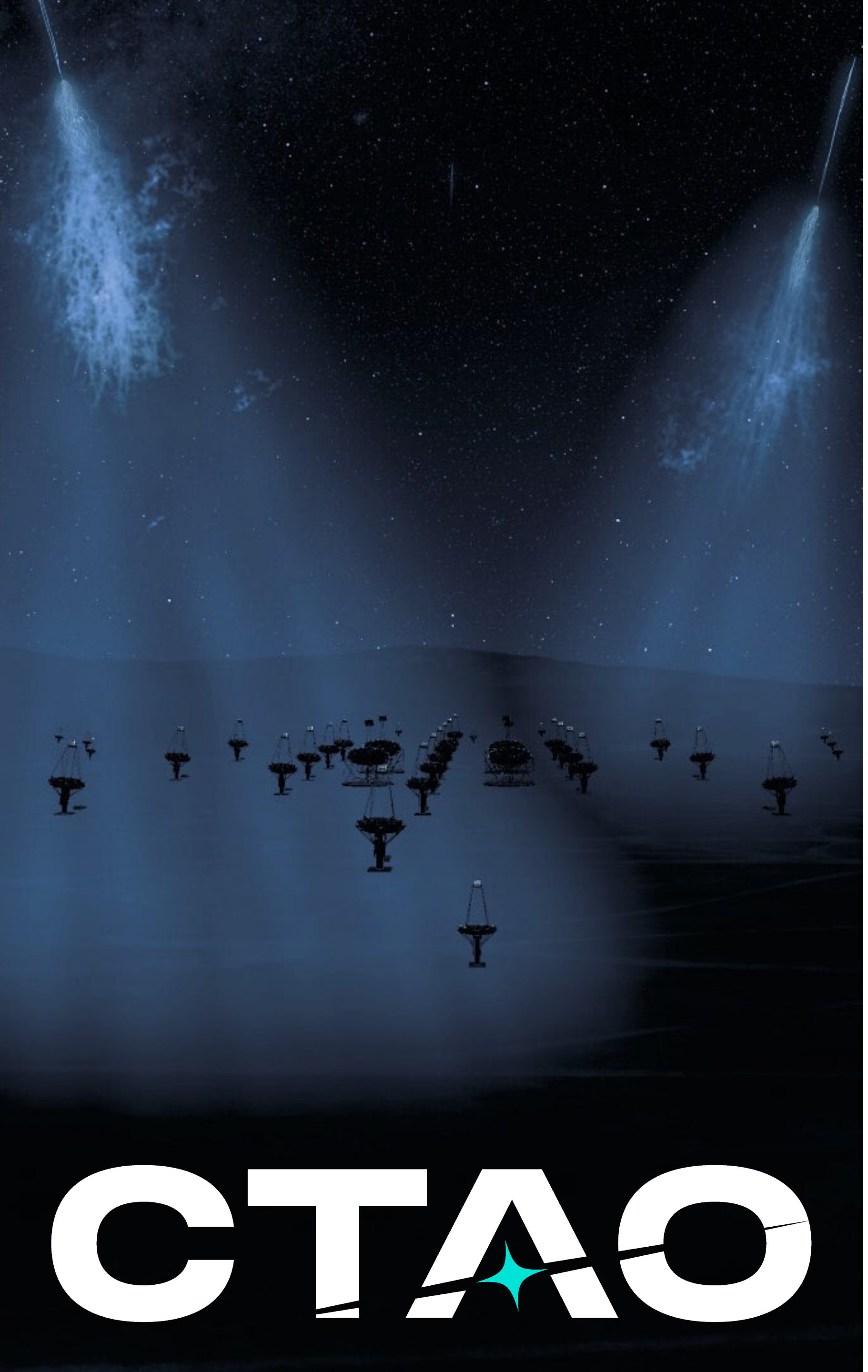

Searching for New Physics with the CTAO

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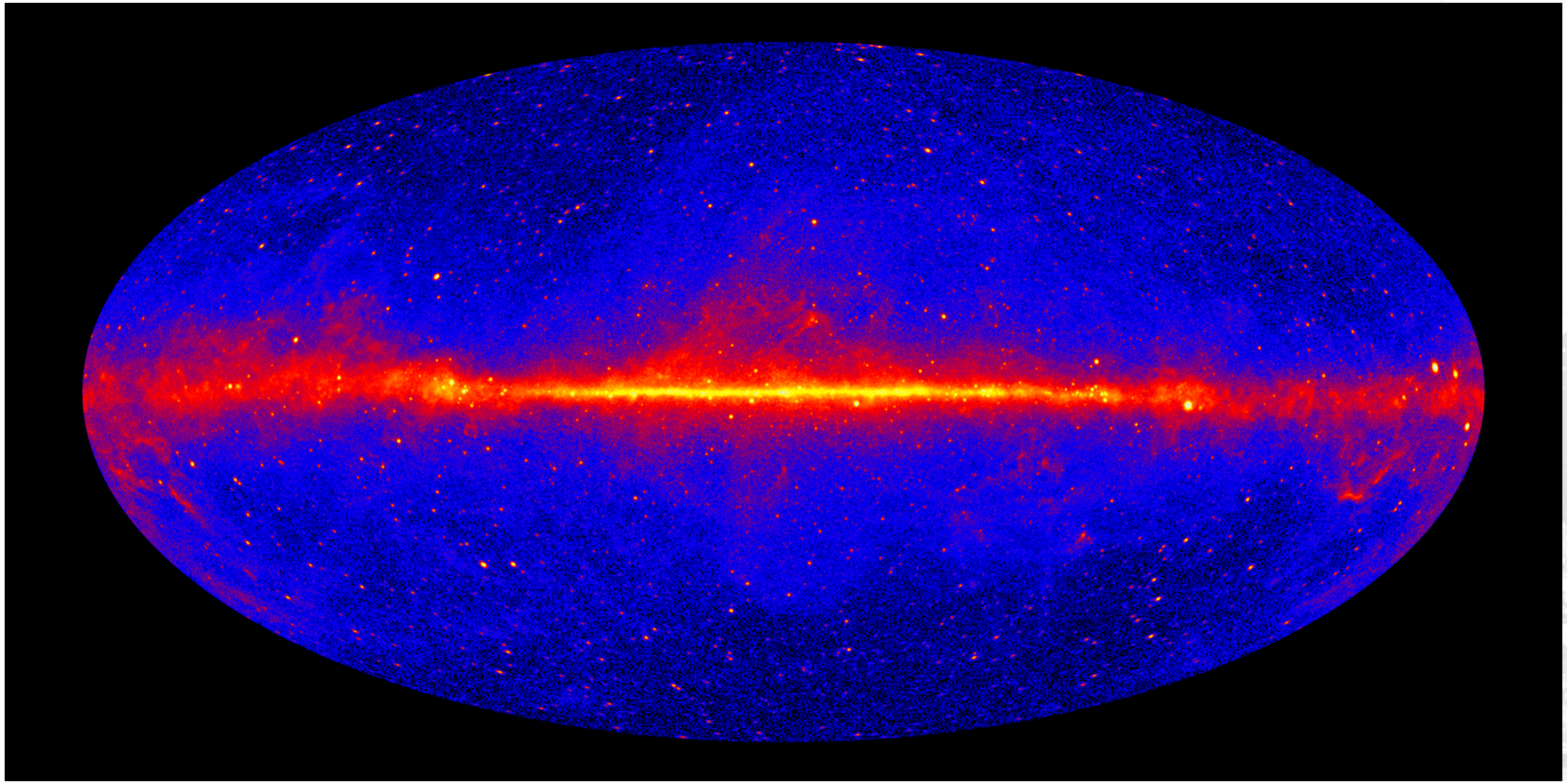
Overview

- We want to determine whether CTAO can distinguish between MSP and DM origins for the GCE.
- Model gamma-ray emission from a population of MSPs in the galactic centre. Analyse using GammaPy. Detection of sources indicates that CTAO would be able to discern differences in spatial morphology of emission that would separate the MSP and DM cases.
- Method closely follows that of (Gautam et al., 2022).



