Current Velocity Data on Dwarf Galaxy NGC 1052-DF2 do not Constrain it to Lack Dark Matter

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Abstract

It was recently proposed that the globular cluster system of the very low surface brightness galaxy NGC 1052-DF2 is dynamically very cold, leading to the conclusion that this dwarf galaxy has little or no dark matter. Here, we show that a robust statistical measure of the velocity dispersion of the tracer globular clusters implies a mundane mass-to-light ratio on the low end for a dwarf galaxy, but many Local Group dwarf galaxies fall well within this contraint. With this study, we emphasize the need to reliably account for measurement uncertainties and to stay as close as possible to the data when determining dynamical masses from very small data sets of tracers.

Key words: galaxies: kinematics and dynamics – methods: statistical

1. Introduction

The dwarf galaxy NGC 1052-DF2 is a satellite of the elliptical NGC 1052 (Mv ≃ −19.4) discovered by Karachentsev et al. (2000) and later studied in detail by the Dragonfly experiment (van Dokkum et al. 2015). It is a very low surface brightness system, owing to its large half-light radius (Mv ≃ −15.3; rhalf ≃ 2.2 kpc; μ0 = 24.4 mag arcsec−2; van Dokkum et al. 2018b). The presence of easily identified globular clusters in the system allowed van Dokkum et al. (2018b, hereafter vD18b) to explore the dynamics of this so-called “ultra-diffuse galaxy.” From the velocities they obtained with LRIS and DEIMOS on the Keck telescopes, the authors isolate 10 likely member globular clusters (GCs), centered around cz = 1803 km s−1. vD18b show that an rms estimate of the velocity dispersion of this sample yields σrms ≃ 14.3 km s−1, while the use of a biweight dispersion (Beers et al. 1990) yields a smaller value σrms ≃ 8.4 km s−1. This is expected, as this latter technique, which they favor, removes potential outliers to the distribution and produces a colder dispersion. After accounting for these uncertainties and under the hypothesis that the furthest point (GC98) is an outlier, vD18b estimate an intrinsic velocity dispersion of σint = 3.2±3.5 km s−1.

However, it is well known that for such small samples of tracers that also have velocity uncertainties of order the measured velocity dispersion, results are extremely sensitive to the technique used and to the way the uncertainties are handled. This is a state of affairs that is, unfortunately, too common for the study of the dynamics of very faint dwarf galaxies in the Local Group for which samples are often restricted to 5–20 stars with velocities (e.g., Martin et al. 2007; Simon & Geha 2007). This community has converged on statistical methods that infer the velocity dispersion of a system by simply building a generative model for the data (e.g., Hogg et al. 2010; to measure a velocity dispersion, we would use a single Gaussian distribution, or the sum of a Gaussian distribution with a simple contamination model that can handle outliers) and evaluating the posterior probability distribution. In favorable cases, the latter can potentially be summarized by its associated modes if it is well behaved.

In this Letter, we revise the estimation of the velocity dispersion of NGC 1052-DF2 by building such a generative model and sampling the posterior probability density function (PDF) of the intrinsic velocity dispersion. We show that the current data does not imply a vanishingly small velocity dispersion (and mass-to-light ratio) for NGC 1052-DF2 and that, in fact, it is compatible with expectations from dynamically hot (i.e., dark-matter dominated) Local Group dwarf galaxies.

2. Method and Results

We base our analysis on the sample of 10 GC velocities presented in van Dokkum et al. (2018a) and vD18b, with their associated uncertainties.

2.1. Model with no Contamination

We first assume that all 10 GCs are members of NGC 1052-DF2, with velocities 〈vi〉 and velocity uncertainties 〈δv〉. In this case, our generative model is a simple Gaussian function with mean 〈v〉 and intrinsic dispersion, σint. The likelihood function can be expressed as

\[
L = \prod_{i=1}^{10} \frac{1}{\sqrt{2\pi \sigma_{\text{obs}}}} \exp \left( -0.5 \frac{\left( v_i - \langle v \rangle \right)^2}{\sigma_{\text{obs}}^2} \right),
\]

with \( \sigma_{\text{obs}}^2 = \sigma_{\text{int}}^2 + \delta_{v}^2 \).

