

Hands-on Session

γ -ray emission with HERMES

ISAPP School **MAD^(r)** 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.

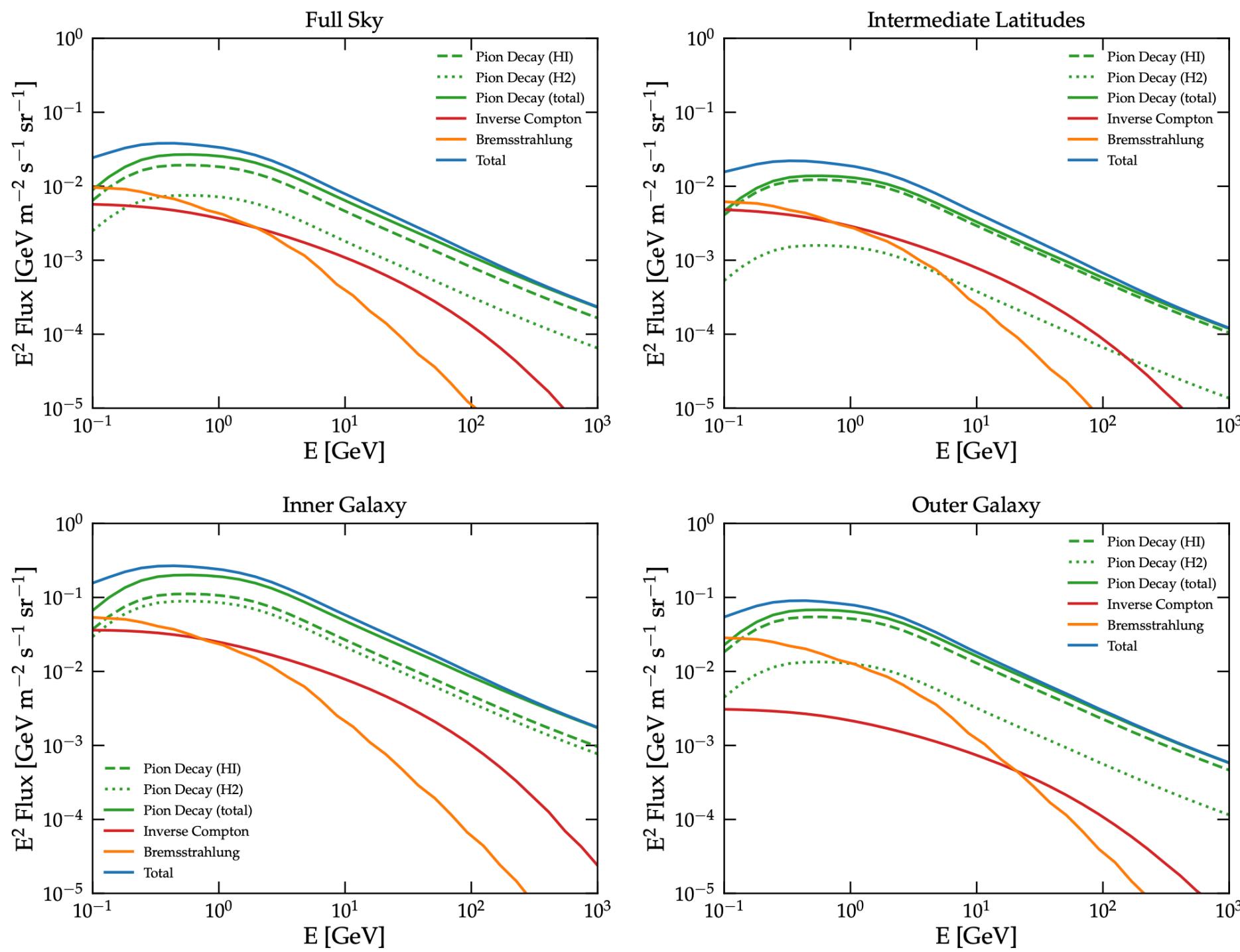
Results. In order to demonstrate the capabilities of the code, we describe in detail a comprehensive set of sky maps and spectra associated to all physical processes included in the code. We comment in particular on the radio, gamma-ray, and neutrino maps, and mention the possibility to study signals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

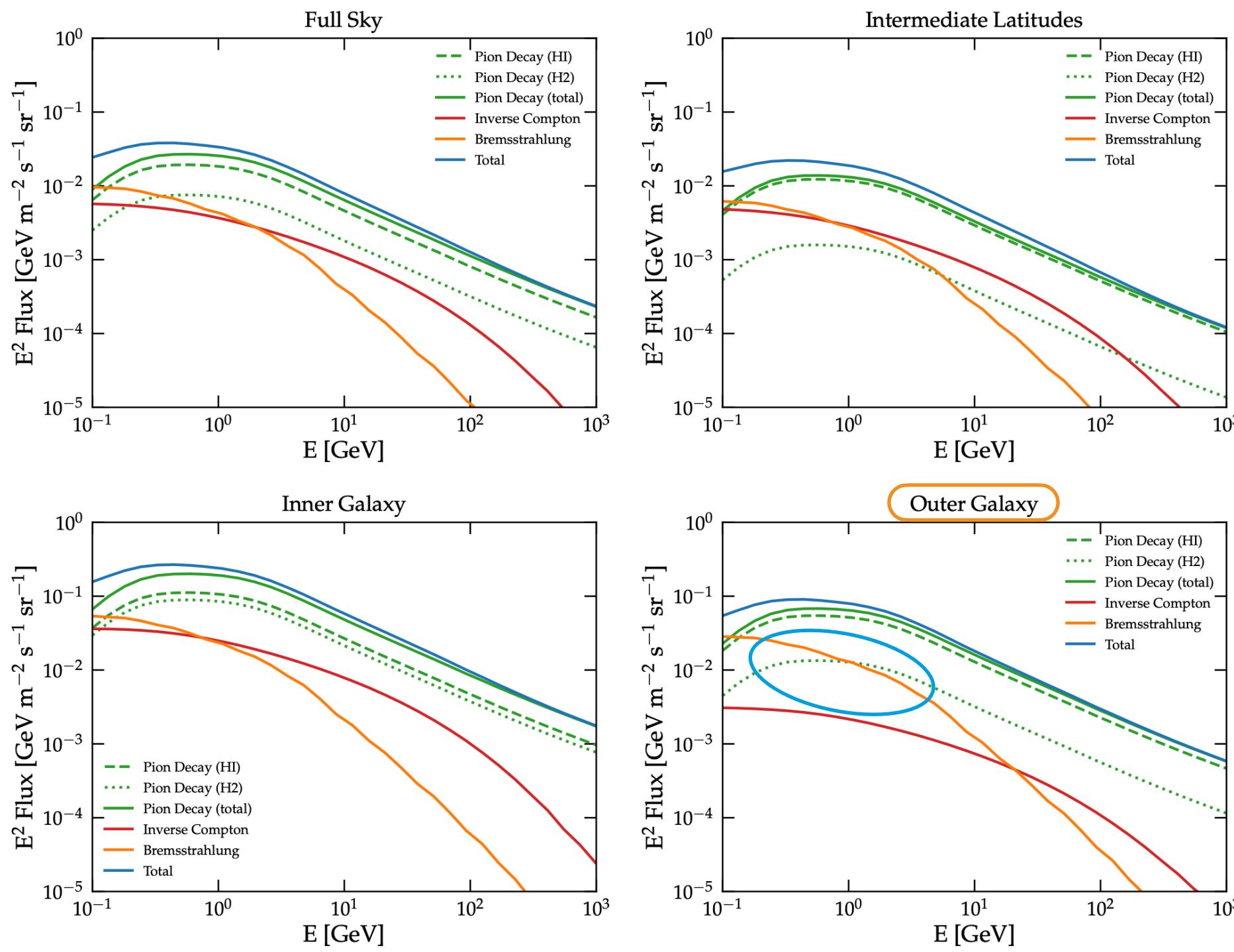
Conclusions. **HERMES** can be successfully applied to constrain the properties of the Galactic cosmic-ray population, improve our understanding of the diffuse Galactic radio, gamma-ray, and neutrino emission, and search for signals associated to particle dark matter annihilation or decay.

