On the slow quenching of $M^*$ galaxies: heavily-obscured AGNs clarify the picture

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ABSTRACT

We investigate the connection between X-ray and radio-loud optically-obscured AGNs and the physical properties of their evolved and massive host galaxies, focussing on the mass-related quenching channel followed by $M^*$ galaxies in the rest-frame NUVrK colour diagram at $0.2 < z < 0.5$. While our results confirm that (1) radio-loud AGNs are predominantly hosted by already-quenched and very massive ($M_*>10^{11}M_\odot$) galaxies, ruling out their feedback as a primary driver of $M^*$ galaxy quenching, we found that (2) heavily-obscured X-ray AGNs are mostly hosted by $M^*$ galaxies in the process of quenching. This argues for a quenching scenario that involves mergers of (gas-poor) $M^*$ galaxies after they have left the star formation main sequence, i.e., after the onset of the quenching process. In that respect, we discuss how our results support a scenario where the slow quenching of $M^*$ galaxies happens along cosmic filaments.

Key words: galaxies: statistics – galaxies: evolution – galaxies: star formation – quasars: supermassive black holes – X-rays: galaxies – radio continuum: galaxies

1 INTRODUCTION

The bimodality between blue/star-forming and red/quiescent galaxies in rest-frame colour-based diagrams has been extensively documented over the last decades (e.g., Chester & Roberts 1964; Hogg et al. 2003; Bell et al. 2004; Baldry et al. 2006; Arnouts et al. 2007; Williams et al. 2009; Arnouts et al. 2013; Ilbert et al. 2013; Bouquin et al. 2015; Moutard et al. 2016a,b; Pacifici et al. 2016a) and the build up of the quiescent population, observed to redshift $z \sim 4$ (e.g., Tomczak et al. 2014; Mortlock et al. 2015; Davidzon et al. 2017), is the statistical expression of the seemingly definitive shutdown of the the star formation, commonly called quenching. However, the diversity observed among quiescent galaxies (e.g., in terms of mass and morphology) suggests that the mechanisms involved in the quenching are multiple, and several studies have stressed the existence of different types of quenching (e.g., Faber et al. 2007; Peng et al. 2010; Schawinski et al. 2014; Moutard et al. 2016b; Pacifici et al. 2016b).

In particular, the fact that star formation is observed to stop earlier in more massive galaxies, on average, underlies the down-sizing of the quenching (see, e.g., Bundy et al. 2006; Davidzon et al. 2013; Moutard et al. 2016b, whose Fig. 15 is edifying), which argues for the existence of mass-related quenching processes that turn out to have been in operation over a wide range of cosmic times, given that quiescent galaxies drive the high-mass end of the stellar mass function (SMF) since $z \sim 1.5 - 2$ (e.g., Baldry et al. 2012; Moustakas et al. 2013; Arcila-Oseo & Sawicki 2013; Tomczak et al. 2014; Moutard et al. 2016b; Davidzon et al. 2017). Complementarily, the exact Schechter function (Schechter 1976) shape of the SMF of star-forming (SF) galaxies implies that the probability of quenching increases exponentially with galaxy stellar mass above the characteristic stellar mass $M^*$, which brought the idea of mass quenching (Ilbert et al. 2010; Peng et al. 2010). Finally, the fact that $M^*$ has actually been found to be very stable for SF galaxies (at least from $z \sim 1$, with $M^* = 10^{10.64+0.06z} M_\odot$ at $0.2 < z < 1.5$; see Moutard et al. 2016b) supports a picture where, on average, galaxies start leaving the SF main sequence when their stellar mass reaches $\sim M^*$, which allows and invites us to consider the quenching of $M^*$ galaxies as the natural expression of mass quenching.

Assuming a stellar-to-halo mass relation (e.g., Coupon et al. 2015; Legrand et al. 2018), the characteristic stellar mass of $M^* \approx 10^{10.6} M_\odot$ corresponds to a dark-matter (DM) halo critical mass of a few $10^{12} M_\odot$. While this critical DM halo mass has been shown to

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be in good agreement with the transition mass above which virial shock heating processes start acting within DM halos (preventing further cold gas accretion; e.g., Kereš et al. 2005; Dekel & Birnboim 2006), other mechanisms able to halt the cold gas supply have been put forth to explain the star formation quenching in massive galaxies. In particular, active galactic nucleus (AGN) feedback has been claimed to have an important part in the quenching of massive galaxies. In particular, active galactic nucleus (AGN) feedback has been put forth to explain the star formation quenching in massive galaxies, through removal (in the so-called "radiative/cold mode"; e.g., Hopkins et al. 2006; Menci et al. 2006) or heating (in the so-called "radio/hot mode"; e.g., Best et al. 2005; Croton et al. 2006) of the gas reservoir.

