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Dark matter signals from the gamma-ray sky

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Recently, a spatially extended excess of gamma rays collected by the *Fermi*-LAT from the inner region of the Milky Way has been detected by different groups and with increasingly sophisticated techniques. Yet, any final conclusion about the morphology and spectral properties of such an extended diffuse emission are subject to a number of potentially critical uncertainties, related to the high density of cosmic rays, gas, magnetic fields and abundance of point sources. We present a thorough study of the systematic uncertainties related to the modeling of diffuse background and to the propagation of cosmic rays in the inner part of our Galaxy and characterize the spatial and spectral properties of such an extended diffuse emission. We scrutinize the most promising interpretations – among others, the possibility that the signal originates from a series of leptonic outbursts at the Galactic centre – in order to shed light onto the origin of this yet unknown extra-emission at the Galactic centre.

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1. Introduction

Since its launch in 2008, the Fermi-LAT is taking snap-shots of the whole gamma-ray sky with unprecedented accuracy and has allowed to shed light onto the fundamental mechanisms of gamma-ray production in the GeV energy band. Besides astrophysical processes, the gamma rays collected by the Fermi-LAT offer the unique possibility to probe dark matter (DM) at the center of the Milky Way. Recently, a spatially extended excess of gamma rays collected by the Fermi-LAT from the inner region of the Milky Way has been claimed by different and independent groups.

Since first indications in 2009, several analyses of gamma-ray data from the Large Area Telescope aboard the *Fermi*, *Fermi*-LAT, claimed the existence of the excess above the standard astrophysical background at GeV energies [1, 2, 3, 4, 5, 6]. The excess emission results from analyses of both the inner few degrees of the Galaxy [7, 8, 9, 3, 4, 10] and *higher* latitudes [11, 12, 4], extending up to tens of degrees. Intriguingly, the observed spectral energy distribution and the spatial properties of the *Fermi* GeV excess match the expectation for a signal from DM particles annihilating in the halo of the Milky Way. Nevertheless, astrophysical explanations were put forward as well, as, for example, the emission from a population of point-like sources below the telescope's detection threshold [13, 14, 15, 16], or violent burst events at the Galactic center (GC) with injection of leptons and/or protons some kilo-/mega-years ago [17, 18].

Recently, Ref. [5] re-assessed the spectral and morphological properties of this excess emission, robustly characterizing the signal against systematic uncertainties related to the high density of cosmic rays (CR), gas, magnetic fields and abundance of point sources within the region $|l| < 20^\circ$ and $2^\circ < |b| < 20^\circ$. The systematic uncertainties due to the Galactic diffuse emission modeling were derived through an innovative method based on a *principal component analysis* of residuals along the Galactic plane (please refer to [5] for more details). The systematic uncertainties are fully encoded in a covariance matrix whose effect in the fit can be interpreted as the result of the variation of slope and normalisation of the Galactic diffuse emission components within the uncertainties allowed by the gamma-ray data (see Refs. [5, 19] for more details). The excess properties in light of background model systematics are significantly different from what was claimed before and allow more freedom for models fitting the excess, as it has been shown in Ref. [19] in the case of dark matter annihilation models.

In what follows, we present a systematic study of the CR leptonic outburst scenario, by evaluating whether and under what circumstances it can indeed explain the GeV excess observed features.

2. A possible interpretation: a series of leptonic outbursts from the Galactic center

Ref. [18] showed that the gamma-ray flux derived by diffusion and energy losses of a population of high-energy electrons injected at the GC about 1 Myr ago might explain the spectrum and morphology of the observed GeV excess. However, a systematic study of this scenario and the exploration of a large parameter space for the CR propagation conditions was lacking. In Ref. [20], we simulate the propagation of electrons in the inner Galaxy region through the publicly available numerical codes `Galprop` [21] and `DRAGON` [22, 23].

