A distance of 13 Mpc resolves the claimed anomalies of the galaxy lacking dark matter

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Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT

The claimed detection of a diffuse galaxy lacking dark matter represents a possible challenge to our understanding of the properties of these galaxies and galaxy formation in general. The galaxy, already identified in photographic plates taken in the summer of 1976 at the UK 48-in Schmidt telescope, presents normal distance-independent properties (e.g. colour, velocity dispersion of its globular clusters). However, distance-dependent quantities are at odds with those of other similar galaxies, namely the luminosity function and sizes of its globular clusters, mass-to-light ratio and dark matter content. Here we carry out a careful analysis of all extant data and show that they consistently indicate a much shorter distance (13 Mpc) than previously indicated (20 Mpc). With this revised distance, the galaxy appears to be a rather ordinary low surface brightness galaxy ($R_e=1.4\pm0.1$ kpc; $M_\star=6.0\pm3.6\times10^7$ $M_\odot$) with plenty of room for dark matter (the fraction of dark matter inside the half mass radius is $>75\%$ and $M_{\text{halo}}/M_\star>20$) corresponding to a minimum halo mass $>10^9$ $M_\odot$. At 13 Mpc, the luminosity and structural properties of the globular clusters around the object are the same as the ones found in other galaxies.

Key words: galaxies: evolution — galaxies: structure — galaxies: kinematics and dynamics — galaxies: formation

1 INTRODUCTION

van Dokkum et al. (2018a) claim the detection of a galaxy lacking dark matter “consistent with zero” dark matter content. If confirmed, this could be one of the most important discoveries in Extragalactic Astrophysics in decades. The galaxy (popularized as NGC1052-DF2) is an extended ($R_e=22.6$ arcsec), very low central surface brightness galaxy with a pure stellar population. This galaxy was already known before the publication by van Dokkum et al. (2018a). It has been identified with alternate names as KKSG04, PGC3097693 and [KKS2000]04 (see e.g. Karachentsev et al. 2000). In this sense, we consider that the correct way of identifying the system is to use the name that follows the IAU rule. As the galaxy has been popularised as NGC1052-DF2, in order to avoid confusion for the casual reader we will use through-

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The velocity of the system (c ± 10.5 km s⁻¹) is the closest (as motivated by the apparent magnitudes of the compact sources, thought to be globular clusters) spatially located close to the galaxy. This group of compact objects has a very narrow velocity distribution, with a central peak at 1803±2 km s⁻¹ and a range of possible intrinsic velocity dispersions 8.8 km s⁻¹ < σint < 10.5 km s⁻¹. Such a narrow dispersion would imply a dynamical mass of only 10⁸ M⊙ (i.e. fully compatible with the absence of dark matter in this system). The system is also compatible with neutral gas (HI: Parkes All-Sky Survey (HIPASS); 3σ HI < 6×10¹⁸ cm⁻²; Meyer et al. 2004).

In addition to the lack of dark matter, another intriguing result is that the luminosity of the compact sources (assuming that they are located at 20 Mpc) are much higher than those of typical globular clusters. In a follow up paper, van Dokkum et al. (2018b) find the peak of the absolute magnitude distribution of the compact sources to be at Mᵥ = -9.1 mag, significantly brighter than the canonical value for globular clusters of Mᵥ = -7.5 mag (Rejkuba 2012). In this sense, [KK52000]04 (NGC1052-DF2) is doubly anomalous; if the compact sources are indeed globular clusters associated with the galaxy, it not only has an unexpected lack of dark matter (compatible with being a "baryonic galaxy"), but also a highly unusual population of globular clusters (with some of them having absolute magnitudes similar to ω Centauri).

Both the absence of dark matter and the anomalous bright population of compact sources around [KK52000]04 (NGC1052-DF2) fully rely on the assumption that the galaxy is at a distance of 20 Mpc. In fact, if the galaxy were located much closer to us, for instance a factor of two closer (as motivated by the apparent magnitudes of the compact sources around the galaxy) then its stellar mass would go down significantly (a fact already mentioned by van Dokkum et al. 2018a). A closer distance would make the properties of [KK52000]04 (NGC1052-DF2) perfectly ordinary. The question is then, how secure are we about the galaxy distance? van Dokkum et al. (2018a) use the surface brightness fluctuation (SBF) technique to infer a distance of 19.0±1.7 Mpc to the galaxy. In addition, the heliocentric velocity of the system (cz = 1803±2 km s⁻¹) is also used as another argument to favor a large distance for this object. However, the validity of the SBF technique in the case of [KK52000]04 (NGC1052-DF2) should be taken with caution, since van Dokkum et al. (2018a) extended the Blakeslee et al. (2010) calibration to a range (in color) where its applicability is not tested. Moreover, the use of heliocentric velocities to support a given distance in the nearby Universe should be done with care, as large departures from the Hubble flow are measured in our local Universe. For all these reasons, in this paper we readdress the issue of the distance to [KK52000]04 (NGC1052-DF2). We show that a distance of 13 Mpc not only resolves all the anomalies of the system but also is favored by the color - magnitude diagram of the system, the apparent luminosity and size of its globular clusters, a revision of the SBF distance and its location in the fundamental plane.

The structure of this paper is as follows. In Section 2 we describe the data used. Section 3 shows the spectral energy distribution of the galaxy from the FUV to IR and the stellar populations properties derived from its analysis. In Section 4 we discuss up to five different redshift independent distance estimations of the galaxy [KK52000]04 (NGC1052-DF2). We explore the velocity field of the galaxies around the system in Sec. 5 and the possibility that the galaxy is associated with other objects in Sec. 6. Section 7 redresses the estimation of the total mass of the system. Finally, in Section 8 we put [KK52000]04 (NGC1052-DF2) in context with other Local Group galaxies and give our conclusions in Section 9. We assume the following cosmological model: Ωm = 0.3, ΩΛ = 0.7 and H₀ = 70 km s⁻¹ Mpc⁻¹ (when other values are used this is indicated). All the magnitudes are given in the AB system unless otherwise explicitly stated.

2 DATA

Given the potential relevance of the galaxy if the lack of dark matter is confirmed, we have made a compilation of all the public (SDSS, GALEX, WISE, Gemini, HST) data currently available for the object with the aim of exploring its stellar population properties, its structure, and the properties of the compact sources around the system.

2.1 Sloan Digital Sky Survey, GALEX and WISE

SDSS u, g, r, i and z band imaging data were retrieved from the DR14 SDSS (Abolfathi et al. 2018) Sky Server. The magnitude zero-point for all the data set is the same: 22.5 mag. The exposure time of the images is 33.9s and the pixel size 0.396 arcsec. Galaxy Evolution Explorer (GALEX) FUV and NUV data (Martin et al. 2005) were obtained from GALEX Mikulecki Archive for Space Telescopes (MAST) archive¹. The exposure times in each band are 2949.55s (FUV) and 3775.7s (NUV). The pixel size is 1.5 arcsec and the zero-points 18.82 mag (FUV) and 20.08 mag (NUV). Finally, Wide-field Infrared Survey Explorer (WISE; Wright et al. 2010) data was downloaded from the WISE archive in IRA². The total exposure time is 3118.5s. The WISE pixel scale is 1.375 arcsec and we use the following two channels

out the text the following notation for the name of the object [KK52000]04 (NGC1052-DF2).

1 The plates were taken mostly during the summer of 1976.

http://galex.stsci.edu/GR6/?page=tilelist&survey=allsurveys
http://wise2.ipac.caltech.edu/docs/release/allsky/

MNRAS 000, 1–26 (2015)
W1 (3.4 μm) and W2 (4.6 μm) whose zeropoints are 23.183 and 22.819 mag, respectively.

### 2.2 Gemini

Very deep (3000s in g and i band) and good quality seeing (0.75 arcsec in g and 0.71 arcsec in i) data using the instrument GMOS-N (Hook et al. 2004) were obtained with the Gemini North telescope (program ID: GN-2016B-DD-3, PI: van Dokkum). Unfortunately, only the i-band data was useful for further analysis as the g-band was taken during non-photometric conditions with clouds passing during the observation. This affected the depth of the data as well as the photometry of the image. For this reason, we decided to use only the g-band in this work. The data was downloaded from the Gemini Observatory archive and reduced using a minimal aggressive sky subtraction with the aim of keeping the low surface brightness features of the image. The images were processed with the reduction package THELI (Schirmer 2013). All images were bias, over-scan subtracted and flat-fielded. Flatfields were constructed from twilight flats obtained during the evening and the morning. The reduced images present gradients across the entire GMOS-N FoV, especially in i-band. To remove the gradients, we modeled the background using a two pass policy, following the THELI recipe. A superflat was constructed as follows: in the first pass, a median-combined image is created without object detection, to remove the bulk of the background signal. In the second pass, SExtractor (Bertin & Arnouts 1996) is used to detect and mask all objects with a detection threshold of 1.3 sigma above the sky and with a minimum area of 5 pixels. Because we did not want to oversubtract the outer part of the galaxy, a mask expansion factor of 5–6 was used to enlarge the isophotal ellipses. The resulting images, after the background modeling subtraction, are flat within 0.5% or less. All images were registered to common sky coordinates and pixel positions using the software SCAMP (Bertin 2006). The astrometric solution was derived using the SDSS DR9 as a reference catalog. The internal (GMOS) astrometric residual from the solution is 0.05" and the external astrometric residual is 0.2". Before the co-addition, the sky of each single exposure was subtracted using constant values. In the second pass, SExtractor (Bertin & Arnouts 1996) is used to detect and mask all objects with a detection threshold of 1.3 sigma above the sky and with a minimum area of 5 pixels. Because we did not want to oversubtract the outer part of the galaxy, a mask expansion factor of 5–6 was used to enlarge the isophotal ellipses. The resulting images, after the background modeling subtraction, are flat within 0.5% or less. All images were registered to common sky coordinates and pixel positions using the software SCAMP (Bertin 2006). The astrometric solution was derived using the SDSS DR9 as a reference catalog. The internal (GMOS) astrometric residual from the solution is 0.05" and the external astrometric residual is 0.2". Before the co-addition, the sky of each single exposure was subtracted using constant values. Finally, the images were re-sampled to a common position each single exposure was subtracted using constant values.

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3 THE SPECTRAL ENERGY DISTRIBUTION

Lacking a spectroscopic analysis of the galaxy, our best way to constrain the age, metallicity and stellar mass to light ratio of the stellar population of the object is by analyzing its spectral energy distribution (SED) from broad band photometry. We measure the SED of the system from FUV to IR (Fig. 2). The photometry (after correcting for Galactic reddening) was derived in a common circular aperture of R=1R_e=22.6" (i.e. containing half of the total brightness of the object) as indicated on the vertical axis. We use such radial aperture to guarantee that we have enough signal to produce a reliable characterization of the SED in all the photometric bands. The images in each filter were masked to avoid the contamination from both foreground and background objects. For those filters with poorer spatial resolution, we use the information provided by the HST data to see whether the addition of extra masking was needed.

