

# Modelling MSP Populations for CTAO Analysis – A Brief Update

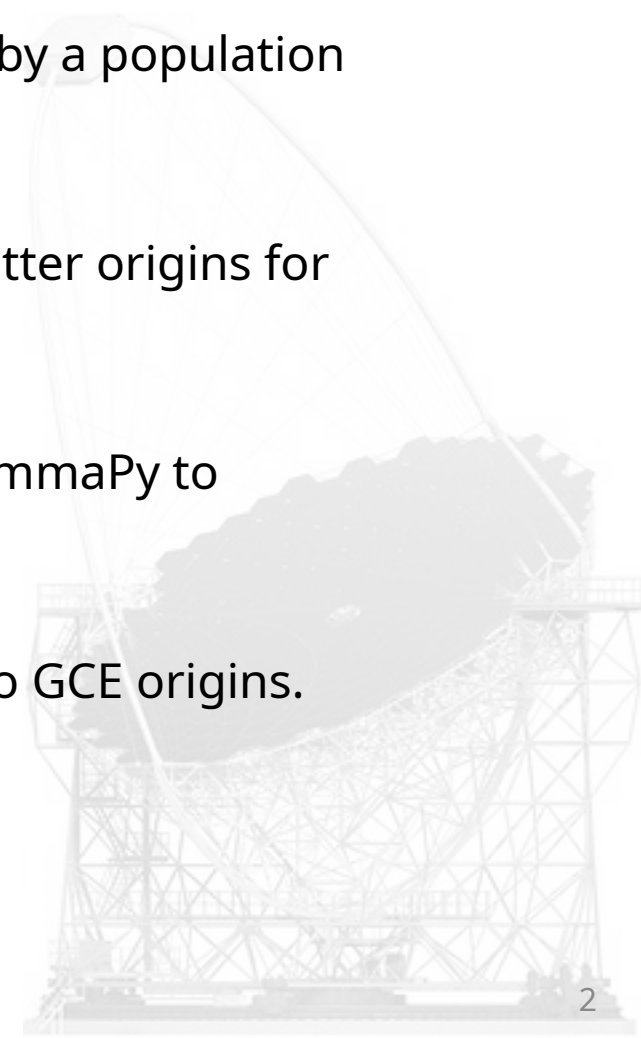
**Hayden James, Prof. Martin White, Prof.  
Gavin Rowell, Dr. Sabrina Einecke**

**CTAO**



April 28th, 2026

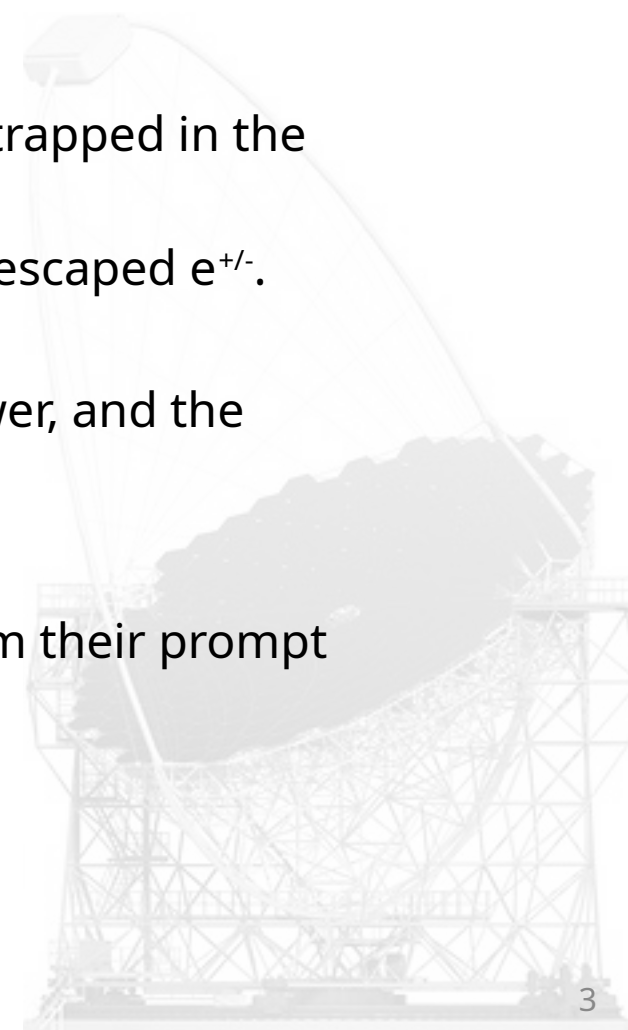
- ◆ Galactic Centre gamma-ray Excess (GCE) is an excess flux of gamma-rays discovered by FERMI in the 2000s.
- ◆ Conflicting hypotheses claim the GCE can be produced either by dark matter, or by a population of as-yet unresolved millisecond pulsars.
- ◆ We want to determine whether CTAO can distinguish between MSP and dark matter origins for the GCE.
- ◆ We model a population of MSPs according to (Gautam et al., 2022). Then use GammaPy to produce significance maps of gamma-ray emission from the population.
- ◆ If point sources are seen, then CTAO will be able to differentiate between the two GCE origins.



# Single MSP Model

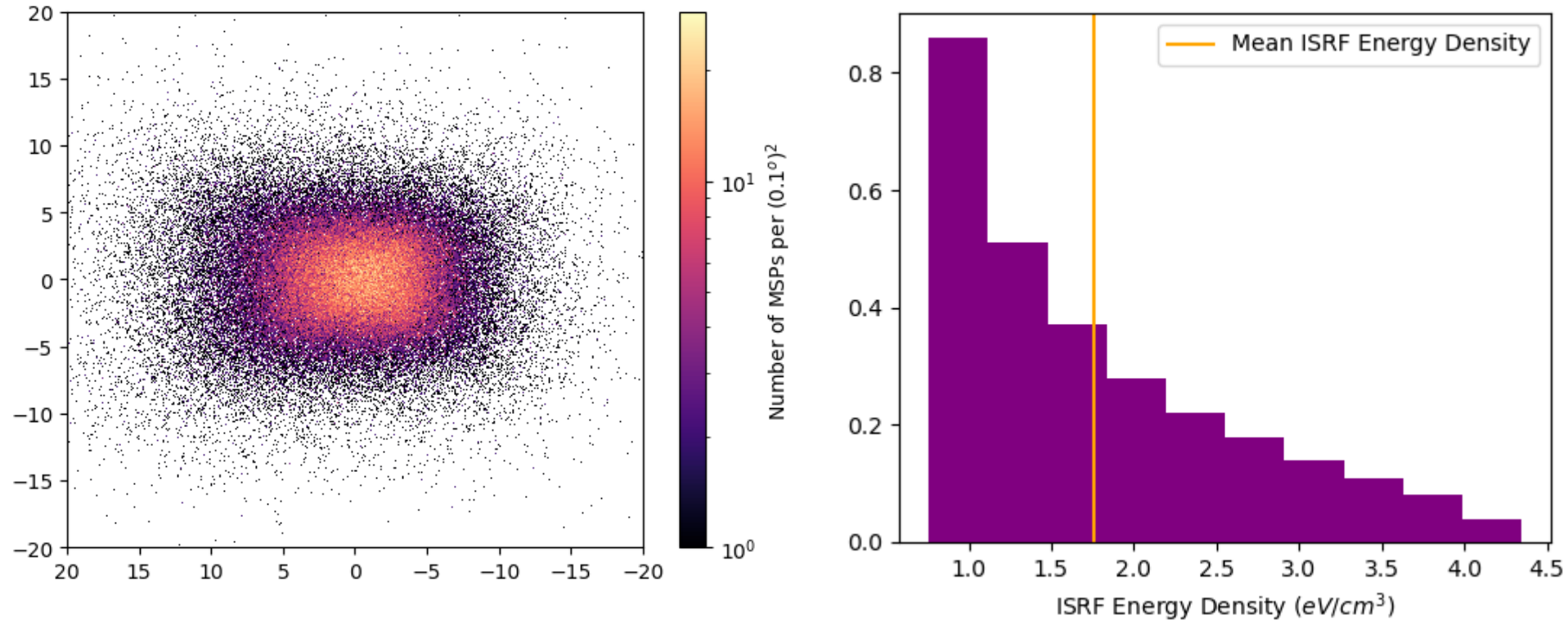
- ◆ Each MSP has three fundamental parameters: spin-down power; 'prompt' spectral index; and 'prompt' cutoff energy.
- ◆ An MSP emits gamma rays through two primary channels:
  - The 'prompt' component are gamma-rays emitted from charged particles trapped in the magnetosphere (i.e. curvature radiation).
  - The secondary component arises from inverse Compton (IC) scattering of escaped  $e^{\pm}$ . These are pair-produced at the edge of the magnetosphere.
- ◆ The luminosity in prompt gamma-rays is taken to be ~10% of the spin-down power, and the luminosity in  $e^{\pm}$  is set as the remainder.
- ◆ The spectral index and cutoff energy for the  $e^{\pm}$  component can be obtained from their prompt counterparts as follows:

$$E_{prompt,cutoff} = \frac{3\hbar c}{2\rho_c} \left( \frac{E_{e^{\pm},cutoff}}{m_e c^2} \right)^3 \quad \gamma_{prompt} = \frac{\gamma_{e^{\pm}} - 1}{3}$$



# Spatial Model

- ◆ MSP positions are drawn from a “boxy bulge” spatial profile, found in (Freudenreich, 1998). Following the findings of (Gautam et al., 2022), we use a population size of 129082.



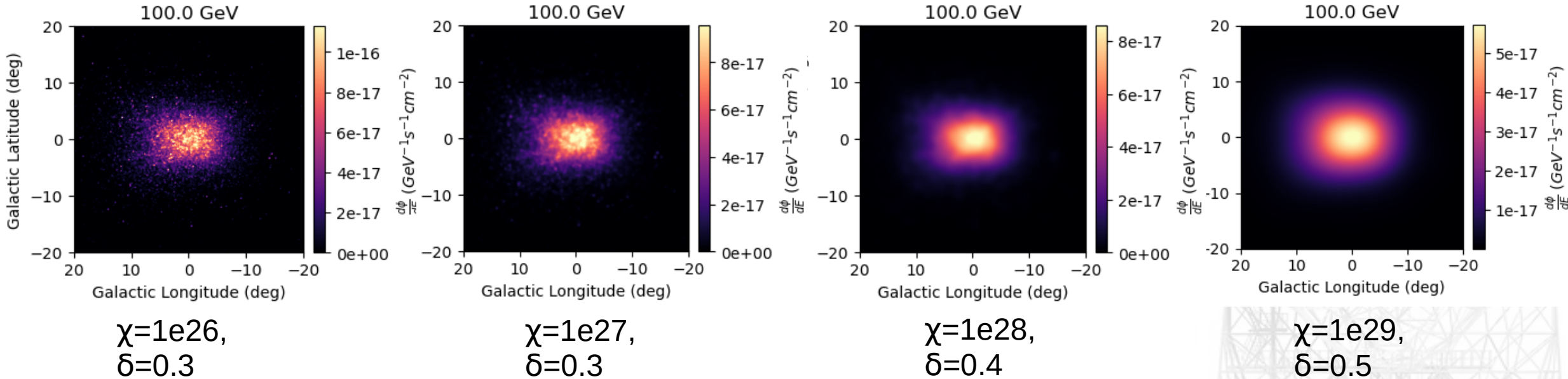
- ◆ Magnetic field is set to a constant 10  $\mu\text{G}$ .
- ◆ ISRF defined in three components, two of which are constant: CMB (2.72 K,  $0.26 \text{ eV}/\text{cm}^3$ ), FIR (30 K,  $0.5 \text{ eV}/\text{cm}^3$ ), and a NIR component with temperature 3000 K, and a spatially-variant energy density with an average value of  $1.0 \text{ eV}/\text{cm}^3$ .

