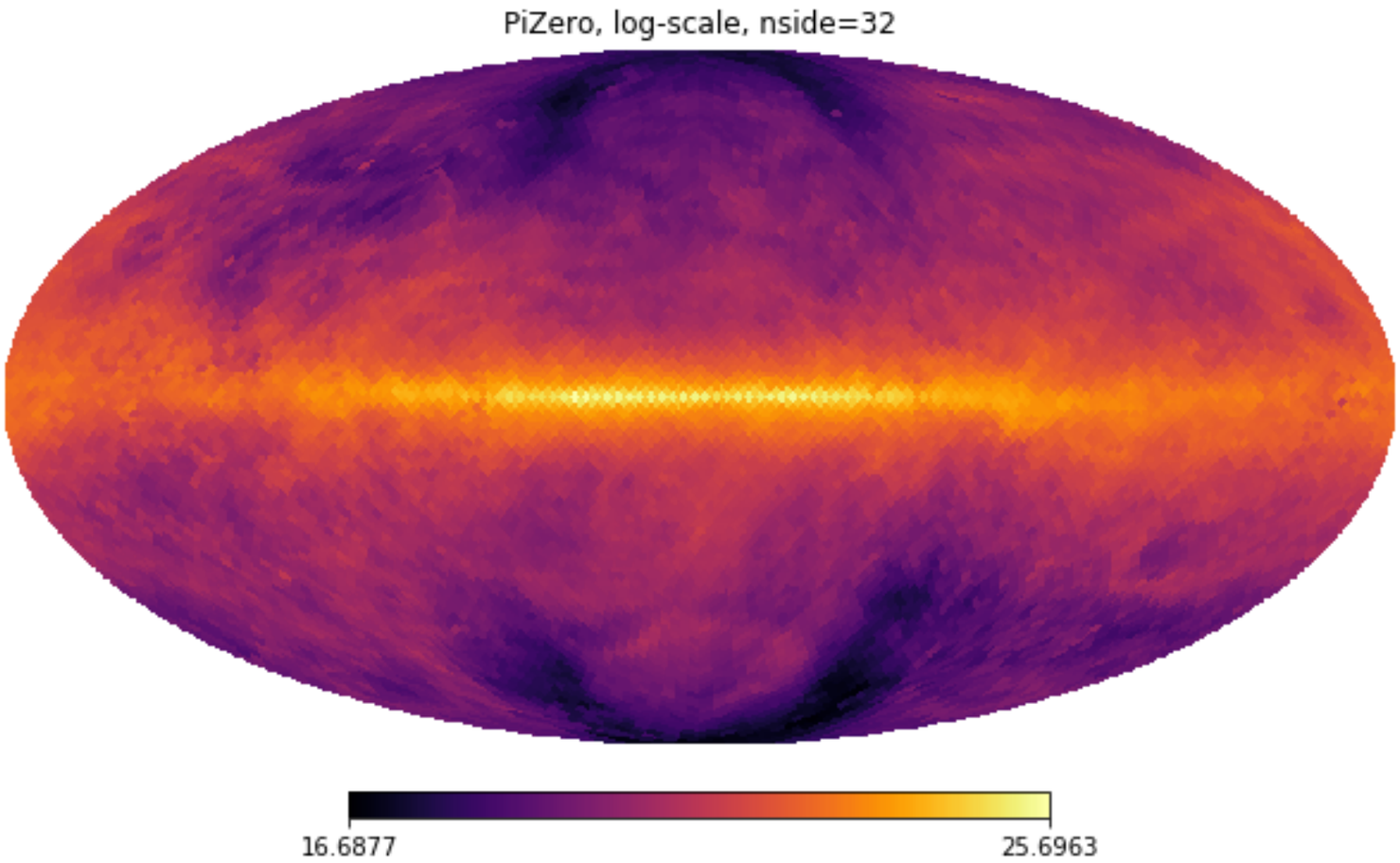
Report on the modeling of diffuse emission



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Diffuse emission: Summary

Goal of the project:
- Identify a **set of large-scale models of the diffuse gamma-ray emission** (π^0, IC, bremsstrahlung) in the **TeV domain**, based on updated modeling of the CR distribution in the Galaxy, up-to-date models for the gas and diffuse photon distribution, and tested on Fermi-LAT data in the multi-GeV domain

Where we stand

- Before 2019: conservative ("base") and an optimistic ("gamma") model.
- "**Base**" assumes constant CR transport properties across the Galaxy.
- "**Gamma**" implements a harder diffusion coefficient scaling in the inner Galaxy

- New **"Base model" almost ready.** Preliminary maps already delivered (mainly for the GPS paper). FITS files and documentation will be available on a public repository.

- New gamma code HERMES will be released soon
- Preliminary version of DRAGON2 now online (**https://github.com/cosmicrays**)

Diffuse emission team

People involved in the diffuse emission modeling

- Daniele Gaggero (IFT Madrid)
- Nicola Marchili (Un. Bologna)
- Ottavio Fornieri (Un. Siena & IFT Madrid) [CR transport model]
- Andrej Dundovic, Carmelo Evoli, Dario Grasso [development of the new gamma-ray transport code HERMES]
- Sofia Ventura, Paolo Da Vela, Dario Grasso [GC-astro project, analysis of CMZ diffuse emission and individual clouds]
- more manpower welcome!

Acknowledgements:
- Quentin Rémy for providing the gas model
- Silvia Vernetto and Paolo Lipari, for providing the ISRF model

In memory of Mathieu Boudaud

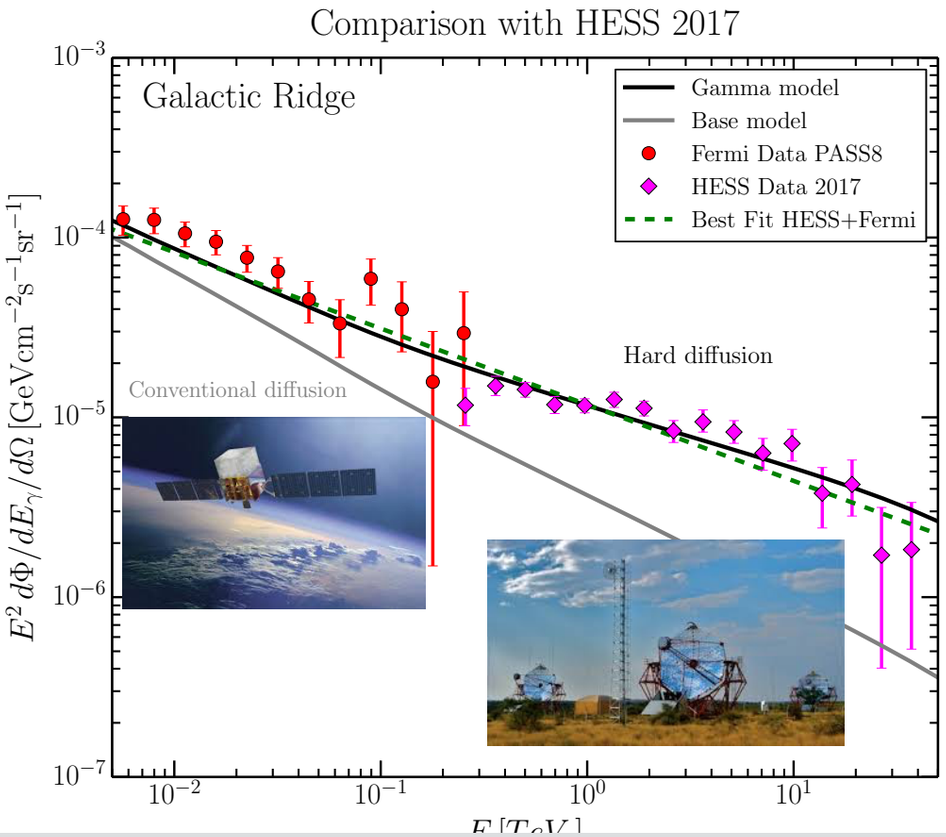
The previous models

Base model:

- CR transport model implemented with **DRAGON** based on [Gaggero et al. 2015]
- Homogeneous diffusion, CR spectrum uniform across the Galaxy
- Gas, ISRF: Ring model taken from **GALPROP** public version
- Tested on Fermi-LAT data (**PASS7**)
- IC based on spiral-arm geometry and provided by the **PICARD** team

Gamma model (used in DCI):

- CR transport model implemented with **DRAGON** based on [Gaggero et al. 2015] *including radial dependence of the diffusion coefficient*
- Compatible with the trends observed in Fermi-LAT data
- IC based on spiral-arm geometry and provided by the **PICARD** team



The new “base model”

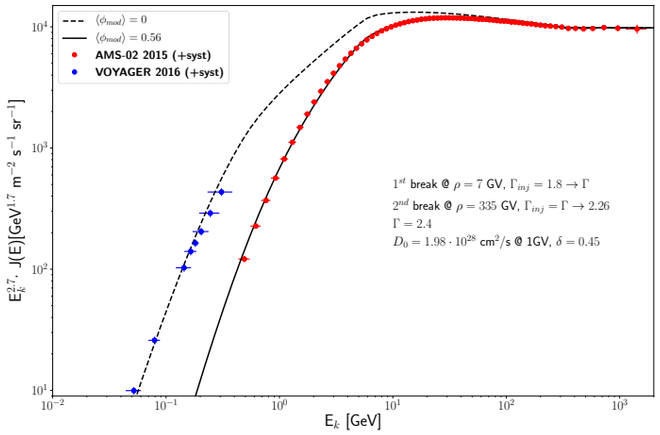
Basic prediction independent from gamma-ray observation. No refitting on Fermi-LAT data

- CR transport model implemented with **DRAGON** based on [O. Fornieri, D. Gaggero, D. Grasso arXiv:1907.03696]

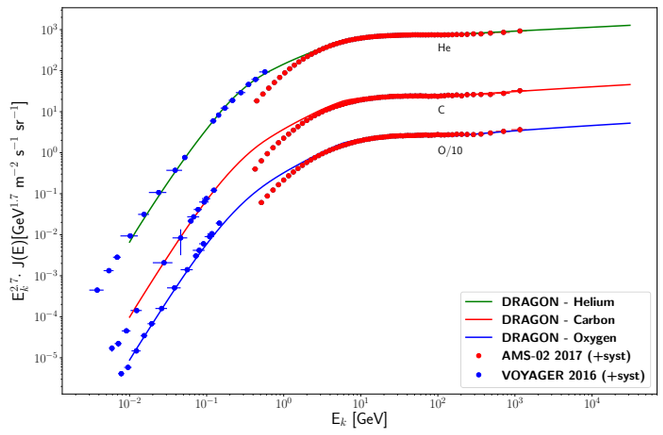
- Homogeneous diffusion, CR spectrum uniform across the Galaxy
- Gas model provided by Q. Remi
- ISRF by S. Vernetto, P. Lipari

The CR propagation model

- **CR transport model** developed with `DRAGON`
- *Cylindrical symmetry*
- *Continuous source distribution* traced by pulsars (for SNII) and disk stars (for SN Ia) [Ferrière 2001]
- *Uniform and isotropic diffusion coefficient*
- *Reacceleration*
- *Energy losses:* ionization, bremsstrahlung, Coulomb scattering, IC and synchrotron (leptons only)
- *Spallation network:* the same as `GALPROP` at the moment
- Alternative models by [Evoli et al. 2018] and [Mazziotta et al. 2017] to be implemented soon
- *20 free parameters* tuned on local data
- **Paper will be out soon** [Fornieri et al., in preparation]



(a)



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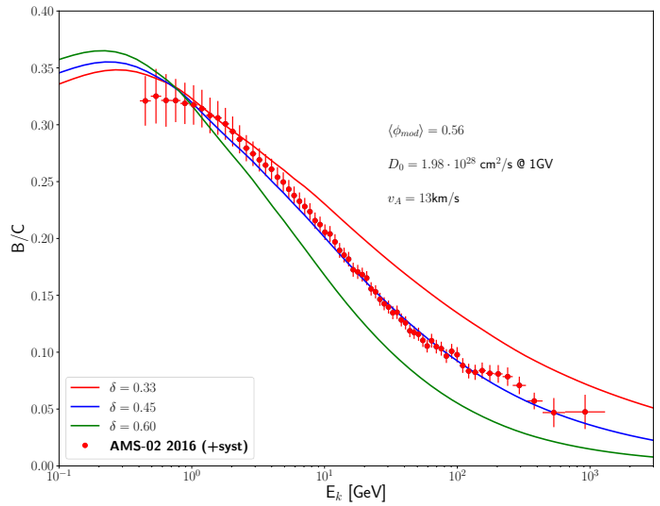

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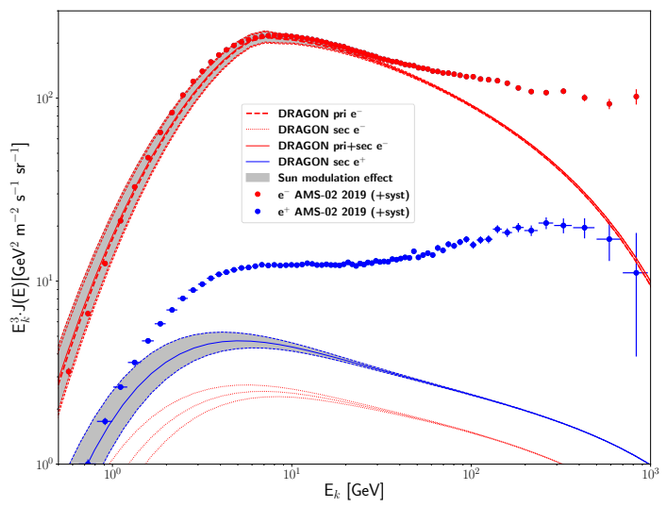


(d)

	v_A [km/s]	D_0 [m^2/s]	δ	$\Gamma_{inj,L}$	$\rho_{b,1}$ [GV]	$\Gamma_{inj,M}$	$\rho_{b,2}$ [GV]	$\Gamma_{inj,H}$
p	13	$1.98 \cdot 10^{24}$	0.45	1.8	7	2.4	335	2.26
He				2.0		2.28	165	2.15
C				2.0		2.38	165	2.15
O				2.0		2.38	165	2.15

