DARK MATTER MASS LOSS IN GALAXY FLYBYS: DEPENDENCE ON IMPACT PARAMETER

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SUMMARY: Galaxy flybys, interactions where two independent halos inter-penetrate but detach at a later time and do not merge, occur frequently at lower redshifts. These interactions can significantly impact the evolution of individual galaxies - from mass loss and shape transformation to the emergence of tidal features and the formation of morphological disc structures. The main focus of this paper is on the dark matter mass loss of the secondary, intruder galaxy, with the goal of determining a functional relationship between impact parameter and dark matter mass loss. Series of N-body simulations of typical galaxy flybys (10:1 mass ratio) with differing impact parameters show that dark matter halo leftover mass of intruder galaxy follows logarithmic growth law with impact parameter, regardless of the way total halo mass is estimated. Lost mass then, clearly, follows exponential decay law. Stellar component stretches faster as impact parameter decreases, following exponential decay law with impact parameter. Functional dependence on impact parameter decreases, following exponential decay law with impact parameter. Interaction parameters and initial conditions (e.g. mass ratio of interacting galaxies, the initial relative velocity of intruder galaxy, interaction duration). While typical flybys, investigated here, could not be the sole culprit behind the formation of ultra-diffuse or dark matter deficient galaxies, their effects should not be disregarded as they can at least contribute substantially. Rare, atypical and stronger flybys are worth exploring further.

Key words. Galaxies: interactions – Galaxies: evolution – Methods: numerical

1. INTRODUCTION

Galaxy flybys are interactions where two independent halos inter-penetrare but detach at a later time, not resulting in a merger. This definition was introduced by Sinha and Holley-Bockelmann (2012), making a clear distinction between galaxy flybys and close galaxy passages where two halos remain separate at all times. The authors based their analysis on cosmological N-body simulations and found that the number of flybys can even surpass the number of mergers on lower redshifts (z <~ 2). Follow-up study (Sinha and Holley-Bockelmann 2015) further explored interaction parameters: in a majority of flybys, secondary halo penetrates deeper than ~ R_{half} with initial relative velocity ~ 1.6 \times V_{vir} of the primary halo. The typical mass ratio of interacting galaxies was found to be ~ 0.1 at high redshifts, or even lower, at the lower redshift end.

The frequency and strength of galaxy flybys suggest that these interactions have the potential to significantly impact the evolution of individual galaxies, with the strongest contribution at the present epoch (An et al. 2019). The focus of previous studies was predominantly on the primary (more massive) galaxy. It was established that flybys can trigger or speed up bar formation (Lang et al. 2014, Lokas 2018), create warps at the edges of the galactic disk, both gaseous and stellar (Kim et al. 2014) or, in general, reproduce diverse morphology of observed galaxies with...
differing interaction parameters (Pettitt and Wadsley 2018).

However, effects on the secondary, intruder galaxy are equally (if not more) important, given the fact that the majority of morphological disturbances seen in dwarf galaxies ($M_* < 10^7 \, M_\odot$) are primarily the result of interactions like these that do not end in a merger (Martin et al. 2021). This is particularly noticeable in galaxy clusters. Tormen et al. (1998) reported that very close, penetrating encounters between satellites within the cluster are frequent, with almost 60% of satellites experiencing at least one such event before losing 80% of their initial mass. They noted that mass loss, which follows these interactions, is comparable to the one caused by global tides. Thus, interactions within galaxy clusters can contribute to the dynamical evolution of individual galaxies as equally as the global, collective effects of the cluster itself. Gnedin (2003) confirmed this, finding that peaks of the tidal force do not always correspond to the closest approach to the cluster centre, but instead to the local density structures (e.g. massive galaxies or the unvirialized remnants of infalling groups of galaxies).

