Digging for red nuggets: discovery of hot haloes surrounding massive, compact, relic galaxies

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ABSTRACT

We present the results of *Chandra* X-ray observations of the isolated, massive, compact, relic galaxies MRK 1216 and PGC 032873. Compact massive galaxies observed at $z > 2$, also called red nuggets, formed in quick dissipative events and later grew by dry mergers into the local giant ellipticals. Due to the stochastic nature of mergers, a few of the primordial massive galaxies avoided the mergers and remained untouched over cosmic time. We find that the hot atmosphere surrounding MRK 1216 extends far beyond the stellar population and has a 0.5–7 keV X-ray luminosity of $L_X = (7.0 \pm 0.2) \times 10^{41}$ erg s^{-1}, which is similar to the nearby X-ray bright giant ellipticals. The hot gas has a short central cooling time of ∼50 Myr and the galaxy has an ∼13-Gyr-old stellar population. The presence of an X-ray atmosphere with a short nominal cooling time and the lack of young stars indicate the presence of a sustained heating source, which prevented star formation since the dissipative origin of the galaxy 13 Gyr ago. The central temperature peak and the presence of radio emission in the core of the galaxy indicate that the heating source is radio-mechanical active galactic nucleus (AGN) feedback. Given that both MRK 1216 and PGC 032873 appear to have evolved in isolation, the order of magnitude difference in their current X-ray luminosity could be traced back to a difference in the ferocity of the AGN outbursts in these systems. Finally, we discuss the potential connection between the presence of hot haloes around such massive galaxies and the growth of super-/overmassive black holes via chaotic cold accretion.

Key words: galaxies: active – galaxies: evolution – galaxies: formation – X-rays: galaxies.

1 INTRODUCTION

The formation and evolution of giant elliptical galaxies are well described by two-phase models (Oser et al. 2010; Rodriguez-Gomez et al. 2016). The first phase is a quick dissipative event, when the core of the galaxy and its supermassive black hole are formed. The results of this first stage are the compact massive galaxies with $r_e \lesssim 2$ kpc and $M_\star \gtrsim 10^{11}$ M$_\odot$, so-called red nuggets observed at $z > 2$. This early rapid growth is followed by a slow accretion phase when the galaxy undergoes dry mergers with lower mass galaxies. These random encounters will place most of the newly accreted material at the periphery of the galaxy, significantly increasing its

size, but leaving the centre unaffected. Semi-analytical models and cosmological simulations indicate that the size of a massive galaxy can increase by a factor of ∼7 during the merger phase, while its velocity dispersion increases by at most a factor of ∼1.1 (Hilz et al. 2012). However, due to the stochastic nature of mergers, a few of the primordial massive galaxies should avoid the second stage, remaining untouched over cosmic time (Quilis & Trujillo 2013).

The first confirmed low redshift *massive relic galaxy*, mimicking the properties of high-redshift compact massive galaxies, is NGC 1277 ($r_e = 1.2$ kpc and $M_\star = 1.3 \times 10^{11}$ M$_\odot$) in the Perseus cluster (Trujillo et al. 2014). This galaxy is also well known for hosting one of the most massive black holes detected to date (van den Bosch et al. 2012; Graham et al. 2016; Walsh et al. 2016). Ferré-Mateu et al. (2015) identified a sample of seven potential massive relic galaxies, all with unusually massive central black holes (3σ–5σ outliers on the M_{BH}–M_{bulge} relation). Recently, Ferré-Mateu et al. (2017) con-

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firmed that two previously identified candidates (MRK 1216 and PGC 032873) are indeed red nuggets in the present-day Universe (see also Walsh et al. 2017). The stellar masses of these galaxies reach $\sim 2 \times 10^{11}$ $M_\odot$ and their stellar populations are highly concentrated in the innermost parts, resulting in effective radii of $R_e \sim 2$ kpc. Ferré-Mateu et al. (2017) conclude that these galaxies were formed quickly and early, and their mean mass-weighted ages are ~ 13 Gyr. They have strongly peaked velocity dispersion profiles with $\sigma \sim 360$ km s^{-1} at R_e and compact morphologies with no signs of interactions. These properties set them clearly apart from typical giant ellipticals; instead, they represent the properties of the early population of red nuggets observed at redshifts $z \gtrsim 2$ (e.g. Buitrago et al. 2008; van der Wel et al. 2011), that only went though the first dissipative phase of galaxy formation. These systems thus allow us to perform a detailed study of red nuggets, the puzzling progenitors of giant elliptical galaxies.

