A single population of red globular clusters around the massive compact galaxy NGC 1277

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Massive galaxies are thought to form in two phases: an initial collapse of gas and giant burst of central star formation, followed by the later accretion of material that builds up their stellar and dark-matter haloes1–4. The systems of globular clusters within such galaxies are believed to form in a similar manner. The initial central burst forms metal-rich (spectrally red) clusters, whereas more metal-poor (spectrally blue) clusters are brought in by the later accretion of less-massive satellites5–10. This formation process is thought to result in the multimodal optical colour distributions that are seen in the globular cluster systems of massive galaxies8,11,12. Here we report optical observations of the massive relic-galaxy candidate NGC 1277—a nearby, un-evolved example of a high-redshift ‘red nugget’ galaxy13–17. We find that the optical colour distribution of the cluster system of NGC 1277 is unimodal and entirely red. This finding is in strong contrast to other galaxies of similar and larger stellar mass, the cluster systems of which always exhibit (and are generally dominated by) blue clusters1. We argue that the colour distribution of the cluster system of NGC 1277 indicates that the galaxy has undergone little (if any) mass accretion after its initial collapse, and use simulations of possible merger histories to show that the stellar mass due to accretion is probably at most ten percent of the total stellar mass of the galaxy. These results confirm that NGC 1277 is a genuine relic galaxy and demonstrate that blue clusters constitute an accreted population in present-day massive galaxies.

We obtained imaging of NGC 1277 from the Advanced Camera for Surveys (in the g475W and z850LP filters) onboard the Hubble Space Telescope (HST/ACS) to characterize the globular cluster system of this galaxy (Extended Data Fig. 1). NGC 1277 has been identified as a massive (about $1.2 \times 10^{11} M_\odot$, where $M_\odot$ is the mass of the Sun)15 relic galaxy on the basis of its high stellar-mass density, compactness, kinematics and old and metal-rich stellar populations14–17. We postulate that if NGC 1277 is a true relic—that is, a nearby, un-evolved example of the ‘red nuggets’ seen at high redshift—then it should have accreted little or no stellar halo and should have few or no blue clusters.

The spatial distributions of cluster candidates from the HST/ACS imaging (Fig. 1) indicate that NGC 1277 and its companion galaxy in projection, NGC 1278, both have relatively rich cluster systems. Separating the clusters in the ACS field by their de-reddened colours by cutting at $(g475W - z850LP)_0 = 1.15$ (the approximate separation between the red and blue peaks for a galaxy of this mass in the ACS Virgo Cluster Survey (VCS)11), we find that NGC 1277 has a rich red cluster population but few blue clusters. This is in strong contrast to NGC 1278, which has a similar stellar mass to NGC 1277 (about $2.4 \times 10^{11} M_\odot$) but both red and blue clusters.

This visual impression is supported by looking at the colour distribution of the globular clusters in NGC 1277 compared with those in galaxies of similar stellar mass from the survey (Fig. 2). No obvious blue peak is seen in the colour distribution of clusters in NGC 1277, which appears red with a tail to bluer colours. By contrast, the composite colour distribution of the similar-stellar-mass galaxies in the survey has both blue and red peaks. We ran Gaussian mixture modelling (GMM) tests (Methods) on these colour distributions, with a null hypothesis that the input colour distributions are unimodal. For NGC 1277, GMM cannot reject the null hypothesis for the globular clusters ($P = 0.371, \chi^2$ test). However, under the assumption that two populations of clusters are present, GMM associates 99 clusters with a red population with a mean colour of $(g475W - z850LP)_0 = 1.31 \pm 0.10$ (errors are 1σ unless otherwise stated) and 21 clusters with a metal-poor population with a mean colour of $(g475W - z850LP)_0 = 0.86 \pm 0.24$. For the survey colour distribution, GMM rejects a unimodal distribution at high confidence ($P < 0.001, \chi^2$ test), finding a roughly even split between blue (101 clusters) and red (110 clusters) clusters with colour peaks at $(g475W - z850LP)_0 = 0.97 \pm 0.04$ and $1.36 \pm 0.04$, respectively.

The results of the survey show that the cluster systems of present-day massive galaxies can have diverse colour distributions, but always have substantial numbers of blue clusters11. For galaxies with stellar masses comparable to that of NGC 1277, the typical fraction of blue globular clusters is $f_{\text{blue}} = 0.50 \pm 0.10$ (ref. 11) or larger.