Dark matter halos of tidally affected galaxies, due to their extended nature, usually suffer significant mass loss - their outermost parts, being loosely gravitationally bound, get stripped first. With prolonged tidal effects or stronger tidal forces, the inner parts become affected and prone to the tidal stripping. Since tidal forces remove mass from outside in, the process is known as outside-in tidal stripping (e.g. Diemand et al. 2007, Choi et al. 2009). At the same time, the stellar counterpart is barely affected (Smith et al. 2015, 2016). Stripping and mass loss of the stellar component typically only starts happening after a significant portion of dark matter ($\sim 80\%$) is already lost (Smith et al. 2016, Lókás 2020). Tidal stripping, in general due to its outside-in nature, is known to be one of the formation mechanisms of ultra-compact dwarfs (Bekki et al. 2001, 2003, Pfeffer and Bongardt 2013, Pfeffer et al. 2014, Martinović and Micic 2017, Ferré-Mateu et al. 2018, Kim et al. 2020), and there is growing evidence for tidal origin of ultra-diffuse galaxies (Carleton et al. 2019, Iodice et al. 2021, Jones et al. 2021, Wright et al. 2021). This is all reflected in stellar-to-halo mass relation (Niemiec et al. 2017, 2019, Engler et al. 2021) - galaxies in high-density environments, such as clusters, tend to have smaller (than expected) halo masses for a given stellar mass. Exotic class of dark matter deficient galaxies can be considered as an extreme example of these mechanisms (Ogiya 2018, Montes et al. 2020, Shin et al. 2020, Jackson et al. 2021, Macciò et al. 2021, Trujillo-Gomez et al. 2021).

The aim of this paper is to explore the role of impact parameter (which will also be referred to as pericentre distance) in galaxy flybys, with emphasis on dark matter mass loss of the secondary, intruder galaxy. The main goal is to answer a question - is there a functional relationship between impact parameter and dark matter mass loss of the secondary galaxy, and if so, what does it look like? This will be done by utilizing a series of N-body simulations of galaxy flybys with differing impact parameter (described in Section 2.). Total dark matter mass of the intruder galaxy after the encounter will be estimated using three different criteria described in Subsection 2.2. As mass loss of the stellar component is not expected, it will be verified if that is the case and if so, changes to its half-mass radius will be explored. Results will be outlined and briefly discussed in Section 3. Finally, Section 4., besides drawing conclusions, will tackle potential issues of this work, and discuss open questions.

2. MODELS, SIMULATIONS AND METHODS

Two galaxy models were constructed using GalactICs software package (Kuijken and Dubinski 1995, Widrow and Dubinski 2005, Widrow et al. 2008). Primary galaxy model (which will be referred to as galaxy) consists of NFW (Navarro et al. 1996) dark matter halo, exponential stellar disc and Hernquist (1990) stellar bulge. Dark matter halo, consisting of $N_H = 6 \cdot 10^5$ particles, has total mass $M_H = 9.057 \cdot 10^{11} \, M_\odot$, scale length $a_H = 13.16$ kpc, and concentration parameter $c = 15$. Exponential stellar disc, consisting of $N_D = 3 \cdot 10^5$ particles, has total mass $M_D = 7.604 \cdot 10^9 \, M_\odot$, scale length $R_D = 5.98$ kpc, scale height $z_D = 0.688$ kpc, and central velocity dispersion $\sigma_R = 98.9 \, \text{km s}^{-1}$. Stellar bulge, consisting of $N_B = 1 \cdot 10^4$ particles, has total mass $M_B = 2.502 \cdot 10^9 \, M_\odot$, and scale radius $R_B = 2.182$ kpc.

Secondary galaxy model (which will be referred to as intruder) consists only of NFW dark matter halo, and stellar bulge, to mimic (dwarf) spherical galaxy for the sake of simplicity. Intruder model was scaled to be 10 times smaller than galaxy model, in both number of particles and total mass. This results in dark matter halo with $N_H = 6 \cdot 10^4$ particles, $M_H = 9.044 \cdot 10^9 \, M_\odot$ total mass, $a_H = 4.578$ kpc scale length, and $c = 20$ concentration parameter. Stellar component has, thus, $N_S = 4 \cdot 10^4$ particles, and $M_S = 1.022 \cdot 10^9 \, M_\odot$ total mass with scale radius $R_B = 3.145$ kpc. Relevant parameters for both galaxies are listed in Table 1.

