Anisotropic satellite galaxy quenching modulated by black hole activity

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The evolution of satellite galaxies is shaped by their constant interaction with the circumgalactic medium surrounding central galaxies, which in turn may be affected by gas and energy ejected from the central supermassive black hole1–6. The nature of such a coupling between black holes and galaxies is, however, much debated7–9 and observational evidence remains scarce10,11. Here we report an analysis of archival data on 124,163 satellite galaxies in the potential wells of 29,631 dark matter halos with masses between 10^{12} and 10^{15} solar masses. We find that quenched satellite galaxies are relatively less frequent along the minor axis of their central galaxies. This observation might appear counterintuitive given that black hole activity is expected to eject mass and energy preferentially in the direction of the minor axis of the host galaxy. We show, however, that the observed anisotropic signal results precisely from the ejective nature of black hole feedback in massive halos, as outflows powered by active galactic nuclei clear out the circumgalactic medium, reducing the ram pressure and thus preserving star formation in satellite galaxies. This interpretation is supported by the IllustrisTNG suite of cosmological numerical simulations, even though the model’s sub-grid implementation of black hole feedback is effectively isotropic12.

We use catalogues of groups and clusters13 to identify satellite galaxies in the Sloan Digital Sky Survey (SDSS)4 data. For each satellite, its star-formation rate (SFR) and stellar mass are measured15,16 (see Methods for details). We proceed to characterize how satellites are distributed around their central galaxies in the plane of the sky. As shown in Fig. 1, the orientation of a given satellite galaxy can be defined as the difference between the photometric position angle (PA) of the central galaxy’s major axis and the PA of the satellite with respect to the central. We retrieve the PA of the central galaxy’s major axis from the SDSS imaging pipeline17 and we use sky coordinates to measure the PA between central galaxies and satellites. We note that a galaxy does not need to be late-type or disk-shaped for a major axis to be defined, and in fact the great majority of the central massive galaxies in our SDSS sample are ellipticals. With this definition, a satellite located along the major axis of its central galaxy would have an orientation equal to 0° (or 180°/360°) and, conversely, a satellite located along the minor axis would have an orientation of 90° (or 270°).

Given this metric for the angular distribution of satellite galaxies and the ancillary SFR and stellar mass measurements, Fig. 2 presents our main results. Figure 2a shows how the fraction of quiescent satellites depends on their orientation with respect to the central galaxy. Each point indicates the fraction of quiescent galaxies among all satellites observed in a given orientation bin, regardless of the properties of the hosting halo. In practice this means that every group and cluster in our sample can contribute to each data point, depending on the location of its satellites. It is evident that the fraction of quiescent satellites is maximal along the major axis of the central galaxy and minimal along the minor axis. To assess the significance of this modulation quantitatively, we fit the observed signal with a cosine function with three free parameters: the median quiescent fraction, the amplitude of the modulation, and a re-scaling of the assumed error to account for any source of uncertainty. The modulation is well represented by a cosine function with an amplitude of 0.025 ± 0.001 on top of a 0.421 ± 0.001 average quiescent fraction. Complementarily, Fig. 2b shows the iso-quiescent fraction contour (f_q = 0.42, the average of our sample) as a function of cluster-centric distance (normalized to the virial radius) and orientation angle. Along the major axis of the central galaxy, satellites are preferentially quenched at larger cluster-centric distances, whereas satellites located in the direction of the minor axis survive in relatively larger numbers as star-forming objects up to much closer distances. Importantly, both panels in Fig. 2 are obtained by stacking every group and cluster in our sample into a single pseudo-cluster, where the major axis of every central galaxy is aligned in the same direction. Moreover, in principle, the signal should be fully symmetrical around the 0°–90° range.

We have tested that this anisotropic modulation in the fraction of quiescent satellites is statistically robust and exhibits a number of interesting features. As noted above, the significance of a positive amplitude is well beyond 3σ (0.025 ± 0.001). Moreover, if we randomize the PA of each central galaxy and we measure again the amplitude of the signal, we find in this case no modulation at all. At the same time, the signal is also robust against the assumed functional form for the surface brightness distribution while measuring the PA of the central...
galaxy. The results shown in Fig. 2 are thus robust and truly dependent on the orientation of satellites. We also find that the amplitude of the signal increases for more massive central galaxies and for less massive satellites. Moreover, the signal becomes stronger for satellites closer to the centre of their host halo. Interestingly, the signal also depends on the mass of the black hole in the centre of a halo: at fixed halo mass, the amplitude of the observed signal is stronger if the black hole hosted by the central galaxy is more massive. All these additional tests are presented in the Methods section.

To investigate the origin of the modulation, we make use of the IllustrisTNG suite of cosmological numerical simulations18, where we find a similar behaviour in the fraction of quiescent satellites. Figure 3 is based on the outcome of the TNG100 run, using high-realism synthetic SDSS-like images19 to measure the central galaxies' PA. As in the SDSS data, the signal can be modelled by a cosine function with an amplitude of 0.032 ± 0.004. We note that the selection function of SDSS satellites suffer from observational biases and completeness issues caused by, for example, fibre collisions. Hence, the absolute fraction of quiescent fractions might differ between SDSS and TNG10020, particularly in groups and clusters. Therefore, in Fig. 3 we have subtracted the average quiescent fraction of both datasets. Furthermore, we have verified that the signal is in place in IllustrisTNG irrespective of whether the photometric PA or the intrinsic stellar angular momentum of the central galaxies are used to identify their major axes.

Two classes of distinct evolutionary mechanisms may be at the origin of the anisotropic distribution of quiescent satellites around central galaxies that we observe both in the SDSS data and in the IllustrisTNG cosmological numerical simulation.

First, this could be the manifestation of a large-scale structure phenomenon, whereby satellites in groups and clusters form and evolve under different conditions than those in the field even before falling into the primary halos and thus, their properties and distribution could be affected by processes unrelated to their current group/cluster environment21. Second, this could be the result of a (host) halo phenomenon, that is, emerging because of the very interaction between satellite galaxies and their host halo. This could be, for example, due to energetic feedback from, for example, the supermassive black holes that reside at the centre of massive halos, which in turn can have an impact beyond the central galaxy itself, modulating also the evolution of the surrounding satellites22 through the alteration of the physical properties of the intra cluster/group medium.

