Abstract. The dark matter density profile in the inner regions of globular clusters is still an open question which is of fundamental importance to the study of radio and $\gamma$-ray emission from dark matter (DM) annihilation in such regions. Here we consider the case of intermediate mass black holes (IMBHs) in the inner regions of three globular clusters, namely 47 Tuc, NGC 6266 and $\omega$ Cen. The existence of a black hole directly affects the matter distribution in its vicinity. These effects are significant for IMBHs as well as supermassive black holes (SMBHs) and can lead to large dark matter overdensities called spikes. In this paper, we study radio synchrotron emission from DM annihilation with spike profile around possible IMBHs in globular clusters. We present our results for synchrotron emission produced by DM annihilation via $b\bar{b}$ channel. We use the best-fit DM mass of 34 GeV and annihilation channel in $b\bar{b}$ used to explain the Galactic center “excess” and perform our analysis for the estimated radio flux. We direct our attention specially to the $\gamma$-ray emission from 47 Tuc. When considering this combined analysis of these multi-wavelength studies, we conclude that some parameter choice used to fit the $\gamma$-ray excess differs by many orders of magnitude from the one necessary to fit the radio observations for this globular cluster.

Keywords: Dark matter, synchrotron radiation, cosmic radio background, globular clusters.
1 Introduction

Despite great advances in Particle Physics, Astrophysics and Cosmology, we still have no knowledge about the nature or composition of dark matter (DM). For particle DM, we have little knowledge of range of parameter space of the model to which it might belong. Together with these uncertainties, there exist questions related to DM density profiles. The structure of DM halos are the subject of ongoing numerical and analytical studies.

N-body simulations have been used to study halo formation. These studies have shown that, although the spherically-averaged density profiles of the simulated halos are very similar, their profiles are significantly different from the single power laws predicted by theory. This conclusion holds even considering different halo masses or different cosmological models [1]. The N-body profiles are characterized by a decline obeying an $r^{-3}$ proportionality at large radii and a cusp profile of the form $r^{-\gamma}$, the so called $\gamma$-models.

Analytical studies of DM halos predict that the density profile of a virialized halo should obey the power-law $\rho \propto r^{-9/4}$. Similar results were also obtained when studying density profiles around density peaks and considering an isotropic velocity dispersion in the core of collisionless halos [1].

The most studied predictions for cold DM establish that DM halos should exhibit steep central cusps, with their density proportional to $r^{-\gamma}$. Semi-analytical approaches indicate the existence of a cusp having $1 < \gamma < 2$. However, other simulations had find values of $\gamma$ ranging from 0.3, 1 and 1.5 [2–5].

There are five common numerical profiles very well studied in the literature, namely Navarro-Frenk-White (NFW), Einasto (EIN), Isothermal (ISO), Burkert (BUR) and Moore (MOO). All of them find a cusp, assuming spherical symmetry. Their forms as functions of the galactocentric coordinate $r$ can be found at [6]. An environment that could enhance and change such distribution profiles is the surroundings of compact objects such as black holes (BH).

The presence of intermediate mass black holes (IMBH) and supermassive black holes (SMBH) modifies the distribution of dark matter in its vicinity, making such regions, very promising locations to detect DM indirectly due to the constant evolution of BH, such as growth, mass accretion, etc. DM annihilation or decay products could be searched for in...
the vicinities of BH since these massive objects could induce overdensities, called “spikes” or lighter overdensities called “mini-spikes”. Indirect searches could also utilize the detection of DM via the detection of fluxes of secondary particles such as $\gamma$-rays, electrons, positrons and neutrinos in such regions.

In the literature there are many theoretical studies of the distribution of DM in the surroundings of a BH. Gondolo and Silk first studied DM spike density profile in the Galactic center, where a supermassive black hole $(2-4) \times 10^6 M_\odot$ dominates the gravitational potential [7–9].

