The Fermi Gamma-ray haze from Dark Matter annihilation and Anisotropic Diffusion

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arXiv:1102.5095 (submitted to ApJ),
ApJ 717,825,(2010) (arXiv:0910.4583) (G. Dobler, D. Finkbeiner, IC, T. Slatyer, N. Weiner), arXiv:0911.4954 (IC, N. Weiner), ApJ 722, 1939, (2010)(arXiv:1002.0587) (D. Malyshev, IC, Y. Gelfand)

Ilias Cholis (SISSA)

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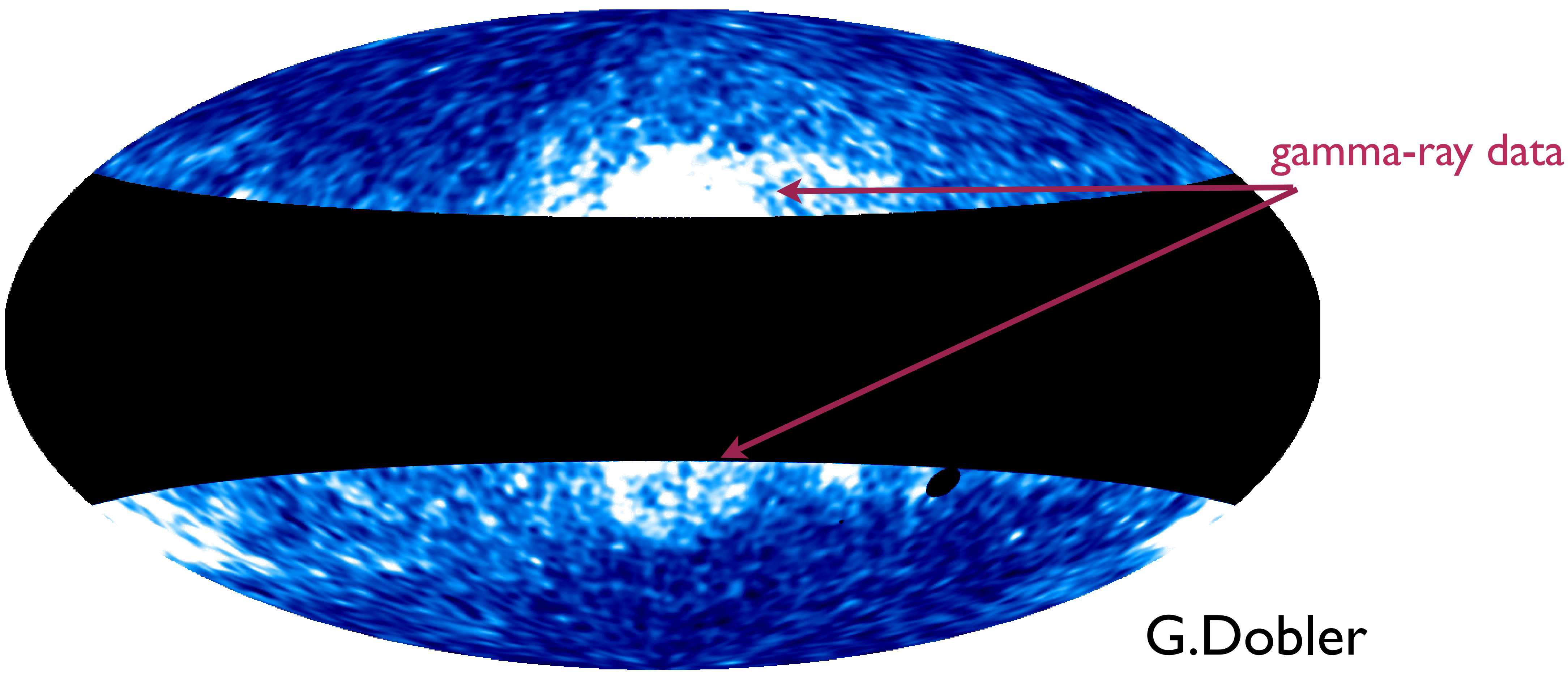
IDMS 2011

Outline

- Fermi haze/(Fermi bubbles) is a true signal
- "Conventional" sources for the Fermi haze
- Dark Matter explanation
- Anisotropic diffusion of CRs in the Galaxy
- Discussion on other astrophysical sources



Fermi (gamma-ray) haze

Since 2004 Finkbeiner has proposed the WMAP (microwave) haze, which suggests the existence of a population of electrons with a spectrum harder than the SNe accelerated electrons, of roughly spherical shape and extending out to at lest 2kpc (~10 kpc considering Fermi data).

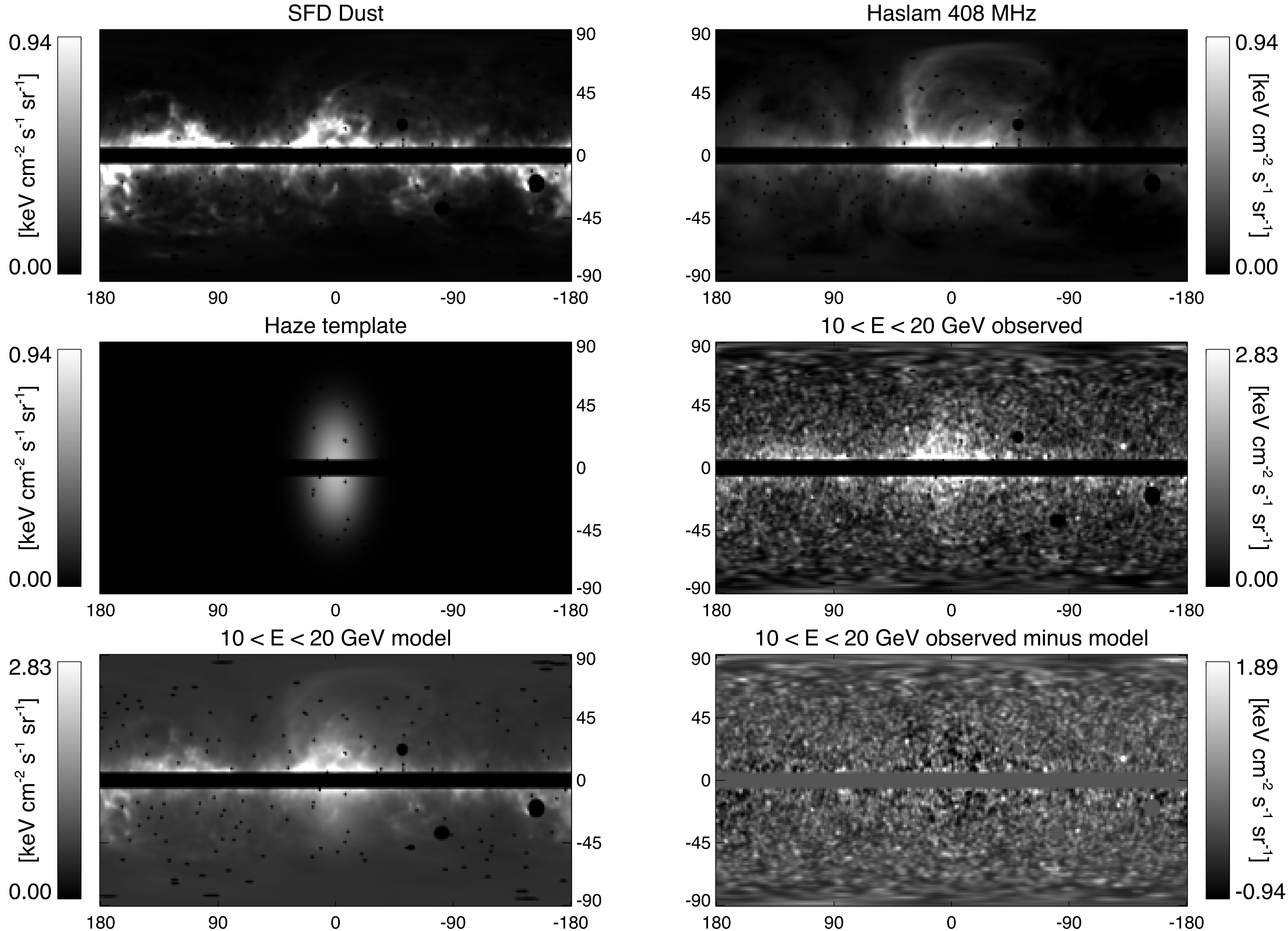
Such a population of hard electrons should also give an ICS signal as well. The Fermi haze is the gamma-ray counterpart of the microwave haze.

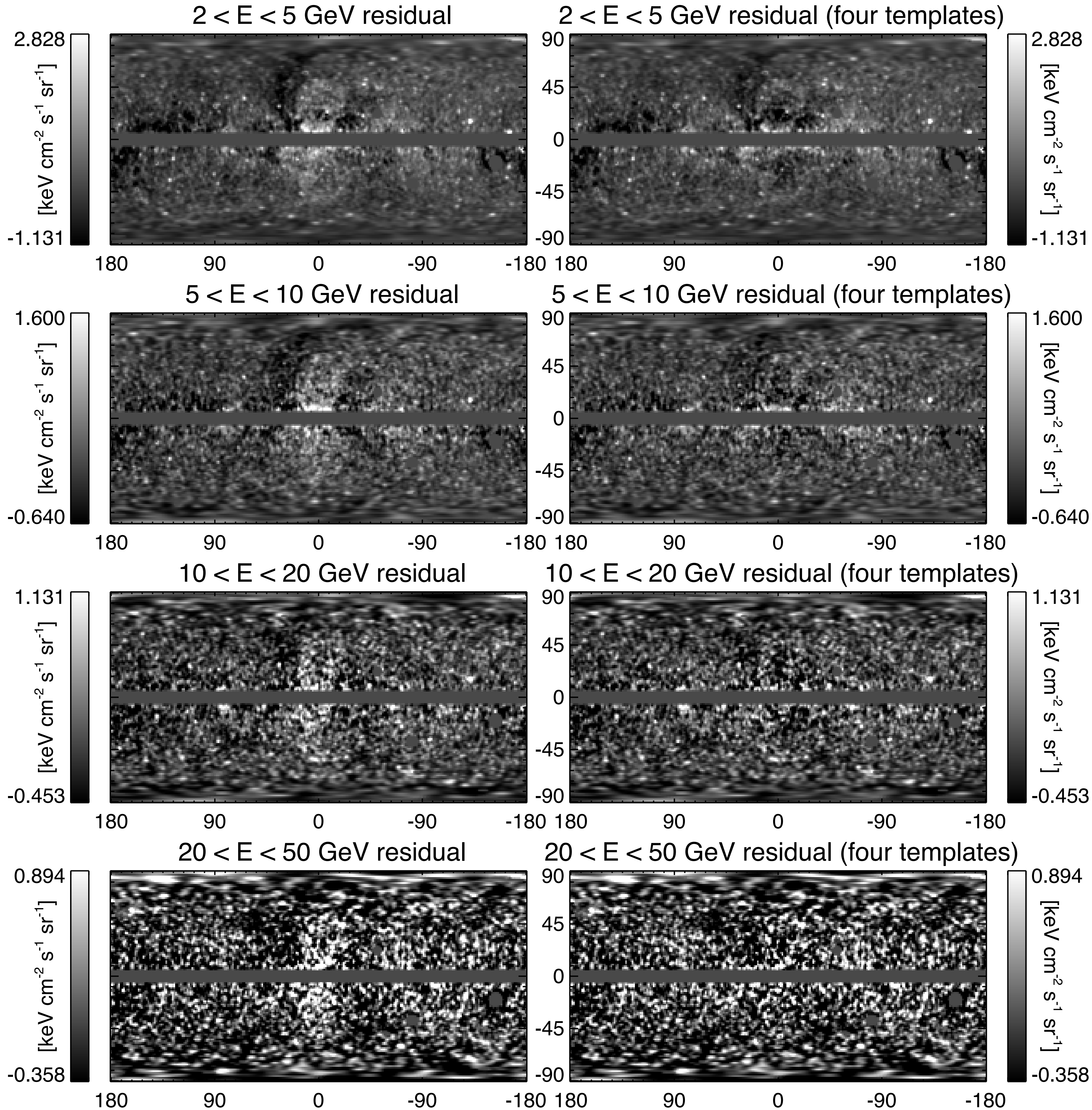
As in the case of the WMAP haze, all-sky templates were used to model the background components.

Background γ s: decaying π^0s produced at inelastic pp collisions, ICS and bremsstrahlung from the softer (SNe) electrons, point sources, isotropic γs.

3 different template sets were used, that all resulted in the need for an extra γ-ray template (the haze template) in order to fit well the entire γ-ray sky. The haze template was in all cases non-disky and suggested a hard population of electrons, similarly to the microwave haze.

