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Rejuvenation triggers nuclear activity in nearby galaxies

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Galaxies, forming and evolving within their host dark matter haloes, are the end-product of a balance between gas cooling, star formation and feedback^{1–3}. Energy/Momentum feedback, in particular from active galactic nuclei (AGN), is believed to play a crucial role in the evolution of galaxies by gradually quenching their star formation^{4,5}. In the local Universe many galaxies with an AGN are indeed observed to reside in the so-called green valley, usually interpreted as a transition phase from a blue star formation epoch to a red quenched state^{6–8}. We use data from the Sloan Digital Sky Survey to show that such an interpretation requires substantial revision. Optically-selected nearby AGN galaxies follow exponentially declining star formation histories, as normal galaxies of similar stellar and dark matter halo mass, reaching in the recent past (~ 0.1 Gyr ago) star formation rate levels consistent with a quiescent population. However, we find that local AGN galaxies have experienced a sudden increase in their star formation rate, unfolding on timescales similar to those typical of AGN activity, suggesting that both star formation and AGN activity were triggered simultaneously. We find that this quenching process followed by an enhancement in the star formation rate is common to AGN galaxies and more pronounced in early type galaxies. Our results demonstrate that local AGN galaxies are not a transition type between star-forming and quiescent galaxies as previously postulated, but simply galaxies experiencing a recent gas accretion episode.

The formation and evolution of galaxies is still an open and unsolved issue. In particular, it is highly unclear how galaxies transition from a star-forming to quenched phase. One of the most popular processes invoked to cease or reduce star formation in galaxies is the so-called energetic/momentum AGN feedback. A supermassive black hole accreting gas from the surroundings can in fact generate enough energy/momentum to heat up/expel the gas from the host galaxy via winds and/or jets. Observational evidence in the local Universe in support of this process was put forward in the past by preliminary results showing that local galaxies hosting AGN are preferentially in the so-called "green" valley, i.e. they indeed appear as galaxies transitioning from a blue star-forming sequence to a red and dead phase⁹. In the present study we revisit this hypothesis by carefully and homogeneously analyzing a large Sloan Digital Sky Server¹⁰ (SDSS) sample of 3,314 nearby ($z \sim 0.1$) galaxies.

The sample was selected as follows. First, we compiled publicly-available black hole masses derived from SDSS single-epoch optical spectroscopy^{11–16} (see Methods for details). We then cross-matched this initial sample with a catalog of groups and clusters, also identified in SDSS¹⁷, with estimated dark matter halo masses. We limited our analysis to central galaxies. Finally, we fitted the optical spectra of our sample with a regularized linear combination^{18,19} of single stellar population models²⁰. Since spectroscopic measurements are more sensitive to changes in the stellar population properties than photometric ones²¹, our approach yields, not only a detailed reconstruction of the star formation histories of our sample of galaxies, but also much more accurate stellar mass measurements than standard broad-band spectral energy distribution fittings. Details on the sample and on the stellar population analysis are extensively discussed

Figure 1. Rejuvenation of active galaxies. Evolution of the sSFR for our sample of active (blue) and control (orange) samples. The sSFR of both AGN and control samples has continuously decreased for more than 10 Gyr, reaching values consistent with a quiescent population ($\log \text{sSFR} < -11 \text{ yr}^{-1}$). However, our AGN sample has experienced a recent (last ~ 0.1 Gyr) increase in the sSFR. Shaded areas indicate the 1σ confidence interval.

in the Methods section, along with a table listing some key properties of each galaxy in the sample.

Our final sample consists of central, currently active galaxies with known halo and stellar masses, and for which we derived detailed, non-parametric star formation histories from their integrated spectra. For reference, we also selected a control sample of central galaxies with the same stellar masses as our main sample but with no optical AGN features (see Methods for more details on the sample selection). This control sample allowed us to investigate whether the formation history of galaxies currently exhibiting nuclear activity (as revealed by their broad line emission) differs from the general population of galaxies with the same stellar mass.

Fig. 1 shows the evolution of the specific star formation rate (sSFR) as function of time for our AGN sample (in blue) and our $M_\star$ -matched control sample (in orange). Interestingly, the sSFR in both samples has been steadily decreasing for most of their (observed) evolution, reaching sSFR values consistent with a quiescent population ($\sim 10^{-11} \text{ yr}^{-1}$) until very recent epochs (~ 0.1 Gyr ago). However, a sudden increase in the sSFR at look-back times of ~ 0.1 Gyr is observed in our sample of active galaxies, gradually departing from the quiescent population at $z \sim 0$.