For NGC 1277, we find $f_{\text{blue}} = 0.17^{+0.12}_{-0.08}$ (systematic) $^{+0.06}_{-0.05}$ (random) (16th–84th percentiles; Fig. 3, Methods). This is an upper limit because the null hypothesis of unimodality is not rejected. NGC 1277 is clearly an outlier in that it has a significantly lower blue fraction than the survey galaxies with similar stellar masses (Fig. 3).

For massive galaxies in the survey, the blue cluster fractions are lower limits because the survey covered only the inner 1–2 effective radii ($R_e$) of these galaxies—a region where red clusters dominate over blue clusters owing to the more concentrated spatial distributions of the red clusters18. In the case of NGC 1277, which is very compact ($R_e = 1.2$ kpc) and located in the more distant Perseus cluster, we have probed the entire radial range (about 10$R_e$) of the cluster system and are not biased against detecting blue clusters. Therefore, NGC 1277 truly lacks blue clusters when compared with normal galaxies (Fig. 3).

We rule out the possibility that a colour–magnitude relation in the blue globular clusters is driving the red-dominated peak of the clusters in NGC 1277. This relation is not seen in our data (Methods, Extended Data Fig. 6). In addition, our results are unaffected by possible non-linear colour–metallicity relations for the clusters19–21. About 70% of the clusters in NGC 1277 have $(g475W - z850LP)_0 > 1.1$, which is the approximate colour at which the empirical $(g475W - z850LP)_0$–metallicity relations for clusters in the Milky Way, M49 and M87 are linear21.

NGC 1277 is roughly five times more compact than the majority of galaxies of the same stellar mass at $z = 0$ (ref. 15). As we have shown, NGC 1277 also lacks an obvious population of blue clusters, which are generally associated with a halo population in galaxies. The lack of a halo is consistent with the surface brightness profile of NGC 1277, which declines sharply beyond about 10 kpc from the centre of the galaxy owing to the presence of fewer stars (by a factor of about five) than in other galaxies of the same mass15. Assuming that NGC 1277

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obey the size–stellar-mass relation as that of quiescent galaxies of the same stellar mass at $z = 2$, our findings suggest either that it has been stripped of its outer envelope and clusters and reduced in size, or that it failed to grow substantially in size and in the number of blue clusters since $z = 2$. We have explored both scenarios and favour the latter, that NGC 1277 is a genuine relic galaxy.

The tidal radius of NGC 1277—at which stars and clusters become unbound from the galaxy—can be estimated analytically. In the extreme case that NGC 1277 is currently at pericentre within the Perseus cluster and that its clusters are on prograde orbits with respect to its orbit within Perseus, we calculate a lower limit for the tidal radius of 11 kpc. This lower limit corresponds to roughly $2R_c - 3R_c$ in galaxies with similar stellar masses to that of NGC 1277 and is a radius at which at least 50% the clusters in the population should be blue. This result suggests that stripping has not affected the physical size or the cluster system of NGC 1277. Furthermore, the central stellar density of NGC 1277 is a factor of 2–3 higher than that of the inner 1 kpc of galaxies of similar stellar mass. Tidal stripping alone cannot increase the central stellar density, which implies that NGC 1277 was born both dense and compact. This raises the question of why NGC 1277 should have suffered severe tidal stripping while larger galaxies of similar mass in the same environment—such as NGC 1278—have not. Finally, there is no evidence for tidal tails or streams in the outer region of NGC 1277, or for stripping in the stellar orbits, rotation curve or mass distribution of NGC 1277.

By contrast, NGC 1277 strongly resembles the low-redshift equivalent of higher-redshift compact systems. It lies on the size–stellar-mass relation of $z = 2$ galaxies and has a high central stellar density that is consistent with massive galaxies at these redshifts. Schwarzschild dynamical modelling shows that NGC 1277 is dominated by high-angular-momentum orbits, which implies that it formed in a largely dissipative process. Previous results suggest that NGC 1277 is essentially a massive disk with no classical, pressure-supported component.

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**Figure 1** | Spatial distribution of clusters in the HST/ACS field. North is up, east is to the right. Individual clusters are shown as red points. The locations of the named galaxies are indicated (grey dashes ellipsoids) by isophotes corresponding to 23 mag arcsec$^{-2}$ in $g_{475W}$. NGC 1277 is left of centre in the plots, with the neighbouring galaxy NGC 1278 located around 50 arcsec (17 kpc) to the southeast in projection. The red (left) and blue (right) clusters have been separated by taking a cut at $(g_{475W} - z_{850LP})_0 = 1.15$, typical of the peak separation between the red and blue clusters in galaxies of this stellar mass. The colour scale shows Gaussian kernel density maps of the globular clusters, constructed with a kernel with a width of 10 arcsec. Galaxies in the field can clearly be identified by the relative prevalence of clusters. NGC 1278 has both red and blue cluster populations, whereas NGC 1277 has a substantial population only of red clusters.