γ -ray emitting processes

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

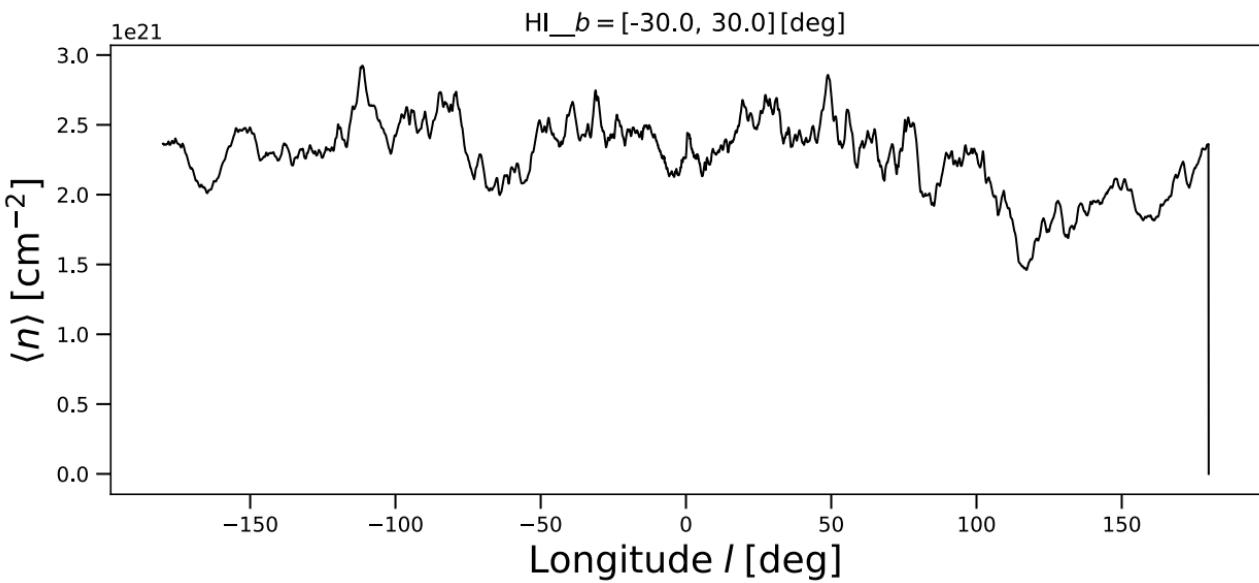
	CR involved	Target	Secondary ID	Secondary E	
Synchrotron	e^\pm	B -field	γ	<i>radio band</i>	$E \lesssim \mathcal{O}(100) \text{ GHz}$
Brems		ISM gas		broadband	
ICS		ISRF		high γ -rays	
$\pi^0 \rightarrow \gamma\gamma$	$p, \text{He, nuclei}$	ISM gas+ decay	ν	high γ -rays	$E > \text{MeV}$
$\pi^\pm \rightarrow \mu_\pm \bar{\nu}_\mu$				high-energy ν	
$\mu^\pm \rightarrow e^\pm \bar{\nu}_\mu \bar{\nu}_e$	sec μ			broadband	$E > \text{GeV}$



