Hands-on Session

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

ISAPP School $\mathbf{MAD}^{(\gamma)}$ 2021
Gamma rays to shed light on Dark Matter
29, June 2021

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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

Simulating the Galactic Multi-messenger Emissions with HERMES

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May 28, 2021

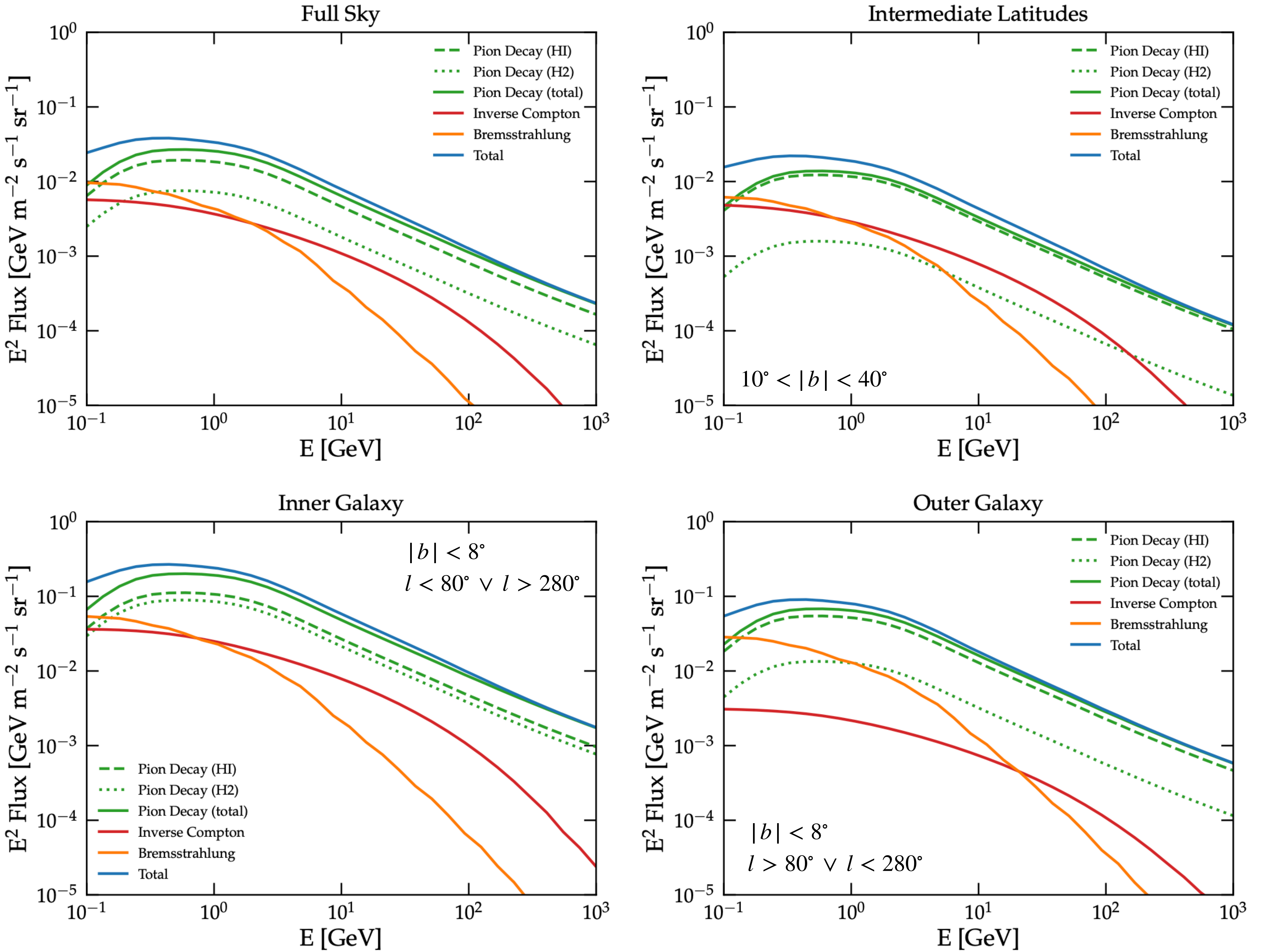
ABSTRACT

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.

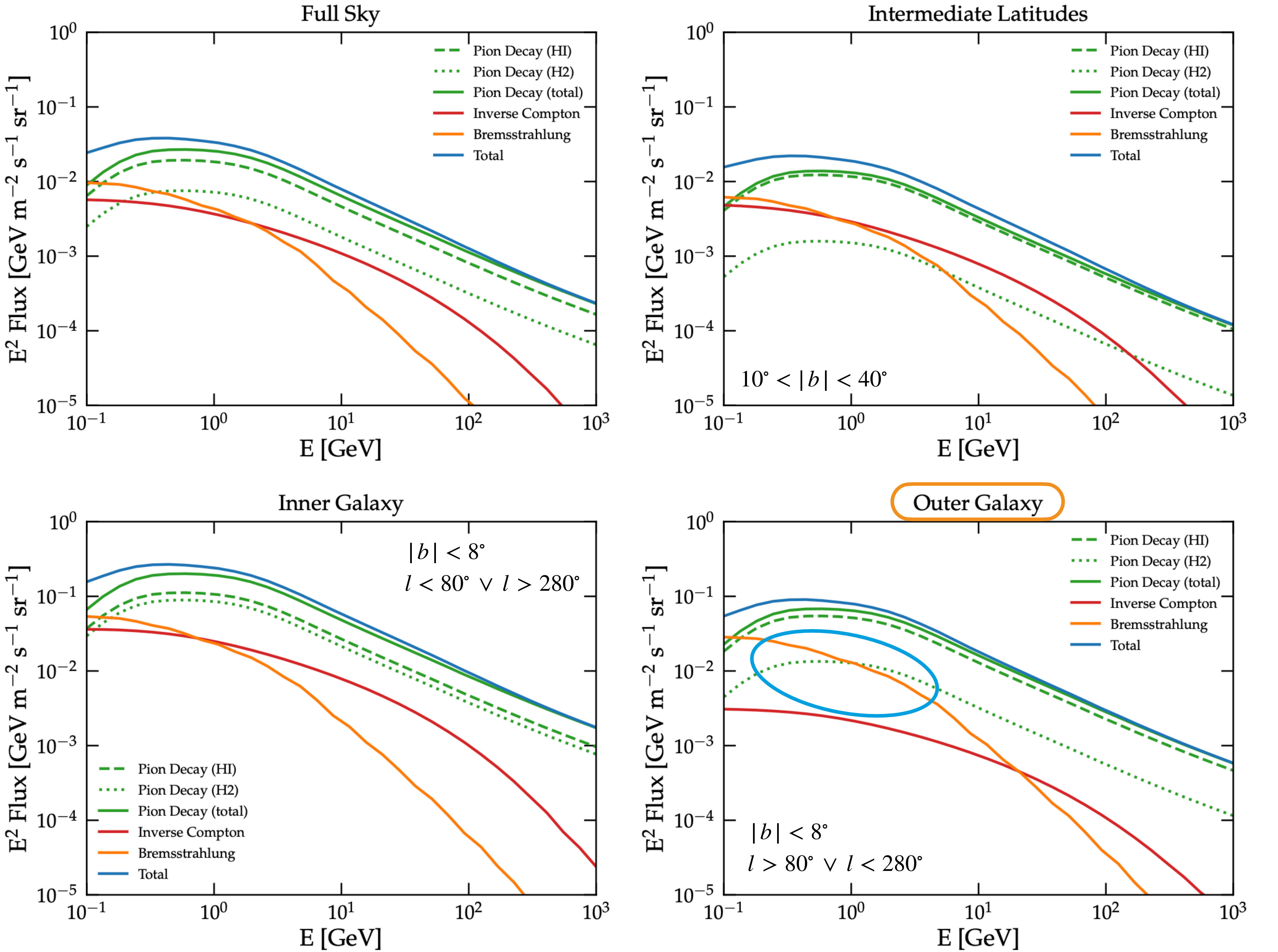
γ-ray emitting processes

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

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



Full Sky
Intermediate Latitudes
Inner Galaxy
Outer Galaxy
Pion Decay (HI)
Pion Decay (H2)
Pion Decay (total)
Inverse Compton
Bremsstrahlung
Total
$10° < |b| < 40°$
$|b| < 8°$
$l < 80° \vee l > 280°$
$|b| < 8°$
$l > 80° \vee l < 280°$
E^2 Flux [GeV m^{-2} s^{-1} sr^{-1}]
E [GeV]


