Quiescent ultra-diffuse galaxies in the field originating from backsplash orbits

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Ultra-diffuse galaxies (UDGs) are the lowest-surface-brightness galaxies known, with typical stellar masses of dwarf galaxies but sizes similar to those of larger galaxies such as the Milky Way. The reason for their extended sizes is debated, with suggested internal processes such as angular momentum, feedback or mergers versus external mechanisms or a combination of both. Observationally, we know that UDGs are red and quiescent in groups and clusters whereas their counterparts in the field are blue and star-forming. This dichotomy suggests environmental effects as the main culprits. However, this scenario is challenged by recent observations of isolated quiescent UDGs in the field. Here we use the ΛCDM (or Λ cold dark matter, where Λ is the cosmological constant) cosmological hydrodynamical simulation to show that isolated quenched UDGs are formed as backsplash galaxies that were once satellites of another galactic, group or cluster halo but are today a few Mpc away from them. These interactions, albeit brief, remove the gas and tidally strip the outskirts of the dark matter haloes of the now quenched and seemingly isolated UDGs, which are born as star-forming field UDGs occupying dwarf-mass dark matter haloes. Quiescent UDGs may therefore be found in non-negligible numbers in filaments and voids, bearing the mark of past interactions as stripped outer haloes devoid of dark matter and gas compared to dwarfs with similar stellar content.

Ultra-diffuse galaxies (UDGs) in groups and clusters are characterized by a puzzling wide range of dark matter and globular cluster content, thick disk-like shapes, old stellar populations and no substantial gas component. Their quiescence is not surprising given the high-density environments they populate. However, for the few quenched UDGs that have been discovered in the field, the mechanism responsible for removing the gas and halting star formation remains unknown. On the theory side, progress requires high-resolution cosmological simulations that are able to resolve the myriad of environments and physics involved in this problem, from the formation of isolated dwarfs in their haloes to their interactions with filaments, groups and clusters. Such simulations have only recently become possible, with the TNG50 simulation (used here) among those with the highest resolution available.

We use the stellar mass–size relation defined by all simulated galaxies (Fig. 1, grey dots) to define our sample of field UDGs as those central galaxies (excluding satellites) with stellar mass in the dwarf range (log(M*/M_☉) = [7.5, 9], shaded pink region) and a stellar size above the 95th percentile at a given mass (magenta stars). Our definition overlaps with observational samples of UDGs whereas 23.7% of our simulated UDGs are along the red sequence. The mass distribution is non-uniform, with red UDGs being more common towards the lower masses, whereas at the same mass, field UDGs have a higher fraction of red objects than normal dwarfs in the field (Supplementary Fig. 2, upper panel). Their colours correlate with their star formation rates (SFRs) (Fig. 2, inset), with the blue UDGs occupying the ‘main sequence’ of star-forming galaxies and the red UDGs showing negligible star formation today.

A close inspection of the histories of our red quiescent UDGs reveals a factor in common: they have all been satellites of another system in the past but are today central galaxies in the field. An example of the orbit of one of our red UDGs is shown in Fig. 3a. This dwarf interacted ~4 billion years ago with a group that has a virial mass M_{vir}(z=0) ≈ 6.46 × 10^13 M_☉ but is found today ~1.5 Mpc away, more than twice the virial radius of the group. (Virial quantities refer to the radius enclosing 200 times the critical density of the Universe.) The colour coding of the orbit, reflective of the dwarf colour at each time, shows that the reddening starts already as it falls into the group and accelerates after the pericentric passage. The images of the simulated UDG (Fig. 3b) clearly show that its gas is removed as it approaches the pericentre, explaining its quiescence and redness today in the field. The stellar size is not largely affected by the interaction; our red UDGs were all already extended before infall (Supplementary Fig. 1).

Objects in such external orbits, which are found far beyond the virial radius of their hosts, are known as backsplash galaxies and are a natural consequence of the hierarchical assembly in ΛCDM. Our red UDGs are backsplash objects of systems in a wide range.
Fig. 1 | Definition of the UDG sample. Stellar mass versus size ($M_\star$ versus $r_e$) relation for all simulated galaxies in the mass range $\log(M_\star/M_{\odot})=[7.4, 9.1]$ in the TNG50 simulation (grey dots). Thin blue dashed curves indicate lines of constant surface brightness assuming a mass-to-light ratio equal to 1. The solid black line indicates the median size at fixed $M_\star$ for the simulated galaxies. Yellow dashed curves show the 5th and 95th percentiles, with the shaded yellow region in between highlighting the sample of normal galaxies. Our sample of field UDGs (magenta stars) is defined as central galaxies with $\log(M_\star/M_{\odot})=[7.5, 9]$ and stellar size above the 95th percentile (pink shaded region). Several observational data are shown in black-edged symbols, where we transform two-dimensional sizes $R_{\text{eff}}$ to three-dimensional assuming $r_e=4/3 R_{\text{eff}}$. Light blue diamonds indicate star-forming UDGs in low-density environments, the dark blue circle is the relatively isolated DGSAT I and the red pentagon is UDG S82-DG-1, an isolated quiescent UDG. For comparison, we also show UDGs in the Virgo cluster (green crosses) and the Coma cluster (pink X symbols). Our UDG definition agrees well with observational samples, in particular for those in low-density environments.