While the logarithmic scale of Fig. 1 facilitates the visualization of recent star formation episodes, quenching time-scales are more evident in linear units. In Fig. 2 we show how the sSFR of the AGN population changes as a function of time, dividing our sample into later (LTG, in turquoise) and earlier (ETG, dark blue) morphological types, according to the SDSS imaging pipeline²². Two distinct phases in the evolution of the sSFR become clear from panel (a) in Fig. 2. An initial *slow quenching*, characterized by a steady decrease in the sSFR for around ~ 10 Gyr ($\Delta \text{sSFR} / \Delta t \sim 0.1 \text{ dex/Gyr}$), is followed by an abrupt *fast quenching* stage where the sSFR drops by up to an order of magnitude (i.e. $\Delta \text{sSFR} / \Delta t \sim 1 \text{ dex/Gyr}$). This *fast quenching* is responsible for driving the sSFR of our AGN sample from the star-forming to the

Figure 2. Slow and rapid quenching in active galaxies. Panel (a) shows how the initial and long-lasting quenching process in our AGN sample is followed by a fast quenching phase. Panel (b) is a zoom-in into the last 2.5 Gyr, revealing the morphological dependence of this fast quenching stage, which happens more abruptly in ETGs. The ubiquitous rejuvenation process becomes clear for ages younger than ~ 0.1 Gyr. Shaded areas indicate the 1σ confidence interval.

quiescent population and it is mainly driven by the (dominant) ETG population. Panel (b) in Fig. 2 reveals how *fast quenching* is morphology-dependent, as it happens faster in ETGs than in LTGs, in agreement with previous results⁶. For both ETGs and LTGs, the rejuvenation process showcased in Fig. 1 is evident.

It is worth noting here that stellar evolution determines the time resolution of star formation histories measured from integrated spectra. Changes in the spectra of young stellar populations are much faster than in old stars. Hence, star formation events can only be measured when the time resolution of stellar population models is of the order of the star formation time-scales, which effectively only happens at young ages. We note that additional rejuvenation events might have occurred in the past histories of these galaxies but they cannot be detected due to the coarse resolution of stellar population models at older ages.

A close inspection reveals two key differences in the star formation histories of our AGN and control samples. First, the typical age of AGN-hosting galaxies is younger (9.6 ± 0.2 Gyr) than the average population of galaxies at the same mass range (11.0 ± 0.2 Gyr). As shown in panel (a) of Fig. 3, this results from a delayed mass growth in AGN galaxies, unrelated to the rejuvenation episode which barely contributes to the actual mass growth. Second, the average halo mass of our AGN sample is also systematically higher than in the control sample ($\log M_{\text{halo}} = 12.45 \pm 0.01$ and 12.30 ± 0.01 $M_{\odot}$, respectively, where the confidence interval accounts for the statistical variance, not the systematic uncertainty). Albeit small, this offset in the average halo mass has a direct effect on the formation histories of galaxies. Panel (b) of Fig. 3 compares the formation history of our AGN sample with a control sample matched in both stellar and halo mass. The comparison between panels (a) and (b) in Fig. 3 evidences a striking observational result: at fixed stellar mass, galaxies grew their stellar component at a different rate depending on the mass of their host halo. Furthermore, active galaxies are indistinguishable from the average population of galaxies with the same stellar and halo mass.

The stellar-to-halo mass relation (SHMR) is a useful tool to probe galaxy evolution in a cosmological context, as it provides the average link between galaxies and host dark matter haloes which can then be tested against galaxy evolutionary models. Also the dispersion (scatter) around the mean of this relation

Figure 3. Formation history comparison. In Panel (a), the cumulative mass growth of our AGN sample (blue) is compared to our M_* -matched control sample (orange). Due to the observed formation delay, AGN galaxies are younger than the average population with the same stellar mass. Similarly, panel (b) shows how the AGN sample compares to the control sample, this time matched in both stellar and halo masses. In this case, the formation history of AGN galaxies is indistinguishable from the control sample. Shaded areas indicate the 1σ confidence interval and horizontal dashed lines mark when 25, 50, 75, and 90% of the stellar mass was formed.

has been suggested to correlate with the properties and formation history of the host dark matter halos²³. Fig. 4 shows the SHMR for our combined AGN and M_* -matched control samples, color-coded by the age of the central galaxy. Interestingly, at fixed halo mass, galaxies with higher stellar masses tend to be older. Isochrones across the SHMR are marked with solid lines, where galaxy ages have been translated into formation redshifts. The observed trend resembles the predicted correlation between halo formation time and the scatter in the SHMR, where galaxies with higher M_*/M_{halo} are hosted by earlier-formed halos²⁴. Note that these differences in age across the SHMR translate into a morphological separation, as ETGs tend to have older stellar population than LTGs.