# Diffusion Model

- The escaped  $e^{\pm}$  are allowed to diffuse before they interact and emit gamma rays. We apply a Gaussian blur when constructing the .fits files required by GammaPy to represent this. The blur is defined by a simple power law in energy:

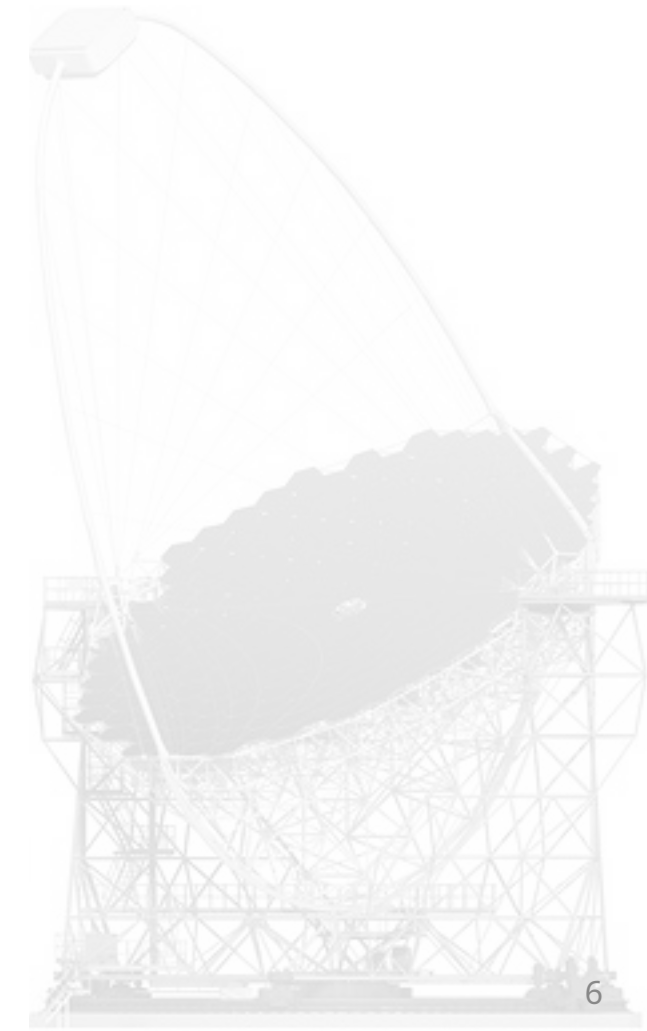
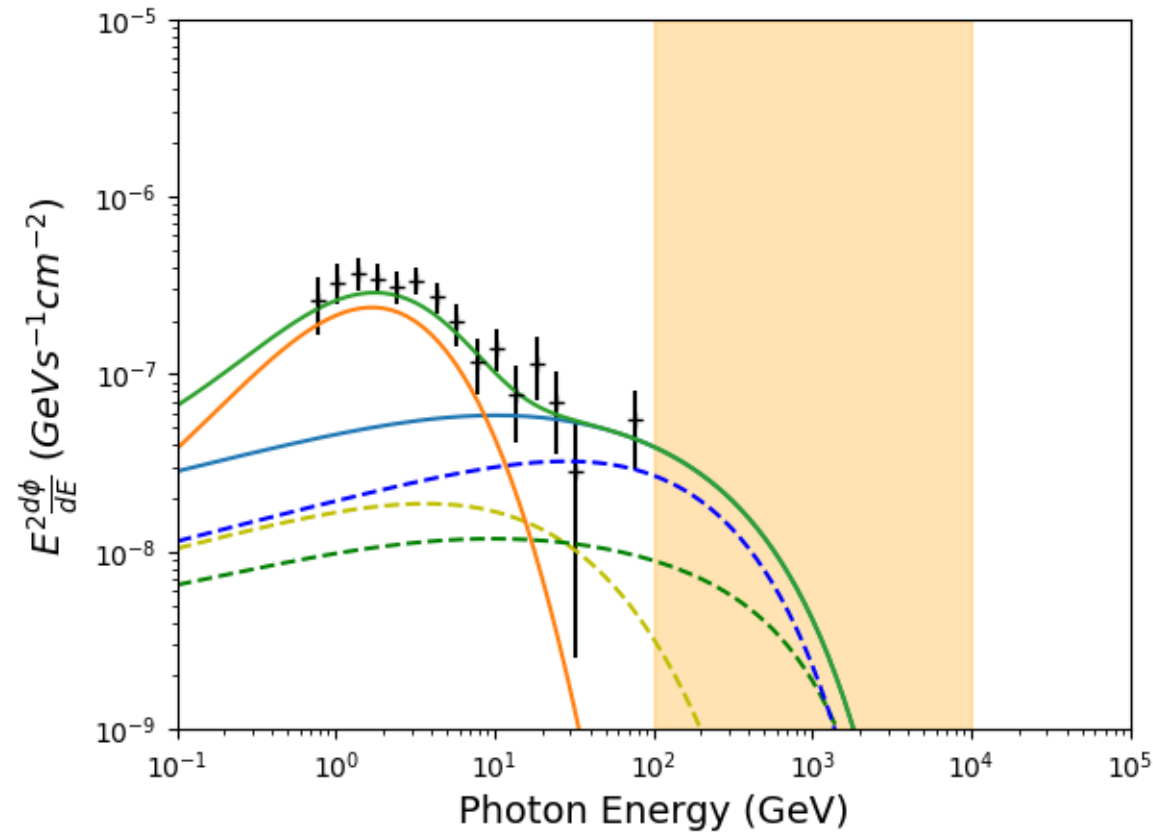
$$D(E_{e^{\pm}}) = \chi \left( \frac{E_{e^{\pm}}}{E_{ref}} \right)^{\delta}$$

- We check the results in a range of different diffusion regimes, from slow ( $\chi=1e26$ ,  $\delta=0.3$ ) to fast ( $\chi=1e29$ ,  $\delta=0.5$ ). We can see that there is no chance of detecting true point sources in the faster diffusion regimes.



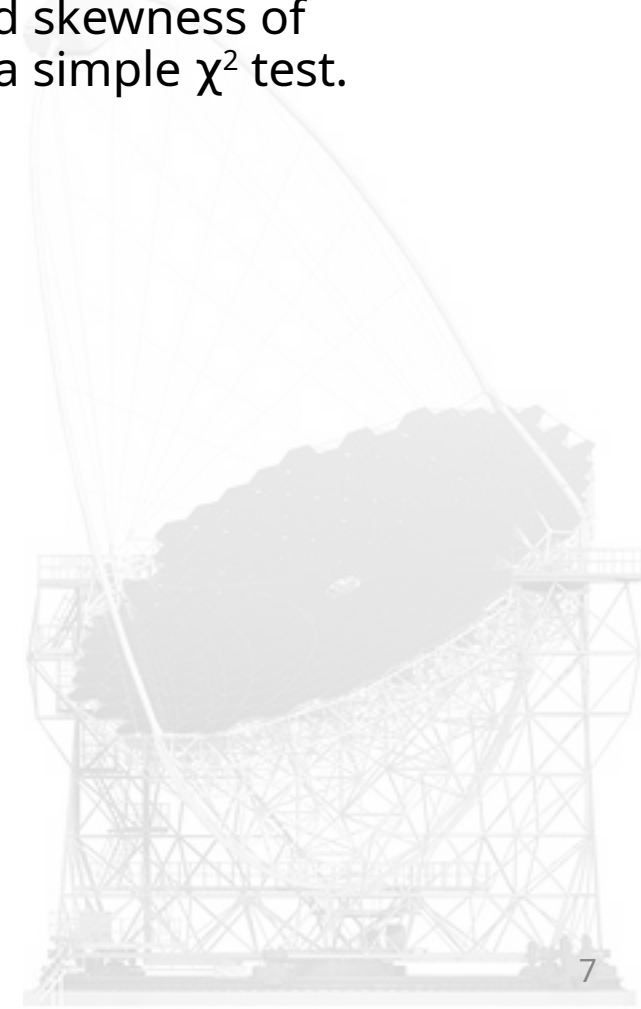
# Results

- Model successfully reproduces the FERMI-LAT excess.



