The Galactic Center: Feeding and Feedback in a Normal Galactic Nucleus
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Dark matter and pulsar model constraints from Galactic center *Fermi*/LAT γ-ray observations

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Abstract. Employing *Fermi*/LAT γ-ray observations, several independent groups have found excess extended γ-ray emission at the Galactic center (GC). Both, annihilating dark matter (DM) or a population of $\sim 10^3$ unresolved millisecond pulsars (MSPs) are regarded as well motivated possible explanations. However, there is significant uncertainties in the diffuse Galactic background at the GC. We have performed a revaluation of these two models for the extended γ-ray source at the GC by accounting for the systematic uncertainties of the Galactic diffuse emission model. We also marginalize over point source and diffuse background parameters in the region of interest. We show that the excess emission is significantly more extended than a point source. We find that the DM (or pulsar population) signal is larger than the systematic errors and therefore proceed to determine the sectors of parameter space that provide an acceptable fit to the data. We found that a population of several thousand MSPs with parameters consistent with the average spectral shape of *Fermi*/LAT measured MSPs was able to fit the GC excess emission. For DM, we found that a pure $\tau^+\tau^-$ annihilation channel is not a good fit to the data. But a mixture of $\tau^+\tau^-$ and $b\bar{b}$ with a $\langle\sigma v\rangle$ of order the thermal relic value and a DM mass of around 20 to 60 GeV provides an adequate fit.

There is considerable evidence that the majority of the matter in the Universe consists of cold dark matter (DM) rather than Standard Model particles (Bertone *et al.* 2005 and Cirelli 2012). Although, there are many dark matter candidates, one of the most strongly motivated are weakly interacting massive particles (WIMPs). Prompt production as well as decays, hadronization and radiative processes associated with the annihilation of WIMPs could result in a measurable signal of γ-ray photons which may be observable by the The Large Area Telescope (LAT) aboard the *Fermi* Gamma-Ray Space Telescope (Baltz *et al.* 2008). A promising location to search for WIMP annihilations is the central region of the Milky Way as it is relatively close by and has a high density of DM. However, the Galactic center (GC) region also contains a large number of bright astrophysical sources. In particular, the interaction of energetic cosmic rays with the interstellar gas constitutes the main source of Galactic diffuse emission. Unfortunately, there is significant uncertainty about the propagation and origin of these cosmic rays, the distribution of the magnetic fields, radiation fields and the interstellar medium. In addition, due to the relatively low angular resolution of the LAT instrument ($\sim$0.2° at 10 GeV), several undetected point-like γ-ray sources could mimic diffuse γ-ray emission, consequently, the task of disentangling a tentative DM signal from the astrophysical background necessarily implies the implementation of detailed techniques to account for the uncertainties of the Galactic diffuse emission model.

The GC hosts a supermassive black hole with a mass of $\sim 4 \times 10^6 \mathrm{M}_\odot$, called Sagittarius A* (Sgr A*). With the *Fermi*/LAT resolution, it can be modeled as point source with curved spectral shape (Nolan *et al.* 2012). The interesting analysis performed in Linden *et al.* (2012) points out that the upcoming Cherenkov Telescope Array (CTA) will be

