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A galaxy lacking dark matter

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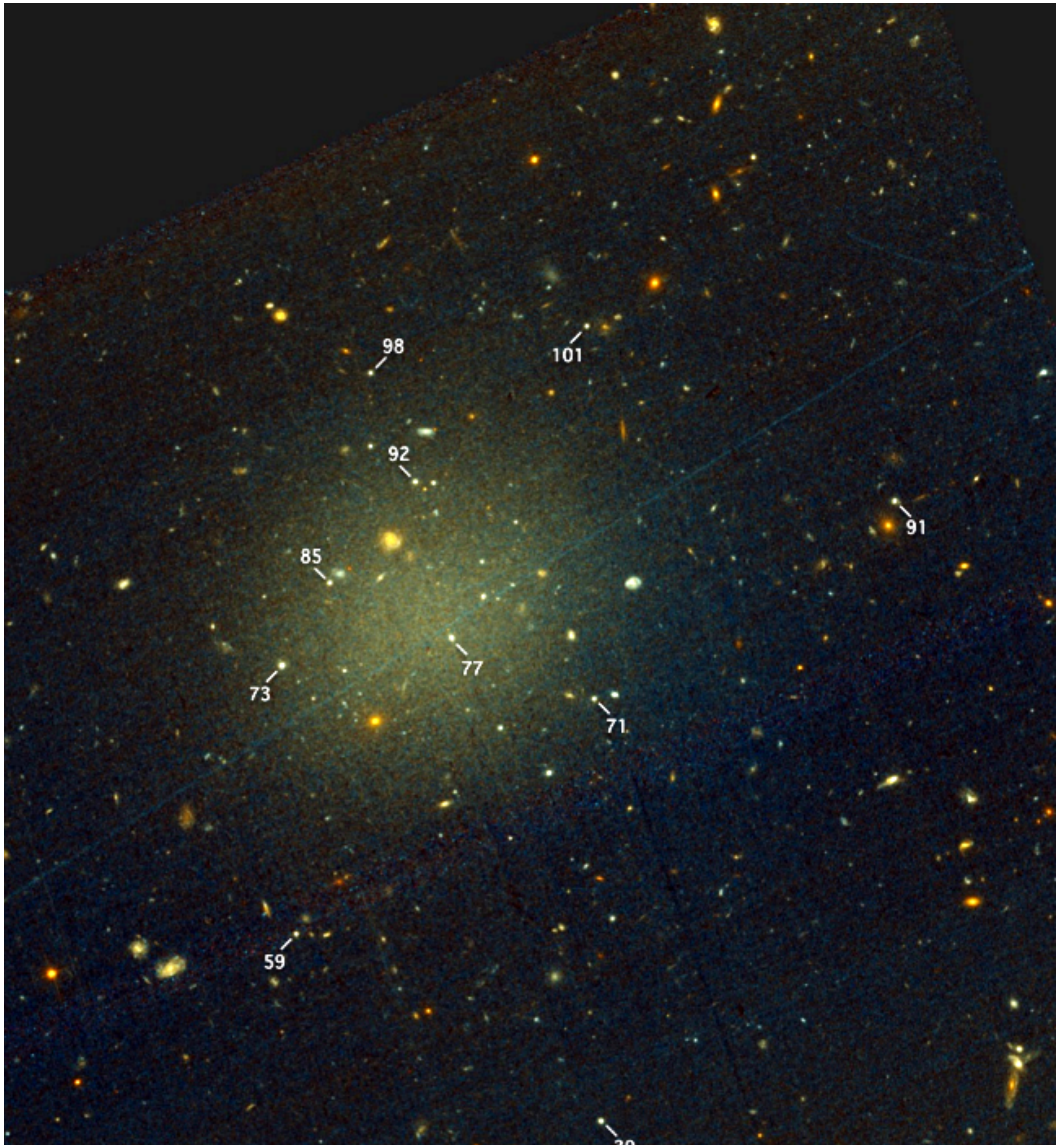
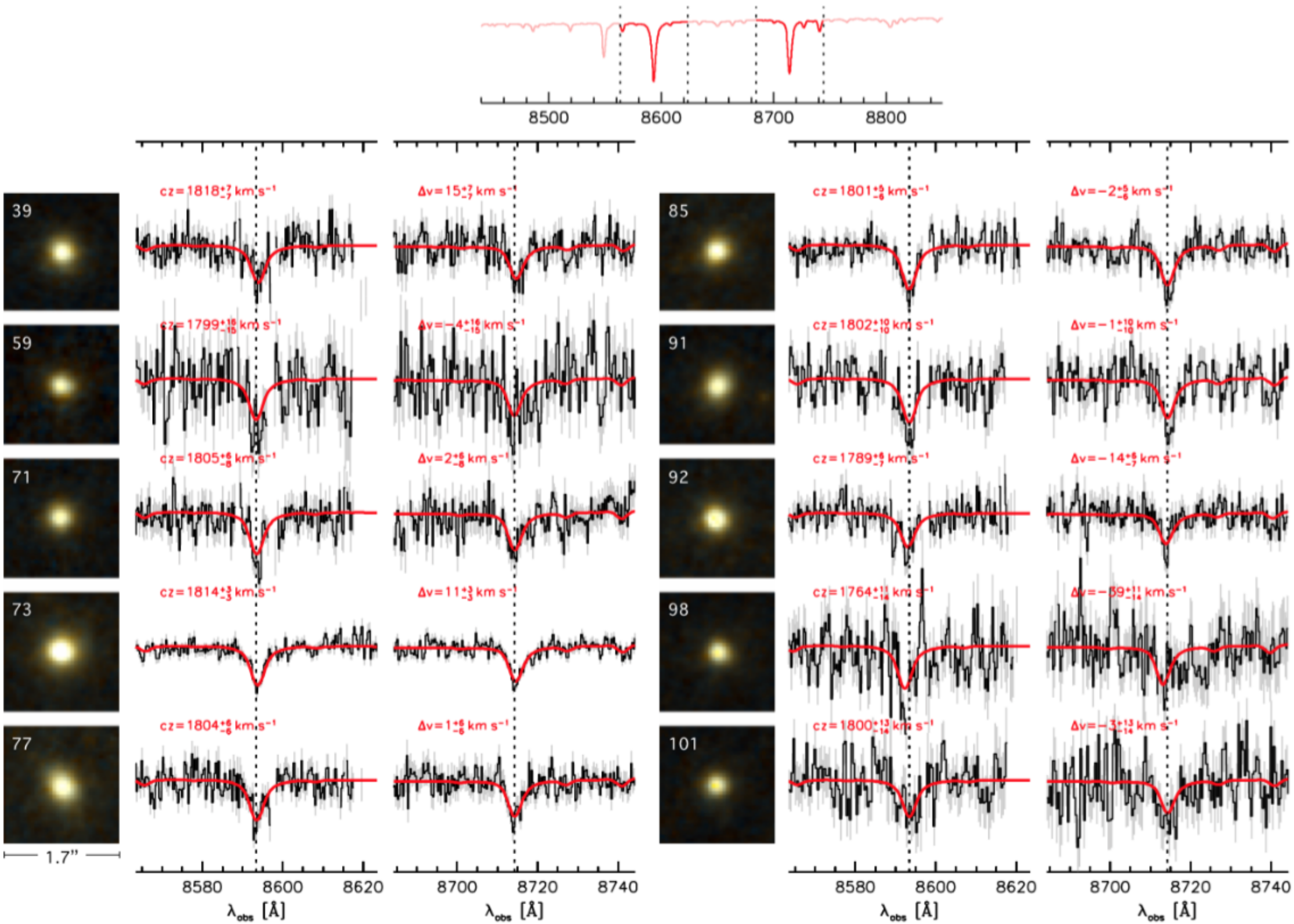
Studies of galaxy surveys in the context of the cold dark matter paradigm have shown that the mass of the dark matter halo and the total stellar mass are coupled through a function that varies smoothly with mass. Their average ratio $M_{\rm halo}/M_{\rm stars}$ has a minimum of about 30 for galaxies with stellar masses near that of the Milky Way (approximately 5×10^{10} solar masses) and increases both towards lower masses and towards higher masses.[1,2] The scatter in this relation is not well known; it is generally thought to be less than a factor of two for massive galaxies but much larger for dwarf galaxies.[3,4] Here we report the radial velocities of ten luminous globular-cluster-like objects in the ultra-diffuse galaxy[5] NGC1052–DF2, which has a stellar mass of approximately 2×10^8 solar masses. We infer that its velocity dispersion is less than 10.5 kilometres per second with 90 per cent confidence, and we determine from this that its total mass within a radius of 7.6 kiloparsecs is less than 3.4×10^8 solar masses. This implies that the ratio $M_{\rm halo}/M_{\rm stars}$ is of order unity (and consistent with zero), a factor of at least 400 lower than expected.[2] NGC1052–DF2 demonstrates that dark matter is not always coupled with baryonic matter on galactic scales.