Full Sky
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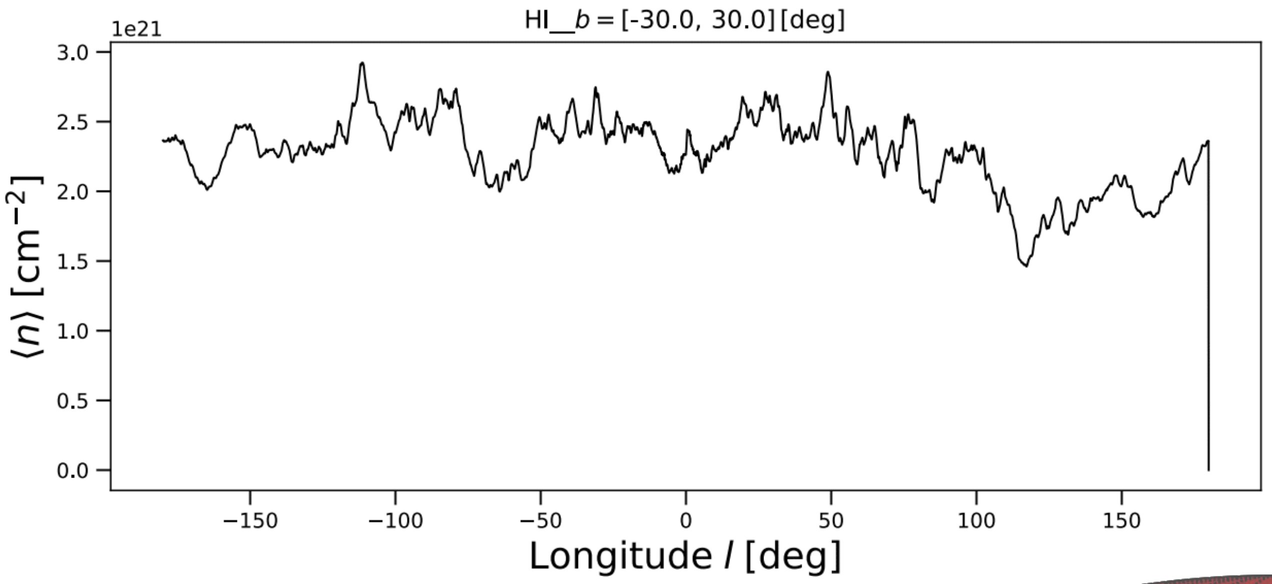
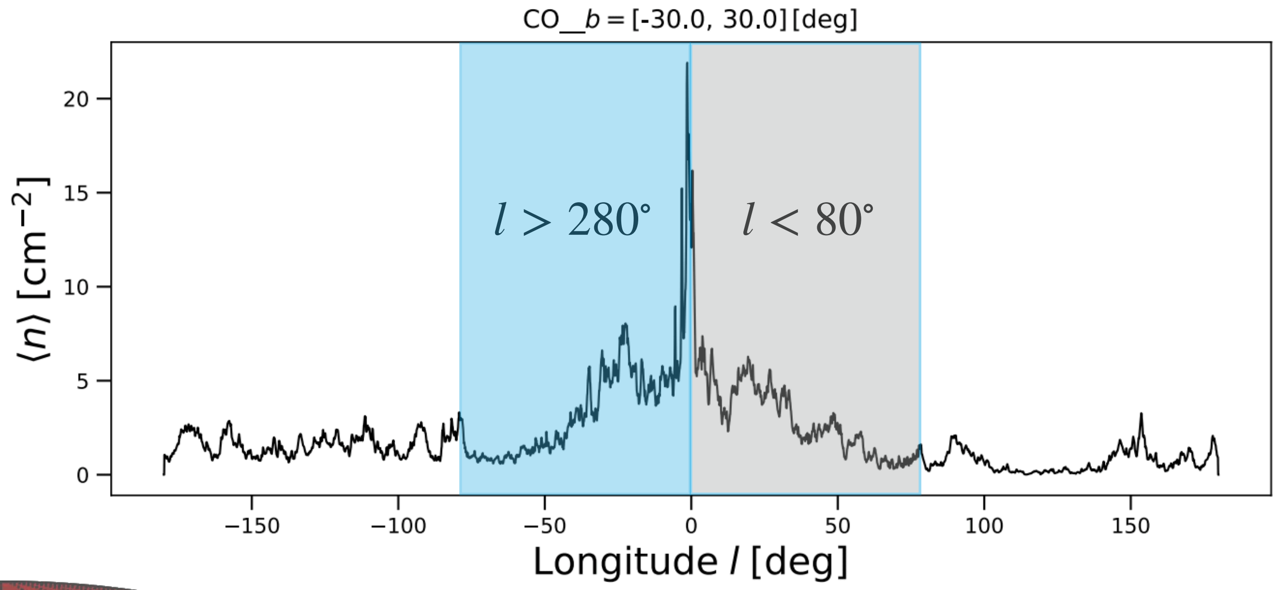
$l > 80^\circ \vee l < 280^\circ$

