

Hands-on Session

γ -ray emission with HERMES [<https://arxiv.org/abs/2105.13165>]

ISAPP School **MAD**^(γ) 2021

Gamma rays to shed light on Dark Matter

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Simulating the Galactic Multi-messenger Emissions with HERMES

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May 28, 2021

ABSTRACT

Context. The study of non-thermal processes such as synchrotron emission, inverse Compton scattering, bremsstrahlung and pion production is crucial to understand the properties of the Galactic cosmic-ray population, to shed light on their origin and confinement mechanisms, and to assess the significance of exotic signals possibly associated to new physics.

Aims. We present a public code called **HERMES** aimed at generating sky maps associated to a variety of multi-messenger and multi-wavelength radiative processes, spanning from the radio domain all the way up to high-energy gamma-ray and neutrino production.

Methods. We describe the physical processes under consideration, the code concept and structure, and the user interface, with particular focus on the python-based interactive mode. We especially present the modular and flexible design that allows to easily further extend the numerical package according to the user's needs.

Results. In order to demonstrate the capabilities of the code, we describe in detail a comprehensive set of sky maps and spectra associated to all physical processes included in the code. We comment in particular on the radio, gamma-ray, and neutrino maps, and mention the possibility to study signals stemming from dark matter annihilation.

Conclusions. **HERMES** can be successfully applied to constrain the properties of the Galactic cosmic-ray population, improve our understanding of the diffuse Galactic radio, gamma-ray, and neutrino emission, and search for signals associated to particle dark matter annihilation or decay.

γ -ray emitting processes

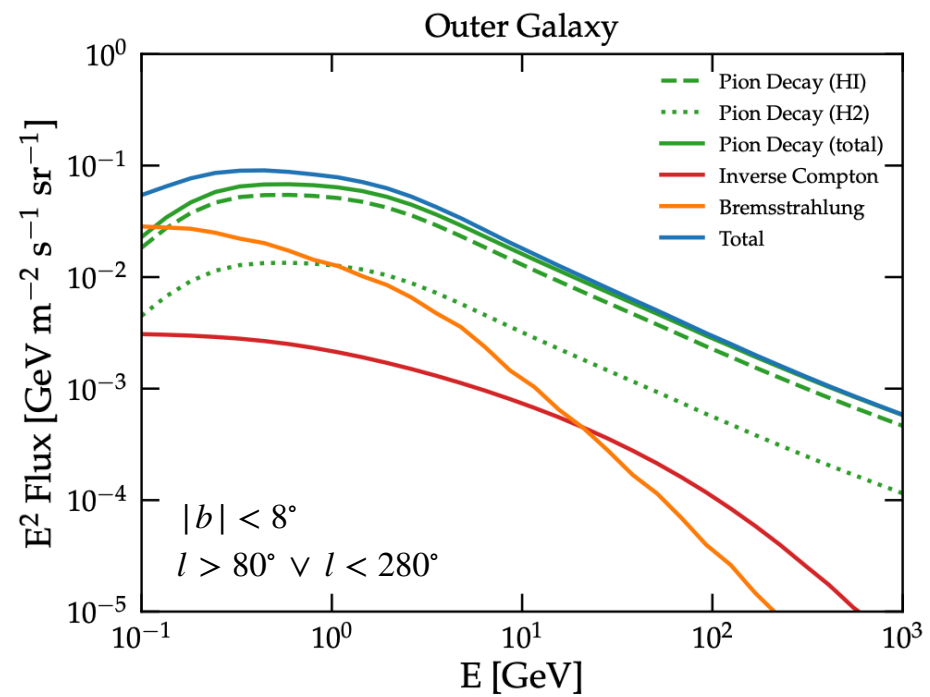
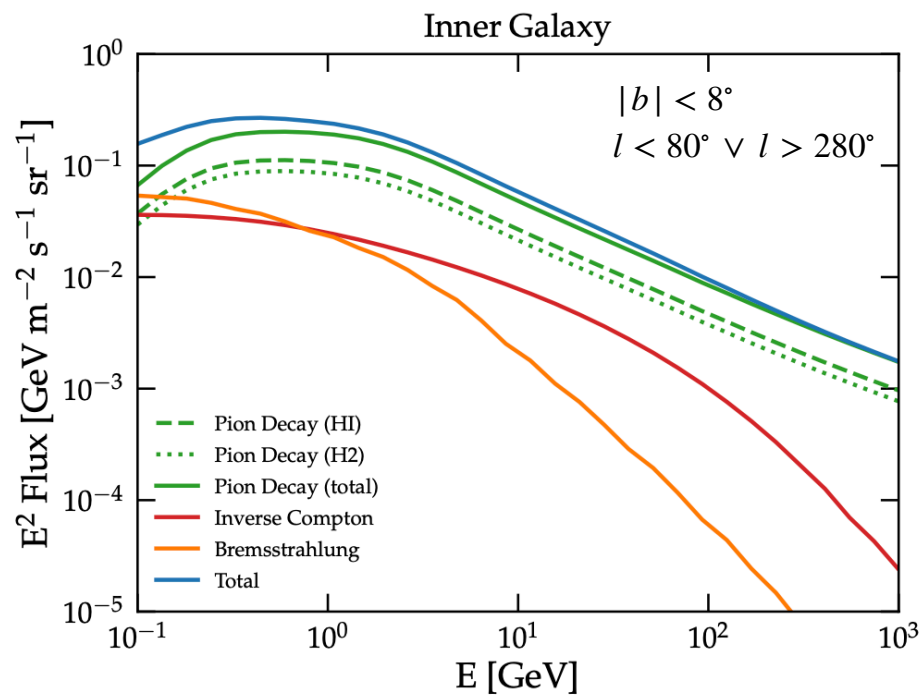
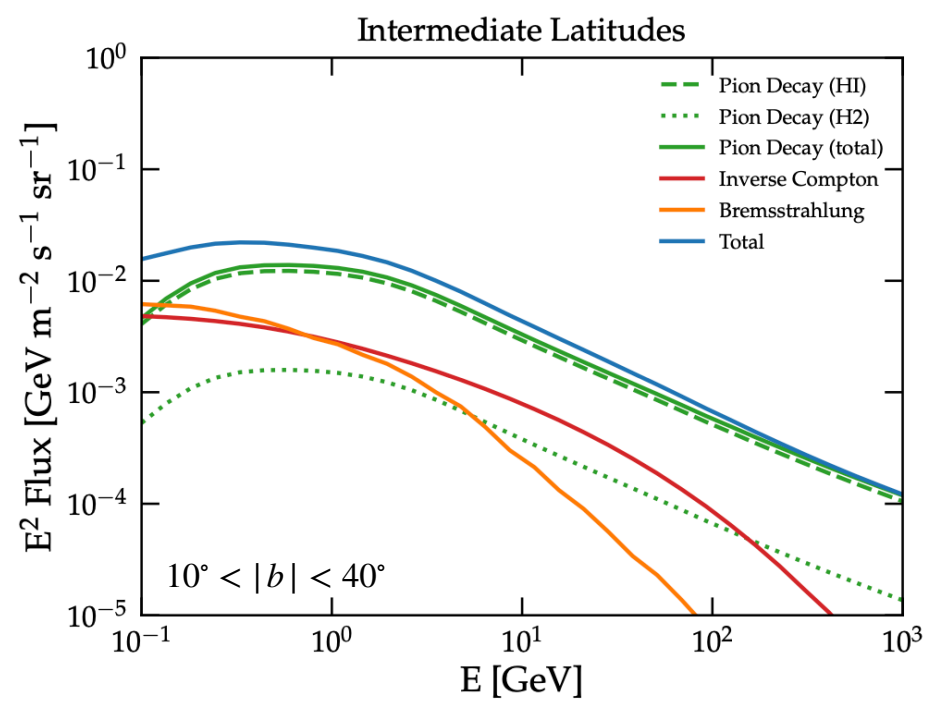
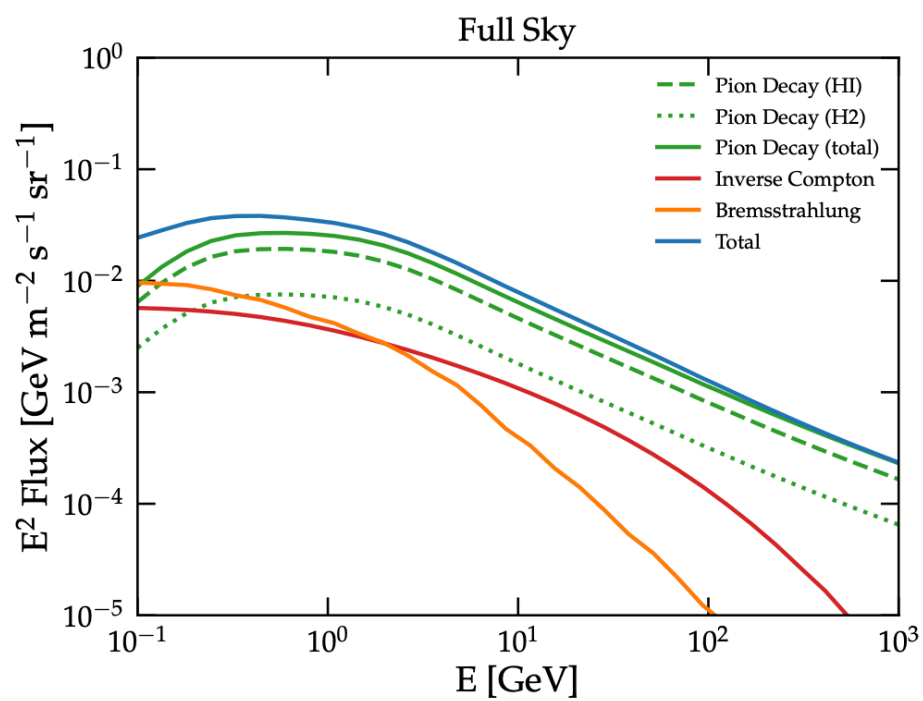
Resulting energy bands [<https://heasarc.gsfc.nasa.gov/docs/heasarc/headates/spectrum.html>]

