

# Hands-on Session

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

ISAPP School **MAD<sup>( $\gamma$ )</sup>** 2021

Gamma rays to shed light on Dark Matter

29, June 2021

Ottavio Fornieri  
[ottavio.fornieri@desy.de](mailto:ottavio.fornieri@desy.de)



# Simulating the Galactic Multi-messenger Emissions with HERMES

A. Dundovic<sup>1,2</sup>, C. Evoli<sup>1,2</sup>, D. Gaggero<sup>3,4</sup>, and D. Grasso<sup>5</sup>

<sup>1</sup> Gran Sasso Science Institute, Viale Francesco Crispi 7, I-67100 L’Aquila, Italy

<sup>2</sup> INFN Laboratori Nazionali del Gran Sasso (LNGS), I-67100 Assergi, L’Aquila, Italy

<sup>3</sup> Instituto de Física Teórica UAM-CSIC, Campus de Cantoblanco, E-28049 Madrid, Spain

<sup>4</sup> INFN Sezione di Pisa, Polo Fibonacci, Largo B. Pontecorvo 3, I-56127 Pisa, Italy

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.

# $\gamma$ -ray emitting processes

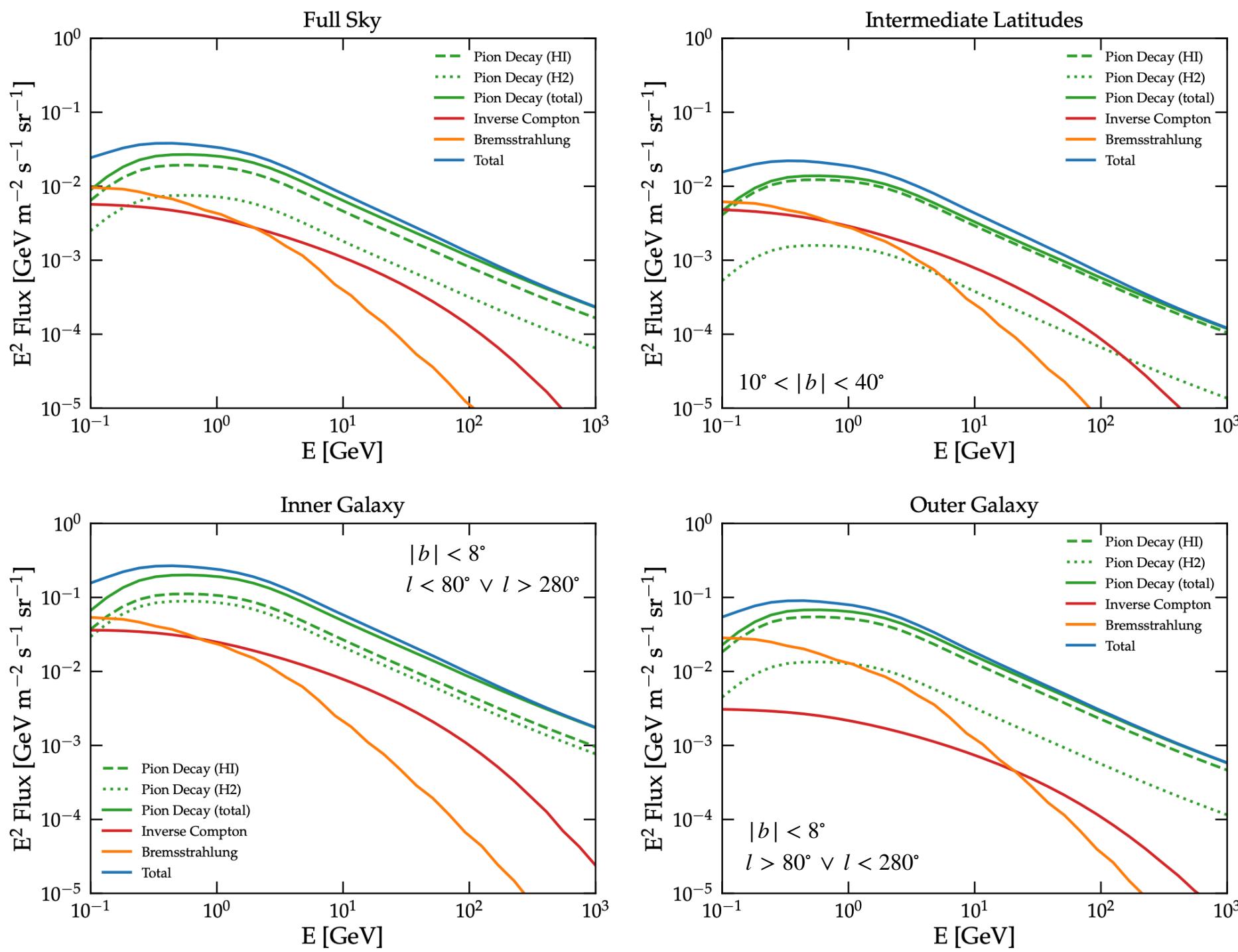
Resulting energy bands [<https://heasarc.gsfc.nasa.gov/docs/heasarc/headates/spectrum.html>]

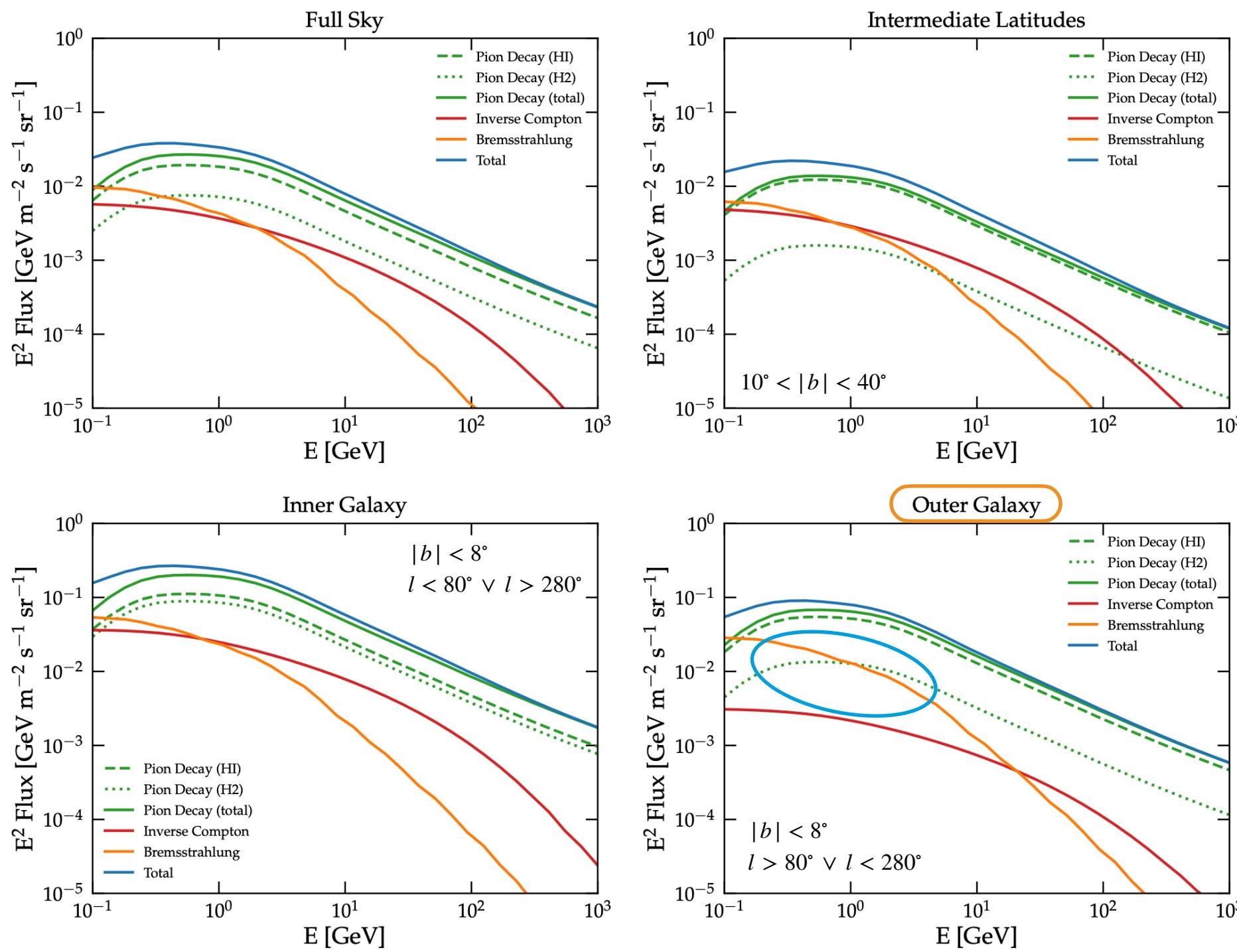
	CR involved	Target	Secondary ID	Secondary $E$
Synchrotron	$e^\pm$	<i>B</i> -field	$\gamma$	<i>radio band</i>
Brems		ISM gas		broadband
ICS		ISRF		high $\gamma$ -rays
$\pi^0 \rightarrow \gamma\gamma$	$p, \text{He, nuclei}$	ISM gas+ decay	$\nu$	high $\gamma$ -rays
$\pi^\pm \rightarrow \mu_\pm \bar{\nu}_\mu$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

