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The Density of Dark Matter in the Galactic Bulge and Implications for Indirect Detection

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Abstract. A recent study, making use of the number of horizontal branch stars observed in infrared photometric surveys and kinematic measurements of M-giant stars from the BRAVA survey, combined with N-body simulations of stellar populations, has presented a new determination of the dark matter mass within the bulge-bar region of the Milky Way. That study constrains the total mass within the $\pm 2.2 \times \pm 1.4 \times \pm 1.2$ kpc volume of the bulge-bar region to be $(1.84 \pm 0.07) \times 10^{10} M_{\odot}$, of which 9-30% is made up of dark matter. Here, we use this result to constrain the Milky Way's dark matter density profile, and discuss the implications for indirect dark matter searches. Although uncertainties remain significant, these results favor dark matter distributions with a cusped density profile. For example, for a scale radius of 20 kpc and a local dark matter density of $0.4 \text{ GeV}/\text{cm}^3$, density profiles with an inner slope of 0.69 to 1.40 are favored, approximately centered around the standard NFW value. In contrast, profiles with large flat-density cores are disfavored by this information.

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1 Introduction

The density of dark matter in the central volume of the Milky Way can strongly impact the prospects for indirect detection, as well as interpretations of the results of indirect detection experiments. This is particularly true for gamma-ray observations of the Galactic Center. The flux of dark matter annihilation products predicted from the innermost degree around the Galactic Center (corresponding to approximately the angular resolution of Fermi’s Large Area Telescope) can vary by several orders of magnitude, depending on the halo profile that is adopted [1, 2]. For ground-based gamma-ray telescopes, with much greater angular resolution, the dependance on the halo profile’s inner slope can be even more significant [3–6].

Although many groups have presented dynamical evidence in support of dark matter’s presence in the Milky Way [7–15], these measurements have until recently had little to say about the density of dark matter in the Galaxy’s innermost kiloparsecs. In this short paper, we make use of the results of Portail *et al.*, who last year published a determination of the stellar mass and dark matter mass for the bulge-bar system of the Milky Way [16]. In that study, the authors made use of the recently measured three-dimensional distribution of horizontal branch stars from infrared photometric surveys [17, 18] and kinematic data for a large number of M-giant stars from the BRAVA survey [19, 20], combined with N-body simulations of stellar populations, to create dynamical models of the Galactic Bulge and Bar. From this information, they were able to constrain the total mass within the volume of the Bulge (taken to be a $\pm 2.2 \times \pm 1.4 \times \pm 1.2$ kpc box centered on the dynamical center of the Milky Way, corresponding to a total volume of 29.6 kpc^3) to be $(1.84 \pm 0.07) \times 10^{10} M_\odot$, including both statistical and systematic errors. While this result is consistent with previous determinations [21–24], it is of unprecedented accuracy and appears to be quite robust to systematic uncertainties. The spatial morphology of stars in the Galaxy’s bulge and bar is also now known in some detail, due in large part to modern photometric surveys [25]. Furthermore, Portail *et al.* find that the stellar mass within this volume, based on the observed number of red giants [26], is consistently smaller than the total mass, allowing one to estimate the fraction of the Bulge’s mass that consists of dark matter. Across the range of models presented by Portail *et al.*, the content of dark matter within the volume of the bulge-bar varies between $1.7 \times 10^9 M_\odot$ and $5.3 \times 10^9 M_\odot$, corresponding to 9-30% of the total mass in the region. The largest source of uncertainty in this result is associated with the initial mass function, which is used to relate the number of red giants to a total stellar mass.

In this paper, we discuss the Milky Way’s dark matter halo profile in light of this information, and assess the implications of this result for the indirect detection of dark matter in the Galactic Center and Inner Galaxy. We find that the results of Portail *et al.* support the existence of a density cusp, and disfavor the presence of a large flat density core in the Milky Way’s dark matter halo profile.