distance. Using the I_{814} band image we derive a surface brightness fluctuation distance of $D_{\mathrm{SBF}} = 19.0 \pm 1.7$ Mpc (see Methods). It is located only $14'$ from the luminous elliptical galaxy NGC 1052, which has distance measurements ranging from 19.4 Mpc to 21.4 Mpc.[9,10] We infer that NGC1052–DF2 is associated with NGC 1052, and we adopt $D \approx 20$ Mpc for the galaxy.

We parameterized the galaxy's structure with a two-dimensional Sérsic profile.[11] The Sérsic index is $n = 0.6$, the axis ratio is $b/a = 0.85$, the central surface brightness is $\mu(V_{606}, 0) = 24.4\,\mathrm{mag\,arcsec^{-2}}$, and the effective radius along the major axis is $R_e = 22.6''$, or 2.2 kpc. We conclude that NGC1052–DF2 falls in the "ultra diffuse galaxy" (UDG) class,[5] which have $R_e > 1.5$ kpc and $\mu(g, 0) > 24\,\mathrm{mag\,arcsec^{-2}}$. In terms of its structural parameters it is very similar to the galaxy Dragonfly 17 in the Coma cluster.[5] The total magnitude of NGC1052–DF2 is $M_{606} = -15.4$, and the total luminosity is $L_V = 1.1 \times 10^8\,\mathrm{L_\odot}$. Its color $V_{606} - I_{814} = 0.37 \pm 0.05$ (AB), similar to that of other UDGs and metal-poor globular clusters.[12] The stellar mass was determined in two ways: by placing a stellar population at $D = 20$ Mpc that matches the global properties of NGC1052–DF2 (see Methods), and by assuming $M/L_V = 2.0$ as found for globular clusters.[13] Both methods give $M_{\mathrm{stars}} \approx 2 \times 10^8\,\mathrm{M_\odot}$.



