Destruction of the central black hole gas reservoir through head-on galaxy collisions

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A massive black hole exists in almost every galaxy. Black holes occasionally radiate a vast amount of light by releasing gravitational energy of accreting gas with a cumulative active period of only a few 10^8 yr, the so-called duty cycle of the active galactic nuclei. Many galaxies today host a starving massive black hole. Although galaxy collisions have been thought to enhance nuclear activity1,2, the origin of the duty cycle, especially the shutdown process, is still a critical issue. Here, we show that galaxy collisions are also capable of suppressing black hole fuelling, by using an analytic model and three-dimensional hydrodynamic simulations and by applying the well-determined parameter sets for the galactic collision in the Andromeda galaxy3-5. Our models demonstrate that a central collision of galaxies can strip the torus-shaped gas surrounding the massive black hole, the putative fuelling source. The derived condition for switching off the black hole fuelling indicates that a notable fraction of currently bright nuclei can become inactive, which is reminiscent of the fading or dying active nucleus phenomena6-8 that are associated with galaxy merging events. Galaxy collisions may therefore be responsible for both switching off and turning on the nuclear activity, depending on the collision orbit (head-on or far-off-centre).

Recent discoveries of very extended (radius > 10 kpc), photo-ionized regions around galaxies often show the fading or dying activity of active galactic nuclei (AGN) over ~10^7 yr (refs. 9,10). These galaxies often show kinematic signatures of outflows and morphological signatures of interacting or merging galaxies or post-merger morphologies (tidal tails). The extended structures seem to be the remnants of interacting or merging galaxies, with gas accretion activity at the massive black holes (MBHs) of the central and/or the colliding satellite galaxies11-14. These galaxies are in general radio-quiet, which undermines the possibility that the large-scale gaseous structure is jet-induced. Subsolar metal abundances (-0.5 Z⊙) are inferred from the line ratios of the gas in the outskirts of these galaxies15. The very extended emission-line regions are most likely tidal debris of galactic interactions illuminated by the past AGN; these AGN have now faded by several orders of magnitudes. The above findings hint at a negative effect on the central activity by the galaxy merger.

The study of galaxy mergers in the local Universe has advanced rapidly in recent years. In the stellar halo of the Andromeda galaxy (M31), the giant southern stream (GSS) is the most prominent tidal debris feature that originates from a past galaxy merger12. So far, gravitational N-body simulations of a central (head-on) collision between a satellite dwarf galaxy and M31 have reproduced the observed features of the GSS13-14. The systematic search for the infalling orbit and the morphology of the progenitor galaxy constrained the possible orbital parameters and physical properties of the progenitor to a narrow range15. The massive dwarf galaxy hits and blankets the galactic centre, and the MBH, originally at the centre of the progenitor, is currently wandering in the halo of M31 (refs. 16). The disk of the dwarf galaxy must have anti-clockwise rotation in the sky to reproduce the observed asymmetric feature along the eastern edge of the GSS12.

In this work, we investigate the possibility that central galaxy collisions diminish AGN activity. First, we focus on M31, which harbours a radiatively quiescent central MBH with a mass of \( M_{\text{BH}} = 1.4 \times 10^8 M_\odot \) (ref. 16) and a quite low X-ray luminosity (\( L_{\text{X}} < 10^{-15} \) times the Eddington luminosity\(^{16} \), a maximum luminosity beyond which radiation pressure will overcome gravity). The reason for its extremely low activity with respect to other inactive galaxies\(^{17} \) is still unknown. We use hydrodynamical calculations on 100 pc scales (Methods and Extended Data Fig. 1), assuming that the activity is fuelled by a torus surrounding the central MBH. We introduce a critical parameter of \( \eta = f_{\text{gas}} \times \left( M_{\text{torus}} / M_{\text{BH}} \right)^{-1} \), where \( f_{\text{gas}} \) is the gas fraction of the infalling satellite and \( M_{\text{torus}} \) is the mass of the torus gas. Given the sizes of the torus and the satellite, \( \eta \) is proportional to the gas column density ratio of the two bodies.

We display the time evolution of the torus density distribution in the meridian plane for \( \eta = 10 \) (Fig. 1, upper) and \( \eta = 100 \) (Fig. 1, lower). The gas is ablated mildly owing to Kelvin–Helmholtz instabilities. As a result, there are many small irregularities in the surface of the torus gas. As the analytic model (Methods) predicts, the torus gas is completely stripped away from the central MBH for \( \eta \geq 100 \) but survives for \( \eta \leq 10 \).

We compare the numerical results (Fig. 2a, symbols) with the analytic model predictions (Fig. 2a, curves) as a function of \( \eta \), and list the stripped fraction of the torus gas \( f_{\text{torus}} \) (Fig. 2b) (Methods). The result of the high-resolution run (1.024\(^3 \) grid points) is almost identical for the normal-resolution run (256\(^3 \) grid points), which indicates convergence with spatial resolution. A sudden change in the stripped fraction occurs within the range of 10 \( \leq \eta \leq 100 \) as predicted by the analytic model (Fig. 2a, solid curve). It implies that a large amount of the torus gas is swept out via momentum transfer when the column density of the torus gas is lower than that of the satellite galaxy (see also Extended Data Fig. 2). Although both calculations show that the essential parameter driving the gas removal is the gas column density ratio, \( \eta \), numerical simulations tend to strip more gas away from the central MBH than the analytic estimation does.

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There is, therefore, a critical value of \( \eta \) (\( \eta \gtrsim 25 \)), beyond which the mass fuelling onto the central MBH may be inhibited owing to a diminished fuel reservoir. By contrast, if the column density of the torus gas is high enough, there is little effect on the structure of the torus.