In that respect, it is interesting to stress that recent studies have shown the quenching of \( \sim M^* \) galaxies to be a relatively slow process from \( z \sim 1 \), characterized by physical durations of 1-to-a few Gyrs for galaxies to become quiescent after leaving the SF main sequence (e.g., Schawinski et al. 2014; Ilbert et al. 2015; Moutard et al. 2016b; Pacifici et al. 2016b; Pandya et al. 2017). Such observations suggest indeed that \( M^* \) galaxy quenching is consistent with strangulation/starvation processes, where the cold gas fuelling is impeded and star formation is allowed until the gas reservoir of the galaxy is consumed (e.g., Larson et al. 1980; Peng et al. 2015). In other words, the quenching of \( M^* \) galaxies appears to be consistent with heating processes of the gas reservoir, which may result from virial shocks and/or AGN feedback.

While highlighting the connection between the properties of AGNs and their host galaxies is challenging when the ultraviolet–to–near-infrared (UV–to–near-IR) part of the spectrum is dominated by the AGN emission (typically the case of Type-1 AGNs), the analysis becomes simpler when focussing on optically-obscured AGNs (i.e., with Type-2 AGNs). For instance, Hickox et al. (2009) and Schawinski et al. (2014) were able to analyse the rest-frame optical–to–near-IR and UV–to–optical colour distributions of Type-2 AGN host galaxies, respectively. However, none of them could have access to the entire rest-frame UV–to–near-IR wavelength range, which is of utmost interest to study galaxies in the process of quenching (Moutard et al. 2016b).

In the present paper, we intended to verify whether AGN feedback could explain the quenching of \( M^* \) galaxies, in particular from radio-loud AGNs. Thanks to the clariﬁcation of \( M^* \) quenching galaxies enabled by the rest-frame NUV–r vs. r–K diagram, we analysed the physical properties of optically-obscured AGN host galaxies (the physical parameter estimation of which is not expected to be affected by the AGN emission).

Throughout this paper, we use the standard cosmology (\( \Omega_m = 0.3, \Omega_{\Lambda} = 0.7 \) with \( H_0 = 70 \) km s\(^{-1}\) Mpc\(^{-1}\)). Magnitudes are given in the AB system (Oke 1974) and galaxy stellar masses are given in units of solar masses (\( M_\odot \)) for a Chabrier (2003) initial mass function.

2 GALAXY SAMPLE

Aiming to analyse the connection between AGNs and the physical properties of their host galaxies, we have focused on galaxies whose rest-frame UV–to–near-IR emission is dominated by stars (to allow the estimation of physical properties from purely stellar population synthesis models) while any potential AGN emission has been tracked in extreme wavelength regimes (not likely to significantly affect the stellar emission).

For this purpose, we made use of the comprehensive photometric coverage of the XMM Large-Scale Structure (XMM-LSS; Pierre et al. 2004) field, which beneﬁts from homogeneous overlap between UV–to–near-IR broad-band photometry, X-ray and radio observations over \( \sim 7 \) deg\(^2\). Specifically, the parent sample of galaxies and associated physical properties (absolute magnitudes, stellar mass, star formation rate...) has been based on UV–to–near-IR observations while hosted optically-weak AGNs were identiﬁed by cross-matching with overlapping X-ray and radio-loud AGN public samples, as detailed the following section.

2.1 UV–to–near-IR observations and physical parameters

The data we used combine photometry from the VIPERS Multi-Lambda Survey (VIPERS-MLS: FUV, NUV, u, g, r, i, z- and Ks-bands; for more details, see Moutard et al. 2016a) and VISTA Deep Extragalactic Observations (VIDEO: Y, J, H, KS-bands; Jarvis et al. 2013) over \( \sim 7 \) deg\(^2\) in the XMM-LSS ﬁeld, which overlap with the Canada-France-Hawaii Telescope Legacy Survey (CFHTLS) in W1. Photometric redshifts (photo-zs) and physical parameters were derived using the template-ﬁtting code Le Phare (Arnouts et al. 2002; Ilbert et al. 2006), as described in Moutard et al. (2016a,b).