One important recent analysis invoking the “spiky” nature of DM where performed at Ref. [10], where it was shown the huge enhancement to the $\gamma$-ray flux from the Galactic center assuming such spike and considering that the 1 – 3 GeV excess observed in Fermi data could be due to DM annihilations. More recent analysis trying to prove the existence of a DM density spike allied to the radial dependence at Galactic center where performed by Lacroix et al. [11], who also presented a solution for the cosmic ray diffusion on very small scales, assuming a radial dependence based on NFW + spike profile.

Following the studies of Gondolo, in 2000s, Silk and Zhao analysed possible lighter overdensities around IMBHs remnants of Pop III stars and presented the first estimative of mini-spikes for the IMBH in the Milky Way [12]. A more recent study used the idea of these lighter overdensities due to DM annihilation in the surroundings of IMBH to account for the $\gamma$-ray excess in the Galactic center [13].

In fact, the DM density profile around IMBHs is still unknown, despite many suggestions of strong enhancements for it. On one hand, some authors claim that effects of dynamical relaxation by stellar interactions, merger between two halos, and the loss of DM falling into the IMBH may smooth the already produced spike [14, 15]. On the other hand, all the range of dynamical effects of IMBH-DM interactions, such as black hole growth time scale, core relaxation, time from stellar dynamical heating and adiabatic response of DM has not been fully explored.

In this paper we will study a special spike profile, already used to explain the $\gamma$-ray emission from the globular cluster 47 Tuc [16]. We then perform our simulations with this profile considering the synchrotron emission from DM annihilations in three globular clusters, namely, 47 Tuc, $\omega$ Cen and NGC 6266. We will study 34 GeV DM particles which annihilates in $b\bar{b}$ channel, motivated by best-fit of the $\gamma$–ray “excess” for the Galactic center (See, e.g., Ref. [16])\(^1\). We then compare our results with the existing constraints from radio signatures for globular clusters. We also compare the parameter results with the ones used to explain the $\gamma$-ray emission from the globular cluster 47 Tuc [16].

The paper is organized as follows: in section 2 we present the globular clusters to be studied, its characteristics and relevance for our analysis. In section 3 we illustrate the DM density spike profile and its parameters used in our simulations. In section 4, we review the techniques for calculation of synchrotron emission from DM annihilations. In section 5 we present our results of the synchrotron flux for the chosen globular clusters and in the final section 6 we summarize and highlight our conclusions.

\(^1\)Although the millisecond pulsar hypothesis for the excess $\gamma$-rays from the Galactic center has been favored, the DM hypothesis has been recently been revived [17]
Globular clusters (hereafter GCs) consist of dense spherical concentrations of stars, typically 100 light years of diameter and belong to the list of the oldest astrophysical objects with typical ages of 11.5 Gyr to 12.5 Gyr. The conditions under which they are formed and their various possible formation mechanisms, both inside and outside of galaxies are open questions. These questions involve the various formation, assembly, and evolution processes of the larger galaxies [18].

The prediction that IMBH (compact objects which mass is in the range \(100M_\odot \lesssim M_{BH} \lesssim 10^5M_\odot\)) might exist in low-mass stellar systems such as GCs was made in the 1970’s by Wyller [19], Silk & Arons [20] and Frank & Rees [21]. Silk & Arons studied X-ray sources in a large sample of GCs concluding that the observed flux of X-rays could be explained considering a mass accretion of \(10^2 - 10^3M_\odot\) of a central BH. This discovery promoted the black-hole hunting in GCs using mainly X-ray and radio emission [22]. The GCs have also been studied several times across the electromagnetic spectrum and led to the discovery of a large number of millisecond pulsars (MSPs).

The existence of a central BH in a globular can be inferred from several properties of the cluster containing the BH, such as the total mass, total luminosity and velocity dispersion profile. Using these properties, it is possible to establish some correlations, which are satisfied by galaxies such as the well known \(M - \sigma_\ast, M_\ast - M_{tot}, M_\ast - L_{tot}\), and which can also be satisfied by IMBH, where some of them \((M - \sigma_\ast)\) are stronger than others [22].