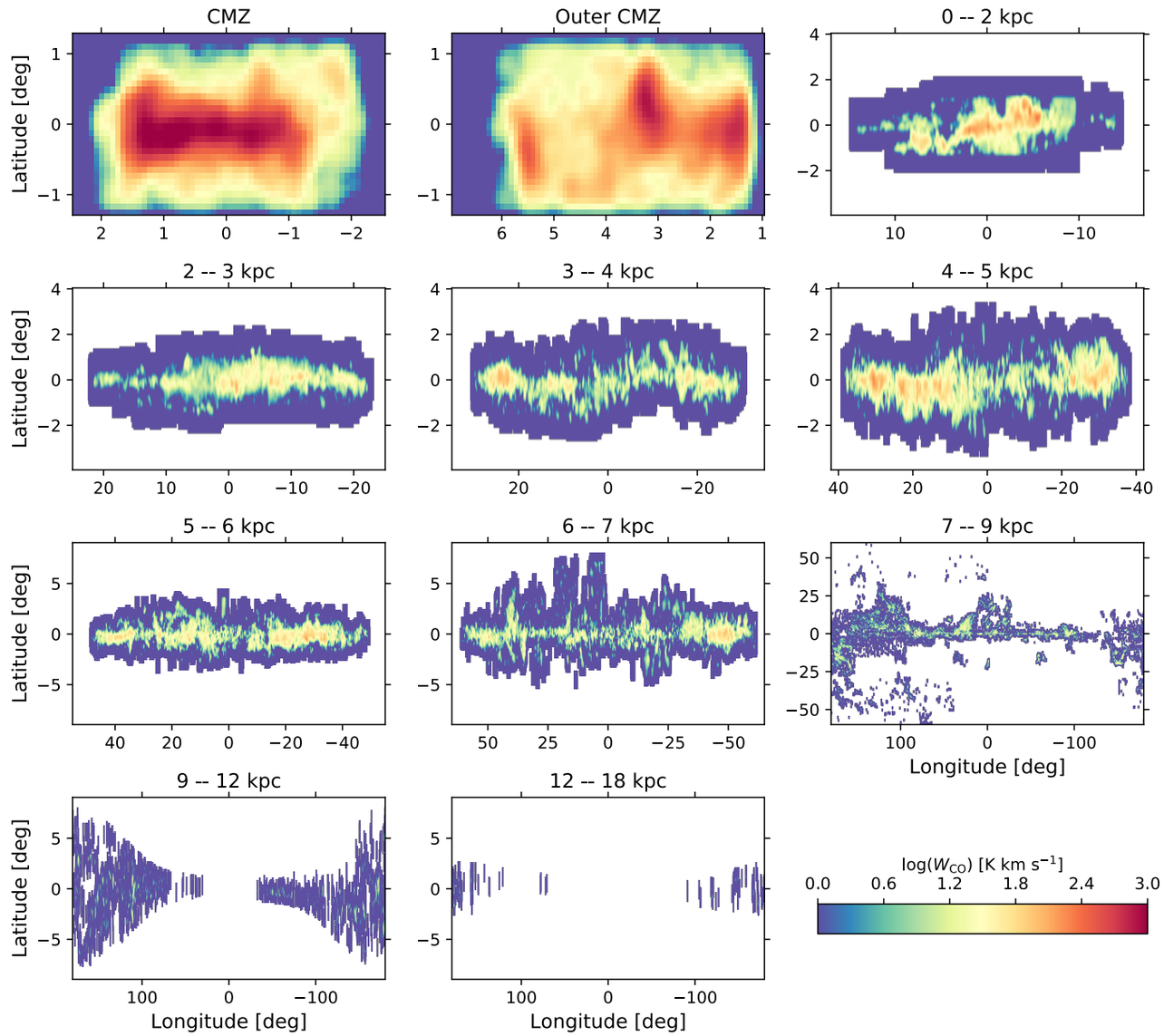
Table 1: The values of the main source and propagation parameters characterizing our reference transport model are reported in this table.

Ring gas model: Molecular component

- Based on 115 GHz dat from the **CfA CO survey** of the Galactocentric plane + mid-latitude survey [Dame et al. 2001, Dame&Thaddeus 2004]
- Sampled on 1/8° grid in the 10° latitude range around the GP
- Local clouds at higher latitude are sampled on 1/4°
- Completeness tested against dust emission observed by IRAS (only 2% missed)
- Good agreement with Planck data (115, 230 and 345 GHz)

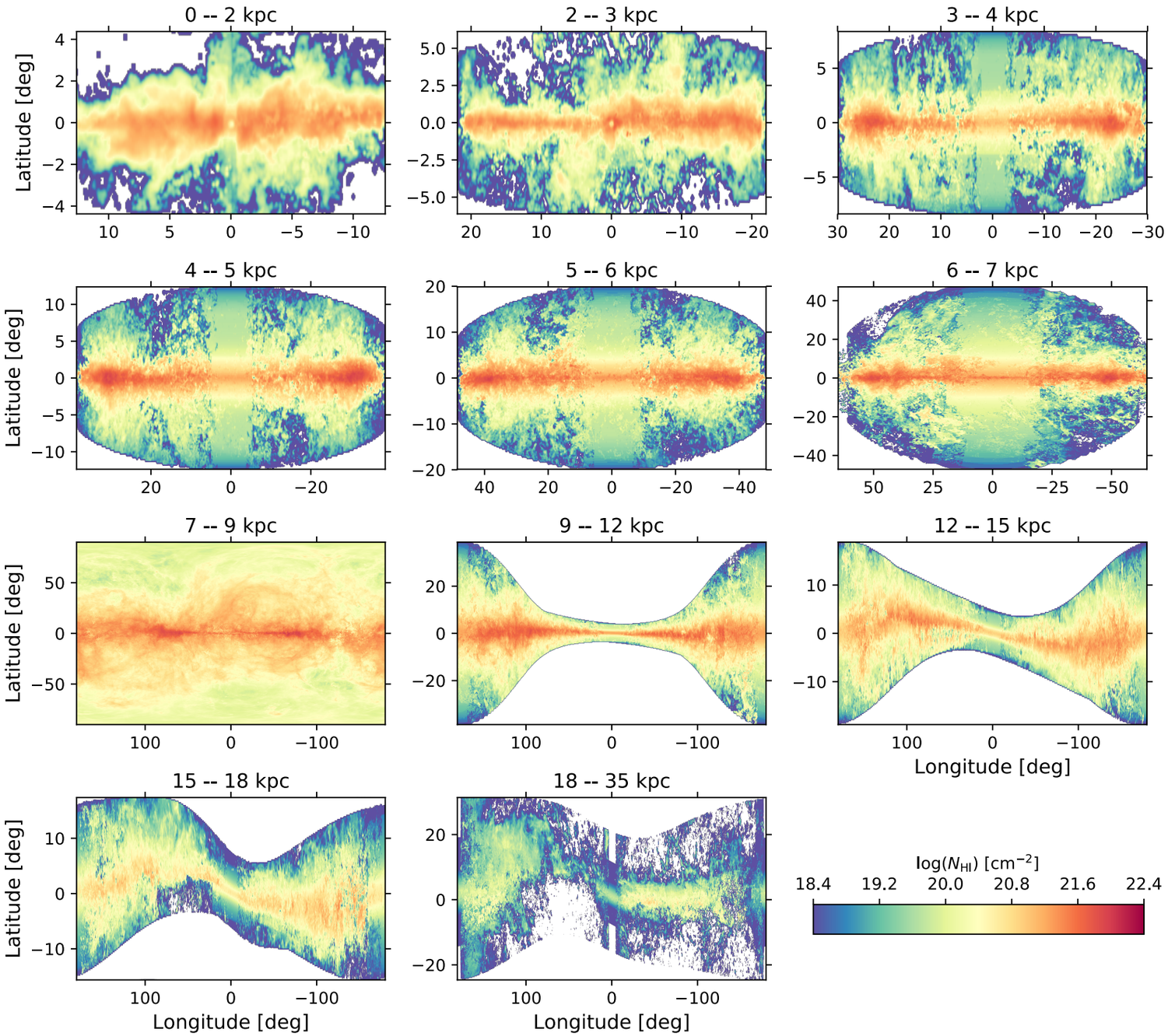
- **Decomposed in Galactocentric rings** [boundaries at R = 0,2,3,4,5,6,7,9,12,15,18,35 kpc] assuming the rotation curve taken from [Sofue 2015]

$$v_{\rm disk}(l,b,R) = \left(\frac{R_\odot}{R} v_\phi(R) - v_\odot\right) \sin(l)\cos(b)$$



Ring gas model: Atomic component

- Based on **HI4PI survey** [Bekhti et al. 2016] of the 21-cm line emission of neutral hydrogen
- Angular resolution 16’
- Sensitivity 43 mK
- Velocity resolution 1.5 km/s
- Traces the whole neutral atomic cas, from cold (CNM) to warm (WNM)



