

Galaxy Zoo: Evidence for rapid, recent quenching across a population of AGN host galaxies

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ABSTRACT

We present a population study of the star formation history of 1,244 Type 2 AGN host galaxies, compared to 123,243 inactive galaxies using a Bayesian method. We find evidence for the Type 2 AGN host galaxies having undergone a recent (within 2 Gyr) and rapid drop in their star formation rate. AGN feedback is therefore important at least for this population of galaxies. This result is not seen for the inactive galaxies whose star formation histories are dominated by the effects of downsizing at earlier epochs, a secondary effect for the AGN host galaxies. We show that histories of rapid quenching cannot account fully for the quenching of all the star formation in a galaxy’s lifetime across the population of AGN host galaxies, and that histories of slower quenching, attributed to secular (non-violent) evolution, are also key in their evolution. This is in agreement with recent results showing both merger-driven and non-merger processes are contributing to the co-evolution of galaxies and supermassive black holes. The availability of gas in the reservoirs of a galaxy, and its ability to be replenished, appear to be the key drivers behind this co-evolution.

1 INTRODUCTION

The nature of the observed co-evolution of galaxies and their central supermassive black holes (Magorrian et al. 1998; Marconi & Hunt 2003; Haring & Rix 2004) and the effects of AGN feedback on galaxies are two of the most important open issues in galaxy evolution. AGN feedback was first suggested as a mechanism for regulating star formation in simulations (Silk & Rees 1998; Croton et al. 2006; Bower et al. 2006; Somerville et al. 2008) and indirect evidence has been observed for both positive and negative feedback in various systems (see the comprehensive review from Fabian 2006).

The strongest observational evidence for AGN feedback in a population is that the largest fraction of AGN are found in the green valley (Cowie & Barger 2008; Hickox et al. 2009; Schawinski et al. 2010), suggesting some link between AGN activity and the process of quenching which moves a galaxy

from the blue cloud to the red sequence. However, concrete statistical evidence for the effect of AGN feedback on the host galaxy population has so far been elusive.

Here we present a large observational population study of the quenching of Type 2 AGN host galaxies. We use a new Bayesian method (Smethurst et al. 2015) to effectively determine the most probable SFH of a galaxy, modelled with two parameters, time of quenching, t_q , and exponential rate, τ , given the observed near ultra-violet (NUV) and optical colours. **This builds on the work of Martin et al. (2007) and Schawinski et al. (2014), improving significantly on previous techniques.** We aim to determine the following: (i) Are galaxies currently hosting an AGN undergoing quenching? (ii) If so, when and at what rate does this quenching occur? (iii) Is this quenching occurring at different times and rates compared to a control sample of inactive galaxies?

The zero points of all magnitudes are in the AB system. Where necessary, we adopt the WMAP Seven-Year Cosmology (Jarosik et al. 2011) with $(\Omega_m, \Omega_\Lambda, h) = (0.26, 0.73, 0.71)$.

* This investigation has been made possible by the participation of over 350,000 users in the Galaxy Zoo project. Their contributions are acknowledged at <http://authors.galaxyzoo.org>

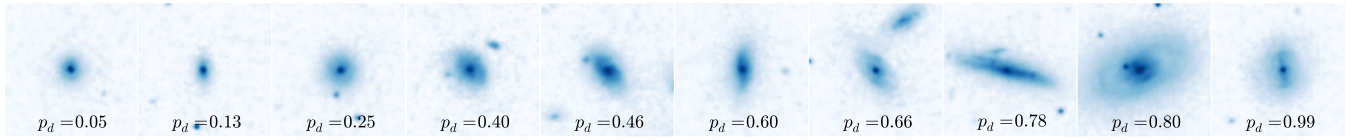


Figure 1. Randomly selected SDSS *gri* composite images from the sample of 1,244 Type 2 AGN in a redshift range $0.04 < z < 0.05$. The galaxies are ordered from least to most featured according to their debiased ‘disc or featured’ vote fraction, p_d (see Willett et al. 2013). The scale for each image is 0.099 arcsec/pixel.

