A study of Gamma rays from local Giant Molecular Clouds and its implications on the cosmic-ray flux

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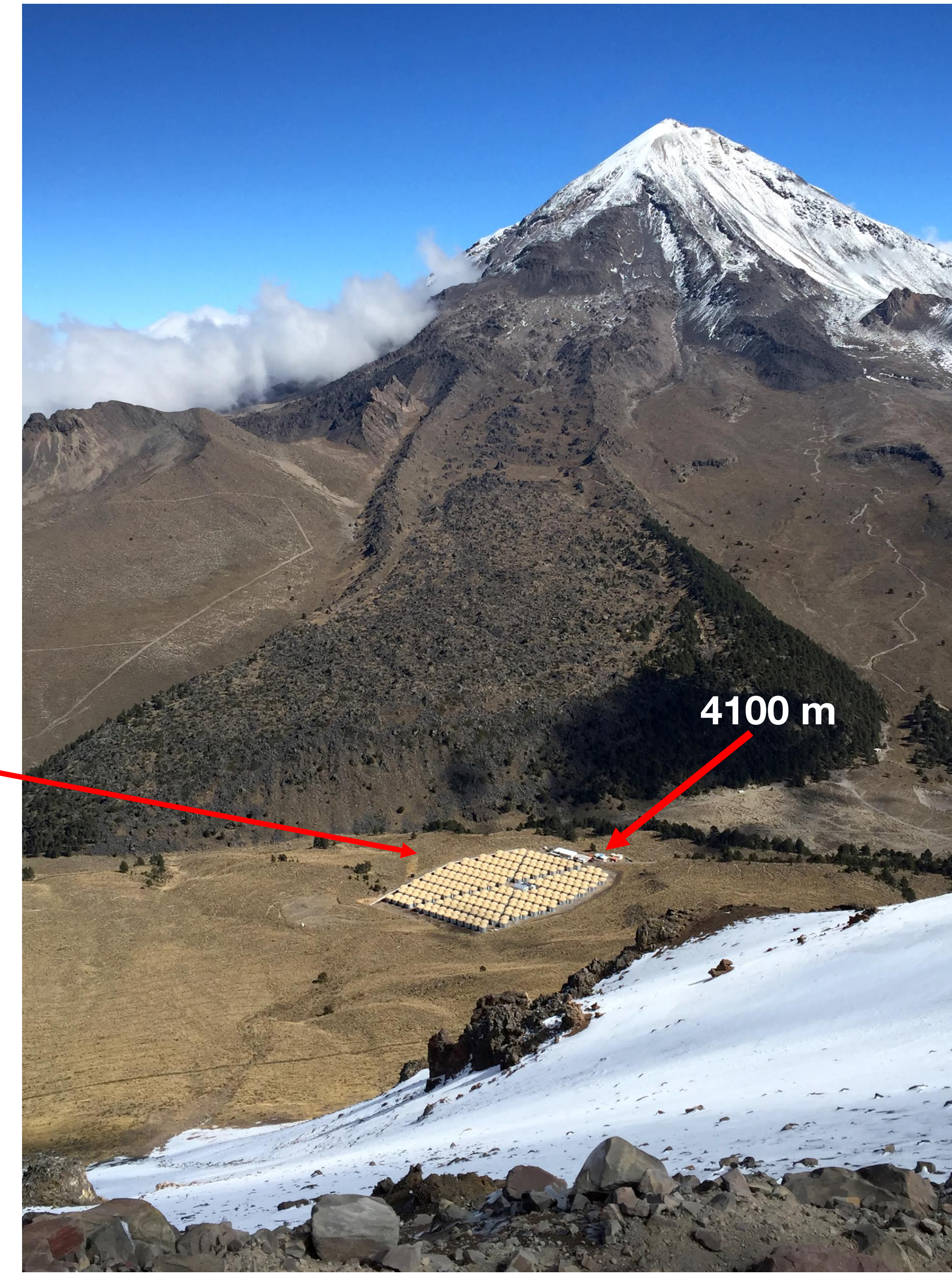
Outline

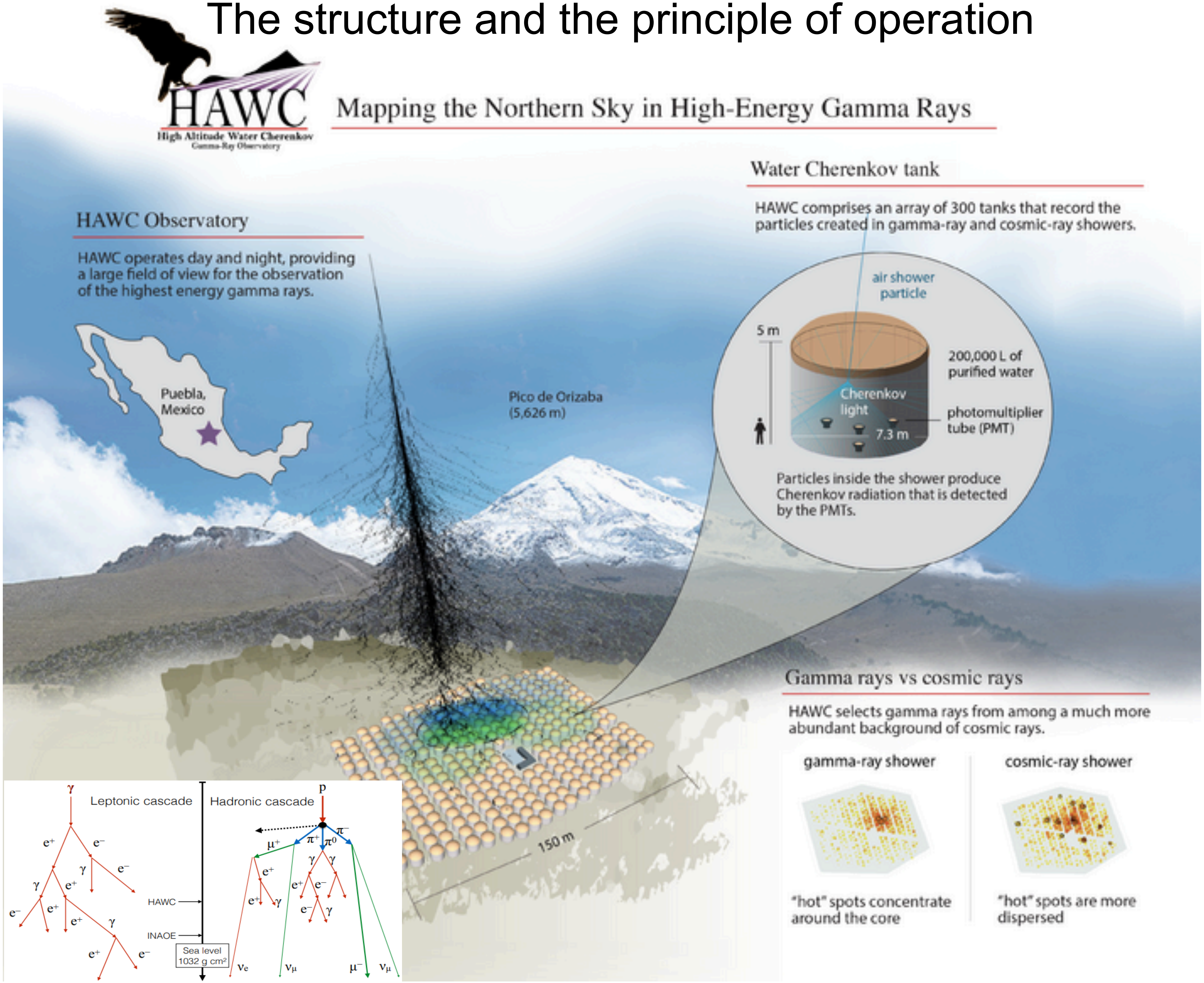
- Introduction to HAWC
- Motivation
- Fermi-LAT data selection and stacking analysis
- HAWC's 95% C.I. combined upper limits
- Gamma-ray spectrum based on AMS-02 CRs data
- Comparison of Fermi-LAT and HAWC data with AMS-02 based gamma-ray spectrum
- Summary & future work