Single MSP Model

- Two TeV MSP emission components: “prompt” gamma-rays, and secondary gamma-rays.
- Prompt gamma-rays are emitted directly from the magnetosphere, while secondary gamma-rays arise from inverse Compton scattering of escaped electrons and positrons ($e^{\pm}$) off the ISRF.
- Prompt and $e^{\pm}$ emission spectrum in particles/GeV/s/cm2 given by exponential-cutoff power law:
  - $$F(E_i) = K\left(\frac{E_i}{E_{i,cutoff}}\right)^{\gamma_i}\left(e^{-\left(\frac{E_i}{E_{i,cutoff}}\right)^{\beta}}\right)$$
- K is a normalisation obtained by integrating. It is proportional to the prompt luminosity.
- Spin-down power, prompt spectral index, and prompt cutoff energy are assigned to MSPs randomly.
- Prompt luminosity taken as a small percentage of the spin-down power (~5 – 10%). The rest of the spin-down power is assumed to be lost to $e^{\pm}$ emission.

Single MSP Model

- The $e^{\pm}$ spectral parameters can be obtained from the prompt spectral parameters.
- The $e^{\pm}$ luminosity is whatever is left of the spin-down power after subtracting the prompt luminosity.
- Prompt spectral index and cutoff energy connected to $e^{\pm}$ by the following relations:
  - $\gamma_{prompt} = \frac{\gamma_{e^{\pm}} - 1}{3}$
  - $E_{prompt,cutoff} = \frac{3\hbar c}{2\rho_c}(\frac{E_{e^{\pm},cutoff}}{m_e c^2})^3$
- Where ρ_c is the radius of the MSP light cylinder. This is kept constant.

Spatial Model

- MSPs sampled from boxy bulge stellar density (Freudenreich, 1998):

$$\rho_{boxy\,bulge}(R_s) \propto sech^2(R_s) \begin{cases} 1, & R \leq R_{end} \\ exp(-(R - R_{end})^2/h_{end}^2), & R > R_{end} \end{cases}$$

- Where R_{end} = 3.128 kpc, h_{end} = 0.461 kpc, and:

$$R = \sqrt{x^2 + y^2}$$

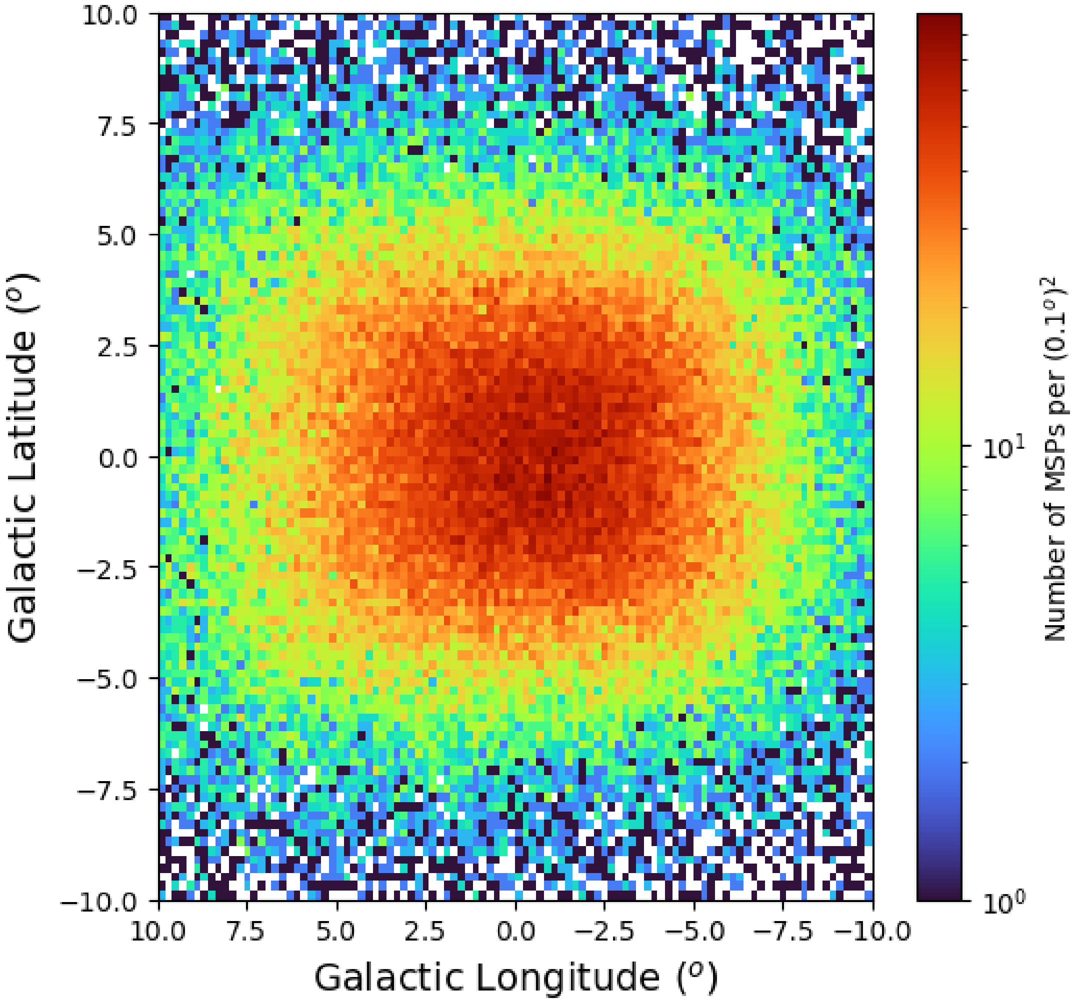
$$R_s^{C_\parallel} = R_\perp^{C_\parallel} + \left(\frac{|z'|}{0.4425\,kpc}\right)^{C_\parallel}$$

$$R_\perp^{C_\perp} = \left(\frac{|x'|}{1.696\,kpc}\right)^{C_\perp} + \left(\frac{|y'|}{0.6426\,kpc}\right)$$

- Each MSP is also assigned a local ISRF energy-density that scales with the stellar density. This is used when calculating inverse Compton emission using the Naima python package.