Flyby simulations, originally designed to follow the evolution of primary galaxy disc long after the encounter in Mitrašinović and Mićić (in prep), were performed using publicly available code GADGET2 (Springel 2005) compiled with the option to calculate and output particle potential energy. The system was evolved for 5 Gyr with outputs being saved every 0.01 Gyr. Galaxy and intruder were initially set as contact system, i.e. distance from their centers is roughly equal to the sum of their virial radii $d_0 = R_{\text{vir,1}} + R_{\text{vir,2}} \approx 290$ kpc, with galaxy being static in the centre of simulation box. Intruder was set on prograde parabolic orbit, co-planar with galaxy disc, with initial relative velocity $v_0 = 500 \, \text{km s}^{-1}$. Different pericentre distances (impact parameters - these terms will be used interchangeably)
2.1. Assessment of intruder’s center

Tidally stripped dark matter particles make the determination of the intruder’s centre fairly challenging. As more dark matter particles get rejected from the intruder and shift further away from it, a simple centre of mass (which comes down to calculating the plain arithmetic mean of each coordinate for equal mass particles) also shifts away from the actual centre of the intruder. To determine the location of the actual centre, a method based on the particle’s potential energy is employed. Since GADGET2 calculates total potential energy, including contributions from the main galaxy, the densest 1 kpc\(^3\) cube with intruder particles (regardless of their type, dark matter or stellar) is first filtered. Then, the filtered particle with the lowest potential energy is chosen to represent the intruder’s centre. The intruder’s velocity is derived using only filtered particles.

Figure 1 illustrates differences between these two estimates and contributions to possible errors from each component (by calculating differences between these estimates separately for dark matter and baryon particles). Despite getting considerably lower as the impact parameter increases, these differences are still significant for dark matter halo, reaching almost 10 kpc at a later stage. Consequently, both the estimate of dark matter halo mass and the shape of its density profile would be wrong if the classical centre of mass is used. As expected, the baryon (stellar) component appears to be unaffected and most likely retains all of its initial mass. Differences between the two centre estimates remain below 0.6 kpc at all times in all simulations. Ideally, the centre of mass for both components should be at roughly the same position pointing to the centre of the intruder galaxy as a whole. The method used here is one way to fix issues caused by the stripped particles of dark matter halo. Alternatively, one can centre the whole intruder galaxy on the stellar centre of mass prior to any dark matter mass estimates, as stellar component does not have significant differences between the two centre estimates.

### Table 1: List of relevant parameters for two galaxy models where the first block is related to dark matter halo, the second one to stellar bulge and the third to stellar disc.

| Parameter | Primary galaxy | Secondary galaxy |
|-----------|----------------|------------------|
| \(N_H\)   | \(6 \times 10^5\) | \(6 \times 10^4\) |
| \(M_H\)   | \(9.057 \times 10^{11} \, M_\odot\) | \(9.044 \times 10^{10} \, M_\odot\) |
| \(\sigma_H\) | 13.16 kpc | 4.578 kpc |
| \(c\)     | 15            | 20               |
| \(N_D\)   | \(1 \times 10^5\) | \(4 \times 10^4\) |
| \(M_D\)   | \(7.604 \times 10^{10} \, M_\odot\) | \(1.022 \times 10^{10} \, M_\odot\) |
| \(R_D\)   | 2.182 kpc     | 3.145 kpc        |
| \(z_D\)   | 0.688 kpc     |                  |
| \(\sigma_R\) | 98.9 km s\(^{-1}\) |                  |

### Table 2: List of flyby simulations where \(b\) is pericentre distance, \(R_{vir,1}\) virial radius of main galaxy, and \(v_b\) pericentre velocity.