The stripped fraction for a torus having double the radius, \( R_{\text{out}} = 100 \) pc, but the same mass (for which we also double the adopted box size and grid point numbers) is 0.700 (Fig. 2a, circle). The larger torus size results in a smaller column density, \( \Sigma_{\text{torus}} \), which leads to the higher stripped fraction. This result confirms that the critical condition for suspending the MBH fuelling by central collisions of galaxies is the gas column density ratio. These results show that the condition for gas stripping is as follows:

\[
M_{\text{gas}} \gtrsim 3 \times 10^7 M_\odot \times \left( \frac{M_{\text{torus}}}{10^6 M_\odot} \right) \times \left( \frac{R_{\text{out}}}{50 \text{ pc}} \right)^{-2} \times \left( \frac{r_{\text{gas}}}{1 \text{ kpc}} \right)^2.
\]

Here, \( M_{\text{gas}} \) and \( r_{\text{gas}} \) are the mass and the radius of the gaseous components in the infalling satellite galaxy. An equivalent formulation that uses the column density ratio is that the column density of the infalling gas, \( \Sigma_{\text{gas}} \), must exceed that of the torus. The larger torus and the smaller satellite galaxy lead to easier gas stripping and effective suppression of MBH fuelling.

So far, we have focused on a specific parameter setting for the central collision that occurred in M31. We expect, however, that central collisions commonly occur in many galaxies, including host galaxies of AGN. We now translate the critical condition for AGN shut-off (equation (1)) to a condition involving AGN parameters. We superimpose in colour the condition onto a plot of the absolute magnitude of a sample of host galaxies in the H band versus the torus mass (Fig. 3) (Methods). Below the critical zone (yellow to cyan coloured patch), where we find a notable fraction of AGN to be located, the AGN activity can cease by a central collision of a satellite galaxy.

Here, we propose that galaxy collisions are potentially the essential process that controls the fate of AGN activity. Galaxy collisions can trigger a starburst and gas flows towards central MBHs via angular momentum transfer, and can trigger AGN. Conversely, luminous merging galaxies, such as ultra-luminous infrared galaxies, do not always harbour AGN. Signatures of major mergers in host galaxies of AGN as seen by Hubble Space Telescope images...
show no clear systematic differences from those in inactive galaxies. Although evidence of multiple episodes in AGN activity has hitherto been accumulated, what controls the AGN activity (for example, ignition and duration) is still unclear. Especially, no conclusion has been drawn regarding the shutdown process of AGN activity, although various mechanisms (for example, accretion towards the central MBH, AGN feedback and galactic bar resonance) have been proposed.

The width of the critical zone (Fig. 3) reflects the uncertainty in the density distribution of the gas disk in the infalling satellite and the uncertainty in the orientation angle \( \theta \) between torus and satellite axis of rotation. Edge-on infall increases the column density of the infalling gas and therefore enhances the torus stripping compared to the face-on infall. Fainter galaxies appear to have torii that are more susceptible to the interaction of the infalling satellite, and therefore the AGN activity would be shut off easily; this is reminiscent of AGN observed predominantly in massive galaxies. Edge-on views of these torii would correspond to heavily obscured (so-called Compton-thick) AGN. Tidal compression of the infalling satellite, not considered here, would enlarge the critical zone by increasing the column density of the infalling gas.

The hierarchical clustering model that is based on standard cold dark matter cosmology predicts that the orbital eccentricity distribution of sub-galactic dark matter haloes in a Milky Way-sized dark matter halo is radially biased relative to that of all subhaloes associated with the host halo. The radial orbit of the sub-galactic haloes can not only inhibit the mass fuelling in the galactic centre but also lead to subhalo depletion, as a consequence of tidal destruction in the proximity of the galaxy centre. By using the most recent proper motion measurements provided by the second data release of the Gaia mission (Gaia DR2), we integrated orbits of the satellite galaxies surrounding the Milky Way (Methods and Extended Data Fig. 3). The distributions of orbital periods, \( T_r \), and pericentres, \( r_{\text{peri}} \), (Fig. 4) show a linear (in logarithmic space) trend from the upper right towards the lower left. Cosmological simulations indicate that about 10–30 subhaloes in a Milky Way-sized halo have been stretched and disrupted by the tidal force of the central galaxy, and that the debris has fallen into the galactic centre. For instance, 10 subhaloes with gas, at \( r_{\text{peri}} \lesssim 15\,\text{kpc} \) and with orbital period \( \lesssim 10^8\,\text{yr} \), would reduce nuclear MBH fuelling in the central galaxy every \( \sim 10^8\,\text{yr} \) on average, at the expense of the infalling subhalo itself. A recent high-resolution cosmological N-body simulation implies that thousands of subhaloes penetrated the central region (\( \lesssim 10\,\text{kpc} \)) in nine Milky Way-sized haloes. The inferred average merger rate over the cosmic age (one per \( 10^8\,\text{yr} \) per single host halo) is consistent with our estimation. In addition, Gaia DR2 recently provided evidence for a central collision event in the Milky Way. The Gaia–Enceladus–Sausage is identified as the remnant of a central collision that the Milky Way experienced about \( 10^{10}\,\text{yr} \) ago with a massive satellite galaxy. As previously stated, the GSS is the remnant of a recent central collision in M31.