The high-energy electrons are injected in the interstellar medium at a given time in the past and their propagation is followed in time steps until today, by solving the propagation equation that accounts for diffusion, convection, re-acceleration and energy losses. The primary injection spectrum is a power-law with exponential cutoff:

$$\frac{dN_e}{dE_e} = \mathscr{N} E_e^{-\alpha} \exp\{-E_e/E_{\rm cut}\} \tag{2.1}$$

where $\mathscr{N}$ is a normalization factor related to the total injected energy ($\sim 10^{51}$ erg) that we will allow to vary freely in the fit to the observed GeV excess data. The spectral index ranges in the interval $\alpha = 1-3$, while the cutoff energies in the range 15 – 100 GeV (or higher for the single burst models). The injection spectrum is thus the spectrum of electrons at $\sim$ 50 pc from the GC, and not necessarily the spectrum at the source.

The CR propagation model is the standard `Galprop` setup, with homogeneous diffusion (described by D_0 and δ), convection (perpendicular to the Galactic disk dv_c/dz) and re-acceleration (v_A) included. Synchrotron energy losses depend on the structure of the magnetic field, whose spatial distribution is assumed to be an exponential in both r and z with parameters B_0 (the magnetic field intensity at the GC), r_c and z_c (the characteristic scale lengths). ICS is instead determined by the Interstellar Radiation Field (ISRF) model. We use the model provided by `Galprop v54` and we allow for the normalizations of the optical and infrared components to vary. The distribution of interstellar atomic hydrogen (HI) and molecular hydrogen (H_2) are the ones provided by `Galprop v54`. Finally, when simulating the outburst with `DRAGON`, we also account for inhomogeneous and/or anisotropic propagation, parameterized by two diffusion coefficients, D_{xx} and D_{zz}, that represent the diffusion parallel to and perpendicular to the Galactic disk, respectively.

Gamma rays from the primary electron population are produced by ICS off the ISRF photons and by bremsstrahlung off the interstellar gas [24].

We compare the ensuing gamma-ray fluxes with the GeV excess spectral and morphological properties as observed by Ref. [5] in the region of interest (ROI) $|\ell| < 20^\circ$ and $2^\circ < |b| < 20^\circ$, fully accounting for the systematic uncertainties due to foreground variations. In particular, Ref. [5] derived the morphology of the GeV excess in ten sub-regions of the main ROI, characterizing spectrum and systematic uncertainties of the excess in each of the ten sub-regions.

We perform a fit of the predicted model spectra to the GeV excess data in the ten sub-regions simultaneously by minimizing the combined χ^2:

$$\chi^2 = \sum_{i=1}^{10} \sum_{j,k=1}^{24} (d_{ij} - \mu_{ij})(\Sigma^i_{jk})^{-1}(d_{ik} - \mu_{ik}) \,, \tag{2.2}$$

where d_{ij} and μ_{ij} are the measured and predicted flux in the sub-region i and energy bin j. The covariance matrix, Σ^i_{jk}, is defined for the energy bins j and k in the sub-region i. The χ^2 is assumed to follow a χ^2_k distribution with $k = 240-1$ degrees of freedom, where the parameter of the model left free in the fitting procedure is the normalization $\mathscr{N}$.

3. Results

In Ref. [20], we set under scrutiny the leptonic outburst model by, firstly, performing a Bayesian scan over CR propagation parameters and burst properties for the single outburst scenario. Owing to the better performance of `DRAGON` (w. .r. to the publicly available version of `Galprop`) in terms

Parameter	Model A	Model B	Model C
α_1	1.2	2.0	1.1
α_2	NA	NA	1.0
$E_{\mathrm{cut},1}$	1 TeV	1 TeV	20 GeV
$E_{\mathrm{cut},2}$	NA	NA	60 GeV
τ_1 (Myr)	0.83	0.46	0.1
τ_2 (Myr)	NA	NA	1.0
N_1 (10^{51} erg)	2.89	9.87	0.1
N_2 (10^{51} erg)	NA	NA	0.88
δ	0.20	0.23	0.3
D_0 (10^{28} cm^2/s)	5.08	9.12	9.0
D_{zz}/D_{xx}	1.12	0.87	NA
v_A (km/s)	176	122	150
B_0 (μG)	11.5	11.5	11.7
r_c (kpc)	10.0	10.0	10.0
z_c (kpc)	2.0	2.0	0.5
dv_c/dz (km/s/kpc)	0.0	0.0	0.0
ISRF	1.0, 1.0	1.0, 1.0	1.8, 0.8
χ^2 ($p-$value)	277 (0.04)	317 (0.0004)	261 (0.14)

