Direct evidence of hierarchical assembly at low masses from isolated dwarf galaxy groups

S. Stierwalt1,2*, S. E. Liss2, K. E. Johnson2, D. R. Patton3, G. C. Privon4, G. Besla5, N. Kallivayalil2 and M. Putman6

The demographics of dwarf galaxy populations have long been in tension with predictions from the cold dark matter (ΛCDM) paradigm1–4. If primordial density fluctuations were scale-free as predicted, dwarf galaxies should themselves host dark-matter subhaloes5, the most massive of which may have undergone star formation resulting in dwarf galaxy groups. Ensembles of dwarf galaxies are observed as satellites of more massive galaxies6–9, and there is observational10 and theoretical11 evidence to suggest that these satellites at redshift z = 0 were captured by the massive host halo as a group. However, the evolution of dwarf galaxies is highly susceptible to environment12–14, making these satellite groups imperfect probes of ΛCDM in the low-mass regime. Here we report one of the clearest examples yet of hierarchical structure formation at low masses: using deep multi-wavelength data, we identify seven isolated, spectroscopically confirmed groups of only dwarf galaxies. Each group hosts three to five known members, has a baryonic mass of \(4.4 \times 10^9\) to \(2 \times 10^{10}\) solar masses \((M_*)\), and requires a mass-to-light ratio of \(<100\) to be gravitationally bound. Such groups are predicted to be rare theoretically and found to be rare observationally at the current epoch, and thus provide a unique window into the possible formation mechanism of more massive, isolated galaxies.

Fewer than 5% of dwarf galaxies are observed to have close companions (see Methods), and most galaxy surveys are too shallow to consistently detect such companions even when they are present. Thus, other than a few cases of tantalizing yet circumstantial evidence for dwarf-dwarf mergers15–17, direct observational evidence of this hierarchical structure formation at the low end of galaxy masses has remained highly elusive. The identification of these dwarf-only groups suggests that, given time, hierarchical merging will turn some of these groups into the isolated, intermediate-mass galaxies more commonly observed at the current epoch.

The seven groups were discovered while investigating dwarf–dwarf galaxy interactions in the panchromatic TiNy Titans (TNT) survey18. As part of an effort to understand the dwarf–dwarf merger sequence, we searched the spectroscopic catalogue of the Sloan Digital Sky Survey (SDSS) for nearby dwarf galaxy pairs in isolation (>1.5 Mpc from more massive neighbours of mass \(M_\text{h} > 5 \times 10^9 M_\odot\)). The distance of 1.5 Mpc from a massive host marks an important boundary between the evolution of satellite dwarf versus field dwarf galaxies. Beyond 1.5 Mpc, the observed quenched fraction of dwarfs falls to zero12, indicating the end of the sphere of influence of the massive host. Also beyond 1.5 Mpc, the escape velocity of a galaxy with \(M_\text{h} \approx 10^{10} M_\odot\) falls below the typical sound speed of 10 km s\(^{-1}\) in the interstellar medium, thus decreasing the possibility for disruption. Our systematic search revealed 60 isolated dwarf pairs caught in a variety of interaction stages.

The SDSS images for all 60 isolated TNT pairs were visually inspected for any potential low-mass neighbours with or without SDSS spectroscopic data. Seven candidate groups were identified and then, when SDSS spectra were not available, targeted for follow-up optical spectroscopy using the long-slit optical spectrograph on the 3.5-m telescope at the Apache Point Observatory. All candidate group members, which range in stellar mass from \(2 \times 10^9 M_\odot\) to \(2 \times 10^7 M_\odot\), were confirmed to have velocities within 200 km s\(^{-1}\) of the mean group velocity (see Table 1). We further obtained very narrowband (10 Å) H\(_\alpha\) imaging for three of the groups with the Maryland–Magellan Tunable Filter (MMTF) Fabry Perot, which confirms all suspected members are within \(\pm 200\) km s\(^{-1}\) of the original pair. One additional group was observed with the narrowband (50 Å) H\(_\alpha\) filter on the Gemini Multi-Object Spectrograph at Gemini-North (see Fig. 1).