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

$E > \text{MeV}$

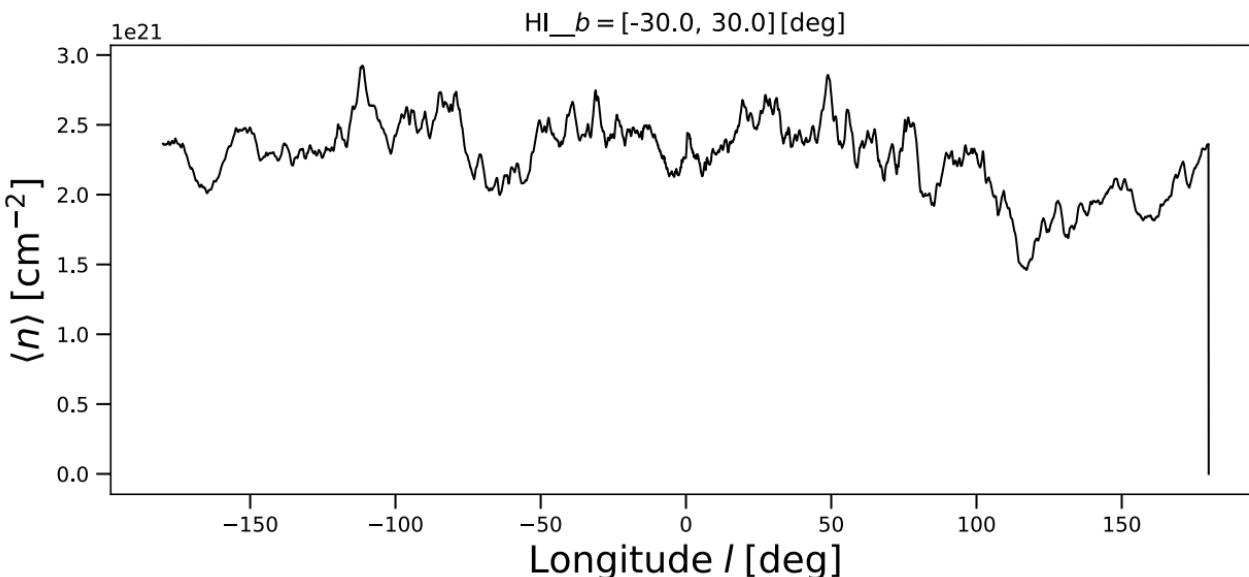
$E > \text{GeV}$



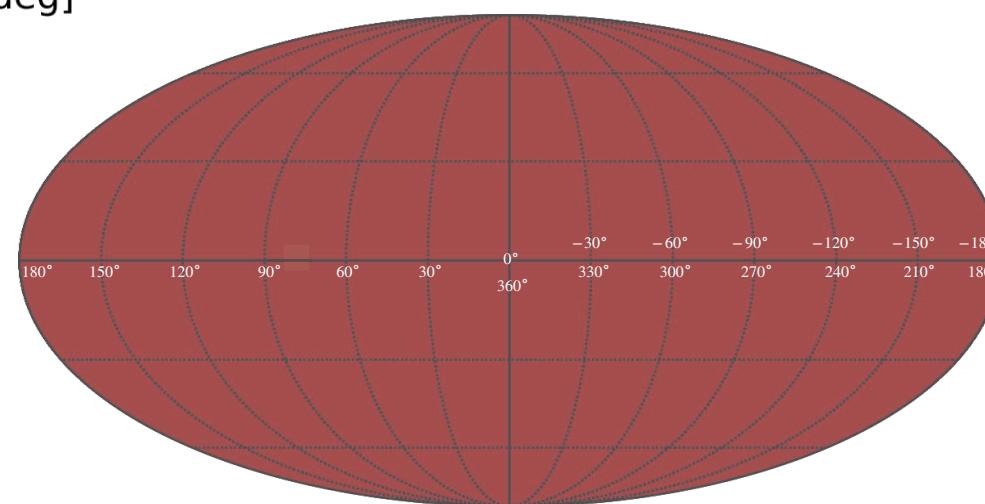
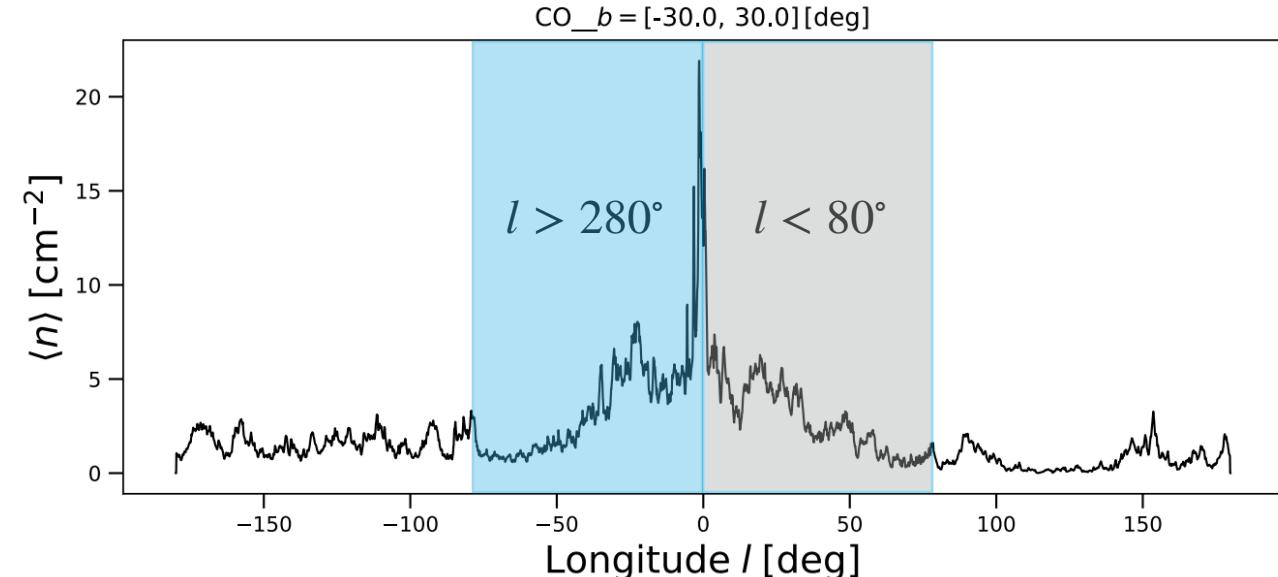


