Strangulation as the primary mechanism for shutting down star formation in galaxies

Y. Peng1,2, R. Maiolino1,2 & R. Cochrane1,3

Local galaxies are broadly divided into two main classes, star-forming (gas-rich) and quiescent (passive and gas-poor). The primary mechanism responsible for quenching star formation in galaxies and transforming them into quiescent and passive systems is still unclear. Sudden removal of gas through outflows1–6 or stripping7–9 is one of the mechanisms often proposed. An alternative mechanism is so-called “strangulation”10–14, in which the supply of cold gas to the galaxy is halted. Here we report an analysis of the stellar metallicity (the fraction of elements heavier than helium in stellar atmospheres) in local galaxies, from 26,000 spectra, that clearly reveals that strangulation is the primary mechanism responsible for quenching star formation, with a typical timescale of four billion years, at least for local galaxies with a stellar mass less than $10^{11}$ solar masses. This result is further supported independently by the stellar age difference between quiescent and star-forming galaxies, which indicates that quiescent galaxies of less than $10^{11}$ solar masses are on average observed four billion years after quenching due to strangulation.

Figure 1 qualitatively illustrates the expected evolution of galaxies in the two quenching scenarios. A more quantitative analysis is provided below. In the scheme of Fig. 1, at $t < t_q$ the galaxy is subject to gas inflow and forms stars, thus increasing the stellar mass and the metallicity of the gas, out of which new stars form; hence the metallicity of the newly formed stars also increases with time. The metallicity increment is modest, since inflowing gas dilutes the metal content in the interstellar medium. At $t = t_q$ quenching occurs. In the scenario of sudden gas removal (for example, expulsion of gas by a strong wind or strong ram pressure stripping) star formation is suddenly quenched (Fig. 1a), and the galaxy evolves into a quiescent system. In this case the stellar metallicity and stellar mass ($M_{\text{star}}$) of the quiescent galaxy are the same as those of its star-forming progenitor just before quenching. In the case of quenching by strangulation, star formation can continue, using the gas available in the galaxy until it is completely used up (Fig. 1b). During this phase the gas metallicity increases more steeply than in the previous case because of the lack of dilution from inflowing gas. The stellar mass also increases slightly. The general product of strangulation is a quiescent galaxy with a stellar metallicity that is much higher than its star-forming progenitor, and a slightly higher stellar mass.

Observationally, obviously we cannot follow the evolution of the stellar metallicity of individual galaxies. However, we can statistically investigate the metallicity difference between star-forming and quiescent galaxies. This statistical approach has already been successfully exploited, for instance, to investigate the dependence of the quenching mechanism on mass and environment15. We have used the Sloan Digital Sky Survey (SDSS) spectra of local (redshift $z < \sim 0.1$) galaxies to extract a subsample of 3,905 star-forming and 22,618 quiescent galaxies whose spectra have a signal to noise ratio of $S/N > 20$ per spectral pixel, which ensures a reliable determination of the stellar metallicities (details of the sample selection and determination of the stellar metallicities are given in the Methods).

Figure 2a shows the average stellar metallicity of star-forming (blue line) and quiescent (red line) galaxies as a function of stellar mass, obtained by using a sliding average of 0.2 dex in $M_{\text{star}}$ (error bars give the 1$\sigma$ uncertainty of the mean stellar metallicity). At a given stellar mass, the stellar metallicity of quiescent galaxies is noticeably higher than for star-forming galaxies, at least for $M_{\text{star}} < 10^{11}M_\odot$, where $M_\odot$ is the solar mass. This is not what is expected in the case of sudden gas removal, but it is qualitatively consistent with the strangulation scenario. Below we investigate more quantitatively the agreement of the data with the strangulation scenario.