As progenitors of giant elliptical galaxies, red nuggets are expected to have large total masses of 10^{12-13} $M_\odot$ and thus, in principle, to hold on to hot X-ray emitting atmospheres. The presence of hot atmospheres around massive galaxies in the early universe would have important consequences for studies of galaxy quenching and maintenance mode feedback. The X-ray morphologies, thermodynamic properties, and metallicities of these atmospheres will also carry important information about the more recent growth and evolution of these systems. The most isolated of the currently confirmed low redshift massive, compact, relic galaxies are MRK 1216 ($z = 0.021328$, $D = 97$ Mpc) and PGC 032873 ($z = 0.024921$, $D = 108$ Mpc), with their closest neighbours at distance $\gtrsim 1$ Mpc (Ferré-Mateu et al. 2017; Yıldırım et al. 2017). However, while PGC 032873 is X-ray faint and its 22.7 ks archival *Chandra* observation only provides 200 counts, which only allow for a temperature measurement (see Section 2 and Buote & Barth 2018), MRK 1216 is X-ray bright and allows to perform a detailed study of the X-ray emitting atmosphere of the galaxy. Therefore, this massive relic system provides the best, albeit indirect, opportunity to study the thermodynamic structure of an extended X-ray emitting halo around a red nugget, long before future large X-ray missions, such as *Athena* or *Lynx*, will allow us to observe the massive high redshift galaxies directly.

2 OBSERVATIONS AND DATA ANALYSIS

MRK 1216 has been observed by *Chandra* for 12.9 ks in 2015 June and PGC 032873 for 22.7 ks in 2015 March using the Advanced CCD Imaging Spectrometer (ACIS) chip 6. We analysed these archival data using standard data analysis procedures (e.g. Lakhchaura, Saini & Sharma 2016; Werner et al. 2014, 2016). The background, for both image analysis and spectroscopy, was extracted from the same chip as the source spectrum.

We modelled the spectra as absorbed single-phase plasma in collisional ionization equilibrium (APEC, AtomDB 3.0.9; Smith et al. 2001; Foster et al. 2012), with the temperature, spectral normalization, and metallicity as free parameters, and a $kT = 7.3$ keV bremsstrahlung model with a free normalization to account for the population of unresolved galactic point sources (Irwin, Athey & Bregman 2003; Boroson, Kim & Fabbiano 2011). The normalization of the unresolved point source component has large errors and is not statistically significant for these galaxies (see also Buote & Barth 2018). The line-of-sight absorption column density was fixed to $N_H = 4.03 \times 10^{20}$ cm^{-2} for MRK 1216 and $N_H = 1.1 \times 10^{20}$ cm^{-2} for PGC 032873, as determined by the Leiden/Argentine/Bonn radio survey of H I (Kalberla et al. 2005). For fitting multitemperature

spectra, we used the SPEX spectral fitting package (Kaastra, Mewe & Nieuwenhuijzen 1996).

The spectrum of PGC 032873 contains around 200 counts and only allows to determine the X-ray luminosity of the gaseous atmosphere of the galaxy and a single temperature value (see Section 3). It is not sufficient to study the spectral properties in multiple radial bins. The data for the significantly brighter MRK 1216 allow us to determine the azimuthally averaged deprojected thermodynamic quantities for the X-ray emitting halo surrounding the system in six annular regions, with ~ 200 background-subtracted counts per annulus (the outermost annulus contains ~ 300 counts). We modelled the spectra, using the PROJCT model implemented in the XSPEC spectral fitting package (Arnaud 1996). The combined set of spectra was modelled in the 0.6–7.0 keV band simultaneously to determine the deprojected electron density (n_e) and temperature (kT) profiles. From the electron densities and temperatures, we determined the entropy, $K = kT_e/n_e^{\frac{2}{3}}$, and cooling time, $t_{cool} = \frac{3}{2}(n_e + n_i)kT/(n_e n_i \Lambda(T))$, profiles, where the ion number density $n_i = 0.92 n_e$, and $\Lambda(T)$ is the cooling function for Solar metallicity tabulated by Schure et al. (2009).