The inverted triangles in the left panel of Fig. 2 correspond to the magnitude detection limits in those images were the galaxy was not detected (FUV, u and z). These upper limits were estimated as the 3σ fluctuations of the

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5 https://archive.gemini.edu/searchform
6 https://mast.stsci.edu/portal/Mashup/Clients/Mast/
Portal.html

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Figure 1. Color composite image of [KKS2000]04 (NGC1052-DF2) combining F606W and F814W filters with black and white background using g-band very deep imaging from Gemini. The ultra-deep g-band Gemini data reveals a significant brightening of the galaxy in the northern region. An inset with a zoom into the inner region of the galaxy is shown. The zoom shows, with clarity, the presence of spatially resolved stars in the HST image.

...sky (free of contaminating sources) in circular apertures of radius 1 $R_e$. In order to characterize the stellar population properties of the galaxy we have fitted its SED using Bruzual & Charlot (2003) single stellar population (instantaneous burst) models. We used a Chabrier Initial Mass Function (IMF; Chabrier 2003). For the fitting we use $\chi^2$ minimization approach (see Montes et al. 2014, for the details of the fitting procedure). From this fitting we derive a most likely age of $7.2^{+5.7}_{-3.5}$ Gyr, a metallicity of $[\text{Fe/H}]=-1.45^{+0.90}_{-0.40}$ and a mass-to-light ratio in the V-band $(M/L)_V=1.28^{+0.77}_{-0.78}$ $\Upsilon_\odot$ (see right panel in Fig. 2). This metallicity is roughly similar to the average metallicity found by van Dokkum et al. (2018b) for the GCs surrounding this object. In what follows we assume that these properties obtained within 1 $R_e$ are representative of the whole galaxy. In Table 1, we provide the total magnitudes of the galaxy in the different filters. The total magnitudes were obtained from the 1 $R_e$ aperture...
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4 THE DISTANCE TO [KKS2000]04 (NGC1052-DF2)

Up to five different redshift-independent distance measurements converge to a distance of 13 Mpc for the galaxy [KKS2000]04 (NGC1052-DF2). In the following we will describe each one of them.

4.1 The color - magnitude diagram distance

When available, the analysis of the color-magnitude diagram (CMD) of resolved stars is one of the most powerful techniques to infer a redshift-independent distance to a galaxy. The data we have used to create the CMD of [KKS2000]04 (NGC1052-DF2) is the HST optical data described above. Data treatment for creating the CMD was carried out following essentially the prescriptions of Monelli et al. (2010). Photometry was performed on the individual flc images using the DAOPHOT/ALLFRAME suite of programs (Stetson 1987, 1994). Briefly, the code performs a simultaneous data reduction of the images of a given field, assuming individual Point Spread Functions (PSF) and providing an input list of stellar objects. The star list was generated on the stacked median image obtained by registering and co-adding the eight individual available frames, iterating the source detection twice. To optimize the reduction, only the regions around the center of [KKS2000]04 (NGC1052-DF2), within 5 $R_e$ (113′′), were considered. We explore different apertures and the main result did not change. The photometry was calibrated to the AB system.

Fig. 3 presents the obtained ($F606W-F814W$, $F814W$) color-magnitude diagram. The four panels show a comparison with selected isochrones from the BaSTI database spanning a wide range of ages and metallicities. Isochrones were moved according to different assumptions of the distance, from 8 Mpc (top left) to 20 Mpc (bottom right). The vast majority of detected sources are compatible with being bright Red Giant Branch (RGB) stars, though a small contamination from asymptotic giant branch stars cannot be excluded with the present data. There is no strong evidence of bright main sequence stars, corresponding to a population younger than few hundred million years. The comparison with isochrones seems to exclude distances as close as 8 Mpc or as distant as 20 Mpc. In fact, a qualitative comparison seems to favor an intermediate distance.

To make a quantitative analysis we have conducted specific artificial star tests. In particular, we created a mock population of 50,000 stars covering a range of ages between 10 and 13.5 Gyr and metallicity between Z=0.001 and Z=0.008. The top panels of Fig. 4 compares the CMD of this mock population (red points) with that of [KKS2000]04 (NGC1052-DF2) (dark grey), for three different assumptions of the distance: 8 Mpc (left), 12 Mpc (center) and 16 Mpc (right). Synthetic stars were injected in individual images and the photometric process was repeated for the three cases. The bottom panels of Fig. 4 present the superposition of the [KKS2000]04 (NGC1052-DF2) CMD and the recovered mock stars (red points). Clearly, the distribution of the recovered stars in the 8 Mpc and the 16 Mpc cases is not compatible with the observed CMD of [KKS2000]04 (NGC1052-DF2). In fact, in the case of the 8 Mpc distance the brightest portion of the RGB would be clearly detected between $F814W = 26$ mag and $F814W = 27$ mag. On the other hand, most of the injected stars assuming a 16 Mpc distance have been lost in the photometric process, resulting in a very sparsely recovered CMD.

A more precise estimate of the distance to [KKS2000]04 (NGC1052-DF2) can be derived using the tip of the red giant branch (TRGB). This is a well-established distance indicator for resolved stellar populations (Lee et al. 1993). From the stellar evolutionary point of view, the TRGB corresponds to the end of the red giant branch phase, when the helium core reaches sufficient mass to explosively ignite He in the center. Observationally, this corresponds to a well-defined discontinuity in the luminosity function, which can be easily identified from photometric data. This method presents two strong advantages. First, the luminosity of the TRGB in the $F814W$ filters has a very mild dependence on the age and the metallicity over a broad range (Salaris & Cassisi 1997). Second, since the TRGB is an intrinsically bright feature ($M_t \sim -4$), this method can be reliably used beyond 10 Mpc.

Fig. 5 shows the TRGB distance estimate in the case of [KKS2000]04 (NGC1052-DF2) based on the current data. We adopted the calibration by Rizzi et al. (2007)

$$M_{F814W}^{ACS} = -4.06 + 0.20 \times [(F606W - F814W) - 1.23]$$

which accounts for the mild dependence on the metallicity by taking into account a color term. Following McQuinn et al. (2017), we applied a color correction to the $F814W$ photometry, as it results in a steeper RGB and therefore a better defined TRGB. The resulting modified and de-reddened CMD (corrected after taking into account the different zero points between the AB and the Vega mag systems) is shown in the left panel of Fig. 5. The right panel presents the luminosity function (in black) and the filter response after con-

| Filter   | $\lambda_{eff}$ | $m_{AB}(<R_e)$ | $m_{AB}$ | $A_1$ |
|----------|-----------------|----------------|----------|------|
| FUV      | 1542.3          | <20.62         | <19.87   | 0.171|
| NUV      | 2274.4          | 20.76 ± 0.05   | 20.01 ± 0.05 | 0.192|
| SDSS u   | 3543            | <17.24         | <16.49   | 0.104|
| Gemini g | 4750            | 17.27 ± 0.012  | 16.52 ± 0.012 | 0.081|
| ACS F606W| 6006            | 16.86 ± 0.013  | 16.11 ± 0.013 | 0.060|
| SDSS r   | 6231            | 16.72 ± 0.08   | 15.97 ± 0.08 | 0.056|
| SDSS i   | 7625            | 16.43 ± 0.07   | 15.68 ± 0.07 | 0.042|
| ACS F814W| 8140            | 16.42 ± 0.013  | 15.67 ± 0.013 | 0.037|
| SDSS z   | 9134            | <15.38         | <14.63   | 0.031|
| WISE W1  | 33680           | 17.61 ± 0.07   | 16.86 ± 0.07 | 0.004|
| WISE W2  | 46180           | 18.21 ± 0.12   | 17.46 ± 0.12 | 0.003|

Table 1. Half $m_{AB}(<R_e)$ and total $m_{AB}$ magnitudes (corrected of foreground Galactic extinction) of [KKS2000]04 (NGC1052-DF2) in different bands. The applied foreground extinction is indicated in the 5th column.

8 http://basti-iac.oa-abruzzo.inaf.it/
volving with a Sobel kernel (Sakai et al. 1996, 1997) $K=[-2,-1,0,1,2]$ (red). The filter presents a well defined peak which we fitted with a Gaussian curve, obtaining $F_{814W_{\text{ega}}}=26.53$ mag, marked by the green line on the CMD. The distance modulus was derived with the Rizzi et al. (2007) zero points, obtaining $(m-M)_0=30.59\pm0.07$ (systematic) mag, corresponding to a distance $D=13.12\pm0.42\pm0.72$ Mpc. The error budget includes the uncertainty of the calibration relation by Rizzi et al. (2007) and the error on the determination of the TRGB position.

4.2 The size and magnitudes of the globular clusters as distance indicators

The globular clusters around [KKS2000]04 (NGC1052-DF2) can be used to give two independent distance estimators. The first is based on the fact that the peak of the luminosity function of globular clusters is rather invariant from galaxy to galaxy with a value of $M_V=-7.5\pm0.2$ (Rejkuba 2012). The second takes advantage of the fairly constant (and independent from magnitude) half-light radii of globular clusters.

van Dokkum et al. (2018b) have explored 11 spectroscopically confirmed clusters around [KKS2000]04 (NGC1052-DF2). These authors acknowledge the possibility that further clusters may exist around the galaxy but lacking a spectroscopic confirmation they refrain to include new objects. Note that van Dokkum et al. (2018b) target selection gave priority to compact objects with $F814W<22.5$ mag. We have probed whether new GCs can be found around the galaxy. To do that we created a SExtractor catalog with all the sources in the $F814W$ image satisfying the following: a FWHM size less than 5 pixels (their spectroscopically confirmed GCs have FWHM<4.7 pixels; van Dokkum et al. 2018b) and a range in color 0.2<$F606W-F814W<0.55$ mag\(^9\) (the range in color for their spectroscopically confirmed GCs is 0.28-0.43). We used SExtractor AUTO magnitudes to build this catalog. The distribution of magnitudes of all the sources in the $F814W$ image satisfying the color and size cut are shown in Fig. 6. Motivated by the shape of the luminosity distribution shown in Fig. 6, we added another restriction to create our final sample of GC candidates around the galaxy: $F814W<24$ mag.

As expected, our criteria recovers the 11 clusters found by van Dokkum et al. (2018b) but also adds another 8 new candidates. The final sample of GCs explored in this paper is shown on Fig. 7. It is worth noting that the majority of the new GC candidates added in this work are spatially located close to the galaxy, suggesting a likely association with this object.