Spatial Model

- MSPs number density (per 0.1 degrees squared) from this model:



Spatial Model

- Assign each MSP a local $e^{\pm}$ energy loss time:

$$t_{total} = (1/t_{brem} + 1/t_{syn} + 1/t_{IC})^{-1}$$

$$t_{brem} = 4.0 \times 10^7 (\frac{n_H}{cm^{-3}})^{-1} yr$$

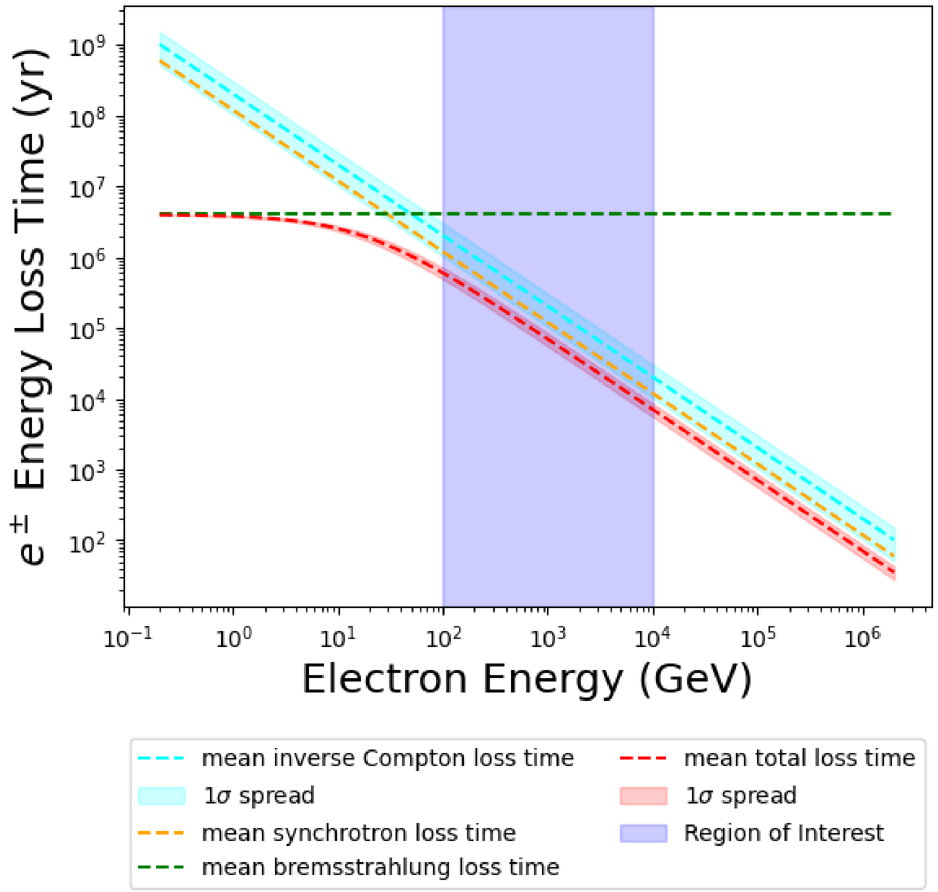
$$t_{syn}(E_e) = 12 \times 10^6 (\frac{B}{\mu G})^{-2} (\frac{E_e}{TeV})^{-1} yr$$

$$t_{IC}(E_e) = 3.1 \times 10^8 (\frac{U_{rad}}{eVcm^{-3}})^{-1} (\frac{E_e}{GeV})^{-1} yr$$

- Only the radiation field energy density U_{rad} is allowed to change per MSP. The magnetic field B and hydrogen gas density n_H are kept constant.

Inverse Compton Emission

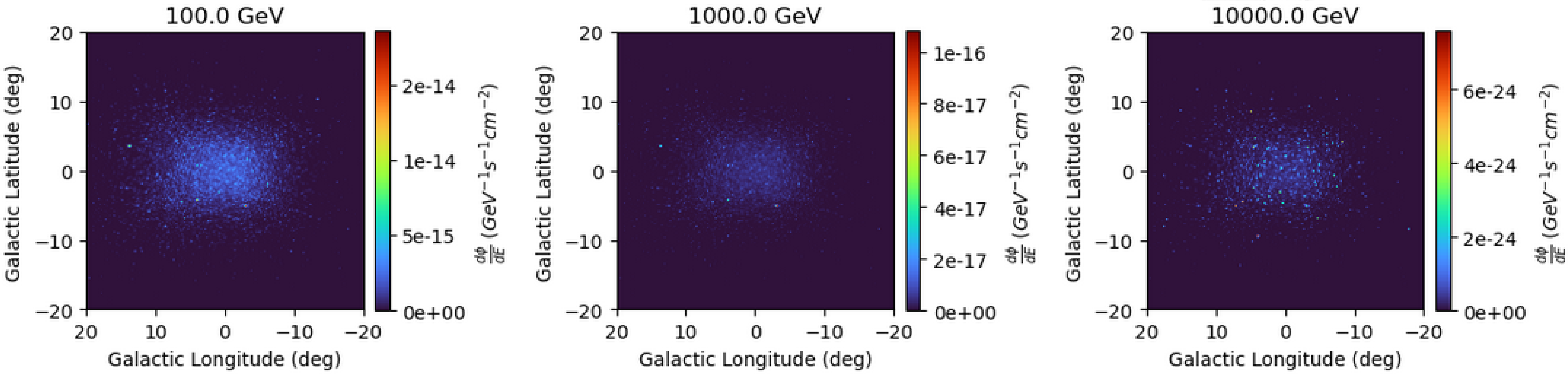
- Loss time is multiplied with the e± emission spectrum to obtain a steady-state e± distribution (GeV-1) per MSP.



- This is then passed to the Naima python package to calculate the inverse Compton gamma-ray emission.

Spatial Model

- MSP population weighted by flux (GeV-1 s-1 cm-2) at various energies:



Diffusion

- Apply diffusion to $e^{\pm}$ to get extended inverse Compton emission.

$$d(E_{e^{\pm}}) = \sqrt{6\, D(E_{e^{\pm}})\, t_{total}(E_{e^{\pm}})}$$

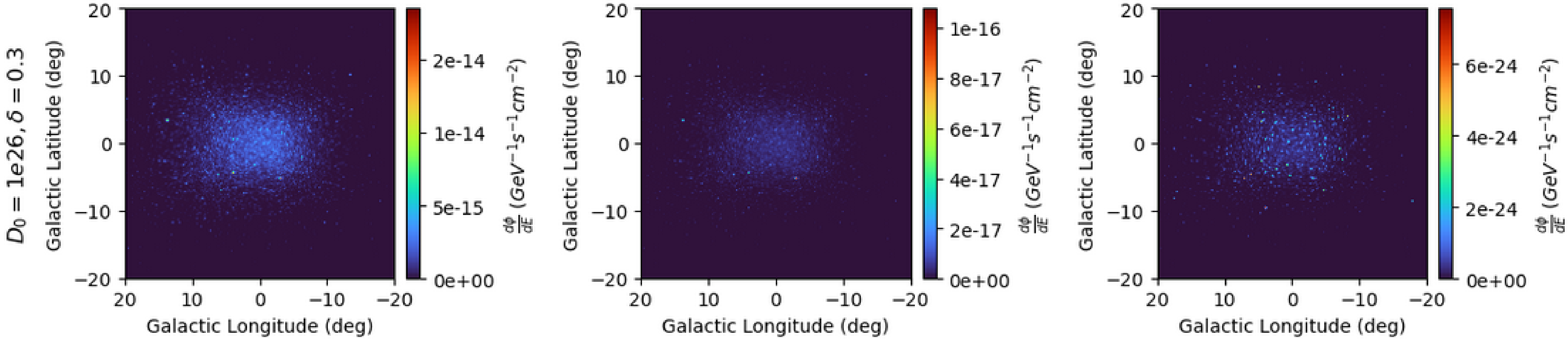
- Use the loss times shown previously and the following diffusion coefficient:

$$D(E_{e^{\pm}}) = \chi(\frac{E_{e^{\pm}}}{E_{ref}})^{\delta}$$

- The amplitude χ takes values 1e26 – 1e29 (cm2 s-1), which have corresponding δ values of 0.3 – 0.5.