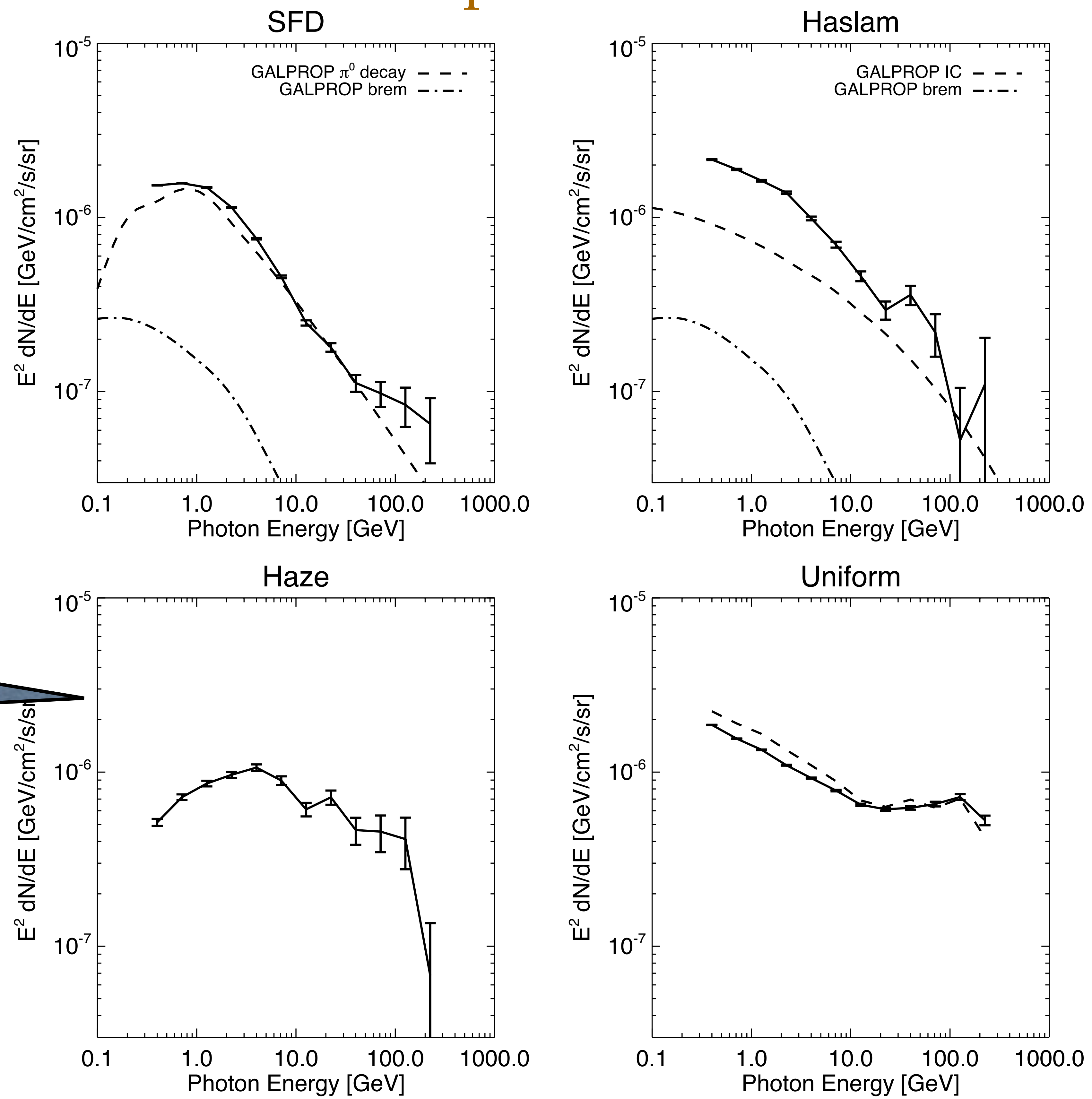
The Fermi haze template



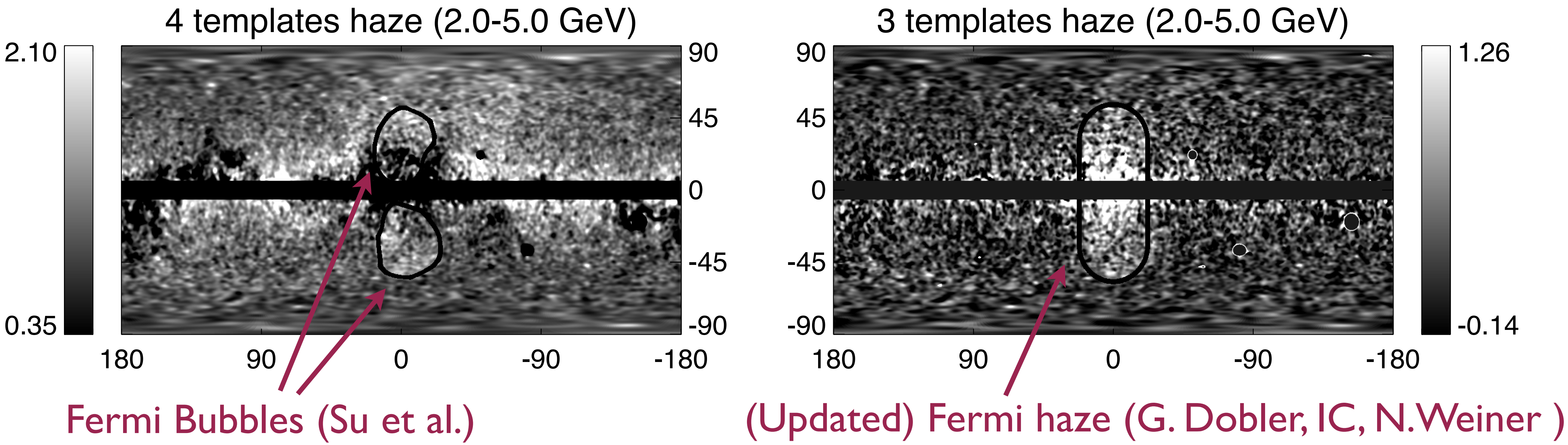


2 < E < 5 GeV residual
2 < E < 5 GeV residual (four templates)
5 < E < 10 GeV residual
5 < E < 10 GeV residual (four templates)
10 < E < 20 GeV residual
10 < E < 20 GeV residual (four templates)
20 < E < 50 GeV residual
20 < E < 50 GeV residual (four templates)
[keV cm^-2 s^-1 sr^-1]
2.828
-1.131
1.600
-0.640
1.131
-0.453
0.894
-0.358
90
45
0
-45
-90
180
90
0
-90
-180

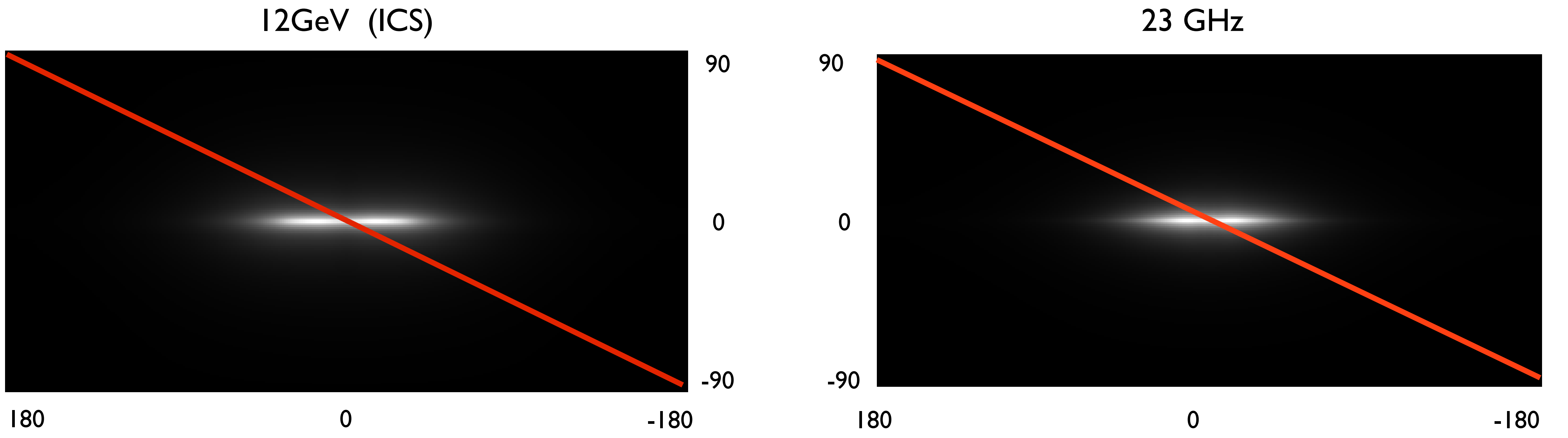
Spectra



Harder than typical galactic



Young pulsars, are probed still pretty well by the SNe distribution.



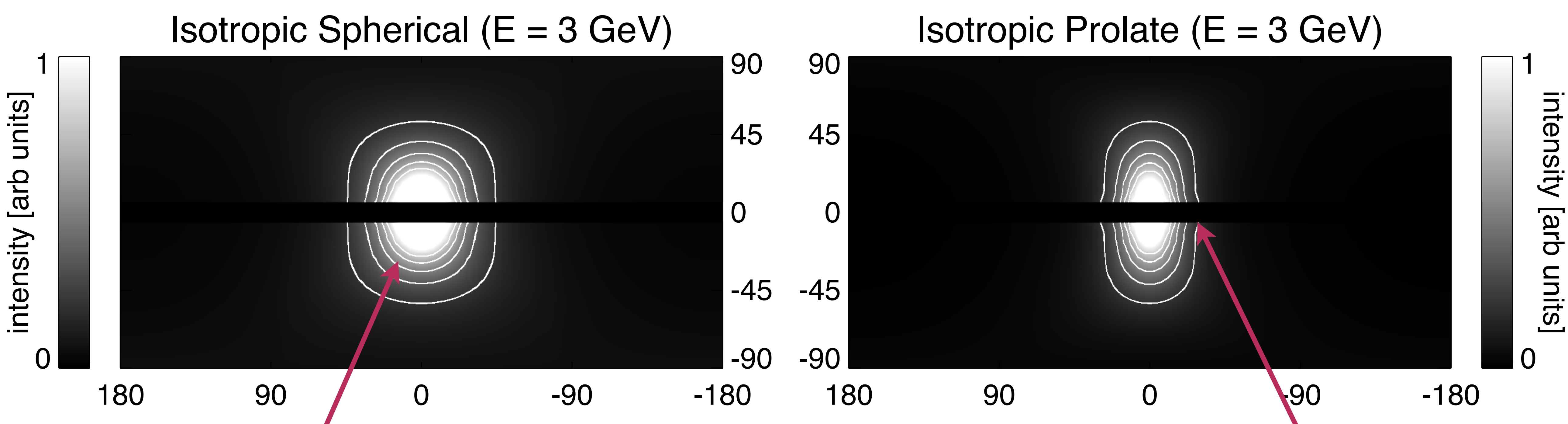
So clearly astrophysical sources with disk-like distributions, CAN NOT explain the Fermi haze signal.

What about Dark Matter?

The DM smooth halo has an approximately Spherical distribution, a possible candidate.

DM can explain the haze signal (WMAP + Fermi) as has been shown in arXiv:0911.4954 (IC + N. Weiner) based on solely energetic/spectral arguments (XDM electrons with local annihilation BF ~ 100 (~50 at the haze region)).

Numerical models of galactic propagation of cosmic rays (such as GALPROP) assume homogeneous and isotropic diffusion.



Too spherical

Better but still too peaked in the center

Anisotropic and inhomogeneous CR diffusion in the ISM

Propagation equation:

$$\frac{\partial \psi}{\partial t} = \frac{\partial (b\psi)}{\partial E} + \overrightarrow{\nabla}(D\overrightarrow{\nabla}\psi) + Q \qquad \text{(A)}$$

ψ is the CR number density at time t and position $\vec{x}$

b : energy loss coefficient (above 5GeV dominated by IC and synchrotron emission).

D : diffusion constant

Q : source term

Assuming cylindrical symmetry:

$$\overrightarrow{\nabla}(D\overrightarrow{\nabla}\psi) = \frac{1}{r}\frac{\partial}{\partial r}(rD\frac{\partial \psi}{\partial r}) + \frac{\partial}{\partial z}(D\frac{\partial \psi}{\partial z}) \qquad \text{(B)}$$

Anisotropic diffusion:

$$\overrightarrow{\nabla}(D\overrightarrow{\nabla}\psi) = \frac{1}{r}\frac{\partial}{\partial r}(rD_{rr}\frac{\partial\psi}{\partial r} + rD_{rz}\frac{\partial\psi}{\partial z}) + \frac{\partial}{\partial z}(D_{zz}\frac{\partial\psi}{\partial z} + D_{zr}\frac{\partial\psi}{\partial r}) \quad \text{(C)}$$

What we will assume is a strong magnetic field perpendicular to the galactic plane in the inner part of the Galaxy.

Turbulent B-field:

$$B_{\mathrm{tur}} = B_0 e^{(R_\odot - r)/r_1 - |z|/z_1}$$

$$R_\odot = 8.5kpc$$

Ordered B-field:

$$B_{\mathrm{ord}} = B_1 e^{-r/r_2 - |z|/z_2} \times \left(1 + Ke^{-r/r_3 - |z|/z_3}\right)$$

What remains is to relate the elements of the diffusion tensor to the magnetic field.

$$D \propto \lambda_{sc} \propto r_{gyr} \propto B^{-1}$$

Also assuming that the ordered field is along z-axis and much stronger than the turbulent field we expect:

$$\lambda_{sc_z} \gg \lambda_{sc_r}$$

Following Parker (1965)

v : frequency by which CRs scatter off from their spiral orbit

$\Omega \gg$ v : in the central part of the Galaxy

$\Omega \ll$ v : far from the galactic center we have:

$$D_{zz} \propto B_{tot}^{-1}\left(\frac{\mathrm{v}^2 + \frac{q^2 B_z^2}{\gamma^2 m^2 c^2}}{\mathrm{v}^2 + \frac{q^2 B_{tot}^2}{\gamma^2 m^2 c^2}}\right)$$

setting:

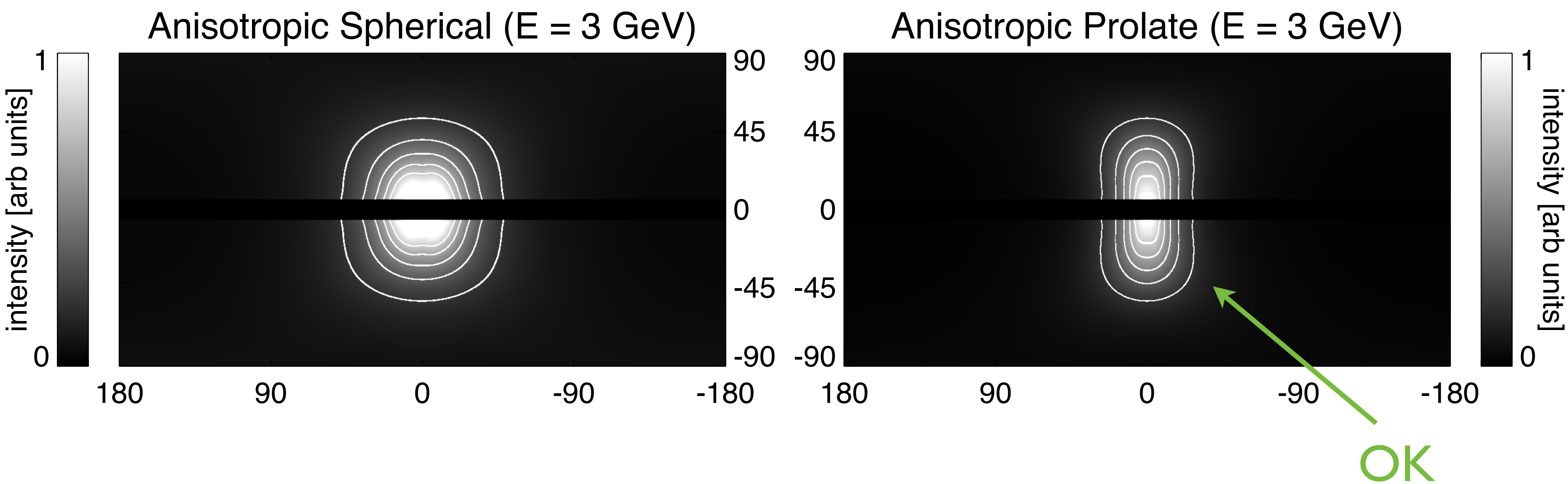
$$A = \frac{q}{\gamma m c \mathrm{v}}$$

we get:

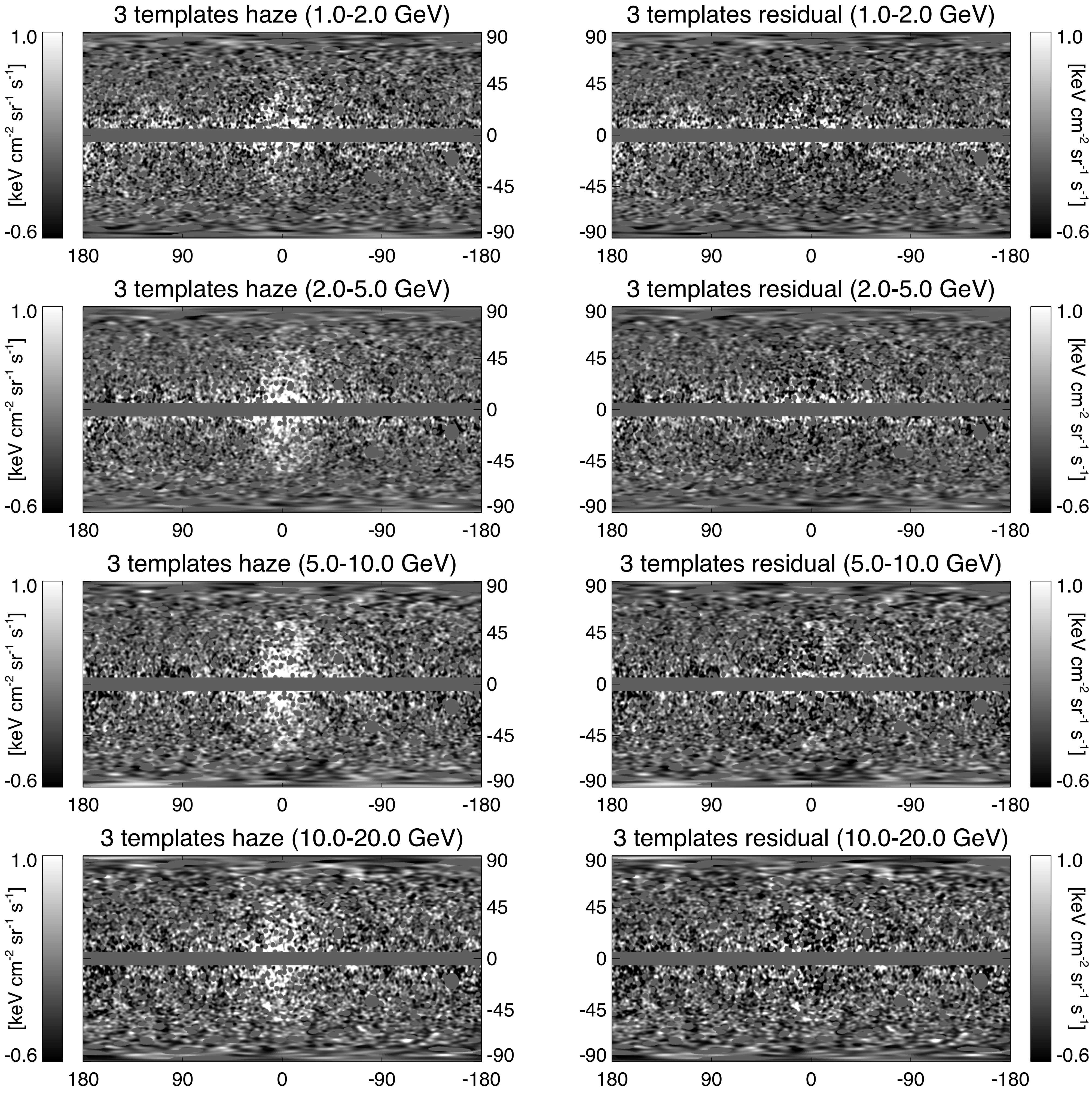
$$D_{zz} \propto B_{tot}^{-1}\left(\frac{1 + A^2 B_z^2}{1 + A^2 B_{tot}^2}\right)$$

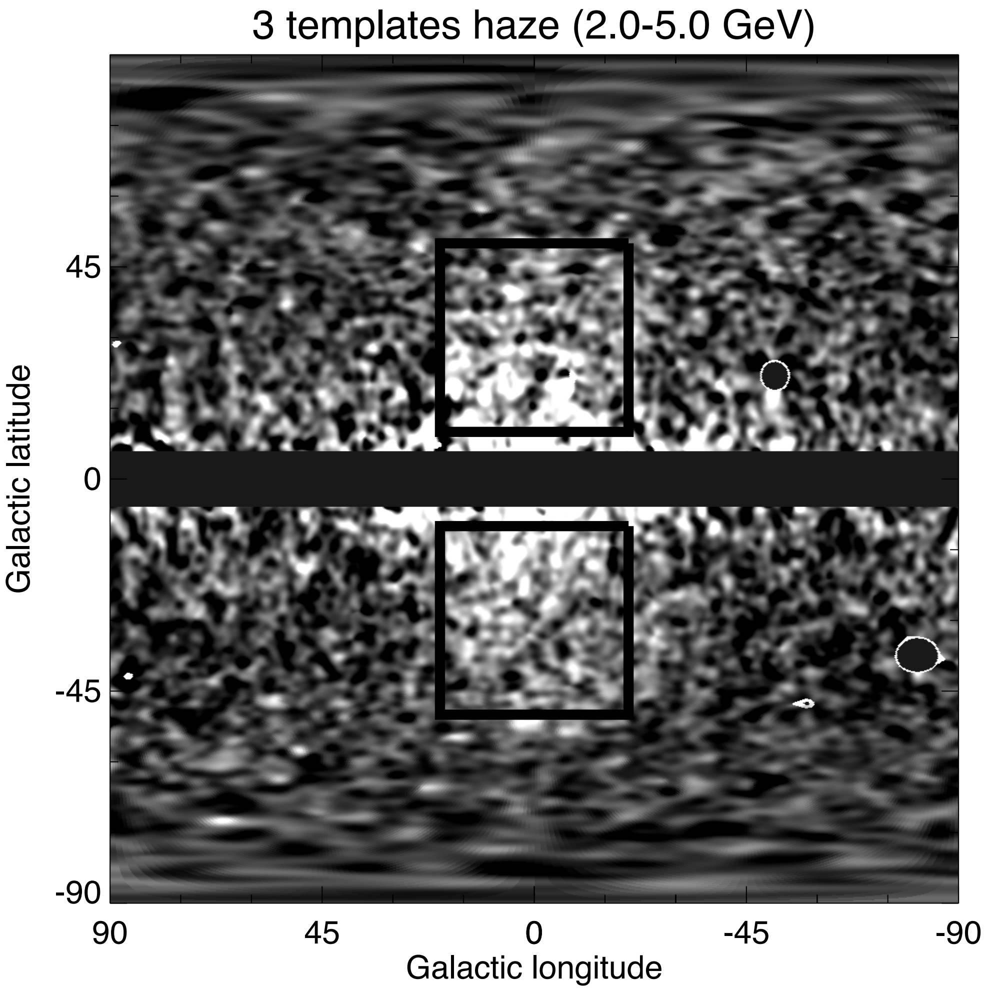
$$\frac{D_{rr}}{D_{zz}} = \frac{1 + A^2 B_r^2}{1 + A^2 B_z^2}, \quad \frac{D_{rz}}{D_{zz}} = \frac{D_{zr}}{D_{zz}} = \frac{A^2 B_r B_z}{1 + A^2 B_z^2}$$

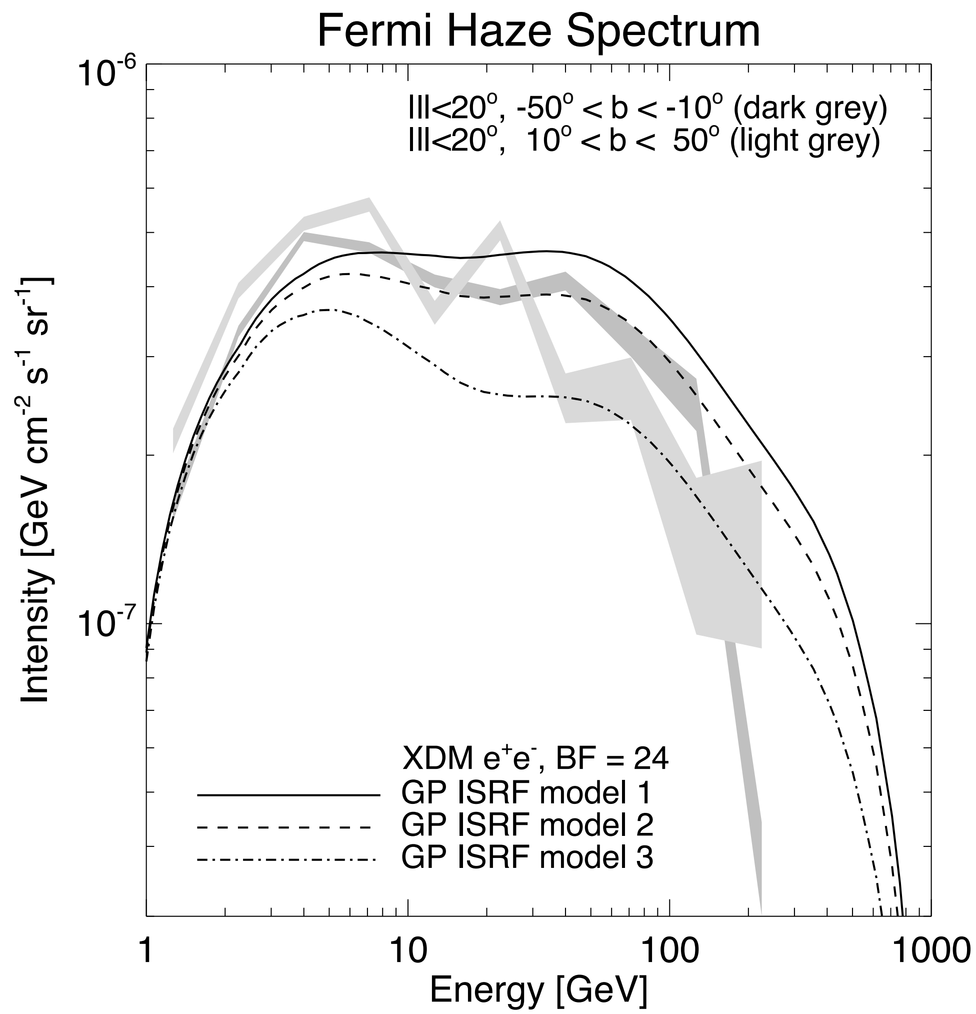
Thus one can get:

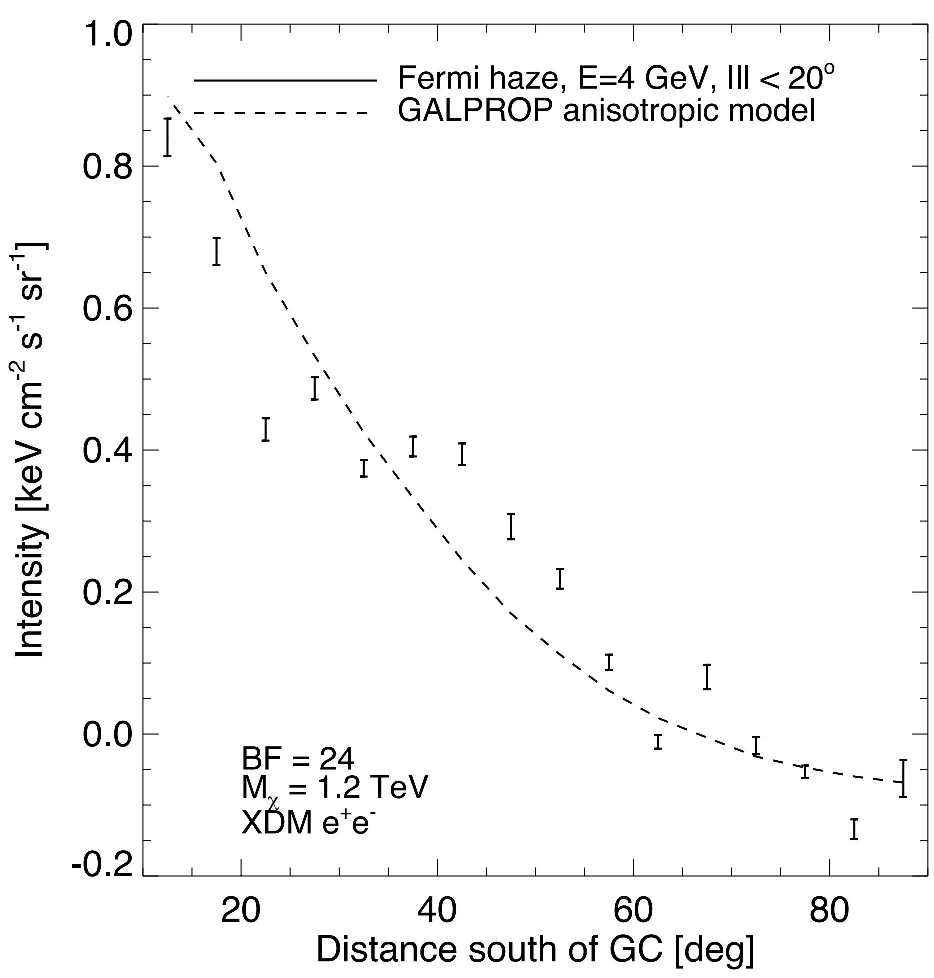


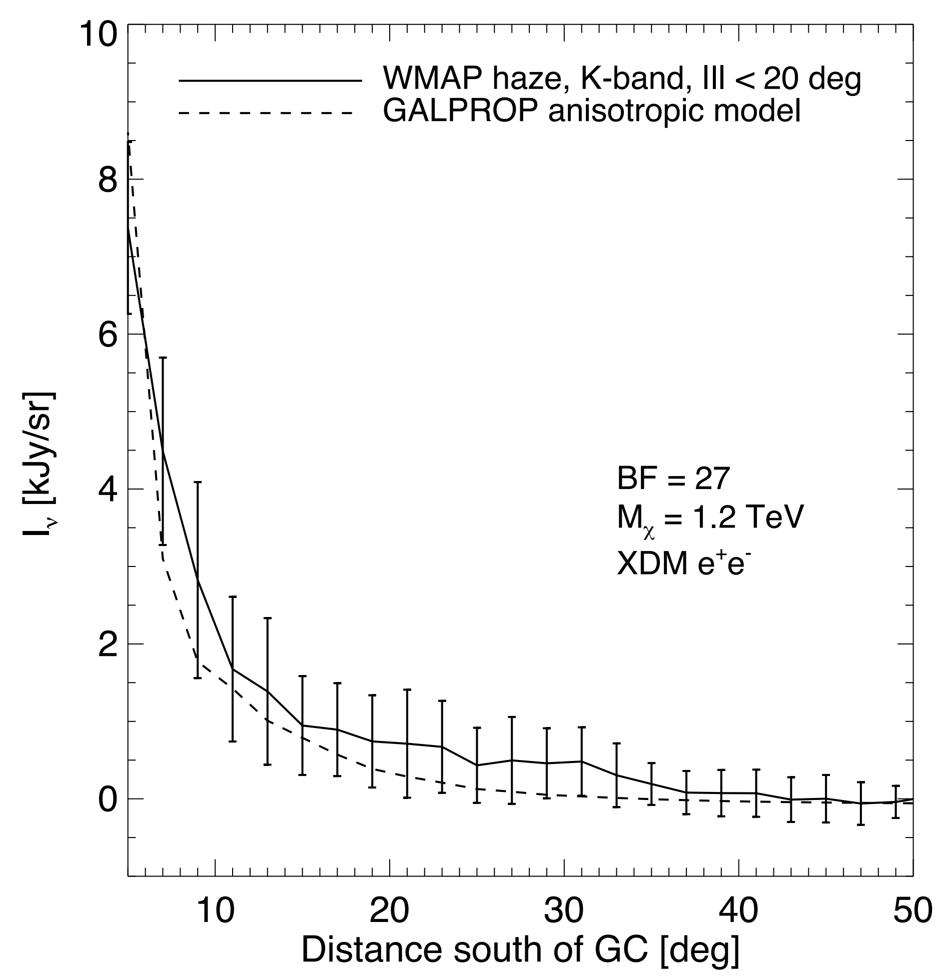
So with annihilating DM and some assumptions on anisotropic and inhomogeneous diffusion we CAN fit the Fermi haze.


3 templates haze (1.0-2.0 GeV)
3 templates residual (1.0-2.0 GeV)
3 templates haze (2.0-5.0 GeV)
3 templates residual (2.0-5.0 GeV)
3 templates haze (5.0-10.0 GeV)
3 templates residual (5.0-10.0 GeV)
3 templates haze (10.0-20.0 GeV)
3 templates residual (10.0-20.0 GeV)
[keV cm-2 sr-1 s-1]
1.0
-0.6
90
45
0
-45
-90
180
90
0
-90
-180

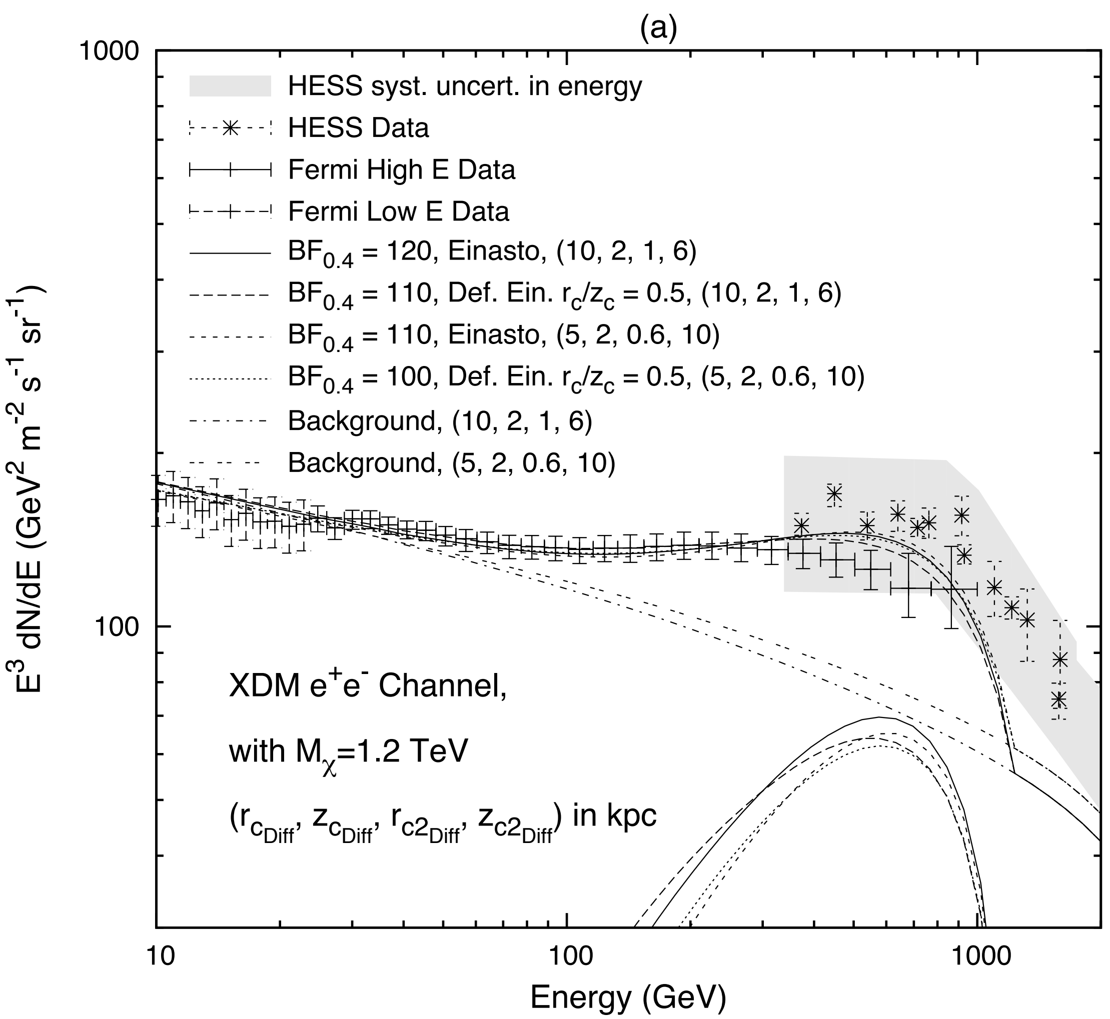

3 templates haze (2.0-5.0 GeV)
Galactic latitude
45
0
-45
-90
90
45
0
-45
-90
Galactic longitude

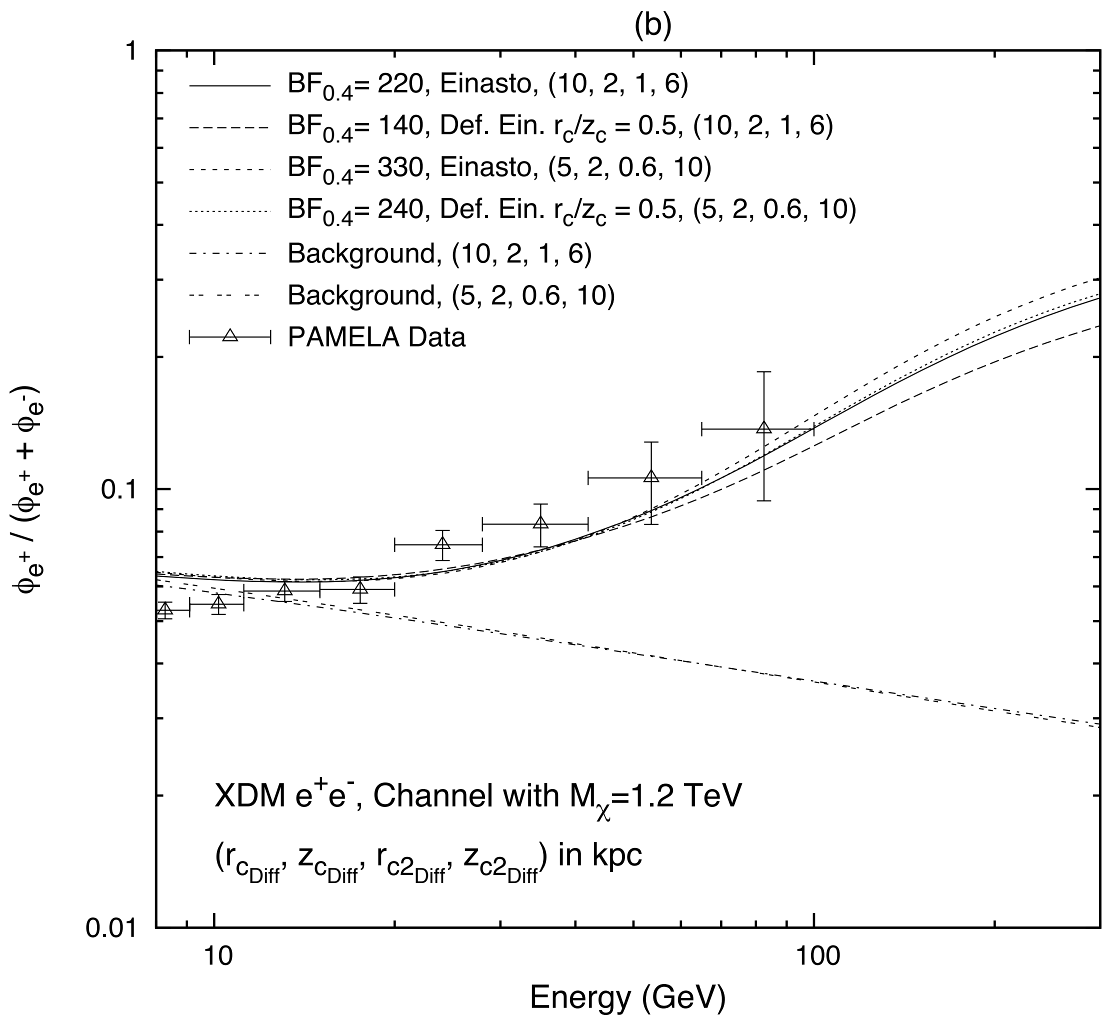

Fermi Haze Spectrum
10^{-6}
10^{-7}
$|l|<20^o$, $-50^o < b < -10^o$ (dark grey)
$|l|<20^o$, $10^o < b < 50^o$ (light grey)
XDM e^+e^-, BF = 24
GP ISRF model 1
GP ISRF model 2
GP ISRF model 3
Intensity [GeV cm^{-2} s^{-1} sr^{-1}]
1
10
100
1000
Energy [GeV]


Fermi haze, E=4 GeV, $|l| < 20^o$
GALPROP anisotropic model
Intensity [keV cm^{-2} s^{-1} sr^{-1}]
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
BF = 24
M_χ = 1.2 TeV
XDM e^+e^-
20
40
60
80
Distance south of GC [deg]


WMAP haze, K-band, $|l|$ < 20 deg
GALPROP anisotropic model
I_ν [kJy/sr]
10
8
6
4
2
0
BF = 27
M_χ = 1.2 TeV
XDM e^+e^-
10
20
30
40
50
Distance south of GC [deg]

Apart form getting the right morphology for the Fermi (and WMAP) haze, and having good spectral agreement, we also have agreement with local CRs and background gamma-rays.