Once the sample of GCs is built, to use both distance estimators based on the GCs properties, we need to quantify the apparent magnitudes, sizes and ellipticities of the GC population around [KKS2000]04 (NGC1052-DF2). As mentioned before, the magnitudes we used were those produced by SExtractor. Following van Dokkum et al. (2018b),

\(^9\) This color range is a compromise between maximizing the detection of metal-poor GCs and minimizing the contamination of background red sources (Blakeslee et al. 2012).
to derive the size and ellipticities of the GCs we use PSF-convolved King (1962) and Sérsic (1968) models. The PSFs used were synthetic PSFs from Tiny Tim (Krist 1993). The model fitting of the globular clusters was conducted using IMFIT (Erwin 2015). Note that for this we account for the spatial distortions of the HST PSF along the field-of-view. This is key due to the small sizes of the GCs (subtending only a few pixels) and necessary for a correct fitting. The results of the model fitting were comparable in both F606W and F814W, but slightly more accurate in the F814W band. For this reason, we use this band to characterize the structural parameters of the objects. The values measured (with their typical errors) are shown in Table 2. The magnitudes in the table correspond to SExtractor magnitudes (corrected for foreground Galactic extinction: 0.06 mag for F606W and 0.037 mag for F814W). The structural parameters provided are those obtained adopting a Sérsic model.

We have compared the difference in the magnitudes using SExtractor with those retrieved using King and Sérsic models. The mean difference between the SExtractor AUTO magnitudes and the King model magnitudes is 0.06 mag with a standard deviation of 0.05 mag. Similarly, the difference between the King and Sérsic models is 0.06 mag with a standard deviation of 0.12 mag. As the model-based magnitudes are prone to overestimation (particularly if one of the fitting parameters as the Sérsic index or the tidal King radius is wrong) we conservatively decided to continue our analysis with the SExtractor magnitudes. Nonetheless, we will show how using the model magnitudes barely affects the results.

The luminosity functions of the globular clusters in each HST band are shown in Fig. 8. The location of the peaks of the luminosity functions and their errors were obtained using a bootstrapping median. For the 19 GCs found in this work, we derive the following peak locations: 22.82$^{+0.08}_{-0.21}$ mag (F606W) and 22.43$^{+0.14}_{-0.23}$ mag (F814W). Using only the 11 van Dokkum et al. (2018b) GCs we get 22.48$^{+0.38}_{-0.06}$ mag (F606W) and 22.08$^{+0.35}_{-0.06}$ mag (F814W). This last value is also provided by van Dokkum et al. (2018b) and we find here a good agreement with their measurement. Note how the spectroscopic completeness criteria introduced by van Dokkum et al. (2018b) for selecting their GC sample moves the location of the peak of the luminosity function towards brighter values than in our case.

The distribution of F814W Sérsic half-light radii and the circularized half-light radii are shown in Fig. 9. The mean size for all the GCs is $<R_e$(F814W)$>$=0.071$^{+0.004}_{-0.006}$ using the 11 GCs studied in van Dokkum et al. (2018b) and the mean circularized size is $<R_c$(F814W)$>$=0.065$^{+0.004}_{-0.005}$ using the 11 GCs given in van Dokkum et al. (2018b). We do not find any difference between the average sizes of the GCs using F814W and F606W within their uncertainties. Finally, the mean ellipticity obtained in the F814W band is 0.15$^{+0.02}_{-0.02}$ using only the 11 GCs provided by van Dokkum et al. (2018b). The mean ellipticities obtained from the two HST bands are consistent within their error bars. The el-
V (2012) suggested the peak of the luminosity function of the GCs. Rejkuba are measured, we can derive a first distance estimate using the value reported in van Dokkum et al. (2018b).

The same analysis but using the 11 GCs published in van Dokkum et al. (2018a) provides a distance modulus of (m-M)_0=13.2±0.2 Mpc using the 11 GCs given in van Dokkum et al. (2018b) and D_KKS2000=10.3±1.2 Mpc (comparing with the GCs in the MW; D_GC,2=9.4±1.1 Mpc using the 11 GCs given in van Dokkum et al. 2018b). In what follows we assume the determination of the distance to [KKS2000]04 (NGC1052-DF2) based on the comparison with the GCs in dwarf galaxies since [KKS2000]04 (NGC1052-DF2) has all the characteristics of a dwarf galaxy.

Finally, the mean ellipticity of the GCs of [KKS2000]04 (NGC1052-DF2) is <\epsilon>=0.18±0.02 for the 11 clusters provided by van Dokkum et al. (2018b). This mean ellipticity is anomalously high compared to the Milky Way GCs but rather normal in dwarf galaxies such as in the Small and Large Magellanic Clouds (Staneva et al. 1996). In this sense, [KKS2000]04 (NGC1052-DF2) has a normal population of GCs if compared to GCs in dwarf galaxies since [KKS2000]04 (NGC1052-DF2) has all the characteristics of a dwarf galaxy.

Table 2. Structural parameters of the globular clusters surrounding [KKS2000]04 (NGC1052-DF2).

| ID     | R.A. (J2000) | Dec. (J2000) | V_{606} (mag) | I_{814} (mag) | R_{e,F814W} (arcsec) | \epsilon_{F814W} |
|--------|--------------|--------------|---------------|---------------|----------------------|-----------------|
| GC9    | 40.43779     | -8.423583    | 22.38         | 22.02         | 0.083                | 0.05            |
| GC9    | 40.45034     | -8.415695    | 22.87         | 22.44         | 0.107                | 0.27            |
| GC71   | 40.43807     | -8.406378    | 22.70         | 22.30         | 0.083                | 0.15            |
| GC73   | 40.45093     | -8.409526    | 21.52         | 21.19         | 0.077                | 0.14            |
| GC7    | 40.44395     | -8.403900    | 22.03         | 21.66         | 0.118                | 0.25            |
| GC8    | 40.44896     | -8.416159    | 22.42         | 22.01         | 0.060                | 0.31            |
| GC91   | 40.42571     | -8.398324    | 22.49         | 22.08         | 0.114                | 0.20            |
| GC92   | 40.44544     | -8.397534    | 22.39         | 21.88         | 0.055                | 0.13            |
| GC73   | 40.44469     | -8.397590    | 22.97         | 22.59         | 0.046                | 0.26            |
| GC38   | 40.44728     | -8.393103    | 22.90         | 22.49         | 0.056                | 0.13            |
| GC101  | 40.43837     | -8.391198    | 23.01         | 22.58         | 0.050                | 0.06            |

Once the structural parameters of the GC population are measured, we can derive a first distance estimate using the peak of the luminosity function of the GCs. Rejkuba (2012) suggested M_V=-7.66±0.09 for the absolute magnitude of the peak of the GC luminosity distribution. It is worth noting that this value is the one recommended for metal-poor clusters. The globular clusters of [KKS2000]04 (NGC1052-DF2) have an average metallicity of [Fe/H]=-1.35 (van Dokkum et al. 2018b). In this sense, this choice is well justified. To transform our V_{606} (F606W HST filter) into V magnitudes, we apply the following correction: V=V_{606}+0.118. The correction is obtained assuming a single stellar population model with age=9.3 Gyr and [Fe/H]=-1.35 (the values measured spectroscopically by van Dokkum et al. 2018b). Thus, the peak of the luminosity function has a magnitude of V=22.94±0.08 mag which corresponds to a distance modulus of (m-M)_0=12.3±0.2 Mpc (comparing with GCs in Dwarfs; D_GC,2=12.4±1.4 Mpc (comparing with GCs in Dwarfs; D_GC,2=11.6±1.5 Mpc using the 11 GCs given in van Dokkum et al. 2018b) and D_GC,2=10.3±1.2 Mpc (comparing with the GCs in the MW; D_GC,2=9.4±1.1 Mpc using the 11 GCs given in van Dokkum et al. 2018b). In what follows we assume the determination of the distance to [KKS2000]04 (NGC1052-DF2) based on the comparison with the GCs in dwarf galaxies since [KKS2000]04 (NGC1052-DF2) has all the characteristics of a dwarf galaxy.

It is worth exploring how this distance estimate changes if instead of SExtractor AUTO magnitudes we would have used the model magnitudes described above. Using both the Sersic and the King models, the distances are: D_{GC,1}=12.0^{+1.5}_{-1.3} Mpc (Sersic model magnitudes) and D_{GC,1}=12.3^{+2.0}_{-0.9} Mpc (King model magnitudes). As expected, the distances using the model magnitudes are slightly smaller than the ones using the SExtractor magnitudes (although compatible within the uncertainties).
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Figure 5. Left panel- De-reddened CMD of [KKS2000]04 (NGC1052-DF2) stars. The green line shows the estimated position of the TRGB. Right panel- Luminosity function (black line), and the response filter (red curve).

Figure 6. Left panel: Sextractor AUTO magnitudes (corrected by foreground Galactic extinction) of all the sources (grey, blue and red histograms) in the F814W image with FWHM<5 pixels and color 0.2<F606W-F814W<0.55 mag. The vertical dashed line corresponds to F814W=24 mag. Right panel: Color distribution of the GC candidates around [KKS2000]04 (NGC1052-DF2). The vertical dashed lines encircle our color cut in the sample selection. In both panels, red corresponds to the GCs detected by van Dokkum et al. (2018b) whereas blue indicates the new candidates found in this paper.

Table 3. Globular cluster structural properties (effective radius $R_e$, circularized effective radius $R_{e,c}$ and ellipticity) for different galaxy hosts. The errors correspond to the 1σ interval.

|            | MW       | Dwarfs | [KKS2000]04 (NGC1052-DF2) (at 13 Mpc) |
|------------|----------|--------|-------------------------------------|
| Mean $R_e$ (pc) | 3.6$^{+0.2}_{-0.2}$ | 4.3$^{+0.2}_{-0.2}$ | 4.4$^{+0.3}_{-0.3}$ |
| Median $R_e$ (pc) | 2.0$^{+0.2}_{-0.2}$ | 3.2$^{+0.2}_{-0.2}$ | 3.9$^{+0.3}_{-0.3}$ |
| Mean $R_{e,c}$ (pc) | 3.4$^{+0.2}_{-0.2}$ | 4.0$^{+0.2}_{-0.2}$ | 4.1$^{+0.2}_{-0.2}$ |
| Median $R_{e,c}$ (pc) | 2.6$^{+0.1}_{-0.1}$ | 3.0$^{+0.1}_{-0.1}$ | 3.8$^{+0.2}_{-0.2}$ |
| Mean $\epsilon$ | 0.08$^{+0.01}_{-0.01}$ | 0.14$^{+0.01}_{-0.01}$ | 0.15$^{+0.02}_{-0.02}$ |
| Median $\epsilon$ | 0.06$^{+0.01}_{-0.01}$ | 0.13$^{+0.01}_{-0.01}$ | 0.14$^{+0.01}_{-0.01}$ |

dwarf galaxies. Fig. 10 shows the location of the GCs of [KKS2000]04 (NGC1052-DF2) in the size - absolute magnitude plane, and in the ellipticity - absolute magnitude plane. The sizes and ellipticities of the [KKS2000]04 (NGC1052-DF2) are very similar to those found in regular dwarf galaxies. To quantify this statement, Table 3 shows the mean and median structural properties of the GCs of [KKS2000]04 (NGC1052-DF2) (under the assumption this galaxy is at a distance of 13 Mpc) compared to both MW and dwarf galaxy GCs.