Table 1: Parameter values of the single- (Model A, B) and double-outburst (Model C) benchmark models. Parameters associated with the burst properties are α, E_{cut}, τ and N, while the others are related to the CR propagation conditions (see text for details). We also quote the χ^2 (with 240 - 1 degrees of freedom) and p-values.

of memory management and computation time, we run a multi-dimensional parameter scan by using the nested sampling algorithm of `MultiNest` [25]. The parameters (ranges/priors) are: the diffusion coefficient D_0 in units of $10^{28}\,\mathrm{cm}^2/\mathrm{s}$ (0.1 – 20/linear), the diffusion index δ (0.1 – 1/linear), the diffusion anisotropy coefficient D_{zz}/D_{xx} (0.1 – 10/log), the Alfvén velocity v_A (0 – 200 km/s/linear), the injection spectral index α (1 – 3/linear) and the burst age τ (0.1 – 5 Myr/linear). The cutoff is here fixed to E_{cut} = 1 TeV.

The best-fit found by the scan corresponds to a model with a rather hard injection spectral index (α=1.2), age of about 1 Myr and total energy injected of a few 10^{51} erg. The CR propagation parameters preferred by the fit indicate a value for the diffusion coefficient compatible with local CR measurements, as well as the diffusion index δ, while in general high re-acceleration is required. We define two single-burst benchmark models: Model A is the best-fit of the parameter scan, while Model B is the best-fit corresponding to the prior $2 < \alpha < 2.4$ (as in Ref. [18]). In Table 1 we quote the parameters of the benchmark models as well as the corresponding p-values, from which one can infer that none of these models give a very good fit to the GeV excess data. Indeed, in Figure 1, left panel, we show the fluxes predicted by Model A and B in the ten sub-regions analyzed in Ref. [5], together with the observed GeV excess data. While fitting well the GeV observed data in the innermost regions (ROIs I – IV), the single-outburst benchmarks clearly fail to describe the observed fluxes in the outermost regions (ROIs V – X). Indeed the electrons cannot efficiently cool further out radially if they were required to have a significant flux in the inner 5°. We thus showed that a single leptonic outburst is not enough to explain the observed morphology of the GeV excess. This conclusion justify our decision to explore a two-outburst scenario where a

