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# Improved Galactic diffuse emission model strengthens the case for a Millisecond Pulsar explanation of the Fermi GeV excess

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## Abstract

**After more than a decade since its discovery, the Galactic center gamma-ray excess – discovered with the Fermi Large Area Telescope – remains puzzling. While the spectrum of the signal can be explained by either dark matter or an unresolved population of millisecond pulsars, the spatial morphology of this excess seems to hold the key to separate the two theories. In this contribution, we present the results of a recent study in which we use bleeding edge models for interstellar gas, inverse Compton emission, and stellar mass models to reanalyze the Galactic center excess. We find that the spatial morphology of the excess is highly correlated with stellar matter in the Galactic bulge, providing strong support for the millisecond pulsar hypothesis.**

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## Contents

## 1 Introduction

Searches for new physics with gamma-ray telescopes are limited by our understanding of the astrophysical background, specially in the center of the Milky Way. Despite this limitation, analyses [1–7] of Fermi-LAT data from the Galactic center (GC) have observed an excess of extended GeV gamma rays which is not readily explained by known astrophysical sources.

This GC excess (GCE) could in principle be explained by the self-annihilation of GeV-scale dark matter particles (e.g., [1,4,7–11]) or by a large population of gamma-ray emitting pulsars [4, 6, 12, 13]. While the predicted spectrum for either of these two hypothetical sources is degenerate, their spatial morphologies are expected to be quite different [14]. Interestingly, a string of recent articles [15–20] have found a correlation[1] between the spatial morphology of the GCE and that of stellar mass in the Galactic bulge. If these results are confirmed with realistic (good-fitting in an absolute sense) Galactic diffuse emission models (GDE), then it would completely clarify the nature of the Fermi GeV excess.

In this contribution (see Ref. [23] for in-depth discussions), we present a much improved model for the GDE in the inner Galaxy, and evaluate its impact on the characteristics of the GCE. Consistent with previous results by some of us (e.g., Ref [15–17]), we find that the spatial morphology of the GCE is best matched by stellar bulge rather than dark matter templates.

## 2 Description of our new Galactic diffuse emission model

We have constructed a new GDE model[2] for the Galactic center region which contains numerous substantial improvements with respect to previous studies. First, our atomic hydrogen model is based on explicit radiation-transport modeling of line, absorption, and continuum emission [23] which allows for a more realistic representation of the distribution of hydrogen in the GC. Second, our inverse Compton (IC) templates reproduce the state-of-the-art templates recently constructed by the GALPROP team [24]. Following the methodology pioneered by the Fermi collaboration [25], we have divided these two components of the GDE in Galactocentric rings so that they have sufficient freedom to accommodate for any potential negative/positive residuals present in the data. Third, we used bleeding-edge models for the stellar bulge [18] and Fermi bubbles [17]. Figure 1 shows residual maps for the atomic hydrogen distribution in the GC. These are constructed by subtracting the standard hydrogen gas maps in Ref. [26] from our new hydrodynamic hydrogen models. The observed differences between the new and old models are due to a combination of factors: (i) the hydrodynamic gas maps assume a gas flow model constructed from smoothed-particle-hydrodynamic simulations whereas the standard ones assume circular orbits of gas, (ii) while we account for continuum emission and absorption lines in the construction of the new gas maps, the standard ones do *not*, and (iii) we allow for the hydrogen excitation temperature to vary along the longitudinal and latitudinal directions (in Galactic coordinates), whereas the standard maps assume a constant excitation temperature across the Galaxy [26]. Interestingly, we have found that our new GDE model fit the GC data significantly better than the previous generation of hydrodynamic gas models [15, 17, 27], as well as the standard gas templates [28].

The recovered spectra for the different interstellar gas ring templates are presented in Fig. 2. As can be seen, the spectra for each ring displays a marked hadronic/bremsstrahlung-like behaviour, demonstrating the adequacy of the particular ring subdivision adopted in our pipeline. The total gas-correlated spectra in our region of interest was presented in Fig. 13 of Ref. [23].

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[1] Though we note that Refs. [21, 22] have claimed different results.

[2] All the astrophysical templates are publicly available at https://doi.org/ 10.5281/zenodo.6276721.

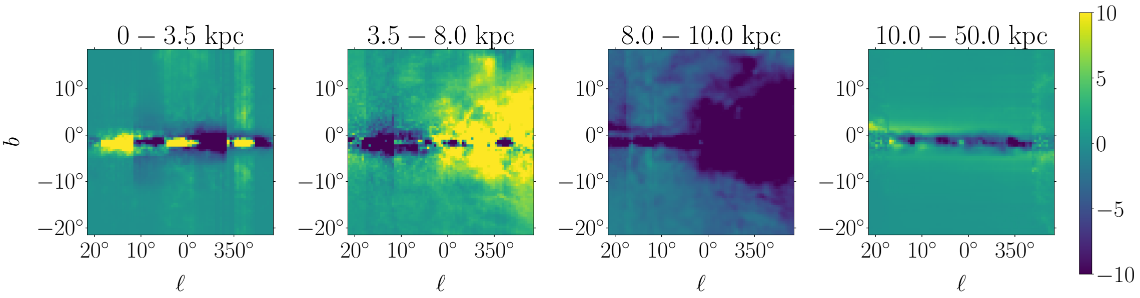

Figure 1: Residual atomic hydrogen maps ($\mathrm{H}I_{\mathrm{hydrodynamic}} - \mathrm{H}I_{\mathrm{interpolated}}$) in units of $10^{20}\mathrm{cm}^{-2}$, where $\mathrm{H}I_{\mathrm{hydrodynamic}}$ refers to the new hydrodynamic gas maps introduced in Ref. [23], and $\mathrm{H}I_{\mathrm{interpolated}}$ to the standard gas maps widely used in the community (e.g., Ref. [28]). The new hydrodynamic gas maps account for continuum emission and absorption, allow for the hydrogen excitation temperature to vary with $l$ and $b$, and do *not* assume circular orbits for the motion of interstellar gas.