Furthermore, Fig. 4 helps to provide a coherent interpretation of the observed differences between our AGN and control samples. At fixed stellar mass, AGN galaxies are on average hosted by more massive halos which, as noted above, are known to have formed later. Therefore, the delayed mass growth of AGN galaxies, and hence their younger ages, compared to the overall population of galaxies with the same stellar mass can be interpreted as the result of a late formation time of their host halos. In this scenario, AGN galaxies and their host halos would be systems less evolved than the mean population of galaxies in the same stellar mass range. Moreover, we propose that the rejuvenation process exhibited by AGN galaxies is also a consequence of their relatively younger evolutionary stage, as more gas is expected to be available than in more evolved halos hosting older galaxies. At fixed stellar and halo mass, local active and inactive galaxies show the same formation history, and whether a galaxy is optically classified as AGN or not likely relies on a stochastic gas infall process that is able to fuel the central black hole, leading as well to the observed rejuvenation phase²⁵. Halo mass is therefore a critical quantity to understand the formation history of galaxies.

Our results have also direct implications on our understanding of the quenching process of massive galaxies. Given the average stellar and black hole mass of our sample ($10.4 M_\odot$ and $7.4 M_\odot$, respectively),

Figure 4. Stellar-to-halo mass relation. The SHMR is shown for our sample of AGN galaxies and the M_* -matched control sample, color-coded by the mean age of the central galaxy. Lines of constant age (isochrones) are shown with a solid line, where ages have been translated into formation redshifts. Our sample of AGN galaxies (blue dot) is hosted by more massive halos than the M_* -matched one (orange dot), which also results in AGN galaxies being younger than the average population at the same stellar mass.

the expected AGN lifetime is $\sim 10^8$ year²⁶, which is of the order of the rejuvenation time-scale as shown in Fig. 1. Therefore, our observations suggest that both AGN and star formation activity are triggered simultaneously. Moreover, as revealed by Fig. 2, a prolonged star formation quenching preceded this onset of recent star formation and AGN activity in our sample. Note that this does not imply that AGN feedback is not responsible for quenching the star formation. Successive rejuvenation and nuclear activity episodes can be part of the expected quenching process of local galaxies, heating up the gas within halos up until it becomes too hot to further sustain any steady star formation²⁷.

More generally, our results invalidate a naïve interpretation of local AGN galaxies as a transition type between the star forming and quiescent population of galaxies⁹. On the contrary, galaxies currently showing nuclear activity and located in the green valley were effectively part of the quiescent population but have recently moved towards (and not from) the main sequence. This interpretation is in line with the idea that AGN activity and quenching time-scales are decoupled²⁸, explaining the rather weak correlation between AGN luminosity and SFR observed in galaxies²⁹.

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Author contributions statement

All three authors participated in the discussion, the interpretation of the results, and in detailed editing of the manuscript. IMN performed the stellar population analysis and wrote the manuscript.

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Methods

1 Stellar population analysis

In order to measure the star formation history (SFH) of each galaxy we fit the observed SDSS optical spectrum using the Penalized Pixel-Fitting (pPXF) method^{18,19}. The basic idea behind pPXF is to find the best-fitting linear combination of single stellar population (SSP) models that reproduces a given input spectrum. In short, given an set of SSPs arranged in a sorted array, pPXF finds the optimal weight of each SSP model in order to match the observed spectrum. Therefore, the SFH of a galaxy, i.e., the fraction of mass contained in stars of different ages, is naturally recovered in an non-parametric manner from our modeling approach. Following the same idea, the evolution in time of the SFR can be recovered from an integrated spectra by simply dividing the observed mass fractions by the time-step of the SSP models.

Given the ill-conditioned nature of this inversion problem^{30,31}, the best linear combination of SSPs needs to be regularized in order to avoid non-physical distributions. In pPXF this is done by means of the regularization parameter λ in Equation 27 of¹⁹. In practice, λ controls the *smoothness* of the best-fitting solution and there is not a unique way of determining its ideal value³². For consistency, we adopted the same value of $\lambda = 1/0.05$ for every galaxy in our sample. Note that changes in λ only lead to subtle variations in the recovered SFHs, but low-order moments of the age distribution (e.g. mean ages) are robustly measured, as well as overall trends (e.g quenching and rejuvenation events). The reliability of pPXF-based SFHs has been thoroughly tested on a wide variety of spectroscopic data, including synthetic predictions^{31,33}, semi-resolved systems³⁴, AGN galaxies³⁵, compact objects^{36–38}, and both quiescent and star-forming galaxies^{39–43}.

