Perseus in Sicily: From Black Hole to Cluster Outskirts
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The AGN dependence on cluster mass

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Abstract. We present the results of a study of the AGN density in a homogeneous and well studied sample of 167 bona-fide X-ray galaxy clusters ($0.1 < z < 0.5$). Our aim is to study the AGN activity in 167 XXL X-ray galaxy clusters as a function of the cluster mass and the location of the AGN in the cluster. We report a significant AGN excess in our low-mass cluster sub-sample between $0.5r_{500}$ and $2r_{500}$. In contrast, the high-mass sub-sample presents no AGN excess. The AGN excess in poor clusters indicates AGN triggering, supporting previous studies that reported enhanced galaxy merging in the cluster outskirts. This effect is probably prevented by high velocity dispersions in high-mass clusters. Comparing also with previous studies of massive or high-redshift clusters, we conclude that the AGN fraction in cluster galaxies anti-correlates strongly with cluster mass.

Keywords. galaxies: active – galaxies: Clusters: general – X-rays: galaxies: clusters – galaxies: interactions – galaxies: evolution – cosmology: large scale structure of Universe

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1. Introduction

As the most massive self-gravitating entities of the universe, clusters are ideal laboratories to investigate the impact of dense environments on AGN demographics. However, the effect of the group and cluster environment on the activity of the central supermassive black hole (SMBH) of galaxies is still fairly undetermined. Several studies reported a significant lack of AGNs in rich galaxy clusters with respect to the field (e.g. Haines *et al.* 2012; Ehlert *et al.* 2013, 2014; Koulouridis & Plionis 2010), while spectroscopic studies of X-ray point-like sources in rich galaxy clusters have concluded that low-X-ray-luminosity AGNs are equally present in cluster and field environments (e.g. Martini *et al.* 2007; Haggard *et al.* 2010). Furthermore, most of the X-ray sources found in clusters present weaker optical AGN spectrum than AGNs in the field (Marziani *et al.* 2017), or show no signs of an optical AGN (e.g. Martini *et al.* 2006; Davis *et al.* 2003), while luminous AGNs are rarely found in clusters (e.g. Popesso *et al.* 2006; Caglar & Hudaverdi 2017).

Although AGNs avoid cluster cores (e.g. Ehlert *et al.* 2014; Melnyk *et al.* 2017, XXL paper XXII), there is evidence that X-ray AGNs found in massive clusters are an infalling population located mostly in the outskirts (Haines *et al.* 2012). Furthermore, Ehlert *et al.* (2015) argued that an important part of the cluster AGN population is triggered by galaxy mergers. Indeed, galaxy interaction and merging can lead to AGN triggering (e.g. Kawakatu *et al.* 2006; Koulouridis *et al.* 2006b,a, 2013; Koulouridis 2014; Ellison *et al.* 2011; Hopkins *et al.* 2014), rendering the high-density cluster outskirts a favourable AGN environment. However, in innermost cluster regions the ram pressure stripping from the intra-cluster medium (ICM) is probably able to strip or evaporate the

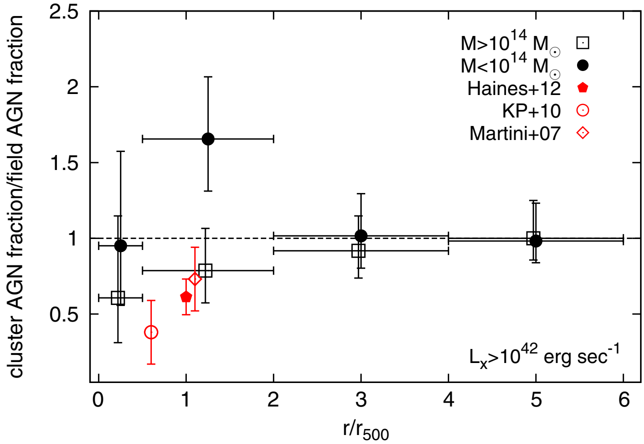

Figure 1. Fraction of XXL bright cluster galaxies hosting an X-ray AGN ($L_{X[0.5-10\,\mathrm{keV}]} > 10^{42}$ erg sec^{-1}), divided by the field fraction. Error bars indicate the 1σ confidence limits for small number of events. For comparison we plot results from the analyses of massive clusters by Martini *et al.* (2007, 8 clusters, 0.06< z <0.31) Koulouridis & Plionis (2010, 16 clusters, 0.07< z <0.28) and Haines *et al.* (2012, 26 clusters, 0.15< z <0.30). A significant AGN excess is found between $0.5r_{500,MT}$ and $2r_{500,MT}$, at the 95% confidence level.

cold gas reservoir of galaxies (e.g. Cowie & Songaila 1977; Poggianti *et al.* 2017) and can strongly affect the fueling of the AGN.

If the AGN activity depends on the gravitational potential, we would expect the AGN presence to anti-correlate with cluster mass. Previous studies of small poor cluster samples reported evidence of this anti-correlation (Arnold *et al.* 2009; Oh *et al.* 2014; Koulouridis *et al.* 2014). In addition, Ehlert *et al.* (2015) argued that the number of AGNs in a sample of 135 clusters scales with $M^{-1.2}$. On the other hand, Bufanda *et al.* (2017) reported no differences between groups and clusters in the DES cluster sample.

In the current work we study the X-ray AGN density in 167 spectroscopically confirmed X-ray selected clusters of the XXL survey (The Ultimate XMM-Newton Survey, Pierre *et al.* 2016). This homogeneous collection of low-mass X-ray clusters provides a far larger sample of such clusters than previous studies. This mass range is largely unexplored but is nevertheless an essential link between optical galaxy groups and massive clusters.