DM Contribution

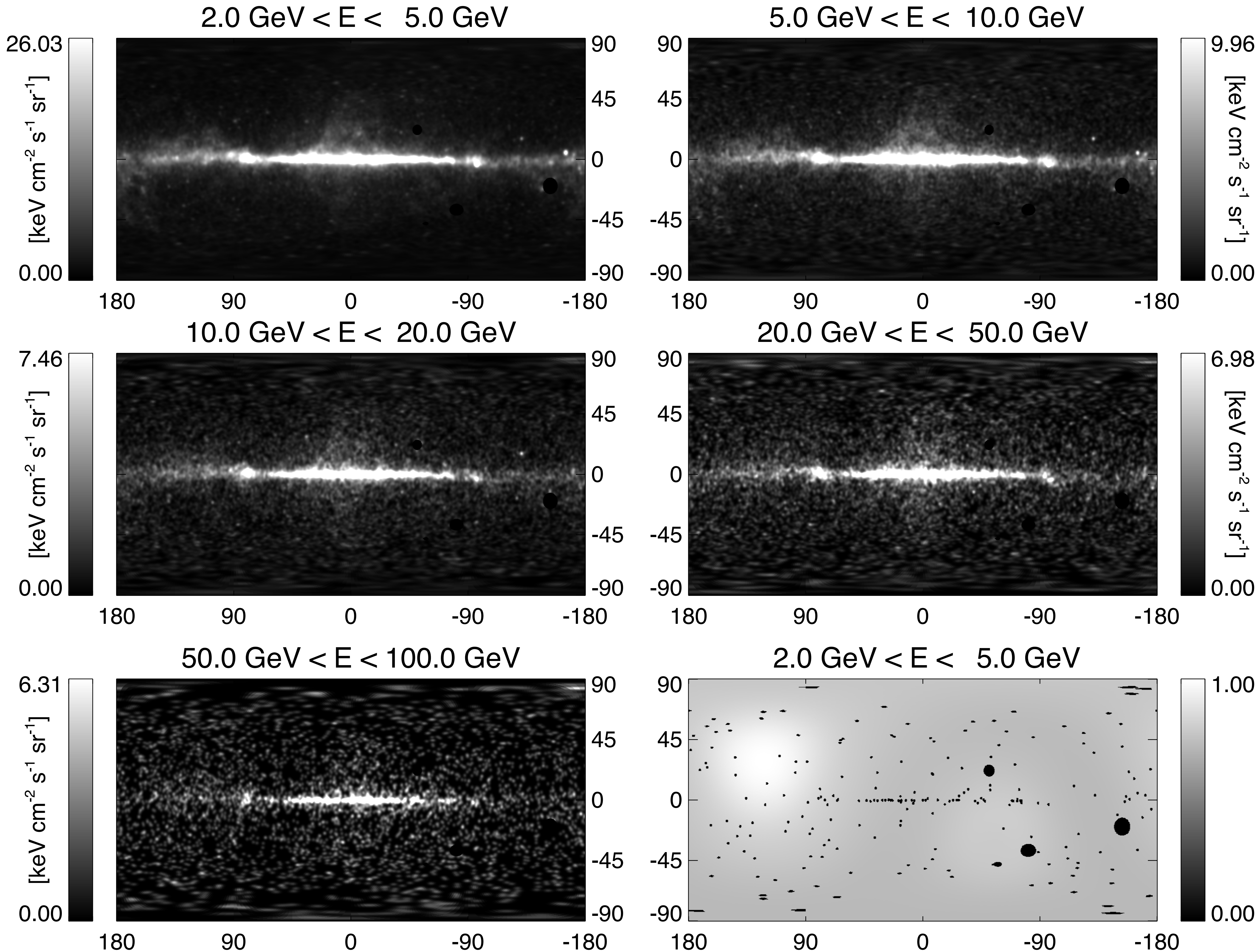
Conclusions

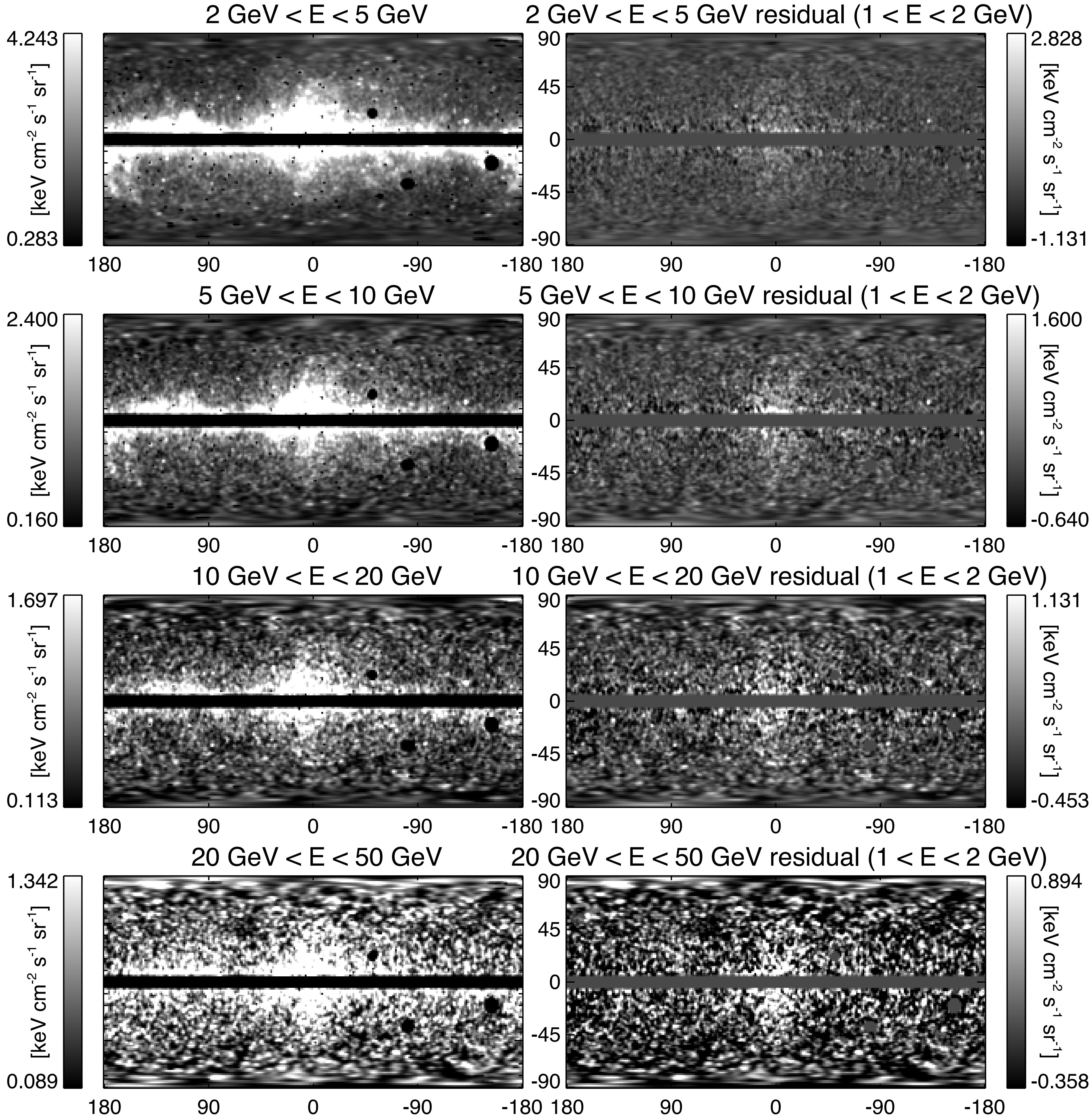
- The Fermi haze is a signal of a population of harder spectrum electrons (seen before only at microwave)
- "Conventional" sources for the Fermi haze seem to fail in explaining it
- DM with Anisotropic and inhomogeneous diffusion may be the answer
- Astrophysical explanations including MSPs (Malyshev, Cholis, Gelfand ApJ 722, p.1939-1945 (2010)), or a strong AGN activity may be in order(Guo & Mathews arXiv:1103.0055), strong Galactic wind (Crocker&Aharonian PRL 106:101102,2011), 2nd order Fermi acc. (Mertsch&Sarkar arXiv:1104.3585)
- Need further modeling and independent measurements in order to better understand the gamma-ray backgrounds AND work out the signals from the possible sources

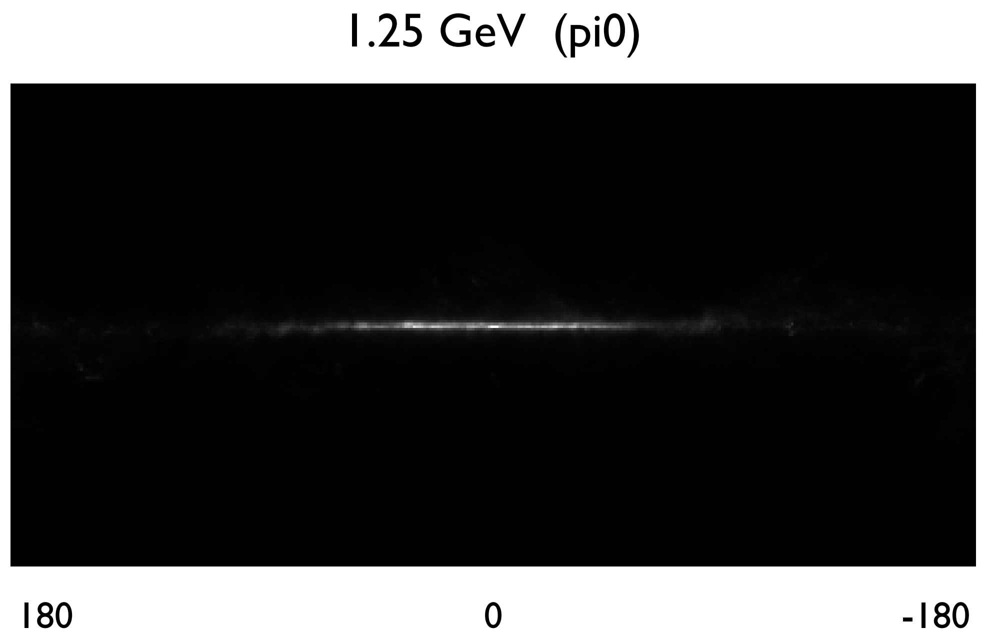
Additional slides

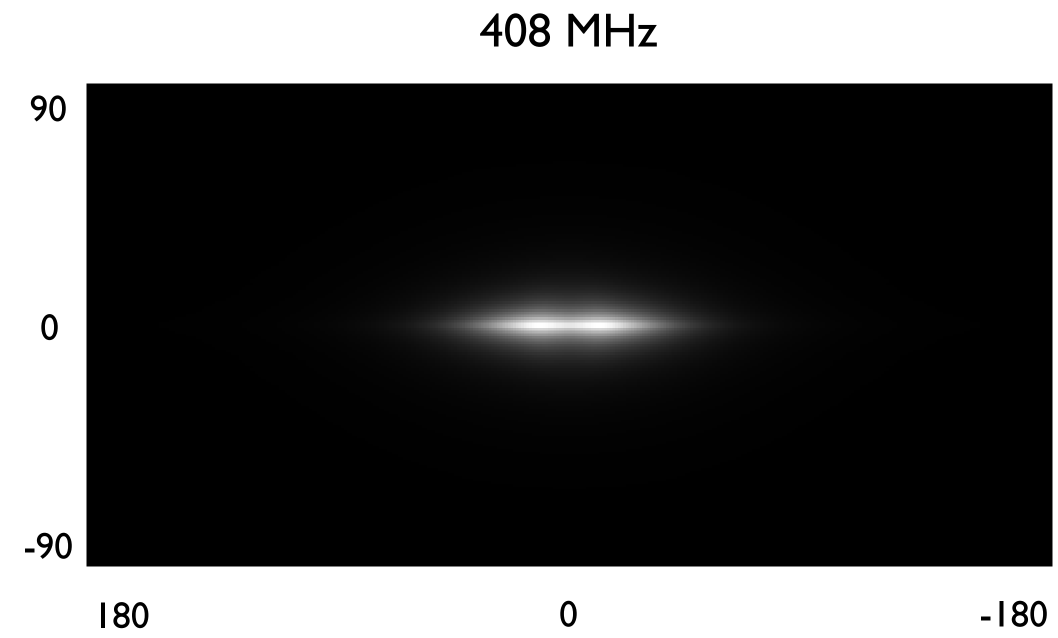
Alternative way

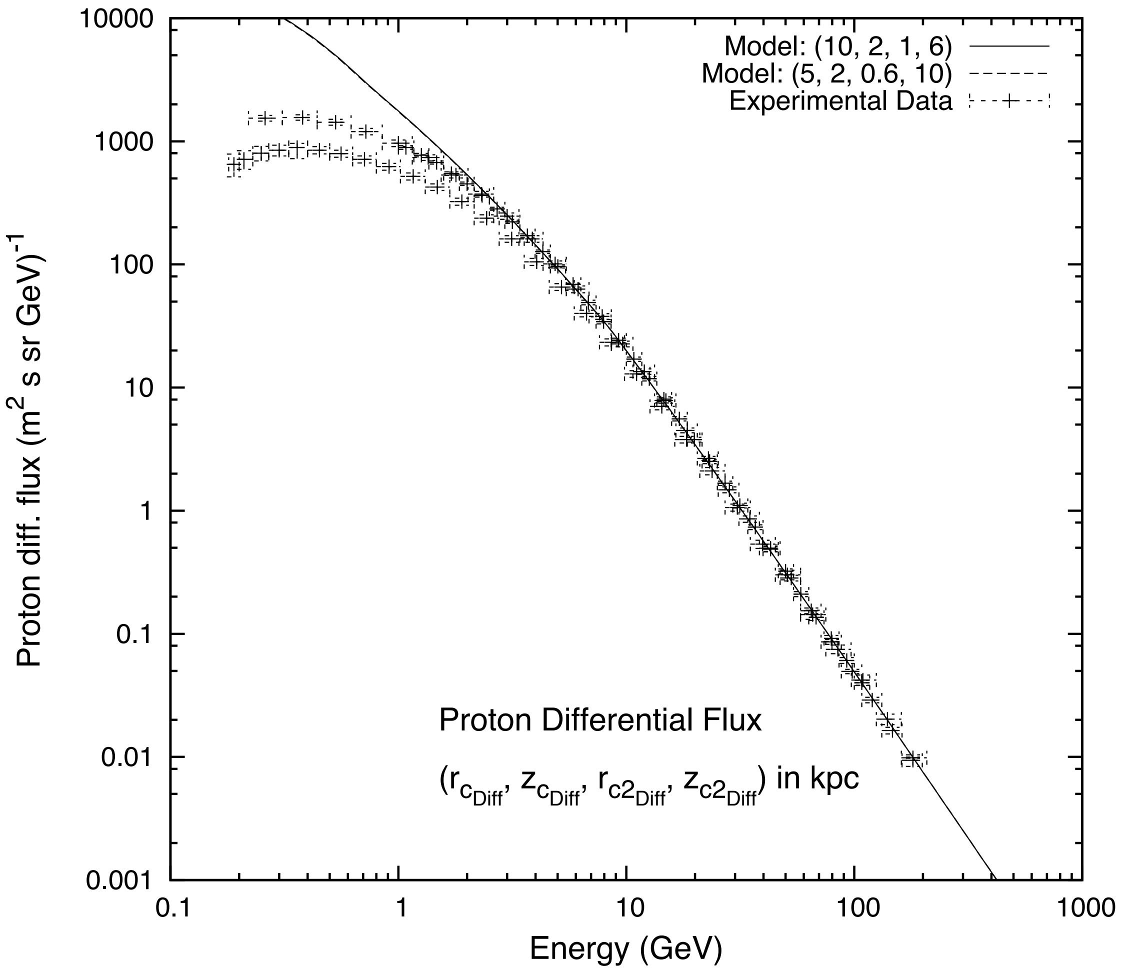
Instead of SFD and Haslam 408MHz maps, use for the galactic background, as a template the observed gamma-ray map by Fermi at a lower energy (1-2 GeV).