2 DATA & METHODS

In this investigation we use visual classifications of galaxy morphologies from the Galaxy Zoo 2¹ (GZ2) citizen science project (Willett et al. 2013), which obtains multiple independent classifications for each optical image. The full question tree for an image is shown in Figure 1 of Willett et al. The GZ2 project used 304,022 images from the Sloan Digital Sky Survey Data Release 7 (SDSS; York et al. 2000; Abazajian et al. 2009) all classified by *at least* 17 independent users, with a mean number of classifications of ~ 42 .

Further to this, we required NUV photometry from the GALEX survey (Martin et al. 2005), within which $\sim 42\%$ of the GZ2 sample was observed, giving 126,316 galaxies total ($0.01 < z < 0.25$). This will be referred to as the GZ2-GALEX sample. The completeness of this sample ($-22 < M_u < -15$) is shown in Figure 2 of Smethurst et al. (2015).

Observed fluxes are corrected for galactic extinction (Oh et al. 2011) by applying the Cardelli et al. (1989) law. We also adopt *k*-corrections to $z = 0.0$ and obtain absolute magnitudes from the NYU-VAGC (Blanton et al. 2005; Padmanabhan et al. 2008; Blanton & Roweis 2007).

2.1 Bayesian SFH Determination

STARPY² is a PYTHON code which allows the user to derive the quenched star formation history (SFH) of a galaxy through a Bayesian Markov Chain Monte Carlo method (Foreman-Mackey et al. 2013)³ with the input of the observed $u-r$ and $NUV-u$ colours, a redshift, and the use of the stellar population models of Bruzual & Charlot (2003). These models are implemented using solar metallicity (varying this does not substantially affect these results; Smethurst et al. 2015) and a Chabrier IMF (Chabrier et al. 2003). The SFH is modelled as an exponential decline of the SFR described by two parameters $[t_q, \tau]$, where t_q is the time at the onset of quenching [Gyr] and τ is the exponential rate at which quenching occurs [Gyr]. Under the simplifying assumption that all galaxies formed at $t = 0$ Gyr with an initial burst of star formation, the SFH can be described as:

$$SFR = \begin{cases} i_{sfr}(t_q) & \text{if } t < t_q \\ i_{sfr}(t_q) \times \exp\left(\frac{-(t-t_q)}{\tau}\right) & \text{if } t > t_q \end{cases} \quad (1)$$

where i_{sfr} is an initial constant star formation rate dependent on t_q (Schawinski et al. 2014; Smethurst et al. 2015). A smaller τ value corresponds to a rapid quench, whereas a larger τ value corresponds to a slower quench. This SFH

model has previously been shown to appropriately characterise quenching galaxies (Weiner et al. 2006; Martin et al. 2007; Noeske et al. 2007; Schawinski et al. 2014).

The probabilistic fitting methods to this SFH for an observed galaxy are described in full detail in Section 3.2 of Smethurst et al. (2015), wherein the STARPY code was used to characterise the SFHs of the GZ2-GALEX sample. We assume a flat prior on all the model parameters and a double Gaussian likelihood function for the $u-r$ and $NUV-u$ colours (Equation 2 in Smethurst et al. 2015). The output of STARPY is probabilistic in nature and provides the posterior probability distribution across the entirety of the two parameter space for an individual galaxy. To study the SFH across a population of galaxies, these individual posterior probability distributions can be combined by summing each binned distribution. We obtain separate summed posterior probability distributions for both smooth and disc populations by using the GZ2 debiased vote fractions for disc (p_d) or smooth (p_s) morphologies as weights when summing, as in Smethurst et al. (2015). This ensures that the entirety of the population is used, with galaxies with a higher p_d contributing more to the disc weighted than the smooth weighted posterior distribution. This negates the need for a threshold on the GZ2 vote fractions (e.g., $p_d > 0.8$ as used in Schawinski et al. 2014).