| Name | \(b\) [kpc] | \(b/R_{vir,1}\) | \(v_b\) [km s\(^{-1}\)] |
|------|-------------|-----------------|--------------------------|
| B30  | 22.50       | 0.114           | 660.14                   |
| B35  | 26.53       | 0.135           | 650.86                   |
| B40  | 30.69       | 0.156           | 641.80                   |
| B45  | 35.07       | 0.178           | 632.86                   |
| B50  | 39.62       | 0.201           | 624.25                   |
| B55  | 44.27       | 0.224           | 616.16                   |
| B60  | 48.99       | 0.248           | 608.09                   |
| B65  | 53.72       | 0.272           | 601.28                   |
negative total energies (potential and kinetic sum) are filtered. Despite GADGET2 calculating total potential energy, due to high enough intruder’s velocity, particles possibly captured by the primary galaxy would end up with positive total energies. However, a major pitfall of this mass measure is the inclusion of barely gravitationally bound particles forming tidal features.

- **Virial mass** filters dark matter particles inside intruder’s virial radius. Virial radius is determined by fitting the NFW profile to the intruder’s (dark matter component) density profile.

- **Core mass** measure is based on mass estimate of Klimentowski et al. (2009), Kazantzidis et al. (2011). First, circular velocity profile is calculated as \( V_{\text{circ}}(r) = \sqrt{GM(<r)/r} \), where \( M(<r) \) is cumulative mass of dark matter halo and \( r \) spherical radius. Radius \( r_{\text{max}} \) where this profile reaches maximum \( V_{\text{max}} \) is chosen as cutoff, and \( M(<r_{\text{max}}) \) represents dark matter halo core mass.

By definition, at later stages of simulations, virial and core mass measures should remain fairly constant. Core mass, accounting for the majority of dark matter particles, should be seen as a lower limit for total dark matter mass, whereas bound mass should represent an upper limit. Bound mass should continue to decline over time as tidal features slowly dissolve and the majority of particles become detached from the intruder. Some particles might get recaptured by the intruder, which would result in a slight increase in virial mass. Due to this, as the main measure of intruder’s dark matter mass, virial mass averaged over the last 3 Gyr will be used.

Baryon (stellar) component of the intruder is not expected to lose a significant amount of mass. Moreover, based on the previous centre of mass estimates for the stellar component, it is likely that all of its particles remain within the virial radius. However, that does not imply stellar component doesn’t undergo any changes. Evolution of half-mass radius \( R_{\text{B,0.5}} \) will be followed. Note that, with the total stellar mass remaining constant, changes in half-mass radius imply changes in the average spherical density of the stellar component: when half-mass radius increases density decreases and vice versa.

3. RESULTS

The evolution of dark matter halo mass estimates defined in 2.2, is shown on Figure 2. These estimates are expressed in relative form as:

\[
 f_M = \frac{M(t)}{M(t = 0)}
\]

where \( M(t) \) is the approximate estimate (bound, virial or core) during simulation(s), \( M(t = 0) \) its value at the start of simulation(s), and \( f_M \), thus, represents leftover fraction of initial dark matter mass. Supplementary to Figure 2, Figure 3 shows the evolution of dark matter mass change rate expressed as a percentage of its initial mass per Gyr. It has to be noted that initial values of both bound and virial estimates, in all simulations, are equivalent to \( M = 9.044 \times 10^{10}M_\odot \) (initial dark matter halo total mass), while dark matter core mass equates to \( M = 3.684 \times 10^{10}M_\odot \).

As expected, a significant mass change rate is observed after pericentre is reached for all mass estimates. During the encounter intruder stretches, becoming heavily distorted for a brief period, which is best visible on core mass plots. Core distortion is followed by abrupt mass loss, after which the dark matter core stabilizes and remains fairly constant with negligible variations until the end of every simulation. The whole process takes place before the encounter is even over. The final leftover fraction of dark matter core mass estimate is higher than the leftover fraction of virial mass estimate in most simulations (evident...
from Figure 4 as well). This implies that despite the strong gravitational influence of the main galaxy, the core part of the intruder’s dark matter halo remains semi-preserved. It is also the key in understanding why the baryon component can retain almost all of its initial mass - gravitational potential of preserved dark matter halo’s core protects the baryon component against significant mass loss.