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**Fig. 3 | Relation between the torus mass and the host galaxy of AGN.** Absolute magnitude of host galaxy in the H band, \( M_{\text{host}}^{H} \), and corresponding stellar mass, \( M_{\text{host}}^{\text{stell}} \), as a function of torus mass, \( M_{\text{torus}} \) (Methods). Uncertainties indicate the 1σ confidence level. Blue squares correspond to quasi-stellar objects (QSOs) and other symbols correspond to Seyfert galaxies (red circles, brown triangles and purple diamonds for type 2, type 1.8/1.9 and type 1 Seyfert galaxies, respectively). The right axis is column density for either torii or infalling satellites. When converting the gas mass to the column density of torii, we use the approximation of \( \Sigma_{\text{torus}} = \frac{M_{\text{torus}}}{\pi R_{\text{torus}}^2} \), assuming that \( R_{\text{torus}} = 50\,\text{pc} \). The shaded zone indicates the stripping criterion (equation (1)) for various orientation angles \( \theta \) between torus and satellite rotation axis. (See Methods for detailed estimation of \( M_{\text{torus}} \) and of the column density of the infalling gas \( \Sigma_{\text{inf}} \)).

**Fig. 4 | Distribution of orbital periods and pericentres for satellite galaxies.** Orbital periods, \( T_r \), and pericentres, \( r_{\text{peri}} \), for satellite galaxies in the Milky Way (MW). Blue boxes represent classical dwarfs and green circles represent ultra-faint dwarfs; uncertainties indicate the 1σ confidence level. The solid line represents the best-fit model for the Milky Way satellites:

\[
T_r = 170 \left( \frac{r_{\text{peri}}}{\text{kpc}} \right)^{-0.77} \,\text{Myr}.
\]

The vertical lines at \( r_{\text{peri}} \approx 10\,\text{kpc} \) indicate the tidal-stripping radii for 10^7\,\text{M}_\odot, 10^8\,\text{M}_\odot, and 10^9\,\text{M}_\odot haloes from left to right (Methods). For comparison, the progenitor for the GSS around M31 is plotted in red, based on the top and right axes. These axes are normalized by the virial radius, \( r_{\text{vir}} \), and by the corresponding orbital period of \( T_r = 9.1\,\text{Gyr} \) and 8.6 Gyr at \( r_{\text{peri}} = 207\,\text{kpc} \) and 195 kpc for the Milky Way and M31, respectively.
The GSS progenitor had a smaller pericentre and shorter orbital period compared to the Milky Way satellites known in Gaia DR2. Besides the GSS, the 10kpc ring structure observed in M31 may be another signature of a recent central collision that occurred in M31 (ref. 29).

An important point to be emphasized is that only central collisions of galaxies open up this new channel for suppressing central MBH fuelling. Far-off-centre collisions or encounters are thought to trigger gas flows to the central MBH via angular momentum transfer and then enhance AGN activity occasionally20. Once gas fuelling is triggered, however, the nuclear activity could be suppressed by the central collisions, which happen every ~10^8 yr, consistent with the current estimate of the AGN durations. If orbital properties of satellite galaxies make a critical impact on the turning on/off of MBH fuelling, merging events of galaxies may play an essential role in the AGN duty cycle.

Here, we assume a smooth torus, although the torus may in fact be clumpy (Methods and Extended Data Figs. 4, 5 and 6). Uncertainties and dependencies on various collision parameters (such as infalling direction, velocity and pericentric distance) are not considered in this work. It is also worth investigating how long this suppression mechanism of the AGN activity lasts. Future studies that use detailed simulations with a larger computational box for a longer duration, and that include gas inflow towards the torus from the galactic disk, self-gravity of the torus gas and radiative cooling processes, will reduce such uncertainties.

Methods

Earlier studies focusing on AGN activity. In many studies, the shutdown mechanism of AGN activity has been investigated comprehensively. Accretion towards the central black hole reduces the torus gas and leads to the depletion of the fuelling source. However, the lifetime of clumpy tori is estimated to be a few Myr to 10 Myr (ref. 1), which is much longer than the duration of the simulations in this work. This means that the accretion in the torus does not influence the torus destruction process during the central collision of galaxies, which is the focus of this work. AGN feedback (via jet or radiative processes) may destroy the dusty torus. Numerical simulations that included strong AGN feedback demonstrated the regulation of the gas fuelling to the central region under the assumption of isotropic feedback12. High-resolution, radiation hydrodynamic simulations showed that the AGN feedback leads to bipolar outflows with little influence in the gas fuelling12. Other possible channels for the AGN shutdown are the termination of the gas fuelling process from the galactic disk via the galactic bar and/or the Lindblad resonance. These processes will need a dynamical timescale at a galactic scale (that is, kpc scale) to vary their efficiency; therefore, they seem to be longer in duration than the lifetime of AGN events (for example, the bar destruction takes a few Gyr (ref. 1)).

Merger-triggered enhancement of the AGN activity has been investigated. Numerical simulations showed that the galaxy collisions triggered mass fuelling to the central region and suggested AGN activity enhancement13,14. Recent high-resolution simulations that modelled multi-phase interstellar medium by incorporating realistic physical processes resolved the mass fuelling down to sub-parsec scales15.

Set-up for the M31 collision simulations. We describe the model assumptions and parameters for the gas around M31’s centre and the infalling satellite. We focus on the central region of the galaxy, which is dominated by the MBH and the bulge. The gravitational potentials of the MBH and of a bulge with a mass of M_BH = 3.24 × 10^6 M_s and a scale length of h = 610 pc (ref. 29) are modelled as a fixed point mass and Hernquist potential:

$$\Phi(r) = -\frac{GM_{\text{Bulge}}}{r} - \frac{GM_{\text{Hernquist}}}{r^2 + h^2}$$

(2)

where G is the gravitational constant and r is calculated as

$$\sqrt{10^{-8} \text{pc}^2 + x^2 + y^2 + z^2}$$

to remove the divergence due to division by zero. This treatment is sufficiently accurate for the central 10 pc to 100 pc of M31.