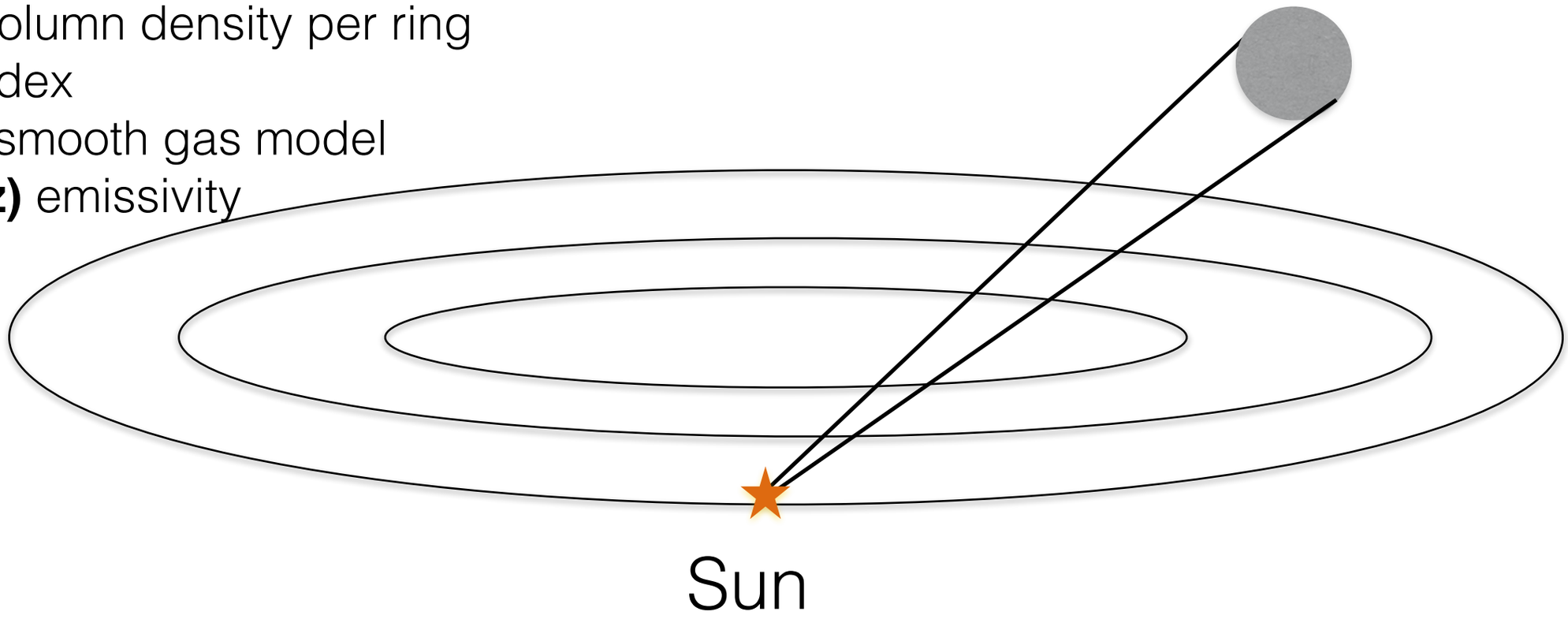
The integration along the l.o.s.

$$\epsilon_{\pi^0}(E_\gamma, \vec{r}) = [n_{\rm HI}(\vec{r}) + 2n_{\rm H_2}(\vec{r})]\,\tilde{\epsilon}_{\pi^0}(E_\gamma, \vec{r}) = [n_{\rm HI}(\vec{r}) + 2X_{\rm CO}(r) w_{\rm CO}(\vec{r})]\,\tilde{\epsilon}_{\pi^0}(E_\gamma, \vec{r})$$

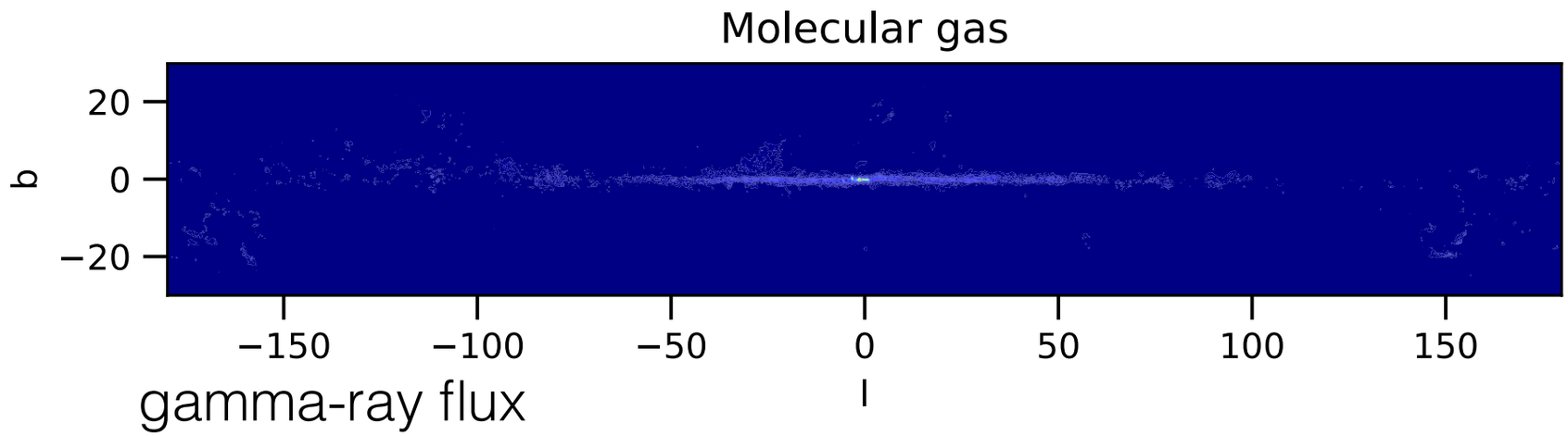
$$I_\gamma(l, b, E_\gamma) = \frac{1}{4\pi}\int_0^\infty {\rm d}s\, n_{\rm HI}(\vec{r})\tilde{\epsilon}(E_\gamma, \vec{r})$$

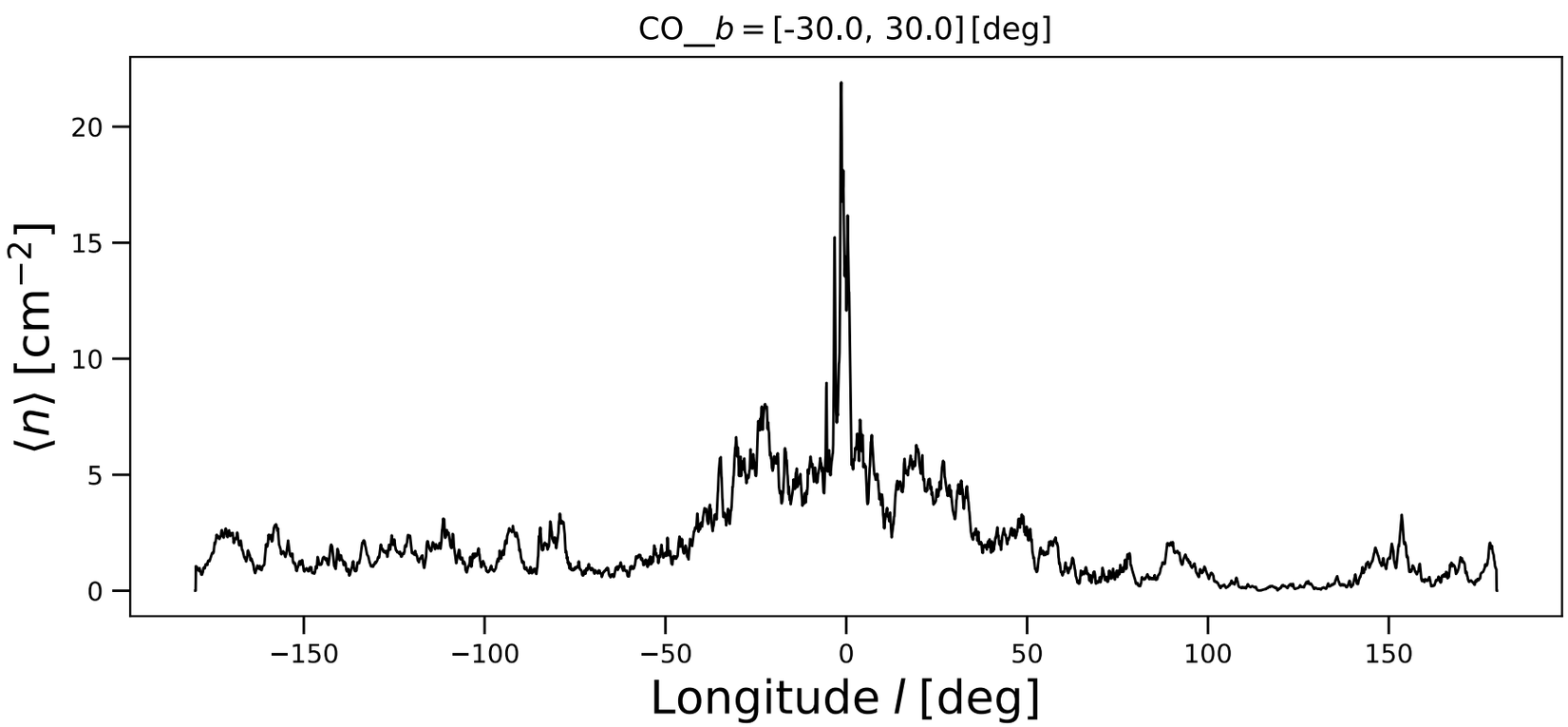
$$= \frac{1}{4\pi}\sum_{\rm j} \frac{N^{\rm j}_{\rm HI}(l,b)}{\int_0^\infty {\rm d}s'\, p_{\rm HI}(\vec{r'})\Theta^j_{\rm in}(\vec{r'})} \int_0^\infty {\rm d}s\, \tilde{\epsilon}(E_\gamma, \vec{r}) p_{\rm HI}(\vec{r})\Theta^j_{\rm in}(\vec{r})$$