Of interest for the present study is the photo-z accuracy, \( \sigma_z \lesssim 0.03 \) (1+z) down to \( K_s \sim 22 \) (i.e., for any galaxy with stellar mass \( M_\star \sim 10^{9} M_\odot \) and thus for the \( \sim M^* \) galaxies we considered in the following). Moreover, a great care has been taken in the derivation and the use of absolute magnitudes, to minimize the impact of the k-correction: while rest-frame magnitudes were ﬁrst computed using the k-correction: while rest-frame magnitudes were ﬁrst computed from \( z < 0.5 \) to limit the k-correction on rest-frame \( K_s \) magnitude computed from \( K_s \) observations (our reddest band).\(^1\)

2.2 Radio-loud and X-ray AGN properties

Aiming to identify the X-ray and radio-loud AGN host galaxies and explore associated properties, we made use of public catalogues of X-ray and radio-loud AGNs in the XMM-LSS/CFHTLS-W1 field.

2.2.1 Radio-loud and X-ray AGN catalogues

While associating X-ray and radio sources with optical counterparts can be challenging, we made use of well-documented photometric catalogues where the determination of X-ray and radio sources optical counterparts has been done.

Regarding radio-loud AGNs, we made use of the catalogue produced by Tasse et al. (2008a), where radio-loud AGNs were identiﬁed based on multi-frequency radio observations with ﬂux density limits of \( \sim 4 \) and \( \sim 1.5 \) mJy/beam at 325 and 610 MHz, respectively (i.e., complete for radio powers \( P_{\text{radio}} \gtrsim 6 \times 10^{21} \) W/Hz at \( z < 0.5 \); see also Tasse et al. 2006, 2007, 2008b), and carefully associated to their optical counterparts from the CFHTLS. More speciﬁcally, we selected radio-loud AGNs with high optical counterpart association probability (\( P \geq 80 \) per cent) and no signiﬁcant contribution from Type-1 AGN or starburst activity (for more details, see Tasse et al. 2008a).

For X-ray AGNs, we made use of the catalogue of X-ray AGNs and associated X-ray properties of Melsky et al. (2013), with ﬂux limits of \( 3 \times 10^{-15} \text{ergs}^{-1}\text{cm}^{-2} \) and \( 1 \times 10^{-14} \text{ergs}^{-1}\text{cm}^{-2} \) in the soft (0.5–2 keV) and hard (2–10 keV) bands, respectively.\(^1\)

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\(^{1}\) All rest-frame magnitudes were derived with two different template libraries, which allowed us to verify, in particular, that our rest-frame \( K_s \) magnitude estimates are consistent to \( 0.2 \leq z \leq 0.5 \).
2.2.2 Matching of AGN and host galaxy physical properties

Radio-loud and X-ray AGN host galaxy properties were recovered from position matching with their NUV−to−K counterparts from the parent sample (Sect. 2.1), by using a 0.5″ tolerance radius. Aiming to quantify the fraction of galaxies hosting an AGN (see Sect. 3), we defined the control galaxy samples associated with radio and X-ray observations: namely, the radio and X-ray control samples were selected as the sub-samples (of the parent sample) lying within the footprint of radio and X-ray observations, respectively.

Thereby, at 0.2 < z < 0.5, we obtained 28 radio-loud AGN host galaxies in a parent population of 24386 galaxies and 117 X-ray AGN host galaxies in a parent population of 24619 galaxies, within effective areas of 6.51 deg\(^2\) and 6.45 deg\(^2\), respectively.

