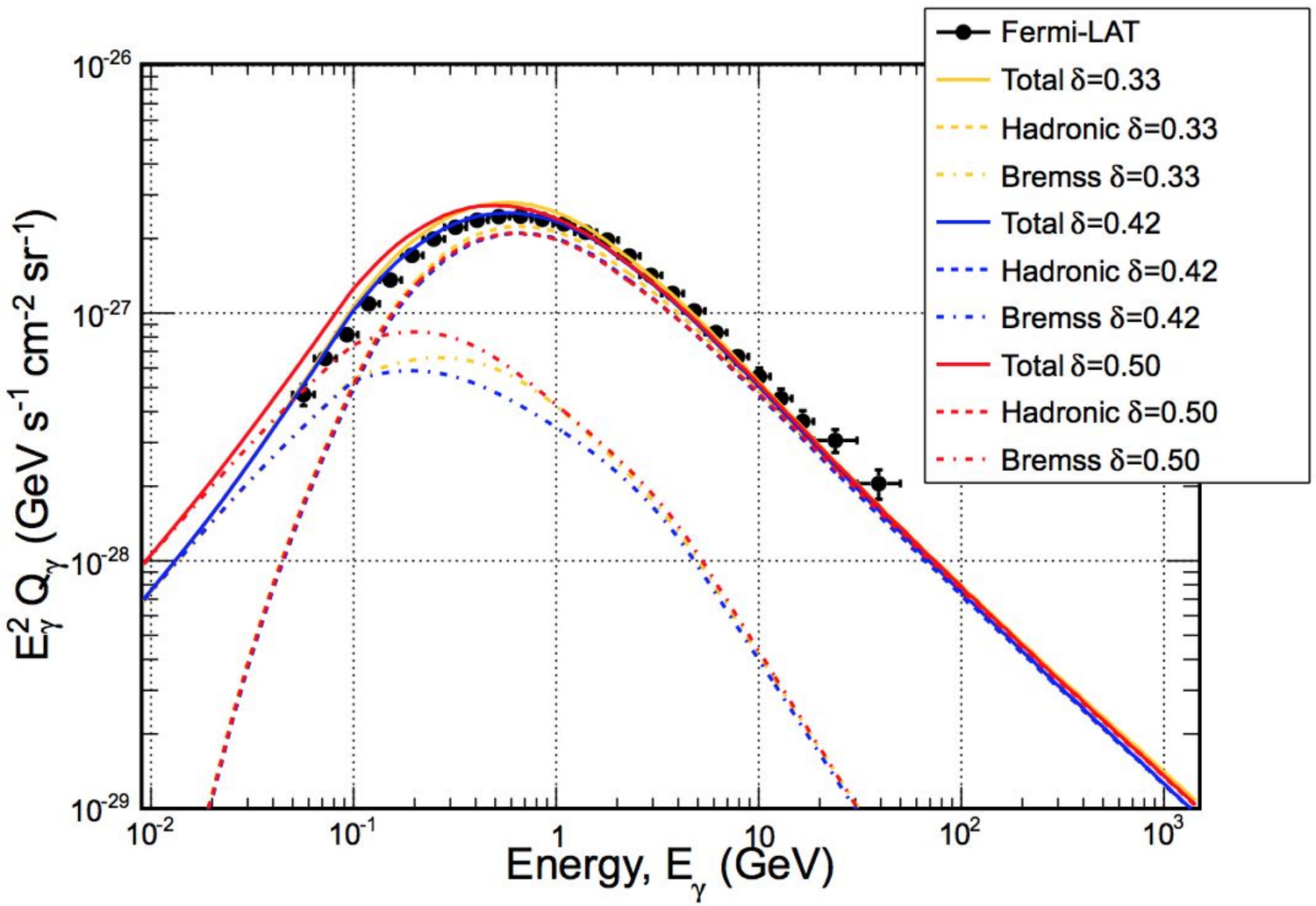


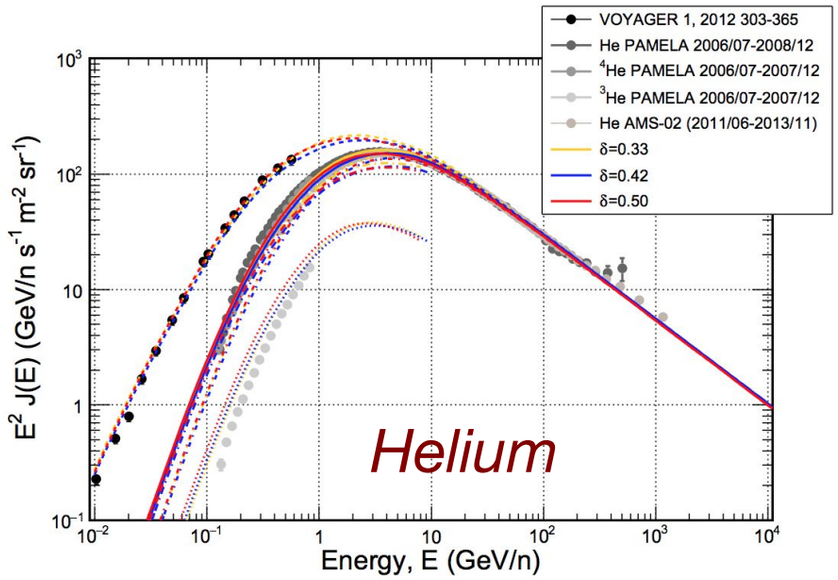
Figure 2: Inclusive cross sections for the production of π^0 (blue), π^+ (red) and π^- (green) in $p-p$ collision as function of the incoming proton kinetic energy. Lines: FLUKA simulation; points: data from Ref. [28].