For a system forming stars without any inflow, the temporal evolution of the gaseous and stellar metallicity, as well as of the stellar mass, can be trivially solved analytically, as discussed in the Methods. The key parameters are: (1) the total gas mass at the time of quenching, $M_{\text{gas}}(t_q)$ or, equivalently, the gas fraction $f_{\text{gas}}(t_q)$; (2) the global efficiency of star formation $\varepsilon$, defined as the star-formation rate (SFR) = $\varepsilon M_{\text{gas}}$ (where $M_{\text{gas}}$ is in this case the total gas mass, both atomic and molecular); (3) the amount of any outflowing gas that is lost (that is, which does not fall back onto the galaxy and is not recycled), which can be approximated as being proportional to the SFR and parameterized through the so-called outflow mass loading factor $\lambda$, defined as $M_{\text{outflow}} = \lambda SFR$ (note that if part of the gas falls back and is recycled16–18, then $\lambda$ would account only for the fraction of gas that is lost, that is, it is an ‘effective’ outflow loading factor).

We are dealing with differential quantities (in particular, differential stellar metallicities $\Delta Z_{\text{star}}$, so the metallicity of the gas and stars at the beginning of the quenching ($t = t_q$) is unimportant. Yet, the value of $M_{\text{star}}$ at $t = t_q$ is relevant because it defines the gas fraction, and hence the gas mass available for further star formation. Indeed, it is observationally well known that the gas fraction in star-forming galaxies decreases with $M_{\text{star}}$ (refs 18–21; see Methods for the detailed functional form). The global star-formation efficiency $\varepsilon$ is also known from observations (see Methods).

Figure 2b shows the stellar metallicity difference, as a function of stellar mass (solid thin lines in colours), as expected from the strangulation scenario, at five different times after the quenching/strangulation event ($\Delta t = t - t_q$). In this plot we are assuming that the effective outflow loading factor is $\lambda = 0$ (that is, any outflowing gas falls back and is recycled), implying that the system behaves as a closed box after strangulation (no inflow and no effective outflow). The case of substantial outflow after strangulation is discussed below. The decline of the curves at high $M_{\text{star}}$ is primarily a consequence of the gas fraction of star-forming galaxies decreasing as a function of $M_{\text{star}}$: massive galaxies have low gas content, and so once such a galaxy has been strangled, its available gas can produce few stars relative to those already present, and the average stellar metallicity is not much affected. The thick black line with error bars shows the observed stellar metallicity difference between quiescent and star-forming galaxies (that is, the difference between red and blue data in Fig. 2a). The observed difference is consistent, within uncertainties, with the strangulation scenario in which quiescent galaxies at $M_{\text{star}} < 10^{11}M_\odot$ are,
The metallicity difference decreases with increasing stellar mass.

Figure 2 | Stellar metallicities for star-forming and quiescent galaxies. a. Average stellar metallicity as a function of stellar mass for all star-forming galaxies (thick blue line with error bars) and all quiescent galaxies (thick red line with error bars) for galaxies at \( \log M/M_\odot = 9.5 \). Error bars correspond to the 1σ error on the mean value. b. Average metallicity difference between all star-forming and all quiescent galaxies (thick black line with error bars). Error bars on the black line indicate the 1σ uncertainty in the metallicity difference. The metallicity difference decreases with increasing stellar mass.

We also investigate the case of a substantial ‘effective’ outflow, after strangulation, by setting \( \lambda = 1 \), which is a typical loading factor observed in star-forming galaxies\(^{26-28} \). Figure 4 shows the resulting \( \Delta Z_{\text{star}} \) curves, which are completely inconsistent with the observed data. This further confirms that gas removal by outflows plays a minor part in quenching galaxies. This includes any external environmental effect such as gas removal in satellite galaxies when falling into a more massive halo, or feedback process such as outflow driven by an active galactic nucleus.

Overall, our results strongly support the scenario in which local quiescent galaxies with \( M_{\text{star}} < 10^{10} M_\odot \) (that is, the vast majority of galaxies) are primarily quenched as a consequence of strangulation. However, this analysis does not clarify what the strangulation mechanism is (for example, hot halo environmental strangulation or strangulation via various preventive feedback mechanisms, such as circumgalactic gas heating\(^{29} \)). Additional analysis is needed to investigate the strangulation mechanism (for example, by studying the central/satellite and environmental dependence; see Methods subsection ‘Stellar metallicity for central and satellite galaxies’). We also note that

