Yale Observing Proposal *Standard proposal* **Semester:** *2018B*
Date: March 2, 2018

A possible second galaxy without dark matter in the NGC 1052 group

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Abstract of Scientific Justification *(will be made publicly available for accepted proposals)***:**
We recently discovered a galaxy in the NGC 1052 group, NGC 1052-DF2, that is seemingly devoid of dark matter: its dark matter halo is a factor of $\gtrsim 400$ less massive than expected from the standard stellar mass – halo mass relation. The dark matter constraint comes from the radial velocities of ten very luminous globular clusters that appear to be associated with the galaxy. We now have obtained HST imaging of 22 other Dragonfly-discovered low surface brightness galaxies, and we identified a galaxy that closely resembles NGC 1052-DF2. It has the same combination of extended low surface brightness emission and luminous globular clusters. Also, *it is in the same group as NGC 1052-DF2!* Here we propose to use LRIS to measure the radial velocities and stellar populations of the globular clusters of NGC 1052-DF4, just as we did in October 2016 for NGC 1052-DF2. Discovering a second galaxy without dark matter would have significant implications, as it would show that NGC 1052-DF2 is not a "pathological" object but that both galaxies are representative of a hitherto unknown mode of galaxy formation.

Summary of observing runs requested for this project

Run	Telescope	Instrument	No. Nights	Min. Nights	Moon	Optimal months	Accept. months
1	Keck I	LRIS/ADC	3	2	dark	Oct-Nov	
2							
3							
4							
5							

Scheduling constraints and non-usable dates *(up to four lines).*

Scientific Justification *Be sure to include overall significance to astronomy. Limit text to one page with figures, captions and references on no more than two additional pages.*

Background: We have built a low surface brightness-optimized telescope, the Dragonfly Telephoto Array (Abraham & van Dokkum 2014). Among other things, we have used Dragonfly to image bright nearby galaxies in the Dragonfly Nearby Galaxy Survey (Merritt et al. 2016). One of the goals of the DNGS is to identify and study low luminosity satellite galaxies. In an initial search we identified 23 low surface brightness "blobs" in the Dragonfly fields, and in Cycle 24 we were granted time on HST to obtain images of all these blobs to determine distances (from the tip of the red giant branch or from surface brightness fluctuations).

Discovery of an apparently "baryonic galaxy": The first galaxy that was imaged with HST was NGC 1052-DF2 (see Fig. 1), in the field of the giant elliptical NGC 1052 at a distance of 20 Mpc. The galaxy is remarkable for three reasons: 1) It is very large, with a half-light radius of 2.2 kpc, $\sim 5\times$ larger than Local Group galaxies of the same luminosity; 2) It has an enigmatic population of very bright globular clusters. The luminosities and sizes of these cluster rival Ω Centauri, the largest and most massive globular cluster in the Milky Way; and 3) Follow-up spectroscopy with DEIMOS and LRIS showed that the radial velocities of the ten globular clusters have an extremely small dispersion, < 10.5 km/s at $> 90\,\%$ confidence (see Fig. 2). The implication of this small dispersion is that the galaxy has little or no dark matter: it falls a factor of > 400 below the canonical Behroozi et al. (2013) relation between stellar mass and dark halo mass.

We published these results in two papers: a Nature paper on the lack of dark matter, and an ApJ Letter on the unprecedented population of luminous globular clusters. The papers will appear on astro-ph on March 28, the date of publication of the Nature paper.[1] The 2018B KCWI proposal of the PI aims to confirm the velocity dispersion of the galaxy by measuring its stellar kinematics.

A second galaxy without dark matter? We unexpectedly found a second galaxy *in the same group* that shares several key characteristics with NGC 1052-DF2: it is a low surface brightness "blob" with a population of associated very luminous compact objects. The galaxy is shown in Fig. 3, with the same scaling and color table as Fig. 1. There are several bright compact "white" objects visible within the low surface brightness emission, and several similar objects at larger distances. We investigate this further by creating a modified version of Fig. 3, where we masked all objects in the field except those that have both the sizes and the colors of the spectroscopically-confirmed globular clusters in NGC 1052-DF2 (the galaxy that we already analyzed). The result is shown in Fig. 4: there are ~ 10 bright compact objects in the vicinity of NGC 1052-DF4.