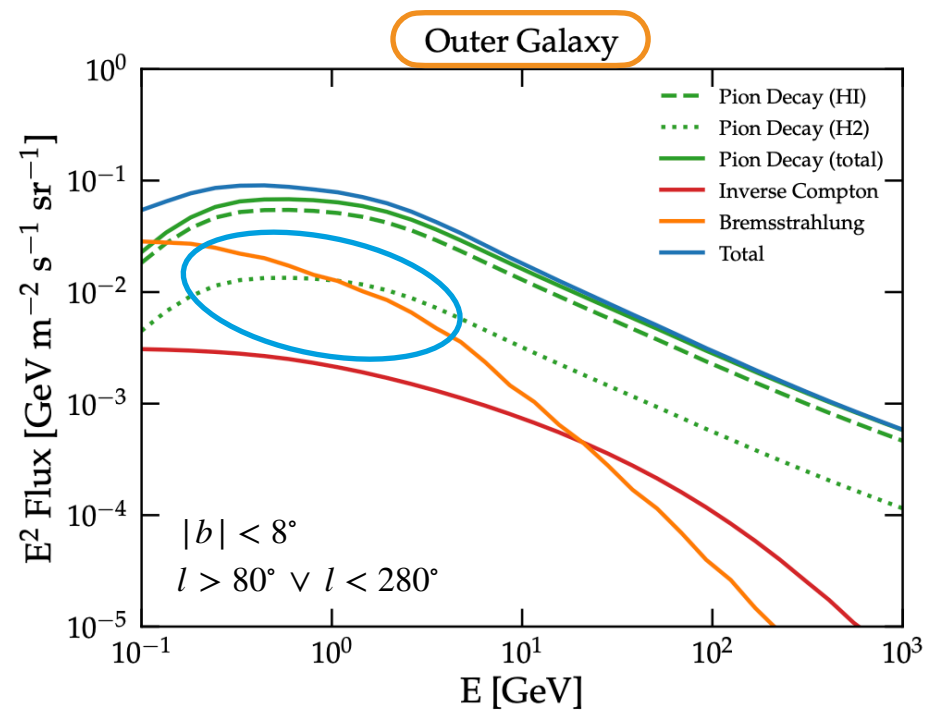
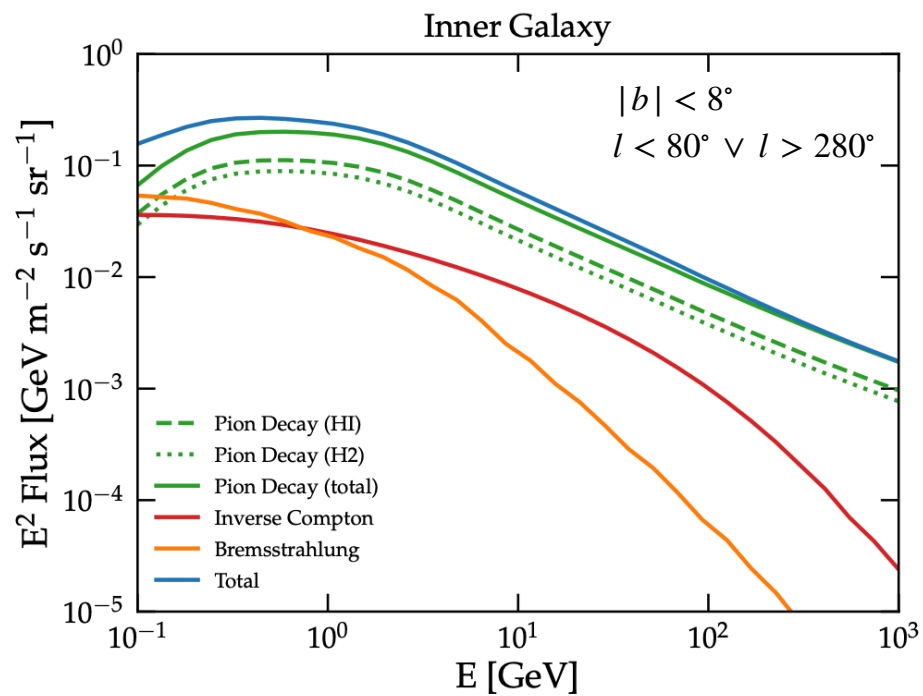
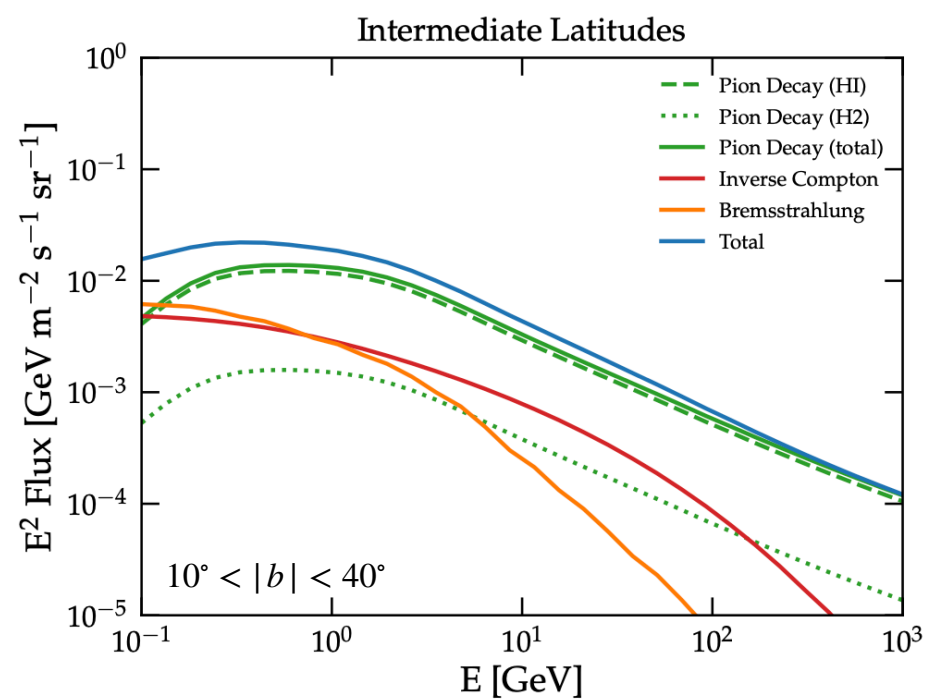
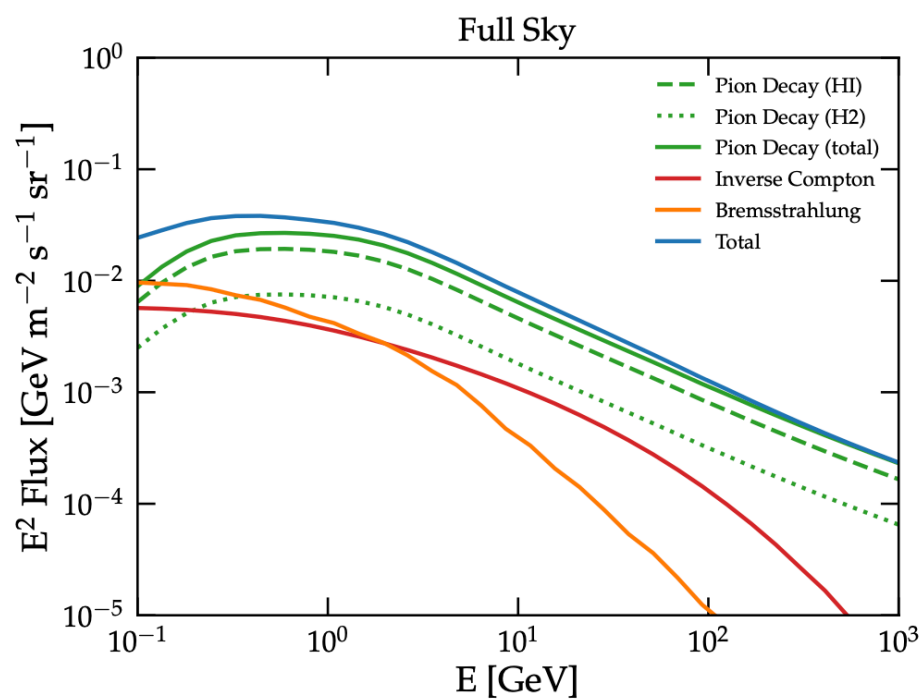
	CR involved	Target	Secondary ID	Secondary E
Synchrotron	e^\pm	B -field	γ	<i>radio band</i>
Brems		ISM gas		broadband
ICS		ISRF		high γ -rays
$\pi^0 \rightarrow \gamma\gamma$	$p, \text{He, nuclei}$	ISM gas+ decay	ν	high γ -rays
$\pi^\pm \rightarrow \mu_\pm \bar{\nu}_\mu^{(-)}$				high-energy ν
$\mu^\pm \rightarrow e^\pm \bar{\nu}_\mu^{(-)} \bar{\nu}_e^{(-)}$	sec μ			broadband