Because the uncertainties \( \delta_{v} \) provided by vD18b are asymmetric, we use the positive uncertainty when \( v_i < \langle v \rangle \) and the negative one otherwise.
Figure 1. Joint PDF of the two-parameter Gaussian model (bottom left) and the marginalized PDF for the mean velocity ($\langle v_i \rangle$) (right) and the velocity dispersion $\sigma_{\text{int}}$ (top). This model yields $\sigma_{\text{int}} = 9.5^{+0.5}_{-0.5}$ km s$^{-1}$.

We assume uniform priors on $\langle v \rangle$ and $\sigma_{\text{int}}$ over the ranges 1750 to 1850 km s$^{-1}$ and 0 to 30 km s$^{-1}$, respectively. We then sample the posterior PDF with our own Markov Chain Monte Carlo algorithm (Martin et al. 2016; Longeard et al. 2018). The resulting joint PDF is shown in Figure 1, along with the marginalized PDFs for the two parameters. The PDF on the intrinsic velocity dispersion of NGC 1052-DF2 is well behaved and yields a significantly higher dispersion than the one reported by vD18b: $\sigma_{\text{int}} = 9.5^{+0.5}_{-0.5}$ km s$^{-1}$ (<18.8 km s$^{-1}$ at the 90% confidence level) versus $\sigma_{\text{int}} = 3.2^{+1.1}_{-1.1}$ km s$^{-1}$ (<10.5 km s$^{-1}$ at the 90% confidence level). Note that our measurement is by design corrected for the velocity uncertainties, as those are specifically included in the model. Our inference is compatible with the rms estimate of vD18b ($\sigma_{\text{rms}} \sim 12.2$ km s$^{-1}$); this is expected, as of all three methods used by vD18b, the rms estimate most closely resembles our formalism.

2.2. Priors

The inference described above assumes a uniform prior on $\sigma_{\text{int}}$, but it is known that such a prior can be biased for small values. We also test the use of Jeffreys’s prior, which does not suffer from this bias, but has the uncomfortable property of being improperly defined (i.e., the PDF does not integrate to unity) if it is not bound at the lower end. Doing so and forcing $\sigma_{\text{int}} > 1$ km s$^{-1}$ yields $\sigma_{\text{int}} = 7.4^{+4.5}_{-4.5}$ km s$^{-1}$ (<15.5 km s$^{-1}$ at the 90% confidence level), which does not significantly change our inference. Alternatively, one can argue that, because the dynamical mass of NGC 1052-DF2 is the physical quantity we aim to constrain and because this quantity scales as $\sigma_{\text{int}}^2$, it would be more appropriate to assume a uniform prior on $\sigma_{\text{int}}^2$. Unsurprisingly, doing so yields larger value for the most likely intrinsic dispersion, with $\sigma_{\text{int}} = 13.1^{+6.4}_{-4.3}$ km s$^{-1}$ (<27.2 km s$^{-1}$ at the 90% confidence level).

While changing the prior on $\sigma_{\text{int}}$ does not change the main conclusion of this paper (the velocity dispersion of the NGC 1052-DF2 velocity sample is not very well constrained), the fluctuations on the constraint stemming from the choice of prior displays the poor constraining power of the data set.

2.3. Model with Contamination

A Kolmogorov–Smirnov test yields a high probability of 0.4 to 0.8 that the sparse data set is drawn from the range of models constrained in Section 2.1. It is therefore not possible to reject the simple Gaussian model as a bad model for this data set. Nevertheless, it is a priori possible that the sample of 10 GCs includes some contamination by field GCs (e.g., from the neighboring NGC 1052) and we now test a model that allows for contamination. We assume a uniform contamination model, $\mathcal{U}$ over the range $1750 < v < 1850$ km s$^{-1}$. With $\eta$ the fraction of the data that is in the contamination, the likelihood function becomes

$$L = \prod_{i=1}^{i<10} \left[ \eta \mathcal{U} + \frac{1 - \eta}{\sqrt{2\pi \sigma_{\text{obs}}}} \exp \left( -0.5 \left( \frac{v_i - \langle v \rangle}{\sigma_{\text{obs}}} \right)^2 \right) \right],$$