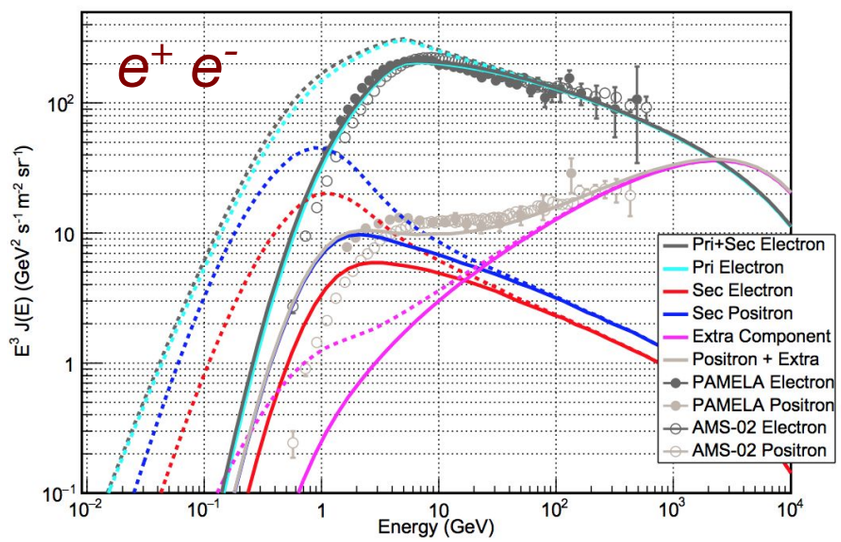
Carbon and Boron



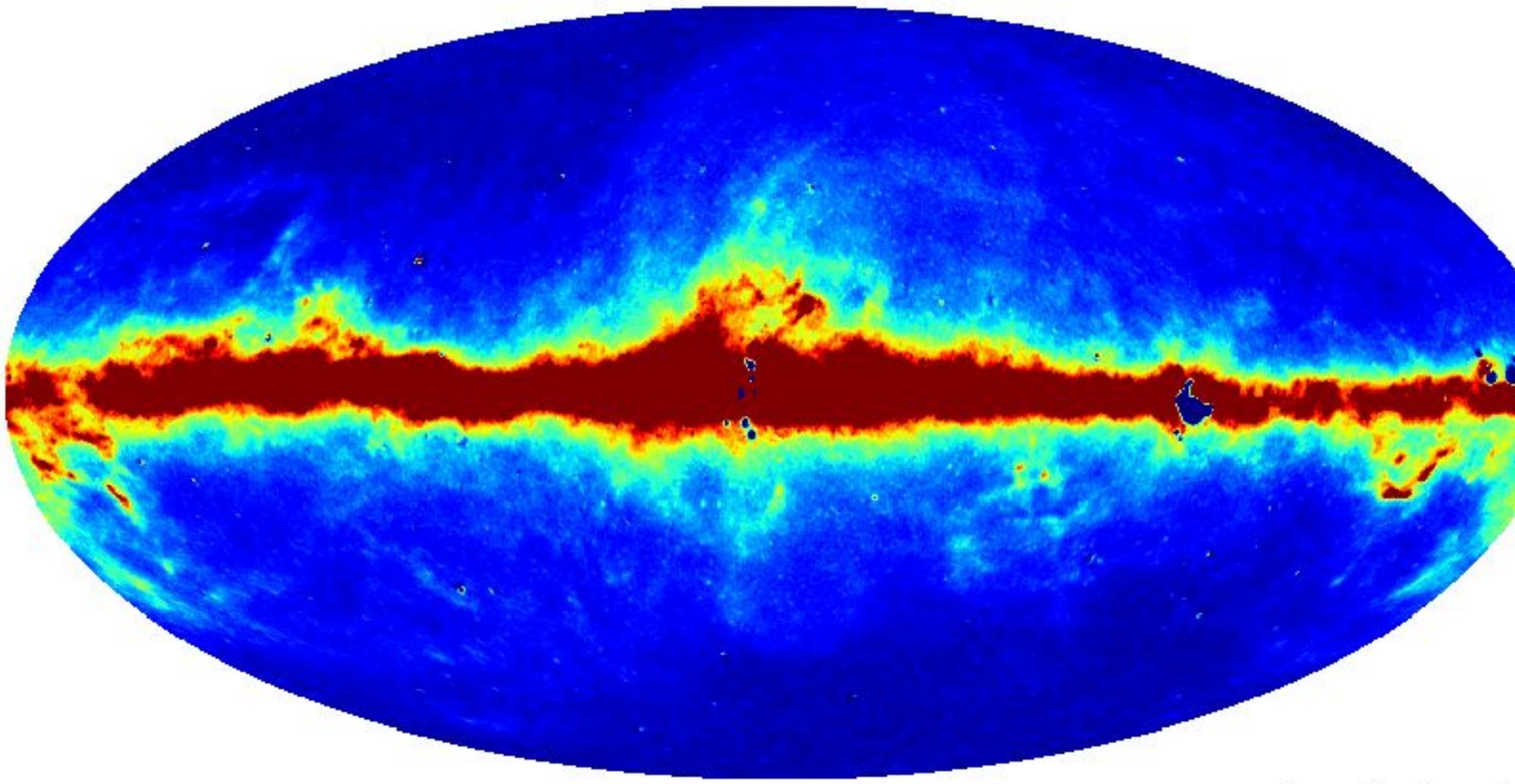








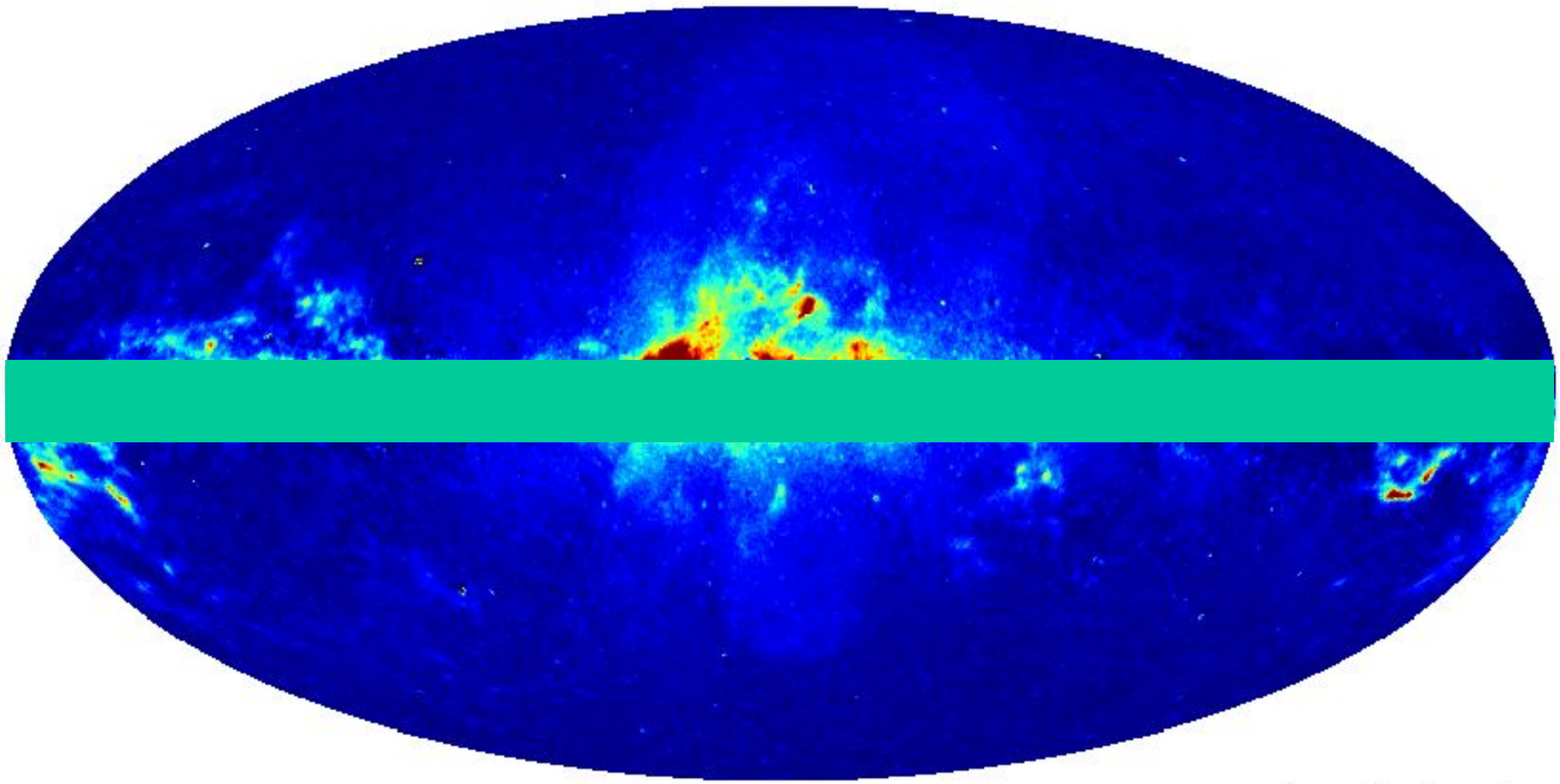
Interstellar emission: case of the interaction between CR protons and atomic hydrogen



