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Formation of massive globular clusters with dark matter and its implication on dark matter annihilation

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ABSTRACT

Recent observational studies of γ-ray emission from massive globular clusters (GCs) have revealed possible evidence of dark matter (DM) annihilation within GCs. It is, however, still controversial whether the emission comes from DM or from millisecond pulsars. We here present the new results of numerical simulations, which demonstrate that GCs with DM can originate from nucleated dwarfs orbiting the ancient Milky Way. The simulated stripped nuclei (i.e. GCs) have the central DM densities ranging from 0.1 to several $\mathrm{M_{\odot}\,pc^{-3}}$, depending on the orbits and the masses of the host dwarf galaxies. However, GCs born outside the central regions of their hosts can have no/little DM after their hosts are destroyed and the GCs become the Galactic halo GCs. These results suggest that only GCs originating from stellar nuclei of dwarfs can possibly have DM. We further calculate the expected γ-ray emission from these simulated GCs and compare them to observations of ω Cen. Given the large range of DM densities in the simulated GCs, we suggest that the recent possible detection of DM annihilation from GCs should be more carefully interpreted.

Key words: globular clusters: general – globular clusters: individual: Omega Centauri – dark matter.

1 INTRODUCTION

The Galactic globular cluster (GC) ω Cen has a number of very unique characteristics, such as the very large mass (e.g. Meylan et al. 1995), retrograde orbits (e.g. Dinescu, Girard & van Altena 1999), and multiple distinct subpopulations (e.g. Bellini et al. 2018). These unique properties have been investigated both observationally and theoretically (e.g. Meylan & Mayor 1986; Watkins et al. 2013; Baumgardt et al. 2019). Recent observations detected γ-ray emission from massive GCs like ω Cen and 47 Tucanae (Abdo et al. 2010; Dai et al. 2020). The source of this γ-ray emission is still subject to debates. The most popular hypotheses include the presence of millisecond pulsars (Abdo et al. 2010; Dai et al. 2020) and dark matter (DM) annihilation (Gaskins 2016; Brown et al. 2019). For a direct comparison of the two possibilities, see Reynoso-Cordova et al. (2019). If the source of the γ-rays is DM, then the question would be: Where did the DM come from?

It has been suggested that nucleated dwarf galaxies can be transformed into massive GCs like ω Cen and ultra-compact dwarfs (UCDs) due to tidal stripping of the dwarfs by the strong gravitation field of their host environments (‘galaxy threshing’; Bekki, Couch & Drinkwater 2001; Bekki & Freeman 2003, hereafter BF03). In particular, ω Cen has been proposed to be the tidally stripped nucleus of a dwarf galaxy (BF03). This is further supported by its density profile (Ideta & Makino 2004). However, previous simulations did not include a DM halo (Ideta & Makino 2004), which is known to exist in dwarf galaxies (Kormendy & Freeman 2004, 2016; Das et al. 2020). Therefore, if ω Cen is the nucleus of a tidally stripped dwarf, could there be any DM be left over from the progenitor galaxy? Similar suggestions have been made to explain the elevated mass to luminosity ratio in UCDs (Chilingarian et al. 2011). Dark stellar clusters around Centaurus A are also believed to be remnants of a stripped dwarf (Bovill et al. 2016).

The purpose of this paper is to investigate how much DM can be left in the stripped stellar galactic nuclei that can be progenitors of massive GCs. To this end, we run a set of simulations of dwarfs with different initial parameters on different orbits around the Milky Way (MW). We also calculate the *J*-factor resulting from our final DM distribution and discuss whether or not the observed flux of γ-ray emission in ω Cen can be really explained by annihilation of DM gravitationally trapped by the GC.

