Signatures of the Time-Dependent Cosmic Ray Production and Propagation in the Very High Energy γ-ray Sky

Troy Porter
with Guðlaugur Jóhannesson, Peter Marinos, Igor Moskalenko, and Gavin Rowell

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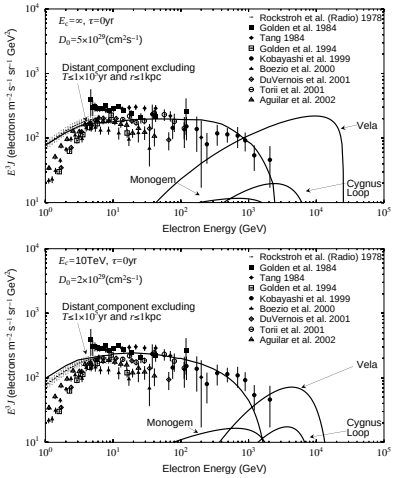
Motivation

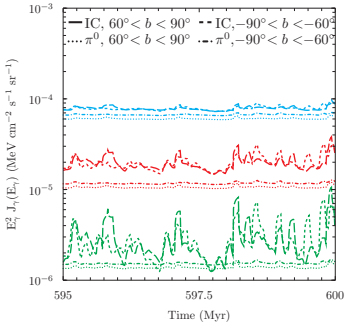
- Steady-state models have been main stay since 1960s.
  - Work generally okay for $\sim$0.1–10s of GeV energies where losses and diffusion time scales are comparable to escape from Galaxy.
- But CR sources are likely spatially and temporally discrete.
  - Results in localised enhancements in CR flux over the "steady state" background.
- Application of discrete picture mainly for explanation of local VHE CR data $\gtrsim$50 GeV.
- CR intensities elsewhere in the Galaxy are similary affected $\rightarrow$ traced by diffuse γ-ray emissions.
- Fluctuations in CR intensity mean unlikely that VHE emissions do not scale directly from the GeV energy range.

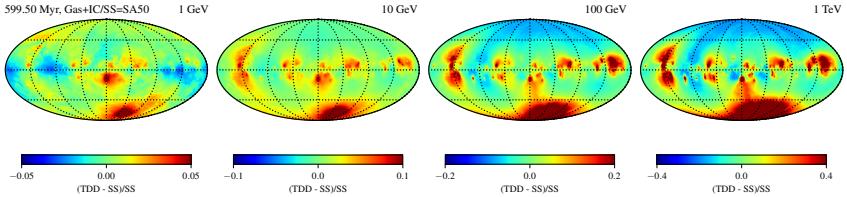


From Kobayashi et al. 2004 ApJ 601, 340.

Predict Signatures in the γ-ray Sky

- Time-dependent discrete source CR/non-thermal modelling using GALPROP framework (v57).
- Fluctuations with time coming mostly from CR lepton component $\rightarrow$ increase significantly with energy.
- Surface brightness variations over all scales due to spatial proximity of individual sources and historical injection/propagation.

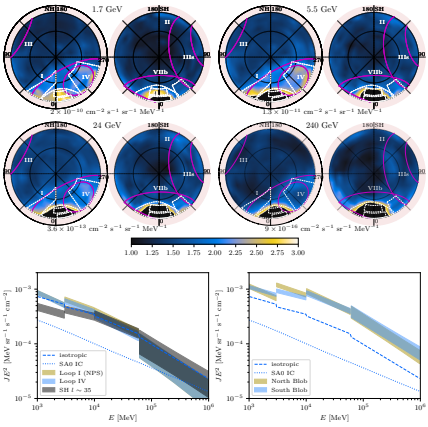




From Porter, et al. 2019 ApJ 887, 250.

Search for Signatures in the γ-ray Sky at High Latitudes

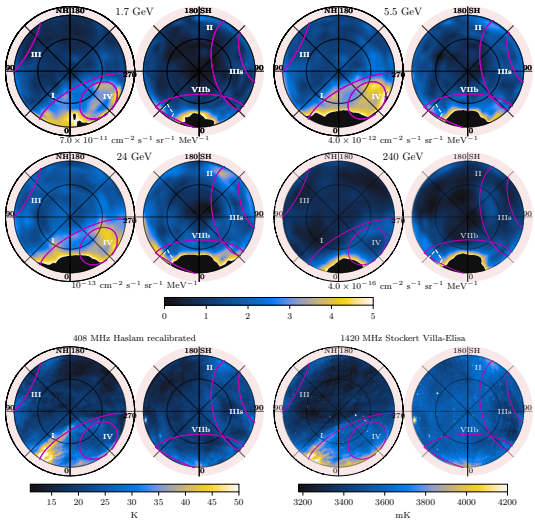
- Signatures from modelling indicate high-latitude regions most likely to show evidence for discrete local source activity.
- Looking for a-priori unknown spatial distributions $\rightarrow$ standard template methods will not work.
  - Use Gaussian Processes modelling with structured (gas) and smooth (IC, isotropic) components.
- Analysis of 10 years data find evidence for extended low-surface brightness features in smooth component over background.
- 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.



From Jóhannesson & Porter 2021, ApJ 917, 30.