Diffusion

- When applied as a Gaussian blur to the previous image:



Diffusion

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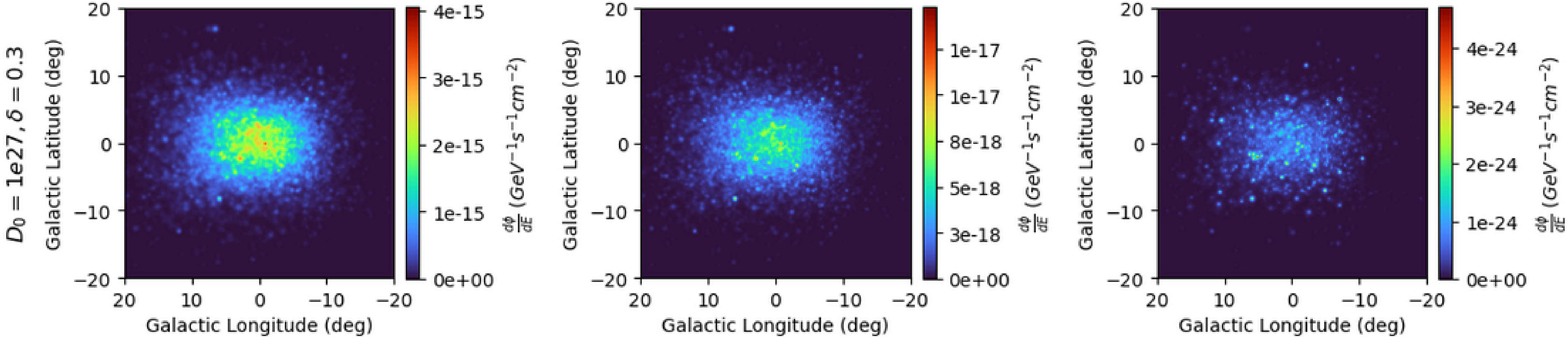

Diffusion

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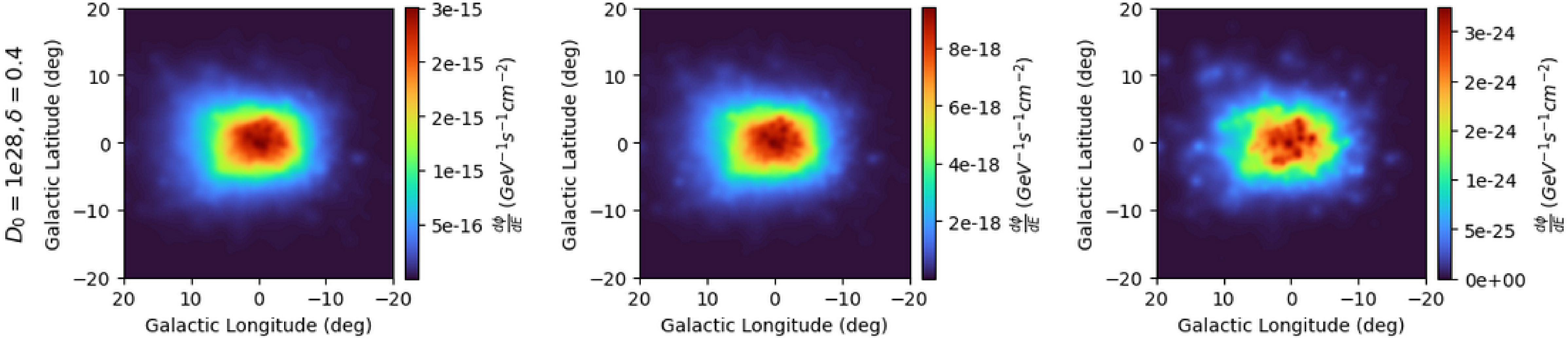