The \(M - \sigma_\ast\) relation can be obtained from theoretical N-body simulations in combination with from dynamical methods [23]. Recent radio continuum observations of some GCs have put an upper limit on central IMBHs. However, we emphasize that the existence of IMBH in GCs is still a subject of debate by many groups. Stronger evidence concerning the presence of these massive objects in GCs may be unveiled by future experiments such as LISA [24], which will be the first dedicated space-based gravitational wave detector. More theoretical work will also be very useful in investigating the existence of central IMBH in GCs.

Ref. [25] explored a model which unified the cosmic star formation rate with the local galactic star formation rate via a hierarchical structure formation scenario. As a consequence of the model, it was predicted that dark matter halos of great mass could contain a number of halos of much smaller mass, being able to form structures very similar to GCs. In particular, [26] estimate the fraction and distribution of dark matter in the innermost regions of NGC 6218 (M12) and NGC 288. They concluded that there is a large mass fraction of non-luminous matter in these objects.

In this article we concentrate our efforts studying three GCs, namely, 47 Tuc also known as NGC 104, \(\omega\) Cen, also known as NGC 5139 and M62, also known as NGC 6266. 47 Tuc and \(\omega\) Cen are the two most concentrated and massive GCs in our galaxy. The observations of Fermi-LAT satellite very early discovered that 47 Tuc and \(\omega\) Cen were \(\gamma\)-ray bright [27] \(^2\). NGC 6266 is among the ten most massive and luminous GCs in the galaxy. Simulations suggest that these clusters may have an IMBH on their core.

\(^2\)On the other hand, some atypical properties of \(\omega\) Cen suggest that it might be the remnant core of a dSph. If this statement is confirmed, \(\omega\) Cen is considered to be the best place to search for DM annihilation due to its proximity to Earth and since it contains high density of DM as compact dwarf galaxies and also emits \(\gamma\)-rays [28].
These three GCs were observed by the Hubble Space Telescope (HST). The results of these observations placed limits on the mass a possible IMBH [23]. X-ray and radio observations were used to settle limits on the mass of a central accreting black hole for 47 Tuc. [29].

NGC 6266 was found to be the most suitable object to search by HST which measured this cluster’s internal proper motion dispersion profile and then compared the results to those ones produced by N-body simulations of NGC 6266 with/without an IMBH [30].

In Table 1, we present the main characteristics for these GCs.

|                  | 47 Tuc | ω Cen | NGC 6266 |
|------------------|--------|-------|----------|
| l (Degrees)      | 305.9  | 309.1 | 353.6    |
| b (Degrees)      | -44.9  | +15   | +7.3     |
| d (kpc)          | 4.59   | 5.21  | 7.05     |
| $t_{BH}$ (Gyr)   | 11.75  | 11.52 | 11.78    |
| $M_{BH}$ ($M_\odot$) | $2.3\times10^4$ | $5\times10^4$ | $2\times10^4$ |
| $\sigma_*$ (km/s) | 10     | 10    | 15       |

Table 1: Data from 47 Tuc, ω Cen and NGC 6266. The parameter $l$ denotes the Galactic latitude of the GC, $b$ denotes Galactic longitude, $d$ is the distance of the GC from Earth, taken from Refs. [23, 31–34]. The parameter $t_{BH}$ denotes the age of the IMBH which the GC might hold, $M_{BH}$ denotes the mass of the IMBH and $\sigma_*$ is the stellar velocity dispersion. The numerical values for these parameters can be found at Refs [35–37].

In the next sections, we will study the impact of the existence of IMBH in these GCs, considering a scenario of DM annihilation in the vicinity of the IMBH. For the three GCs we will use the data of Table 1. We will study the implication of the DM spike enhanced distribution in the synchrotron signal of these GCs.