3 RESULTS

The *Chandra* X-ray observation revealed a gaseous X-ray halo surrounding MRK 1216, extending far beyond its stellar population (see Fig. 1). The X-ray emission is detected with a significance greater than 3σ out to a radius of 55 kpc. The spectrum of the central region is entirely consistent with thermal emission. The upper limit on the 0.5–7 keV X-ray luminosity of a power-law-like emission component from the active galactic nucleus (AGN) and possibly unresolved point sources within the radius of 1 kpc is 9.47×10^{39} erg s^{-1}, which is about 3.4 per cent of the thermal emission in this region. The total 0.5–7 keV X-ray luminosity within the radius of 10 kpc is $L_X = (7.0 \pm 0.2) \times 10^{41}$ erg s^{-1}. Around PGC 032873, *Chandra* X-ray observations revealed a hot halo extending only to $r \sim 20$ kpc (10 arcsec; see also Buote & Barth 2018) with a total 0.5–7 keV X-ray luminosity within $r = 10$ kpc of $L_X = (5.6 \pm 0.5) \times 10^{40}$ erg s^{-1}.

By fitting a model of a single-temperature plasma in collisional ionization equilibrium to the spectrum of MRK 1216 extracted within the radius of $r = 10$ kpc, we determine a best fit temperature of $kT = 0.80 \pm 0.03$ keV and a metallicity of $Z = 0.6 \pm 0.1$ Solar (consistent values are obtained using both XSPEC/APEC and the SPEX spectral fitting packages; we have assumed the Solar abundances of Lodders & Palme 2009, throughout). This metallicity is likely to be biased low due to an intrinsically multitemperature structure of the gas (see Buote 2000; Werner et al. 2008). When fitting the spectrum with a Gaussian emission measure model (GDEM) available in SPEX (see e.g. de Plaa et al. 2017, for details), we find a multitemperature distribution with a central temperature of 0.92 ± 0.9 keV, width $\sigma = 0.3 \pm 0.1$ keV and a metallicity of 1.2 ± 0.3 Solar. For the spectrum of PGC 032873 extracted within $r = 10$ kpc, we find a temperature of $kT = 0.55 \pm 0.11$ keV. The low number of counts does not allow us to measure the metallicity of this system.