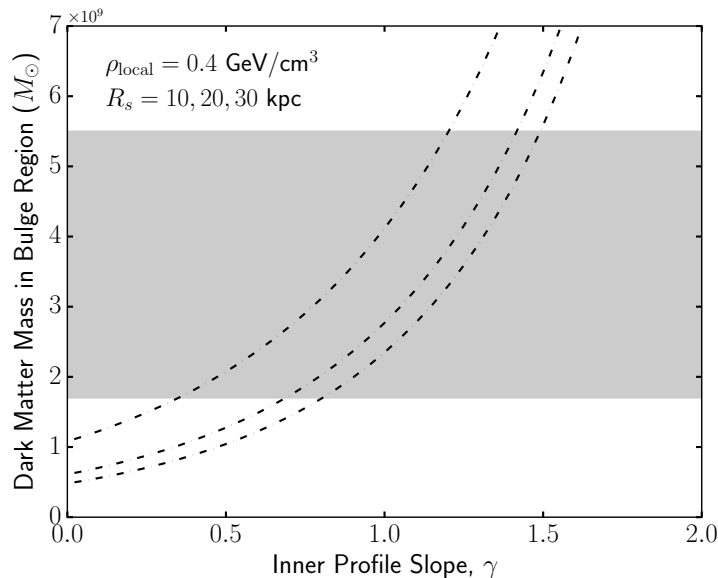


Figure 1. The total mass in dark matter within the bulge-bar region of the Milky Way (defined as a $\pm 2.2 \times \pm 1.4 \times \pm 1.2$ kpc box, centered around the Galactic Center), as a function of the inner slope of a generalized NFW halo profile, and for three values of the scale radius (10, 20 and 30 kpc, from left-to-right). We adopt a local dark matter density (at $r=8.5$ kpc) of 0.4 GeV/cm^3 . The shaded grey region represents the range favored by the determination of Portail *et al.* [16].

2 Constraining The Milky Way’s Dark Matter Density Profile

In this study, we parameterize the Milky Way’s dark matter halo distribution using the following generalized Navarro-Frenk-White (NFW) profile [27, 28]:

$$\rho(r) \propto \frac{1}{r^\gamma [1 + (r/R_s)]^{3-\gamma}}. \quad (2.1)$$

In this expression, γ is the inner slope of the profile ($\gamma = 1$ corresponds to the case of a standard NFW profile), and R_s is the scale radius. The flux of gamma rays or neutrinos generated by dark matter annihilation from a given direction of the sky is proportional to what is known as the J -factor [29], which is given by:

$$J(\psi) = \int_{\text{los}} \rho^2(l, \psi) dl(\psi), \quad (2.2)$$

where ψ is the angle observed and the integral is performed over the line-of-sight (los). In practice, one generally integrates the J -factor over a solid angle representing the field-of-view under consideration.

In Fig. 1, we plot the total mass in dark matter within the bulge-bar region as defined by Portail *et al.* (a $\pm 2.2 \times \pm 1.4 \times \pm 1.2$ kpc rectangular box, centered around the Galactic Center), as a function of the inner slope of the halo profile, and for three values of the scale radius. In this figure, we adopt a local dark matter density (at $r=8.5$ kpc) of 0.4 GeV/cm^3 . The shaded grey region of this figure represents the range of values favored by Portail *et al.* ($1.7 \times 10^9 M_\odot$ to $5.3 \times 10^9 M_\odot$) [16]. From this figure, it is clear that cusped halo profiles, of

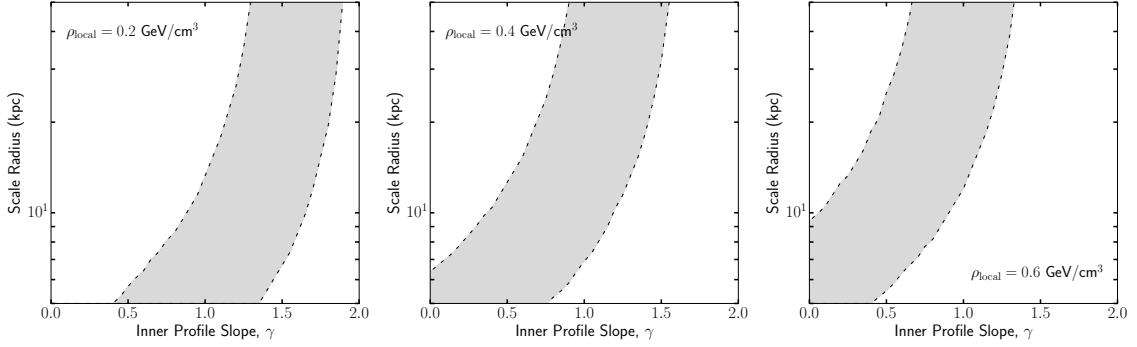


Figure 2. Values of the scale radius and inner slope which correspond to a quantity of dark matter in the bulge-bar region that falls within the range favored by Portail *et al.* [16], for three values of the local dark matter density.