# Gas longitudinal profile

Atomic gas

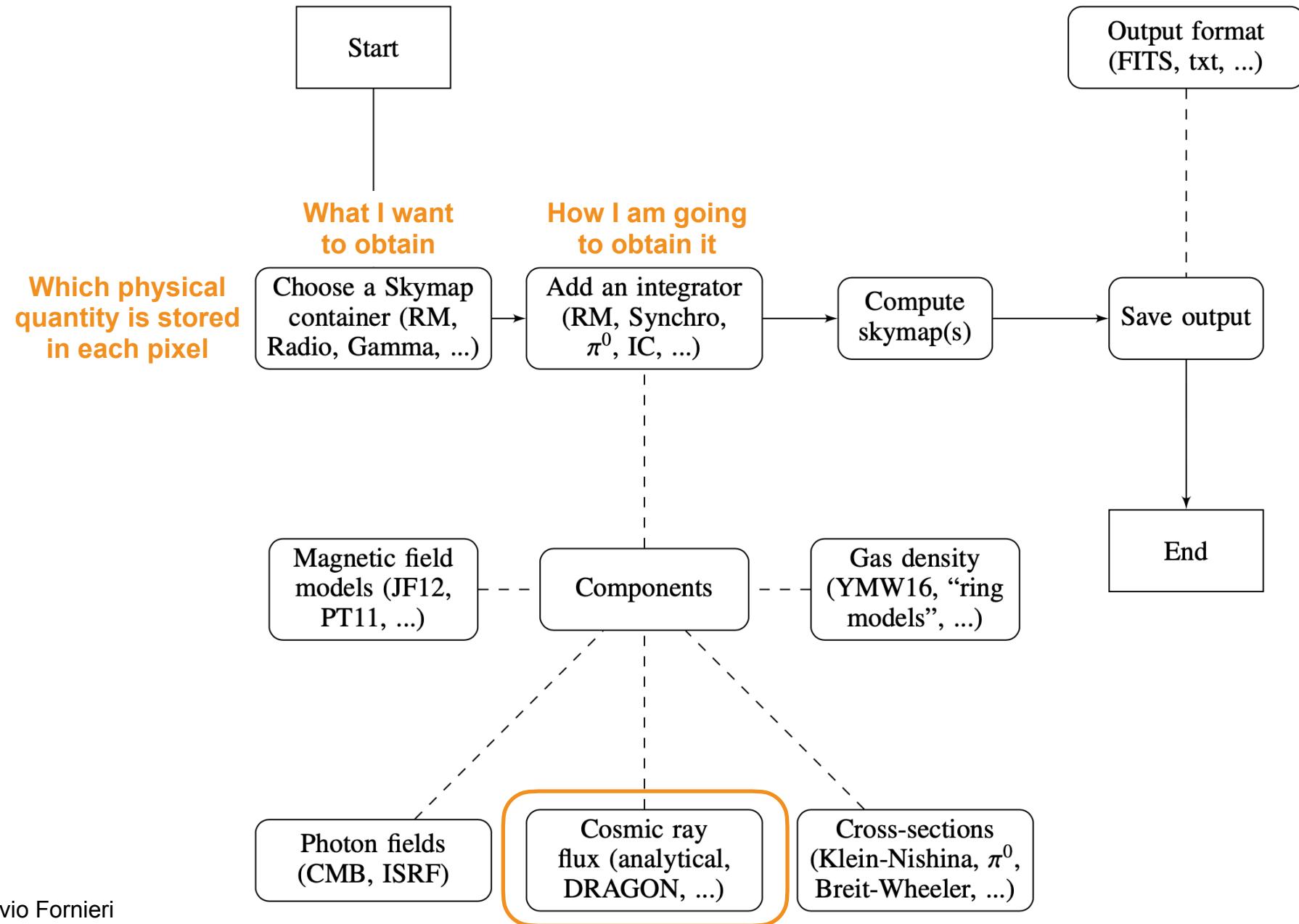


Molecular gas



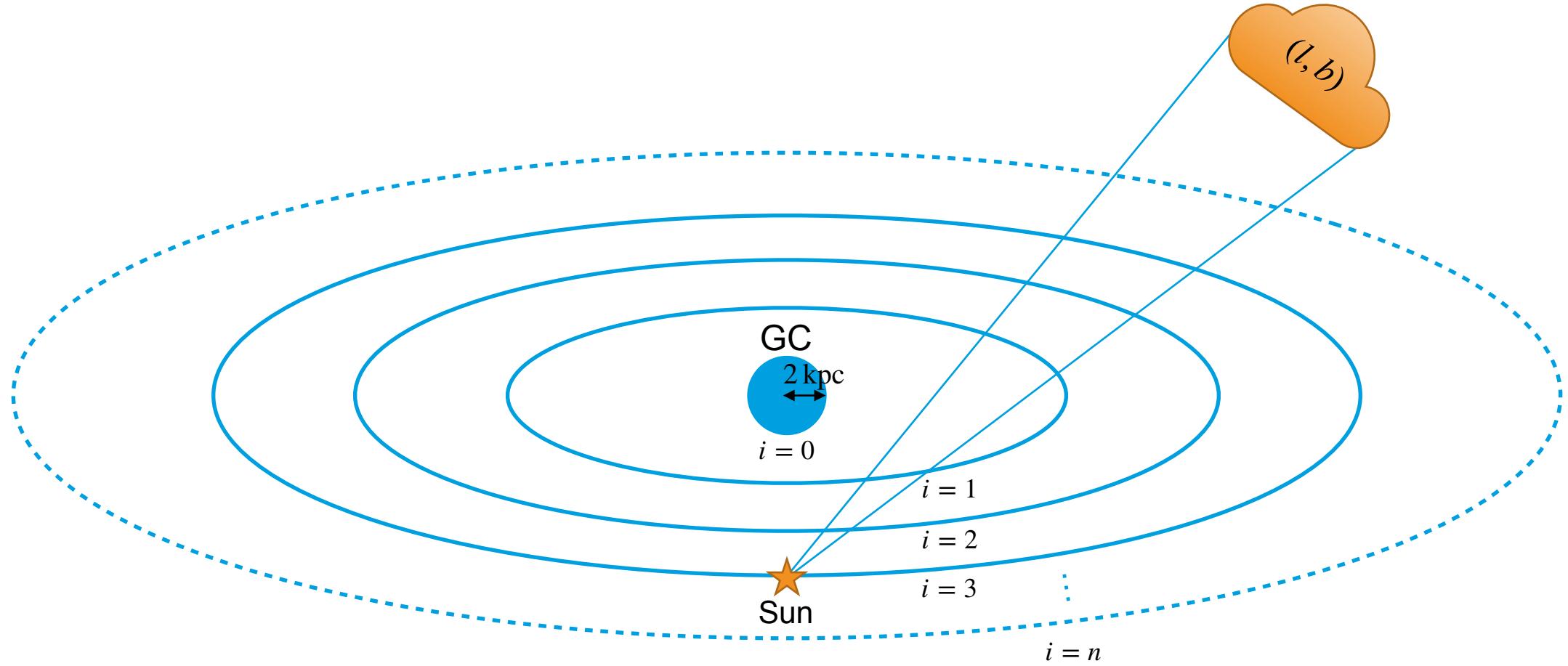
# **Introduction to $\gamma$ -rays with HERMES**

# HERMES work-flow



# Ring model

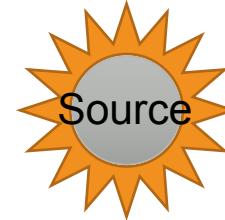
[Strong&Mattox, A&A, 308, L21 (1996)] → based on HI and CO emissivity maps



# The observable quantity

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

Emissivity at the source

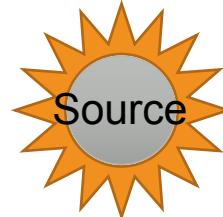


$$\epsilon_{\pi^0}(E_\gamma, \mathbf{r}) = 4\pi n_{\text{H}}(\mathbf{r}) \int dE \left[ \frac{d\Phi_{\text{p}}}{dE}(E, \mathbf{r}) \left( \frac{d\sigma_{\text{p-p}}}{dE_\gamma} + f_{\text{He}} \frac{d\sigma_{\text{He-p}}}{dE_\gamma} \right) + \frac{d\Phi_{\text{He}}}{dE}(E, \mathbf{r}) \left( \frac{d\sigma_{\text{p-He}}}{dE_\gamma}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

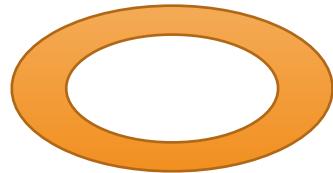
# The observable quantity

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

Emissivity at the source



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



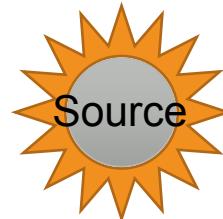
Emissivity averaged over the ring  $i$ -th