3 DM Spike Density Profile in Globular Clusters

We will use here the DM spike profile of Ref. [16] in order to study the effect of DM on halos surrounding an IMBH in a GC. We emphasize that the full range of dynamical effects of a BH was not explored in considering the spike. Here, we just focus on a well motivated dense inner spike profile and try to evaluate its effects on the synchrotron emission of DM in the GCs. We then compare our results with the one obtained by Brown et al. ([16]) to fit the $\gamma$-ray excess.

The spike profile considered here presents a sharply peaked radial dependence, which accounts for both the presence of IMBH and dynamical processes in the GC. The spike structure of this profile was motivated by the strong evidence of DM mass with 47 Tuc. Brown et al. analysed the full 9-year Fermi-LAT data in attempt to find a possible explanation of the $\gamma$-ray excess, not only considering DM, but also millisecond pulsars (MSP). Approximations like this were already used to study a DM population clustered in the vicinities of a SMBH at the center of Centaurus A [16, 38].
The existence of a spike enhances the $\gamma$-ray signal from DM annihilation. It can be represented by

$$
\rho(r) = \begin{cases} 
0 & r < 2R_s \\
\rho_{sp}(r)\rho_{sat} & 2R_s \leq r < R_{sp} \\
\rho_0 \left( \frac{r}{R_{sp}} \right)^{-5} & r \geq R_{sp}
\end{cases}
$$

(3.1)

where $R_s = 2GM_{BH}/c^2$ denotes the Scharzschild radius, $R_{sp} = GM_{BH}/\sigma^2_*$ [39] denotes the radius of the spike, where $G$ denotes the Newton's constant of gravity, $M_{BH}$ is the mass of the black hole and $\sigma_*$ is the stellar velocity dispersion, $\rho_{sp}(r) = \rho_0 (r/R_{sp})^{-5}$ and $\rho_0 \approx (3-\gamma_{sp})M_{BH}/(4\pi R_{sp}^3)$, The parameter $\gamma_{sp} = (9-2\gamma)/(4-\gamma)$ is expected to be between 2.25 and 2.5, taking into account that $0 < \gamma < 2$. The parameter $\rho_{sat}$ is the saturation density established by DM annihilations. In this case, this corresponds to make $\rho_{sat} = \rho_{ann}$, where $\rho_{ann} = \frac{m_{DM}}{\langle \sigma v \rangle \tau_i}$

(3.2)

basically establishing $\rho_{sat} = \rho_{ann}$ corresponds to the equality of characteristic annihilation time and infall time ($\tau_i$) of DM towards the IMBH. Here, we will assume conservatively that $\tau_i = t_{BH}$, where $t_{BH}$ denotes the age of the black hole, $m_{DM}$ is the mass of DM candidate and $\langle \sigma v \rangle$ is the annihilation cross section.

For $r \geq R_{sp}$ Brown et al. [16] assumed a radial dependence $r^{-5}$ (from tidal stripping). This profile is normalized by requiring that the mass inside the spike $M_{sp}$ be of order of the BH mass, resulting that the total DM mass in the cluster is $\sim 1\%$ of the mass of 47 Tuc. In the end, the authors fit 47 Tuc’s $\gamma$-ray spectrum considering MSP+DM spike. Their best-fit solution had a DM candidate with mass 34 GeV and $\langle \sigma v \rangle \sim 6 \times 10^{-30}$ cm$^3$/s.

There are some comments and reply to comments related to MSP & DM interpretation in Brown’s papers [40, 41]. In the reply to comments they conclude that such discussion motivates a deeper radio study of 47 Tuc. In this paper, we present a first analysis of the radio signature from dark matter annihilation, studying the same channel proposed by [16] to explain the gamma excess in 47 Tuc. We will also present the theoretical radio flux for other two GCs, namely, $\omega$ Cen and NGC 6266.