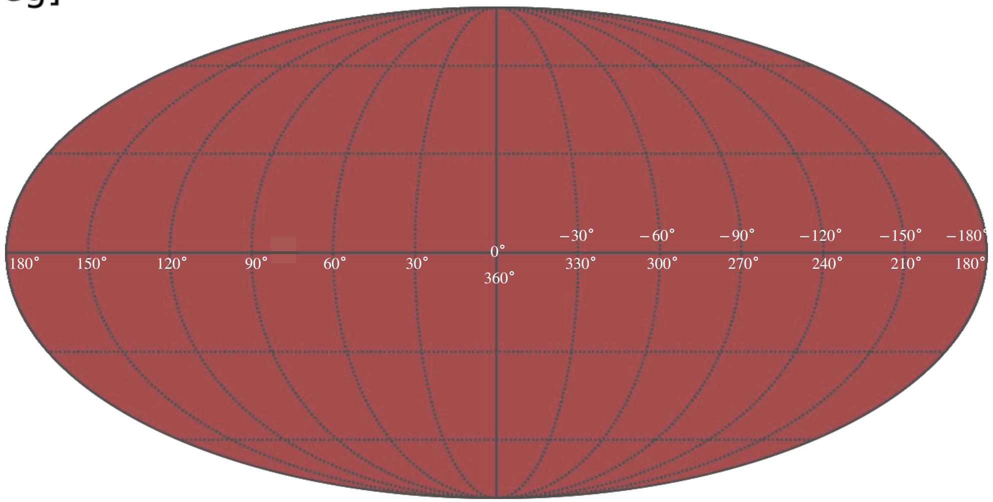
Gas longitudinal profile

Atomic gas



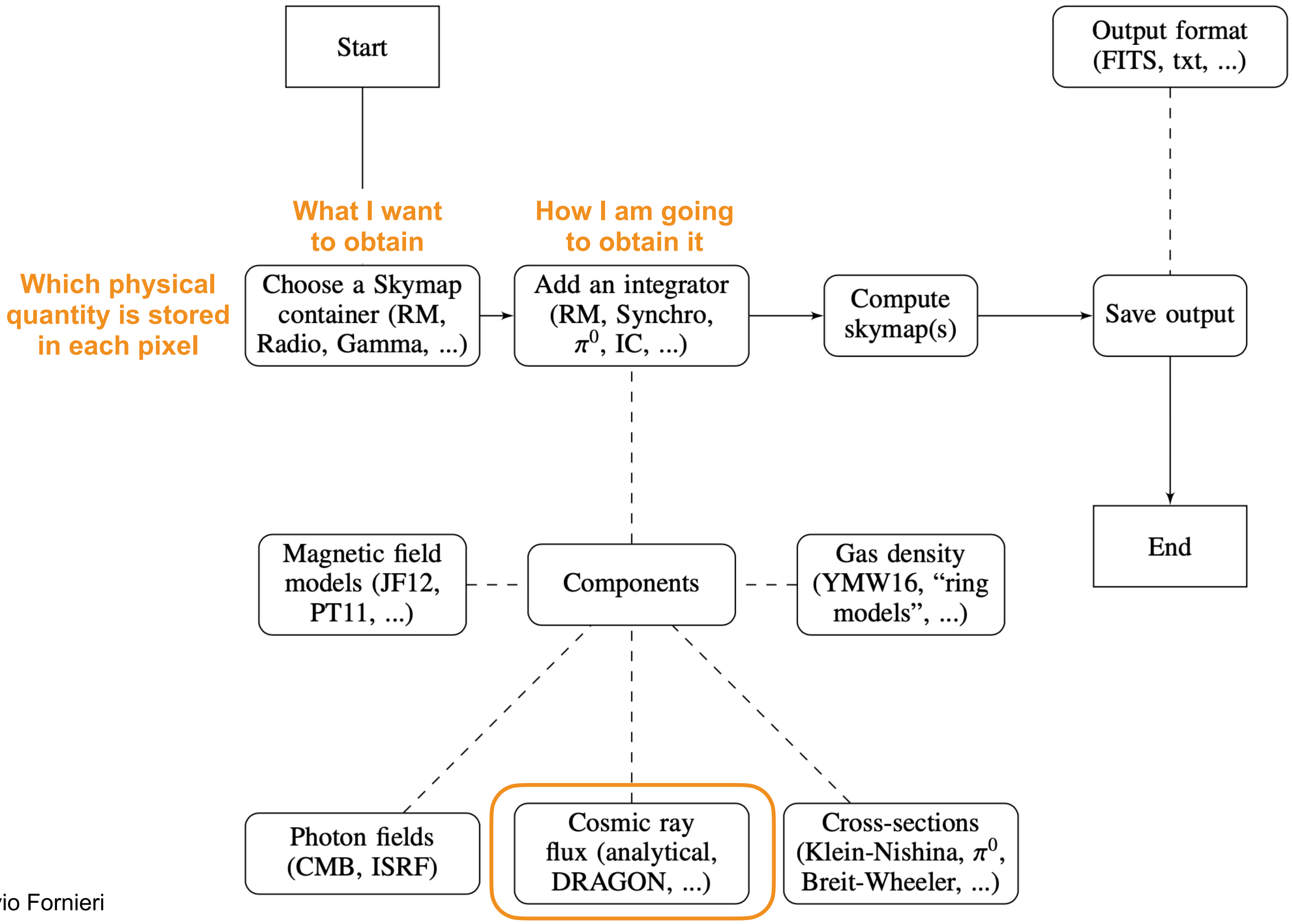
Molecular gas





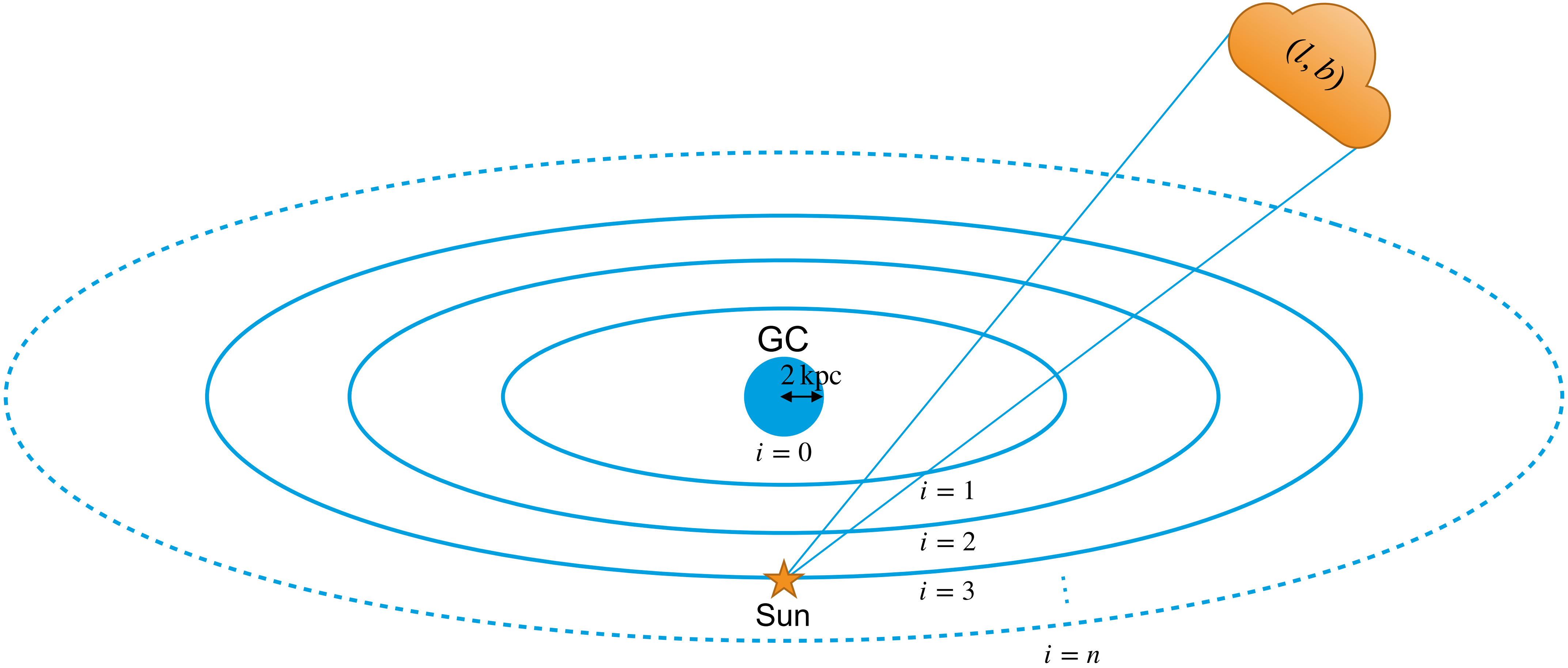
Introduction to γ-rays with HERMES

HERMES work-flow



Ring model

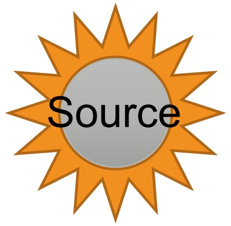
[Strong&Mattox, A&A, 308, L21 (1996)] → based on HI and CO emissivity maps



The observable quantity

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

Emissivity at the source

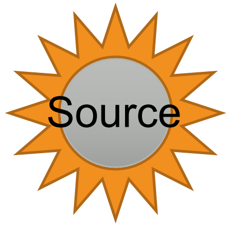


$$\epsilon_{\pi^0}(E_\gamma, \mathbf{r}) = 4\pi n_{\mathrm{H}}(\mathbf{r}) \int dE \left[\frac{d\Phi_{\mathrm{p}}}{dE}(E, \mathbf{r}) \left(\frac{d\sigma_{\mathrm{p-p}}}{dE_\gamma} + f_{\mathrm{He}} \frac{d\sigma_{\mathrm{He-p}}}{dE_\gamma} \right) + \frac{d\Phi_{\mathrm{He}}}{dE}(E, \mathbf{r}) \left(\frac{d\sigma_{\mathrm{p-He}}}{dE_\gamma}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