8500
8600
8700
8800
39
59
71
73
77
85
91
92
98
101
1.7"
8580
8600
8620
8700
8720
8740
λ_{obs} [Å]

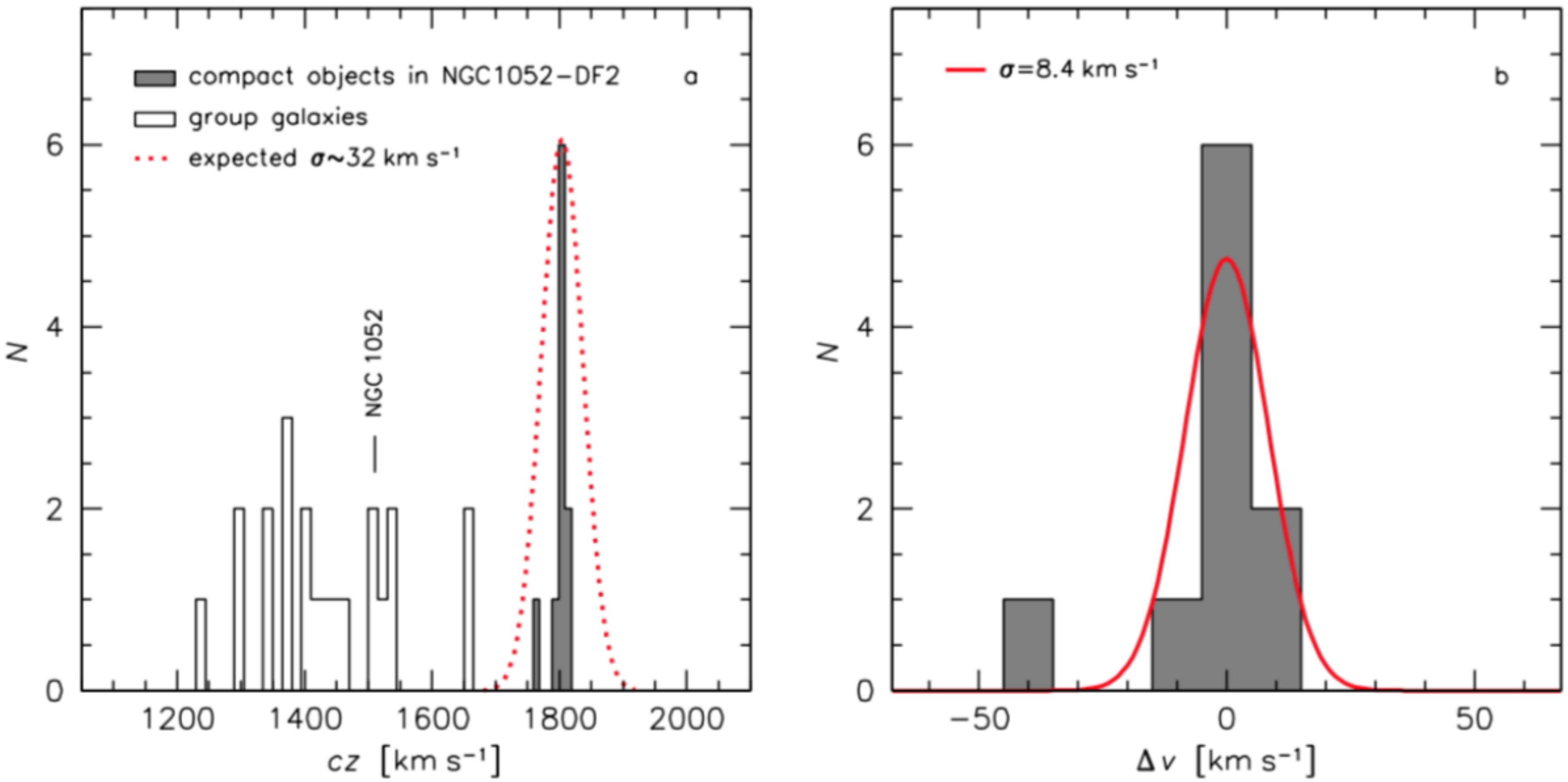


Figure 3: **Velocity dispersion.** The filled grey histograms show the velocity distribution of the ten compact objects. Panel a shows a wide velocity range, and includes the velocities of all 21 galaxies in the NASA/IPAC Extragalactic Database with $cz < 2,500$ km s^{-1} that are within a projected distance of two degrees from NGC 1052. The red dotted curve shows a Gaussian with a width of $\sigma = 32$ km s^{-1}, the average velocity dispersion of Local Group galaxies with $8.0 \leq \log(M_{\rm stars}/{\rm M}_\odot) \leq 8.6$. Panel b shows a narrow velocity range centered on $cz = 1,803$ km s^{-1}. The red solid curve is a Gaussian with a width that is equal to the biweight dispersion of the velocity distribution of the compact objects, $\sigma_{\rm obs} = 8.4$ km s^{-1}. Taking observational errors into account, we derive an intrinsic dispersion of $\sigma_{\rm intr} = 3.2^{+5.5}_{-3.2}$ km s^{-1}. The 90 % confidence upper limit on the intrinsic dispersion is $\sigma_{\rm intr} < 10.5$ km s^{-1}.

To our knowledge this is the coolest known galaxy outside of the Local Group.

We calculate the corresponding 90 % confidence upper limit on the mass of NGC1052–DF2 using the tracer mass estimator (TME) method,[15] which provides an estimate of the dynamical mass within the radius of the outermost discrete tracer. We find $M_{\rm dyn} < 3.4 \times 10^8\,{\rm M}_\odot$ within $R_{\rm out} = 7.6$ kpc. We also determine the dynamical mass within the projected half-number radius of the globular cluster system,[16] and find $M_{\rm dyn} < 3.2 \times 10^8\,{\rm M}_\odot$ within $R_{\rm gc} = 3.1$ kpc.