molecular hydrogen
and
atomic hydrogen

$$N_\gamma = q \times N(H) + stuff$$

Interstellar emission: case of the interaction between CR protons and molecular hydrogen

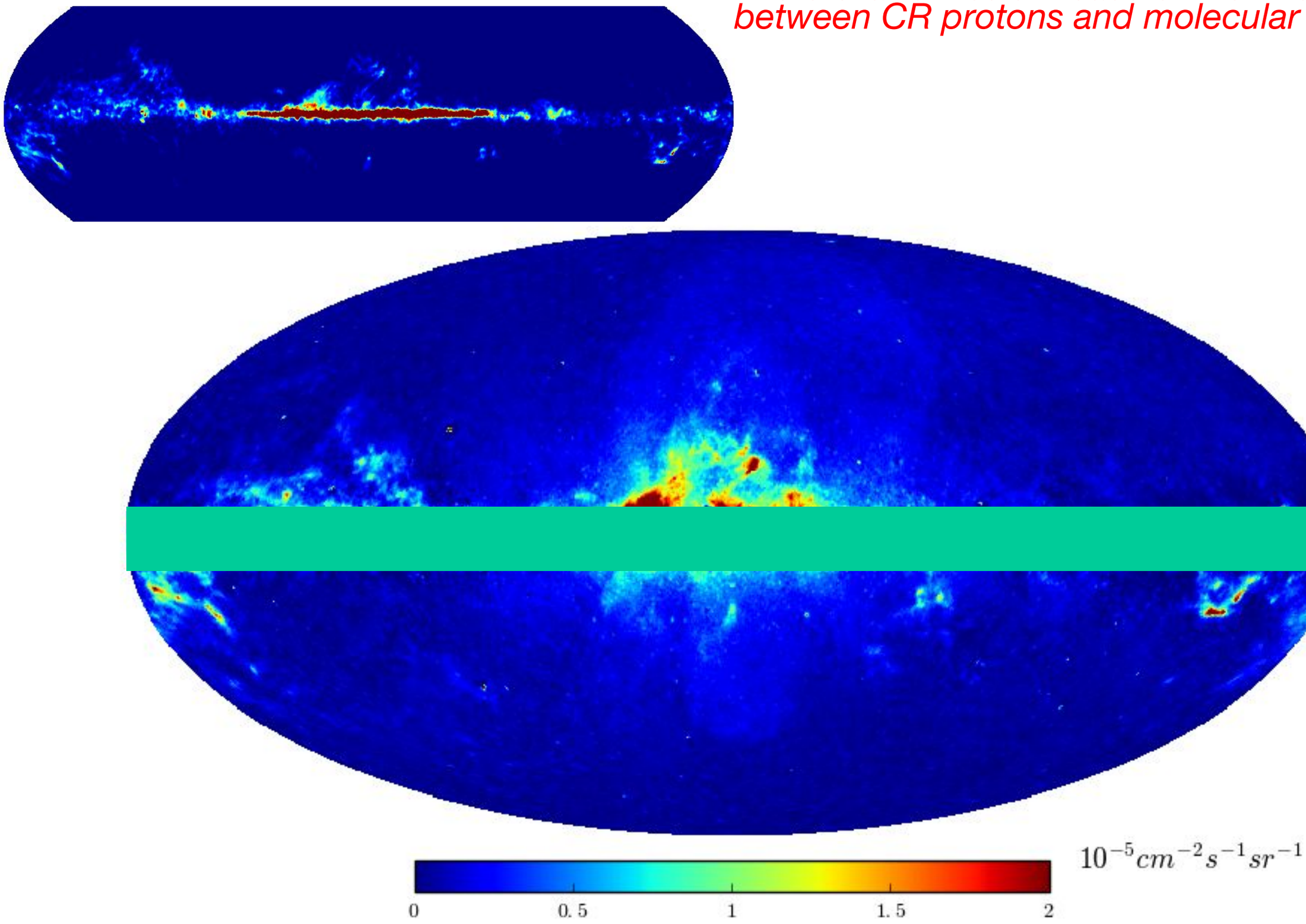


no permanent dipole moment
not have rotation spectrum (radio)