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**Figure 2** | The colour distribution of clusters in NGC 1277 compared with that of the composite cluster system. The colour distribution for NGC 1277 (orange histogram) is constructed over the full radial extent of its cluster system (11 kpc) and has been corrected for the contamination from NGC 1278 clusters; in projection, NGC 1278 is 17 kpc from NGC 1277. The composite cluster system (ACS VCS; green histogram) is constructed from four galaxies with stellar masses similar to that of NGC 1277 (roughly $1.2 \times 10^{11} M_\odot$). The dashed curves indicate the Gaussian components of the cluster systems obtained from GMM; the solid curves show the sum of these components. The composite cluster system is clearly bimodal, whereas NGC 1277 lacks an obvious blue peak.

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**Figure 3** | The fraction of blue clusters in galaxies of a given stellar mass. Data for the survey galaxies (ACS VCS; open blue circles) come from ref. 11. NGC 1277 (filled orange circle) has a very small fraction of blue clusters when compared with other galaxies of similar stellar mass. For the binned survey data (filled blue circles), the 16th–84th percentiles of the distributions are shown as error bars; the blue fractions for the brightest survey galaxies are lower limits (indicated by the arrowheads) because only the central parts of the galaxy cluster systems were observed. The systematic uncertainty on the blue fraction for NGC 1277 is shown as the faint, dashed error bar (16th–84th percentiles); the random uncertainties from Monte Carlo simulations are smaller and shown as the solid error bar (16th–84th percentiles). The blue fraction for the clusters in NGC 1277 is an upper limit (indicated by the arrowhead) because the null hypothesis of unimodality cannot be rejected on the basis of observations.
Figure 4 | Predictions from the simulated merger histories of NGC 1277. The specific frequency—the number of clusters per unit galaxy luminosity—is shown against the number ratio of clusters formed in situ (N_{insitu}) and those accreted (N_{acc}) in the simulated merger histories. The colours represent the average accretion fraction for each merger history. The constraints for NGC 1277 (black circle, with error bars indicating the 16th–84th percentiles, the arrow indicates that our measurements are an upper limit for the accreted fraction) that we determined from the observations are often satisfied in histories with low accretion fractions (about 10%). Merger histories with higher accretion fractions rarely lead to the colour ratio that we observed without overproducing the total number of clusters. By contrast, similar-mass galaxies in the ACS VCS (grey box) are well reproduced by merger histories with accretion fractions of around 50%.

These kinematic properties are remarkably similar to those of the lensed ‘dead disk’ at z ≈ 2.1 (ref. 25), which has similar stellar mass to NGC 1277 and is similarly compact (R_e = 1.73^{+0.24}_{-0.35} kpc). In addition, the old, metal-rich stellar population of NGC 1277 is similar to that of other nearby relic-galaxy candidates, to that expected for passively evolving z = 2 red nuggets and to that predicted for the redshift evolution of massive, compact systems in cosmological simulations. Finally, the fact that NGC 1277 is in a massive galaxy cluster is not unexpected, observationally or theoretically (Methods).

Our findings for the cluster system of NGC 1277 provide further constraints on the evolutionary histories of relic galaxies. In accretion models for the formation of the blue cluster population in massive galaxies, the location of the blue peak and the relative fraction of blue clusters provides insight into the total mass and the properties of accreted satellites of any given galaxy. We ran a series of analytic merger models based on our observations (Fig. 4, Methods, Extended Data Figs 7, 8) to constrain the accreted mass fraction of NGC 1277. From this modelling we find that the observed blue cluster fraction of NGC 1277 is characteristic of galaxies that have accreted about 10% or less of their stellar mass, with the rest of the stars having formed in situ. By contrast, mass-matched ACS VCS galaxies have accretion fractions of 50%–90%. We therefore find that the blue fraction of globular clusters approximately traces the total fraction of accreted mass in galaxies, and that NGC 1277 has accreted very little mass (if any) over its lifetime compared with other galaxies of similar stellar mass.

We conclude that NGC 1277 provides a benchmark for the detailed study of the properties of massive galaxies that have not evolved since z = 2. High-resolution imaging of the cluster systems of more relic galaxies will enable the reconstruction of their mass-accretion histories.

Online Content Methods, along with any additional Extended Data display items and Source Data, are available in the online version of the paper; references unique to these sections appear only in the online paper.