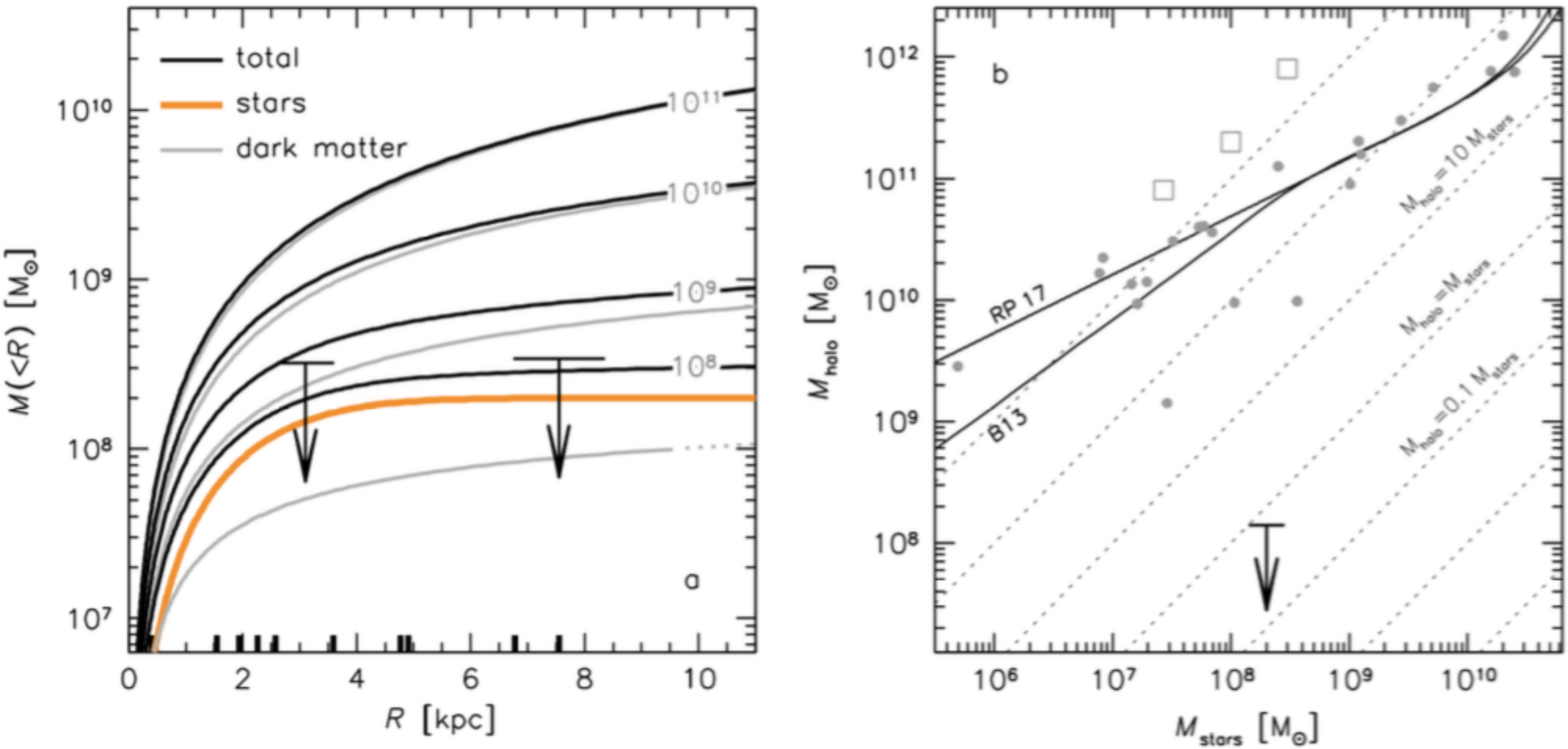
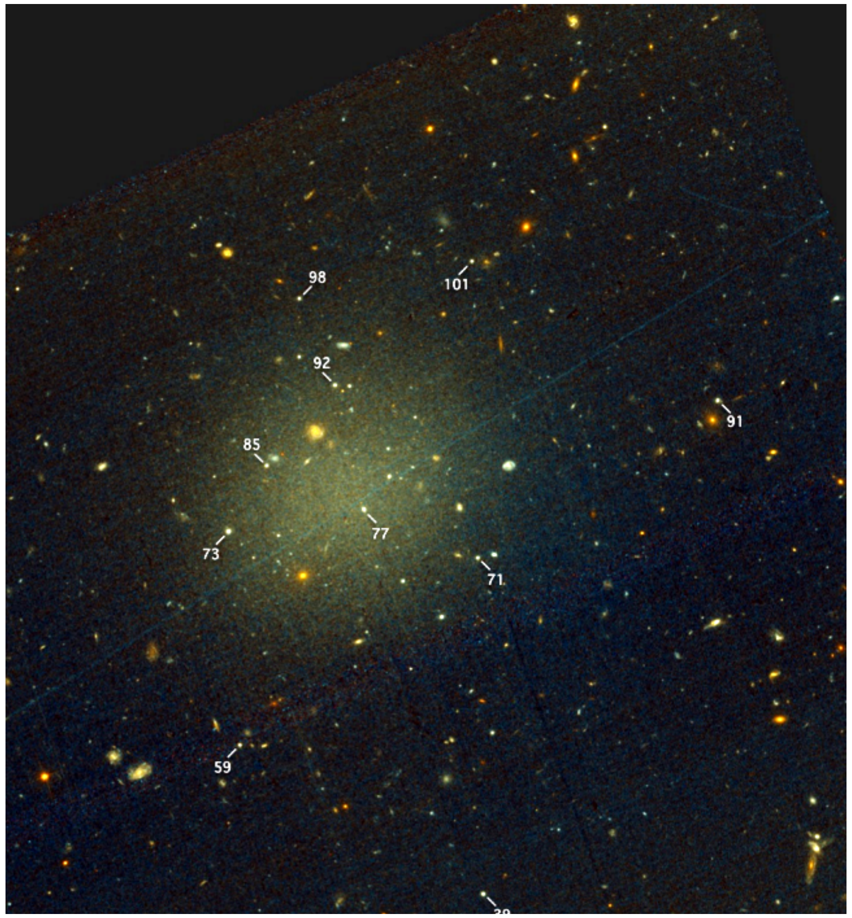
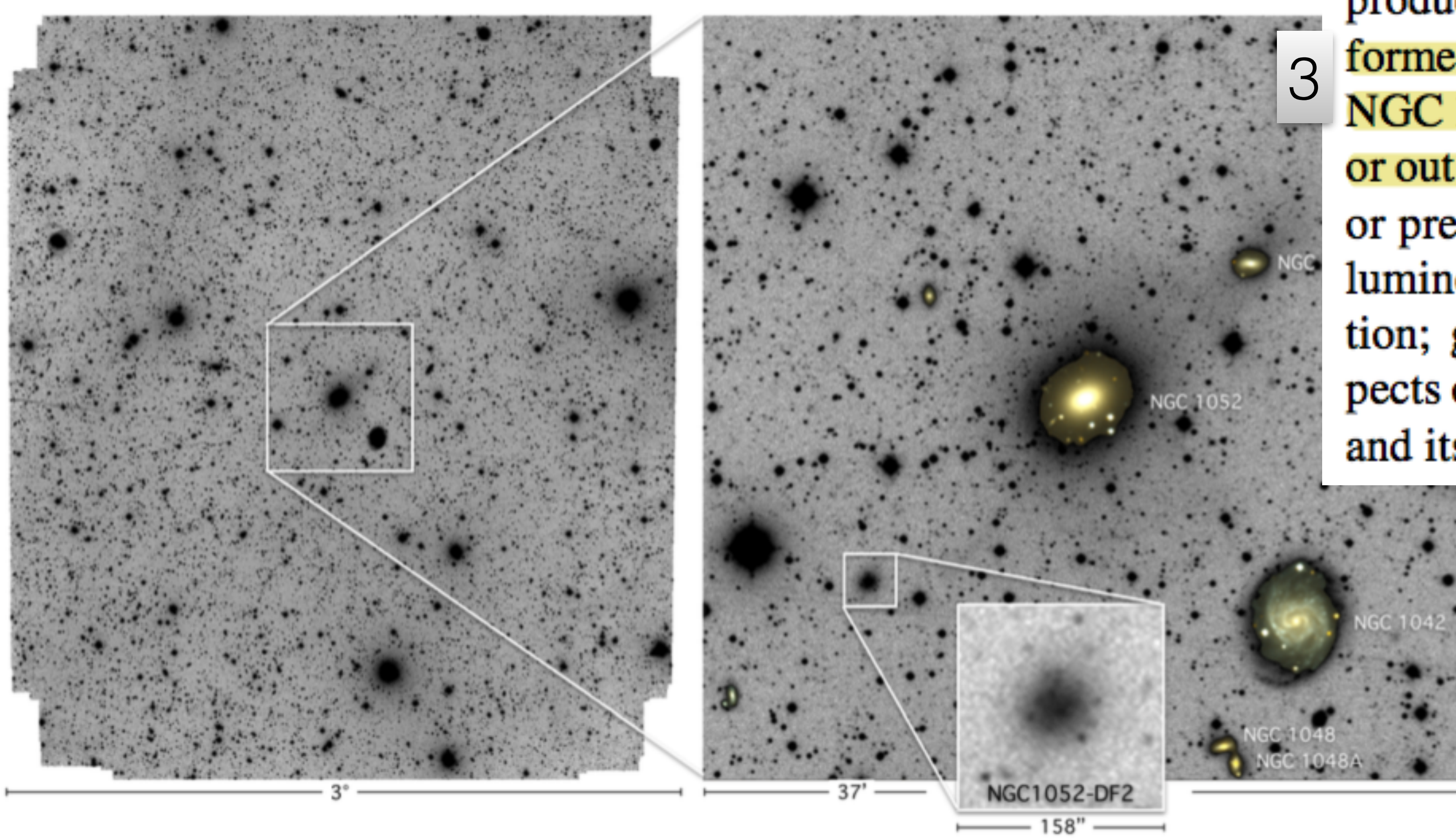