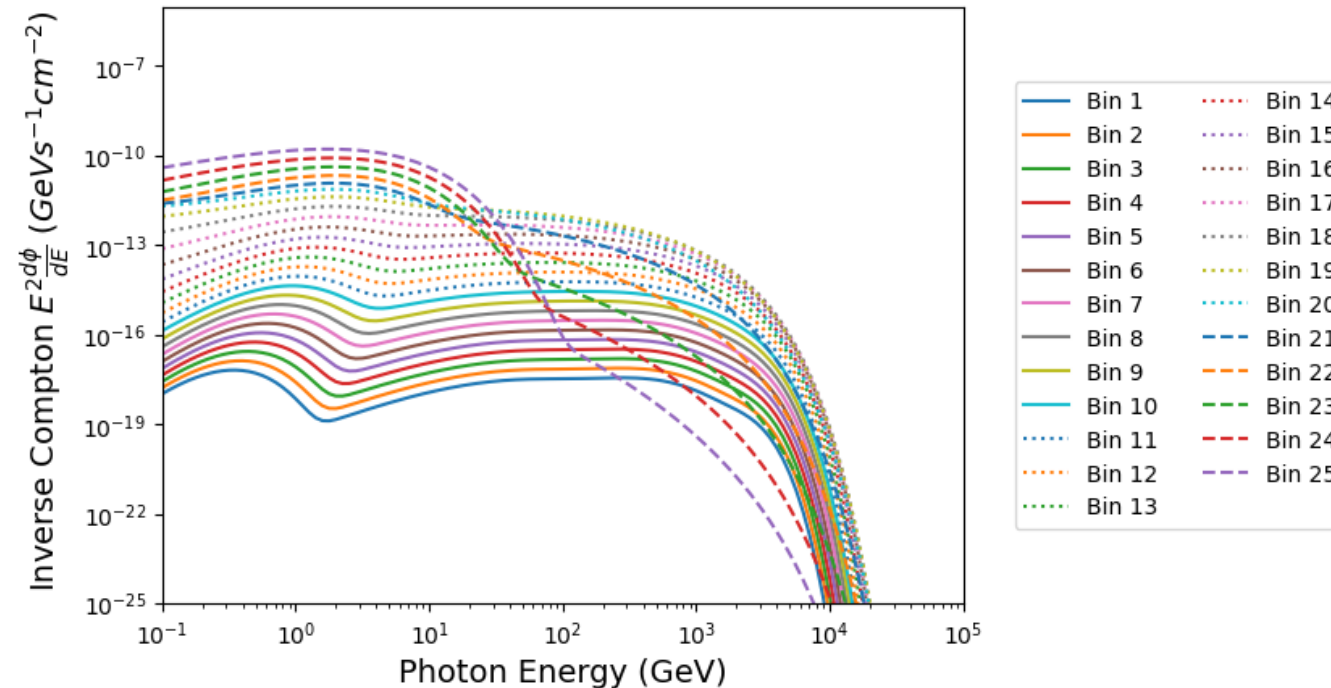
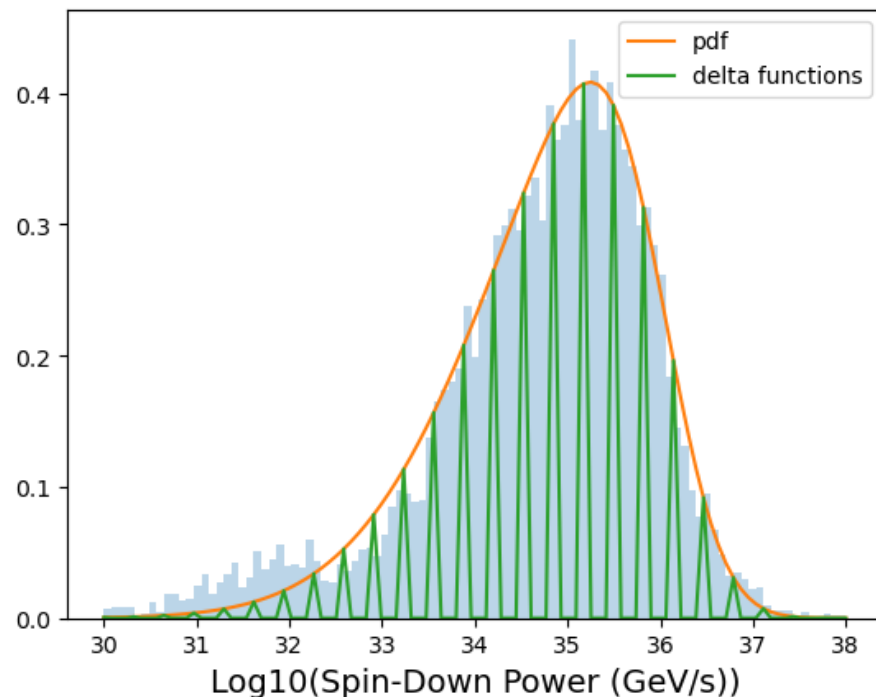
# Generalised Spin-down Power Distributions

- ◆ These results are all well and good, but can we do better?
- ◆ We hence explore the space of modifications that can be made to the spin-down power distribution of MSPs. We make adjustments to the mean, standard deviation, and skewness of the spin-down power PDF, compute a spectrum, and determine fit quality using a simple  $\chi^2$  test.



# Generalised Spin-down Power Distributions

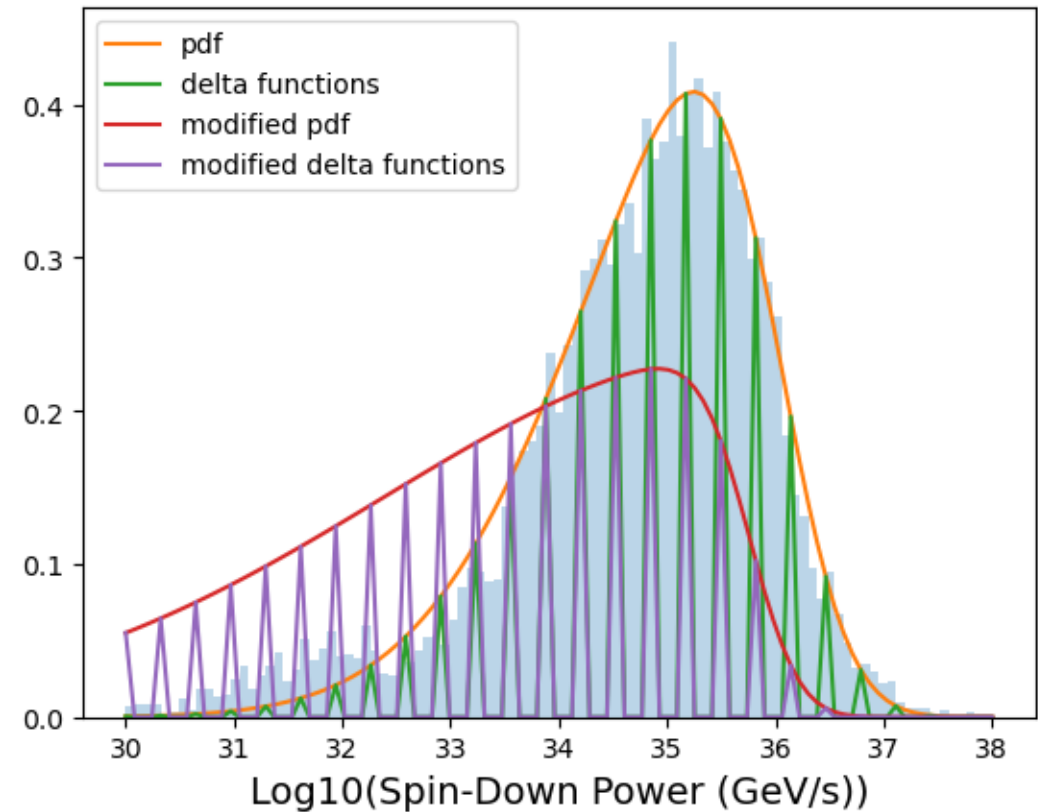
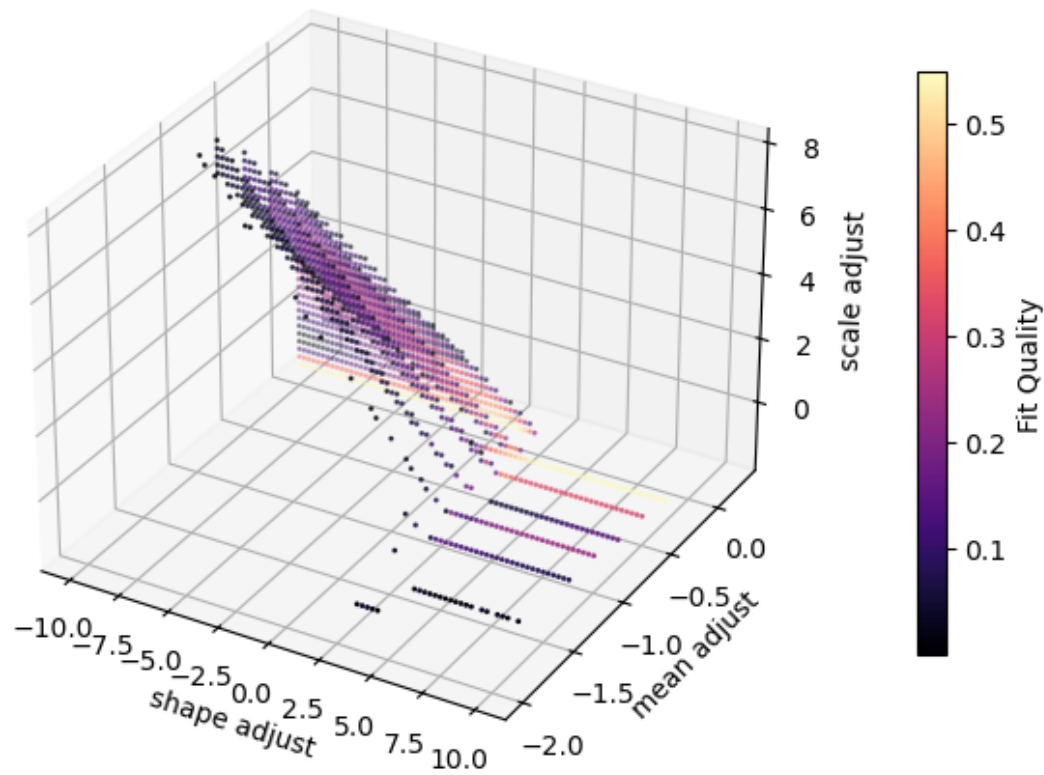
- However, this requires that we make approximations. We divide the spin-down power into 25 equally-spaced delta functions from  $1e30$  to  $1e38$  (in log space). The relative amplitudes of the deltas is set by the shape of the PDF, and determines the number of MSPs with that spin-down power. The total spin-down power ( $\sim 1e40$  GeV/s) is always conserved.



- It should be noted, the spin-down power also sets the prompt spectral index and cutoff energy, as the three parameters possess a strong linear correlation. This results in each delta function possessing a unique spectral shape.

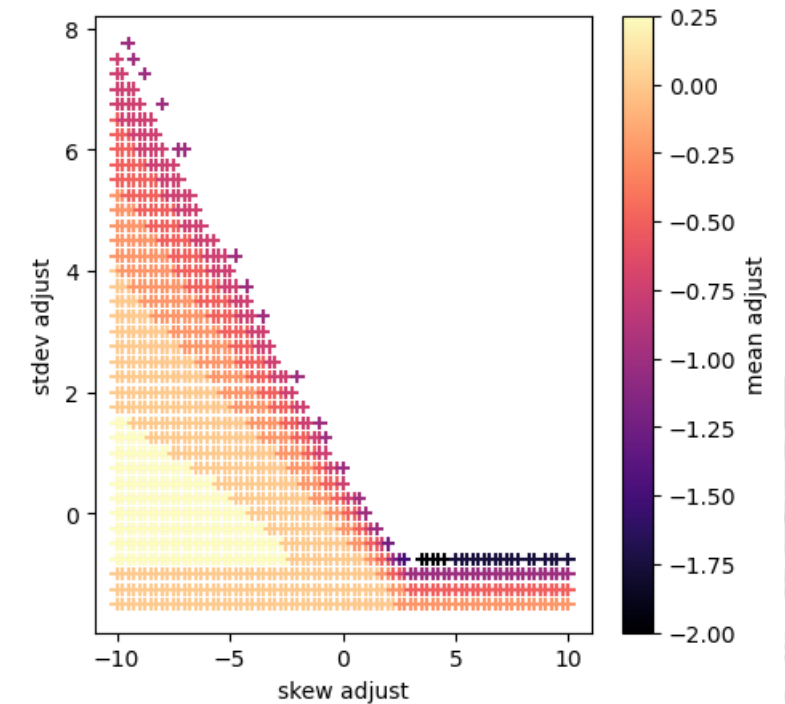
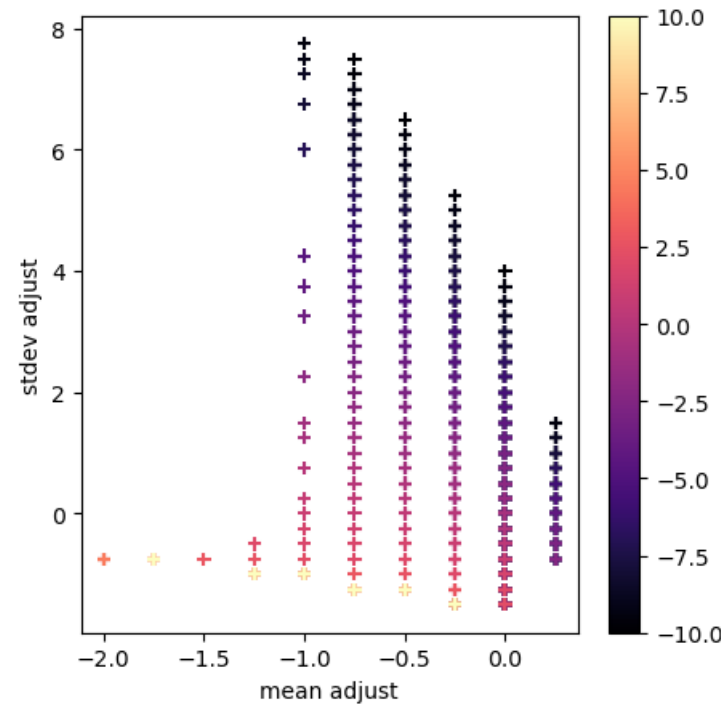
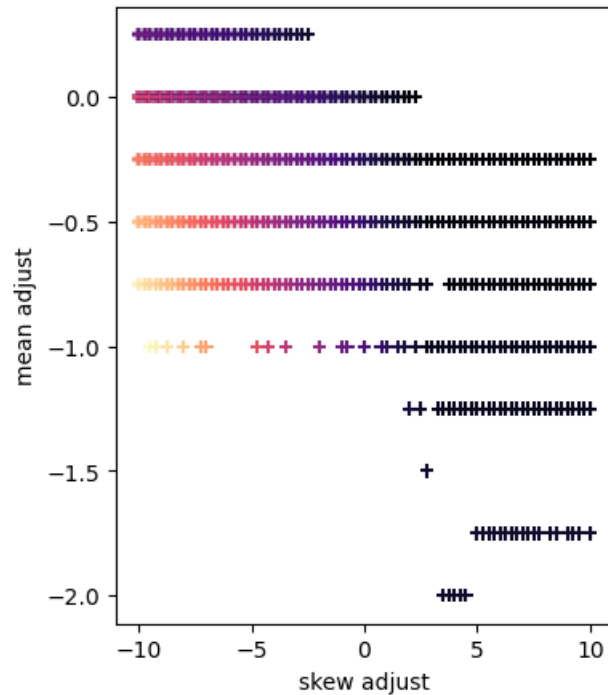
# Generalised Spin-down Power Distributions