The apparent magnitudes of these objects are $I = 21.5 - 22.5$, similar to what we found for NGC 1052-DF2. We determined the distance to the galaxy from its surface brightness fluctuations: it is ≈ 20 Mpc, which means it is at the same distance as NGC 1052-DF2 (and the galaxy NGC 1052 itself). *We conclude that we have found a galaxy that appears to be a twin of NGC 1052-DF2.* This is incredibly exciting: it would mean that that galaxy is not a "pathological" anomaly, but that both objects represent a hitherto unknown class of galaxies.

This proposal: Here we propose to obtain radial velocities of the compact objects associated with NGC 1052-DF4, using LRIS on Keck I. We performed very similar observations in 2016 for NGC 1052-DF2. As discussed in the Observing Run Details, we expect to be able to measure velocities with an accuracy of $5 - 10$ km/s, sufficient to determine the velocity dispersion of the galaxy even if it is another "baryonic galaxy" with $\sigma \sim 10$ km/s. The immediate goals are todetermine the dynamical mass of the galaxy, by measuring its velocity dispersion, and to determine the luminosity function of the globular cluster population.

[1] They are available to the TAC from http://www.astro.yale.edu/dokkum/papers/

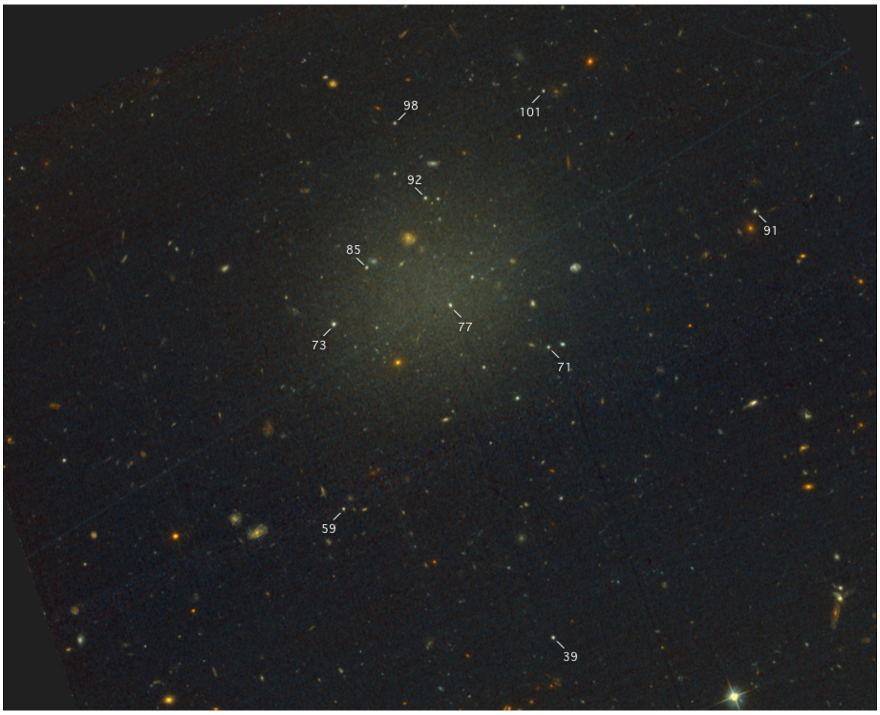

Figure 1: The "baryonic galaxy" NGC 1052-DF2. It is a smooth "blob" Globular clusters confirmed with Keck LRIS and DEIMOS spectroscopy are marked. From van Dokkum et al. (2018ab); Cohen et al. (in prep).