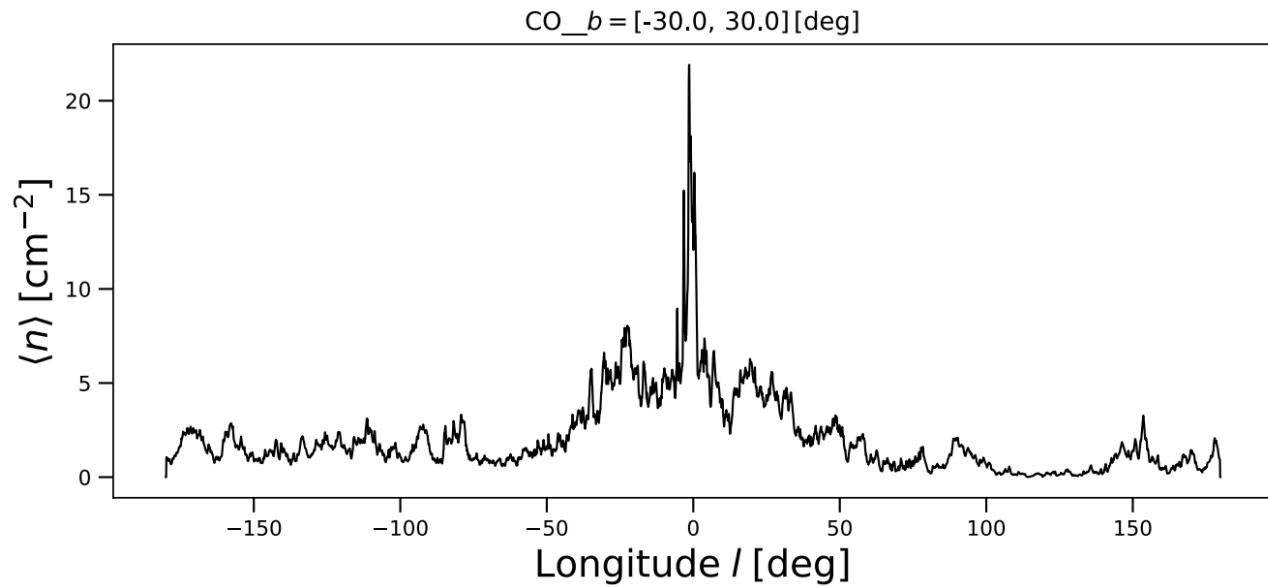


Gas longitudinal profile

Atomic gas

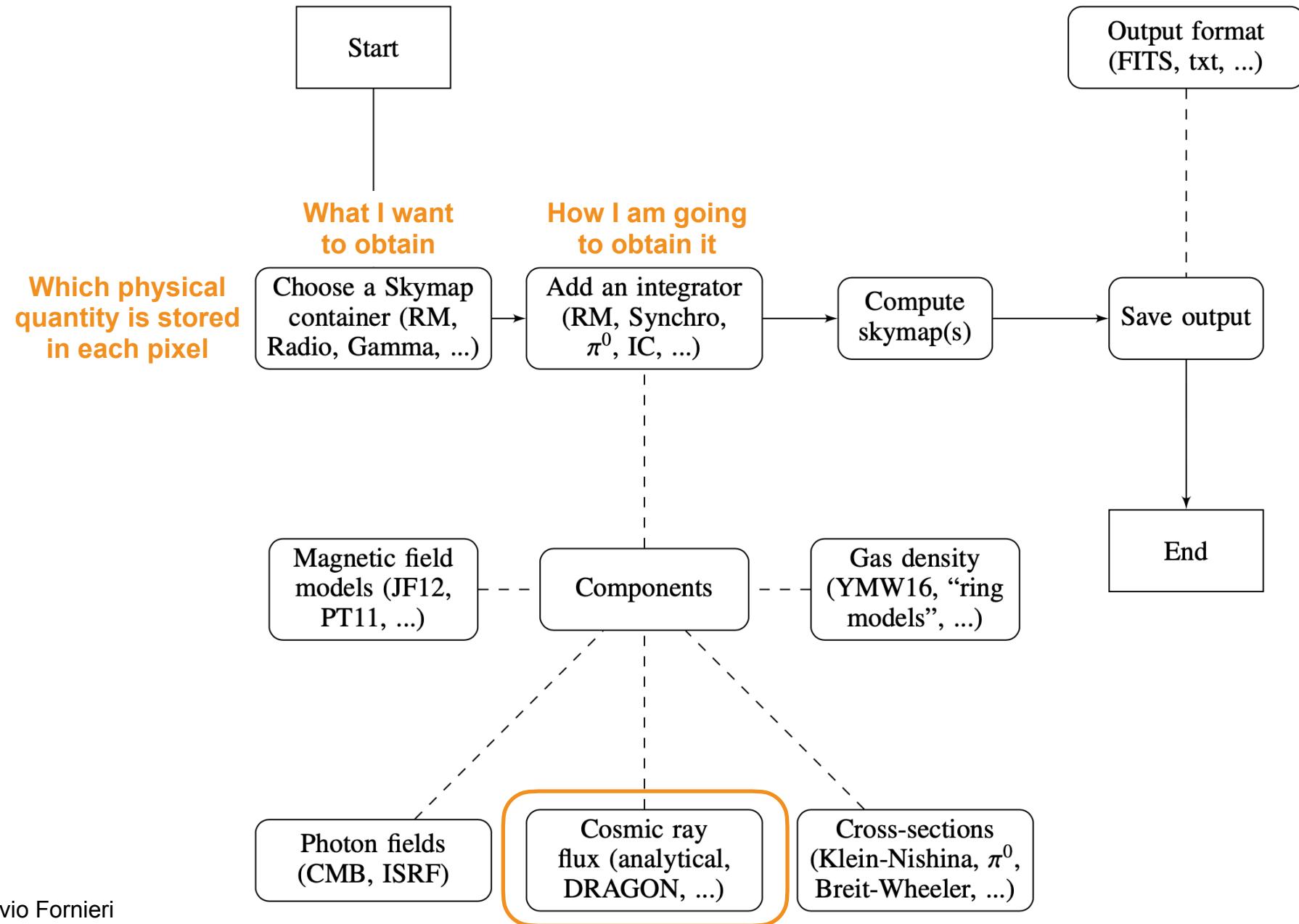


Molecular gas



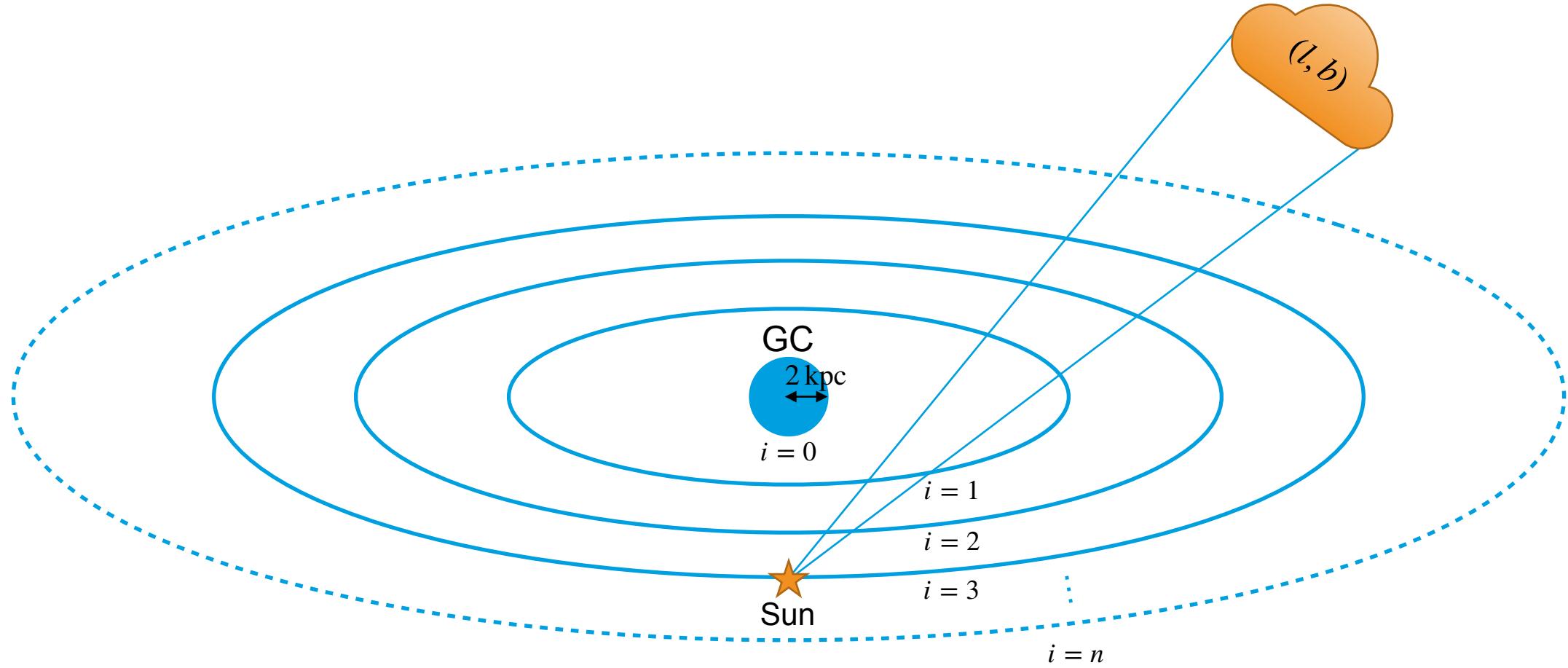
Introduction to γ -rays with HERMES

HERMES work-flow



Ring model

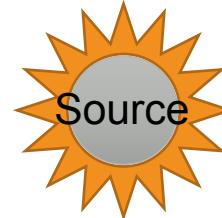
[Strong&Mattox, A&A, 308, L21 (1996)] → based on HI and CO emissivity maps



The observable quantity

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

Emissivity at the source

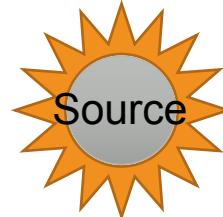


$$\epsilon_{\pi^0}(E_\gamma, \mathbf{r}) = 4\pi n_{\text{H}}(\mathbf{r}) \int dE \left[\frac{d\Phi_{\text{p}}}{dE}(E, \mathbf{r}) \left(\frac{d\sigma_{\text{p-p}}}{dE_\gamma} + f_{\text{He}} \frac{d\sigma_{\text{He-p}}}{dE_\gamma} \right) + \frac{d\Phi_{\text{He}}}{dE}(E, \mathbf{r}) \left(\frac{d\sigma_{\text{p-He}}}{dE_\gamma}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