- Define a vector of modifiers to the skewness, mean, and standard deviation of the PDF. Accepted modifications are accurate to within  $1\sigma$  of the data.



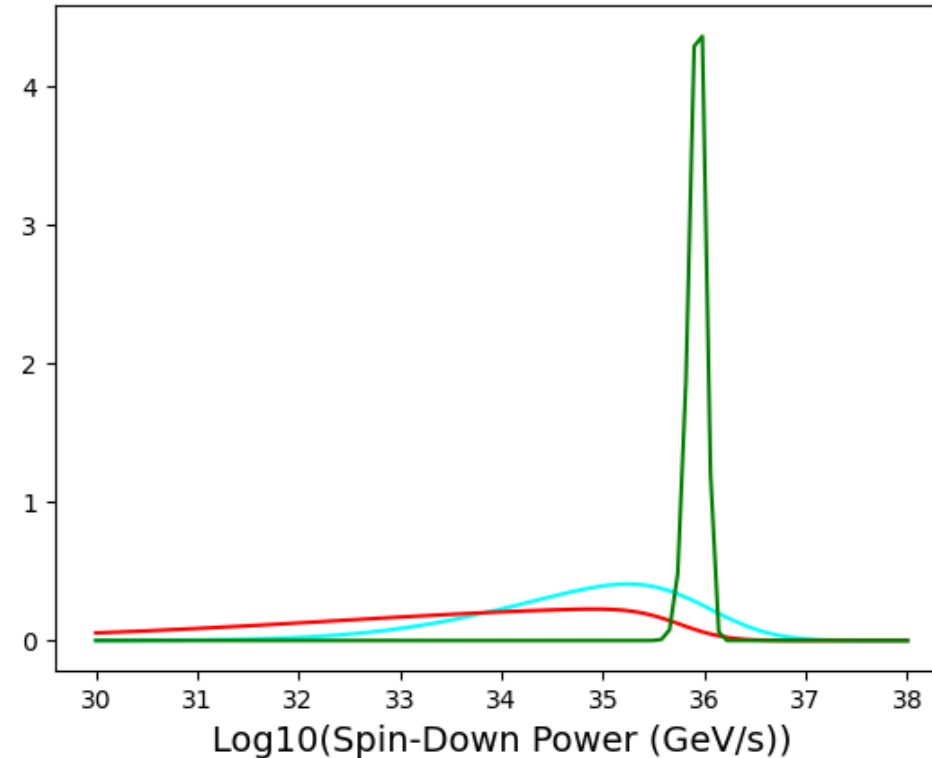
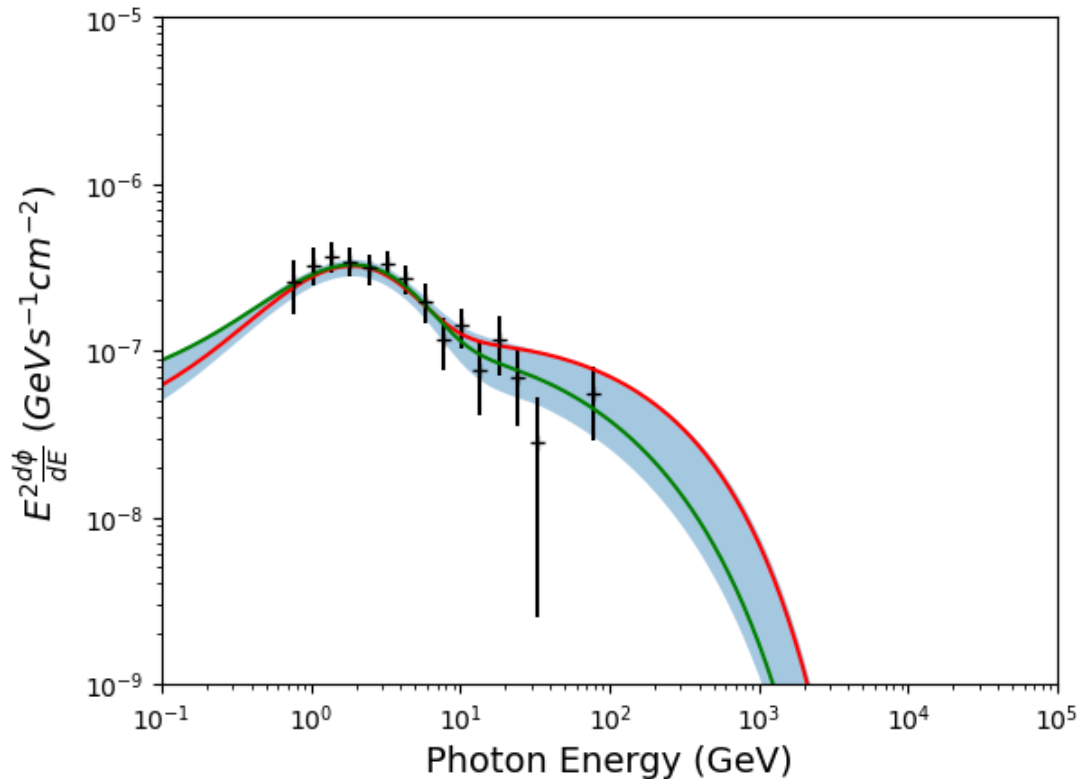
# Generalised Spin-down Power Distributions

- Define a vector of modifiers to the skewness, mean, and standard deviation of the PDF. Accepted modifications are accurate to within  $1\sigma$  of the data.



# Generalised Spin-down Power Distributions

- ◆ We isolate two standout cases to examine any changes in the significance maps. The best fit case, and the case with maximum flux at 100 GeV.



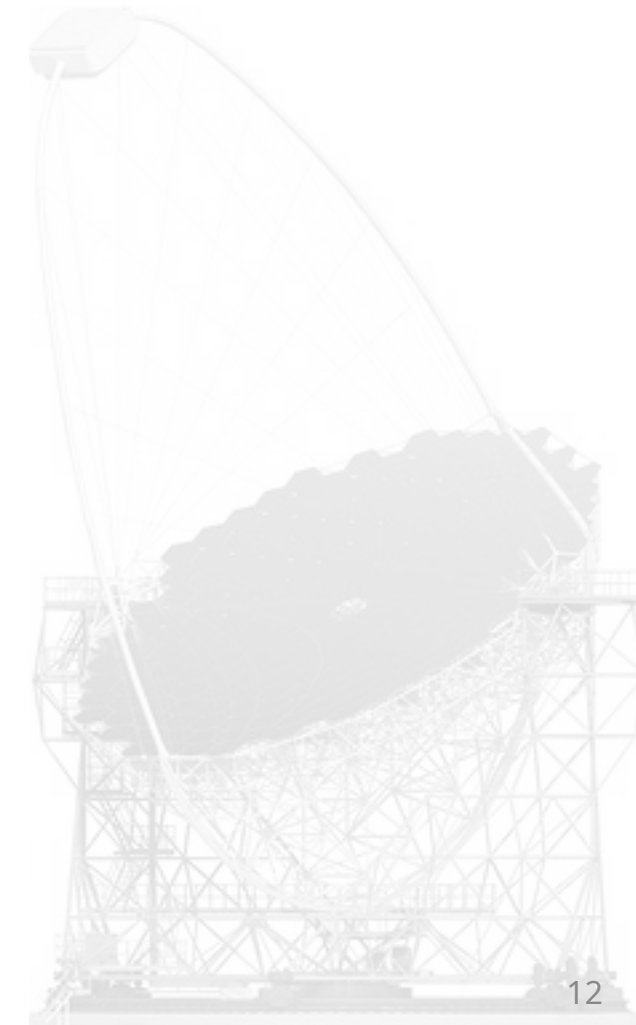
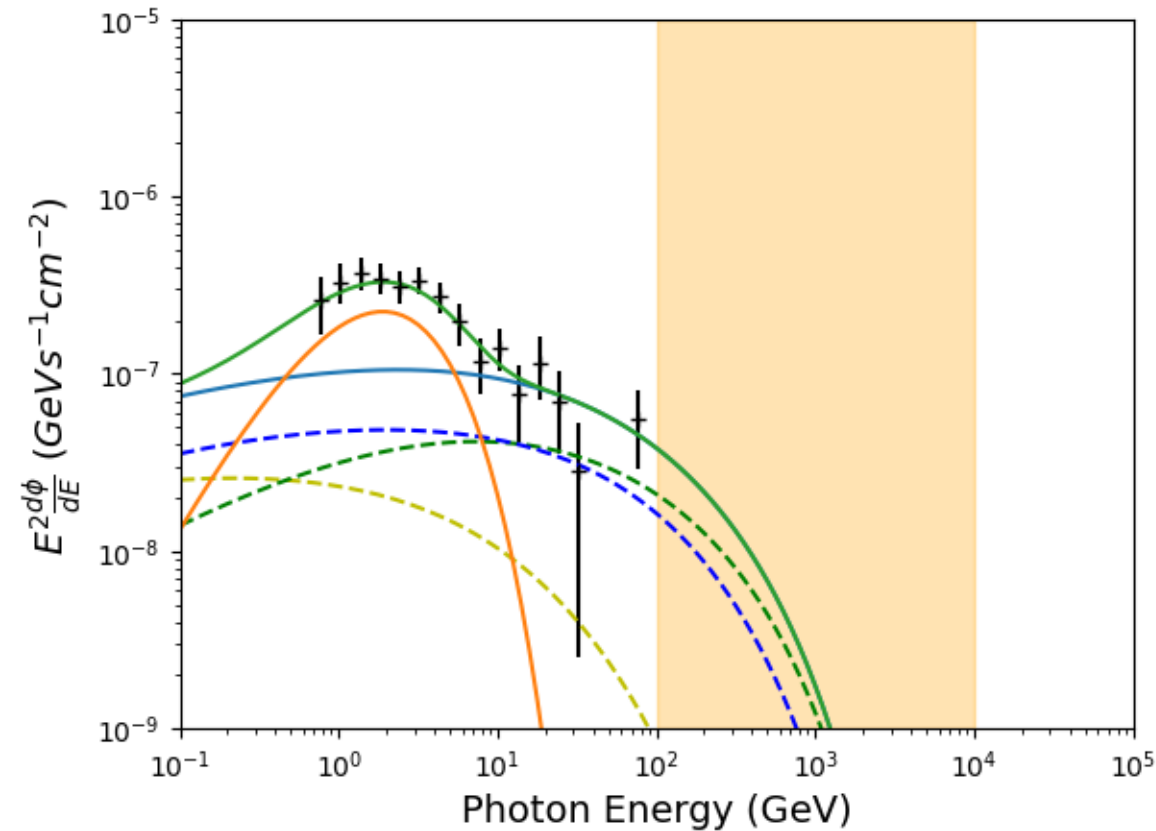
■ range of valid solutions  
— flux for  $[-6.25 \ -0.25 \ 1.75]$  (max at 100GeV)  
— flux for  $[[ \ 1.25 \ 0. \ -1.5 \ ]]$  (best fit)  
+ GCE from FERMI

