A Disk and No Signatures of Tidal Distortion in the Galaxy “Lacking” Dark Matter NGC 1052-DF2

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Abstract

Using ultra-deep imaging ($\mu_g = 30.4$ mag arcsec$^{-2}$; $3\sigma$, $10'' \times 10''$), we probed the surroundings of the first galaxy “lacking” dark matter (DM) KKS2000[04] (NGC 1052–DF2). Signs of tidal stripping in this galaxy would explain its claimed low content of DM. However, we find no evidence of tidal tails. In fact, the galaxy remains undisturbed down to a radial distance of 80″. This radial distance triples previous spatial explorations of the stellar distribution of this galaxy. In addition, the distribution of its globular clusters (GCs) is not extended in relation to the bulk of the galaxy (the radius containing half of the GCs is 21″). We also found that the surface brightness radial profiles of this galaxy in the g and r bands decline exponentially from 35″ to 80″. Together with a constant ellipticity and position angle in the outer parts of the galaxy, this strongly suggests the presence of a low-inclination disk. This is consistent with the evidence of rotation found for this object. This finding implies that the dynamical mass of this galaxy is a factor of 2 higher than previously reported, which brings the DM content of this galaxy in line with galaxies of similar stellar mass.

Unified Astronomy Thesaurus concepts: Low surface brightness galaxies (940); Galaxy formation (595); Dark matter (353)

Supporting material: data behind figures

1. Introduction

Dark matter (DM) is a key constituent in the currently-favored models of galaxy formation. Consequently, the claimed existence of two old and long-lived galaxies “lacking” DM (van Dokkum et al. 2018b, 2019) in the field of view (FOV) of the massive elliptical galaxy NGC 1052 has sparked a lot of controversy (Martin et al. 2018; Laporte et al. 2019; Monelli & Trujillo 2019; Nusser 2019; Trujillo et al. 2019, to name a few). These galaxies have been argued to have a stellar versus dark matter mass ratio of ~1, while for similar galaxies the observed ratios are $\lesssim$0.1 (e.g., Mancera Piña et al. 2019; Müller et al. 2020). Their existence could imply a challenge to the current galaxy formation paradigm because without DM the gas would not have collapsed and formed stars.

A growing number of theoretical studies suggest an explanation for the existence of these galaxies within the current cosmological paradigm: tidal stripping of the DM of these galaxies (Ôgiya 2018; Nusser 2020; Yang et al. 2020; Doppel et al. 2021; Jackson et al. 2021; Macciò et al. 2021). In a recent paper, Montes et al. (2020, hereafter, M20) found that the second galaxy “lacking” DM, NGC 1052–DF4, shows tidal tails pointing to an interaction with its nearby neighbor, NGC 1035. Because stars are more centrally concentrated than the DM, this means that tidal stripping has removed a significant fraction of the DM before starting to affect the stars of the galaxy.

The current cosmological paradigm, Lambda Cold Dark Matter ($\Lambda$CDM), predicts significant numbers of faint stellar streams in the outskirts of the majority of nearby massive galaxies (e.g., Bullock & Johnston 2005; Cooper et al. 2010). These structures start to show up at surface brightness fainter than 30 mag arcsec$^{-2}$. However, the detection and characterization of faint substructures in stellar halos is still a work in progress because their intrinsic low surface brightness prevents a complete census of these structures.

In this paper, we take advantage of ultra-deep observations and recent advances in low surface brightness data processing to explore the tidal stripping scenario in KKS2000[04], which is better known as NGC 1052–DF2 (for convenience, this is the name that we will use throughout this paper). The presence of tidal tails surrounding NGC 1052–DF2 will serve as the smoking gun of ongoing tidal disruption and will therefore explain the “lack” of DM observed in the first galaxy of this kind. We follow the same steps as in M20 to search for signs of interaction in this galaxy. Section 2 presents the data used in this work. We then explore the distribution of GCs in Section 3 because tidal stripping will place them along the orbit of the galaxy. Next, we explore the stellar light of the galaxy, deriving its surface brightness profiles in Section 4.1 and its shape in Section 4.2. Finally, we discuss the implications of our findings for the claimed rotation of the galaxy (Section 5.1) and its association with its closest (in projection) neighbors (Section 5.2). All of the magnitudes in this work are given in the AB magnitude system.

2. Data

The data that we have used in this paper come from three different facilities: the Hubble Space Telescope (HST) and two ground-based telescopes: the 10.4 m Gran Telescopio Canarias (GTC) and the 2.5 m Isaac Newton Telescope (INT). We describe the details of each observation in the following subsections.
2.1. Hubble Space Telescope Imaging

NGC 1052–DF2 was observed with HST ACS Wide-Field Channel (WFC) as part of the program GO-14644 (PI: van Dokkum), which is available through the MAST archive. The data consists of one orbit in the F606W and one in the F814W band. The total exposure time is 545 s in F606W and 580 s in F814W.

The data reduction of the HST imaging of NGC 1052–DF2 is described in detail in Trujillo et al. (2019) and is summarized below. The charge transfer efficiency corrected data were downloaded from MAST and flc files were used to build the final drizzled mosaics with Astrodrizzle (Gonzaga et al. 2012). To estimate the sky, we thoroughly masked the images using a combination of NoiseChisel (Akhlaghi & Ichikawa 2015) and manual masking of the galaxy. The centroid of the sky distribution derived using the masked images was calculated using bootstrapping. Finally, to mitigate the gradients present in the images, NoiseChisel was used to generate a final sky background model of the final co-added images that was subtracted from the images.

Following M20, we use these high-resolution HST observations together with photometry from the GTC HiPERCAM deep data to characterize and potentially find new GCs around NGC 1052–DF2.

2.2. Deep Ground-based Imaging

One of the biggest challenges in low surface brightness imaging is to process ultra-deep observations in a manner that preserves the faint light of the object of interest while correcting for all systematic effects introduced by the instrument/telescope. In this section, we describe the data reduction performed for our ground-based ultra-deep imaging. Both the data acquisition and data processing are aimed at preserving the low surface brightness light around NGC 1052–DF2. Most of the reduction steps are common for both datasets and are described in the following. Specific steps for each of the telescopes are discussed later.