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METHODS

HST/ACS photometry. We obtained HST/ACS imaging of NGC 1277 in F475W ($g_{\text{F475W}}$) and F850LP ($z_{\text{F850LP}}$) (two orbits; GO programme ID, 14215; Extended Data Fig. 1). The total exposure time was 2,280 s (F475W) and 2,432 s (F850LP). We adopt a standard cosmological model with $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.3$ and $\Omega_{\Lambda} = 0.7$. The redshift assumed here for NGC 1277, $z = 0.0169$, corresponds to a galaxy distance of 73.3 Mpc ($m - M_b = 34.33$) and a spatial scale of 344 pc arcsec$^{-1}$.

The F475W data were pipeline-reduced, including correction for charge-transfer efficiency. We calculated zero-points for the AB magnitude system using the file header information. Aperture and point spread function (PSF) photometry was performed on the ACS imaging using Source Extractor$^{28}$ with the add-on PSFEx$^{30}$. Our photometry was corrected for foreground extinction using line-of-sight redening estimates$^{54}$. Source Extractor was run in dual-image mode using un-sharp masks as detection images with photometry performed on the original images. We selected matched sources in the $g_{\text{F475W}}$ and $z_{\text{F850LP}}$ filters. Aperture magnitudes were measured using a range of aperture radii from 3 to 50 pixels. We applied aperture corrections to the three-pixel aperture magnitudes by correcting to ten-pixel (0.5 arcsec) apertures based on bright, isolated stars, and then correcting to infinity using the corrections tabulated in ref. 32. For artificial point-source tests, we used PSFEx to construct PSFs based on bright, isolated stars across the ACS field.

Completeness tests. Completeness tests were performed by injecting artificial point sources into the images (using the PSFEx PSFs) and determining the recovery fraction as a function of magnitude with Source Extractor. In regions approximately 20 arcsec from bright galaxies, we are 100% complete to $g_{\text{F475W}} = 27.3$ mag and $z_{\text{F850LP}} = 26.7$ mag, with typical colour uncertainties of $(g_{\text{F475W}} - z_{\text{F850LP}}) = 0.08$ mag. We take this as a conservative photometric limiting magnitude. However, the completeness varies as a function of position and therefore we also created a completeness map by repeating our tests at a function of position and magnitude across the field. In the very central regions (less than 1.5 arcsec; 0.5 kpc) of NGC 1277 and the neighbouring NGC 1278, we recover few clusters owing to the high surface brightness of the galaxies. Photometric errors were characterized by measuring the difference between the input and output magnitudes of 50,000 artificial point sources placed randomly across the images.

To separate point sources (globular cluster candidates) from extended sources, we obtained the Source Extractor output $\text{flux}$ $\text{radius}$ as a function of magnitude for our artificial point sources. All real sources identified within the region defined by the artificial sources were regarded as cluster candidates. In total, to $g_{\text{F475W}} = 27.3$ mag, we detect 2,286 objects in the magnitude range consistent with being clusters. Colour–magnitude diagrams for all of the cluster candidates, and for cluster candidates around NGC 1278, NGC 1277 and an example background field are shown in Extended Data Fig. 2.

Characterizing the colour distributions of the cluster systems. The spatial density distribution of candidate clusters (Fig. 1) was constructed directly from the photometry, after masking a small region (radius of 3 arcsec) centred on an unclassified dwarf located about 16 arcsec to the west of NGC 1277 (right panel). The area was limited to 20 arcmin. The $g_{\text{F475W}}$ colour–magnitude distribution of candidate clusters around NGC 1278, NGC 1277 and an example background field are shown in Extended Data Fig. 2.

To create the colour distribution of NGC 1277 (Fig. 2), we had to take into account interloping clusters from the neighbouring NGC 1278 and contributions from intrACLuster clusters. We constructed a ‘master background’ by selecting five regions from NGC 1278 that are at an angular distance from NGC 1277 equal to the separation between NGC 1277 and NGC 1278, and sufficiently distant from NGC 1277 so as to not overlap with its cluster system (which has an extent of about 11 kpc; Extended Data Fig. 3). The colour distribution of NGC 1277 clusters was built by selecting all cluster candidates within 11 kpc (about 10$R_e$) and subtracting the master background normalized to the area covered by the master system of NGC 1277. This process also removes intrACLuster clusters from the cluster system of NGC 1277. The colour distribution of this master background is shown in Extended Data Fig. 4.

