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GeV excess and phenomenological astrophysics modeling

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Abstract. Predefined spatial templates to describe the background of γ-ray emission from astrophysical processes, like cosmic ray interactions, are used in previous searches for the γ-ray signatures of annihilating galactic dark matter. In this proceeding, we investigate the GeV excess in the inner Galaxy using an alternative approach, in which the astrophysical components are identified solely by their spectral and morphological properties. We confirm the reported GeV excess and derive related parameters for dark matter interpretation, which are consistent with previous results. We investigate the morphology of this spectral excess as preferred by the data only. This emission component exhibits a central Galaxy cusp as expected for a dark matter annihilation signal. However, Galactic disk regions with a morphology of that of the hot interstellar medium also host such a spectral component. This points to a possible astrophysical origin of the excess and requests a more detailed understanding of astrophysical γ-ray emitting processes in the galactic center region before definite claims about a dark matter annihilation signal can be made.

1. Introduction

Identifying its annihilation signatures is a promising way to probe the nature of dark matter (DM). Targets, which are favored by indirect detection of DM using γ-ray data, should contain DM in high density, be relatively nearby, and show little flux of astrophysical (not-DM-annihilation related) γ-rays. The Galactic Center (GC) region is ideal with respect to the first two conditions, however, due to supernovae explosions injecting cosmic rays (CRs) into the interstellar medium (ISM) and compact sources of high energy particles and radiation, it exhibits significant amounts of astrophysical γ-ray emissions [1]. Several groups have reported a spatially extended GeV γ-ray excess from the region surrounding the GC with respect to the expected diffuse Galactic γ-ray emission (DGE) of astrophysical origin[2, 3, 4, 5, 6, 7, 8, 9, 10]. It is shown that the spectral shape could be fitted by DM with mass around several tens of GeV annihilating into $b\bar{b}$ or $\tau^+\tau^-$ final states [11, 12], and the spatial extension of this excess could be explained by a generalized NFW profile [13, 14] with an inner slope $\alpha = 1.2$ [9, 10, 11]. It is

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considerable that the DGE model uncertainties affect the apparent GeV γ-ray excess towards the GC, which implies considerable systematic uncertainties for the deduced DM properties or upper limits [15, 11, 16]. It is also shown that γ-ray emission from unresolved millisecond pulsars could also be the origin of the GeV excess [17, 18]. We will present here part of the analysis performed in [19], where we use an alternative, template-free, non-parametric, and phenomenological DGE and point source model, which significantly differs from that of the Fermi collaboration and other groups, to investigate the possible DM signal in γ-ray data.

2. Methods

Assuming the γ-ray sky to be a superposition of a diffuse component and a point source component, Selig et al. [20] used D^{3}PO algorithm [21] to decompose the observed photon flux into these two components probabilistically while also taking into account the instrument response and the Poisson statistics of the γ-ray events. It was shown that more than 90% of the decomposed diffuse component at all sky locations and all investigated energies could be further accounted for by a simple, phenomenologically constructed two components model [20]: The γ-ray spectra derived from a molecular cloud complex in the Galactic anti-center and those derived from the southern tip of the southern Fermi bubble [22, 23] served as spectral templates in a pixel-by-pixel spectral fitting of the nine D^{3}PO maps at different energies. Sinc the phenomenological two components description captures the dominant γ-ray properties of the Milky Way, we will take the “cloud-like” and “bubble-like” components as well as the point source model of the D^{3}PO analysis by Selig et al. [20] as our astrophysical Galactic γ-ray model.

Apart from these astrophysical components, we model the radial distribution of Galactic DM as a generalized NFW profile [13, 14] with an inner slope of $\alpha = 1.2$. The normalization is determined by fixing the DM density at the solar radius to $\rho(r_\odot = 8.5\ kpc) = 0.4$ GeV cm^{-3}. Following previous works, we investigate the most common annihilation final states $b\bar{b}$ and $\tau^+\tau^-$ with spectrum derived from PPPC4DMID [24].

