# The Fermi haze from Dark Matter Annihilation and Anisotropic Diffusion


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arXiv:1102.5095 (accepted by ApJ),

ApJ 717,825,(2010) (arXiv:0910.4583) (G. Dobler, D. Finkbeiner, IC, T. Slatyer, N. Weiner), arXiv:0911.4954 (IC, N. Weiner)



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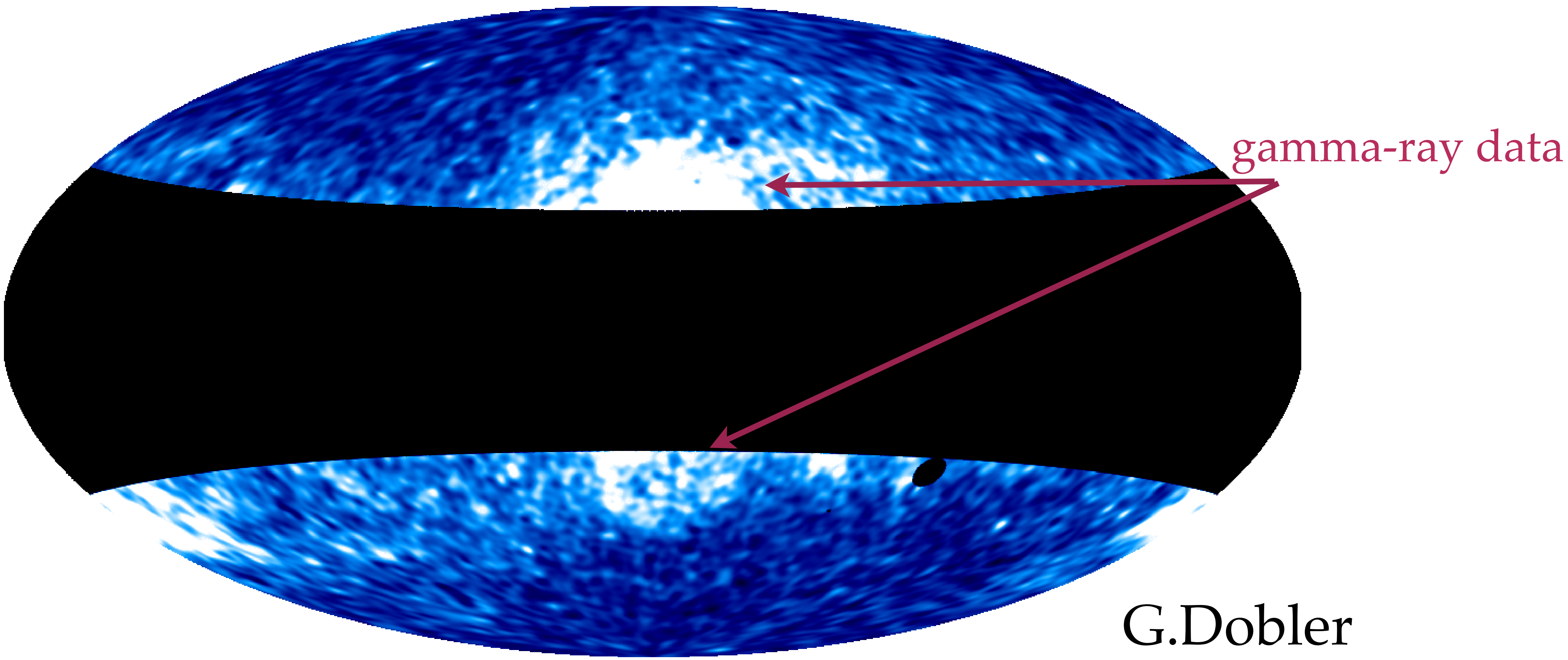
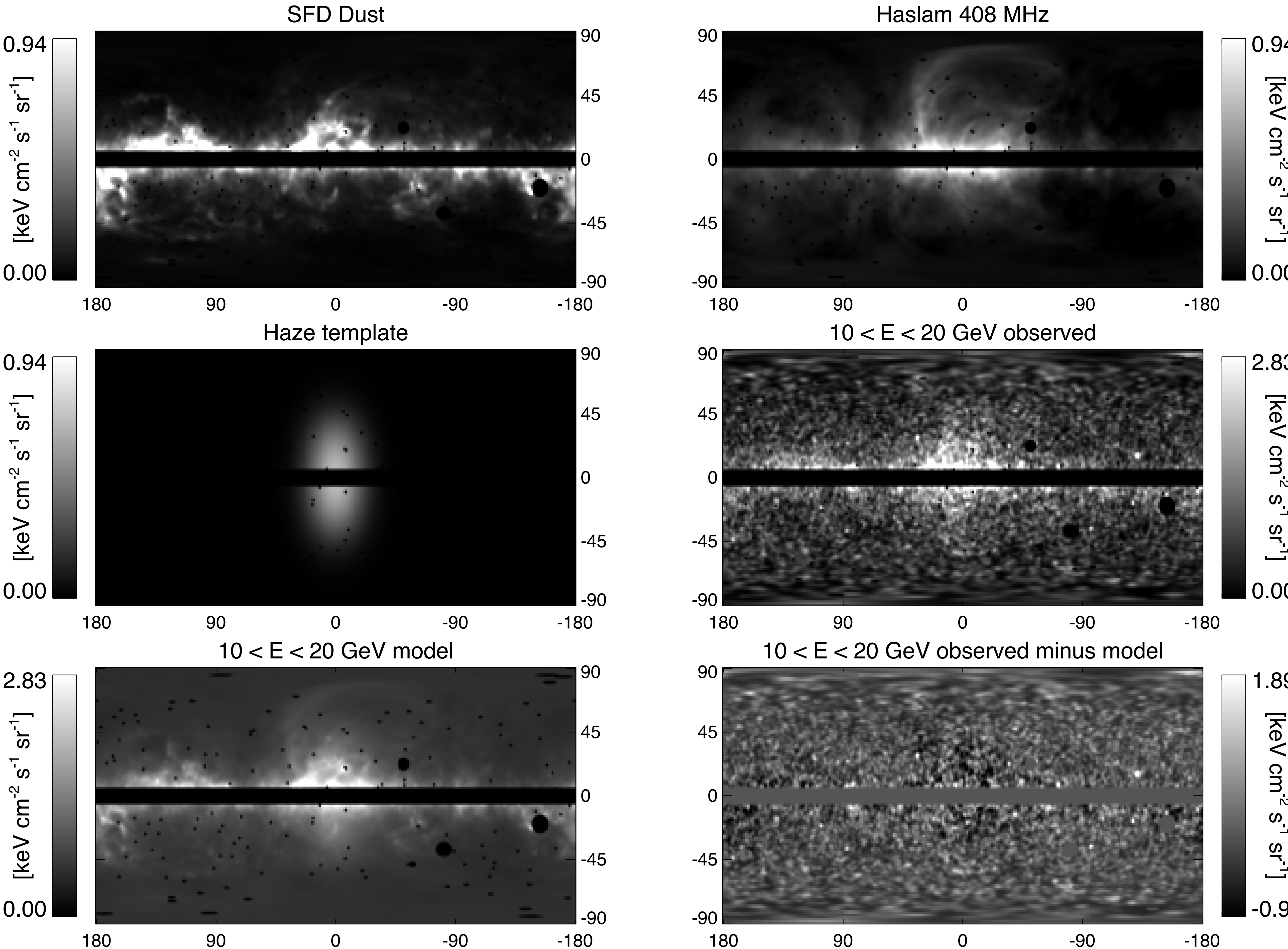
4/8/2011

# Outline

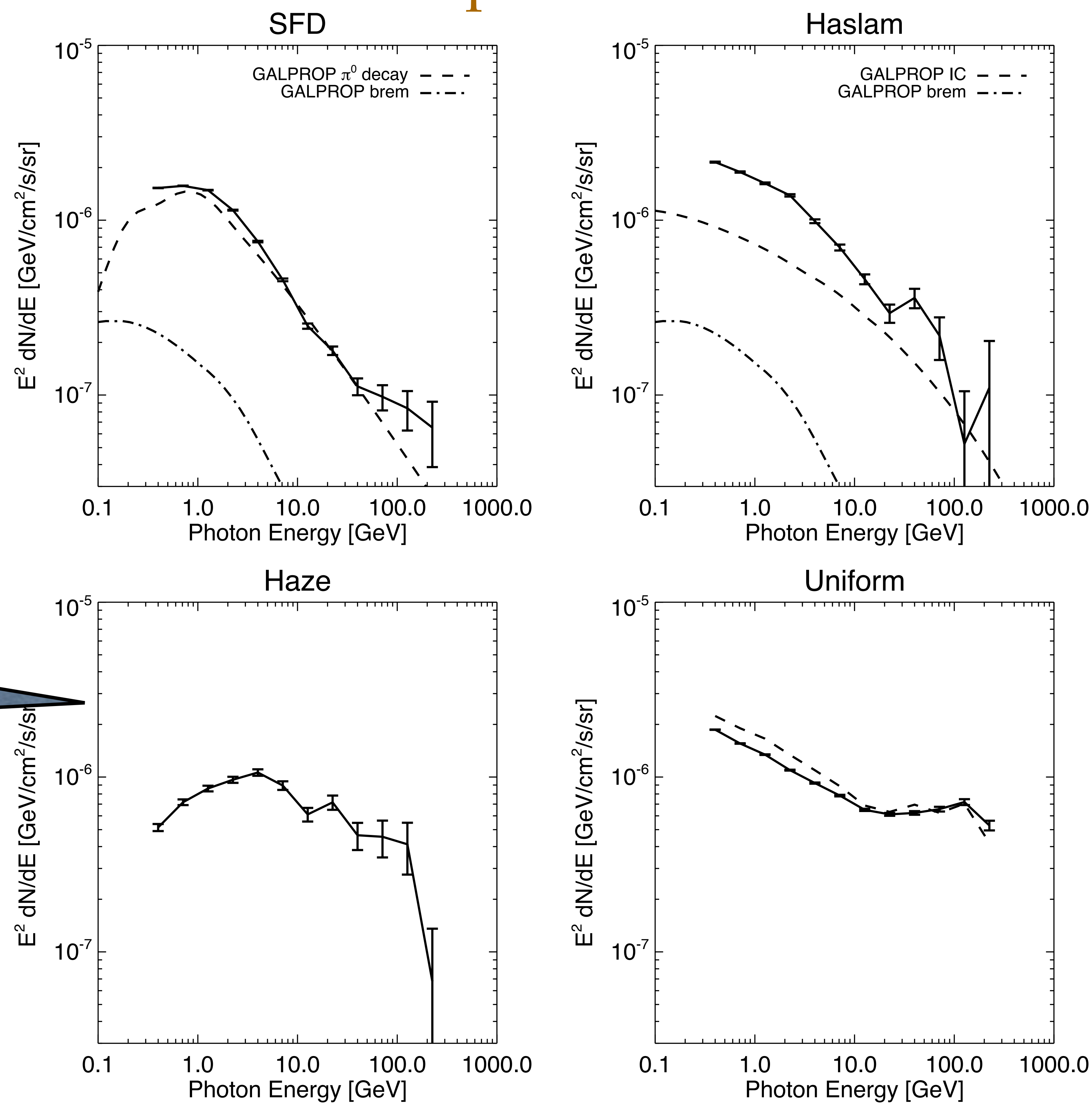
- Fermi haze/Fermi bubbles a true signal. Lower latitudes uncertainties
- Dark Matter case (models that work)
- Anisotropic diffusion of CRs in the Galaxy
- Conclusions