It reaches the maximum value around 0.4 dex for galaxies at \( M_{\text{star}} \approx 10^{9.5} M_\odot \) and becomes negligible at \( M_{\text{star}} \approx 10^{11} M_\odot \). The coloured lines show the metallicity difference predicted by a simple close-box model at different times \( \Delta t \) after strangulation. Solid lines are for the final mass (at time \( t = t_q + \Delta t \)), while dotted lines are for the mass at strangulation (\( t = t_q \)). The observed mass-dependent metallicity difference between quiescent and star-forming galaxies (thick black line) can be very well reproduced by a close-box model with a constant \( \Delta t = 4 \) Gyr, largely independent of stellar mass.
our results do not imply any claim about the morphological changes of the galaxy population, as it is not completely clear whether the morphological transformation is associated with star-formation quenching.

The data presented in this paper cannot shed light on the quenching mechanism at $M_{\text{star}} \gtrsim 10^{11}M_\odot$. At $M_{\text{star}} \approx 10^{11}M_\odot$, the stellar metallicity of quenched galaxies is similar to the stellar metallicity of star-forming galaxies (Fig. 2), which can be interpreted equally well as quenching by sudden gas removal (such as by outflows; Fig. 1a) or as quenching by strangulation of gas-poor massive galaxies (indeed, in massive galaxies the small amount of available gas, as shown in Extended Data Fig. 1a, does not allow much star formation, and hence there is little variation of the stellar metallicity, even if the galaxy is strangled; see also discussions in Methods subsection ‘Fraction of galaxies quenched by rapid gas removal’). At even higher stellar masses our analysis is not feasible, since star-forming galaxies with $M_{\text{star}} > 10^{11}M_\odot$ are extremely rare in the local Universe, hence preventing our statistical approach. To shed light on the quenching mechanism of massive galaxies a similar analysis has to be performed at high $z$, where massive star-forming galaxies are abundant and gas-rich.

The results obtained in this paper apply on average to the bulk of the local galaxy population. However, for individual galaxies, other quenching mechanisms such as fast gas removal via outflows (which can also help to explain the $\alpha$-element enhancement in massive elliptical galaxies) and environmental effects (such as ram-pressure stripping, tidal stripping, harassment and mergers), may work together with, or cause, strangulation to shape the detailed quenching process (see Methods subsection ‘Fraction of galaxies quenched by rapid gas removal’). These additional quenching mechanisms may modify the amount of stellar metallicity enhancement, the quenching timescale, and/or the gas content, which may all contribute to the scatter in the stellar metallicity and age differences between star-forming and quiescent galaxies.

**Figure 3** | Stellar ages for star-forming and quiescent galaxies. 
**a** Luminosity-weighted stellar age as a function of stellar mass for star-forming (blue line), quiescent (red line) and all galaxies (black line) at $\langle \tau \rangle = 0.05$. Error bars are the 1σ error on the mean value. The average age for all galaxies (black line) strongly depends on the stellar mass, largely due to the fact that the red fraction (that is, the mixture of quiescent and star-forming galaxies) strongly depends on stellar mass. However, the dependence on stellar mass becomes much weaker once the whole sample is split into star-forming and quiescent galaxies. 
**b** Average age difference between quiescent and star-forming galaxies as a function of stellar mass. Error bars on the black line indicate the 1σ uncertainty in the age difference. Remarkably, the age difference for all galaxies is largely independent of mass, with a mean value of around 4 Gyr, which is consistent with the mass-independent time $\tau$ from strangulation required to explain the difference in stellar metallicities.

**Figure 4** | The effect of outflows on stellar metallicity evolution. As for Fig. 2b, but for the case of an effective mass-loading factor $\lambda = 1$ after strangulation. In this case, the observed stellar metallicity difference (black thick line) is clearly not reproduced by the model, further suggesting that outflows do not play a major part. Error bars on the black line indicate the 1σ uncertainty in the metallicity difference.
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Acknowledgements We thank A. Gallazzi and her collaborators for making their SDSS DR4 version of the stellar ages and metallicities catalogues publicly available. We thank S. Lilly, A. Renzini, H.-W. Rix and M. Haehnelt for useful discussions. We acknowledge NASA’s IDL Astronomy Users Library, the IDL code base maintained by D. Schlegel, and the idlcorrect software package of M. Blanton.