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2 THE MODEL

2.1 Nucleated dwarfs orbiting the Galaxy

The present code for direct *N*-body simulations of nucleated dwarf galaxies is essentially the same as the one used in Bekki & Tsujimoto (2016, hereafter BT16) in which the dynamical evolution of GCs in a dwarf galaxy orbiting the Galaxy is investigated. Since the details of the simulation code are given in BT16, we here briefly describe the code. It should be stressed here that the adopted code does not allow us to investigate how gas and star formation can control the evolution of interacting dwarfs and stellar nuclei that were investigated in our other works (e.g. Bekki 2007; Bekki & Chiba 2007; Bekki, Diaz & Stanley 2019). The DM halo with the total mass of $M_{\rm h}$ in a nucleated dwarf galaxy is represented by the 'NFW' one (Navarro, Frenk & White 1996) with a central cusp predicted by the cold dark matter model:

$$\rho(r) = \frac{\rho_0}{(r/r_{\rm s})(1+r/r_{\rm s})^2}, \quad (1)$$

where r, ρ_0, and $r_{\rm s}$ are the distance from the centre of the cluster, the central density, and the scale length of the dark halo, respectively. The virial radius ($r_{\rm vir}$), the scale radius ($r_{\rm s}$), and the 'c' parameter ($=r_{\rm vir}/r_{\rm s}$) are chosen such that the values are consistent with recent cosmological simulations for the adopted $M_{\rm h}$ (Neto et al. 2007).

In order to estimate the total mass and density of DM in the stripped stellar nuclei ($R < 100$ pc) in a much better way, we here adopt the following original set-up for the dwarf's DM halo: We first divide the DM halo into two regions with $R \geq 100$ pc ('outer') and $R < 100$ pc ('inner') and use a particle mass ($m_{\rm dm}$) of only 0.02 times that of the outer particles and a factor of 50 shorter time-step width (Δt) for the inner halo. The details of this new method will be described extensively in a forthcomming paper. Here, we investigate models (labelled as S1, etc.) in which $m_{\rm dm} = 200$ M$_\odot$ and $\Delta t = 10^4$ yr were adopted for the inner halo, so that we can resolve the inner 10 pc scale dynamical evolution of nucleated dwarf galaxies.

The nucleated dwarf is assumed to be as a bulge-less disc galaxy with the total stellar mass of $M_{\rm s}$ and the size of $R_{\rm s}$. The radial (R) and vertical (Z) density profiles of the stellar disc are assumed to be proportional to $\exp(-R/R_0)$ with scale length $R_0 = 0.2R_{\rm s}$ and to ${\rm sech}^2(Z/Z_0)$ with scale length $Z_0 = 0.04R_{\rm s}$, respectively. The initial radial and azimuthal velocity dispersions are assigned to the disc component according to the epicyclic theory with Toomre's parameter $Q = 1.5$. The stellar disc is assumed to have a stellar nucleus with a mass of $M_{\rm nuc}$ and a 5× scale radius of $R_{\rm nuc}$. The nucleus is represented by a Plummer model with the free parameters $M_{\rm nuc}$ and $R_{\rm nuc}$. Our dwarf galaxy models have $M_{\rm dm} = 10^{10}$ M$_\odot$, $M_{\rm s} = 1.2 \times 10^8$ M$_\odot$, $R_{\rm s} = 1.3$ kpc, and mostly $M_{\rm nuc} = 10^7$ M$_\odot$ and $R_{\rm nuc} = 30$ pc, which is reasonable for the formation of massive GCs from nucleated dwarfs (e.g. BF03; Bekki & Yong 2012). The mass resolutions (and softening lengths) of the disc and stellar nucleus are 1200 (18.4) and 1000 M$_\odot$ (0.3 pc), respectively.

2.2 The MW model

We investigated the 'young' MW models rather than the 'present-day' ones (BT16) to discuss the formation of massive GCs from stripped nuclei of dwarfs. The Galaxy in the present MW models is assumed to have a *fixed* three-component gravitational potential and the following logarithmic DM halo potential is adopted for the Galaxy:

$$\Phi_{\rm halo} = v_{\rm halo}^2 \ln(r^2 + d^2), \quad (2)$$

where $d = 12$ kpc, $v_{\rm halo} = 93$ km s^{-1} (instead of 131.5 km s^{-1} suitable for the present-day Galaxy), and r is the distance from the centre of the Galaxy. The gravitational potential of the Galactic disc is represented by a Miyamoto–Nagai potential (Miyamoto & Nagai 1975):