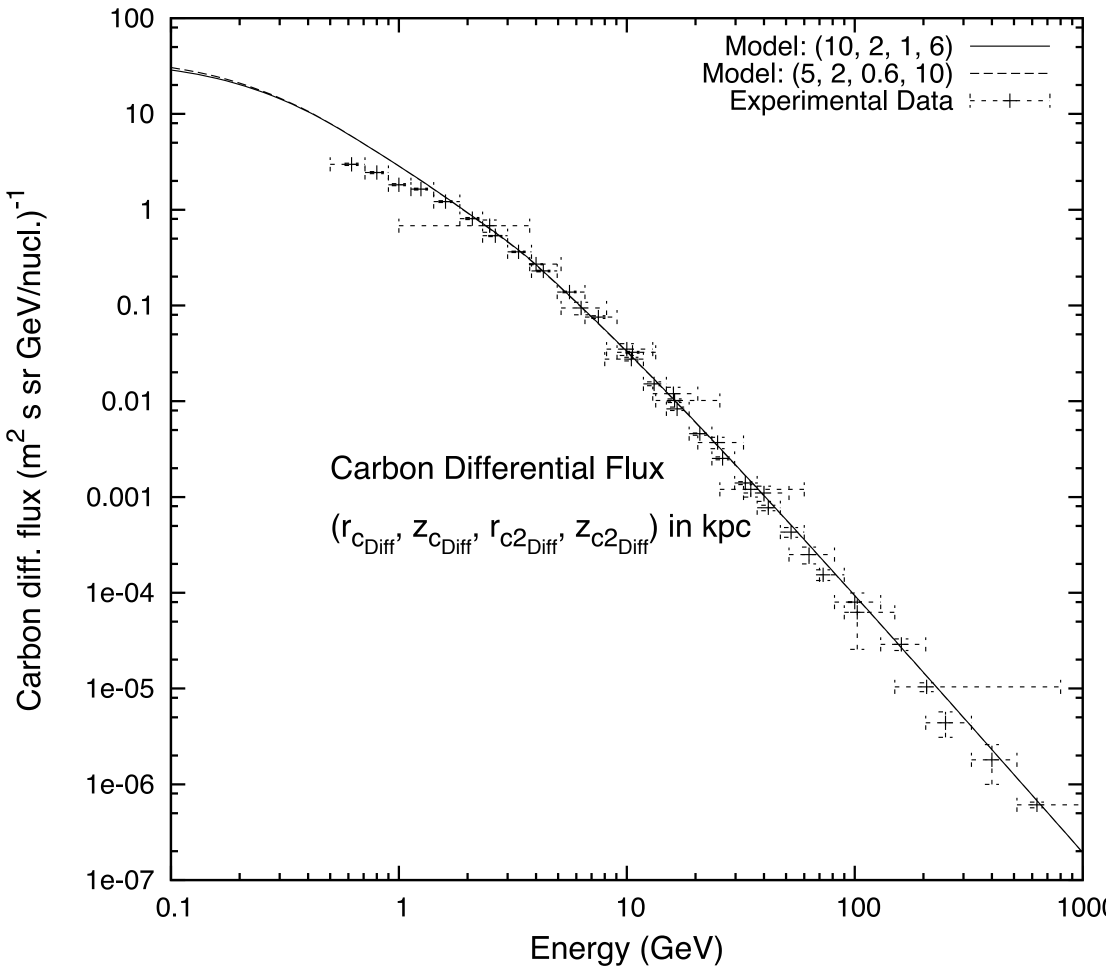

2.0 GeV < E < 5.0 GeV
26.03
0.00
[keV cm^-2 s^-1 sr^-1]
5.0 GeV < E < 10.0 GeV
9.96
0.00
[keV cm^-2 s^-1 sr^-1]
10.0 GeV < E < 20.0 GeV
7.46
0.00
[keV cm^-2 s^-1 sr^-1]
20.0 GeV < E < 50.0 GeV
6.98
0.00
[keV cm^-2 s^-1 sr^-1]
50.0 GeV < E < 100.0 GeV
6.31
0.00
[keV cm^-2 s^-1 sr^-1]
2.0 GeV < E < 5.0 GeV
1.00
0.00
90
45
0
-45
-90
180
90
0
-90
-180


2 GeV < E < 5 GeV
2 GeV < E < 5 GeV residual (1 < E < 2 GeV)
5 GeV < E < 10 GeV
5 GeV < E < 10 GeV residual (1 < E < 2 GeV)
10 GeV < E < 20 GeV
10 GeV < E < 20 GeV residual (1 < E < 2 GeV)
20 GeV < E < 50 GeV
20 GeV < E < 50 GeV residual (1 < E < 2 GeV)
[keV cm-2 s-1 sr-1]
4.243
0.283
2.828
-1.131
2.400
0.160
1.600
-0.640
1.697
0.113
1.131
-0.453
1.342
0.089
0.894
-0.358
180
90
0
-90
-180
45
-45


1.25 GeV (pi0)
90
0
-90
180
0
-180

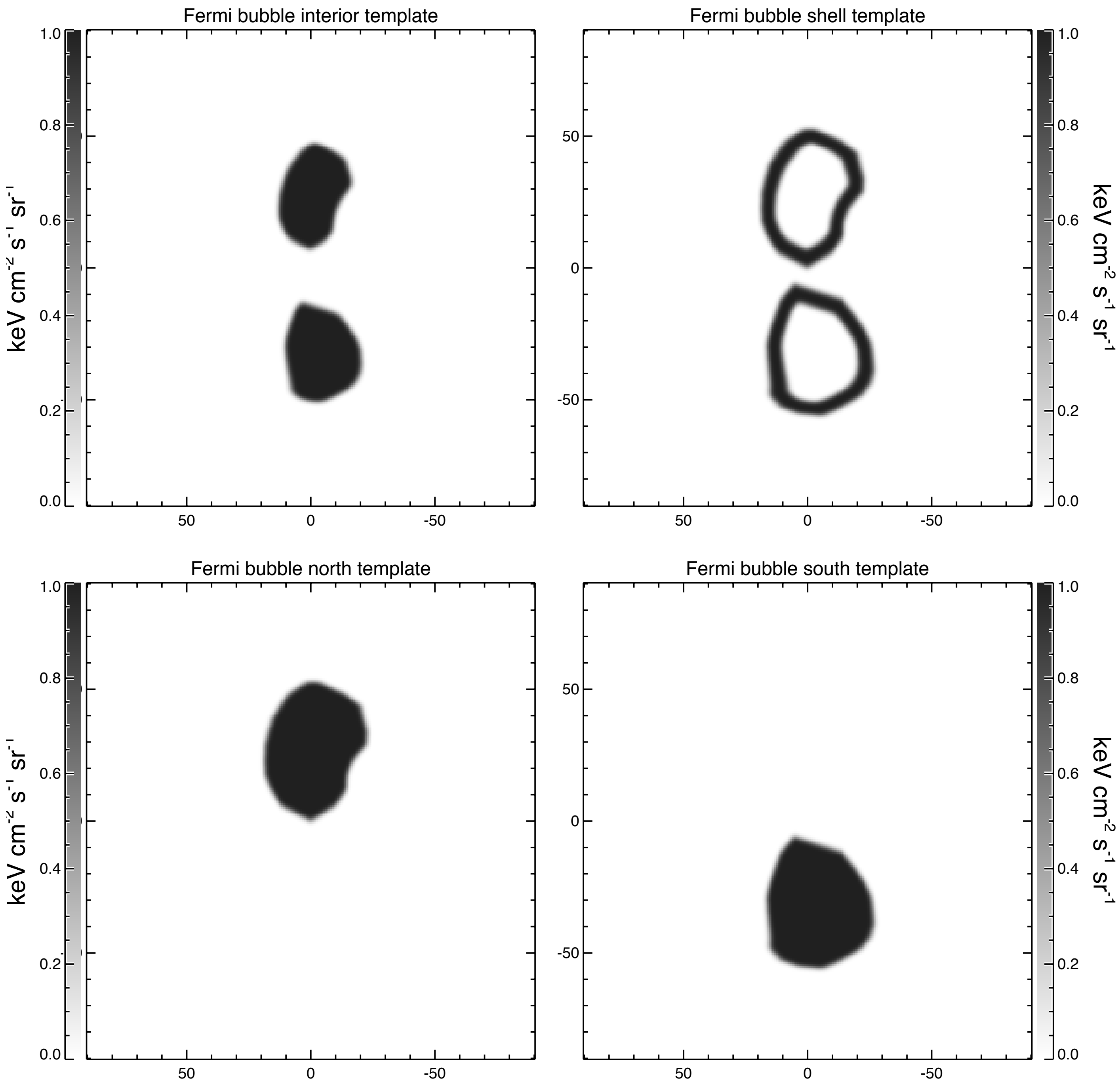

408 MHz
90
0
-90
180
0
-180


Model: (10, 2, 1, 6)
Model: (5, 2, 0.6, 10)
Experimental Data
Proton diff. flux (m^2 s sr GeV)^-1
Energy (GeV)
Proton Differential Flux
(r_cDiff, z_cDiff, r_c2Diff, z_c2Diff) in kpc

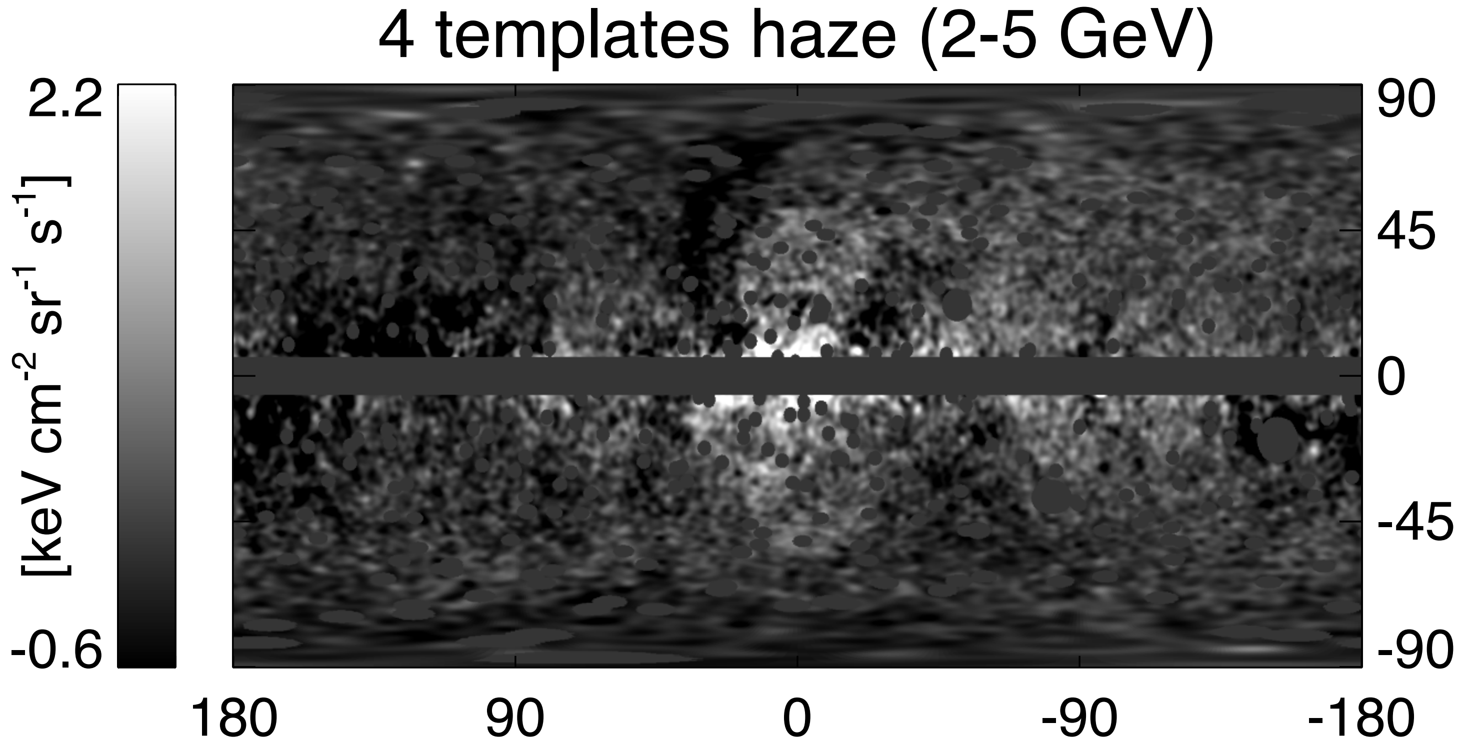

Model: (10, 2, 1, 6)
Model: (5, 2, 0.6, 10)
Experimental Data
Carbon diff. flux (m^2 s sr GeV/nucl.)^-1
Energy (GeV)
Carbon Differential Flux
(r_cDiff, z_cDiff, r_c2Diff, z_c2Diff) in kpc