2.3 NUVrK diagram and the \(M^*\) quenching channel

The rest-frame NUV−r vs. r−K diagram (hereafter NUVrK diagram) introduced by Arnouts et al. (2013) has been shown to be a powerful alternative to the rest-frame U−V vs. V−J diagram (UVJ; Williams et al. 2009), as it is sensitive to very different star life-times on each of its axis: < 0.1 Gyr along the rest-frame NUV−r colour, rest-frame NUV tracing almost instantaneous star formation rate (SFR) through the emission of massive young stars (typically, O/B stars; Salim et al. 2005; Martin et al. 2007) and > 1 Gyr along the rest-frame r−K colour, which results from the combination of stellar ageing (the accumulation of low-mass stars) and dust reddening (the UV absorption and IR re-emission of the dust; Arnouts et al. 2007; Williams et al. 2009). In other words, while the (NUV − r)\(^0\) colour varies with specific SFR (sSFR), one can expect the (r − K)\(^0\) colour to redden with cosmic time. Thereby, the NUVrK diagram allows to properly resolve the region of the colour space between quiescent (Q) and star-forming (SF) galaxies (see Moutard et al. 2016a,b; Moutard et al. 2018; Siudek et al. 2018), which corresponds to what is often referred to as the so-called green valley (GV). While the green valley has been defined in different ways in the literature (rest-frame optical colour vs. stellar mass, rest-frame optical−to−near-IR colours, ...), the use of the NUVrK diagram really allows us to follow GV galaxies as their sSFR evolves between the SF and Q sequences.

The number of degeneracies affecting the NUVrK diagram is indeed quite limited (Moutard et al. 2016b; Siudek et al. 2018), which makes the NUVrK diagram particularly well suited to distinguish star-formation histories (SFHs) characterized by different quenching time-scales (Arnouts et al. 2013; Moutard et al. 2016b). Provided that the galaxy sample one considers is sufficiently large to probe rare populations, one can isolate the NUVrK pathway that is followed by evolved and massive quenching galaxies on their way to join the quiescent population (80 per cent of green-valley galaxies are concentrated within the rest-frame colour channel (0.76 < (r − K)\(^0\) < 1.23, cf. dark green arrow in Fig. 1a below; see Moutard et al. 2016b, for more details).

Typically followed by fairly massive galaxies after reaching a characteristic stellar masses around \(M^* = \) \(10^{10.5}M_\odot\) (60 per cent of these green-valley galaxies have stellar masses of \(10^{10.5} < M_\star / M_\odot < 10^{11}\)), this \(M^*\) quenching channel has turned out to be characterised by fairly long quenching timescales,\(^3\) in contrast to the quenching of low-mass (\(M_\star \leq 10^{10.5}M_\odot\)) galaxies that is expected to be 2−9 times faster and driven by environment (cf. light green arrow in Fig. 1a below; see Moutard et al. 2016b; Moutard et al. 2018).

3 RESULTS

In Fig. 1a, we show the distribution of radio-loud and X-ray AGN host galaxies over the distribution of galaxies in the NUVrK diagram (black contours). One can clearly identify the quenching channel (marked with dark green arrow) followed by \(M^*\) galaxies in the green valley when they leave the SF main sequence around (NUV − r)\(^0\) ∼ 4 (i.e., sSFR ∼ \(10^{-10.4} M_\odot yr^{-1}/M_\odot\)) to eventually join the quiescent population around (NUV − r)\(^0\) ∼ 5 (i.e., sSFR ∼ \(10^{-12} M_\odot yr^{-1}/M_\odot\)), all concentrated in a slice of the colour space with 0.76 < (r − K)\(^0\) < 1.23. In the following, we focused on this slice of the colour space, aiming to study the incidence and the properties of radio-loud and X-ray (optically-obscured) AGN host galaxies along this \(M^*\) quenching channel.

3.1 NUVrK colours of AGN host galaxies

The first remark emerging from Fig. 1 is that radio-loud and X-ray AGNs appear to be two distinct populations, essentially hosted by different galaxies. More specifically, while radio-loud AGNs appear to be predominantly hosted by old quiescent galaxies, X-ray AGNs are observed in all kinds of old (i.e., (r − K)\(^0\) > 0.76) galaxies over the entire (NUV − r)\(^0\) range, following the distribution of galaxies. However, when considering the hardness of X-ray AGN emission, i.e., the prevalence of hard [2−10keV] over soft [0.5−2keV] X-ray emission, high hardness ratios (HR\(^s\)) appear to be favoured in the green valley.