$$\Phi_{\rm disc} = -\frac{GM_{\rm disc}}{\sqrt{R^2 + (a + \sqrt{z^2+b^2})^2}}, \quad (3)$$

where $M_{\rm disc} = 1.0 \times 10^{10}$ M$_\odot$ (instead of 1.0×10^{11} M$_\odot$ for the present-day Galaxy), $a = 6.5$ kpc, $b = 0.26$ kpc, and $R = \sqrt{x^2+y^2}$. The following spherical Hernquist (1990) model is adopted for the potential of the Galactic bulge:

$$\Phi_{\rm bulge} = -\frac{GM_{\rm bulge}}{r+c}, \quad (4)$$

where $M_{\rm bulge} = 3.4 \times 10^{10}$ M$_\odot$ and $c = 0.7$ kpc.

To investigate how much DM can be left in the stripped nucleus, we take the following steps: First, we evolve the dwarf through relaxation only (no tidal field) for 1.41 Gyr, and then we expose the dwarf to the tidal field of the young MW, where it is stripped. We investigate dwarfs with different initial orbital velocities, dwarf positions, $M_{\rm nuc}$, and DM properties of dwarf galaxies. The orbits of the dwarfs with respect to the Galactic disc have an inclination (i) of 30 or 60 deg, and the stellar discs are inclined by 45 deg with respect to the orbital planes. Although we mainly investigate 'standard' models (labelled as 'S') with $R_{\rm vir} = 17.9$ kpc and $c = 16$ for DM, we also investigate 'low-density' models ('L') with $R_{\rm vir} = 17.9$ kpc and $c = 8$. Furthermore, we investigate model S11_O with a GC 200 pc outside of the dwarf's centre of mass (COM) and several models with a GC 500 pc away from the COM. We will add an '_O' to the label of those models.

2.3 Estimation of γ-ray flux from DM annihilation in stripped nuclei

Based on the mass and the density of DM in a stripped nucleus, we estimate the expected γ-ray emission stemmed from DM annihilation using the CLUMPY code (Hütten, Combet & Maurin 2019). To this end, we calculate the J-factor that is the integral of the squared DM density along a line of sight over the cone with a solid angle $\Delta\Omega$:

$$J(\Delta\Omega) = \int_{\Delta\Omega} {\rm d}\Omega \int_{\rm l.o.s} {\rm d}\ell \rho_{\rm DM}^2(r(\ell, \Omega)), \quad (5)$$

where ℓ is the line-of-sight coordinate. Under the spherical symmetry assumption, we can rewrite $\Delta\Omega$ as $\Delta\Omega = 2\pi \sin\theta \, {\rm d}\theta$, where θ is the angular radius from the centre of the object, and $r(\ell, \Omega) = \sqrt{\ell^2 + d^2 - 2\ell d \cos\theta}$, where d is the distance from the Sun ($d = 5.4$ kpc for ω Cen). Taking the value of $\rho_{\rm DM}$ listed in the last column of Table 1, we perform the integration over an angular radius $\Delta\Omega = 0.7°$. For the estimation of the γ-ray energy spectrum, we adopt DM particle mass $m_{\rm DM} = 31.4$ GeV estimated by Brown et al. (2019) and the velocity-averaged annihilation cross-section $\log_{10}(\langle\sigma v\rangle) = -27.3$ [cm^3 s^{-2}], which is consistent with the upper limit on the cross-section derived from a stacked analysis of dwarf spheroidal galaxies by *Fermi*-LAT data (e.g. Ackermann et al. 2015; Hayashi et al. 2016). We will use the following definitions: $F_{\rm DM} = M_{\rm DM}/M_{\rm nuc}$ and $F_{\rm s} = M_{\rm s}/M_{\rm nuc}$ and consider nuclei with $F_{\rm s}(R < 30\ {\rm pc}) < 0.1$ to be stripped.