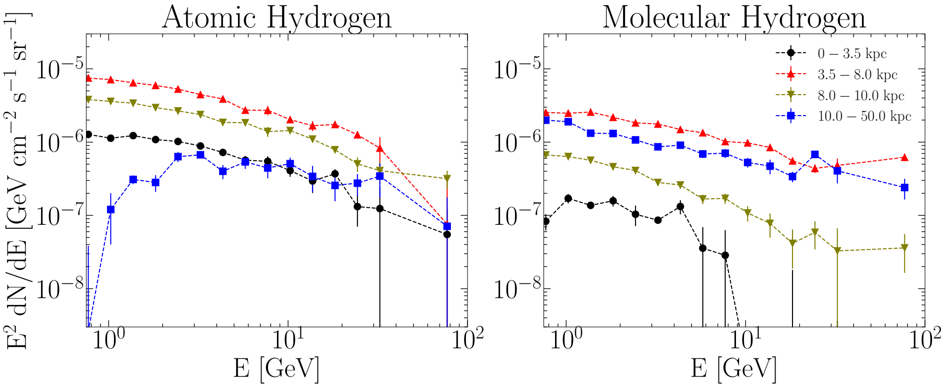

Figure 2: Spectra of the different interstellar annular gas templates included in the fit. See Fig. 1 and Fig. 5 in Ref. [23] for further details. These were obtained using a bin-by-bin analysis technique [15, 19] with which we agnostically reconstruct the spectra of each template based solely on their spatial morphology. The left panel shows the spectra for atomic hydrogen and the right panel the spectra of the molecular hydrogen, assumed to be traced by Carbon monoxide (CO) [15]. Both appear physically plausible and stable.

## 3 Main results

By running a maximum-likelihood procedure independently at each different energy bin (bin-by-bin method described in Ref. [23]) we computed the statistical significance of various templates for the GCE. In particular, we included four classes of dark matter (DM) profiles, and two maps tracing the distribution of stars in the inner Galaxy (as described in the Appendix of Ref. [23]). The statistical significance for each new source is obtained by computing the probability of ΔTS as shown in Eq. 2.5 of [17], and noting that each additional template has 15 degrees of freedom. Table 1 shows a summary of our statistical tests for different combinations of templates for the GCE. As can be seen in this table, using this procedure we find that the data strongly supports the inclusion of the Nuclear Bulge (NB) template first, and subsequently, the Boxy Bulge (BB) template. Importantly, in consistency with previous analyses [15–17, 19, 20], we find that once the NB and BB templates have been added to the ROI model, the data no longer require any of the DM templates that have been considered in the literature.

Table 1: **Statistical significance of the GCE templates for the H$I$ maps with varying $T_{\text{exc}}$.** The Base model comprises the new hydrodynamic gas maps introduced in this work (divided in four concentric rings), dust correction maps, inverse Compton maps, the 4FGL point sources, and templates for the Fermi Bubbles, Sun, Moon, Loop I, and isotropic emission (see the Appendix of Ref. [23]). Additional sources considered in the analysis are: Nuclear bulge (NB) [29], boxy bulge (BB) [18], NFW profile with $\gamma = 1.2$, cored dark matter [30], and ellipsoidal versions of these (see Fig. 3 in [19]). Note that as usual, all dark matter model templates are squared as is appropriate for pair-pair annihilation.

| Baseline model | Additional source | ΔTS | Significance |
|---|---|---|---|
| Base | Cored ellips. | 0.0 | 0.0 $\sigma$ |
| Base | Cored | 0.1 | 0.0 $\sigma$ |
| Base | BB | 282.2 | 15.3 $\sigma$ |
| Base | NFW ellips. | 647.2 | 24.2 $\sigma$ |
| Base | NFW | 807.1 | 27.3 $\sigma$ |
| Base | NB | 1728.9 | 40.8 $\sigma$ |
| Base+NB | Cored ellips. | 0.1 | 0.0 $\sigma$ |
| Base+NB | Cored | 0.7 | 0.0 $\sigma$ |
| Base+NB | NFW ellips. | 1.0 | 0.0 $\sigma$ |
| Base+NB | NFW | 3.4 | 0.2 $\sigma$ |
| Base+NB | BB | 261.0 | 14.7 $\sigma$ |
| Base+NB+BB | NFW ellips. | 0.1 | 0.0 $\sigma$ |
| Base+NB+BB | Cored ellips. | 0.4 | 0.0 $\sigma$ |
| Base+NB+BB | Cored | 0.7 | 0.0 $\sigma$ |
| Base+NB+BB | NFW | 2.6 | 0.1 $\sigma$ |

## 4 Conclusions

We obtained with high significance an improved fit to the diffuse gamma-ray emission observed by *Fermi*-LAT. When our new GDE model is used to estimate the statistical significance of the various spatial templates that have been proposed for the GCE, we confirm that that the fit strongly prefers the stellar template to the DM-like template at high significance. Once the stellar templates are included in the fit, there is no longer any evidence for a DM-like signal in the data be it cuspy or cored. This finding is robust under the variation of various parameters, for example the excitation temperature of atomic hydrogen, and a number of tests for systematic issues.

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