In the right panels of Fig. 1, one can see how the increase of the hardness ratio of X-ray AGNs in the green valley (the mean lower and upper (NUV − r)\(^0\) limits of which are marked with blue and red dotted lines, respectively) is due to the decrease of the soft X-ray emission. In Fig. 1b, we show the AGN X-ray luminosity as a function of the (NUV − r)\(^0\) colour of its host galaxy in the hard and soft bands, along the \(M^*\) quenching channel. While the hard emission appears to be stable over the entire (NUV − r)\(^0\) range (i.e., before, in and after the green valley), with a median luminosity of \(L_X = 8.1_{-4}^{+2} \times 10^{42}\) erg/s, the soft X-ray emission decreases in green-valley galaxies from \(L_X = 3.5_{-2}^{+3.8} \times 10^{42}\) erg/s in SF galaxies to

\(^3\) Namely, physical durations of ∼ 1−3.5 Gyrs to cross the green valley, as estimated from models of average SFHs with SFR(t < \(t_Q\)) = constant and SFR(t ≥ \(t_Q\)) = \(e^{-(t-t_Q)/\tau_0}\) where \(t_Q\) and \(\tau_0\) are the cosmic time, quenching time and timescale, respectively (for more detail, please refer to Moutard et al. 2016b; Moutard et al. 2018).

\(^4\) HR = (\(H−S\))/(\(H+S\)), where \(H\) and \(S\) are the numbers of hard [2−10keV] and soft [0.5−2keV] X-ray photons, respectively.
Figure 1. NUVrK distribution and X-ray properties of AGN host galaxies. a) NUVrK distributions of parent sample (grey contours), radio-loud (black open circles) and X-ray (color coded filled circles) AGN host galaxies (colour coded according to their hardness ration, HR) at 0.2 < z < 0.5. Vertical black dashed and dotted lines delineate the slice of the colour space associated with the $M^*$ galaxy quenching channel (the direction of which is illustrated by the dark green arrow), separated from both young galaxies with $(r - K_s)^0 < 0.76$ (prone to a much faster quenching, shown by the light green arrow) and from very dusty SF galaxies with $(r - K_s)^0 > 1.23$, the (NUV − r)$^0$ colour of which is strongly affected by dust absorption. Grey shaded regions indicate the corresponding regions of the colour space, excluded from our study (cf. Sects. 2.3 and 3). The blue and red dashed lines separate green valley galaxies from star-forming (SF) and quiescent (Q) galaxies, respectively. Horizontal blue and red dotted lines show the corresponding mean lower and upper (NUV − r)$^0$ limits that can be associated with the green valley in the $M^*$ galaxy quenching channel, as benchmarks. In the right hand panels, b) hard [2–10 keV] (magenta) and soft [0.5–2 keV] (cyan) X-ray luminosity ($L_X$), c) corresponding fractions of hard and soft X-ray non-detections, and associated d) hardness ratio (blue) are plotted as a function of the (NUV − r)$^0$ colour along the $M^*$ quenching channel, i.e., for host galaxies with 0.76 < $(r - K_s)^0$ < 1.23. Median values are shown with solid lines while shaded envelopes show corresponding ±1σ uncertainties (as derived from 10000 bootstrap resamples excluding non-detections in panels b and d, and from the Poissonian standard deviation in panel c). Vertical blue and red dotted lines show the mean lower and upper (NUV − r)$^0$ limits associated with the green valley, respectively, within the $M^*$ quenching channel (the direction of which is illustrated by the green arrow in panel b). The threshold HR = −0.2 between soft and hard X-ray dominated AGNs is shown by the horizontal blue dashed line in panel d.

$L_X = 0.7^{+2.1}_{-1.1} \times 10^{42}$ erg/s before recovering to a level comparable to that of SF galaxies in Q galaxies, with a median luminosity of $L_X = 3.2^{+1.2}_{-0.7} \times 10^{42}$ erg/s. Consistently, the median fraction of soft X-ray non-detections increases drastically in the green valley, rising from ~10 per cent in SF galaxies to more than ~40 per cent in the green valley, and then decreasing in Q galaxies down to ~20 per cent, as shown in Fig. 1c.

If we conservatively exclude non-detections (i.e., where $HR = \pm 1$), this results in a clear increase of the median hardness ratio to $HR = 0.26$ in the green valley, against $HR = -0.4$ in SF and Q galaxies, as observed in Fig. 1d. Thereby, one can see how the threshold $HR = -0.2$, as used by Melnyk et al. (2013) to separate hard ($HR > -0.2$) and soft ($HR < -0.2$) X-ray dominated sources, may be relevant to identify heavily-obscured ($HR > -0.2$) AGNs at 0.2 < z < 0.5.