# The first Fermi haze template

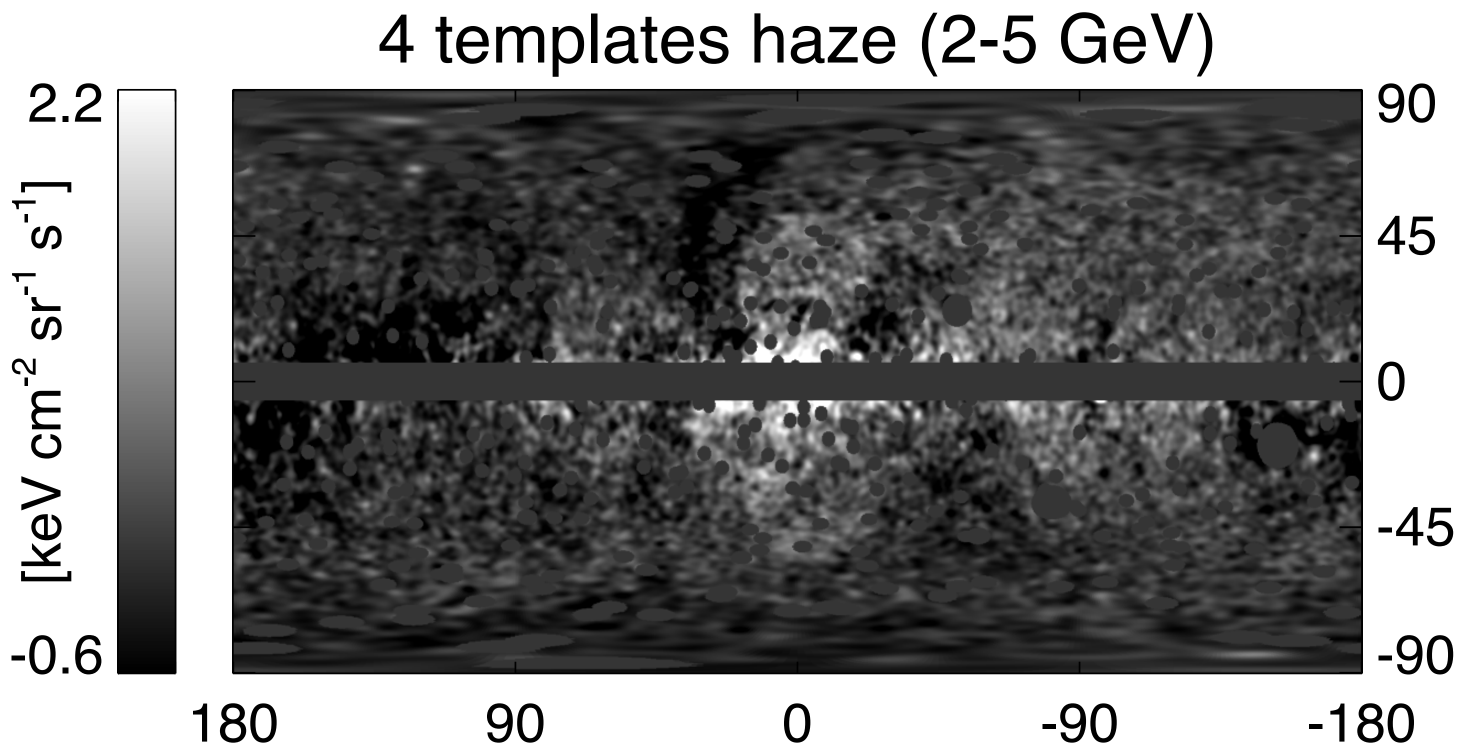


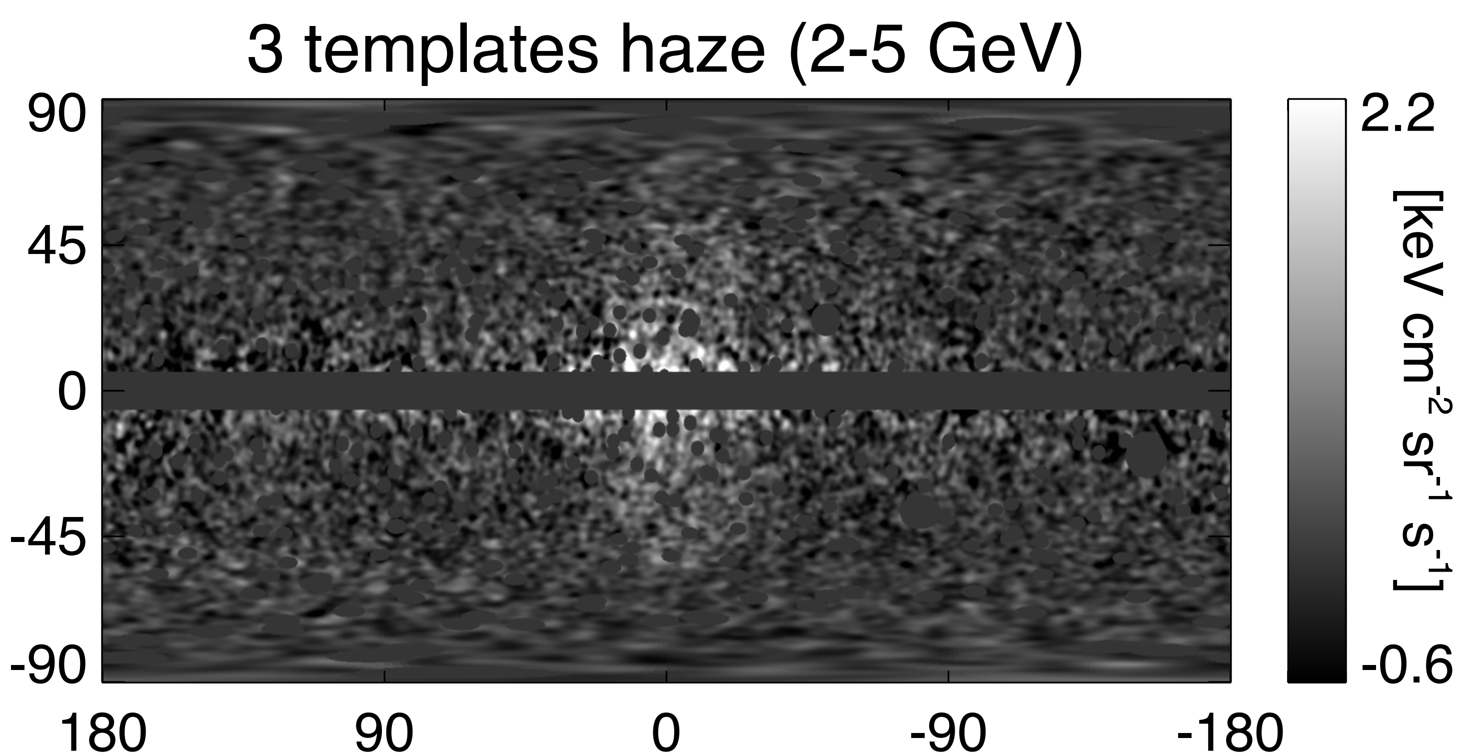
# Spectra




Harder than typical galactic

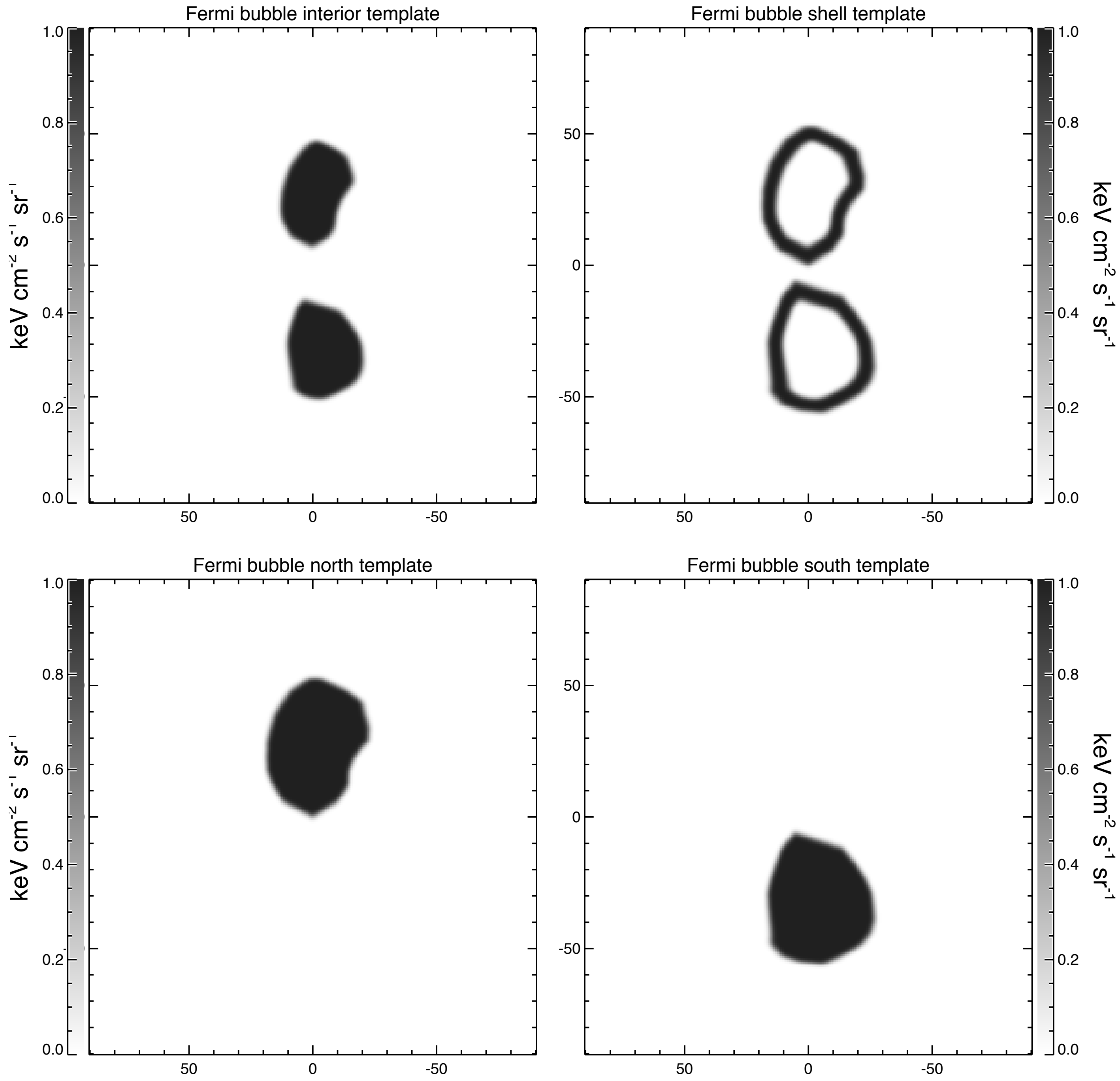
One needs to be very careful for small (but significant in the interpretation) caveats with using templates.