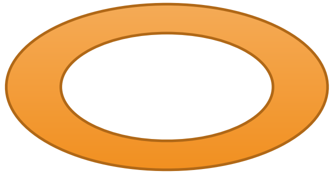
The observable quantity

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

Emissivity at the source



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



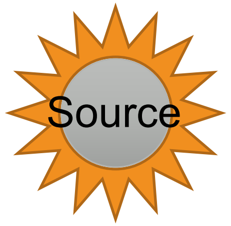
Emissivity averaged over the ring i-th

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

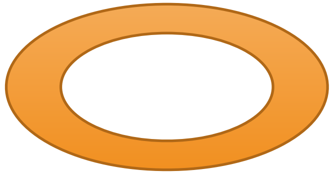
The observable quantity

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

Emissivity at the source



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

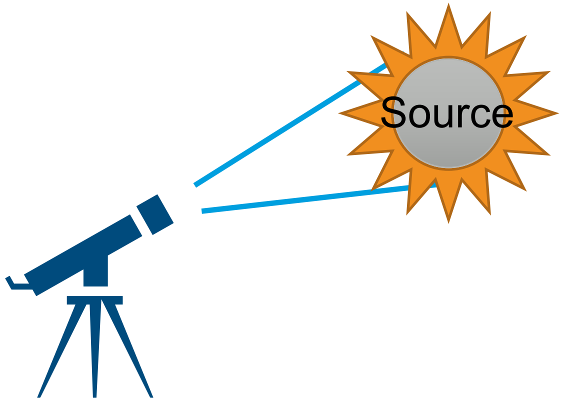


Emissivity averaged over the ring i-th

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

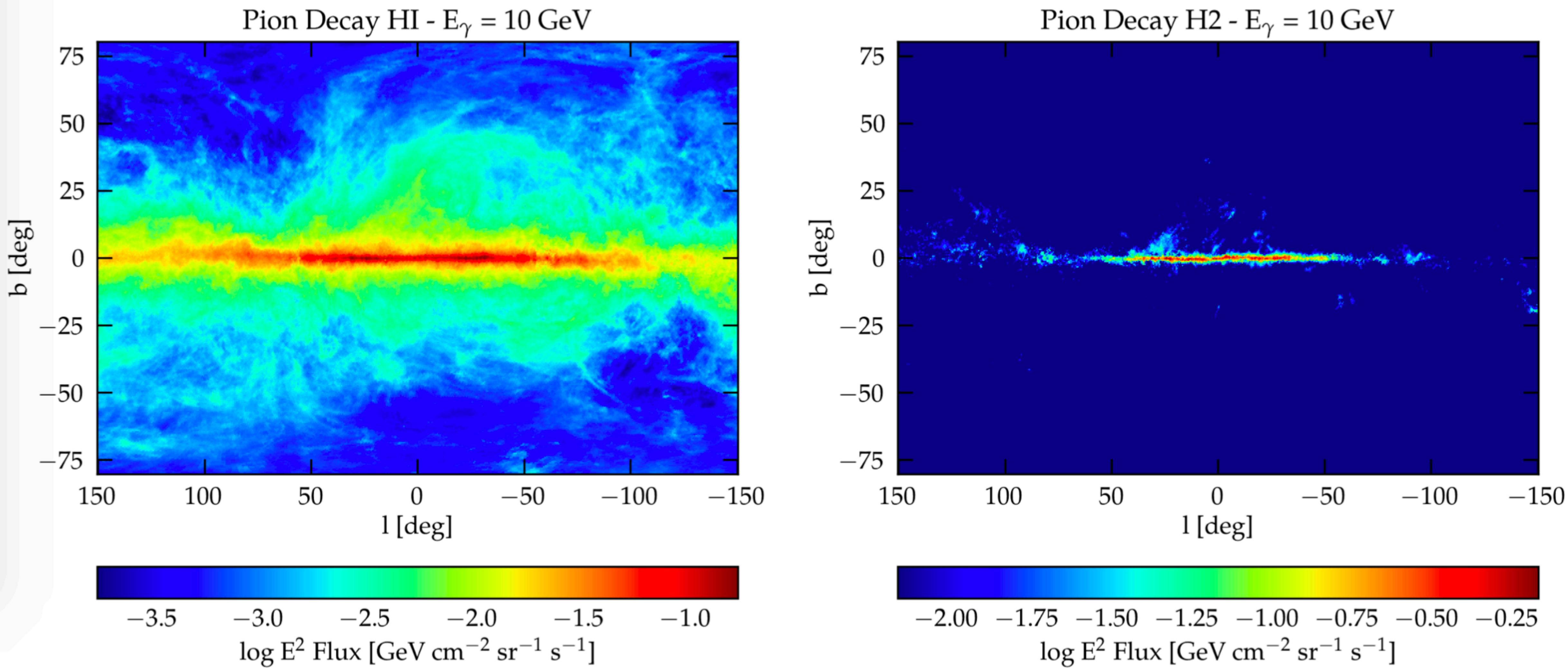
Observed intensity

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



The outcome

π^0-decay at given energy



Support slides

Run HERMES Full-Sky

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

$$\mathrm{nside} = 32$$
$$t \sim 58\,\mathrm{min}$$

Resolution parameters

HEALPix convention

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

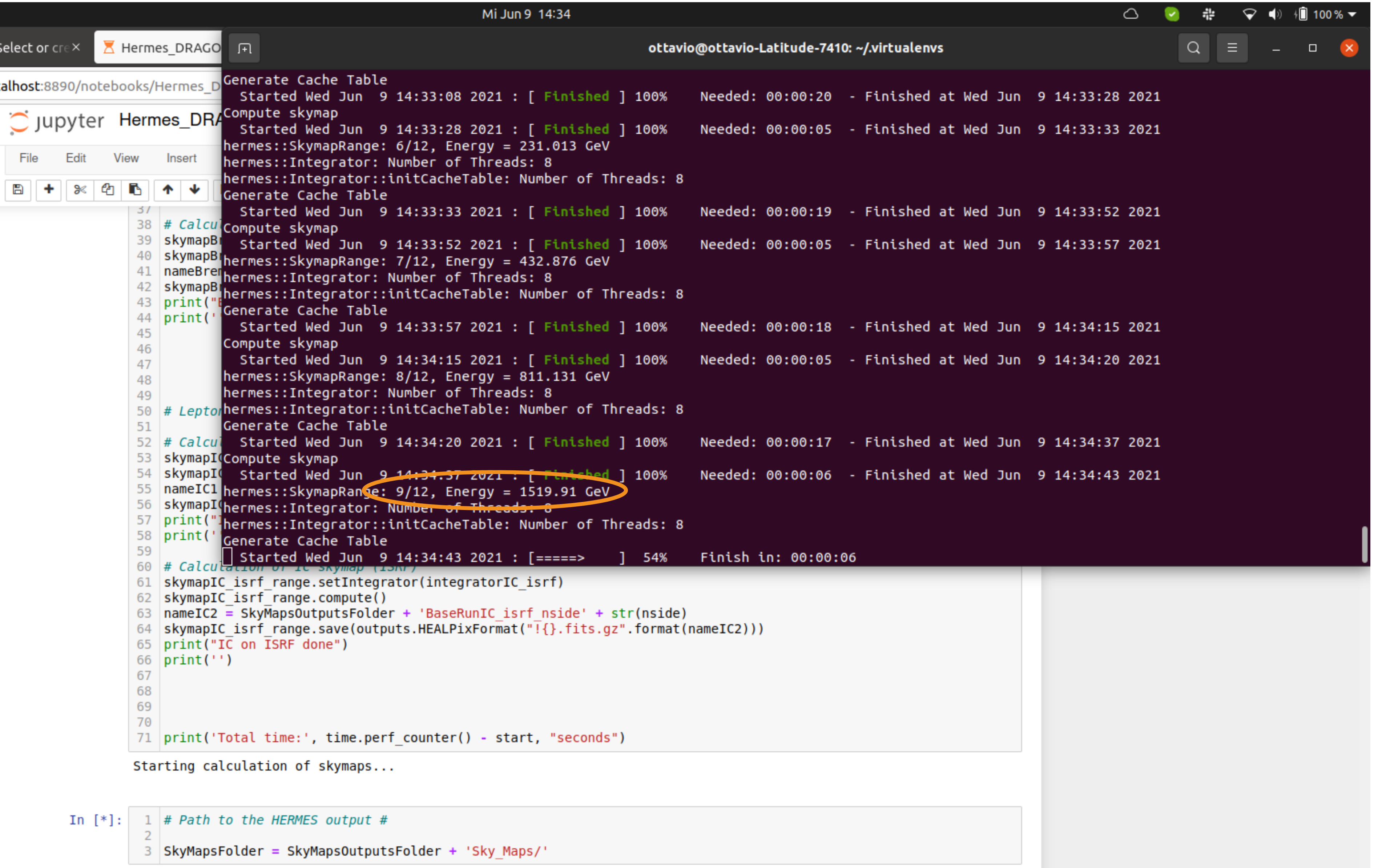
nside $= 2^{res}$: The number of pixels per side.