of virial masses, from galaxy-sized haloes with $M_{200}\approx 2\times 10^{12}M_{\odot}$ to galaxy clusters, and are today on average at $2.1\,r_{200}$ from those systems, or $1.7\pm 0.7\,\text{Mpc}$, but can reach as far as $3.35\,\text{Mpc}$ in some cases (Supplementary Fig. 3). In the large majority of cases (64.3%), the system responsible for the quenching and the launching beyond the virial radius is the same, with the remaining cases being ‘pre-processing’, meaning that the UDG was first quenched in a moderate mass host, which subsequently fell into a more massive system responsible for the energetic orbit.

A section of the simulated box with the location of red and blue UDGs is illustrated in Fig. 3c, highlighting the red UDGs that are back splash objects of galaxy-size haloes (green circles), located mainly in low-density regions of the Universe. Red field UDGs cluster more than the blue ones, but they are all at substantial distances from their once-hosts. On average, the interactions occurred 5.5 $\pm$ 2.5 Gyr ago and were moderately quick, with red UDGs spending typically 1.5 Gyr (median) within the virial radius of the systems they are back splash of (Supplementary Fig. 4).

Interestingly, there are extreme cases in which the close pericentre passage of the UDG results in its total ejection from the system in a way that is reminiscent of those in multiple-body interactions. Our most extreme UDG resides $\approx 3.35\,\text{Mpc}$ away from its host and would appear as an extremely isolated object in a void-like environment (Fig. 3c, yellow circle). This UDG fell in as part of a galaxy-size group into a group-size halo with $M_{200}(z=0)=3.36\times 10^{13}M_{\odot}$ and was ejected more than 6 Gyr ago after its first pericentre (Supplementary Fig. 5).

This scenario for the formation of quiescent UDGs in the field has a number of observational implications. First, the stellar populations are old due to the quenching during the backsplash interaction. As shown in Fig. 4a, blue UDGs are comparatively younger, characterized by an extended star formation history as argued in the case of observed field UDGs, and consistent with the overall simulated population of field dwarfs (grey symbol). Note that the ages inferred for isolated UDGs in observations are mostly in agreement with our blue UDG population.

Second, the morphologies of red UDGs are always more spheroid-dominated than their blue counterparts with similar stellar mass, which might show spheroid or disk structure (Fig. 4b), in agreement with previous work. Here, morphology is quantified by the $\kappa_{\text{sd}}$ parameter (Methods). We predict a shift towards early-type morphologies for red UDGs (low $\kappa_{\text{sd}}$), which is consistent with the picture in which satellite galaxies are preferentially spheroid-dominated due to transformations induced by the environment.

Third and most important, backsplash galaxies have been stripped to some degree of their mass during the tidal interaction with their past host system. Blue UDGs form in dwarf-mass haloes with virial mass in the range $\log(M_{200}/M_{\odot})=[10.3–11.2]$, whereas red UDGs at the same stellar mass show lower virial masses, with a median of $\log(M_{200}/M_{\odot})=9.73$ (Fig. 4c) due to this interaction. Red UDGs in the field should be clear outliers compared to predictions...
from abundance-matching models\textsuperscript{33}. The stripping occurs mostly in the outer halo, where the dark matter density profile of red UDGs falls more steeply than that of the unperturbed blue UDG population (Supplementary Fig. 6). Unfortunately, the inner stellar velocity dispersion of red and blue UDGs—a possible observable—is statistically indistinguishable in our simulation.

A fourth implication in this scenario is that red UDGs are fully devoid of halo gas, which was all removed via ram pressure\textsuperscript{34,35} along with the inner gas during the interaction with their hosts. We have checked that no gas is re-accreted in these dwarfs, in contrast with the gas mass $M_{\text{gas}} = 10^8$ to $10^{10} M_\odot$ predicted in the haloes of blue UDGs in the field (this includes gas with distance (in kpc) of $2r_\star < r < r_{200}$, where $r_\star$ is the stellar half-mass radius). A promising way to study the circumgalactic medium of these galaxies down to very low column densities is to use background quasars to provide different absorption lines-of-sight across a halo\textsuperscript{36}. Although this would be prohibitive on an individual UDG basis, a statistical detection (or lack of thereof) might be achieved once a sufficiently large number of red field UDGs are found. Neutral gas and H$\alpha$ studies of red UDGs should also confirm a lack of gas in their interstellar medium.