Author Contributions Y.P. and R.M. co-developed the idea; both contributed to the interpretation and manuscript writing. Y.P. and R.C. contributed to the measurements and analysis.

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METHODS
Sample and observational data. The parent sample of galaxies analysed in this paper is the SDSS DR7 sample that is used in refs 15 and 31 for similar statistical investigations of the quenching process. Briefly, it is a magnitude-selected sample of galaxies in the redshift range of 0.02 < z < 0.085 that have clean photometry and Petrosian SDSS r-band magnitudes in the range 10.0 < r < 18.0 after correcting for Galactic extinction. The parent photometric sample contains 1,579,314 objects after removing duplicates, of which 238,474 have reliable spectroscopic redshift measurements. As a consequence of the relatively broad redshift range 0.02 < z < 0.085, the projected physical aperture of the SDSS spectroscopic fibre changes substantially across the sample. To test whether there are any noticeable aperture effects, we further split the whole redshift range into two narrower redshift ranges at 0.02 < z < 0.05 and 0.05 < z < 0.085. The results are shown in the Extended Data Fig. 2. It is clear that the results change little as a function of redshift.

Each galaxy is weighted by 1/\text{TSR} \times 1/V_{\text{max}} where TSR is a spatial target sampling rate, determined using the fraction of objects that have spectra in the parent photometric sample within the minimum SDSS fibre spacing of 55 arcsec of a given object. The \(V_{\text{max}}\) values are derived from the k-correction program v4_1.4 (ref. 32). The use of \(V_{\text{max}}\) weighting allows us safely to include representatives of the galaxy population down to a stellar mass of about 10^9M_\odot.

The stellar masses are determined from the k-correction code using population synthesis models and a Chabrier initial mass function. The galaxy population is then divided into star-forming and passive galaxies, based on their spectroscopic emission line classifications and rest-frame \((U - B)\) colours. Star-forming galaxies are defined to have the classification flag (that is, the "class" keyword), in the SFR catalogue set to 1. This also excludes those hosts hosting an active galactic nucleus, for which the derived metallicities are probably not reliable. Passive galaxies are defined to have their \((U - B)\) colours redder than a threshold colour that is given by equation (2) in ref. 15 and without H\alpha emission (that is, undetected with S/N < 3).

The stellar metallicities and r-band weighted stellar ages were derived by ref. 35 from the spectral absorption features of SDSS Data Release 4 spectra, which are then cross-matched with our parent galaxy sample. We refer to ref. 35 for a detailed description of the method. Here, we mention only that the method consists of measuring the strength of a set of carefully selected spectral absorption features, including several well calibrated Lick indices and the 4,000 Å break. Then they compute the median-likelihood estimates of the stellar metallicities and r-band weighted ages by comparing the spectral absorption features to a large library of 150,000 Monte Carlo realizations spanning a full range of physically plausible star-formation histories. The stellar metallicities are derived for both passive and star-forming galaxies, for which the contamination of stellar absorption features by nebular emission has been carefully removed. To ensure a reliable metallicity measurement, we restrict our galaxy sample to galaxies that have a median S/N per pixel of at least 20 over the whole spectrum. This ensures the average uncertainty of the stellar metallicity and light-weighted age to be less than ±0.15 dex. The requirement on the S/N could, in principle, be lowered to increase the statistics, but this would result in higher uncertainties in the metallicity and age measurements. Since the statistical errors on the mean metallicity and mean age are already reasonably small with the above S/N selection, the analysis benefits more from solid measurements than from improved statistics.

With the selection criteria given above, the final sample consists of 22,618 passive galaxies and 3,965 star-forming galaxies. All of these galaxies have reliable stellar mass, stellar metallicities and age measurements.