with $\sigma_{\text{obs}}$ as defined in Equation (2). The resulting PDFs are shown in Figure 2 for uniform priors. Interestingly, the inference on the intrinsic velocity dispersion of the GC sample remains unchanged, despite $\eta$ reaching an upper limit of ~0.3. While this may seem surprising at first, it can easily be explained by the datum with the most discrepant velocity (GC98; $v = 1764^{+11}_{-14}$ km s$^{-1}$) having one of the largest velocity uncertainties. The model does not feel the need to separate this datum and fold it in the contamination model (indeed, that GC has the high probability of ~0.9 to belong to the dwarf galaxy part of the model). After marginalization, we infer $\sigma_{\text{int}} = 9.2^{+1.4}_{-1.3}$ km s$^{-1}$ (~17.3 km s$^{-1}$ at the 90% level) for our baseline model with contamination. If we use a less-constraining contaminant model using a second Gaussian with only loose priors on the contamination (uniform from 1700 to 1900 km s$^{-1}$ for the center and uniform between 100 and 200 km s$^{-1}$ for the dispersion of this Gaussian representing the contamination), we get $\sigma_{\text{int}} = 11.4^{+5.8}_{-4.3}$ km s$^{-1}$. Finally, even if we nevertheless decide to forego the outcome of the modeling with contamination and abruptly remove GC98 from the data set.
set (which is not advisable) to fit a single Gaussian model to the velocities of the remaining 9 GCs, we still only infer $\sigma = 7.1^{+3.6}_{-3.0}$ km s$^{-1}$ (<14.3 km s$^{-1}$ at the 90% confidence level). These variable results for different contamination assumptions highlight the challenges in interpreting such small-number data sets, while also demonstrating that these cases yield dispersions significantly higher than the vD18b limit.

In the following, we will use the model with the uniform contamination as our baseline model as it is among the most agnostic models discussed above.

2.4. Impact on the Mass-to-light Ratio

To infer the mass-to-light ratio of NGC 1052-DF2, we rely on the velocity dispersion from the model with contamination and use the mass estimator of Walker et al. (2009) that provides the mass within the half-light radius of the dwarf galaxy (\sim 2.2 kpc) under the usual assumption of dynamical equilibrium and sphericity. This estimator yields $M(r_{\text{half}}) < 3.7 \times 10^8 M_\odot$ at the 90% confidence level. Because this radius naturally includes half of the light of the system (\sim 0.55 \times 10^8 L_\odot), we can infer the mass-to-light ratio $M/L(r_{\text{half}}, V)$ within the half-light radius. The corresponding PDF is shown in black in Figure 3 and yields an upper limit of 6.7 at the 90% confidence level.

Wolff et al. (2010) describe an alternate mass estimator to the one of Walker et al. (2009) that, beyond highlighting the difficulty of modeling the dynamical mass from a population of tracers, yields larger masses than the ones we give here ($M/L(r_{\text{half}}, V) < 10.7$). The difference is driven by different choices for the profiles of the tracers, their (axi)symmetry and/or anisotropy assumption (see the discussion in Appendix C of Wolff et al. 2010). We focus on the Walker et al. (2009) estimator to allow for an easier comparison with vD18b, but recognize that the mass-to-light ratio limit of NGC 1052-DF2 would be even higher than the one we infer if we had used the Wolf et al. (2010) estimator.

2.5. Additional Tests

2.5.1. Measuring the Velocity Dispersion by Resampling the Observed Data

Even though it amounts to making the data more noisy than they truly are and we do not recommend it, a common technique for measuring the dispersion from a small number of data points with significant uncertainties (i.e., similar to the size of the dispersion this is being measured), is to run a Monte Carlo resampling of the data. Here, we take the observed velocities of the vD18b sample and perturb them based on their uncertainties by randomly sampling from a Gaussian centered on the velocity measurement, with a dispersion equal to the uncertainties quoted by vD18b. We then follow their method for measuring the observed dispersion by recomputing the bi-weighted midvariance for this perturbed sample. We repeat this process 10,000 times, resulting in a distribution of values for $\sigma_{\text{obs, bi}}$ (see Figure 4). From this process, we can use the mean and standard deviation of the distribution as a value for the observed dispersion, giving $\sigma_{\text{obs, bi}} = 14.3 \pm 3.5$ km s$^{-1}$ (very comparable with the observed r.m.s dispersion from vD18b). Following this, we must also correct for the effects of the observational uncertainties, which will inflate this

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5 Based on the structural parameters of NGC 1052-DF2 (vD18b), this radius includes 98% of the overall luminosity of the dwarf galaxy, or $\sim 1.08 \times 10^8 L_\odot$. 