Diffusion

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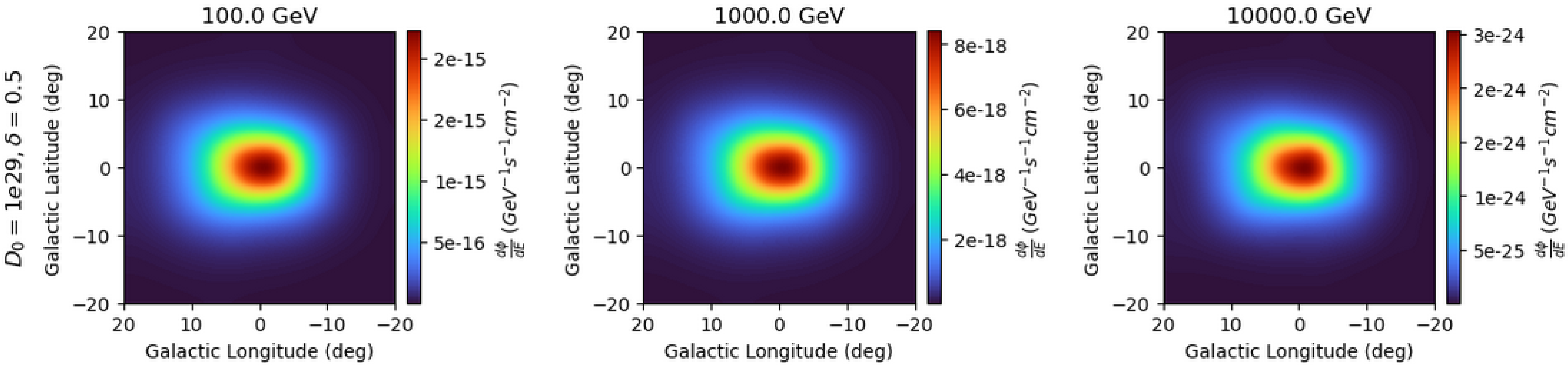
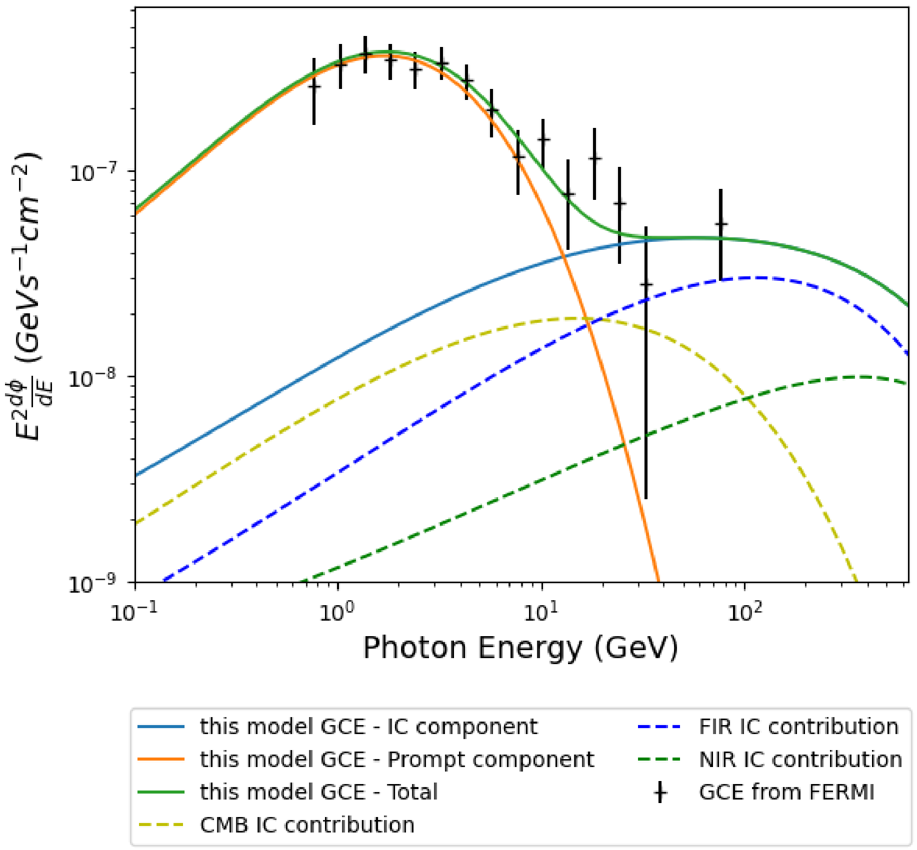
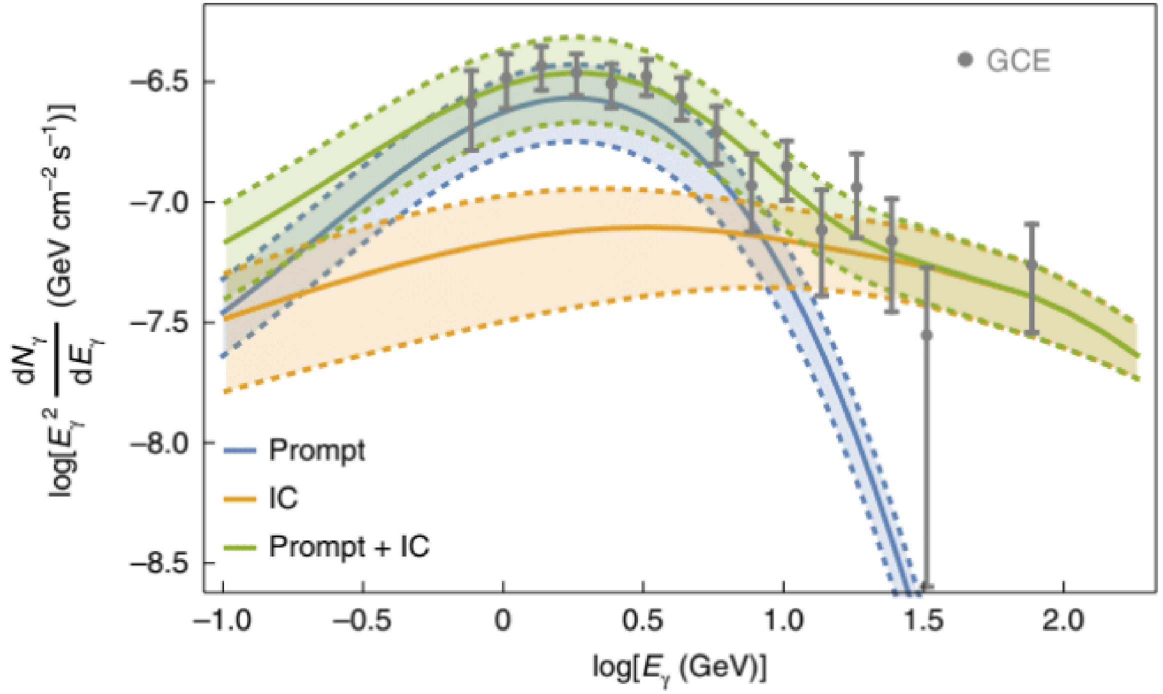


Results

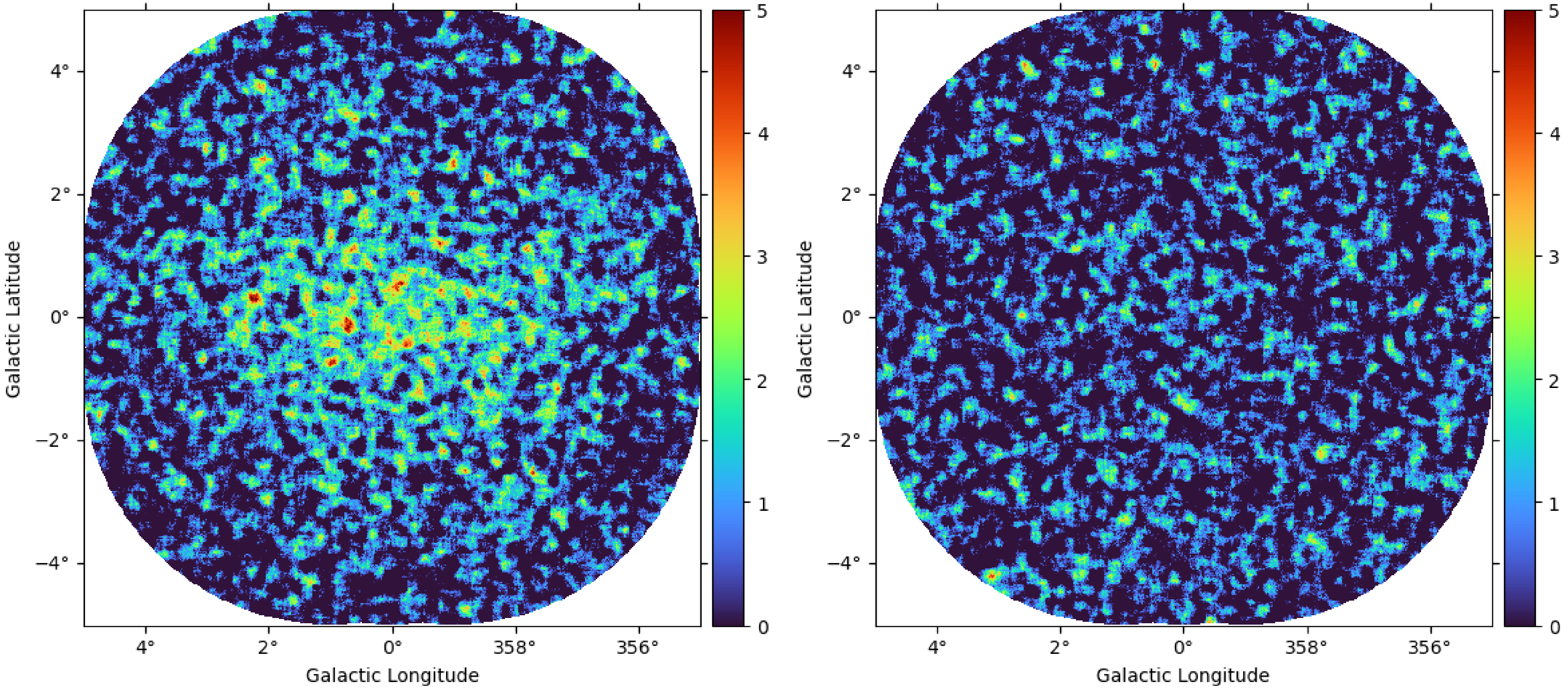
- Model (left) successfully reproduces the FERMI-LAT excess.
- Gamma-ray fluxes are not identical to those of (Gautam et al., 2022) (right), but this is because we calculate inverse Compton flux per MSP instead of fitting the residual from the prompt flux.