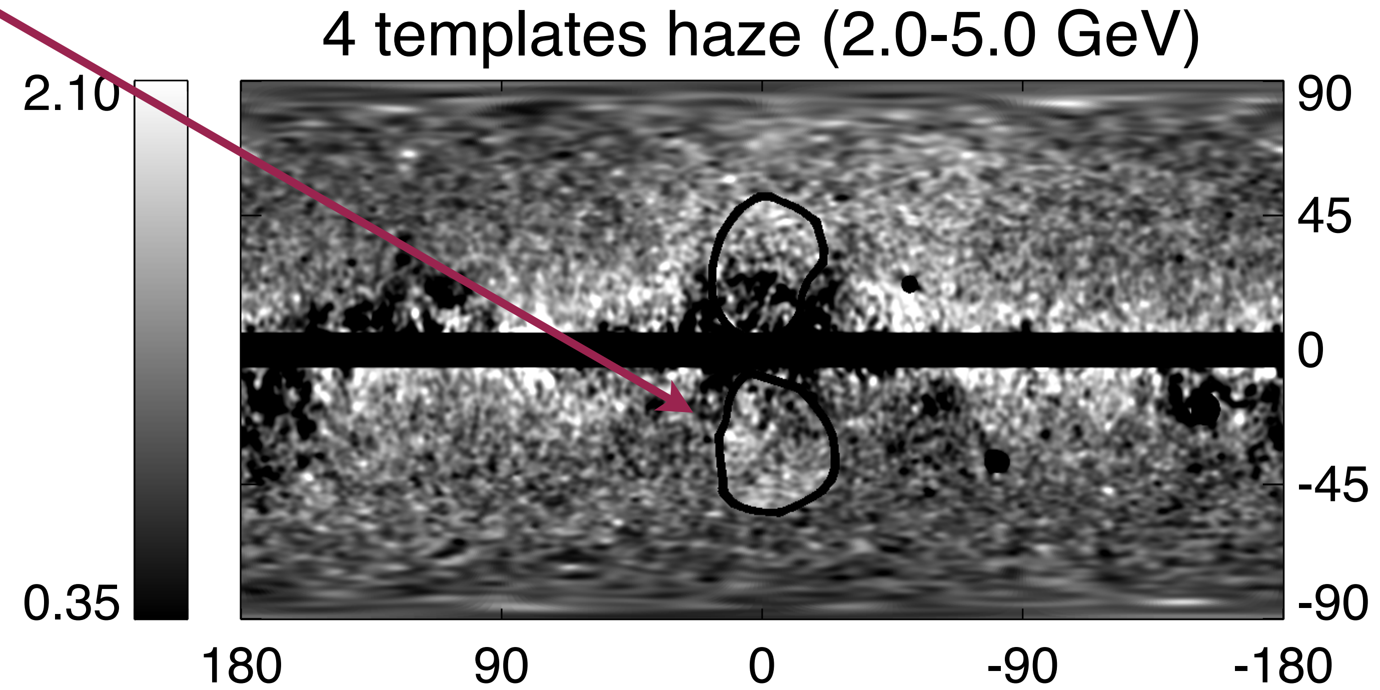



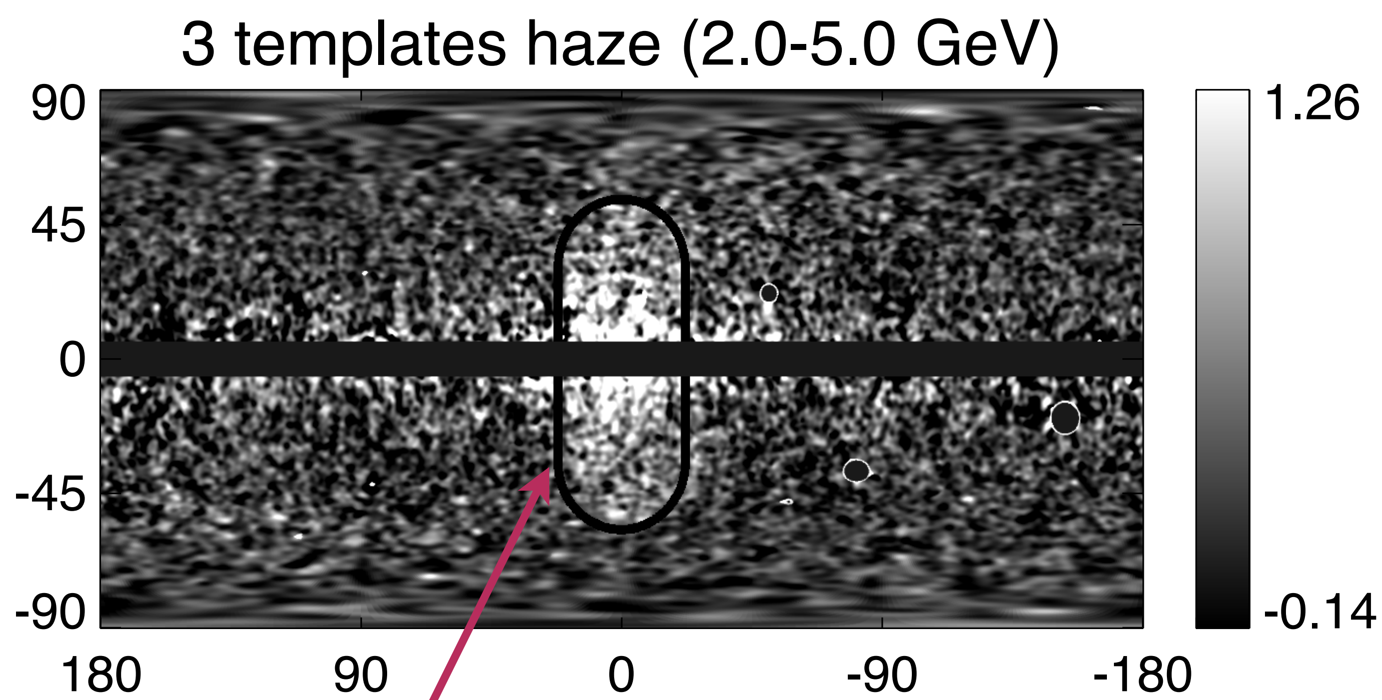
# Su, Slatyer and Finkbeiner work

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



Fermi Bubbles (Su, Slatyer, Finkbeiner) (SFD+disk+uniform+bubbles)

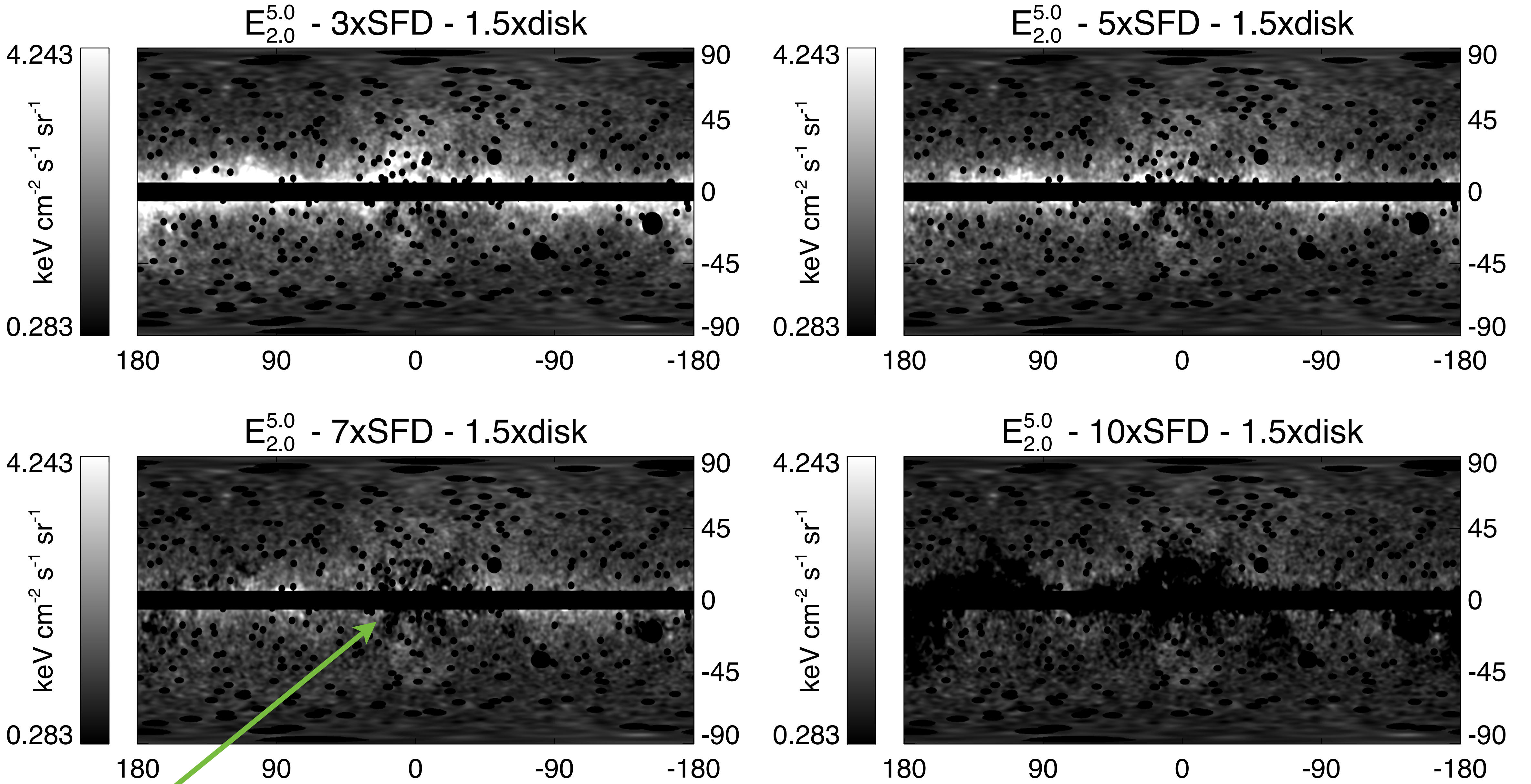



(Updated) Fermi haze (G. Dobler, IC, N.Weiner )

We used the Fermi gamma-ray map at 0.5-1 GeV as a background galactic template+uniform + haze(modeled by GALPROP Dark Matter IC signal)

# SFD template used as a pi0 tracer may be the root of difference

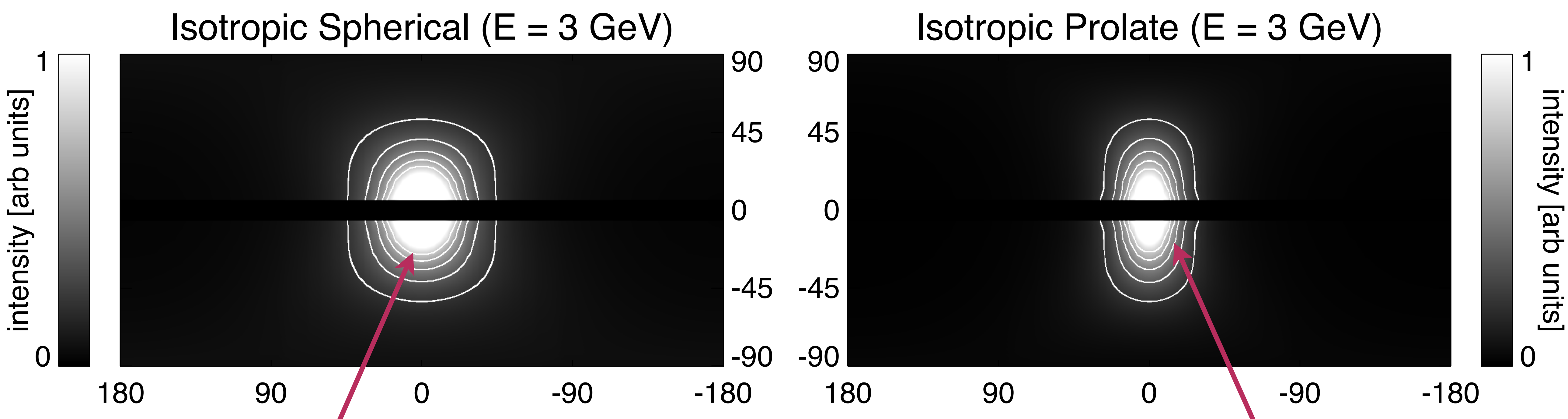



X-shape that could indicate an over-subtraction (of pi0 gamma-rays) in the SFD template scheme. The pi0 to dust column ratio needs not to be constant (for instance a source heating up the region and giving also the signal in X-rays). So while at the high latitudes the signal is clear (even some edge effect at high latitudes is confirmed) BUT at lower latitudes the template selection is important.

# 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)).




Too spherical

Better but still too peaked in the center

Leptophilic DM models can explain the signal. Models that annihilate to taus or have large BRs to hadrons can not explain the angular morphology of the signal.

# Anisotropic and inhomogeneous CR diffusion in the ISM

Propagation equation:

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

$\psi$ 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:

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

Anisotropic diffusion:

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

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

Random(irreg.) B-field component:

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

$$R_\odot = 8.5kpc$$

Ordered B-field component:

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

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 formulation developed by 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:

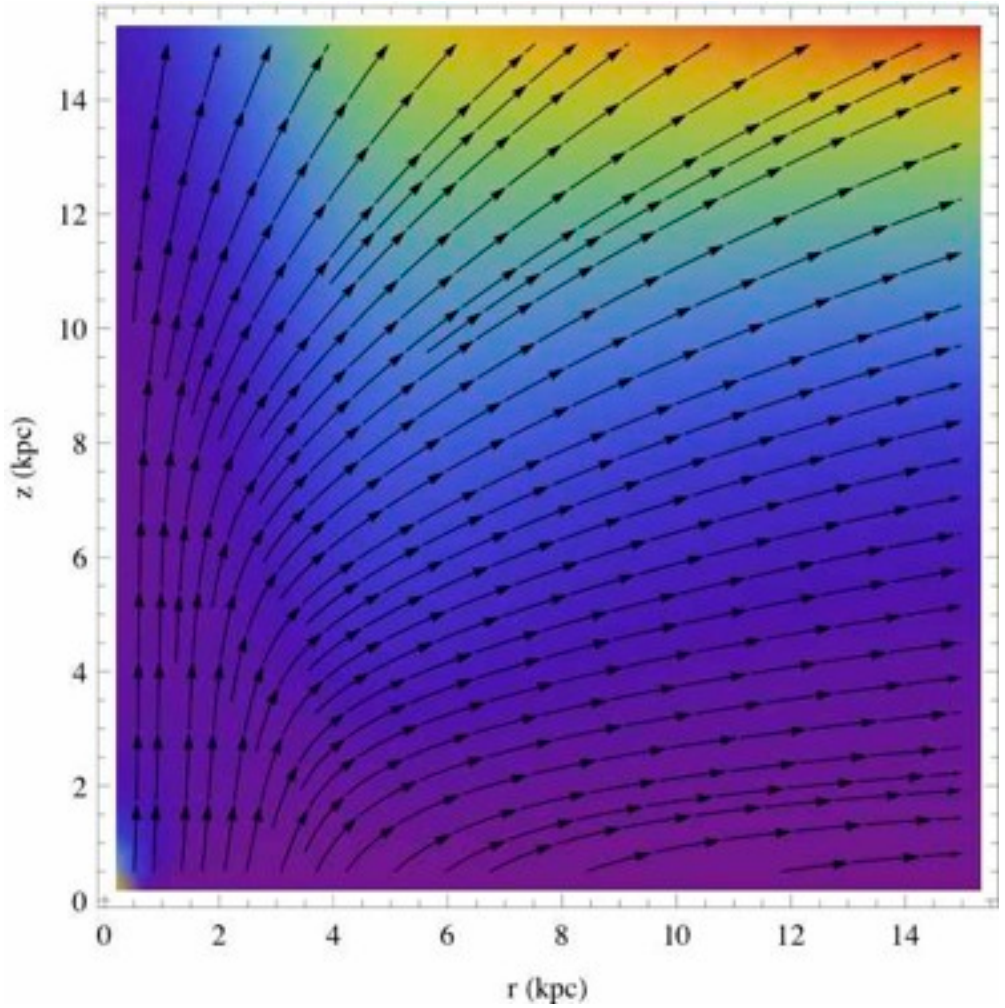
$$A = \frac{q}{\gamma m c \mathrm{v}}$$

we get:

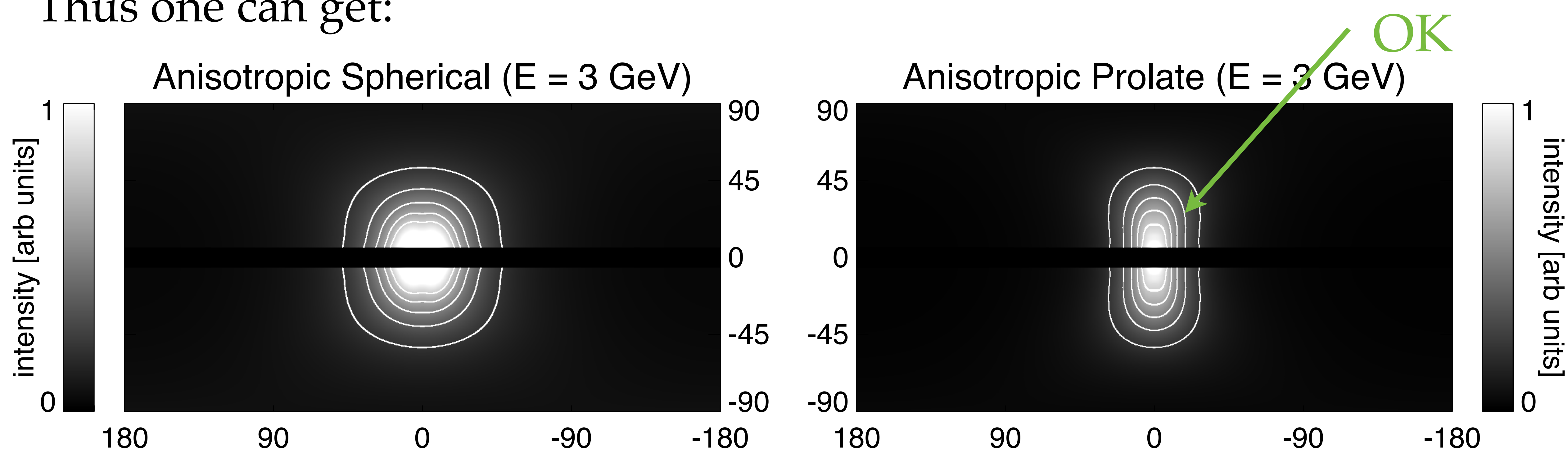
$$D_{zz} \propto B_{tot}^{-1} \left( \frac{1 + A^2 B_z^2}{1 + A^2 B_{tot}^2} \right)$$

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

*(extreme example)*



Thus one can get:

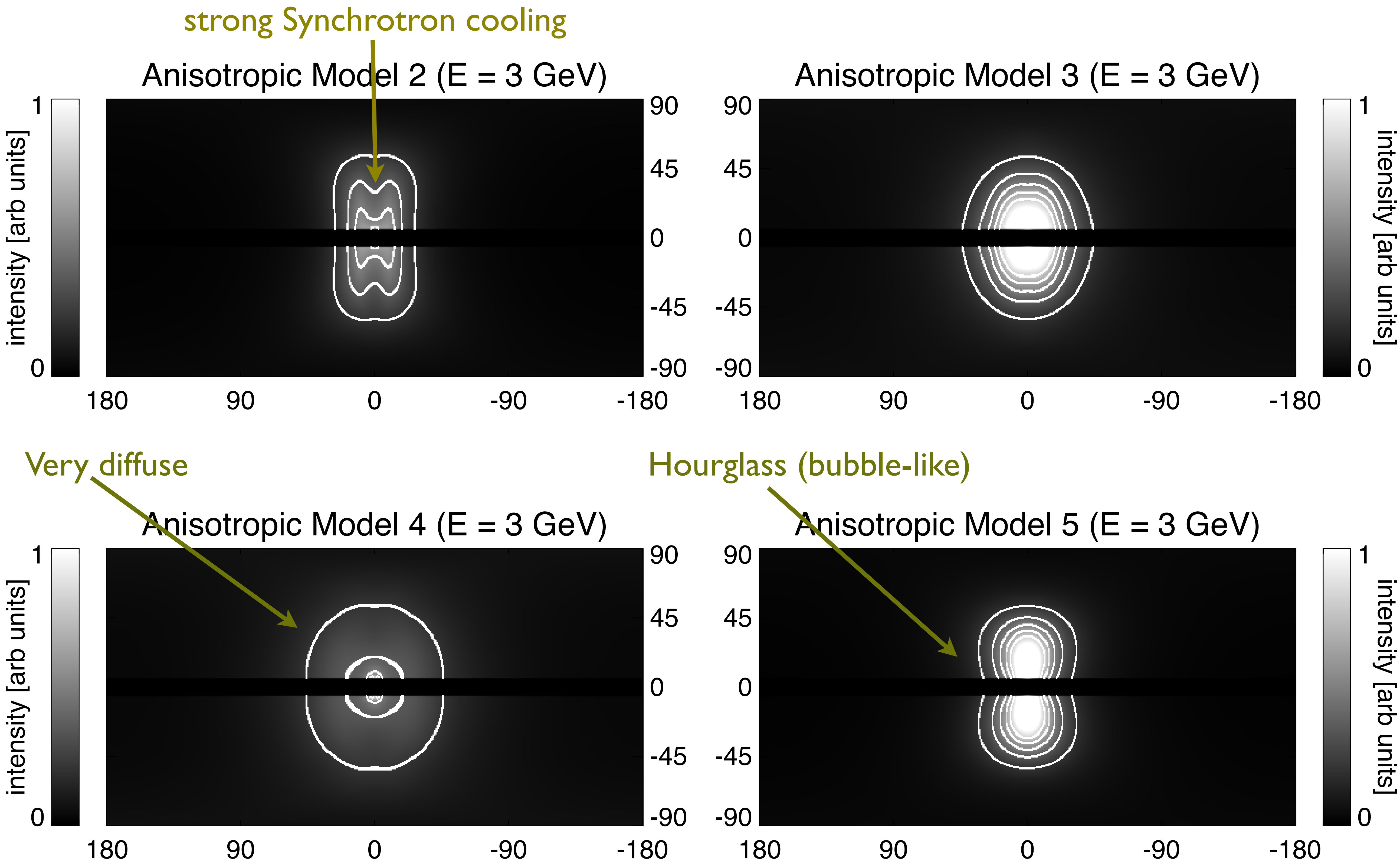


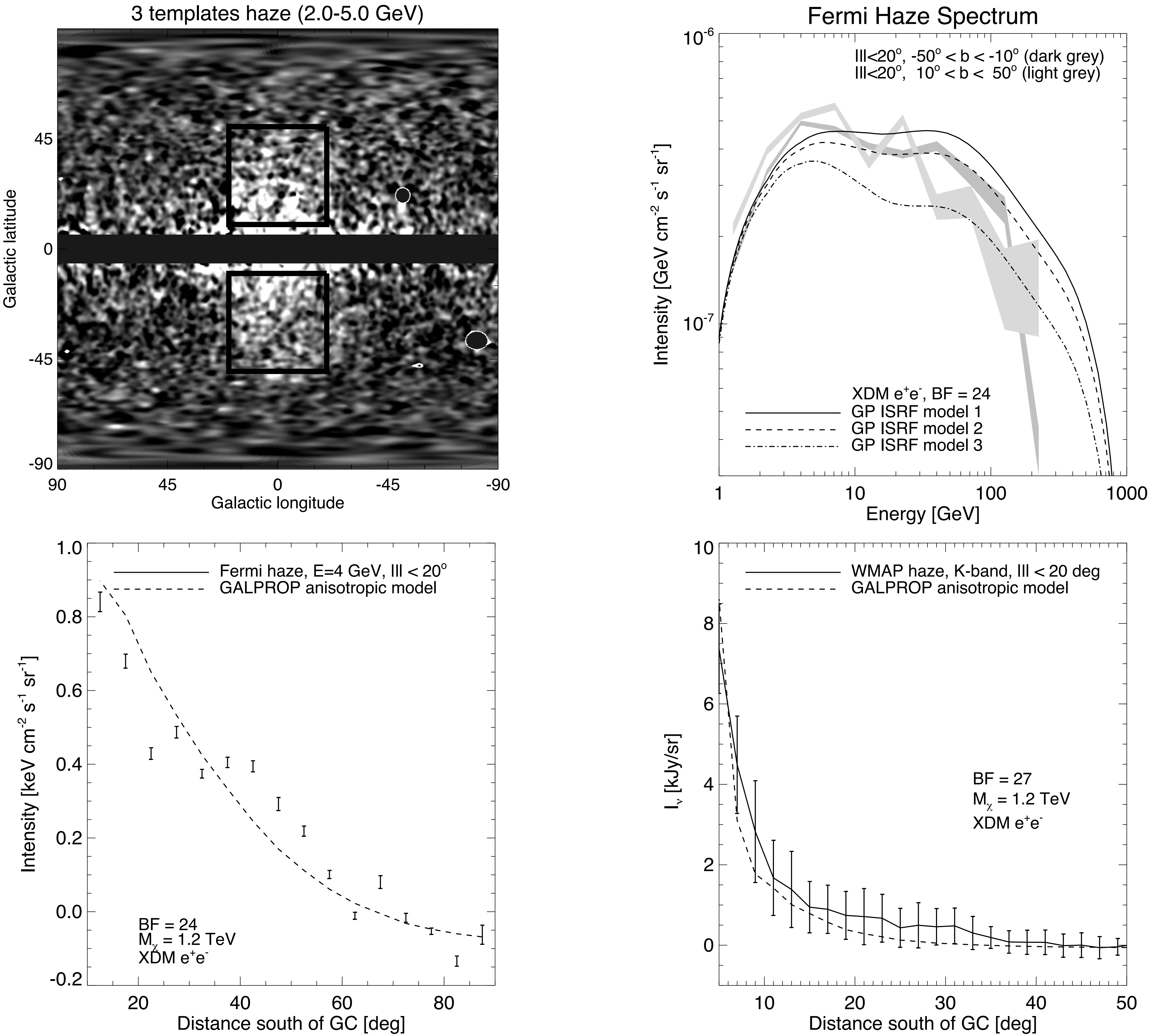

So with annihilating DM and specific assumptions on anisotropic and in-homogeneous diffusion we CAN fit the Fermi haze morphology spectrum and amplitude.

Different assumptions for the B-field can have apart from different synchrotron maps, different IC maps.