To test these two scenarios, we compare the signal measured in IllustrisTNG and shown in Fig. 3 with the signal measured from the previous generation of Illustris cosmological simulation23. For the purposes of this work, the most noticeable difference between these two simulations is that IllustrisTNG includes an improved treatment of active galactic nuclei feedback, in particular in the low accretion rate regime3,12. Thus, by comparing the two simulations, we are controlling for large-scale structure effects, isolating the role of black hole feedback in shaping the observed signal. We find that the modulation in the quiescent fraction differs between the two simulations, being larger in IllustrisTNG (see Methods). For the first Illustris simulation, results are actually consistent with no modulation at a -2σ level (0.013 ± 0.07).

**Fig. 1** Orientation of satellite galaxies around central galaxies. For a given dark matter halo with a central galaxy, we define the orientation of each satellite as the difference between the PA of the central galaxy’s major axis and the PA of the satellite with respect to the central galaxy, as indicated. A satellite located along the major axis of the central galaxy would have an orientation of 0° (or 180°/360°); conversely, a satellite located along the minor axis would have an orientation of 90° (or 270°).

**Fig. 2** Anisotropic distribution of quiescent satellite galaxies in SDSS. 

The fraction of quiescent galaxies depends on their orientation with respect to the central galaxy’s major axis. Quiescent galaxies are relatively enhanced along the direction of the major axis and conversely, relatively deficient in the direction of the minor axis. The signal is well represented by a cosine function with an amplitude of 0.025 (black solid line), and the shaded area represents the 1σ confidence interval (±0.001). Error bars represent the best-fitting standard deviation, as described in the Methods. 

**b** Iso-quiescent fraction (f_q = 0.42)
acting far beyond the extension of the central host galaxy. This is an observable manifestation of active galactic nuclei (AGN) feedback. Pre-processing) and by the star-forming population of satellite galaxies. Furthermore, within the IllustrisTNG galaxy population, the anisotropic behaviour in the distribution of quiescent galaxies is driven by satellites that quenched within their current host halo (that is, were not quenched before infall owing to, for example, pre-processing) and by the star-forming population of satellite galaxies. We therefore conclude that the anisotropic behaviour in the distribution of quiescent galaxies is a host halo phenomenon and, in particular, an observable manifestation of active galactic nuclei (AGN) feedback acting far beyond the extent of the central host galaxy. This AGN-driven origin is particularly supported by the reported connection between the amplitude of the signal and the mass of the central black hole in the observed data, and more explicitly by the relation between energy injection and signal modulation in the simulations. Additionally, in both SDSS and IllustrisTNG data, the anisotropic quenching signal is stronger around quiescent rather than star-forming central galaxies, further suggesting a connection to the activity of the supermassive black holes at the centres. Moreover, it is consistent with our analysis of the IllustrisTNG sample, where, in the explored halo mass range, most satellite galaxies become quiescent after infalling in their current halo and the anisotropic signal in the simulation is dominated by such galaxies. Furthermore, AGN feedback is expected to affect more prominently the halo gas in the vicinity of the centre, and in the SDSS data we find that satellites at smaller galactocentric distances exhibit a larger anisotropic modulation of quiescence.

The relative lower fraction of quiescent satellites along the minor axis of central galaxies and its relation with AGN feedback may at first seem counterintuitive because the energy and mass radiated by AGN activity are expected to escape the central galaxy preferentially along that direction. However, we argue that it is precisely the ejection of energy along the minor axis that drives the observed signal, as AGN feedback carves low-density bubbles in the circumgalactic medium (CGM) surrounding the central galaxy. This is exemplified in Fig. 4, where we show how the average mass density of the CGM around central galaxies in IllustrisTNG displays exactly such anisotropic behaviour, despite the fact that feedback processes are isotropic at the scale of energy injection. The interaction of the outflows with the galactic gas and the inner CGM is also likely to be responsible for the observed geometry, as the outflowing gas would tend to follow the path of least resistance, decoupled from the direction of energy injection at the smallest scales. This is supported by the fact that in the IllustrisTNG simulations, energy injection from supermassive black holes does not have a preferred direction, and yet outflows appear to be bipolar on large scales. In any case, the anisotropic distribution of the CGM around central galaxies shown in Fig. 4, a direct IllustrisTNG prediction for the proposed scenario, should be observable in X-rays with sufficient statistics. All our findings support the idea that it is the interaction between satellites and the CGM, in turn modulated by AGN activity, that drives the observed signal. We suggest that, as satellite galaxies pass through these low-density regions, processes directly responsible for their quenching, such as ram pressure stripping, become less efficient, increasing the relative abundance of star-forming galaxies along the direction of the minor axis. This interpretation is consistent with our observations. 

![Fig. 3 SDSS versus IllustrisTNG.](image)

**Fig. 3 | SDSS versus IllustrisTNG.** Black symbols and lines are the SDSS observed data as in Fig. 2. Green symbols show the anisotropic distribution of quiescent satellites as measured in the IllustrisTNG 100-Mpc volume cosmological numerical simulation (TNG100). In the latter the amplitude (0.032) is similar to that observed in SDSS, and the green shaded area indicates the 1σ confidence interval (±0.004). Error bars represent the best-fitting standard deviation, as described in the Methods. Since the absolute fraction of quiescent galaxies may differ between observed and simulated data, the mean quiescent fraction is subtracted from both datasets. Owing to the lower number of satellites, IllustrisTNG measurements correspond only to the 0–180 interval. To show them together with the SDSS data we have assumed that the 180–360 interval behaves exactly like the 0–180 interval.

Furthermore, within the IllustrisTNG galaxy population, the anisotropic signal is driven by satellites that quenched within their current host halo (that is, were not quenched before infall owing to, for example, pre-processing) and by the star-forming population of satellite galaxies. (see Methods).