Table 1. The physical properties of the simulated stripped nuclei (and GCs) at $T = 2.82$ Gyr. As described in Section 2.1, we label our standard models with ‘S’, our low-density models with ‘L’, and we add an ‘_O’ if the model has an off-centre nucleus.

ID	$M_{\rm nuc}$ ($\times 10^6$ M$_\odot$)	$R_{\rm nuc}$ (pc)	$R_{\rm ini}$ (kpc)	$R_{\rm peri}$ (kpc)	i (°)	$R < 30$ pc: $F_{\rm DM}$ ($\times 10^{-3}$)	$F_{\rm s}$ ($\times 10^{-3}$)	$\rho_{\rm DM}$ (M$_\odot$ pc^{-3})	$R < 100$ pc: $F_{\rm DM}$ ($\times 10^{-3}$)	$F_{\rm s}$ ($\times 10^{-3}$)	$\rho_{\rm DM}$ (M$_\odot$ pc^{-3})
S1	10.0	30.0	17.50	2.0	60	15.4	0.0	1.66	61.3	2.3	0.23
S2	30.0	50.0	35.00	8.5	60	17.3	0.1	5.08	118.9	5.2	1.34
S3	10.0	30.0	8.75	3.0	60	14.5	0.0	1.49	42.1	2.8	0.15
S4	1.0	30.0	17.50	7.0	60	13.6	4.0	0.19	67.3	40.5	0.03
S5	1.0	30.0	35.00	6.0	60	85.4	48.8	1.22	2888.2	1432.9	1.20
S6	10.0	30.0	17.50	2.5	60	15.4	0.0	1.66	61.3	2.3	0.23
S7	10.0	30.0	17.50	2.0	30	13.8	0.0	1.33	43.8	2.3	0.14
L8	10.0	30.0	17.50	2.0	60	4.5	0.0	0.47	21.5	4.8	0.08
S9	10.0	30.0	8.75	2.0	30	13.0	0.6	1.33	81.4	13.2	0.27
L10	10.0	30.0	8.75	1.0	60	4.5	0.0	0.45	14.0	1.0	0.05
S11_O	1.0	30.0	17.50	7.0	60	0.5	6.9	0.01	45.9	89.6	0.02
S12	10.0	30.0	5.25	5.0	30	19.8	1.4	1.05	308.5	52.2	0.47
S13_O	1.0	30.0	17.50	7.0	60	11.7	5.4	0.16	33.4	53.7	0.01
S14_O	30.0	50.0	17.50	2.0	60	0.6	0.0	0.17	5.3	0.6	0.06
S15_O	10.0	30.0	17.50	0.5	60	0.0	0.0	0.00	3.6	1.8	0.01
S16_O	30.0	50.0	35.00	9.0	60	0.0	0.2	0.01	30.6	8.6	0.33
S17	0.1	10.0	17.50	7.0	60	121.4	2756.9	0.18	4058.0	45882.6	0.17
S18	10.0	30.0	17.50	3.0	60	12.8	0.0	1.35	56.0	1.5	0.21

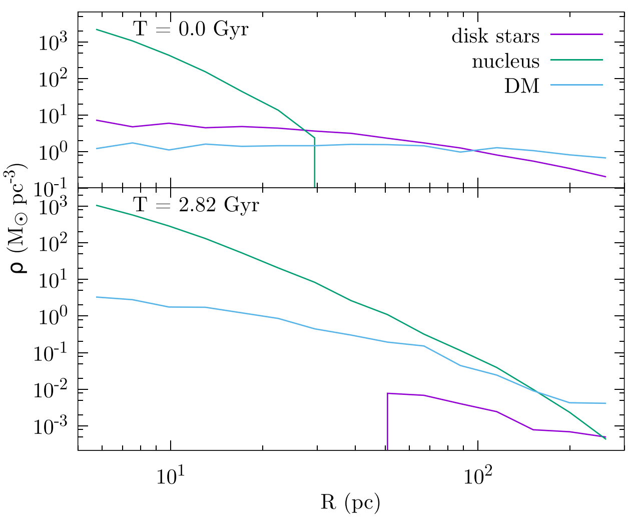

Figure 1. The radial mass density profile of disc stars (purple), nucleus stars (green), and DM (blue) of model S1 at $T = 0.0$ Gyr (upper panel) and $T = 2.82$ Gyr (lower panel). The sudden cut-off for the nucleus in the upper panel is a binning effect.