2.2 AGN Sample

We selected Type 2 AGN using a BPT diagram (Baldwin, Phillips & Terlevich 1981) using line and continuum strengths for [OIII], [NII], [SII] and [OII] obtained from the MPA-JHU catalogue (Kauffman et al. 2003a; Brinchmann et al. 2004) for galaxies in the GZ2-GALEX sample. We then required the $S/N > 3$ for each emission line as in Schawinski et al. (2010). Those galaxies which satisfied all of the inequalities defined in Kewley et al. (2001) and Kauffman et al. (2003b) were selected as Type 2 AGN, giving 1,299 host galaxies ($\sim 10\%$ of the GZ2-GALEX sample). Sarzi et al. (2010); Yan & Blanton (2012) and Singh et al. (2013) have all demonstrated that LINERs are not primarily powered by AGN, therefore for purity, we excluded these galaxies from the sample using the definition from Kewley et al. (2006) (55 galaxies total) with no change to the results. These 1,244 galaxies will be referred to as the AGN-HOST sample.

We refrain from using Type 1 AGN due to concerns about contamination of the SFH analysis from potentially strong NUV emission by unobscured nuclei. The obscuration of Type 2 AGN is highly efficient, considerably more so in the NUV than the optical (Simmons et al. 2011); residual NUV flux from a Type 2 AGN can be neglected in comparison to that of the galaxy. We also investigated the possibility of contamination of optical galaxy colours by residual

¹ <http://zoo2.galaxyzoo.org/>

² Publicly available: <http://github.com/zoouniverse/starpy>

³ <http://dan.iel.fm/emcee/>

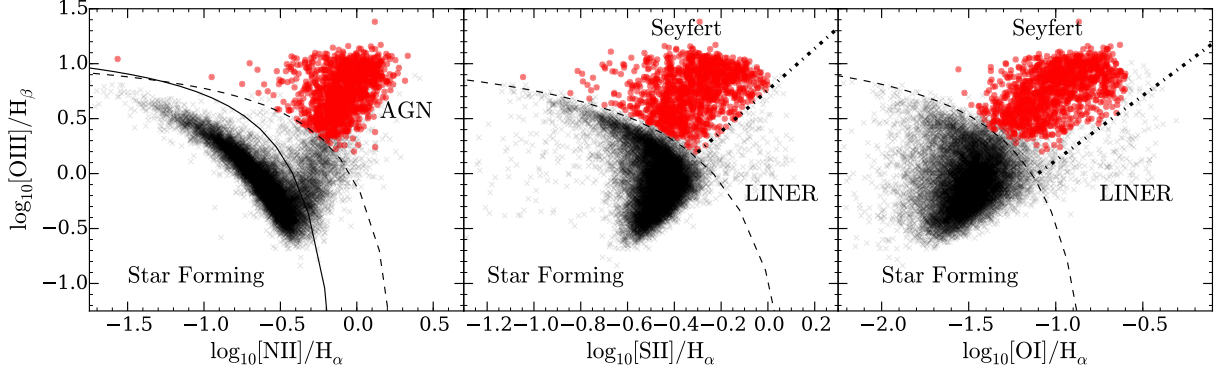


Figure 2. BPT diagrams for galaxies in the GZ2-GALEX sample (black crosses) with $S/N > 3$ for each emission line. Inequalities defined in: Kewley et al. (2001) to separate SF galaxies from AGN (dashed lines), Kauffman et al. (2003b) to separate SF from composite SF-AGN galaxies (solid line) and Kewley et al. (2006) to separate LINERS and Seyferts (dotted lines). Galaxies are included in the AGN-HOST sample (red circles) if they satisfy all the inequalities to be classified as Seyferts. LINERS are excluded for purity.

AGN emission, finding that subtracting measured nuclear magnitudes (SDSS *psfMag*) produces a negligible change in host galaxy colour ($\Delta(u-r) \sim 0.09$). We therefore use the uncorrected colours to avoid unnecessary complexity and minimise the propagation of uncertainty from the colours through to the SFHs. However, we note that including these corrected colours does not change our results.

SDSS images for 10 randomly selected galaxies from the AGN-HOST sample are shown in Figure 1; Figure 2 shows the entire AGN-HOST sample and the matched GZ2-GALEX galaxies on a BPT diagram. For the AGN-HOST sample the mean $\log(L[OIII])$ [erg s^{-1}] ~ 41.3 and median $\log(L[OIII])$ [erg s^{-1}] ~ 41.0 , with a range of $\log(L[OIII])$ [erg s^{-1}] luminosities of $39.4 - 43.0$.