The data for MRK 1216 allow us to determine the radial distribution of azimuthally averaged spectral properties in six concentric annuli. Our best-fitting deprojected profile shown in Fig. 2 and Table 1 has a C-statistics value of 1284 for 1842 degrees of freedom. The galaxy has a relatively high central density of $n = 0.30 \pm 0.02$ cm^{-3}, a centrally peaked temperature distribution
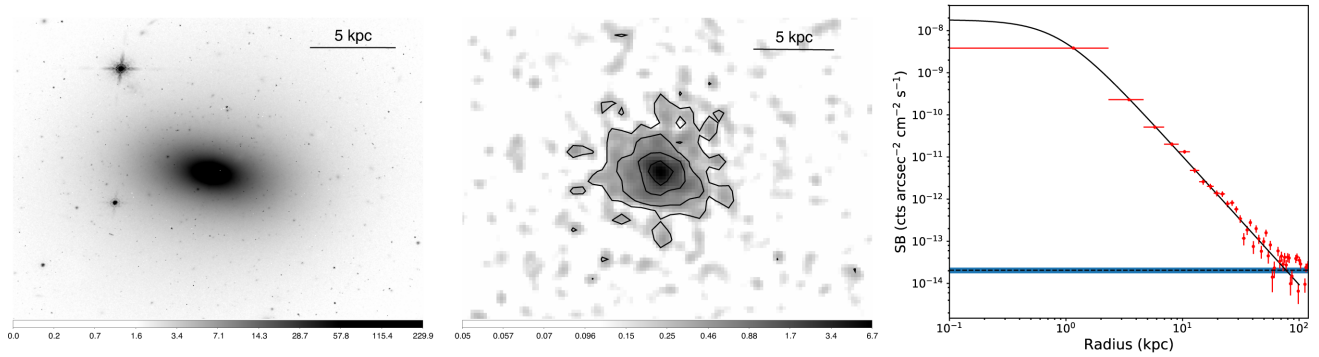
Figure 1. *Left panel: Hubble Space Telescope (HST)* Advanced Camera for Surveys filter F160W archive image of MRK 1216. For a circularized stellar mass density profile, see Ferré-Mateu et al. (2017). *Central panel:* The *Chandra* X-ray data reveal a hot X-ray emitting atmosphere around the isolated, massive, compact, relic galaxy Mrk 1216. *Right panel:* The X-ray surface brightness profile in the 0.5–7.0 keV band shows that the X-ray emitting atmosphere of this relic galaxy extends far beyond its stellar population, out to radii of over 55 kpc. The emission is fit with a beta model of $\beta = 0.66 \pm 0.15$ and $r_c = 0.7 \pm 0.1$ kpc.
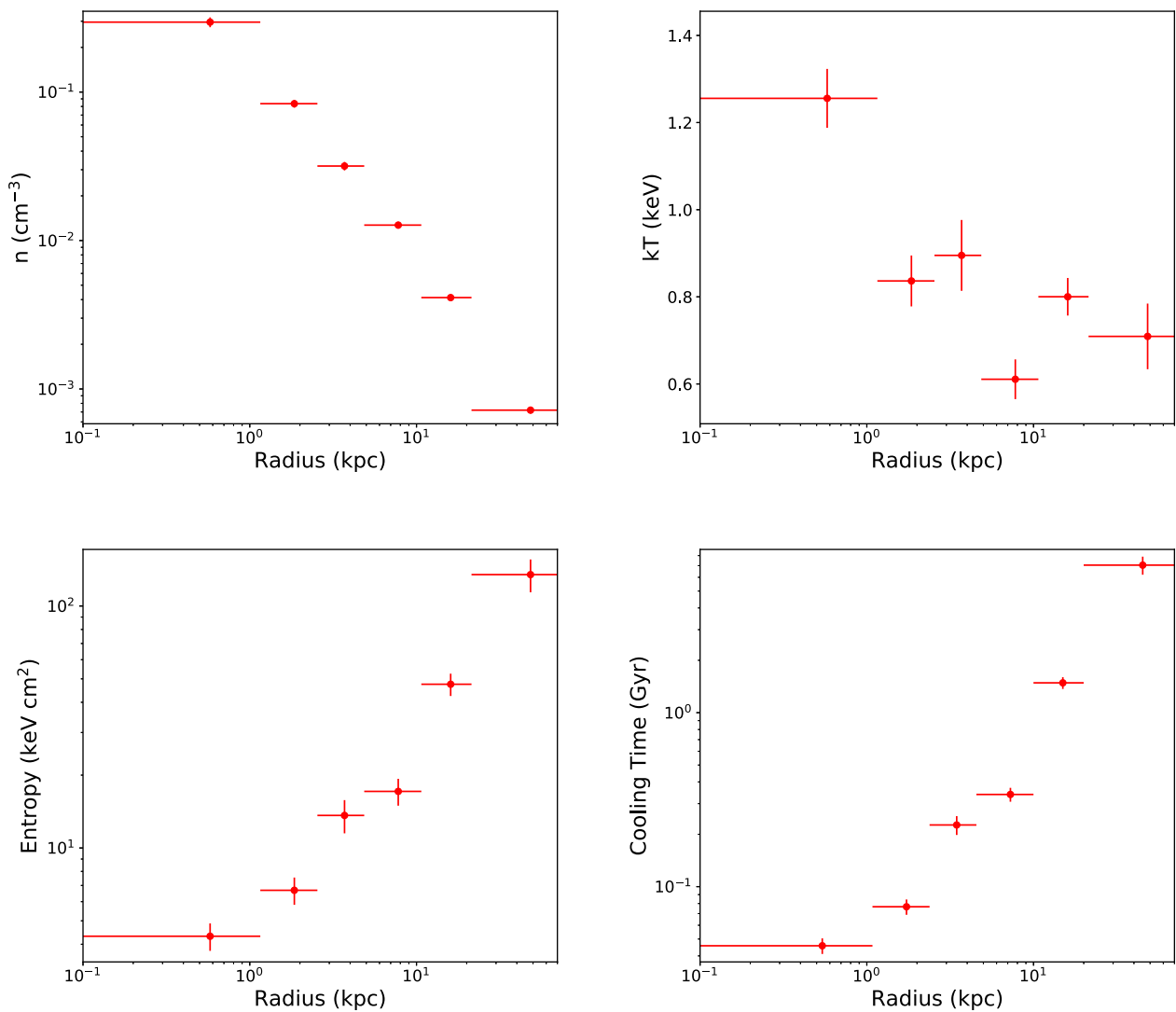
Figure 2. Radial distributions of the deprojected thermodynamic properties of the X-ray emitting atmosphere of the massive relic galaxy Mrk 1216: total density $n = n_e + n_i$ (top left), temperature (top right), entropy (bottom left), and cooling time (bottom right).