$$N_\gamma = q_{H_2} \times N(H_2) + stuff$$

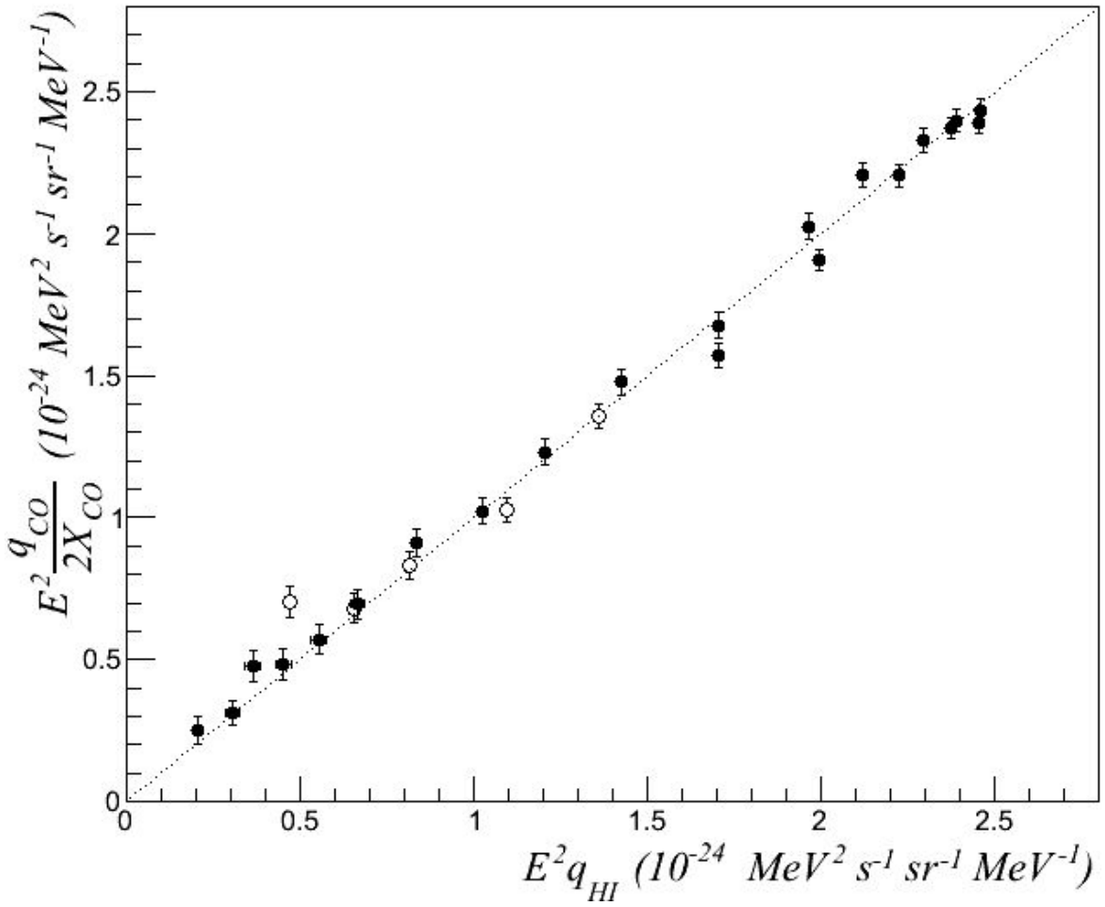
Electronic transition and transition between vibrational states: absorbed

Interstellar emission: case of the interaction between CR protons and molecular hydrogen



$$N_\gamma = (2 \times q_{HI}) \times (X_{CO} \times W(CO)) + stuff$$

casandjian 2015



We can derive XCO with LAT !

$$X_{\mathrm{CO}} = (0.902 \pm 0.007) \times 10^{20}\ \mathrm{cm}^{-2}\ \ (\mathrm{K\,km\,s}^{-1})^{-1}$$

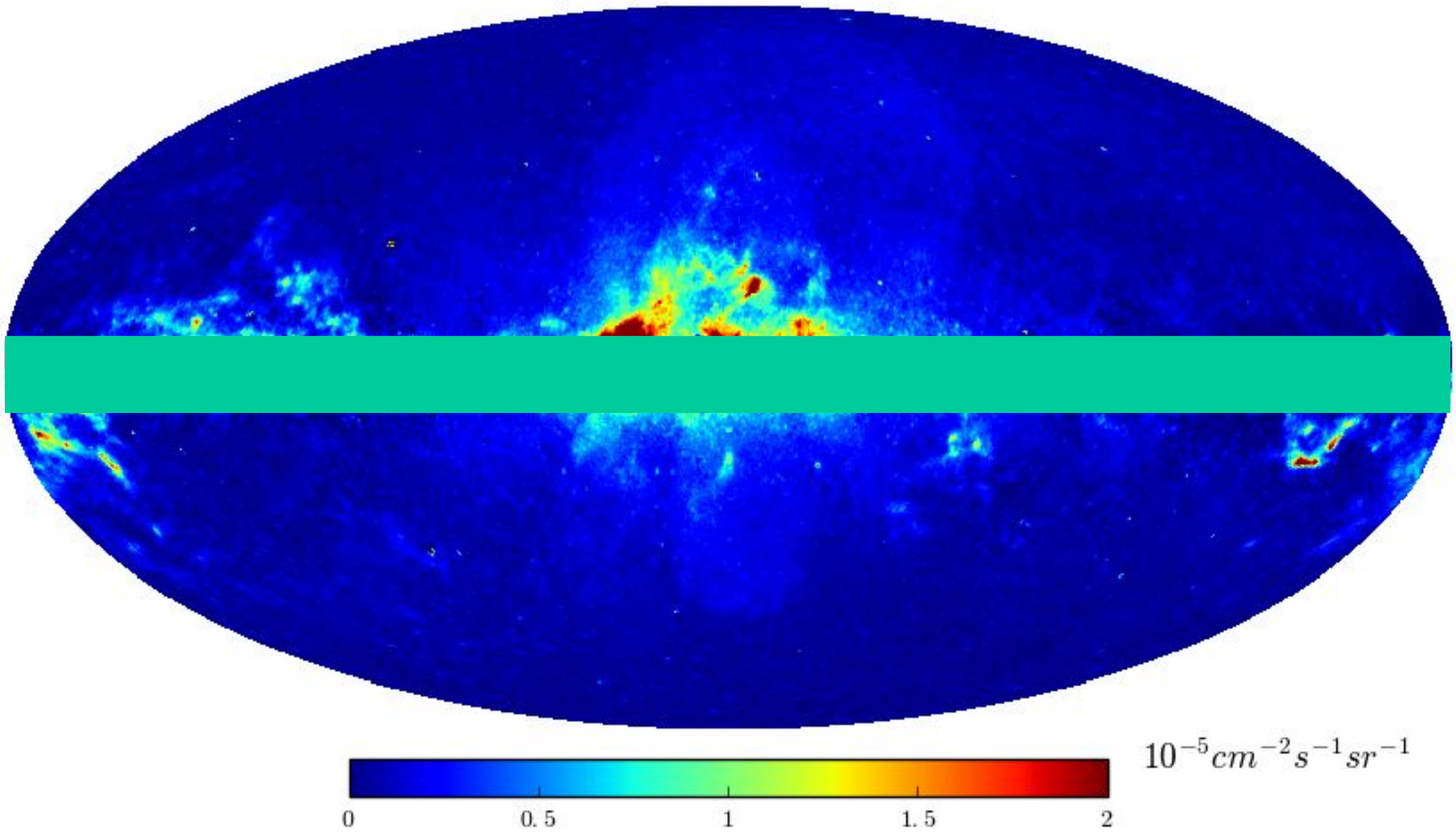
The CO-to-H_2 Conversion Factor

Alberto D. Bolatto,[1] Mark Wolfire,[1] and Adam K. Leroy[2]

Annu. Rev. Astron. Astrophys. 2013. 51:207–68

X_{CO}, in different environments. In the Milky Way disk, we recommend a conversion factor of $X_{\mathrm{CO}} = 2 \times 10^{20}$ cm^{-2} (K km s^{-1})$^{-1}$ with ±30% uncertainty. Studies of other "normal galaxies" return similar values in Milky

