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The characterization of the gamma-ray signal from the central Milky Way: A case for annihilating dark matter

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ABSTRACT

Past studies have identified a spatially extended excess of ∼1–3 GeV gamma rays from the region surrounding the Galactic Center, consistent with the emission expected from annihilating dark matter. We revisit and scrutinize this signal with the intention of further constraining its characteristics and origin. By applying cuts to the *Fermi* event parameter CTBCORE, we suppress the tails of the point spread function and generate high resolution gamma-ray maps, enabling us to more easily separate the various gamma-ray components. Within these maps, we find the GeV excess to be robust and highly statistically significant, with a spectrum, angular distribution, and overall normalization that is in good agreement with that predicted by simple annihilating dark matter models. For example, the signal is very well fit by a 36–51 GeV dark matter particle annihilating to $b\bar{b}$ with an annihilation cross section of $\sigma v = (1-3) \times 10^{-26}$ cm^3/s (normalized to a local dark matter density of 0.4 GeV/cm^3). Furthermore, we confirm that the angular distribution of the excess is approximately spherically symmetric and centered around the dynamical center of the Milky Way (within ∼0.05° of Sgr A*), showing no sign of elongation along the Galactic Plane. The signal is observed to extend to at least ≃10° from the Galactic Center, which together with its other morphological traits disfavors the possibility that this emission originates from previously known or modeled pulsar populations.

1. Introduction

Weakly interacting massive particles (WIMPs) are a leading class of candidates for the dark matter of our universe. If the dark matter consists of such particles, then their annihilations are predicted to produce potentially observable fluxes of energetic particles, including gamma rays, cosmic rays, and neutrinos. Of particular interest are gamma rays from the region of the Galactic Center which, due to its proximity and high dark matter density, is expected to be the brightest source of dark matter annihilation products on the sky, hundreds of times brighter than the most promising dwarf spheroidal galaxies.

Over the past few years, several groups analyzing data from the *Fermi* Gamma-Ray Space Telescope have reported the detection of a gamma-ray signal from the inner few degrees around the Galactic Center (corresponding to a region several hundred parsecs in radius), with a spectrum and angular distribution compatible with that anticipated from annihilating dark matter particles [1–7]. More recently, this signal was shown to also be present throughout the larger Inner Galaxy region, extending kiloparsecs from the center of the Milky Way [8,9]. While the spectrum and morphology of the Galactic Center and Inner Galaxy signals have been shown to be compatible with that predicted from the annihilations of an approximately 30–40 GeV WIMP annihilating to quarks (or a ∼7–10 GeV WIMP annihilating significantly to tau leptons),

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other explanations have also been proposed. In particular, it has been argued that if our galaxy's central stellar cluster contains several thousand unresolved millisecond pulsars, they might be able to account for the emission observed from the Galactic Center [2,4–7,10]. The realization that this signal extends well beyond the boundaries of the central stellar cluster [8,9] disfavors such interpretations, however. In particular, pulsar population models capable of producing the observed emission from the Inner Galaxy invariably predict that *Fermi* should have resolved a much greater number of such objects. Accounting for this constraint, Ref. [11] concluded that no more than ∼5%–10% of the anomalous gamma-ray emission from the Inner Galaxy can originate from pulsars. Furthermore, while it has been suggested that the Galactic Center signal might result from cosmic-ray interactions with gas [2,4–6], the analyses of Refs. [12] and [13] find that measured distributions of gas provide a poor fit to the morphology of the observed signal. It also appears implausible that such processes could account for the more spatially extended emission observed from throughout the Inner Galaxy.

In this study, we revisit the anomalous gamma-ray emission from the Galactic Center and the Inner Galaxy regions and scrutinize the *Fermi* data in an effort to constrain and characterize this signal more definitively, with the ultimate goal being to confidently determine its origin. One way in which we expand upon previous work is by selecting photons based on the value of the *Fermi* event parameter CTBCORE. Through the application of this cut, we select only those events with more reliable directional reconstruction, allowing us to better separate the various gamma-ray components, and to better limit the degree to which emission from the Galactic Disk leaks into the regions studied in our Inner Galaxy analysis. We produce a new and robust determination of the spectrum and morphology of the Inner Galaxy and the Galactic Center signals. We go on to apply a number of tests to this data, and determine that the anomalous emission in question agrees well with that predicted from the annihilations of a 36–51 GeV WIMP annihilating mostly to b quarks (or a somewhat lower mass WIMP if its annihilations proceed to first or second generation quarks). Our results now appear to disfavor the previously considered 7–10 GeV mass window in which the dark matter annihilates significantly to tau leptons [2,4,6–8] (the analysis of Ref. [6] also disfavored this scenario). The morphology of the signal is consistent with spherical symmetry, and strongly disfavors any significant elongation along the Galactic Plane. The emission decreases with the distance to the Galactic Center at a rate consistent with a dark matter halo profile which scales as $\rho \propto r^{-\gamma}$, with $\gamma \approx 1.1$–1.3. The signal can be identified out to angles of $\simeq 10°$ from the Galactic Center, beyond which systematic uncertainties related to the Galactic diffuse model become significant. The annihilation cross section required to normalize the observed signal is $\sigma v \sim 10^{-26}$ cm^3/s, in good agreement with that predicted for dark matter in the form of a simple thermal relic.