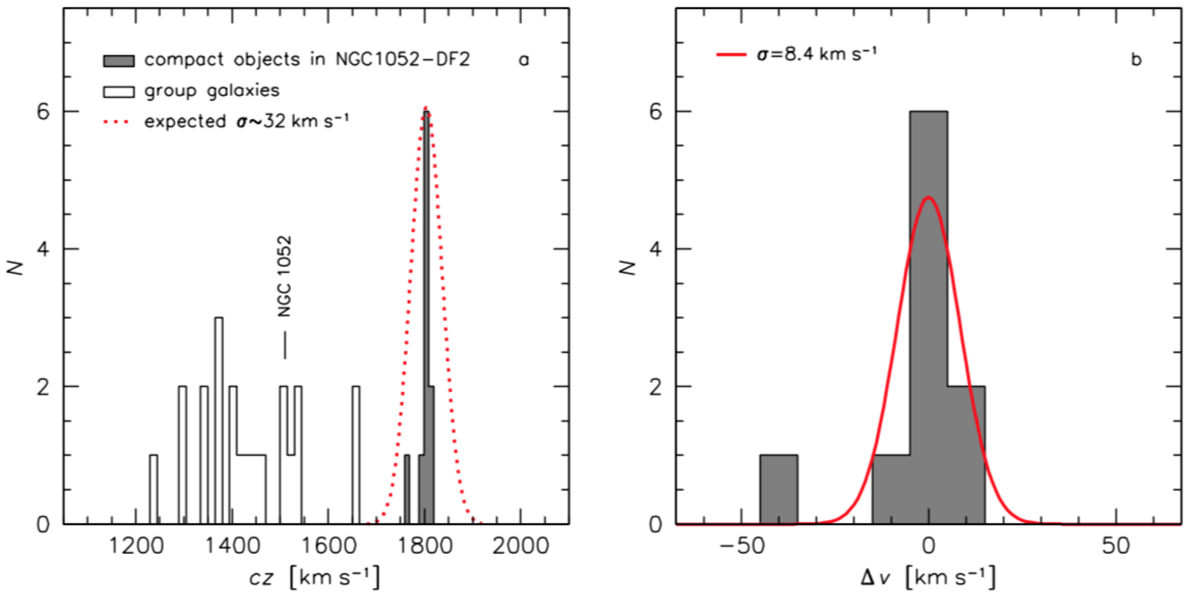

Figure 2: Left: velocities of the globular clusters, along with known members of the NGC 1052 group. The broken red curve indicates the expected velocity spread if the galaxy had a normal amount of dark matter. Right: zoom in on the velocity histogram of the clusters with respect to the mean (1803 km/s). The solid red curve shows the best-fitting observed dispersion of 8.5 km/s. The observed dispersion is consistent with the measurement errors; the 90 % upper limit to the intrinsic dispersion is $\sigma_{\rm gc} < 10.5$ km/s.

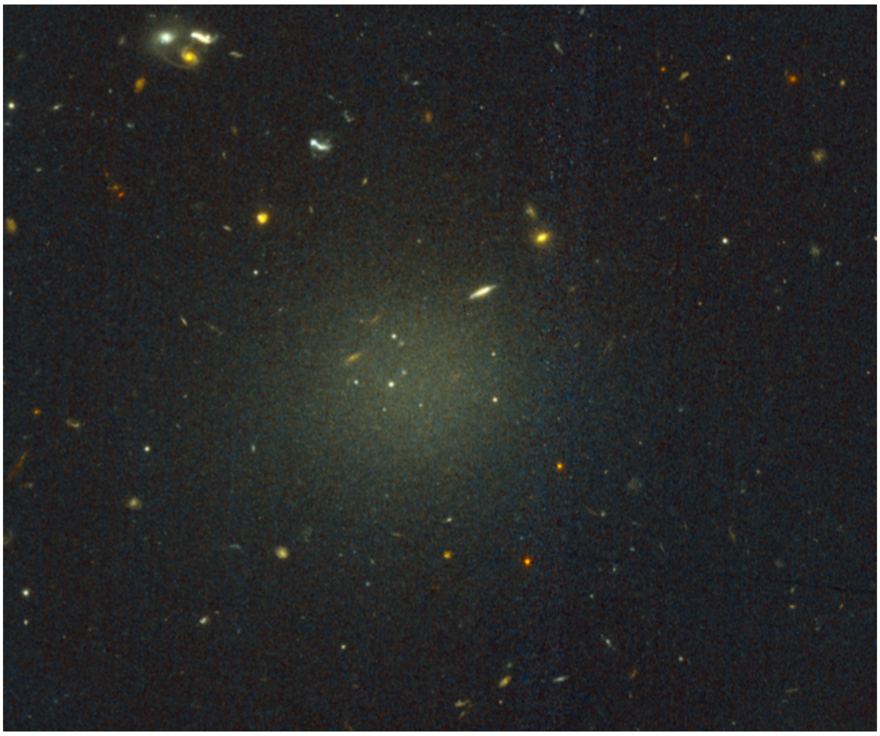

Figure 3: The newly identified galaxy NGC 1052-DF4. The galaxy's appearance is similar to NGC 1052-DF2. We measured the same distance of ~ 20 Mpc from its surface brightness fluctuations, and we find a similar overdensity of bright compact objects that are associated with the galaxy.