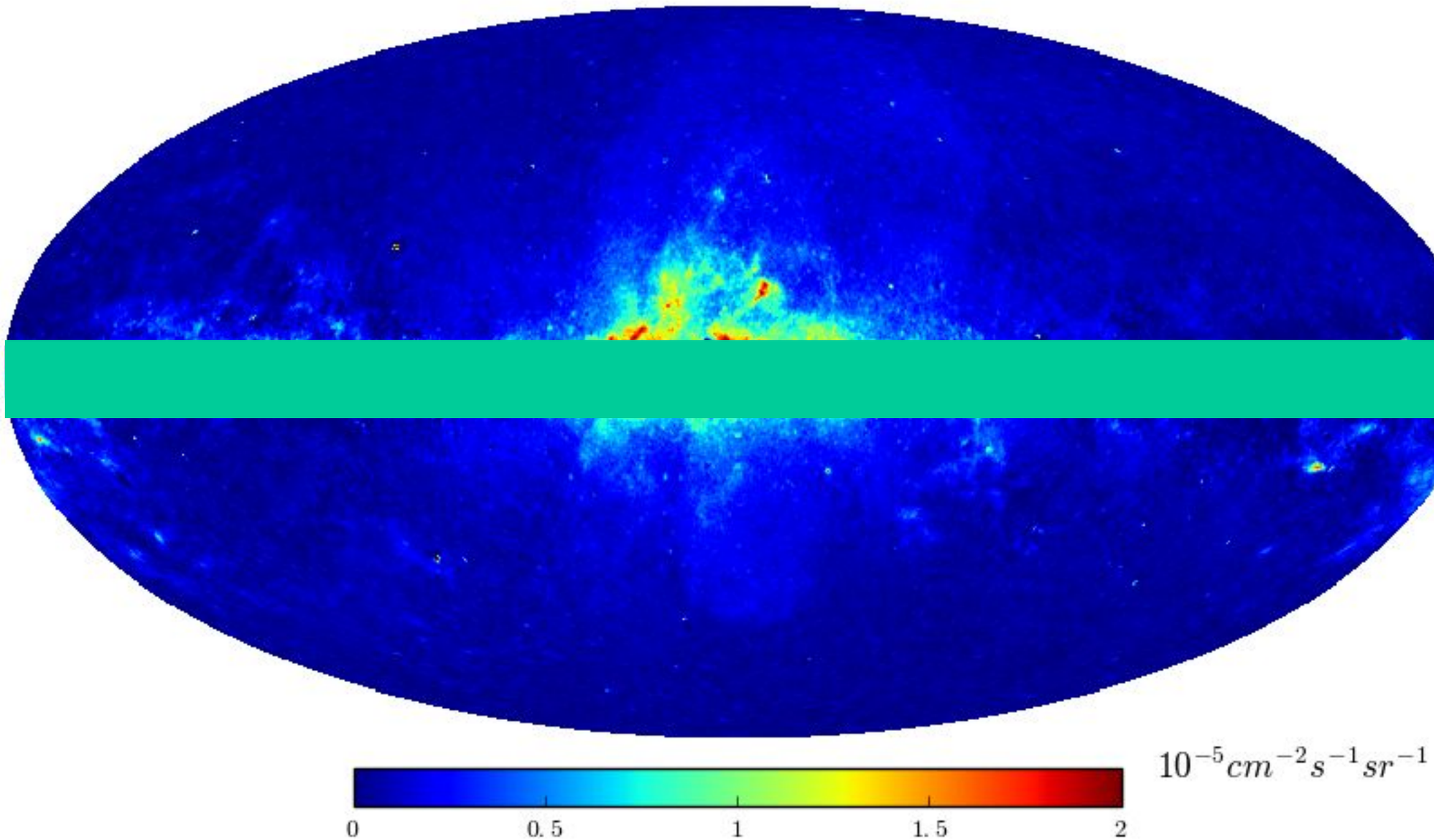
Interstellar emission: case of the interaction between CR protons and molecular hydrogen



IC

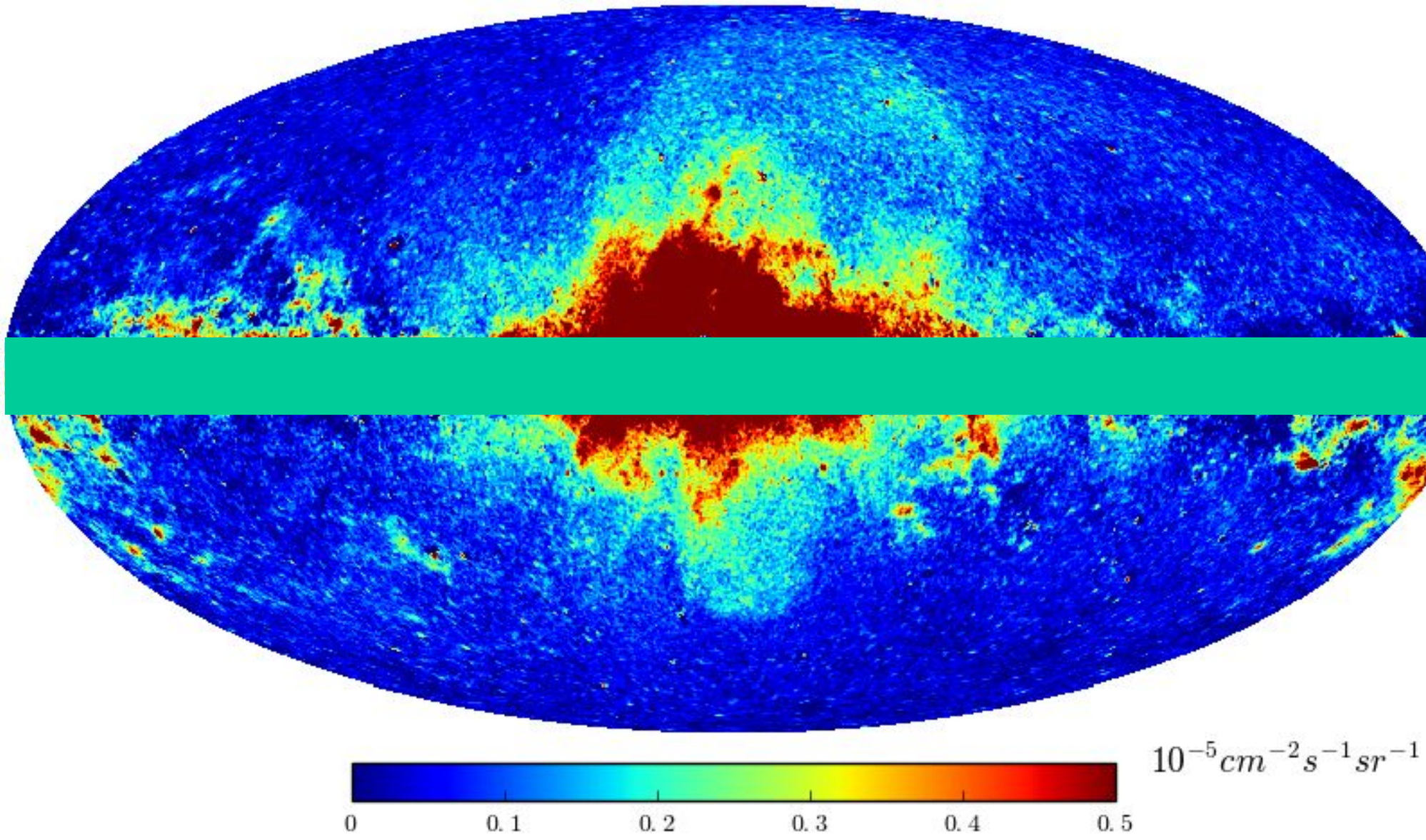
$$N_\gamma = (2 \times q_{HI}) \times (X_{CO} \times W(CO)) + stuff$$