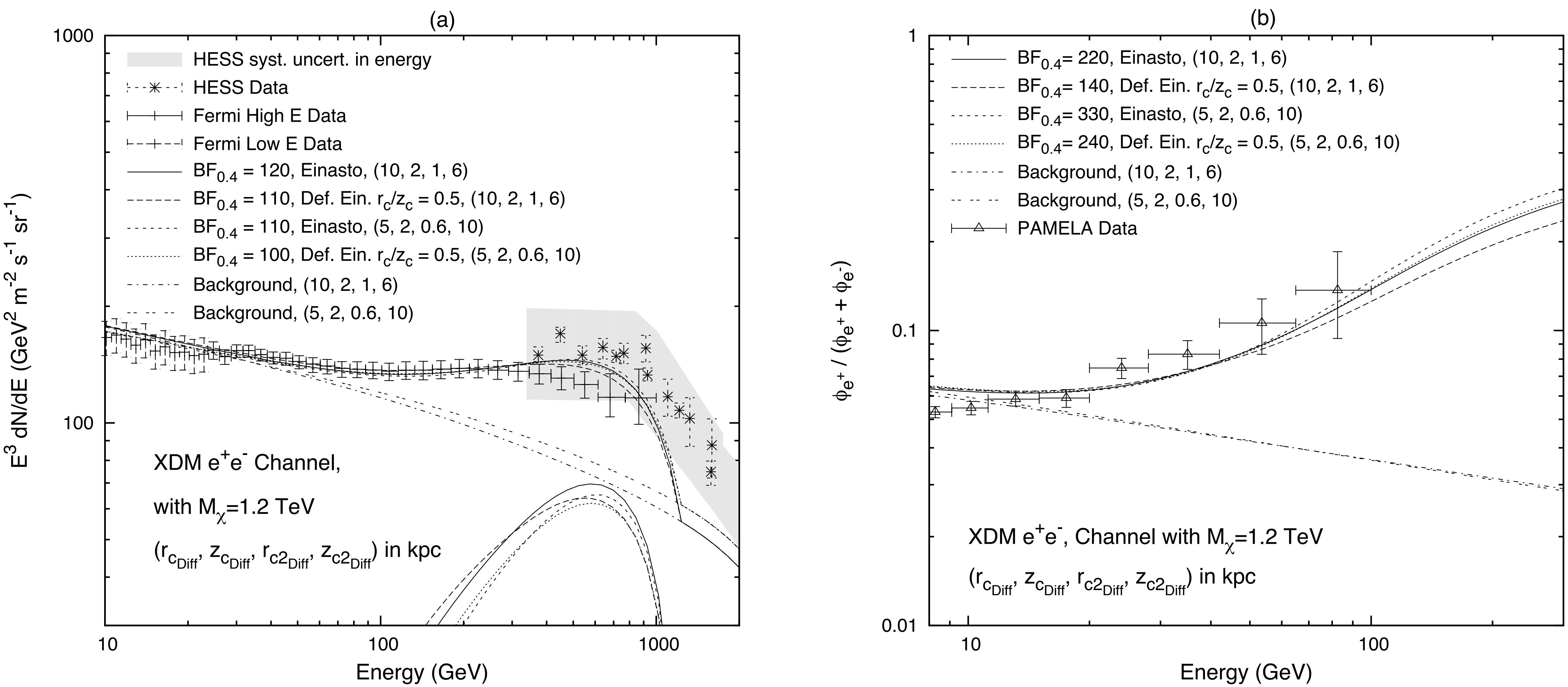
| Model | $B_{\text{ord}}$ Formula | $B_0$ ($\mu$G) | $r_1$ (kpc) | $z_1$ (kpc) | $B_1$ ($\mu$G) | $K$ | $r_2$ (kpc) | $z_2$ (kpc) | $r_3$ (kpc) | $z_3$ (kpc) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | $B_1 e^{-r/r_2-\|z\|/z_2} \times \left(1+Ke^{-r/r_3-\|z\|/z_3}\right)$ | 3 | 7 | 4 | 8 | 10 | 7 | 2 | 0.8 | 10 |
| 2 | $B_1 e^{-r/r_2-\|z\|/z_2} \times \left(1+Ke^{-(r/r_3)^2}\sqrt{\cos(\|z\|/z_3\times\pi/2)}\right)$ | 3 | 5 | 4 | 10 | 11 | 5 | 4 | 1 | 40 |
| 3 | $B_1 e^{-r/r_2-\|z\|/z_2} \times \left(1+Ke^{-(r/r_3)^{1.5}-\|z\|/z_3}\right)$ | 3 | 10 | 2 | 10 | 6 | 10 | 3 | 1.2 | 20 |
| 4 | $B_1 e^{-r/r_2-\|z\|/z_2} \times \left(1+Ke^{-(r/r_3)^{1.5}-(\|z\|/z_3)^{1.5}}\right)$ | 3.7 | 5 | 2 | 12.5 | 8 | 7 | 5 | 2.5 | 20 |
| 5 | $B_1 e^{-r/r_2-\|z\|/z_2} \times \left(1+Ke^{-r/r_3-\|z\|/z_3}\right)$ | 3.7 | 5 | 2 | 3.7 | 12 | 5 | 2 | 2 | 6 |

Anisotropic diffusion of CRs can have a strong effect on the IC map from annihilating DM:




3 templates haze (2.0-5.0 GeV)
Galactic latitude
Galactic longitude
45
0
-45
-90
90
45
0
-45
-90
Fermi Haze Spectrum
|l|<20°, -50° < b < -10° (dark grey)
|l|<20°, 10° < b < 50° (light grey)
Intensity [GeV cm^-2 s^-1 sr^-1]
10^-6
10^-7
XDM e+e-, BF = 24
GP ISRF model 1
GP ISRF model 2
GP ISRF model 3
1
10
100
1000
Energy [GeV]
Fermi haze, E=4 GeV, |l| < 20°
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
Mχ = 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
Iν [kJy/sr]
10
8
6
4
2
0
BF = 27
Mχ = 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

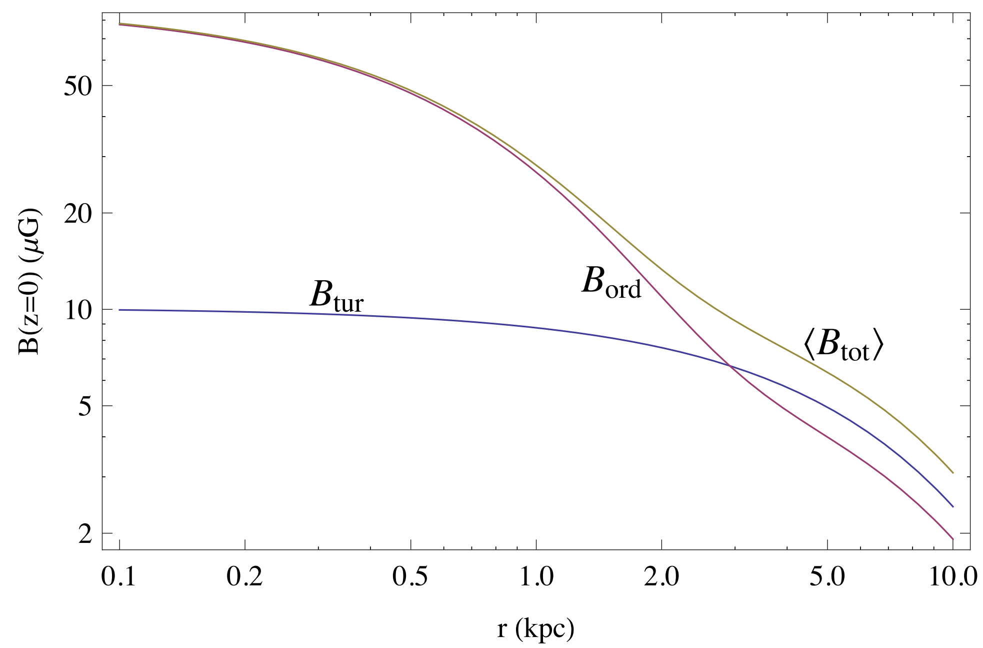
# Conclusions

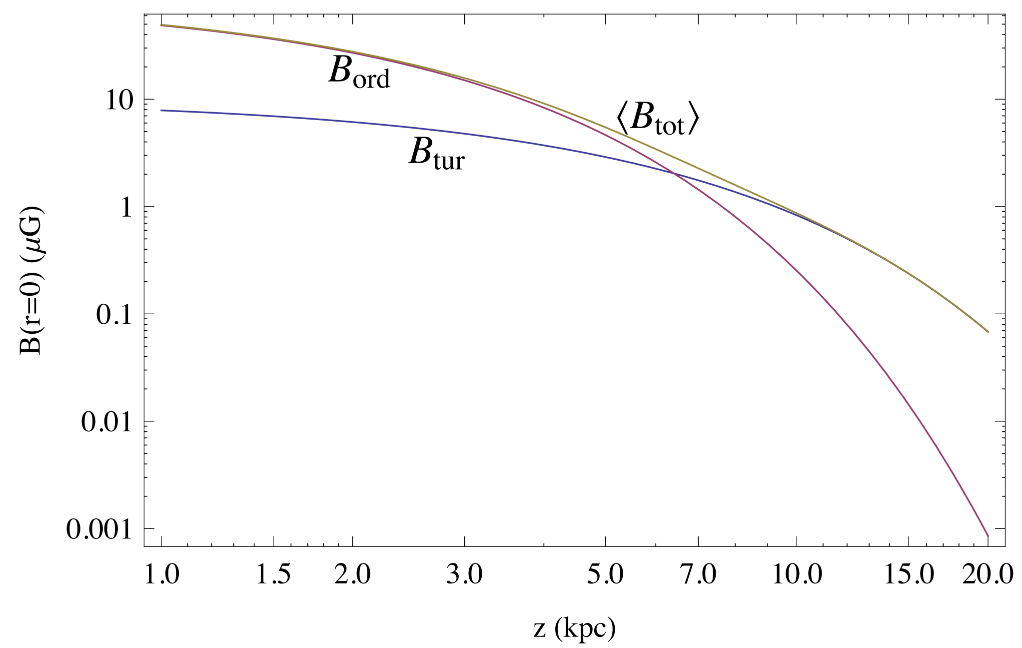
- The Fermi haze is a signal of a population of harder spectrum electrons (seen before only at microwave) that "conventional" sources of electrons such as middle-aged pulsars can not explain
- DM with Anisotropic and inhomogeneous diffusion may be the answer
- Astrophysical explanations including MSPs (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 (PRL))
- Need further modeling and calculations on the signal in order to better understand the gamma-ray backgrounds AND work out the signals from the possible sources
- neutrinos can be drastically different among the different models