With these assumptions and with given dark matter parameters, we can calculate the total expected γ-ray counts

$$\lambda^{ijk} = n^{ijk}_{dm} + \alpha_i n^{ijk}_c + \beta_i n^{ijk}_b + n^{ijk}_{point} \tag{1}$$

in each pixel i, each energy bin j, and for each photon detection mode k (FRONT or BACK). Here α_i and β_i are two free parameters to re-normalize the strength of “cloud-like” and “bubble-like” components in each pixel. Then it is possible to compare these expected counts with the actually observed number of photons n^{ijk}_{obs} to infer these parameters $p = (m_{\rm dm}, \langle\sigma v\rangle, (\alpha_i), (\beta_i))$. We do this by minimizing the objective functions given by the negative log-likelihood

$$\begin{gathered}\chi^2_{\rm ROI}(p) = \textstyle\sum_{i\in{\rm ROI}} \chi^2_i(p) \\ \chi^2_i(p) = -2\textstyle\sum_{jk}\left[n^{ijk}_{\rm obs}\ln\lambda^{ijk} - \lambda^{ijk} - \ln\left(n^{ijk}_{\rm obs}!\right)\right]\end{gathered} \tag{2}$$

for any region of interest (ROI) pixel-by-pixel with respect to α_i and β_i while scanning through the DM parameter subspace.

Because of the complexity of the central Galactic region, we define a ROI which excludes this area from our analysis. Furthermore, since the Galactic plane contains numerous faint, undetected and therefore not-modeled point sources, which nevertheless might contaminate the diffuse emission, we also mask the Galactic plane for the ROI to ensure the validity of our phenomenological two components astrophysical diffuse model. Similar to the ROI used in [11], we select Galactic latitudes $4^\circ < |b| < 20^\circ$ and Galactic longitudes $|l| < 20^\circ$ as our ROI, but masking a bit more of the Galactic plane region, as shown in the left panel of Fig. 1.

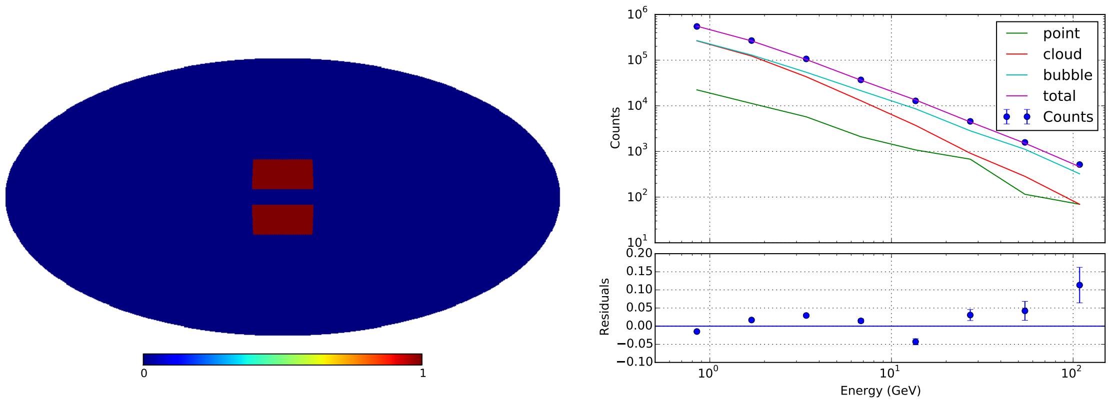

Figure 1. Region used in our analysis (left) and photon counts and relative residuals for a purely astrophysical sky model within this region (right).

3. Results and Discussion

First, we fit observational data using a purely astrophysical γ-ray sky without DM annihilation contribution, which means to set $n_{dm}^{ijk} = 0$ while fitting the remaining model parameters α_i and β_i for all locations $i \in$ ROI. The right panel of Fig. 1 shows the observed and modeled counts within the ROI as well as the residuals between model and data. It seems that a purely astrophysical model fits the data reasonably well. The largest residual appears in the bin with highest energy, where the limited photon statistics might still cause problems to D^{3}PO in separating point sources from diffuse emission. Therefore, we do not consider the residual at this energy as an serious indicator of DM or other new physics. However, around several GeV there is a small, but significant photon count excess in the ROI. This excess seems to be coincident with the GeV excess reported in the literature and might indicate a possible DM annihilation signature.