We constructed a sample of inactive galaxies by removing from the GZ2-GALEX sample all galaxies with line strengths indicative of potential AGN activity (Kauffman et al. 2003b), as well as sources identified as Type 1 AGN by the presence of broad emission lines (Oh et al. 2015). We select mass- and morphology-matched inactive samples by identifying between 1 and 5 inactive galaxies for each AGN-HOST galaxy with the same stellar mass (to within $\pm 5\%$) and GZ2 ‘smooth’ and ‘disc’ vote fractions (to within ± 0.1); this selects 6107 galaxies. We refer to this sample as the INACTIVE sample. A Kolmogorov-Smirnov test revealed the redshift distributions of the INACTIVE and AGN-HOST samples are statistically indistinguishable ($D \sim 0.16$, $p \sim 0.88$).

Since this investigation is focussed on whether an AGN can have an impact on the SF of its host galaxy, we must consider possible selection effects. The extent to which SF could obscure AGN emission was addressed by Schawinski et al. (2010). They showed, via analysis of simulated AGN emission added to star-forming galaxies, that BPT-based selection of AGN produces a complete sample at luminosities of $L[OIII] > 10^{40} \text{erg s}^{-1}$. Above this limit we therefore assume we have selected a complete sample of AGN independent of host galaxy SFR.

We also split both the AGN-HOST and INACTIVE samples into low, medium and high mass ranges (see Table 1) to investigate any trends in the SFH with mass. The mass boundaries were chosen to give roughly equal numbers of in-

active galaxies in each bin prior to the mass matching to the AGN-HOST sample. Masses were calculated using the $(u-r)$ colour and absolute r -band magnitude with the method outlined in Baldry et al. (2006).

3 RESULTS

Figures 3 and 4 show the summed posterior probability distributions for the quenching time, t_q and exponential quenching rate, τ , respectively. In each figure the summed 1-dimensional normalised posterior probability distribution across the given parameter is shown for smooth and disc galaxy populations across three mass bins for the AGN-HOST and INACTIVE samples. In Table 1 the percentage of the summed posterior distribution in each quenching regime for rapid ($\tau < 1$ Gyr), intermediate ($1 < \tau$ [Gyr] < 2) and slow ($\tau > 2$ Gyr) quenching timescales, are shown. Errors on the percentages are calculated from the range of values spanned by $N = 1000$ bootstrap iterations each sampling 90% of the population. Figures 3 and 4 show a distinct difference between the posterior probability distributions of AGN-HOST and INACTIVE populations.

At all masses, the posterior distribution for the AGN-HOST population across the quenching time t_q parameter (left panels of Figure 3) is different from that of the inactive galaxies (right panels of Figure 3). Recent quenching ($t > 11$ Gyr) of AGN-HOST galaxies is the dominant history for low and medium mass galaxies, particularly for the smooth galaxy population. However, this effect is less dominant in higher mass galaxies where quenching at earlier times has significant probability.

The distributions of probability for the quenching rate, τ , in Figure 4 and Table 1 show the dominance of rapid quenching ($\tau < 1$ Gyr) across the AGN-HOST population, particularly for smooth galaxies. With increasing mass the dominant quenching rate becomes slow ($\tau > 2$ Gyr) especially for disc galaxies hosting an AGN. Similar trends in the probability are observed for the INACTIVE population but the overall distribution is very different.

The posterior probability distribution for the AGN-HOST

Table 1. Table showing the number of galaxies in each of the three mass bins for both the AGN-HOSTS and INACTIVE galaxy samples and the percentage of the summed probability distribution across each morphologically weighted population found in the rapid, intermediate and slow quenching regimes.