We therefore conclude that the anisotropic behaviour in the distribution of quiescent galaxies is a host halo phenomenon and, in particular, an observable manifestation of active galactic nuclei (AGN) feedback acting far beyond the extension of the central host galaxy. This AGN-driven origin is particularly supported by the reported connection between the amplitude of the signal and the mass of the central black hole in the observed data, and more explicitly by the relation between energy injection and signal modulation in the simulations. Additionally, in both SDSS and IllustrisTNG data, the anisotropic quenching signal is stronger around quiescent rather than star-forming central galaxies, further suggesting a connection to the activity of the supermassive black holes at the centres. Moreover, it is consistent with our analysis of the IllustrisTNG sample, where, in the explored halo mass range, most satellite galaxies become quiescent after infalling in their current halo and the anisotropic signal in the simulation is dominated by such galaxies. Furthermore, AGN feedback is expected to affect more prominently the halo gas in the vicinity of the centre, and in the SDSS data we find that satellites at smaller galactocentric distances exhibit a larger anisotropic modulation of quiescence.

The relative lower fraction of quiescent satellites along the minor axis of central galaxies and its relation with AGN feedback may at first seem counterintuitive because the energy and mass radiated by AGN activity are expected to escape the central galaxy preferentially along that direction. However, we argue that it is precisely the ejection of energy along the minor axis that drives the observed signal, as AGN feedback carves low-density bubbles in the circumgalactic medium (CGM) surrounding the central galaxy. This is exemplified in Fig. 4, where we show how the average mass density of the CGM around central galaxies in IllustrisTNG displays exactly such anisotropic behaviour, despite the fact that feedback processes are isotropic at the scale of energy injection. The interaction of the outflows with the galactic gas and the inner CGM is also likely to be responsible for the observed geometry, as the outflowing gas would tend to follow the path of least resistance, decoupled from the direction of energy injection at the smallest scales. This is supported by the fact that in the IllustrisTNG simulations, energy injection from supermassive black holes does not have a preferred direction, and yet outflows appear to be bipolar on large scales. In any case, the anisotropic distribution of the CGM around central galaxies shown in Fig. 4, a direct IllustrisTNG prediction for the proposed scenario, should be observable in X-rays with sufficient statistics. All our findings support the idea that it is the interaction between satellites and the CGM, in turn modulated by AGN activity, that drives the observed signal. We suggest that, as satellite galaxies pass through these low-density regions, processes directly responsible for their quenching, such as ram pressure stripping, become less efficient, increasing the relative abundance of star-forming galaxies along the direction of the minor axis. This interpretation is consistent with our observations. 

![Fig. 4 Anisotropic CGM density in IllustrisTNG.](image)

**Fig. 4 | Anisotropic CGM density in IllustrisTNG.** a. The mean relative gas overdensity changes as a function of orientation for central galaxies in the TNG100 simulation with stellar masses around the median of our SDSS sample ($M_{cen} = 10^{10.8} M_\odot$). Error bars represent the best-fitting standard deviation, as described in the Methods. Averaged within the virial radius, the relative gas overdensity exhibits a behaviour similar to that measured for the fraction of quiescent galaxies in Fig. 2, because the circumgalactic medium gas density is relatively lower along the minor axis of central galaxies. b. A stacked average image of the gas overdensity (relative to its azimuthal average) over the same mass range, with the iso-quiescent fraction contour of Fig. 1 overlaid in white. For reference, the size of the average virial radius is also indicated (dashed grey circle).
analysis of the SDSS data, as ram pressure stripping is expected to affect low-mass satellites hosted by more massive central galaxies more severely, as indeed is observed. We cannot in fact exclude a different scenario, whereby the star-formation activity of the satellites is enhanced rather than their quenching suppressed; it is possible that star-formation is enhanced along the outflowing material, further increasing the fraction of star-forming satellites in the direction of the minor axis.

Online content
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**Methods**

**Sample properties**

**Sloan Digital Sky Survey data.** Galaxy groups and clusters are selected\(^\star\) from the Tenth Data Release of the Sloan Digital Sky Survey\(^4\). For each group and cluster, the Navarro–Frenk–White\(^3\) mass of the dark matter halo is provided, along with an estimation of the virial radius. In addition, the catalogue also contains a list of satellites and identifies the central of each halo. We cross-match this catalogue of groups and clusters with a catalogue of SFR\(^3\) and stellar mass\(^1\) measurements, also based on spectro-photometric data from the SDSS. This matching of catalogues provides a final sample of 124,165 satellites with stellar masses in the range \(M_*=10^{9.5} - 10^{11} \, M_\odot\), associated with 29,631 galaxy groups and clusters, hosted in halos with masses ranging from \(M_{\text{halo}} \approx 10^{13} \, M_\odot\) to \(M_{\text{halo}} \approx 10^{15} \, M_\odot\), and with central galaxy mass in the range \(M_*=10^{8} - 10^{10} \, M_\odot\), at a median redshift of \(z=0.08\). The typical distance of satellites with respect to central galaxies ranges from around 50 kpc to 900 kpc. No cuts were imposed on the basis of the b/a axis ratios of central galaxies. The separation between star-forming and quiescent satellites is based on their location with respect to the star-formation main sequence. In particular, we find that the star-formation main sequence in our sample of satellites is well fitted\(^3\) by \(\log \text{SFR} = 0.7 \log M_* - 7.5\). As described in the main text, given this definition of the star-formation main sequence and having stellar masses and SFR measurements for each satellite, we label as star-forming any satellite departing less than 1 dex from the star-formation main sequence. Conversely, a satellite is labelled as quiescent if its SFR is below the star-formation main sequence by more than 1 dex. To define the orientation of a satellite (see Fig. 1) the PA of the central galaxy's major axis has to be estimated. Thus, for each central galaxy in our sample, we use photometric information retrieved from the SDSS imaging pipeline\(^3\). Since two measurements of the PA are given, depending on whether the central galaxy is better fitted by an exponential or a de Vaucouleurs\(^\star\) profile, we choose the parametrization with the highest likelihood given by the \(\text{IntExp}\) (exponential) or \(\text{IntDev}\) (de Vaucouleurs) keywords. To increase the robustness of the assumed quantities, we average likelihoods and PA over the g, r, and i bands.

