GeV excess in the Milky Way: Depending on Diffuse Galactic gamma ray Emission template?

Bei Zhou,1, 2 Yun-Feng Liang,1, 2 Xiaoyuan Huang,1, Xiang Li,1, 2 Yi-Zhong Fan,1 Lei Feng,1 and Jin Chang1

1Key Laboratory of Dark Matter and Space Astronomy, Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing 210008, China
2University of Chinese Academy of Sciences, Yuquan Road 19, Beijing, 100049, China

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Several groups have analyzed the publicly-available Fermi-LAT data and reported a spatially extended gamma rays excess of around $1 - 3$ GeV from the region surrounding the Galactic Center that might originate from annihilation of dark matter particles with a rest mass $m_{\chi} \sim 30 - 40$ GeV. In this work we examine the role of the diffuse Galactic gamma ray emission (DGE) templates in shaping the GeV excess. For such a purpose, we adopt in total 128 background templates that have been generated by Ackermann et al. [1] in the study of the Fermi-LAT observations of the diffuse gamma ray emission considering the effects of cosmic rays and the interstellar medium. The possible GeV excess(es) in the regions of $|l| < 80^\circ$ and $|b| > 5^\circ$ (with and without the emission from the Fermi GeV Bubbles, respectively) or $|b| > 10^\circ$ have been analyzed. The general trend found in our analysis is that the higher likelihood we get for the DGE fitting, the smaller TS we get for the possible dark-matter-like GeV excess. The minimal TS value for the dark-matter-like excess component is $\approx 663$ (568 excluding regions of Fermi Bubbles) in the region of $|b| > 5^\circ$, and $\approx 82$ in the region of $|b| > 10^\circ$, suggesting that the excess is indeed statistically significant. The prospect of confirming or ruling out the dark matter annihilation origin of the GeV excess is discussed.

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I. INTRODUCTION

In the standard $\Lambda$CDM cosmology model, the current universe consists of $\sim 4.9\%$ baryonic matter, $\sim 26.8\%$ cold dark matter and $\sim 68.3\%$ dark energy [2]. Though abundant, the nature of dark matter particles is still poorly understood. Among various viable dark matter candidates, weakly interacting massive particles (WIMPs) have been the most extensively discussed and are suggested to be the leading ones [3–7]. WIMPs may be able to annihilate with each other (or alternatively decay) and then produce energetic particles, including gamma rays, charged particles, and neutrinos. Thanks to the specific radiation spectrum of such components, the dark matter-originated gamma-rays or cosmic rays may be identifiable from the dense astrophysical background. The cosmic rays are deflected by the magnetic fields and lose energies before reaching us. As a result, the direction information is lost and the dark matter origin of some cosmic ray anomaly, for example the electrons/positrons excesses [8–12], is somewhat challenging to establish. The prompt photons from the annihilation (or decay) events instead trace the dark matter distribution. The morphology of the gamma ray signal is hence valuable for confirming the dark matter origin. The Galactic Center, the dwarf galaxies and the galaxy clusters are the regions of interest for dark matter indirect detection in gamma rays. While for most of the dwarf galaxies and the galaxy clusters they can only be observed as point sources and the morphology information is missed. The Galactic Center, benefited from its proximity and high dark matter density, is expected to be the brightest prompt photon source of dark matter annihilation on the sky, and an spatial extension of the dark matter annihilation signal is expected. Since the launch of the Fermi Gamma-Ray Space Telescope [13, 14], many groups have studied the possible dark matter induced signal in the Galactic Center. One tentative signal is a monochromatic gamma ray line with energy $\sim 130$ GeV [15–20]. Another interesting signal is a statistically-very-important GeV excess concentrating at the Galactic Center [21–26] but extending to a Galactic latitude $|b| \sim 10^\circ–20^\circ$ [27]. For the GeV excess both the spectrum and the morphology of the Galactic Center and Inner Galaxy signals are found to be compatible with that predicted from the annihilations of WIMPs with a rest mass $\sim 30 - 40$ GeV via the channels mainly to quarks [28]. Together with the electron/positron data, the annihilation channels can be further constrained. For example, the dark matter annihilates to combination of channels, with cross sections proportional to the square of the charge of the final state particles or democratically to all kinetically allowed standard model fermions (note that the quark final states win by additional factor 3 from color), are found to be ruled out [29].