Although their three-dimensional (3D) structure is not known, all seven groups are consistent with being bound structures. First, all observed group members are within roughly a virial radius of the most massive group member (~100 kpc for a halo mass of \(10^{11} M_\odot\)). Second, by equating the 3D velocity dispersion for each group with its escape velocity and by adopting the largest 2D distance between any two group members as the group size, we determine a lower limit on the total (baryonic plus dark matter) mass required for the group to be gravitationally bound. As expected, the total masses required to be gravitationally bound exceed the known baryonic masses for each group. The resulting minimum required total mass-to-light (M/L) ratios range from ~0.7 to 11 \(M_\odot/L_\odot\) (see Table 2), which are consistent with the M/L ratios of 10–100 that have previously been determined for individual dwarf galaxies19–20. We further use our knowledge of the velocities and projected distances of individual group members (see Fig. 2) to determine a projected total mass (baryonic plus dark matter) estimate for each group (see Methods). The resulting M/L ratios from those mass predictions range from 12 to 70 \(M_\odot/L_\odot\) and thus also suggest that the TNT dwarf groups do not require an unusual amount of dark matter to be bound systems.

Without independent distance information, projection effects can affect both our distance and velocity estimates, either of which could lead to either interlopers or unbound groups. For example,
large transverse motions could lead to 3D velocities that are too high for the systems to be bound. However, this would only be true for the TNT groups if their 3D velocity dispersions were >10 times
those measured in 1D. Further increasing the likelihood that the
TNT groups are bound structures, the TNT groups have relative line-of-sight velocity differences ($\Delta v_{\text{los}}$) between group members consistent with those measured for bound groups found in mock catalogues based on the Millennium-II simulation ($\Delta v_{\text{los}}$ up to 200–300 km s$^{-1}$ for groups with $<\log(M_*/M_\odot)<9.5$)21. The observed groups could also be transient systems caught at a moment of passing but not gravitationally bound distinct systems. An estimated 59% of groups of more massive galaxies identified from their projected radial and velocity separations in the Millennium simulation are found to be actually physically associated22. If this result holds to lower masses, a similar fraction (at least four of the seven) of the identified TNT groups are expected to be bound groups. To further probe the 3D structure, we have an ongoing project to obtain a low-resolution neutral hydrogen gas map for each group to look for bridges, streams or other features connecting the group members physically to one another.

The compact dwarf groups identified here are distinct from previously known groups and loose associations of dwarf galaxies23–26 in two primary ways: previously known systems are significantly more extended and/or they are in close proximity to a massive galaxy ($<$1.5 Mpc) and thus serve as imperfect laboratories for studying hierarchical structure formation at low masses. Seven associations of dwarf galaxies were identified in the Local Volume (distance $D<$8 Mpc) and are close enough for primary distance measurements using tip of the red giant branch stars27,28. These associations all have much larger projected and 3D sizes than the TNT groups (see Fig. 2). A consequence of the larger observed sizes is the extremely large MIL ratios (all $>100$ with some as high as 700) required for the known dwarf associations to be gravitationally bound. Additionally, two of the seven associations are within 0.6 Mpc of a massive ($M_* > 10^8 M_\odot$) host and a third is $\sim 1.2$ Mpc from the Milky Way. Another previously known group that more closely resembles the TNT groups is Hickson Compact Group 31 (HCG31). HCG31 includes seven to eight members within ~75 kpc all with stellar masses27,28 in the range $10^7$–$10^8 M_\odot$. The five galaxies toward the core of the group are clearly interacting, and the group has been identified as a pre-merger. However, at least three massive galaxies reside within 1.5 Mpc of HCG31, the most massive ($\log(M_*/M_\odot)=10.7$) at a projected distance of 0.97 Mpc and a velocity separation of only 55 km s$^{-1}$. Thus, the competing larger-scale environmental effects (including possible ram-pressure or tidal stripping) may be a challenge to disentangle. The TNT-selected dwarf groups are thus the first detection of dwarf-only groups whose isolation enables us to study hierarchical structure formation at low masses.

ΛCDM not only predicts the existence of dwarf groups but also the statistics of how often they should be observed. According to Millennium-II, dwarf galaxies with $M_* \approx 10^7 M_\odot$, the average for the TNT primary (most massive) galaxies, have a $\sim 1\%$ chance29 of having a companion of similar mass (that is, a satellite with a mass ratio of $M_*^{\text{satellite}}/M_*^{\text{primary}} > 0.2$). This prediction is consistent