Virial mass takes longer to stabilize - while dark matter mass loss starts around the time pericentre is reached, mass loss rate (Figure 3) peaks right after the encounter, at $t \geq 1.08$ Gyr. The peak itself shows dependence on pericentre distance, ranging from $< 50\%$ of initial dark matter mass per Gyr, in simulation with the lowest pericentre distance (B30), to $\approx 16\%$ of initial dark matter mass per Gyr, in simulation with the highest pericentre distance (B65). Following the peak, mass loss rate sharply declines from $\approx 10\%$ of initial dark matter mass per Gyr at $t = 2$ Gyr to no mass loss at $t = 3$ Gyr in all simulations, irrespective of pericentre distance. After $t = 3$ Gyr, there is an almost constant mass gain of $\lesssim 1\%$ of initial dark matter mass per Gyr in all simulations. Thus, the most significant virial mass loss is observed for 1 Gyr following the end of the encounter. Bearing that in mind, for fitting purposes (i.e. exploring the functional relationship between leftover virial mass and impact parameter relative to the virial radius of the primary) virial mass fraction averaged over the last 3 Gyr will be used.

Bound dark matter mass, expectedly, declines until the end of each simulation. Its mass loss is much slower than the one of virial mass, even during peak, which happens after the pericentre is reached and before the encounter is over. During the last 1 Gyr, mass loss rate is almost constant in all simulations, varying between $1 - 2\%$ of initial dark matter mass per Gyr. Given that the final fraction of bound dark matter mass is still higher than virial mass fraction at the end, and that mass loss rate is non-zero at $t = 5$ Gyr, bound dark matter mass will likely continue to decline past simulation cutoff at 5 Gyr until it converges with virial mass.

Note that bound dark matter mass discussed here should be considered as an upper limit for truly bound mass. Other than the inclusion of particles forming tidal features outside of the virial radius, our method possibly includes dark matter particles that might not be gravitationally bound to the intruder’s core. Precise determination of bound mass would, ideally, require the use of the ”snowballing” method (Smith et al. 2015). However, said method is robust and was not feasible, due to our limited computing resources.

3.1. Leftover dark matter mass - dependence on impact parameter

Leftover dark matter mass fraction, for each type of mass estimate, as a function of impact parameter (pericentre distance) relative to the virial radius of the primary, is shown on Figure 4, with different types of mass estimates denoted by different colours. Filled circles represent simulation data, and lines represent logarithmic growth fit in a form:

$$y = A \cdot \ln x + B$$

where $y$ corresponds to the leftover dark matter mass fraction, $x$ corresponds to impact parameter (pericentre distance) relative to the virial radius of the primary, and $A$ and $B$ are fitting parameters. As evident, virial and core leftover dark matter mass’s dependence on impact parameter is perfectly described with logarithmic growth law. Bound dark matter mass fraction, albeit deviating from the fitted line, can still be described with logarithmic growth law. Fitting parameters are different for all three types of mass: virial mass has $A = 0.3123$ and $B = 1.2811$, core mass has $A = 0.2069$ and $B = 1.1443$, and bound mass has $A = 0.2384$ and $B = 1.2935$. These fitting parameters are likely not universal but dependent on multiple interaction parameters, e.g. the mass ratio of interacting galaxies, the initial relative velocity of intruder galaxy, interaction duration.