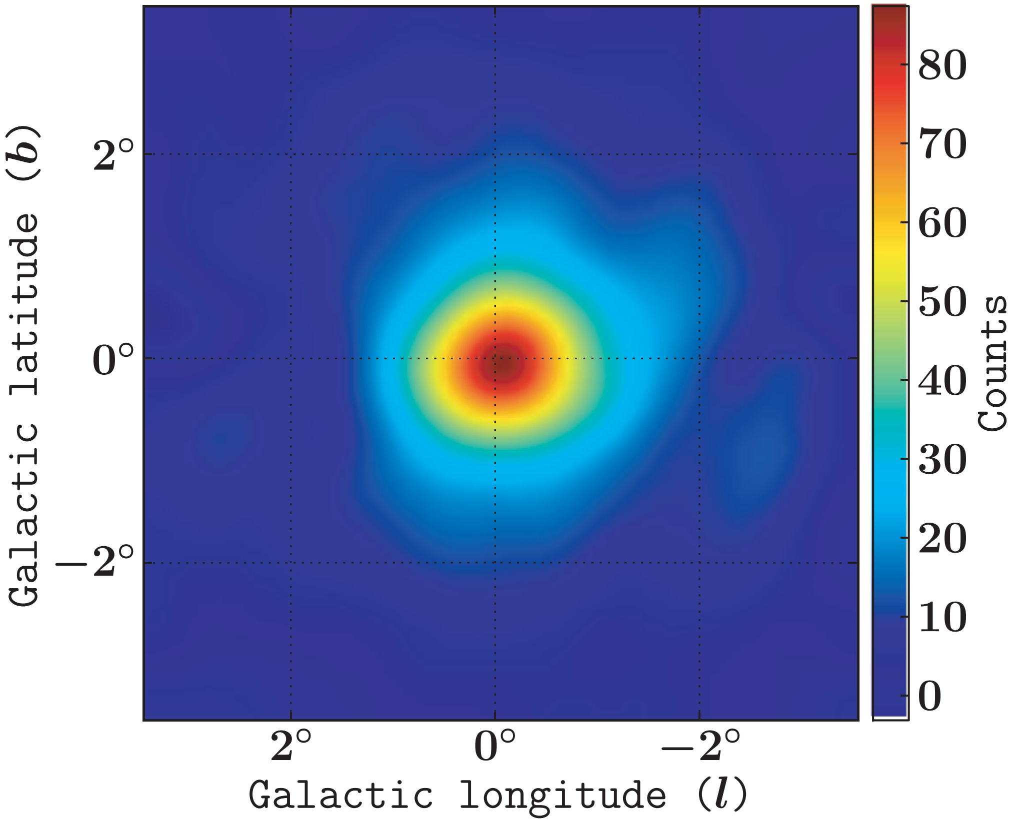

Figure 1. LAT residual map after subtraction of our best fit model with an extended GC source, but without subtracting the extended source model component. The counts were summed over the energy range 300 MeV−10 GeV. The map spans a 7° × 7° region of the sky centered at the Sgr A* position with pixel size of 0.1° × 0.1°. The residual has been smoothed with a $\sigma = 0.3°$ Gaussian. [A COLOR VERSION IS AVAILABLE ONLINE.]

key in the understanding of the physical mechanisms powering high energy photons from Sgr A*.

Several studies have found an excess of $\gamma-$rays in the GC that are consistent with roughly $10-100$ GeV DM mass annihilating into $\tau^+\tau^-$, $b\bar{b}$ final states or a combination of both Goodenough & Hooper 2009, Hooper & Goodenough 2010, Boyarksy *et al.* 2010, Hooper & Linden 2001, Abazajian & Kaplinghat 2012, and 2013. The *Fermi*/LAT Collaboration have not yet published a full analysis of GC excess, but a preliminary study by them using one year of data, reported an excess in observed counts around energies of $2-5$ GeV Vitale *et al.* 2009 and Vitale *et al.* 2011) at the GC.

The signal was also shown to be consistent with a population of millisecond pulsars (MSPs) in the GC (Abazajian 2010, Abazajian & Kaplinghat 2012; 2013). Studies have also looked at the possibility of the signal arising from cosmic-ray interaction with gas in the GC (Hooper and Linden 2011, Linden *et al.* 2012, and Yusef-Zadeh 2013). In Ref. (Abazajian 2010, Abazajian & Kaplinghat 2012; 2013), they highlighted the need to marginalize over the point source (PS) parameters, due to their degeneracy with any proposed model for the excess GC emission.

In this article we summarize some of the main results of Gordon & Macias (2013) where we extended the treatment of Abazajian & Kaplinghat (2012; 2013) in a number of ways.

