Self-Interacting Dark Matter and the Origin of NGC1052-DF2 and -DF4

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Observations of ultra-diffuse galaxies NGC1052-DF2 and -DF4 show they contain little dark matter, challenging our understanding of galaxy formation. Using controlled N-body simulations, we explore the possibility to reproduce their properties through tidal stripping from elliptical galaxy NGC1052, in both cold dark matter (CDM) and self-interacting dark matter (SIDM) scenarios. To explain the dark matter deficiency, we find that a CDM halo must have a very low concentration so that it can lose sufficient mass in the tides. In contrast, SIDM favors a higher and more reasonable concentration as core formation enhances tidal mass loss. Stellar distributions in our SIDM benchmarks are more diffuse than CDM one, and hence the former provide a better match to the data. We further show that the presence of stellar particles is critical for preventing the halos from being totally disrupted and discuss its implications. Our results indicate that the dark matter-deficient galaxies may provide important tests for the nature of dark matter.

Introduction. Dark matter plays a crucial role in galaxy formation and evolution [1]. In the standard scenario, a luminous galaxy is hosted by a dark matter halo, which dominates the overall mass of the galactic system. However, using globular clusters as a tracer, the Dragonfly team shows ultra-diffuse galaxy NGC1052-DF2 (DF2) contains little dark matter [2]. Its total stellar mass is \(2 \times 10^8 \, M_\odot\), while the estimated total dynamical mass within 7.6 kpc is less than \(3.4 \times 10^8 \, M_\odot\). Intriguingly, the team has discovered a second galaxy lacking dark matter: NGC1052-DF4 (DF4). Both galaxies are members of the NGC 1052 group [4, 5] and they exhibit many similar properties. In particular, their dark matter contents are at least a factor of \(\sim 400\) lower than expected from the canonical stellar-to-halo mass relation [7, 8].

The dark matter deficiency of the galaxies may be related to their environments. Both DF2 and DF4 are likely to be satellite galaxies of massive elliptical galaxy NGC 1052, which has a distance of 20 Mpc from the earth. A satellite can experience significant mass loss due to tidal stripping after evolving in its host’s tides [9–15]. It has been shown that cosmological hydrodynamical cold dark matter (CDM) simulations can produce analogs of dark matter-deficient galaxies due to tidal stripping [16–18], but it is hard to find simulated galaxies that can match observations of DF2 and DF4 [19]. Ref. [20] constructs a DF2-like system based on controlled N-body simulations. It argues that a cored dark matter halo is required to match with the observations, as a CDM cuspy halo does not lose sufficient mass in the NGC 1052’s tides. In addition, stars also expand more significantly in a cored halo in response to tidal stripping [21].

In this paper, we study realizations of DF2 and DF4-like galaxies in the self-interacting dark matter (SIDM) scenario [22, 23]; see [24] for a recent review. Dark matter self-interactions can thermalize the inner halo and naturally lead to a density core in the inner halo for low-surface brightness galaxies, see, e.g., [25–31]. Recent studies show that SIDM may provide a unified explanation to dark matter distributions in galactic systems over a wide mass range, including satellite galaxies in the Milky Way [14, 15, 25, 26], spiral galaxies in the field [32–36] and galaxy clusters [23]. It is intriguing to see how the newly-observed dark matter-deficient galaxies can shed further light on the nature of dark matter.

Using controlled N-body simulations, we model evolution of satellite galaxies in the tidal field of NGC 1052 and study their properties in both SIDM and CDM scenarios. After choosing a radial orbit to enhance tidal stripping, we impose observational constraints from the dark matter-deficient galaxies and derive conditions on initial halo parameters for the satellites. We will show that SIDM is more likely to populate DF2 and DF4-like galaxies than CDM, in terms of reproducing their little dark matter contents and diffuse stellar distributions. We further demonstrate that stellar particles can prevent a satellite halo from being totally disrupted in the tidal field. This may help distinguish halo models predicted in SIDM and those in CDM with strong baryonic feedback. We find a cored CDM halo modified by the feedback can be destroyed within much less than 10 Gyr.