the type long favored by numerical simulations of cold collisions dark matter [30, 31], are in good agreement with the results of Ref. [16]. For example, for $R_s = 20$ kpc and $\rho_{\text{local}} = 0.4$ GeV/cm^3 , Portail *et al.* favor an inner slope of 0.69 to 1.40, approximately centered around the standard NFW value of $\gamma = 1.0$. In Fig. 2, we show the values of the scale radius and inner slope that fall within the range favored by Portail *et al.*, for three values of the local dark matter density. We also note that the results of Portail *et al.* appear to modestly disfavor dark matter distributions that follow an Einasto profile [32]. For example, an Einasto profile with $\alpha = 0.17$, $\rho_{\text{local}} = 0.4$ GeV/cm^3 and $R_s = 20$ kpc, yields a dark matter mass for the bulge-bar region of $0.90 \times 10^9 M_\odot$, well below the range favored by Portail *et al.*

Despite the fact that numerical simulations of cold, collisionless dark matter favor cusped halo profiles [30, 31], such simulations often do not include the potentially important effects of baryons. And although hydrodynamical simulations of Milky Way like systems have improved significantly in recent years, a consensus has not yet emerged regarding whether baryonic effects are more likely to steepen or flatten the dark matter density profile in the innermost kiloparsecs of the Galaxy [33–48]. With this in mind, we show in Fig. 3 results for dark matter halos with a constant density core. From this figure, we see that any profile with a core larger than a few kpc in radius is disfavored by the results of Portail *et al.*

In Fig. 4, we show the range of values of the local dark matter density and the inner profile slope that are favored by the results of Portail *et al.*, for a scale radius of 20 kpc. As dashed lines, we show contours of constant J -factor, evaluated over the a 1° radius around the Galactic Center, normalized such that a value of one corresponds to the case of $\gamma = 1$ and $\rho_{\text{local}} = 0.4$ GeV/cm^3 . Over most of the parameter space favored by Portail *et al.*, we find J -factors that lie within approximately an order of magnitude of the value predicted in the standard NFW case.

Analyses of Fermi data have identified a bright and statistically significant excess of GeV-scale gamma-rays from the region surrounding the Galactic Center [49–58], with morphological and spectral features consistent with those predicted from annihilating dark matter. To fit the data with annihilating dark matter, these analyses generally find that a halo profile with an inner slope of $\gamma \simeq 1.0 - 1.4$ is required [52–58]. For the best-fit value of $\gamma = 1.28$, as found in Ref. [56] (for $R_s = 20$ kpc), the results of Portail *et al.* favor a local density in the range of 0.156 to 0.504 GeV/cm^3 . This range of halo normalizations corresponds to annihilation cross sections of $\sigma v = (0.25 - 2.6) \times 10^{-26}$ cm^3/s , for the best-fit mass

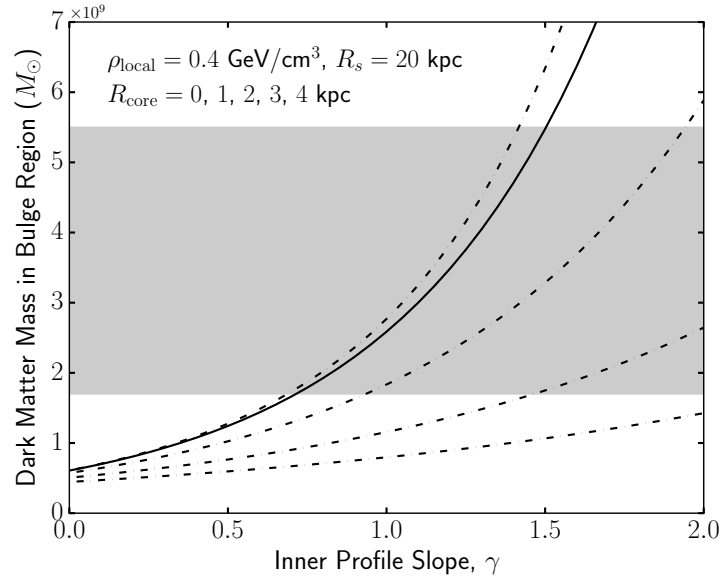


Figure 3. As in Fig. 1, but for profiles with a constant density core. Profiles with a core that is larger than a few kpc in radius are disfavored by the results of Portail *et al.* [16].