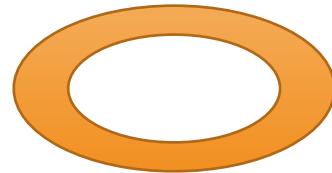
The observable quantity

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Emissivity at the source



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



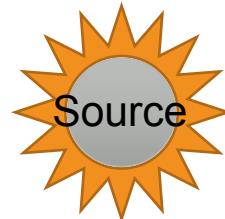
Emissivity averaged over the ring i -th

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

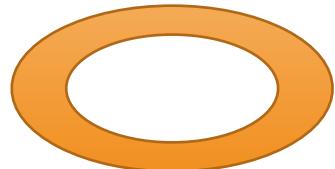
The observable quantity

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

Emissivity at the source



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

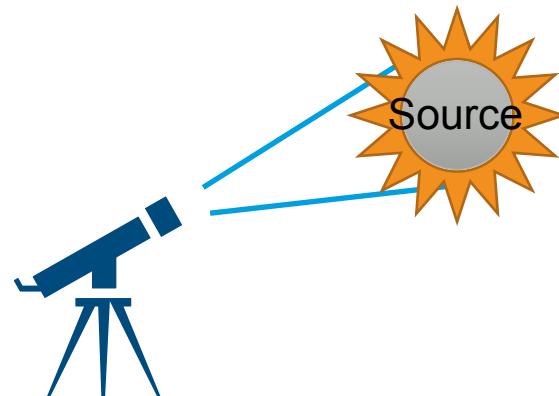


Emissivity averaged over the ring i -th

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

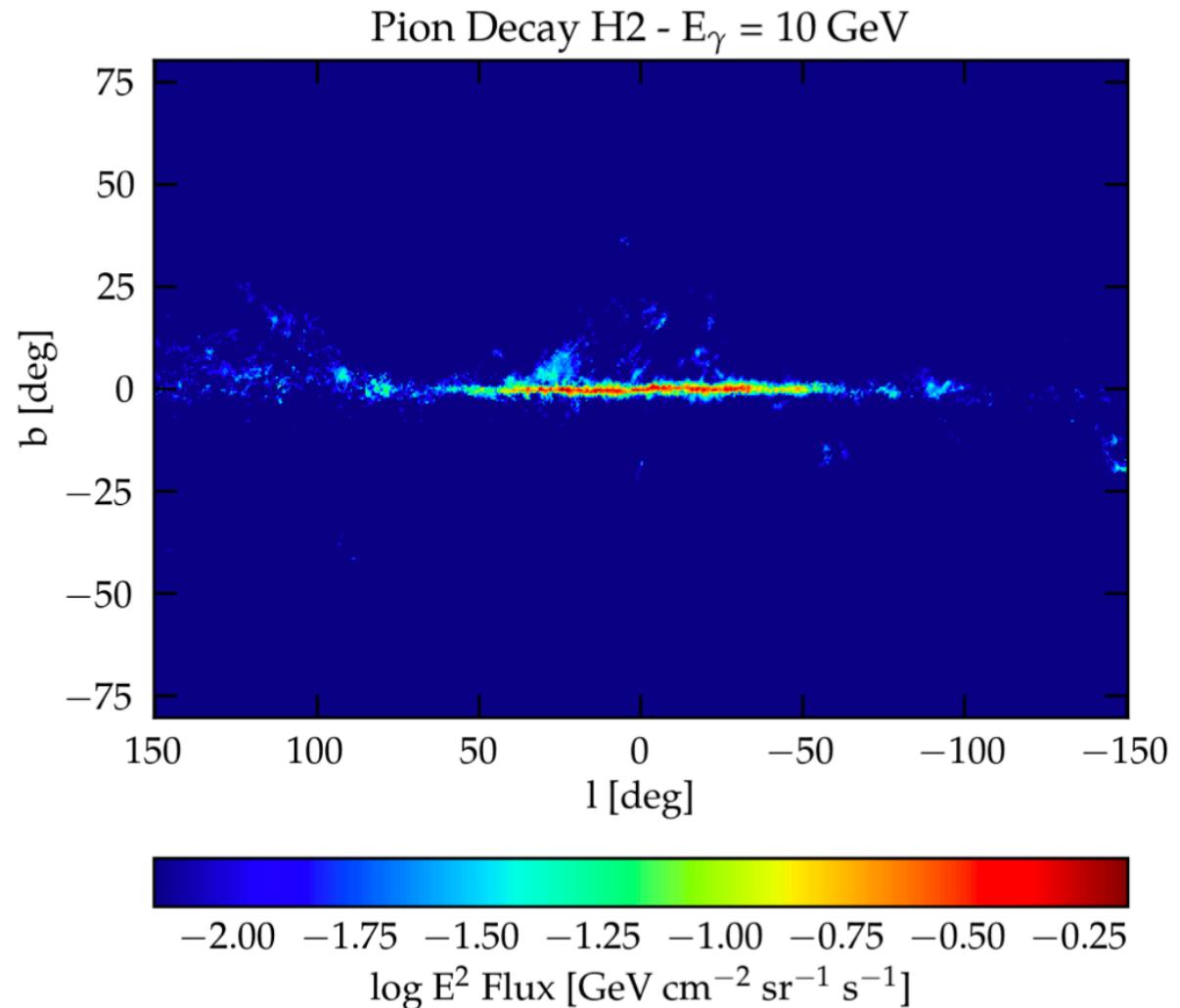
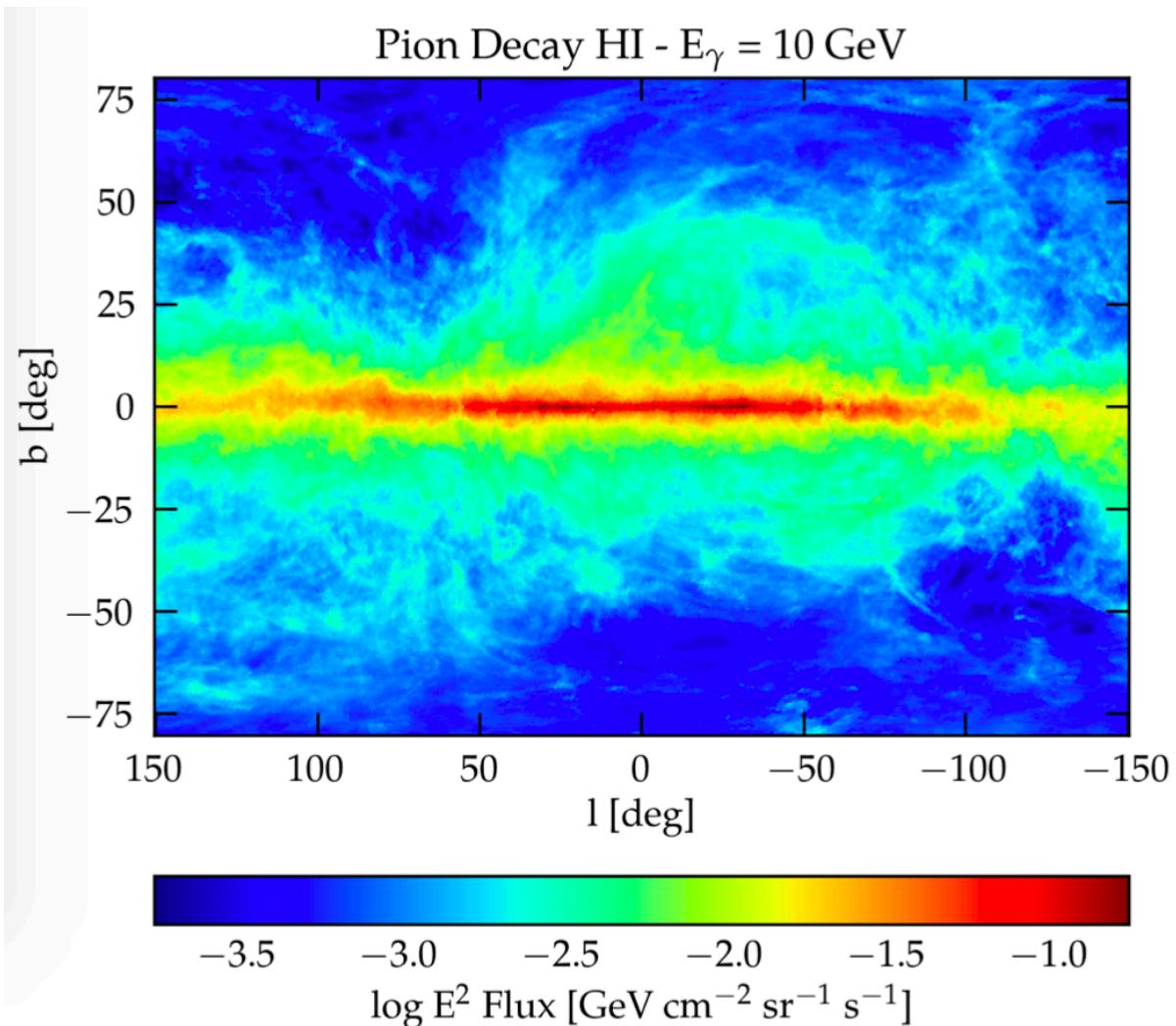
Observed intensity