N(l,b): column density per ring
j: ring index
p(x,y,z) smooth gas model
ε(E,x,y,z) emissivity

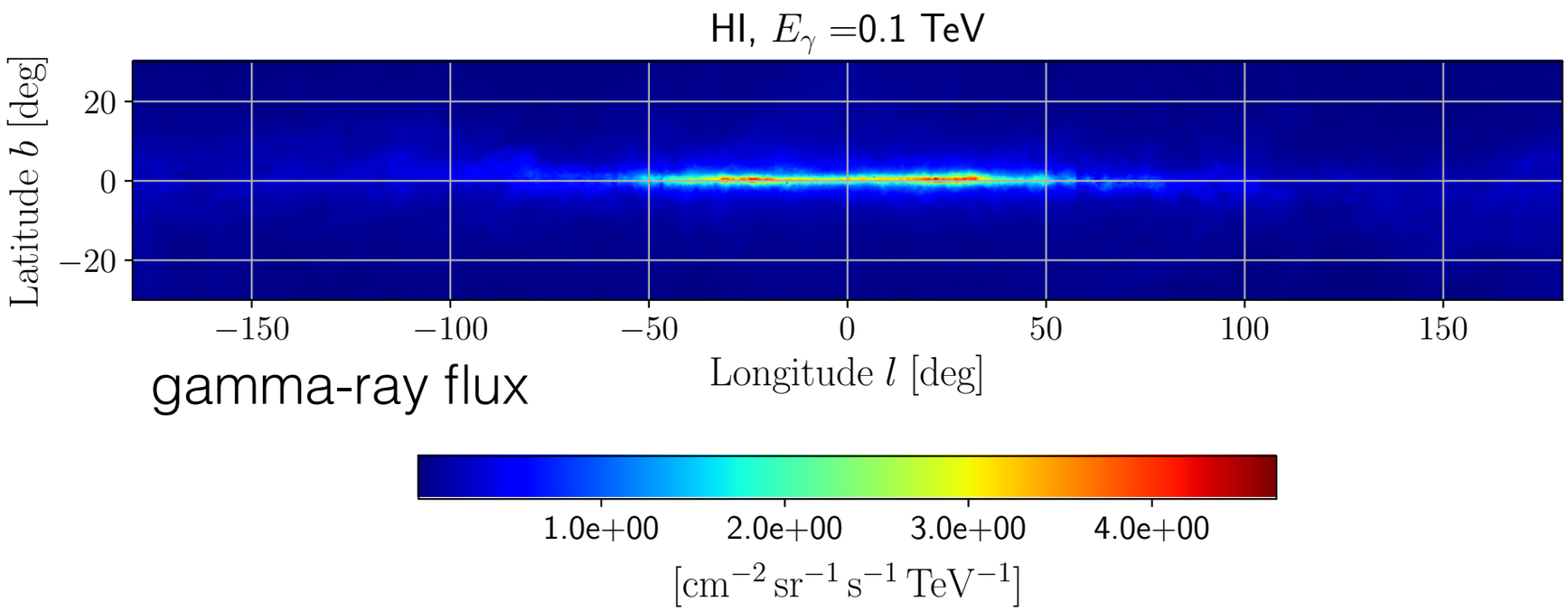


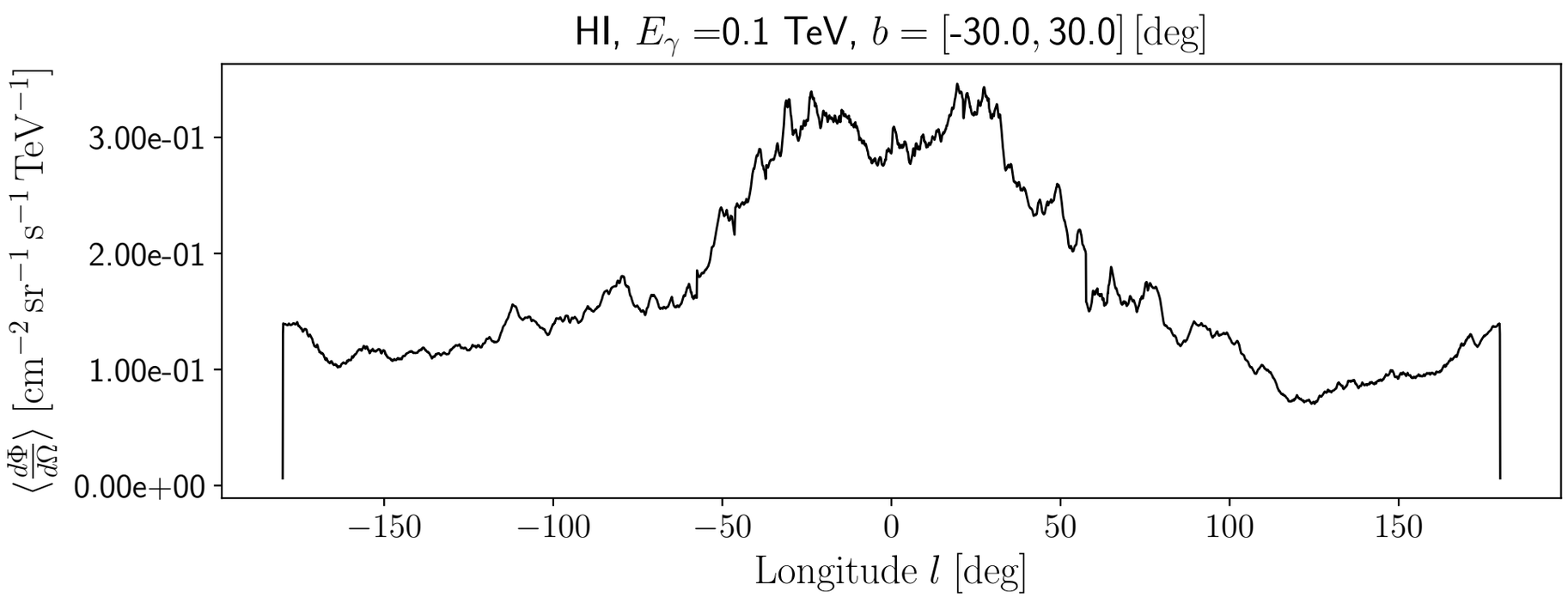
Testing the model





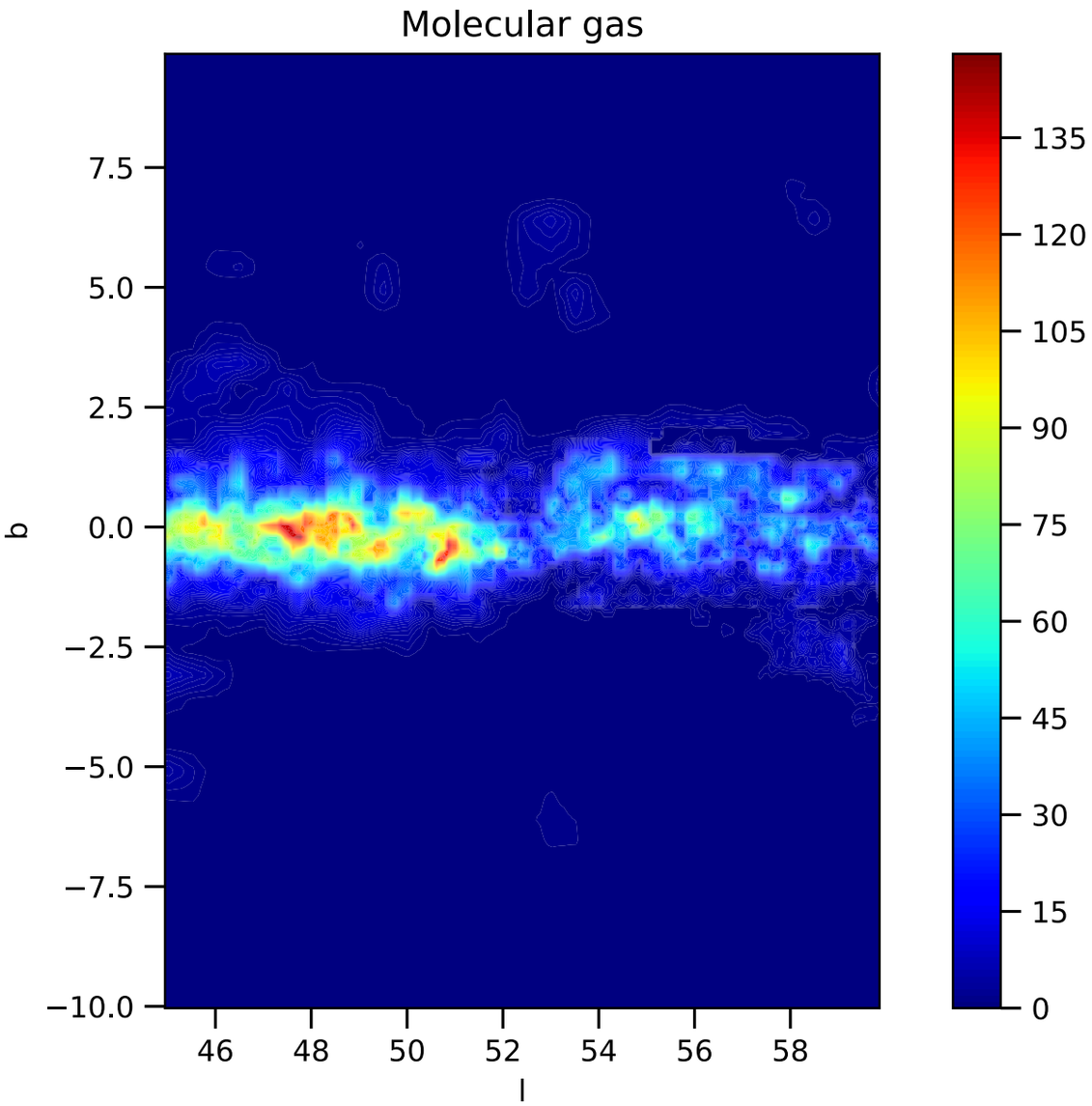