The progress on identifying a possible GeV excess around the center of the Galaxy was remarkable in the past few years. And statistically the significance of the GeV excess is so high that it could not be a fluctuation. Nevertheless, the role of the diffuse Galactic gamma ray emission (DGE) template in shaping the GeV excess signal is to be examined. For such a purpose, in this work, following [1] we adopt in total 128 background templates that have been used in the gamma ray study of the Fermi-LAT observations of the DGE considering the effects of cosmic rays and the interstellar medium. These diffuse Galactic gamma ray emission background templates (models), created by varying
within observational limits the distribution of cosmic-ray sources, the size of the cosmic-ray confinement volume, and the distribution of interstellar gas, are constrained by local cosmic rays observations [1]. With each template we evaluate the statistical significance of the possible GeV excess component in three regions, including the regions of $|b| > 5^\circ$ with and without the contribution from the Fermi Bubbles [30] and the region of $|b| > 10^\circ$.

This work is structured as the following. In section 2 we briefly introduce the background templates used in the data analysis and also regions of interest. In section 3 we present the method and results of our data analysis. In section 4 we summarize our results with some discussion on the prospect of confirming or ruling out the dark matter annihilation origin of the GeV excess.

II. THE DIFFUSE GALACTIC GAMMA RAY EMISSION TEMPLATES AND REGION OF INTEREST USED IN THIS ANALYSIS

Cosmic rays propagating through the Milky Way interact with interstellar gas, magnetic fields as well as the soft photons, and then generate the observed DGE that dominates in the energy range of Fermi-LAT. In the search of signal from large-scale regions using Fermi-LAT data, it is essential to know the DGE well to get a robust result unless the searched signal has very special spectral features [15–20]. But in reality, the distribution of cosmic rays, interstellar gas, magnetic fields as well as radiation fields are still not precisely known. Correspondingly, the predicted DGE suffers from some uncertainties, which in turn weakens the robustness of the observed signal. Such a fact motivates us to investigate the role of DGE templates in shaping the GeV excess signal.

DGE can be divided into three components based on the radiation mechanisms [1]: (a) hadronic emission from neutral pion decay produced by inelastic collision of cosmic ray protons with the interstellar gas, (b) inverse Compton scattering of interstellar soft photons by cosmic ray electrons and positrons, and (c) bremsstrahlung produced by scattering of cosmic ray electrons and positrons with protons/nuclei in interstellar gas. The neutral pion decay and bremsstrahlung emission are both generated by cosmic ray particles interacting with interstellar gas, and their spatial distributions will both follow the morphology of the target gas. That is why in some literature, such as what Fermi Collaboration did in getting source catalog [31, 32], the spatial templates of interstellar gas have been used to fit with Fermi-LAT data directly to get the spectral energy distribution and to model the effect of pion decay and bremsstrahlung emission, with the assumption that the cosmic rays flux is uniform within each template. However, in such an approach the spectral information of these two kinds of radiation processes have not been used and the constraints from local cosmic ray observations have been ignored. Possible extra emission will be more or less absorbed in the fitting procedure. As pointed out in [33, 34] the templates generated in such a way are optimized for point sources and small scale extended sources and are not ideal templates to be used for analyses of spatially extended sources and/or large-scale diffuse emission.

One way to get both the spatial and spectral information of DGE models is to use the GALPROP code [35] to calculate the propagation and distribution of cosmic rays in the Milky Way, and then calculate the interactions of cosmic rays with interstellar gas and radiation fields [1]. Because of large uncertainties for the cosmic ray sources distributions, four different models (SNR distribution [36], Lorimer pulsar distribution [37], Yusifov pulsar distribution [38] and OB stars distribution [39]) were chosen to trace the distribution of cosmic ray sources, and eight combinations of different sizes for the cosmic rays confinement region were used, namely two radial boundaries ($R_h=20$ and 30 kpc, respectively) and four vertical boundaries ($z_h=4, 6, 8, and 10$ kpc, respectively), respectively. Solving the diffusion equations and comparing with local cosmic rays observations, other cosmic rays injection and diffusion parameters which determine the cosmic rays intensity and spectrum were inferred. Then 4 different assumptions on the column density of the gas, two for spin temperature ($T_s = 150 K$ and $10^5 K$, respectively) which affect the derived HI column densities and two for dust ($E(B - V) = 2$ mag and 5 mag, respectively) as the tracer of gas, were applied. We refer the readers to Section 3 of [1] for the details of the model input parameters. Finally, interactions of cosmic rays with targets were calculated to get the prediction of the induced gamma ray distribution and an all sky fit to the Fermi-LAT data is performed to get the remaining parameters. Thus a grid of 128 DGE models was created, and we use the supplementary online material to generate templates in mapCube format which could be easily convolled with Point Spread Function (PSF) of Fermi-LAT using Fermi Science Tools. The same as the Table 3 in [1], a mapping between model numbers and model input parameters is made, and in the following sections we will use