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



The outcome

π^0 -decay at given energy



Support slides

Run HERMES Full-Sky

nside = 32

$t \sim 58$ min

Resolution parameters

HEALPix convention

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

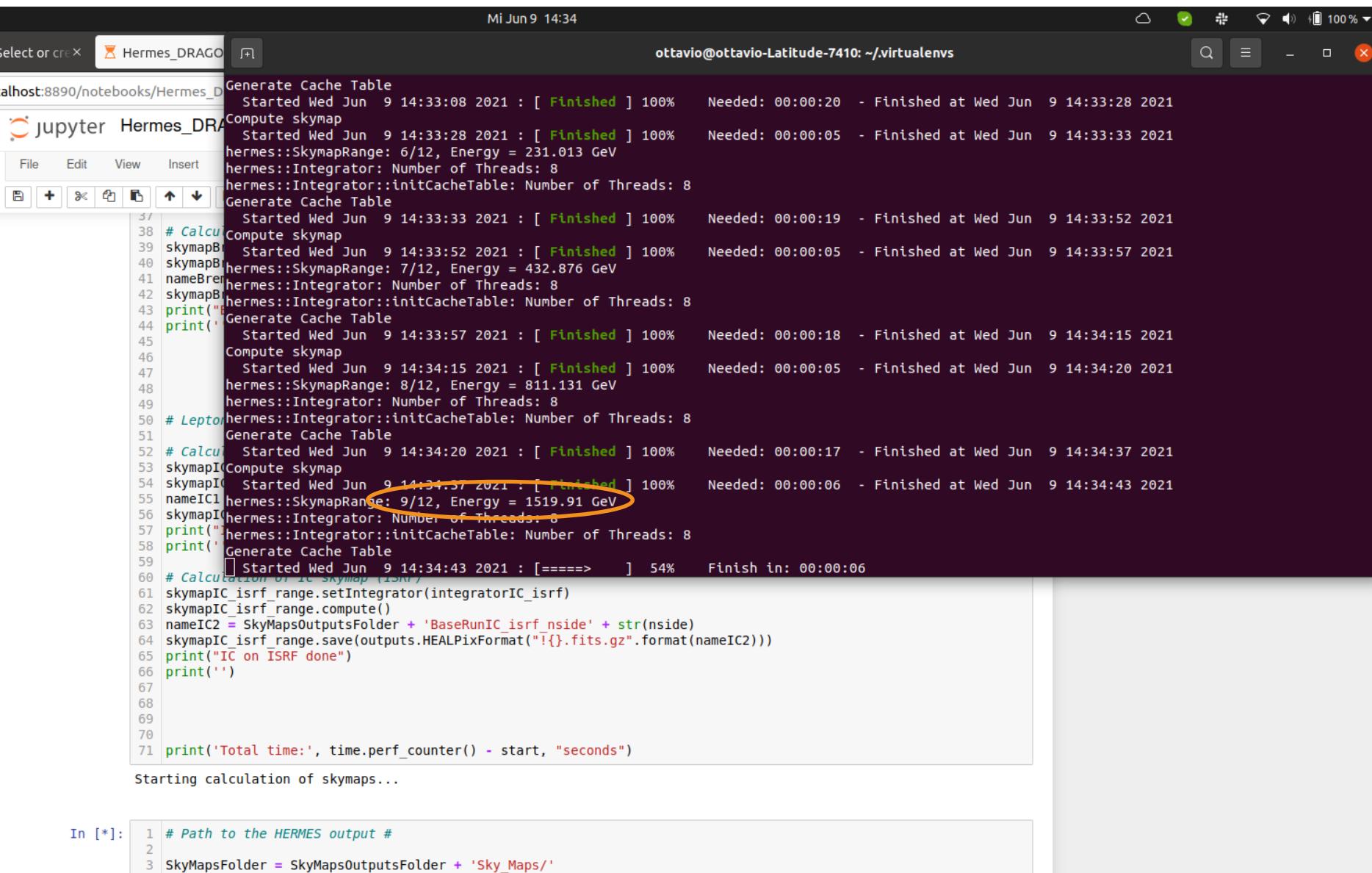
$n_{\text{side}} = 2^{\text{res}}$: The number of pixels per side.

$n_{\text{pix}} = 12 n_{\text{side}}^2$: 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 nside = 32

12 log-spaced energy points for each process



Mi Jun 9 14:34

ottavio@ottavio-Latitude-7410: ~/virtualenvs

```
alhost:8890/notebooks/Hermes_DRAG... Hermes_DRAG... jupyter File Edit View Insert
Generate Cache Table
Started Wed Jun 9 14:33:08 2021 : [ Finished ] 100% Needed: 00:00:20 - Finished at Wed Jun 9 14:33:28 2021
Compute skymap
Started Wed Jun 9 14:33:28 2021 : [ Finished ] 100% Needed: 00:00:05 - Finished at Wed Jun 9 14:33:33 2021
hermes::SkymapRange: 6/12, Energy = 231.013 GeV
hermes::Integrator: Number of Threads: 8
hermes::Integrator::initCacheTable: Number of Threads: 8
Generate Cache Table
Started Wed Jun 9 14:33:33 2021 : [ Finished ] 100% Needed: 00:00:19 - Finished at Wed Jun 9 14:33:52 2021
Compute skymap
skymapB0 Started Wed Jun 9 14:33:52 2021 : [ Finished ] 100% Needed: 00:00:05 - Finished at Wed Jun 9 14:33:57 2021
hermes::SkymapRange: 7/12, Energy = 432.876 GeV
nameB0 hermes::Integrator: Number of Threads: 8
skymapB0 hermes::Integrator::initCacheTable: Number of Threads: 8
print("P")
print("Generate Cache Table")
Started Wed Jun 9 14:33:57 2021 : [ Finished ] 100% Needed: 00:00:18 - Finished at Wed Jun 9 14:34:15 2021
Compute skymap
Started Wed Jun 9 14:34:15 2021 : [ Finished ] 100% Needed: 00:00:05 - Finished at Wed Jun 9 14:34:20 2021
hermes::SkymapRange: 8/12, Energy = 811.131 GeV
hermes::Integrator: Number of Threads: 8
hermes::Integrator::initCacheTable: Number of Threads: 8
# Lepton
Generate Cache Table
# Calculation of IC Skymap (ISRF)
Started Wed Jun 9 14:34:20 2021 : [ Finished ] 100% Needed: 00:00:17 - Finished at Wed Jun 9 14:34:37 2021
skymapIC Compute skymap
skymapIC Started Wed Jun 9 14:34:37 2021 : [ Finished ] 100% Needed: 00:00:06 - Finished at Wed Jun 9 14:34:43 2021
nameIC1 hermes::SkymapRange: 9/12, Energy = 1519.91 GeV
skymapIC hermes::Integrator: Number of Threads: 8
print("H")
hermes::Integrator::initCacheTable: Number of Threads: 8
print("Generate Cache Table")
Started Wed Jun 9 14:34:43 2021 : [ =====> ] 54% Finish in: 00:00:06
# Calculation of IC Skymap (ISRF)
skymapIC_isrf_range.setIntegrator(integratorIC_isrf)
skymapIC_isrf_range.compute()
nameIC2 = SkyMapsOutputsFolder + 'BaseRunIC_isrf_nside' + str(nside)
skymapIC_isrf_range.save(outputs.HEALPixFormat("!{}.fits.gz".format(nameIC2)))
print("IC on ISRF done")
print('')

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

Starting calculation of skymaps...

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

Progress of a full-sky run with nside = 32

12 log-spaced energy points for each process

```
Mi Jun 9 14:36
ottavio@ottavio-Latitude-7410: ~/virtualenvs
Select or cre X Hermes_DRAGO
File Edit View Insert
jupyter Hermes_DRAGO
Generate Cache Table
Started Wed Jun 9 14:34:43 2021 : [ Finished ] 100% Needed: 00:00:15 - Finished at Wed Jun 9 14:34:58 2021
Compute skymap
Started Wed Jun 9 14:34:58 2021 : [ Finished ] 100% Needed: 00:00:06 - Finished at Wed Jun 9 14:35:04 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 14:35:04 2021 : [ Finished ] 100% Needed: 00:00:13 - Finished at Wed Jun 9 14:35:17 2021
Compute skymap
skymapB Started Wed Jun 9 14:35:17 2021 : [ Finished ] 100% Needed: 00:00:06 - Finished at Wed Jun 9 14:35:23 2021
hermes::SkymapRange: 11/12, Energy = 5336.7 GeV
nameBren hermes::Integrator: Number of Threads: 8
skymapB hermes::Integrator::initCacheTable: Number of Threads: 8
print("Generate Cache Table
print("Started Wed Jun 9 14:35:23 2021 : [ Finished ] 100% Needed: 00:00:12 - Finished at Wed Jun 9 14:35:35 2021
Compute skymap
Started Wed Jun 9 14:35:35 2021 : [ Finished ] 100% Needed: 00:00:06 - Finished at Wed Jun 9 14:35:41 2021
hermes::SkymapRange: 12/12, Energy = 10000 GeV
hermes::Integrator: Number of Threads: 8
hermes::Integrator::initCacheTable: Number of Threads: 8
# Lepton
Generate Cache Table
# Calculating the Skymap (lon)
Started Wed Jun 9 14:35:41 2021 : [ Finished ] 100% Needed: 00:00:11 - Finished at Wed Jun 9 14:35:52 2021
skymapI Compute skymap
skymapI Started Wed Jun 9 14:35:52 2021 : [ Finished ] 100% Needed: 00:00:05 - Finished at Wed Jun 9 14:35:57 2021
nameIC1 hermes::SkymapRange: 1/12, Energy = 10 GeV
skymapI hermes::Integrator: Number of Threads: 8
print("hermes::Integrator::initCacheTable: Number of Threads: 8
print("Generate Cache Table
Started Wed Jun 9 14:35:57 2021 : [=====>      ] 54% Finish in: 00:00:10
# Calculation of the Skymap (lon)
skymapIC_isrf_range.setIntegrator(integratorIC_isrf)
skymapIC_isrf_range.compute()
nameIC2 = SkyMapsOutputsFolder + 'BaseRunIC_isrf_nside' + str(nside)
skymapIC_isrf_range.save(outputs.HEALPixFormat("!.fits.gz".format(nameIC2)))
print("IC on ISRF done")
print('')
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 nside = 32