— baseline PDF  
— flux for  $[-6.25 \ -0.25 \ 1.75]$  (max at 100GeV)  
— flux for  $[[ \ 1.25 \ 0. \ -1.5 \ ]]$  (best fit)



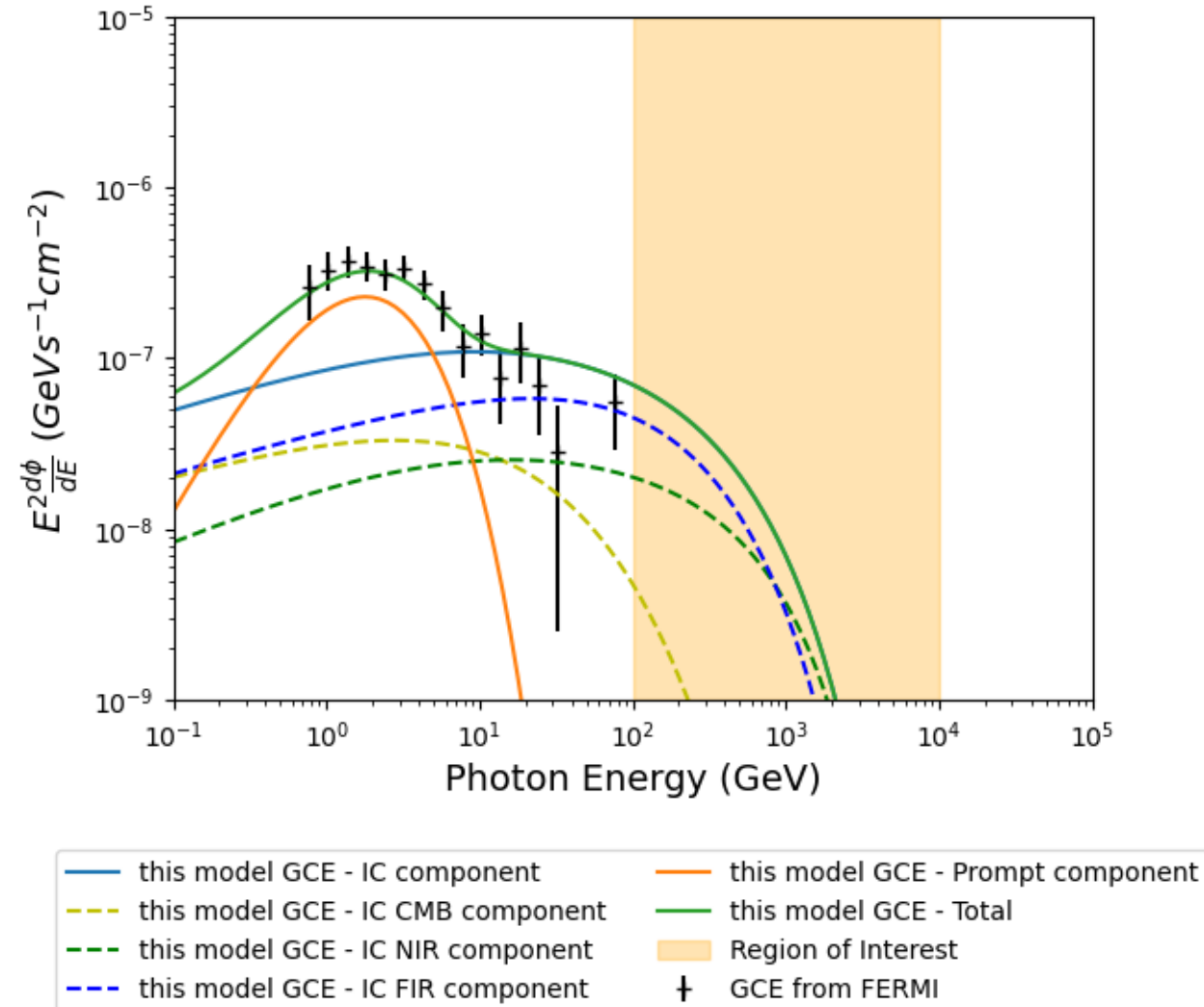
# Results

◆ The best fit case flux:



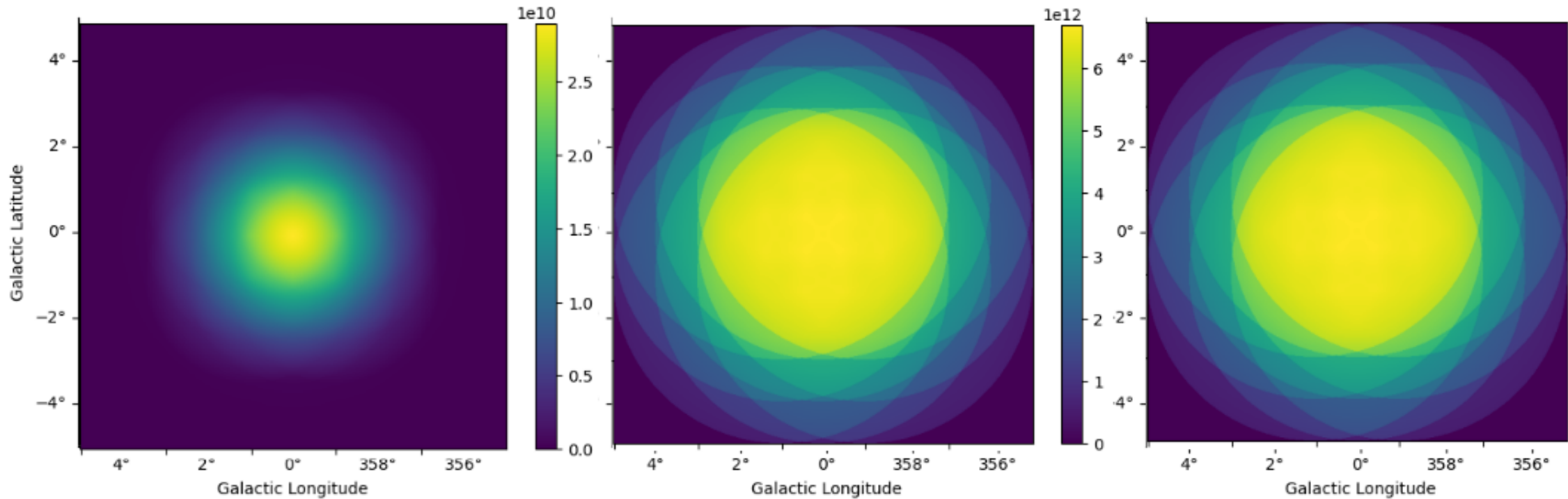
# Results

- ◆ The case with maximum flux at 100 GeV:



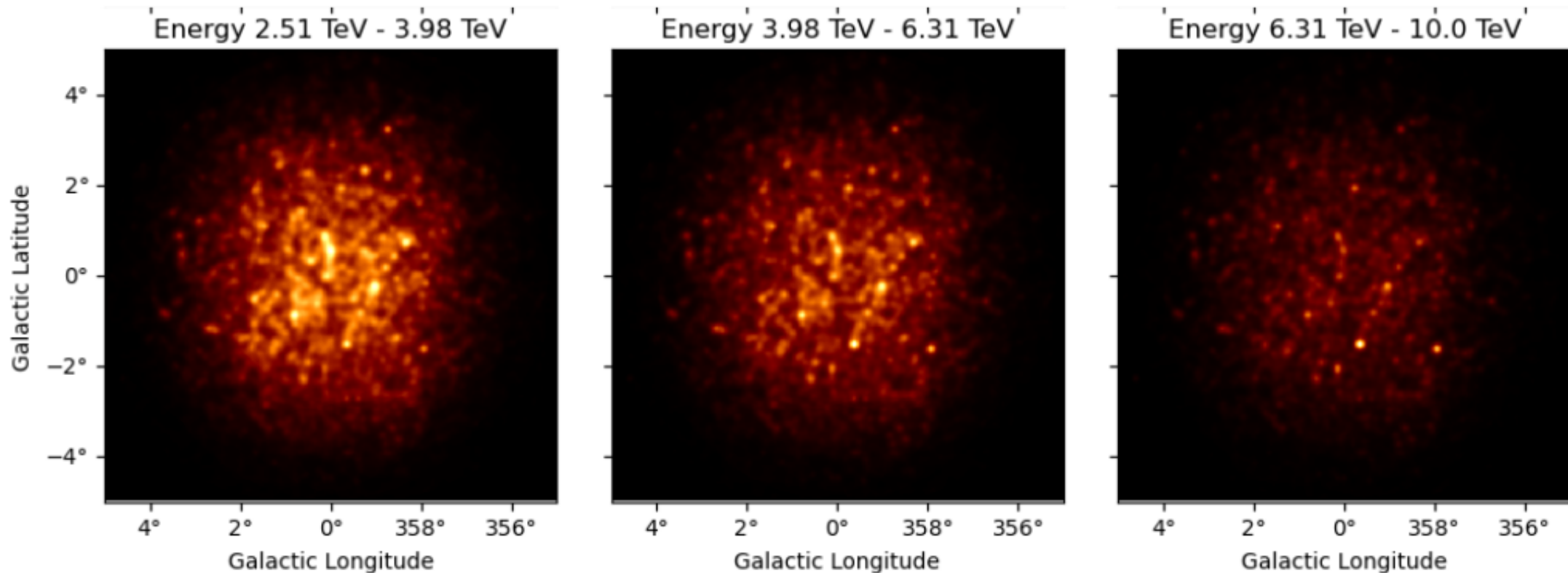
## Exposure Maps

9 pointings, spaced on 1 deg x 1 deg grid; 50h each



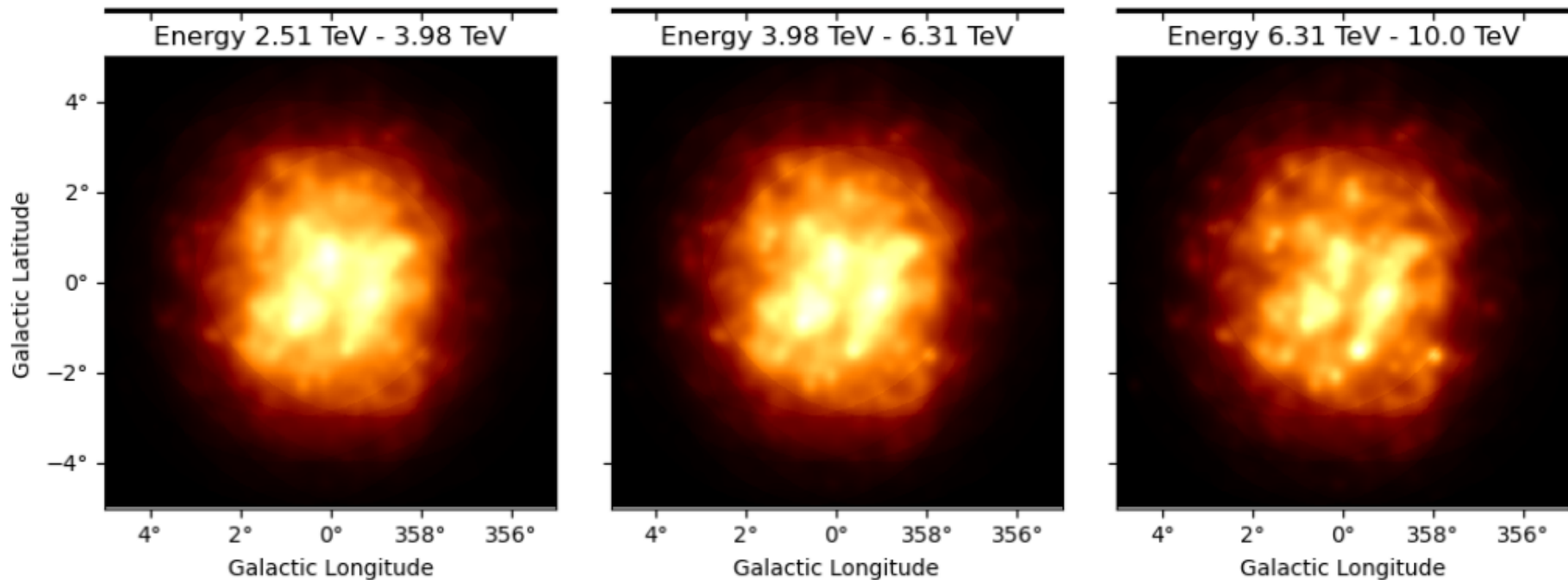
## Predicted Signal (1e26 model)

9 pointings, spaced on 1 deg x 1 deg grid; 50h each



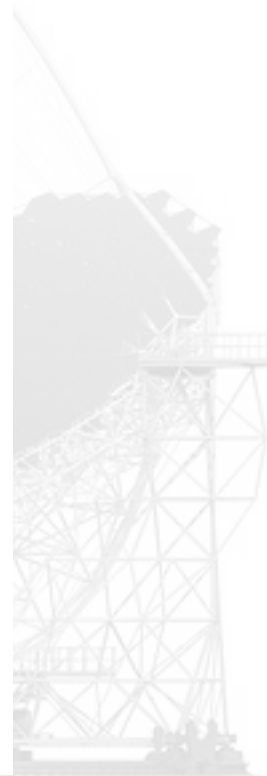
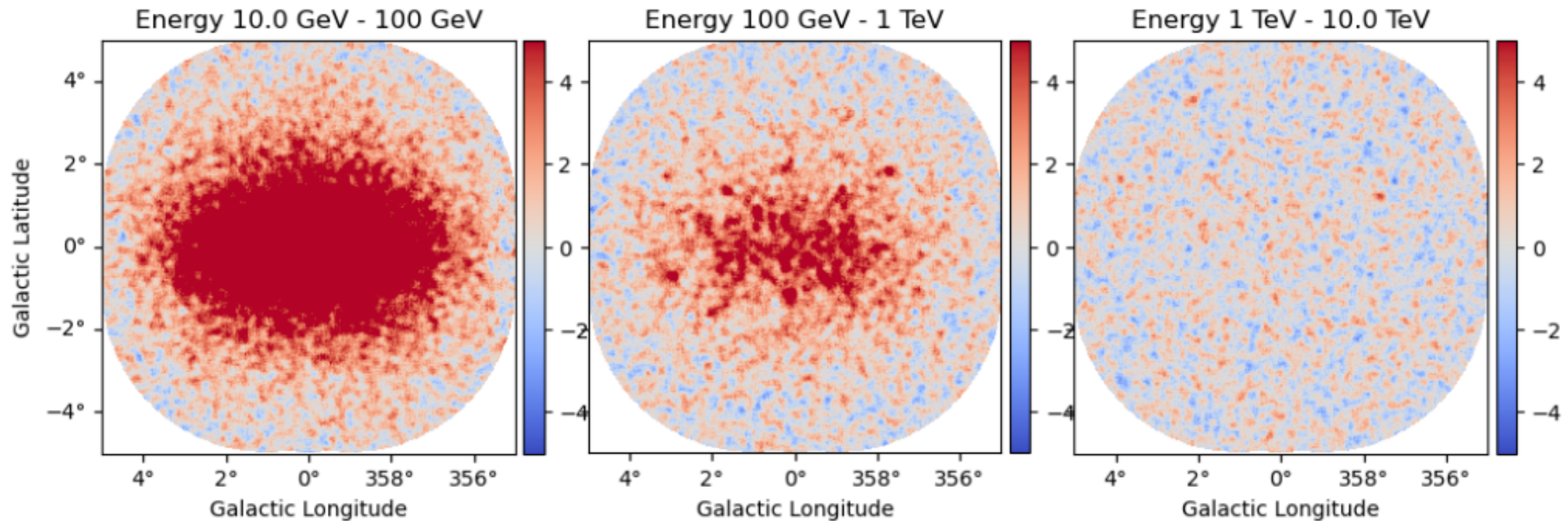
## Predicted Signal (1e27 model)

9 pointings, spaced on 1 deg x 1 deg grid; 50h each

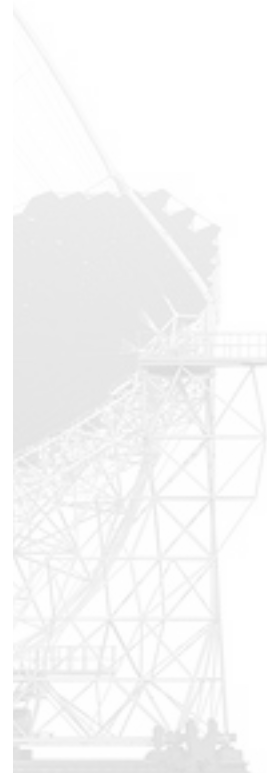
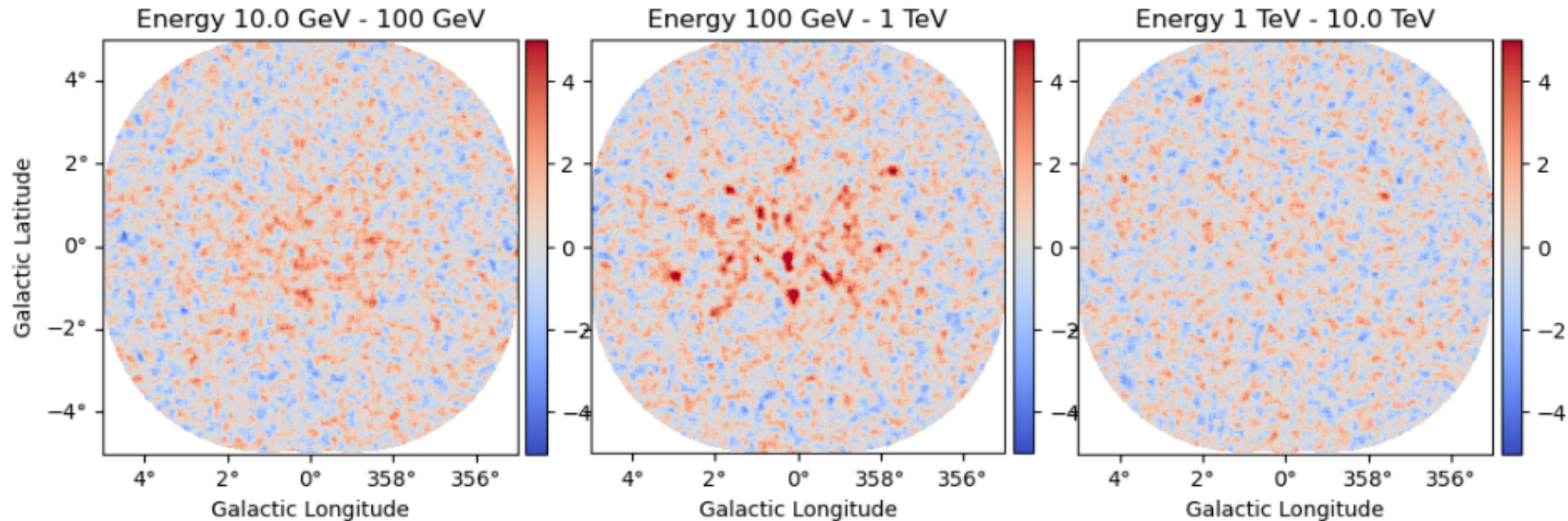
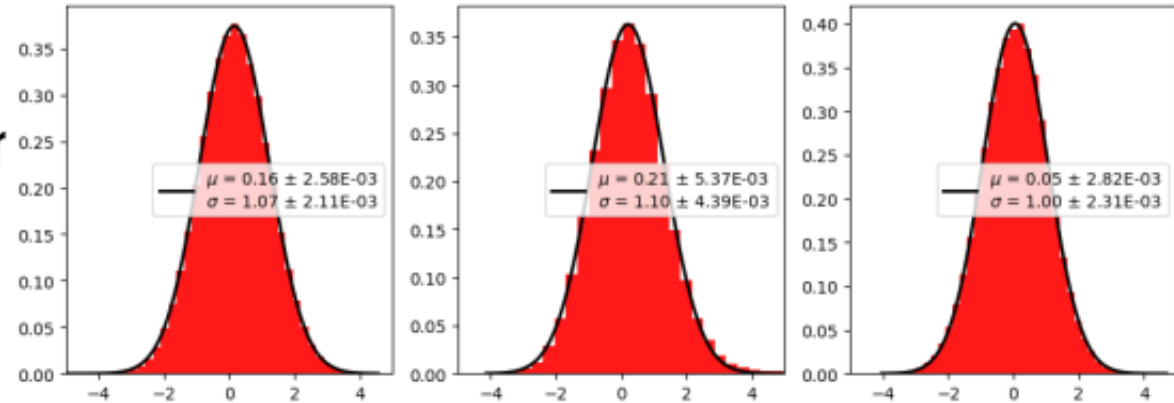