Metallicity evolution during quenching via strangulation. The quenching process via strangulation can be quantitatively described by using the analytical framework discussed in refs 36 and 37. These simple analytical models take into account the key physical processes of inflow, star formation, outflow and metal production. We assume the star-formation law holds in the same way before and during the quenching process, that is, the instantaneous average SFR of the galaxy is always related to the gas mass present within the galaxy as:

\[
\text{SFR} = \epsilon M_{\text{gas}}
\]

where \(M_{\text{gas}}\) is the total gas mass (both atomic and molecular). In fact, equation (1) can be regarded as the definition of effective, global star-formation efficiency \(\epsilon\) or, more properly, the inverse of the total gas depletion time \(t_{\text{dep}} = M_{\text{gas}}/\text{SFR}\) = \(1/\epsilon\). Note that, from equation (1), the specific SFR can be expressed as: specific SFR = \(SFR/M_{\text{star}} = \epsilon M_{\text{gas}}/M_{\text{star}}\).

The mass-loss rate of the gas \(\Psi\), that is, the outflow rate, is very likely to be closely related to the average SFR of the galaxy. Analogously to equation (1), we link these two quantities together via \(\lambda\), to give:

\[
\Psi = \lambda SFR
\]

where \(\lambda\) is the mass-loading factor. Similar to \(\epsilon\), equation (2) can be regarded as the definition of \(\lambda\). It should be noted that strangulating the gas inflow does not necessarily turn the gas regulator model to a simple close-box model, since the galaxy can continue to have an outflow.

The general evolution of the gas metallicity \(Z_{\text{gas}}\), without assuming any equilibrium condition, is given by equation (32) in ref. 37, that is:

\[
\frac{dZ_{\text{gas}}}{dt} = ye - (Z_{\text{gas}} - Z_0) \frac{\Phi}{M_{\text{gas}}}
\]

where \(y\) is the average yield per stellar generation and it is assumed to be a constant, \(\Phi\) is the inflow rate, \(Z_0\) is the metallicity of the infalling gas and \(M_{\text{gas}}\) is the gas mass. When quenching via strangulation starts, \(\Phi\) is set to zero and equation (3) can be easily solved:

\[
Z_{\text{gas}}(t) = Z_{\text{gas}}(t_q) + ye t
\]

where \(Z_{\text{gas}}(t_q)\) is the gas metallicity at the time when quenching begins. It is clear from equation (4) that \(Z_{\text{gas}}(t)\) is proportional to the yield \(y\) if \(Z_0 = 0\). By inserting it into the right-hand side of equation (5), \(y\) will cancel out from both the numerator and denominator. Therefore, when the inflow is truncated, the gas metallicity is independent of the outflow.

From equation (4), the logarithmic increase of the gas metallicity when quenching begins is given by:

\[
\log Z_{\text{gas}}(t) - \log Z_{\text{gas}}(t_q) = \log[(1 + ye t) Z_{\text{gas}}(t_q)]
\]

Before the start of the quenching, according to equation (35) in ref. 37, \(Z_{\text{gas}}\) is proportional to the yield \(y\) if \(Z_0 = 0\). By inserting it into the right-hand side of equation (5), \(y\) will cancel out from both the numerator and denominator. Therefore, the outflow is truncated, the amount of logarithmic increase of the gas metallicity is independent of the yield. Hence, any uncertainty on the yield is completely irrelevant to our analysis.

The general evolution of the stellar metallicity \(Z_{\text{star}}\), without assuming any equilibrium condition, is given by equation (40) in ref. 37 as:

\[
\frac{dZ_{\text{star}}}{dt} = \frac{y}{M_{\text{t}}} (1 - R)(Z_{\text{gas}} - Z_{\text{star}})
\]

where \(R\) is the fraction of the mass of the newly formed stars that is quickly returned to the interstellar medium through stellar winds and supernovae. It is clear from equation (6) that the stellar metallicity simply evolves towards the gas metallicity on a timescale controlled by (specific SFR)^{-1}.

The change of stellar mass of the galaxy per unit time is given by:

\[
\frac{dM_{\text{star}}}{dt} = (1 - R)\frac{\text{SFR}}{M_{\text{gas}}}
\]

where \((1 - R)\text{SFR}\) is the net SFR that contributes to the net stellar mass increase of the galaxy, that is, the fraction of newly produced stars in the form of long-lived stars. The change of the gas mass of the galaxy per unit time is given by:

\[
\frac{dM_{\text{gas}}}{dt} = -(1 - R)\text{SFR} - \Psi = -(1 - R + \lambda) M_{\text{gas}}
\]

To calculate the change of the stellar metallicity during quenching, we need to know, at a given stellar mass, the gas mass (or equivalently the gas fraction), the star-formation efficiency \(\epsilon\) and the mass-loading factor \(\lambda\).