There are a few observational detections of quiescent UDGs in low-density environments and they seem consistent with the picture emerging from our analysis. One of the first reported non-cluster detections of quiescent UDGs in low-density environments is that red UDGs are fully devoid of halo gas, which was all removed via ram pressure along with the inner gas during the interaction with their hosts. We have checked that no gas is re-accreted in these dwarfs, in contrast with the gas mass $M_{\text{gas}} = 10^8$ to $10^{10} M_\odot$ predicted in the haloes of blue UDGs in the field (this includes gas with distance (in kpc) of $2r_\star < r < r_{200}$, where $r_\star$ is the stellar half-mass radius). A promising way to study the circumgalactic medium of these galaxies down to very low column densities is to use background quasars to provide different absorption lines-of-sight across a halo. Although this would be prohibitive on an individual UDG basis, a statistical detection (or lack of thereof) might be achieved once a sufficiently large number of red field UDGs are found. Neutral gas and H$\alpha$ studies of red UDGs should also confirm a lack of gas in their interstellar medium.

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UDGs is DGSAT I (ref. 17), which is located in the filament of the Pisces-Perseus supercluster. This is in excellent agreement with our predictions, which show that most red field UDGs are nearby but outside groups and clusters. DGSAT I lacks gas (as measured by Hα (ref. 13)) and has a relatively old stellar population (8.1 ± 0.4 Gyr mass-weighted age), which is also within the range predicted by our simulations.

Another interesting object is S82-DG-1, an extremely isolated quenched UDG in a nearby void. Its isolation has been used to favour internal effects such as feedback to explain the possible origin of UDGs, rather than high-density environmental effects. Here, we argue that S82-DG-1 fits the characteristic expected for our simulated population of passive UDGs that were satellites of a galactic-size host. S82-DG-1 is located at ~55 kpc in projection and at a redshift distance of less than Δv = 145 km s⁻¹ from NGC 1211, a lenticular galaxy with stellar mass $M_\odot = 1 \times 10^{10} M_\odot$ (Methods). Three of our simulated red UDGs have been backsplash objects in galaxy-mass haloes $M_{200} < 1 \times 10^{13} M_\odot$ and are found today ~650 kpc from their hosts. Moreover, 12 red isolated UDGs (28.5%) were quenched in galactic environments ($M_{200} < 10^{13} M_\odot$). Although the exact distance of S82-DG-1 to NGC 1211 is unknown, our analysis provides support for the possible external nature of quenching in S82-DG-1 induced by NGC 1211. The old stellar population inferred for S82-DG-1, 6 Gyr of age, is in excellent agreement with the average time of the interactions found in our simulated sample.

We therefore propose backsplash orbits as a new mechanism to explain the presence of quiescent UDGs in low-density environments. This population of red and diffuse dwarfs results from the inflow of normal star-forming field UDGs into galactic, group or cluster-size haloes responsible for stripping off their gas and propelling them to distances ~1 Mpc and beyond. In the most extreme cases, UDGs may even be ejected several Mpc away from these systems. The predicted fraction of red UDGs in our simulation in the studied mass range is ~24%. Mild clustering and old stellar populations, along with dark matter haloes of lower mass and the complete absence of gas in the galactic and circumgalactic region, are the expected telltale of this formation scenario for red UDGs.
The morphology parameter $k_m$ is calculated following ref. \(^\text{19}\) as follows. After rotating each galaxy to a reference frame where the angular momentum of the stars (within $r_{\text{g}}$) points along the z direction, we compare the energy in rotation around z axis to the total kinetic energy $K = \text{rot} = (1/2) \sum (1/2m_i r_i^2 v_i^2)$, where $j_i$ is the angular momentum of each stellar particle in the rotated system, $m_i$ is their mass and $r_i$ is their cylindrical radius, and the sum is over stars within $r_{\text{g}}$. Defined in this way, the morphology parameter $k_m$ has been shown to correlate with other definitions of galaxy morphology\(^\text{19}\). Low $k_m$ values correspond to spheroid-dominated objects, whereas $k_m > 0.6$ is used to identify disk-dominated objects.