Inverse Compton



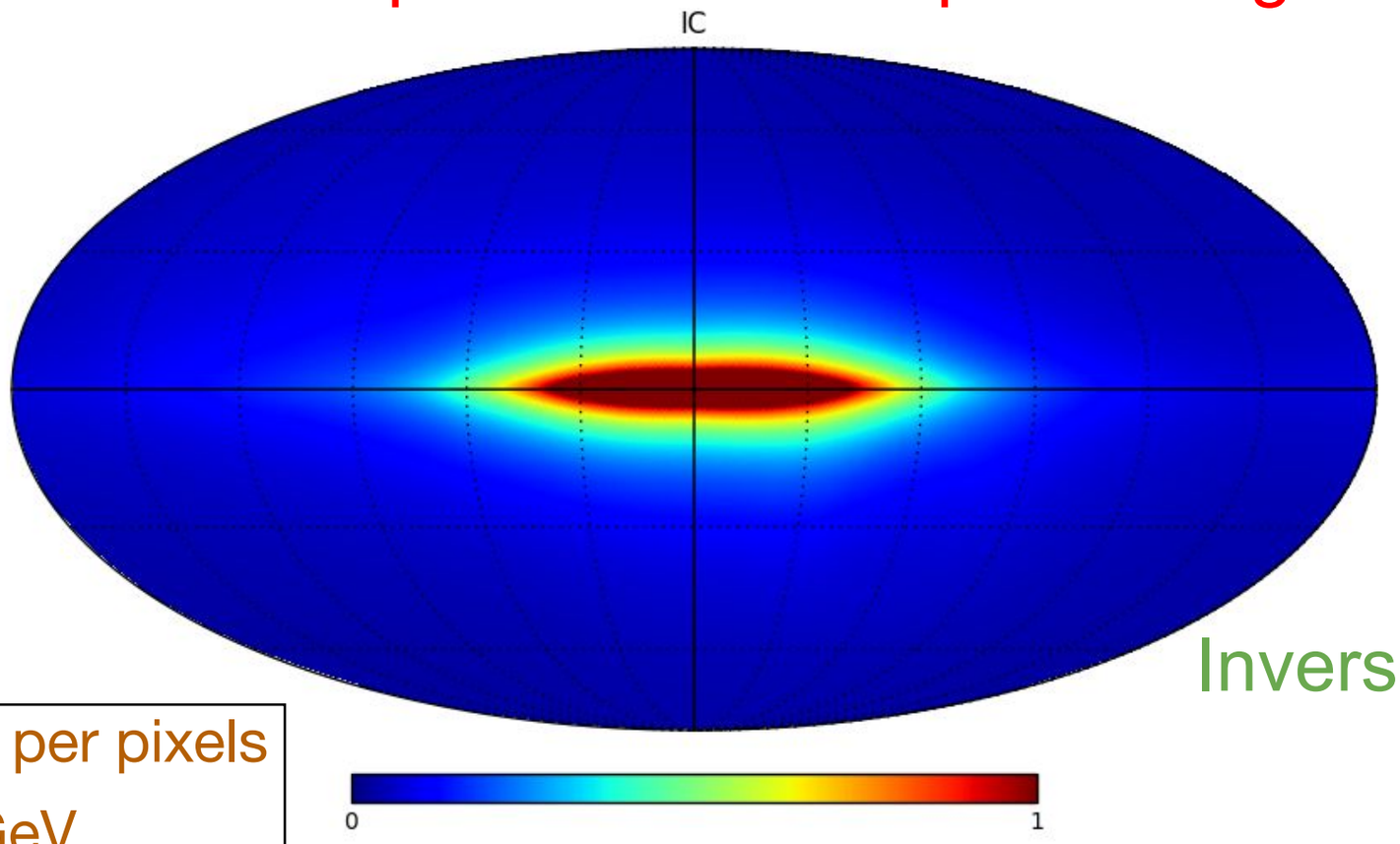
$$N_\gamma = IC + stuff$$

Inverse Compton



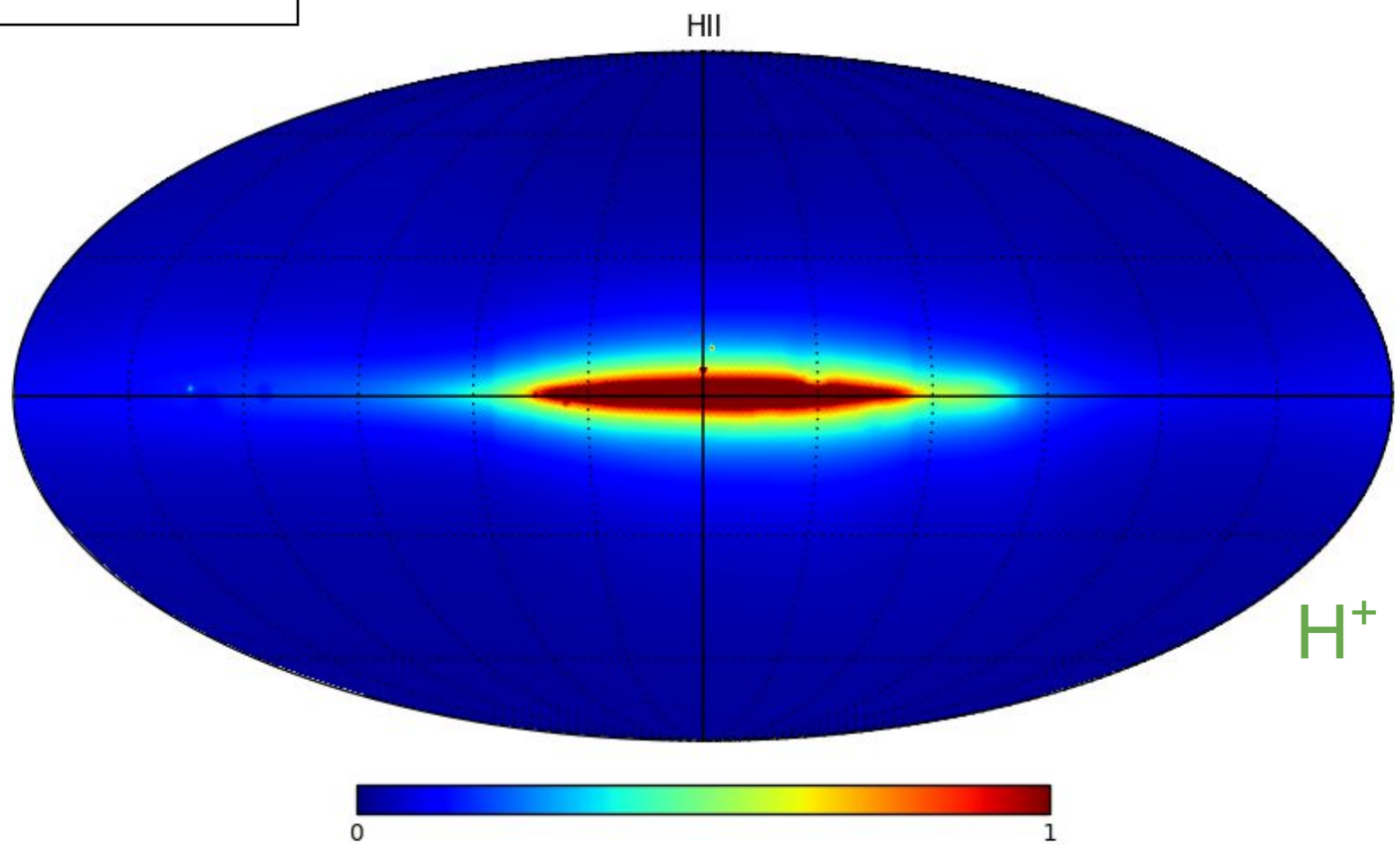
$$N_\gamma = IC + stuff$$

When template method stops working



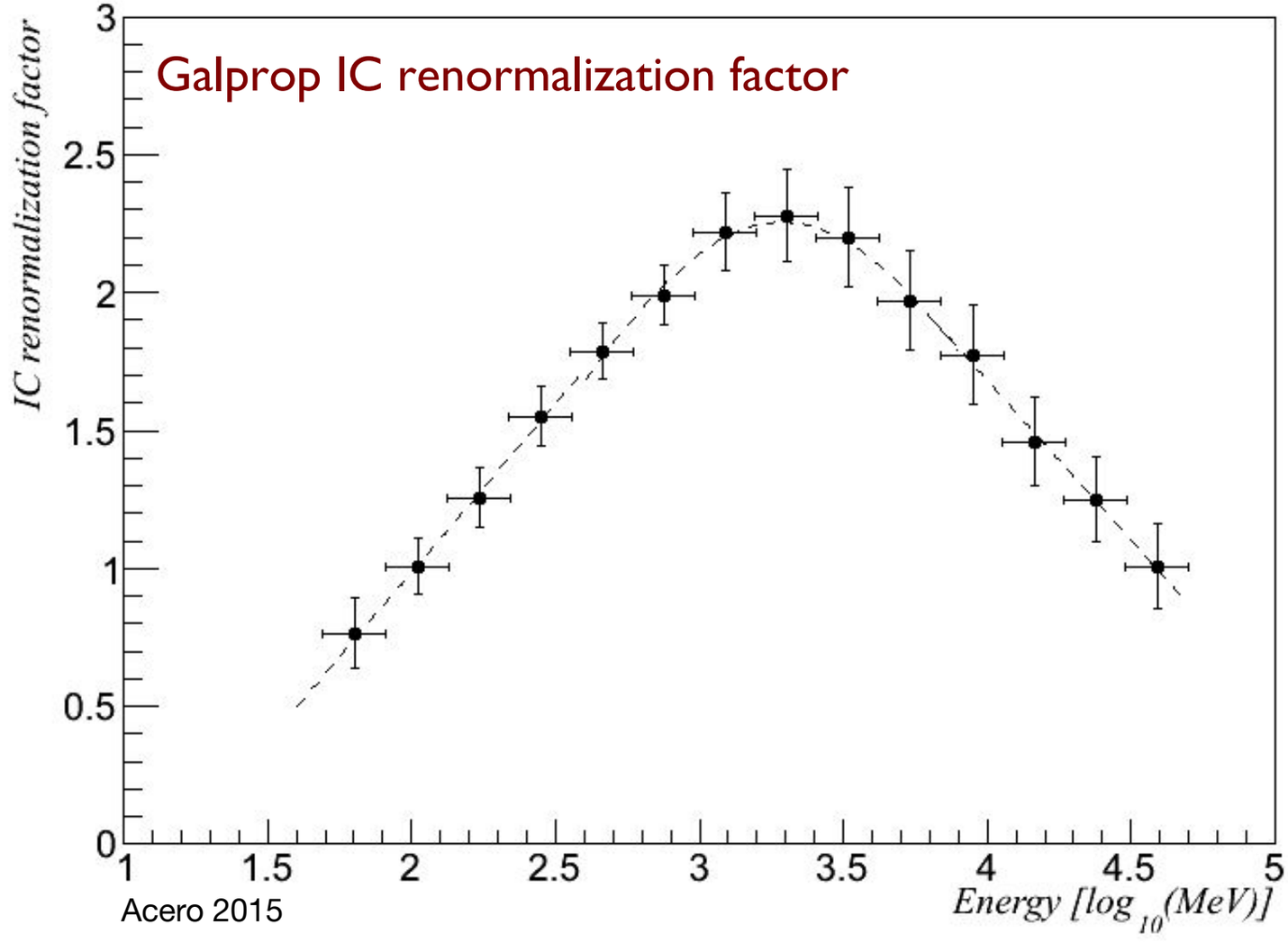
Inverse Compton

Prediction of counts per pixels for Fermi at Eγ > 9 GeV

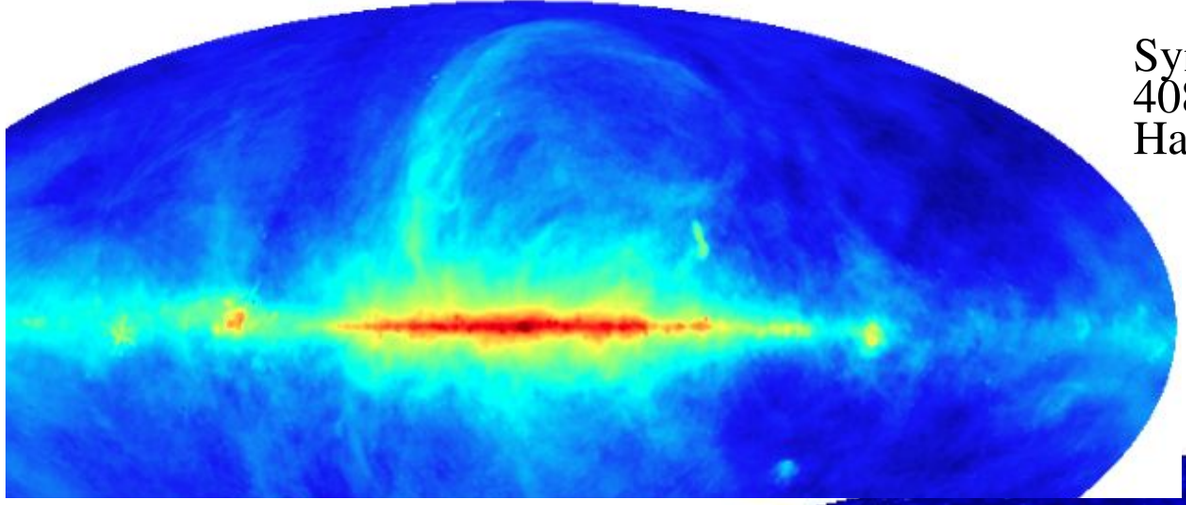