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1 http://fermi.gsfc.nasa.gov/ssc/data/analysis/LAT_caveats.html
2 http://galprop.stanford.edu/PaperIISuppMaterial/
3 http://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/Cicerone_LAT_IRFs/IRF_PSF.html
4 http://fermi.gsfc.nasa.gov/ssc/data/analysis/software/
these model numbers to refer corresponding DGE models. These DGE models will be used in our analysis of the template-dependent GeV excess analysis.

In order to search for extra signals, we should optimize our region of interest to reduce the uncertainties from background modeling. Galactic center is a complex region which hosts a lot of sources with energetic activity which could be accelerators of cosmic rays, for example the supermassive black hole Sgr A* and supernova remnants. Young populations of cosmic rays are likely to inhabit the Milky Way center and to contribute to the hadronic emission. These gamma ray emissions will not be predicted in the templates generated in [40], because the four distributions of cosmic ray sources have not included these possible accelerators of cosmic rays in this region. Thus this hadronic emission beyond current DGE models could be the source of GeV excess. Moreover, the interaction between high energy electrons and molecular clouds in the galactic center could produce significant bremsstrahlung radiation, and these emissions may partially contribute to the central region GeV excess too [41]. In addition to these unpredicted radiations which should be part of DGE models, millisecond pulsars, which are predicted to be abundant in the Milky Way center and could not be resolved because of limited PSF of Fermi-LAT, can generate extended gamma ray emission with a peak around GeV [25, 26, 42, 43]. Moreover, the fluxes and spectra of central point source 2FGL J1745.6-2858 which is associated with Sgr A* have some degeneracies with those of the central region GeV excess [25].

As shown above, Galactic center is not a perfect region to investigate the dark matter origin of the GeV excess signal because many astrophysical processes could generate similar diffusion emission around several GeV. As pointed in [1], DGE models created there always under-predict the gamma ray emission above a few GeV in the Galactic plane, possibly because the contribution from unresolved point sources such as pulsars, SNRs and pulsar wind nebulae has not been taken into account. Then in this work we mask the $|b| < 5^\circ$ and $|b| < 10^\circ$ regions respectively to minimize the possible “misleading” components from Galactic center and Galactic plane. The likelihood fitting performed in [1] found out that the outer Galaxy would dominate in an all sky likelihood ratio test. But if the GeV excess signal is from dark matter annihilation, we would anticipate that the outer Galaxy region will not contribute too much to the signal. Then in our work we also mask the $|l| > 80^\circ$ to minimize the effect of outer Galaxy region which will dilute the GeV excess signal. In [27] authors showed that large features, Fermi Bubbles [30], may have a uniform brightness intensity while including another template to absorb the low latitude emission. But in fact the astrophysical origin of the Fermi Bubbles is unknown, and as pointed in [30, 44], it seems that the Fermi Bubbles are not uniform but with some hot spots. Also as shown in Fig. 2, in the SED analysis the low latitude region of the Fermi Bubbles will have a degeneracy with the dark matter template in the low energy bins. In order to test the possibility that the GeV excess originated from Fermi Bubbles, we also select a region where the Fermi Bubbles are also masked besides above-mentioned masked regions. Therefore we define three regions of interest for our analysis (see Fig. 1).

### III. DATA ANALYSIS: METHOD AND RESULTS

#### A. Methodology and consistence check

We use the public gamma ray data of Fermi-LAT from 300 MeV to 300 GeV between August 4, 2008 (MET 239557417) and April 7, 2014 (MET 418537497). We use ULTRACLEAN events selection (Pass 7 reprocessed Version 15) defined by Fermi-LAT collaboration, in order to reduce the contamination from charged cosmic rays. We also employ standard cuts for diffuse analysis including zenith angle $< 100^\circ$, DATA\_QUAL = 1, LAT\_CONFIG = 1 and instrumental rocking angle (i.e. angle of the spacecraft Z-axis from zenith) $< 52^\circ$.