The dithering pattern is a key step for obtaining ultra-deep images. NGC 1052–DF2 was observed by the GTC and INT following the dithering strategy outlined in Trujillo & Fliiri (2016), which aimed to reduce scattered light from the telescope structure as much as possible. In short, this consists in a dithering pattern with large steps (typically the size of the source under investigation) and whenever possible rotation of the camera. This ensures that we achieve the flat background that is required for our goals.

Bias frames were taken the same night of the observations as part of the different observing programs. The master bias frames were created as the 3σ-clipped mean of the individual frames and subtracted from the original images. The flat-field frames are derived using the same science exposures obtained for this work. The bias-corrected CCD frames present steep gradients that make the proper masking of the sources difficult in those science frames, which is a crucial step to achieve an accurate flat-field correction. For this reason, the flat-field frames were built following a two-step process. First, we derive a preliminary flat by stacking each bias-corrected frame. This preliminary flat is used to correct each CCD frame to flatten and consequently properly mask the science exposures. Second, we combine these masked and normalized images to create the final master flat-field frames.

We then performed the astrometric calibration of the different frames. We used the astrometry.net software (Lang et al. 2010) to produce an approximate astrometric solution, later refining it with SCAMP (Bertin 2006).

Once all of the frames were corrected of all systematic effects and in a common astrometric solution, they were resampled into a common grid using SWarp (Bertin 2010) and stacked using a 3σ-clipped mean into a final image, one per filter.

2.2.1. GTC HiPERCAM Images

HiPERCAM (Dhillon et al. 2018) is a quintuple-beam, high-speed astronomical imager that is able to obtain images of celestial objects in five different filters (u, g, r, i, z) simultaneously. The image area of each of the five CCDs is 2048 × 1024 pixels (2/7 × 1/4; 1 pixel = 0.0708) divided into four channels of 1024 × 512 pixels. NGC 1052–DF2 was observed on the 2019 January 11. The whole reduction process was done within a controlled and enclosed software environment, as described in Akhlaghi et al. (2021).

The data reduction of the NGC 1052–DF2 images follows the steps detailed in M20 for NGC 1052–DF4. After the standard calibration per CCD channel (bias and flat-field), each set of four channels were assembled into a single image. The different exposures that went into the final images were visually inspected and those with low quality or strong gradients were rejected. The photometric calibration of these images was done using SDSS DR12 (Alam et al. 2015). The final exposure time is 0.6 hr for each band, corresponding to point-like source depths (5σ in 2″ diameter apertures) of: 25.32 ± 0.05, 24.69 ± 0.05, 24.63 ± 0.07, 24.18 ± 0.06, 23.71 ± 0.06, in the u, g, r, i, z bands, respectively. The sky subtraction was done by subtracting a constant value that was computed from the masked image.

Unfortunately, the FOV of HiPERCAM is comparable to the size of the galaxy, which makes it impossible to reliably measure the sky. This results in over-subtraction in the outer parts of the galaxy. Therefore, we will use these images to study only the photometry of the GC system around NGC 1052–DF2.

2.2.2. INT Images

The Isaac Newton Telescope is a 2.5 m telescope that is situated in the Roque de los Muchachos Observatory on the island of La Palma. This telescope is equipped with a wide-field camera (WFC) that is mounted at the prime focus, providing imaging over a 33′ FOV with a wide variety of broad- and narrow-band filters. The WFC consists of four thinned EEV 2k × 4k CCDs. The pixel scale of the camera is 0″33. The data were taken between 2020 October 12 and 16 in two different filters, g and r, for a total exposure time of 4.4 hr and 3.2 hr, respectively.

In this case, after following the data reduction outlined above, the photometric calibration of the images was done using the SDSS DR15 (Aguado et al. 2019). Thanks to the high quality of the flat-field correction, the sky subtraction was done

8 https://mast.stsci.edu/portal/Mashup/ Clients/ Mast/ Portal.html
7 Using the code Bootmedian, available at https://github.com/Borlaff/ bootmedian.
8 Dome or twilight flats can introduce gradients in the data due to inhomogeneities in illumination. Using the same science images to derive the flat-field frames ensures that we do not introduce gradients (e.g., Trujillo & Fliiri 2016).
by using only an average constant applied to the entire image.
No gradients were present in the final co-adds of each band.

The nominal depth of the final images measured in 10^6 × 10^6 boxes is 30.4 and 29.5 mag arcsec^{-2} in the g and r bands (3σ above the background), respectively, measured using the method in Appendix A in Román et al. (2020). For comparison, the limiting surface brightness (3σ; 12^6 × 12^6) of the Dragonfly images in the field of NGC 1052 are between μ_{g}/r = 27.4 and 28.0 mag arcsec^{-2} (Merritt et al. 2016) and μ_{r} = 28.5 mag arcsec^{-2} in Müller et al. (2019) (3σ; 10^6 × 10^6).

2.3. Scattered Light Removal from Nearby Stars

The careful modeling and removal of stars in deep images is now a common technique in low surface brightness science (e.g., Slater et al. 2009; Trujillo & Fliri 2016; Infante-Sainz et al. 2020; Montes et al. 2021). To reliably explore low surface brightness features around NGC 1052–DF2, it is key to remove the light scattered by the brightest objects in the image. In fact, there is the bright star HD 16873 (R.A. = 2h42m9.3, decl. = −8°22′32″218, V = 8.34 mag), ~350″ to the east of NGC 1052–DF2, which creates a source of extra light contamination that can bias our results. The removal of this scattered light contamination is particularly imperative for the images where we are exploring the distribution of light around NGC 1052–DF2: the INT g and r images.

To correct for this scattered light, we first need to model the 2D profile of the star. We use the software ellipse in IRAF. ellipse fits elliptical isophotes to the 2D images of sources using the method described in Jedrzejewski (1987).