$E \lesssim \mathcal{O}(100) \text{ GHz}$

$E > \text{MeV}$

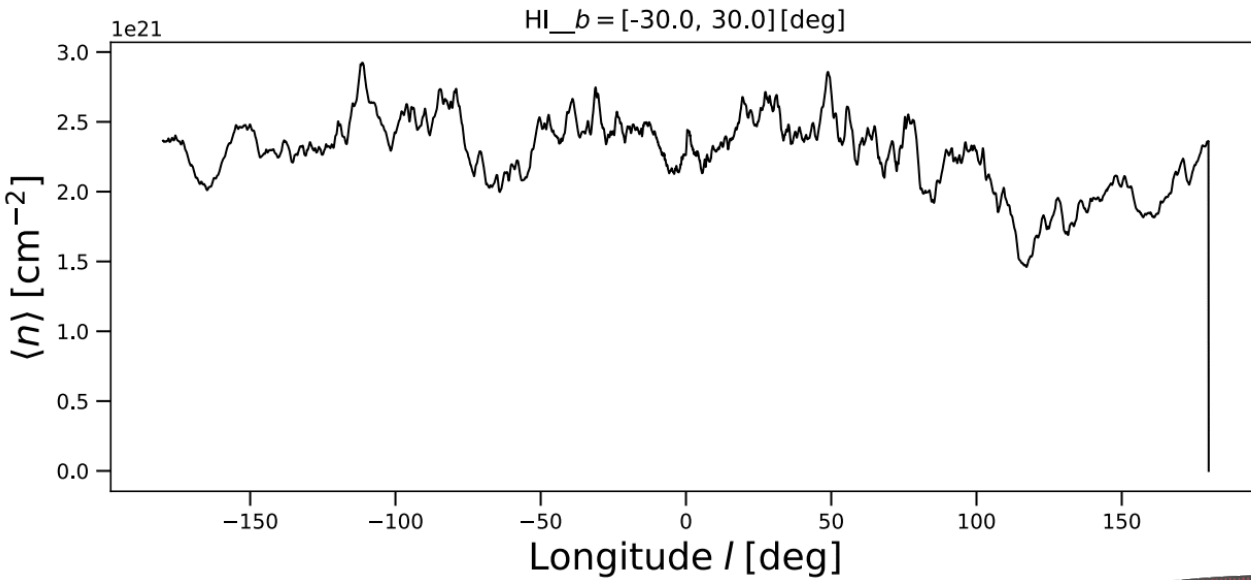
$E > \text{GeV}$



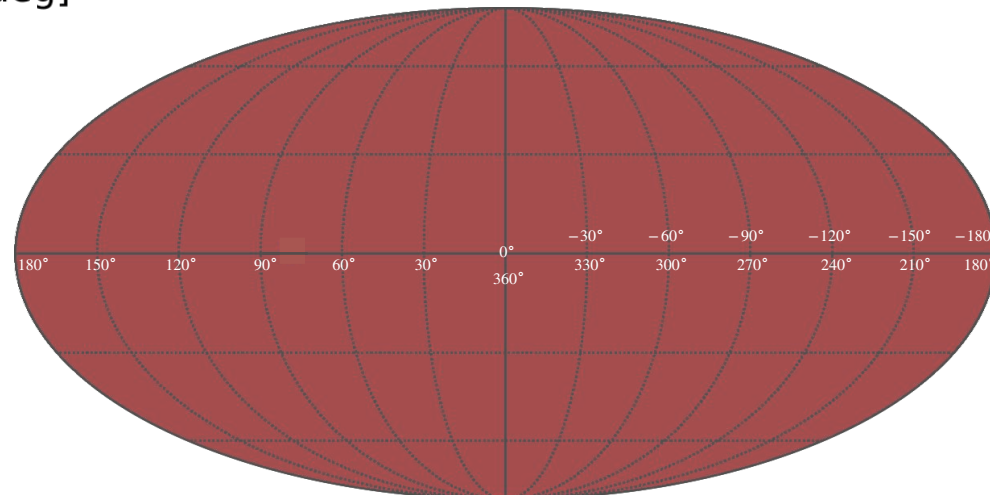
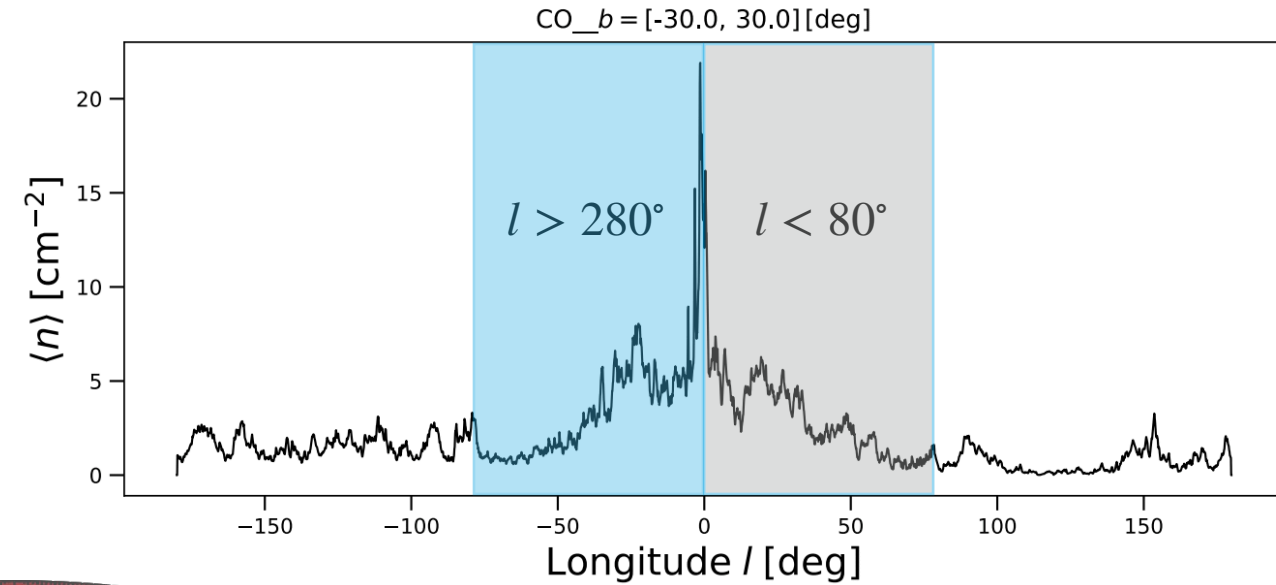


Gas longitudinal profile

Atomic gas

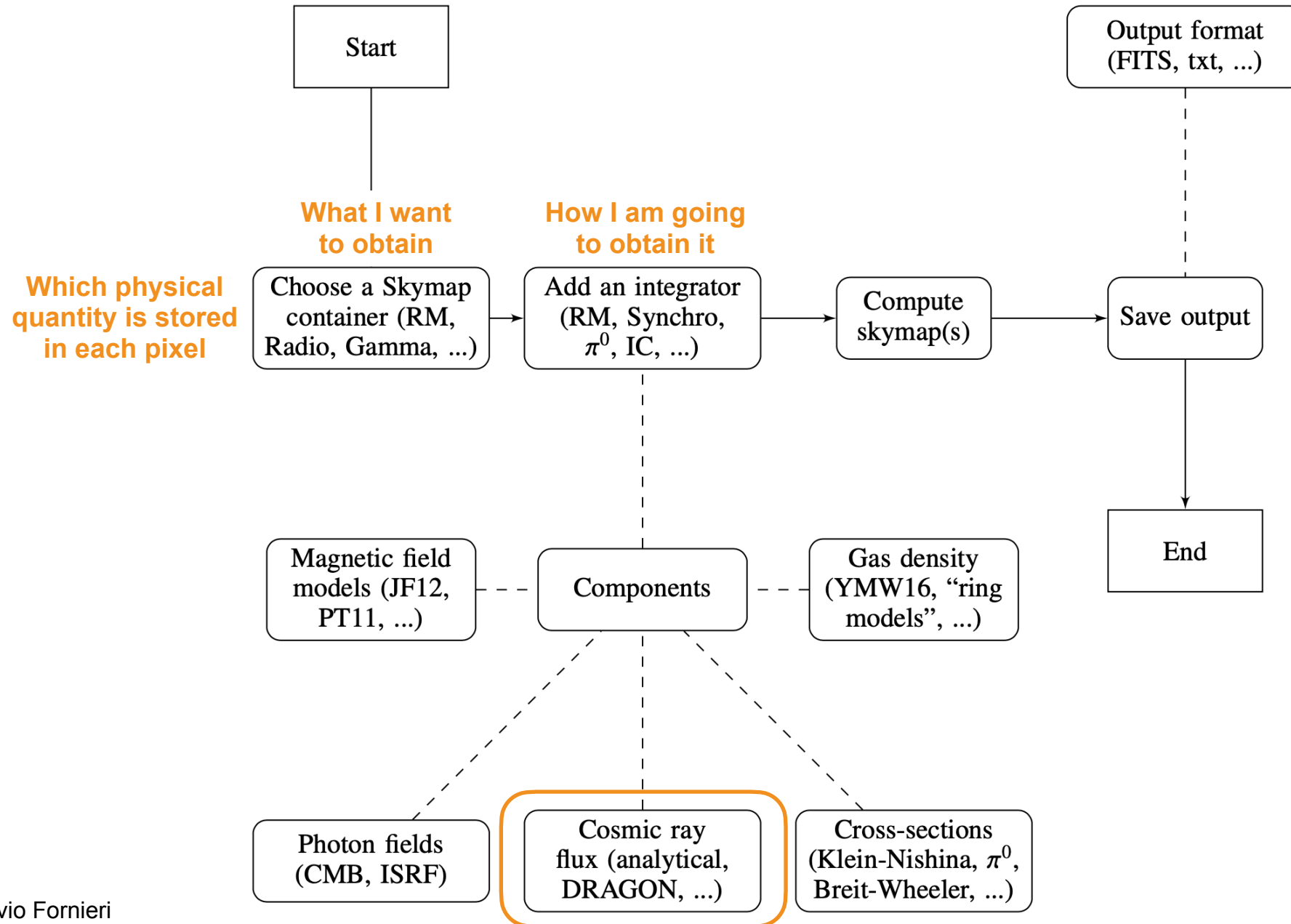


Molecular gas



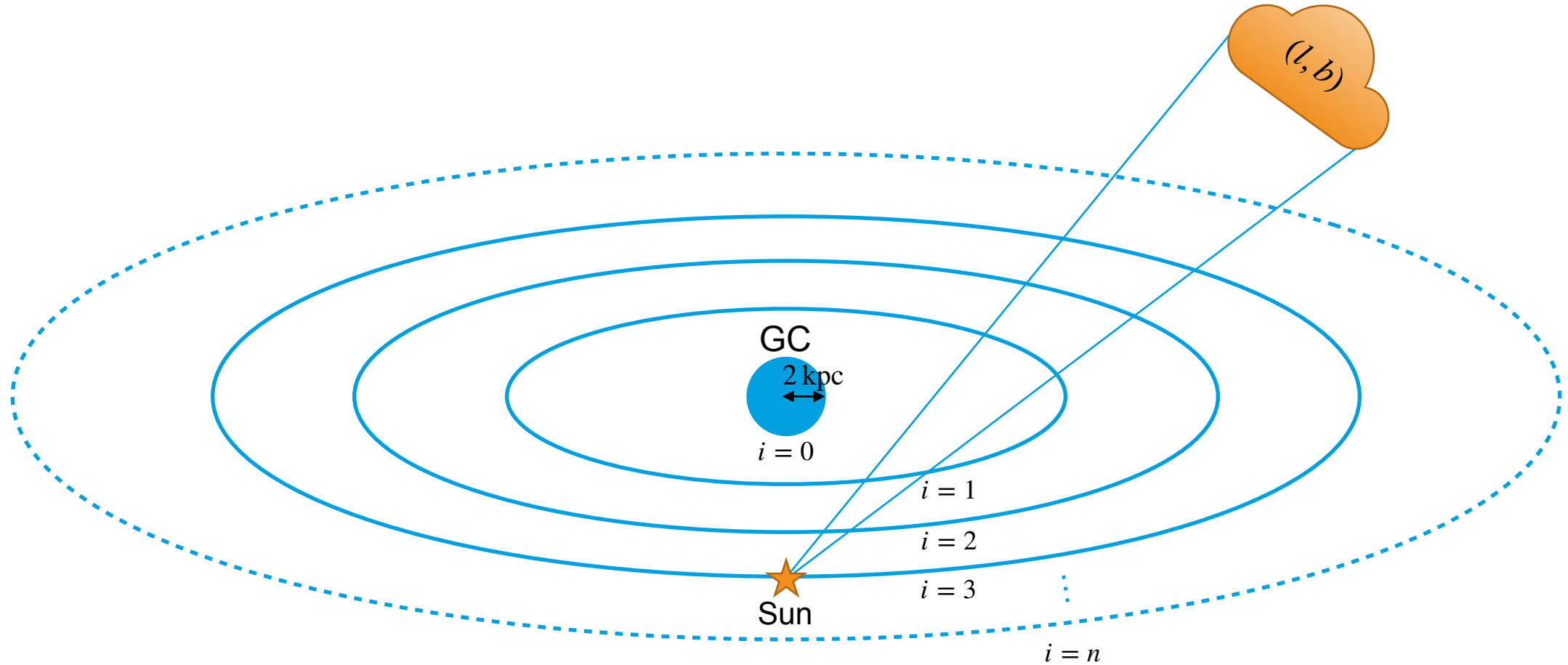
Introduction to γ -rays with HERMES

HERMES work-flow



Ring model

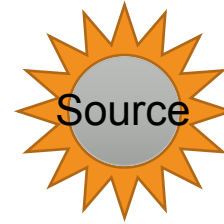
[Strong&Mattox, A&A, 308, L21 (1996)] → based on HI and CO emissivity maps