4.3 The surface brightness fluctuation (SBF) distance

A promising way to measure distances is the method put forward by Tonry & Schneider (1988) using surface brightness fluctuations. The method relies on measuring the luminosity fluctuations that arise from the counting statistics of the stars contributing the flux in each pixel image of a galaxy. The amplitude of these fluctuations is inversely proportional to the distance of the galaxy. The SBF method is precise enough to resolve the depth of the Virgo cluster (Mei et al. 2007) and is therefore ideal to measure the distance to [KKS2000]04 (NGC1052-DF2). van Dokkum et al. (2018a) used this technique and measured a fluctuation magnitude of $\Delta M_{814} = 29.45 \pm 0.10$ to infer a distance of 19.0±1.7 Mpc for [KKS2000]04 (NGC1052-DF2). This determination relies on two key steps. First, they assume a colour transformation which does not use the actual SED of the galaxy, namely,

$$g_{475} = I_{814} + 1.852 (V_{606} - I_{814}) + 0.096,$$

and which, for their observed colour $V_{606} - I_{814} = 0.37 \pm 0.05$, yields $g_{475} - I_{814} = 0.78 \pm 0.05$, while the actual value is 0.85±0.02 (see Table 1; where we have used the Gemini g-band as a proxy for $g_{475}$). Second, and much more importantly, they adopt the calibration by Blakeslee et al. (2010; their Eq.(2))

$$\overline{M}_{814} = (-1.168 \pm 0.013 \pm 0.092) + (1.83 \pm 0.20) \times [g_{475} - I_{814} - 1.2].$$

This calibration is only valid for the colour range 1.06 ≤ ($g_{475} - I_{814}$) ≤ 1.32, which corresponds to a range in absolute fluctuation magnitude $-1.4 \leq \overline{M}_{814} \leq -0.8$. van Dokkum et al. (2018a) extrapolate this relation well outside...
its validity range, yielding an absolute fluctuation magnitude $M_{814} = -1.94$ which is therefore highly unreliable. Not only a linear extrapolation to bluer colours is not warranted, but both observations (Mei et al. 2007; Blakeslee et al. 2009; Jensen et al. 2015) and theoretical models (Blakeslee et al. 2001; Cantiello et al. 2003; Raimondo et al. 2005; Mieske et al. 2006) predict a non-linear behaviour for bluer colours. This is illustrated in Figure 11, where the absolute fluctuation magnitude is shown as a function of the $g_{475} - I_{814}$ colour for a variety of ages and metallicities (including the ones inferred from the fitting of the SED), and for two sets of stellar evolutionary tracks, as predicted by the Vazdekis et al. (2016) models. While the models agree rather well with the empirical calibration, they also show a dramatic drop in the absolute fluctuation magnitude at colours bluer than $g_{475} - I_{814} \approx 1.0$, well below the values given by a linear extrapolation. This pattern does not depend strongly on the filter set. Figure 12 shows that, using the observed HST colour (without interpolations which depend upon the assumed or fitted SED), the absolute fluctuation magnitude is consistently brighter and would therefore imply an even larger distance than the one derived by van Dokkum et al. (2018a),
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Figure 8. The luminosity functions of the globular clusters surrounding [KKS2000]04 (NGC1052-DF2). The magnitudes have been corrected for foreground Galactic extinction. The left panel shows the magnitude distribution in the F606W band whereas the right panel shows F814W. In red we show the location of the globular clusters identified by van Dokkum et al. (2018b) and in blue the new sources found in this work. The vertical solid lines represent the location of the median values of the distributions for the entire sample of 19 clusters. The dashed lines show the 1σ uncertainties on the location of the median values using bootstrapping.

Figure 9. Left panel. Effective radii using Sérsic models for the sample of GCs analyzed in this work. Right panel. Same as in the left panel but using circularized effective radii. Vertical solid lines correspond to the mean values whereas the dashed lines show the uncertainty region. The red histograms show the distribution for the GCs in van Dokkum et al. (2018b) whereas the blue histograms show the new GCs found in this work.

well beyond 25 Mpc (in tension with the spatially resolved stellar population of [KKS2000]04 (NGC1052-DF2)).

The predicted behaviour of the SBF magnitude at bluer colours depends on a number of factors which are difficult to assess. First, it is more sensitive to sampling fluctuations and statistical effects on the effective number of stars (Cerviño & Valls-Gabaud 2003; Cerviño et al. 2008) than older and redder populations, which is the reason why the SBF method is generally applied to globular clusters and elliptical galaxies. Second, theoretical predictions become somewhat unreliable at ages younger than about 3 Gyr and low metallicities (see Blakeslee et al. 2001) mostly due to uncertainties in the modelling of stellar evolutionary phases such as intermediate-mass asymptotic giant branch stars and horizontal branch stars, (e.g. Cantillo et al. 2003). Also, a given luminosity-weighted age does not guarantee that there are contributions from much younger populations which may also bias the measure of the sampled variance.

To bypass the uncertainties in the theoretical models, we use purely empirical SBF measures. While the SBF method has been applied to a variety of mostly red galaxies, there are very few attempts towards bluer colours (Mieske et al. 2006; Biscardi et al. 2008), given the complications mentioned above. The only survey, as far as we are aware of, that extends SBF measurements systematically towards bluer galaxies is part of the Next Generation Virgo Cluster Survey (NGVS) (Cantiello et al. 2018). In this survey, carried out at the CFHT, the SBF analysis is performed in several filters, from $u^*$ to $z$, and, in this first analysis to all galaxies brighter than $B=13$ mag. Cantiello et al. (2018) found several tight single-colour calibrations. The relation that uses magnitudes available for [KKS2000]04 (NGC1052-DF2) is (see their Table 3):

$$M_i = (-0.93 \pm 0.04) + (3.25 \pm 0.42) \times [(g-i) - 0.95]$$

which is valid in the range $0.825 \leq (g-i) \leq 1.06$ (see Fig. 13). We find in this work (see Table 1) $g-i=0.84\pm0.07$, and hence $M_i=-1.29\pm0.26$. Finally, in order to estimate $M_{814}$ we use the following correction $M_{814} = M_i - 0.1$ based on the models by Vazdekis et al. (2016) for the best-fit SED. Hence, we obtain $(m-M)_0=30.84\pm0.26$ mag which corresponds to a distance of $D_{SBF}=14.7\pm1.7$ Mpc. As [KKS2000]04 (NGC1052-DF2) is not detected in the $u^*$ and $z$ bands, the dual-colour calibrations from Cantillo et al. (2018) cannot be used, but the slight improvement in precision would not lead
Figure 11. The absolute fluctuation (AB) magnitude in the $F814W$ filter as a function of the $g - I_{814}$ colour for a variety of SSP models using the E-MILES library (Vazdekis et al. 2016), assuming a Kroupa Universal IMF and two sets of stellar tracks: Padova00 (left panel, Girardi et al. 2000) and BaSTI (right panel, Pietrinferni et al. 2004). The symbols are colour-coded with metallicity, ranging from metal-poor (purple) to metal-rich (red) populations, while their sizes are proportional to their ages. The black line is the Blakeslee et al. (2010) calibration (Eq. 3) within its validity range. The grey vertical line is the $g - I_{814}$ colour as inferred from the best-fit SED.

Figure 12. The same as Fig. 11 but in terms of the directly observed $V_{606} - I_{814}$ colour, which is independent of the assumed or fitted SED. In both cases, the theoretical predictions show a non-linear behaviour at colours redder than the observed one, making unreliable any linear extrapolation of Eq. 3 beyond its validity range. The grey vertical line is the $V_{606} - I_{814} = 0.37$ colour given by van Dokkum et al. (2018a).

Figure 13. Absolute fluctuation magnitude in the $i$ band as a function of $g - i$ colour for the NGVS sample analysed by Cantiello et al. (2018). The range of validity of the calibration (Eq. 4) is given by the pink area. [KKS2000]04 (NGC1052-DF2) (blue rhombus) is within this range, and the relation yields a distance of $14.7 \pm 1.7$ Mpc.

An interesting outcome of this analysis is the future recalibration of the relation between the fluctuation star count $N$ and dispersion velocity. The fluctuation star count $N$ is a measure of the luminosity-weighted number of stars or the total luminosity of a galaxy $L_{\text{tot}}$ in terms of the luminosity dispersion.
unlike the distance proposed by van Dokkum et al. (2018a). [KKS2000]04 (NGC1052-DF2) is well within the range expected, a function of distance. Once again, the distance inferred for Figure 14.

of a typical giant star (Tonry et al. 2001), and is defined as

\[ \overline{N} = m - m_{\text{tot}} = 2.5 \log \left( \frac{L_{\text{tot}}}{L} \right) \]  \hspace{1cm} (5)

Since it is measured in the same band, it has the obvious advantage of being independent of extinction and zero points. Furthermore it correlates with the dispersion velocity for massive galaxies in the form

\[ \log \sigma = 2.22 + 0.10 \times (\overline{N} - 20) \]  \hspace{1cm} (6)

In the case of [KKS2000]04 (NGC1052-DF2), the fluctuation star count in the F814W filter is \( \overline{N}_{\text{F814}} = 13.78 \pm 0.26 \), and the linearly-extrapolated dispersion velocity would be 39.6 km s\(^{-1}\), an overestimation by a factor of less than 5 (assuming the velocity dispersion of the globular clusters of [KKS2000]04 (NGC1052-DF2) is representative of the velocity dispersion of the galaxy itself). With further measures of the dispersion velocity in low surface brightness galaxies, a new calibration of the relation can be envisioned, yielding redshift-independent distances.