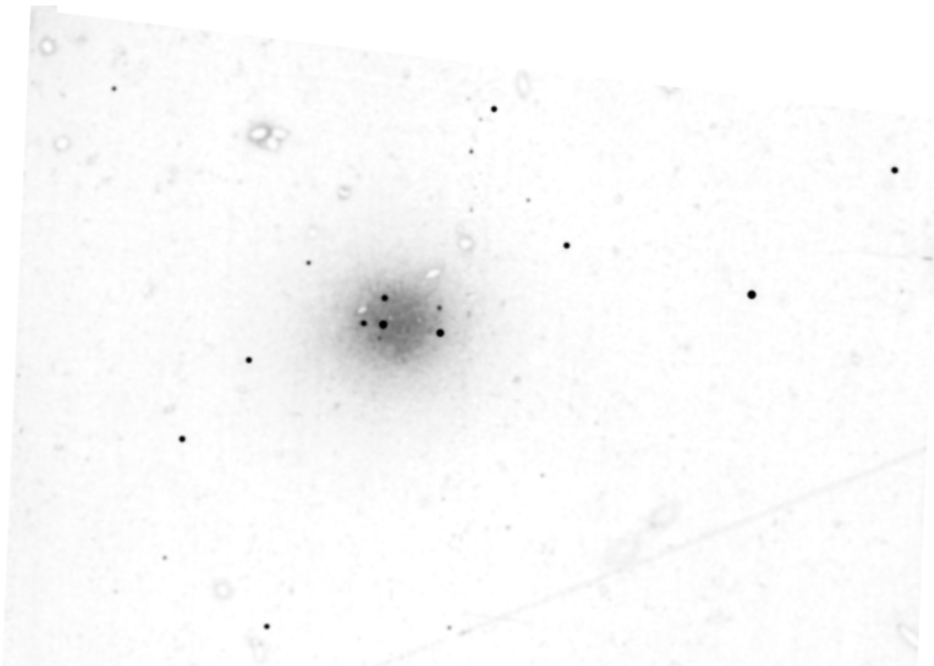

Figure 4: Wider (smoothed) view of NGC 1052-DF4, with the compact objects highlighted. All detected sources in the HST image were masked, except compact objects with the approximate colors of the confirmed globular clusters in NGC 1052-DF2. We can target most of these objects in a single LRIS slit mask, and all of them in two masks.

Impact to Yale Astronomy *Describe how this program fits into the Yale astronomy program. Will the data analysis and resulting papers be based at Yale? If the project is led by a faculty member, does the project involve students? What is the role of the PI viz-a-viz other non-Yale co-Is. Are the resources in place to analyze the data and come to a timely publication? (limit text to one page)*

The work is firmly rooted at Yale. It builds on the Dragonfly Nearby Galaxy Survey, which was Allison Merritt's thesis, a follow-up HST program (PI: van Dokkum), and three Yale-led papers (one in Nature) that are based on this HST program plus Yale Keck time.

The analysis will be led by Yotam Cohen, who is interested in making this topic the core of his PhD thesis. He can have a quick start, as most of the reduction and analysis procedures are already in place. In particular, the PI has written an LRIS reduction pipeline specifically for the NGC 1052-DF2 data; this means that there is a straight path from observations to publication.

Previous Use of Yale Facilities and Publications *Please list previous use of Yale observing facilities and any publications resulting from these data in the past 3 years. If this is a long term project, please state this here and describe the overall strategy of the project.*

An overview of Keck time allocated to the PI in the six previous semesters is given below.

• 2015B: 2 OSIRIS nights, December 2015. Weathered out. Also 2 NIRES nights in January 2016, which we converted to DEIMOS nights as NIRES was not available. These DEIMOS nights were combined with the 4 nights from 2016A, for a deep study of the ultra diffuse galaxies Dragonfly 44 and DFX1 in the Coma cluster.