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

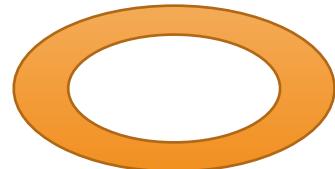
# The observable quantity

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

Emissivity at the source



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

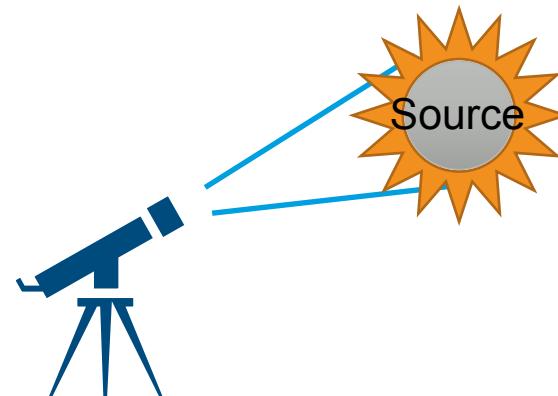


Emissivity averaged over the ring  $i$ -th

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

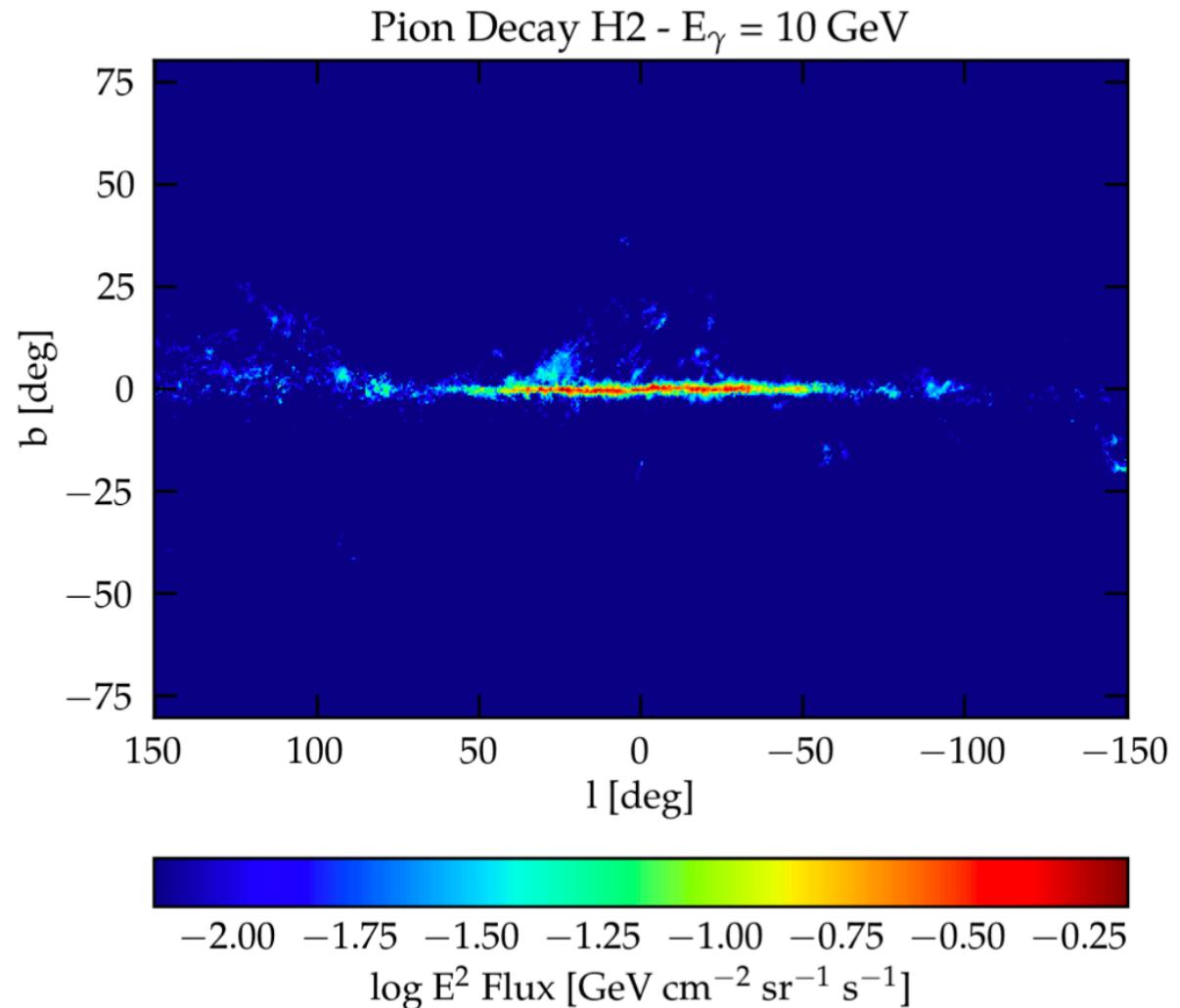
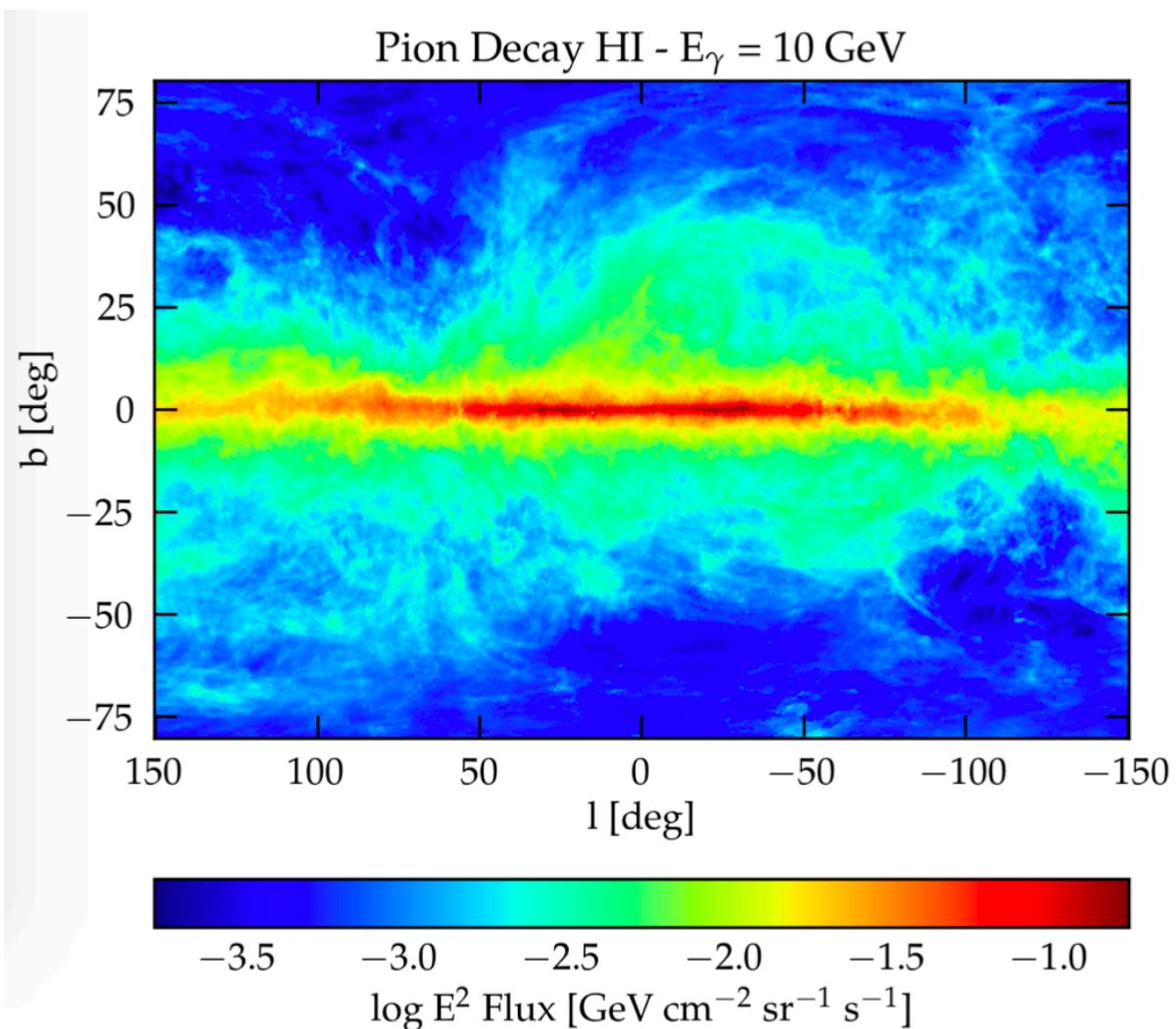
Observed intensity