Simulation setup. We model host galaxy NGC 1052 with a static spherical potential including both halo and stellar components. Assuming a Navarro-Frenk-White (NFW) density profile [38] for the host halo, we fix the characteristic scale density and radius as \(\rho_s = 1.6 \times 10^6 \, M_\odot/\text{kpc}^3\) and \(r_s = 80 \, \text{kpc}\), respectively, similar to those used in [20]. The total halo mass is \(M_{200} = 1.1 \times 10^{13} \, M_\odot\). The luminosity of the galaxy follows a 2D Sersic profile [39] with the index parameter \(n = 3.4\) and the effective radius \(R_e = 2.06 \, \text{kpc}\); the total stellar mass is \(10^{11} \, M_\odot\) [40]. In our simulations, we use a Hernquist profile \(\rho_l = \rho_0 / (r/r_s(1 + r/r_s))^{3}\) [41] to model the stellar distribution, where we take \(\rho_0 = 1.1 \times 10^{10} \, M_\odot/\text{kpc}^3\)
and $r_h = 1.2$ kpc such that both Hernquist and 3D deprojected Sérsic profiles have the same total enclosed mass and half-mass radius. For an NGC 1052-like system, where stars dominate the central regions, an SIDM halo profile can be similar to an NFW one, because SIDM thermalization with the baryonic potential increases the inner halo density [12–40]. Thus our halo model for the host is also valid if dark matter has self-interactions. We also have checked that the effect of dynamical friction is negligible for the purpose of this work and the approach with a static potential is well justified.

For the satellite system, we use live particles. The initial halo and stellar masses are chosen to be $M_{200} = 6.0 \times 10^{10} \, M_\odot$ and $M_* = 3.2 \times 10^8 \, M_\odot$, respectively, and their ratio is consistent with expected from the canonical stellar-to-halo mass relation [7]. We assume the halo follows an NFW profile. We perform a coarse scan of the concentration parameter $c_{200}$ from 4 to 10, and find a proper value such that simulated satellites after tidal evolution can match with observed dark matter contents of DF2 and DF4. While for the stellar component, we use a Plummer profile $\rho_p = \rho_p/[1 + (r/r_p)^2]^{3/2}$ [47] to model its initial distribution, where $\rho_p = 5.8 \times 10^7 \, M_\odot$/kpc$^3$ and $r_p = 1.1$ kpc.

We perform both SIDM and CDM simulations. For the former, we consider two values of the self-scattering cross section per mass, $\sigma/m = 3$ cm$^2$/g (SIDM3) and 5 cm$^2$/g (SIDM5), consistent with the ones used to explain dark matter distributions in field spiral and Milky Way satellite galaxies [14–35]. We use public code GADGET-2 [48–49] to perform simulations. To model dark matter self-interactions, we have developed and implemented an SIDM module based on the Monte Carlo-based algorithm as in [50]. We have checked our code for a test halo and found that the simulated density and velocity-dispersion profiles well agree with the results obtained using a semi-analytical model [29], which has been calibrated to other SIDM simulations, see [35]. For the satellite system, we use code SpherIC [61] to generate initial conditions. The mass of simulated particles is $10^4 \, M_\odot$ for both halo and stellar components, and the softening length is 50 pc.

**Orbital parameters.** We confine orbits of the satellite in a plane in our simulations. Initially, it is placed at the apocenter, which is 380 kpc away from the center of the host, and has a tangential velocity of 9 km/s. We find that the orbital period of the satellite is about 2.5 Gyr, the pericenter is 2.4 kpc, and the velocity at the passage is 740 km/s. The orbits we choose are rather radial so that the stripping effects are significant.