**IllustrisTNG simulation data.** We focus our analysis of the IllustrisTNG cosmological magnetohydrodynamical simulations on the 100 Mpc volume run, known as TNG100, for which synthetic SDSS-like images and photometric measurements have been made in a forward-modelling fashion\(^\star\). In particular, for simulated galaxies with stellar mass above \(M_* = 10^{10} M_\odot\), we generate a SDSS-like synthetic image using the SKIRT radiative transfer code\(^3\) and perform a two-dimensional Sérsic fit using the \texttt{starmorph} code\(^\star\). We then use the best-fitting PA in the same way as in the SDSS data. This approach has two main advantages. First, image fitting is done on the projected \(X-Y\) plane of the simulation, which naturally emulates the distribution of orientations expected for central galaxies in the SDSS data. Second, a Sérsic fit generalizes the exponential and de Vaucouleurs profiles used in the SDSS imaging pipeline, ensuring a relatively fair comparison between observations and simulations. Images were synthesized using the snapshot 99 corresponding to redshift \(z=0\) and we adopt the same metric and definition of quiescent and star-forming as in the SDSS data: note that the star-formation main sequence of TNG100 is consistent with observational constraints at low redshifts\(^\star\).

Flagging out those central galaxies with unsuccessful Sérsic fits, we make use of a total of 880 halos (and central galaxies) in the host halo mass range of \(M_{\text{halo}} = 10^{12} - 10^{14} M_\odot\) and of 8,552 satellites with stellar masses ranging from \(M_* = 10^{9} M_\odot\) to \(M_* = 10^{10} M_\odot\). At the resolution of TNG100, the less massive satellites would contain on the order of about 100 stellar particles\(^\star\). For central galaxies, stellar masses range from \(M_* = 10^{8} M_\odot\) to \(10^{10} - 10^{12} M_\odot\). Details on galaxy and halo identification can be found in the IllustrisTNG presentation papers\(^3\). Despite the large cosmological volume of 100 Mpc, the number of objects is substantially lower than in SDSS, although enough to reveal the presence of a modulation in the number of quiescent satellites (see Fig. 3).

It is worth emphasizing that the goal of comparing SDSS and IllustrisTNG data are to understand the origin of the observed modulation in the fraction of quiescent galaxies, and not to provide an even-handed comparison between observed and simulated properties of galaxies in absolute terms: previous work has shown that the IllustrisTNG galaxy population is in good agreement with SDSS results, for example, in terms of galaxy colours, global and small-scale stellar morphologies, SFRs and quenched fractions\(^3\). In particular, the IllustrisTNG outcome is in striking quantitative agreement in comparison to SDSS data (differences smaller than \(<5\%\) percentage points) for global central and satellite quenched fractions at \(z=0.1\) and, in terms of satellite quenched fractions as a function of halo-centric distance, for intermediate, group-mass scale hosts \((10^{13} - 10^{14} M_\odot))\), which dominate the host mass distribution of both the SDSS and IllustrisTNG samples adopted here. We rely on those findings in choosing IllustrisTNG as our simulation counterpart. At the same time, we note that an exact matching between the SDSS and IllustrisTNG samples is not critical for the purpose of this work, as we are able to obtain insights by focusing on the relative effects of the satellite locations and by marginalizing over the possibly different absolute fractions of quiescent galaxies. On the other hand, exactly matching the galaxy samples would lead to an even lower number of available satellites, hampering the reliability of the comparison.

**Signal characterization**

In this section we detail the most meaningful tests done, both in the observed and simulated galaxy datasets, to understand the origin of the observed modulation in the number of quiescent satellites.

**Fitting the observed signal.** With no other motivation than quantifying the angular dependence of the fraction of quiescent galaxies, we fit the observed signal with a cosine function. In practice, we use a Bayesian Markov chain Monte Carlo sampler\(^3\) to evaluate the following likelihood function

\[
\ln p(f_q | \theta, a, b, f) = - \frac{1}{2} \sum_i \left[ \frac{(f_{q,i} - a - b \cos 2 \theta_i)^2}{s_i^2} + \ln(2\pi s_i^2) \right],
\]

where \(f_{q,i}\) is the observed fraction of quiescent galaxies at the \(\theta_i\) orientation, \(a\) is the median quiescent fraction, and \(b\) is the amplitude of the modulation. The error term is given by \(s_i^2 = \sigma^2 + f^2\), where \(\sigma\) is the estimated error, in our case estimated by bootstrapping, and \(f\) is the re-scaling term.

This Bayesian framework allows us to explore the full posterior distribution and to naturally test the null hypothesis (that is, is the signal consistent with an amplitude equal to zero?). In Extended Data Fig. 1 we show the posterior distribution for the best-fitting solution of the SDSS data (Fig. 2). With these assumptions, we can reject the null hypothesis at a \(-6\sigma\) level.

We note that error bars shown in all figures represent the combined \(\sigma^2 + f^2\) uncertainty, and, for practical reasons, we fit for logarithmic re-scaling of the error \(\ln f\). The inclusion of this additional error term \(f\) allows us to account for the various sources of error that might affect the observed data, such as the uncertainty on the estimated PA of the central galaxy, on the stellar mass and SFR measurements of the satellites, and on their stochastic distribution around central galaxies.

**Robustness of the signal against the assumed PA.** Since the orientation of satellites strongly depends on the assumed PA of the central galaxy, we test the robustness of our results against errors and
systematics on the PA determination. First, we test the sensitivity of the observed signal to the functional form assumed for the surface brightness distribution of central galaxies. This is motivated by the fact that the light profile of galaxies is not accurately fitted by either a single exponential or de Vaucouleurs function as assumed by the SDSS photometric pipeline. Similarly to Fig. 2, Extended Data Fig. 2a shows the modulation in the fraction of quiescent satellites, but this time intentionally assuming the worst-fitting functional form according to SDSS. For example, if the SDSS photometric pipeline indicates that a galaxy is better fitted by an exponential profile, we selected the PA derived using a de Vaucouleurs, and vice versa. As becomes obvious from Extended Data Fig. 2a, the observed modulation in the fraction of quiescent satellites is insensitive to the functional form used to fit the brightness profile of the central galaxy.