npix $= 12\ nside^2$: 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	$9.9868541 \times 10^{-07}$

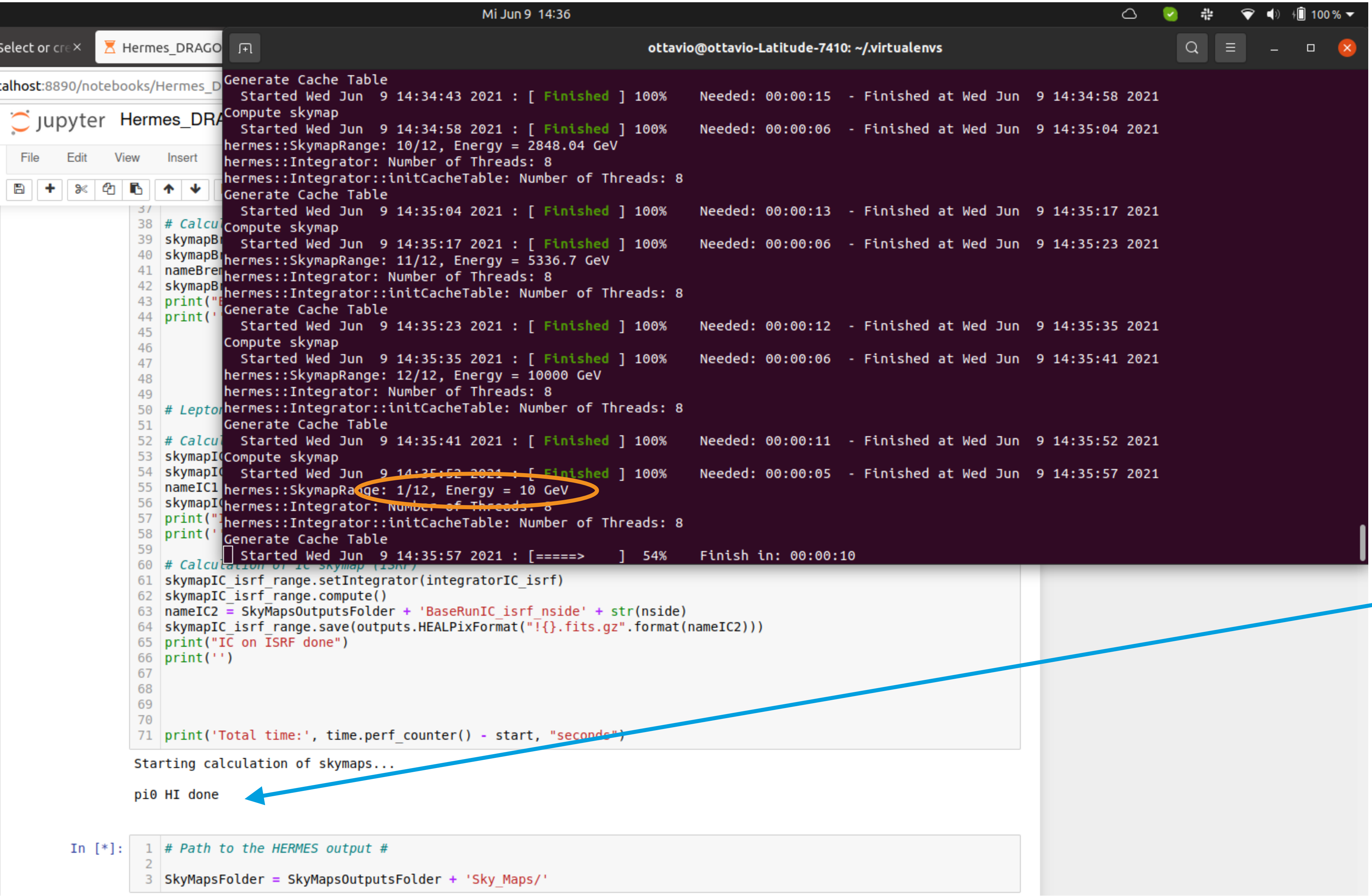
Progress of a full-sky run with $\mathrm{nside} = 32$

12 log-spaced energy points for each process



Progress of a full-sky run with $\mathrm{nside} = 32$

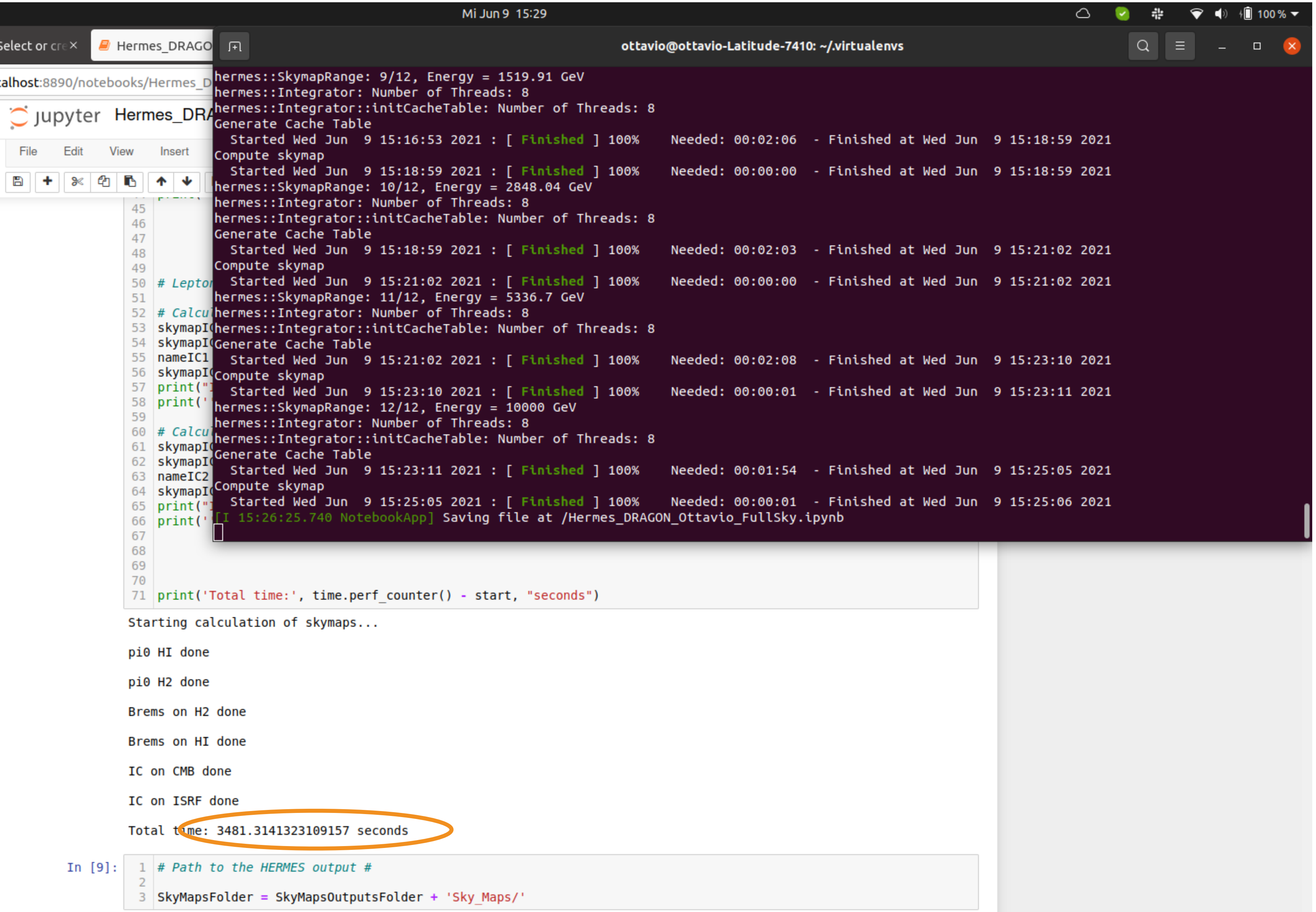
12 log-spaced energy points for each process



First process gone!