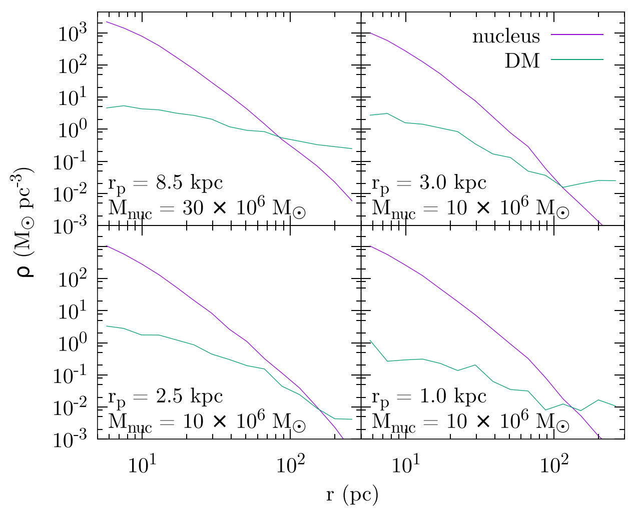

Figure 2. The radial density profiles of different models at $T = 2.82$ Gyr. From the top left to the bottom right: S2, S3, S6, and L10.

3 RESULTS

Fig. 1 shows how the radial density profiles of DM, stellar disc, and nucleus evolve with time during tidal disintegration of the dwarf in the model S1 with $M_{\rm nuc} = 1 \times 10^7$ M$_\odot$ and $R_{\rm peri} = 2$ kpc. In this model, we saw a strong decrease of $F_{\rm s}(R < 30\,{\rm pc})$ from 4.92×10^{-2} to 0.0 within the first 2.82 Gyr. However, if we look at the stellar density of the disc between 40 and 50 pc, we notice that it is only $\approx 10^{-2}$ M$_\odot$ pc^{-3}. With this, we would expect only 0.9 stars within the central 40 pc. Therefore, the sudden cut-off is likely to be caused by the low mass resolution. Nevertheless, this nucleus is considered stripped, according to our definition. The DM is dynamically relaxed under the presence of the disc in isolation for 1 Gyr (before the dwarf model is run). The flattened profile seen in the upper plane is due to this dynamical evolution consistent with Pasetto et al. (2010) and Oh et al. (2015). Meanwhile, $F_{\rm DM}(R < 30\,{\rm pc})$ decreased from 1.63×10^{-2} to 1.54×10^{-2} and to 1.12×10^{-2} during the following 2.82 Gyr. The absolute DM density within 30 pc decreases from 2.57 to 1.66 M$_\odot$ pc^{-3} and $F_{\rm DM}(R < 100\,{\rm pc})$ decreases from 0.50 to 0.06 during this time. Only the lighter inner DM particles were found within 100 pc after evolution. Mass segregation can therefore not be the cause for the remaining DM.

A compilation of density profiles for different models at $T = 2.82$ Gyr can be seen in Fig. 2. An important observation here is that the DM profile steepens again after being exposed to the tidal field of the young MW. It becomes dominant compared to stars close to the COM and we also find more DM than stars in the inner region at $T = 5.64$ Gyr. We can see that the central density is lower