Figure 4: **Constraints on the halo mass.** Panel a shows enclosed mass profiles for NFW halos[14] of masses $M_{200} = 10^8\,\mathrm{M}_\odot$, $10^9\,\mathrm{M}_\odot$, $10^{10}\,\mathrm{M}_\odot$, and $10^{11}\,\mathrm{M}_\odot$ (grey lines). The $10^8\,\mathrm{M}_\odot$ halo profile is shown by a dotted line beyond $R = R_{200} \sim 10\,\mathrm{kpc}$. The orange curve is the enclosed mass profile for the stellar component, and the black curves are the total mass profiles $M_{\mathrm{total}} = M_{\mathrm{stars}} + M_{\mathrm{halo}}$. The ten globular clusters are at distances ranging from $R = 0.4\,\mathrm{kpc}$ to $R = 7.6\,\mathrm{kpc}$; short vertical bars on the horizontal axis indicate the locations of individual clusters. The 90 % upper limits on the total enclosed mass of NGC1052–DF2 are shown by arrows. The limit at $R = 7.6\,\mathrm{kpc}$ was determined with the TME method.[15] The arrow at $R = 3.1\,\mathrm{kpc}$ is the mass limit within the half-number radius of the globular cluster system.[16] The dynamical mass of NGC1052–DF2 is consistent with the stellar mass, and leaves little room for a dark matter halo. Panel b shows the upper limit on the halo mass, and compares this to the expected dark matter mass from studies that model the halo mass function and the evolution of galaxies.[2,17] Grey solid symbols are nearby dwarf galaxies with rotation curves extending to at least two disk scale lengths.[4] Open squares are three cluster UDGs with measured kinematics: VCC 1287,[18] Dragonfly 44,[12] and DFX1.[12] NGC1052–DF2 falls a factor of $\gtrsim 400$ below the canonical relations.