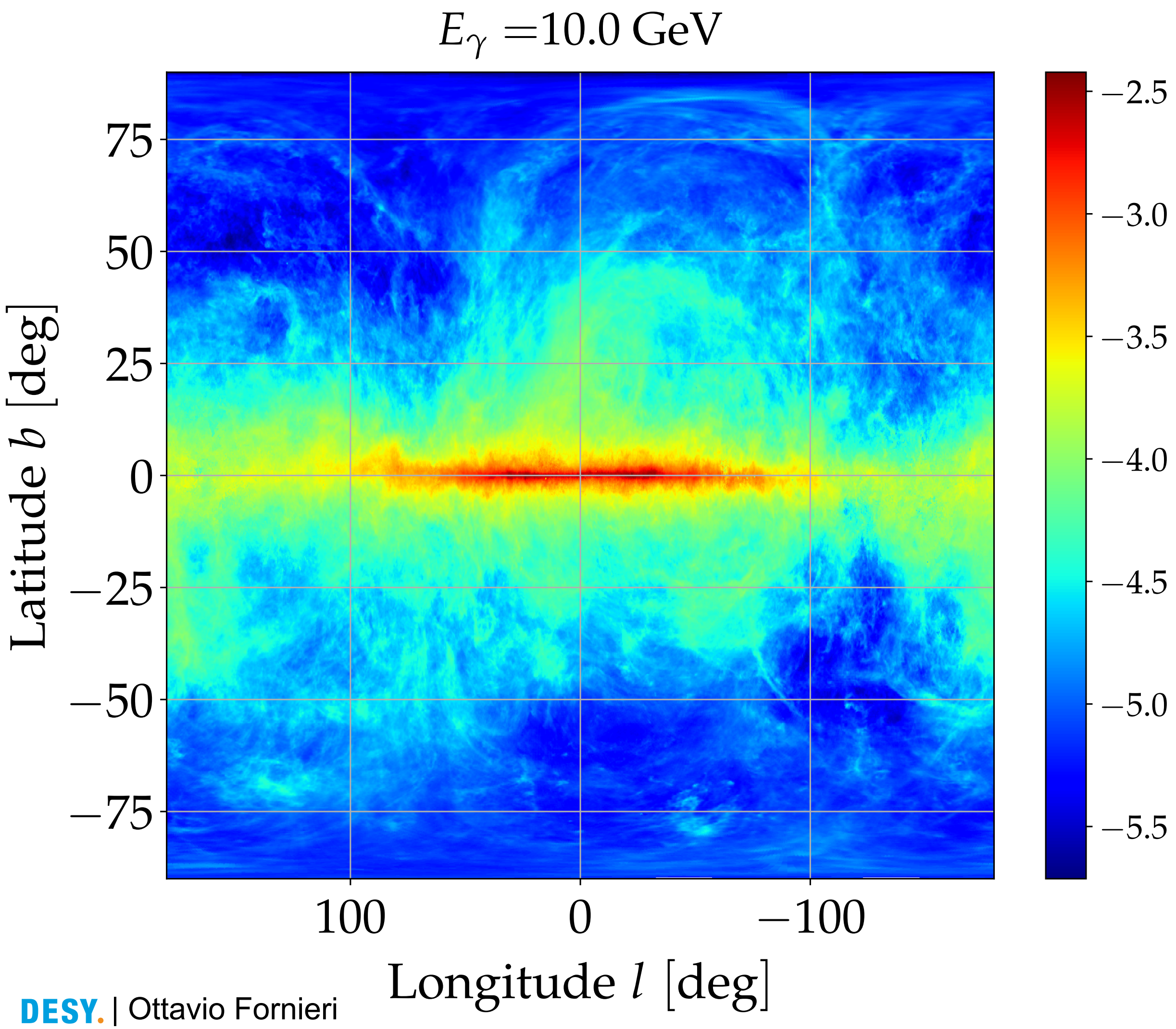
Progress of a full-sky run with $\mathrm{nside} = 32$