The HAWC observatory



- **Site: Sierra Negra, Mexico, 19°N, 4,100 m altitude.**
- **Instantaneous FOV 2 sr. (15%) and daily 8sr (66%).**
- **Duty cycle >90%.**
- **300 WCDs covering 22,000 m2 area.**

The structure and the principle of operation

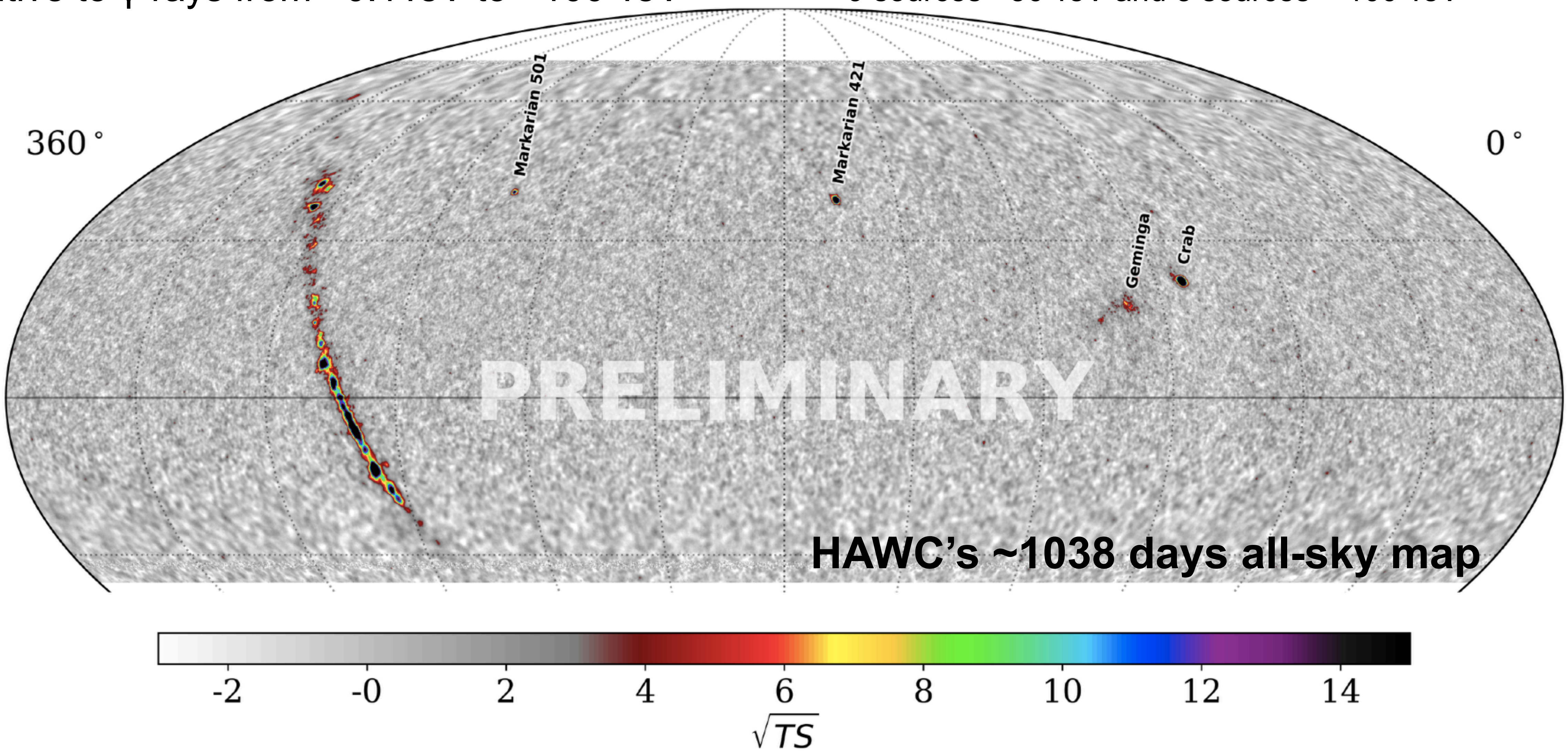


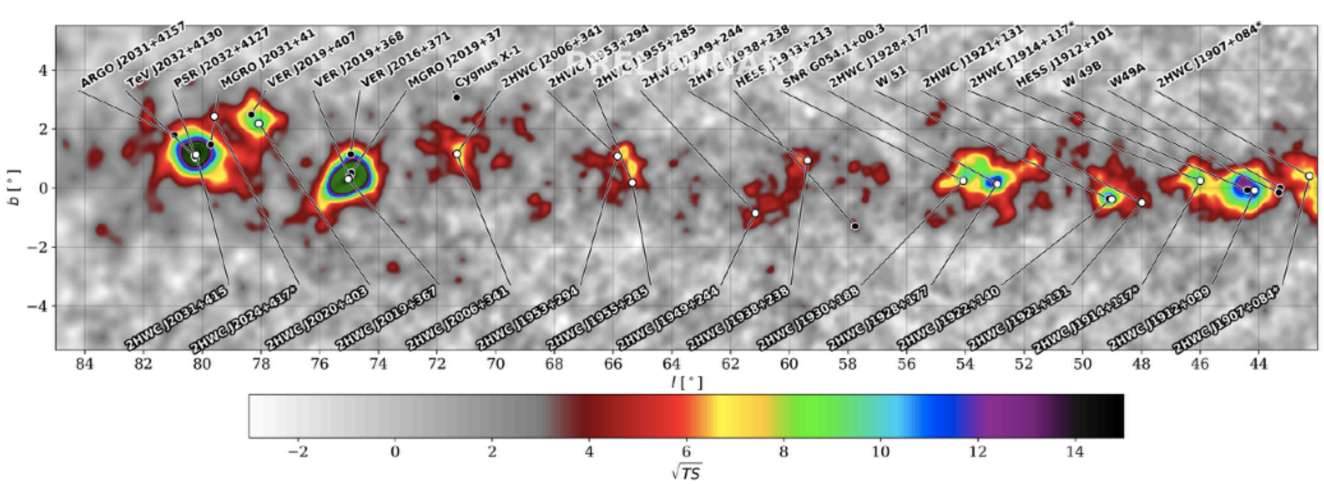
HAWC Sky

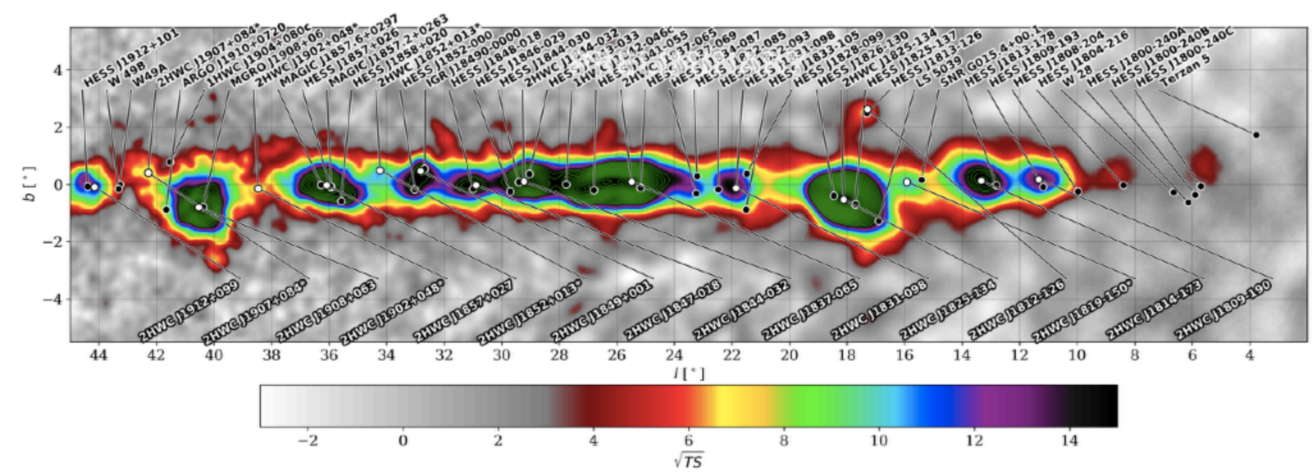
- Wide Field-of-View: ~2 sr
- ~2/3 of the sky per day
- Sensitive to γ-rays from ~0.1TeV to ~100 TeV

