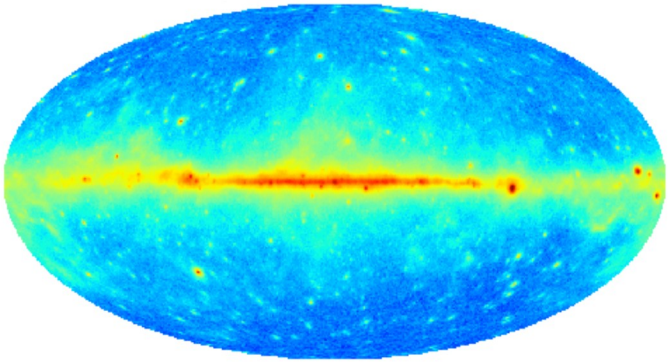
Robust inference of the Galactic centre gamma-ray excess spatial properties

Chris Gordon (University of Canterbury, NZ)

- **Based on:** D. Song, **C. Eckner**, **CG**, **F. Calore**, O. Macias, K. N. Abazajian, S. Horiuchi, M. Kaplinghat and M. Pohl, MNRAS **530** (2024) no.4, 4395-4411

- **Some directly related talks:** Dan Hooper (Wednesday, Thursday); Francesca Calore (Thursday); Jason Kumar (Thursday)

Fermi-LAT Gamma-ray Sky



Data

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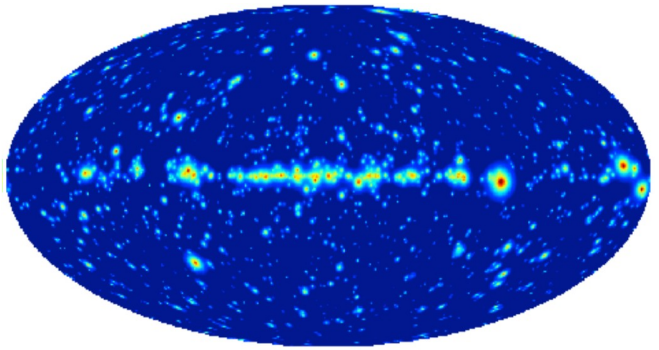

Point sources

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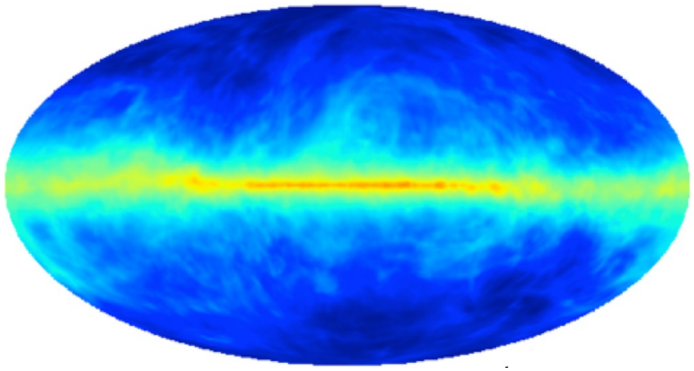

Galactic Diffuse

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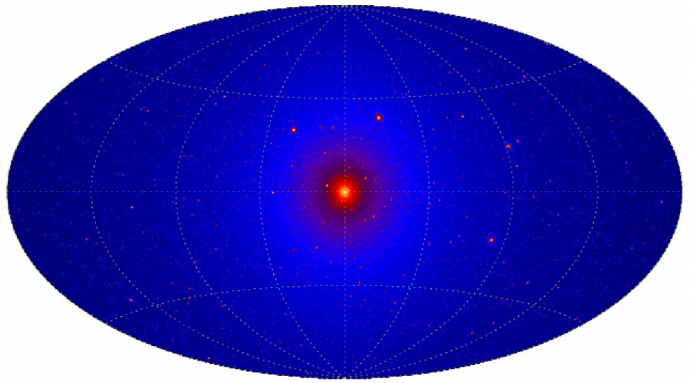
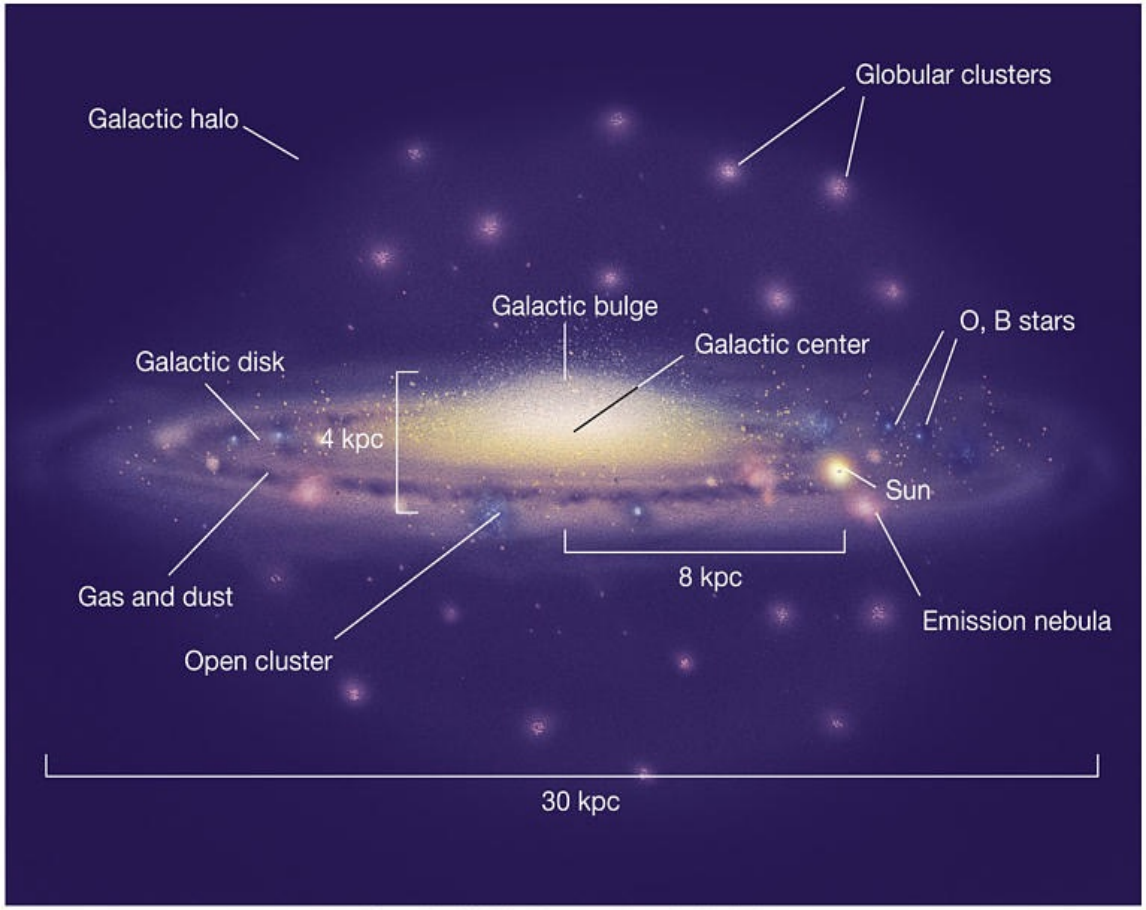
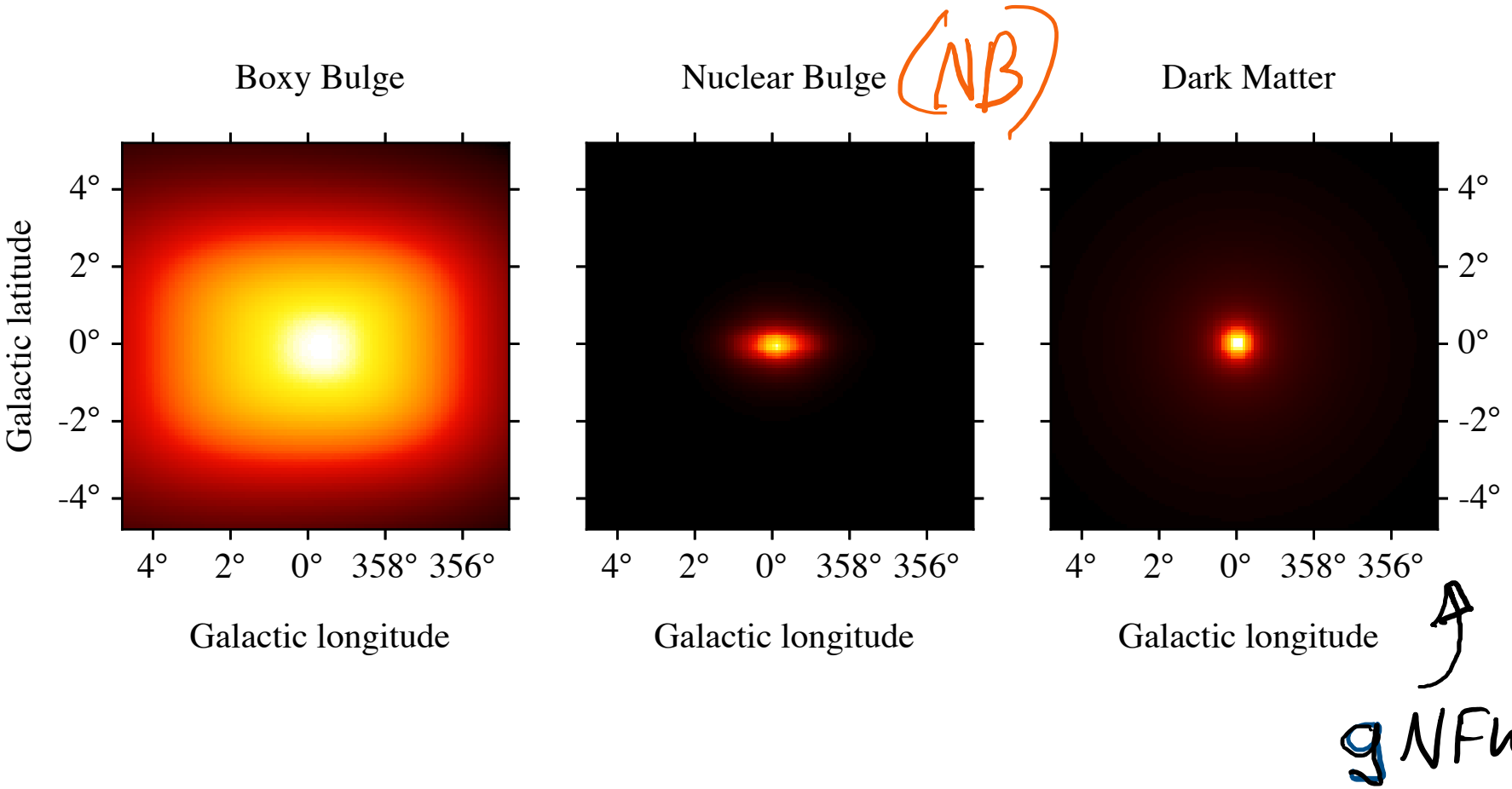