12 log-spaced energy points for each process

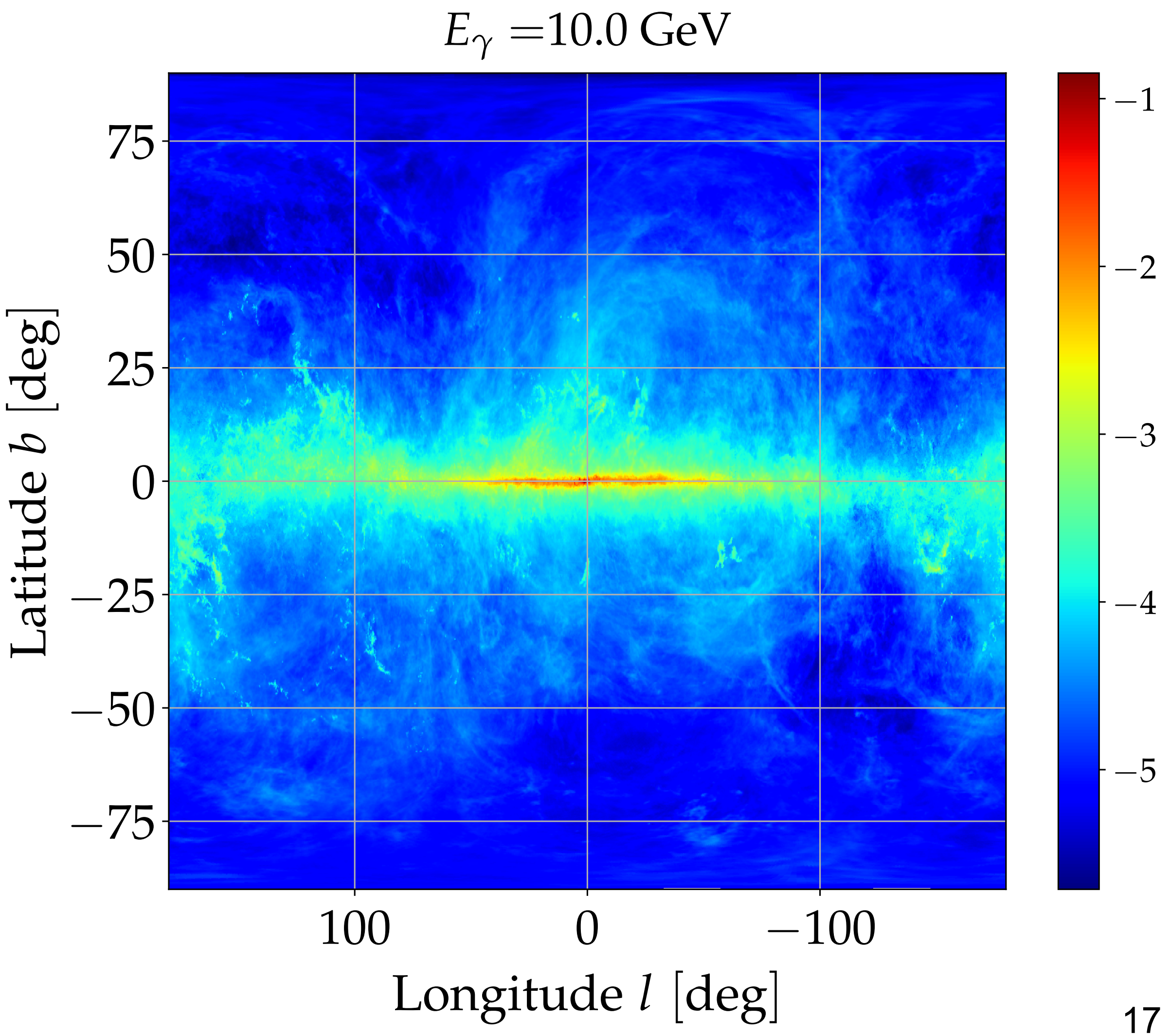


Cartesian projection of the Full Sky

Paper plot: π^0 on HI



π^0 on $HI + H_2$



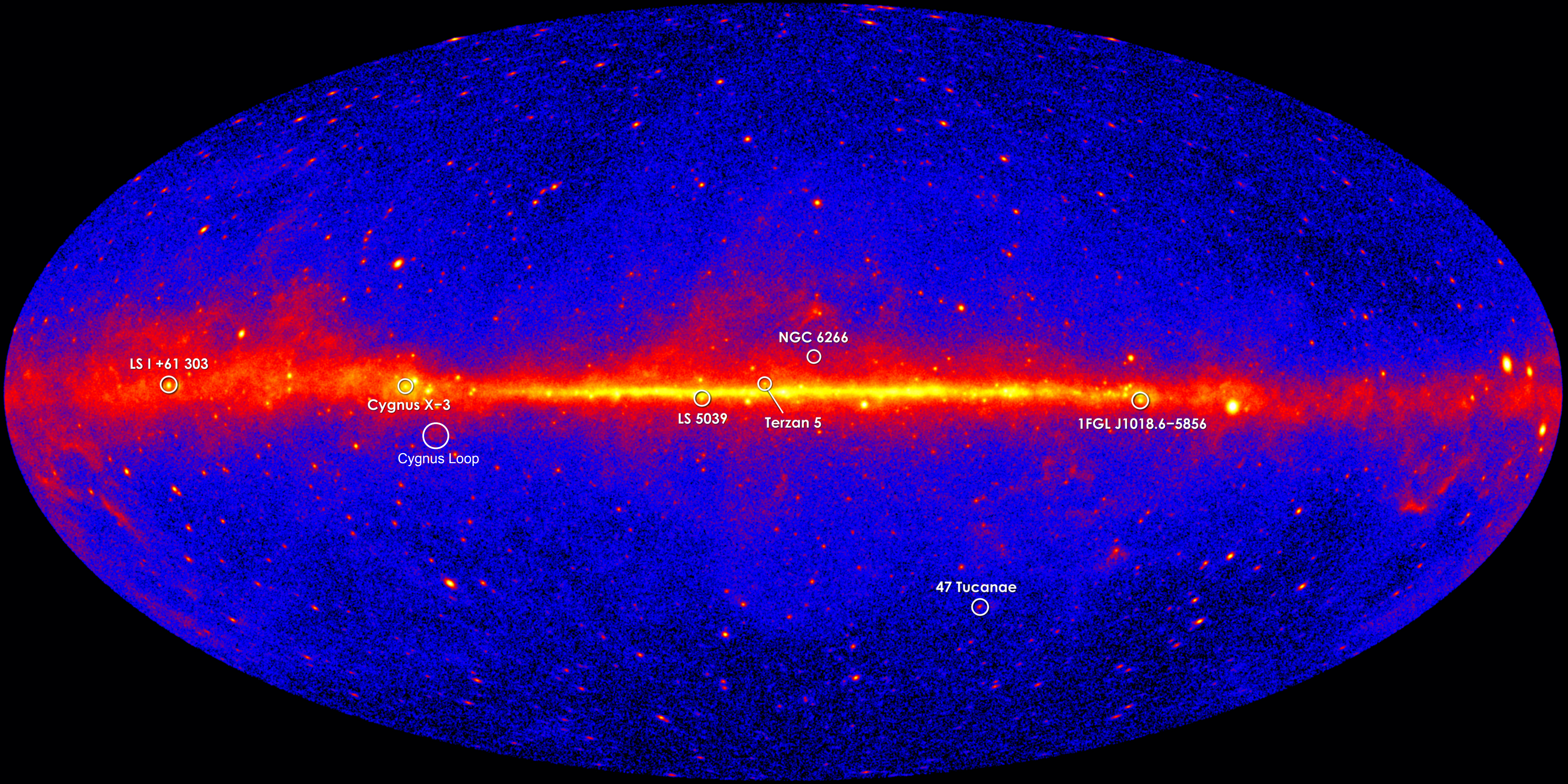
Runs HERMES Cygnus-X region

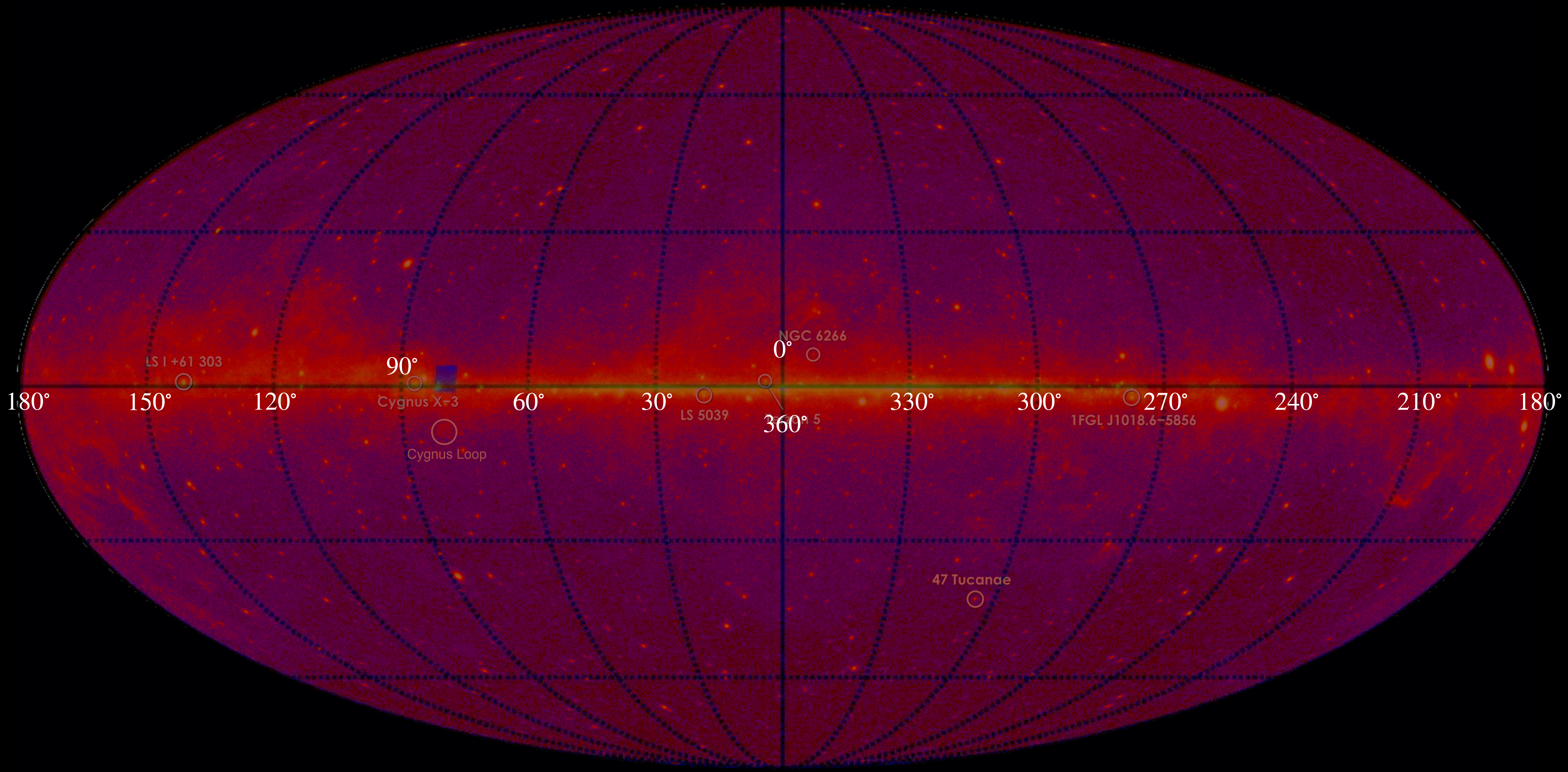
https://github.com/ottavioforniieri/ISAPP-school-2021_HandsOn-Diffuse_HERMES