We determine a timescale for the final snapshot from the following consideration. DF2 has an 80 kpc projected distance from NGC 1052 and a relative velocity of 293 km/s along the line-of-sight direction [2]. Suppose the angle between the host–satellite plane and the line-of-sight direction is $\theta$ and the satellite’s orbit is nearly radial, as in our setup, we have the relations, $d \sin \theta \approx 80$ kpc and $v \cos \theta \approx 293$ km/s. For $t \approx 9.4$ Gyr and 11 Gyr, corresponding to the moments right before and after passing the apocenter, respectively, our simulated satellites satisfy condition $(80 \, \text{kpc}/d)^2 + (293 \, \text{km/s}/v)^2 \approx 1$. The difference between the two snapshots is small, and we show results with $t = 11$ Gyr.

**Mass profiles.** Our simulations search for upper limits of $c_{200}$ such that the simulated satellites can match overall with the observations. We find three benchmark cases, $c_{200} = 4, 7,$ and 10 for CDM, SIDM3 and SIDM5, respectively. Fig. 1 shows their enclosed dark matter and stellar masses vs radii at $t = 0$ Gyr and 11 Gyr, as well as the final total mass profiles. For all three benchmarks, the simulated halos experience significant mass loss in the tidal field of NGC 1052 and the final halo masses.
become almost a constant for $r \gtrsim 4$ kpc, approximately $M_{DM} \approx 1.5 \times 10^8 M_\odot$, reduced by a factor of 400 compared to the initial value, $6.0 \times 10^8 M_\odot$. While tidal mass loss for the stars is much more mild, resulting in a total stellar mass of $M_{\text{star}} \approx 1.3 \times 10^8 M_\odot$. The mass ratio is $M_{DM}/M_{\text{stars}} \sim 1$ at $t = 11$ Gyr after tidal evolution.

Observationally, DF2 has a total stellar mass of $2 \times 10^8 M_\odot$ and the dynamical mass within 7.6 kpc is $M_{\text{dyn}} \lesssim 3.4 \times 10^8 M_\odot$ [2], based on the analysis of globular clusters using the tracer mass estimator method [52]. Other studies show the upper limit of $M_{\text{dyn}}$ could be higher due to uncertainties [53–57]. Further measurements using stellar spectroscopy show that its stellar and dynamical masses within the half-light radius $R_{1/2} = 2.7$ kpc are $M_{\text{star}} = (1.0 \pm 0.2) \times 10^8 M_\odot$ and $M_{\text{dyn}} = (1.3 \pm 0.8) \times 10^8 M_\odot$ [58], respectively; see also [59, 60]. For DF4, $M_{\text{star}} = (1.5 \pm 0.4) \times 10^8 M_\odot$ and $M_{\text{dyn}} = 0.4^{+1.2}_{-0.3} \times 10^8 M_\odot$ within 7 kpc [8]. We see our three benchmarks well reproduce the observations. For a reference, we display the upper limits of $M_{\text{dyn}}$ for DF2 from Ref. [2] in Fig. 1 for $3.2 \times 10^8 M_\odot$ and $3.4 \times 10^8 M_\odot$, within 3.1 kpc and 7.6 kpc, respectively.

**Halo concentration.** Using tailored simulations, we have shown that the tidal interactions can cause low dark matter contents of DF2 and DF4 in both CDM and SIDM scenarios. It is important to note the benchmark halos have different concentrations. The CDM one has the lowest $c_{200} = 4$, even though we have chosen a radial orbital to enhance the mass loss. Using the concentration-mass relation at $z = 0$ [57] as a reference, we find it corresponds to $4\sigma$ below the median. While SIDM favors a higher concentration, SIDM3 has $c_{200} = 7$, $1.8\sigma$ below the median; SIDM5 $c_{200} = 10$, $0.4\sigma$ below.

We see that the dark matter-deficient galaxies are more likely to be realized in SIDM than in CDM. Since the inner density cusp in a CDM halo is resilient to tidal stripping, a low concentration is required. In contrast, dark matter self-interactions can thermalize the inner halo and push dark matter from inner to outer regions, lowering the inner gravitation potential. Thus, SIDM satellite halos are more prone to tidal stripping (if there is no core collapse; see [14, 15]), and a higher and more reasonable $c_{200}$ value can match with the observations.