Dark Matter or Millisecond Pulsars?

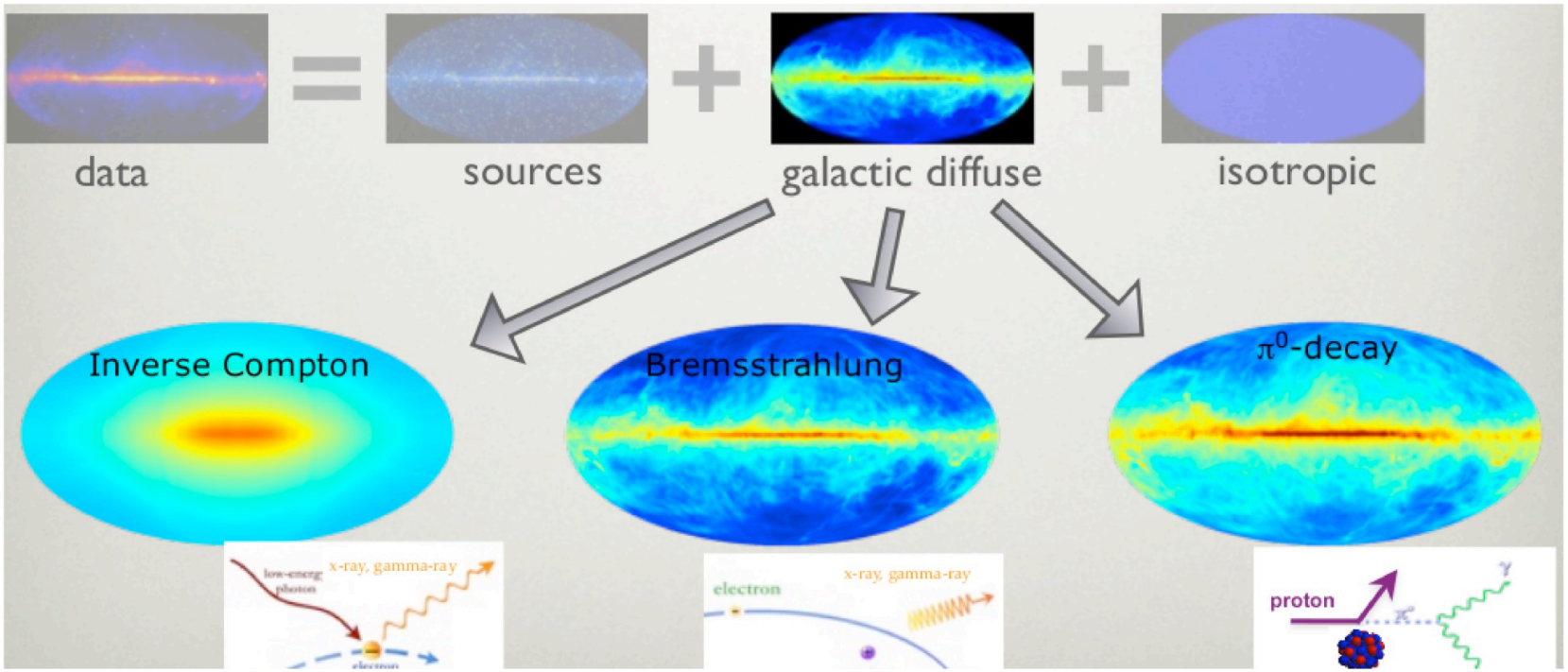
Edge-on view of the Milky Way




Boxy Bulge
Nuclear Bulge
Dark Matter
Galactic latitude
4°
2°
0°
-2°
-4°
4°
2°
0°
358°
356°
Galactic longitude

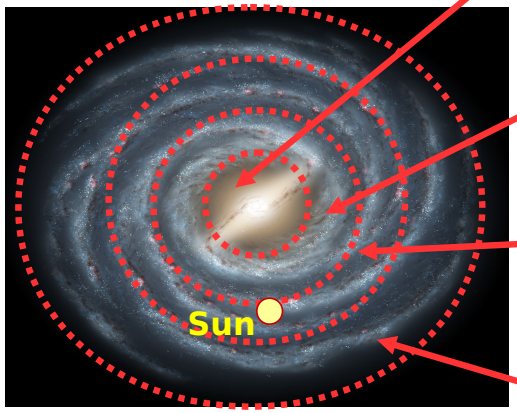
Galactic Diffuse Emission

- Generated using gas column densities, and a GALPROP (Strong+2007) generated Inverse Compton (IC) intensity map.