Figure 3. Mass-to-light ratio of NGC 1052-DF2 inferred from the marginalized velocity dispersion PDF of the model with contamination and for the Walker et al. (2009) mass estimator within the half-light radius (black) and the TME mass estimator of Watkins et al. (2010) favored by vD18b (red). In both cases, we infer a much less strict limit, as can be seen by the 90% confidence limits implied by our analysis (black and red limits and arrow) and that of vD18b (gray limit and arrow).

Figure 4. Results for measuring the observed biweight-midvariance dispersion from 10,000 resamples of the vD18b data set. Here, the original velocities are perturbed within their 1σ uncertainties as described in the text. The mean observed biweight for the sample comes out as $\sigma_{\text{obs, bi}} = 14.3 \pm 3.5$ km s$^{-1}$, giving $\sigma_{\text{obs, bi}} = 12.0 \pm 2.5$ km s$^{-1}$, higher than the 90% upper limit from vD18b, and consistent with our MCMC analysis.

The mass estimator favored by vD18b and based on Watkins et al. (2010) gives the mass within the last datum, i.e., within 7.6 kpc for the sample of GCs. The resulting mass-to-light ratio inference is similar but slightly less constrained (the red curve in Figure 3; $M/L_{\text{TME}} < 8.1$ at the 90% confidence level).

Both mass estimators are therefore consistent with each other, and the data set is not strongly constraining, contrary to the finding of vD18b who found $M/L_{\text{TME, V}} < 3.3$ at the 90% confidence level. It is also worth noting that folding in the uncertainties on $r_{\text{half}}$ and $L_V$ would make the constraint weaker, but vD18b unfortunately do not provide those for their measurement of the size and luminosity of NGC 1052-DF2. As such, the confidence limits provided here should only be seen as lower limits.
2.5.2. On the Reliability of Using Small Samples of Globular Clusters to Compute the “True” Dispersion

Two key issues with interpreting any measured velocity dispersion in this instance are (1) the small number of tracers available and (2) knowing whether these are truly relaxed tracers of the underlying dark-matter halo. For the latter, we know from observations of the outskirts of both the Milky Way and Andromeda that GCs are often associated with substructure at large radii (e.g., Mackey et al. 2010; Veljanoski et al. 2014). In Andromeda in particular, between 50% and 80% of all GCs at distances beyond 30 kpc show both spatial and kinematic correlations with stellar streams (Mackey et al. 2010), meaning that they are not fully relaxed mass tracers.

Given point (2), the effects of point (1) could be severe. Measuring a single dispersion from 10 tracers that may not be relaxed could lead to either a significant over- or under-estimate of the halo velocity dispersion. This can be straightforwardly demonstrated using the GC system of M31. We take the kinematics for 72 clusters from Veljanoski et al. (2014). As the globular cluster system of M31 is known to rotate, we use their rotation-corrected velocities to ensure we are not artificially inflating our measured mass. We then randomly draw 10 clusters and measure the biweight-midvariance of their velocity distribution, following the technique used by vD18b. This sample has a much larger intrinsic dispersion than DF2, but the data are of similar quality (mean velocity uncertainties of ~10 km s$^{-1}$).

Repeating this process 10,000 times gives us a distribution of observed velocity dispersions (see Figure 5) that we can compare to both the biweight from the full sample ($\sigma_{\text{hi,all}} = 105.0$ km s$^{-1}$; the dashed line in Figure 5), and the average velocity dispersion of the M31 halo from its stars ($\sigma_{\text{M31,stars}} \sim 90$ km s$^{-1}$; the dashed-dotted line; Gilbert et al. 2018).