The data was binned into 30 logarithmic energy ranges and we make the counts maps into each energy bin for FRONT and BACK events respectively to HEALPIX grids with NSIDE=256. Additionally, we do not take into account the BACK events in the first 6 energy bins because of the low data quality especially for the PSF that is considerably worse than that of the FRONT events. Therefore in the following procedures, we always do analysis for FRONT and BACK maps separately.

Although the effect of point sources is subordinate for large sky region analysis (We do a further test in Appendix A), to make our analysis more robust, we take into account the point and extended sources in the Fermi-LAT 2-year catalog$^5$ (2FGL) [32] and we recognize them as one part of the models in the subsequent data fitting (for the details see Appendix B). The parameters of these sources are fixed to avoid its computational expensiveness. Nonetheless, the 2-year catalog can’t perfectly represent the average flux of the sources with more than 5.5 years data especially for the brightest sources. So we mask the brightest 200 sources throughout our analysis and the size of masked regions are determined by Fermi-LAT PSF.

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$^5$ http://fermi.gsfc.nasa.gov/ssc/data/access/lat/2yr_catalog/
FIG. 1: The region of interest is defined in order to minimize the uncertainties from background modeling. In the top panel, we masked $|b| < 5^\circ$ to reduce the effects from known under-predicted gamma ray emission above a few GeV in the Galactic plane [1] and also to avoid analyzing the complex Galactic center. Again we also mask $|l| > 80^\circ$ to minimize the effect of outer Galaxy region which dominates in an all sky likelihood ratio test but will not contribute to the dark matter annihilation signal [1]. In the bottom (left) panel, besides above mentioned masked region, we also masked the Fermi Bubbles because of its possible degeneracy with dark matter signal in low latitude region. In the bottom (right) panel, we masked $|b| < 10^\circ$ plus $|l| > 80^\circ$ to minimize the effect of confusion GeV emission, which would be less extended, from millisecond pulsars, bremsstrahlung or neutral pion decay.

The templates employed in the fitting procedure incorporate (1) 128 groups of galactic diffuse emission templates, each contains three templates accounting for bremsstrahlung, $\pi^0$ decay as well as the inverse Compton radiation of the galaxy respectively, as described in Section II; (2) a uniform-brightness template of Fermi GeV Bubbles defined by [30]; (3) a dark matter template defined by generalized NFW profile $\rho \propto (r/r_s)^{-\alpha}(1 + r/r_s)^{-3+\alpha}$ [45, 46], where $r_s = 20$ kpc is the scale radius and the $\alpha =1.2$ is the slope index $^6$; (4) a collection of all point and extended sources in the LAT 2-year catalog; (5) an isotropic map used to absorb residual cosmic-ray contamination and isotropic diffuse emission. Furthermore, we convolve the templates with the Fermi-LAT PSF to make them consistent with the data in each energy bin for FRONT and BACK events respectively. As found in [28], the galactic center GeV excess can be well explained by the dark matter particles with the mass of 30 – 40 GeV annihilating to $b\bar{b}$ pairs. So in our likelihood fit of the GeV excess, the spectrum of $\sim 35$ GeV dark matter particles annihilating to $b\bar{b}$ will be adopted. We fit the count maps with linear combinations of the 5 sets of templates, maximizing the pixel-based Poisson likelihood, and each time we just change the template (1).

We make use of Fermi Science Tools (v9r32p5) to complete data selection, calculate the exposure maps and convolve model templates with the PSF. For everything else we use our own code. As a test of our code, we firstly analyze the data with P6V11 Galactic diffuse template that has been widely used in the GeV excess analysis. In particular