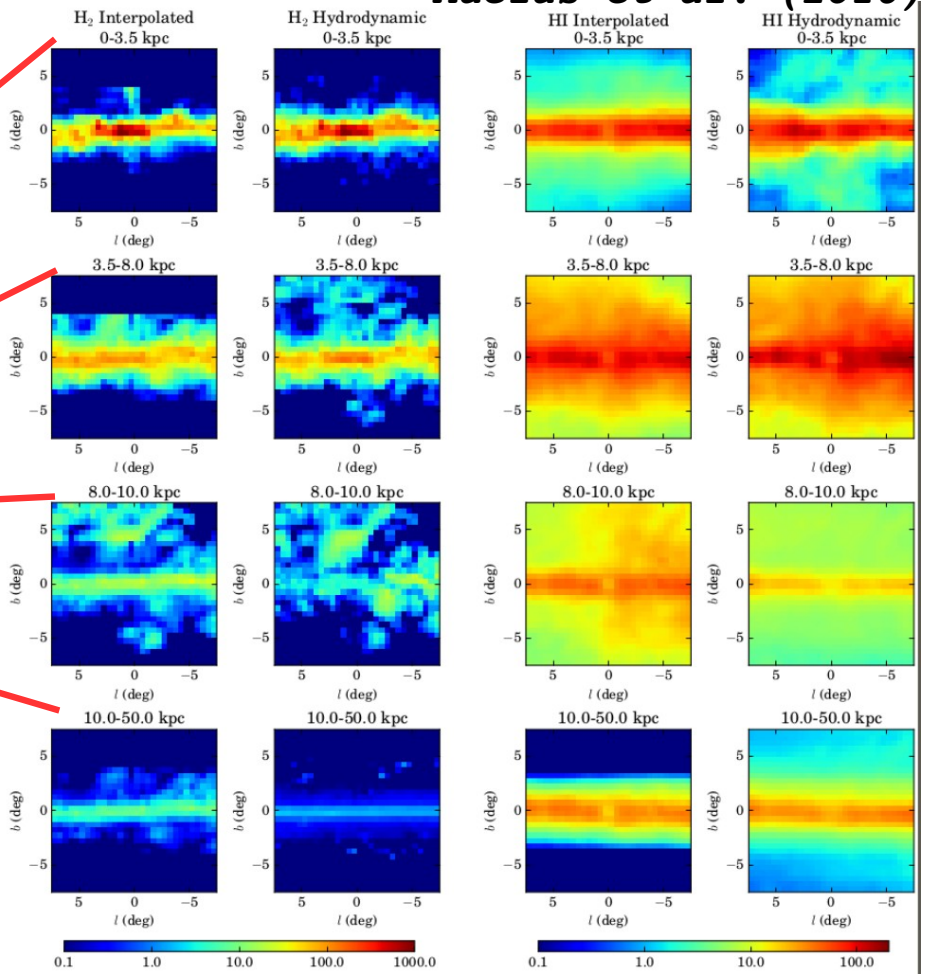


Interpolated vs Hydrodynamical method

Used Pohl et al. (2008)
3D hydrodynamic model.



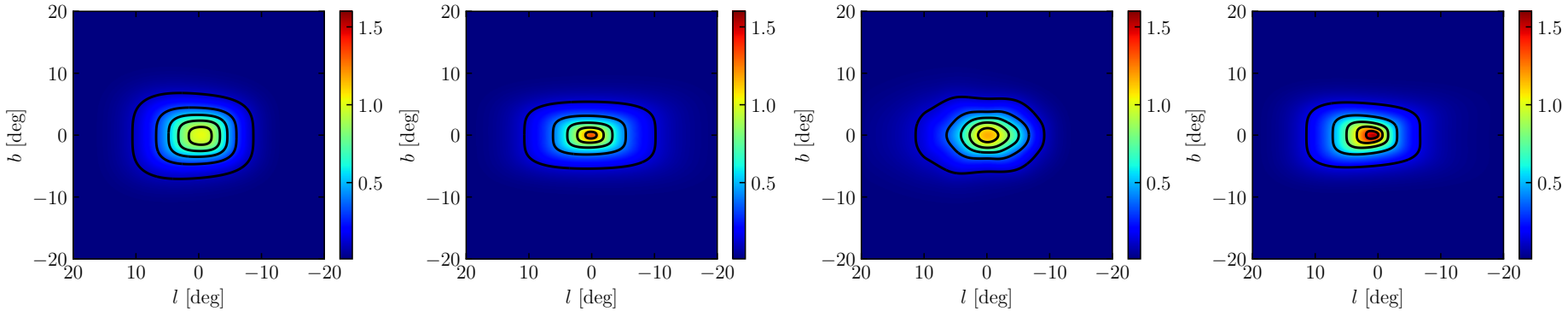
Macias et al. (2016)



There are noticeable morphological differences between the two methods.

Bulge Templates

Non-parametric fit to red clump stars from the UVV survey.



Freudenreich (1998) ("F98")

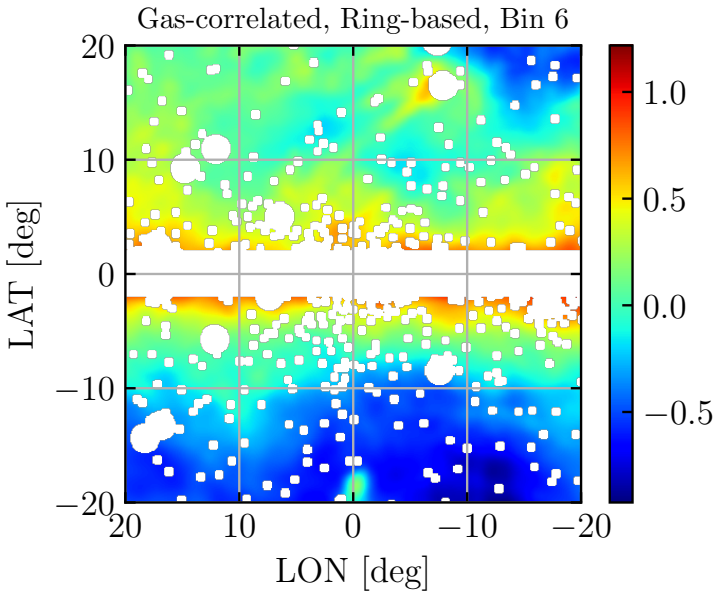
Cao et al. (2013)

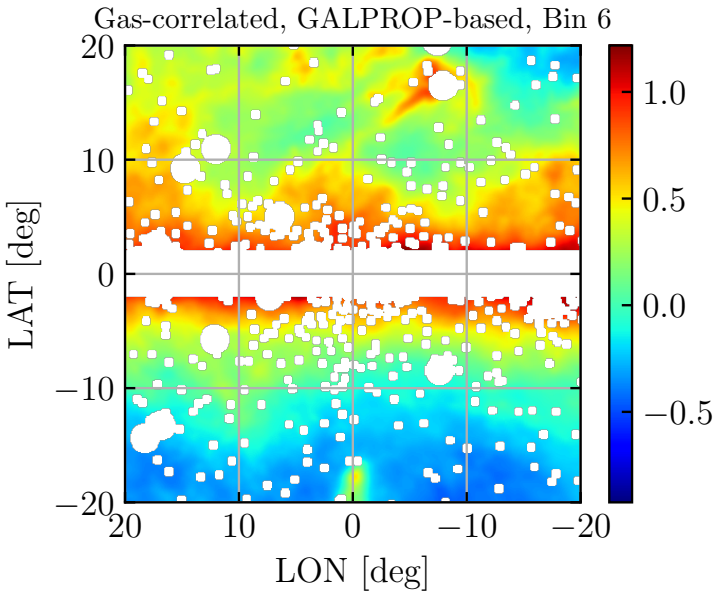
Coleman et al. (2020)

McDermott et al. (2023) (gcepy)

- Bulge templates after they are convolved with the point spread function (PSF) at 1.02-1.32 GeV.

