Searching for Signatures of Recent Cosmic-Ray Acceleration in the High-Latitude γ-Ray Sky

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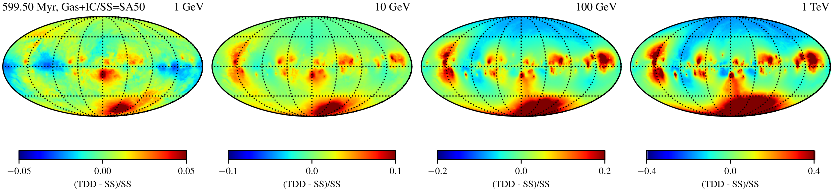
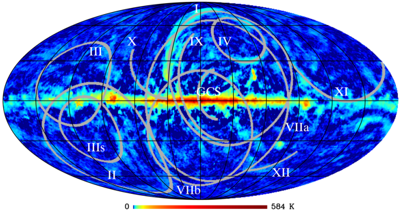
Motivation and Main Objective



From Porter, et al. 2019 ApJ 887, 250

- CR sources are likely spatially and temporally discrete.
  - Results in localised enhancements in CR flux over a "steady state" background.
- Most prominent for local sources at high-latitude.
- The radio loops are a possible low-energy signature.
- Can we find similar structures in the γ-ray high-latitude sky in LAT data?



From Vidal et al. 2015 MNRAS 452, 656

Our Model and Data

- The γ-ray sky can be segmented into the following three components:
  - A structured component arising from the distribution of gas in the Galaxy.
  - A smooth component to account for the inverse-Compton (IC) emission, unresolved point sources, and irreducible CR background in the data.
  - Point sources and slightly extended sources as listed in the second data release of the fourth Fermi LAT catalog (4FGL-DR2)
- Utilize Gaussian processes (GPs) to model the directional CR emissivity and the smooth component intensity, keeping the 4FGL-DR2 component fixed.
  - Base the GPs on the HEALPix pixelization and use $N_{\rm side} = 4$ ($\sim 15^\circ$) for the gas and $N_{\rm side} = 8$ ($\sim 7^\circ$) for the smooth component with linear interpolation to $N_{\rm side} = 256$ ($\sim 0.2^\circ$) used for the data.
- Use 10 yr of ULTRACLEANVETO FRONT+BACK data, same time range as 4FGL-DR2
- Fit each hemisphere ($|b| > 30^\circ$) independently in each of the 4 energy bands (1-3, 3-10, 10-60, and 60-1000 GeV) with each bin split logarithmically into 4 smaller bins.
  - Allow for power-law spectral modulation for the emissivity and smooth component within each coarse energy bin.

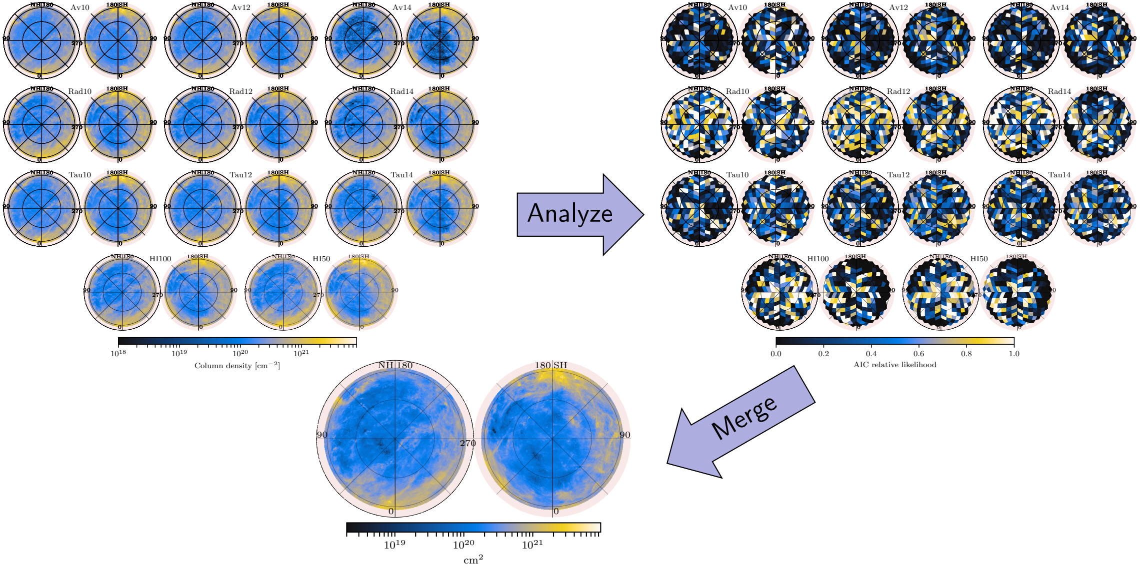
The Gas Templates

- Simulations show that the structured gas component is the most important source of systematic uncertainty.
- Use four different gas tracers, resulting in 11 gas templates:
  - HI4PI 21-cm observations ($T_S \in \{50\text{K}, 100\text{K}\}$)
  - Dust optical depth (τ_{353}), dust radiance, and dust optical extinction (A_v) from *Planck*.
  - Dust turned to gas column using