Prior to modeling the star, we need to carefully mask the foreground and background sources because their presence can affect the fitting. For this, we used a two-step SExtractor setting: a “hot+cold” mode (Rix et al. 2004; Montes et al. 2021). The “cold” mode masks extended sources, while the “hot” mode is optimized to detect the more compact and faint sources that are embedded within the galaxy light. We run SExtractor in a deep combined INT g+r image. The “cold” mask was further expanded by 8 pixels, while the “hot” was expanded by 2 pixels, leaving the bright star that we want to model unmasked. Because the PSF in our INT images is highly asymmetric, which is especially noticeable in bright stars, we only modeled the section of the star that is close to NGC 1052–DF2, masking the rest manually. This way we ensure that the output model is suitable for our purposes. In addition, we manually masked NGC 1052–DF2 to cover any diffuse light that has remained unmasked from the above procedure that could contaminate the flux of the star at large radius.

Once ellipse was run in the masked image, we created the model of the star with bmodel and subtracted it from the images. We also modeled and subtracted two fainter stars ~150″ to the east and west of NGC 1052–DF2 (R.A. = 2h41m36;88 decl. = −8°24′56″80, and R.A. = 2h41m54;47 decl. = −8°24′20″80).

3. The Spatial Distribution of the Globular Cluster System of NGC 1052–DF2

Due to the compact sizes (half-light radii of a few parsecs) and masses of globular clusters (GCs, 10^4–10^6 M_·; Harris 1996), they appear as good tracers of the properties of their host galaxy because they are easily observable in distant system even at large radial distances (see Brodie & Strader 2006).

The spatial distribution of the GC system of a galaxy reveals clues about its present state. In an accretion event, the stripped material is placed along the orbit of the parent satellite galaxy, forming tidal streams (e.g., Toomre & Toomre 1972; Johnston et al. 1996). In the same way, the GCs will also be placed along the orbit. Therefore, exploring their observed spatial distribution can indicate if this process is happening and the direction of the orbit.

One of the goals of this work is to explore whether the GCs align through a particular direction, suggesting that NGC 1052–DF2 is undergoing tidal stripping or, on the contrary, the GCs are more spherically distributed around NGC 1052–DF2, which is expected if the galaxy is not experiencing any interaction.

3.1. GC Selection

In this section, we combine the high resolution of HST with the multicolor information from HiPERCAM to identify new GCs for NGC 1052–DF2. Recent works have shown the increased effectiveness of identifying GCs using more information from their spectral energy distributions (Montes et al. 2014; Muñoz et al. 2014).

Recently, van Dokkum et al. (2018b) and Shen et al. (2021b) confirmed spectroscopically 12 GCs in NGC 1052–DF2. Here, we try to identify more GCs following the steps in M20. First, we run SExtractor (Bertin & Arnouts 1996) on the HST images in dual-mode using F814W as the detection image. In the same way, SExtractor was also run in the HiPERCAM images using r as our detection image. Both catalogs were matched based on the position of the sources in the sky.

We pre-selected GC candidates thanks to the high-resolution of the HST data. This selection is based upon the properties of the confirmed GCs in Shen et al. (2021b). In addition to the morphology selection with HST similar to that in M20, we also used the measured F606W – F814W color to eliminate sources that are clearly too red to be a GC candidate.

The pre-selection criteria is as follows.

1. 0.1 < FWHM < 0.23.
2. 0 < ellipticity < 0.23.
3. 21 < m_{F606W} < 24 mag.
4. m_{F606W}–m_{F814W} < 0.8 mag.

The aim of this selection is to find GCs that are similar to the confirmed GCs, while allowing for sources that might have been too faint for spectroscopic follow-up. Figure 1 shows the histograms of FWHM, ellipticity and m_{F606W} of all the sources detected with SExtractor (filled in gray), the confirmed GCs in Shen et al. (2021b) (dashed in magenta) and the GC candidates based in our preliminary selection (filled in mint green). In total, 19 objects fall within this pre-selection, including 11 objects in Shen et al. (2021b) (see below).

The next step is to use the colors of the GCs from HiPERCAM to narrow down the selection. Figure 2 shows the (u–r) versus (v–z) color–color diagram for the pre-selected GC candidates (mint green) from our preliminary selection. We have marked 11 GCs in Shen et al. (2021b) as the magenta circles.10 As seen in Figure 2, the confirmed GCs fill a very narrow region in the color–color space. Therefore, we further

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9 We have rerun the analysis with the images of NGC 1052–DF2 from GO-15851 (PI: van Dokkum) and the results obtained do not change with this deeper dataset.
10 One of the GCs identified in Shen et al. (2021b) (GC-39) is outside the FOV of HiPERCAM, and has been added manually after this step.
narrowed down the initial selection to objects within $1.4 < u - r < 2.2$ mag and $0.24 < r - z < 0.51$ mag (blue box). These ranges in color are based on the $\pm 2\sigma$ around the median colors of the confirmed GCs (magenta circles), with $\sigma$ being their dispersion in color. One of the spectroscopically confirmed GCs (C-14) fall outside this selection box because it appears to be blended with another source and therefore its photometry might be contaminated, but was not discarded from the final selection.

We identified 14 GCs, two in addition to the ones confirmed spectroscopically. The coordinates and magnitudes of all the objects are listed in Table 1. The magnitudes are corrected by the extinction of our Galaxy (Schlafly & Finkbeiner 2011): $A_u = 0.10, A_r = 0.08, A_z = 0.06, A_r = 0.03, A_{F606W} = 0.06$ and $A_{F814W} = 0.04$. Two of the GCs (C-6 and C-10) have ground-based magnitudes that are brighter than their HST magnitudes, which suggests that they are affected by blending.