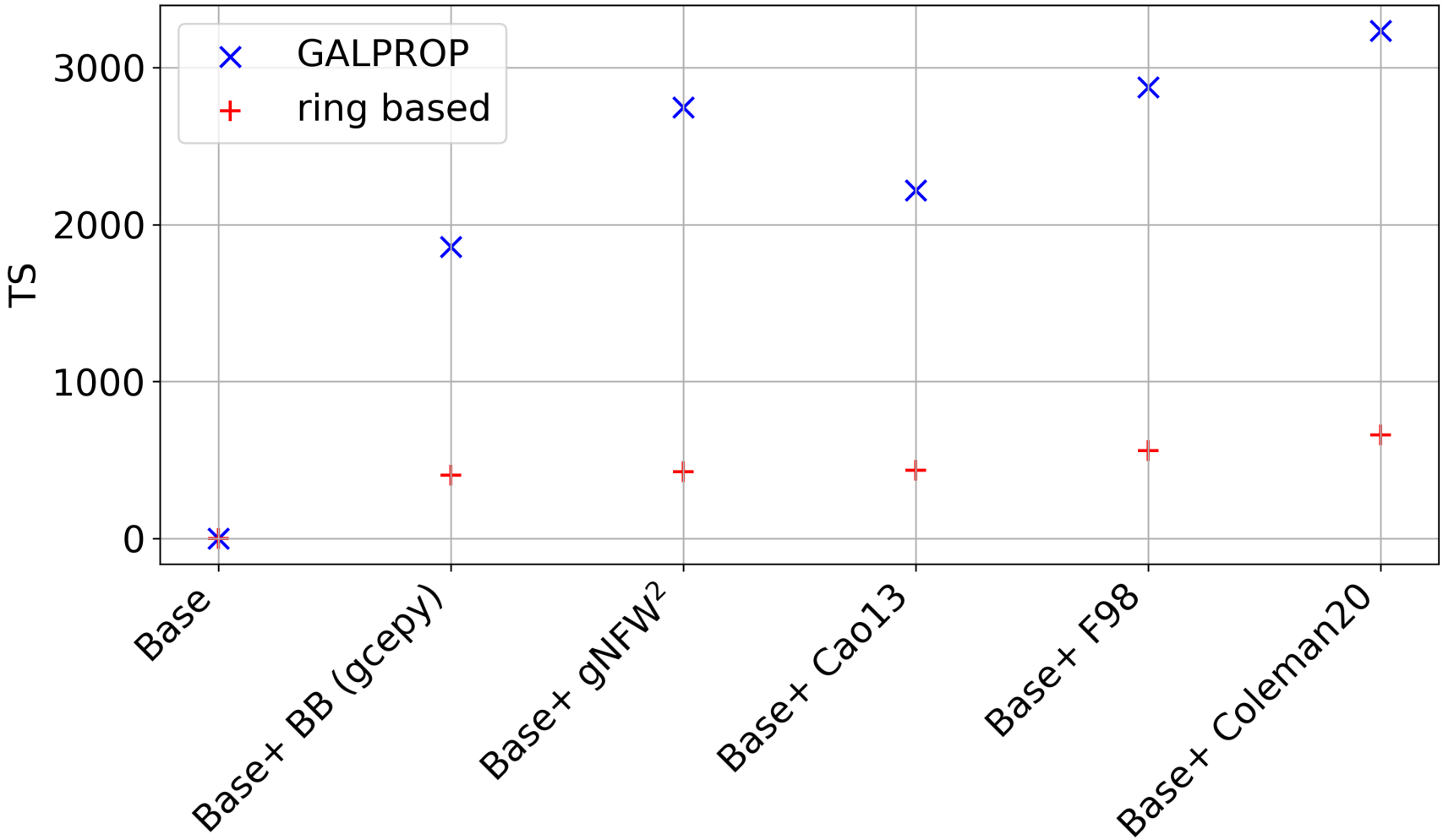
Masks





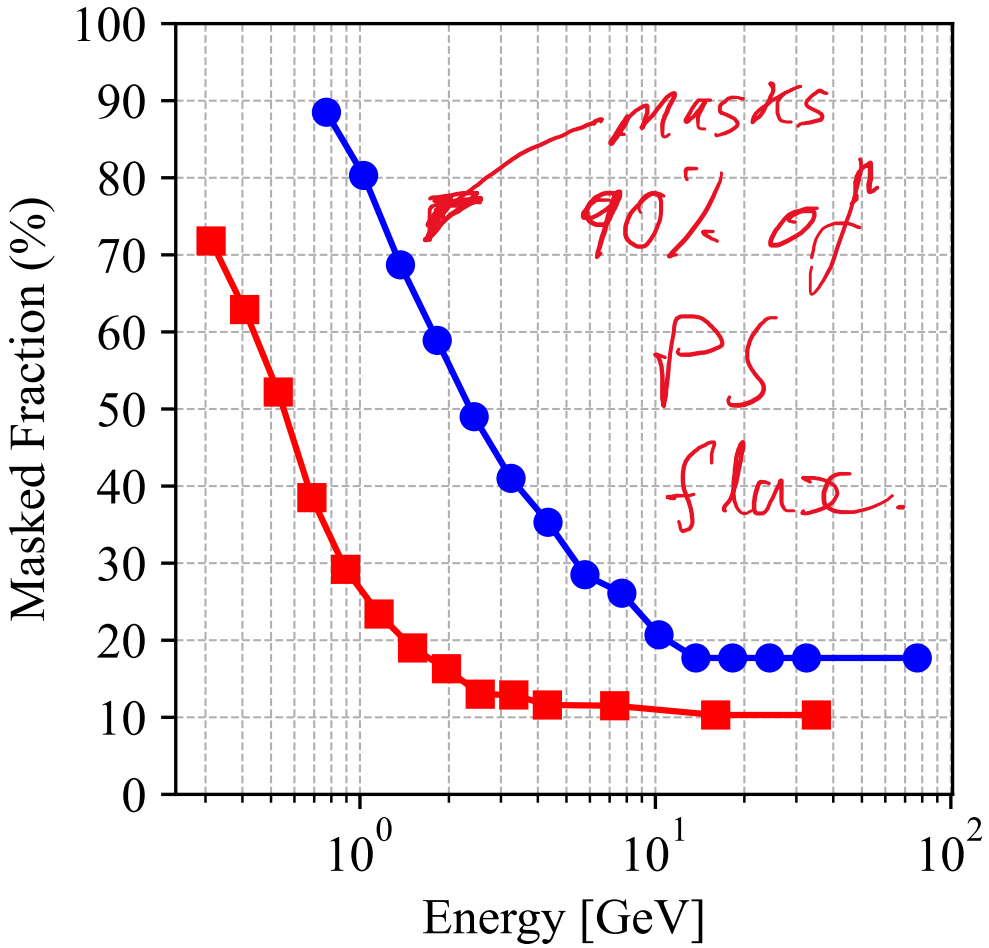
- As used by McDermott, Zhong, and Cholis, MNRAS (2023).
- Best-fit count maps (in $\log_{10}$ scale) for the gas-correlated component.
- The GALPROP-based is the GALPROP 7_p based background model.
- We show the 6th energy bin $(1.02 - 1.32\mathrm{GeV})$.

$$\mathrm{TS} = 2\ln(\mathcal{L}[\mathrm{base} + \mathrm{GCE}] - \mathcal{L}[\mathrm{base}])$$