Before the collision, the torus is modelled as an axisymmetric polytrope gas with a heat capacity ratio of γ = 5/3 at equilibrium under a spherical gravitational field Φ(r), which is a function of the three-dimensional distance r from the centre. The gas density ρ, the effective potential Φ_eff and the specific angular momentum l in cylindrical coordinates are as follows16–19:

$$\rho(R, z) = \rho_0 \left( \frac{C - \Phi_{\text{eff}}(R, z)}{C - \Phi_{\text{eff}}(R, z = 0)} \right)^{1/(\gamma - 1)}$$

(3)

The constant C in equation (3) is determined by requiring C = Φ_{eff}(R = R_{out}, z = 0) at the outermost radius R_{out} of the torus gas. Here, we assume R_{out} = 50 pc (ref. 20) as a fiducial value. The maximum value of the aspect ratio, the scale height of the torus H(R) over R, should be about unity18. Setting the scale radius R_0 to be 9pc and R_{out} = 50 pc meets this requirement. The mass of the torus gas M_{torus} is in the range of 10^4 ≤ M_{torus}/M_\odot ≤ 1 (refs. 16–18).

The total mass, the scale radius, the velocity and the pericentric distance of the infalling satellite are 3 × 10^8 M_\odot, 1 kpc, 850 km s^{-1} and 1 kpc (refs. 21). As the progenitor of the GSS interacts with the central region of M31 over a crossing time of 1.1 Myr, the gas of the infalling satellite is modelled as gas inflowing lasting for 1.1 Myr. The central mass density of the infalling satellite is estimated to be 4.5 × 10^{-2} g cm^{-3}, where f_{gas} is the gas fraction in the range of 10^{-5} ≤ f_{gas} ≤ 1 (refs. 22). The gas temperature of the infalling satellite is assumed to be 10^4 K.

One-dimensional analytical estimations. We estimate analytically the stripped fraction of the torus gas owing to the hydrodynamic interaction with the infalling gas in the satellite galaxy. For simplicity, we consider the case in which the satellite moves along the rotation axis of the torus gas (z axis) and solve the one-dimensional problem along the z axis. The initial volume density of the torus gas is set to be $\rho_{\text{torus}}(R) = \frac{4\pi}{3}f_{\text{gas}} \rho_{\text{satellite}}(R, z = 0, z<H(R))$. The initial vertical velocity of the torus is assumed to be zero.

Solving the one-dimensional Riemann problem yields the velocity, v_z, pressure, p, and density, $\rho_{\text{satellite}}$, of the torus gas just after shock passage. Based on previous studies of the GSS, we determine whether the gas is stripped or still bound at 10kpc ($r_{\text{max}}$) from the centre, at which location the free-fall time is about 100 Myr.

We set three independent and necessary conditions for gas stripping to estimate the stripped fraction of the torus gas. The first condition is that the velocity of the torus gas after the collision exceeds the escape velocity:

$$\frac{1}{2} v_z^2 + \Phi(R, z = 0) > \Phi(R_{\text{max}})$$

(6)

The second condition is that the sum of the kinetic and thermal energy of the torus gas exceeds the potential difference:

$$\frac{1}{2} v_z^2 + \frac{p}{\rho_{\text{torus}}} + \Phi(R, z = 0) > \Phi(R_{\text{max}})$$

(7)

In this case, the stripped torus gas will re-accrete within the cooling timescale. The third condition is the momentum transfer:

$$\frac{1}{2} v_z^2 + \Phi(R, z = 0) > \Phi(R_{\text{max}})$$

(8)

where

$$v_{\text{both}} = \frac{\Sigma_{\text{torus}} v_{\text{torus}} + \Sigma_{\text{satellite}} v_{\text{satellite}}}{\Sigma_{\text{torus}} + \Sigma_{\text{satellite}}}$$

(9)

The stripped fraction of the torus gas, $f_{\text{strip}}$, for each condition is defined as a fraction of the swept gas mass over the initial entire torus mass.

We solved the Riemann problem above for 32,768 cells over a range of cylindrical radii from R = 4.6 pc to R = 50 pc, and then integrated the gas mass over the radii where at least one of the conditions (equations (6)–(8)) was satisfied.

We provide the results of the analytic estimation for $f_{\text{strip}}$ (Fig. 2a). The stripping due to momentum transfer (Fig. 2a, black solid curve) always predicts the highest stripped fraction. Models with $\eta > 100$ predict that a notable fraction of the torus gas will be stripped away.

We compare the ratio of the column density of the infalling satellite gas $\Sigma_{\text{satellite}}$, to that of the torus gas $\Sigma_{\text{torus}}$ for $\eta = 100$ (Extended Data Fig. 2, solid curve) and $\eta = 10$ (Extended Data Fig. 2, dotted curve). In models with $\eta = 100$, the column density of the infalling gas is higher than that of the torus gas for all radii. Conversely, for models with $\eta = 10$, the column density of the infalling gas is lower compared to that of the torus gas in most regions. The ratio of the column densities determines the critical value of $\eta$, which underlines the importance of momentum transfer for gas stripping.