Surprisingly, outside-in nature of the tidal stripping, which is one of the main formation mechanisms of ultra-compact dwarf galaxies (mentioned in the introductory part of this paper), is less evident in flybys with larger impact parameters (i.e. weaker ones). Examining extreme cases, simulation B30 with the lowest and simulation B65 with the highest impact parameter yields interesting insights. In B30, the leftover dark matter core mass fraction is by $\approx 9\%$ higher than the leftover virial mass fraction, while they are almost equal in B65. Generally, decreasing difference between these two dark matter mass estimates with increasing impact parameter indicates that outer parts of dark matter halo are more affected in closer (i.e. stronger) flybys and thus lose more mass than inner (core) parts. As the impact parameter increases, dark matter mass loss becomes almost uniform with radius. This might lead to an assumption that density profiles, and thus shapes and slopes of NFW profiles, are heavily affected. In reality, this is not entirely the case (Figure 5) - while differences become visible on larger radii ($R \geq 18$ kpc), density profiles are not significantly altered in inner parts where the majority of leftover particles reside. Normalized density profiles (relative to their fitted analytical NFW profile) are shown on the lower panel on Figure 5. High deviations at the centre are understandable as the analytical form has unrealistically high densities on low radii ($R \rightarrow 0$). Well outside dark matter half-mass radius ($R \geq 18$ kpc)$^1$, deviations of density profiles from the analytical NFW increase drastically. The effect is more prominent in closer flybys where higher fractions of dark matter mass are stripped. This confirms that, due to the outside-in nature of the tidal stripping, outer parts of the dark matter halo density profiles are steeper than the analytical NFW (e.g. Okamoto and Habe 1999, Genina et al. 2021). Thus, the NFW does not

$^1$Half-mass radius, which encloses half of the leftover dark matter mass, varies between $\sim 5.5$ kpc (B30) and $\sim 7.5$ kpc (B65). These can be approximated for each simulation using the data listed in Table 3 - namely leftover mass $M_{DM}$, virial radius $R_{vir}$, and concentration parameter $c$. 
Fig. 2: Evolution of dark matter halo mass estimates defined in 2.2. (from left to right): bound (first panel), virial (second panel), core mass (third panel). Different colors are assigned to different simulations. Estimates are expressed in relative form, compared to initial mass, and thus represent fractions of leftover mass.

Fig. 3: Mass change rate $\Delta M/\Delta t$ for different mass estimates and simulations with the same annotations as in Figure 2. Mass change rate is expressed as percentage of initial mass per Gyr (contrary to Figure 2 which shows fractions).

describe the dark matter halo density profiles well overall, while the approximation is still consistent in the inner parts.

Dependence of leftover dark matter mass (of intruder galaxy in flybys) on impact parameter is, undisputedly, perfectly described with logarithmic growth law. Naturally, the lost mass would then follow the exponential decay law. As such, decreasing impact parameter is followed by considerable and ever so faster dark matter mass loss. This will be discussed in detail, while keeping in mind constraints of this work, in Section 4.

3.2. Changes to stellar component and dark-to-stellar mass ratio

Contrary to the dark matter halo, the stellar component does not suffer any mass loss. The total stellar mass was estimated by applying the method for bound dark matter mass estimate to stellar particles. Since it remains constant in all simulations, visualisation of it is omitted. However, the total stellar mass remaining constant does not imply there are no changes to the stellar component. Final half-mass radius of the stellar component, $R_{0.5}$, as a function of impact parameter (relative to the virial radius of the primary), is shown on the lower panel of Figure 6. Exponential decay law, $R_{0.5} = A \cdot \exp(-B \cdot b/R_{\text{vir},1}) + C$ describes its behaviour the best, with fitting parameters: $A = 2.2$, $B = 18.23$, and $C = 4.24$. While it stretches
faster as impact parameter decreases, the value of $R_{0.5} = 4.5097$ kpc in the strongest flyby simulation (B30) is not considerably larger than initial one of $R_{0.5} = 4.153$ kpc. Typical flybys, hence, can contribute to the formation of ultra-diffuse galaxies but cannot be its sole formation mechanism.

Unsurprisingly, given that stellar component does not suffer mass loss, dark-to-stellar mass ratio $M_D/M_S$ shown on the upper panel of Figure 6 follows logarithmic growth law (similar to that of leftover virial mass), with fitting parameters $A = 2.75$ and $B = 11.32$. From initial value of $M_D/M_S = 8.86$, this ratio drops to $M_D/M_S = 5.317$ in the most extreme case (simulation B30). Despite losing almost half of its initial dark matter mass, the intruder galaxy remains dark matter dominated, albeit less so. Variations in this ratio caused by galaxy flybys, however, can contribute to the scatter in SHMR (stellar-to-halo mass relation) at the lower mass end, $M_{\text{halo}} \lesssim 10^{11} M_\odot$. Scatter in SHMR in this, dwarf regime has received very little attention so far. Its importance is becoming more clear, as extreme cases could successfully explain the formation of dark matter deficient galaxies (Trujillo-Gomez et al. 2021).