| Name          | $v_{\text{los}}$ (km s$^{-1}$) | $g$ (unc)       | $g - r$ | log($M_*$) | $R_{\text{proj}}$ (kpc) | Velocity source |
|---------------|-------------------------------|----------------|--------|------------|-------------------------|----------------|
| dm1049+09a    | 10.037 (±3)                   | 16.28 (0.06)   | 0.29   | 9.32 (0.1) | 0.0                     | SDSS           |
| dm1049+09b    | 10.064 (±2)                   | 16.19 (0.06)   | 0.14   | 9.11 (0.1) | 47.7                    | SDSS           |
| dm1049+09c    | 10.277 (±1)                   | 18.72 (0.19)   | 0.20   | 8.19 (0.2) | 65.0                    | APO            |
| dm1049+09d    | 10.141 (±1)                   | 19.44 (0.27)   | 0.19   | 7.66 (0.3) | 67.0                    | APO            |
| dm1049+09e    | 9.911 (±1)                    | 20.39 (0.41)   | -0.25  | 7.10 (0.3) | 24.9                    | APO            |
| dm1623+15a    | 10.280 (±2)                   | 17.47 (0.11)   | 0.28   | 8.77 (0.1) | 0.0                     | SDSS           |
| dm1623+15b    | 10.031 (±2)                   | 17.59 (0.11)   | 0.18   | 8.61 (0.1) | 42.7                    | SDSS           |
| dm1623+15c    | 10.004 (±1)                   | 16.71 (0.08)   | 0.14   | 8.98 (0.1) | 58.1                    | APO            |
| dm1623+15d    | 10.139 (±1)                   | 17.62 (0.12)   | 0.16   | 8.76 (0.1) | 78.6                    | APO            |
| dm1403+41a    | 10.580 (±2)                   | 16.73 (0.08)   | 0.18   | 8.81 (0.1) | 0.0                     | SDSS           |
| dm1403+41b    | 10.619 (±2)                   | 17.52 (0.11)   | 0.21   | 8.61 (0.1) | 22.1                    | SDSS           |
| dm1403+41c    | 10.319 (±2)                   | 16.63 (0.07)   | 0.29   | 9.19 (0.1) | 22.9                    | SDSS           |
| dm1403+41d    | 10.370 (±1)                   | 17.11 (0.09)   | 0.23   | 8.80 (0.1) | 16.7                    | APO            |
| dm1440+14a    | 5.429 (±3)                    | 16.54 (0.07)   | 0.39   | 8.78 (0.1) | 0.0                     | SDSS           |
| dm1440+14b    | 5.423 (±2)                    | 17.60 (0.11)   | 0.28   | 8.14 (0.1) | 46.5                    | SDSS           |
| dm1440+14c    | 5.381 (±1)                    | 18.30 (0.16)   | 0.24   | 7.88 (0.2) | 32.0                    | SDSS           |
| dm1718+30a    | 4.446 (±2)                    | 15.56 (0.05)   | 0.43   | 8.96 (0.1) | 0.0                     | SDSS           |
| dm1718+30b    | 4.428 (±2)                    | 17.00 (0.09)   | 0.45   | 8.52 (0.1) | 30.9                    | SDSS           |
| dm1718+30c    | 4.569 (±1)                    | 17.54 (0.11)   | 0.19   | 7.77 (0.1) | 4.6                     | APO            |
| dm0909+06a    | 14.021 (±2)                   | 17.22 (0.10)   | 0.35   | 9.31 (0.1) | 0.0                     | SDSS           |
| dm0909+06b    | 13.799 (±2)                   | 17.53 (0.11)   | 0.41   | 9.35 (0.1) | 32.2                    | SDSS           |
| dm0909+06c    | 13.704 (±1)                   | 19.52 (0.28)   | 0.15   | 8.17 (0.3) | 31.8                    | APO            |
| dm1349-02a    | 6.913 (±3)                    | 17.33 (0.10)   | 0.25   | 8.41 (0.1) | 0.0                     | SDSS           |
| dm1349-02b    | 6.988 (±2)                    | 18.15 (0.15)   | 0.20   | 8.13 (0.2) | 14.3                    | SDSS           |
| dm1349-02c    | 6.898 (±1)                    | 18.91 (0.21)   | 0.14   | 7.55 (0.3) | 15.8                    | APO            |

$\Delta v_{\text{los}}$, line-of-sight velocity measured from the optical spectra derived from the source in the last column. $R_{\text{proj}}$, 2D projected distance between each group member and the primary or most massive group member in kpc. The last column notes the source of the velocity given in the second column, either from the SDSS spectroscopic catalogue or from original observations presented here using the Dual Imaging Spectrograph at the APO. $g$ (unc), the g-band magnitude and associated uncertainty; $g - r$, the colour in magnitudes.
with the upper limit that we estimate for the SDSS spectroscopic catalogue on the fraction of dwarfs observed to have a close companion of <5% (see Methods). The FIRE simulations, which push to even lower primary galaxy masses and focus specifically on isolated environments, produce consistent results\(^5\), specifically that ~5% of isolated dwarf galaxies are found to host a satellite with \(M_{\text{satellite}} / M_{\text{primary}} \gtrsim 1/3\).