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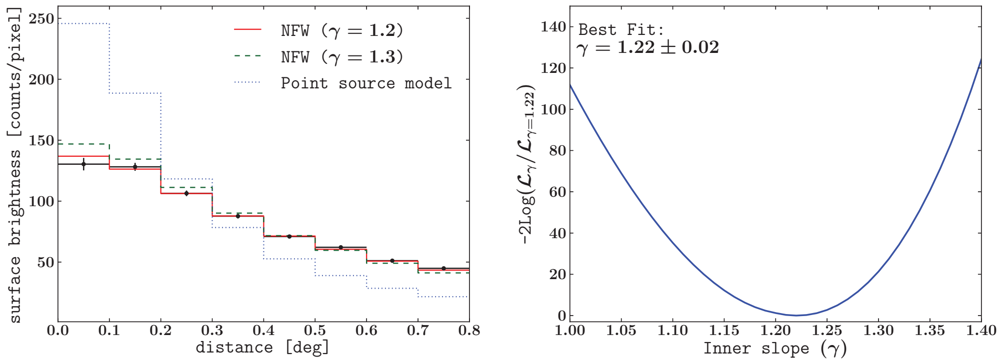

Figure 2. (a) Radial profile of the LAT residuals shown in Figure (1) as obtained from a ring analysis computed around Sgr A*. The histograms show the effective LAT point spread function (PSF) for three different profile models: (i) NFW with inner slope $\gamma \simeq 1.2$ (red continuous line) for which we get $\chi^2/\mathrm{dof} = 5.5/7$. (ii) NFW with $\gamma = 1.3$ (green dashed line) and $\chi^2/\mathrm{dof} = 44.6/7$, and lastly (iii) the profile for a PS model (blue dotted line) with $\chi^2/\mathrm{dof} = 2479.9/7$. For all cases the spectra was modeled with a Log Parabola. **(b)** Shown is the significance of NFW profiles with varying inner slope, where $\mathcal{L}_\gamma$ represents the likelihood function at a given γ. This was assessed by performing a set *Fermi* Tools runs where for each case the relaxation method was used. The spectra was fitted with a Log Parabola function and only statistical uncertainties were taken into account. [A COLOR VERSION IS AVAILABLE ONLINE.]

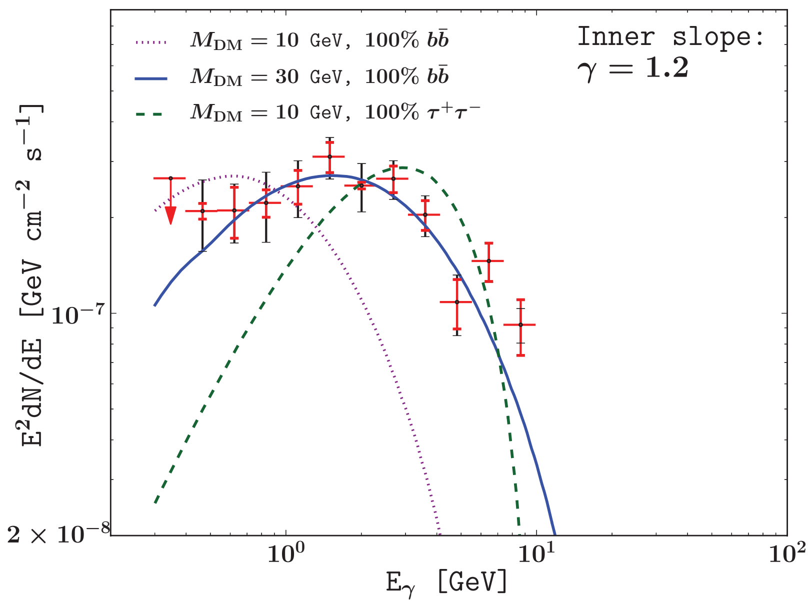

Figure 3. Spectrum of the extended source measured with the *Fermi*/LAT. As shown in the legend, the model for the spatial distribution of the source is a NFW profile with inner slope $\gamma = 1.2$. The red and black error bars show the (1σ) systematic and statistical errors, respectively. The upper limit is 2σ. The fit over the full range is overlaid over the twelve band energy fluxes. The figure shows 3 different examples of DM spectra with high TS values as obtained with *Fermi* Tools, where just $\langle\sigma v\rangle$ was allowed to vary in the fit. Although WIMPs of 10 GeV annihilating all the times into $\tau^+\tau^-$ or $b\bar{b}$ only satisfy the $TS > 25$ criteria, they in fact do not pass the goodness of fit threshold. As it can be seen, $M_{\mathrm{DM}} = 30$ GeV, 100% $b\bar{b}$ exemplifies a good fitting model with significant curved spectra. [A COLOR VERSION IS AVAILABLE ONLINE.]