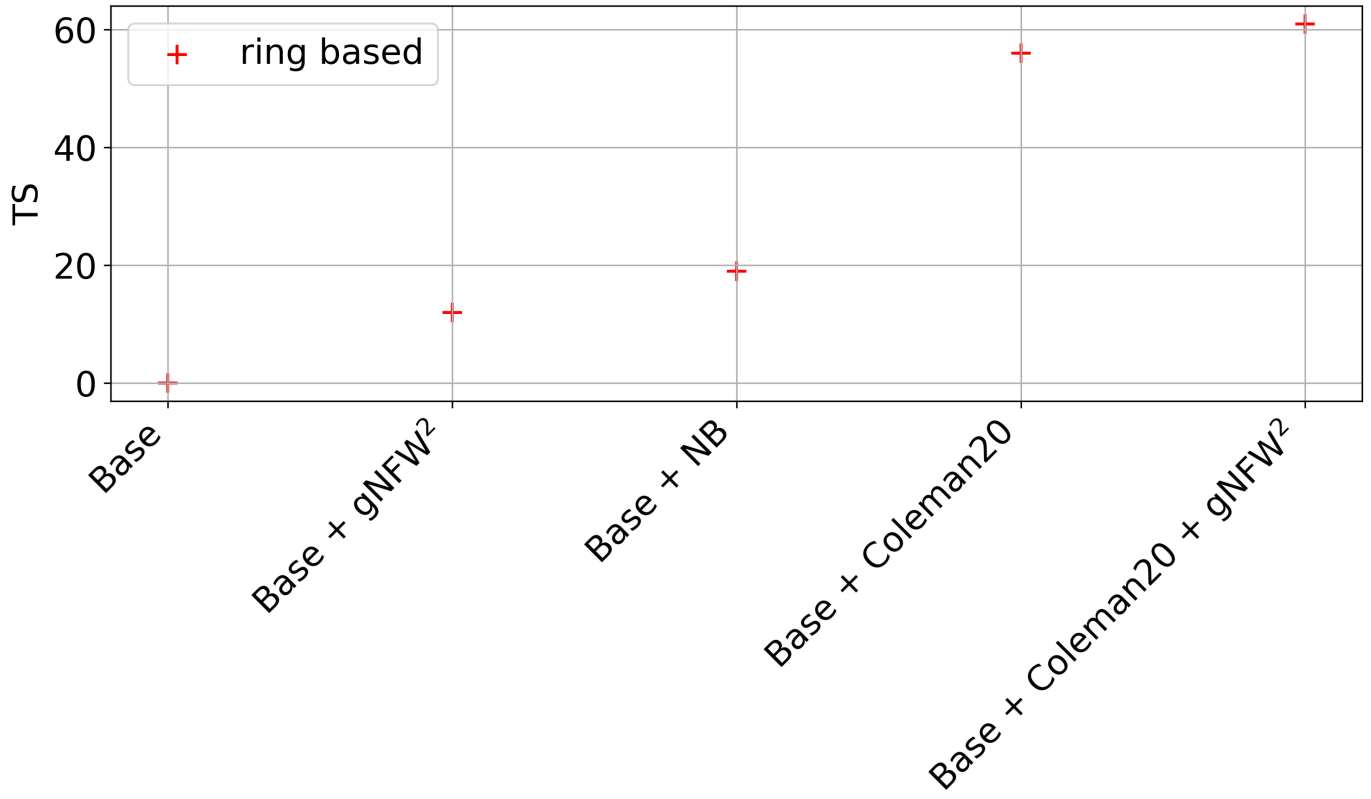


Larger Mask

- A comparison of the fraction of the sky masked.
- Note that in both cases, the plot is for the combined point source and Galactic plane mask.



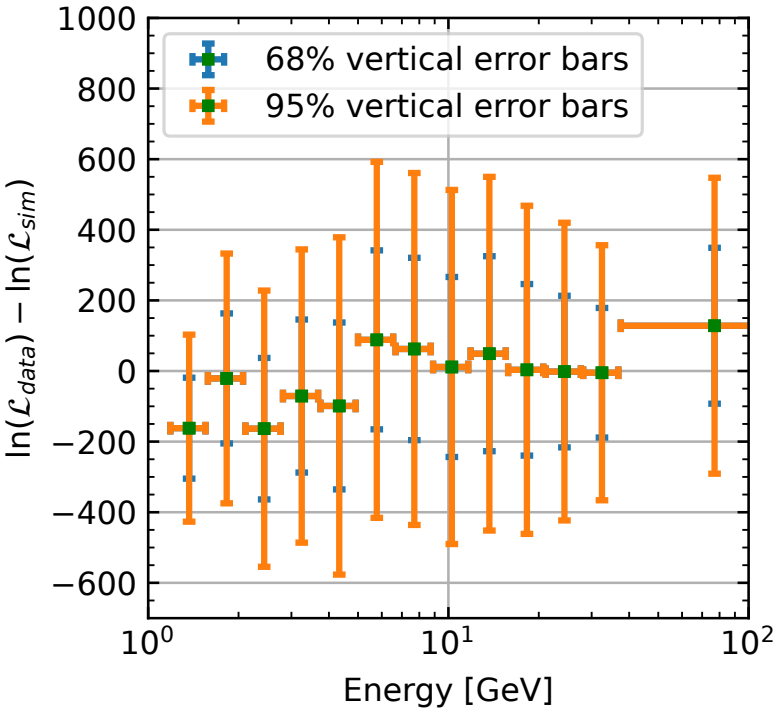
Larger Mask



$$\mathrm{TS} = 2\ln(\mathcal{L}[\mathrm{base} + \mathrm{GCE}] - \mathcal{L}[\mathrm{base}])$$

Monte Carlo Simulations

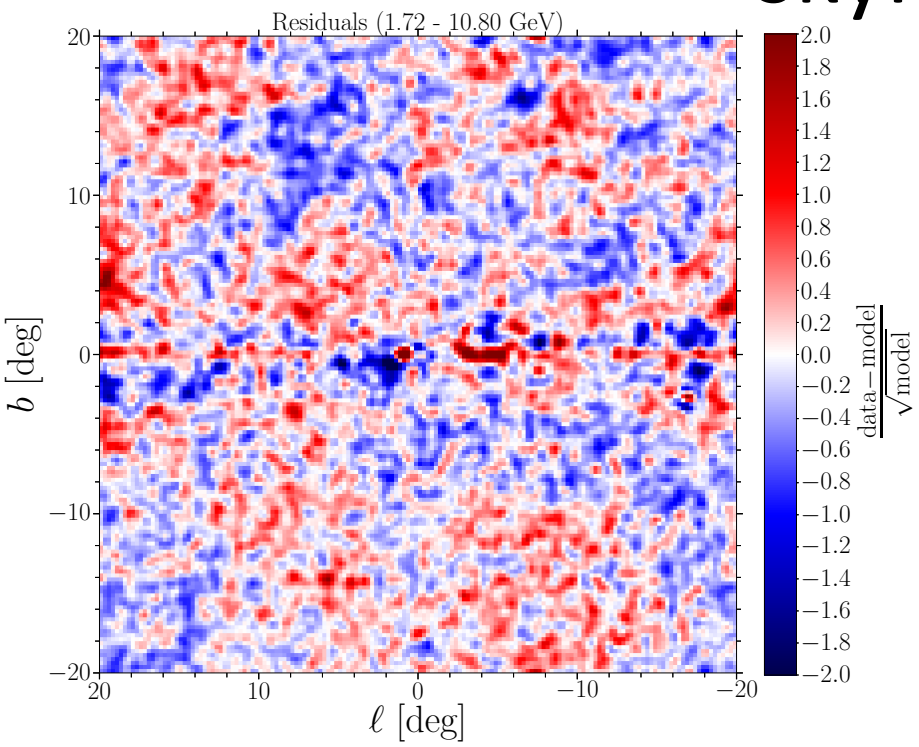
- The ring-based+Coleman20 model was used.
- The point sources and the $|b|<2^\circ$ Galactic plane was masked.
- Poissonian simulations were generated for the best-fit parameters of this model.
- Each simulation was fit using the ring based+Coleman20 model.
- The maximum likelihood for the simulation ($\mathcal{L}_{\text{sim}}$) was compared to the maximum likelihood for the ring-based+Coleman20 model fit to the Fermi-LAT data (ln $\mathcal{L}_{\text{data}}$).
- The vertical error bars were estimated from the mean and standard deviation of the simulation samples.
- The horizontal error bars indicate the energy bin widths.