The observable quantity

γ -ray intensity $I_\gamma \equiv I_\gamma(l, b, E_\gamma)$

Emissivity at the source

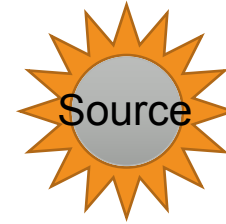


$$\epsilon_{\pi^0}(E_\gamma, \mathbf{r}) = 4\pi n_{\text{H}}(\mathbf{r}) \int dE \left[\frac{d\Phi_{\text{p}}}{dE}(E, \mathbf{r}) \left(\frac{d\sigma_{\text{p-p}}}{dE_\gamma} + f_{\text{He}} \frac{d\sigma_{\text{He-p}}}{dE_\gamma} \right) + \frac{d\Phi_{\text{He}}}{dE}(E, \mathbf{r}) \left(\frac{d\sigma_{\text{p-He}}}{dE_\gamma} + f_{\text{He}} \frac{d\sigma_{\text{He-He}}}{dE_\gamma} \right) \right]$$

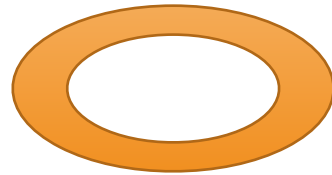
The observable quantity

γ -ray intensity $I_\gamma \equiv I_\gamma(l, b, E_\gamma)$

Emissivity at the source



$$\epsilon_{\pi^0}(E_\gamma, \mathbf{r}) = 4\pi n_{\text{H}}(\mathbf{r}) \int dE \left[\frac{d\Phi_{\text{p}}}{dE}(E, \mathbf{r}) \left(\frac{d\sigma_{\text{p-p}}}{dE_\gamma} + f_{\text{He}} \frac{d\sigma_{\text{He-p}}}{dE_\gamma} \right) + \frac{d\Phi_{\text{He}}}{dE}(E, \mathbf{r}) \left(\frac{d\sigma_{\text{p-He}}}{dE_\gamma} + f_{\text{He}} \frac{d\sigma_{\text{He-He}}}{dE_\gamma} \right) \right]$$



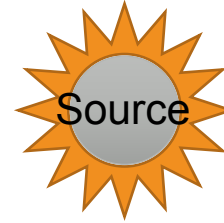
Emissivity averaged over the ring i -th

$$\langle \epsilon_{\pi^0}(E_\gamma, \mathbf{r}) \rangle^i = \frac{\int d\mathbf{r} \epsilon_{\pi^0}(E_\gamma, \mathbf{r}) p_{\text{HI}}(\mathbf{r}) \Theta^i(\mathbf{r})}{\int d\mathbf{r} p_{\text{HI}}(\mathbf{r}) \Theta^i(\mathbf{r})}$$

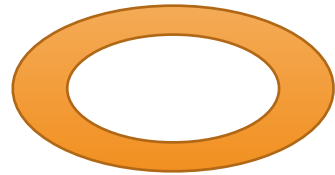
The observable quantity

γ -ray intensity $I_\gamma \equiv I_\gamma(l, b, E_\gamma)$

Emissivity at the source



$$\epsilon_{\pi^0}(E_\gamma, \mathbf{r}) = 4\pi n_{\text{H}}(\mathbf{r}) \int dE \left[\frac{d\Phi_{\text{p}}}{dE}(E, \mathbf{r}) \left(\frac{d\sigma_{\text{p-p}}}{dE_\gamma} + f_{\text{He}} \frac{d\sigma_{\text{He-p}}}{dE_\gamma} \right) + \frac{d\Phi_{\text{He}}}{dE}(E, \mathbf{r}) \left(\frac{d\sigma_{\text{p-He}}}{dE_\gamma} + f_{\text{He}} \frac{d\sigma_{\text{He-He}}}{dE_\gamma} \right) \right]$$

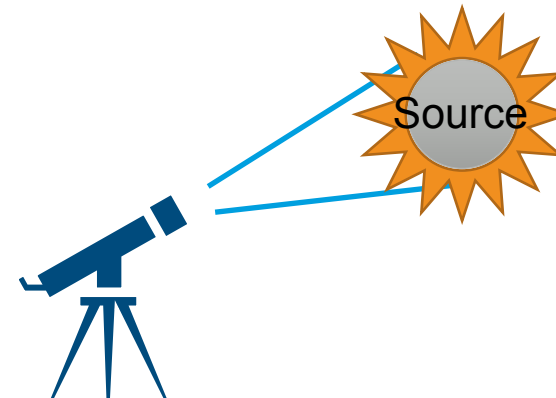


Emissivity averaged over the ring i -th

$$\langle \epsilon_{\pi^0}(E_\gamma, \mathbf{r}) \rangle^i = \frac{\int d\mathbf{r} \epsilon_{\pi^0}(E_\gamma, \mathbf{r}) p_{\text{HI}}(\mathbf{r}) \Theta^i(\mathbf{r})}{\int d\mathbf{r} p_{\text{HI}}(\mathbf{r}) \Theta^i(\mathbf{r})}$$

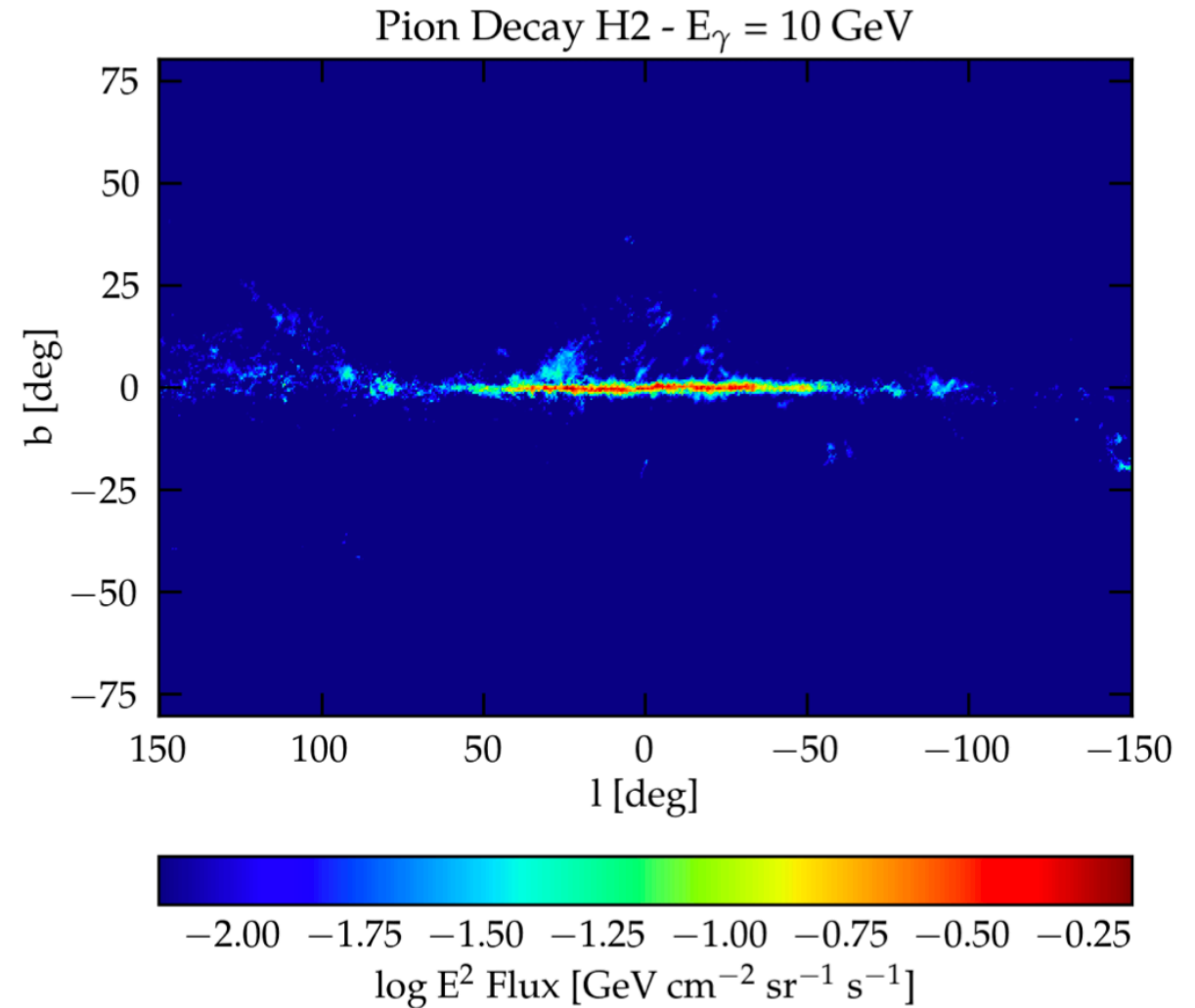
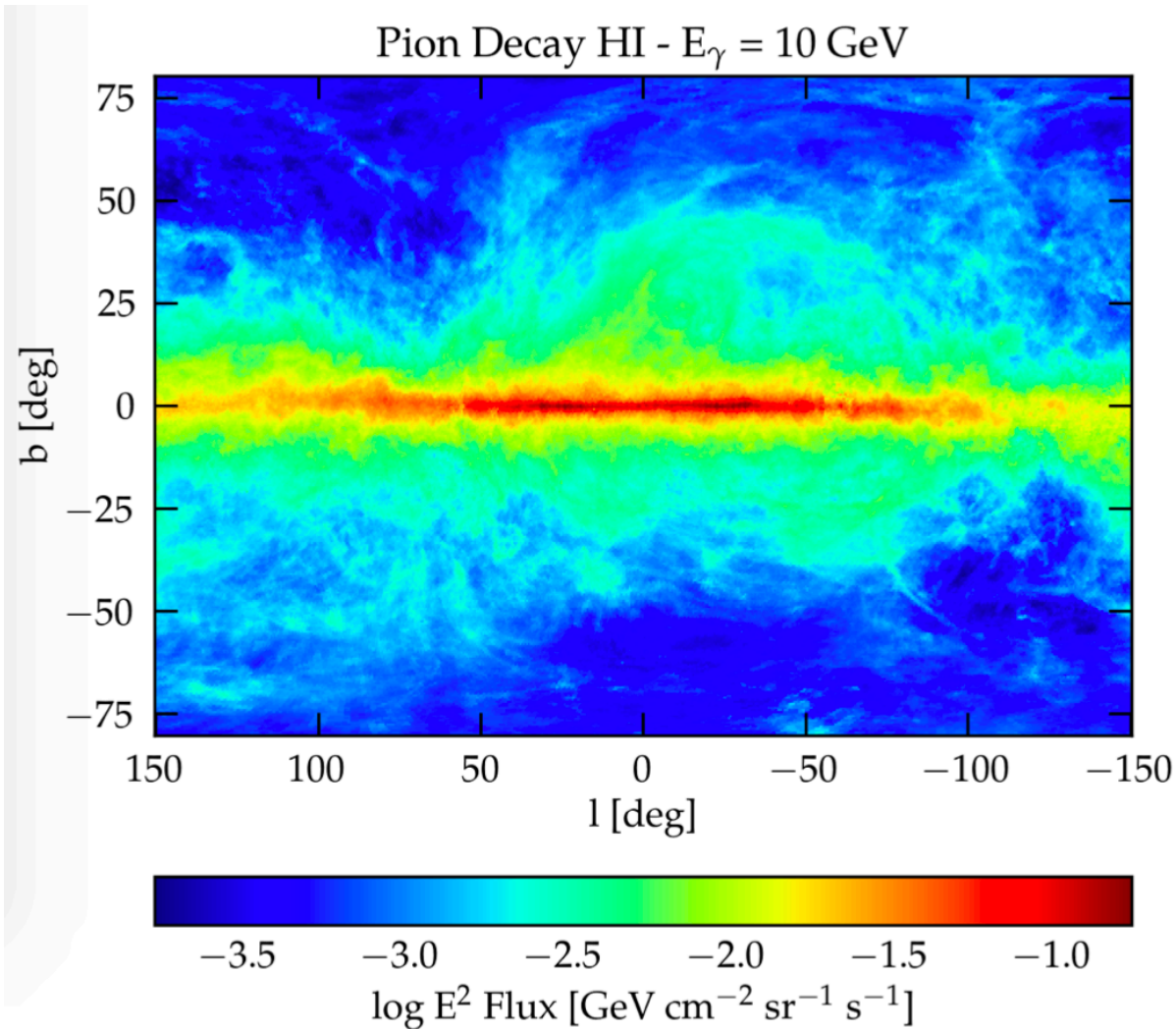
Observed intensity