Galaxies are followed over time by means of Sublink merger trees\(^\text{11}\). This allows us to track the mass, size and star formation histories of our sample over time. Note that the circumbulge gas properties in galactic-size and group-size haloes in TNG50 are in good agreement with observational constraints\(^\text{10,11}\) and may therefore provide a solid theoretical ground to study environmental effects in our UDG sample.

The stellar mass for the lenticular galaxy NGC 1211 was estimated from its V-band luminosity in ref. \(^\text{18}\) and assuming a mass-to-light ratio of 1 for simplicity.

### Sample of field UDGs

The criterion to define UDGs varies across different works in the literature. Here we define UDGs as the most extended outliers of the stellar mass–size relation, following the philosophy introduced in ref. \(^\text{18}\). The galaxy modelling used in the TNG100 and TNG50 simulations has been shown to agree well with observational constraints on the stellar mass–size relation of the galaxy population. In this work, we construct the mass–size relation using well-resolved galaxies, defined as those with dark matter mass $m_{\text{halo}} \geq 5 \times 10^{10} M_\odot$ (with total dark matter mass assigned by SUBFIND to each subhalo), stellar mass $M_\star \geq 5 \times 10^9 M_\odot$ and size $r_e \geq 0.3$ kpc; this results in a minimum number of ~60 stellar particles and 110 dark matter particles.

Figure 1 shows the stellar mass–size relation, where the median of fixed $M_\star$ is indicated by the thick black line. We notice that for log($M_\star/M_\odot$) $> 7.5$ the median starts to steadily increase towards lower-mass objects, an effect not found in observation and of origin likely numerical. To be conservative, we study only dwarf galaxies in the stellar mass range log($M_\star/M_\odot$) = [7.5, 9]. More than 8,600 dwarf galaxies in TNG50 satisfy this mass cut. The distribution of sizes at a given stellar mass is approximately log-normal. We therefore select the 5% most extended outliers at fixed $M_\star$ as our UDG population, deeming all galaxies within the 5th to 95th percentile range to be ‘normal’ galaxies. This results in an average half-mass radius of 2.3 $\pm$ 0.8 kpc for our UDG population. From the UDGs identified in this way, 176 are centrals to their haloes (or ‘field’ population) and constitute the sample analysed here (the study of UDGs as satellites is presented elsewhere by J.A.B. et al., manuscript in preparation). Figure 1 shows that our definition for UDG galaxies is in very good agreement with several observational samples of star-forming and quenched UDGs in low-density environments\(^\text{24,25}\).

### Visualizations

Images shown in Fig. 3 were made using the Py-SPHViewer code\(^\text{16}\), v1.0.0. This code smooths the particle information into two-dimensional histograms to reflect the underlying continuous density field. For the specific case of the small panels in Fig. 3b, we combined the information from the gas cells (blue hues) and the stellar particles (red). Each stamp has 150 $\times$ 150 pixels, and we use 12 neighbours for the smoothing. We use all gas or stellar particles identified to belong to this subhalo by SUBFIND that are within the image box (12 kpc) (physical) on a side. For Fig. 3c, we use the x and y coordinates of each subhalo in the halo catalogue. The image is smoothed using a three-neighbour kernel density estimation and has 1,000 $\times$ 500 pixels.

### Data availability

This letter is based on snapshots, subhalo catalogues and merger trees from the cosmological hydrodynamical TNG50 simulation\(^\text{15}\) of the IllustrisTNG project\(^\text{14,15}\). These data are publicly available at https://www.tng-project.org/. ASCII tables with the simulation data for our sample of UDGs in Figs. 1, 2 and 4 are available in the public repository https://github.com/josegit88/public_data_files/tree/main/ascii_files_isolated_UDGs_TNG50. Source data are provided with this paper.

### Code Availability

Scripts used for reading of and access to the snapshot, merger trees and subhalo data are publically available at the TNG database. Visualizations were made using the publicly available Py-SPHViewer code\(^\text{16}\). Any correspondence and/or request for materials pertaining to this manuscript should be directed to J.A.B.

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**Author contributions**

The listed authors made substantial contributions to this manuscript; all co-authors read and commented on the document. J.A.B. led the analysis of the simulation, compiled observational data from the literature and made all figures. L.V.S. and M.G.A. are responsible for the original idea and mentorship of J.A.B. throughout the project. L.V.S. led the writing of the manuscript and the response to the referee report with substantial contributions from J.A.B., M.G.A., A.P., D.N., F.M. and L.H. Co-author M.C. provided the expertise on the observational consequences of the results and on the study of quenching of dwarf galaxies. A.P., D.N., F.M., R.P., P.T., M.V. and L.H. are core members of the TNG50 simulation who set up, developed and ran the simulation that this manuscript is based on.

**Competing interests**

The authors declare no competing interests.

**Additional information**

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