3.2. Spatial Distribution of the GCs

In this section, we address the spatial distribution of the GCs in NGC 1052–DF2 to obtain clues about the interaction state of the galaxy. As a satellite galaxy is interacting with a massive galaxy, the stripped material (both stars and GCs) of the satellite will be deposited along its orbit. This is the case for NGC 1052–DF4, where its GC system aligns in a particular axis along the galaxy (see Figure 4 in M20) and the spatial distribution of GCs is more extended than that of the stellar body of the galaxy.

Figure 3 shows an RGB image created using the HiPERCAM $g$, $r$ and $z$ and a black and white INT $g$ image for the background. The highlighted sources are the 12 confirmed GCs from Shen et al. (2021b, magenta) and the two new candidates obtained in the previous section (mint green). From Figure 3, it is evident that the distribution of GCs of NGC 1052–DF2 is remarkably different from that of NGC 1052–DF4. In particular, the spatial distribution of the GCs in NGC 1052–DF2 is more concentrated. The radius containing half of the GCs ($R_{g,GC}$) is $21.0 \pm 0.1$ kpc. This is similar to the value of the effective radius published for the stellar light distribution of this galaxy using HST data ($R_e = 22.6');$ van Dokkum et al. (2018b). In contrast, the radius containing half of the GCs in NGC 1052–DF4 was nine times larger than the $R_e$ of the stellar light (M20). Furthermore, all but two of the GCs are contained in the stellar body of the galaxy ($<3R_e$). This concentrated distribution of GCs with respect to the galaxy body (i.e., $R_{GC}/R_e \sim 1$) has been found in other UDGs that present no signatures of tidal distortions (see Saifollahi et al. 2021). There is no preferred direction, or axis, in the spatial distribution of GCs in this galaxy.
6, as reported in van Dokkum et al.2018b

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Table 1
Confirmed and Candidate GCs of NGC 1052–DF2

| ID     | Other ID | R.A.        | Decl. | $m_v$ (mag) | $m_r$ (mag) | $m_i$ (mag) | $m_r$ (mag) | $m_{F814W}$ (mag) | $m_{F814W}$ (mag) |
|--------|----------|-------------|-------|-------------|-------------|-------------|-------------|-----------------|-----------------|
| C-1b   | GC-59    | 23°41'48".09 | −8°24'56".82 | 24.23 ± 0.28 | 22.86 ± 0.04 | 22.58 ± 0.03 | 22.22 ± 0.07 | 22.82 ± 0.01 | 22.38 ± 0.01 |
| C-2b   | GC-71    | 23°41'45".14 | −8°24'22".31 | 24.51 ± 0.20 | 22.79 ± 0.03 | 22.47 ± 0.03 | 22.14 ± 0.06 | 22.66 ± 0.01 | 22.26 ± 0.01 |
| C-3b   | GC-73    | 23°41'48".22 | −8°24'17".49 | 22.96 ± 0.06 | 21.55 ± 0.01 | 21.31 ± 0.01 | 20.96 ± 0.02 | 21.49 ± 0.01 | 21.15 ± 0.01 |
| C-4    | GC-93    | 23°41'47".61 | −8°24'18".21 | 25.59 ± 0.61 | 23.87 ± 0.08 | 23.63 ± 0.07 | 23.12 ± 0.15 | 23.73 ± 0.03 | 23.33 ± 0.03 |
| C-5b   | GC-77    | 23°41'46".55 | −8°24'13".36 | 23.54 ± 0.09 | 21.96 ± 0.02 | 21.78 ± 0.01 | 21.30 ± 0.03 | 21.98 ± 0.01 | 21.61 ± 0.01 |
| C-6b   | GC-85    | 23°41'47".75 | −8°24'05".30 | 20.89 ± 0.13 | 19.42 ± 0.02 | 19.10 ± 0.02 | 18.73 ± 0.04 | 23.29 ± 0.01 | 21.97 ± 0.01 |
| C-7    | GC-91    | 23°41'45".91 | −8°23'56".43 | 25.77 ± 0.73 | 24.09 ± 0.09 | 23.67 ± 0.08 | 23.20 ± 0.18 | 23.82 ± 0.03 | 23.39 ± 0.03 |
| C-8b   | GC-92    | 23°41'42".17 | −8°23'53".27 | 24.20 ± 0.25 | 22.43 ± 0.02 | 22.16 ± 0.02 | 21.72 ± 0.05 | 22.44 ± 0.01 | 22.04 ± 0.01 |
| C-9b   | GC-92    | 23°41'46".89 | −8°23'50".69 | 23.32 ± 0.12 | 21.96 ± 0.02 | 21.61 ± 0.02 | 21.24 ± 0.04 | 23.25 ± 0.01 | 21.83 ± 0.01 |
| C-10b  | GC-93    | 23°41'46".72 | −8°23'50".75 | 21.87 ± 0.26 | 20.08 ± 0.04 | 19.78 ± 0.03 | 19.36 ± 0.07 | 22.91 ± 0.02 | 22.53 ± 0.02 |
| C-11b  | GC-98    | 23°41'47".34 | −8°23'34".54 | 24.44 ± 0.24 | 22.90 ± 0.03 | 22.65 ± 0.03 | 22.27 ± 0.07 | 22.85 ± 0.01 | 22.44 ± 0.01 |
| C-12b  | GC-101   | 23°41'45".20 | −8°23'27".73 | 24.56 ± 0.28 | 22.95 ± 0.04 | 22.66 ± 0.04 | 22.39 ± 0.09 | 22.98 ± 0.02 | 22.54 ± 0.01 |
| C-13b  | GC-39    | 23°41'45".07 | −8°25'24".87 | ...          | ...           | ...          | ...          | 22.31 ± 0.01 | 21.93 ± 0.01 |
| C-14b  | GC-80    | 23°41'46".23 | −8°24'07".32 | 23.54 ± 0.12 | 22.35 ± 0.03 | 22.22 ± 0.02 | 21.70 ± 0.05 | 22.56 ± 0.01 | 22.17 ± 0.01 |

Notes.

* ID in Shen et al. (2021b).
* GC spectroscopically confirmed in Shen et al. (2021b).