Three-dimensional hydrodynamic simulations. We have developed a flat MPM (message passing interface) parallelized code that adopts the HLLC (Harten–Lax–van Leer contact) scheme23,24 for the approximate Riemann solver with the second-order MUSCL (monotonic upstream-centred scheme for conservation laws) interpolation. We performed 12 runs with a grid of 256^3 cells for a (200 pc)^3
box as a parameter study, a run with a grid of 1,024^3 cells (for a 200 pc^3) box as a convergence check and a run with a torus twice the size of the fiducial model using a grid with 512^3 cells for a (400 pc)^3 box (see Extended Data Fig. 1for a summary of the parameters in the simulations). The computational box is aligned with the inflow direction of the satellite. The infalling gas is modelled by a steady and uniform inflow boundary condition (the gas density is 4.5 × 10^{-21} f_{	ext{gas}} \text{g cm}^{-3}, the velocity is 850 km s^{-1} and the temperature is 10^4 K) for t = 1 Myr from t = 0, which is switched to a force-free boundary condition at t = 1 Myr. The remaining five boundaries are force-free boundaries at all times. Although no correlation is observed between the rotation axis of the torus and that of the galactic disk, we assume here that the galactic disk (with the rotation axis inclined by 44.1° with respect to the direction of the satellite infall) and the torus share a rotation axis. We estimate the stripped fraction of the torus f_{\text{strip}} based on the bound gas mass at t = 1.3 Myr. As the bound fraction f_{\text{bound}} is defined as the gas mass bound by the gravitational potential of the MBH and bulge as a fraction of the initial gas mass, f_{\text{strip}} is simply 1 - f_{\text{bound}}.

Dynamical evolution of the infalling satellite in the vicinity of the galactic centre. Here, we discuss possible processes that change the column density of the infalling gas, such as ram-pressure stripping and tidal stripping or compression. First, systematic studies have concluded that the efficiency of the ram-pressure stripping within a certain period of time depends on a total mass of the satellite galaxies, that is, less massive dwarfs lose their gasses more quickly than more massive dwarfs. A critical mass M_c, which is the minimum mass for bearing the gas remnants, is estimated to be between 10^9 M_\odot to 10^10 M_\odot for an ambient gas density of 10^{-21} cm^{-3} and a velocity of 1,000 km s^{-1} (refs. 35,36). The mass of the GSS’s progenitor lies in this marginal range. However, previous studies of the GSS formation indicate that this combination of density and high velocity is realized only at the central high-density region in the M31, and the progenitor of the GSS takes only 10 Myr to pass through the central 4 kpc region. It is clear that this transit time is too short to strip the gas from the infalling galaxies even in the environment of the galactic centre. Therefore, the effect of the ram-pressure stripping is negligible, and most of the gas will certainly reach the galactic centre.

Second, satellite galaxies that have smaller pericentres will be influenced more heavily by tidal stripping in the direction of the galactic centre and by tidal compression along the other two axes when the satellites pass through their pericentres. Such satellite galaxies could then form narrower stellar streams. To show the effect of these processes, we estimated the tidal-stretching radius of infalling satellite galaxies in the Milky Way, and obtained about 10 kpc for total satellite masses of 10^10 M_\odot to 10^12 M_\odot (Fig. 4, vertical lines). However, the tidal stripping will not substantially change the column density of the infalling gas, although it extends the duration of the gas inflow. By contrast, pressure stripping.

Availability of torus modelling. The half-light radius or full-width-at-half-maximum of the mid-infrared continuum emission from the AGN torus is a measure of the size of the inner part under direct illumination from the central nucleus, and is around one to several pc (refs. 65,66). Emissions from cold molecular or fluorescence lines are more confined with radii on the order of 10 pc (refs. 67,68). For instance, the radius of the central molecular torus in the Circinus galaxy is estimated using ALMA to be about 30 pc (ref. 67). In radiative transfer calculations for torii, the outer radii are assumed to be 12–56 pc (ref. 69). In our calculations, we generally adopt an outer radius of 30 pc, and for the simulation with the larger torus, an outer radius of 100 pc.

Although the torus is likely to be composed of numerous clumps, we assume a smooth distribution of gas in the torus in this study, for simplicity. We expect that clumps are destroyed almost instantaneously during the passage of the infalling gas and that the approximation of a smooth density distribution is appropriate. To show that each clump is destroyed immediately by the infalling satellite gas, we performed three-dimensional hydrodynamic simulations. At the outer edge of a torus, clumps have low temperatures (~100 K) (ref. 70). At 10–50 pc from the central 1.4×10^10 M_\odot black hole, such a clump would have a density of 10^{-16}–10^{-10} g cm^{-3} and a mass of several M_\odot to tens of M_\odot (ref. 71). The simulations were carried out using the HLLC scheme with MUSCL interpolation and periodic boundary conditions. The time evolution of a clump exposed to a fast gas flow (512×512×2,048 grid points for a 1.6 pc×1.6 pc×6.4 pc box) is provided (Extended Data Fig. 4). The clump initially has a uniform density of 2.3×10^{-10} g cm^{-3} with a temperature of 10^4 K, and the ambient flow has a density of 4.5×10^{-20} g cm^{-3}, a temperature of 10^4 K and a velocity of 850 km s^{-1}. Within a timescale much shorter than that of the torus evolution, the clump is deformed and expands to much lower densities. For a variety of clump parameters in simulations with 256×256×1,024 grid points, we find that the time evolution of gas stripping from a clump is extensively similar (Extended Data Fig. 5). In about 10 times the flow crossing timescale, a clump loses about half of its initial mass (Extended Data Fig. 6).

Estimation of the torus mass. We estimate the torus mass following ref. 72. Under the assumption of a sharp-edge angular distribution of clumps; the torus mass is expressed as

\[ M_{\text{torus}} = 4\pi m_\odot n_\odot N_y \beta_\odot \sin \theta \sigma R_{\text{trans}}(Y) \]  

Estimation of the stellar mass of AGN host galaxies. We estimate the stellar mass of host galaxies through their absolute magnitude in the H band (SOGs and Seyfert galaxies) and the corresponding stellar mass via the M_H – M_\odot relation (Fig. 3, top axis).