For \(\lambda\), we first assumed that, during the strangulation process, the galaxy can recycle all the outflow gas by setting \(\lambda = 0\), that is, we assumed a close-box model. Then, as discussed in the text, we also investigated the case of \(\lambda = 1\) during strangulation.

Both gas fraction and star-formation efficiency \(\epsilon\) (or equivalently the gas depletion timescale \(t_{\text{dep}}\)) have been measured observationally\cite{36,37,38}. In fact, the predicted gas fraction and \(\epsilon\) determined using the model in ref. 37 match the latest observations in the local Universe extremely well, as shown in the Extended Data Fig. 1. We stress again that the gas fraction and star-formation efficiency in all our calculations are defined with the total gas mass (including both atomic and molecular). While in some previous work, such as ref. 38, the average gas depletion time is found to be constant at about 2 Gyr, which refers to the molecular gas depletion time (see subsection 'Effect of constant \(i\) on stellar metallicity evolution' below).

The change in stellar metallicity as a function of stellar mass at different times \(\Delta t\) after strangulation is shown in Fig. 2b (for \(\lambda = 0\)). During strangulation galaxies will continue to form stars with the available gas following the star-formation law given by equation (1) and their stellar mass will hence continue to grow. The coloured solid lines show the stellar metallicity increase as a function of the final
stellar mass, while the coloured dashed lines show the stellar metallicity increase as a function of the stellar mass at the epoch when the strangulation starts. As shown in Fig. 2b, the stellar metallicity increase is slightly larger if the stellar mass considered is the final stellar mass, but there are no substantial differences between these two stellar masses.

At a given stellar mass, the amount of stellar metallicity increase is nearly proportional to the time $\Delta t$ elapsed from the beginning of strangulation. At a given $M$ the stellar metallicity increase is larger for low-mass galaxies than for more-massive galaxies. This is because the variation of stellar metallicity depends on the size of the gas reservoir, that is, the gas fraction, at the epoch when the strangulation starts (the larger the gas reservoir, the more metals can be produced in the strangulation phase). For massive galaxies, which have a low gas fraction (Extended Data Fig. 1a), the relative amount of gas available for star formation is small, while the existing stellar population (with relatively low metallicity) is large compared to the amount of new stars (with higher metallicity) that will form during the strangulation. Therefore, although the star-formation efficiency is higher for massive galaxies (Extended Data Fig. 1b), the increase in stellar metallicity is smaller for massive galaxies than for low-mass galaxies (Fig. 2b).

It is evident, as discussed in the main text, that the observed metallicity difference can be very well reproduced by a simple close-box model with a constant mass-independent $\Delta t = 4$ Gyr across the entire observed range of stellar masses, which is consistent with the age difference between the two populations (Fig. 3b). We stress that a different stellar metallicity calibration and age calibration methods may give different scales and different slopes of the stellar mass versus metallicity/age relations, but the results illustrated above are preserved regardless of the adopted calibration. This is because our results are mainly based on metallicity differences and age differences between star-forming and passive galaxies, that is, we are dealing with differential quantities, and therefore uncertainties in the metallicity/age scale are much less critical than in studies dealing with absolute quantities.

Finally, we discuss one second-order effect that we have not taken into consideration, but which would further reinforce our results. The star-forming progenitors of passive (quenched) galaxies observed locally should be star-forming galaxies at $z = 0.5$ (that is, 4 Gyr ago), and not the star-forming population observed locally in SDSS. Unfortunately, SDSS does not have the sensitivity to deliver star-forming galaxies at high redshifts in large numbers and with the same $S/N$ as local star-forming galaxies. However, star-forming galaxies at $z = 0.5$ should have a metallicity even lower than local galaxies. Therefore, if any, the metallicity difference between passive and star-forming galaxies observed in Fig. 2 should be even larger. However, this effect is expected to be very small, since the mass–metallicity relation evolves very little from $z = 0$ to $z = 0.5$ (refs 39 and 40).