However, from Figure 3, there is a hint that a larger number of GCs are located toward the northern side of the galaxy. To explore whether this excess is statistically significant, we computed its significance by deriving the probability that the GCs are distributed in that way using a binomial distribution. We divided the GCs north and south from the minor axis of the galaxy (PA = −31°, defined in Section 4.1). Nine (eight) clusters are north of the minor axis and five (four) are south, for the total (spectroscopically confirmed) sample of GCs. We find a probability of 0.64 ± 0.13 for the total sample and 0.66 ± 0.14 for the spectroscopically confirmed (Shen et al. 2021b) sample. Within the errors (∼1σ), the spatial distribution of the GCs is consistent with the null hypothesis (i.e., the GCs are distributed with similar probability in the two sides of the galaxy, probability of 0.5). Therefore, we cannot reject the idea that the observed distribution of GCs in this galaxy is compatible with a random distribution.

4. The Stellar Component of NGC 1052–DF2

In this section, we use ultra-deep INT imaging to address the question of whether or not this galaxy presents tidal features that can point to tidal interactions with one of the nearest massive galaxies and explain its seemingly low content of DM.

4.1. Surface Brightness Profiles

The goal of this paper is to investigate whether NGC 1052–DF2 shows any signs of interaction with a massive nearby neighbor. Note that this galaxy’s distance has remained controversial and therefore which massive galaxy it is associated with is unclear. While van Dokkum et al. (2018b, 2018a) claimed a distance of ∼20 Mpc, which connects it with NGC 1052,11 Trujillo et al. (2019) and Monelli & Trujillo (2019) place the galaxy at ∼13.5 Mpc, which associates it with the spiral galaxy NGC 1042.12

In surface brightness profiles, signs of interactions will appear as an excess of light at large radius and deviations from the morphology of the inner parts of the galaxy (e.g., Johnston et al. 2002). To explore whether or not this is the case for NGC 1052–DF2, we derived the radial profiles for the INT images using ellipse. This provides the median intensity, ellipticity and position angle (PA) for each of the fitted isophotes.

Beforehand, we need to mask thoroughly the image. For this, we used the same procedure described in Section 2.3. In this

11 This same group has claimed a distance of 22.1 ± 1.2 Mpc using deeper HST data (Shen et al. 2021a).
12 The revised surface brightness fluctuation estimation in Zonoozi et al. (2021) places an upper limit to the distance to NGC 1052–DF2 of 17 Mpc.
case, the “cold” mask was further expanded by six pixels while the “hot” was expanded by two pixels, leaving NGC 1052–DF2 unmasked in the “cold” mask. This leaves the diffuse light of the galaxy unmasked, while all compact sources such as background galaxies and GCs are masked. The mask is shown in the Appendix.

Once we have masked all of the contaminant sources, we derived the radial profiles for the INT g and r images with ellipse. In this case, we run ellipse in three steps, similar to the approach followed in Huang et al. (2018). We first ran the task while allowing all parameters to vary freely. In the second run, we fixed the centers to the median centers of the isophotes returned by ellipse in the first iteration. In the third iteration, we hold the ellipticity and PA fixed to derive the surface brightness profiles in both g and r bands. This last step ensures that we reach regions where the signal-to-noise ratio is low.

Figure 4 shows the output of ellipse for the g and r bands. In the left-hand panel, a postage stamp of a 200″ × 200″ region around NGC 1052–DF2 is shown with the fitted ellipses overplotted. The right-hand panel shows the ellipticity (top) and PA (bottom) as a function of the semimajor axis (SMA).

The 1D radial surface brightness profiles as a function of the SMA are shown in the middle panel, to a radius of ∼80″. The shaded regions represent the error in each elliptical isophote. The error is computed as a combination of the error in the intensity of each isophote, as provided by ellipse, and the error of the sky given by the distribution of background pixels in each image. The 1D surface brightness profiles in both bands are derived with a fixed ellipticity and PA (0.17 and −31°, respectively, shown as the pink lines in the right-hand panel).

These profiles derived for NGC 1052–DF2 show that the structure of the galaxy is more complex than previously reported. Figure 5 shows that the observed profile in the g-band is well described with a Sérsic model in the inner ∼30″ with $n = 0.6$. However, this cannot provide a faithful description of the galaxy at larger radius. Meanwhile, an exponential fit ($R_e = 24.4 \pm 0.1$) cannot reproduce the galaxy in its inner regions. Interestingly, the fact that the outer exponential cannot describe the inner regions suggests that if the outer part of the galaxy is a disk structure, then it is truncated in the central region of the galaxy. Exponentially truncated disks in their inner regions have been proposed by Breda et al. (2020) to explain the structure of many spiral galaxies.

The exponential decline seen in Figure 4 is reinforced by the behavior of the ellipticity and PA with radius. Once they reach $r \sim 35″$, they become roughly constant. Signs of interaction or a warp in the galaxy will show up as an increase in PA and ellipticity with radius, which are not seen here. The change in the PA with radius seen within 35″ was also reported in Müller et al. (2019) for
this galaxy. From the profiles in Figure 4, we computed the new effective radius of the galaxy to be $R_e = 28.4 \pm 0.3$ kpc.

In addition, we derived the radial $g-r$ profile and the stellar mass density profile of NGC 1052–DF2. This is shown in Figure 6. In the left-hand and middle panels, we plot the $g-r$ color profile to a radius of 70". (beyond this radius, the errors are larger than 0.2 mag and are therefore not reliable). The left-hand panel shows the color estimate for different metallicities derived from the Vazdekis et al. (2016) models for a fixed age of 8.5 Gyr (i.e., the age of NGC 1052–DF2 estimated spectroscopically, Ruiz-Lara et al. 2019) as horizontal dashed lines. The black-horizontal dashed line corresponds to the metallicity derived for the central part of this galaxy in Ruiz-Lara et al. (2019) using spectroscopy. Similarly, the dashed lines in the middle panel are the different colors of the models for a fixed metallicity, $[\text{Fe}/\text{H}] = -1.18$, but varying age. The right-hand panel of Figure 6 shows the stellar mass density profile for this galaxy. To derive this value, we apply Equations (1) and 2 in Montes & Trujillo (2014) (see also Bakos et al. 2008) to link the observed surface brightness in the $g$-band to a stellar mass to light ($M/L$) ratio. The $M/L$ ratio was derived from the prescriptions given in Roediger & Courteau (2015). For this, we assumed a Chabrier (2003) initial mass function.