SAMPLE	MASS BIN	WEIGHTING	$\tau < 1$ [Gyr]	$1 < \tau$ [Gyr] < 2	$\tau > 2$ [Gyr]	NUMBER
AGN-HOSTS	$\log[M_*/M_\odot] < 10.25$	p_d	60 ± 5	13 ± 9	28 ± 19	165(13.3%)
		p_s	69 ± 14	17 ± 6	14 ± 3	
	$10.25 < \log[M_*/M_\odot] < 10.75$	p_d	33 ± 3	15 ± 4	51 ± 7	630(50.6%)
		p_s	69 ± 5	7 ± 4	26 ± 9	
	$\log[M_*/M_\odot] > 10.75$	p_d	20 ± 5	25 ± 7	56 ± 12	449(36.1%)
		p_s	24 ± 4	26 ± 6	50 ± 7	
INACTIVE	$\log[M_*/M_\odot] < 10.25$	p_d	37 ± 8	39 ± 8	24 ± 8	807(13.2%)
		p_s	47 ± 14	36 ± 5	17 ± 5	
	$10.25 < \log[M_*/M_\odot] < 10.75$	p_d	30 ± 4	18 ± 3	51 ± 4	3094(50.7%)
		p_s	42 ± 3	29 ± 3	30 ± 4	
	$\log[M_*/M_\odot] > 10.75$	p_d	36 ± 3	24 ± 4	41 ± 3	2206(36.1%)
		p_s	38 ± 2	28 ± 3	34 ± 3	

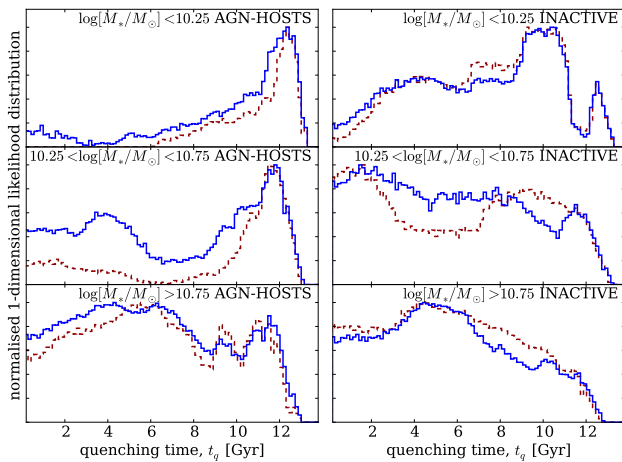


Figure 3. Posterior probability distribution for the quenching time (t_q) parameter normalised so that the areas under the curves are equal. AGN-HOST (left) and INACTIVE (right) galaxies are split into low (top), medium (middle) and high (bottom) mass for smooth (red dashed) and disc (blue solid) galaxies. A low (high) value of t_q corresponds to the early (recent) Universe.

galaxies therefore shows evidence for the dominance of rapid, recent quenching having occurred across the entire population. This result implies the importance of AGN feedback for the evolution of these galaxies.

4 DISCUSSION

The differences between the probability distributions of the AGN-HOST and INACTIVE galaxy populations reveal that an AGN can have a significant effect on the SFH of its host galaxy. Both recent, rapid quenching and early, slow quenching are observed in the probability distribution of the AGN-HOST population.

There are minimal differences between the smooth and disc weighted probability distributions of the quenching parameters across the AGN-HOST population. This is agreement with the conclusions of Kauffman et al. (2003b) who found that the structural properties of AGN hosts depend very little on AGN power.

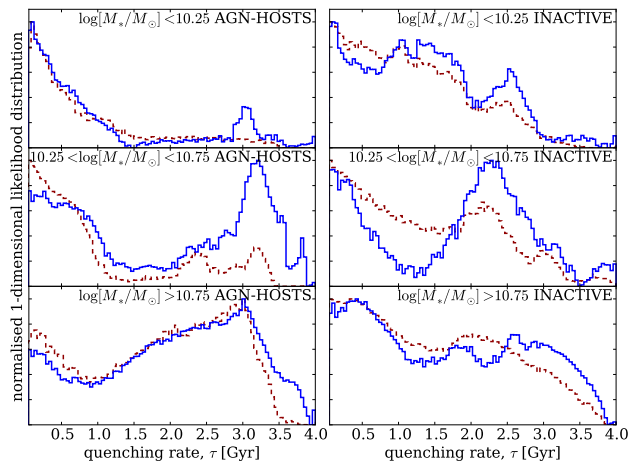


Figure 4. Posterior probability distribution for the quenching rate, (τ) normalised so that the areas under the curves are equal. AGN-HOST (left) host and INACTIVE (right) galaxies are split into low (top), medium (middle) and high (bottom) mass for smooth (red dashed) and disc (blue solid) galaxies. A small (large) value of τ corresponds to a rapid (slow) quench.