4.4 The Fundamental Plane distance

Since the work of Djorgovski & Davis (1987) and Dressler (1987) it has been known that pressure supported structures (i.e., ellipticals galaxies and bulges of spiral galaxies) occupy a well-defined plane determined by a relation between their global properties. The Fundamental Plane (FP), as it is known, is a direct consequence of the virial theorem, which relates the potential and kinetic energy of a galaxy in equilibrium (Binney & Tremaine 1987). The FP can be expressed as a relation among the velocity dispersion \( \sigma_e \), the mean surface brightness within the effective radius \( < \mu_e > \) and the effective radius \( R_e \)

\[ \log R_e = a \log \sigma_e + b < \mu_e > + c \]  \hspace{1cm} (7)

where \( a, b \) and \( c \) are the FP coefficients. \( R_e \) is expressed in kpc, \( \sigma_e \) in km s\(^{-1}\) and \( < \mu_e > \) in mag arcsec\(^{-2}\).

Saulder et al. (2013, see also Bernardi et al. (2003)) provide a compilation of literature FP coefficients and a calibration of the FP using 93000 elliptical galaxies from the SDSS DR8. For the r-band (their Table 1) the FP coefficients are \( a = 1.034, b = 0.3012 \) (assuming \( \log I_e = - < \mu_e > / 2.5; \) their Eq. [17]) and \( c = -7.77 \). The work of de Rijcke et al. (2005, their Fig. 2 left) show that dwarf ellipticals (dE) and dwarf spheroids (dSph), and presumably the case of [KKS2000]04 (NGC1052-DF2), lie above the FP projection; for the same \( \sigma_e \) and \( < \mu_e > \), dEs and dSphs have smaller physical effective radii than bulges and bright and intermediate luminosity ellipticals (Fig. 15). Discrepancies can be larger than two orders of magnitudes in physical effective radius for the more extreme dSph cases.

As \( \sigma_e \) and \( < \mu_e > \) are distance-independent quantities, the FP plane can be used to derive the physical effective radius, and, hence, the distance, when the observed effective radius is measured. In the case of [KKS2000]04 (NGC1052-DF2), not being a massive elliptical, the FP will provide an upper limit to the physical effective radius, and, hence, an upper limit to the distance (de Rijcke et al. 2005). Adopting the Saulder et al. (2013) r-band coefficients (which is the closest match for the V-band data of van Dokkum et al. 2018a), assuming \( < \mu_e > = 24.9 \) mag arcsec\(^{-2}\) (the central surface brightness in V\(_{\text{606}}\) is 24.4 mag arcsec\(^{-2}\); van Dokkum et al. 2018a), adding the color correction \( r-V_{606} = -0.14 \) (obtained from Table 1), and using a representative intrinsic central velocity dispersion of \( \sigma_e = 8 \) km s\(^{-1}\) (van Dokkum et al. 2018a) provides an effective radius upper limit of \( R_e = 4.1 \) kpc (Fig. 15; orange pentagon). Using the observed effective radius provided by van Dokkum et al. (2018a), \( R_e = 22.6 \) arcsec, the previous \( R_e = 4.1 \) kpc would imply a distance upper limit of 37.8 Mpc. For the same \( \sigma_e \) and \( < \mu_e > \) as [KKS2000]04 (NGC1052-DF2), dEs (Fig. 15; blue open squares) show effective radii that are approximately one order of magnitude smaller than that predicted from the FP relation. Hence, if a conservative 0.5 dex decrease in effective radius is applied (i.e. assuming [KKS2000]04 (NGC1052-DF2) is among the largest dE or UDG), this provides a distance of 12 Mpc for [KKS2000]04 (NGC1052-DF2) (Fig. 15; orange arrow). Considering an uncertainty of 0.1 dex, this will imply the following distance range: 12±3 Mpc. So, although not very conclusive, a mean FP distance of 12±3 Mpc for [KKS2000]04 (NGC1052-DF2) also fits well with the FP properties of the galaxy assuming this object is an extended dEs.

To summarize section 4, up to five different distance indicators converge to a distance of ~13 Mpc for [KKS2000]04 (NGC1052-DF2). Figure 16 summarizes the independent measurements obtained in this work and their uncertainties. In what follows we assume a distance of 13 Mpc as the most likely distance to [KKS2000]04 (NGC1052-DF2). Under this assumption, the properties of the galaxy which depends on the distance are as follow: effective radius \( R_e = 1.4\pm0.1 \) kpc, absolute V-band magnitude \( M_V = -14.34\pm0.05 \) mag and total stellar mass \( M_* = 6.0\pm3.6\times10^7 \) M\(_\odot\) (based on the \( M/L \)\(_V\) obtained in the SED fitting). We have also fitted the surface
Figure 15. An edge-on view of the FP projected onto the plane defined by log \( R_e \) and 1.03 log \( \sigma_e + 0.3 \mu_e > -7.77 \). E = ellipticals, iE = intermediate luminosity ellipticals, dE = dwarf ellipticals, and dSph = dwarf spheroidals. B92 = Bender et al. (1992), G03 = Geha et al. (2003) (Virgo cluster), vz04 = van Zee et al. (2004) (Virgo cluster) and R05 de Rijcke et al. (2005).

brightness profile in the HST bands using Sérsic models. The total magnitudes we retrieve using those fittings are compatible with the ones obtained using aperture photometry. With the new estimate for the size of the galaxy, the object would no longer belong to the category of UDGs but it would classify as a regular dwarf spheroidal galaxy.

5 THE VELOCITY FIELD OF THE GALAXIES IN THE LINE-OF-SIGHT OF [KKS2000]04 (NGC1052-DF2)

At first sight, a distance of 13 Mpc might imply an implausible large peculiar velocity, given the observed heliocentric velocity of \( v_{hel} = 1803 \pm 2 \) km s\(^{-1}\) (the mean velocity of the 10 GCs detected by van Dokkum et al. 2018a). van Dokkum et al. (2018a) argue that a distance as short as 8 Mpc would imply a large peculiar velocity of 1200 km s\(^{-1}\) assuming a velocity of 1748 \( \pm 16 \) km s\(^{-1}\) once corrected from the Virgo-centric infall and the effects of the Shapley supercluster and Great Attractor. Given the uncertainties in the assumed corrections, the way to deal properly with peculiar velocities is to use the CMB reference frame (Fixsen et al. 1996), that is,

\[
\nu_{pec} = \nu_{CMB} - H_0 \cdot d
\]

with \( d \) is the distance and \( H_0 \) is the Hubble constant, for which we adopt the value of 73\( \pm 2 \) km s\(^{-1}\) Mpc\(^{-1}\) (Riess et al. 2012, 2016). In the CMB reference frame, the velocity of [KKS2000]04 (NGC1052-DF2) is 1587 km s\(^{-1}\), and its peculiar velocity 640\( \pm 25 \) km s\(^{-1}\), a seemingly large value but (as we will show) not unusually so. Interestingly, the field of galaxy velocities around [KKS2000]04 (NGC1052-DF2) is rather complex. Figure 17 shows the distribution of peculiar velocities for galaxies with heliocentric velocities in the range 500 km s\(^{-1}\) < \( v_{hel} < 3000 \) km s\(^{-1}\), as given in the compilation of the Extragalactic Distance Database (EDD, Tully et al. 2009), and in particular its latest version cosmicflows-3 (Tully et al. 2016).

Within a projected radius of 1.75 Mpc (at a distance of 10 Mpc), the peculiar velocity field shows huge variations, with galaxies with large infalling velocities in excess of \( -500 \) km s\(^{-1}\) being angularly close to galaxies with large outflowing velocities, a reflection of strong gradients in the tidal tensor. There is a large-scale filament crossing the field with typical heliocentric velocities around \( v_{hel} \sim 1600 \) km s\(^{-1}\), and another more extended structure around \( v_{hel} \sim 2200 \) km s\(^{-1}\) with a local minimum around \( v_{hel} \sim 1800 \) km s\(^{-1}\). This is also illustrated in Figure 18 which shows the distribution of measured peculiar velocities (top) and distances (bottom) as a function of the observed heliocentric velocity, in the range of interest. Overall, the peculiar velocity field shows an average peculiar velocity of \( -230 \) km s\(^{-1}\), significantly larger than the expected null value, and a dispersion much larger than the standard pairwise velocity dispersion on these scales. The bottom panel shows no tell-tale S-shaped signature of a cluster (e.g., Virgocentric infall). This complex anisotropic pattern can be accounted for if several filaments (as traced by a number of groups present in this volume, see § 6) and small voids coexist in this volume, giving raise to large amplitudes in the tidal tensor on small scales. The vertical

\[ \text{http://edd.ifa.hawaii.edu} \]
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Figure 17. The peculiar velocity field around [KKS2000]04 (NGC1052-DF2), as traced by galaxies with heliocentric velocities in the range $500 \text{ km s}^{-1} < v_{\text{hel}} < 3000 \text{ km s}^{-1}$. [KKS2000]04 (NGC1052-DF2), NGC 1042 and NGC 1052 are shown as star, triangle and open circle, respectively. Filled red circles give galaxies with positive peculiar velocities, while filled blue circles are galaxies with negative peculiar velocities. The amplitude and sign of the peculiar velocity is given by the side of each galaxy. Note the large shear in the peculiar velocity field, as traced by galaxies with large positive peculiar velocities lying close to galaxies with large negative peculiar velocities. For reference, the right vertical axis provides the physical scale of the projected distance at 10 Mpc.

The blue line in Fig. 18 gives the observed heliocentric velocity of [KKS2000]04 (NGC1052-DF2), and shows that a wide range of peculiar velocities, from around $-1400 \text{ km s}^{-1}$ to $+700 \text{ km s}^{-1}$ is possible, although only distances larger than 20 Mpc appear to be present. This, however, could be misleading, as the peculiar velocity field is not well-sampled and relies on the existence of redshift-independent distances in the catalog by Tully et al. (2009). The presence of large positive peculiar velocities around $+600 \text{ km s}^{-1}$, and galaxies as close as 11 Mpc, within a small angular range and around the observed heliocentric velocity makes the likelihood of the expected peculiar velocity of [KKS2000]04 (NGC1052-DF2) much larger than anticipated.

To quantify this, given the sparse sampling of the cosmicflows-3 catalogue in this area, we compute the probability that the inferred peculiar velocity of [KKS2000]04 (NGC1052-DF2) could arise in similar volumes of the nearby universe. Figure 19 shows the distribution of peculiar velocities for the field at hand (red histogram), and the one for all cosmicflows-3 galaxies.
The peculiar velocity field in the area around $v_{pec} \approx -230 \, \text{km s}^{-1}$ superimposed on infalling filaments and small-scale voids which give rise to an unusually wide distribution of peculiar velocities for a given heliocentric velocity. The measured distances to the galaxies in this field show no signature of large-scale Virgocentric-like flows. The vertical blue line gives the observed heliocentric velocity. (Bottom) The measured distances to the galaxies in the shell around [KKS2000]04 (NGC1052-DF2), which corresponds to a wide range of possible peculiar velocities and distances.