$$I_\gamma(l, b, E_\gamma) = \frac{1}{4\pi} \sum_i N_{\text{H}}^i(l, b) \langle \epsilon_{\pi^0}(E_\gamma, \mathbf{r}) \rangle^i$$



The outcome

π^0 -decay at given energy



Support slides

Run HERMES Full-Sky

https://github.com/ottaviofornieri/ISAPP-school-2021_HandsOn-Diffuse_HERMES

$n_{\text{side}} = 32$

$t \sim 58 \text{ min}$

Resolution parameters

HEALPix convention

The number of pixels in a file is computed from its resolution index (Res).

$n_{\text{side}} = 2^{\text{res}}$: The number of pixels per side.

$n_{\text{pix}} = 12 n_{\text{side}}^2$: The total number of pixels in the map.

HEALPix Pixel Information				
Res	NSide	NPixels	Mean Spacing (deg)	Area (sterad)
0	1	12	58.6323	$1.0471976 \times 10^{+00}$
1	2	48	29.3162	$2.6179939 \times 10^{-01}$
2	4	192	14.6581	$6.5449847 \times 10^{-02}$
3	8	768	7.3290	$1.6362462 \times 10^{-02}$
4	16	3072	3.6645	$4.0906154 \times 10^{-03}$
5	32	12288	1.8323	$1.0226539 \times 10^{-03}$
6	64	49152	0.9161	$2.5566346 \times 10^{-04}$
7	128	196608	0.4581	$6.3915866 \times 10^{-05}$
8	256	786432	0.2290	$1.5978967 \times 10^{-05}$
9	512	3145728	0.1145	$3.9947416 \times 10^{-06}$
10	1024	12582912	0.0573	$9.9868541 \times 10^{-07}$

Progress of a full-sky run with $n_{\text{side}} = 32$

12 log-spaced energy points for each process

```
Mi Jun 9 14:34
ottavio@ottavio-Latitude-7410: ~/virtualenvs
Hermes_DRAGO
jupyter Hermes_DRA
File Edit View Insert
+ %< >
37
38 # Calcul
39 skymapB
40 skymapB
41 nameBref
42 skymapB
43 print("
44 print("
45
46
47
48
49
50 # Lepto
51
52 # Calcul
53 skymapIC
54 skymapIC
55 nameIC1
56 skymapIC
57 print("
58 print("
59
60 # Calculation of IC skymap (ISRF)
61 skymapIC_isrf_range.setIntegrator(integratorIC_isrf)
62 skymapIC_isrf_range.compute()
63 nameIC2 = SkyMapsOutputsFolder + 'BaseRunIC_isrf_nside' + str(nside)
64 skymapIC_isrf_range.save(outputs.HEALPixFormat("{}_fits.gz".format(nameIC2)))
65 print("IC on ISRF done")
66 print("")
67
68
69
70
71 print('Total time:', time.perf_counter() - start, "seconds")

Starting calculation of skymaps...

In [*]: 1 # Path to the HERMES output #
        2
        3 SkyMapsFolder = SkyMapsOutputsFolder + 'Sky_Maps/'
```

Progress of a full-sky run with $n_{\text{side}} = 32$

12 log-spaced energy points for each process

```
Mi Jun 9 14:36
Select or cre x Hermes_DRAGO
ottavio@ottavio-Latitude-7410: ~/virtualenvs
jupyter Hermes_DRA
File Edit View Insert
37
38 # Calcul
39 skymapB
40 skymapB
41 nameBre
42 skymapB
43 print("
44 print("
45
46
47
48
49
50 # Lepto
51
52 # Calcul
53 skymapI
54 skymapI
55 nameIC1
56 skymapI
57 print("
58 print("
59
60 # Calcul
61 skymapIC_isrf_range.setIntegrator(integratorIC_isrf)
62 skymapIC_isrf_range.compute()
63 nameIC2 = SkyMapsOutputsFolder + 'BaseRunIC_isrf_nside' + str(nside)
64 skymapIC_isrf_range.save(outputs.HEALPixFormat("!{}.fits.gz".format(nameIC2)))
65 print("IC on ISRF done")
66 print("")
67
68
69
70
71 print('Total time:', time.perf_counter() - start, "seconds")

Starting calculation of skymaps...

pi0 HI done

In [*]: 1 # Path to the HERMES output #
        2
        3 SkyMapsFolder = SkyMapsOutputsFolder + 'Sky_Maps/'
```

First process gone!

Progress of a full-sky run with $n_{\text{side}} = 32$

12 log-spaced energy points for each process

```
MI Jun 9 15:29
Hermes_DRAGON
ottavio@ottavio-Latitude-7410: ~/virtualenvs
hermes::SkymapRange: 9/12, Energy = 1519.91 GeV
hermes::Integrator: Number of Threads: 8
hermes::Integrator::initCacheTable: Number of Threads: 8
Generate Cache Table
Started Wed Jun 9 15:16:53 2021 : [ Finished ] 100% Needed: 00:02:06 - Finished at Wed Jun 9 15:18:59 2021
Compute skymap
Started Wed Jun 9 15:18:59 2021 : [ Finished ] 100% Needed: 00:00:00 - Finished at Wed Jun 9 15:18:59 2021
hermes::SkymapRange: 10/12, Energy = 2848.04 GeV
hermes::Integrator: Number of Threads: 8
hermes::Integrator::initCacheTable: Number of Threads: 8
Generate Cache Table
Started Wed Jun 9 15:18:59 2021 : [ Finished ] 100% Needed: 00:02:03 - Finished at Wed Jun 9 15:21:02 2021
Compute skymap
Started Wed Jun 9 15:21:02 2021 : [ Finished ] 100% Needed: 00:00:00 - Finished at Wed Jun 9 15:21:02 2021
# Lepton
hermes::SkymapRange: 11/12, Energy = 5336.7 GeV
hermes::Integrator: Number of Threads: 8
hermes::Integrator::initCacheTable: Number of Threads: 8
skymapIC1Generate Cache Table
nameIC1 Started Wed Jun 9 15:21:02 2021 : [ Finished ] 100% Needed: 00:02:08 - Finished at Wed Jun 9 15:23:10 2021
skymapIC1Compute skymap
Started Wed Jun 9 15:23:10 2021 : [ Finished ] 100% Needed: 00:00:01 - Finished at Wed Jun 9 15:23:11 2021
print("hermes::SkymapRange: 12/12, Energy = 10000 GeV
hermes::Integrator: Number of Threads: 8
hermes::Integrator::initCacheTable: Number of Threads: 8
skymapIC2Generate Cache Table
skymapIC2 Started Wed Jun 9 15:23:11 2021 : [ Finished ] 100% Needed: 00:01:54 - Finished at Wed Jun 9 15:25:05 2021
nameIC2Compute skymap
skymapIC2 Started Wed Jun 9 15:25:05 2021 : [ Finished ] 100% Needed: 00:00:01 - Finished at Wed Jun 9 15:25:06 2021
print("
print("[I 15:26:25.740 NotebookApp] Saving file at /Hermes_DRAGON_Ottavio_FullSky.ipynb

```

```
print('Total time:', time.perf_counter() - start, "seconds")
```

Starting calculation of skymaps...