4 Synchrotron/Radio Flux From Dark Matter Annihilation

In this section we revisit the techniques to calculate the radio flux originated from the propagation of electrons/positrons resulting from DM annihilation processes. Then we compute the resulting synchrotron emission for three GCs. The radio flux emission depends mainly on the magnetic field strenght ($B$), on the DM mass ($m_{DM}$), annihilation channels and density profile, $\rho(r)$, and on the density of the ionized gas ($n$).

The integrated synchrotron flux density produced by a generic distribution reads:

$$
S_{\nu}(\nu) \approx \frac{1}{D^2} \int_0^{R_a} drr^2 j_{\nu}(\nu, r),
$$

(4.1)

where $R_a$ is the radial extent of the region of interest [42]. The parameter $D$ is the distance from the GC to Earth. The result is usually given in Janskys. In eq. (4.1), $j_\nu$ denotes the
synchrotron emissivity, which can be expressed as
\[ j_\nu(\nu, r) = 2 \int_{m_e c^2}^{m_{DM}} dE \frac{dn_e}{dE}(E, r)P_\nu(\nu, E) \]  
(4.2)
where the factor 2 takes into account the electrons and positrons, \( \frac{dn_e}{dE}(E, r) \) is the electron equilibrium spectrum and \( P_\nu(\nu, E) \) denotes the synchrotron power for a certain frequency \( \nu \). Considering the isotropy in the distribution of relativistic electrons with energy \( E \) and uniform magnetic field, we develop the steps necessary to obtain \( P_\nu(\nu, E) \). We consider the analysis presented in Ref. [6]. First we have that:
\[ P_\nu(\nu, E, \alpha) = \frac{\sqrt{3}e^3 B \sin \alpha F(x)}{m_e c^2}, \]
(4.3)
with \( x = \nu/\nu' \), \( \nu' = \nu_c \sin \alpha/2 \) and \( \nu_c = 3eB\gamma^2/(2\pi m_e c) \), \( e \) denotes the electric charge, \( B \) is the magnetic field, \( c \) is the velocity of light, \( \gamma \) is the Lorentz factor, related to the energy of a single electron by \( E = \gamma m_e c^2 \) and \( F(x) \) is given by
\[ F(x) = x \int_x^\infty K_{5/3}(x')dx', \]
(4.4)
where \( K_n \) the modified Bessel function of the second kind and order \( n \). As the next step we need to average the randomly oriented magnetic field over the pitch angle \( \alpha \) and after, we can express \( P_\nu(\nu, E) \) as:
\[ P_\nu(\nu, E) = \frac{1}{2} \int_0^\pi d\alpha \sin \alpha P_\nu(\nu, E, \alpha), \]
(4.5)
and finally we have
\[ P_\nu(\nu, E) = 2\sqrt{3}e^3 B \left[ \frac{e^3}{m_e c^2} y^2 \left( K_{1/3}(y)K_{1/3}(y) - \frac{3}{5} y \left( K_{4/3}(y) - K_{1/3}(y) \right) \right) \right], \]
(4.6)
where \( y = \nu/\nu_c \). The term \( \frac{dn_e}{dE}(E, r) \) in the eq. (4.2) is the electron equilibrium spectrum.

In an astrophysical medium, the diffusion and energy losses modify the injection spectrum from DM annihilation or decay. In the end, all of these mechanisms should be taken into account and the electron equilibrium spectrum is obtained from the diffusion equation
\[ \frac{\partial}{\partial t} \frac{dn_e}{dE} = \nabla \left[ D(E, r) \nabla \frac{dn_e}{dE} \right] + \frac{\partial}{\partial E} \left[ b_{\text{loss}}(E, r) \frac{dn_e}{dE} \right] + Q(E, r), \]
(4.7)
where \( Q(E, r) \) is the source term, \( D(E, r) \) is the coefficient for spatial diffusion and \( b_{\text{loss}} \) is the loss term. If we neglect the diffusion coefficient term, we have
\[ \frac{dn_e}{dE}(E, r) = \frac{\langle \sigma v \rangle \rho(\mathbf{r})^2}{2m_{DM}^2 b_{\text{loss}}(E, r)} \int_E^{m_{DM}} dE' \frac{dN}{dE'_{\text{inj}}}, \]
(4.8)
where \( \langle \sigma v \rangle \) denotes de annihilation cross section, \( \rho(\mathbf{r}) \) is the spatial distribution of DM, \( m_{DM} \) is the mass of DM candidate, \( b_{\text{loss}} \) is the energy loss term and \( dN/dE'_{\text{inj}} \) is part of the