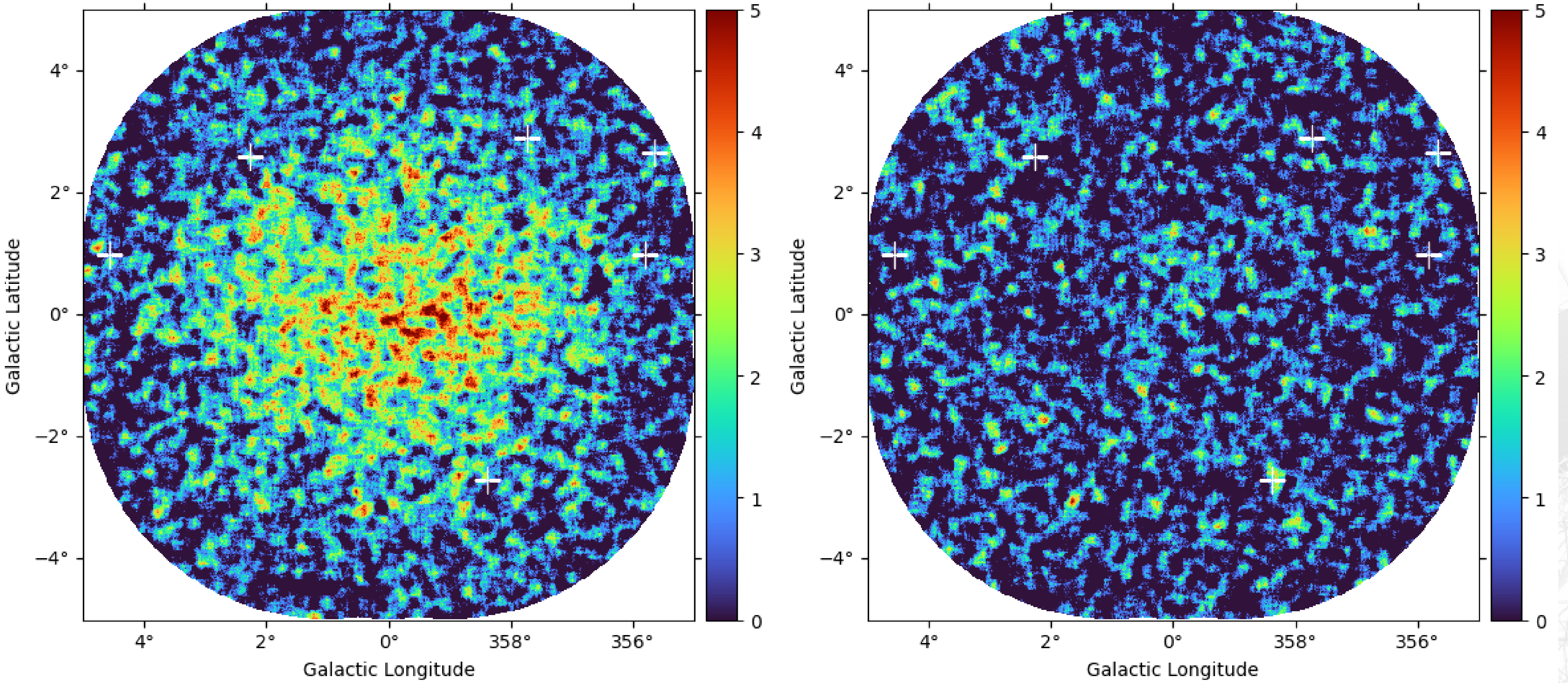
Results

- Background for energies 0.1 – 1.0 TeV (left) and 1.0 – 10 TeV (right). Generated by running GammaPy's ExcessMapEstimator on a stacked counts dataset of a zero datacube.