Estimation of the gas column density of the infalling satellites. Observations show that the radial profiles of the neutral gas (atomic hydrogen, molecular hydrogen and helium) in nearby disk galaxies are universal 75,76:

\[ \Sigma_g(r) = 2.1 \Sigma_{\text{gas}} \exp \left( -1.65 \frac{r}{R_{\odot}} \right) \]

where \( \Sigma_{\text{gas}} = 14 M_\odot pc^{-2} \) is the gas surface density at the transition radius (where HII and H2 column densities are equal), and \( R_\odot \) is the radius of the 25 mag arcsec^{-2} B-band isophote. Under the assumption of a constant density profile in the vertical direction with thickness 105 K, and the ambient flow has a density of 4.5 × 10^{-21} g cm^{-3}, the hydrogen mass fraction is estimated to be around 50%.

Orbital parameters of the satellite galaxies in the Milky Way. We performed a series of test-particle simulations in a fixed potential field of the Milky Way to estimate the pericentric distance and orbital period of Milky Way satellite. The location and velocity of the satellites, which include 12 classical dwarfs and 28 ultra-faint dwarfs, are taken from recent observations 77 and from the NASA/IPAC Extragalactic Database (NED). The number of test particles is 10^6. We assumed that Sagittarius A* was the fixed Galactic centre by rejecting the gravitational Brownian motion of Sgr A*. The location of Sgr A* is (l, b) = (−0.056, −0.046) degrees and the distance to Sgr A*, R_A* = 8.249 ± 0.009 ± 0.0045 kpc (ref. 5). The proper motion of Sgr A* is (v_\alpha, v_\delta) = (−6.369 ± 0.026, −0.202 ± 0.019) mas yr^{-1} (ref. 5) and the line-of-sight velocity of Sgr A* is −7.2 ± 8.5 km s^{-1} (ref. 5). The potential of the Milky Way model78 (composed of a Navarro–Frenk–White (NFW) halo79,80, a McMillan bulge81,82, two exponential disks representing the thin and thick stellar disks, two exponential disks with a central hole83 representing the HII and H2 disks, and the circumgalactic medium described in a single-power-law model) is generated by an updated version of the MAGI code84.

Orbit integration backwards in time over the cosmic age was performed using the fourth-order Hermite scheme with adaptive time steps to resolve highly eccentric orbits. The results of the test-particle simulations (median values with 84.1 and 15.9 percentiles at the 1σ confidence level) are summarized (Fig. 4 and Extended Data Fig. 3). As estimation of the orbital parameters of test particles that are unbound or have longer orbital period than the integration time (13.8 Gyr) is impossible, a subset of satellites suffers from poor statistics: Leo I, Phoenix dwarf, Eridanus II, Leo V, Hydra II, Pucos II, and Gru 1. We exclude these satellites with an unreliable estimation of the orbital parameters from the figure (Fig. 4) and table (Extended Data Fig. 3).

Estimation of the tidal-stripping radius of satellite galaxies. We estimate the tidal-stripping radius of satellite galaxies by solving the force balance between the
self-gravity of the satellite and the tearing force by the central galaxy (half of the tidal force). The mass model of the central galaxy is the spherically averaged Milky Way model $M_{MW}(r)$ that was exploited in the previous section. We assume an NFW profile as a satellite galaxy and set the concentration parameter, $c$, by using the $c-M$ relation as a function of the satellite mass $M_{sat}$. With the assumption that 95% of the initial mass of the satellite is tidally stripped, the tidal-stripping radius $r_{tid}$ must satisfy the following equation:

$$1 - \frac{GM_{MW}(r_{tid})}{(r_{tid} - r_{5\%})^2} = 0.05 \frac{GM_{MW}}{r_{5\%}^2},$$

where $r_{tid}$ is the radius within which 5% of the satellite mass is contained. Solving this equation numerically, we obtain a resultant radius $r_{tid}$ of 8.41 kpc, 10.4 kpc and 13.0 kpc for a satellite mass of $10^7 M_\odot$, $10^8 M_\odot$, and $10^9 M_\odot$, respectively. The tidal-stripping radii (Fig. 4, vertical lines) are located near the lower bound for the pericentres of the current orbiting satellites.

**Data availability**

Source data are provided with this paper. The data that support the findings of this study are available from the corresponding author upon reasonable request. The requestor will be responsible for providing the very considerable resources needed for transferring and storing these data.

**Code availability**

The parent code MAGI has been made publicly available at https://bitbucket.org/ymiki/magi. It is expected that most of the extensions and modifications made to meet the specific requirements for this project will be made available in the future release; those interested can contact the corresponding author for further information.

Received: 12 August 2020; Accepted: 2 December 2020; Published online: 25 January 2021

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| Parameter                        | Symbol | Value             | Note                                      |
|---------------------------------|--------|-------------------|-------------------------------------------|
| M31 potential:                  |        |                   |                                           |
| Black hole mass                 | $M_{\text{BH}}$ | $1.4 \times 10^8 \, M_\odot$ |                                           |
| Bulge mass                      | $M_{\text{bulge}}$ | $3.24 \times 10^{10} \, M_\odot$ |                                           |
| Bulge scale length              | $h$    | 610 pc            |                                           |
| Torus properties:               |        |                   |                                           |
| Torus mass over black hole mass | $M_{\text{torus}}/M_{\text{BH}}$ | $10^{-3}, 10^{-2}, 0.1, 1$ | fiducial model                           |
| Outermost radius                | $R_{\text{out}}$ | 50 pc, 100 pc     | a torus twice the size of fiducial models |
| Scale radius                    | $R_0$  | 9 pc, 30 pc       | fiducial model, for $R_{\text{out}} = 100$ pc model |
| Satellite properties:           |        |                   |                                           |
| Mass density                    | $\rho_\text{gas}$ | $4.5 \times 10^{-23} \, \text{g cm}^{-3}$ |                                           |
| Gas fraction                    | $f_{\text{gas}}$ | $10^{-3}, 10^{-2}, 0.1, 1$ |                                           |
| Velocity                        | $v_0$  | $850 \, \text{km s}^{-1}$ |                                           |
| Temperature                     |        | $10^4 \, \text{K}$ |                                           |
| Duration                        |        | $1.1 \, \text{Myr}$ |                                           |
| Inclination                     |        | 44.1 deg          | angle between the rotation axis of the M31’s disc and the infalling direction |
| Simulation box:                 |        |                   |                                           |
| Box size                        |        | $(200 \, \text{pc})^3$ | for $R_{\text{out}} = 100 \, \text{pc}$ model |
| Grid number                     |        | $(400 \, \text{pc})^3$ | normal resolution                         |
|                                |        | $256^3$           |                                           |
|                                |        | $512^3$           | for $R_{\text{out}} = 100 \, \text{pc}$ model ($f_{\text{gas}} = 0.1, M_{\text{torus}}/M_{\text{BH}} = 10^{-2}$) |
|                                |        | $1024^3$          | for convergence check ($f_{\text{gas}} = 0.1, M_{\text{torus}}/M_{\text{BH}} = 10^{-2}$) |