To explore the subpopulations in the colour distributions, we ran a GMM code$^{38}$ on the binned colour distributions. For the visibly bimodal colour distribution of the survey composite, in the heteroscedastic (different variances between populations) case we obtain means of $(g_{\text{F475W}} - z_{\text{F850LP}}) = 0.97 \pm 0.04$ and $1.36 \pm 0.04$ with Gaussian full-widths at half-maximum (FWHM$\sigma$s) of 0.12 $\pm$ 0.02 and 0.15 $\pm$ 0.02, respectively. 101 clusters are associated with the blue peak and 110 clusters with the red peak. A unimodal distribution is rejected at high confidence ($P < 0.001$, $\chi^2$ test). Similar results were obtained in the homoscedastic case.

For NGC 1277, a unimodal distribution cannot be rejected because the null hypothesis cannot be rejected. We consider two sources of uncertainty for $f_{\text{blue}}$. The uncertainty returned from GMM on the number of blue and red clusters we regard as our systematic uncertainty. In addition, a random uncertainty on $f_{\text{blue}}$ comes from our background subtraction. To quantify the true value of $f_{\text{blue}}$ and this uncertainty, we performed 1,000 Monte Carlo simulations in which we selected clusters randomly from our background regions (until the observed background level was reached), and varied the radial aperture of the background and NGC 1277 selection regions by $\pm 3$ kpc ($\pm 9$ arcsec). From this we built new colour distributions and ran GMM on these colour distributions to obtain $f_{\text{blue}}$ (Extended Data Fig. 5). For the homoscedastic case, we obtain $f_{\text{blue}} = 0.18^{+0.12}_{-0.11}$ (systematic) $\pm 0.04$ (random) (16th–84th percentiles); for the heteroscedastic case, we obtain $f_{\text{blue}} = 0.17^{+0.12}_{-0.01}$ (systematic) $\pm 0.06$ (random) (16th–84th percentiles). We conservatively take this latter value as the true fraction and its associated uncertainties. From the Monte Carlo simulations, we find $f_{\text{blue}}/f_{\text{red}} = 0.21^{+0.25}_{-0.20}$ (16th–94th percentiles). We consider these as upper limits because the unimodal hypothesis cannot be rejected.

As a sanity check, we compared the colour distributions of NGC 1277 with those of NGC 1278 (Extended Data Fig. 4). We remove contributions from intrACLuster clusters to the colour distribution of NGC 1278 by selecting clusters in a region away from bright galaxies (centred on a right ascension of 3 h 19 min 50.1 s and declination of $+41^\circ 35' 30.0''$) over an area normalized to that of our cluster-selection region. NGC 1278 shows a prominent blue peak of clusters and a less prominent red peak. GMM (heteroscedastic case) locates peaks at $(g_{\text{F475W}} - z_{\text{F850LP}}) = 0.95 \pm 0.24$ and $1.40 \pm 0.10$. These solutions are in excellent agreement with expectations$^{11}$.

Surface-density profiles of the clusters. The surface-density profile of clusters (Extended Data Fig. 3) was constructed by counting globular clusters in semi-circular annuli and dividing by the area of each semi-annulus. We only counted clusters in the northern half of the galaxy—biseected by the major axis of the galaxy—to minimize contamination from the cluster system of NGC 1278. The inner two radial bins have been corrected on the basis of our completeness tests. The clusters closely follow the galaxy light$^{12}$. This is a characteristic property of red clusters in massive galaxies$^{48}$. By contrast, blue clusters generally have spatial distributions that are more extended than the galaxy stars$^{16,24}$. To define the radial extent of the system, and to locate the background level, we fitted the data with a modified Sérsic function$^{25}$:

$$N_{\text{gc}}(R) = N_{\text{gc}} \exp \left( -\frac{R}{R_e} \right)^{1/n} R^n - 1 \right) + \text{bkg}$$

with $N_{\text{gc}}$ the surface density of clusters at radius $R$, $n$ the Sérsic index and bkg the background value; $b_{\text{gc}}$ is related to $n$ by $b_{\text{gc}} = 1.9992 n - 0.3271$.

A Sérsic fit (with $N_{\text{gc}} = 7.8 \pm 0.7$ kpc$^{-2}$, $R_e = 2.6 \pm 0.2$ kpc, $n = 0.9 \pm 0.3$, $b_{\text{gc}} = 0.27 \pm 0.01$ kpc$^{-2}$) to the surface-density profile of the clusters (Extended Data Fig. 3), along with visual inspection, indicates that we reach the background limit at about 11 kpc, or 1.32$R_e$. This corresponds to a galaxy magnitude of $M_{\text{F475W}} = -26.95 \pm 0.15$ mag (25.80 $\pm$ 0.20 mag) and $M_{\text{F850LP}} = -34.15 \pm 0.15$ mag (34.20 $\pm$ 0.20 mag). These values are in excellent agreement with our adopted distance to NGC 1277.