The difference between the AGN-HOST and INACTIVE population probability distributions in Figure 4 for the rate of quenching, τ , tells a story of gas reservoirs. The distribution of probability for higher mass AGN-HOST galaxies is dominated by slow, early quenching implying another mechanism is responsible for the cessation of star formation in these high mass galaxies prior to the triggering of the current AGN. This preference for slow evolution timescales follows from the ideas of previously isolated discs evolving slowly by the Kennicutt-Schmidt (Schmidt 1959; Kennicutt 1997) law which can then undergo an interaction or merger to reinvigorate star formation, feed the central black hole and trigger an AGN (Varela et al. 2004; Emsellem et al. 2015). These galaxies would need a large enough gas reservoir to fuel both SF throughout their lifetimes and the recent AGN. These high mass galaxies also play host to the most luminous AGN (mean $\log(L[\text{OIII}]) [\text{erg s}^{-1}] \sim 41.6$) and so this SFH challenges the usual explanation for the co-evolution of luminous black holes and their host galaxies driven by merger growth.

Quenching at early times is also observed for the INACTIVE population, where the probability distribution for the quenching time is roughly constant until recent times where the distribution drops off. This drop-off occurs at earlier times with increasing mass with a significant lack of probability of quenching at early times for low mass INACTIVE galaxies (right panels Figure 3). This is evidence of downsizing across the entire INACTIVE galaxy population whereby stars in massive galaxies form first and quench early (Cowie et al. 1996; Thomas et al. 2010).

The most massive AGN-HOST galaxies also show a preference for earlier quenching (bottom left panel Figure 3) occurring at slow rates; we speculate that this is also due to the effects of downsizing rather than being caused by the current AGN. This earlier evolution would first form a slowly ‘dying’ or ‘dead’ galaxy typical of massive elliptical galaxies which can then have a recent infall of gas either through a minor merger, galaxy interaction or environmental change, triggering further star formation and feeding the central black hole, triggering an AGN (Kaviraj et al. 2014). In turn this AGN can then quench the recent boost in star formation. This track is similar to the evolution history proposed for blue ellipticals (Kaviraj et al. 2013; McIntosh et al. 2014; Haines et al. 2015). This SFH would then give rise to the probability distribution seen across the high mass AGN-HOST population for both time and rate parameters.

These recently triggered AGN in both massive disc and smooth galaxies do not have the ability to impact the SF across the entirety of a high mass galaxy in a deep gravitational potential (Ishibashi et al. 2012; Zinn et al. 2013). This leads to the lower peak for recent, rapid quenching in the high mass AGN-HOST population for both morphologies.

Conversely, rapid quenching, possibly caused by the AGN itself through negative feedback, is the most dominant history for low mass AGN-HOST galaxies with lower gravitational potentials from which gas may be more readily expelled or heated (Tortora et al. 2009).

Tortora et al. (2009) model the effects of jet induced AGN feedback on a typical early type (i.e. smooth) galaxy and observe a drastic suppression of star formation on a timescale of ~ 3 Myr. Comparing their synthetic colours with observed colours of SDSS elliptical galaxies, they find the time between the current galaxy age, t_{gal} and the time that the feedback began, t_{AGN} , peaks at $t_{gal} - t_{AGN} \sim 0.85$ Gyr. This agrees with the location of the peak in Figure 3 for low mass galaxies, where the difference between the peak of the probability and the average age of the population (galaxy age is calculated from the redshift by assuming all galaxies form at $t = 0$) is ~ 0.83 Gyr. This implies that this SFH dominated by recent quenching is caused directly by negative AGN feedback.

However, there still remains the possibility that the AGN is merely a consequence of an alternative quenching mechanism. This idea is supported by simulations showing that the exhaustion of gas by a merger fuelled starburst could cause such a rapid quench in star formation and in turn also trigger an AGN (Croton et al. 2006; Wild et al. 2009; Snyder et al. 2011; Hayward et al. 2014). Yesuf et al. (2014) also showed that AGN are more commonly hosted by post starburst galaxies, with the peak AGN activity appearing $\geq 200 \pm 100$ Myr after the starburst. Such a SFH is not accounted for in the models presented here, however

this scenario is still consistent with the results presented in this paper; that AGN which are currently active have been detected in host galaxies ~ 1 Gyr after the onset of quenching.