### 4. DISCUSSION AND CONCLUSION

Series of N-body simulations of typical (10:1 mass ratio), deep galaxy flybys was performed, with differing impact parameters, ranging from 0.114 to 0.272 of the virial radius of the primary galaxy. The focus of the analysis was on dark matter mass loss of the secondary, intruder galaxy with three different methods of estimating the total dark matter mass of the intruder. Dependence on impact parameter for all of those, for leftover dark matter mass, is that of logarithmic growth, and exponential decay for lost dark matter mass. This functional dependence seems universal, while fitting parameters may vary with different initial conditions and interaction parameters (such as the mass ratio of interacting galaxies, the initial relative velocity of intruder
Bound dark matter mass calculated here should be taken as an absolute upper limit of truly bound dark matter leftover mass, given the rough nature of this estimate. Furthermore, such an estimate has very little applicability. Virial mass, conversely, is a much better indicator of intruder galaxy’s total dark matter mass as it’s suitable for comparison with results and data of cosmological simulations. However, this value should be taken with a dose of scepticism due to considerable deviations of dark matter density profiles from the analytical NFW on higher radii. Still, it is not the only noteworthy dark matter mass estimate. Core dark matter mass, estimating the total mass of the inner dark matter halo, is an appropriate one for comparison with observationally derived dark matter fractions, which can typically only probe regions where baryons are present. Particularly of interest is that this estimate stabilizes faster than the virial one, reaching its final values even before the encounter is over. This makes it convenient to estimate, to an extent, total virial mass and its loss which happens 1-2 Gyrs later, based on observationally derived dark matter masses. Disparities may, of course, arise due to the outside-in nature of tidal stripping, especially in closer flybys.

Typical flybys investigated here could not be the sole culprit behind the formation of ultra-diffuse or dark matter deficient galaxies, but their effects and contributions should not be disregarded. Considering their frequency at the present epoch (Sinha and Holley-Bockelmann 2012, An et al. 2019), combined with other possible close encounters and collective effects of galaxy clusters, where such events are likely to take place, these scenarios become highly plausible.

Given the nature of exponential decay with impact parameter, of both lost dark matter mass, and half-mass radius of the stellar component, it is fairly safe to assume that closer (or stronger in a different way, e.g. slower) flybys than the ones investigated here, could alone lead to the formation of ultra-diffuse and dark matter deficient galaxies with just the right impact parameters. The formation of ultra-diffuse galaxies might not require a narrow range of impact parameters. Stellar component stretches at a faster rate than the dark matter mass loss. While stretching and getting extended, it might become prone to the mass loss itself, although that usually only starts happening after a significant portion of dark matter (~ 80%) is already stripped (Smith et al. 2016, Lokas 2020). Since this was not observed even in the simulation with the closest flyby presented here, an estimate of the required impact parameter for such a case would be pure speculation at this point.

The possible formation of dark matter deficient galaxies through galaxy flybys is much more sensitive. It would require flybys with extremely low impact parameters, or much slower deep flybys, in addition to the faster rate of dark matter stripping compared to stellar one. Moreover, it might require specific shapes of density profiles for both dark matter, and baryon component. While such flybys are extremely rare, they are still detected in cosmological simulations (Sinha and Holley-Bockelmann 2015), which is in line with the exotic nature of these objects.

This is, of course, entirely speculative. The approach and methods, presented in this work, are unfit to deal with flybys with lower impact parameters. Simulations being pure N-body are rather simplified, and have no way of dealing with various and complex physical processes which would occur in such interactions. Rare, atypical and stronger (in any way, with lower impact parameters, lower initial velocities or higher differences in initial masses of interacting galaxies) flybys are, however, worth exploring further. The best approach would be trying to reconcile complex hydrodynamical simulations of isolated flybys with cosmological simulations, and hopefully observational data.