Testing the model

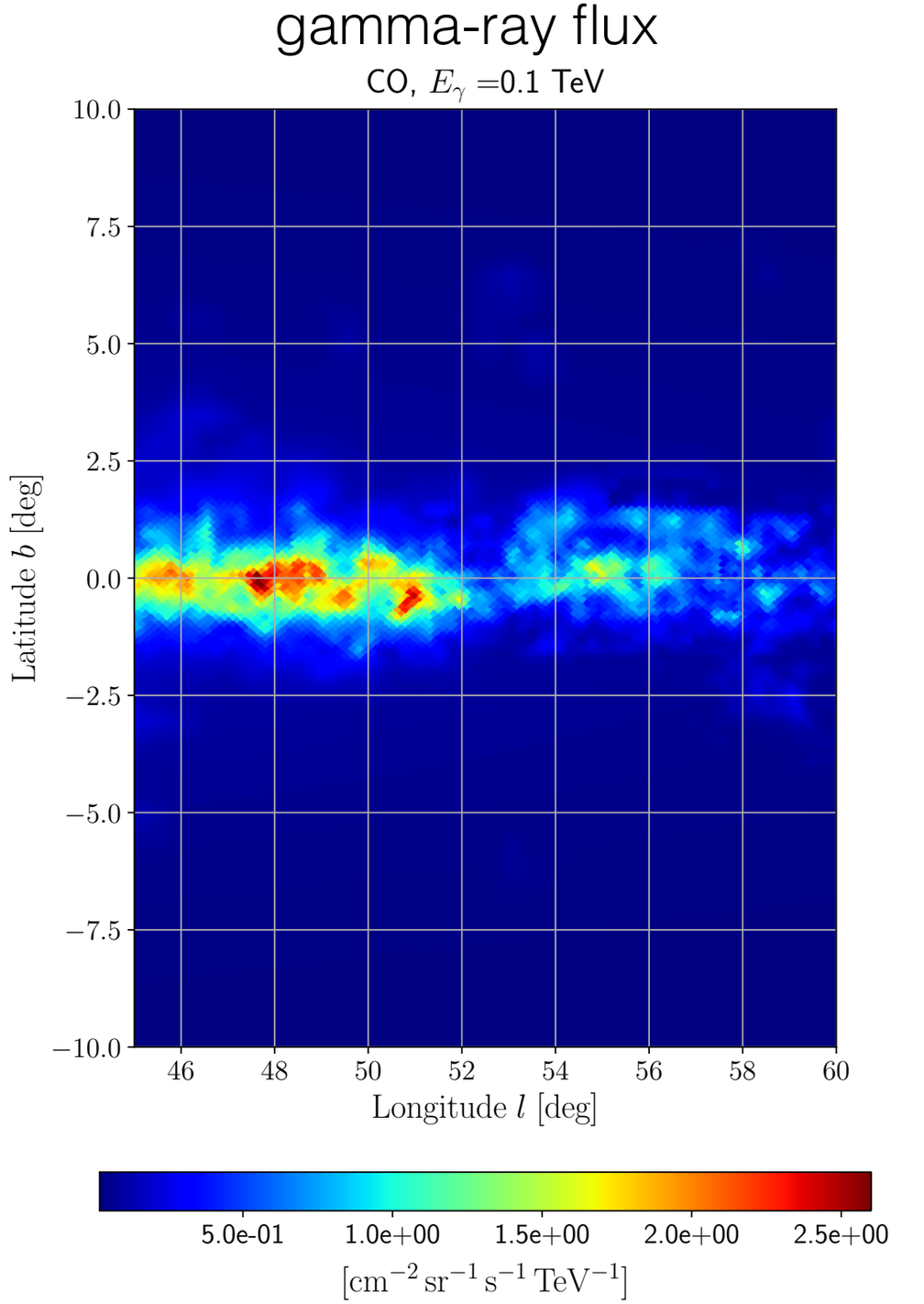




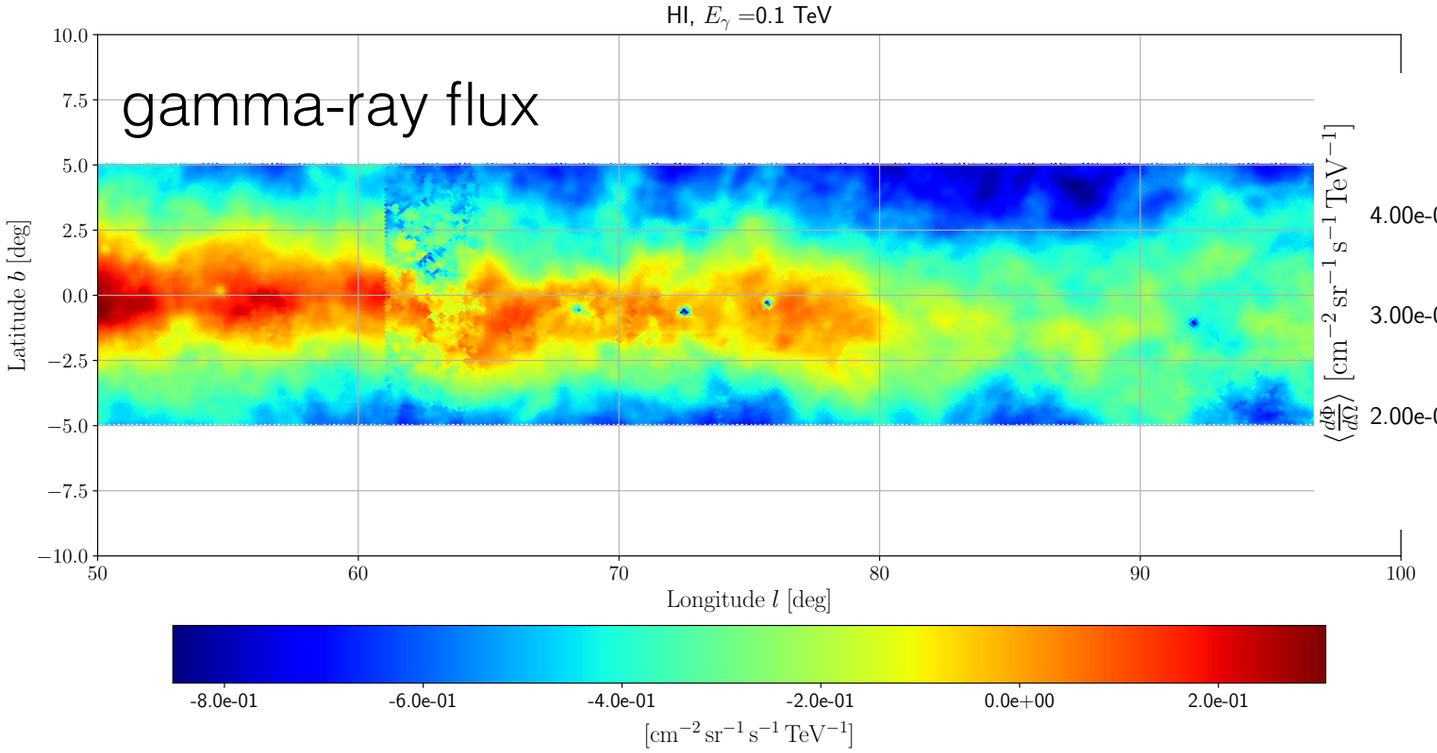
Testing the model: spatial patterns

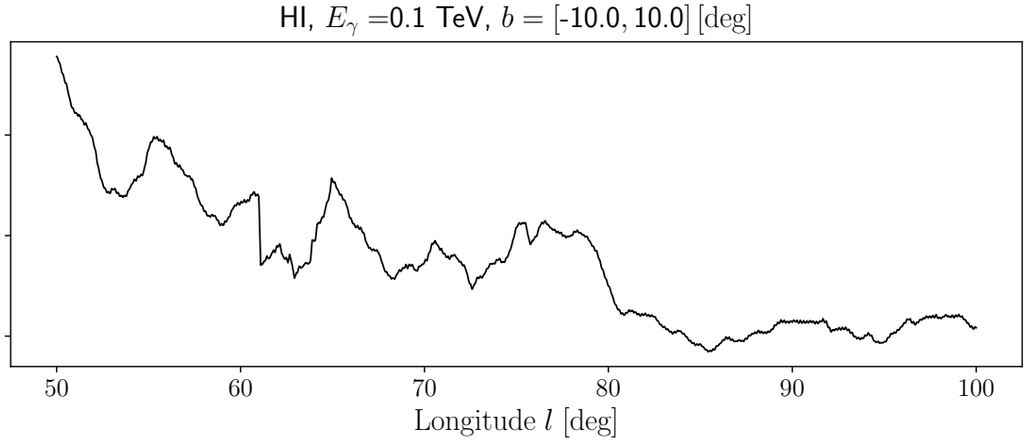
Gas vs gamma





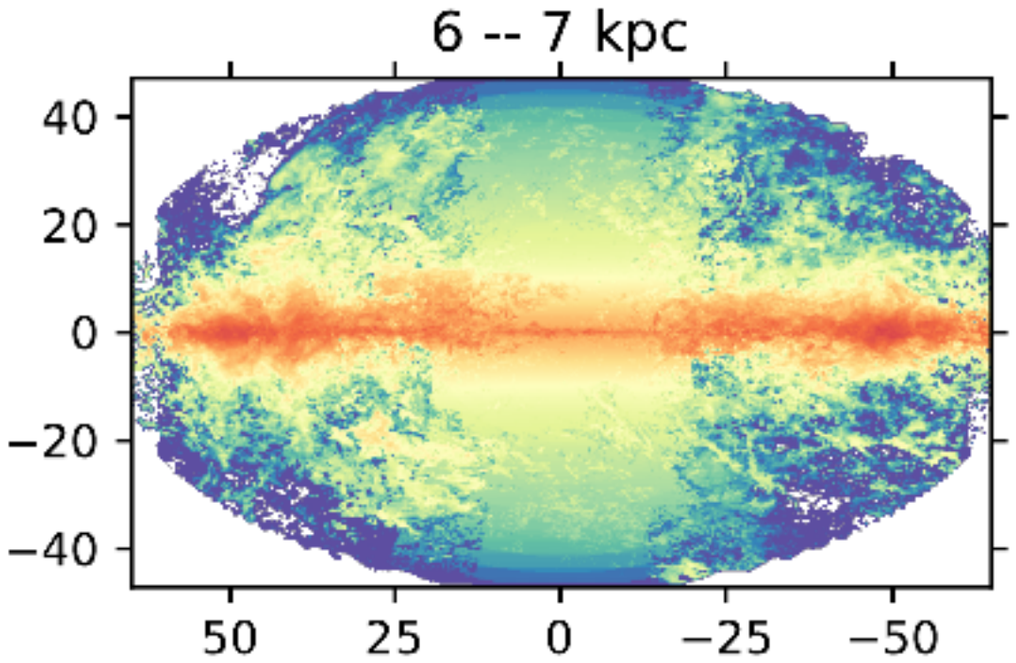
Testing the model. Discontinuity at l = 60°





- Independently checked with gammasky and HERMES
- Independent of the smooth gas model used in the integration

- The feature is already present in the gas model. (minor) problem with ring 6 and 7