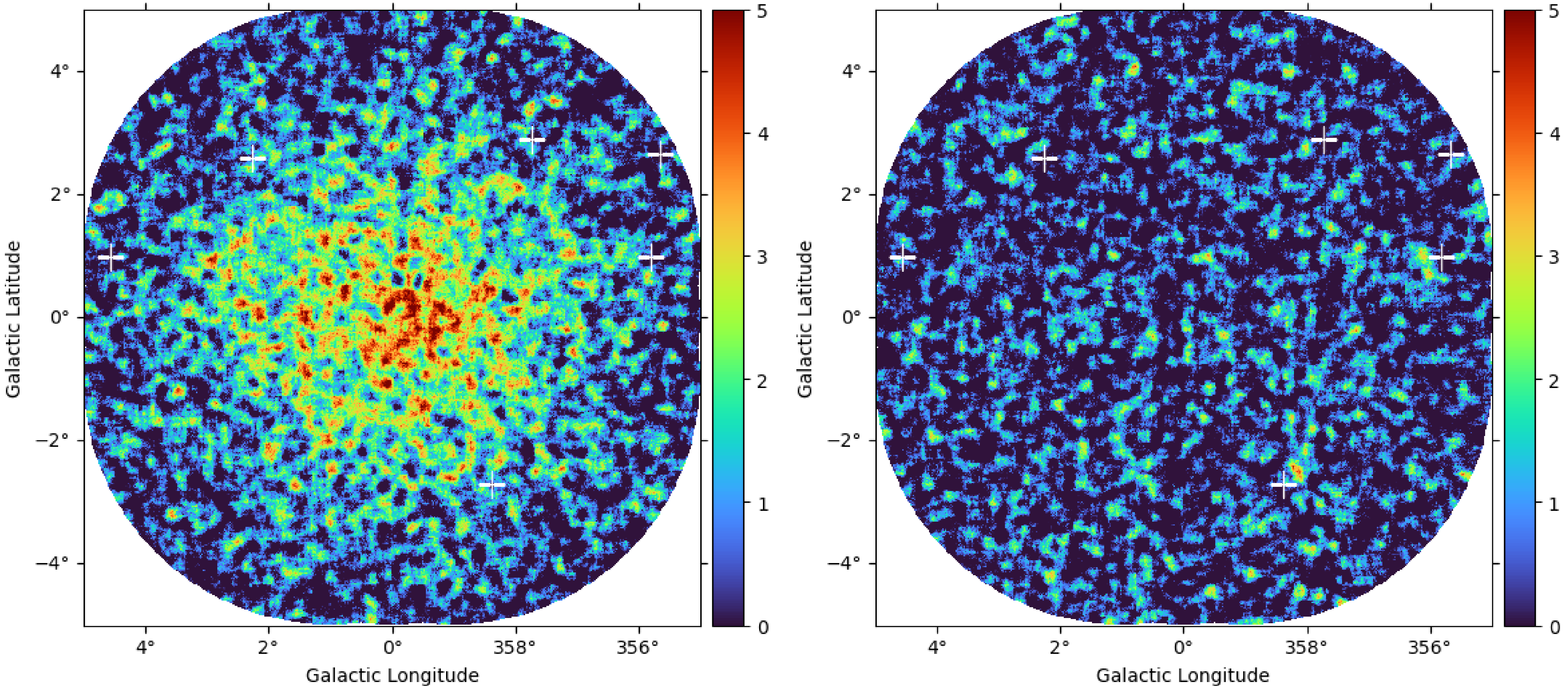
Results

- Significance maps for χ=1e26 (cm2 s-1) from GammaPy analysis using ExcessMapEstimator from 0.1 – 1.0 TeV (left) and 1.0 – 10.0 TeV (right). Locations of the brightest MSPs are marked with white crosses.



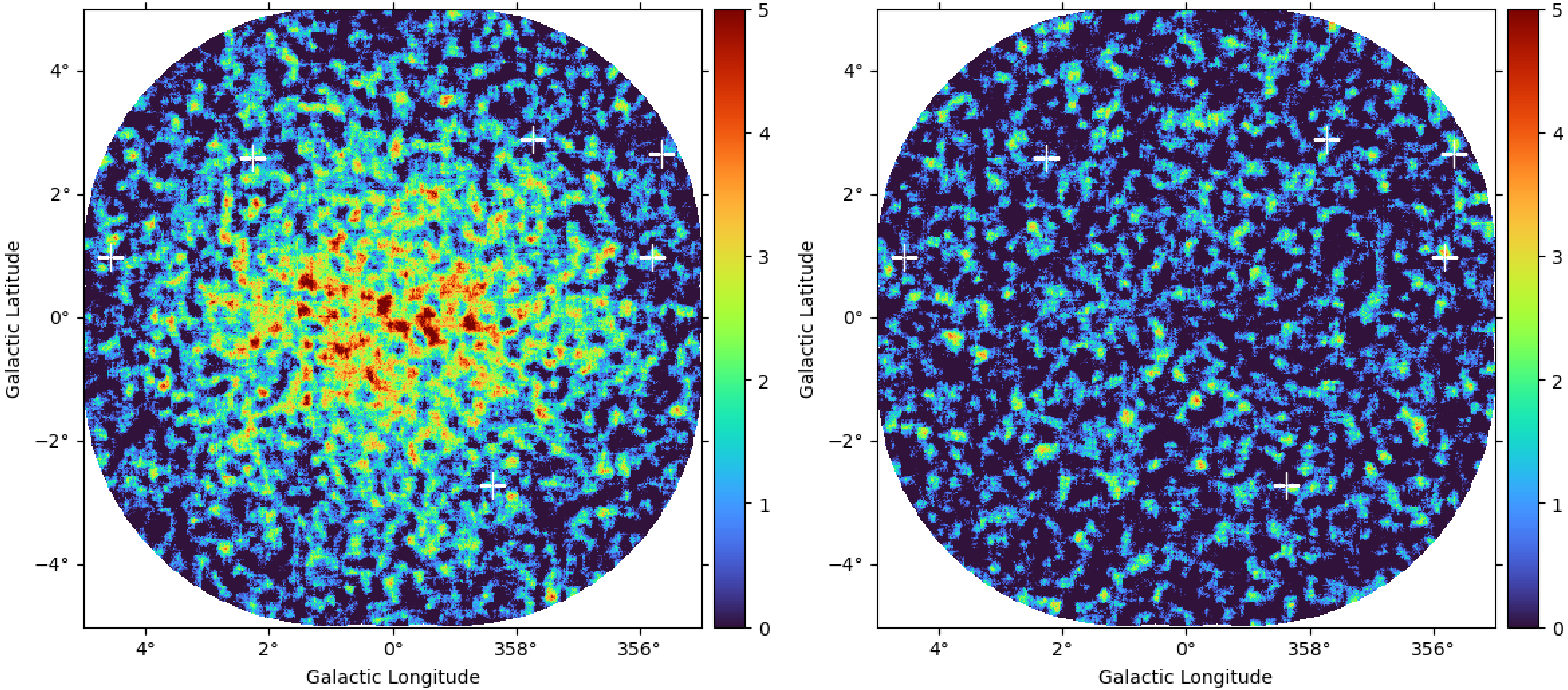
Results

- Significance maps for χ=1e27 (cm2 s-1) from GammaPy analysis using ExcessMapEstimator from 0.1 – 1.0 TeV (left) and 1.0 – 10.0 TeV (right). Locations of the brightest MSPs are marked with white crosses.