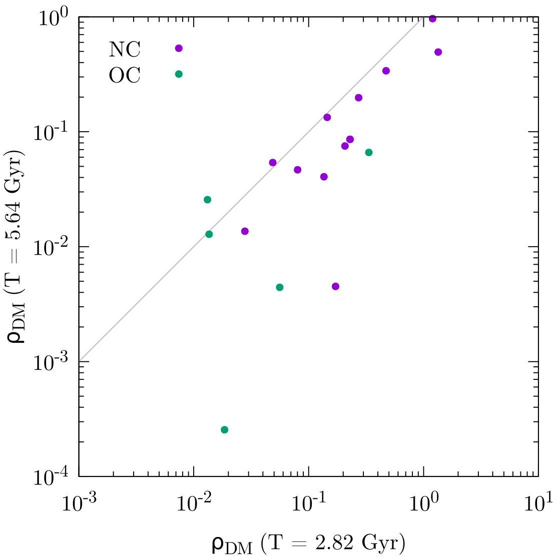

Figure 3. The average DM density (in $M_\odot\ pc^{-3}$) within the inner 100 pc at $T = 5.64$ Gyr over the DM density at $T = 2.82$ Gyr. The identity is shown in grey.

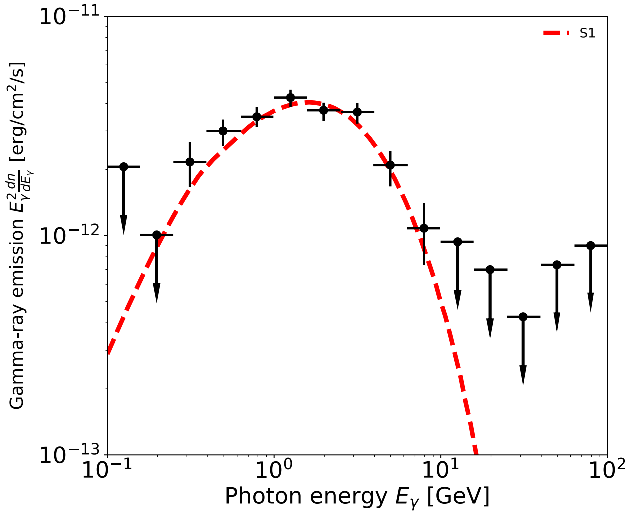

Figure 4. The γ-ray spectrum of simulated data from model S1 (red line) and compared to observations of ω Cen (black dots). The observational data are taken from Brown et al. (2019) who integrated the data from Fermi-LAT Collaboration (2020) over 10 yr.

for lower pericentres, which we will discuss further in the following paragraph.

A compilation of model properties at $T = 2.82$ Gyr can be seen in Table 1. One result is that the DM density around the nucleus is smaller for models with a smaller pericentre. This is due to the tidal forces being stronger closer to the centre of the MW. In S5, tidal stripping is weaker, because of its large $R_{\rm ini}$. Theoretically, we would expect that heavier nuclei are able to retain more DM. While no such correlation could be found, we cannot exclude it due to our small number of models. Apart from models S11_O and S15_O, all the models show a higher average DM density within the inner 30 pc and then within a 100 pc radius around the COM. This points to there still being non-stripped DM in the nucleus.

The two low-density models L8 and L10, with smaller NFW c parameter (=8), show a significantly lower final DM density ($R < 30$ pc) than the standard model, with $c = 16$ but otherwise similar parameters. This implies that there is a dependence between the initial and the final DM density. In most of the models with off-centre GCs, disc stars and DM are stripped rapidly. This leads to a DM density of less than 0.2 $M_\odot\ pc^{-3}$ within the central 30 pc and only a few hundredths of $M_\odot\ pc^{-3}$ within the central 100 pc after 2.82 Gyr. This result can be understood easiest by viewing the nucleus as being stripped from the galaxy due to its large distance from the dwarf's COM and the lack of time for it to spiral in due to dynamic friction. In S16_O, the massive GC can spiral into the central region before the disintegration of its host dwarf, because the pericentre is quite large and thus tidal stripping is significantly weaker.

Fig. 3 shows a comparison of the DM densities at two different times. Most of the points are below the identity, which means that models in general lose DM slowly due to tidal stripping during the long-term dynamical evolution of the nuclei. Again, we can see that the models with an off-centre GC instead of a nucleus have on average far less DM than the other models. The exception to this is again S16_O, which is visible as the green point at 0.3.