$^6$ The slope index is fixed otherwise it is very time-consuming. For the same reason, in our likelihood fit of the GeV excess, the spectrum of $\sim 35$ GeV dark matter particles annihilating to $b\bar{b}$, as found in [28], will be adopted.
we analyze the possible GeV excess in the regions of the Fermi Bubbles, which has been divided into five slices, as that done in [27]. The results are presented in Fig. 2. Unaccounted gamma ray emission presents in the low latitude regions ($b < 20^\circ$). However, after the dark matter template is added, the spectrum of all the five sliced bubbles is nearly the same. These results are remarkably consistent with that of [27] and in turn suggest that our code is reliable. We should caution that, in the right panel of Fig. 2, around several hundreds MeV, the spectra of the bubbles within $0^\circ - 10^\circ$ and $10^\circ - 20^\circ$ are different from the three higher latitude slices, owing to the reason that the bad PSF in these energy ranges brings forth the coupling of the bubbles and the dark matter template in low latitude. Also around the tens GeV, there also exits some disgusting coupling of dark matter and bubbles within $0^\circ - 10^\circ$ because of limited photon numbers at high energy, bringing forth poor statistics. Data smoothing could make features more remarkable which will suppress the coupling. Whereas in our fitting, we use the whole bubbles instead of five slices. This will decrease the amount of our calculation, and this could also avoid the coupling between the Fermi Bubbles and the dark matter template.

Then we fit the counts map with 128 groups of galactic diffuse emission templates with all the other templates unchanged and, as discussed in the last section, we didn’t fit the region of $|l| > 80^\circ$. Moreover, in the arguments of [27] and [28], the excess extends to outside $10^\circ$ of the galactic plane. So we mask $|b| < 5^\circ$, $|b| < 10^\circ$ respectively. We also considered that there might be still coupling, in some way, between the bubbles and the dark matter template. So we also test another situation for the aforementioned 128 times of fitting, i.e. masking the whole bubbles in addition to the galactic plane ($|b| < 5^\circ$).

**B. Results**

Now we proceed to analyze the possible GeV excess with the 128 DGE templates, respectively. The main results, i.e., the log-likelihood values fitted for each group of galactic diffuse template in each region of interest, are presented in Fig. 3, where the left and right columns are the cases of with and without the dark-matter-like excess component, respectively. The addition of a dark-matter-like radiation component indeed improves the goodness of fit in all these fits. The DGE templates with pulsar-traced cosmic ray distributions have larger log-likelihood values than the OB star traced cosmic ray distribution [39] and SNR-traced cosmic ray distribution [36]. The Lorimer’s pulsar-traced cosmic
FIG. 3: Log-likelihood values obtained from the separate fits for each group of galactic diffuse gamma ray emission template: without and with the dark matter component (left and right panel, respectively). The zero levels of the log-likelihood values are arbitrary but are equivalent in the same region. Therefore the difference of the value between two models within a region gives their likelihood ratio for that region. For each group of template, three regions of interest are considered, including (1) $|b| > 5^\circ$ and $|l| < 80^\circ$ (top), (2) masking $|b| < 5^\circ$, Fermi bubble and $|l| > 80^\circ$ (middle), and (3) $|b| > 10^\circ$ and $|l| < 80^\circ$ (bottom). In each panel, the model number as well as the color settings are the same as that used in [1]: $z_h = (4, 6, 8, 10)$ kpc are in (black, blue, green, red), respectively; $R_h = (20, 30)$ kpc are represented by squares and circles, respectively; the filled and open points are for $T_s = (150 \text{ K}, 10^5 \text{ K})$, respectively; and the dark and light colors are for $E(B-V) = (2, 5)$ magnitude cuts, respectively. The dotted vertical lines are the boundary of different CR source distribution models.
ray distribution model \cite{37} which forces the source spatial distribution to zero at $R = 0$ yields larger log-likelihood value than the Yusifov’s pulsar distribution model \cite{38}. Interestingly, Lorimer’s pulsar-traced cosmic ray distribution model \cite{37} also yielded the lowest $\chi^2$ in the fits to the nuclei data (see the left panel of Fig.35 in \cite{1}). The most general trend shown in Fig. 3 is that increasing $z_h$ improves the likelihood in all regions, consistent with that found in the cosmic ray modeling in \cite{1}. No strong dependence of the log-likelihood values on $R_h$ is found in Fig. 3.