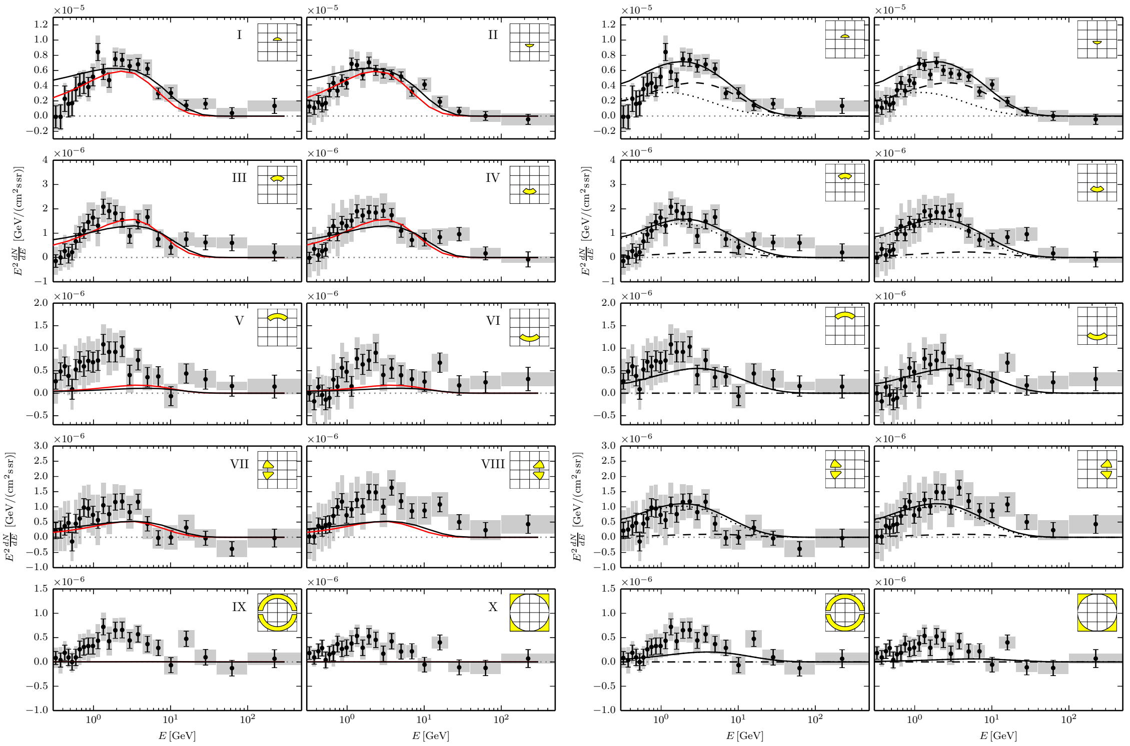

Figure 1: Left panel: GeV excess fluxes in the ten sub-regions of the analysis in Ref. [5] and expected fluxes from the single-outburst benchmark models A (red) and B (black). None of this models provides a good fit to the data (p-values of 0.04 and 0.0004, respectively), although the harder injection spectral index ($\alpha = 1.2$) of Model A improves the fit. Right panel: Same as left panel for the two-outburst benchmark, Model C. The dashed (dotted) curve represents the flux of the younger (older) outburst, while the solid line is the total model emission.

younger burst, $\mathscr{O}(0.1)$ Myr, is responsible for the emission in the inner sub-regions, while an older one, $\mathscr{O}(1)$ Myr, for the emission at higher latitudes.

We again explore a large parameter space for the CR propagation conditions, allowing the ISRF normalizations and the magnetic field parameters to vary (see Ref. [20] for more details about the parameter variation). The best-fit model in the case of two outbursts shows again hard injection spectral indices for the two bursts (α_1 =1.1 and α_2 = 1.0), total amount of injected energy of the order of 1×10^{50} and 9×10^{50} for the younger (0.1 Myr) and older (1 Myr) burst, respectively. The energy cutoff is $E_{\rm cut} = 20$ GeV and 60 GeV, for the younger and older burst respectively. The cutoffs are required in order to guarantee the total gamma-ray spectrum to be approximately uniform in the whole ROI. As for the CR parameters, the best-fit two-outburst model (Model C) prefers standard value for the diffusion parameters and high re-acceleration values ($v_A \sim 150\,\mathrm{km/s}$). The p-value (0.14) for Model C is better than the one of single-burst scenario, because of the possibility to describe simultaneously the innermost and outermost sub-regions. As it can be seen from Figure 1, right panel, indeed the two-burst benchmark accounts for the emission in regions I – IV thanks to the younger burst, while it can explain the observed flux up to region IX owing to the emission from the older burst.

4. Conclusions

We have systematically scrutinized the possibility that the GC GeV excess in the inner Galaxy originates from the diffuse emission of a new injected population of high-energy electrons some Myr ago. The spectrum of the GeV excess might easily be explained by the natural cutoff of the inverse Compton flux that occurs because of energy losses. However, we demonstrated that, contrary to previous findings, the morphology of the GeV excess at $|b| > 2°$ cannot be explained by a single burst model, despite exploring a large parameter space. Instead, two outbursts – one older (1 Myr) and one younger (0.1 Myr) – provide a good fit to the spatial properties of the excess signal although the parameter space preferred for this model is somewhat unlikely: it requires hard spectral indices and a fine tuning of the propagation parameters, so that the predicted total spectrum appears to be uniform in the whole region of interest as suggested by the data. In particular, the values of the spectral indices are much harder than what generally predicted by first-order Fermi acceleration. Such indices are also incompatible with the observed electron injection spectra of gamma-ray blazars [26]. Still, an hardening of the injection index might result from strong diffusive re-acceleration and turbulence (that might cause the spectral cutoff from synchrotron energy losses) in the GC region. Finally, even in models with two outbursts, it is not possible to account for the spatial properties of the signal in the inner few degrees This suggests that either an additional younger burst is required or that the dominant fraction of the signal might be due to unresolved point-sources, as recently claimed by Refs. [27, 28]. In summary, we cannot observationally rule out a series of leptonic outbursts as explanation of the GeV excess but we stress that the required features of such bursts (as for example the hard injection index) are quite extreme and make this scenario observationally viable, albeit quite unlikely.

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