3.2 AGN host galaxies along the $M^*$ quenching channel

In Fig. 2, we make use of such distinction between hard ($HR > -0.2$) and soft ($HR < -0.2$) X-ray dominated AGNs when showing the (NUV − r)$^0$ distribution of X-ray AGN host galaxies along the $M^*$ quenching channel together with radio-loud ones. We show the AGN host galaxy number counts as a function of (NUV − r)$^0$ in the top panel (Fig. 2a), and the corresponding fraction of galaxies hosting an AGN in the bottom panel (Fig. 2b).

While Fig. 2 confirms radio-loud AGNs to be mostly concentrated in already quiescent galaxies (75 per cent radio-loud AGNs are hosted by galaxies with sSFR < $10^{-11}M_\odot yr^{-1}/M_\odot$), one can see how the fraction of galaxies hosting a radio-loud AGN increases with increasing (NUV − r)$^0$ colour (i.e., with decreasing sSFR) to finally become the most probable kind of AGN in the most quiescent galaxies with (NUV − r)$^0$ ~ 6 (i.e., sSFR < $10^{-13}M_\odot yr^{-1}/M_\odot$), ~0.6 per cent of which hosts a radio-loud AGN. To complete the picture, 75 per cent of radio-loud AGNs are hosted by galaxies with stellar mass $M_*>10^{11}M_\odot$, confirming radio-loud AGNs to be hosted by very massive quiescent galaxies, which we may expect to inhabit DM halos with masses of a few $10^{13}M_\odot$ (assuming a stellar-to-halo-mass relation, e.g., Coupon et al. 2015; Legrand et al. 2018). Our results are therefore in line with previous studies where radio-loud AGNs were also found to be highly clustered or to reside in rich environments (e.g., Hickox et al. 2009; Malavasi et al. 2015).

On the other hand, Fig. 2 confirms that X-ray AGN host galaxies globally follow the distribution of galaxies, with a peak of their
incidence in the green valley, as observed previously for optically obscured AGN host galaxies (e.g., Hickox et al. 2009; Schawinski et al. 2014). More interestingly, our results do show that hard X-ray dominated AGNs are the very reason why the incidence of X-ray AGNs peaks in the green valley where their fraction outranks any other kind of optically obscured AGN. The median fraction of hard X-ray dominated AGNs is indeed observed to rise from less than 0.2 per cent in SF galaxies up to 0.8 per cent in the green valley, and then to decrease down to less than 0.2 per cent in Q galaxies. Conversely, soft X-ray dominated AGNs prevail in SF and Q galaxies with a maximum of 0.4 per cent of host galaxies. Consistently, the stellar mass of galaxies hosting hard X-ray dominated AGNs peaks around $M^*$, with a median mass of $M_*/M_\odot \approx 10^{10.65}$ and 60 per cent of these galaxies with $10^{10.4} \leq M_*/M_\odot \leq 10^{10.9}$.

4 DISCUSSION
As described in Sect. 3, the NUVrK distributions of our samples of radio-loud and (soft- and hard-) X-ray dominated AGN host galaxies are quite different. In particular, the NUVrK colours of the galaxies hosting radio-loud and hard X-ray dominated AGNs suggest these two kinds of AGNs to be associated with different stages of galaxy evolution. In the following sections, we discuss the implications of these findings for the quenching scenario of $M^*$ galaxies.

4.1 Radio-loud AGNs are mostly hosted by quiescent galaxies
As suggested by Figs. 1a and 2, some galaxies develop a radio-loud AGN as they leave the green valley and move into the quiescent population. The presence of a radio-loud AGN, inefficiently accreting hot gas (see, e.g., Hardcastle et al. 2007), is often regarded as a viable mechanism to prevent further gas cooling, accretion and subsequent star-formation (e.g., see Croton et al. 2006). Still, the probability of a galaxy developing a radio AGN at its core may depend on its mass (with radio-loud AGNs preferentially found in more massive galaxies, see Best et al. 2005; Bardelli et al. 2009, and references therein) or on the environment in which it resides (e.g., Malavasi et al. 2015; Bardelli et al. 2010). This may explain why, while radio-loud AGNs are the most probable kind of AGN among quiescent galaxies, only a small fraction of these galaxies exhibit radio-loud AGNs (Fig. 2b).