The value of $T_s$ also shows a trend independent of the dark matter template. However, the trend is different between the fitting regions and is correlated with the $E(B−V)$ cut. For the region of $|b| > 5^\circ$, when a $E(B−V)$ cut of 2 mag is adopted, all the fits prefer a larger $T_s$. While there is no constant favored $T_s$ value when $E(B−V)$ cut of 5 mag is assumed. This trend shows no bias between different $R_h$ values and different source distributions. For the region of $|b| > 5^\circ$ and outside Fermi Bubbles, it shows a simpler trend: all the fit favor a greater $T_s$ value. What’s more, the difference between the log-likelihood values is the largest in the case of $z_h = 6$ kpc. An interesting phenomenon happens when a larger galactic plane is masked (i.e. $|b| < 10^\circ$). All the fits favor a smaller $T_s$ value, which is contrary to the region of $|b| > 5^\circ$, outside the Fermi Bubbles. What’s more, the pulsar-traced cosmic ray distribution models with larger log-likelihood values show lighter dependence on $T_s$ than the SNR-traced or OB star-traced cosmic ray distribution models. $E(B−V)$ also plays a role in modifying the likelihood value, in particular if the dark matter component is excluded. For instance, in the region of $|b| > 5^\circ$ and $|l| < 80^\circ$, all fits favor a $E(B−V)$ cut of 5 magnitudes for the two kinds of pulsar-traced cosmic ray distributions. In the cosmic ray distribution models tracing SNR and OB star, for $T_s = 150$ K the fits also favor the $E(B−V)$ cut of 5 magnitudes, while in the optical thin scenarios (i.e., $T_s = 10^5$ K) the fits favor the 2 magnitude cut of $E(B−V)$.

In Fig. 4 we present the TS values of the dark-matter-like component obtained in each fit, which can be straight-
FIG. 5: Log-likelihood versus TS values, which are from Fig. 3 and Fig. 4, respectively. The top, bottom left and bottom right panels correspond to three regions defined in Fig. 1. The solid (dashed) lines are the log-likelihood values without (with) dark-matter-like component.

forwardly evaluated by subtracting the values of the right panels from the values of the corresponding left panels of Fig. 3 and then multiply by a factor of $-2$. The TS values of the GeV excess in the regions of $|b| > 5^\circ$ (masking the Fermi bubbles or not) and $|l| < 80^\circ$ are much larger than the corresponding ones in the region of $|b| > 10^\circ$ and $|l| < 80^\circ$, simply due to the much lower signal-to-noise in the latter region. Intriguingly, masking the whole Fermi bubble (which extends to $b = 0^\circ$ in the north and $b = -5^\circ$ in the south) doesn’t reduce the TS value considerably, suggesting that the GeV excess component is intrinsic and is not dominated by the Fermi bubble. The minimal TS value we find for the dark-matter-like excess component is $\approx 670$ in the region of $|b| > 5^\circ$ and $\approx 82$ in the region of $|b| > 10^\circ$, suggesting that the excess is indeed statistically significant. The corresponding velocity-averaged cross section is $\langle \sigma v \rangle \sim 1 - 3 \times 10^{-26}$ cm$^3$ s$^{-1}$ ($\rho_0/0.3$ GeV cm$^{-3}$)$^{-2}$, where $\rho_0$ is the local energy density of the dark matter. Some interesting trends of TS values on the input parameters can be identified in Fig. 4, too. The most remarkable one may be that the Lorimer’s pulsar-traced cosmic ray distribution models have the lowest TS values. This is reasonable since such a kind of cosmic ray distribution model has the lowest $\chi^2$ in modeling the nuclei data [1] and the largest log-likelihood value in our gamma ray fitting (see Fig. 3), since the difference between the data and the background templates is “minimal”. For the same reason, the templates with larger log-likelihood values tend to have smaller TS values (see Fig. 5).
IV. DISCUSSION

In this work we have analyzed the gamma-ray emission measured by the Fermi Gamma-ray Space Telescope from the inner regions of the Milky Way. In total 128 Galactic diffuse emission background templates/models have been taken into account, in each of which the possible dark-matter-originated radiation components in the regions of $l < 80^\circ$ and $|b| > 5^\circ$ (including and excluding the Fermi Bubbles) or $|b| > 10^\circ$ have been explored and the dark matter energy density distribution has been taken as the generalized NFW profile with $r_s = 20$ kpc and the slope index $\alpha = 1.2$. The minimal TS value we find for the dark-matter-like excess component is $\approx 670$ in the region of $l < 80^\circ$ and $|b| > 5^\circ$ and $\approx 82$ in the region of $l < 80^\circ$ and $|b| > 10^\circ$, strongly suggesting that the excess is indeed statistically significant and robust. The corresponding cross section of the dark matter particles with rest mass $m_\chi \sim 35$ GeV annihilating into $\bar{b}b$ is $(\sigma v) \sim 1 \times 10^{-26}$ cm$^3$ s$^{-1}$ ($\rho_0/0.3$ GeV cm$^{-3}$)$^{-2}$, consistent with what was found in [28].