The result here is clear: a single biweight dispersion measure from 10 GCs can give a huge range of dispersion measures. The mean value from this redraw gives $\sigma_{\text{hi,10}} = 96 \pm 24$ km s$^{-1}$, but the tails extend to far higher and smaller values. Such a large statistical uncertainty would mean that, from a sample of 10 GCs in M31, halo masses ranging from 0.2 < $M < 1.2 \times 10^{12} M_\odot$ could be measured within the 90% confidence limit. Given that M31 has a stellar mass of $\sim 10^{11} M_\odot$ (Sick et al. 2015; Williams et al. 2017), the mass-to-light ratio could also be compatible with no dark matter based on this analysis.

3. Discussion

It is evident from Figure 3 that the current velocity data set on NGC 1052-DF2 is not very constraining beyond pointing out that the dwarf galaxy is not massively dominated by dark matter. At the moment, it is not possible to rule out any mass-to-light ratio below $M/L < 6.7$ within the half-light radius or $M/L < 8.1$ within the radius covered by the tracers (at the 90% confidence level in both cases). Could NGC 1052-DF2 host no dark matter and its inferred mass (or mass-to-light ratio) be entirely consistent with an old stellar population ($M/L_\gamma \sim 2$)? Certainly, but so could a much more mundane, dark-matter dominated mass-to-light ratio.

The mass-to-light ratio of NGC 1052-DF2 is compatible with that of other nearby dwarf galaxies. For instance, IC 1613 shares the luminosity of NGC 1052-DF2, has a radius that is only half as small and a velocity dispersion of $10.8^{+3.0}_{-0.9}$ km s$^{-1}$ from which Kirby et al. (2014) inferred $M/L_\gamma(r_{\text{half}}) = 2.2 \pm 0.5$. The M31 companions Cas III and Lac I, albeit somewhat fainter, share similar properties to those of NGC 1052-DF2: their large half-light radii ($\sim 1.5$ kpc; Martin et al. 2013) and velocity dispersion $\sim 10$ km s$^{-1}$ imply mass-to-light ratios ($M/L_\gamma(r_{\text{half}}) = 8.5^{+3.9}_{-1.5}$ and $15^{+12}_{-3}$, respectively; Martin et al. 2014) that are entirely compatible with the constraint on NGC 1052-DF2.$^6$ The well-studied Milky Way satellite dwarf galaxy, Fornax, also shares similar properties (Irwin & Hatzidimitriou 1995; Walker et al. 2009). Finally, NGC 1052-DF2’s velocity dispersion and mass, despite being poorly constrained, fall perfectly on the Walker et al. (2009) universal mass profile proposed for Local Group dwarf galaxies. It also follows the locus of most dwarf galaxies in the $M/L$ versus $M$ plane, contrary to the peculiar dwarf galaxy Dragonfly 44, which appears as exceptionally massive (van Dokkum et al. 2016, their Figure 3). A conservative and cautious approach would therefore be to conclude that the mass-to-light ratio of NGC 1052-DF2 appears to be the low end of that measured for other dwarf galaxies, but share the properties of other local dwarf galaxies and relies on a noisy measurement. Other “ultra-diffuse dwarf galaxies” studied with data sets of similar quality also yield only weak constraints on the dark-matter content (Toloba et al. 2018). Significant additional proof is required before claiming a lack of dark matter in NGC 1052-DF2, even more so since rotation could also be present and its contribution to the dynamics of the galaxy could further increase its dynamical mass. An independent study by Laporte et al. (2018) shows that NGC 1052-DF2 can comfortably live in a dark-matter halo of $10^9 M_\odot$ or even $10^{10} M_\odot$ within the uncertainties.

The different conclusions reached by vD18b and this study show the difficulty in extracting information from a small

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$^6$ The fairly large uncertainties on $M/L_\gamma(r_{\text{half}})$ for these two systems, despite being based on 100–200 tracers further imply that the 10 NGC 1052-DF2 tracers with velocities are unlikely to yield a strong constraint.
velocity data set, especially when the measurement uncertainties on the individual data points are of order the dispersion that is being inferred. In such cases, reverting back to the simplest model and techniques (using a generative model) yields more robust and tractable results.

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