For comparison, we also perform CDM runs for the halos with $c_{200} = 7$ and 10. At $t = 11$ Gyr, their total stellar masses are close to $2 \times 10^8 M_\odot$; while the halo masses are approximately $3.2 \times 10^8 M_\odot$ and $6.6 \times 10^8 M_\odot$ for the CDM runs with $c_{200} = 7$ and 10, respectively; see Fig. 1 for their total enclosed mass profiles (dotted). Apparently, they fit the data much worse than their SIDM counterparts.

**Stellar distributions.** Fig. 2 (left) shows stellar density profiles at $t = 0$ Gyr and 11 Gyr for the benchmarks. From our simulations, we find the half-mass radii are $R_{1/2} = 1.3$ kpc, 1.7 kpc and 2.3 kpc for CDM, SIDM3 and SIDM5 benchmarks, respectively. We further use a 3D deprojected Sérsic profile to fit the simulated stellar distributions within 5 kpc and find a good agreement. The inferred Sérsic indices, characterizing the stellar concentration, are $n = 1.2, 0.91$ and 0.65 for CDM, SIDM3 and SIDM5, respectively; the associated effective radii $R_e$ are consistent with the half-mass radii from simulations ($R_{1/2} \approx 4/3R_e$ [11]).

As $\sigma/m$ increases, the stellar distributions become

![Stellar density profiles and bound halo masses](image-url)
more diffuse and baryon concentration decreases. This is because SIDM core formation leads to a shallow gravitational potential and the stars expand more significantly through tidal stripping; see also [24]. The measured 3D half-light radii and Sésic indices are $R_{1/2} = 2.7$ kpc and $n = 0.6$ for DF2 [2], and $R_{1/2} = 2.0$ kpc and $n = 0.79$ for DF4 [3]. Thus, our SIDM benchmarks provide a better match with the observed stellar distributions than the CDM one, although all three cases have similar $M_{DM}/M_{\text{star}}$ ratios, as shown in Fig. 1.

**Tidal evolution.** Fig. 2 (right) shows the bound halo masses vs. evolution time for the benchmarks (solid). All the halos pass through the pericenter, 2.8 kpc from the center of the host, four times over 11 Gyr. Their masses are similar right after the first pericenter passage, but differ significantly afterwards before the last one. The SIDM5 halo has the lowest rate of tidal mass loss, as it has the highest concentration. At this middle stage, the concentration is the dominant factor controlling the mass loss. But, after the fourth passage, the SIDM5 halo mass drops most significantly, because it has the highest cross section, resulting in the largest density core. Eventually, all three halos have about the same mass at $t = 11$ Gyr.

We find the stars are crucial for preventing the satellite halos from being completely disrupted in the tidal field. Fig. 2 (right) also shows the evolution of the bound halo masses without including stellar particles in simulations. All of them are destroyed right after their third pericenter passages at $t = 7$ Gyr. Even though the SIDM5 halo has a concentration of $c_{200} = 10$, close to the median as in [37], dark matter self-interactions make it vulnerable to tidal disruption in the absence of the stars. For comparison, we take the same initial halo, $c_{200} = 10$, and perform CDM runs without stellar particles. The halo survives from total disruption and its final bound mass is $2.5 \times 10^5 M_\odot$, even higher than predicted in the SIDM5 run with the stars.

Our results have implications for understanding the population of the dark matter-deficient galaxies. If CDM satellite halos host DF2 and DF4 galaxies, they must be on the very low end of the concentration distribution. We expect that a large number of satellite halos with higher concentrations would populate the NGC 1052 group. They would have deep gravitational potentials to collect gas to form stars and prevent them from total disruption. It seems odd that we have observed only two that contain little dark matter. On the other hand, SIDM satellite halos have higher concentrations towards the median, and they are more prone to tidal disruption if the stellar distributions are not concentrated enough. Thus, it is natural to expect that luminous satellite galaxies in the NGC 1052 group are rare in SIDM.