The presence of a spatially-extending GeV excess component that is well consistent with the signal expected in dark matter particle annihilation is very attractive. We caution that these 128 background templates have not represented all possibilities of the cosmic rays induced background gamma rays emissions, and due to the trend shown in Fig. 5, it might be possible that in a more detailed analysis with better background modeling the significance of this GeV excess component gets smaller or even vanished. The other caution is that some astrophysical objects may also give rise to rather similar GeV radiation signal. For example, a population ($\sim 10^4$) of less-luminous millisecond pulsars (MSPs) may be able to account for the GeV excess for the following reasons: (1) MSPs are known strong GeV gamma ray emitters that peak at a few GeV; (2) Estimates of the spatial distribution of M31 low mass X-ray binary population indicate that the number of MSPs located in the Galactic center could scale as steeply as $1/r^{2.4}$ [25]; (3) a population of hard ($\Gamma < 1$) “under-luminous” MSPs either endemic to the innermost region or part of a larger nascent collection of hard MSPs that appears to be emerging in the second Fermi LAT Pulsar Catalogue, which could reproduce the observed flux of the GeV excess [42, 43]. Alternatively, the “Galactic center excess” has been argued to be explained by a recent cosmic-ray injection burst, with an age in the $10^3 - 10^4$ year range, while the extended “inner Galaxy excess” has been suggested to point to mega-year old cosmic-ray injection [40]. Distinguishing between the dark matter model and the astrophysical model is not a trivial task. The most straightforward way to confirm the dark matter origin of the GeV excess, if it is, may be the detection of a rather similar component in the nearby dwarf galaxies. In a dedicated study, 4-year gamma ray observation results of 25 dwarf spheroidal satellite galaxies of the Milky Way have been reported and a combined analysis of 15 dwarf galaxies under the assumption that the characteristics of the dark matter particle are shared between the dwarfs has been carried out. No globally significant excess was found for any of the spectral models tested and the largest deviation from the null hypothesis occurs for soft gamma ray spectra and is fit by dark matter in the mass range from 10 to 25 GeV annihilating to $\bar{b}b$ with a cross section in the order of $10^{-26}$ cm$^3$ s$^{-1}$ and has TS $\sim 8.7$ [47]. If the signal is intrinsic, the TS value should increase linearly with the exposure time. A reliable test of such a possibility will be available when the PASS 8 data releases because its novel event reconstruction and event selection will both increase the LAT sensitivity to point-like sources and help mitigate systematic effects present in P7REP [48]. Suppose such an increasing tendency has been well established in the data of dwarf galaxies, the dark matter origin of the Galactic GeV excess will be favored. Less “indirect” test of the dark matter origin of the Galactic GeV excess may come from the direct detection or collider experiment. The ongoing Large Underground Xenon experiment is very efficient in probing the dark matter mass region favored by the Galactic GeV excess and the sensitivity is expected to increase by a factor of 10 in 2015 [49]. When work at CERN’s Large Hadron Collider is completed in 2015, the collider should push power up to 14 TeV and be able to help unlock more of the universe’s mysteries, including the dark matter. As dark matter particle has been discovered in either direct detection or collider experiment, the mass will be precisely measured and can be used to test the physical origin of the Galactic GeV excess. Current antiproton data from PAMELA [50, 51] has been used to constrain the dark matter annihilation origin of the Galactic GeV excess. The results however are controversial. For example, Fornengo et al. [52] found out that the data is not at odds with the dark matter annihilation interpretation of the Galactic GeV excess while Bringmann et al. [53] argued that the model of dark matter annihilation into $\bar{b}b$ had been ruled out. The upcoming AMS-02 data$^7$ may solve this puzzle.