**Extended Data Fig. 1 | Simulation parameters.** Parameters of three-dimensional hydrodynamic simulations are summarized.
Extended Data Fig. 2 | Radial profile of the ratio of the gas column-densities of the infalling satellite galaxy to that of the central torus, $\Sigma_{\text{satellite}}/\Sigma_{\text{torus}}$. The solid and dotted curves show the gas column-densities ratio for $\eta = 100$ and 10, respectively.
| Name                        | $r_{\text{peri}}$ (kpc) | $r_{\text{apo}}$ (kpc) | e       | $T_r$ (Gyr) |
|-----------------------------|-------------------------|-------------------------|---------|-------------|
| LMC                         | 49.6$^{+1.3}_{-1.3}$    | 314.2$^{+204.7}_{-108.4}$ | 0.73$^{+0.10}_{-0.10}$ | 6.8$^{+7.1}_{-2.7}$ |
| SMC                         | 50.4$^{+12.9}_{-22.2}$  | 128.2$^{+175.0}_{-30.6}$  | 0.57$^{+0.09}_{-0.13}$ | 2.5$^{+4.5}_{-0.7}$  |
| Sagittarius dwarf           | 9.7$^{+0.9}_{-0.9}$     | 52.7$^{+12.4}_{-9.2}$    | 0.69$^{+0.05}_{-0.05}$ | 0.7$^{+0.2}_{-0.1}$  |
| Fornax dSph                 | 96.8$^{+24.6}_{-41.1}$  | 161.4$^{+32.0}_{-24.1}$  | 0.26$^{+0.17}_{-0.04}$ | 4.0$^{+1.2}_{-1.2}$  |
| Sculptor dSph               | 43.4$^{+30.5}_{-19.5}$  | 113.6$^{+368.3}_{-16.6}$ | 0.56$^{+0.18}_{-0.11}$ | 2.1$^{+11.5}_{-5.5}$ |
| Leo II                      | 183.2$^{+47.1}_{-135.9}$ | 235.3$^{+62.5}_{-30.7}$  | 0.37$^{+0.35}_{-0.19}$ | 5.9$^{+5.4}_{-5.4}$  |
| Sextans                     | 80.0$^{+7.3}_{-6.7}$    | 558.0$^{+136.2}_{-255.9}$ | 0.75$^{+0.04}_{-0.13}$ | 16.3$^{+6.0}_{-9.7}$ |
| Carina dSph                 | 99.7$^{+9.0}_{-40.0}$   | 118.9$^{+38.6}_{-14.1}$  | 0.17$^{+0.17}_{-0.11}$ | 3.5$^{+0.7}_{-1.3}$  |
| Draco dwarf                  | 35.6$^{+13.6}_{-12.8}$  | 98.2$^{+14.0}_{-11.4}$   | 0.46$^{+0.15}_{-0.09}$ | 1.8$^{+0.5}_{-1.4}$  |
| Ursa Minor                  | 42.1$^{+15.2}_{-17.1}$  | 88.7$^{+8.9}_{-6.3}$     | 0.35$^{+0.19}_{-0.09}$ | 1.6$^{+0.5}_{-0.2}$  |
| Canes Venatici I            | 154.5$^{+35.5}_{-81.8}$ | 335.1$^{+172.4}_{-78.3}$ | 0.58$^{+0.16}_{-0.05}$ | 7.8$^{+9.0}_{-2.6}$  |
| Crater II                   | 22.1$^{+20.6}_{-11.9}$  | 131.6$^{+75.8}_{-4.1}$   | 0.71$^{+0.16}_{-0.16}$ | 2.2$^{+0.7}_{-0.3}$  |
| Hercules dSph               | 39.5$^{+35.8}_{-16.4}$  | 271.5$^{+47.8}_{-4.1}$   | 0.77$^{+0.09}_{-0.08}$ | 5.6$^{+2.2}_{-1.3}$  |
| Boötes I                    | 48.8$^{+7.5}_{-16.3}$   | 108.7$^{+29.4}_{-21.3}$  | 0.43$^{+0.07}_{-0.08}$ | 2.2$^{+0.5}_{-0.7}$  |
| Ursa Major I                | 101.9$^{+6.0}_{-6.0}$   | 273.3$^{+239.1}_{-119.0}$ | 0.48$^{+0.21}_{-0.21}$ | 6.9$^{+8.7}_{-2.9}$  |
| Canes Venatici II           | 73.9$^{+31.5}_{-48.3}$  | 291.9$^{+139.2}_{-86.3}$ | 0.58$^{+0.17}_{-0.06}$ | 7.4$^{+1.8}_{-3.9}$  |
| Hydrus I                    | 17.4$^{+3.5}_{-4.1}$    | 211.6$^{+103.3}_{-48.5}$ | 0.86$^{+0.02}_{-0.02}$ | 3.6$^{+1.8}_{-1.0}$  |
| Carina II                   | 27.5$^{+2.3}_{-2.4}$    | 334.5$^{+209.9}_{-108.4}$ | 0.85$^{+0.06}_{-0.03}$ | 7.2$^{+7.1}_{-3.0}$  |
| Aquarius II                 | 103.2$^{+4.3}_{-5.4}$   | 171.7$^{+231.2}_{-68.1}$ | 0.49$^{+0.21}_{-0.17}$ | 4.3$^{+7.1}_{-2.5}$  |
| Ursa Major II               | 25.4$^{+10.7}_{-9.8}$   | 115.4$^{+74.5}_{-29.6}$  | 0.70$^{+0.07}_{-0.18}$ | 1.9$^{+1.3}_{-0.6}$  |
| Coma Berenices dwarf        | 35.4$^{+10.4}_{-18.5}$  | 139.9$^{+139.6}_{-47.3}$ | 0.68$^{+0.10}_{-0.09}$ | 2.5$^{+3.5}_{-1.0}$  |
| Tucana II                   | 29.7$^{+6.7}_{-7.8}$    | 226.8$^{+207.8}_{-74.8}$ | 0.78$^{+0.05}_{-0.04}$ | 4.0$^{+3.8}_{-1.4}$  |
| Reticulum II                | 27.9$^{+10.0}_{-19.9}$  | 64.0$^{+14.4}_{-13.3}$   | 0.33$^{+0.05}_{-0.05}$ | 1.1$^{+0.3}_{-0.3}$  |
| Horologium I                | 73.2$^{+10.5}_{-17.6}$  | 181.8$^{+99.6}_{-141.7}$ | 0.40$^{+0.18}_{-0.22}$ | 4.0$^{+4.1}_{-2.5}$  |
| Willman 1                   | 24.6$^{+17.2}_{-9.2}$   | 43.8$^{+11.6}_{-7.0}$    | 0.28$^{+0.19}_{-0.17}$ | 0.7$^{+0.2}_{-0.1}$  |
| Boötes II                   | 48.3$^{+4.2}_{-5.2}$    | 275.8$^{+210.9}_{-130.3}$ | 0.69$^{+0.10}_{-0.14}$ | 5.1$^{+4.6}_{-2.5}$  |
| Segue 2                     | 21.1$^{+21.2}_{-4.2}$   | 76.1$^{+52.5}_{-16.4}$   | 0.54$^{+0.06}_{-0.08}$ | 1.2$^{+1.2}_{-0.3}$  |
| Carina III                  | 23.5$^{+6.2}_{-3.7}$    | 192.1$^{+147.3}_{-74.1}$ | 0.81$^{+0.06}_{-0.11}$ | 3.2$^{+5.2}_{-1.2}$  |
| Segue 1                     | 14.9$^{+5.1}_{-4.0}$    | 54.7$^{+26.2}_{-14.5}$   | 0.58$^{+0.06}_{-0.05}$ | 0.8$^{+0.4}_{-0.2}$  |
| Tucana III                  | 6.3$^{+1.7}_{-1.9}$     | 46.2$^{+3.4}_{-4.1}$     | 0.76$^{+0.07}_{-0.06}$ | 0.6$^{+0.1}_{-0.1}$  |
| Triangulum II               | 22.7$^{+6.9}_{-5.5}$    | 182.2$^{+83.2}_{-37.9}$  | 0.80$^{+0.05}_{-0.08}$ | 3.3$^{+1.9}_{-0.9}$  |
| Draco II                    | 25.5$^{+10.9}_{-8.6}$   | 146.9$^{+61.8}_{-46.2}$  | 0.69$^{+0.14}_{-0.16}$ | 2.6$^{+1.2}_{-0.8}$  |