Thank you

# Additional slides

# Magnetic field profiles

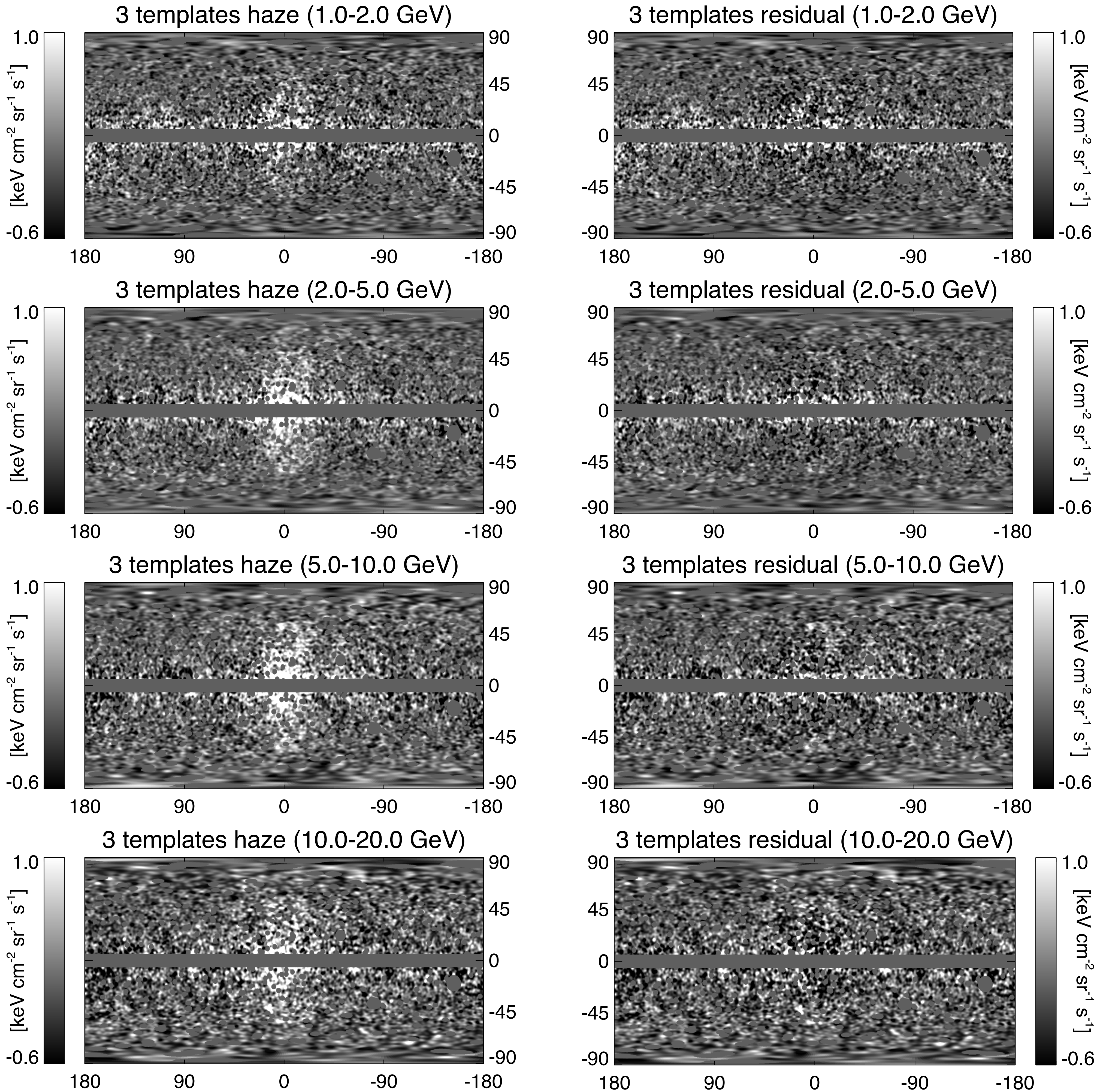


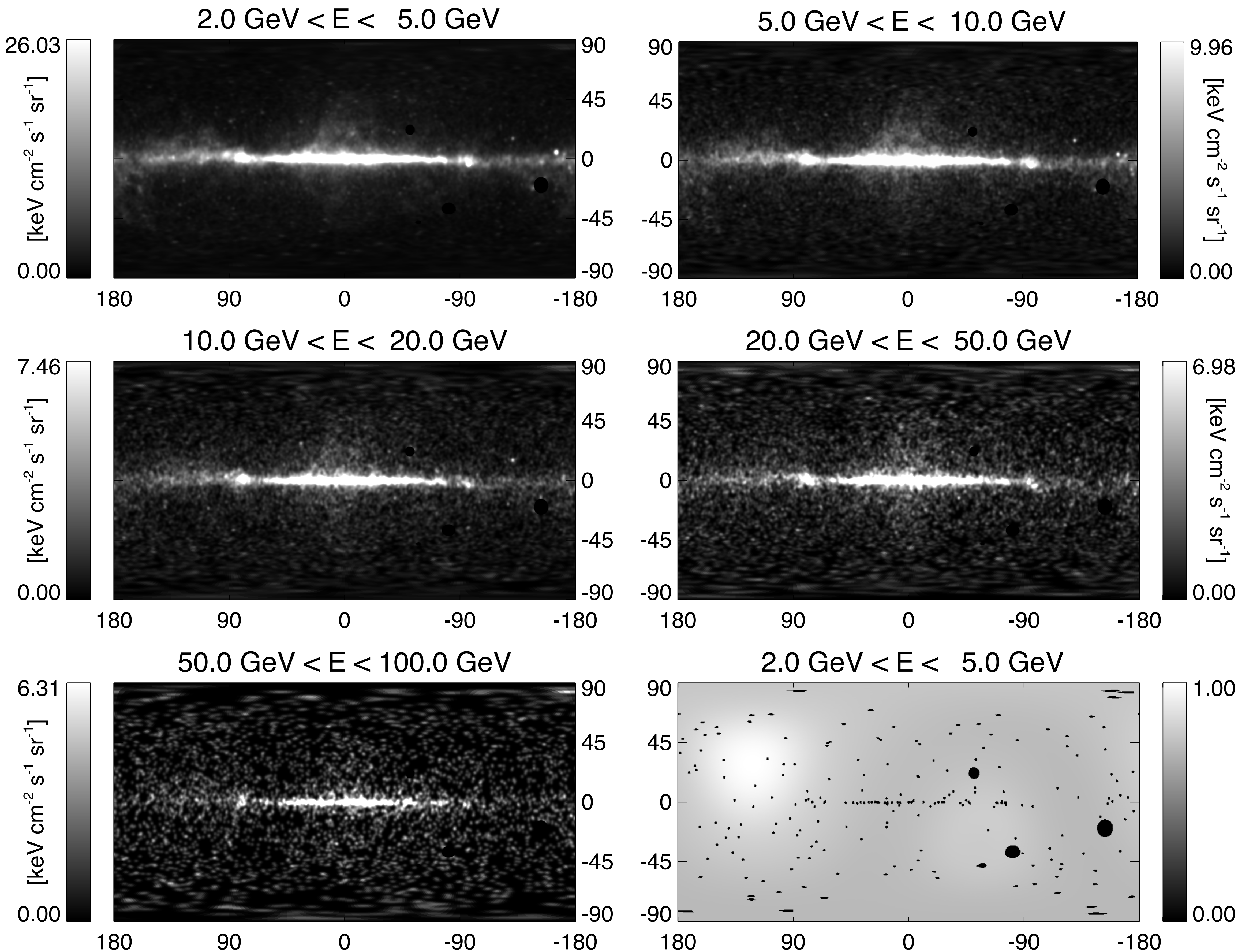

Yusef-Zadeh & Morris (1987), Morris & Yusef-Zadeh (1989), Morris (2007), have suggested mag. fields up to few mG in large non-thermal radio filaments (with widths of pc and lengths ~ 50pc). Beck (2008) suggested 0.5 mG. Those non-thermal filaments seen by VLA are directed perpendicular to the disk plane, 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.

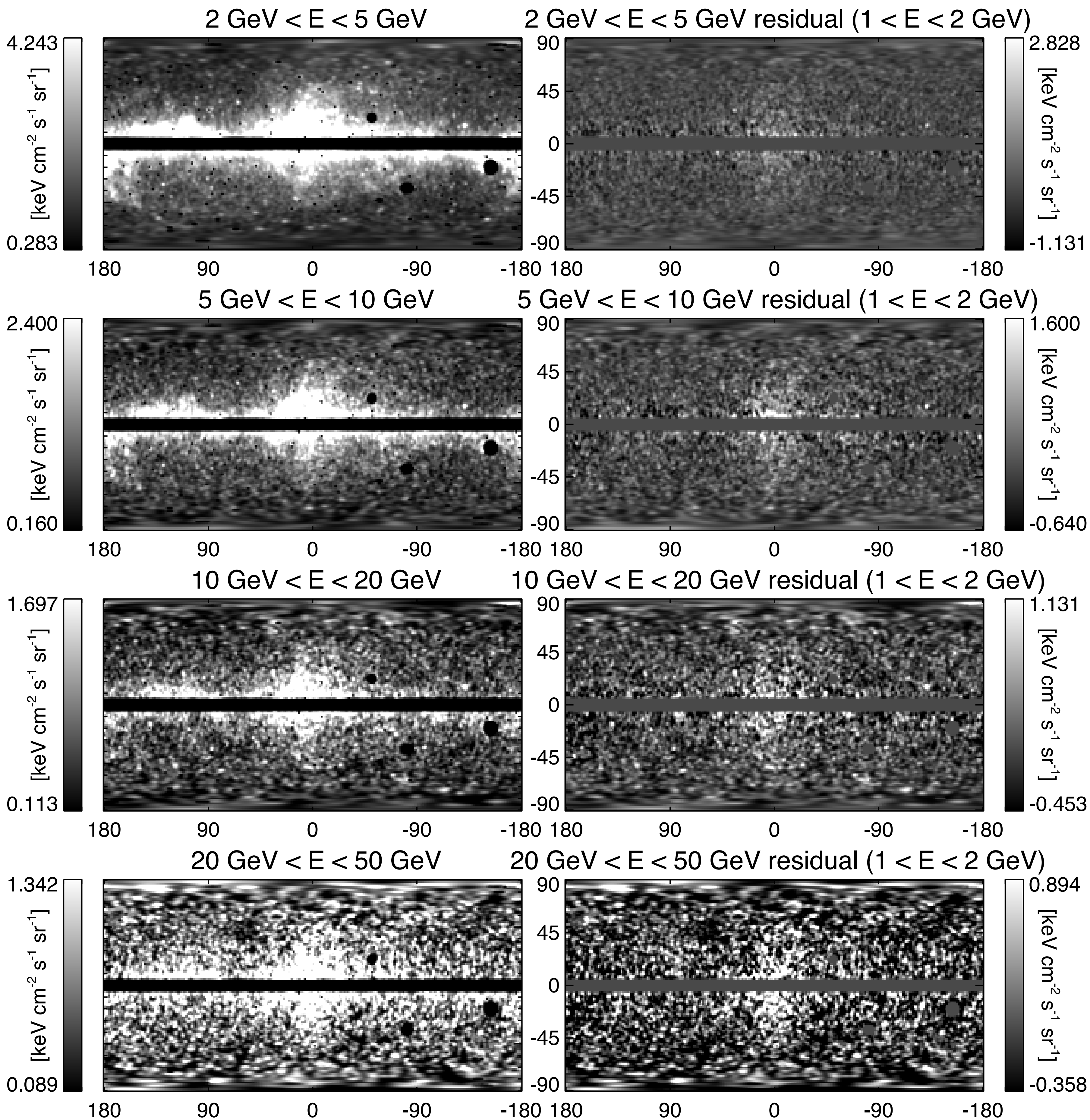
Residual and the fit from the Anisotropic Galprop model