Fig. 4 shows the γ-ray energy spectrum calculated from DM annihilation via the $b\bar{b}$ channel in the case of model S1. In this case, the estimated J-factor value is $J(0.7^\circ) = 1.78 \times 10^{22}$ GeV^2 cm^{-5}. Comparing with the observed energy flux of ω Cen based on *Fermi*-LAT data (visible as dots in the Fig. 4; Brown et al. 2019; Fermi-LAT Collaboration 2020), S1 can explain the observed γ-ray emissions from DM annihilation. To estimate the size and mass, we choose a cut-off density of 10 $M_\odot\ pc^{-3}$. This gives us a radius of 30 pc and a mass of $6.8 \times 10^6\ M_\odot\ pc^{-3}$. This mass is a little below the highest estimate found in the literature for ω Cen's mass of $7.13 \times 10^6\ M_\odot$ (Richer et al. 1991). However, other sources give significantly lower values, i.e. $4.55 \times 10^6\ M_\odot$ (D'Souza & Rix 2013). Additionally, the small pericentre distance of S1 is consistent with corresponding observations. Although S2 shows a high central density of DM in the GC, its $R_{\rm peri}$ is too large for ω Cen. This could be a good model for the outer Galactic GCs with DM. S6, S7, and S9 also show high DM densities ($\approx 1.5\ M_\odot\ pc^{-3}$ within 30 pc and $\approx 0.2\ M_\odot\ pc^{-3}$ within 100 pc) and small $R_{\rm peri}$ so that they can be the reasonable model for ω Cen.

However, not all of the present models show the required high-density DM within the GCs, because the final DM densities within the central 30 pc depend on the model parameters. For example, S4, which has a low $M_{\rm nuc}$, shows $\rho_{\rm dm}$ of 0.19 $M_\odot\ pc^{-3}$, which means that the γ-ray emission from DM annihilation should be too weak owing to the dependence of the emission flux on the DM density squared. Similarly, the low-density models and the models with an off-centre GC instead of a nucleus show a very low final DM density. Thus, the large range of the DM densities in simulated massive GCs suggests that (i) the observed fluxes of γ-ray emission from 47 Tuc and ω Cen could be possibly explained by GC formation from stripped nuclei but (ii) it is also possible that the DM density in GCs is not high enough to reproduce the observed γ-ray emission if they originate from dwarfs with lower DM densities.

4 DISCUSSION AND CONCLUSION

We have shown that massive GCs like ω Cen can still contain a significant amount of DM, if they originate from nuclei of massive dwarf galaxies. Also, we have shown that GCs formed well outside the central regions of their host dwarfs can have no DM after they are stripped from the host, even if they are massive at their birth. We therefore suggest that the formation sites of GCs in their hosts rather than their original masses can determine whether they can contain DM thus be sources of γ-ray emission from DM annihilation.

A number of the Galactic GCs are observed to have large stellar haloes (e.g. Carraro, Zinn & Moni Bidin 2007; Olszewski et al. 2009), and recent numerical simulations have shown that these stellar haloes can be explained, if the GCs are stripped nuclei of defunct dwarf galaxies (Bekki & Yong 2012). These previous studies combined with the present results therefore suggest that there can be other possible candidates of GCs with DM. On the other hand, Baumgardt et al. (2009) found no evidence for the presence of substantial DM in NGC 2419. How common DM is in GC remains therefore up for debate. Since these clusters are not so close to us, the future Cherenkov Telescope Array will be ideal to detect the γ-ray signals of DM annihilation from these clusters.

Although we have demonstrated that the observed γ-ray flux in ω Cen is consistent with the threshing formation scenario, it is yet to be determined whether the γ-ray observation can be explained better by DM annihilation or by millisecond pulsars. One way to distinguish between the two competing scenarios is to observe ω Cen in radio wavelengths (e.g. Brown et al. 2019). It is thus our future study to investigate the expected radio properties of massive GCs with a significant amount of DM like ω Cen based on our dynamical models.

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