$$G = X_d(D - d_0)^{1/\alpha}$$

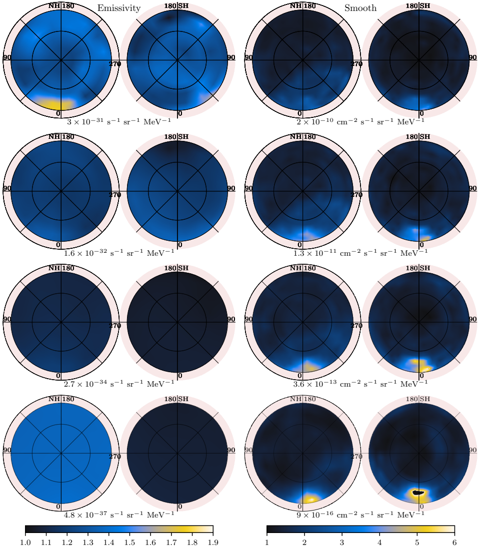
    where $\alpha \in \{1.0, 1.2, 1.4\}$ and X_d and d_0 adjusted in a fit to optically thin HI column density
- Run the analysis using these maps and compare the Akaike information criterion (AIC) in HEALPix $N_\mathrm{side} = 8$ pixels
- Create a new map using the best AIC at the center of each pixel
  - Use a linear combination of the maps based on linear interpolation between the pixel centers to avoid sharp borders.
- Simulations show that this method reduces the systematic uncertainty to $\lesssim 20\%$.

Visualization of the Procedure



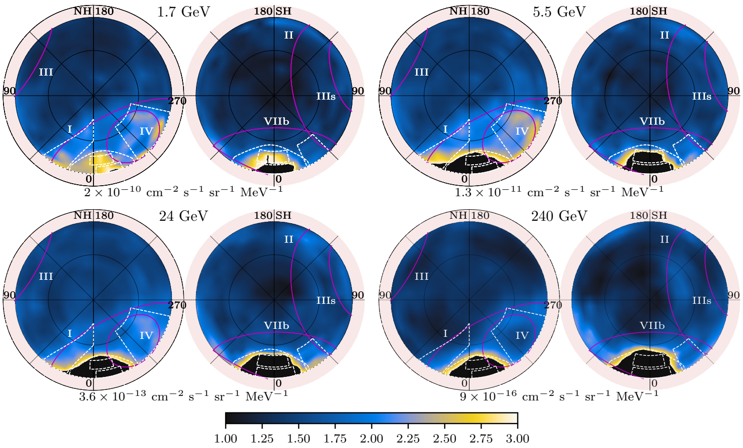
The Spatial Results – Overview

- Emissivity of gas (left) and intensity of smooth component (right) after final analysis
- A low significance signal ($\lesssim 3\sigma$) in the emissivity towards the Galactic center in the north hemisphere (NH)
- Significant structure in the smooth component in NH, less in SH
- Largest feature spatially associated with Fermi-bubbles (FBs)
  - South feature shows up as two separate blobs, with a measurably lower intensity in between
  - Exact location depends on the underlying pixelisation of the GPs
  - Result is qualitatively similar to previous analysis of the FBs



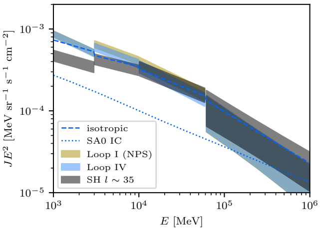
The Spatial Results – Zooming in

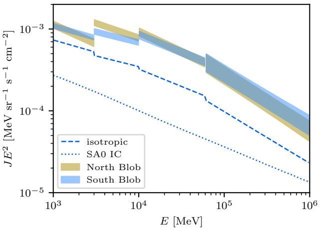
- Using a reduced range for the color scale, the structure in the smooth component becomes more evident
- Magenta arcs trace features in radio synchrotron maps
  - Clear emission from Loops I and IV
  - Other loops with less significant emission
- White regions used for plotting spectra