The Millennium-II results further predict that the same TNT primary group members have a 1–10% chance of hosting the second and third most massive satellites observed in the TNT groups (that is, a satellite with mass ratios of 0.02 < \(M_{\text{satellite}} / M_{\text{primary}} < 0.4\)). Of the 60 systematically selected, isolated TNT pairs, seven have additional observable companions, or 11%. The observed TNT fraction of 11% is consistent with the higher end of the range from predictions from simulations (10%). If only 59% of the TNT groups prove to be bound structures, as observed for more massive galaxies\(^2\), the observed fraction of 11% reduces to ~6% and thus lies right amid the range of predictions.

Thus, multiple theoretical approaches predict that dwarf groups like those presented here, with multiple detectable dwarf members with \(M_s > 10^9–10^9 M_\odot\), are rare at the current epoch. Below a primary galaxy stellar mass of \(10^{10} M_\odot\), the number of satellites is expected to decouple from the stellar mass of the primary galaxy, according to the semi-analytical mock catalogues derived from the cosmological Millennium-II simulation\(^3\). Thus, for primary galaxy masses less than that of the Milky Way (and down to the Millennium-II resolution limit of \(M_s \approx 10^7 M_\odot\)), the number of observed satellites is uniformly low as confirmed by the FIRE simulation results.

Unfortunately, matching observations to theoretical predictions at lower satellite masses than those probed by the more massive TNT group members is currently beyond the reach of large surveys like SDSS. Simulations predict that the fraction of satellites will increase. Again according to Millennium-II, for a primary galaxy mass of \(10^9 M_\odot\) there is a 40% chance that galaxy will host a satellite with \(M_s \approx 10^5 M_\odot\) (the lowest-mass satellite found in our sample). Results from the FIRE simulations are again consistent with 35% of such primaries hosting an ultrafaint satellite\(^3\) with \(M_{\text{satellite}} / M_{\text{primary}} \approx 0.005\). Although the TNT groups probe masses as low as \(\sim 10^7 M_\odot\), the survey is far from complete in this mass regime. The current SDSS spectroscopic catalogues are only complete\(^2\) down to \(M_s \approx 10^{10.4} M_\odot\) for galaxies bluer than the green valley (with an even higher mass limit for redder galaxies) and only out to a redshift of \(z=0.04\).
Thus, a direct comparison to theoretical predictions of the frequency and size of dwarf groups that reliably probe masses near the lower limit and below those of the TNT groups is not yet possible. However, observations have uncovered at least one individual example, that of the dwarf DDO68 and its two stellar streams which are consistent with being cannibalized satellites of even lower mass\(^4\). Placing this intriguing example into context with more statistical investigations will be fertile ground for future 30-m class telescopes and dwarf associations from the literature (orange squares and yellow filled circles (dm1623\(^+\))). No weighting is applied. The groups are filled stars (dm1049\(^+\)) and dwarf associations from the literature which are consistent with being cannibalized satellites of even lower mass\(^15\). While this is the first evidence that these objects may be cannibalized satellites, it is not unique. Two other dwarf galaxies with masses of $<9\,\sigma(M/L) < 10$. Additionally, a rescaling to lower masses of group merger simulations designed to represent massive galaxies\(^16\) implies that the TNT dwarf groups (if bound) would coalesce into a single remnant within ~1 Gyr. Thus, at least some of the galaxies observed to exist at the current epoch in this mass range may have been built up from mergers within dwarf groups. The TNT dwarf groups presented here provide direct probes of hierarchical structure formation in action at the low mass end, giving us a new window into a process expected to be common at earlier times, but nearly impossible to observe at such redshifts.