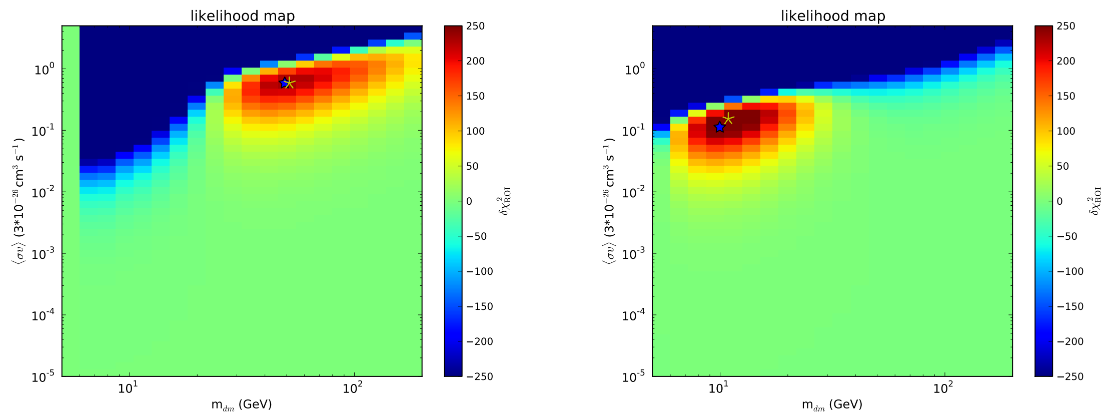

Figure 2. The improvment of fitting function in our ROI for $b\bar{b}$ (left) and for $\tau^+\tau^-$ (right) annihilation final states. Best fit values from [11] are shown as blue stars and our best fit DM parameters $(m_{\rm dm,}\langle\sigma v\rangle)_\star$ are shown as yellow stars

Then we scan the dark matter parameters $m_{\rm dm}$ and $\langle\sigma v\rangle$ while fitting the astrophysical parameter sets α and β to investigate the improvement of our objective function

$$\delta\chi^2_{\rm ROI}(m_{\rm dm}, \langle\sigma v\rangle) = \\ \min_{\alpha,\beta}\chi^2_{\rm ROI}(0,0,\alpha,\beta) - \min_{\alpha,\beta}\chi^2_{\rm ROI}(m_{\rm dm}, \langle\sigma v\rangle, \alpha, \beta). \quad (3)$$

As shown in Fig. 2, including DM with $b\bar{b}$ or $\tau^-\tau^+$ annihilation final states could indeed improve the fitting result. The best fit DM parameters $(m_{\rm dm,}\langle\sigma v\rangle)_\star$ agree well with those found by Calore et al. [11].

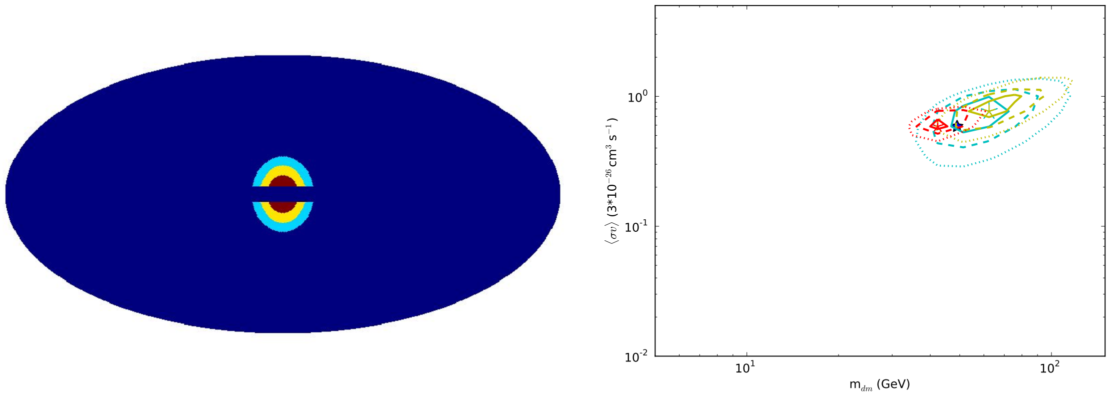

Figure 3. Left: Different ROIs to test the consistency of the best fit DM parameters $(m_{\rm dm,}\langle\sigma v\rangle)_\star$. Right: Corresponding best fit points and contours (1, 2 and 3 σ) for different regions, using the same colors for the associated regions. Best fit value from [11] is shown as blue star.

