Offset of the dark matter cusp and the interpretation of the 130 GeV line as a dark matter signal

Dmitry Gorbunov  
*Institute for Nuclear Research of the Russian Academy of Sciences,  
60-th October Anniversary pr. 7a, 117312 Moscow, Russia and  
Moscow Institute of Physics and Technology,  
Institutsky per. 9, Dolgoprudny, 141700, Russia*

Peter Tinyakov  
*Service de Physique Théorique, Université Libre de Bruxelles (ULB),  
CP225 Boulevard du Triomph, B-1050 Bruxelles, Belgium*

We show that the cusp in the dark matter (DM) distribution required to explain the recently found excess in the gamma-ray spectrum at energies $\sim 130$ GeV in terms of the DM annihilations cannot survive the tidal forces if it is offset by $\sim 1.5^\circ$ from the Galactic center as suggested by observations.

**I. INTRODUCTION**

Recently, a line-like feature in the gamma-ray spectrum observed by the Fermi LAT experiment in the direction of the Galactic center has been found. It has been suggested that it can be interpreted in terms of the dark matter (DM) annihilation signal [1, 2].

More refined analysis has confirmed the significance of the feature in the spectrum [3, 4]. The best fit to the DM annihilation line was obtained with the modified Navarro-Frenk-White (NFW) DM profile with the inner slope of $\alpha = -1.2$ (as may have resulted, e.g., from the adiabatic contraction). It also revealed the offset of the signal with respect to the central region of only about 10\%.

In order to address this question, numerical simulations of the Galactic center including the effect of the bar were used in Ref. [5]. It was found that an offset of a few hundred parsec between the GC and the maximum of the DM distribution could in principle exist (see also Ref. [6] and references therein). However, the DM distribution in this case is not cuspy but cored and has an overdensity with respect to the central region of only about 10 \textendash} 20\%. In addition, it was found that the core density is formed by the gravitationally unbound DM particles.

Here we address the same question from a different perspective. Rather than trying to constrain possible mechanisms by which an offset cusp could be produced (one may think, e.g., of a merger event in the past), we consider how long such a cusp would survive. Making use of the analytical estimates we show that only a small central region of the DM cusp can survive the tidal forces produced by the baryons which dominate the gravitational potential near the Galactic center. The surviving part of the cusp is too small to explain the observed feature in the $\gamma$-ray spectrum.

**II. BARYONIC AND DM PROFILES IN THE GALACTIC CENTER**

The baryon distribution in the GC is known from the 2 \textmu m light distribution (see, e.g., Refs. [7, 8]) and confirmed by the study of the kinematic properties of the OH/IR stars [9].

For our purposes the exact behavior of the baryon density is not necessary, and a crude approximation in the inner $\sim 200$ pc is sufficient. From Fig. 10 of Ref. [10] we adopt the following approximation for the baryonic mass $M_B(r)$ enclosed within the radius $r$,

$$M_B(r) = 6 \times 10^8 M_\odot \left( \frac{r}{100 \text{ pc}} \right)^{1.25} ,$$

where $M_\odot$ is the solar mass. From this equation, the baryonic density $\rho_B(r)$ is

$$\rho_B(r) = 60 M_\odot \text{ pc}^{-3} \left( \frac{r}{100 \text{ pc}} \right)^{-1.75}$$

$$= 2.3 \times 10^3 \text{ GeV cm}^{-3} \left( \frac{r}{100 \text{ pc}} \right)^{-1.75} .$$

This relation is consistent, within the errors, with the one derived in Refs. [8, 11]. It is clear from eq. (1) that at distances $\gtrsim 100$ pc from the Galactic center the effect of the central black hole is subdominant, and we ignore it in what follows.

Now we turn to the DM distribution. In Ref. [4] several DM profiles were shown to fit the gamma-ray data, namely the Einasto profile [12] and modified NFW profiles of the form

$$\rho(r) = \frac{\rho_x}{(r/r_s)^\alpha(1 + r/r_s)^{3-\alpha}} ,$$

where $r_s = 20$ kpc and the slope $\alpha$ ranges from 1 to 1.3, with the best fit value $\alpha = 1.2$. The normalization factor $\rho_x = 0.27 \text{ GeV/cm}^3$ is fixed by setting the DM density around the Earth to 0.4 GeV/cm$^3$. To illustrate
our point it is sufficient to consider the simpler and more cuspy NFW profile \( [2] \). The less cuspy Einasto profile is subject to even stronger tidal effects.