On the other hand, the fact that radio-loud AGNs are mostly concentrated in already quiescent galaxies tends to rule out their feedback as a primary source for the quenching of $M^*$ galaxies.

4.2 Heavily-obscured AGNs as a final stage of major mergers
As detailed in Sect. 3.2, our results argue for a mechanism that favours hard X-ray dominated AGNs – i.e., AGNs with heavily-obscured soft X-ray emission – in $M^*$ galaxies that are transitioning in the green valley (see Fig. 2b). Heavy obscuration of soft X-ray emission is generally associated with obscuring material surrounding the supermassive black hole (SMBH) on fairly small scales, e.g., associated with the SMBH torus observed edge-on in the AGN unified model (Antonucci 1993; Urry & Padovani 1995). However, in such orientation-based model, heavy obscuration should randomly affect the galaxy population and not a specific phase of the galaxy evolution or, in our case, a specific region of the NUVrK colour space as observed in Sect. 3.2. Rather, our results argue for an evolutionary model, where the heavy obscuration of soft X-rays is caused by a dramatic event like a merger (for a review about obscured AGNs, see Hickox & Alexander 2018).

As a matter of fact, the soft X-ray obscuration of an AGN –as traced by its X-ray hardness ratio– can be associated with an equivalent hydrogen column density $N_H$ in the line of sight, and both models (e.g., Hopkins et al. 2006; Blecha et al. 2018) and observations (e.g., Satyapal et al. 2014; Kocevski et al. 2015; Ricci et al. 2017a) have highlighted the tight connection between galaxy mergers and very high column densities (i.e., typically $N_H \sim 10^{22-24} \text{cm}^{-2}$). The maximum column density reached during the merger has been predicted to vary with the gas content of the galaxies and to decrease after the coalescence of the SMBHs (Blecha et al. 2018). This is consistent with the decreasing obscuration (and conversely, increasing luminosity) of soft X-rays observed after the green valley (Figs. 1b,c) and may be related to the expulsion of the circumnuclear material by the AGN radiation pressure when reaching high accretion rates (typically with Eddington ratios of $\lambda_{\text{Edd}} \approx 10^{-2}$; Ricci et al. 2017b).

In our case, the median hardness ratio $HR = 0.26$ of green-valley $M^*$ galaxies is typical of column densities of $N_H \sim 3 \times 10^{22} \text{cm}^{-2}$ at $0.2 < z < 0.5$ (see, e.g., Hickox et al. 2007). This is for instance in very good agreement with what is predicted by high-resolution simulations in the final stage of major mergers of gas-poor galaxies with stellar masses of $M_\star \sim 2.5 - 5 \times 10^{10} M_\odot$ (Blecha et al. 2018), which is consistent with the decreasing gas content of quenching galaxies. Moreover, the fraction of heavily-obscured ($HR < -0.2$) AGN host galaxies we observe in the green...
valley is consistent with the duration predicted for the late stage of $M^*$ galaxy mergers, namely, 10–150 Myr (Blecha et al. 2018). Indeed, assuming $M^*$ galaxies to spend 1–3.5 Gyr in the green valley (Moutard et al. 2016b), the fraction of heavily-obscured AGN host galaxies is expected to be between 0.3 and 15 per cent, which is consistent with the 0.4–0.8 per cent we found (see Fig. 2b).

In summary, the incidence of heavily-obscured AGNs observed in $M^*$ galaxies in the green valley argues for a scenario that favours the mergers of these galaxies after they left the SF main sequence. While mass-related mechanisms have been successfully put forth to explain the quenching of the star formation in galaxies reaching the characteristic stellar mass $M^*$, such as virial shock heating within DM halos reaching a few $10^{12} M_\odot$ (e.g., Kereš et al. 2005; Dekel & Birnboim 2006), these models alone would fail to explain the increasing incidence of mergers after the beginning of the quenching. Our observations seem, however, to fit quite naturally within the theoretical framework developed by Pichon et al. (2011) and Codis et al. (2015), as discussed in the next section.