(core temperature of $kT = 1.25 \pm 0.07$ keV), a relatively flat entropy profile with a power-law index of 0.78 ± 0.05, and a central cooling time of $t_{cool} = 52 \pm 5$ Myr. The short cooling time means that

unchecked radiative cooling would lead to reservoirs of cold gas and star formation. If we fit the spectra with a simple isobaric cooling flow model (although in reality the presence of simple isobaric

Table 1. Deprojected thermodynamic properties of MRK 1216.

Radial range (kpc)	n (cm^{-3})	kT (keV)	K (keV cm^2)	P (10^{-11} erg cm^{-3})	t_{cool} (Gyr)	t_{ff} (Myr)	t_{cool}/t_{ff}
0–1.2	0.296 ± 0.022	1.25 ± 0.07	4.3 ± 0.6	59 ± 6	0.052 ± 0.005	1.52 ± 0.07	34 ± 4
1.2–2.5	0.084 ± 0.005	0.84 ± 0.06	6.7 ± 0.9	11.2 ± 1.0	0.086 ± 0.009	6.0 ± 0.3	15 ± 2
2.5–4.9	0.032 ± 0.002	0.90 ± 0.08	13.6 ± 2.1	4.5 ± 0.5	0.26 ± 0.03	12.1 ± 0.6	21 ± 3
4.9–10.7	0.0143 ± 0.0007	0.61 ± 0.05	17.1 ± 2.2	1.24 ± 0.11	0.38 ± 0.04	27.4 ± 1.3	14 ± 1
10.7–21.3	0.0041 ± 0.0002	0.80 ± 0.04	48 ± 5	0.53 ± 0.04	1.67 ± 0.13	54 ± 3	31 ± 3
21.3–75.2	0.0007 ± 0.0001	0.71 ± 0.08	135 ± 21	0.082 ± 0.010	7.9 ± 0.9	$151. \pm 10$	53 ± 7

cooling is unlikely), we obtain a mass deposition rate between 0.1 and 1.2 keV of $\dot{M} = 1.18 \pm 0.14\,M_{\odot}\,\mathrm{yr}^{-1}$. Taken together with the old stellar population of the galaxy (mean mass weighted age of 12.8 ± 1.5 Gyr, with 99 per cent of the stellar population more than 10 Gyr old; Ferré-Mateu et al. 2017), the short cooling time implies the presence of a heating source, which prevents the radiative cooling of the halo. The temperature distribution is strongly centrally peaked consistent with the presence of a nuclear heating source. The presence of warm/cool ionized gas has not been reported for this system. The Very Large Array (VLA) NVSS survey (Condon et al. 1998) shows a central radio source in the galaxy, with a flux of 9.2 ± 0.6 mJy at 1.4 GHz, corresponding to a radio luminosity of 1.9×10^{38} erg s^{-1}.