• 2016A: 4 DEIMOS nights (partially shared with Marla Geha) for Dragonfly 44 and DFX1. The combination of the 2015B and 2016A DEIMOS time yielded spectra with a depth of 33.5 hrs for both galaxies. The velocity dispersions derived from these spectra are published in two ApJ Letters: van Dokkum et al. 2016, ApJ, 828, L6, and van Dokkum et al. 2017, ApJ, 844, L11.

• 2016B: 3 DEIMOS nights. Partly weathered out, but several hours on candidate globular clusters in NGC 1052-DF2. Also 3 LRIS nights; these were allocated as OSIRIS nights but OSIRIS was taken off the telescope due to its failure. Partly weathered out; we took more data on the globular clusters. The combined LRIS+DEIMOS dataset led to the two papers that are the basis of the present proposal: one accepted to Nature, the other an ApJ Letter. Both will be on astro-ph on March 28, and are available at http://www.astro.yale.edu/dokkum/papers/

• 2017A: 2 LRIS nights, to study the stellar populations of three Coma UDGs. Weathered out. Also 3 NIRSPEC nights, in February 2017. These were as successful as is possible with NIRSPEC: we obtained spectra for paired high redshift galaxies for Lamiya Mowla's thesis. We expect that these data will be combined with NIRES spectra that we are proposing for in another 2018B proposal.

• 2017B: 2 KCWI nights, in January 2018, to begin studying the radial dispersion profile of Dragonfly 44. We had asked for 10 nights over two semesters. Largely weathered out, unfortunately. The 2.5 hrs we did get will be added to the 2018A time from Yale, Caltech, and UC (see below).

• 2018A: 2 KCWI nights (as 4 half-nights) in February 2018, to continue the study of the radial dispersion profile of Dragonfly 44. Three of the 4 half-nights were good; we added 9 hrs to the on-source exposure time. This will be added to the 2018A time from Caltech and UC. The Caltech time was also largely weather out; the UC time is scheduled for April 2018. Also 1 LRIS night, for April 2018, to measure distances of "blobs" discovered with Dragonfly.

Observing Run Details for Run :

Technical Description *Describe the observations to be made during the requested observing run. Justify the specific telescopes, the number of nights, the instrument, and the lunar phase. List objects, coordinates, and magnitudes (or surface brightness, if appropriate) in the Target Tables section.* **For Keck proposals only:** *Please include below whether your proposal can be implemented on a different instrument and describe what the resulting impact to your program. This information will not be used unless a program will not otherwise be awarded time on the primary instrument requested.*

Instrumental setup: We will use the same technique as used for the successful NGC 1052-DF2 observations in 2016. In the red, the 1200 lines mm^{-1} grating with a slit width of 0.75″ gives a spectral resolution of $\sigma_{\rm instr} \approx 25$ km/s, sufficient to measure radial velocities with an accuracy down to $\lesssim 5$ km/s for the brightest ($I \approx 21.5$) objects and ~ 10 km/s for the faintest ($I \approx 22.5$). In the blue we will use the low resolution 300 lines mm^{-1} grism, to cover a large wavelength range and constrain the stellar populations of the globular clusters.

Integration time and strategy: We can fit all compact objects with the colors of globular clusters in two masks. The total integration time for the NGC 1052-DF2 objects was ≈ 8 hrs, and so 16 hrs, or 3 nights, are required for this program. If only two nights are allocated we will observe a single mask, containing $60 - 70$ % of the candidate globular clusters.

Alternative instrument: An alternative is to measure the stellar kinematics rather than the globular cluster kinematics, using KCWI rather than LRIS (see KCWI proposal). The required integration time is about the same. We would not be able to characterize the globular cluster population (which is very interesting in its own right, as evidenced by the ApJ Letter on NGC 1052-DF2), but it is certainly a viable option. Another alternative is to use DEIMOS. DEIMOS gives slightly higher spectral resolution and a larger wavelength range in the red, at the expense of not getting the low resolution blue spectra. On balance we prefer LRIS, and that also nicely aligns with the telescope balance and our other proposals.

R.A. range of principal targets (hours): One target, with RA = $2^{\rm h}40^{\rm m}$

Dec. range of principal targets (degrees): One target, with DEC = −8 degrees.

Instrument Configuration

Filters:	Slit:	Fiber cable:
Grating/grism: 1200	Multislit: 0.75	Corrector:
Order: 1	λ_{start}:	Collimator:
Cross disperser:	λ_{end}:	Atmos. disp. corr.:

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