Another feature of Fig. 17 is the large shear in peculiar velocities between a galaxy and its nearest neighbour at an angular distance of 12$^\circ$3 and lies at 117 km s$^{-1}$? These large differences are actually not that strange in that field, as there are many more extreme cases. For example, PGC013612 which has $v_{pec} = -908$ km s$^{-1}$ and lies at 15$^\circ$ of PGC013612 which has $v_{pec} = +630$ km s$^{-1}$. Likewise NGC936 and NGC 941 are within 12$^\circ$ and yet their peculiar velocities differ by more than 970 km s$^{-1}$ (~824 and 149 km s$^{-1}$ respectively).

To go beyond the classical estimation of the average line-of-sight dispersion (Ferreira et al. 1999), we show in Figure 21 the difference in peculiar velocities between a galaxy and its nearest neighbour at an angular distance of 12$^\circ$ as $\Delta v_{pec} = v_{pec1} - v_{pec2}$. In the shaded area which corresponds to the nearest (catalogued) galaxies around

Note that the peculiar velocity of NGC1042 is rather uncertain as its distance has not been well settled in the literature, with a likely range from 8 to 13 Mpc; see discussion in Sec. 6.

**Figure 18.** (Top) The peculiar velocity field in the area given in Fig. 17 appears to show a very perturbed Hubble flow centred around $v_{pec} \approx -230 \, \text{km s}^{-1}$ superimposed on infalling filaments and small-scale voids which give rise to an unusually wide distribution of peculiar velocities for a given heliocentric velocity. (Bottom) The measured distances to the galaxies in this field show no signature of large-scale Virgocentric-like flows. The vertical blue line gives the observed heliocentric velocity. (Bottom) The measured distances to the galaxies in the shell around [KKS2000]04 (NGC1052-DF2), which corresponds to a wide range of possible peculiar velocities and distances.

**Figure 19.** The distribution of peculiar velocities in the area given in Fig. 17 (red histogram) and in the shell 500 km s$^{-1} < v_{hel} < 3000$ km s$^{-1}$ (black histogram), as probed by the cosmicflows-3 catalogue (Tully et al. 2016). The cumulative distribution function (solid line) shows that a peculiar velocity of 640 km s$^{-1}$ is rather likely (88% quantile). The top box-whisker plot gives the median and interquartile range (IQR=Q3-Q1; upper/lower hinges), along with the lengths of the whiskers at $Q_{1,3} \pm 1.5 \cdot IQR$. $Q_1$ and $Q_3$ are the upper and lower quartiles corresponding to the 75th and 25th percentiles of the distribution.
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Figure 20. The peculiar velocity field of the sky area shown in Fig. 17 projected on the super-galactic plane. The length of the arrow gives the scale of the peculiar velocity.

Figure 21. The difference in peculiar velocity of nearest neighbour galaxies, separated by an angular distance $\theta_{12}$, in the surveyed area (Fig. 17, blue circles) and in the shell $500 \text{ km s}^{-1} < v_{\text{hel}} < 3000 \text{ km s}^{-1}$ (filled circles). The grey rectangle gives the range of angular distance between [KKS2000]04 (NGC1052-DF2) and its nearest neighbours ($13.7$ to NGC 1052 and $20.8$ to NGC 1042), and shows that differences as large as $\pm 600 \text{ km s}^{-1}$ are rather common, as quantified by the histogram on the right hand side.

[KKS2000]04 (NGC1052-DF2), very large differences are found, ranging from $-1600 \text{ km s}^{-1}$ to $+1520 \text{ km s}^{-1}$. As the volume probed is small, Figure 21 also shows the distribution in the control sample. Once again, differences as large as $\pm 600 \text{ km s}^{-1}$ are rather common, as quantified by the histogram on the right hand side.

In summary, all the properties of the expected large peculiar velocity of [KKS2000]04 (NGC1052-DF2), $v_{\text{pec}} \sim 640 \text{ km s}^{-1}$, appear to be not only rather normal in that particular field, but also in the nearby universe, as traced in the state-of-the-art cosmicflows-3 catalogue. Hence the distance of 13 Mpc cannot be ruled out on the basis of the inferred peculiar velocity.

6 [KKS2000]04 (NGC1052-DF2) A MEMBER OF THE NGC 988 GROUP?

The two most prominent galaxies in the line of sight of [KKS2000]04 (NGC1052-DF2) are NGC1052 and NGC1042 (see Fig. 22). van Dokkum et al. (2018a) have used the vicinity ($13.7$ in projection) of [KKS2000]04 (NGC1052-DF2) to NGC1052 to support their claim that [KKS2000]04 (NGC1052-DF2) is at 20 Mpc. If this were the case, [KKS2000]04 (NGC1052-DF2) would be a satellite located at $\sim 80 \text{ kpc}$ from NGC1052 (van Dokkum et al. 2018a).

However, these authors do not explore the possibility that the system could be physically linked to the also very close in projection (20.8) NGC1042 ($cz=1371 \text{ km s}^{-1}$).

The distance to NGC1042 has been estimated in the literature following different approaches. Making use of the Tully-Fisher relation, a distance estimation independent of the redshift, several authors have found that the galaxy NGC1042 is located at $\approx 8 \text{ Mpc}$ (8.4 Mpc Tully et al. (1992); 7.8 Theureau et al. (2007); 8 Mpc Luo et al. (2016)). Interestingly, Theureau et al. (2007) obtained a distance of 13.2 Mpc reconstructing the proper motions of the galaxies in

12 The redshift-independent distance measurement to NGC1052 is $\approx 20 \text{ Mpc}$ (see e.g. Tonry et al. 2001; Blakeslee et al. 2001).
the local universe, which includes considering both the peculiar velocities of our Galaxy and NGC1042. Consequently, if [KKS2000]04 (NGC1052-DF2) were a satellite of NGC1042 its distance would be within a range from ~8-13 Mpc\textsuperscript{13}. If this were the case, the projected distance of [KKS2000]04 (NGC1052-DF2) to NGC1042 would be between 49 to 80 kpc (i.e. physically closer than if the object were a satellite of NGC1052). Still, even if the NGC1042 were located at 13.2 Mpc a physical association with [KKS2000]04 (NGC1052-DF2) could be debatable considering their difference in heliocentric velocities are ~400 km s\(^{-1}\). In Sec. 5 we argue that a difference in velocities as large as 400 km s\(^{-1}\) is not implausibly high considering the small-scale shear in that region. Since the distance estimate to NGC1042 is still rather uncertain (8-13 Mpc), it is worth exploring whether there are other associations of galaxies in the line-of-sight of [KKS2000]04 (NGC1052-DF2) and at a distance around 13 Mpc.

As diffuse galaxies are normally found in clusters (see e.g. Conselice et al. 2003; van Dokkum et al. 2015; Koda et al. 2015; Mihos et al. 2015; Muñoz et al. 2015; Venhola et al. 2017) and groups (Román & Trujillo 2017a,b; Trujillo et al. 2017) and much more rarely in the field (Dalcanton et al. 1997; Martínez-Delgado et al. 2016; Bellazzini et al. 2017; Leisman et al. 2017) the probability that [KKS2000]04 (NGC1052-DF2) belongs to a group should be high.

Given that the first turnaround radii of groups of galaxies have typical sizes of a few Mpc (Kourkchi & Tully 2017), which also corresponds to the present scale (Fig. 17), could [KKS2000]04 (NGC1052-DF2) be a member of a known group of galaxies? The nearest group is that containing NGC 988 which is also associated with NGC 1032 and NGC 1068 (Makarov & Karachentsev 2011), and whose center (R.A.(2000)=39.5716 and Dec(2000)= 8.4943; Kourkchi & Tully 2017) is only 57 kpc away from [KKS2000]04 (NGC1052-DF2). Interestingly, galaxies in this group and its associations span a wide range in redshift from 1160 km s\(^{-1}\)<\(v_{hel}\)<2750 km s\(^{-1}\) and enclose a total mass of about ~10\(^{13}\) M\(_{\odot}\) (Makarov & Karachentsev 2011). The rich NGC 988 group (22 members with measured radial velocities) lies at a distance of 15.1 Mpc and has \(<v_{hel}> = 1550\) km s\(^{-1}\) (Tully et al. 2016) with a dispersion velocity of 143 km s\(^{-1}\) (Kourkchi & Tully 2017). NGC988 has a peculiar velocity of +193 km s\(^{-1}\). The difference in velocity with [KKS2000]04 (NGC1052-DF2) is less than 450 km s\(^{-1}\), and as shown in Fig. 21 differences in peculiar velocities as large as ±450 km s\(^{-1}\) at angular separations of order of the degree are very frequent in the nearby universe.

For [KKS2000]04 (NGC1052-DF2) to be bound to the NGC 988 group itself, its total energy must be negative:

\[
\frac{1}{2} \frac{\Delta v_{12}^2 \Delta R_{12}}{G (M_1 + M_2)} < 1, \tag{9}
\]

\textsuperscript{13} It is worth noting that based on the Tully-Fisher relation, Tully et al. (2008) claimed that NGC1042 is located as close as 4.2 Mpc. This distance was based on the inclination of 57 deg they measured for this galaxy using the B-band. However, measurements both in the near infrared using 2MASS as well as kinematical measurements find a more likely inclination for the system of 37-38 deg (Luo et al. 2016), which moves the galaxy to a distance of 8 Mpc.

where \(\Delta v_{12}\) and \(\Delta R_{12}\) are the differences in velocity and separation, respectively. \(M_1\) and \(M_2\) are the mass of the system and the group and \(G\) is the gravitational constant. Observationally, we have the projected separation, \(R_L = 215\) kpc (assuming a distance of 13 Mpc), the difference in radial velocities, \(\Delta v_{pec12} = 450\) km s\(^{-1}\), and also the group mass \(M_{NGC988} = 7 \times 10^{12}\) M\(_{\odot}\) (Kourkchi & Tully 2017). Since the mass of [KKS2000]04 (NGC1052-DF2) is much smaller by some three orders of magnitude, we can safely assume that \(M_{NGC988} + M_{KK2000}04 \approx M_{NGC988} \approx 7 \times 10^{12}\) M\(_{\odot}\). In terms of these quantities, Eq. 9 becomes (see Eq. (3) in Makarov & Karachentsev 2011):

\[
\frac{R_L}{215\text{ kpc}} \left( \frac{\Delta v_{pec12}}{450 \text{ km s}^{-1}} \right)^2 < \frac{1.4 \, M_{NGC988}}{7 \times 10^{12}\, M_{\odot}}. \tag{10}
\]

which indeed is fulfilled. This is not surprising given that the projected separation of \(R_L = 215\) kpc is smaller than the mean harmonic radius (a good measure of the effective radius of the gravitational potential of the system) of the NGC 988 group which is 379 kpc (Makarov & Karachentsev 2011). In this sense, [KKS2000]04 (NGC1052-DF2) could be bound to the NGC 988 group.