pi0 HI done

pi0 H2 done

Brems on H2 done

Brems on HI done

IC on CMB done

IC on ISRF done

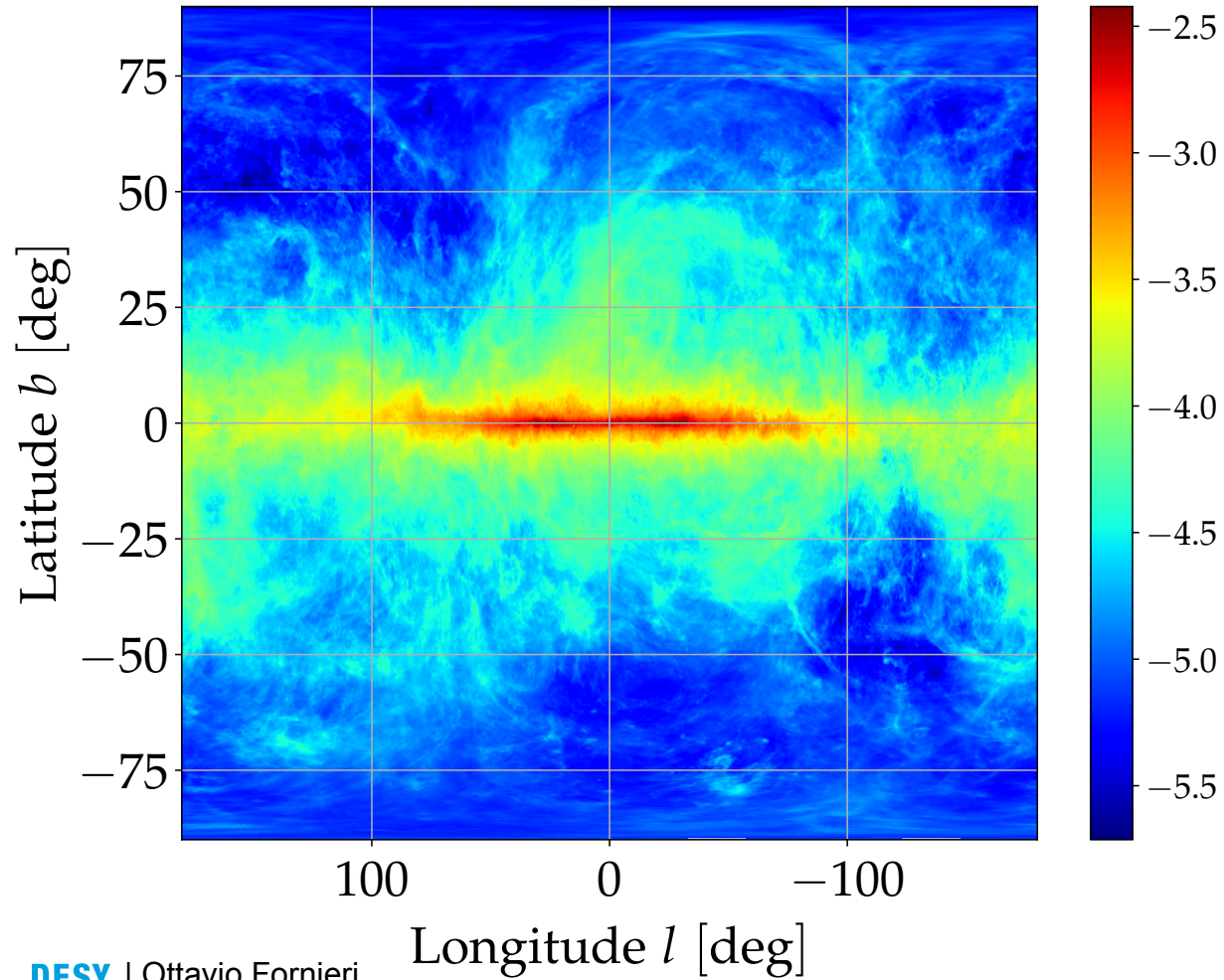
Total time: 3481.3141323109157 seconds

```
In [9]: 1 # Path to the HERMES output #
2
3 SkyMapsFolder = SkyMapsOutputsFolder + 'Sky_Maps/'
```