Additionally, we also test whether errors in the determination of the central galaxy’s PAs could have a large impact on the observed signal. This is done by perturbing the PA of each central galaxy by a factor ΔPA, drawn from a normal distribution N(0, ΔPA). By doing this we practically investigate the effect that a typical error of ΔPA would have on the recovered signal, as shown in Extended Data Fig. 2b. For errors on the individual PAs of up to 30°, there is still a clear modulation in the fraction of quiescent satellites. We note that the expected typical error in our sample of galaxies40 is of the order of around 2°, an order of magnitude smaller than the extreme test shown in Extended Data Fig. 2. Hence, we conclude that systematics and uncertainties related to the PA measurements based on the available photometric data in our sample of SDSS galaxies do not substantially affect our findings and thus our conclusions. For illustrative purposes, Extended Data Fig. 2c, d show examples of galaxies with de Vaucouleurs and an exponential light profiles, respectively. The uncertainty in the assumed PA is indicated with the white dashed area.

As a final test, we repeated our analysis but completely randomizing the PA of each central galaxy. In this case, the orientation of satellites becomes meaningless and therefore it is expected that the signal disappears. This is indeed the case as shown in Extended Data Fig. 3a. Extended Data Fig. 3b shows the posterior distribution, demonstrating that the amplitude of the signal vanishes when the central galaxies’ PAs are randomized.

**Dependence on galaxy properties in SDSS data.** The large number of objects in the SDSS sample of satellites allows us to investigate the dependence of the observed signal on different properties of central galaxies and satellite galaxies. Extended Data Fig. 4 summarizes the more meaningful trends we find in the SDSS dataset. In particular, in Extended Data Fig. 4a we split our sample into satellites close to the centre of their halos/central galaxies (Rsat < 0.5Rvir) and satellites farther out from the centre (Rsat > 0.5Rvir). Here Rsat is the distance of a satellite to the central galaxy in units of the virial radius of the cluster, Rvir. For those satellites closer to the centre we find an amplitude of 0.038 ± 0.002 in the modulation of the signal, while for those in the outskirts the modulation is weaker, with an amplitude of 0.023 ± 0.002.

In addition, we also looked at how the amplitude of the signal changes with the mass of the central galaxy, illustrated in Extended Data Fig. 4b. It is clear from this panel that the signal is stronger for satellites orbiting more massive central galaxies (logM* > 11M☉), with an amplitude of 0.024 ± 0.002 compared to what is observed for halos with a lower mass central (logM* < 11M☉), where the amplitude is 0.007 ± 0.002. (Here M* is the stellar mass of the central galaxy.) The opposite behaviour is, however, observed when splitting our sample according to the mass of the satellites, as demonstrated in Extended Data Fig. 4c. Interestingly, the modulation of the signal is stronger for lower-mass satellites (logM* < 10.5M☉) with an amplitude of 0.027 ± 0.002. The amplitude measured for higher-mass satellites (logM* > 10.5M☉) is 0.014 ± 0.002.

Here we also demonstrate what is mentioned in the main text, namely that the strength of the observed modulation correlates with the (relative) mass of the supermassive black hole hosted by the central galaxy; see Extended Data Fig. 4d. Following previous work41, black hole masses are estimated using the empirical M* – σ relation42, and the stellar velocity dispersion of each central σ is measured using the available SDSS spectroscopic data. (Here M* is the black hole mass, that is, the empirical relation between the stellar velocity dispersion of galaxies and the mass of the central supermassive black holes.) At fixed halo mass, the amplitude of the observed signal is higher for those halos with a over-massive black hole in their centres (0.028 ± 0.002). For halos hosting under-massive black holes, the observed amplitude in the signal is 0.016 ± 0.002. The expected uncertainty in these black hole mass estimates is of about 0.3 dex owing to the intrinsic scatter in the M* – σ relation43. In individual galaxies, this over-massive versus under-massive black hole metric has now been widely used to probe the interplay between black hole activity and star formation44–48, further supporting a black hole-related origin for the observed signal. For completeness, Extended Data Fig. 4e–h shows the same analysis as in Extended Data Fig. 4a–d but without removing the offset between the different sub-samples.

**Additional metrics for the satellite star-formation properties.** Although we have focused mostly on the fraction of quiescent galaxies as a proxy for the properties of the satellite populations, alternatives measurements can be explored that could provide further insights on the origin of the signal. For example, the mean specific SFR at each orientation, or the average distance of satellites with respect to the star-formation main sequence provide a less bimodal and more continuous characterization of the satellite population. The behaviour of these two quantities is shown in Extended Data Fig. 5, and also exhibits the characteristic modulation reported for the fraction of quiescent galaxies. The consistency between Extended Data Fig. 5 and the trend shown in Fig. 2 is an additional proof of the robustness of our results.

**Residual dependencies.** We have shown how the observed modulation in the fraction of quiescent satellites is stable and well behaved. However, its peak-to-peak variation is only about 5%, smaller than the expected change in the quiescent fraction when, for example, varying halo mass or cluster-centric distance. Thus, we also explored whether the modulation could arise from variations in these properties. This was done by first, characterizing the dependence of the quiescent fraction on Rvir and Rsat with a quadratic polynomial fit. Then, we use these fits to estimate the amplitude of the signal that would result from a variation in halo mass or cluster-centric distance with orientation. The result of these tests is shown in Extended Data Fig. 6.

For both halo mass and average radial distance we find subtle trends with orientation, but at a level much lower than it would be required to explain the modulation shown in Fig. 2. In particular, the average halo mass along the minor axis tends to be slightly higher (0.05 dex) than along the major axis. Because more massive halos tend to host more massive galaxies, the observed variation in halo mass would lead to a variation in the fraction of quiescent satellites of 0.005 ± 0.0001, much smaller than what is observed. Once corrected for halo mass, no other secondary trends are found. Regarding the typical radial distance, satellites along the minor axis are marginally farther away from the central that along the major axis. In this case the variation is even weaker than for the halo mass, with a best-fitting amplitude of only −0.0002 ± 0.00005.