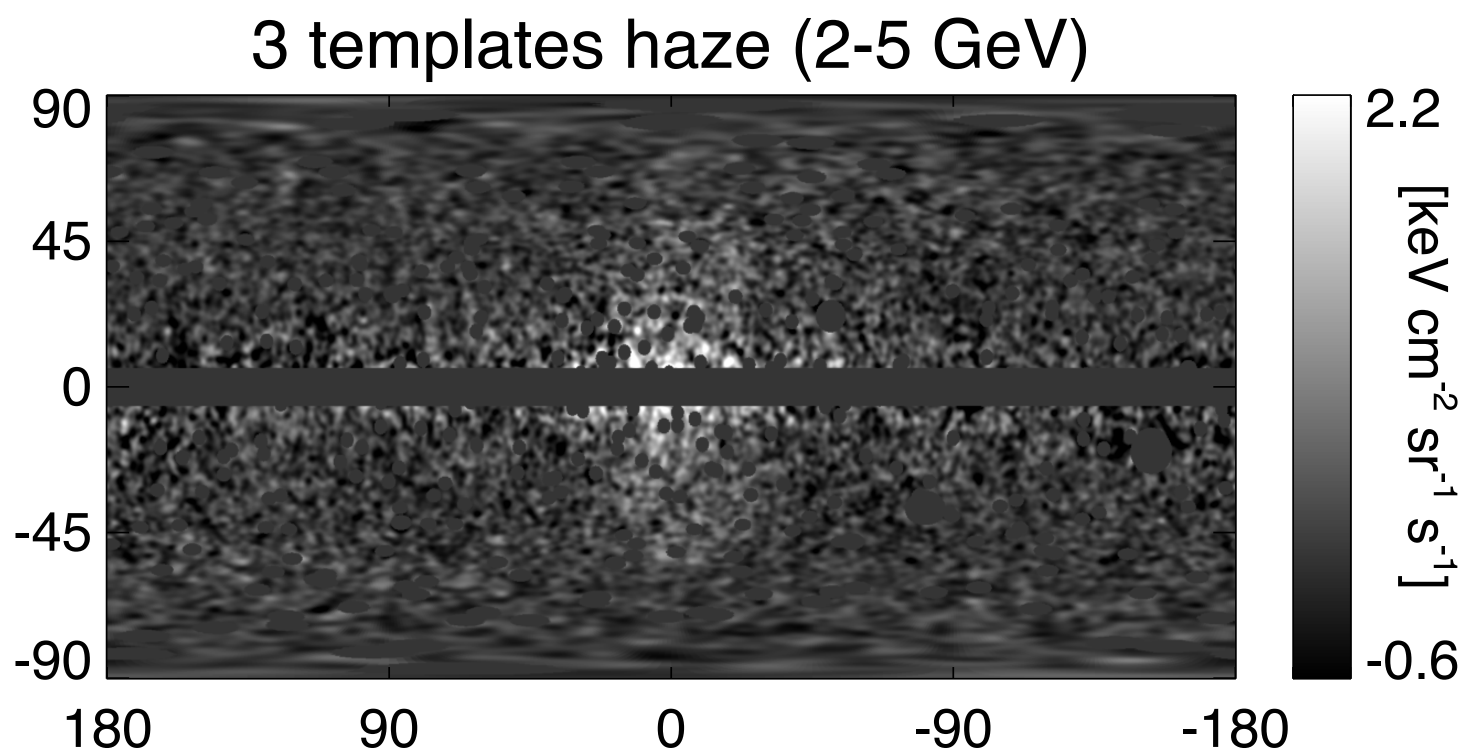
Su, Slatyer and Finkbeiner work

ApJ 724, 1044 (2010) (arXiv:1005.5480)

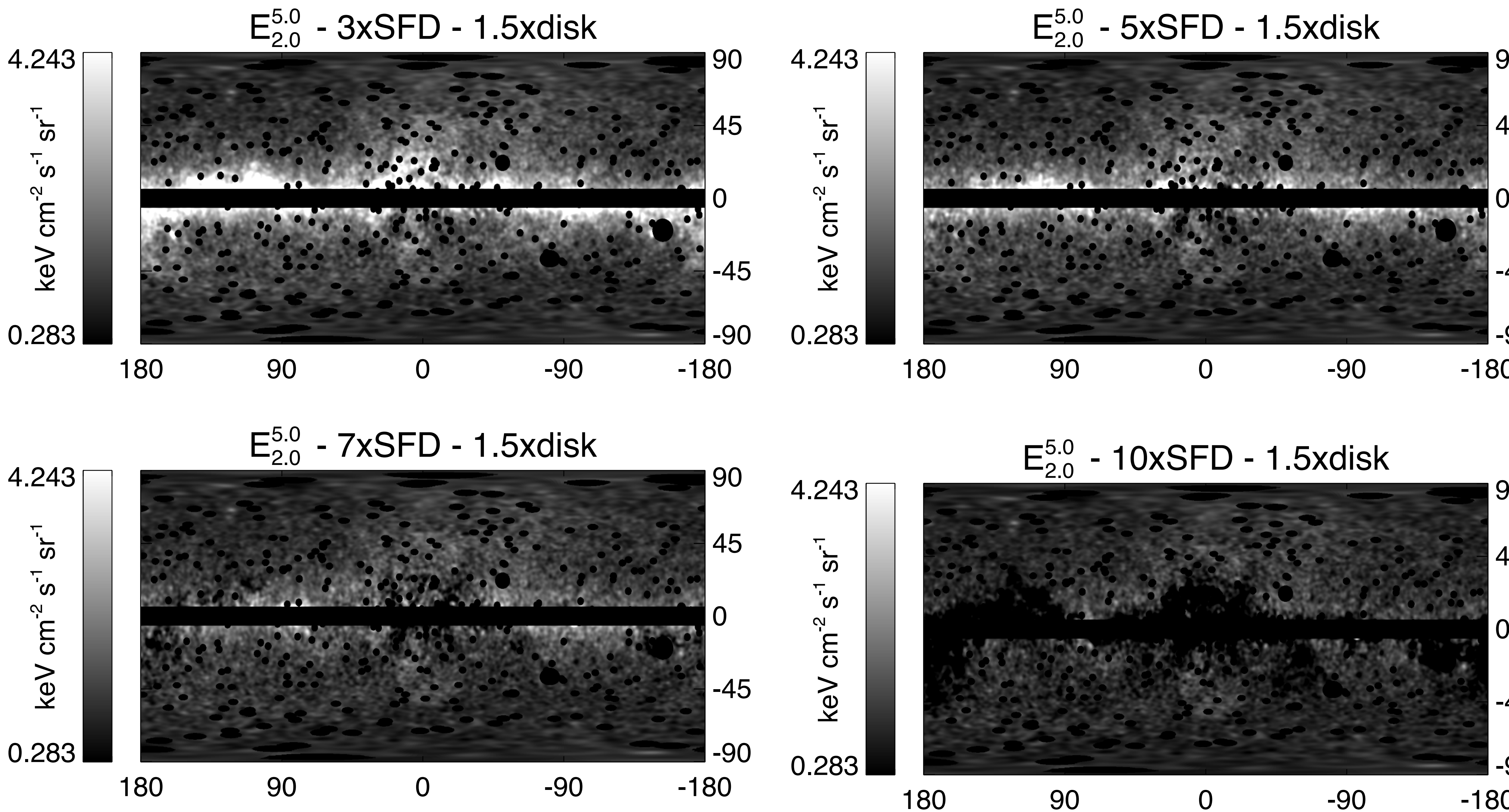


One needs to be very careful for small (but significant in the interpretation) caveats with using templates.



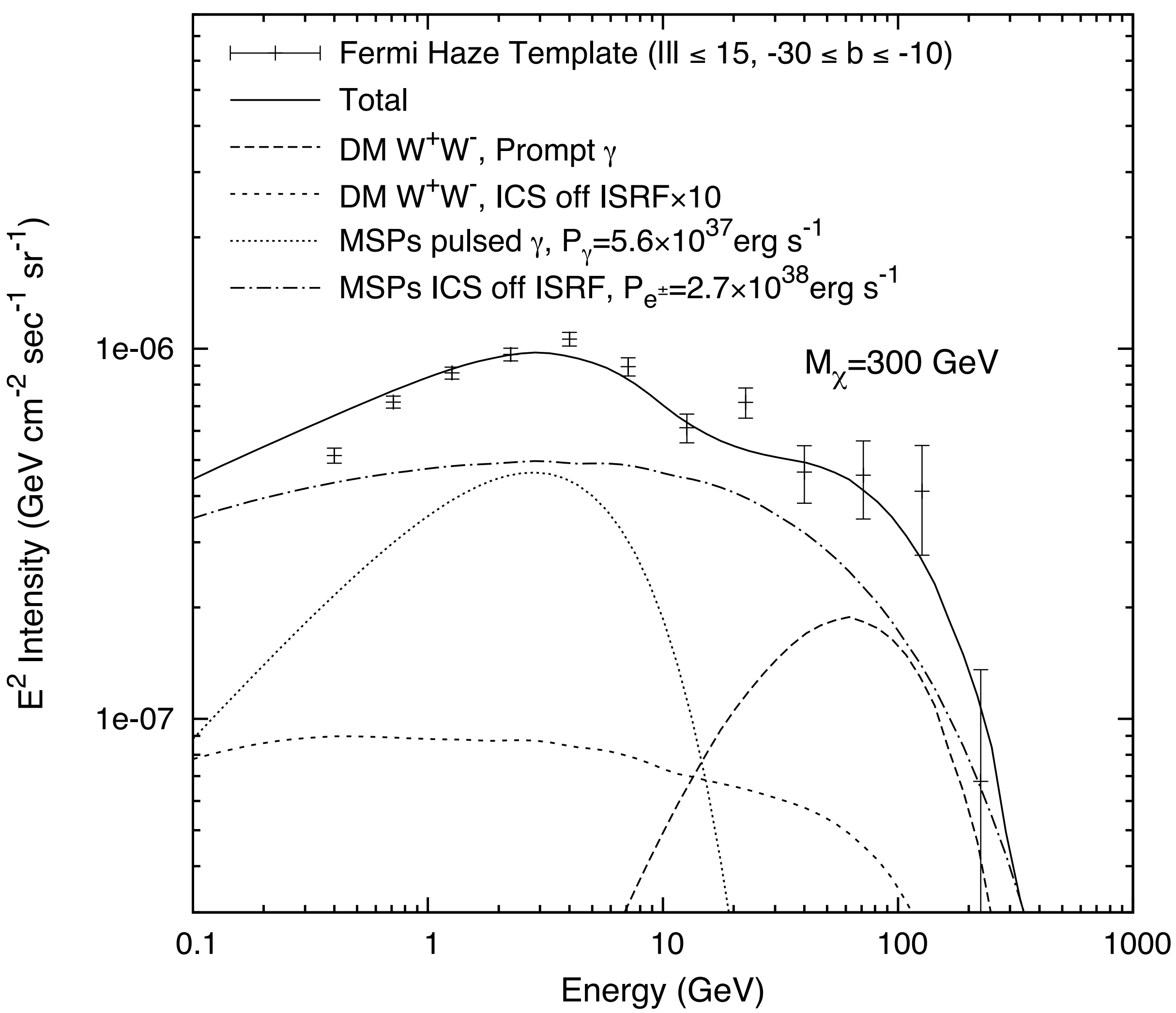


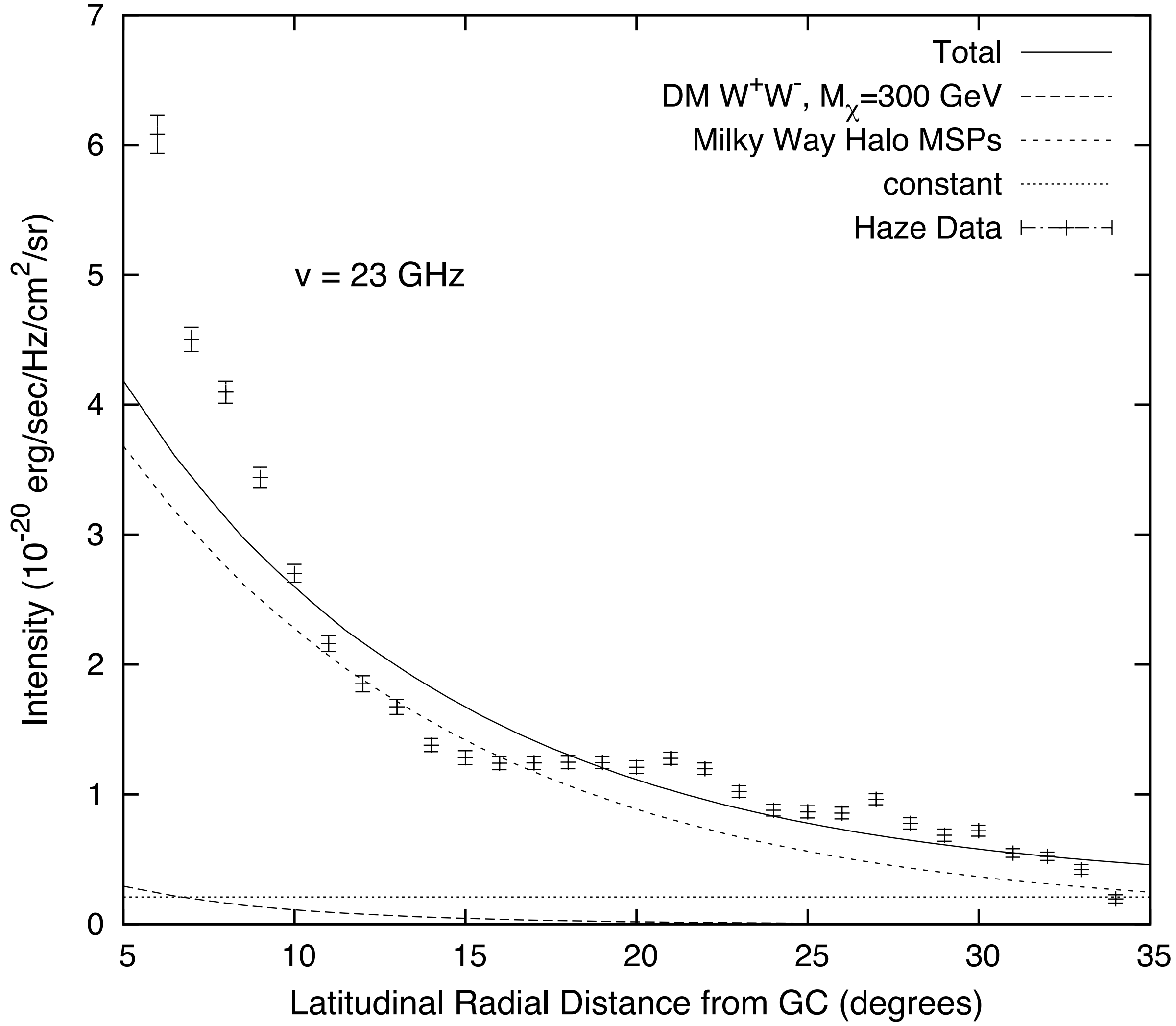
SFD template



X-shape that could indicate an over-subtraction in the 4-template scheme.