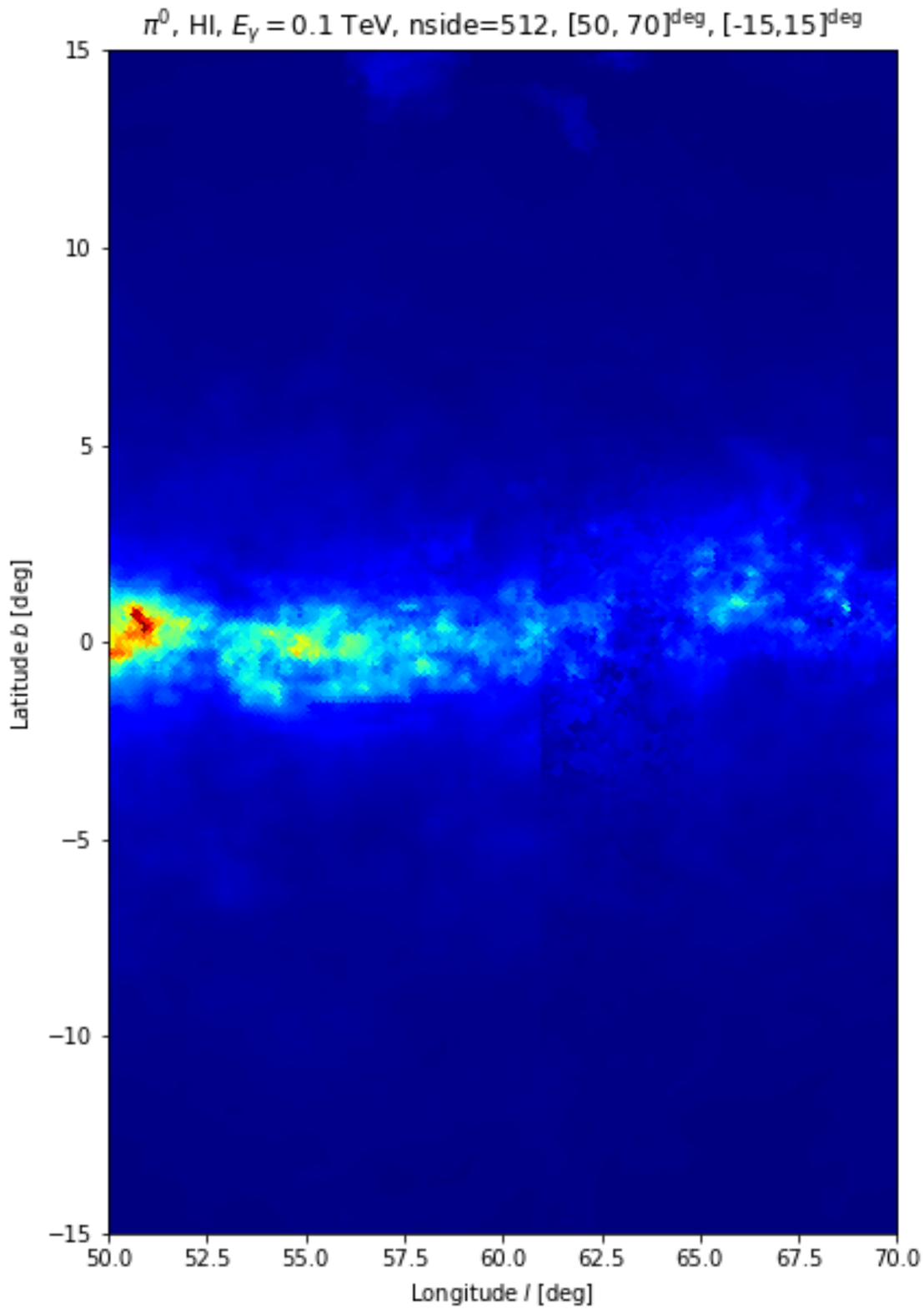


gas model: ring 6

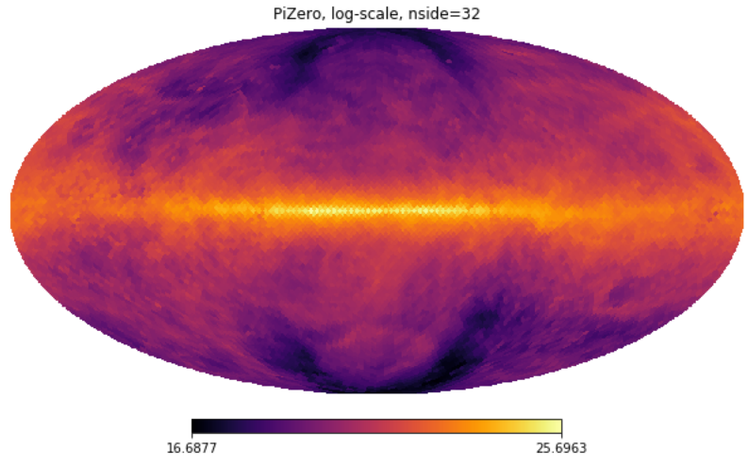
Testing the model. Discontinuity at l = 60°

- Independently checked with gammasky and HERMES
- Independent of the smooth gas model used in the integration

- The feature is already present in the gas model. (minor) problem with ring 6 and 7
- Stacking of rings 6 and 7 shows the feature



The HERMES code



- **HERMES** will be a publicly available computational framework for calculating **sky maps of various radiative processes in our Galaxy**

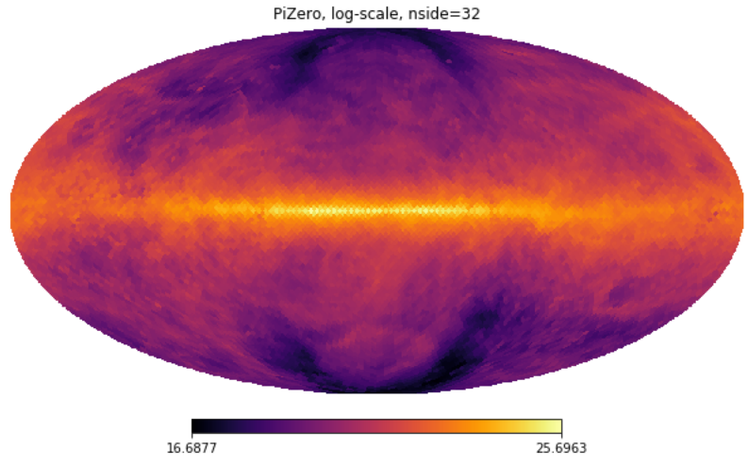
- It performs an i**ntegration over the line of sight** from the Sun to the edge of the Galaxy to obtain either a flux, temperature or other quantities for a given direction

- It is capable of calculating rotation measurements, synchrotron radiation, Bremsstrahlung, Inverse Compton, Pion decay emission

$$I_\gamma(E_\gamma) = \frac{1}{4\pi}\int_0^\infty \mathrm{d}s \epsilon_\gamma(E_\gamma, \vec{r})$$

$$\begin{aligned}\epsilon_\gamma(E_\gamma, \vec{r}) &= 4\pi \cdot n_{\mathrm{HI}}(\vec{r}) \int_0^\infty \mathrm{d}E_p \frac{\mathrm{d}\Phi_p}{\mathrm{d}E}(E_p, \vec{r}) \frac{\mathrm{d}\sigma_{pp}}{\mathrm{d}E}(E_p, E_\gamma) \\ &\quad + 2 \cdot 4\pi \cdot X_{\mathrm{CO}}(\vec{r}) w_{\mathrm{CO}}(\vec{r}) \int_0^\infty \mathrm{d}E_p \frac{\mathrm{d}\Phi_p}{\mathrm{d}E}(E_p, \vec{r}) \frac{\mathrm{d}\sigma_{pp}}{\mathrm{d}E}(E_p, E_\gamma) \\ &= 4\pi \cdot (n_{\mathrm{HI}}(\vec{r}) + X_{\mathrm{CO}}(\vec{r}) w_{\mathrm{CO}}(\vec{r}))\, \mathcal{I}_E(E_\gamma, \vec{r})\end{aligned}$$

The HERMES code



What HERMES includes:

A. Radio emissions:

1. Free-free emission
   - depends only on non-relativistic electron density models (implemented YMW16)
2. Rotation measure (RM)
   - same dependence as Free-free
   - galactic magnetic field models (JF12, PT11, Sun08, WMAP07)
3. Synchrotron emission (+ Free-free absorption)
   - depends on galactic magnetic field models as RM
   - relativistic cosmic ray (electron) flux models (DRAGON, Sun08, WMAP07)
   - (+ non-relativistic electron density models for Free-free absorption)

B Gamma-ray emissions:

4. Inverse-Compton
   - depends on relativistic cosmic ray (electron) flux models (DRAGON, Sun08, WMAP07)
   - photon field models (Vernetto16)
5. Pi-Zero
   - depends on neutral gas density models (i.e. "ring models", included Remy18)
   - relativistic cosmic ray (electron) flux models
   - cross section models (Kamae06)
6. Bremsstrahlung (implementation in progress)

Next steps

- Delivery of the model. The FITS file and the documentation will be publicly available on a repository

- Delivery of the new gamma-ray code HERMES

- Construction of a gamma-optimized model and testing against Fermi-LAT data.

Thanks for your attention!

Backup slides