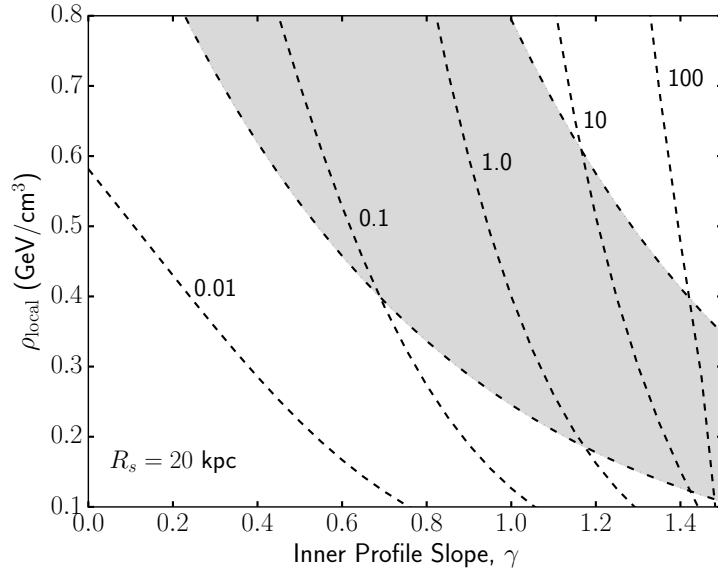


Figure 4. The shaded grey region in this figure represents the values of the local density and the inner slope that are favored by the determination of Portail *et al.* [16], for a scale radius of 20 kpc. The dashed lines represent contours of constant J -factor, evaluated over the a 1° radius around the Galactic Center, with values equal to 0.01, 0.1, 1.0, 10.0 and 100 times that obtained for the case of a standard NFW profile ($\gamma = 1$) with $\rho_{\text{local}} = 0.4 \text{ GeV/cm}^3$.

of $m_{\text{DM}} = 49 \text{ GeV}$ (annihilating to $b\bar{b}$). Note that this range does not include uncertainties in the determination of the intensity or inner slope.

Lastly, we point out that the J -factor for the Galactic Center could be larger than

those inferred in this paper if there exists a density spike in the immediate vicinity around the Galaxy’s supermassive black hole [59, 60]. Such a feature could plausibly enhance the flux of annihilation products from the direction of the Galactic Center, but without impacting the flux from other directions of the sky.

3 Summary and Conclusions

In this paper, we have made use of a recent dynamical determination of the dark matter mass in the Galactic Bulge-Bar region [16] to constrain the Milky Way’s dark matter density profile. We find that these results favor a cusped distribution, consistent with commonly used profile models. For example, for a halo with local density of $0.4 \text{ GeV}/\text{cm}^3$ and a scale radius of 20 kpc, we find that these results favor an inner slope in the range of $\gamma = 0.69$ to 1.40, consistent with the standard NFW value of $\gamma = 1.0$. Profiles with large flat-density cores are disfavored by this determination. Dark matter scenarios capable of accounting for the GeV excess observed from the Inner Galaxy require profiles with $\gamma \simeq 1.0 - 1.4$, in good agreement with the results presented here.

Our ability to constrain the Milky Way’s dark matter halo profile is expected to improve very significantly in the future. In particular, we expect observations from the Wide-Field Infrared Survey Telescope (WFIRST) to improve upon existing dynamical measurements of the Inner Galaxy by an order-of-magnitude [61, 62]. Combining such observations with those from Gaia and LSST will make it possible to constrain the Milky Way’s dark matter halo profile over a wide range of scales, and with much greater precision than is currently possible.

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