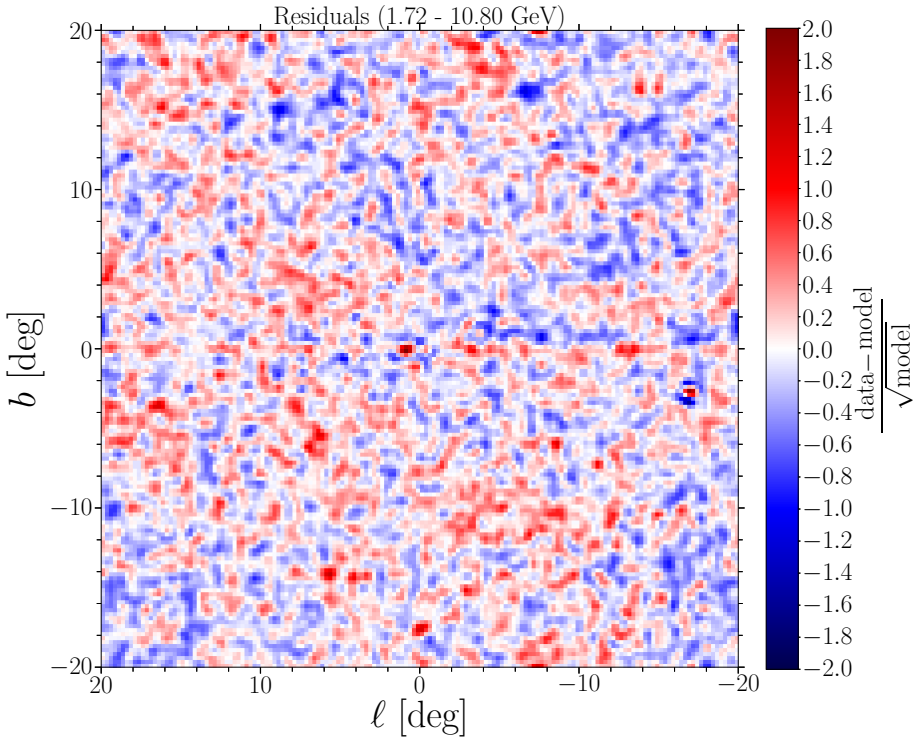


skyFACT Modulation

- skyFACT (Storm et al. 2017; Bartels et al. 2018; Calore et al. 2021) uses adaptive template fitting, invoking a large number of modulation parameters whose ranges are controlled by user-input hyper-parameters.
- The degree of variation in these modulation parameters is restricted via a penalising likelihood function adding to a standard Poisson likelihood term to prevent overfitting.
- For each of the considered background model setups, we performed a fit to the Fermi-LAT data by enabling spatial re-modulation.
- We obtain what we call "optimised" versions of the original background model setups.

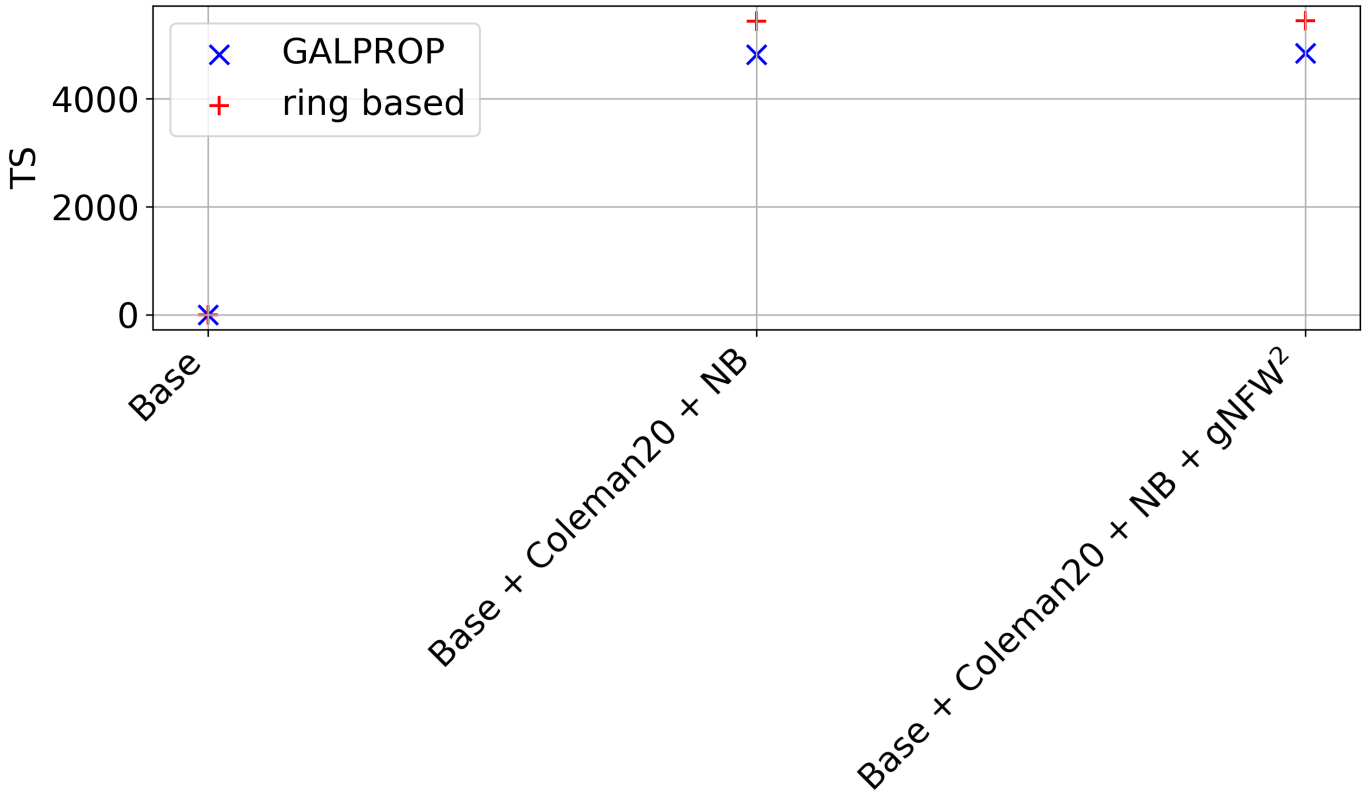
skyFACT Modulation





- (Left:) Employing skyFACT to perform a template fit with the ring-based astrophysical model components with a GCE represented by the Coleman20 + NB + gNFW [2].
- (Right:) Running the same model setup with the full re-modulation power of skyFACT to optimize the employed components.

skyFACT Modulation



$$\mathrm{TS} = 2\ln(\mathcal{L}[\mathrm{base} + \mathrm{GCE}] - \mathcal{L}[\mathrm{base}])$$