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



# The outcome

$\pi^0$ -decay at given energy



# Support slides

## Run HERMES Full-Sky

[https://github.com/ottaviofornieri/ISAPP-school-2021\\_HandsOn-Diffuse\\_HERMES](https://github.com/ottaviofornieri/ISAPP-school-2021_HandsOn-Diffuse_HERMES)

nside = 32

$t \sim 58$  min

# Resolution parameters

## HEALPix convention

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

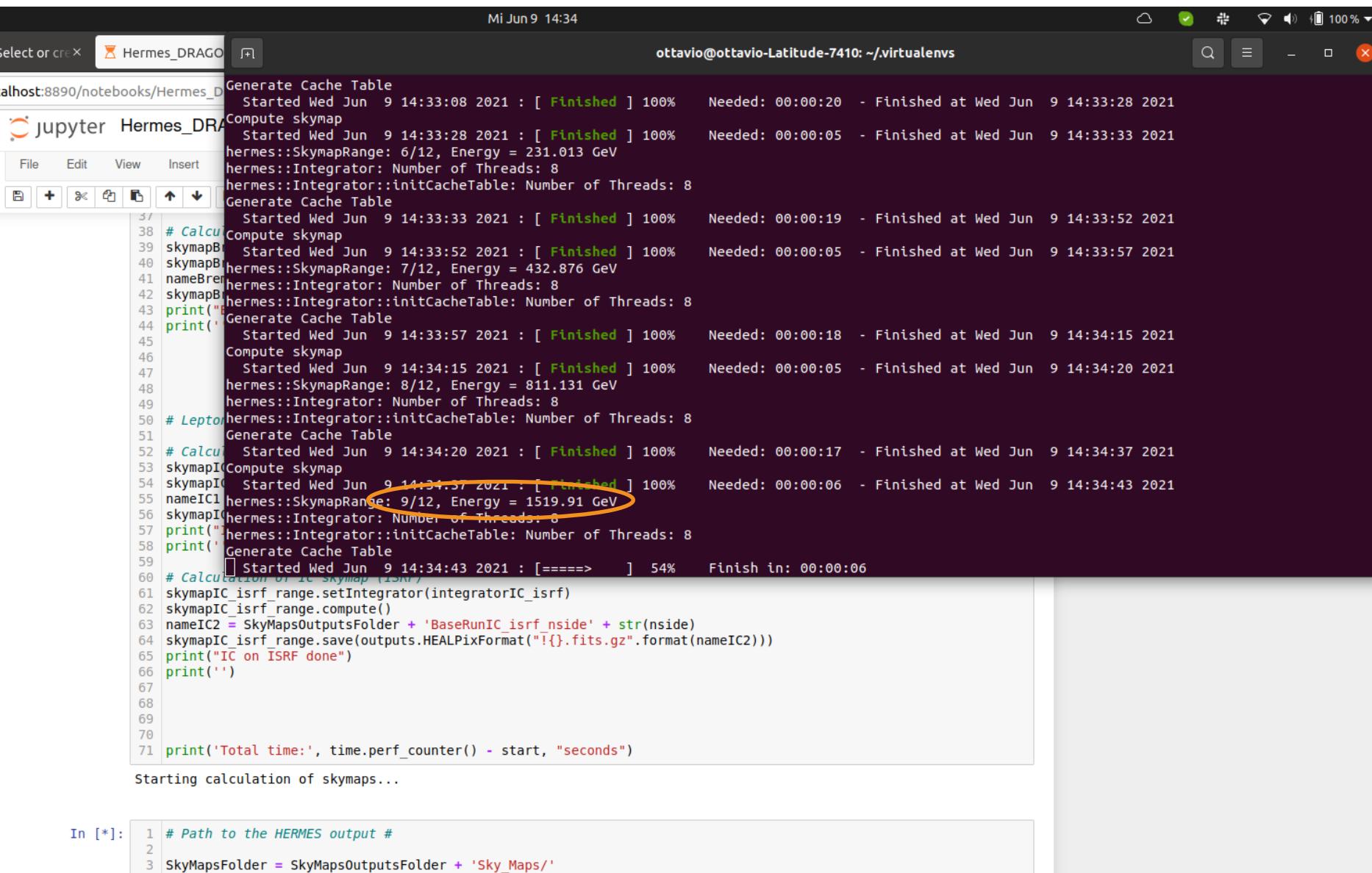
$n_{\text{side}} = 2^{\text{res}}$  : The number of pixels per side.

$n_{\text{pix}} = 12 n_{\text{side}}^2$  : 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_DRAG0
jupyter Hermes_DRAG0
File Edit View Insert
[ 37 ] 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
# Calculating 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("Generating Cache Table")
print("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
# Lepton
hermes::Integrator::initCacheTable: Number of Threads: 8
Generate Cache Table
# Calculating IC Skymap (ISRF)
skymapIC0
      Started Wed Jun 9 14:34:20 2021 : [ Finished ] 100%    Needed: 00:00:17 - Finished at Wed Jun 9 14:34:37 2021
skymapIC0
      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
skymapIC0
hermes::Integrator: Number of Threads: 8
print("Hermes::Integrator::initCacheTable: Number of Threads: 8")
print("Generating 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/'
```

# Progress of a full-sky run with nside = 32

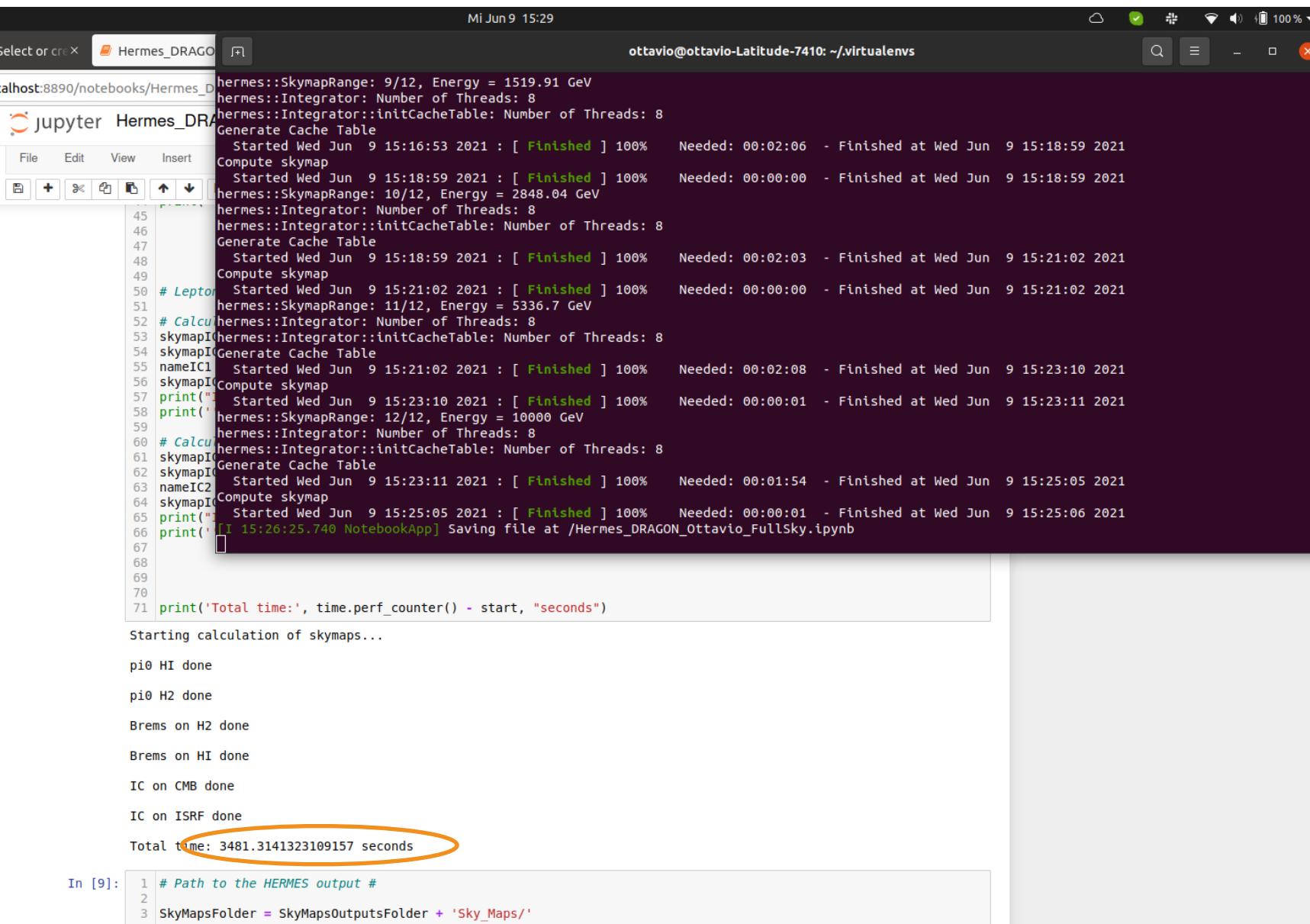
12 log-spaced energy points for each process