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$^7$ www.ams02.org/
Appendix A: The consideration of sources in 2FGL

In all the fitting procedures, we just make the source maps as one of the model but, to simplify our calculation, we don’t let the value of the maps to vary. Here we show some instances to attest the validity of this simplification. In the standard fitting procedure of our analysis, we get the minimum TS values of the dark matter template in the three region are 663 for $|b| > 5^\circ$, 568 for $|b| > 5^\circ$ and outside the bubble and 82 for $|b| > 10^\circ$. All the minimum TS values derive from the template with Lorimer distribution, $z_h = 10$ kpc, $R_h = 20$ kpc, $T_s = 150$ K and a $E(B-V)$ cut of 2 mag. We redo the fitting of this template but don’t incorporate the source maps in the model (i.e. just mask the 200 most luminous sources) to see if these point sources and extended source can bring about significant bias to the result. We get 732 for $|b| > 5^\circ$, 655 for $|b| > 5^\circ$ and outside the bubble and 69 for $|b| > 10^\circ$. The TS values don’t change too much.

We also go further for this discussion to see if ignoring all the 1873 point and extended sources (i.e, don’t mask any sources or put source maps into model) would make the trend of the TS values different from Fig. 4. We take the Lorimer distribution and the region of $|b| > 5^\circ$ for a inspection. As shown in the two panels of Fig. 6, ignoring the sources would not considerably change the TS values especially for the smaller ones and the trend is also unchanged. These smaller TS values also represent the diffuse templates with larger log-Likelihood values. We then conclude that the point sources do not play an important role in modifying the analysis results.

Appendix B: Likelihood method

In this appendix we are going to give a brief introduction to the principle of probability involved in our work. The total number of all sky gamma-ray photons is a Poisson variable and the sequence of the number of photons in each spatial bin obeys polynomial distribution. So the numbers of photons in each spatial bin are independent Poisson variables, which can be proved as following.

If $n_i = \sum_{i=1}^{N} n_i$ is a Poisson variable (with expected value $\mu_i$), and $\vec{n} = (n_1, n_2, \ldots, n_l)$ ($\sum_{i=1}^{l} n_i = n_t$) obeys polynomial distribution, the combined distribution is equal to the product of probabilities of polynomial distribution and Poisson distribution

$$P(n_1, n_2, \ldots, r_l, n_t) = M(\vec{n}; n_t, \vec{p}) \cdot P(n_t; \mu_t)$$

$$= \frac{n_t!}{n_1! n_2! \cdots n_l!} p_1^{n_1} p_2^{n_2} \cdots p_l^{n_l} \cdot \frac{1}{n_t!} \mu_t^{n_t} e^{-\mu_t}, \quad (B1)$$
where $\sum_{i=1}^{l} p_i = 1$, $\sum_{i=1}^{l} n_i = n_t$.
So it can be refined to

$$P(n_1, n_2, \cdots, r_1, n_t) = P(r_1; \mu_t p_1) P(r_2; \mu_t p_2) \cdots P(r_l; \mu_t p_l),$$

indicating that $n_1, n_2, \cdots, n_l$ are independent Poisson variables.

The logarithm of the combined likelihood function of independent Poisson variables is defined as

$$\ln \mathcal{L} = \sum_i n_i \ln \mu_i - \mu_i - \ln n_i!,$$

where $n_i$ is the observed photon counts in each spatial bin (DATA), and $\mu_i$ is the expected counts in each bin (MODEL). It is unnecessary to evaluate the $(-\ln n_i!)$ term because it does not depend on the model parameters. The error bars of model parameters are simply the square root of the diagonals of the covariance matrix.

We employ spatially binned data from Fermi-LAT as DATA. And the MODEL consists of these components: diffuse Galactic emission (DGE), isotropic background, Fermi bubbles, Dark Matter annihilation and the LAT 2-year catalog (2FGL) sources. We consider the 2FGL sources as a part of MODEL but not a simple subtraction from DATA, since the ”raw data - 2FGL sources” is not a Poisson variable. The likelihood function Eq.(B3) is reasonable only if DATA is a Poisson variable and MODEL is the expected value of Poisson distribution.

The test statistic of the DM component is defined as

$$\text{TS} = -2 \ln \left( \frac{\mathcal{L}_{\text{null}}}{\mathcal{L}_{\text{best}}} \right),$$

where $\mathcal{L}_{\text{null}}$ is the best fit likelihood without DM component, and $\mathcal{L}_{\text{best}}$ is the best fit likelihood with DM.