### Methods

#### Data reduction

**Optical imaging with the Maryland–Magellan Tunable Filter.** We obtained narrowband H\(\alpha\) and continuum observations for three of our candidate groups (dm1049+09, dm1349-02, and dm1623+15) on 20–21 April 2015 using the Inamori–Magellan Areal Camera and Spectrograph (IMACS) with the MMTF on the 6.5-m Magellan Baade Telescope. The groups selected for imaging were observable from Magellan in April and within the redshift range of 0.0220 to 0.0549 so that the H\(\alpha\) emission line would fall within a single MMTF order-blocking filter centred at 6,815 Å with a total available width of ~200 Å. Each field was observed using staring mode with the 10-Å spread-function matching and image stacking. Images were flux-calibrated using standard stars\(^32\) observed with the same filters as the science targets. Optical imaging with the Gemini Multi-Object Spectrograph. H\(\alpha\) and r-band continuum observations of an additional group candidate (dm1718+30) were obtained as part of a larger TNT follow-up programme using the Gemini Multi-Object Spectrograph on the 8.1-m Gemini-North Telescope\(^11\). We observed the field for a total of 460 (280) seconds for H\(\alpha\) (r-band), split into individual exposures of 20 minutes each. The individual exposures were dithered by between 30° and 300° to fill in inter-chip gaps, and care was taken to ensure all targets fell within the Fabry Perot monochromatic spot. We reduced the data using IRAF and the MMTF pipeline\(^11\), which includes bias subtraction, flat fielding, bad pixel masking (including cosmic rays), sky background subtraction, image registration and chip mosaicing, point-spread-function matching and image stacking. Images were flux-calibrated using standard stars\(^32\) observed with the same filters as the science targets.

#### Optical spectroscopy with the Apache Point Dual Imaging Spectrograph.

We obtained long-slit optical spectra of the group candidate members without SDSS spectroscopic observations of an additional group candidate (dm1718+30) which includes bias subtracting, flat fielding, chip mosaicing, and image alignment and combining. Flux calibration was done using observations of Landolt standard fields.

#### Optical spectroscopy with the Apache Point Dual Imaging Spectrograph.

We obtained long-slit optical spectra of the group candidate members without SDSS spectroscopic observations of an additional group candidate (dm1718+30) which includes bias subtracting, flat fielding, chip mosaicing, and image alignment and combining. Flux calibration was done using observations of Landolt standard fields.
depending on weather conditions. The red (blue) channel was centred at the approximate wavelength of Hα (Hβ) of the group members that were already confirmed by SDSS spectroscopy. We reduced the spectra using standard IRAF tools, including bias subtraction, scattered light correction, and flat fielding. Wavelength calibration was done using helium, neon and argon arc lamps. We measured velocities from Gaussian fits to the Hα emission line, and the uncertainties derived from the fit parameters are very low (−1−2 km s⁻¹) owing to the high-resolution spectra.

Mass, mass-to-light ratio, size and velocity dispersion calculations. We derived stellar masses based on SDSS 'ugriz' photometry as described for the original TNT pairs. The brightness of each dwarf is measured by summing the flux within a contour tracing the 2σ noise level (usually 0.03 to 0.04 nanomaggies, where a maggie is a measure of flux density with 1 maggie having an AB magnitude of 0) as determined by the r-band image. We applied the same aperture to the remaining four bands and used the galactic dust maps from the COBE/DIRBE satellite to determine the galactic extinction correction to be applied along each line of sight and for each SDSS filter. Stellar masses were then derived by taking advantage of the spectral energy distribution (SED) fitting built into the kcorrect software but without applying a k-correction correction to observed photometry due to redshift to our (low-redshift) dwarfs. The software assumes a Chabrier initial mass function. Group neutral masses (fifth column of Table 2) were derived from the single-dish Green Bank Observatory 21-cm line spectrum. At L-band, the Green Bank beam size is 1.8 kpc and thus covers the entire group in each case.

We use the projected mass estimator method to estimate the total mass (baryonic and dark matter) present in each group. More specifically:

\[ M = \frac{f_{pm}}{G(N - 1)} \sum_{i=1}^{N} R_{ig} \Delta v_i^2 \]

where \( M \) is the array of flux density with 1 maggie having an AB magnitude of 0) where \( R \) is the 2D projected distance between an individual group member and the (unweighted) centroid of the group, \( \Delta v \) is the difference in the line-of-sight velocity between an individual group member and the mean group velocity, and the sum for each group is performed over all group members given in Table 1. The constant values used are the total number of group members \( N, f_{pm} = 20/n, \) the gravitational constant \( G, \) and \( c = 1.3 \) as adopted in the literature.