The color profile shows a clear negative gradient with radius. Two different scenarios could explain why NGC 1052–DF2 becomes bluer with radius. In Figure 6, we interpret the color gradient as an age and/or a metallicity gradient. We cannot rule out any of these two alternatives because it is not possible to disentangle between age and metallicity with only one color. However, the lack of H1 detection in this galaxy (Chowdhury 2019) suggests that it is similarly old everywhere and that the color trend could be explained as a metallicity gradient along its radial profile. In fact, there is a hint at a metallicity gradient, but no age gradient, in the MUSE data of NGC 1052–DF2 in Fensch et al. (2019). Assuming that the age of the galaxy is the same along its entire structure, the color gradient would indicate that the stellar population is getting more metal-poor toward the outskirts. If this was the case, then the derived metallicity using spectroscopy would only be representative of the innermost parts of the galaxy ($<1R_e$).

The stellar mass density profile also exhibits the two components, Sérsic and exponential, that are present in the surface brightness profiles. There is a shallow core down to $\sim 23''$, followed by an exponential decline down to the limit where the data allows us to reliably trace the galaxy (i.e., down to 0.07 $M_\odot$ pc$^{-2}$).

4.2. The Shape of NGC 1052–DF2

Matter stripped from satellite galaxies forms tidal tails, which will eventually become completely unbound and form larger tidal features. In N-body simulations (e.g., Klimentowski et al. 2009), dwarf galaxies orbiting a massive host galaxy potentially show two tidal tails emanating from the two opposite sides of the dwarf as the particles are seen to move in the direction of the tidal forces, creating a shape reminiscent of an $S$.

To explore whether we can rule out the presence of tidal features up to the depth of our data, we derive the isocountours of this galaxy at four different surface brightness limits. For this, we use our deepest image: the INT $g$-band. As in M20, we used matplotlib's contour to draw the contours in the left-hand panel of Figure 7. We use the same mask derived in Section 4.1 and convolve the image with a Gaussian of $\sigma = 5$ pix (1 pix = 0.333 arcsec) to further enhance structures that might be buried in the noise of the outer parts of the galaxy. The different surface brightness levels that we explore are: 26.0 (darker teal shade), 27.0, 28.0 and 29.5 mag arcsec$^{-2}$ (lightest teal shade).

From the contours in Figure 7, we can confirm the results in Section 4.1: the outer parts of NGC 1052–DF2 appear symmetric and do not show any sign of tidal stripping down to a surface brightness of 29.5 mag arcsec$^{-2}$. This image supports what we found for the surface brightness profiles in the previous section: a structure compatible with a low-inclination disk.

The limiting surface brightness of the image in the $g$-band (30.4 mag arcsec$^{-2}$; 3$\sigma$ in $10'' \times 10''$ boxes) can be used to make a rough estimation (upper limit) of the amount of stellar mass that could be hidden under our detection limit. The outer parts of the galaxies have a color $g-r \sim 0.4$. At 30 mag arcsec$^{-2}$, this is equivalent to 0.03 $M_\odot$ pc$^{-2}$. Therefore, if there were any stellar

![Figure 6. Left-hand and middle panel: the INT $g-r$ color profile of NGC 1052–DF2 shows a clear negative gradient. The horizontal dashed lines in the left-hand panel indicate the $g-r$ color of the Vazdekis et al. (2016) models at a fixed age of 8.5 Gyr and different $[\text{Fe}/H]$ (as labeled), while in the middle panel they indicate different ages at a fixed metallicity of $[\text{Fe}/H] = -1.18$. Right-hand panel: Stellar mass density profile of NGC 1052–DF2.](image)
mass with such density in the radial range between 80″ to 100″ (i.e., ~9000 arcsec²), then that would correspond to a total stellar mass in that region of ~1.1 × 10⁶ M☉ (at 13 Mpc) or ~2.5 × 10⁷ M☉ (at 20 Mpc). In other words, the amount of potentially stripped stellar mass of DF2 is ~2% or less of its total stellar mass.

4.3. Tidal Radius of NGC 1052–DF2

Tidal forces are dependent on the gradient of a gravitational field, and so tidal effects are usually limited to the immediate surroundings of a galaxy. The two most prominent galaxies in the FOV, and therefore the ones that could produce tidal stripping in NGC 1052–DF2, are NGC 1052 and NGC 1042. While van Dokkum et al. (2018b) used the vicinity of NGC 1052–DF2 to NGC 1052 (13′7 in projection) to support its distance of 20 Mpc, Monelli & Trujillo (2019) find two groups in the same line of sight, one at 13.5 Mpc, containing NGC 1042, and one at ~20 Mpc, containing NGC 1052. They associated NGC 1052–DF2 to the former (NGC 1042), at a projected separation of 20′.5.

Even though the projected physical distance of NGC 1052–DF2 to both galaxies would be equivalent to 80 kpc, the total mass of NGC 1052 (M₁₀⁵₂,dyn(<40 kpc) = (4.14 ± 0.71) × 10¹¹ M☉, Forbes et al. 2019) is more than 10 times larger than that of NGC 1042 (M₁₀⁴₂,dyn(<8 kpc) = 3.0±0.3 × 10¹⁰ M☉). Trujillo et al. (2021, in preparation). To estimate the dynamical mass of NGC 1042 to the same radial distance as NGC 1052 (i.e., 40 kpc), we can assume that the rotational velocity of NGC 1042 is constant. Using this, the dynamical mass is proportional to the radius. Therefore, the dynamical mass of NGC 1042 (very likely an upper limit due to our assumption) is M₁₀⁴₂,dyn(<40 kpc) = 1.5±0.5 × 10¹¹ M☉. Given this mass difference between the two galaxies, we would expect to see a different tidal effect on NGC 1052–DF2, depending on its associated host.