The 2HWC catalog based 507 days of data contains 39 sources

- 19 sources were not previously reported at TeV energies
- 9 sources >56 TeV and 3 sources > 100 TeV

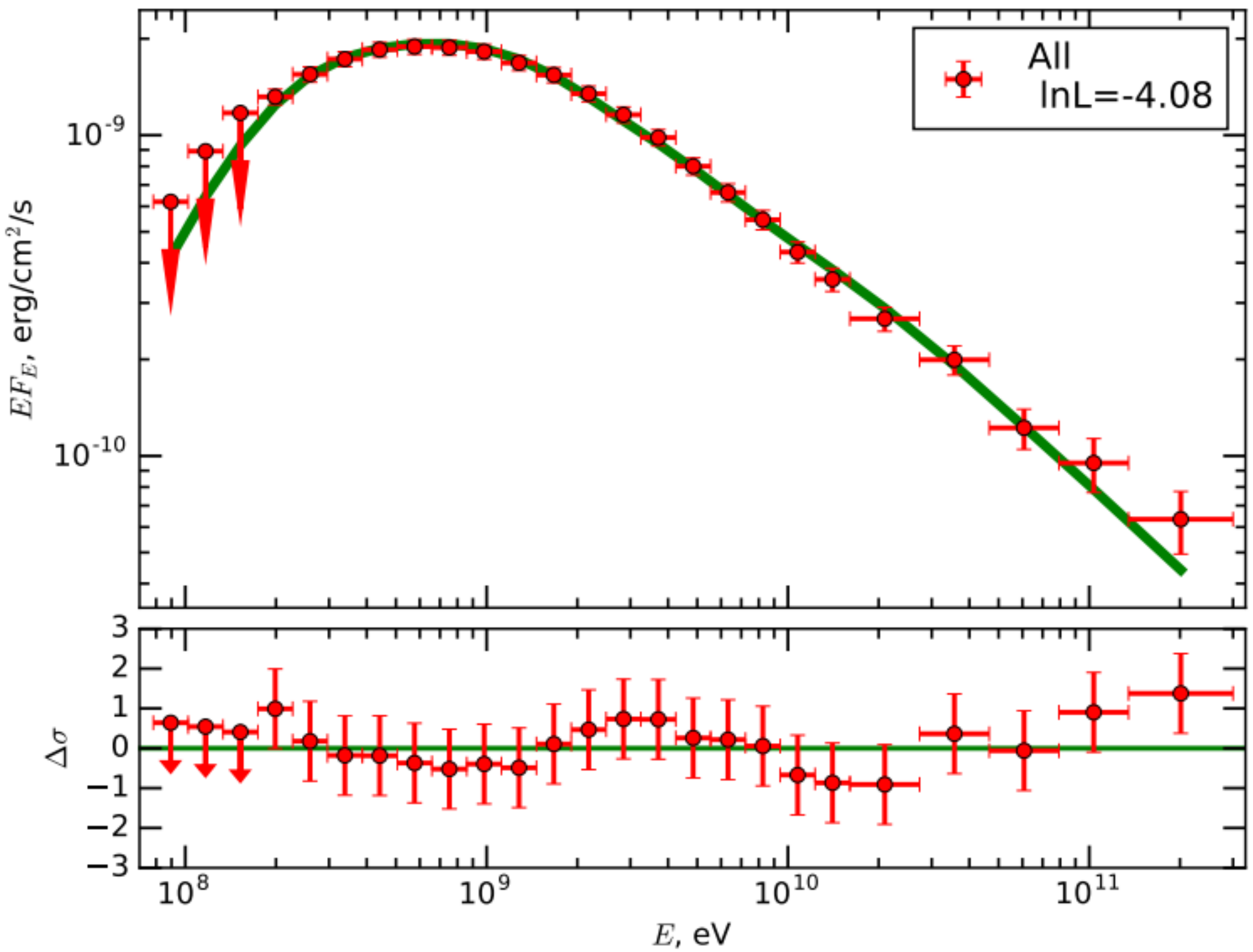


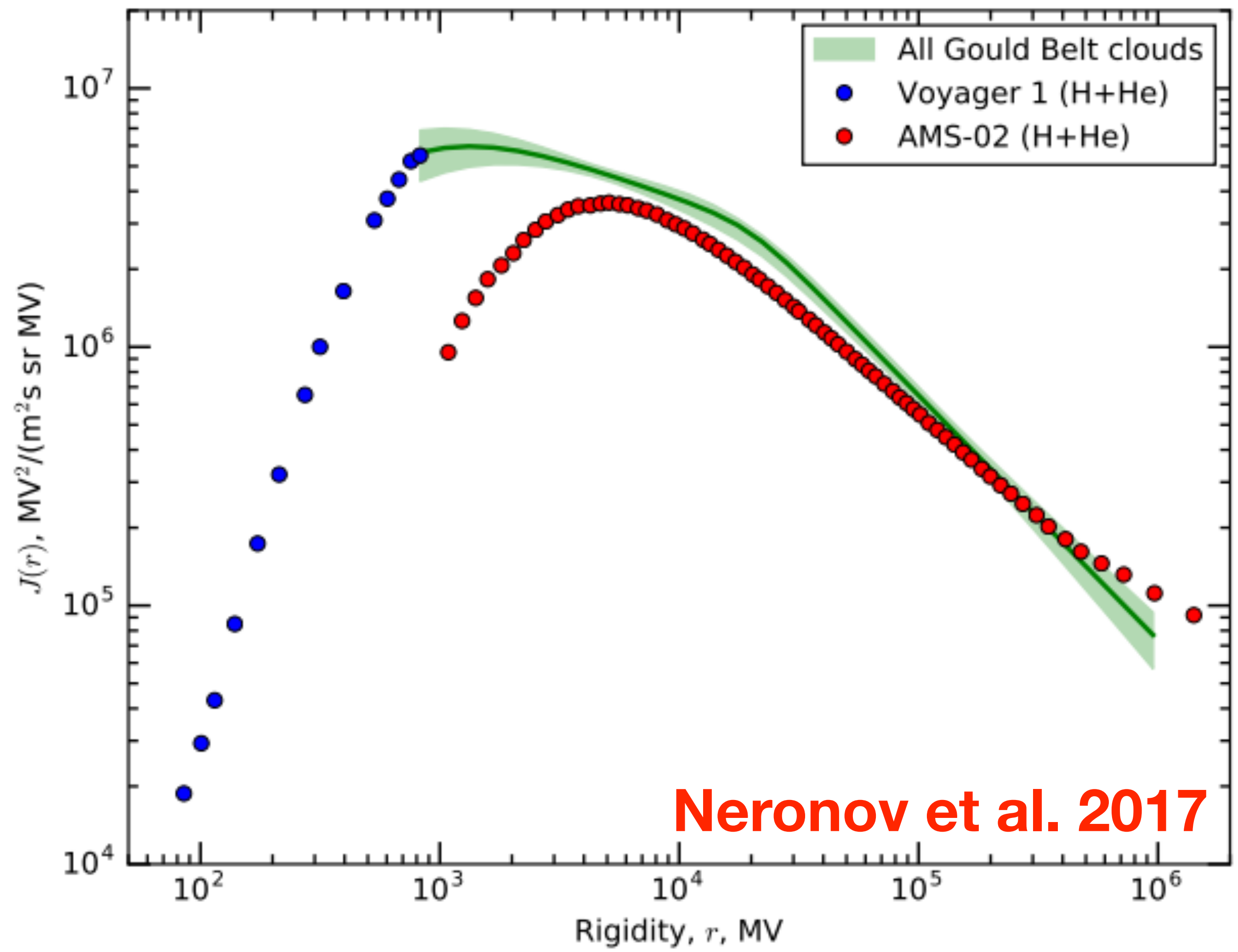




Motivation

Set meaningful constraints on the average CR protons spectrum in the local giant molecular clouds using Fermi-LAT stacked spectrum extending up to 1 TeV and HAWC's 95% C.I. combined upper limits in 1-100 TeV energy range and compare it with the direct local measurement of AMS-02 experiment.

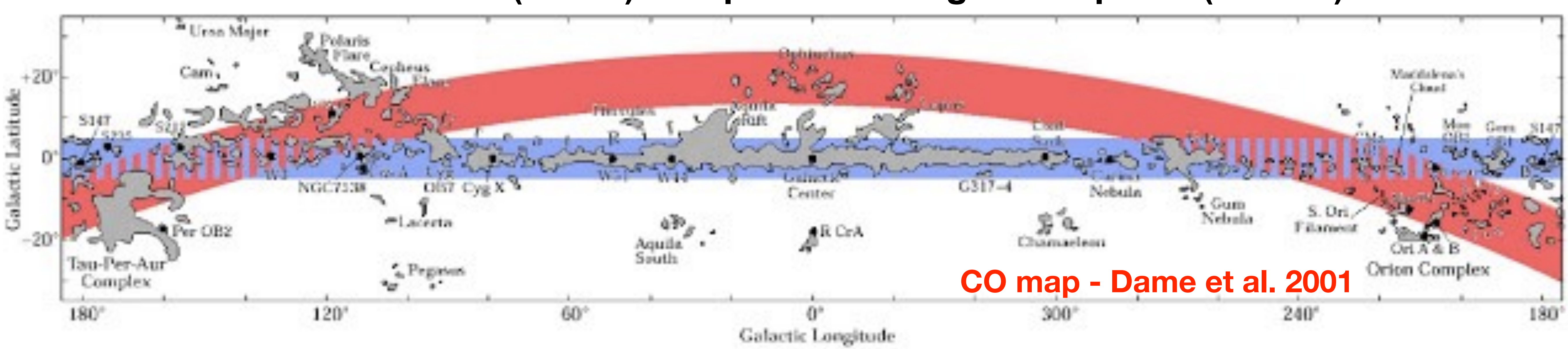




List of the high altitude molecular clouds used in the stacking analysis

Names	GLON, GLAT	D_{kpc}	$M_{CO}(10^5 M_{Sun})$
Aquila Rift	24.138, 17.446	0.225 ± 0.06	1.5
Taurus	171.038, -15.316	0.40 ± 0.03	0.3
Rho Oph	354.337, 16.822	0.125 ± 0.02	0.3
Orion A	211.834, -18.795	0.49 ± 0.05	1.6
Orion B	205.142, -13.689	0.49 ± 0.05	1.7
Per OB2	159.094, -20.532	0.315 ± 0.03	1.3
Mon R2	214.247, -12.410	0.830 ± 0.08	1.2
Dame et al. 1987	Center of the templates	Schlafly et al. 2014	Dame et al. 1987

The Gould Belt (in red) compared to the galactic plane (in blue)