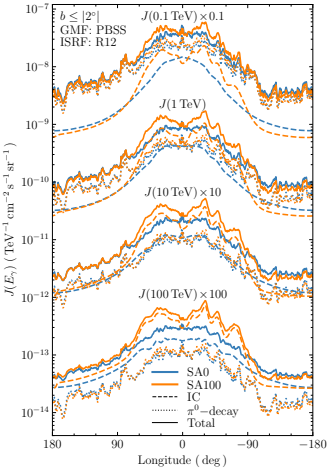
Results – Isotropic Subtracted vs. Radio

- 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.



Systematic Study of Large-Scale VHE Emissions

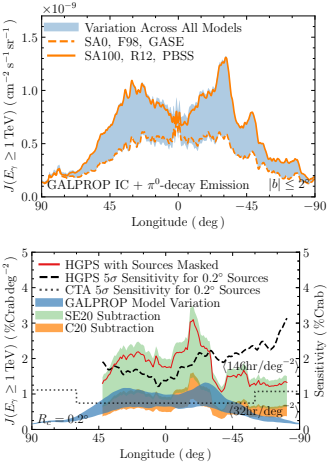
- Connecting GeV and TeV range not a simple direct scaling with energy.
- Make systematic study using grid of 3D GALPROP models categorised according to CR source and ISM density distributions.
  - 5 source distributions corresponding to disc/arm relative contributions.
  - 2 ISRF models (R12, F98).
  - 2 GMF models (GASE, PBSS).
- Each model configuration assume diffusive-reacceleration propagation phenomenology with 3D gas model from Jóhannesson et al. 2018.
- Propagation model parameters for each configuration normalised to reproduce local CR data.
- Predict diffuse emissions for nuclei-induced and Compton interactions using CR solution with target ISM models.



From Marinos et al. 2023, MNRAS 518, 5036.

Results – Steady-State Models vs. HGPS

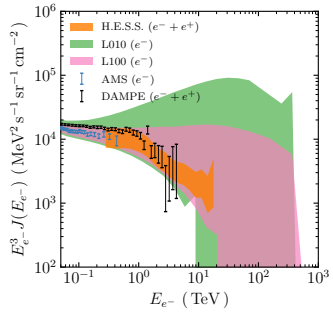
- Contribution of Compton component increases with energy.
  - Compton and gas components comparable up to $\sim$10 TeV, then Compton increasing dominant.
  - Effect of GMF distribution appears in Compton component $\gtrsim$30 TeV due to KN suppression of ISRF (Opt,IR/FIR) $\rightarrow$ synchrotron losses shape electron energy density distribution.
- Factor $\sim$2 variation between model using 2D source and GMF to that with 3D arm structures in source and GMF/ISRF.
- Model predictions are brighter than simple scaling of GeV range *Fermi* background model.
- Accounting for instrumental/observation effects HGPS, diffuse emission is near threshold.



From Marinos et al. 2023, MNRAS 518, 5036.

Discretised VHE/UHE Modelling

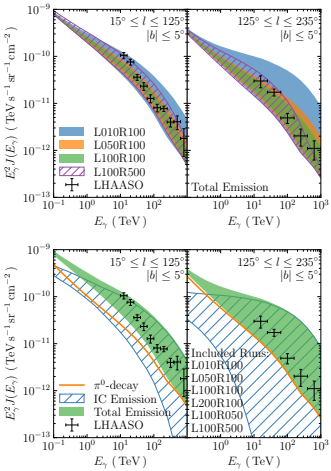
- Establish likely systematic effects using the steady-state models → can investigate also discretised effects on the VHE/UHE emissions.
- Select SA50 configuration, R12 ISRF, PBSS GMF and make simulations for individual region active injection times and occurence rate → showing samples at 10 kyr over 5 Myr following initial ∼100s Myr evolution of simulation.
- Not so important for nuclei → can continue using steady-state for these.
- Electrons strongly affected by the rate and active time.
- When folded through the HGPS 'response' the envelope showing the fluctuations for the Compton emissions over single model configurations comparable to the total envelope over steady-state configurations.



From Marinos et al. 2023, in prep.

Discretised VHE/UHE Modelling

- With higher energies the fluctuations for the Compton component produce even broader envelopes.
- The total emissions from the discretised runs can account, or exceed, the data (takes into account LHAASO masking regions).
- Not shown are the neutrino predictions for this model $\rightarrow$ consistent with the IceCube results.
- Gas-related component cannot be arbitrarily tuned 'up' so it seems necessary that the contribution of discrete lepton-dominated emissions regions is a necessity.



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Summary

- We began a programme to model the effect of discretised CR sources on the diffuse emissions back in 2019.
- Predictions made in that work were tested and to some extent verified by analysis of LAT data using GP, showed energy-dependent morphology.
  - Standard template analysis would not have revealed the evidence found.
- Want to make connection between GeV and >TeV ranges so we investigated the TeV emissions using steady-state models to establish likely sysematic factors.
- Predicted emissions have contribution by Compton component increasing with energy $\rightarrow$ direct scaling of GeV map from *Fermi* based on gas tracers incomplete picture.
- comparison with HGPS showing they are close-to bright enough to be necessary to consider for data analysis.
- Discretised VHE/UHE modelling shows that the electron sources and their properties (rate, etc.) are a strong factor for interpreting the data at these energies.