\[ \text{We note that reference [42] considers a series approach for } F(x). \text{ In their approximation, } s = x/\alpha \text{ and } F(s) \approx 1.25s^{3/2} \exp(-s)[648 + s^2]^{1/2}. \]
source term which relates the electron injection spectrum from DM annihilations. We took $dN/dE_{\text{inj}}$ from ref. [6], it can be also obtained from packages presented in refs. [43, 44]. The source term is expressed by:

$$Q(E, r) = \langle \sigma v \rangle \rho(r)^2 \frac{dN}{dE_{\text{inj}}};$$

(4.9)

The energy loss term is given by

$$b_{\text{loss}}(E, r) = b_{\text{syn}} + b_{\text{IC}} + b_{\text{brem}} + b_{\text{coul}}$$

(4.10)

where the terms $b_{\text{syn}}$, $b_{\text{IC}}$, $b_{\text{brem}}$ and $b_{\text{coul}}$ denote the loss by synchrotron radiation, inverse Compton scattering, bremsstrahlung and Coulomb interactions, respectively.

Since we are working with GCs in the galaxy, in energies below $\sim 5$ GeV, ionization and bremsstrahlung dominate. At higher energies Compton and synchrotron processes dominate [45].

The energy loss due to all these processes can be expressed by [42].

$$b_{\text{loss}}(E, r) \approx 0.0254 \left( \frac{E}{1\text{GeV}} \right)^2 \left( \frac{B(r)}{1\mu\text{G}} \right)^2 + 0.25 \left( \frac{E}{\text{GeV}} \right)^2$$

$$+ 1.51n(0.36 + \log(\gamma/n)) + 6.13n(1 + \log(\gamma/n)/75.0),$$

(4.11)

where this loss term has units of $10^{-16} \text{ GeV/s}$, $E = \gamma m_e c^2$, $B$ denotes the magnetic field, which we consider as $10 \mu\text{G}$ in all of our analysis. In our simulations $n$ denotes the number of free electrons which corresponds to the density of ionized gas. Here we have considered $n = 1 \times 10^{-3} \text{ cm}^{-3}$. For GCs, some authors also consider the gas density expressed as an exponential profile $n = n_0 \exp(-r/r_D)$, where $n_0$ is the initial gas density [46].

5 Numerical Results

In this section we present the numerical results for synchrotron emission theoretically predicted by our calculations for the GCs 47 Tuc, NGC 6266 and $\omega$ Cen, assuming a DM candidate with $m_{\text{DM}} = 34$ GeV annihilating into a $b\bar{b}$ channel. When solving the diffusion-loss differential equation, we assume that the cooling time scale of high energy electrons and positrons is much smaller than their diffusion scale, so that the diffusion term in Eq. (4.7) can be neglected.

For illustration, in Figure 1, we show the behavior of DM spike density profile for 47 Tuc considering two situations. Spike-1 denotes the parameters we used to fit the radio spectrum of this GC using the existing experimental limits and upper bounds on 47 Tuc. Spike-2 denotes a best-fit scenario of $\gamma$-rays presented by [16], where $\langle \sigma v \rangle = 6 \times 10^{-30} \text{ cm}^3/\text{s}$. The spikes are formed with the typical radius of influence of the BH, $R_{\text{sp}} = GM_{\text{BH}}/\sigma_*^2$. Out of the region of influence, the density goes as $\rho \propto r^{-5}$.