In addition to the stellar population content, with pPXF we also measured the kinematical properties of each spectra, in particular its systemic velocity and its stellar velocity dispersion. No higher moments of the line-of-sight velocity distribution were measured as their impact on the recovered stellar population properties is negligible. Both kinematics and stellar populations were measured simultaneously on the observed spectra.

We fed pPXF with the last generation of MILES stellar population synthesis models²⁰. These models rely on the empirical MILES stellar library⁴⁴ and have an intrinsic resolution of $2.51 \text{ \AA}$ ⁴⁵, high enough to be used along with the SDSS spectroscopic data. We adopted the version of the MILES models based on the BaSTI isochrones^{46,47}, covering a range in age from 0.03 to 14 Gyr, and from -2.27 to 0.26 in total metallicity $[M/H]$. These models also allow for variations in the $[\alpha/Fe]$ ratio, with predictions at $[\alpha/Fe] = 0.0$ and $[\alpha/Fe]=0.4$.

The final ingredient needed for a proper modeling of the SDSS data are the emission line templates. By construction, our sample of AGN galaxies exhibits clear broad Balmer lines on top of a series of narrower emission lines across the whole optical range. We modeled narrow and broad emission lines by including in the pPXF fitting three kinematically independent components, one broad for the Balmer lines, and two narrow components for all lines (including the Balmer ones). The inclusion of this second narrow component is meant to account for deviations from a pure gaussian profile, as it was needed for the most prominent emission lines, but with no particular physical meaning. The relative amplitude of the different Balmer lines was fixed to the theoretical expectations. For the AGN sample, we also included the possible emission from ionized iron lines⁴⁸ as a separate kinematical component. All lines within a kinematical component share their same kinematical properties, namely, V and σ . For the control samples, a single narrow-line emission component was enough to properly fit the data. Emission and absorption templates were all fit simultaneously not to bias the best-fitting stellar population solution.

In short, for every galaxy, we fit its SDSS optical spectra using pPXF in order to non-parametrically measure its SFH. This fitting scheme included MILES SSP models to reproduce the stellar absorption

Extended Data Figure 1. Optical SDSS spectrum and best-fitting model. The red line in the top panel shows the observed SDSS data over the fitted wavelength range. We show the best-fitting FeII and gas emission templates in fuchsia and green, respectively, and in blue the stellar absorption spectra. The black line indicates the total best-fitting model while the gray dots show the fitting residuals. The bottom panel shows a closer look to the stellar absorption spectrum after corrected from the emission lines (in blue), with the best-fitting model included in black.

spectra, plus a series of narrow a broad emission lines to model the flux radiated by ionized gas. The complexity of the gas emission in AGN galaxies required a higher number of kinematical components, while the control samples were properly fitted with a simpler combination of templates. Our stellar population fitting focused on rest-frame wavelengths from $\lambda = 4000 \text{ Å}$ to $\lambda = 5500 \text{ Å}$, as it is the range where SSP models are more reliable and stellar population parameters can be more easily measured. We masked out those wavelengths affected by strong telluric lines. An example of the SDSS spectrum and best-fitting model is shown in Extended Data Figure 1.

2 Sample selection

Main sample: AGN galaxies

Our main sample of AGN galaxies compiles information from six published sources of black hole mass measurements^{11–16}. These black hole mass measurements are based on single-epoch SDSS spectroscopy of sources with prominent broad emission lines, assuming that the gas is virialized and obeys the following equation

$$\log M_{\bullet} = \alpha + \beta \log \left(\frac{L_{H\alpha}}{10^{42} \text{ erg s}^{-1}} \right) + \gamma \log \left(\frac{\text{FWHM}_{H\alpha}}{10^3 \text{ km s}^{-1}} \right)$$

To homogenize as much as possible the sample, we referenced all black hole mass measurements to the same virial factor $\alpha = \log 3.5/4$ since this assumption leads to a consistent comparison between quiescent and AGN galaxies⁴⁹. Black hole masses were compiled from the reference above, and only corrected to the same virial factor.