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Total cluster population of NGC 1277. We counted the total number of clusters brighter than the turn-over of the luminosity function of the clusters (26.95 ± 0.15 mag in g9750) that lie within 11 kpc of the galaxy centre within the northern half of NGC 1277. In so doing, we detect 92 ± 18 clusters to our photometric limit, where the uncertainties come from the uncertainty of ±0.2 mag in the peak position of the luminosity function. From this number we subtracted the expected contribution from NGC 1278 clusters (27 ± 8 clusters). Correcting for radial incompleteness, this number becomes 93.9 ± 23.0. We then doubled the total to account for the undetected faint half of the luminosity function, and doubled it again because we constructed the surface-density profile in the northern half of the galaxy. We arrive at a total cluster population of \( N_{\text{total}} = 376 ± 94 \). For \( M_\odot = -20.87 \) (NASA Extragalactic Database, https://ned.ipac.caltech.edu/), this cluster population yields a specific frequency of \( S_N = 1.7 ± 0.4 \), consistent with galaxies in the stellar mass range of NGC 1277, which typically have \( S_N ≈ 2.0 \) ref. (39).The blue tilt. The ‘blue tilt’ manifests as a colour–magnitude relation in the blue clusters whereby the brightest blue clusters become redder with increasing luminosity40–42. This can make the colour distributions for the brightest clusters look unimodal. We investigated this issue by making colour distributions from the median bin values of our Monte Carlo simulations for the NGC 1277 clusters binned by magnitude (Extended Data Fig. 6). The mean colours of all three bins are very similar and predominantly red, with \( \langle g_{9750} - z_{4400} \rangle = 1.22 \) (22.9 < \( z_{950} < 24.0 \)), \( \langle g_{9750} - z_{4400} \rangle = 1.19 \) (24.0 < \( z_{950} < 25.0 \)) and \( \langle g_{9750} - z_{4400} \rangle = 1.23 \) (25.0 < \( z_{950} < 26.5 \)). This behaviour is not expected if a blue tilt were driving the observed colour distributions. The majority of the clusters with \( \langle g_{9750} - z_{4400} \rangle ≤ 1.1 \) are consistent with the background residuals. However, a few of the brightest clusters (eight) are above the background. These ‘blue’ clusters constitute a small fraction of the overall cluster population. The environments of relic galaxies. NGC 1277 lies 3.8 arcmin (roughly 80 kpc) in projection to the north of the central massive galaxy NGC 1275 in the Perseus cluster of galaxies. However, it is not unexpected that such a relic galaxy should be found in such a dense environment. Observational studies that have looked specifically at the preferred environments of massive compact galaxies in the nearby Universe find that the fraction of present-day compact, quiescent galaxies with stellar masses of more than about \( 3 \times 10^{10} M_\odot \) that lie in low-density environments is approximately 4.4%43. The corresponding fraction in nearby galaxy clusters is about 22%44. Similar dependencies on environmental density have been obtained from different samples45,46. Of the 16 best-studied nearby, massive, compact galaxies (including NGC 1277), 7 are in clusters, 4 in groups and 5 in isolated systems47. On the theoretical side, dark-matter-only simulations have been used to explore the clustering properties of massive, compact galaxies, and reveal that the fraction of massive, compact galaxies is about five times larger in the most massive structures than in low-mass dark-matter haloes. Similarly, semi-analytic models have been used to explore the environments of compact, massive galaxies, and reveal that these galaxies represent about 0.04% of the total galaxy population, but about 0.18% of the galaxy population in clusters. In addition, compact galaxies preferentially lie in the centres of clusters of the typical 0.2 virial radius, which corresponds to 400 kpc in Perseus), whereas non-compact galaxies of the same mass have mean cluster-centric radii of around 0.4 virial radii45. The evolution of massive compact systems at \( z = 2 \) has previously been explored in cosmological, hydrodynamical simulations: of a sample of 35 galaxies, roughly 30% remained sufficiently undisturbed to be defined as relics at \( z = 0 \). Of these relics, about 20% survive as satellites in galaxy clusters. In summary, although massive, compact, ‘relic’ galaxies are rare in the nearby Universe (with space densities of \( 10^{-3} Mpc^{-3} \))48,49, they are expected to be preferentially found in the most massive structures, such as the Perseus cluster of galaxies. Accretion histories of NGC 1277. To obtain a quantitative understanding of the link between the colour distributions of clusters and the accretion history of a galaxy, we constructed a library of analytic merger histories for NGC 1277. We ran 1.5 × 10^5 model realizations of NGC 1277 in which we reconstruct its total cluster population of the in situ component of NGC 1277 in every realization. Finally, the cluster metallicities are converted to \( g_{9750} - z_{4400} \) colours41. This exercise is qualitatively similar to that used previously with the added benefit that we allow for a flexible slope of the sub-halo mass function, rather than constraining it on the basis of average accretion histories in cold dark matter simulations. This addition allows us to explore how the cluster colour distributions and galaxy stellar mass could arise in potentially rare scenarios with either very low or high numbers of mergers or consecutive extreme-mass-ratio mergers. Although simple, these models recover the ensemble properties of the observed cluster colour and number distributions for galaxies of the mass of NGC 1277. Extended Data Fig. 7 shows the accreted fraction of each realization of NGC 1277 (with each dot