Taking the set of parameters described in Table 1 together with those described in Section 4, in order to fit the radio spectrum with a DM candidate annihilating in $b\bar{b}$ with $m_{\text{DM}} = 34$ GeV, we find that $\langle \sigma v \rangle$ must be $\sim 5 \times 10^{-37} \text{ cm}^3/\text{s}$.

In Table 2, we give the numerical values for the three GCs. We had obtained these values with the set of parameters described in Table 1 and in Section 4. In order to fit the
Figure 1: The figure shows the spike density profile created around the IMBH. We present here two scenarios, shown in orange (Spike-1) and dashed-red (Spike-2). The spikes are formed within the radius of influence of the BH ($R_{sp}$) of the globular cluster 47 Tuc. We take $m_{DM} = 34$ GeV, $\langle \sigma v \rangle = 5 \times 10^{-37} \text{ cm}^3/\text{s}$ for Spike-1 and $\langle \sigma v \rangle = 6 \times 10^{-30} \text{ cm}^3/\text{s}$ for Spike-2 scenario.

radio spectrum with a DM candidate annihilating in $b\bar{b}$ with mass $m_{DM} = 34$ GeV, for $\omega$ Cen, we find that $\langle \sigma v \rangle$ must be $\sim 6 \times 10^{-36} \text{ cm}^3/\text{s}$; for NGC 6266 $\langle \sigma v \rangle$ must be $\sim 8 \times 10^{-38} \text{ cm}^3/\text{s}$.

|                      | 47 Tuc | $\omega$ Cen | NGC 6266 |
|----------------------|--------|--------------|-----------|
| $R_a$ (pc)           | 56.7   | 55.1         | 30.7      |
| $R_s$ (pc)           | $2.19 \times 10^{-10}$ | $4.76 \times 10^{-9}$ | $1.90 \times 10^{-10}$ |
| $R_{sp}$ (pc)        | $9.84 \times 10^{-2}$ | 2.14         | $3.79 \times 10^{-2}$ |
| $\rho_{sat}$ (GeV/cm$^3$) | $1.83 \times 10^{20}$ | $1.55 \times 10^{19}$ | $1.14 \times 10^{21}$ |
| $\langle \sigma v \rangle$ (cm$^3$/s) | $5 \times 10^{-37}$ | $6 \times 10^{-36}$ | $8 \times 10^{-38}$ |

Table 2: The parameter $R_a$ denotes the radial extension of the globular cluster used in the integration of Eq. 4.1, $R_s$ denotes the Schwarzschild radius, $R_{sp}$ is radius of influence of the BH, $\rho_{sat}$ denotes saturation density for the BH in the globular clusters, and $\langle \sigma v \rangle$ represents the annihilation cross section. The $\langle \sigma v \rangle$ values are determined so that the radio flux predicted by the model does not exceed the observational limits inferred for each GC.
The expected flux from DM as a function of frequency for the GCs. Our DM candidate has mass $m_{DM} = 34$ GeV and annihilates in $b\bar{b}$. We had considered $\langle \sigma v \rangle \sim 5 \times 10^{-37}$ cm$^3$/s for 47 Tuc, $\langle \sigma v \rangle \sim 6 \times 10^{-36}$ cm$^3$/s for ω Cen and $\langle \sigma v \rangle \sim 8 \times 10^{-38}$ cm$^3$/s for NGC 6266. The GCs have observational upper limits taken from radio continuum observations on the frequency 5 GHz (see [23]). The straight line on 5 GHz indicates the 3σ-upper limits whose values are: 40 µJy for 47 Tuc, 20 µJy for ω Cen and 36 µJy for NGC 6266. For comparison only, we have included the measured flux densities of 47 Tuc X9. This source is near to the center of 47 Tuc and the data are available at 5.5 GHz and 9 GHz [47].