## TS Maps (via ExcessMapEstimator)

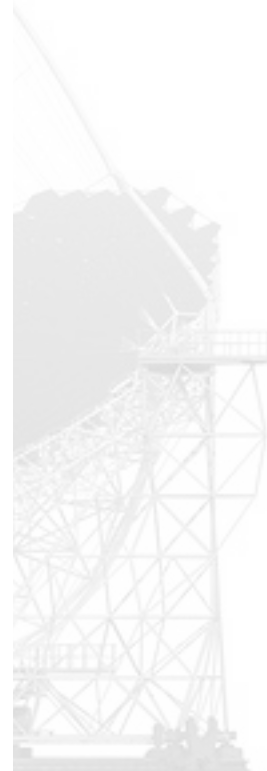
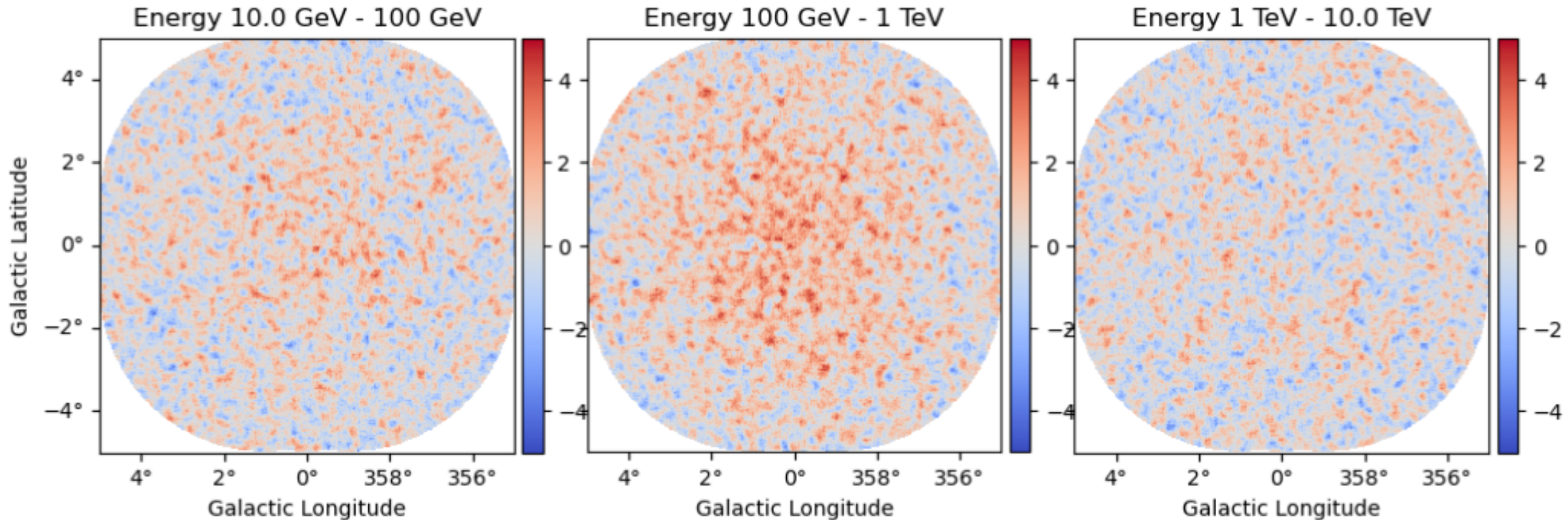
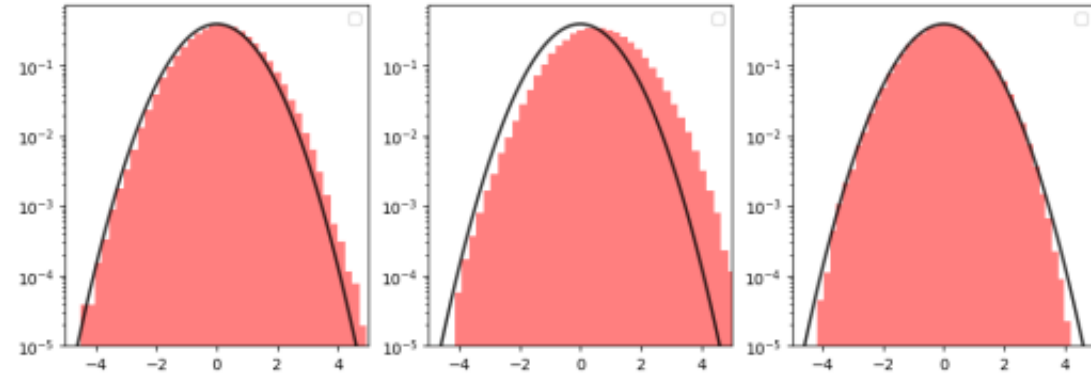
Without subtraction of diffuse emission



## TS Maps WITH subtraction of diffuse er

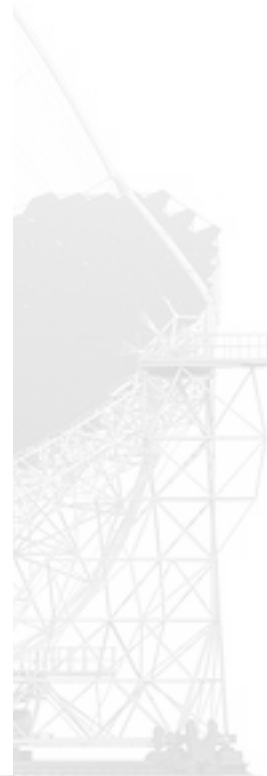
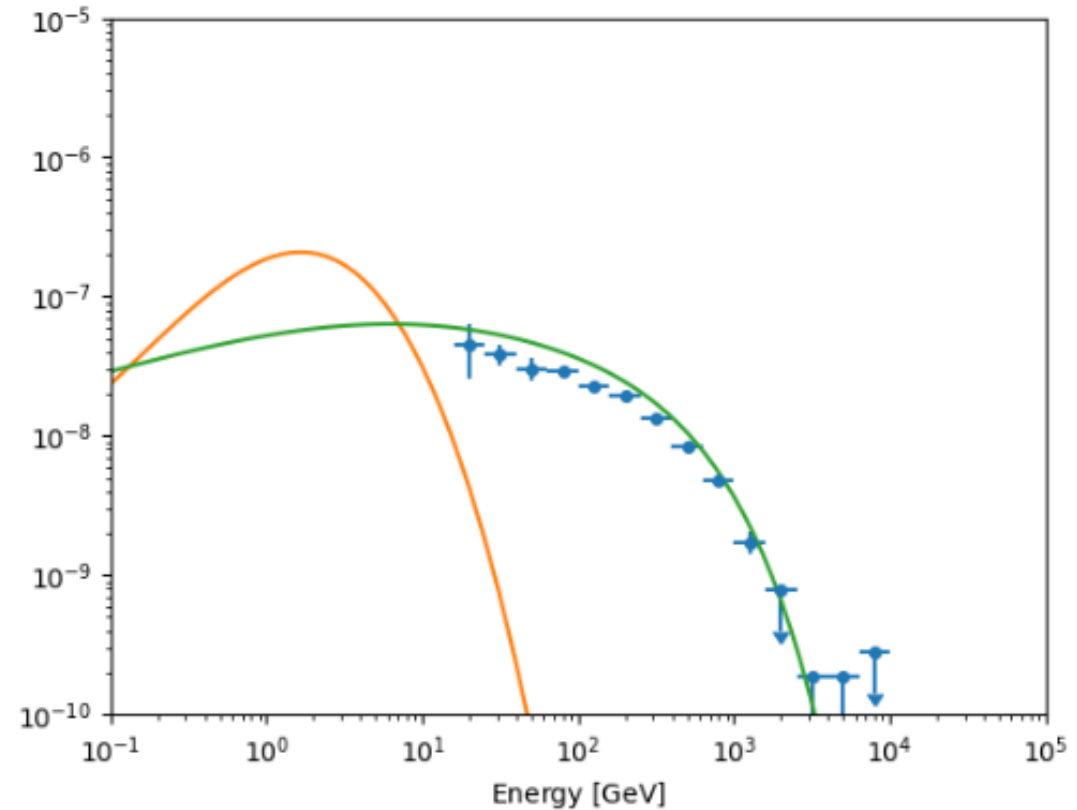
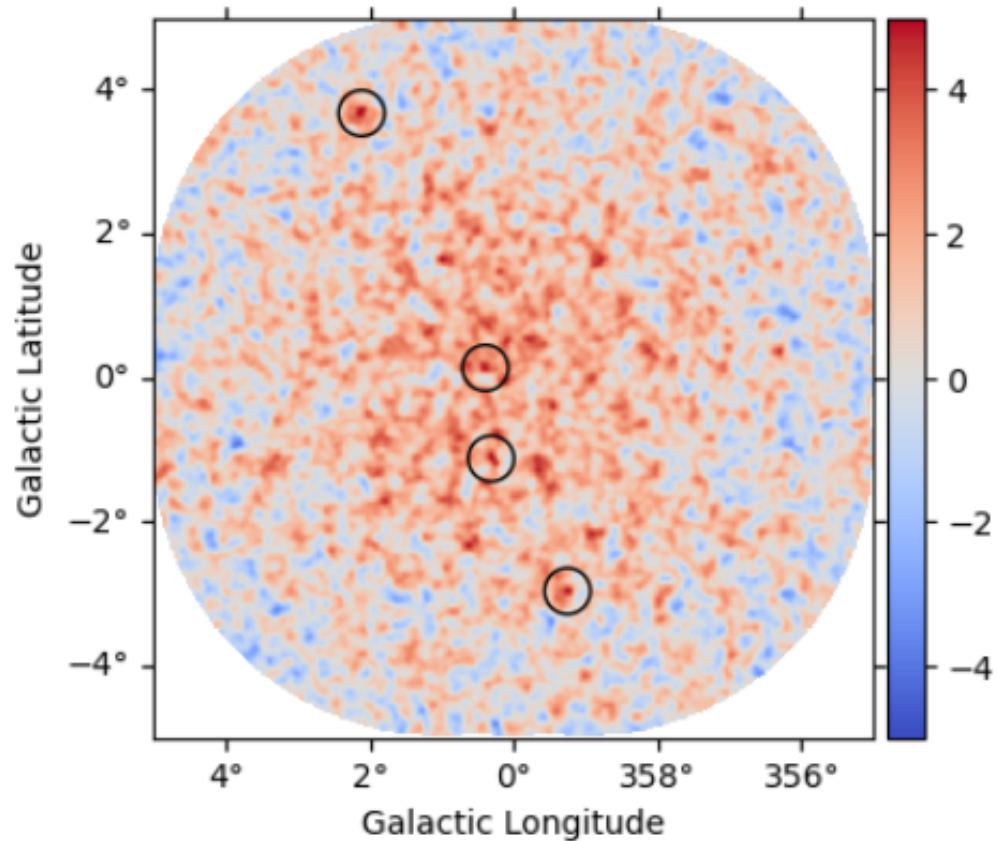