```
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

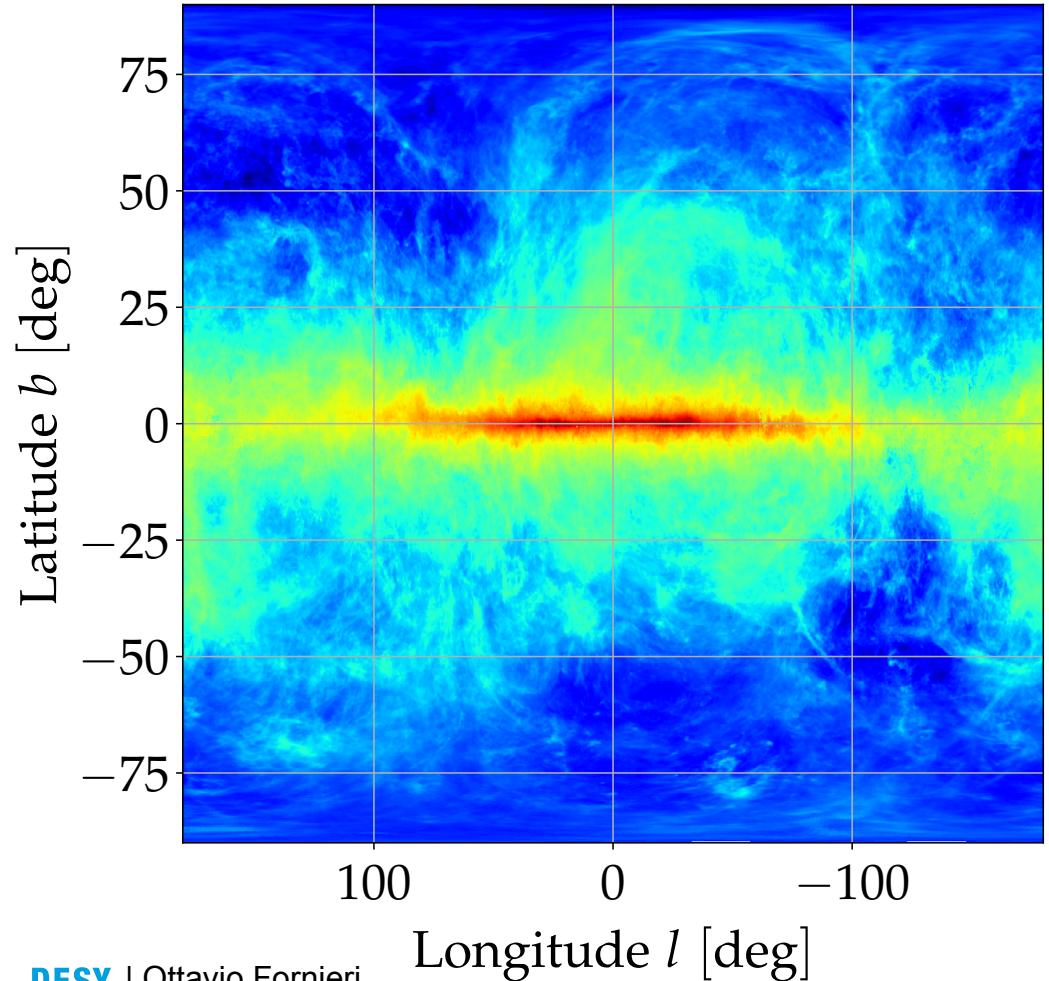


```
Mi Jun 9 15:29
ottavio@ottavio-Latitude-7410: ~/virtualenvs
jupyter Hermes_DRAG
Select or cr X
File Edit View Insert
Compute skymap
hermes::SkymapRange: 9/12, Energy = 1519.91 GeV
hermes::Integrator: Number of Threads: 8
hermes::Integrator::initCacheTable: Number of Threads: 8
Generate Cache Table
    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
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