# The gamma-ray sky

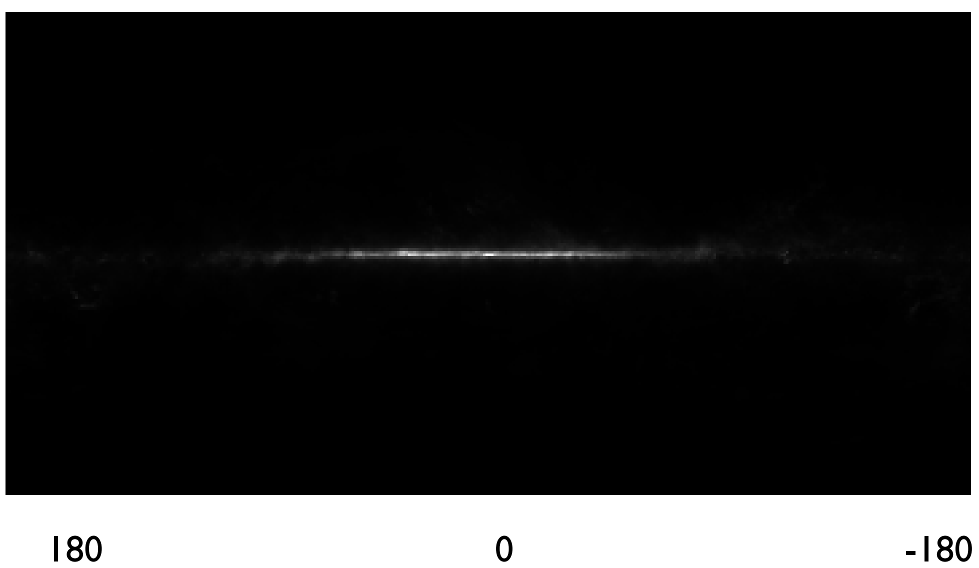


# The gamma ray map and the haze residual

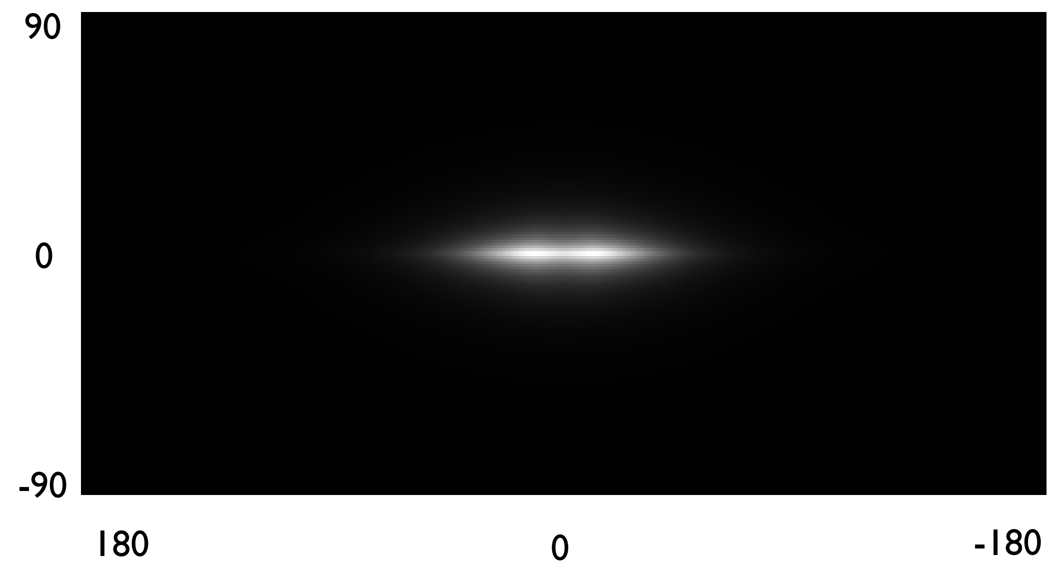


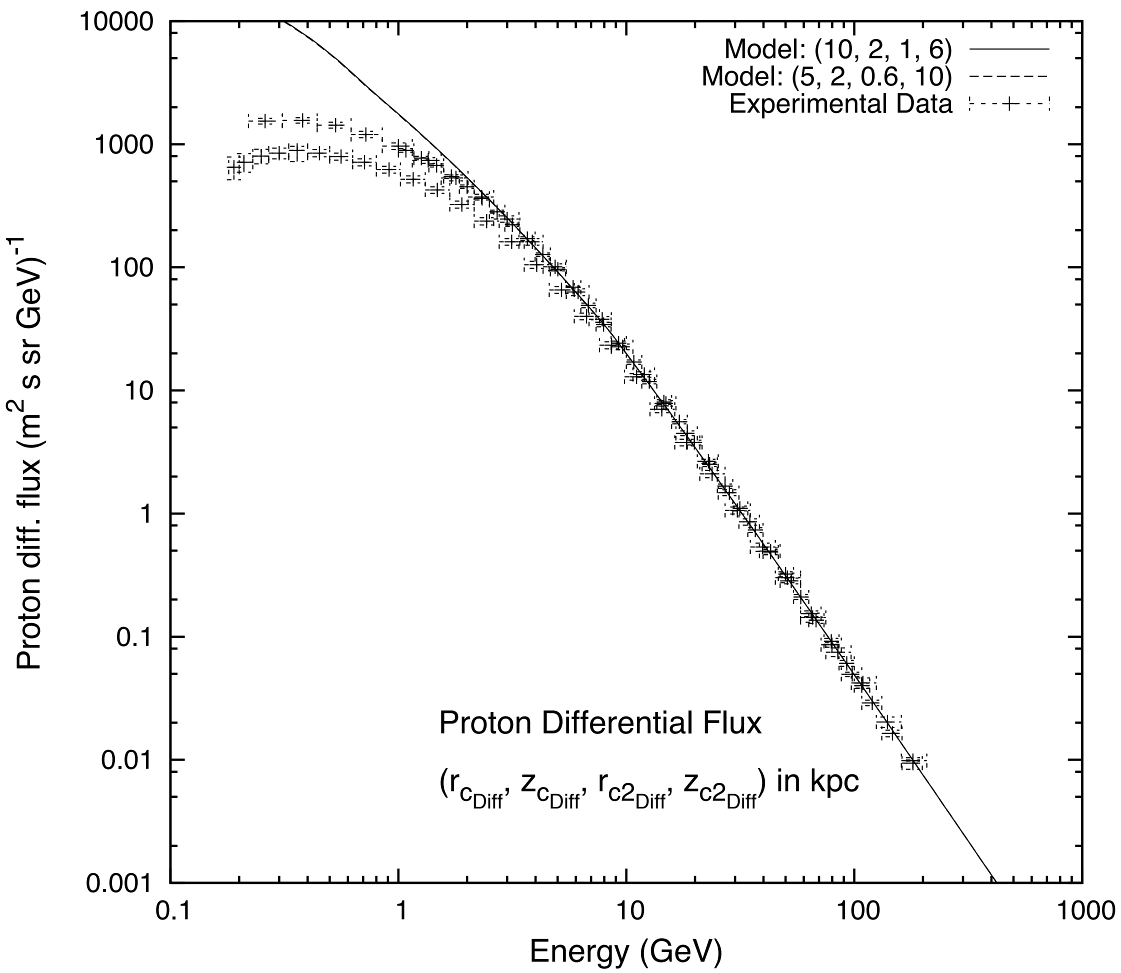
# Anisotropic diffusion assumptions tests

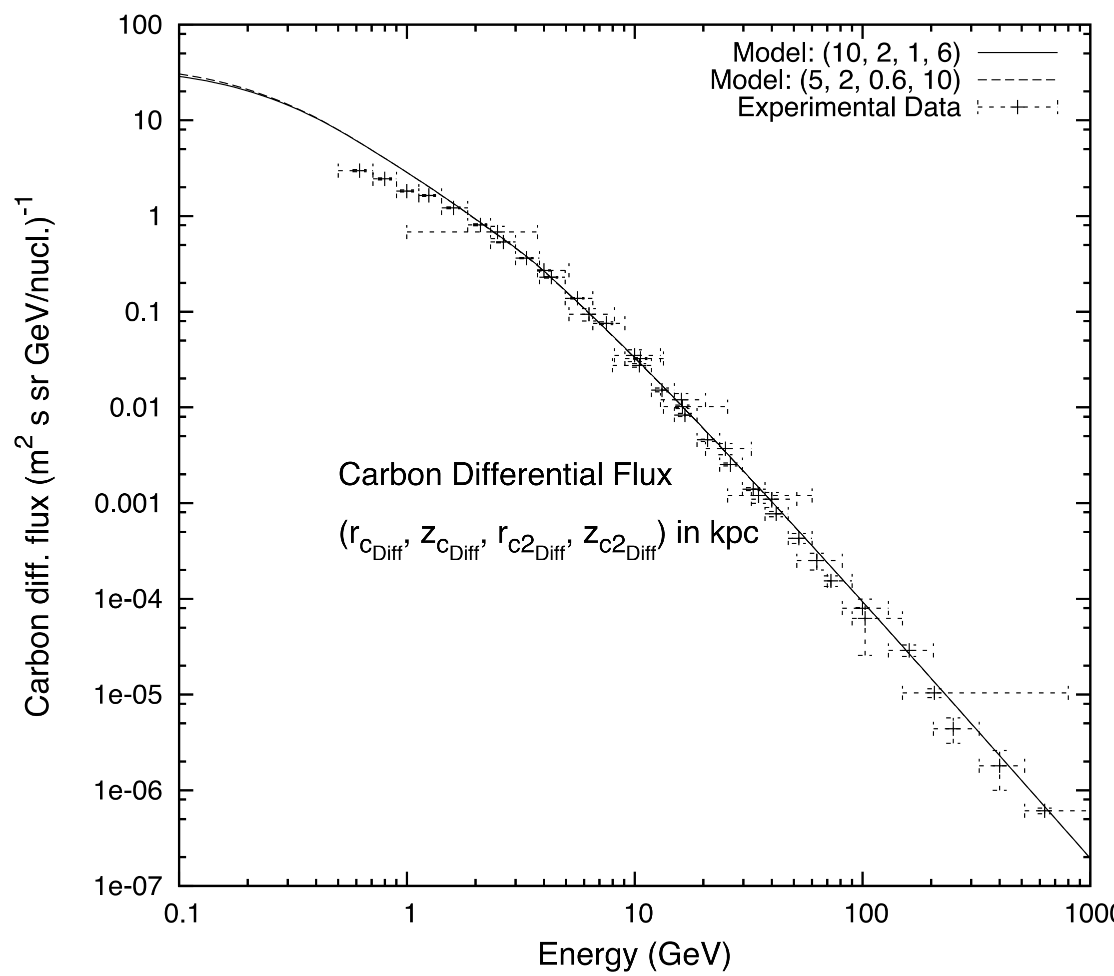
1.25 GeV (pi0)