The 2D projected size for each group given in the seventh column of Table 2 represents the largest 2D projected distance between any two group members. Sizes are calculated by placing all group members at the adopted distance for the group (second column of Table 2) which is the average distance to all members based on line-of-sight optical velocities and an assumption of Hubble flow. We adopt the value of 69 km s⁻¹ Mpc⁻¹. The 2D projected sizes for the TNT dwarf groups and for groups in the literature are also shown in the right panel of Fig. 2. We note that additional group members have been proposed for some of the literature groups — most notably the Antila B dwarf in the NGC3109 group, but for consistency we include only the original identified group members. The total mass estimation for each group is performed by converting fluxes from SDSS g- and r-band photometry to B-band fluxes:

\[ m_{B} = m_{g} + 0.2354 + 0.3915(m_{g} - m_{r} - 0.6102) \]

where \( m_{g}, m_{r}, \) and \( m_{B} \) are the summed apparent magnitudes of the dwarf galaxy group members in B-, g-, and r-band respectively.

The mass-to-light ratio of Table 2 represents the lower limit on the mass-to-light ratio required for the group to be a gravitationally bound structure. Thus, the mass used to calculate \( (M/L)_B\) is determined by setting the escape velocity of the group equal to the 3D velocity dispersion. In each case, the minimum mass required for the group to be gravitationally bound exceeds the known mass of baryonic matter (stellar and H I gas). The total mass-to-light ratio suggested by these mass estimates are further consistent with those typically observed for dwarf galaxies. In the last column of Table 2, \( (M/L)_B\) represents the mass-to-light ratio calculated using the estimated total (baryonic + dark matter) mass for the group and the B-band luminosity for the group. In other words, the last column of Table 2 is simply the ninth column divided by the third column of that same table. (where \( g \) and \( r \) refer to the g-band and r-band magnitudes for the dwarf galaxies).

Calculation of isolation fraction in SDSS. To estimate that <5% of dwarf galaxies are observed to have close companions as stated in the first paragraph of the main text, we have used a stellar mass catalogue which is based on the SDSS Data Release 7 spectroscopic catalogue and a further value-added catalogue of improved photometry. We then restricted this list to only low-mass galaxies (<5 × 10^⁷ M☉) that are at least 10 times as massive as the limiting stellar mass of the sample at that redshift. In other words, we limited our analysis to those dwarf galaxies for which a potential lower-mass neighbour with a stellar mass ratio as low as 1:10 would be detectable in the SDSS spectroscopic survey. The limiting stellar mass required for completeness at each redshift was determined using the conservative 'red sequence + 3δ fit', ensuring that the sample completeness is independent of galaxy colour.

A total of 186 dwarf galaxies satisfy these criteria. As expected, these galaxies all lie within the low-redshift portion of SDSS (z < 0.015). Owing to the small sample size, we do not further restrict this sample based on proximity to the nearest massive galaxy. Of those 186 galaxies, only seven have companions both within a 2D projected separation of 50 kpc and within a relative velocity difference of 225 km s⁻¹ (parameters that define the minimal separations observed for the TNT groups). Each of the seven systems was visually inspected and confirmed to be genuine galaxy pairs. Thus only 3.8% of dwarf galaxies are observed to have close companions within the detection completeness limits of SDSS.

The observed fraction of galaxies with a close companion must be corrected to account for the overall spectroscopic incompleteness of the SDSS main galaxy sample, which is estimated to be 12%. This incompleteness leads to an underestimate of the fraction of galaxies that have close companions, but can be corrected for by applying statistical weights corresponding to the reciprocal of the spectroscopic completeness (1/0.88 in this case) to each galaxy.

This correction increases our estimate of the fraction of dwarfs with close companions from 3.8% to 4.3%, thus still below 5%.

We must also account for the additional small-scale spectroscopic incompleteness that is present in SDSS owing to fibre collisions. In particular, the inability to place two spectroscopic fibres closer together than 55" biases SDSS against close spectroscopic galaxy pairs. In principle, this source of incompleteness can be corrected for by applying statistical weights. However, this source of incompleteness is negligible because of the very low redshifts of the dwarf galaxies under consideration here. In particular, a minimum angular separation of 55" corresponds to a minimum projected physical separation of 6–16 kpc for the galaxies in our sample. Moreover, none of the detected close companion lies within these minimum separations. As such, no statistical correction to the observed fraction of dwarfs with close companions is warranted.

We address one final source of incompleteness by considering whether any of the 186 dwarfs lie within 50 kpc of the survey boundaries, thus leading to missed companions that fall outside the SDSS spectroscopic coverage. However, estimates of the projected distance to the survey boundary for each galaxy in our SDSS catalogue reveal that none of the 186 dwarf galaxies in our sample are found to be within 50 kpc of the survey boundaries. As such, the survey boundaries have no effect on our measurement of the fraction of dwarf galaxies with close companions.