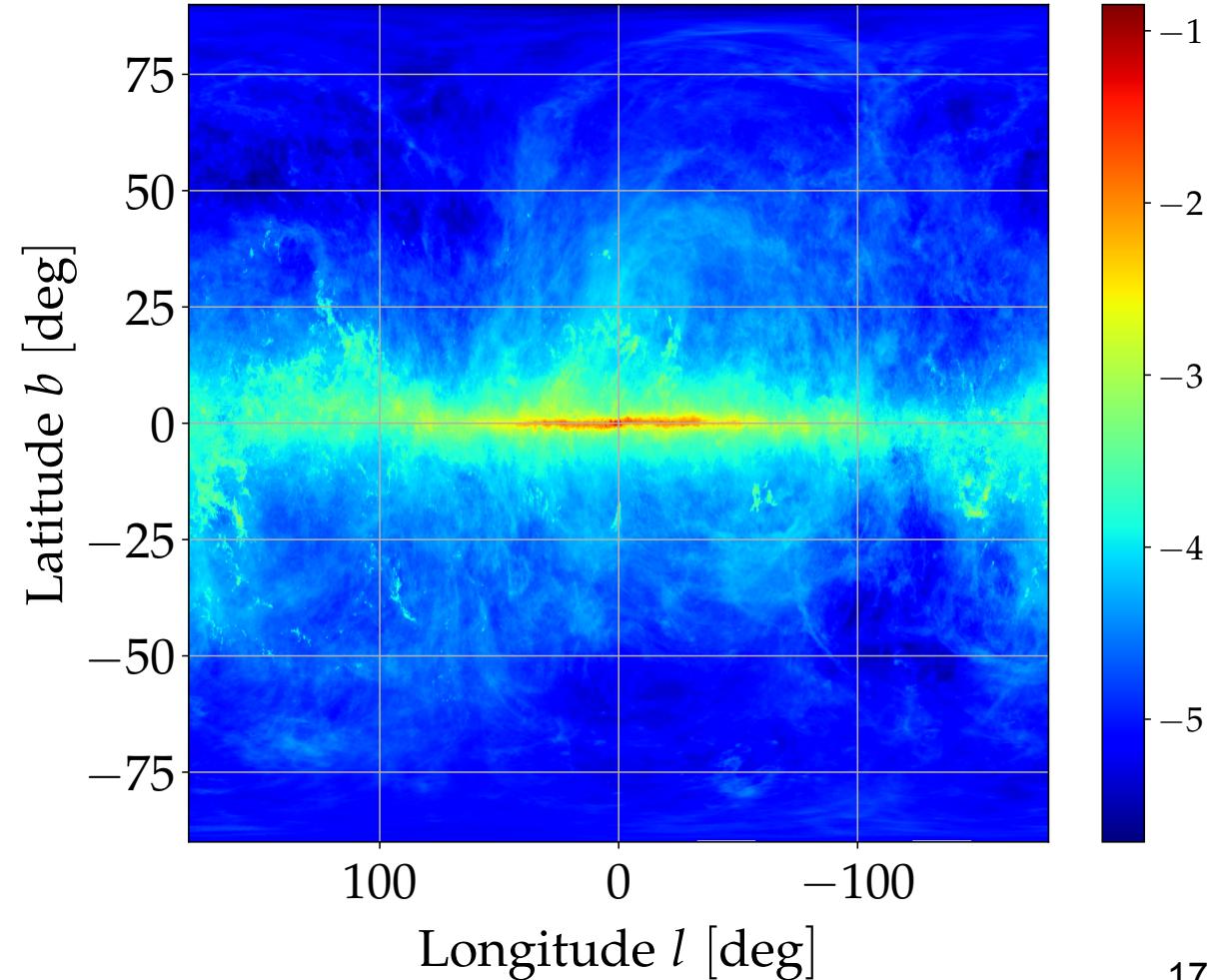
Paper plot:  $\pi^0$  on  $HI$

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



$\pi^0$  on  $HI + H_2$

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



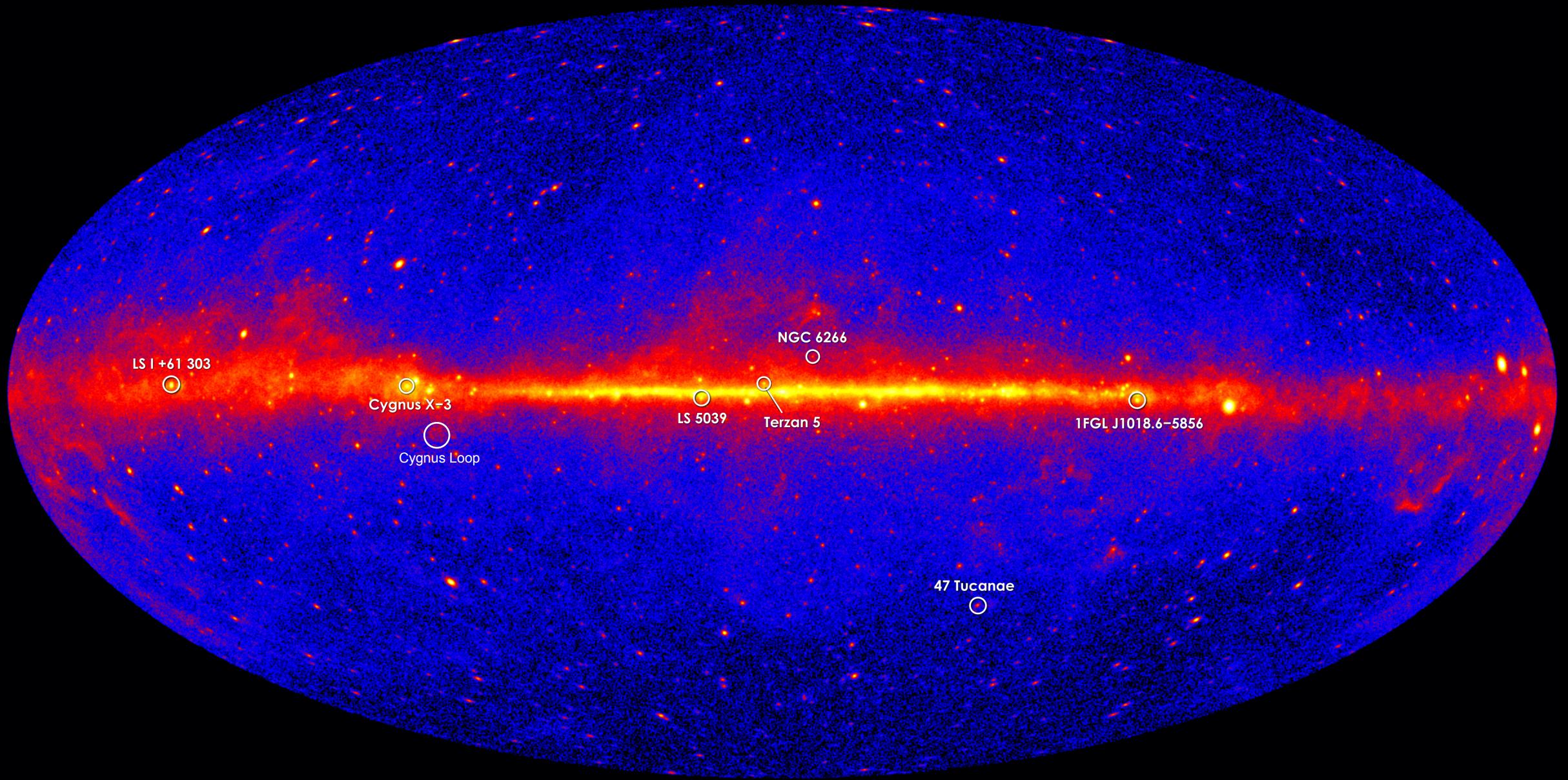
## Runs HERMES Cygnus-X region

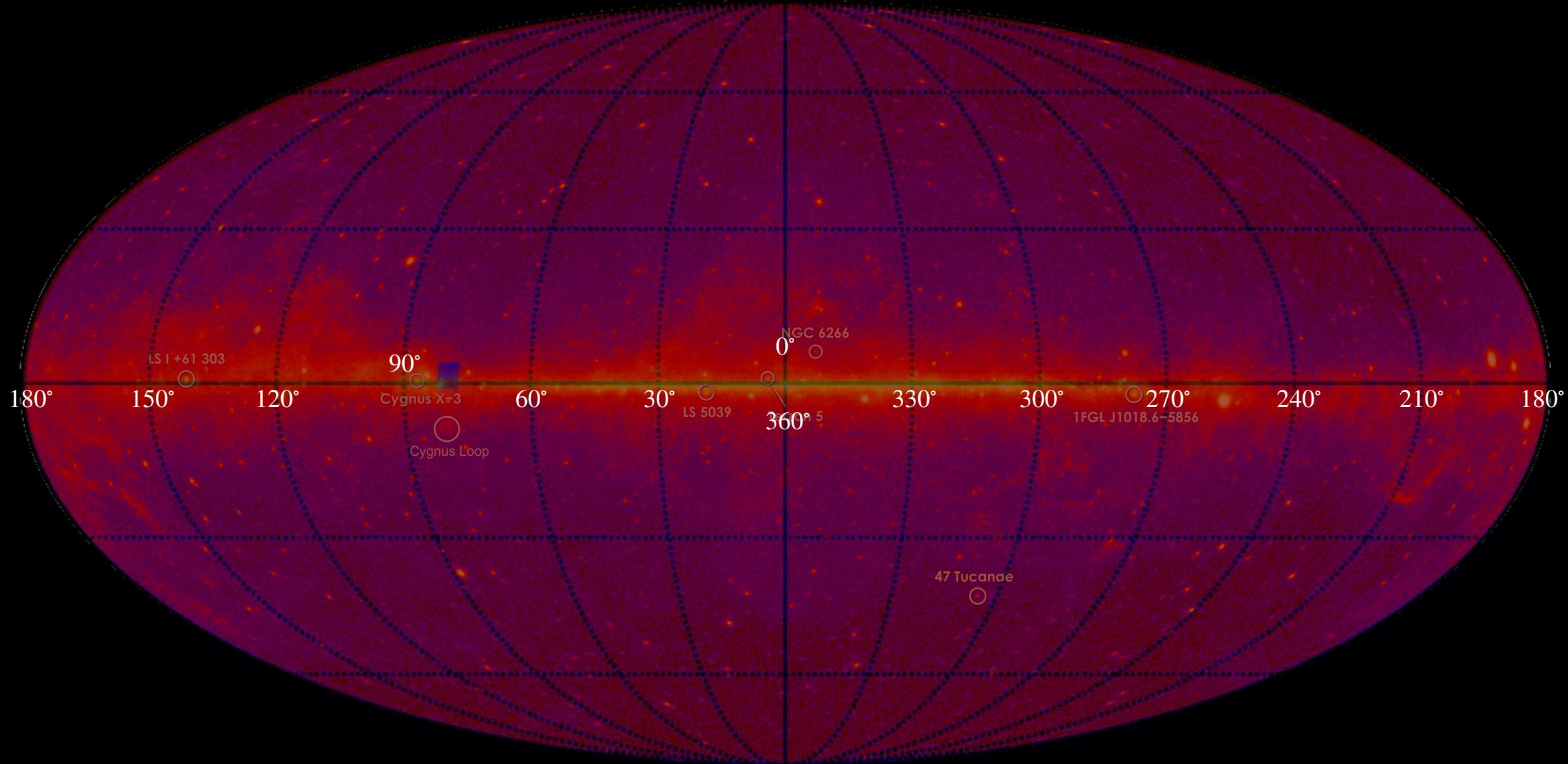
[https://github.com/ottaviofornieri/ISAPP-school-2021\\_HandsOn-Diffuse\\_HERMES](https://github.com/ottaviofornieri/ISAPP-school-2021_HandsOn-Diffuse_HERMES)