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| Name | $b$ [kpc] | $b/R_{\text{vir},1}$ | $M_{\text{DM}}$ [%] | $M_{\text{DM}}/M_{\text{B}}$ | $R_{\text{vir},2}$ [kpc] | $\Delta R_{\text{vir},2}$ [kpc] | $R_{B,0.5}$ [kpc] | $c$ |
|------|-----------|---------------------|-----------------------|-----------------|------------------|------------------|----------------|------|
| B30  | 22.5      | 0.114               | 59.96                 | 5.317           | 87.95            | 0.92             | 4.5097         | 28.94 |
| B35  | 26.53     | 0.135               | 65.46                 | 5.798           | 89.74            | 1.03             | 4.4277         | 29.35 |
| B40  | 30.69     | 0.156               | 70.23                 | 6.218           | 92.48            | 1.09             | 4.3616         | 26.62 |
| B45  | 35.07     | 0.178               | 74.55                 | 6.597           | 93.69            | 1.17             | 4.3211         | 26.47 |
| B50  | 39.62     | 0.201               | 78.43                 | 6.939           | 94.75            | 1.04             | 4.2948         | 26.56 |
| B55  | 44.27     | 0.224               | 81.61                 | 7.221           | 95.83            | 1.14             | 4.2700         | 26.10 |
| B60  | 48.99     | 0.248               | 84.45                 | 7.472           | 96.90            | 1.10             | 4.2581         | 25.63 |
| B65  | 53.72     | 0.272               | 86.92                 | 7.690           | 97.77            | 1.09             | 4.2547         | 24.94 |
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Fig. 6: On both panels, filled circles represent simulation data, solid line initial value (at $t = 0$), and dashed line best fit curve, with fitting functions and parameters included in the legend; as a function of impact parameter relative to virial radius of the primary. Upper panel: Dark-to-stellar mass ratio, where $M_D$ is final (at $t = 5$ Gyr) virial mass, and $M_S$ final mass of the stellar component. Lower panel: Final half-mass radius of the stellar component, $R_{0.5}$.

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ГУБИТАК МАСЕ ТАМНЕ МАТЕРИЈЕ У ПРОЛЕТИМА ГАЛАКСИЈА: ЗАВИСНОСТ ОД ПАРАМЕТРА СУДАРА

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Оригинални научна рад

Пролети галаксија, интеракције где два независна халоа међусобно пролиду, али се затим одвоје и не сударе, су често појава на најлим црвеним помацима. Ове интеракције могу имати значајан утицај на еволуцију појединачних галаксија, вочев од губитка масе и промена облика галаксија, па до појаве плимских ефеката и својстава, и формирања различитих морфолошких структура у дисковима галаксија. Главни фокус овог рада је на губитку масе тамне материје секундарне, "уљез" галаксије, са циљем одређивања функционалне зависности губитка масе тамне материје од параметра судара. Серија симулација N-тела типичних пролета галаксија (однос маса 10:1) са различитим параметрима судара, показује да преостала маса тамног халоа "уљез" галаксије прати закон логаритмског раста са параметром судара, без обзира на начин на који је укупна маса проценета. Изгубљена маса онда, јасно, прати закон експоненцијалног распада. Звезdana компонента се брже шири са смањењем параметра судара, пратећи закон експоненцијалног распада. Функционална зависност од параметра судара у свим случајевима се чини универсална, али су њени одговарајући параметри вероватно остати на параметрима интеракције и почетне услове (нпр. однос маса интерагујућих галаксија, релативна почетна брзина "уљез" галаксије, трајање интеракције). Док типични пролети, прочувани овде, не могу бити једини узрок избиравања ултра-дифузних галаксија, или галаксија без велике количине тамне материје, њихови ефекти не смеју бити игнорисани јер могу бар значајно да допринесу овим појавама. Стога су ретки, нетипични, и јачи пролети предни један и детаљнијег истраживања.