Cartesian projection of the Full Sky

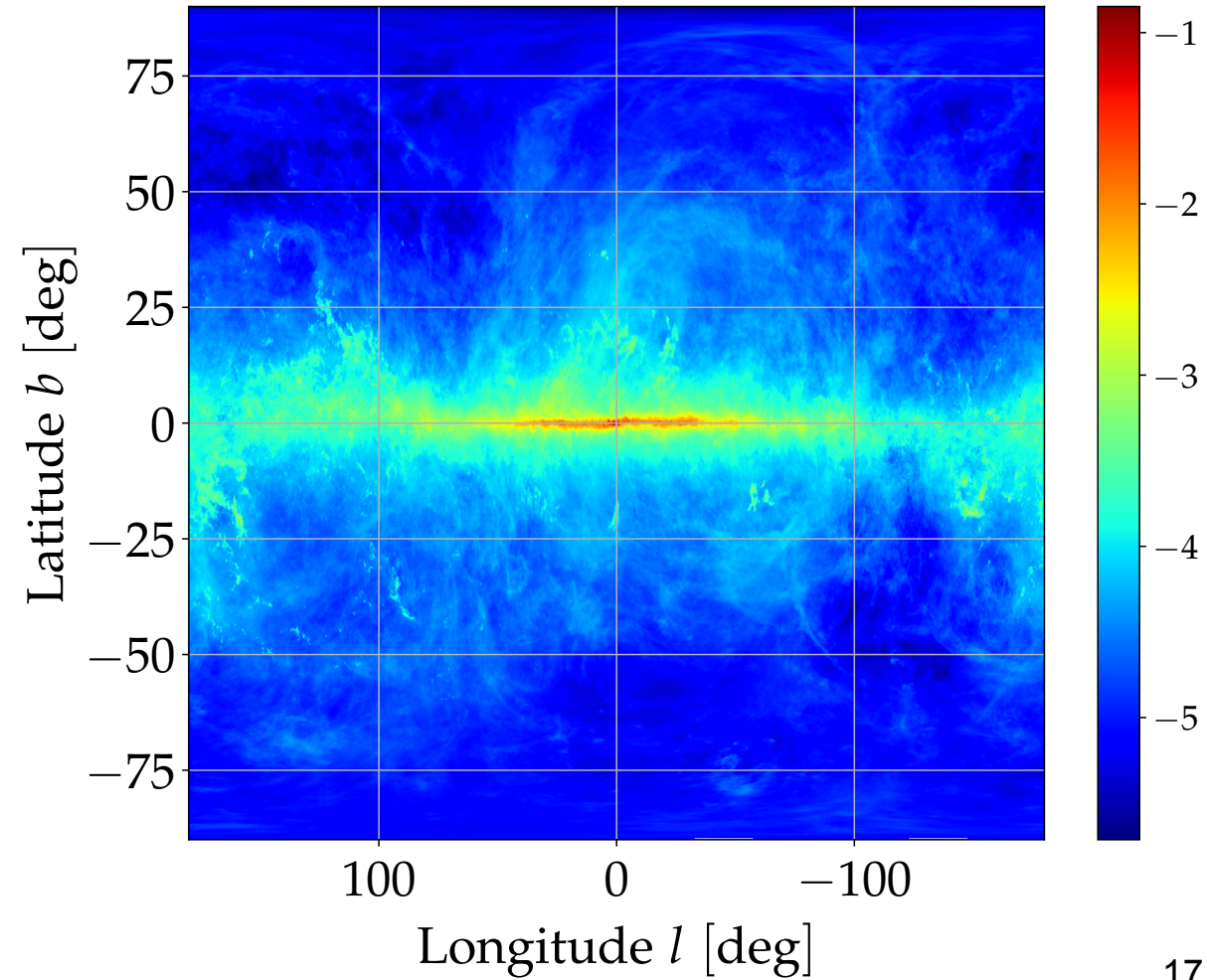
Paper plot: π^0 on HI

$E_\gamma = 10.0$ GeV



π^0 on $HI + H_2$

$E_\gamma = 10.0$ GeV



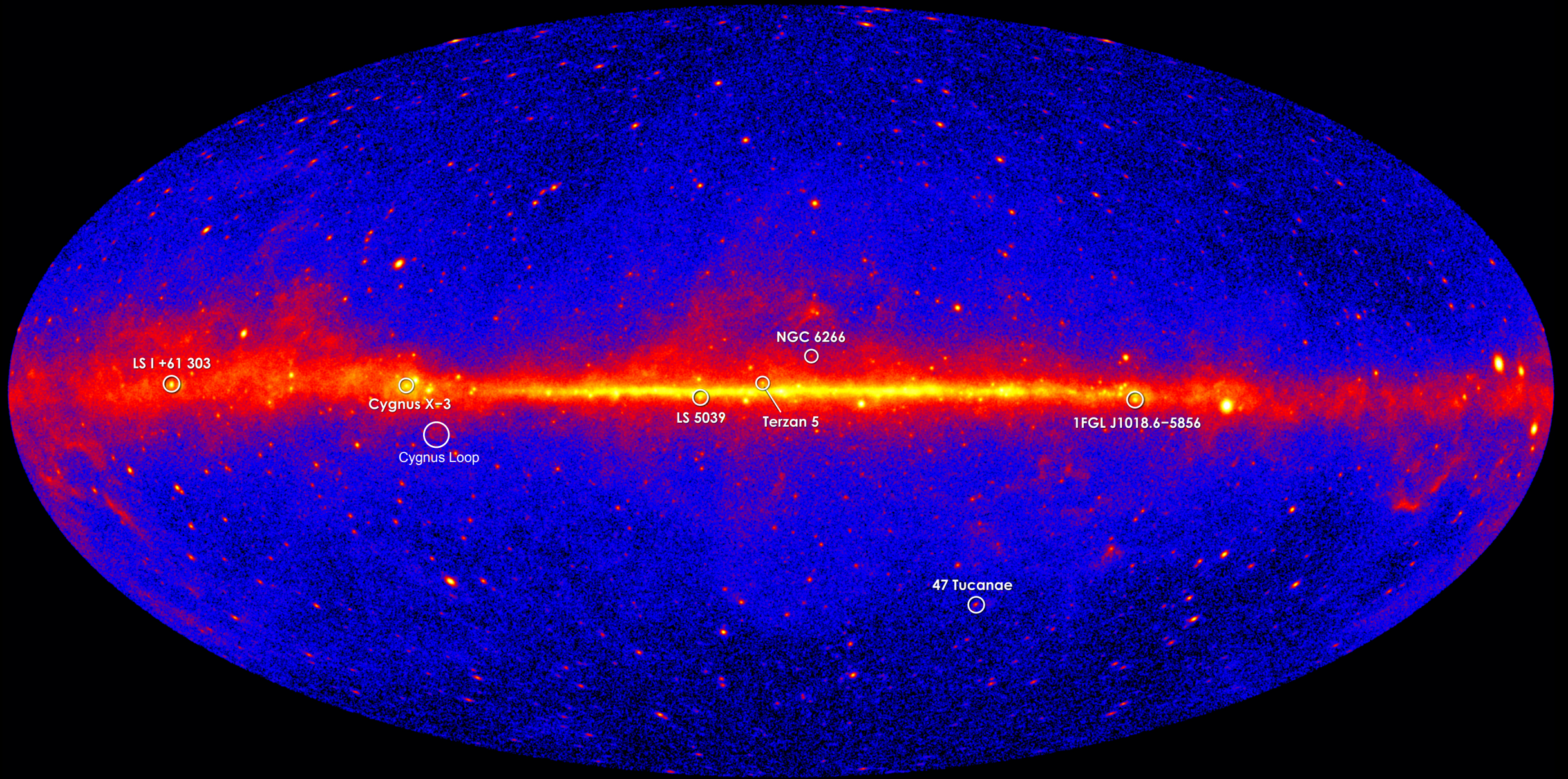
Runs HERMES Cygnus-X region

https://github.com/ottaviofornieri/ISAPP-school-2021_HandsOn-Diffuse_HERMES

$l \in [77^\circ, 82^\circ], b \in [-1^\circ, 4^\circ]$

nside = 512, 1024, 2048

$t \lesssim 30$ min



LS I +61 303

Cygnus X-3

Cygnus Loop

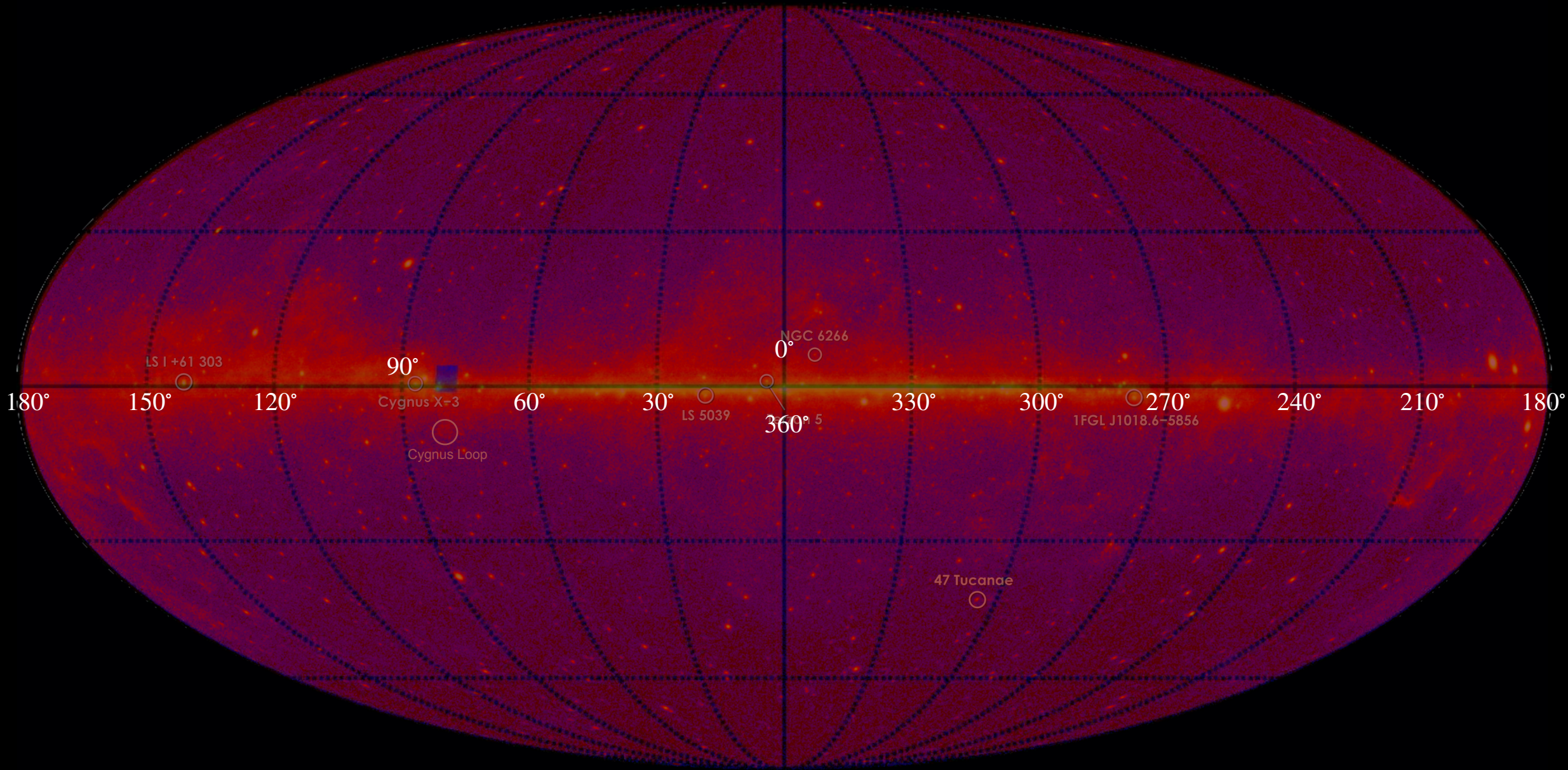
LS 5039

Terzan 5

NGC 6266

1FGL J1018.6-5856

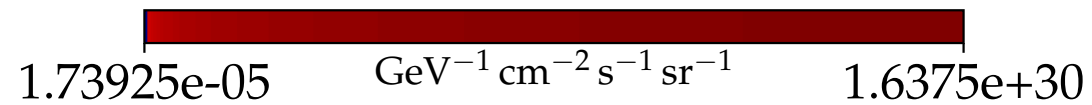
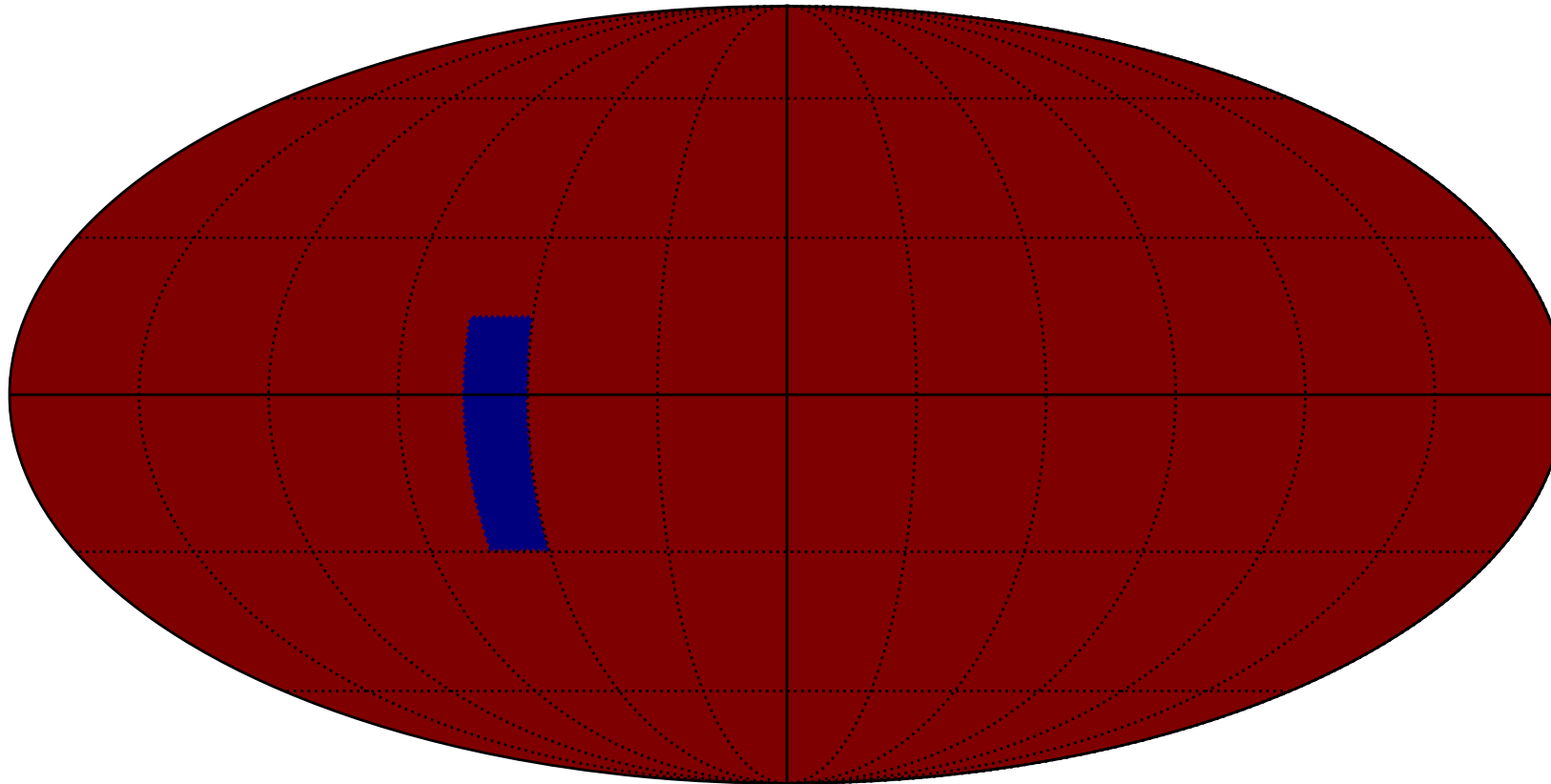
47 Tucanae