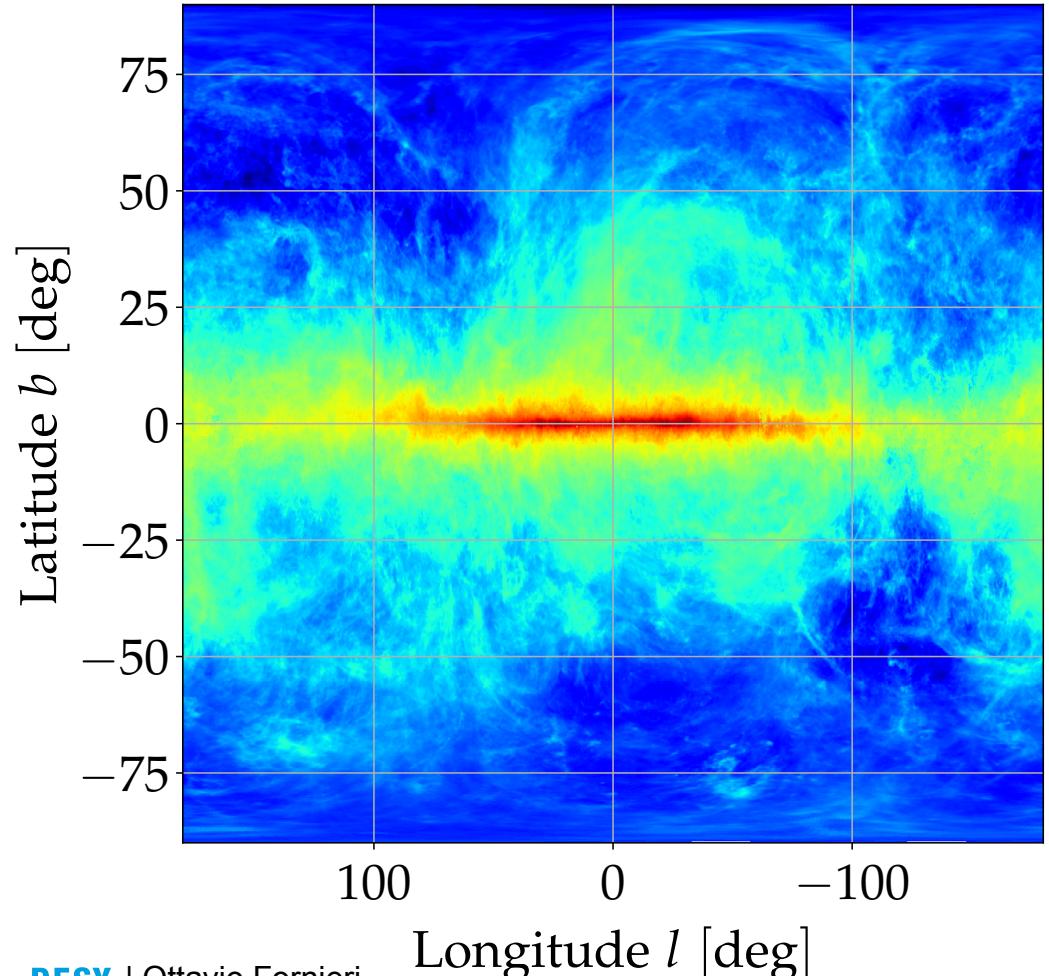
12 log-spaced energy points for each process

```
Mi Jun 9 15:29
ottavio@ottavio-Latitude-7410: ~/virtualenvs
jupyter Hermes_DRAG
Select or cr X
File Edit View Insert
Compute skymap
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
# Lepton
    Started Wed Jun 9 15:21:02 2021 : [ Finished ] 100%    Needed: 00:00:00 - Finished at Wed Jun 9 15:21:02 2021
hermes::SkymapRange: 11/12, Energy = 5336.7 GeV
hermes::Integrator: Number of Threads: 8
skymapI
hermes::Integrator::initCacheTable: Number of Threads: 8
skymapi
Generate 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
skymapi
Compute skymap
print(")