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

nside = 512, 1024, 2048

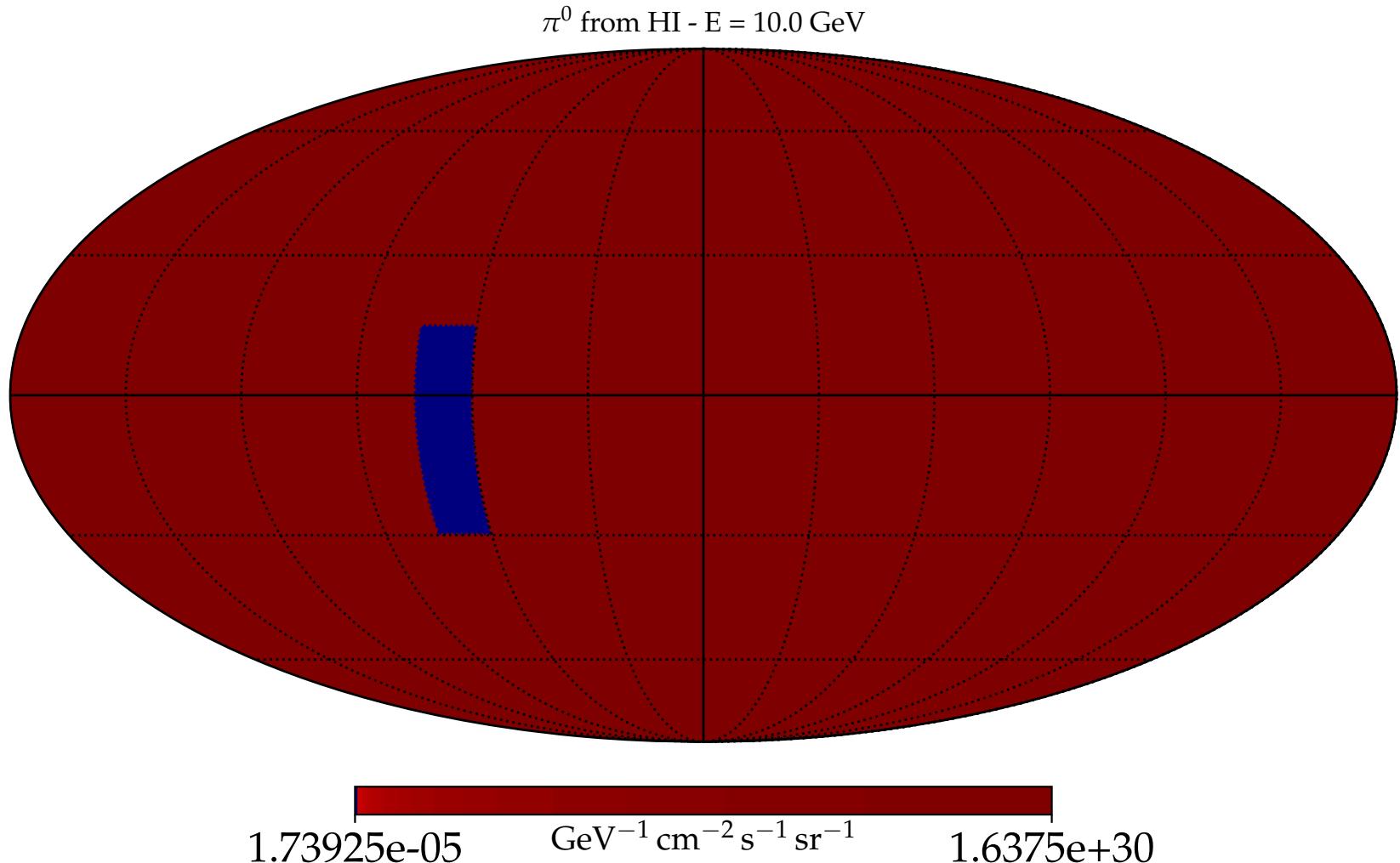
$t \lesssim 30$  min





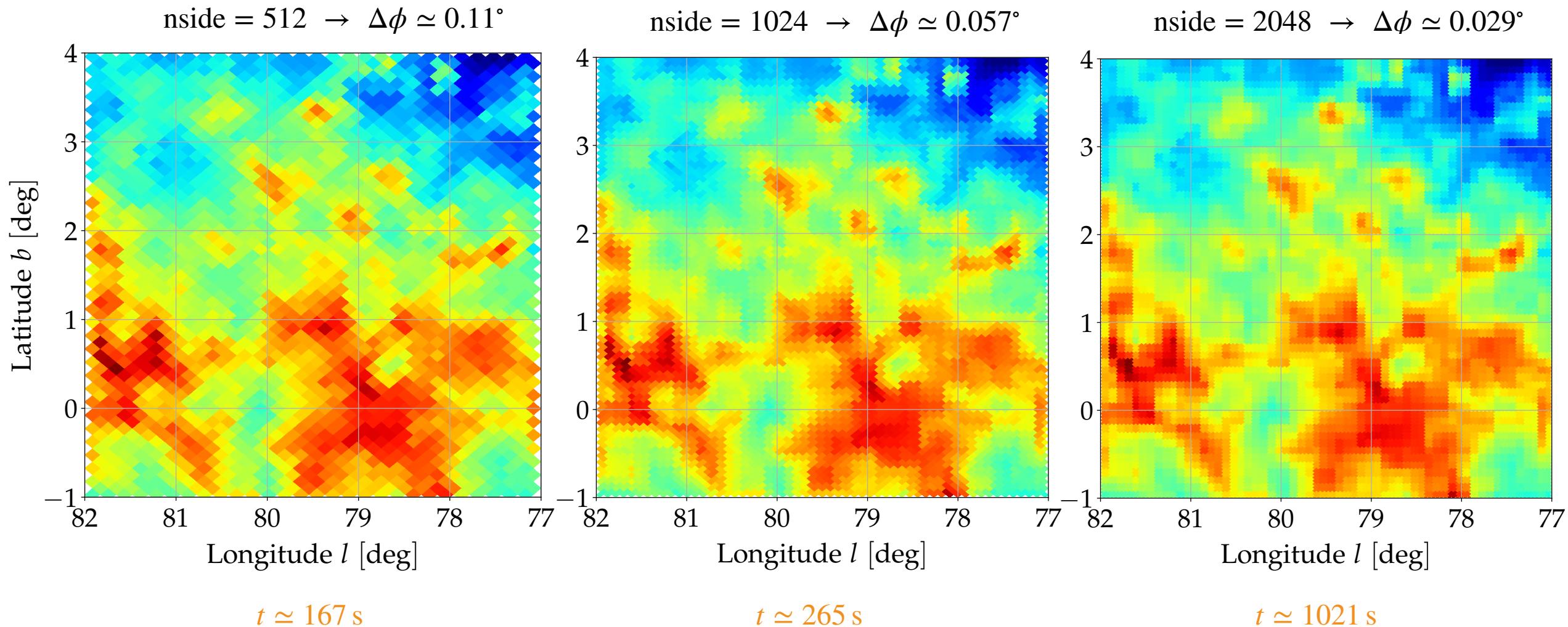
# Rectangular mask: cross-check

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



# Diffuse emission from DRAGON CR distribution

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



# Integral map for $HI$ and $H_2$

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