In conclusion, after taking into account all of the standard sources of incompleteness, we estimate that 95.7% of dwarf galaxies in SDSS have no companions within 50 kpc and 225 km s⁻¹ and above a stellar mass ratio of 1:10. Assuming an uncertainty derived from Poisson statistics (\( \sqrt{N} \)), the resulting fraction of dwarf galaxies with close companions is observed to be 4.3 ± 1.6%.

We further note that the sample of 186 galaxies used in this calculation represents only 0.3% of the dwarf galaxies in our SDSS galaxy catalogue. Thus, only a small fraction of dwarfs lie in the region of stellar mass–redshift parameter space where they and all of their close companions would be detectable by SDSS. Not only are dwarf pairs, and by extension dwarf groups, intrinsically rare, but they are also a challenge to detect given the completeness limits of current surveys. The combination of these two factors have thus required a sample as large as SDSS to reveal the first (albeit small) sample of dwarf galaxy groups presented here.

Data availability. The data that support the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request.

Received 5 October 2016; accepted 5 December 2016; published 23 January 2017

References

1. Boylan-Kolchin, M., Bullock, J. S. & Kaplinghat, M. Too big to fail? The puzzling darkness of massive Milky Way subhaloes. *Mon. Not. R. Astron. Soc.* 415, 40–44 (2011).
2. Kauffmann, G. & White, S. D. M. The merging history of dark matter haloes within the cold dark matter scenario. *Mon. Not. R. Astron. Soc.* 261, 186–208 (1993).
3. Klypin, A., Kravtsov, A. V., Valenzuela, O. & Prada, F. Where are the missing galactic satellites? *Astrophys. J.* 522, 82–92 (1999).
4. Moore, B. et al. Dark matter substructure within galactic halos. *Astrophys. J.* 524, 19–22 (1999).
5. Wheeler, C. et al. Sweating the small stuff: Simulating dwarf galaxies, ultra-faint dwarf galaxies, and their own tiny satellites. *Mon. Not. R. Astron. Soc.* 453, 1303–1316 (2015).

© 2017 Macmillan Publishers Limited, part of Springer Nature. All rights reserved.
6. Tollersud, E. J., Boylan-Kolchin, M. & Bullock, J. S. M31 satellite masses compared to ACDM subhaloes. Mon. Not. R. Astron. Soc. 440, 3511–3519 (2014).
7. Bechtol, K. et al. Eight new Milky Way companions discovered in first-year Dark Energy Survey data. Astrophys. J. 807, 50–66 (2015).
8. Belokurov, V. et al. Leo V: A companion of a family of the Milky Way galaxy? Astrophys. J. 686, 83–86 (2008).
9. Koposov, S. E., Belokurov, V., Torrealba, G. & Evans, N. W. Beasts of the Southern Wild: Discovery of nine ultra faint satellites in the vicinity of the Magellanic Clouds. Astrophys. J. 805, 130–148 (2015).
10. Ibata, N. G., Ibata, R. A., Famaey, B. & Lewis, G. F. Velocity anti-correlation of diametrically opposed galaxy satellites in the low-redshift Universe. Nature 511, 563–566 (2014).
11. Tollerud, E. J., Boylan-Kolchin, M. & Bullock, J. S. M31 satellite masses compared to ACDM subhaloes. Mon. Not. R. Astron. Soc. 440, 3511–3519 (2014).
12. Rashkov, V., Madau, P., Kuhlen, M. & Diemand, J. On the assembly of the Antlia B: A faint dwarf galaxy member of the NGC 3109 group. Mon. Not. R. Astron. Soc. 457, 1845–1852 (2016).
13. Martínez-Delgado, D. et al. Dwarf galaxies: A hierarchical universe: Infall histories, group preprocessing, and reionization. Astrophys. J. 807, 49–61 (2015).
14. Geha, M., Blanton, M. R., Yan, R. & Tinker, J. L. A stellar mass threshold for accretion rates: Application to the Second Southern Redshift Survey. Astrophys. J. 536, 153–172 (2000).
15. Martinez-Delgado, D. et al. Dwarf galaxies: A hierarchical universe: Infall histories, group preprocessing, and reionization. Astrophys. J. 807, 49–61 (2015).
16. Bell, E. F., McIntosh, D. H., Katz, N. & Weinberg, M. D. The optical and near-infrared properties of galaxies. I. Luminosity and stellar mass functions. Astrophys. J. Suppl. 149, 289–312 (2003).
17. Abazajian, K. N. et al. The seventh data release of the Sloan Digital Sky Survey. Astrophys. J. Suppl. 182, 543–558 (2009).
18. Sinard, L., Mendel, J. T., Patton, D. R., Ellison, S. L. & McCaughrean, A. W. A catalog of bulge-disc decompositions and updated photometry for 1,12 million galaxies in the Sloan Digital Sky Survey. Astrophys. J. Suppl. 196, 11–31 (2011).
19. Patton, D. R. & Atfield, J. E. The luminosity dependence of the galaxy merger rate. Astrophys. J. 685, 235 (2008).
20. Patton, D. R. et al. New techniques for relating dynamically close galaxy pairs to mergers: Application to the Second Southern Redshift Survey. Astrophys. J. 565, 208–222 (2002).
21. Patton, D. R. et al. Galaxy pairs in the Sloan Digital Sky Survey — XI. A new method for measuring the influence of the closest companion out to wide separations. Mon. Not. R. Astron. Soc. 461, 2589–2604 (2016).