This rapid quenching is particularly dominant for low-to-medium mass smooth galaxies. Smethurst et al. (2015) suggest that incredibly rapid quenching rates could be attributed to mergers of galaxies in conjunction with AGN feedback, which are thought to be responsible for creating the most massive smooth galaxies (Conselice et al. 2003; Springel, Di Matteo & Hernquist 2005; Hopkins et al. 2008). This dominance of rapid quenching across the smooth AGN-HOST population supports the idea that a merger, having caused a morphological transformation to a smooth galaxy, can also trigger an AGN, causing feedback and cessation of star formation (Sanders et al. 1988).

For the medium mass AGN-HOST population we see a bimodal probability distribution between these two quenching histories, highlighting the strength of this method which is capable of detecting such variation in the SFHs across a population of galaxies.

We have used morphological classifications from the Galaxy Zoo 2 project to determine the morphology-dependent star formation histories of a population of 1,244 Type 2 Seyfert AGN host galaxies, in comparison to an inactive galaxy population, via a Bayesian analysis of an exponentially declining star formation history model. We determined the most likely parameters for the quenching onset time, t_q , and exponential quenching rate, τ , and find clear differences in the combined population probabilities between inactive and AGN host galaxy populations. We have demonstrated a clear dependence on a galaxy currently hosting an AGN and its SFR. There is strong evidence for downsizing in massive inactive galaxies, which appears as a secondary effect in AGN host galaxies. The dominant quenching mechanism for galaxies currently hosting an AGN is for rapid quenching which has occurred very recently. This result demonstrates the importance of AGN feedback across the entire host galaxy population, in driving the evolution of galaxies across the colour-magnitude diagram.

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⁴ <http://galex.stsci.edu/GR6/>

⁵ <https://www.sdss3.org/collaboration/boiler-plate.php>

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APPENDIX A: MASS MATCHED INACTIVE SAMPLE

Each galaxy in the AGN-HOST sample has been matched to at least one and up to five inactive galaxies. These were matched to within $\pm 5\%$ of the stellar mass and ± 0.1 of each of the disc and smooth GZ vote fractions, p_d and p_s .

Both the AGN-HOST and INACTIVE galaxy samples are shown on an optical-NUV colour colour diagram in Figure A1. The INACTIVE sample across all mass bins can be seen to encompass the entirety of the colour magnitude diagram, unlike the AGN-HOST sample which reside at increasingly green colours with increasing mass.

APPENDIX B: LUMINOSITY DEPENDENCE

An investigation into the dependence of the quenching in the AGN-HOST sample with $L[OIII]$ was also conducted, with the summed weighted posterior probability distributions for the quenching time and rate parameters shown in Figures B1 & B2. The AGN-HOST sample was split into low, medium and high luminosity as with the stellar mass. Since the $L[OIII]$ is dependent on the accretion rate, which is correlated with the mass of the black hole, which is in turn correlated with the stellar mass of the host galaxy, the stellar mass was used in the main investigation to allow a direct comparison to the control INACTIVE sample.