representing one possible merger history that reproduces the total mass of NGC 1277) versus the ratio of the number of in situ to accreted (red to blue) clusters for NGC 1277 in that realization. We have conservatively used the minimum \( N_{\text{in situ}}/N_{\text{acc}} \) value allowed within the error bars \( (N_{\text{in situ}}/N_{\text{acc}} = 2.17) \) rather than \( N_{\text{in situ}}/N_{\text{acc}} < 99/21 = 4.76 \). The observed colour ratio of the clusters in NGC 1277 is characteristic of galaxies that have undergone merger histories resulting in the host accreting 12% of the present-day stellar mass. In comparison, galaxies of comparable mass to NGC 1277 in the ACS VCS sample have observed colour distributions \( (N_{\text{in situ}}/N_{\text{acc}} ≤ 1) \) typical of having accreted 50%–90% of their stellar mass. A very small percentage (about 0.02%) of these high-f_{\text{acc}} models can produce cluster colour ratios similar to that for NGC 1277. However, Fig. 4 and Extended Data Fig. 8 show that these high-f_{\text{acc}} assembly histories tend to over-predict the total number of clusters per unit mass (\( N_C \)) by 2 and that the ACS VCS sample is consistent with 0.8% of these models being ruled out for NGC 1277 by dynamical modelling7,21. Extended Data Fig. 8 illustrates that the typical merger histories in our models that successfully reproduce the \( S_N \) and colour distribution of NGC 1277 tend to have accreted only \( f_{\text{acc}} = 12% ± 8% \) of their stellar mass, to have had a merger event with a mass ratio of at most 1:10 and to reside in under-massive dark-matter haloes (\( M_\odot/M_{\Delta M} ≈ 0.06 \)) when compared with galaxies of the same stellar mass as NGC 1277. These models support the idea that NGC 1277 has not accreted substantial amounts of dark-matter-rich sub-haloes, leaving it deficient both in dark-matter mass and in blue, accreted clusters. Sample size. No statistical methods were used to predetermine sample size. Code availability. The photometry software Source Extractor and PSFEx are publicly available at https://www.astromatic.net/software/sExtractor and https://www.astromatic.net/software/psfex. The GMM code is publicly available at http://www-personal.umich.edu/~ognedin/gmm/. A version of the global cluster luminosity function fitting code is available on request. The code used for the modelling of the accretion histories of NGC 1277 will be made available in the future. Data availability. The HST data used was obtained under GO programmes 14215 and 10546 and are publicly available at https://archive.stsci.edu/proposal_search.php?pid=14215&mission=– and has been obtained from the Hubble Legacy Archive (https://archive.stsci.edu/proposal_search.php?pid=10546&mission=–. Data products such as the point-source photometry and results of the Monte Carlo simulations are available from the corresponding author on request. 29. 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Extended Data Figure 1 | Colour-composite HST image of the massive relic galaxy NGC 1277. The image was constructed from $g_{475W} + r_{625W} + z_{850LP}$ bands. The $g_{475W}$ and $z_{850LP}$ imaging was obtained with the HST programme GO-14215 and the $r_{625W}$ imaging with the programme GO-10546. NGC 1277 is the best example found so far in the nearby Universe with characteristics equivalent to those of the first massive galaxies to form more than 11 Gyr ago. The image is oriented with north pointing up and east to the left. The field of view is 42.2 arcsec $\times$ 30.6 arcsec, corresponding to a physical scale of 14.5 kpc $\times$ 10.5 kpc at our adopted distance of 73.3 Mpc to the galaxy. The images have been scaled with logarithmic intensity to highlight the various structures in the galaxy. The vast majority of point sources surrounding NGC 1277 are clusters associated with the galaxy. Two example clusters have been marked with ticks.
Extended Data Figure 2 | Colour–magnitude diagrams of cluster candidates. From left to right, the plots show all point sources in the field, NGC 1278 clusters, raw (not background-corrected) NGC 1277 clusters and an example background field. Also shown are the photometric uncertainties (1σ; blue crosses) based on our artificial point-source test, and the 100% completeness limit (red dashed lines; see Methods).
Extended Data Figure 3 | Surface-density profile of NGC 1277 clusters. The figure shows the raw (blue circles) and completeness-corrected (orange stars) counts. Uncertainties are 16th–84th percentiles. Within the range 3–10 kpc, the clusters closely follow the light distribution of the galaxy. This is typical of red clusters. The background is determined from the Sérsic function fits (which include a background term; green line) to the cluster data and defines the radial extent of the cluster system, which ends at 11 kpc (about 10R_e). The stellar-mass density profile (red line) has arbitrary normalization. GCs, globular clusters.
Extended Data Figure 4 | Colour distribution of clusters in NGC 1277 compared with that for the companion galaxy in projection NGC 1278. The figure shows that NGC 1278 (blue) has a strong peak of blue clusters that is not seen in NGC 1277 (orange). The expected background contamination of NGC 1278 clusters and of intracluster clusters to the cluster system of NGC 1277, with which we have corrected the colour distribution of NGC 1277, is also shown (green). The predominantly blue colours of the contaminating clusters is expected because they correspond to the outskirts of NGC 1278 (see Fig. 1). Solid curves are two-Gaussian solutions from the GMM code\cite{gmm}; dashed curves are individual Gaussian components from GMM. A single Gaussian fit to the NGC 1277 clusters with GMM gives $\langle g_{755W} - z_{850LP} \rangle = 1.22 \pm 0.03$, with a FWHM of $0.28 \pm 0.02$. 