    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
# Calculations
hermes::Integrator::initCacheTable: Number of Threads: 8
skymapi
Generate Cache Table
nameIC2
    Started Wed Jun 9 15:23:11 2021 : [ Finished ] 100%    Needed: 00:01:54 - Finished at Wed Jun 9 15:25:05 2021
skymapi
Compute skymap
print(")
    Started Wed Jun 9 15:25:05 2021 : [ Finished ] 100%    Needed: 00:00:01 - Finished at Wed Jun 9 15:25:06 2021
print('[I 15:26:25.740 NotebookApp] Saving file at /Hermes_DRAGON_Ottavio_FullSky.ipynb
71 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

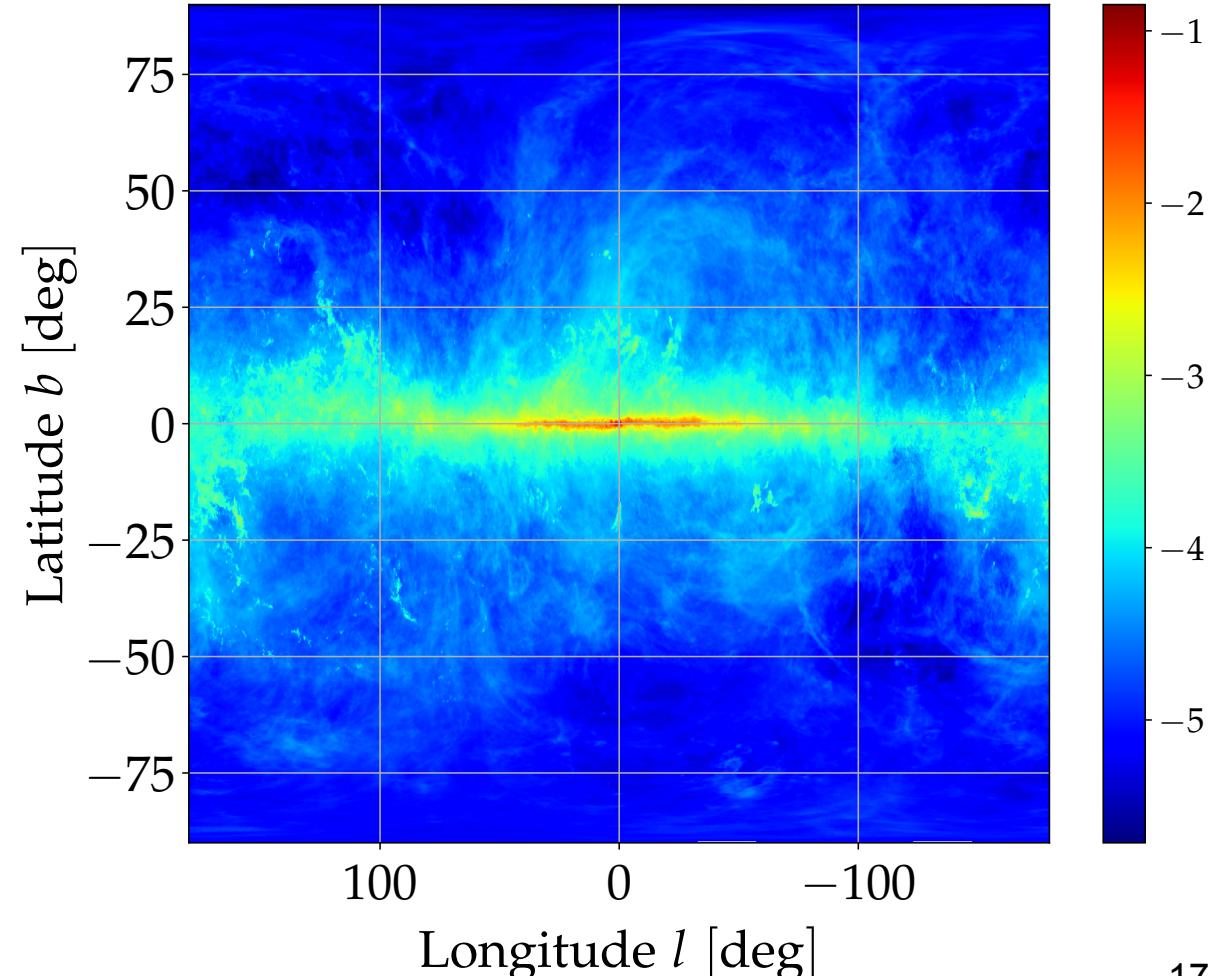
Paper plot: π^0 on HI

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