As described in the section above, the optical spectra of each galaxy in our sample was analyzed in order to estimate its best-fitting stellar population properties as a combination of SSP models. Therefore, our stellar population analysis naturally retrieves an expected mass-to-light ratio, more accurate and less degenerated than broad-band photometry estimates^{21,50}. We combined these spectroscopic-based mass-to-light estimates with k-corrected *r*-band photometry from the SDSS^{51,52} to derive our fiducial stellar masses.

Two additional quantities were needed to characterize our sample of AGN galaxies. First, the stellar velocity dispersion is generally regarded as the best proxy for the stellar population properties of galaxies^{53–55}, and it is also highly correlated with the measured black hole masses^{49,56–58}. As noted above, for each spectra we used pPXF to estimate the best-fitting stellar velocity dispersion. However, these measurements are based on the fixed size of the SDSS fibers and therefore they probe different physical scales depending on the distance and size of the observed galaxy. We homogenized our pPXF stellar velocity dispersion measurements using empirical calibrations of the velocity dispersion gradients in the CALIFA survey⁵⁹. Finally, we completed the characterization of our sample of AGN galaxies with halo mass estimates based on a catalog of SDSS groups and clusters¹⁷. We limit our sample to central galaxies only so we can more confidently compare the properties of the halo to those of the analyzed galaxy.

Having gathered all this information, our final sample consists of 3,314 central galaxies with black hole mass and halo mass estimates, and for which accurate stellar population properties, kinematical, and stellar mass measurements are available. Note that this final sample does not include galaxies whose SDSS optical spectra has not enough signal-to-noise to be properly fitted. These galaxies with an unreliable best-fitting model were easily identified as outliers in the distribution of kinematical and stellar population parameters. In practice, we excluded galaxies with velocity dispersions between 50 and 400 km s^{−1}, and with a reduced $\chi^2 < 1.2$ as derived from pPXF. The exact value for these thresholds does not significantly affect the reported trends but ensures that only properly fitted galaxies are included in the analysis. Extended Data Table 1 contains all the relevant information of our AGN galaxy sample.

Control samples

Relying on spectroscopic-based stellar mass-to-light measurements means that a detailed stellar population analysis is needed in order to measure stellar masses. Unfortunately, only color-based stellar mass estimates are available for the general population of SDSS galaxies and these can not be directly compared to our more precise measurements. Therefore, we selected our control samples in a two-step process. First, for each galaxy in our AGN sample, we used color-based stellar mass estimations to select a control galaxy with a similar stellar mass in the SDSS sample⁶⁰. Second, the spectrum of each galaxy in this initial control sample was analyzed in the same way as our AGN sample, i.e., fitting its observed spectra with a linear combination of SSP models using pPXF. This led to a detailed measurement of the stellar population properties and to a better estimate of the stellar mass as described above, consistent with our analysis of the AGN galaxies. We then removed galaxies optically classified as AGN and we selected again only central galaxies. Finally, we cross-matched for a second time the AGN sample with these

newly estimated stellar masses in order to define our final $M_{\star}$ -matched sample. In the case of the $M_{\star}$ plus M_{halo} -matched sample, we followed an identical approach, but in this case selecting galaxies with the same stellar and halo mass, although halo masses are not (explicitly) affected by our stellar population analysis and therefore were not recalculated.

ID	R.A.	Dec	$M_{\bullet}$	M_{halo}	$M_{\star}$	σ_{Reff}	Source
	[Deg]	[Deg]	[log $M_{\odot}$]	[log $M_{\odot}$]	[log $M_{\odot}$]	[km s ⁻¹]	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
J152143.15+054033.9	230.429	5.676	9.18	12.34	10.64±0.03	191.5 ± 4.6	5
J130008.00+035556.6	195.033	3.932	9.18	12.71	10.97±0.01	272.9 ± 12.3	5
J164331.91+304835.6	250.882	30.809	9.08	12.89	10.59±0.04	269.3 ± 12.4	5
...							

Extended Data Table 1. Main sample properties. (1) SDSS ID; (2), (3) Right ascension and declination (J2000); (4) Black hole mass, from the literature and corrected to the same virial factor; (5) Estimated halo mass, from the literature; (6) Stellar mass measurement based on the best-fitting stellar population properties derived from the optical SDSS spectrum; (7) Stellar velocity dispersion, measured from the SDSS optical spectrum and corrected to the effective radius of the galaxy; (8) Reference for the black hole mass measurement (0¹³, 1¹⁴, 2¹¹, 4¹², 5¹⁶, 6¹⁵).

Figures

Figure 1

Rejuvenation of active galaxies.

Figure 2

Slow and rapid quenching in active galaxies.

Figure 3

Formation history comparison.

Figure 4

Stellar-to-halo mass relation.