**Radial behaviour.** Figure 2b demonstrates that the observed signal is radially well behaved, as it allows us to measure the contours of iso-quiescent fractions. For simplicity, Fig. 2 only shows one isocountour, but this idea can be further applied to different thresholds. In Extended Data Fig. 7 we show these contours at three different levels f0 = |0.36, 0.42, 0.48|. 
**Illustris versus IllustrisTNG simulation comparison.** As an additional way to investigate the origin of the observed signal, Extended Data Fig. 8 illustrates how the outcomes of the IllustrisTNG and Illustris cosmological numerical simulations compare. To marginalize over the possible differences in the overall quenching of galaxies between IllustrisTNG and Illustris, here we also subtract the average quiescent fraction of both datasets.

As mentioned in the text, the TNG100 run of the IllustrisTNG series and the Illustris simulations both sample an approximately similar cosmological volume of 100 comoving megaparsecs: they in fact evolve the same initial conditions—but for small variations in the values of the adopted cosmological parameters—and have been performed at very similar numerical resolution. Illustris and IllustrisTNG differ in certain aspects of the underlying galaxy formation model\(^3\). In addition to an accurate treatment of the magneto-hydrodynamics within the simulation, IllustrisTNG improves upon the original Illustris galaxy formation model on three fronts (see section 2.3 in ref. \(^3\)): chemical enrichment, galactic winds and black hole feedback. The first one is unrelated to the topic of this work and the physical functioning of the stellar feedback under the form of galactic winds is similar albeit not identical in the two models. On the other hand, different mechanisms are invoked and implemented for the feedback from the super massive black holes in the two models, specifically at low accretion rates\(^1\). In particular, in both Illustris and IllustrisTNG, supermassive black hole feedback is implemented by invoking three mechanisms\(^2\): thermal energy injection at high mass accretion rates, mechanical feedback at low mass accretion rates, and a sort of radiative feedback where gas cooling is further modulated by the radiation field of nearby AGNs. The two simulation models differ substantially only in the way the mechanical, low-accretion rate channel functions\(^2\): in IllustrisTNG, kinetic energy is injected into the surrounding gas as a pulsed wind, oriented in a different random direction at each supermassive black hole timestep, and thus is isotropic when averaged across any cosmological timescale of relevance; in contrast, in Illustris, thermal energy is injected in a highly burst-like fashion into about 50–100 kpc bubbles of gas at distances of a few tens to hundreds of kiloparsecs from the central galaxy. These differences—whereby, in one case, AGN feedback affects gas at large radii rather than acting directly from the innermost regions of galaxies as in the case of IllustrisTNG—result in important changes not only in the onset of galaxy quenching in central galaxies\(^2,30\) but also in the properties of the circumgalactic medium (for example, gas density)\(^2,28,30,41\). This implies that, in practice, by comparing Illustris and IllustrisTNG in Extended Data Fig. 8, we are effectively testing and varying the effects of different black hole feedback mechanisms on the satellite population.

For the blue curve in Extended Data Fig. 8, Illustris galaxies are considered within similar ranges of host halo mass, and stellar mass of satellites and central galaxies as for the TNG100 sample (red curve). The signal is clear in IllustrisTNG, with an amplitude of \(0.032 \pm 0.004\), whereas in Illustris the signal is weaker (0.013 \pm 0.007), consistent with almost no variation. We note that, since the number of satellites in these large simulated volumes is still small compared to SDSS, we symmetrize the data along 180 and the binning is also coarser. As the assembly of the larger scale-structure is the same in the two simulations, this piece of evidence favours the proposed scenario whereby feedback from supermassive black holes is responsible for the anisotropic quenching signal, through its effects on the properties of the circumgalactic medium.

We note that since the mass function of Illustris differs from that of IllustrisTNG\(^\ast\), in principle, it is possible that the larger amplitude in IllustrisTNG is due to a bias in the mass distribution even if galaxies were selected to cover the same mass range. Green symbols in Extended Data Fig. 8 show the variation in the fraction of quiescent IllustrisTNG satellites, but intentionally selected to reproduce the stellar mass distribution of satellites in Illustris. The fact that the amplitude of this signal remains unchanged for this \(M_\ast\) matched sample suggests that a mass bias is not responsible for the differences between Illustris and IllustrisTNG.

**Ejective AGN feedback at the origin of the quenching directionality in IllustrisTNG.** In IllustrisTNG, whether a massive galaxy is quenched or not is a direct indication of the effectiveness of black hole feedback at low accretion rates\(^30\). Thus, a complementary way to assess the role of black hole feedback in shaping the observed modulation is by comparing the amplitude of the observed signal for quiescent and star-forming central galaxies at fixed stellar mass. The outcome of this comparison is shown in Extended Data Fig. 9a, for central galaxies with stellar masses of \(\log M_\ast = 10.5M_\odot\). This particular mass range is selected so that both star-forming and quiescent central galaxies are abundant enough. Owing to the additional constraints in stellar mass and SFR, the number of available satellites is rather small (typically around 100 per angular bin) and therefore the angular binning is coarser.

It is apparent from Extended Data Fig. 9 that a systematic difference exists between the amplitude of the modulation in IllustrisTNG depending on the SFR of the central galaxy, as the signal is stronger for groups and clusters with a quiescent central galaxy, vanishing for satellites hosted by star-forming central galaxies. Since quiescence in massive IllustrisTNG galaxies is the consequence of an efficient and long-lasting AGN activity, the fact that the modulation is stronger for quiescent central galaxies further supports the black-hole-related origin of the observed signal. Because of the low number of satellites in this test, however, the implications of Extended Data Fig. 9 should not be overstated.

For completeness, we also investigate whether the differences between quiescent and star-forming central galaxies shown in Extended Data Fig. 9a, is present in the SDSS observed data. As proved by Extended Data Fig. 9b, this is in fact the case for SDSS central galaxies with stellar masses of \(\log M_\ast = 10.5M_\odot\).