Extended Data Fig. 3 | Orbital parameters of the Milky Way satellites. Pericentres, $r_{\text{peri}}$, apocentres, $r_{\text{apo}}$, orbital eccentricities, $e$, and orbital periods, $T_r$, are tabulated (median values with 84.1 and 15.9 percentiles at the 1σ confidence level).
Extended Data Fig. 4 | A series of snapshots of a clump exposed to the fast gas travelling from the left side of the simulation box. From a to e, each panel shows the volume-density distribution $\rho(z, x)$ in the $y = 0$ plane at 0, 1, 2, 3, 4 kyr after the simulation starts.
Extended Data Fig. 5 | Time evolution of various clumps exposed to fast infalling gas. Different colours and linetypes indicate various clump masses $M_{\text{clump}}$ and clump radii ($r_{\text{clump}}$): $M_{\text{clump}} = 1.4 M_\odot$ (blue), $14 M_\odot$ (red) and $140 M_\odot$ (black); $r_{\text{clump}} = 10^{-3}$ pc (solid), $10^{-2}$ pc (dotted) and $0.1$ pc (dashed).
Extended Data Fig. 6 | Time evolution of various clumps examined in Extended Data Fig. 5, presented with the normalized quantities in both axes. The crossing time of a clump $t_{\text{cross}}$ is defined as $r_{\text{clump}}$ divided by the infalling gas flow velocity of 850 km s$^{-1}$: $t_{\text{cross}} = 1.2$ yr, 12 yr and 120 yr for $r_{\text{clump}} = 10^{-3}$ pc, $10^{-2}$ pc and 0.1 pc, respectively. All nine curves are totally overlapping in the normalised axes.