Millisecond pulsars & DM





DM annihilating to W^+W^- with a thermal relic cross-section.

Need 3x10^4 MSPs in the galactic halo! (significant implications about the evolution of the Milky way)

ApJ 722, p.1939-1945 (2010) (arXiv:1002.0587)

Template assumptions

pi0 gammas and bremsstrahlung are produced by interactions of protons and electrons (respectively) with the ISM.
Should be morphologically correlated to other ISM traces such as the SFD dust map based on the 100 microns FIR data.

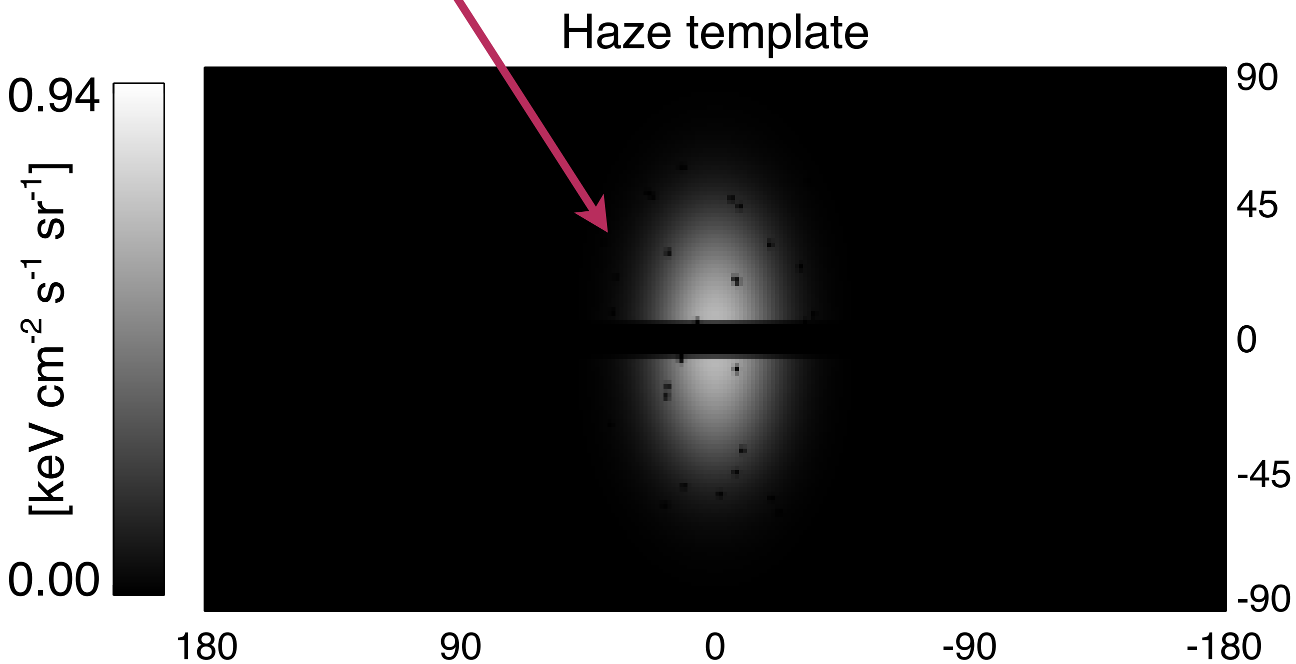
pi0 gamma-ray intensity scales with ISM density times the proton CR density integrated along the line of sight. In the approximation that the proton CR density is spatially uniform the ISM column density is a good tracer of the pi0 emission.

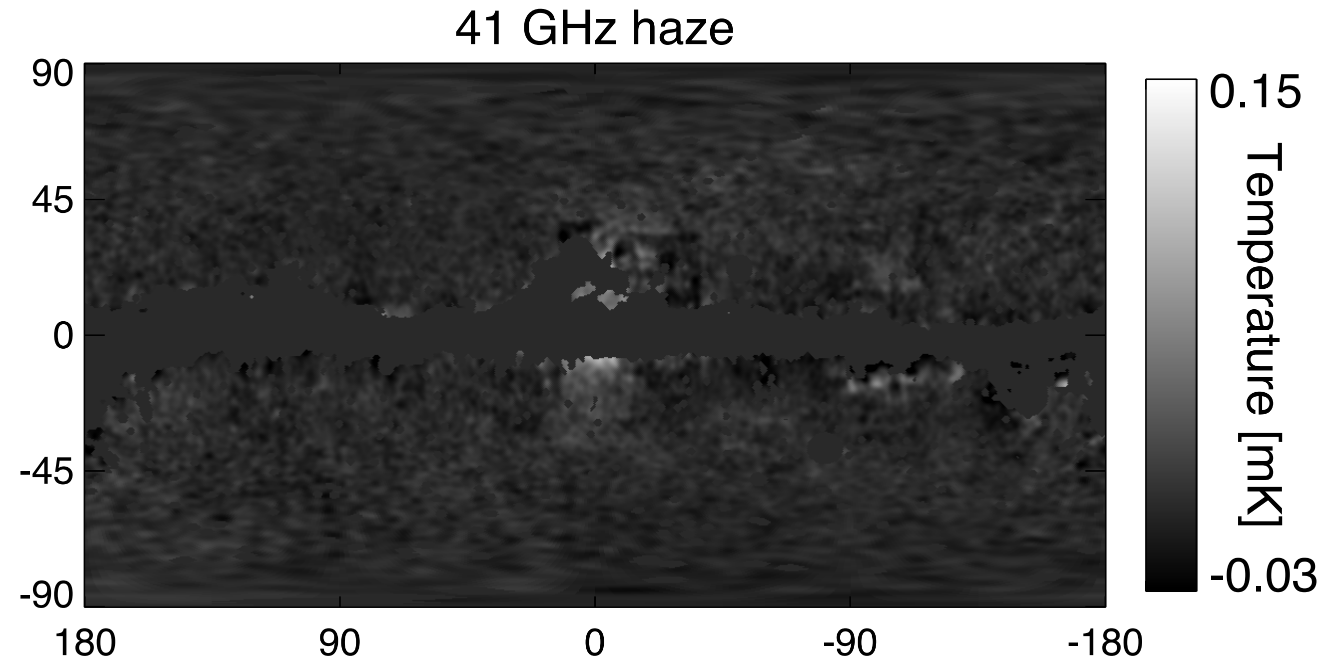
Similarly for spatially uniform CR electron density for the bremsstrahlung emission.

Our analysis was done in $|b| > 5^o$ thus the assumption of uniform CR is more valid than in the case of the entire galaxy.

The two haze signals

First template





Probe a distribution of hard-spectrum electrons, (steady state diff. spectrum of $\frac{dN_e}{dE} \sim E^{-2}$)

Fermi haze: inverse Compton scattering

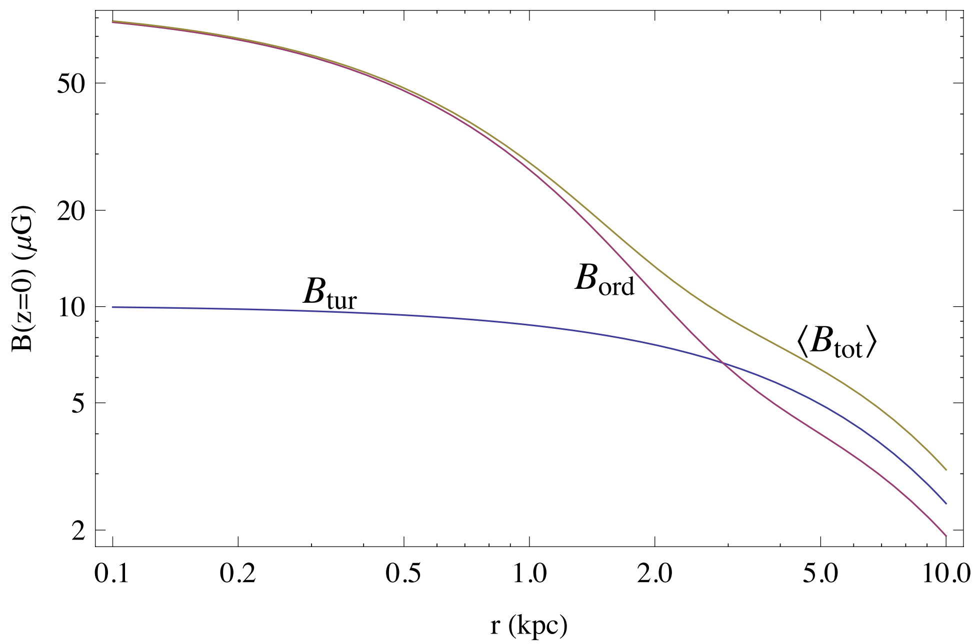
WMAP haze: synchrotron radiation

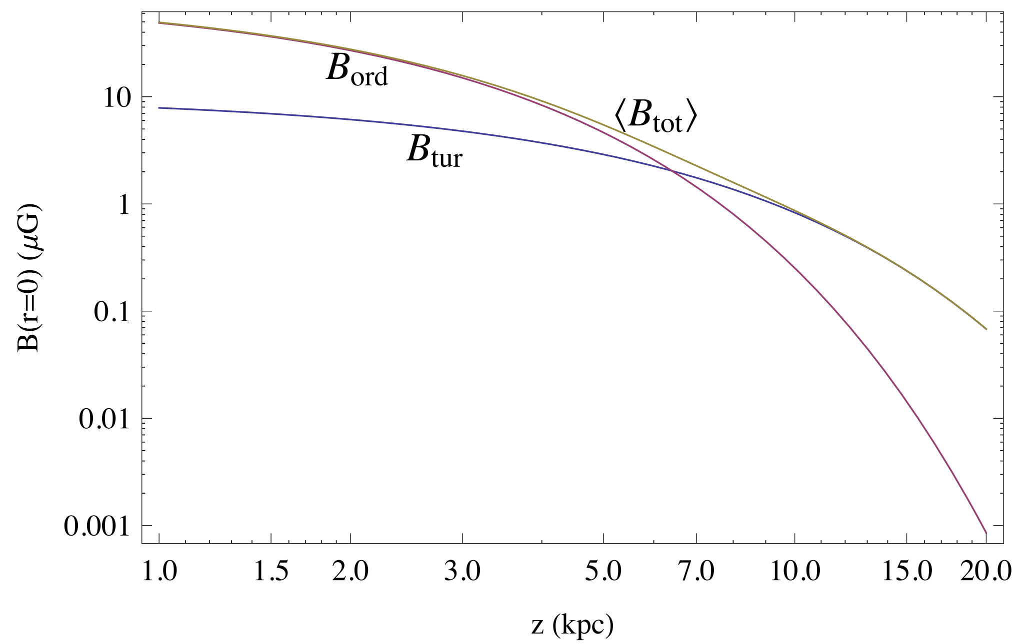
Non-trivial morphology of the Fermi haze (template:bivariate Gaussian)

The source(s) responsible for the signal must explain both spectra AND the non-disk-like morphology

DM can explain the haze signal (WMAP + Fermi) as has been shown in arXiv:0911.4954 (IC + N. Weiner) based on solely energetic/spectral arguments (XDM electrons with local annihilation BF ~ 100 (~50 at the haze region)).

Still DM with homogeneous and isotropic diffusion assumptions for the cosmic rays, while significantly better than young pulsars, can't explain the haze morphology.





Yusef-Zadeh & Morris (1987), Morris & Yusef-Zadeh (1989), Morris (2007), have suggested mag. fields up to few mG in large non-thermal radio filaments (with widths of pc and lengths ~ 50pc). Beck (2008) suggested 0.5 mG. Those non-thermal filaments seen by VLA are directed perpendicular to the disk plane, and are probes of the general B-field properties, suggesting a predominantly bipolar field extending ~200pc in r (Nord et. al. (2004)).

Also arguments of CR cooling by synchrotron radiation in the inner 500pc have been used to avoid over-production of gamma-rays by ICS.