Rectangular mask: cross-check

$l \in [60^\circ, 75^\circ]$, $b \in [-30^\circ, 15^\circ]$

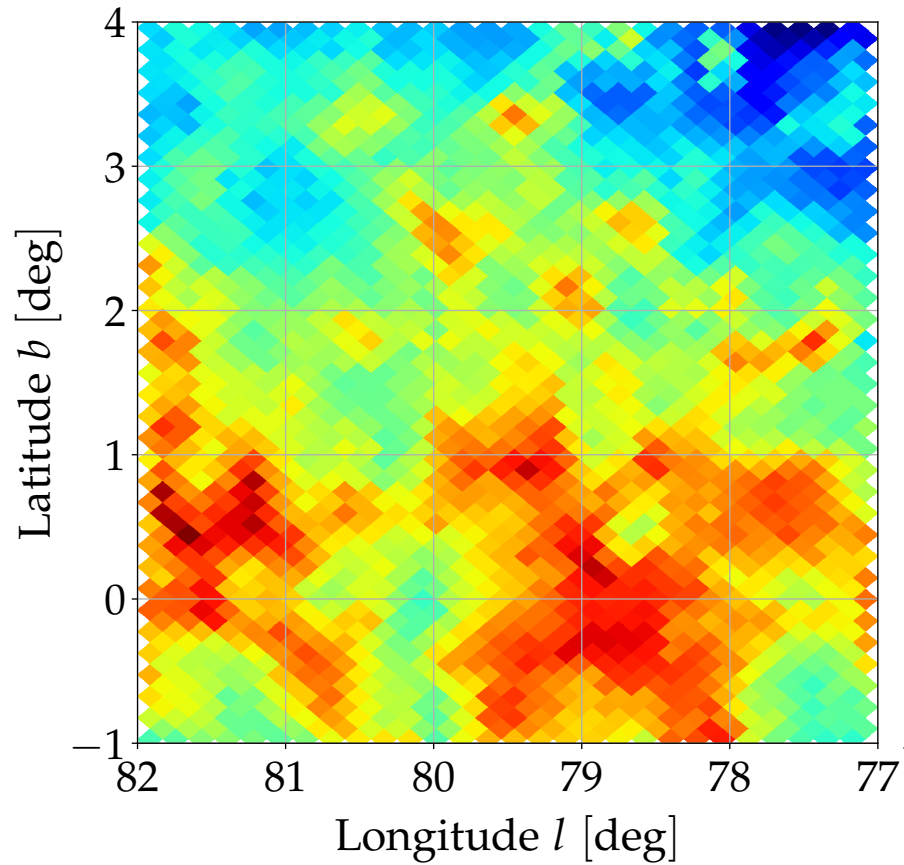
π^0 from HI - E = 10.0 GeV



Diffuse emission from DRAGON CR distribution

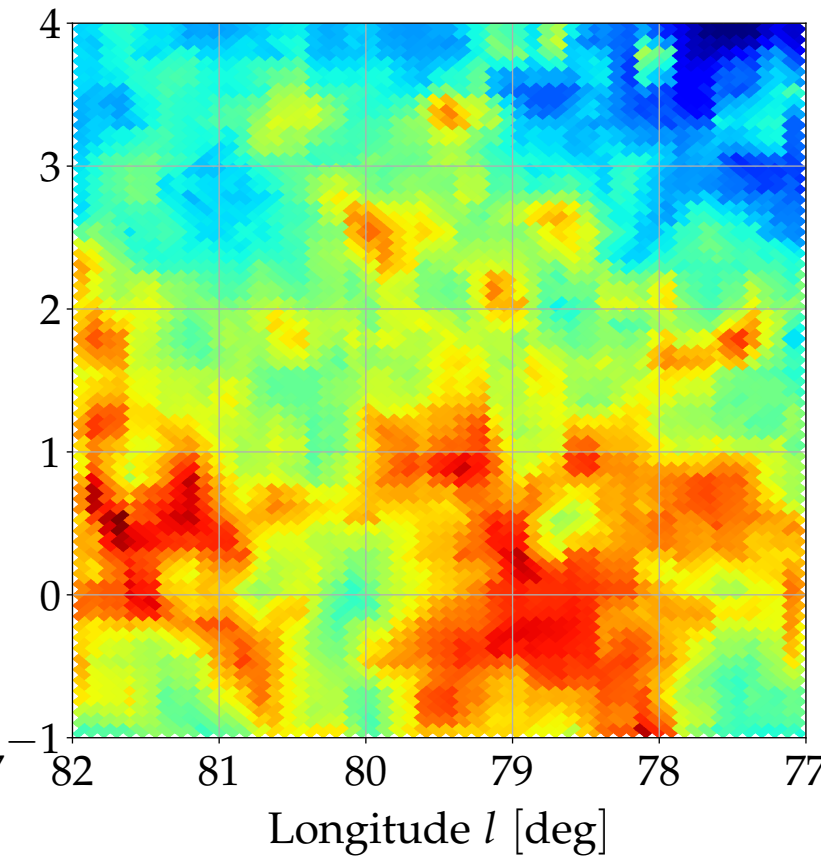
$$E_\gamma = 10 \text{ GeV}$$

nside = 512 $\rightarrow \Delta\phi \simeq 0.11^\circ$



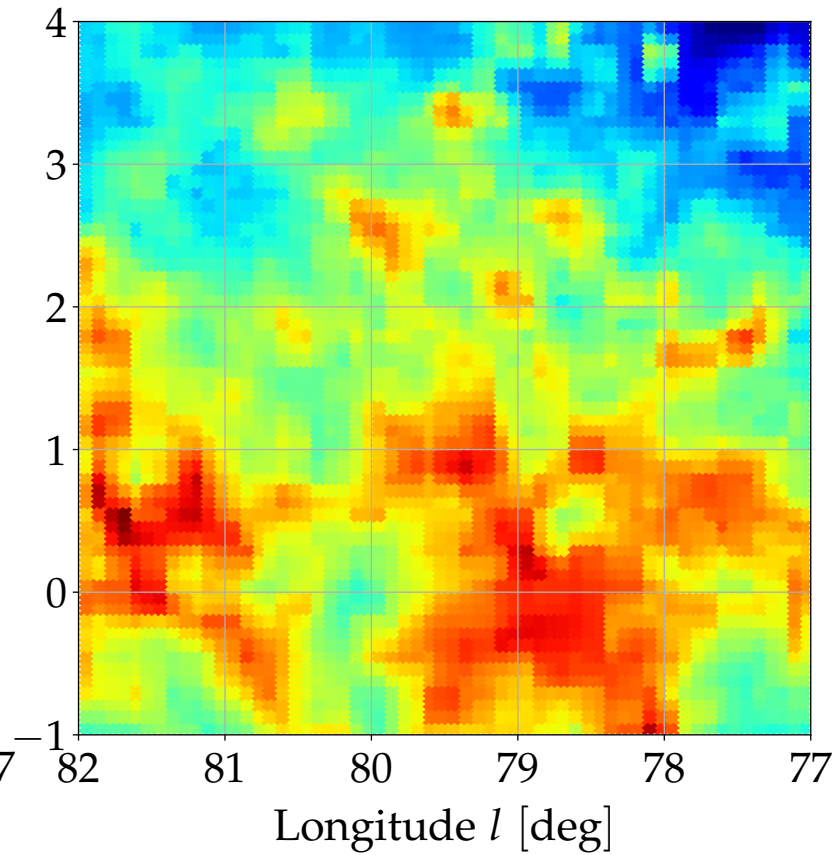
$t \simeq 167 \text{ s}$

nside = 1024 $\rightarrow \Delta\phi \simeq 0.057^\circ$



$t \simeq 265 \text{ s}$

nside = 2048 $\rightarrow \Delta\phi \simeq 0.029^\circ$

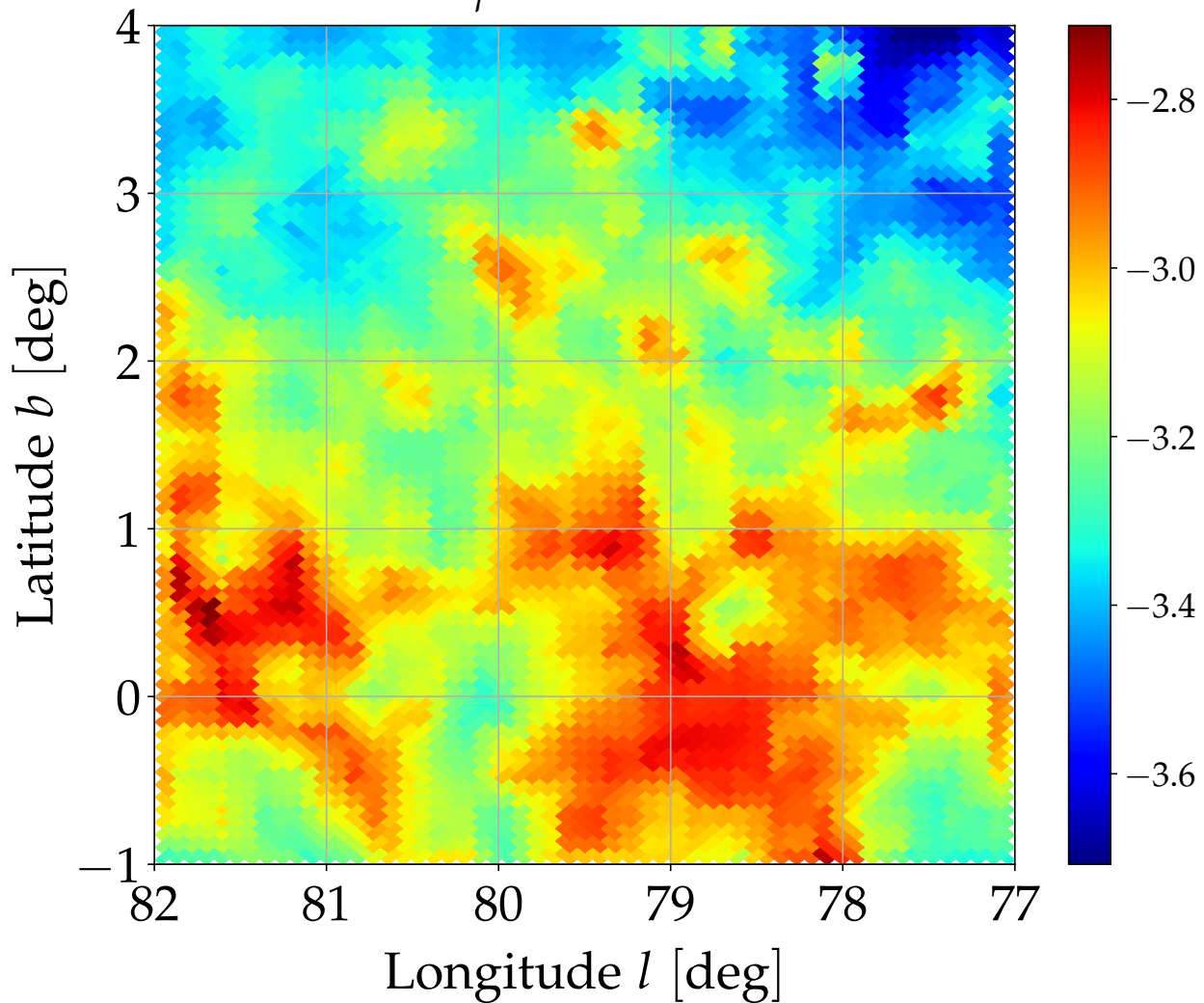


$t \simeq 1021 \text{ s}$

Integral map for HI and H_2

$10 \text{ GeV} < E_\gamma < 10 \text{ TeV}$, $\Delta\phi \approx 0.057^\circ$

$E_\gamma = 10.0 \text{ GeV}$



Integrated