While the total hot gas mass within 70 kpc is $(1.9 \pm 0.5) \times 10^{10}\,M_{\odot}$, the gas mass within the smaller radius of $r < 10$ kpc is only $M_{gas} = (1.40 \pm 0.06) \times 10^{9}\,M_{\odot}$, comparable to the gas mass in nearby giant ellipticals (e.g. Werner et al. 2014). The gas mass is a small fraction of the stellar mass, which is $M_{\star} = (2.0 \pm 0.8) \times 10^{11}\,M_{\odot}$. The total mass within the same radius, calculated from the pressure profile assuming hydrostatic equilibrium, is $M_{tot} = (7 \pm 5) \times 10^{11}\,M_{\odot}$, consistent with the dynamical mass of the system (see Yıldırım et al. 2015). The gas mass fraction is also within the range measured in the nearby, mature, massive elliptical galaxies (see e.g. Werner, Allen & Simionescu 2012). For a more detailed mass modelling of MRK 1216 based on its X-ray properties, see Buote & Barth (2018). They extrapolated the mass profile out to the virial radius yielding a total mass within r_{200} of $M_{200} = (9.6 \pm 3.7) \times 10^{12}\,M_{\odot}$ for this system, which is consistent with the masses of group scale haloes.

4 DISCUSSION

The isolated, massive, compact relic galaxies MRK 1216 and PGC 032873 harbour extended hot X-ray emitting atmospheres. The X-ray gas surrounding MRK 1216 extends far beyond its stellar population and its luminosity within $r = 10$ kpc is $L_X = (7.0 \pm 0.2) \times 10^{41}$ erg s^{-1}, which is similar to the luminosities of the hot atmospheres of nearby bright giant ellipticals, most of which are found in the centres of groups of galaxies (e.g. Werner et al. 2014). On the other hand, the X-ray luminosity of PGC 032873, which has a similar stellar mass to MRK 1216 (Ferré-Mateu et al. 2017), is about an order of magnitude lower, $L_X = (5.6 \pm 0.5) \times 10^{40}$ erg s^{-1}. This luminosity difference is well within the scatter in the X-ray luminosities of early-type galaxies (e.g. O'Sullivan, Forbes & Ponman 2001; Su et al. 2015; Kim & Fabbiano 2015). The hydrostatic mass estimates (Buote & Barth 2018) and the stellar velocity dispersions (Ferré-Mateu et al. 2017) do not indicate that the gravitational potential well of PGC 032873 is significantly shallower than that of Mrk 1216.

Hot atmospheres might be leftover material from the process of galaxy formation and stellar mass loss may also have contributed significantly to the X-ray emitting gas mass (for a review, see Mathews & Brighenti 2003). Hydrodynamic simulations predict that about 75 per cent of the ejecta produced by red giant stars moving supersonically relative to the ambient medium will be shock heated to approximately the temperature of the hot gas (Parriott & Bregman 2008; Bregman & Parriott 2009). The evolved stellar population of the galaxy is expected to contribute $\sim 1\,M_{\odot}\,\mathrm{yr}^{-1}$ per $10^{11}\,M_{\odot}$ (Canning et al. 2013), which means that at the current mass loss rate the amount of gas within the inner 10 kpc of MRK 1216 could be built up in less than 1 Gyr. The surface brightness and density profiles in MRK 1216 do not show the presence of abrupt jumps, indicating that the atmosphere of this isolated galaxy is continuous. We note that various parts of the hot gaseous atmosphere, with increasing radius, could in principle be labeled as interstellar medium (ISM), circum-galactic medium, and intergalactic medium.