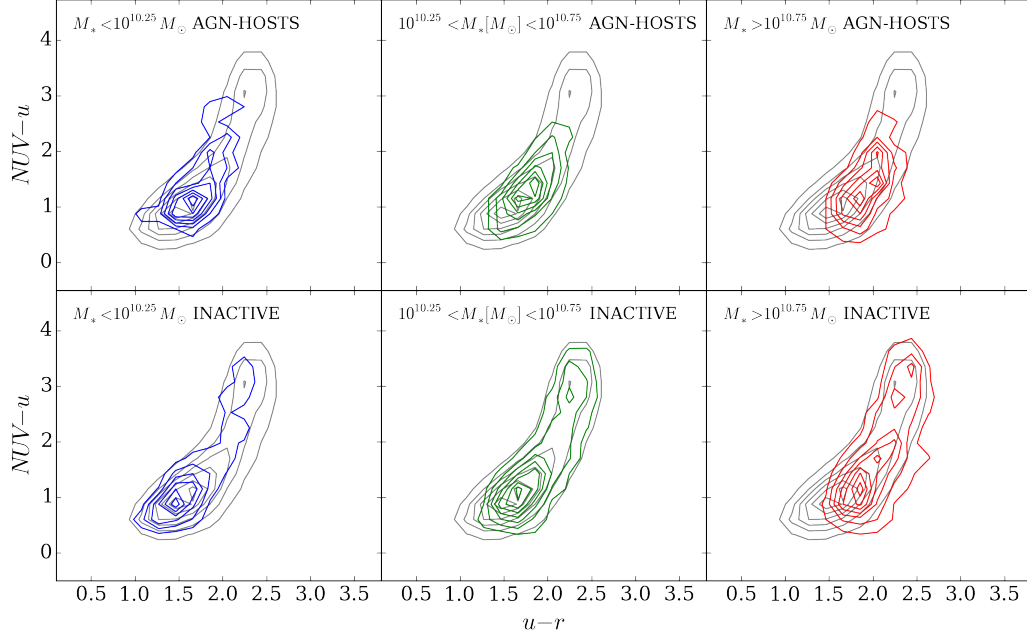


Figure A1. Optical-NUV colour-colour contour diagrams for the AGN-HOST (top) and INACTIVE galaxy samples split into low (blue), medium (green) and high (red) stellar mass samples. Underlying each diagram are the contours of the GZ2-GALEX sample (grey).

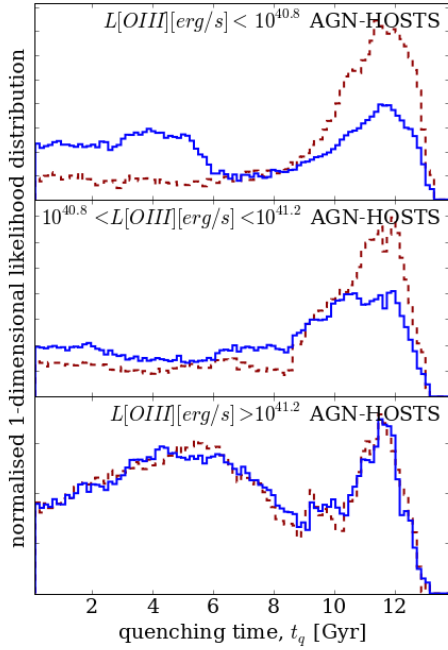


Figure B1. Likelihood distribution for the quenching time, t_q normalised so that the areas under the curves are equal. AGN-HOST galaxies are split into low (top), medium (middle) and high (bottom) $L[OIII]$ for smooth (red dashed) and disc (blue solid) galaxies. A low value of t_q corresponds to the early Universe and a high value to the recent Universe.

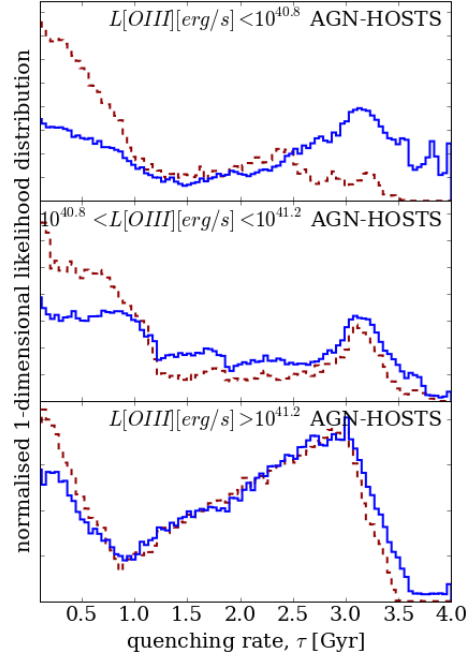


Figure B2. Likelihood distribution for the quenching rate, τ normalised so that the areas under the curves are equal. AGN-HOST galaxies are split into low (top), medium (middle) and high (bottom) $L[OIII]$ for smooth (red dashed) and disc (blue solid) galaxies. A small (large) value of τ corresponds to a rapid (slow) quench.