To verify the consistence of the best fit DM parameters $(m_{\rm dm,}\langle\sigma v\rangle)_\star$ inferred from different regions, we choose three regions with different angular distances to the GC as in the left panel of Fig. 3. As shown in the right panel of Fig. 3, derived DM parameters are consistent with each other for $b\bar{b}$ annihilation final states.

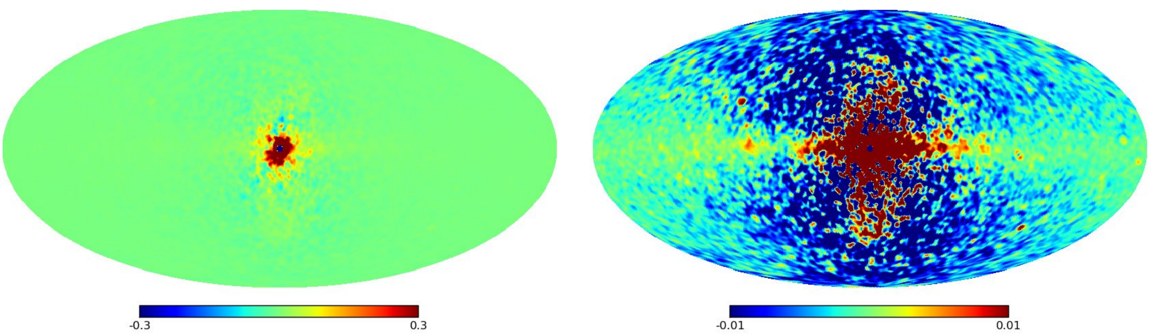

Figure 4. Left: The map of the likelihood improvements $\delta\chi^2_{\star i}$ while including a DM component with parameters $(m_{\rm dm,}\langle\sigma v\rangle)_\star$ for $b\bar{b}$ final annihilation states. Right: Like left panel, but with rescaled color to highlight non-central regions.

In order to investigate the possibility for a potential astrophysical, non-DM annihilation related origin of this signal, we try to find out the sky locations driving $\delta\chi^2_{\rm ROI}$. To this end we use the best fit DM parameters $(m_{\rm dm\star}, \langle\sigma v\rangle_\star)$ to construct all sky maps of $\delta\chi^2_\star$ as

$$\delta\chi^2_{\star i} = \min_{\alpha_i,\beta_i}\chi^2_i(0,0,\alpha_i,\beta_i) - \min_{\alpha_i,\beta_i}\chi^2_i(m_{\rm dm\star}, \langle\sigma v\rangle_\star, \alpha_i, \beta_i). \quad (4)$$

The left panel of Fig. 4 shows that the improvement $\delta\chi^2_{\star i}$ due to the inclusion of DM annihilation contribution is almost spherically distributed around the GC. This is consistent with the anticipation that this signal has a DM annihilation origin. However, while we tune the colorbar (right panel of Fig. 4), the morphology of the Fermi bubbles as well as of the galactic disk is shown at locations more distant from the GC in in $\delta\chi^2_{\star i}$ map. These morphologically suspect regions only contribute marginally to the total $\delta\chi^2_{\rm ROI}$, but this could indicate a problem also prevailing within our ROI since a DM contribution for the signal should not take a morphology with astrophysical structures. Permitting the "DM-annihilation-like" spectral component to exhibit any morphology preferred by the data, and not be derived from a NFW profile, we find a morphology of this component which resembles largely that of the "bubble-like" component. This possibly indicates that an astrophysical spectral component in the hot interstellar medium is behind the excess emission [19].

In order to confirm or refute the apparent GeV excess as annihilation signal, we need a better understanding of the astrophysical γ-ray radiation, since our current sensitivity is more limited by astrophysical modeling uncertainties than by the photon count statistics. In order to deal with the large spatial and spectral complexity of the real Galactic γ-ray emission, the phenomenological and morphological methods presented here, as well as the physical modeling approaches by other groups, need to be refined.

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