Stellar metallicity for central and satellite galaxies. Since a distinction between central and satellite galaxies appears in many theoretical models for the evolution of galaxies and may potentially shed light on the strangulation mechanism, we further divide the whole sample into central and satellite galaxies and the results are shown in the Extended Data Fig. 3. As discussed in ref. 31, there are difficulties in the identification of true central galaxies due to over-fragmentation of groups by the group-finding algorithm, which would lead to some satellites being misidentified as central galaxies. This effect is expected to be most severe for low-mass galaxies in high-density regions. To obtain a clean sample of true central galaxies, we further select the central galaxies in the fields, where their over-densities are below the mean over-density of the local Universe. The stellar metallicity enhancement of satellites is slightly larger than that of central galaxies at $M_{\text{star}} < 10^{11}M_\odot$. This suggests that low-mass satellites are likely to suffer more from the strangulation than central galaxies and hence implies an environmental origin of strangulation at these low masses (for example, inflow of gas being halted as satellite galaxies plunge into the hot halos). At masses $M_{\text{star}} > 10^{11}M_\odot$ no difference between central galaxies and satellites is detected. This suggests that at high masses the strangulation process may operate similarly for both central galaxies and satellites. A more detailed analysis, in different environments, is required to untie the origin of strangulation at high masses, which will be presented in a future work.

Fraction of galaxies quenched by rapid gas removal. We argue here that the majority of local quiescent galaxies with $M_{\text{star}} < 10^{11}M_\odot$ is primarily quenched as a consequence of strangulation. This is a statistical statement, based on the average properties of the galaxy population. It is, however, interesting to quantify the fraction of galaxies whose data may potentially allow for rapid quenching by sudden gas removal (which does not cause a metallicity change) as an alternative viable process.

In each panel of Extended Data Fig. 4, we show the probability density function (PDF) of the stellar metallicity of star-forming galaxies (blue line) and that of the passive galaxies (red line) at a given stellar mass. Each PDF is normalized (that is, the area beneath each curve is unity). The overlapping region of the two PDFs is shaded (light red). The fraction of the shaded over the total area given by the blue PDF is noted as $f_{\text{max}}$ in the label. If all star-forming galaxies were eventually to be quenched, the star-forming PDF (blue line) should eventually evolve into the passive PDF (red line).

The evident difference between star-forming and passive metallicity implies that strangulation is the primary quenching process. The opposite is not necessarily true: a similar metallicity for star-forming and passive galaxies may be caused either by sudden gas removal (such as outflows and gas stripping) or strangulation of galaxies with modest gas content. Furthermore, we also note that if the metallicity of a star-forming galaxy is similar to those of passive ones, this could mean that this galaxy initially had large gas content, was strangled, and we are observing it during the last stage of star formation in its strangulation phase. Therefore the shaded area, and hence $f_{\text{max}}$, give a very conservative upper limit to the fraction of galaxies for which sudden gas removal can potentially be an alternative quenching mechanism.

The value of $f_{\text{max}}$ is 50% at low masses, confirming that most of the galaxies at low masses must be quenched by strangulation. We recall, as discussed above, that this is a very conservative approach. $f_{\text{max}}$ progressively increases with increasing stellar mass. This effect is due to the fact that the observed stellar metallicity enhancement decreases with increasing stellar mass, as shown in Fig. 2b, in which the lines with different $\Delta t$ converge to zero with increasing mass. This implies that, as already discussed, the constraining power of the stellar metallicity data on the quenching mechanism decreases with increasing mass. In the most massive cases of $M_{\text{star}} > 10^{11}M_\odot$, the stellar metallicity data cannot shed light on the quenching mechanism, because the small metallicity difference can be interpreted equally well as rapid quenching by sudden gas removal or as quenching by strangulation.