In order to constrain the radio fluxes, we need to theoretically calculate their signal and estimate the sensitivity of the existing radio surveys to diffuse emission from these GCs. For the experimental values of radio flux, we had considered the data of Ref. [23, 36]. In Figure 2 we give the expected flux from DM annihilation as a function of frequency for the 47 Tuc, ω Cen and NGC 6266. Radio surveys of GCs have produced only upper limits for the flux density, the latest data being mainly derived by [23] through observations supported by the Australia Telescope Compact Array (ATCA). The upper limit flux densities at 5 GHz are presented in Fig. 2 and the values for $\langle \sigma v \rangle$ were chosen to respect these constraints.

For comparison, we present the recent measurements for the 47 Tuc X9 source [47]. This source possesses a double-peaked C IV emission line in its ultraviolet spectrum, an indicative of matter accretion. Although it was initially classified as a cataclysmic variable, the results of [47] show that the spectral density is proportional to $\nu^{-0.4\pm0.4}$ and may indicate that X9 is a black hole accreting matter. The measurements for 47 Tuc X9 at 5.5 GHz and 9 GHz are just above our estimated radio spectrum for 47 Tuc.

In examining the individual radio flux densities, we see that the dark matter annihilation
cross section is much smaller than the one inferred from 47 Tuc \( \gamma \)-ray flux. Through the observed upper limits, \( \langle \sigma v \rangle \) must be within the range \( \sim 10^{-35} - 10^{-37} \text{cm}^3/\text{s} \) for the \( b\bar{b} \) channel with \( m_{DM} = 34 \text{ GeV} \). We normalized the spike profile similarly to the one derived by \cite{16}, so that an increase in the cross section to approximate the gamma–radio signatures should be accompanied by a decrease in the amount of dark matter in the spike’s influence region.

All of these results can change in order of magnitude if we consider for instance, the diffusion term in the diffusion-loss differential equation. In this case, the radio flux can be reduced and the soft cutoff of the signal decreases faster for lower frequencies when compared to the situation where diffusion term was neglected. Different magnetic field configurations, gas density and annihilation cross section, as well as the dark matter mass can also change our results. However, even exploiting the parameter space defined by these variables, it is not possible to obtain signatures that are consistent with the observational radio limits when we use, e.g., \( \langle \sigma v \rangle \sim 10^{-30} \text{ cm}^3/\text{s} \) for 47 Tuc.

6 Final Remarks

We give here the results we obtained for the radio flux of three GCs, namely, 47 Tuc, \( \omega \) Cen and NGC 6266 and the constraints for these signals obtained from radio observations. In particular, to study the fluxes we had considered an enhanced DM spike density profile, modeled for explaining the observed \( \gamma \)-ray flux of 47 Tuc \cite{16} and further extended our analyses for other two GCs. We find that the annihilation cross section \( \langle \sigma v \rangle \) used to explain the observed \( \gamma \)-ray spectrum of 47 Tuc is much too high to agree with the continuum radio observations of 47 Tuc. For this GC, our simulations indicate that \( \langle \sigma v \rangle \sim 5 \times 10^{-37} \text{ cm}^3/\text{s} \) would be in agreement with the radio surveys. We have here assumed that the DM population is dominant over the MSP population in producing the \( \gamma \)-ray and radio emission.

In considering a spike profile motivated to fit \( \gamma \)-ray flux of 47 Tuc, we have assumed the popular scenario of a 34 GeV DM candidate annihilating into a \( b\bar{b} \) channel. We have also investigated the possibility of probing DM in the inner part of two other GCs containing IMBHs, exploring the ranges of most important parameters used in determining synchrotron flux.

Although we have performed a simplified analysis, neglecting the diffusion terms in our calculations and considering a fixed magnetic configuration, we have shown that the spike profile studied here can leave strong signatures for the synchrotron flux from GCs. In the future it would be interesting to investigate other channels for dark matter annihilation or decay, exploring different values for \( m_{DM} \) and simultaneously, taking account of the inferred \( \gamma \)-ray and radio constraints.

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