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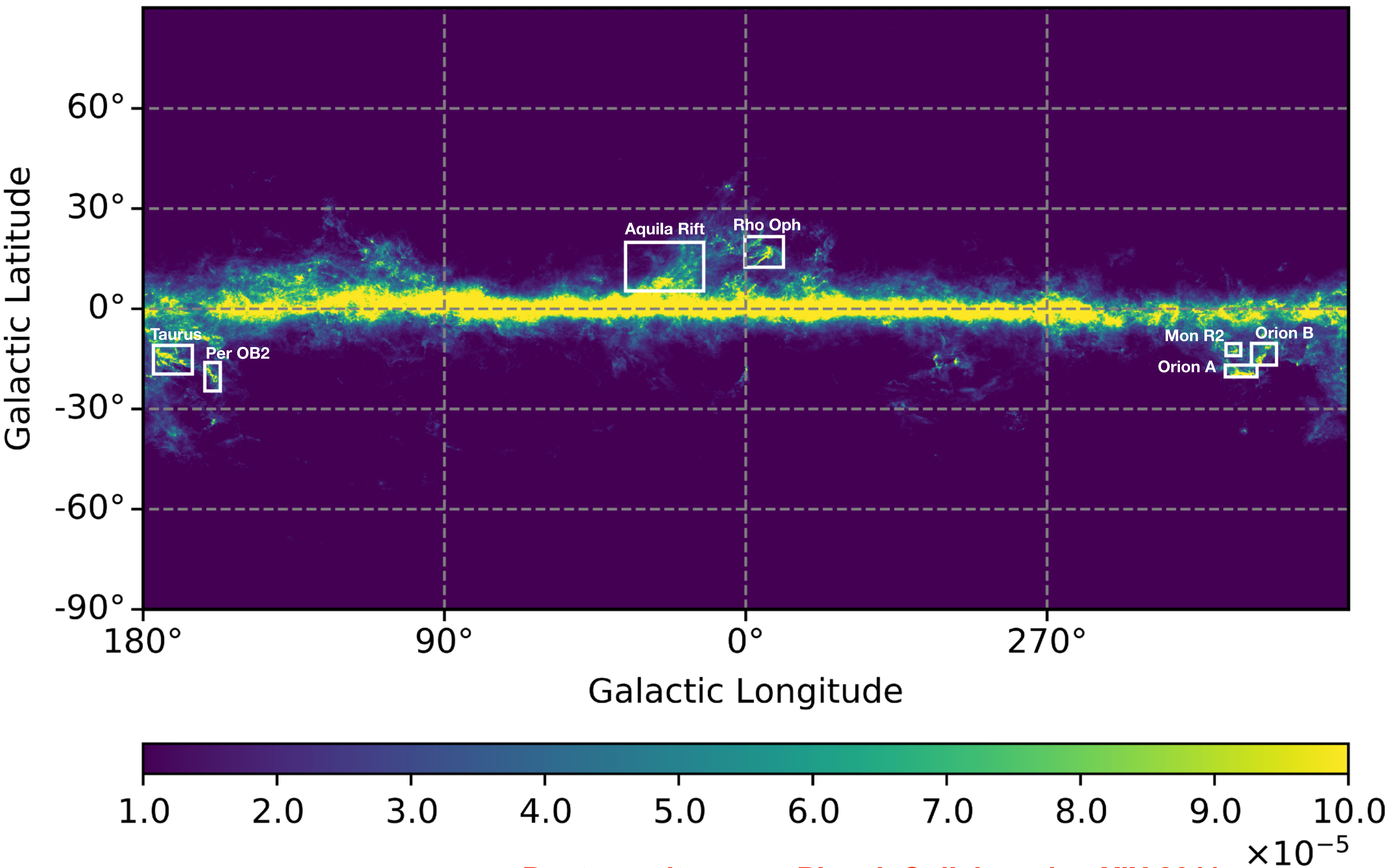
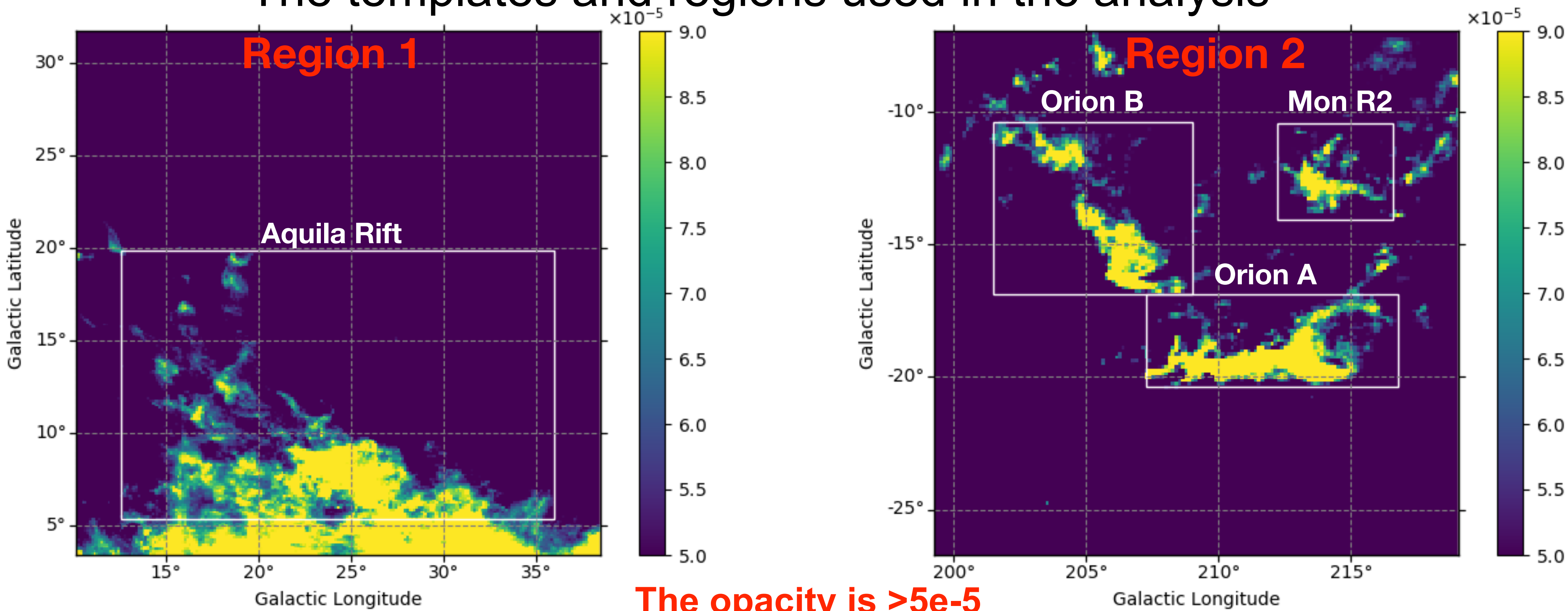
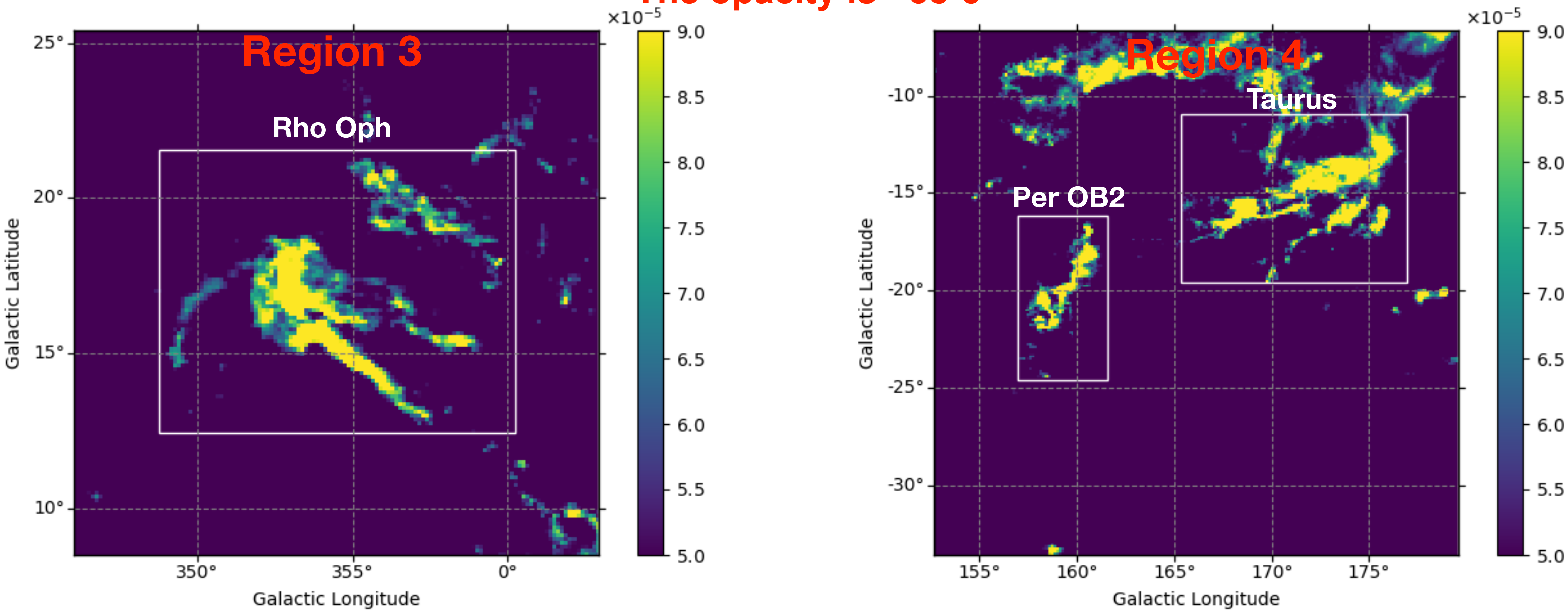


Dust opacity map - Planck Collaboration XIX 2011

The templates and regions used in the analysis



The opacity is >5e-5



Dust opacity map - Planck Collaboration XIX 2011

Fermi LAT data selection and analysis of individual regions

Data selection

- Time period - 2008 Aug 04-2019 Aug 04
- Energy range - 3 GeV - 1 TeV

Standard analysis of selected 4 regions using Fermipy

- 4 spatial templates have been considered during each analysis: Cloud and diffuse galactic based on Planck dust maps, IC galprop and standard Fermi extragalactic isotropic emission templates
- 4FGL catalog
- PL model for cloud and Galactic diffuse emission