The presence of an X-ray atmosphere with a short nominal cooling time and the lack of young stars indicates the presence of a sustained heating source, which prevented star formation for 13 Gyr, since the quick dissipative formation of the galaxy. The current Type Ia supernovae rate in the old stellar population of $2 \times 10^{11}\,M_{\odot}$ is around 0.16 per 100 yr (Maoz, Mannucci & Brandt 2012). This rate would be insufficient to balance the radiative cooling of the hot atmosphere of MRK 1216 even if the entire explosion energy of 10^{51} ergs per supernova would go into the heating of the X-ray emitting gas. The heating rate would fall short by at least an order of magnitude. Assuming that the supernova rate is decreasing with cosmic time as $(t/13\mathrm{Gyr})^{-1}$, already 1 Gyr after the formation of the stellar population of the galaxy, supernovae would not have been able to balance the radiative cooling of the hot atmosphere that today surrounds MRK 1216.

The central temperature peak, the relatively flat entropy profile (index of 0.78 ± 0.05, which is flatter than the value of ~ 1.1 expected from gravitational collapse; Voit, Kay & Bryan 2005), and the presence of a radio source in the core of the galaxy indicate that, similarly to cooling core clusters and giant ellipticals, the heating source is radio-mechanical AGN feedback (for review, see McNamara & Nulsen 2007, 2012). The cooling time over free-fall time $t_{cool}/t_{ff} \sim 15-30$ within the central $r \lesssim 10$ kpc of MRK 1216 is also similar to the values measured in the centres of many clusters, groups, and giant elliptical galaxies (Hogan et al. 2017; Pulido et al. 2018). The radially decreasing temperature profile is consistent with compressional heating in a steep central gravitational potential in the presence of sustained gentle heating (see e.g. Gaspari et al. 2012a). Similarly to the brightest cluster galaxies of luminous cooling core clusters (Hlavacek-Larrondo & Fabian 2011; Russell et al. 2013) and nearby giant ellipticals (Werner et al. 2012, 2014), the AGN is accreting at a very small X-ray luminosity $L_X < 9.47 \times 10^{39}$ erg s^{-1}, corresponding to an Eddington ratio of $L_X/L_{\mathrm{Edd.}} \lesssim 10^{-8}$. The ra-

dio luminosity is also similar to the giant ellipticals with ongoing radio-mechanical AGN feedback. The number of counts is unfortunately too small to find AGN blown X-ray cavities in the X-ray images.

The black hole mass of $M_{BH} = (4.9 \pm 1.7) \times 10^9$ M$_\odot$ in MRK 1216 is a factor of 10 larger than the expectations from the black hole mass–bulge mass relation established at $z = 0$ (Ferré-Mateu et al. 2017; Walsh et al. 2017), but is within the intrinsic scatter measured by Saglia et al. (2016) for the black hole mass–stellar velocity dispersion relation. PGC 032873 possibly also hosts an overmassive black hole, with a mass upper limit of $M_{BH} < 10^{10}$ M$_\odot$ (Ferré-Mateu et al. 2015). The fraction of the current mass that these black holes already reached during the early stages of the fast dissipative growth ∼13 Gyr ago remains unknown. In light of the lack of significant mergers and star formation in these cold gas free galaxies over the past 13 Gyr, the remaining black hole mass could only have been accreted from the hot halo. Gaspari & Sądowski (2017) show that the accretion rate on to the supermassive black hole is tightly linked to the X-ray properties of the hot halo, since it is the progenitor source of the feeding mechanism. In a physical process known as chaotic cold accretion (CCA; Gaspari, Ruszkowski & Oh 2013), multiphase gas condenses out of the hot halo (Gaspari et al. 2018), raining on to the central region, and via inelastic collisions the cold/warm clouds are rapidly funnelled towards the central black hole. High-resolution hydrodynamic simulations (e.g. Gaspari, Ruszkowski & Sharma 2012b) show that an isolated elliptical galaxy undergoing cycles of CCA and mechanical AGN feedback can grow a BH mass of several 10^9 M$_\odot$ over 10 Gyr ($M_{BH} = E_{inj}/(\epsilon c^2)$, with a mechanical efficiency $\epsilon = 10^{-4}$ and total injected mechanical energy of several 10^{59} erg). It is important to note that during CCA the galaxy experiences rapid flicker noise variability in time, thereby a currently low AGN X-ray luminosity does not necessarily imply low accretion rates throughout the cosmic time. Moreover, the nuclear radiative luminosity is expected to be low during the maintenance mode of feedback, since most of the power is released through the mechanical channel (e.g. Russell et al. 2013) and the radiative efficiency strongly decreases with declining Eddington ratios. Finally, other observational studies have suggested that the total halo mass (which in the case of Mrk 1216 is $M_{200} = 9.6 \pm 3.7 \times 10^{12}$ M$_\odot$; Buote & Barth 2018) correlates better with the black hole mass than the stellar populations of the host galaxies (Bogdán et al. 2012; Bogdán & Goulding 2015; Bogdán et al. 2018). The study of the X-ray emitting gas in massive relic galaxies is therefore key to advance our knowledge of AGN feeding and feedback at the different evolutionary stages of giant ellipticals.