A second condition for [KKS2000]04 (NGC1052-DF2) to belong to this group is that their separation must remain at least within the zero-velocity sphere (Sandage 1986), a condition which translates into the following inequality, again in terms of observable quantities (see Eq. (4) in Makarov & Karachentsev 2011):

\[
\frac{R_L}{215\text{ kpc}}^3 < 1452 \left( \frac{M_{NGC988}}{7 \times 10^{12}\, M_{\odot}} \right) \left( \frac{H_0}{73\text{ km s}^{-1}\text{ Mpc}^{-1}} \right)^{-2}. \tag{11}
\]

This relation also appears to be fulfilled, and provides tantalizing evidence that [KKS2000]04 (NGC1052-DF2) might indeed belong to this galaxy group associated to NGC 988.

\textbf{7 REVISITING THE TOTAL MASS OF [KKS2000]04 (NGC1052-DF2)}

On the basis of the adopted distance to [KKS2000]04 (NGC1052-DF2) of 13 Mpc, we revisit how this new distance affects the estimate of the total mass of the system. The total mass of the system is derived from its dynamical mass \(M_{\text{dyn}}\).

To derive the dynamical mass of [KKS2000]04 (NGC1052-DF2) based on its GCs, we used the Tracer Mass Estimator (TME) of Watkins et al. (2010). The TME was also used by van Dokkum et al. (2018a) and was first employed for UDGs in Boasley et al. (2016). For [KKS2000]04 (NGC1052-DF2) we have line-of-sight radial velocities and projected radii and so we use Eq. (26) of Watkins et al. (2010). Three parameters enter into the TME prefactor: \(\alpha\), the power law index of the host potential, \(\beta\), the velocity anisotropy parameter and \(\gamma\), the power law slope of the volume density profile.

Simulations constrain \(\alpha\) to lie in the range between 0 and 0.6 (Di Cintio et al. 2012; Watkins et al. 2018) and we fix \(\beta = 0\) (which corresponds to isotropic orbits for the GCs). We measured \(\gamma\) by fitting a power-law function of the

\[ M_{\text{dyn}} = 0.6 \left( \frac{H_0}{73\text{ km s}^{-1}\text{ Mpc}^{-1}} \right)^{\frac{2}{3}} \left( \frac{v_{pec}}{215\text{ kpc}} \right)^{1.5} \left( \frac{M_{\odot}}{7 \times 10^{12}} \right)^{-1}. \]
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Table 4. Dynamical (median) mass ($M_{\text{dyn}}(r)$) of [KKS2000]04 (NGC1052-DF2) computed within different radial distances from the galaxy center, using an increasing number of GCs ($N_{\text{GC}}(<r)$). The second and fourth column represent the 10th and 90th percentile of the distribution of TME, as presented in Fig. 24.

| r (kpc) | 10thile $M_{\text{dyn}}(<r)[10^8M_\odot]$ | 90thile $N_{\text{GC}}(<r)$ |
|--------|------------------------------------------|-----------------------------|
| 1.47   | 0.29                                     | 1.00                        | 1.52 | 4 |
| 2.23   | 0.95                                     | 2.59                        | 4.56 | 6 |
| 3.27   | 1.23                                     | 2.88                        | 5.02 | 8 |
| 4.46   | 1.36                                     | 3.14                        | 5.49 | 9 |
| 5.02   | 2.39                                     | 4.32                        | 6.83 | 10 |

form $n(r) \propto r^{3-\gamma}$ (Watkins et al. 2010) to the cumulative radial distributions of the GCs (Fig. 23). We did this for the combined sample of 19 GCs, and also for the 10 GCs with velocities. For the sample of 19 GCs we obtain $\gamma = 2.44 \pm 0.11$. We obtain consistent, though slightly higher values for the reduced sample of 10 GCs ($\gamma = 2.78 \pm 0.25$). This approach is preferable to measuring $\gamma$ from a differential volume density plot since it is not dependent on the choice of binning.

To constrain [KKS2000]04 (NGC1052-DF2)’s highest (lowest) allowed mass in the case of NFW DM halo mass, including the contribution of the stars, we added the upper (lower) bounds of each DM halo to the upper (lower) bounds of the stellar distributions; in this way, each color contour

14 van Dokkum et al. (2018c) have very recently remeasured the velocity of GC98. With the new estimation, our dynamical mass within 5 kpc changes slightly: $M_{\text{dyn}} = 2.9^{+1.3}_{-1.0} \times 10^9 M_\odot$.

15 Note that the value $r_c$ represents roughly the radius at which the Burkert density profile becomes shallower than a NFW model, such that the actual core, defined as the position where the log slope of the profile is zero, is smaller than $r_c$. 
Figure 23. Cumulative radial distributions of GCs in [KKS2000]04 (NGC1052-DF2) for the full sample of 19 GCs (left panel), and for the 10 GCs with radial velocities (right panel). The solid lines indicate fits to these data with the values of $\gamma$ indicated. The uncertainties given are the statistical uncertainties from linear, least-squares fits.

Figure 24. Distribution of TME (i.e. dynamical) masses for [KKS2000]04 (NGC1052-DF2) from Monte Carlo simulations for $D = 13$ Mpc. The solid orange line indicates the median mass of the distribution, the dashed lines indicate the 10, 90 percentiles of the distribution. The vertical black line indicates the stellar mass of [KKS2000]04 (NGC1052-DF2) obtained in this work and the gray shaded region indicates the range of uncertainties on the stellar mass.

represents the highest and lowest possible mass profile associated to a specific DM halo, once the 1σ error in the c-M relation and the uncertainties in the derivation of the stellar mass profile have been considered.

The best NFW halo mass describing the dynamical mass of [KKS2000]04 (NGC1052-DF2) at every radius is $M_{\text{tot}} \sim 10^{9.5} M_\odot$. Specifically, a NFW halo of mass $M_{\text{tot}} = 1.26 \times 10^{9} M_\odot$ best fits the outermost dynamical mass measured at ~5 kpc. Altogether, the range of halo masses spanned by the derived dynamical mass of [KKS2000]04 (NGC1052-DF2), including its uncertainties, varies between $M_{\text{tot}} \sim 10^{8.5} M_\odot$ and $M_{\text{tot}} \sim 10^{9.5} M_\odot$. Similarly, we constrained the best halo mass for [KKS2000]04 (NGC1052-DF2) to be $M_{\text{tot}} = 10^{8.5} M_\odot$ and $M_{\text{tot}} = 10^{9.5} M_\odot$ in the case of assuming a Burkert profile with a 2 or 4 kpc scale-radius, respectively. Clearly, the larger the core radius the higher the halo mass that can fit the data.

In Fig. 26 we show the expected stellar mass-halo mass relation from abundance matching techniques, together with the derived $M_\star$-$M_{\text{halo}}$ of [KKS2000]04 (NGC1052-DF2), as well as other UDGs and local dwarfs. We show three different abundance matching results as solid (Moster et al. 2013), dashed (Behroozi et al. 2013) and dot-dashed (Brook et al. 2014) lines. Note that while the Brook et al. (2014) relation has been constrained using Local Group data, and reaches $M_\star \sim 3 \times 10^6 M_\odot$, the other relations are simply extrapolated to such low masses.

Different estimates of the total mass of [KKS2000]04 (NGC1052-DF2) are shown as red circles, specifically, from dark to light red we indicate the estimated mass assuming a Burkert profile with $r_c = 4$ and 2 kpc, and a NFW profile (lowest mass estimate, bright red point). Uncertainties in stellar and halo mass are indicated as red error bars: the uncertainty in the halo mass represents the highest and lowest possible $M_{\text{tot}}$ compatible with the highest and lowest mass estimates of [KKS2000]04 (NGC1052-DF2) at ~5 kpc, as in Fig. 25. Other known UDGs for which a constraint on halo mass exists are shown as orange symbols. Data for VCC1287, UGC2162, DF44 and HUDs (HI-bearing Ultra Diffuse sources) are taken from Beasley et al. (2016), Trujillo et al. (2017), van Dokkum et al. (2016) and Leisman et al. (2017), respectively. For these objects, the best fit halo masses have been determined (or reassessed) by comparing...
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Figure 25. The dynamical mass of [KKS2000]04 (NGC1052-DF2) vs. distance from the galaxy center. Each dark circle corresponds to measurements of the dynamical mass at different radial distances, between the effective radius and the radius of the outer-most GC (~5 kpc). The data-points are correlated as indicated by the connecting dashed line. Vertical lines indicate the 10th and 90th percentile in the derivation of $M_{\text{dyn}}$. The contribution from the stellar surface density is indicated as dashed blue lines, including the uncertainty in the (M/L)$_V$. Left panel: NFW mass profiles for halos of increasing masses are shown as colored solid lines. For each DM halo, we indicated the upper and lower bound in their $M(<r)$, taking into account the c-M relation scatter and the uncertainties in the stellar component. The best NFW halo that describes the dynamical mass of [KKS2000]04 (NGC1052-DF2) for increasing radii has a total mass of $M_{\text{tot}} \sim 10^{9.1}M_{\odot}$. Right panel: Burkert cored mass profiles for haloes of increasing masses, using a core radius $r_c$ of 2 (dashed lines) and 4 kpc (solid lines) respectively. The largest the core the more massive is the DM halo that can fit [KKS2000]04 data. The best halo describing [KKS2000]04 (NGC1052-DF2), at its outermost measured point, is $M_{\text{tot}} \sim 10^{9.25}M_{\odot}$, for a core radius of 2 kpc, and $M_{\text{tot}} \sim 10^{9.6}M_{\odot}$, for $r_c = 4$ kpc.

data with mass profiles of NIHAO hydrodynamical simulations, as in Fig. 2 of Di Cintio et al. (2017). The mass of DF17, from Peng & Lim (2016) and Bessey & Trujillo (2016), is based on GC counts. Simulated UDGs from the NIHAO project (Wang et al. 2015; Di Cintio et al. 2017) are shown as purple crosses. Light gray circles represent Local Group isolated galaxies whose masses have been estimated from their stellar velocity dispersions at $R_e$ as in Brook & Di Cintio (2015), assuming a NFW profile, while dark gray circles are Local Volume dwarfs with HI rotation curves extending to at least two disk scale lengths, as presented in Oman et al. (2016), and for which we have re-computed the expected halo mass in a Planck cosmology.