**Effect of constant $e$ on stellar metallicity evolution.** As discussed in the subsection ‘metallicity evolution during quenching via strangulation’, although the star-formation efficiency $e$ defined with the total gas mass ($e = \text{SFR}/(M_{\text{H2}} + M_{\text{HI}})$) is very unlikely to be constant, it is useful to test the validity of the result further in Fig. 2b against a putative constant $e$. We keep all other parameters unchanged in the model, except that when strangulation starts we set $e$ to be constant at 0.5 Gyr$^{-1}$, that is, a constant gas depletion timescale of $\tau_{\text{gal}} = 2$ Gyr. The results are shown in the Extended Data Fig. 5. It is clear that at $M_{\text{star}} \approx 10^{10}M_\odot$, the prediction from the model is very similar to Fig. 2b and is still consistent with $\Delta t = 4$ Gyr or 5 Gyr. This is because the average $e$ in the Extended Data Fig. 1b at $M_{\text{star}} \approx 10^{10}M_\odot$ is roughly 0.5 Gyr$^{-1}$. However, below about $10^{10}M_\odot$, the model now predicts a much steeper metallicity increase, owing to the adopted constant value of $e = 0.5 \text{ Gyr}^{-1}$ that is much higher than the one shown in the Extended Data Fig. 1b. This suggests that, to achieve the same observed metallicity enhancement, a higher $e$ will need a shorter $\Delta t$. In other words, the strangulation process can be fast (for example, less than 1 Gyr) if the $e$ is large (for instance, at higher redshifts$^{31}$).

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Extended Data Figure 1 | Gas fraction and star-formation efficiency for star-forming galaxies. a, The observed total gas fraction for local galaxies determined using a constant $X_{\text{CO}}$ (black dashed line) and an H-band luminosity-dependent conversion factor (black solid line) in Boselli et al. The predicted total gas fraction (molecular and atomic) for star-forming galaxies as a function of stellar mass from the Peng and Maiolino model at $z = 0.05$ (red solid line). b, Star-formation efficiency $\epsilon$, defined as $\epsilon = \text{SFR}/M_{\text{gas}}$, that is, the reverse of the gas depletion timescale, as a function of stellar mass.
Extended Data Figure 2 | Stellar metallicity difference for different redshift bins. To investigate any aperture effects, the sample over the whole redshift range $0.02 < z < 0.085$ is further divided into two narrower redshift ranges of $0.02 < z < 0.05$ and $0.05 < z < 0.085$. It is clear that the derived stellar metallicity difference changes little as a function of redshift, that is, as a function of projected aperture. The error bars on each line indicate the 1σ uncertainty in the metallicity difference.
Extended Data Figure 3 | Stellar metallicity difference for central and satellite galaxies. The whole sample is further divided into central galaxies and satellites. The orange line shows the central galaxies in the field, which represents a clean sample of true central galaxies, as explained in the text. The stellar metallicity enhancement of satellites is slightly larger than that of central galaxies at $M_{\text{star}} < 10^{10} M_\odot$ (suggesting that environment may play a part in the strangulation mechanism at these low masses), while no detectable difference between them is seen at higher stellar masses. The error bars indicate the $1\sigma$ uncertainty in the metallicity difference.
Extended Data Figure 4 | Probability density function of star-forming and passive galaxies. In each panel the blue line shows the probability density function (PDF) of the stellar metallicity of star-forming galaxies for a given stellar mass and the red line shows the corresponding PDF of passive galaxies. The overlapping region of the two PDFs is shaded (light red). The fraction of the shaded area over the total area given by each of PDF ($f_{\text{max}}$) gives the maximum fraction of galaxies for which rapid gas removal may be an allowed alternative quenching mechanism.
Extended Data Figure 5 | Effect of a constant star-formation efficiency on stellar metallicity evolution. As for Fig. 2b, but for the case of a constant star-formation efficiency of $\varepsilon = 0.5 \text{ Gyr}^{-1}$ (that is, a constant gas depletion timescale of $\tau_{\text{dep}} = 2 \text{ Gyr}$) after strangulation. At $M_{\text{star}} > 10^{10} M_\odot$, the observed mass-dependent metallicity enhancement is still consistently $\Delta t = 4$ or 5 Gyr, while at lower stellar masses it requires a shorter $\Delta t$, as explained in the text. Error bars on the black line indicate the 1σ uncertainty in the metallicity difference.