Acknowledgements
S.S., S.E.L. and G.C.F. thank S. Veilleux and M. Donald for their use of their PI instrument, MMFT, and M. Donald for sharing his advice and work throughout the MMFT observations and data reduction. S.S. acknowledges the L‘Oréal USA For Women in Science programme for their grant to conduct this research. S.E.L. acknowledges support from a National Science Foundation (NSF) Graduate Research Fellowship under Grant No. DGE-1315231. S.E.L. was also partially funded by a Virginia Space Grant Consortium Graduate STEM Research Fellowship and a Clare Boothe Luce Graduate Fellowship. D.R.P. acknowledges a Discovery Grant from the Natural Sciences and Engineering Research Council (NSERC) of Canada which helped to fund this research. G.C.F. was supported by a FONDECYT Postdoctoral Fellowship (No. 3150361). N.K. is supported by the NSF CAREER award 1455260. These results are based on observations obtained with the APO 3.5-m telescope, which is owned and operated by the Astrophysical Research Consortium. This work has also used catalogues and imaging from the SDSS. Funding for the SDSS and SDSS-II has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the NSF, the US Department of Energy, NASA, the Japanese Monbukagakusho, the Max Planck Society, and the Higher Education Funding Council for England. The SDSS website is http://www.sdss.org/. The SDSS is managed by the Astrophysical Research Consortium for the Participating Institutions. The Participating Institutions are the American Museum of Natural History, Astrophysical Institute Potsdam, University of Basel, University of Cambridge, Case Western Reserve University, University of Chicago, Drexel University, Fermilab, the Institute for Advanced Study, the Japan Participation Group, Johns Hopkins University, the Joint Institute for Nuclear Astrophysics, the Kavli Institute for Particle Astrophysics and Cosmology, the Korean Scientist Group, the Pan-STARRS Project Office, the University of Hawaii, the Instituto deAstrofísica de Canarias, the Universidad Nacional de Colombia, the University of Portsmouth, the United States Naval Observatory and the University of Washington. Results are also based on observations obtained at the Gemini Observatory (Program ID: GN-2016A-Q-16) and processed using the Gemini IRAF package, which is operated by the Association of Universities for Research in Astronomy, Inc., under a cooperative agreement with the NSF on behalf of the Gemini partnership: the NSF (United States), the National Research Council (Canada), CONICYT (Chile), Ministerio de Ciencia, Tecnología e Innovación Productiva (Argentina) and Ministério da Ciência, Tecnologia e Inovação (Brazil).

Author contributions
S.S. identified the group candidates, led the Magellan proposal and reduced the APO data. S.E.L. led the Gemini and APO proposals and led the Magellan and Gemini data reduction. S.S. and K.E.J. coordinated the analysis, interpretation and writing of the paper. S.S., S.E.L. and G.C.F. conducted the Magellan and APO observations. D.R.P. led the SDSS-based analysis including identifying the original pairs and calculating the isolation fraction. All authors discussed the results, their interpretation and the presentation of the paper.

Additional information
Reprints and permissions information is available at www.nature.com/reprints. Correspondence and requests for materials should be addressed to S.S.

How to cite this article: Stierwalt, S. et al. Direct evidence of hierarchical assembly at low masses from isolated dwarf galaxy groups. Nat. Astron. 1, 0025 (2017).

Competing interests
The authors declare no competing financial interests.