The remainder of this article is structured as follows. In the following section, we review the calculation of the spectrum and angular distribution of gamma rays predicted from annihilating dark matter. In Section 3, we describe the event selection used in our analysis, including the application of cuts on the *Fermi* event parameter CTBCORE. In Sections 4 and 5, we describe our analyses of the Inner Galaxy and Galactic Center regions, respectively. In each of these analyses, we observe a significant gamma-ray excess, with a spectrum and morphology in good agreement with that predicted from annihilating dark matter. We further investigate the angular distribution of this emission in Section 6, and discuss the dark matter interpretation of this signal in Section 7. In Section 8 we discuss the implications of these observations, and offer predictions for other upcoming observations. Finally, we summarize our results and conclusions in Section 9. In the paper's appendices, we include supplemental material intended for those interested in further details of our analysis.

2. Gamma rays from dark matter annihilations in the halo of the milky way

Dark matter searches using gamma-ray telescopes have a number of advantages over other indirect detection strategies. Unlike signals associated with cosmic rays (electrons, positrons, antiprotons, etc.), gamma rays are not deflected by magnetic fields. Furthermore, gamma-ray energy losses are negligible on Galactic scales. As a result, gamma-ray telescopes can potentially acquire both spectral and spatial information, unmolested by astrophysical effects.

The flux of gamma rays generated by annihilating dark matter particles, as a function of the direction observed, ψ, is given by:

$$\Phi(E_\gamma, \psi) = \frac{\sigma v}{8\pi m_X^2} \frac{dN_\gamma}{dE_\gamma} \int_{\rm los} \rho^2(r)\, {\rm d}l, \quad (1)$$

where m_X is the mass of the dark matter particle, σv is the annihilation cross section (times the relative velocity of the particles), dN_γ/dE_γ is the gamma-ray spectrum produced per annihilation, and the integral of the density squared is performed over the line-of-sight (los). Although N-body simulations lead us to expect dark matter halos to exhibit some degree of triaxiality (see [14] and references therein), the Milky Way's dark matter distribution is generally assumed to be approximately spherically symmetric, allowing us to describe the density as a function of only the distance from the Galactic Center, r. Throughout this study, we will consider dark matter distributions described by a generalized Navarro–Frenk–White (NFW) halo profile [15,16]:

$$\rho(r) = \rho_0 \frac{(r/r_s)^{-\gamma}}{(1 + r/r_s)^{3-\gamma}}. \quad (2)$$

Throughout this paper, we adopt a scale radius of $r_s = 20$ kpc, and select ρ_0 such that the local dark matter density (at 8.5 kpc from the Galactic Center) is 0.4 GeV/cm^3, consistent with dynamical constraints [17,18]. Although dark matter-only simulations generally favor inner slopes near the canonical NFW value ($\gamma = 1$) [19,20], baryonic effects are expected to have a non-negligible impact on the dark matter distribution within the inner ∼10 kpc of the Milky Way [21–31]. The magnitude and direction of such baryonic effects, however, are currently a topic of debate. With this in mind, we remain agnostic as to the value of the inner slope, and take γ to be a free parameter.

In the left frame of Fig. 1, we plot the density of dark matter as a function of r for several choices of the halo profile. Along with generalized NFW profiles using three values of the inner slope ($\gamma = 1.0, 1.2, 1.4$), we also show for comparison the results for an Einasto profile (with $\alpha = 0.17$) [32]. In the right frame, we plot the value of the integral in Eq. (1) for the same halo profiles, denoted by the quantity, $J(\psi)$:

$$J(\psi) = \int_{\rm los} \rho^2(r)\, dl, \quad (3)$$

where ψ is the angle observed away from the Galactic Center. In the NFW case (with $\gamma = 1$), for example, the value of J averaged over the inner degree around the Galactic Center exceeds that of the most promising dwarf spheroidal galaxies by a factor of ∼50 [33]. If the Milky Way's dark matter halo is contracted by baryons or is otherwise steeper than predicted by NFW, this ratio could easily be ∼10^3 or greater.

The spectrum of gamma rays produced per dark matter annihilation, dN_γ/dE_γ, depends on the mass of the dark matter particle and on the types of particles produced in this process. In the left frame of Fig. 2, we plot dN_γ/dE_γ for the case of a 30 GeV WIMP mass, and for a variety of annihilation channels (as calculated using PYTHIA [34], except for the e^+e^- case, for which