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Extended Data Figure 5 | Distribution of the blue cluster fraction from Monte Carlo simulations. The vertical dashed lines indicate the medians of the distributions and the vertical dotted lines show the 16th and 84th percentiles.
Extended Data Figure 6 | Colour distributions of NGC 1277 and NGC 1278 in three magnitude bins. The bin values for the NGC 1277 clusters represent the medians of the bin values from Monte Carlo simulations. Uncertainties are the 16th–84th percentiles of the distributions.
Extended Data Figure 7 | Accretion models for the build-up of the NGC 1277 cluster system. Each point is a single merger history for NGC 1277, characterized by the total fraction of accreted stellar mass versus the number ratio of \textit{in situ} to accreted clusters for that realization. The observed ratio for NGC 1277 is indicated by the cyan dashed line ($N_{\text{blue}}/N_{\text{red}} = 0.21$) and is characteristic of galaxies with merger histories leading to $f_{\text{acc}} \approx 10\%$ (orange). The cyan arrow indicates that the \textit{in situ} fraction is a lower limit. Galaxies with comparable stellar mass to NGC 1277 in the ACS VCS tend to have equal numbers of blue and red clusters, which is more common for accretion histories of $f_{\text{acc}} \approx 50\%–90\%$ (green). The extremely rare (about 0.02\%) high-mass-accretion realizations, which produce the observed blue/red fraction in NGC 1277, are shown in magenta. Contours represent 10\%, 25\%, 50\%, 75\%, 90\% and 99\% of the maximum of the two-dimensional distribution.
Extended Data Figure 8 | Predictions of galaxy properties from accretion models. From left to right, the black lines show the accretion fraction, the number of mergers, the maximum mass ratio of the merger and the final ratio of stellar to dark-matter mass for all of the merger realizations. The magenta distributions (top) show the high-$f_{\text{acc}}$ merger histories that satisfy the constraint on the colour ratio of the clusters (which happens rarely; see, for example, Extended Data Fig. 7). The cyan distributions (bottom) show the low-$f_{\text{acc}}$ merger histories that satisfy the observed colour ratio of the clusters and the $S_N$ constraints. The high-accretion-fraction models (magenta) also predict a dark-matter-halo mass for NGC 1277 that is larger than the observational constraints$^{17}$ (indicated by the arrow in the bottom right panel). The vertical dashed lines represent the median of the distributions and the vertical dotted lines show the 16th and 84th percentiles.