In IllustrisTNG, the nature of the observed signal can be also tested by looking at how it depends on the amount of energy radiated, and on the mode in which this energy was radiated. In Extended Data Fig. 10, we select for TNG100 galaxies around \(\log M_\ast = 10.5M_\odot\) and we split them into two groups, depending on the cumulative energy injected by their supermassive black holes. Extended Data Fig. 10a shows how the modulation in the quenching directionality signal is stronger for satellites around central galaxies whose black holes have injected, at a given stellar mass, more total (kinetic plus thermal) energy than the average: these results suggested by IllustrisTNG further link the observed signal with the black hole activity. Extended Data Fig. 10b shows the result of splitting central galaxies but only according to the kinetic energy injected by their black holes when accreting at low rates. In this case, the signal almost vanishes for central galaxies that have undergone a relatively low amount of kinetic energy, once again supporting the idea that the signal is due to the ejective nature of black hole feedback, at least in the IllustrisTNG model. Whether, on the other hand, implementations of thermal and radiation supermassive black hole feedback that are different from those adopted within Illustris and IllustrisTNG can reproduce the modulation of the fraction of quiescent satellites observed in SDSS remains to be determined.

Complementarily, Extended Data Fig. 10c shows the result of splitting IllustrisTNG galaxies by their relative black hole mass. As for the SDSS data (Extended Data Fig. 4d), the signal is stronger for satellites orbiting central galaxies with over-massive black holes than for central galaxies with under-massive black holes, reinforcing the proposed connection between black hole activity and the observed modulation in the fraction of quiescent galaxies.

In the observed SDSS data, the orientation angle between central and satellite galaxy is a projected one. That is, two satellites at apparently the same orientation may actually be located at a different 3D angle
with respect to the central galaxy. Thus, the true underlying modulation is expected to be higher than the observed (projected) one. To explore this effect, we make use of the three-dimensional information provided by the IllustrisTNG simulation to de-project the observed modulation in the fraction of quiescent satellites. The result of this de-projection is shown in Extended Data Fig. 10d. As expected from a three-dimensional effect such as the proposed black hole feedback mechanism, the amplitude of the signal, once de-projected, is larger than in the projected space.

Finally, it is possible to use IllustrisTNG to control for the effect of large-scale structure in driving the observed quenching directionality by separating satellite galaxies according to when and where they quenched. In particular, as stated in the main text, the observed modulation in the fraction of quiescent satellites could in principle result from processes unrelated to their \( z = 0 \) host halo (for example, pre-processing or quenching as central galaxies of a different halo). Satellite infall times have been studied for IllustrisTNG satellites and each satellite can be classified into four different groups: star-forming satellites, satellites quenched in their \( z = 0 \) host halo, pre-processed satellites (that is, quenched as satellites in a different halo), and satellites quenched as central galaxies of a different halo (before being accreted into their \( z = 0 \) host). By construction, large-scale structure effects would be responsible for regulating the properties of the two last groups (that is, pre-processed satellites and those quenched as central galaxies of a different halo), whereas black hole feedback from the central galaxy and the resulting quenching could only affect either satellites that quenched within their \( z = 0 \) host halo, as well as star-forming satellites (that is, the first two groups).

Extended Data Fig. 11a shows the number of TNG100 satellites belonging to each group as a function of orientation. It is evident from Extended Data Fig. 11 that, for the specific galaxy and host mass ranges adopted in this work, large-scale structure-sensitive satellites (red and orange symbols) are outnumbered by both star-forming, and in particular, satellites that quenched in their \( z = 0 \) host halo, and thus, large-scale effects could affect only a minority of the satellite population.

Moreover, Extended Data Fig. 11b shows the modulation in the number of quiescent satellites but only taking into account star-forming satellites and those quenched within their \( z = 0 \) host halos, compared to the signal observed for the general population of IllustrisTNG satellites. After removing from the analysis those satellites that might be sensitive to large-scale structure effects, the strength of the signal remains the same, following the same trend represented in Fig. 3 and that observed in the SDSS data. We conclude therefore that the observed modulation in the fraction of IllustrisTNG quiescent satellites is indeed a host halo phenomenon, apparently related to the activity of supermassive black holes in the centres of groups and clusters.

Data availability

All data used in this work are publicly available through the Sloan Digital Sky Survey and the Illustris and IllustrisTNG public data releases.

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Author contributions

I.M.-N. and A.P. developed the original idea and characterized the signal in the observed and simulated data. D.N. measured the gas mass density distribution in IllustrisTNG and contributed to the early development of the project. V.R.-G. generated the synthetic SDSS-like images based on IllustrisTNG data, and M.D. provided the information about the infalling time of satellites in IllustrisTNG. L.H. and V.S. contributed to the analysis and interpretation of the observed and simulated data. I.M.-N. and A.P. wrote the text, and all the co-authors contributed to refining and polishing the final manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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Extended Data Fig. 1 | SDSS posterior distributions for the best-fitting description of the angular modulation of satellite quiescence. We fit the observed data with a cosine function with three free parameters, the average quiescent fraction \( f_q \), the amplitude of the modulation, and a re-scaling term for the expected error \( f_r \). Posteriors are well behaved and allowed us to reject the null-hypothesis at a \( \sim 6\sigma \) level. Blue solid vertical lines indicate the best-fitting values and the dashed lines indicate the 1\( \sigma \) confidence interval.
Extended Data Fig. 2 | Sensitivity of the SDSS signal to PA uncertainties. 

(a) The fraction of SDSS quiescent galaxies as a function of the orientation based on the worst-fitting functional form (de Vaucouleurs versus exponential) according to the SDSS photometric pipeline. The stability of the signal demonstrates that our results are robust against the photometric fitting procedure. Error bars represent the best-fitting standard deviation, as described in the Methods. 

(b) Coloured curves indicate the best-fitting solution for SDSS data obtained while randomly perturbing the PA of the central galaxy by ΔPA. For reference, black symbols and curves are the same as in Fig. 2. A clear modulation in the fraction of quiescent galaxies is observed even for ΔPA = 30, which is an order of magnitude larger than the expected error on the individual PAs. 