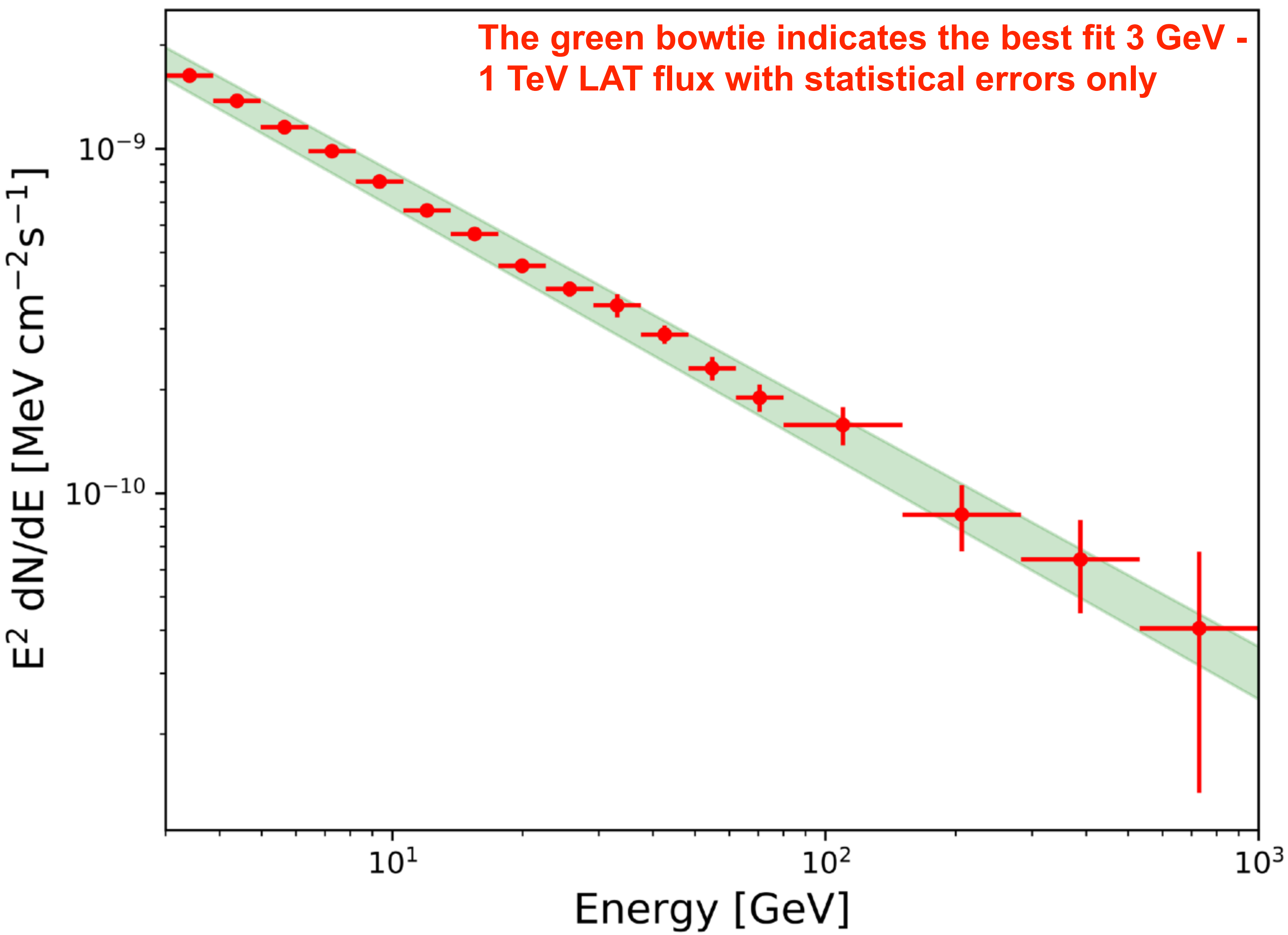
Region 1	$F\,[MeV\,cm^{-2}s^{-1}]$	Index	TS
Cloud	(3.93±0.06)e−04	−2.63±0.01	20919.01
Diffuse	(4.79±0.05)e−02	2.54±0.01	52435.46
Isodiff	(2.2±0.04)e−02	2.24	2997.83
IC	(1.97±0.05)e−02	0.24±0.03	30457.47

Region 2	$F\,[MeV\,cm^{-2}s^{-1}]$	Index	TS
Cloud	(1.32±0.03)e−04	−2.78±0.02	15645.45
Diffuse	(3.29±0.05)e−02	2.74±0.02	25337.72
Isodiff	(1.80±0.05)e−02	2.24	1446.25
IC	(3.18±0.04)e−02	0.20±0.08	751.37

Region 3	$F\,[MeV\,cm^{-2}s^{-1}]$	Index	TS
Cloud	(0.97±0.03)e-04	-2.67±0.03	6226.59
Diffuse	(4.30±0.08)e-02	2.66±0.02	15322.55
Isodiff	(2.16±0.08)e-02	2.24	720.76
IC	(2.96±0.06)e-02	-0.08±0.03	16409.94

Region 4	$F\,[MeV\,cm^{-2}s^{-1}]$	Index	TS
Cloud	(1.12±0.03)e−04	−2.72±0.03	10755.52
Diffuse	(2.99±0.03)e−02	2.78±0.01	60112.35
Isodiff	(1.80±0.04)e−02	2.24	2688.25
IC	(3.53±0.04)e−02	0.27±0.07	1040.19

Fermi-LAT stacking analysis



$$\frac{dN}{dE} = (3.15 \pm 0.02) \times 10^{-12} \left(\frac{E}{5000\, GeV} \right)^{-2.70 \pm 0.01}$$

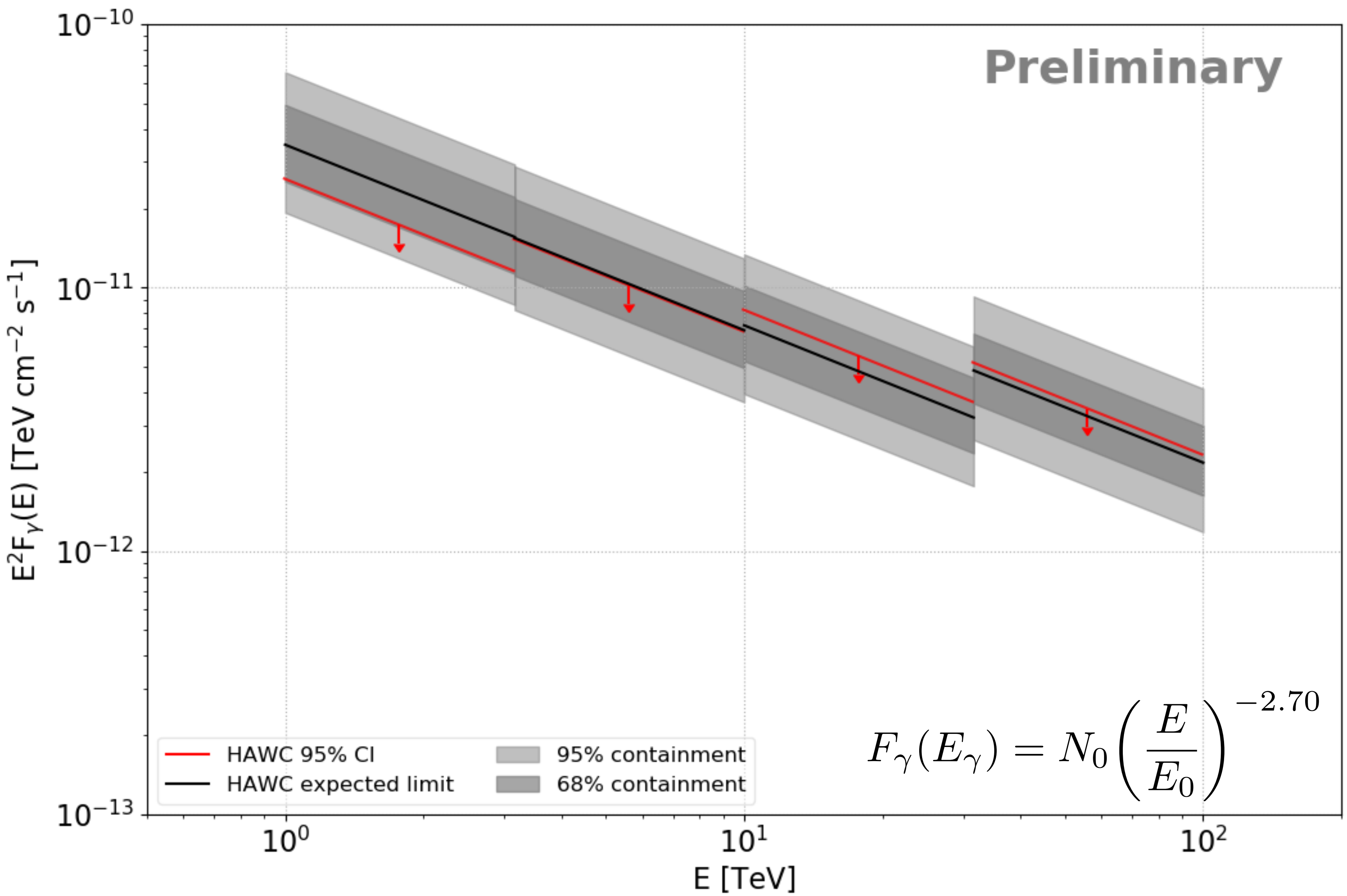
- The likelihood of all regions are summed tying prefactors and indexes of all clouds.
- The parameters of the rest point and extended sources are fixed to the best fit values of the analysis of individual regions.
- During the computation of the SED the index in each energy bin is fixed to the best fit value of global fit.
- (3-80) GeV and (80-1000) GeV energy ranges are divided in equal 13 and 4 logarithmic bins respectively.