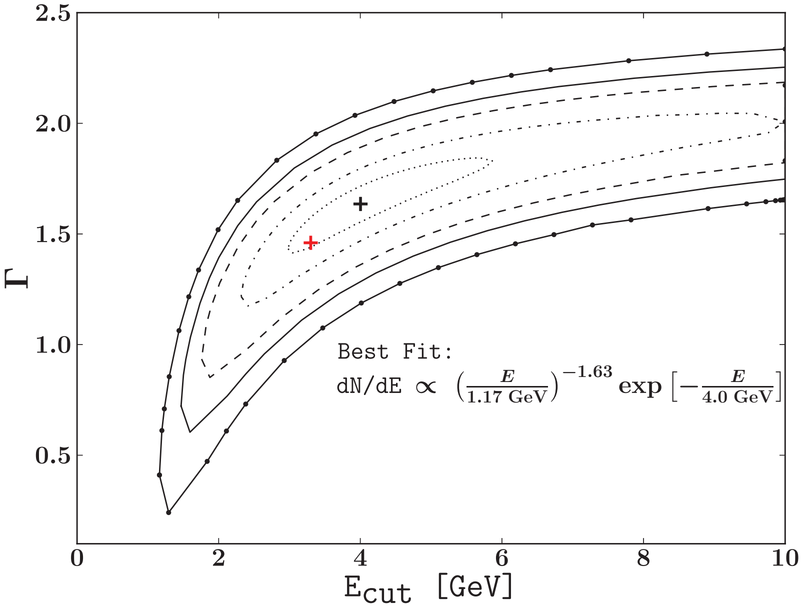

Figure 4. Confidence regions (1σ, 2σ,...5σ) for an unresolved population of Millisecond Pulsars using *Fermi*/LAT data taken from around the GC in the energy range 0.3−10 GeV. The spatial distribution of Pulsars follows a normalized NFW profile with inner slope $\gamma = 1.2$. Best fit parameters are denoted by black crosses. The red cross is the best fit obtained in Hooper *et al.* (2013) as the average best-fit of all the MSPs reported in the 2FGL catalog.

In particular we estimated systematic errors for the galactic diffuse background. We also evaluated marginalized confidence intervals and determined the areas of parameter space that provide an acceptable fit to the data.

As in Abazajian & Kaplinghat (2012); Abazajian & Kaplinghat (2013), we used template maps of DM that assume a generalized Navarro-Frenk-White (NFW) profile

$$\rho(r) = \frac{\rho_s}{\left(\frac{r}{r_s}\right)^{\gamma}\left[1 + \left(\frac{r}{r_s}\right)^{\alpha}\right]^{(\beta-\gamma)/\alpha}}, \tag{0.1}$$

where we fixed $r_s = 23.1$ kpc, $\alpha = 1$, and $\beta = 3$.

It has been suggested that the excess emission seen in the GC can also be explained by a superposition of unresolved millisecond pulsars (MSPs) that might be distributed as a mildly contracted NFW profile. We tested this hypothesis by normalizing to unity the $\langle J(b,l)\rangle$ maps as explained in the `Cicerone`. †

These normalized maps were also used to fit for the inner slope γ as illustrated in Figure 1 and 2.

We have found that either a DM annihilation model (Figure 3) or unresolved pulsar population (Figure 4) is consistent with the observed excess γ-ray emission seen in the GC. Our analysis marginalized over the PS and diffuse background amplitudes in the region of interest. We included an estimated systematic error for the diffuse galactic background of about 20%.

We found that a population of several thousand MSPs with parameters consistent with the average spectral shape of *Fermi*/LAT measured MSPs was able to fit the GC excess

† http://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/extended

emission. For DM, we found that a pure $\tau^+\tau^-$ annihilation channel is not a good fit to the data. But a mixture of $\tau^+\tau^-$ and $b\bar{b}$ with $\langle\sigma v\rangle$ of order the thermal relic value and a DM mass of around 20 to 60 GeV provides an adequate fit.

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