4.3 Proposed framework for $M^*$ galaxy quenching

In this framework, galaxies tend to be formed within DM halos with a spin aligned with their closest cosmic filaments (Pichon et al. 2011), due to cold gas streams flowing toward those filaments. Eventually, DM halos experience a flip of their angular momentum due to (major) mergers with other DM halos (Welker et al. 2014) as they fall along cosmic filaments in the direction of clusters. This flip of the angular momentum is precisely predicted to occur for DM halos reaching masses of a few $10^{12} M_\odot$ (Codis et al. 2012, 2015), i.e., typically the mass of DM halos hosting $M^* \sim 10^{10.6} M_\odot$ galaxies (as derived from stellar-to-halo mass relation, e.g., Coupon et al. 2015; Legrand et al. 2018), which is confirmed by hydrodynamical simulations where the spin flip is typically predicted for $M_\star \sim 10^{10.1-10.5} M_\odot$ (Dubois et al. 2014; Codis et al. 2018).

In other words, in this theoretical framework, mergers of $\sim 10^{12} M_\odot$ DM halos –and eventually mergers of hosted $\sim M^*$ galaxies– are favoured along cosmic filaments. Mergers of $\sim M^*$ galaxy SMBHs are thereby in line with this framework, and the fact that our results show these mergers to happen in the green valley supports a scenario where $M^*$ galaxy quenching happens along cosmic filaments. This is consistent with previous observational evidences that, on average, $\sim M^*$ quiescent galaxies were found to be closer to cosmic filaments than their SF counterparts (e.g., Malavasi et al. 2017; Laigle et al. 2018; Kraljic et al. 2018), i.e., the quenching probability of $\sim M^*$ galaxies increases with decreasing distance to filaments.

The precise mechanism(s) disconnecting $\sim 10^{12} M_\odot$ DM halos from cold-gas streams around filaments are not yet fully understood, but may involve simultaneously mass (virial shock heating) and/or position and size of the halos within filaments (Laigle et al. 2015). We cannot rule out either a significant effect of the interactions between galaxy/DM halo angular momentum and cold-gas streams (Welker et al. 2014; Aragon-Calvo et al. 2016), star formation having been found to be lower in $\geq M^*$ galaxies when they are in pairs (e.g., Coenda et al. 2019), which may suggest the quenching of $\sim M^*$ galaxies to coincide more or less with the merger of their DM host halos.

5 SUMMARY

In the present paper, we analysed the connection between X-ray and radio-loud optically-obscured AGNs and the physical properties of their evolved and massive host galaxies, in particular, regarding the mass-related quenching channel followed by galaxies in the restframe NUVrK diagram, typically when reaching $M^* \approx 10^{10.6} M_\odot$.

Our results confirmed that (1) radio-loud AGNs are mostly hosted by already-quenched galaxies (see also Hickox et al. 2009), tending to rule out radio-loud AGN feedback as the primary reason for $M^*$ galaxy quenching. Furthermore, our analysis showed that (2) heavily-obscured X-ray AGNs are essentially hosted by transitioning $\sim M^*$ galaxies at $0.2 \leq z \leq 0.5$, which argues for a quenching scenario where $M^*$ galaxies experience mergers after they left the SF main sequence. In other words, while tending to discard galaxy mergers as the very cause of $M^*$ quenching, our results show that mergers are more likely to happen after the onset of the quenching. This supports quite naturally the theoretical framework developed by Pichon et al. (2011) and Codis et al. (2015), which predicts the merger-induced spin transition of DM halos reaching masses of a few $10^{12} M_\odot$, i.e., typically the DM halos that are expected to host $\sim M^*$ galaxies (e.g., Legrand et al. 2018; Codis et al. 2018). Thereby, our results support a scenario where $M^*$ galaxy quenching happens along cosmic filaments.

While the quenching of $M^*$ galaxies is expected to be slow and compatible with strangulation processes (Schawinski et al. 2014; Moutard et al. 2016b), the precise mechanism(s) disconnecting their $\sim 10^{12} M_\odot$ host DM halos from cold-gas streams remain unclear and may have multiple causes, from virial shock heating within DM halos (Dekel & Birnboim 2006), to vorticity within filaments (Laigle et al. 2015), which may potentially be affected by major mergers between halos along filaments (Welker et al. 2014; Aragon-Calvo et al. 2016).

The pilot study we presented here is an invitation to confirm and refine the scenario of the quenching of $M^*$ galaxies. In particular, morphological analysis from much deeper imaging will allow us to increase drastically the number of $M^*$ galaxy mergers and pairs observed in the green valley in a future paper, while the connection between $M^*$ green-valley galaxies and cosmic filaments will be specifically investigated in a companion study.

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