Given that over the past ∼13 Gyr both MRK 1216 and PGC 032873 appear to have evolved passively and in isolation, the difference in their current X-ray luminosity can perhaps be traced back to a difference in the ferocity of the AGN outbursts in these systems. The AGN activity in PGC 032873 could have been less gentle than the current activity in MRK 1216, undergoing a powerful outburst displacing most of the gas from its gravitational potential well. A more detailed knowledge of the size of the scatter in the X-ray luminosities of isolated, massive, compact, relic galaxies will be obtained by the future optical and X-ray surveys, which are expected to discover more of these interesting systems in our cosmic backyard.

5 CONCLUSIONS

Here we report the first[1] detection of hot X-ray emitting atmospheres around the isolated, massive, compact, relic galaxies MRK 1216 and PGC 032873. For MRK 1216 within $r < 10$ kpc, we find a 0.5–7 keV X-ray luminosity of $L_X = (7.0 \pm 0.2) \times 10^{41}$ erg s^{-1} and a gas mass of $M_{gas} = (1.4 \pm 0.06) \times 10^9$ M$_\odot$, similar to the local X-ray bright giant ellipticals, many of which reside in the centres of groups.

(i) The galaxy shows a high central density of $n = 0.30 \pm 0.02$ cm^{-3}, a central temperature peak of $kT = 1.25 \pm 0.07$ keV, a short cooling time of $t_{cool} = 52 \pm 5$ Myr, and an ∼13-Gyr-old stellar population. The presence of an X-ray atmosphere with a short nominal cooling time and the lack of young stars indicate the presence of a sustained heating source, which prevented star formation since the dissipative formation of the galaxy 13 Gyr ago. The central temperature peak, the presence of radio emission in the core of the galaxy, and the low Eddington ratio indicate that the heating source is a gentle radio-mechanical AGN feedback.

(ii) The X-ray luminosity of the other isolated, massive, compact, relic galaxy PGC 032873, which has a similar stellar mass to MRK 1216 (Ferré-Mateu et al. 2017), is about an order of magnitude lower, $L_X = (5.6 \pm 0.5) \times 10^{40}$ erg s^{-1}. Given that over the past ∼13 billion years both galaxies appear to have evolved passively and in isolation, the difference in their current X-ray luminosity could be traced back to a difference in the vigour of the AGN outbursts in these systems.

(iii) MRK 1216 and possibly PGC 032873 are outliers above the black hole mass–bulge mass relation at $z = 0$. The fraction of the current mass that these black holes already reached during the early stages of the fast dissipative growth ∼13 Gyr ago remains unknown. Theoretical predictions of CCA indicate that appreciable fractions of the black hole masses could have been accreted from the extended hot X-ray emitting haloes. The study of the X-ray emitting gas in massive relic galaxies is thus key to advance our knowledge of AGN feeding and feedback at the different evolutionary stages of massive galaxies.

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[1]About 2 weeks after submitting this paper and publishing its preprint on the arXiv, a preprint of an independent and complementary X-ray study appeared by Buote & Barth (2018) focused mostly on studying the mass profile of MRK 1216.

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