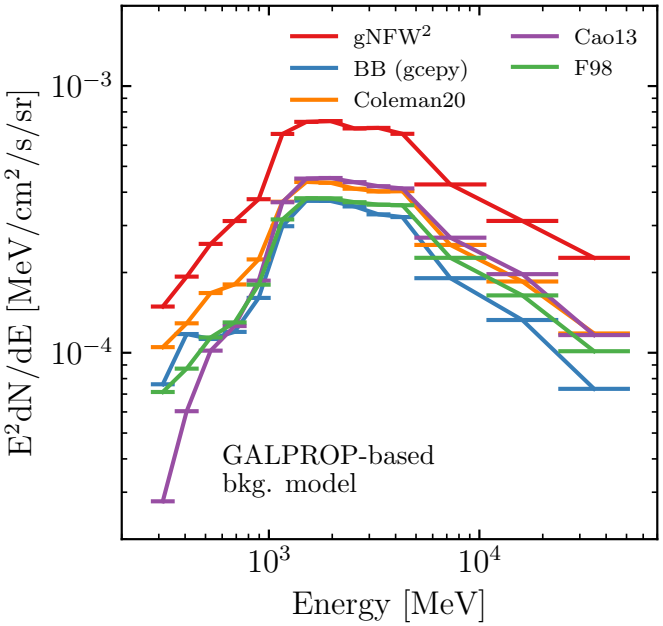
Zhong and Cholis, PRD, 2024

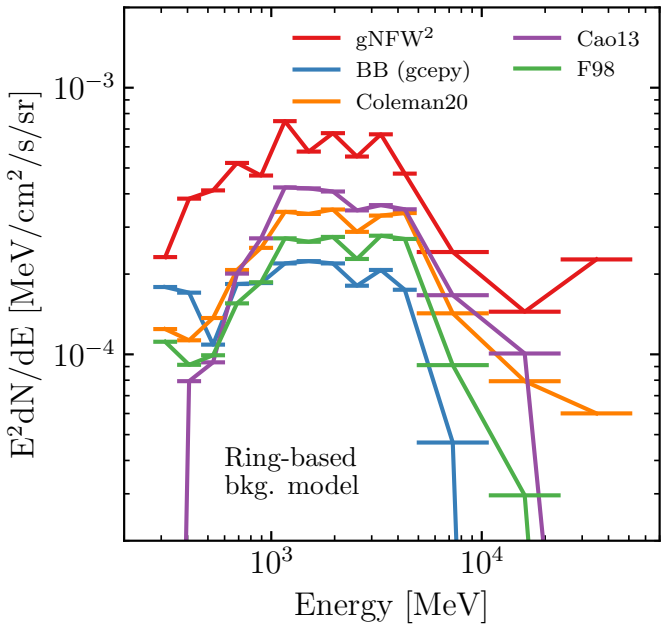
- They use different masks constructed from Fermi point source catalogues and a wavelet method.
- They also look at a range of different GALPROP templates.
- They find that compared to various stellar bulge profiles, a spherical dark matter annihilation profile has a similar TS to the Coleman20 bulge template.
- They use non-gradient descent optimisation.

Conclusions

- Using the same mask and GALPROP background templates as McDermott, Zhong, and Cholis, MNRAS (2023), we found the Coleman20 bulge provided a better fit to the GCE than the dark matter gNFW^2 template.
- This conclusion was robust to using ring-based background templates, significantly larger masks and also skyFACT modulation.

GCE spectra

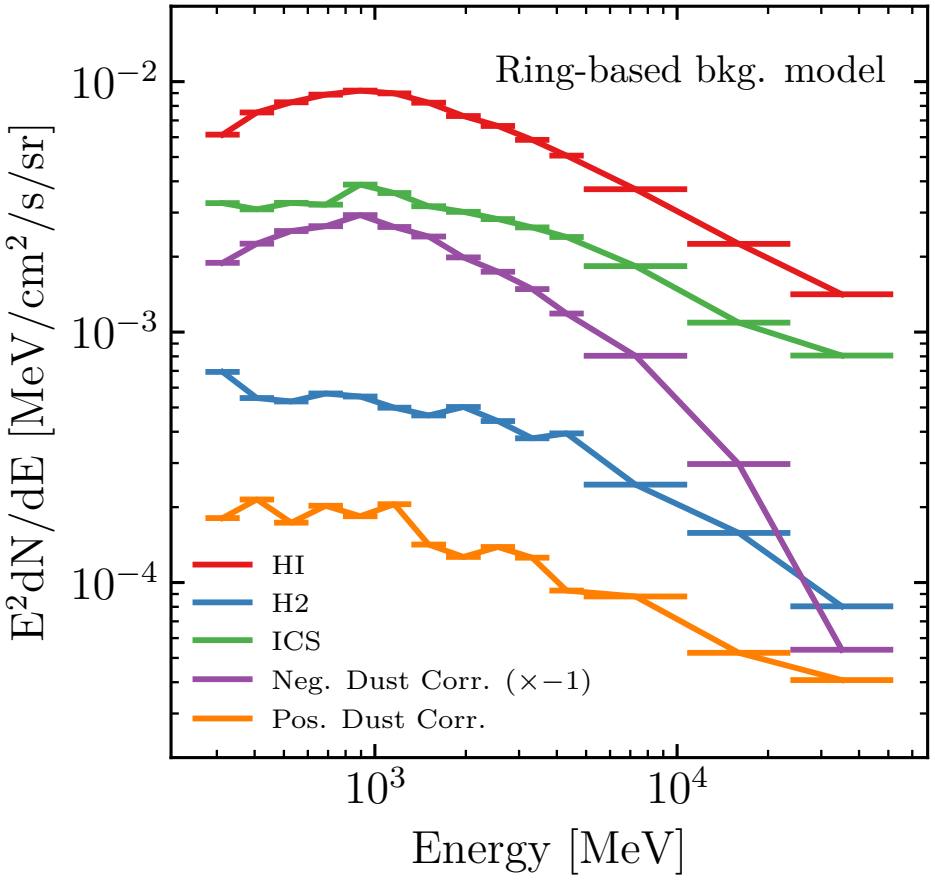




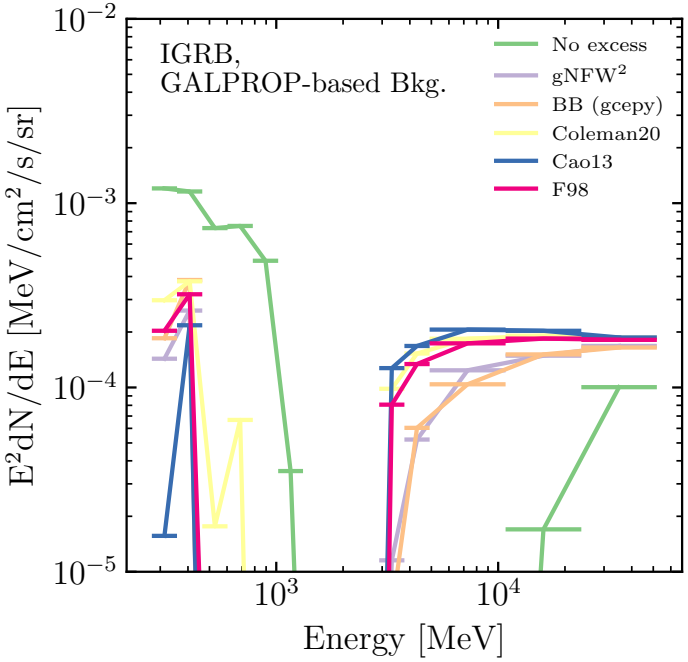
- GCE spectra for the gNFW^2 template as well as the four bulge templates
- In the left panel, the GALPROP $8t$-based background model is used.