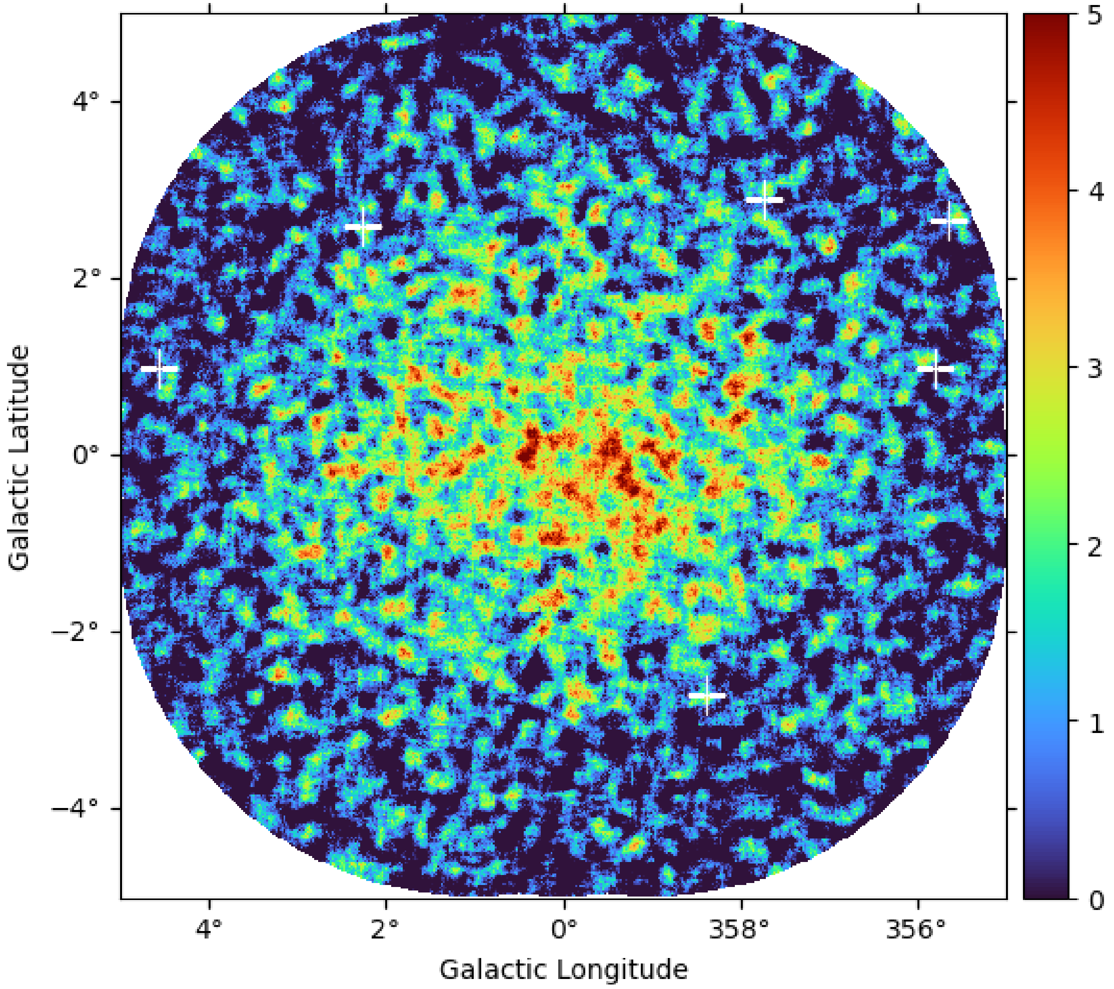
Results

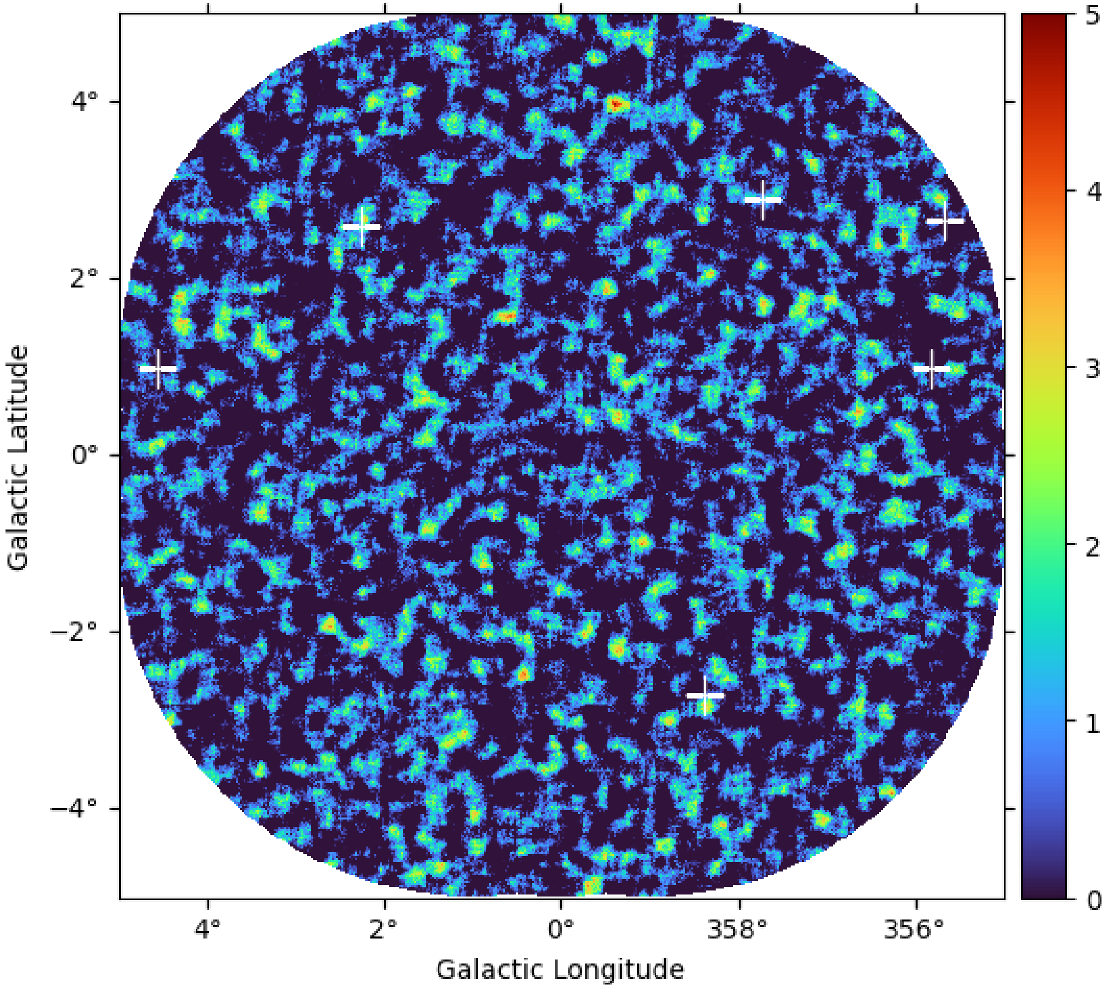
- Significance maps for χ=1e28 (cm2 s-1) from GammaPy analysis using ExcessMapEstimator from 0.1 – 1.0 TeV (left) and 1.0 – 10.0 TeV (right). Locations of the brightest MSPs are marked with white crosses.



Results

- Significance maps for χ=1e29 (cm2 s-1) from GammaPy analysis using ExcessMapEstimator from 0.1 – 1.0 TeV (left) and 1.0 – 10.0 TeV (right). Locations of the brightest MSPs are marked with white crosses.





Results

- We note that the areas of highest significance are generally not coincident with the brightest MSPs.
  - Indicates that any detected sources will comprise contributions from multiple MSPs.
- Also note that significance tends to decrease when moving away from the centre.
  - Indicates that a high number density of MSPs is needed to produce observable gamma-ray emission. So the significance is highest in the centre because there are more MSPs along line of sight, and therefore more contributions to the total gamma-ray flux.
- At higher energies, significance is only slightly higher than the background, but there are few areas of high significance that would indicate sources, so detections with CTAO inconclusive.
  - Subtracting the background could help here.
  - As yet, there has been no spectral/spatial model fitting to these sources. Prospects may improve with a more thorough analysis.

Conclusions

- A population of MSPs according to out model can reproduce the GCE.

- Gamma-ray emission from this population can reach 5σ.

- We still observe sporadic areas of high significance at higher energies (1.0 – 10.0 TeV), although not much difference from the background at these energies. However, analysis is incomplete.

- A population of MSPs can indeed produce gamma-ray emission that is resolvable with a high significance with CTAO.

Next Steps

- What if the model used is significantly different to that proposed by (Gautam et al., 2022)? It may be worthwhile to investigate different models, particularly luminosity/spin-down power distributions. How dim do the MSPs need to be before we stop seeing point-like sources?

- More extensive CTAO analysis is needed beyond just finding areas of high significance. Spectral and spatial models can be fit to sources.

- Might be useful to subtract off the background when generating significance maps.

- Could we investigate emissions from this population of MSPs at other wavelengths, for example X-rays or radio?

Questions?