How the galaxy formed?

It is unknown how the galaxy was formed. One possibil-
ity is that it is an old tidal dwarf, formed from gas that was
1 flung out of merging galaxies. Its location near an elliptical
galaxy and its high peculiar velocity are consistent with this
idea. Its relatively blue color suggests a lower metallicity
than might be expected for such objects,[20] but that depends
on the detailed circumstances of its formation.[21] An alterna-
tive explanation is that the galaxy formed from low metallic-
2 ity gas that was swept up in quasar winds.[22] The lack of dark
matter, the location near a massive elliptical, the peculiar ve-
locity, and the color are all qualitatively consistent with this
scenario, although it is not clear whether the large size and
low surface brightness of NGC1052–DF2 could have been
produced by this process. A third option is that the galaxy
3 formed from inflowing gas that fragmented before reaching
NGC 1052, either relatively close to the assembling galaxy[23]
or out in the halo.[24] This fragmentation may have been aided
or precipitated by jet-induced shocks.[25] In any scenario the
luminous globular cluster-like objects require an explana-
tion; generically, it seems likely that the three peculiar as-
pects of the galaxy (its large size, its low dark matter content,
and its population of luminous compact objects) are related.



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AN ENIGMATIC POPULATION OF LUMINOUS GLOBULAR CLUSTERS IN A GALAXY LACKING DARK MATTER

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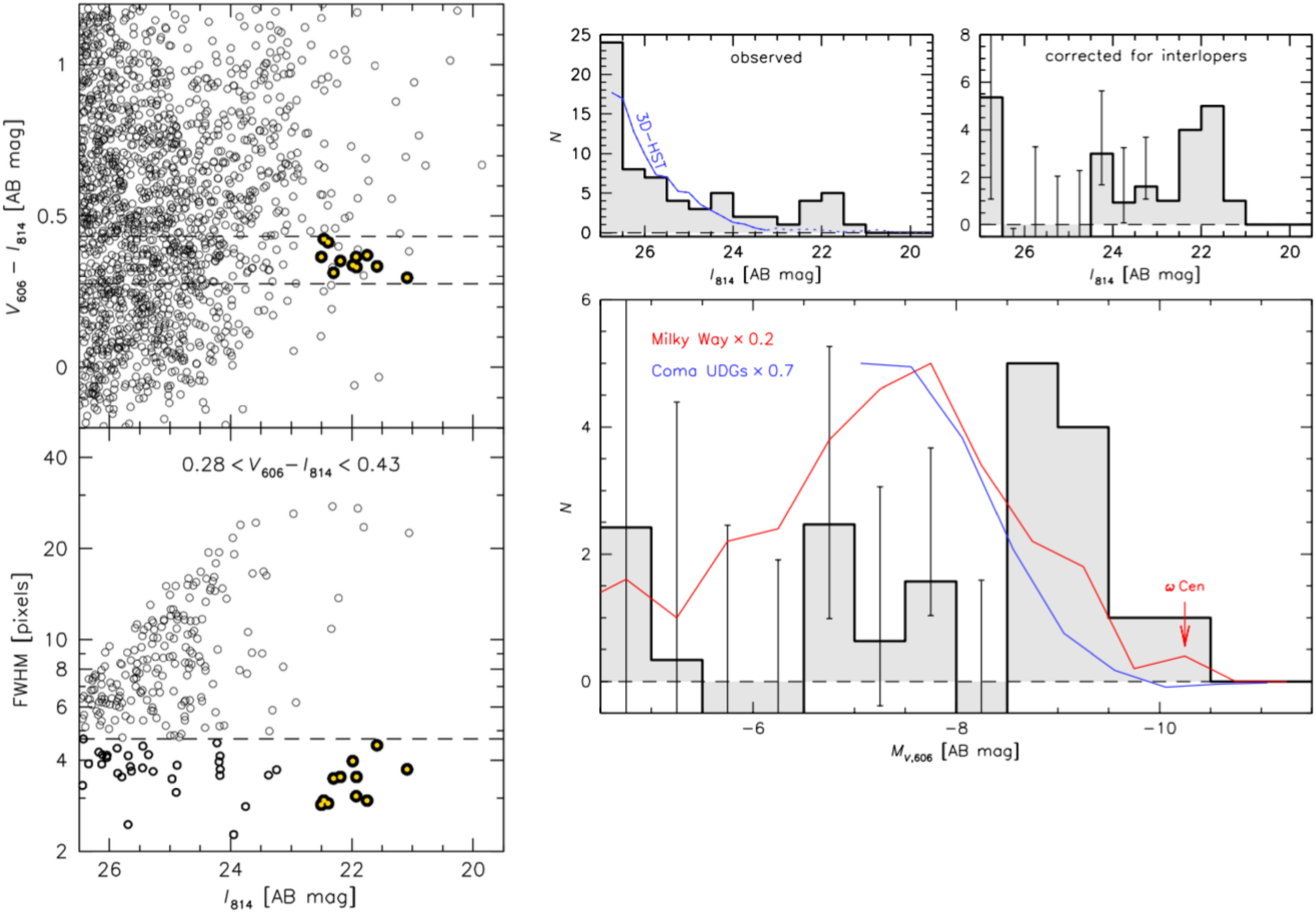
ABSTRACT