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

$$\mathrm{nside} = 512, 1024, 2048$$

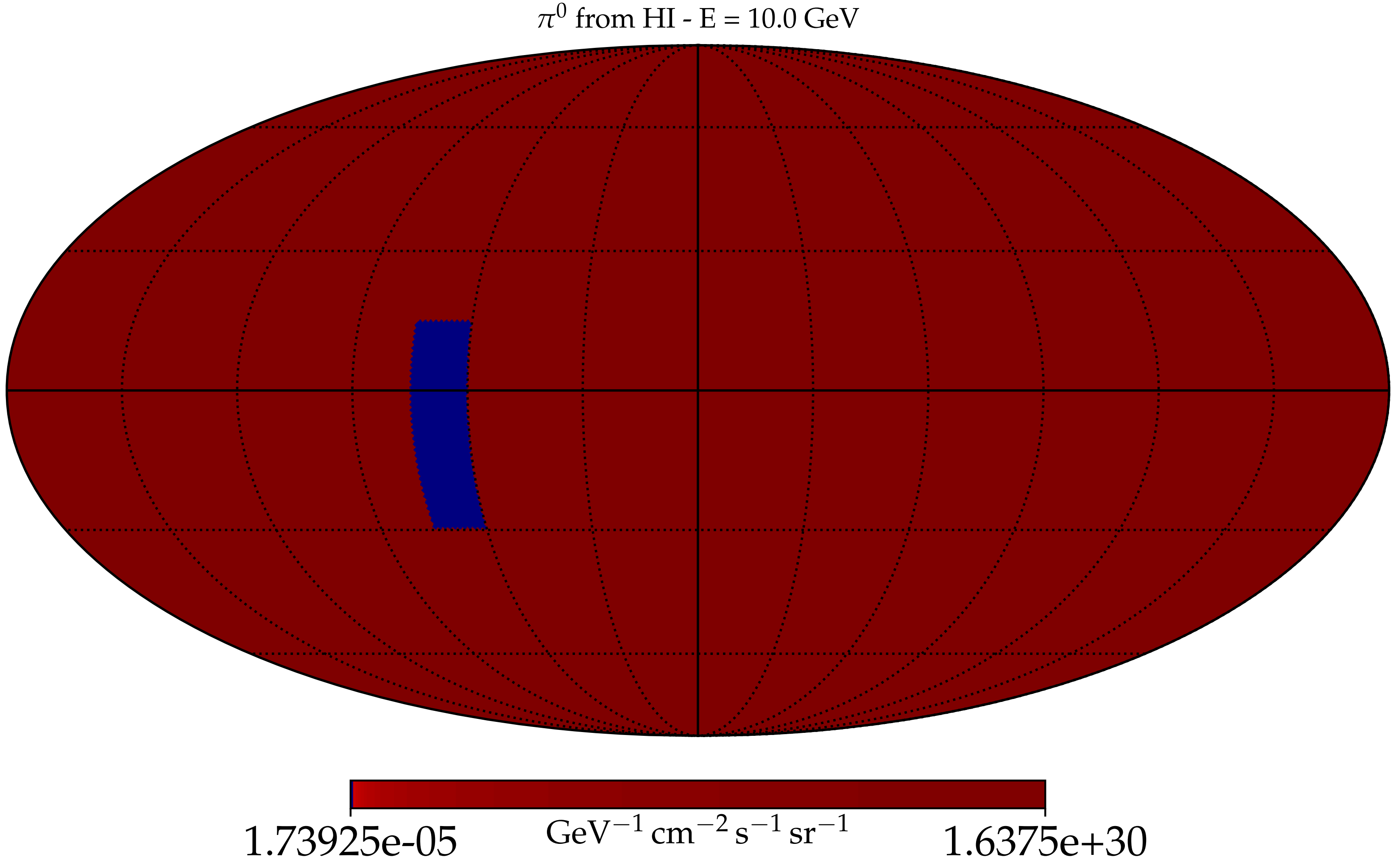
$$t \lesssim 30\,\mathrm{min}$$


NGC 6266
LS I +61 303
Cygnus X-3
LS 5039
Terzan 5
1FGL J1018.6-5856
Cygnus Loop
47 Tucanae


NGC 6266
0°
LS I +61 303
90°
Cygnus X-3
180°
150°
120°
60°
30°
LS 5039
360°
330°
300°
1FGL J1018.6-5856
270°
240°
210°
180°
Cygnus Loop
47 Tucanae

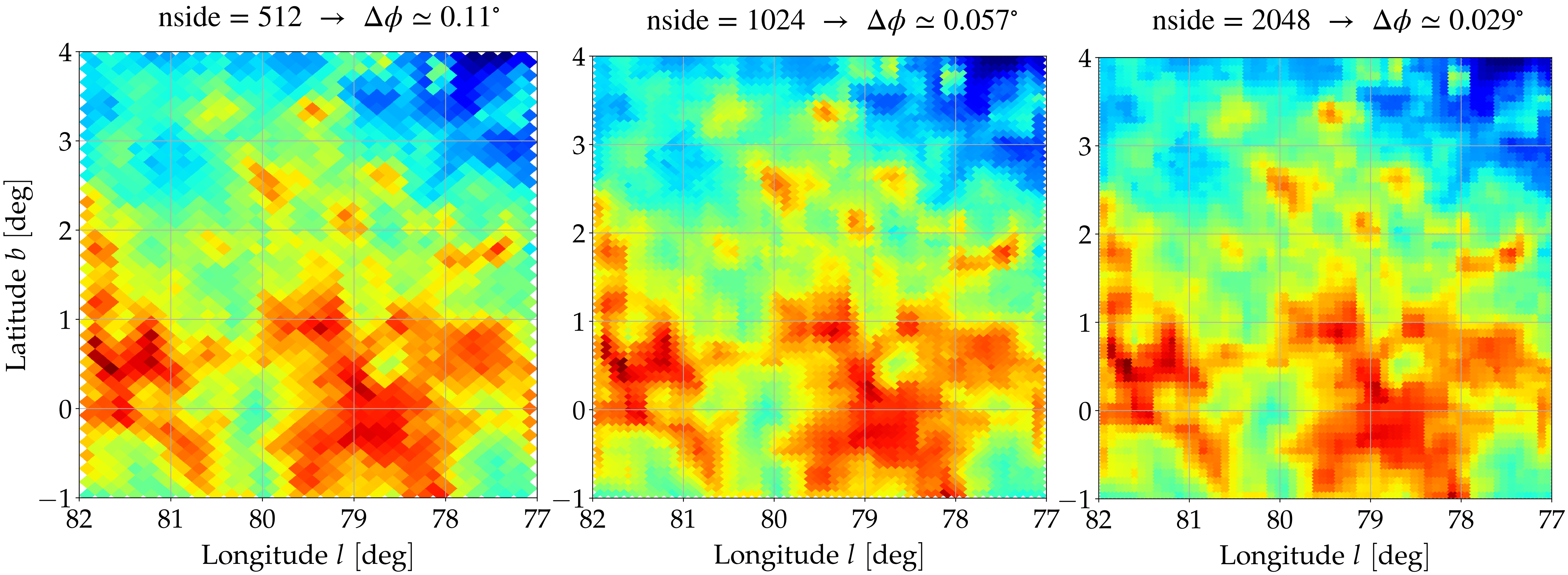
Rectangular mask: cross-check

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



Diffuse emission from DRAGON CR distribution

$E_\gamma = 10\,\mathrm{GeV}$



$t \simeq 167\,\mathrm{s}$ $t \simeq 265\,\mathrm{s}$ $t \simeq 1021\,\mathrm{s}$

Integral map for HI and H_2

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