https://github.com/fermi-lat/pyLikelihood/blob/master/python/Composite2.py

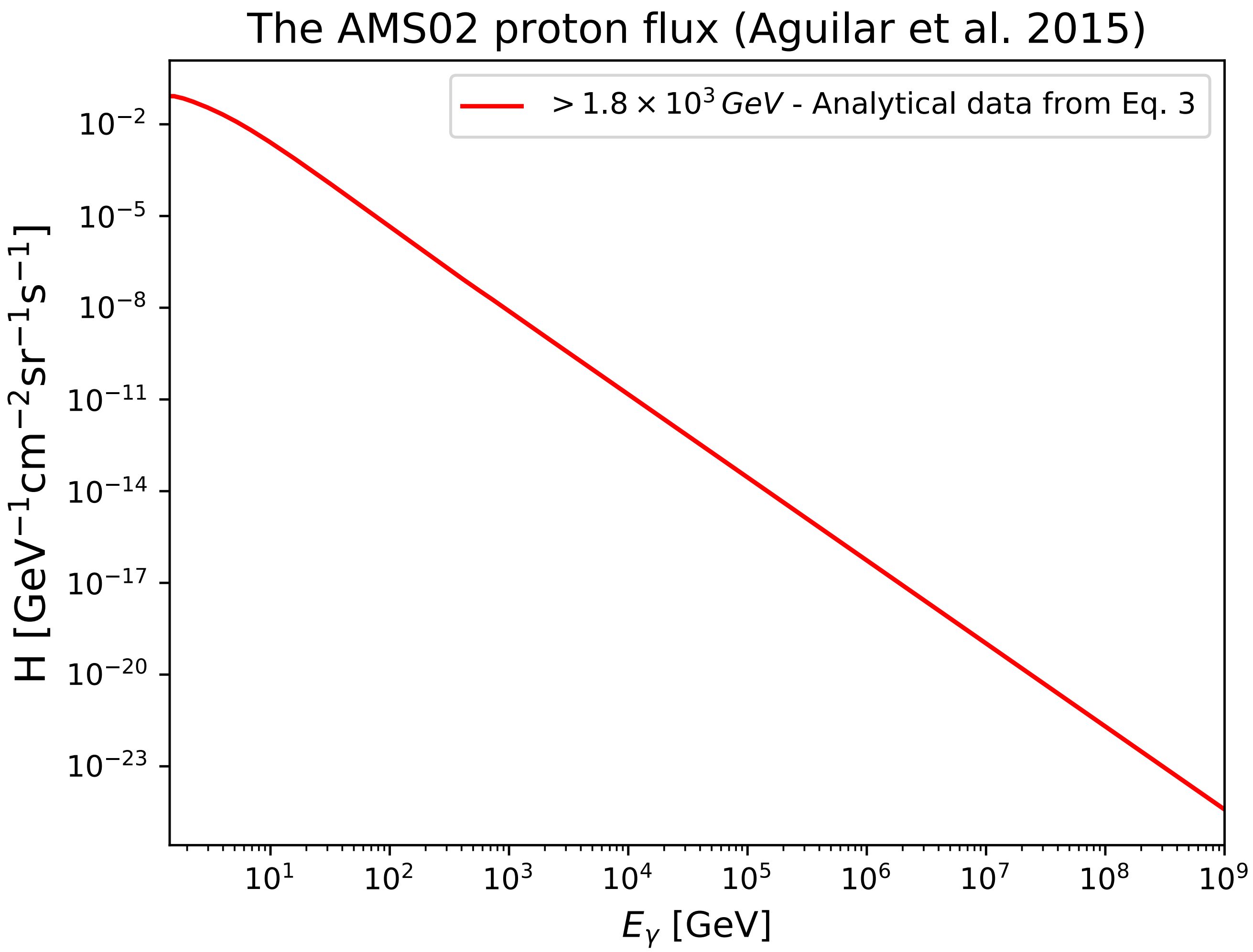
HAWC stacking analysis

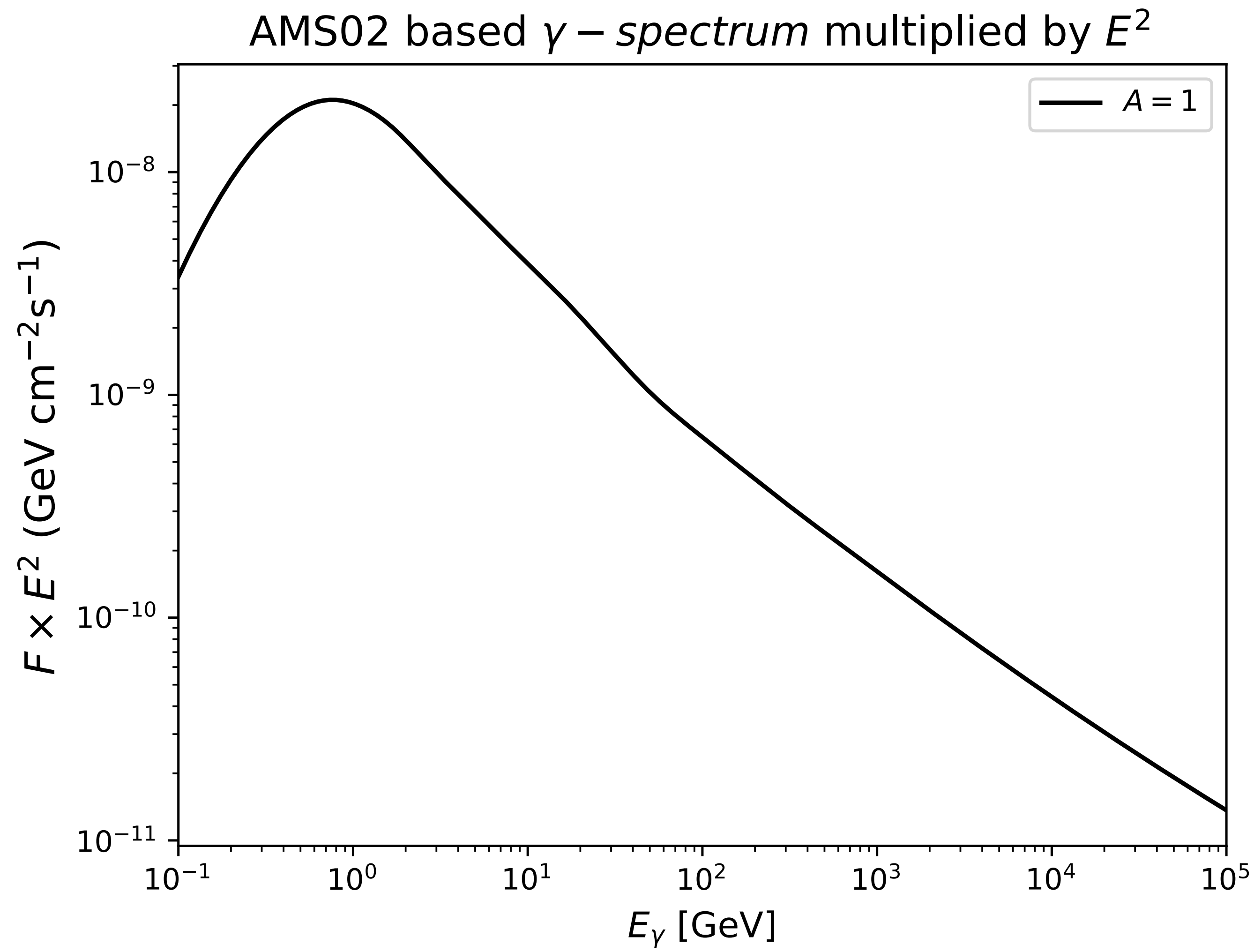
HAWC - HAL framework in addition to 3ML

- Standard fHit (the ratio of the number of hits of events over the total available PMTs) analysis with 37 months count maps (maps-20180523) and associated response
- Models defined by the same Planck dust maps used in Fermi-LAT analysis
- Model - PL (indexes were fixed to 2.7 like the CR flux index)
- 95% CL (CI) ULs for 4 equal logarithmic bins in 1-100 TeV energy range



AMS-02 based gamma-ray spectrum





Differential cross-section parametrisation (Kafexhiu et al. 2014)

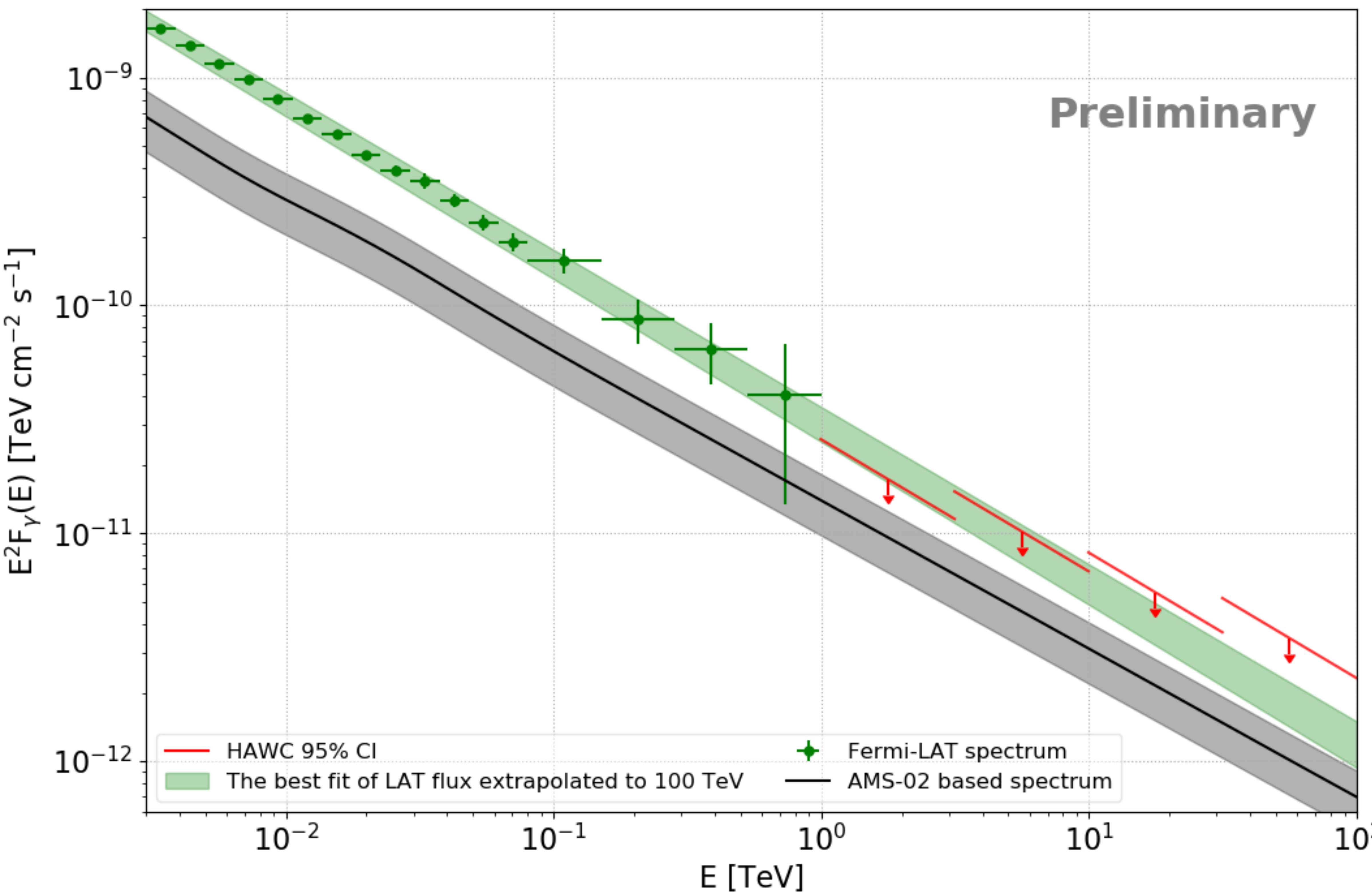
$$F_\gamma(E_\gamma) = 1.25 \times 10^{19} A \xi_N \int dE_p \frac{d\sigma}{dE_\gamma} F_p(E_p) \; (A = M_5/d_{kpc}^2, M_5 = M/M_{Sun})$$

CR proton spectrum reported by the AM (Aguilar et al. 2015)

$$M = m_H N_H A_{cloud} = m_H \tau_D / \left(\frac{\tau_D}{N_H}\right)^{ref} A_{angular} D^2 \qquad \left(\frac{\tau_D}{N_H}\right)^{ref} = (1.18 \pm 0.17) \times 10^{-26} cm^2$$

$\xi_N = 1.8$ **enhancement factor includes contribution of heavy nuclei from both the interstellar medium and CRs**

Fermi-LAT and HAWC joint gamma-ray spectrum



$$A_T = \sum_i \frac{M_i}{D_i^2} = 66.6\,(M_T = 6.11 \times 10^5 M,\ D_{eff} = 0.303\,kpc)$$

Summary & Future work

- 3 GeV - 1 TeV average spectrum is well described by a power-law with a spectral index of 2.70±0.01 in good agreement with the CR flux index although the normalization of the spectrum is slightly higher than the spectrum based on direct measurements of local CRs by the AMS02 experiment, which can imply non-homogeneous distribution of CRs at least within 1 kpc of the Local Galaxy.

- HAWC's 95% C.I. combined upper limits in 1-100 TeV energy range provides no constrain on Fermi-LAT's spectrum and more years of operation are needed to make a definite conclusion in physical models above 1 TeV.

- HAWC measurements don't show evidence against the paradigm that the 'sea' of cosmic rays flux is the same in the whole galaxy.

Derive average energy spectra of CR protons from the Fermi-LAT data and HAWC's ULs with Naima fit and compare it with AMS-02 experimental data.

Thank You!