As a first step, let us find the size of the region which is responsible for the gamma-ray signal assuming the latter is produced by the DM annihilations. The observed signal corresponds to the luminosity \([4]\)

\[
L_0 = (1.7 \pm 0.4) \times 10^{36} \text{ photons/s}. 
\]

On the other hand, the luminosity of a spherical region of the size \( r \) centered on the DM distribution can be written as follows,

\[
L(r) = \frac{4\pi r^3}{m_{DM}^2} \langle \sigma v \rangle \rho_s^2 I(r/r_s), \quad (3)
\]

where \( \langle \sigma v \rangle \approx 2 \times 10^{-27} \text{ cm}^3/\text{s} \) is the velocity-averaged DM annihilation cross section \([2]\), \( m_{DM} \) is the DM mass \( (m_{DM} \approx 130 \text{ GeV} \ [2, 4]) \) in the case of annihilation into \( \gamma \gamma \) and 140-150 GeV \([1, 3]\) in the case of internal bremsstrahlung) and

\[
I(r/r_s) = \int_0^{r/r_s} \frac{x^2 \, dx}{x^{2\alpha}(1 + x)^{6 - 2\alpha}}. \quad (4)
\]

Equating this to the observed luminosity gives the following equation for the size \( r \) of the emission region,

\[
I(r/r_s) = \frac{L_0 \, m_{DM}^2}{4\pi \langle \sigma v \rangle \rho_s^2 r_s^2} = 7.7 \times 10^{-2}. 
\]

This equation is easily solved by noting that the solution corresponds to small values of \( r/r_s \) for which the integral in eq. (4) can be simplified,

\[
I(r/r_s) \approx \frac{1}{3 - 2\alpha} (r/r_s)^{3 - 2\alpha}. 
\]

For the best fit case \( \alpha = 1.2 \) this gives

\[
r \simeq 0.006 \, r_s = 120 \, \text{pc}, \quad (5)
\]

where we have used \( m_{DM} = 140 \text{ GeV} \). Note that when obtaining this estimate we have assumed (cf. eq. (3)) that all of the DM mass is converted into photons, as in the case of the annihilation into \( \gamma \gamma \). If the efficiency were lower, as it would be in the case of the annihilation into a single-photon final state \([1, 3]\), the size of the contributing region would be even larger.

It is instructive to calculate the total amount of DM contained within a given distance from the cusp. Making use of the relation \( r/r_s \ll 1 \) one finds

\[
M_{DM}(r) = 4\pi r_s^3 \frac{1}{3 - \alpha} (r/r_s)^{3 - \alpha},
\]

where \( r \) is the distance from the center of the cusp. This implies for \( \alpha = 1.2 \)

\[
M_{DM}(r) = 2.9 \times 10^7 M_\odot (\frac{r}{100 \text{ pc}})^{1.8}. \quad (6)
\]

The latter value has to be compared to eq. (11). Clearly, at distances \( \sim 200 \) pc from the Galactic center the baryons give a dominant contribution to the total mass. Thus, they dominate the gravitational potential except in the vicinity of the cusp.

III. TIDAL STRIPPING OF THE OFFSET DM CUSP

The DM cusp that is offset with respect to the baryonic distribution is subject to tidal forces. To estimate the importance of these forces one may compare the difference of the gravitational pull of baryons at different parts of the DM distribution and the gravitational force from the DM itself. For the cusp to survive the gravitational force from baryons has to be smaller than the force from DM. This leads to the condition

\[
\frac{GM_{DM}(d)}{d^2} > \frac{GM_B(r)}{r^3} d, \quad (7)
\]

where \( r \sim 200 \) pc is the offset distance and it was assumed that \( d \ll r \). Making use of eqs. (11) and (12) one finds for \( \alpha = 1.2, d \lesssim 22 \) pc. Thus, the tidal radius (the maximum radius where DM particles survive the stripping by tidal forces) is much smaller than the offset distance, which justifies the approximation used.

In fact, the value obtained from eq. (7) is an overestimate. More accurately, the tidal radius \( d \) can be calculated by making use of the formalism developed in Ref. [13]. In principle, one should distinguish tidal radii corresponding to prograde, radial and retrograde DM orbits. However, in the long time limit (that is, at times much longer than the period of the orbital motion \( \sim 10^7 \) yr) these converge to the smallest of the three. Making use of eq. (21) of Ref. [13], one finds at \( \alpha = 1.2 \)

\[
d \simeq 5 \text{ pc}. \quad (8)
\]

At smaller values of \( \alpha \) the DM cusp is weaker and the tidal radius is slightly smaller, while at larger values of \( \alpha \) it is slightly larger, always being of the same order as given by eq. (8). Thus, only a very small central part of the cusp can survive the tidal disruption. This part is much smaller than the region responsible for the annihilation signal.

IV. CONCLUSIONS

It is instructive to calculate the total amount of DM contained within a given distance from the cusp. Making use of the relation \( r/r_s \ll 1 \) one finds

\[
M_{DM}(r) = 4\pi r_s^3 \frac{1}{3 - \alpha} (r/r_s)^{3 - \alpha},
\]

where \( r \) is the distance from the center of the cusp. This implies for \( \alpha = 1.2 \)

\[
M_{DM}(r) = 2.9 \times 10^7 M_\odot (\frac{r}{100 \text{ pc}})^{1.8}. \quad (6)
\]
of about \(\sim 7\) if the annihilation cross section of \(\langle \sigma v \rangle \approx 2 \times 10^{-27} \text{ cm}^3/\text{s}\) is assumed. To make the signal from the surviving part of the cusp compatible with observations, one would have to increase the cross section by the same factor, which would be in contradiction with the limits from Fermi LAT [14] (note that the latter are integral limits which are insensitive to the contribution from the small region around the Galactic center).

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