(c, d) The SDSS g-band images of galaxies best-fitted by a de Vaucouleurs (top row) and an exponential profile (bottom row), with the PA uncertainty indicated by the white-shaded area. The adopted PA is indicated in the top left corner of each image.
Extended Data Fig. 3 | Test with randomized PAs. **a**, The fraction of quiescent satellites in SDSS data after randomizing the PA of the central galaxies. As expected, no signal is recovered in this case. Error bars represent the best-fitting standard deviation, as described in the Methods. **b**, The posterior distributions for this test, where the modelled amplitude is consistent with no angular variation. Blue solid vertical lines indicate the best-fitting values and the dashed lines indicate the 1σ confidence interval.
Extended Data Fig. 4 | Characterization of the SDSS signal. a, We show that the modulation in the observed signal is higher for satellites closer to the centre ($R_{\text{sat}} < 0.5 R_{\text{vir}}$, orange symbols) than for those satellites in the outskirts ($R_{\text{sat}} < 0.5 R_{\text{vir}}$, blue symbols). b, The signal is stronger for halos with more massive central galaxies ($\log M_{\text{cen}} > 11 M_\odot$, orange symbols) compared to the signal observed in halos with less massive central galaxies ($\log M_{\text{cen}} < 11 M_\odot$, blue symbols). c, Less massive satellites ($\log M_{\text{sat}} < 10.5 M_\odot$, orange symbols) exhibit a larger variation than more massive ones ($\log M_{\text{sat}} > 10.5 M_\odot$, blue symbols). d, The signal is also stronger in halos hosting more massive black holes in their centre (orange symbols), compared to those with relatively less-massive central black holes (blue symbols). Panels e–h are equivalent to panels a–d but without removing the offset between the different sub-samples.
Extended Data Fig. 5 | Alternative metrics for the characterization of SDSS satellites’ star-formation status. a, b, The modulation observed in the average specific SFR (a) and distance from the star-formation main sequence (b) of SDSS satellites closely follows that shown by the fraction of quiescent satellites in Fig. 2. Regardless of the metric used to characterize the star-formation properties of satellite galaxies, there is a clear dependence on the orientation with respect to the central galaxy. Error bars indicate the 1σ uncertainty and yellow lines mark the location of the minor and major axes.
Extended Data Fig. 6 | Additional trends with halo mass and distance in SDSS. As in Fig. 2, black symbols represent the observed modulation on the SDSS data. The blue line indicates the change in the quiescent fraction that could be expected because of the average halo mass dependence on orientation, which is much smaller than the reported one. Similarly, satellites along the minor axis are marginally closer to the central galaxy than along the major axis, leading to a negative and even weaker modulation, as shown by the red line. Error bars represent the best-fitting standard deviation, as described in the Methods.
Extended Data Fig. 7 | Iso-quiescent fraction contours. Similarly to Fig. 4, the contours of constant $f_q$ are shown, but this time at three different levels: $f_q = \{0.36, 0.42, 0.48\}$. The background image corresponds to the IllustrisTNG gas over-density and the typical virial radius in the explored halo mass range is shown as a dashed grey circle, as in Fig. 4.
Extended Data Fig. 8 | IllustrisTNG versus Illustris comparison. Modulation in the fraction of quiescent galaxies for the IllustrisTNG (namely, TNG100, red symbols) and the original Illustris (blue symbols) simulations. Error bars represent the best-fitting standard deviation, as described in the Methods. The signal is shown in green for a sample of IllustrisTNG satellites with the same mass distribution as those in Illustris, to assess the possible effect of a mass bias between the two simulations. Both simulations probe a similar ~100-Mpc comoving cosmological volume and thus share the same large-scale structure properties; the treatment of black hole growth and feedback is the most relevant difference between the two. However, it is clear that the amplitude of the modulation is much higher in IllustrisTNG (0.032 ± 0.004) than in Illustris (0.013 ± 0.007).
Extended Data Fig. 9 | Quiescent versus star-forming central galaxies in IllustrisTNG and SDSS. In a, at a fixed central stellar mass of $\log M_{\text{cen}} = 10.5 M_\odot$, the modulation in the fraction of quiescent satellites in TNG100 is shown for star-forming (blue) and quiescent (orange) central galaxies. Although there are a limited number of satellites, the modulation in the signal appears to be stronger for quiescent central galaxies than for star-forming ones. Since quiescentness in IllustrisTNG is a strong indication of an effective black hole feedback, the fact that the signal is stronger for quiescent galaxies is also an indication of the proposed AGN-related origin for the observed quenching directionality. The modulation in the fraction of quiescent satellites is shown for star-forming (blue) and quiescent (orange) central galaxies in b but this time for SDSS galaxies, again of $\log M_{\text{cen}} = 10.5 M_\odot$. The observed modulation is stronger for quiescent than for star-forming central galaxies as seen in IllustrisTNG. Solid lines and shaded areas indicate the best-fitting trends and 1σ confidence interval, respectively. Error bars represent the best-fitting standard deviation, as described in the Methods.
Extended Data Fig. 10 | Dependencies of the signal in IllustrisTNG. a, The fraction of quiescent satellites around central galaxies whose black holes have injected, relatively to their mass, more (red) and less (blue) total energy. b, Similarly, the same separation but in this case considering only the kinetic energy injected by the black holes. In both cases, the amplitude of the modulation is stronger when the total (a) and kinetic (b) energy released by the central black holes increase. Similar to Extended Data Fig. 4, panel c shows how the signal in IllustrisTNG depends on the relative mass of the central black hole, being stronger for more over-massive black hole galaxies. d, The observed signal in IllustrisTNG (red) and the de-projected signal (blue) using the underlying 3D satellite distribution. We note that in d we did not impose any cut in central stellar mass and therefore absolute values are different from the other panels. Error bars and shaded areas represent 1σ confidence intervals, and solid lines are the best-fitting solutions.
Extended Data Fig. 11 | Quenching directionality in IllustrisTNG. a, The number of TNG100 satellites in each orientation bin, depending on whether they are star-forming (blue symbols), quenched in their $z \approx 0$ host halo (green), were pre-processed and quenched in a different halo (orange), or quenched as central galaxies (red). The last two groups (red and orange symbols) are sensitive to large-scale structure effects, but correspond only to a small fraction of the total satellite population. b, The fraction of quiescent satellites as a function of orientation is shown but only for those satellites that quenched in their $z \approx 0$ host halo (green symbols). The amplitude of this modulation mimics that measured for all IllustrisTNG satellites (grey-shaded area and black line).