To explore where we expect to see the tidal features for both NGC 1052 and NGC 1042, we calculated the tidal radius of NGC 1052–DF2 produced by each galaxy. The tidal radius identifies the radius where the tidal effects are expected to be important in the satellite and where we should be looking for tidal distortions. To derive the tidal radius (r_t) for NGC 1052–DF2, we follow Equation (5) in Johnston et al. (2002) but for the instantaneous r_{tidal}, that is, the tidal radius at the current position of the satellite from the parent galaxy assuming a circular orbit. This is given by:

\[ r_{\text{tidal,inst}} = D \times \left( \frac{m_{\text{dyn}}}{M_{\text{host,dyn}}} \right)^{1/3}. \] (1)

Figure 8 shows the expected tidal radii derived for NGC 1052 (in pink) and for NGC 1042 (in mint green) as elliptical rings. The elliptical rings encompass the range of radius from the uncertainties in the total masses of the galaxies. It is evident from the figure that the difference in mass between the two potential hosts will have a different impact in the satellite. The tidal radius produced by NGC 1042 is r_{1042} = 148±39 arcsec. Meanwhile, the tidal radius if the UDG was associated to NGC 1052 is r_{1052} = 55±17 arcsec, which is well within the observed extension of the galaxy in this work.

5. Discussion

In this paper, we study in detail the first galaxy “lacking” DM, NGC 1052–DF2, using ultra-deep images to assess if tidal stripping could explain its claimed low content of DM. In M20, we explored tidal stripping as an alternative scenario to explain the low DM content in NGC 1052–DF4. Our aim in this paper was to repeat the same analysis for NGC 1052–DF2. However, the distribution of GCs (Figure 4), the surface brightness profiles (Figure 4) and the contours (left-hand panel of Figure 7) of this galaxy show no signs of interaction. The lack of tidal features implies that currently there is no significant tidal stripping in this galaxy.

5.1. Evidence of Rotation in NGC 1052–DF2

Dynamical analyses of NGC 1052–DF2 have assumed that this galaxy is pressure supported (e.g., Martin et al. 2018; van Dokkum et al. 2018b; Laporte et al. 2019). However, if a significant rotation...
component is present, then it will influence the current dynamical mass estimate of this galaxy.

Dynamical studies of the stellar light of the innermost regions of this galaxy have found contradictory results. The lack of rotation reported in Danieli et al. (2019) is likely to be caused by the small FOV of the KCWI instrument (20″×16.5″) that coincides with the presence of the bulge-like structure seen in the radial profiles of Figure 4 at $R < 35″$. Meanwhile, evidence for rotation of NGC 1052–DF2 has been presented in Emsellem et al. (2019) and Lewis et al. (2020). Note that the rotation axis found in the stellar component by Emsellem et al. (2019) is almost perpendicular to the axis found in Lewis et al. (2020) using the GC kinematics. While the reason for this disagreement is not clear, we speculate that it might be caused by the limited FOV of MUSE (60″×60″) imaging only one side of the galaxy compared with the larger radial distances probed with the GCs.\footnote{We suggest that the MUSE results should be revisited taking into account the PA of the external parts of the galaxy found in this work.}

The profiles in Figure 4 show that at $R > 35″$, the galaxy presents a component that is best described with an exponential. This suggests the presence of a disk in NGC 1052–DF2 that only shows up in deep images (see also Müller et al. 2019). In the right-hand panel of Figure 7, we show the inner 240″×240″ region of NGC 1052–DF2 with the rotation map from Lewis et al. (2020) overplotted. The rotation map obtained from re-analyzing the dynamics of the GC system is in nice agreement with the disk structure at large radius. We indicated with the mint line the PA of the outer parts ($R > 35″$) of the galaxy derived from the \textit{ellipse} fits in Section 4.1. This stellar PA seems to be perpendicular to the projected rotation axis of the rotation map. To assess this, we have also plotted the PA of the rotation map and its errors as reported in Lewis et al. (2020) (pink area). Both angles agree within the errors.

The presence of a disk-like structure in the outer parts of the galaxy provides further evidence of the rotation of NGC 1052–DF2. We used Equation (9) in Lewis et al. (2020) to calculate a rough estimate of the dynamical mass of the galaxy considering the rotation component measured in that work. Using the axis ratio of the disk measured with \textit{ellipse} in Section 4.1, we can derive a rough estimate of the inclination angle $i$ of this galaxy using $b/a = \cos(i)$ (here we do not consider any thickness for the disk). That gives us an inclination angle of $34^{\circ} \pm 7^\circ$ degrees. The rotation parameters were taken from the analysis in Lewis et al. (2020): $v_{\text{rot}} = 12.44^{+4.40}_{-5.16}$ km s$^{-1}$ and $\sigma = 3.88^{+3.42}_{-2.72}$ km s$^{-1}$.}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure8.png}
\caption{Expected tidal regions on NGC 1052–DF2 produced by NGC 1042 (mint-green elliptical ring, bigger) and NGC 1052 (pink elliptical ring, smaller). The background is a SDSS image of the FOV around NGC 1052–DF2. The nearby massive galaxies, the elliptical NGC 1052 and the spiral NGC 1042, are labeled. For ease of view, we show a zoom-in of the 240″×240″ region around NGC 1052–DF2. The lack of tidal features around NGC 1052–DF2 does not favor the hypothesis that this UDG is physically bound to NGC 1052.}
\end{figure}
Under the assumption that the galaxy is at 20 Mpc, we found that the dynamical mass enclosed by the GCs is $M(<7.6 \text{ kpc}) = 9.0^{+17.1}_{-6.8} \times 10^9 \, M_\odot$. Assuming a stellar mass of $\sim 2 \times 10^7 \, M_\odot$, this corresponds to $M_{\text{DM}}/M_\ast = 4.5^{+3.6}_{-2.4}$. If a distance of 13.5 Mpc is assumed (Trujillo et al. 2019; Zonoozi et al. 2021), then the estimates are: $M(<5.1 \text{ kpc}) = 6.1^{+11.5}_{-4.5} \times 10^8 \, M_\odot$ and $M_{\text{DM}}/M_\ast = 12.1^{+23.0}_{-9.1}$, assuming a stellar mass of $5 \times 10^7 \, M_\odot$ (Trujillo et al. 2019). The dynamical mass derived here is a factor of 2.6 larger than that derived in van Dokkum et al. (2018b) for a distance of 20 Mpc, and a factor of 1.5 larger than in Trujillo et al. (2019) at 13.5 Mpc.