## TS Maps (1e26 model) #1 (via ExcessMapEstimator)

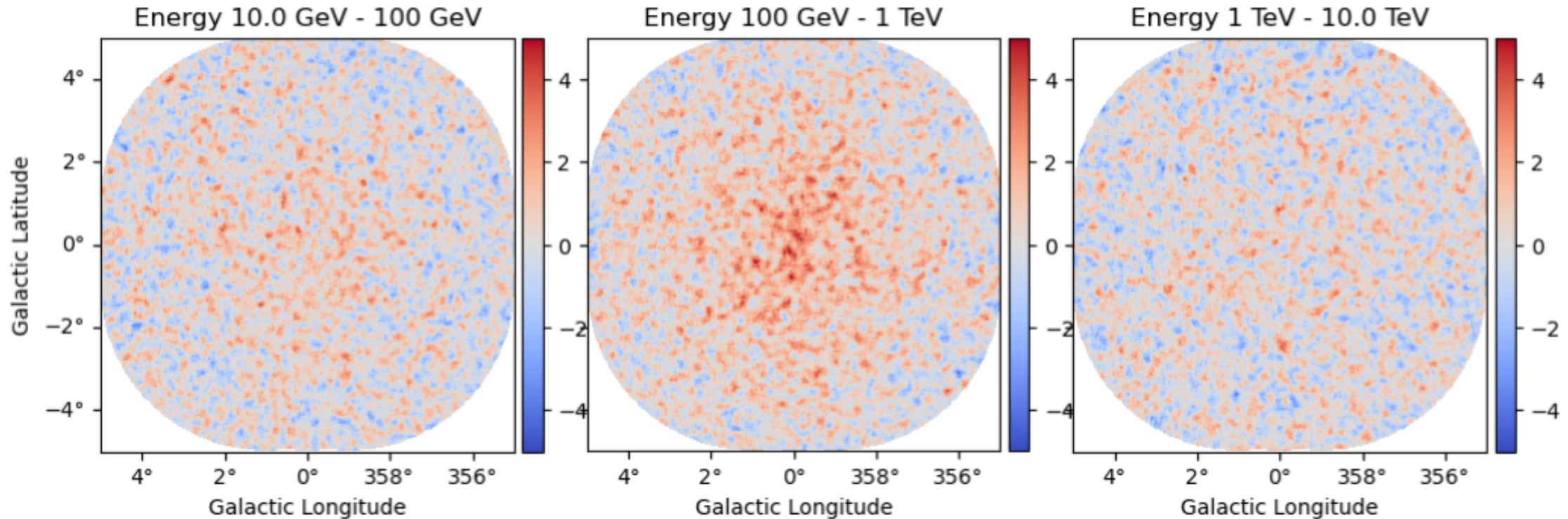
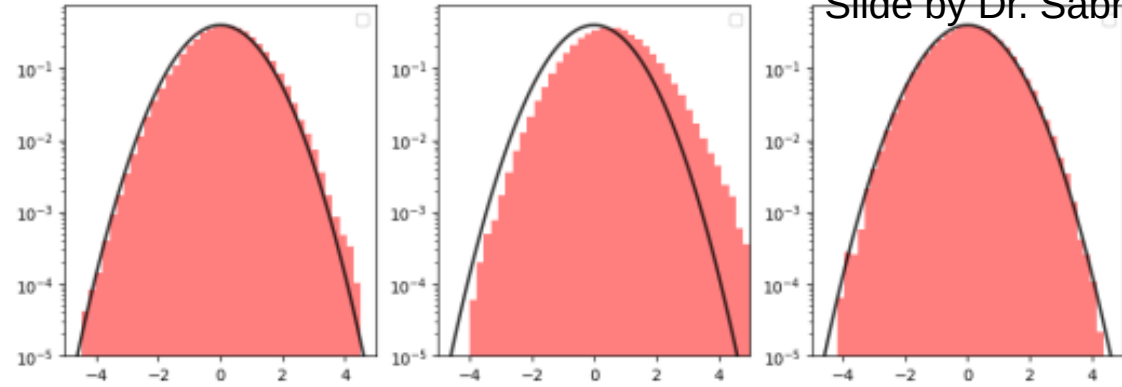


## TS Maps (1e26 model)

#1 (via TSMMapEstimator)

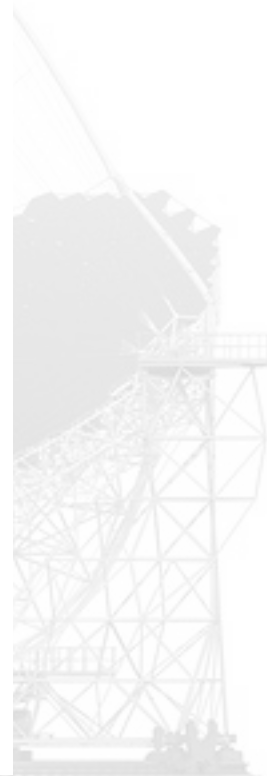
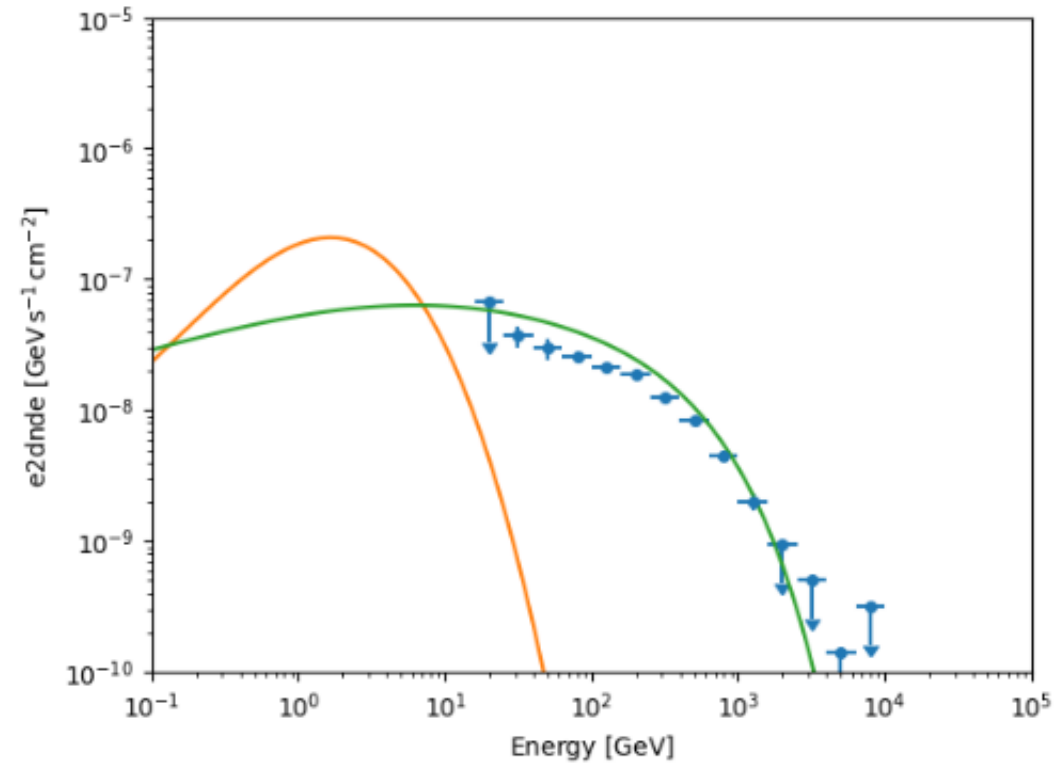
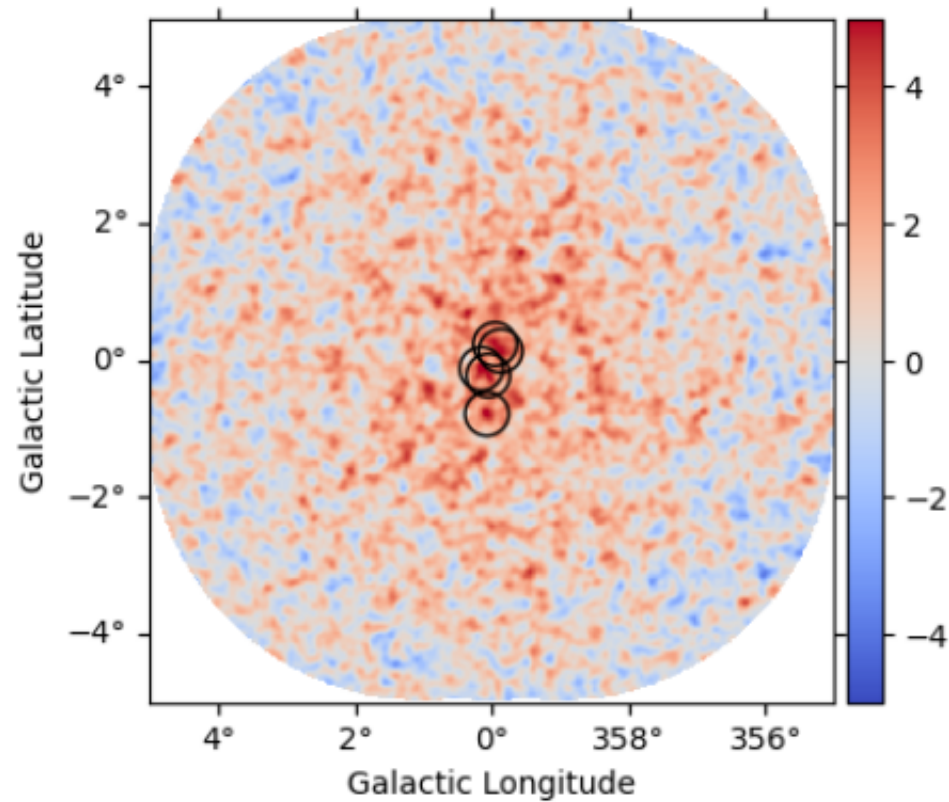


## TS Maps (1e27 model) #1 (via ExcessMapEstimator)



## TS Maps (1e27 model)

#1 (via TSMMapEstimator)



# Conclusions

- ◆ We attempt to determine whether CTAO would see a difference between MSP emission and the diffuse emission expected from dark matter.
- ◆ The 'core' or 'baseline' model is a reproduction of the results of (Gautam et al., 2022). This model successfully reproduced the FERMI-LAT excess.
- ◆ We examine additional cases for the spin-down power distribution that fall within  $1\sigma$  of the data based on a  $\chi^2$  test: a best fit case, and the case with the highest flux at 100 GeV. Both populations emit more brightly than the baseline case.



# Questions?