We recently found an ultra diffuse galaxy (UDG) with a half-light radius of $R_e = 2.2$ kpc and little or no dark matter. The total mass of NGC1052–DF2 was measured from the radial velocities of bright compact objects that are associated with the galaxy. Here we analyze these objects using a combination of *HST* imaging and Keck spectroscopy. Their average size is $\langle r_h \rangle = 6.2 \pm 0.5$ pc and their average ellipticity is $\langle \epsilon \rangle = 0.18 \pm 0.02$. From a stacked Keck spectrum we derive an age of $\gtrsim 9$ Gyr and a metallicity of $[\mathrm{Fe/H}] = -1.35 \pm 0.12$. Their properties are similar to ω Centauri, the brightest and largest globular cluster in the Milky Way, and our results demonstrate that the luminosity function of metal-poor globular clusters is not universal. The fraction of the total stellar mass that is in the globular cluster system is similar to that in other UDGs, and consistent with "failed galaxy" scenarios where star formation terminated shortly after the clusters were formed. However, the galaxy is a factor of ~ 1000 removed from the relation between globular cluster mass and total galaxy mass that has been found for other galaxies, including other UDGs. We infer that a dark matter halo is not a prerequisite for the formation of metal-poor globular cluster-like objects in high redshift galaxies.

Keywords: galaxies: evolution — galaxies: structure



$V_{606} - I_{814}$ [AB mag]
$0.28 < V_{606} - I_{814} < 0.43$
FWHM [pixels]
I_{814} [AB mag]
observed
3D-HST
corrected for interlopers
N
Milky Way × 0.2
Coma UDGs × 0.7
ω Cen
$M_{V,606}$ [AB mag]