While [KKS2000]04 (NGC1052-DF2) appears to be an outlier in the $M_\ast - M_{\text{halo}}$ relation, its inferred dark matter mass is clearly much larger than that obtained in van Dokkum et al. (2018a), making this galaxy a DM dominated object. [KKS2000]04 (NGC1052-DF2) is not the only example of galaxy showing a lower than expected halo mass: IC1613, highlighted in the plot, is an example of galaxy with a similar DM content, as already noted in Oman et al. (2016) (see, however, Brook & Di Cintio (2015) for a larger estimation of the total mass of IC1613, assuming an underlying cored profile). While IC1613’s rotation curve seems difficult to reconcile within $\Lambda$CDM expectations, a possible explanation could be that the inclination errors have been underestimated, which compromises the inferred mass profile. In the same way, caution should be taken when interpreting the derived mass of [KKS2000]04 (NGC1052-DF2): the low number of GCs on which the TME is based might provide biased results (see Martin et al. 2018; Laporte et al. 2018 for a recent discussion).

8 IS [KKS2000]04 (NGC1052-DF2) AN ANOMALOUS GALAXY?

In this paper we have concentrated our attention on the distance to the galaxy [KKS2000]04 (NGC1052-DF2), leaving aside the ongoing discussion (see e.g. Martin et al. 2018; Laporte et al. 2018) about the reliability of the velocity dispersion of the compact sources of the system. Taking into account the velocity of the most discrepant GC-98 source, van Dokkum et al. (2018a) claim the following 90% confidence limit interval for the intrinsic velocity dispersion of the system: $8.8 < \sigma_{\text{int}}< 10.5$ km s$^{-1}$. In the following discussion, we use this interval of velocity dispersion, together with our estimations of the stellar mass, dynamical mass and effective radius to compare the galaxy with other low mass galaxies.

8.1 [KKS2000]04 (NGC1052-DF2) compared to other Local Group galaxies

In Fig. 27 we plot the velocity dispersion and the dynamical mass within 1 $R_e$ versus other properties of the object. The

\footnote{Very recently van Dokkum et al. (2018c) readdressing the velocity of GC98 obtains $\sigma_{\text{int}}=7.8^{+3.4}_{-2.2}$ km s$^{-1}$.}
Figure 26. The stellar mass-halo mass relation of [KKS2000]04 (NGC1052-DF2), shown as red circle with error bars. From dark red to bright red, we show our best mass estimates assuming a Burkert profile with core radius of $r_c=4$ and 2 kpc, and a NFW profile. Other known UDGs for which a constraint on halo mass exists are shown as orange symbols (see text for more details), while simulated UDGs from the NIHAO project (Wang et al. 2015) are indicated as purple crosses. Expectations from several abundance matching relations are shown as solid (Moster et al. 2013), dashed (Behroozi et al. 2013) and dot-dashed (Brook et al. 2014) lines. Isolated LG dwarfs (Brook & Di Cintio 2015) and Local volume dwarfs (Oman et al. 2016) with extended rotation curves are shown as light and dark gray points, respectively. Both datasets assume an underlying NFW profile. We have highlighted the location of IC1613, a galaxy with some characteristics similar to [KKS2000]04 (NGC1052-DF2).

galaxy is shown together with other Local Group galaxies taken from the compilation by McConnachie (2012). Fig. 27 shows that [KKS2000]04 (NGC1052-DF2) is not anomalous in relation to other low mass galaxies in the Local Group.

[KKS2000]04 (NGC1052-DF2) presents some characteristics which are close to the isolated object IC1613 (Kirby et al. 2014) located in our Local Group at a distance of ~760 kpc. This object has $R_e\sim1$ kpc, $\sigma_v=10.8\pm1$ km s$^{-1}$ and $10^8$ L$_\odot$. Interestingly, this galaxy also has a similar amount of dark matter within the effective radius $(M/L_V)_{1/2}=2.2\pm0.5$ T$_\odot$ (in the case of [KKS2000]04 (NGC1052-DF2) this value is $4.3\pm2$ T$_\odot$).

8.2 Is [KKS2000]04 (NGC1052-DF2) a tidal dwarf galaxy?

The existence of galaxies without dark matter have been suggested previously in the literature (see e.g. the case of NGC7507; Lane et al. 2015). This galaxy is an example of a Tidal Dwarf Galaxy (TDG). TDGs have little to no dark-matter (e.g., Ploeckinger et al. 2015, 2018). These objects, due to their surface brightness, could resemble closely the properties of [KKS2000]04 (NGC1052-DF2).

The question then arises as to whether [KKS2000]04 (NGC1052-DF2) could be a TDG. This interpretation seems unlikely. [KKS2000]04 (NGC1052-DF2) does not fit in with the expected properties of TDGs. TDGs are formed from the tidal debris of gas-rich merging galaxies (e.g., Mirabel et al. 1992; Duc & Mirabel 1998). Thus, they inherit many
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9 CONCLUSIONS

With the revised distance to [KKS2000]04 (NGC1052-DF2) of ~13 Mpc, all the claimed anomalies of the galaxy and its system of globular clusters disappear. The revised distance comes from five different redshift-independent distance indicators. [KKS2000]04 (NGC1052-DF2) is a rather ordinary low surface brightness galaxy ($R_e = 1.4^{+0.1}_{-0.1}$ kpc, $M_\star \approx 6 \times 10^7 M_\odot$, $M_{tot} \gtrsim 10^9 M_\odot$ and $M_{halo}/M_\star > 20$), surrounded by globular clusters whose properties are very similar to those found in other systems associated with dwarf galaxies. Moreover, with this new distance estimate, the ratio between the GC mass and the total galaxy mass is high enough to prevent, by dynamical friction, the orbital decay of the GCs in a short period of time. A serious problem already pointed out by Nusser (2018).

We find that the amount of dark matter in [KKS2000]04 (NGC1052-DF2) is not consistent with zero, as claimed by van Dokkum et al. (2018a). We can show this one more time estimating the actual fraction of dark matter inside its 3D half-light radius $r_{1/2}$ following the same procedure as van Dokkum et al. (2016). First, we estimate the stellar mass from the empirical correlation found in the GAMA survey (see Eq. 8 in Taylor et al. 2011), namely

$$\log M_\star = 1.15 + 0.70 \times (g - i) - 0.4 M_i,$$

where $M_\star$ is in solar units and $M_i$ is the absolute AB magnitude in the $i$ band. Our accurate Gemini $g$ magnitude
combined with the SDSS $i$ magnitude (see Table 1) yields $g-i = 0.84\pm0.07$, while the absolute magnitude at the revised distance of 13 Mpc becomes $M_i = -14.89\pm0.07$. From equation 12, the stellar mass of [KKS2000]04 (NGC1052-DF2) is $M_*=4.9^{+1.3}_{-1.0} \times 10^{7} M_\odot$, where we have adopted a 1σ accuracy of $\sim 0.1$ dex (Taylor et al. 2011). This independent estimate agrees with the mass inferred from the SB profile and from the fitting of the SED we have derived in this paper.

Second, we can estimate the mass enclosed within the 3D half-mass radius assuming that [KKS2000]04 (NGC1052-DF2) has an approximately isothermal profile. In this case, we assume $\sigma_* \approx \sigma_{GC} \sim 8$ km s$^{-1}$, and, as argued by Wolf et al. (2010) the deprojected 3D circularised half-mass radius is

$$r_{1/2} \approx \frac{4}{3} R_e \sqrt{\frac{b}{a}}$$

(13)

where $R_e$ is the effective radius from the observed SB profile along the semi-major axis, $b/a$ the axis ratio. Adopting $R_e=1.4$ kpc and $b/a = 0.85$ yields $r_{1/2} = 1.72$ kpc. The mass enclosed within the 3D half-light radius (see Eq. 2 in Wolf et al. 2010) becomes

$$M \left( r < r_{1/2} \right) \simeq 10^8 M_\odot \left( \frac{\sigma_*}{8 \text{ km s}^{-1}} \right)^2 \left( \frac{r_{1/2}}{1.72 \text{kpc}} \right) .$$

(14)

Hence the dark matter fraction within $r_{1/2}$ is $f_{DM} = \left( M \left( r < r_{1/2} \right) - 0.5 M_\star \right)/M \left( r < r_{1/2} \right) \simeq 75\%$. We conclude that [KKS2000]04 (NGC1052-DF2) is a dark matter dominated galaxy.

10 ACKNOWLEDGMENTS

We thank Juan E. Betancort-Rijo for interesting comments on the redshift distribution of the galaxies in the large scale structure. We also thank Gabriella Raimondo and Michele Cantiello for useful advice on the Teramo/SPoT SBF database. I.T. acknowledges financial support from the European Union’s Horizon 2020 research and innovation programme under Marie Skłodowska-Curie grant agreement No 721463 (SUNDIAL ITN network). MAB acknowledges support from the Severo Ochoa Excellence programme under Marie Sklodowska-Curie grant agreement No 721463 to the SUNDIAL ITN network. MAB thanks Michele Cantiello for useful advice on the Teramo/SPoT database. I.T. acknowledges financial support from CONICYT (Chile), Ministerio de Ciencia, Tecnología e Innovación Productiva (Argentina), and Ministério da Ciência, Tecnologia e Inovação (Brazil).

REFERENCES

Abolfathi, B., Aguado, D. S., Aguilar, G., et al. 2018, ApJS, 235, 42
Akhlaghi, M., & Ichikawa, T. 2015, ApJS, 220, 1
Bakos, J., Trujillo, I., & Pohlen, M. 2008, ApJ, 683, L103
Beasley, M. A., Romanowsky, A. J., Pota, V., et al. 2016, ApJ, 819, L20
Beasley, M. A., & Trujillo, I. 2016, ApJ, 830, 23
Behroozi, P. S., Wechsler, R. H., & Conroy, C. 2013, ApJ, 770, 57
Bellazzini, M., Belokurov, V., Magrini, L., et al. 2017, MNRAS, 467, 3751
Bender, R., Burstein, D., & Faber, S. M. 1992, ApJ, 399, 462
Bernardi, M., Sheth, R. K., Annis, J., et al. 2003, AJ, 125, 1866
Bertin, E., & Arnouts, S. 1996, A&AS, 117, 393
Bertin, E., Mellier, Y., Radovich, M., et al. 2002, Astronomical Data Analysis Software and Systems XI, 281, 228
Bertin, E. 2006, Astronomical Data Analysis Software and Systems XV, 351, 112
Binney, J., & Tremaine, S. 1987, Princeton, NJ, Princeton University Press, 1987, 747 p.
Biscardi, L., Raimondo, G., Cantiello, M., & Brocato, E. 2008, ApJ, 678, 168
Blakeslee, J. P., Vazdekis, A., & Ajhar, E. A. 2001, MNRAS, 320, 193

MNRAS 000, 1–26 (2015)