π^0 on $HI + H_2$

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

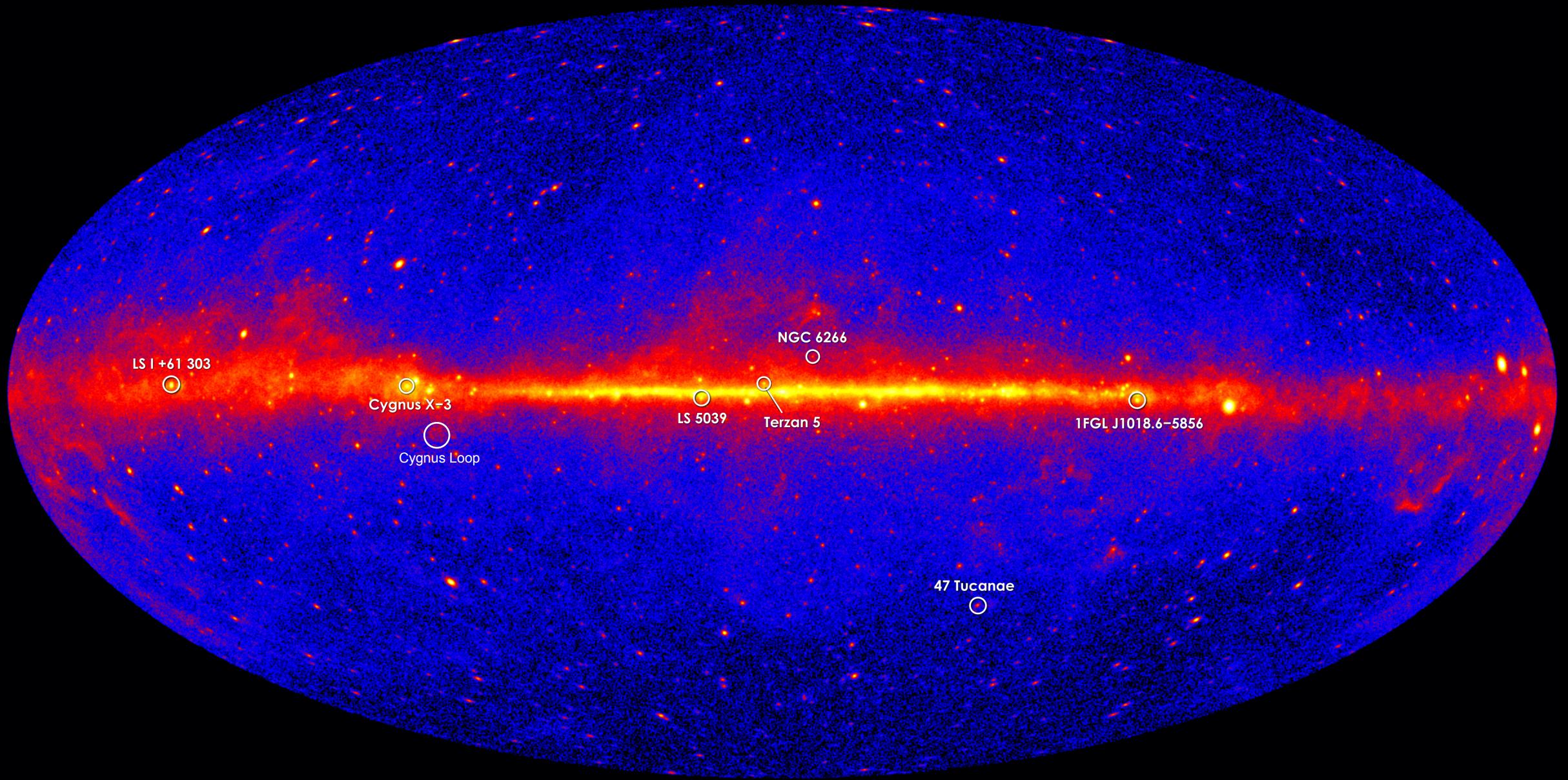


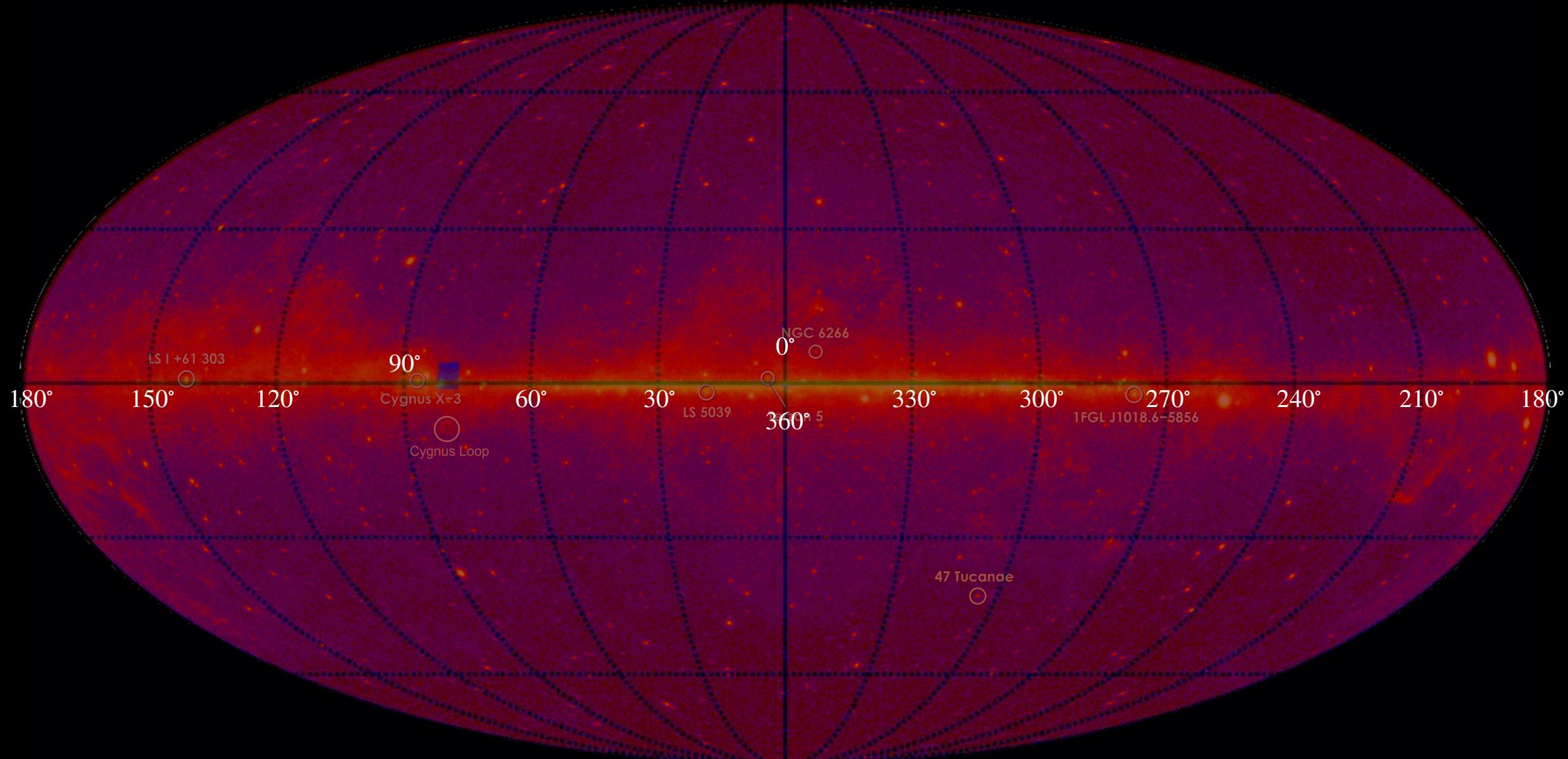
Runs HERMES Cygnus-X region

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

nside = 512, 1024, 2048

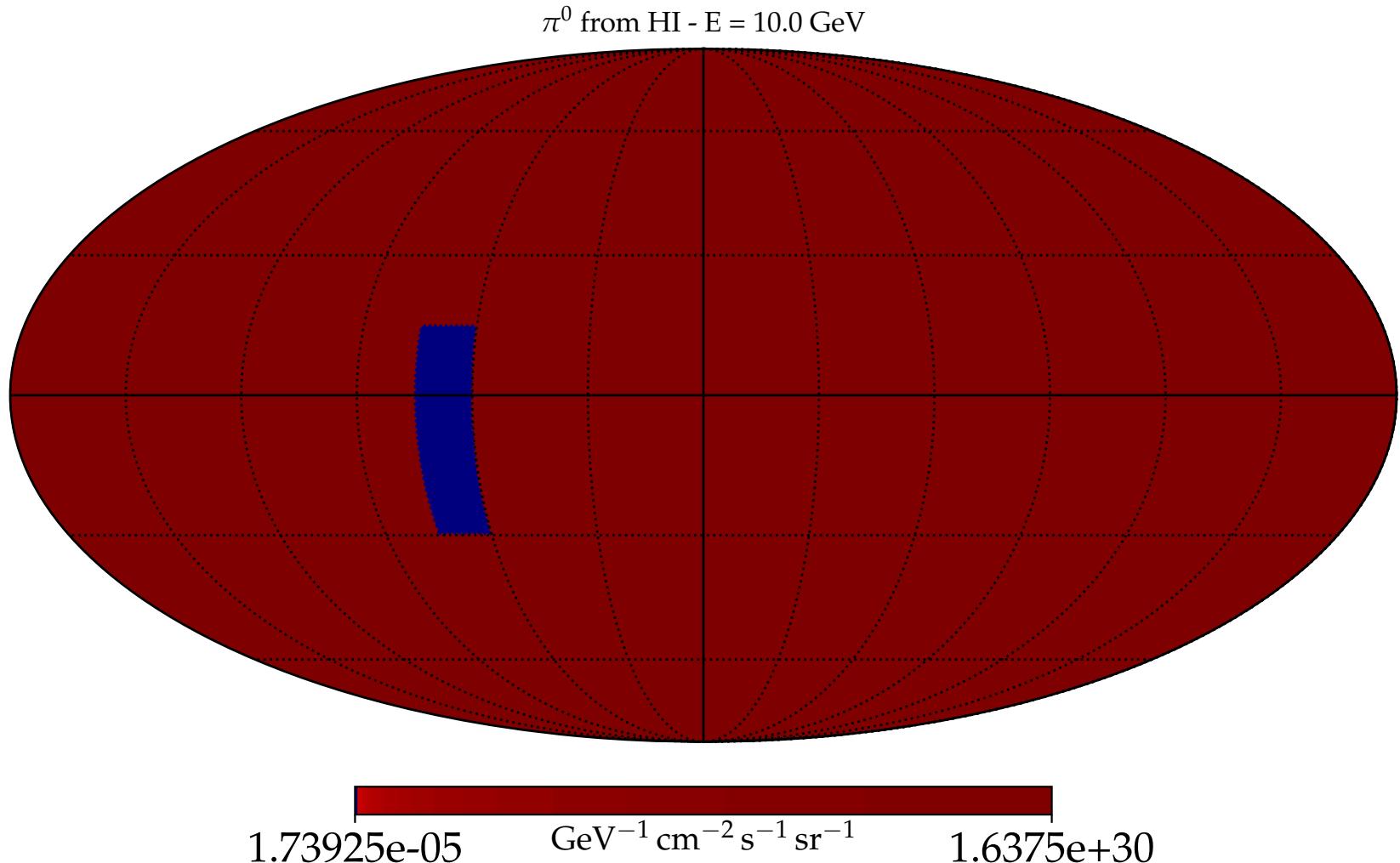
$t \lesssim 30$ min





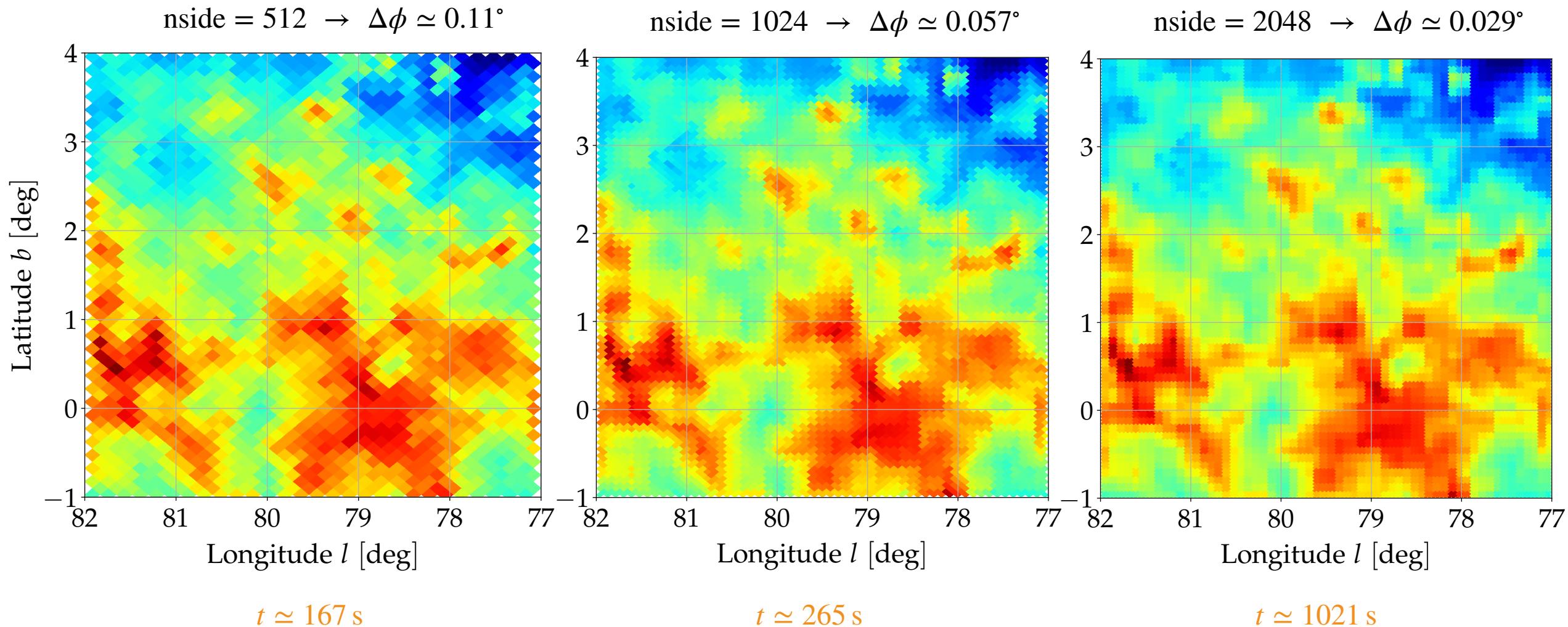
Rectangular mask: cross-check

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



Diffuse emission from DRAGON CR distribution

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



Integral map for HI and H_2

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