H^+

IC probe the Galaxy bulge and halo



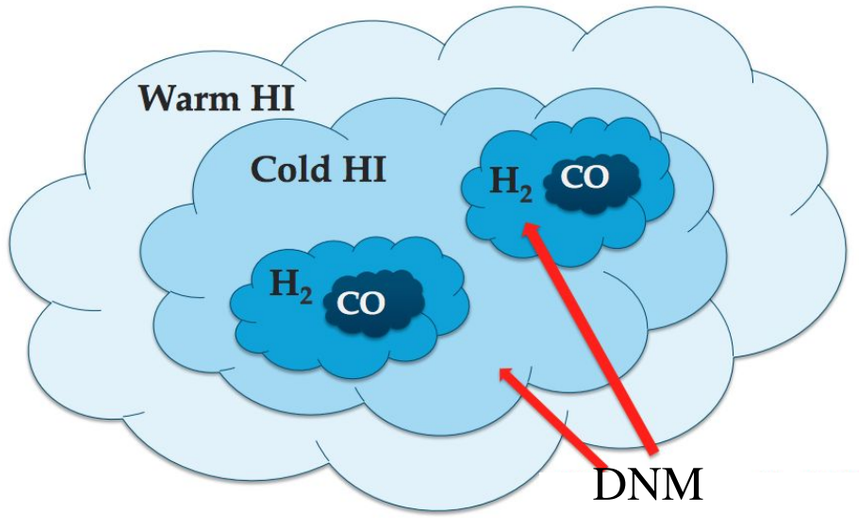
Acero 2015



Synchrotron electrons
408 MHz
Haslam

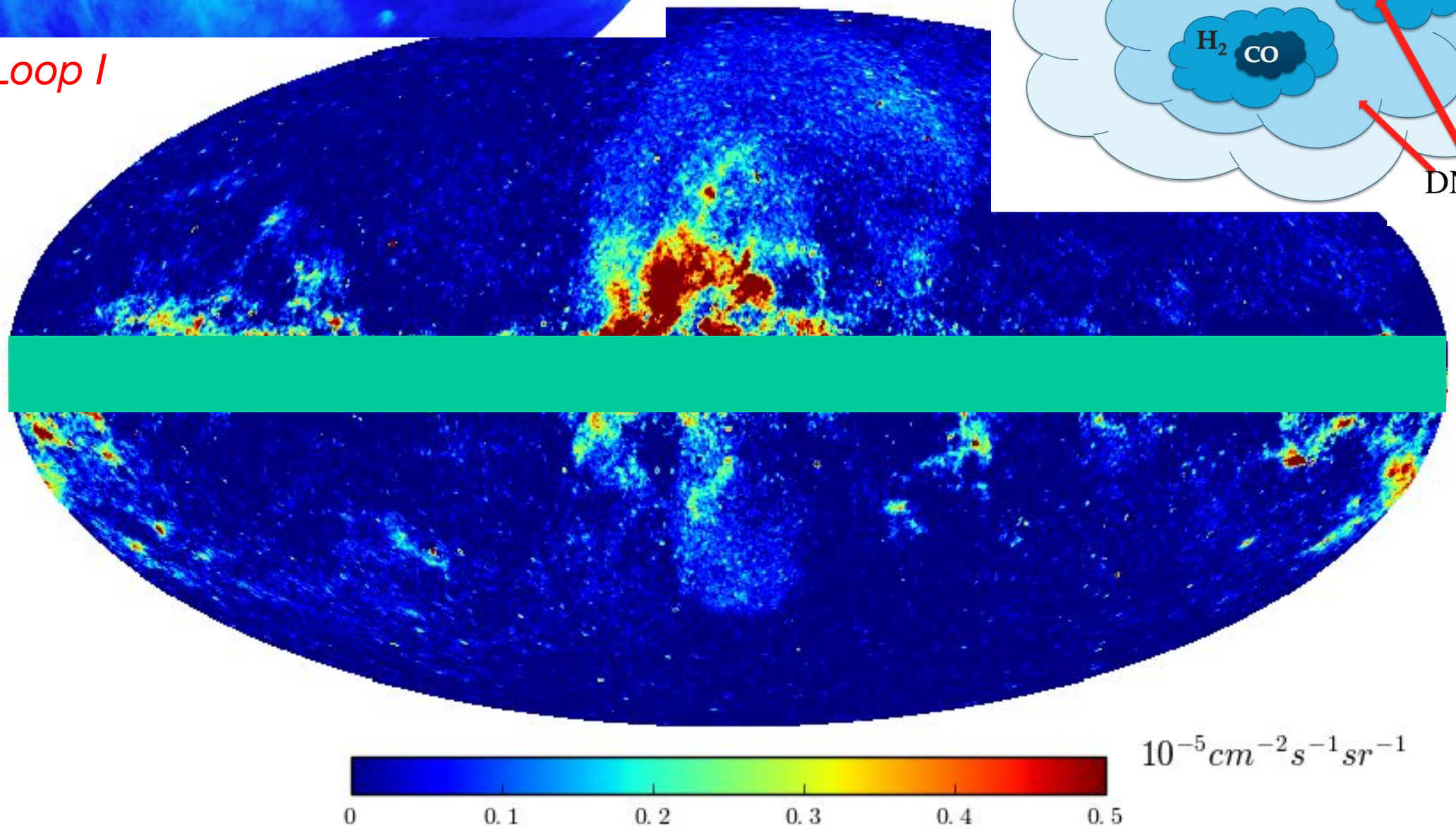
Dark Gas

Inside the clouds Helga Dénes



What is left ?

Loop I



$$N_\gamma = stuff \ (interesting \ stuff \ ..)$$

Conclusions

$$q \propto F_{CR} \times \sigma_{pp \to \gamma}$$

if we can measure q ..

We are / will be able to measure the local emissivity q with a precision of ~5%.
We need the same precision on the XSCR with the ISM to learn about the CR density outside the Local Bubble.

… if not

We need the XSCR to model the emissivity when the template method does not work and when the emissivity is different from the local one (H^+).