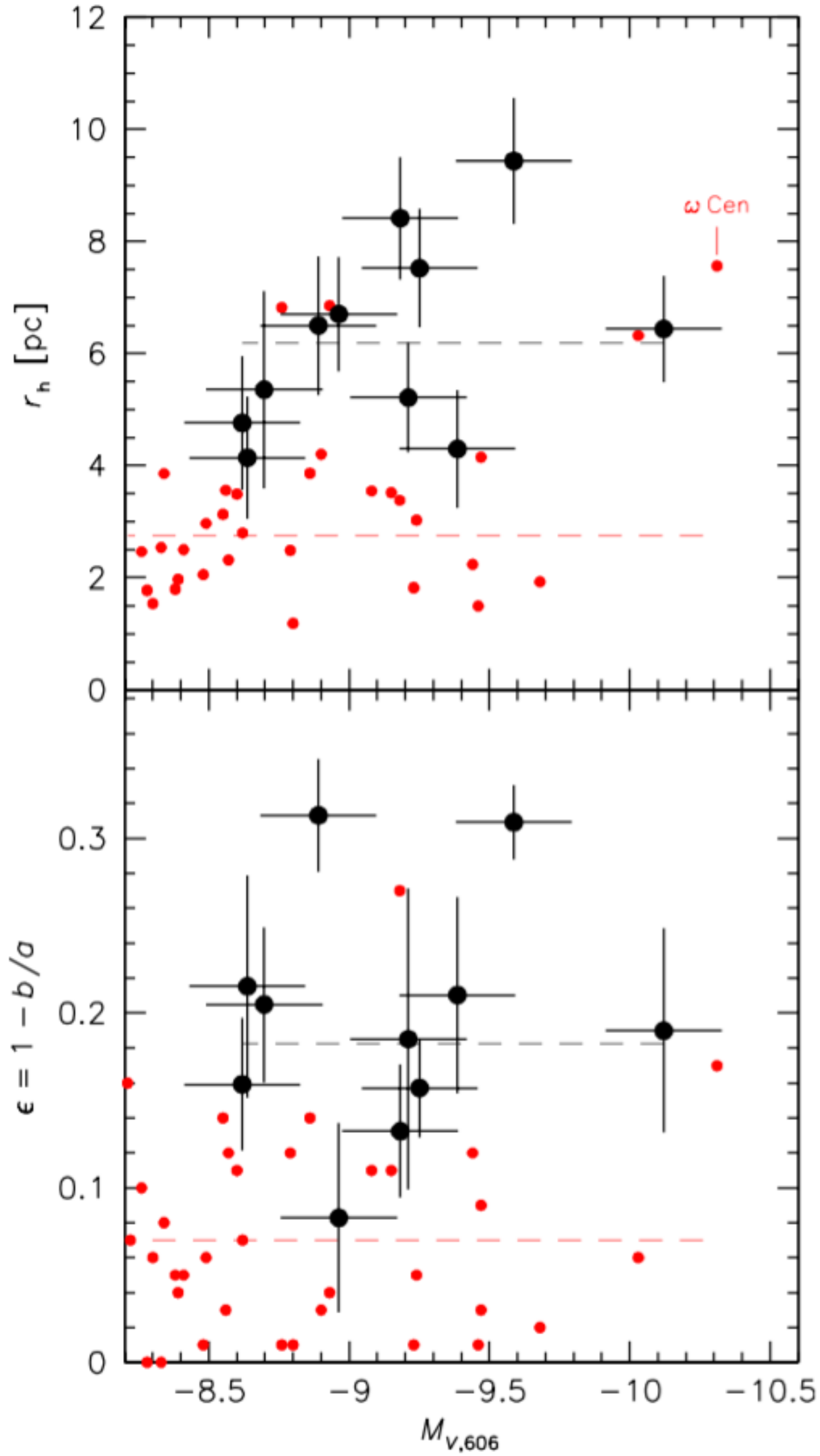
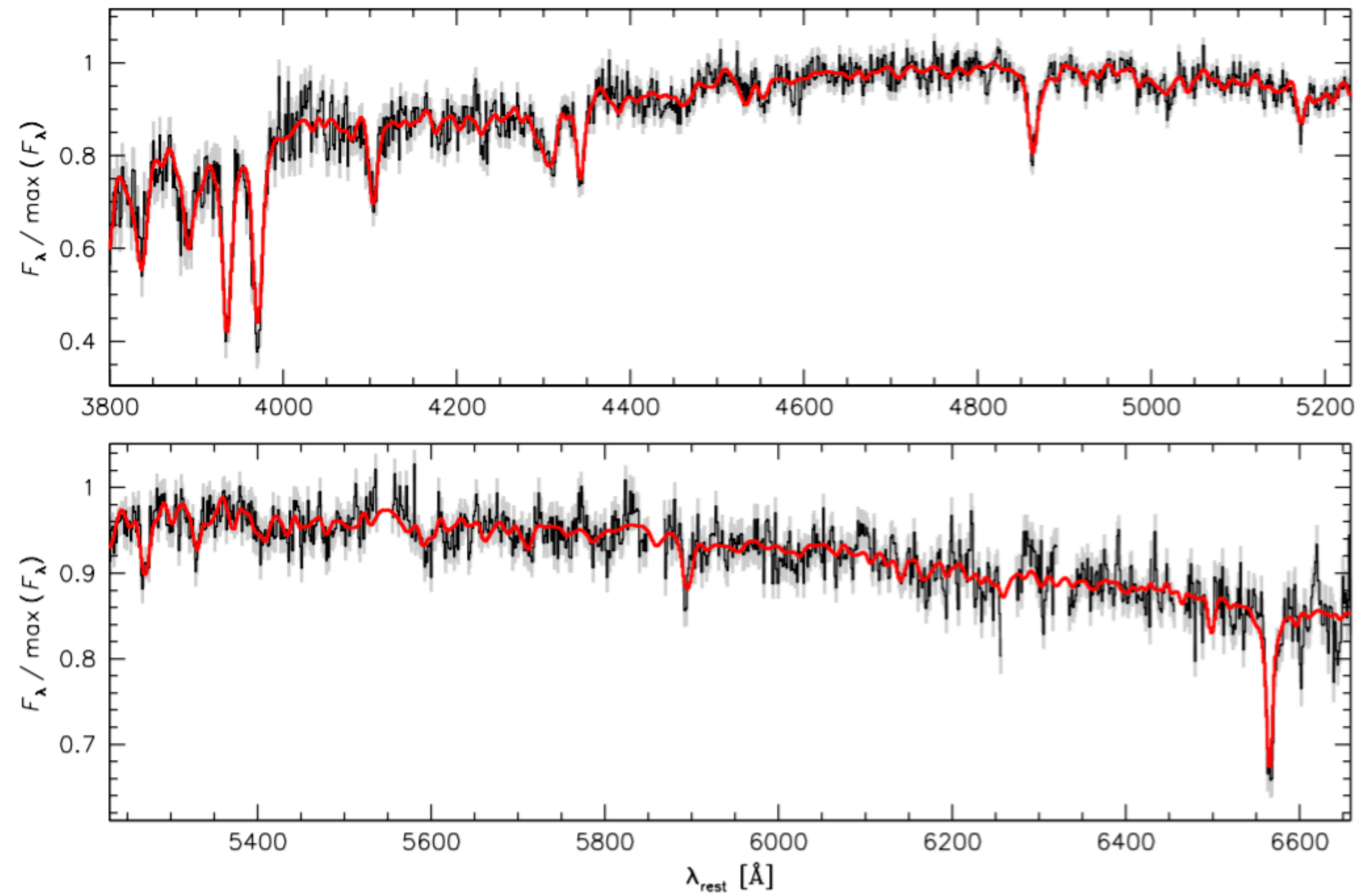


Figure 4. Morphological parameters of the GCs. The top panel shows the circularized half-light radii versus the absolute magnitude, for NGC1052–DF2 (black points with error bars) and the Milky Way (red). Errors in $M_{V,606}$ and r_h include a 10% uncertainty in the distance (see vD18). The bottom panel shows the ellipticity. Means are indicated with dashed lines.



tal galaxy mass. Therefore, the mass in the GC system is $\gtrsim 3\,\%$ of the mass of the galaxy, a factor of ~ 1000 higher than the Harris et al. value. The existence of NGC1052–DF2 suggests that the approximately linear correlation between GC system mass and total galaxy mass is not the result of a fundamental relation between the formation of metal-poor globular clusters and the properties of dark matter halos (as had been suggested by, e.g., Spitler & Forbes 2009; Trenti, Padoan, & Jimenez 2015; Boylan-Kolchin 2017). Instead, the correlation may be a by-product of other relations, with globular cluster formation ultimately a baryon-driven process (see, e.g., Kruijssen 2015; Mandelker et al. 2017).