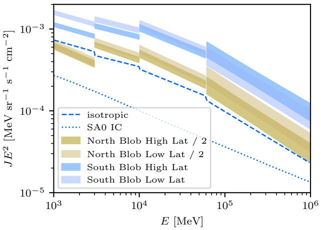


Results – Isotropic-Subtracted Spectrum of Enhanced Features

- Smooth component includes contribution from an isotropic background which is estimated as the lowest intensity of the smooth component in each energy bin.
- Loop spectrum similar to that of isotropic background and IC, while "SH feature" is harder.
  - Points to leptonic origin of the emission
- Spectrum of the FBs overall harder and compatible between north and south
- High-latitude emission in the southern FB clearly harder than mid-latitude emission – not seen in northern FB

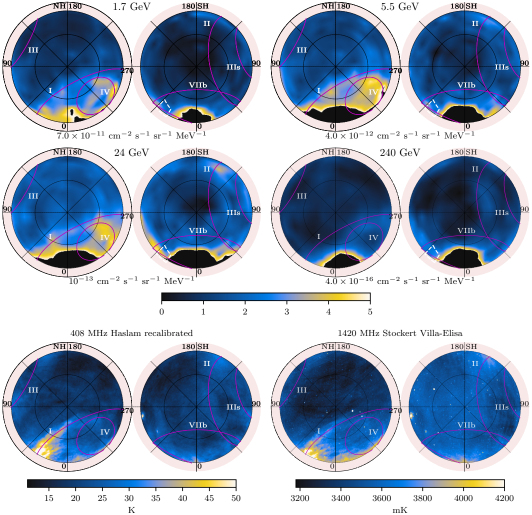






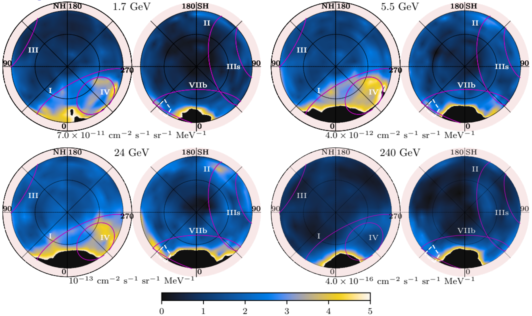
Discussion – Isotropic Subtracted vs. Radio

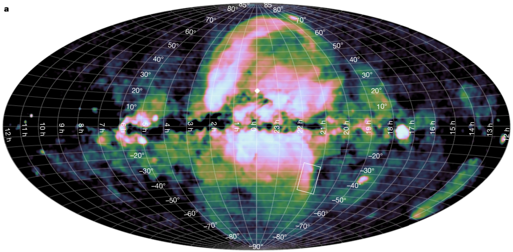
- Subtracting the isotropic highlights the true brightness of the features
  - Loops I and IV around 3 times brighter than background
- Loops I and IV are about equally bright in gamma-rays, while Loop IV is significantly dimmer than Loop I in radio
- Caused by differences in magnetic field strength?
- Particles accelerated to TeV energies in the loops
- Extra feature at base of Loops II and VIIb not seen in radio.



Discussion – Isotropic Subtracted vs. X-rays

- Emission from Loop I is compatible between the two bands, while that of Loop IV is missing in the X-rays.
- X-rays in white box do not correspond to a feature in the γ-ray maps.
- SH feature in γ-ray map does not show up in X-ray map.
- Assuming the ratio of emission of Loop I in γ-rays vs. X-rays, then we should be sensitive to the Greenish extended region observed in the SH by eROSITA.
  - Lack of correspondence does not support the symmetry argument required for the association of Loop I and FBs.





Predehl et al. 2020, Nature, 588

Discussion – Origin of Emission from the Radio Loops

- Lack of emissivity enhancement associated with the Loops requires that they are located above most of the gas-layer in the Galaxy, placing them at distances $\gtrsim 200$ pc.
  - The alternative explanation that they only accelerate electrons is unlikely.
- Their intensity spectrum strongly indicates leptonic origin. This is also supported by low gas density estimated from X-ray observations.
- At the distance of the GC, electrons are expected to be strongly cooled if they are accelerated close to the plane. Lack of strong cutoff poses challanges for such interpretation.
- Discrepancies between radio/X-ray/γ-ray correlations between the loops point to a wide range of properties/origins for the various loops.

Summary

- We have measured the intensity of the smooth component of the gamma-ray emission in an as unbiased way as possible.
- Special treatment of the gas templates is required to reduce systematic uncertainty of the method.
- Significant emission is observed spatially coincident with the Fermi bubbles and radio Loops I and IV
  - A single additional region significantly detected, possibly associated with a recent CR source.
- Emission from Loops I and IV:
  - No signature of the southern counterpart of Loop I in gamma-rays, not even at the lowest latitudes where X-ray emission is about as bright as that in the north
  - Loops I and IV are equally bright in γ-rays while they show strong variations in both radio and X-rays.
  - Our results point to an intermediate distance to the two loops, placing them above/beyond the gas-layer.
- Using GPs or similar methods to extract the smooth component of the LAT emission is a promising method.