As discussed in Lewis et al. (2020), the presence of rotation in this galaxy is also evidenced by the presence of a disk component at large radius, which affects the inferred $M/L$ ratio and brings the DM content of NGC 1052–DF2 more in line with galaxies of similar stellar masses (e.g., Mancera Piña et al. 2019; Müller et al. 2020). Furthermore, a closer distance of $\sim 13.5 \text{ Mpc}$ would make even more room for DM in this galaxy, and would be far from “lacking” DM.

5.2. The Tidal Radius of NGC 1052–DF2 and its Distance

In Section 4.3, we discuss the estimated tidal radii of NGC 1052–DF2 depending on the two potential host galaxies: NGC 1042 at 13.5 Mpc (Trujillo et al. 2019) or NGC 1052 at 20 Mpc (van Dokkum et al. 2018b). Both radii were visually represented in Figure 8.

Our results suggest that if NGC 1052–DF2 was gravitationally bound to NGC 1052, then we would have already seen tidal features around this UDG. However, the lack of any sign of tidal stripping is not in contradiction with a potential association of NGC 1052–DF2 with NGC 1042, and is therefore consistent with the distance of 13.5 Mpc found in Trujillo et al. (2019) and Monelli & Trujillo (2019). One can argue that we are observing the projected distance between NGC 1052–DF2 and its host, which would be the minimum distance between both galaxies. The fact that we are not detecting any feature within a radius of 80′′ means that this would be the minimum tidal radius. This is a factor of $\sim 2$ larger than the $r_{\text{tid}}$ calculated in Section 4.3 and therefore we can infer that the distance between both galaxies has to be larger than $\sim 168 \text{ kpc}$. The virial radius of NGC 1052 is 390 kpc (Forbes et al. 2019). Consequently, we cannot fully reject the scenario where NGC 1052–DF2 and NGC 1052 are associated only on the basis of the absence of tidal features. However, the lack of tidal distortion is indicative that if they are associated, then NGC 1052–DF2 is in its initial infall into the group. If this was not the case, NGC 1052–DF2 would have already experienced the tidal forces of the massive galaxy or even been disrupted. This is in agreement with Forbes et al. (2019). The idea that the absence of tidal features indicates an initial infall of the UDG also holds if we use the dynamical mass derived in the previous section (Section 5.1). A higher dynamical mass (and therefore a larger amount of DM) will “shield” the UDG from the tidal forces produced by NGC 1052. The new tidal radius using the new dynamical mass estimate would be $(2.6)^{1/3} \times r_{1052}^{\text{tid}} = 75^{+10}_{-24} \text{ arcsec}$, which is at the limit of our ultra-deep imaging.

6. Conclusions

The existence of long-lived ($\sim 9 \text{ Gyr}$) and stable (without signatures of tidal distortion) galaxies “lacking” DM present a challenge in our understanding of galaxy formation. This is especially problematic if the galaxy inhabits a dense environment. Here, we explore the tidal stripping scenario to explain the claimed low content of DM in the first of this kind of galaxies: NGC 1052–DF2. We use ultra-deep data to image the outer parts of the galaxy down to $R \sim 80''$ (i.e., three times larger than previous imaging of this galaxy), finding no signs of tidal features. However, we see a disk-like structure from 35'' to 80'', which is in agreement with the rotation previously reported for this galaxy. The dynamical mass derived taking into account the rotation component is a factor 2.6 larger than in van Dokkum et al. (2018b) and is 1.5 larger than the one measured in Trujillo et al. (2019). This translates into a DM versus stellar mass ratio of $4.5^{+3.6}_{-2.4}$ at 20 Mpc ($R < 7.6 \text{ kpc}$) or $12.1^{+23.0}_{-9.1}$ at 13.5 Mpc ($R < 5.1 \text{ kpc}$), bringing the DM content of this galaxy more in line with other galaxies of similar stellar masses ($\gtrsim 10$, Mancera Piña et al. 2019; Müller et al. 2020).

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**Facilities:** HST(ACS), INT, GTC.

**Software:** Astropy (The Astropy Collaboration et al. 2018), SExtractor (Bertin & Arnouts 1996), SCAMP (Bertin 2006), S-Warp (Bertin 2010), Gnuastro (Akhlghhi & Ichikawa 2015), Maneage (Akhlghhi et al. 2021), photutils v0.7.2 (Bradley et al. 2019), pillow (van Kemenade et al. 2020), ellipse (Jedrzejewski 1987), numpy (Oliphant 2006), scipy (Virtanen et al. 2020), Astrodazzle (Gonzaga et al. 2012), Astrometry.net (Lang et al. 2010).

**Appendix Masking of NGC 1052–DF2**

Section 4.1 describes the procedure to create the mask that is used to derive the surface brightness profiles. Figure 9 shows this mask applied to a composite of an RGB HiPERCAM images and a black and white background from the $g$-band INT image.
Figure 9. Mask (teal regions) applied to a HiPERCAM color composite of a postage stamp of a region 140″ × 240″ around NGC 1052–DF2. The black and white background is the g-band INT image. This shows the thorough masking that is necessary in these deep images.

(The data used to create this figure are available.)

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