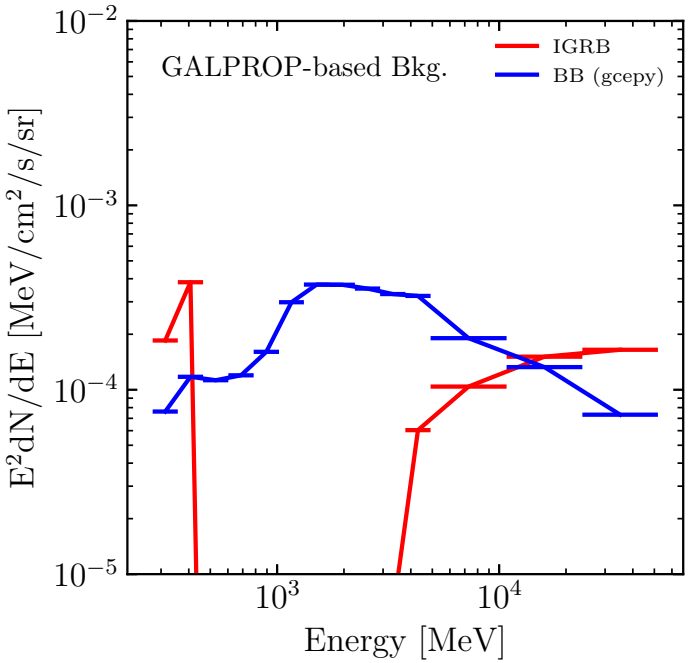
Background Spectra

- Best-fit spectra for the HI, H2, ICS, negative and positive dust corrections
- Ring-based background model.
- The results are obtained with no GCE template and are from the L-BFGS-B algorithm.



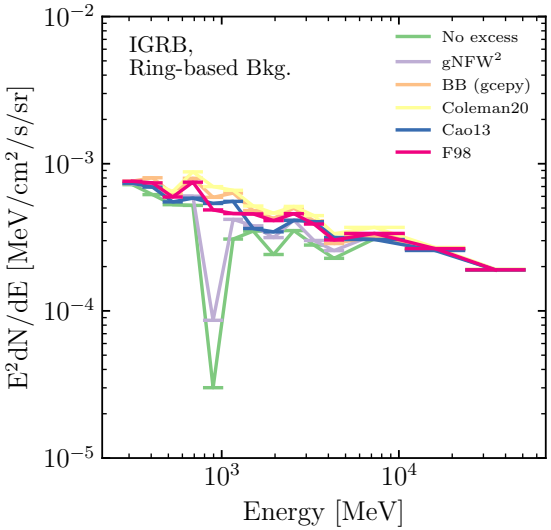
Isotropic Diffuse Gamma-Ray Background Emission (IGRB) Spectrum

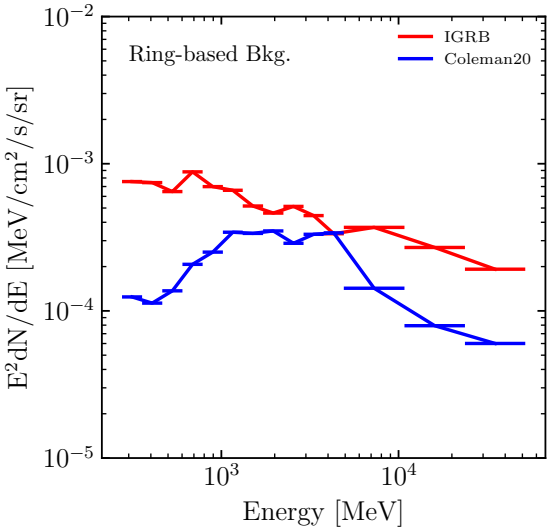




- The above spectra are for the GALPROP-based background model, using different GCE templates (including no excess).

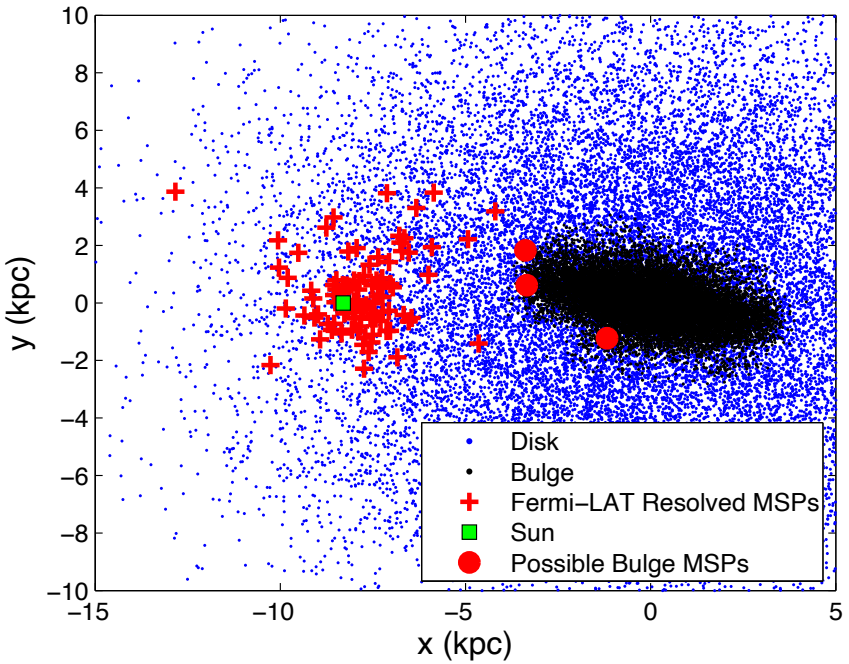
Isotropic Diffuse Gamma-Ray Background Emission (IGRB) Spectrum

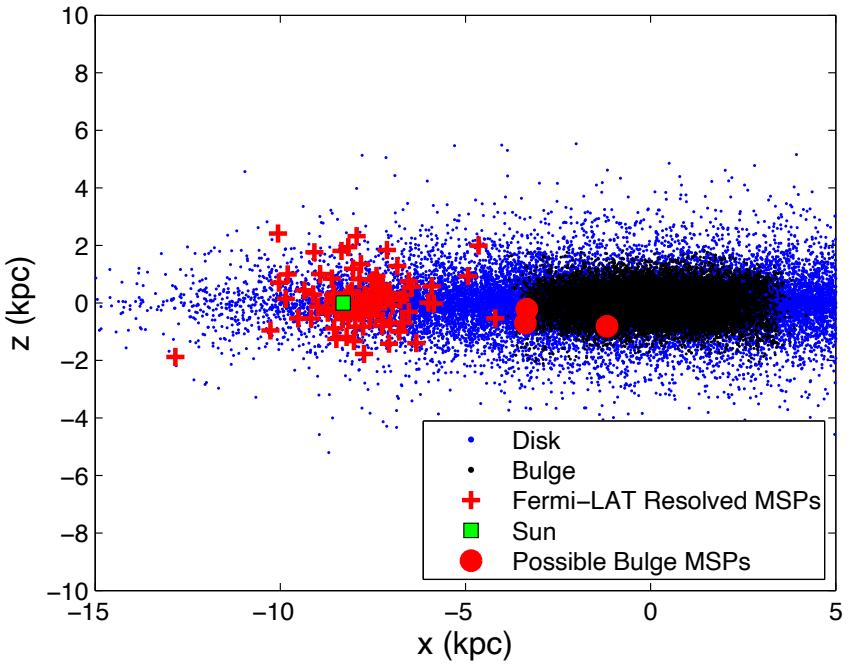




- The above spectra are for the Ring-based background model, using different GCE templates (including no excess).

Distribution of Disk and Bulge Millisecond Pulsars (MSPs)





- See *Ploeg, Gordon, Crocker, and Macias, "Comparing the Galactic Bulge and Galactic Disk Millisecond Pulsars", JCAP12(2020)035* for more details.