**Discussion.** Dark matter self-interaction is not the only mechanism that can create density cores. Hydrodynamical simulations show that strong baryonic feedback may create cores in CDM halos [62][71]. For DF2-like systems we consider, the ratio of initial stellar-to-halo masses is $\sim 5 \times 10^{-3}$, at which the feedback has the strongest impact and the core size is the largest [61][65]. Ref. [20] considers a cored CDM halo motivated by those simulations and finds it may reproduce DF2 observations after evolving in the NGC 1052’s tides, although the halo has a median concentration. It also assumes a steep initial density profile for stars, which dominate in mass for $r \lesssim 1.5$ kpc.

However, CDM simulations that create dark matter cores would also produce diffuse stellar distributions, as stellar particles behave like collisionless dark matter particles in the simulations [33]. We take the cored CDM halo as in [20] and perform simulations without including stellar particles. The halo is totally destroyed at $t \approx 4$ Gyr and 8 Gyr, when our orbital parameters and those in [20] are used, respectively. Thus, it is not clear whether cored CDM halos modified by the feedback can reproduce the dark matter-deficient galaxies. A related issue is that if the feedback is strong enough to produce dark matter cores, the predicted stellar distributions are too diffuse to accommodate field dwarf galaxies with high stellar densities [36].

It is useful to recall tensions of CDM in explaining other galactic systems. For low-surface brightness galaxies in the field, where the tidal effects are absent, NFW halos are too concentrated overall to fit their slowly rising rotation curves [72][79]. The inner halo profiles of well-resolved galaxy clusters are shallower than predicted in CDM [80]. The most massive satellite halos in CDM simulations of Milky Way-like systems are too dense to host the observed brightest spheroidal galaxies [81][83]. All these tensions may have a common cause, i.e., inner CDM halos are too dense, and they can be resolved if dark matter has strong self-interactions; see [24] for an extensive discussion. In this work, we demonstrate that the problem persists in explaining the dark matter-deficient galaxies, and SIDM may again offer a solution.

**Conclusions.** We have studied realizations of the dark matter-deficient galaxies through tidal stripping. Both CDM and SIDM halos can lose the majority of their masses in the NGC 1052’s tides, drastically increasing the ratio of stellar-to-halo masses in accord with the observations. In CDM, the halo must have a very low concentration to explain the dark matter deficiency. In contrast, an SIDM halo can have a higher and more reasonable concentration, as collisional thermalization leads to core formation, boosting tidal mass loss. Our SIDM benchmarks also predict more diffuse stellar distributions, resulting in better agreement with measurements. We have shown the newly-observed DF2 and DF4 are more naturally to be realized in SIDM than in CDM scenarios.

We have also tested a cored CDM satellite halo, motivated by simulations with strong baryonic feedback, and found that it cannot survive in the host’s tides. This further makes SIDM a compelling case for explaining ob-
servations of the dark matter-deficient galaxies through tidal stripping, although more thorough investigations along these lines are required. There are other promising directions we can explore in the future. It is interesting to study correlations between orbital and halo parameters of the satellites. Cosmological simulations are necessary to understand formation and growth of NGC 1052-like systems. Observations of more dark matter-deficient galaxies, see, e.g. [84], will further help test the nature of dark matter.

We would like to thank Ran Huo and Go Ogiya for useful discussions. HBY was supported by the U.S. Department of Energy under Grant No. [810] and in part by the U.S. National Science Foundation under Grant No. NSF PHY-1748958 through the “From Inflation to the Hot Big Bang” KITP program. HA was supported by NSF PHY-1748958 through the “From Inflation to the Hot Big Bang” KITP program, the National Key Research and Development Program of China under Grant No. 2017YFA0402204 and Tsinghua University Initiative Scientific Research Program.

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