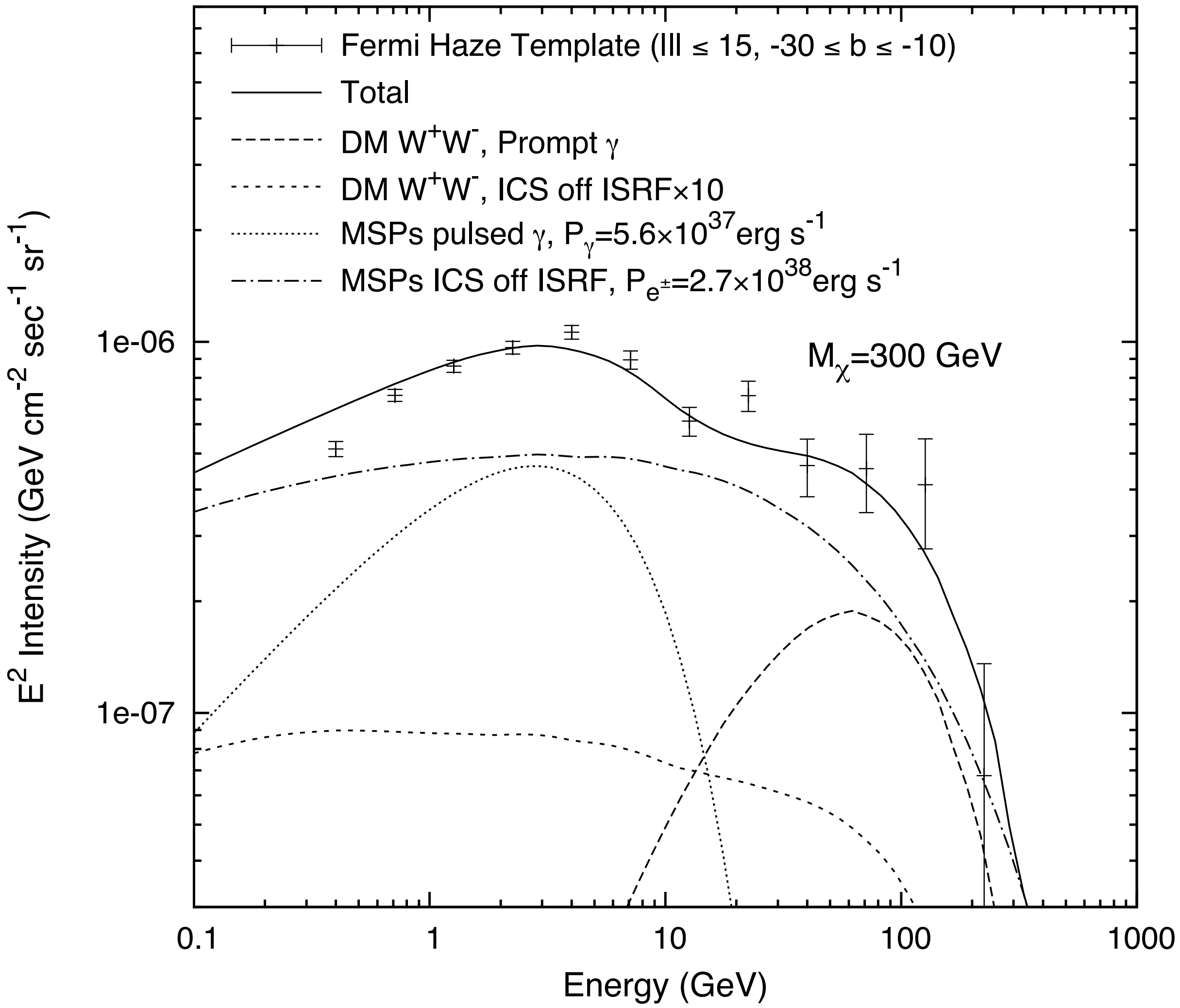

408 MHz

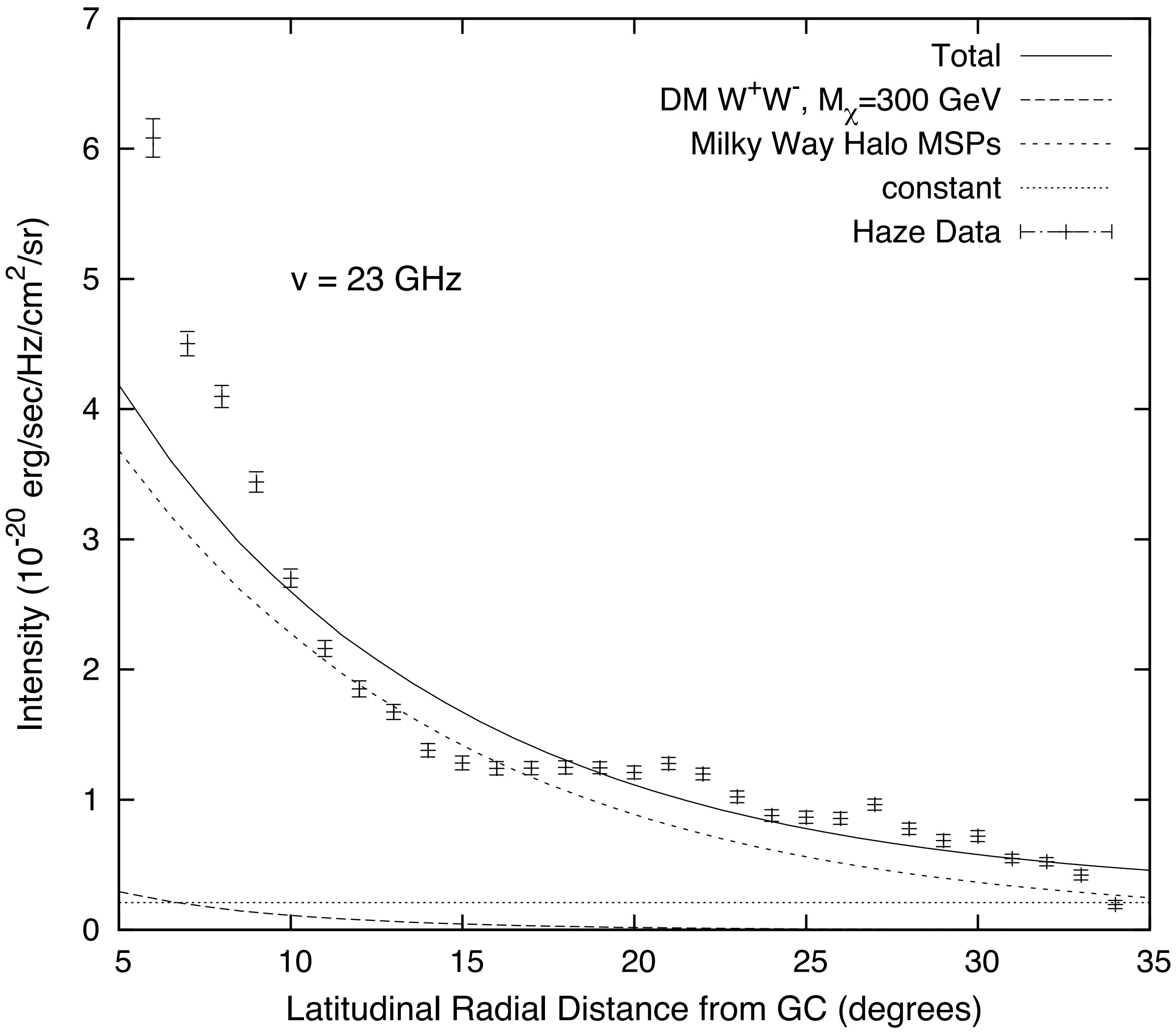


# Millisecond pulsars & DM



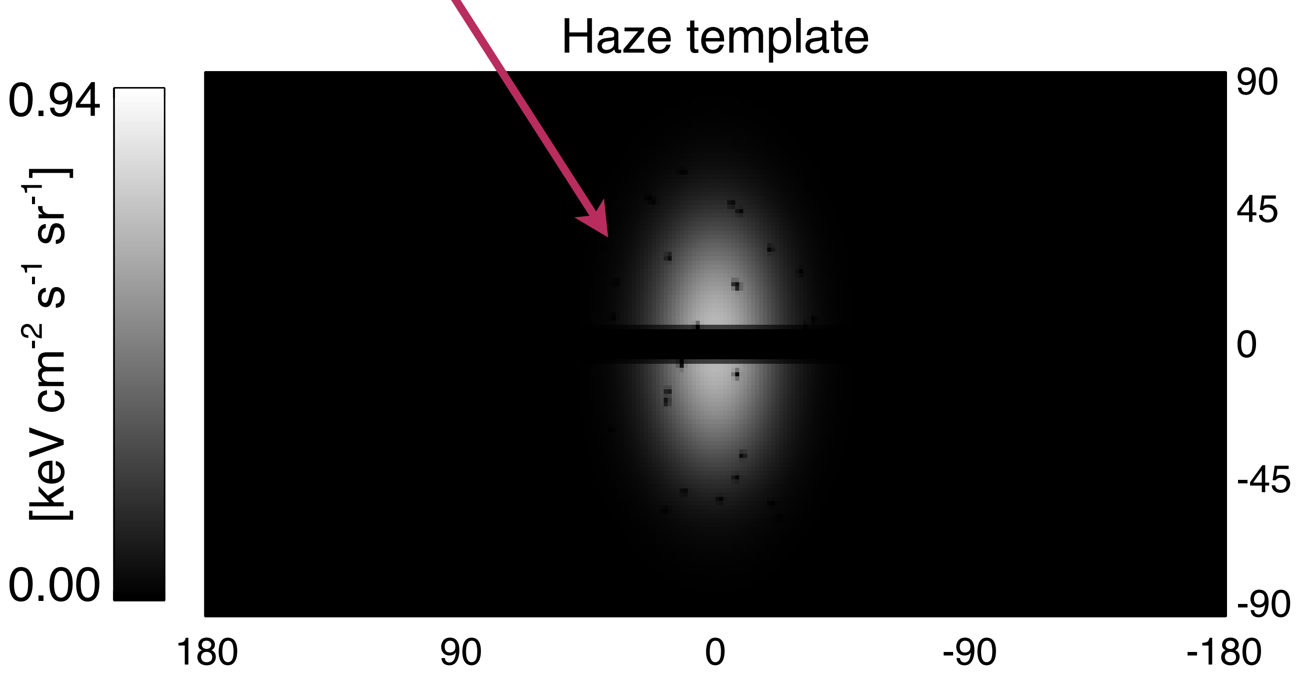

DM annihilating to $W^+W^-$ with a thermal relic cross-section.

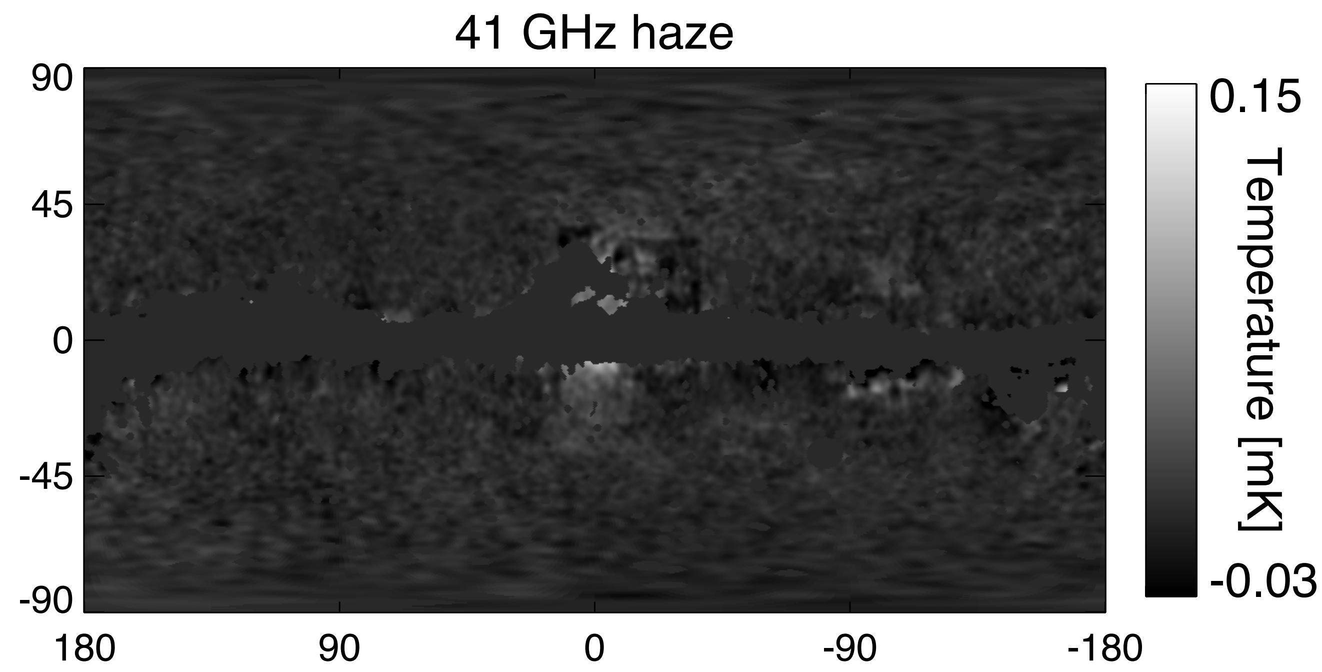
Need 3x10^4 MSPs in the galactic halo! (significant implications about the evolution of the Milky way)

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

# The two haze signals (sum-up)

First template




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

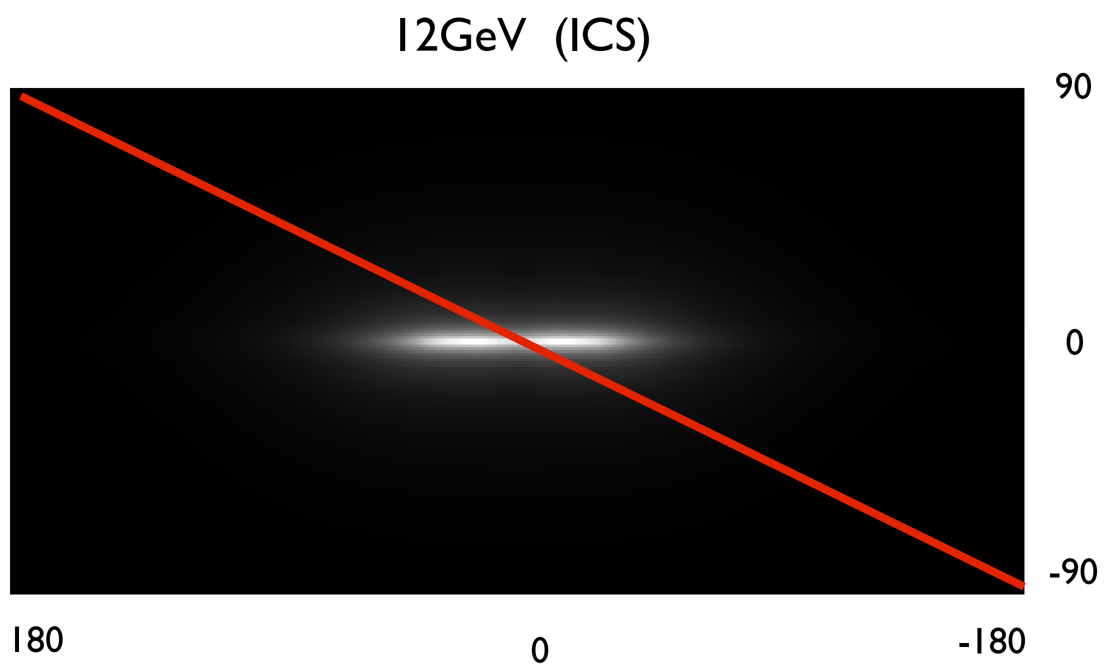
Fermi haze: inverse Compton scattering

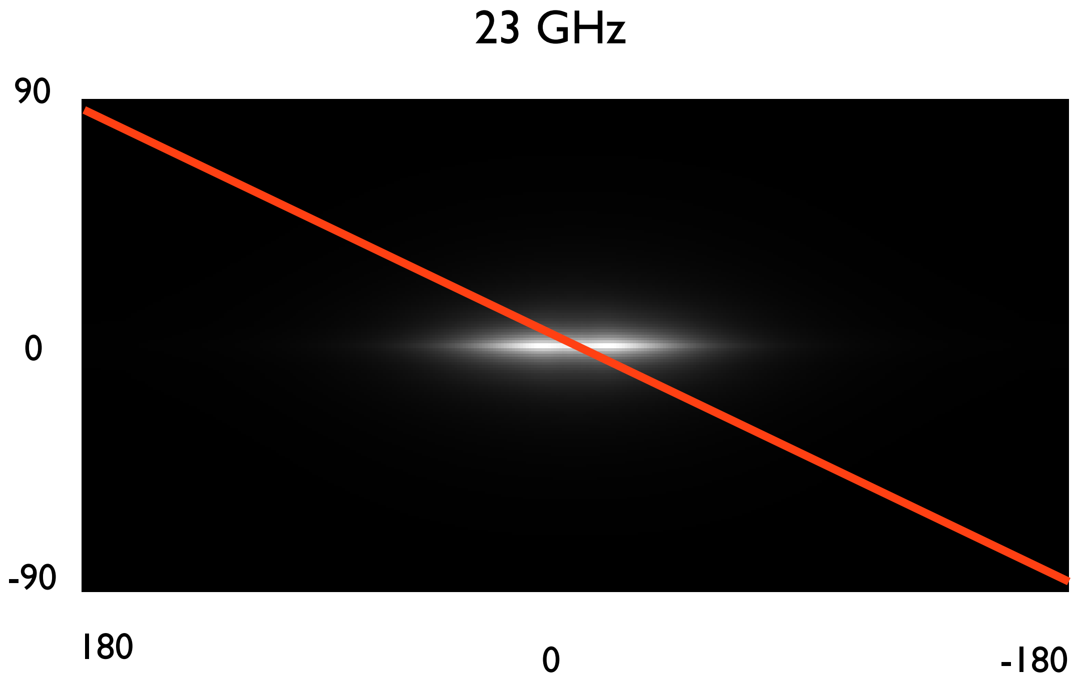
WMAP haze: synchrotron radiation

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

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




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