2. The XXL survey and the sample selection

The XXL Survey is the largest *XMM-Newton* project approved to date (>6 Msec) with a median exposure of 10.4 ks and a depth of $\sim 5\times10^{-15}$ erg sec^{-1} cm^{-2} in the (0.5-2 keV) X-ray band (completeness limit for point-like sources). The two fields have extensive multi-wavelength coverage from X-ray to radio. To date some 450 new galaxy clusters have been detected out to redshift $z\sim2$, as well as more than 25000 AGNs.

We selected all spectroscopically confirmed XXL clusters spanning a redshift range of $0.1 < z < 0.5$. In addition, we limited our sample to these clusters with direct X-ray temperature and luminosity measurements. Our sources cover an estimated mass range of $10^{13} - 5\times10^{14} M_{\odot}$, which classifies them as poor clusters (groups) or moderately rich clusters. This is an important feature of our sample for the current study, in order to investigate the role of the cluster mass in triggering and suppressing AGN activity.

The X-ray point source catalogue is described in Chiappetti *et al.* (2018, XXL paper XXVII). Spectroscopic redshifts were obtained with large spectroscopic surveys or from

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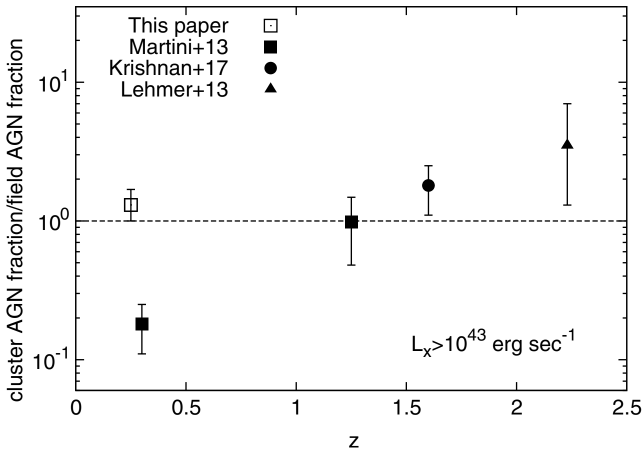

Figure 2. Fraction of XXL bright cluster galaxies hosting an X-ray AGN ($L_{X[0.5-10\,\mathrm{keV}]} > 10^{43}$ erg sec^{-1}) within $2r_{500}$ radius, divided by the field fraction. We overplot the results of similar analyses of cluster samples from Martini *et al.* (2013), or individual high-redshift proto-clusters from Krishnan *et al.* (2017) and Lehmer *et al.* (2013).

a large campaign with the AAOmega spectrograph on the Anglo-Australian Telescope (see Lidman *et al.* 2016, XXL paper XVI). Other smaller-scale spectroscopic observations (e.g. with WHT, Koulouridis *et al.* 2016, XXL paper XII) complement the sample.

3. Results and conclusions

For the presentation of the results we computed the AGN fraction in bright cluster member galaxies, having an absolute magnitude M_i in the i band within $M_i^* - 2 < M_i < M_i^* + 1$, to the respective field AGN fraction. Our results are compared with similar studies of the AGN fraction in bright cluster galaxies selected in various bands. The majority of these studies use an $M^* + 1$ magnitude cut, consistent with the one used in the current study.

Our results show a significant excess of X-ray AGNs in low-mass clusters ($M_{500,MT} < 10^{14} M_{\odot}$) up to a radius of $2r_{500}$ (Overdensity radius with respect to the critical density), at the 95% confidence level. Nevertheless, in the innermost cluster region ($< 0.5r_{500}$) a sharp decrease drives the AGN fraction back to the field level. On the other hand, the high-mass subsample presents a gradually decreasing AGN fraction towards the cluster centres, which reaches down to a factor of three lower than the field level.

We argue that the AGN excess found in the cluster outskirts of low-mass clusters supports an in-falling AGN population scenario. The excess may be attributed to high galaxy densities, which can lead to higher merger rates (Ehlert *et al.* 2015) and finally to AGN triggering. On the other hand, high velocity dispersions in massive clusters may diminish the probability of galaxy interactions, reversing this effect. As an example, Arnold *et al.* (2009) found that 10 groups with velocity dispersion $\sigma < 500$ km sec^{-1} present higher AGN fractions than six clusters above this velocity dispersion limit.

We also argue that the decrease of the AGN fraction in cluster cores, both in low- and high-mass clusters, support the ram pressure stripping scheme produced by the hot ICM. The hotter gas in deep gravitational potentials would be expected to strip the galaxy more effectively than the colder gas in our poor cluster population. Indeed, the density of AGNs within the first $< 0.5r_{500}$ is consistent with the background level, in contrast to the well established lack of AGNs in massive clusters.

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Both the effective galaxy merging and gas stripping may affect differently the AGN activity in poor and massive clusters. The "cluster mass – AGN activity" anti-correlation provides evidence of how deeper gravitational potentials prevent AGN triggering in the outskirts and cause more effective ram pressure gas stripping in the cores.

Finally, we compare our results with similar studies in high-redshift cluster samples and proto-clusters. To this end, we computed the fraction of AGNs with $L_{\mathrm{X}[0.5-10\,\mathrm{keV}]} > 10^{43}$ erg sec^{-1} within a $2r_{500,MT}$ radius. In Fig. 2 we plot our results along with two samples of low- and high-redshift clusters, a proto-cluster at $z = 1.6$, and a candidate proto-cluster at $z = 2.23$. The 13 clusters between $z = 1$ and 1.5 in Martini *et al.* (2013) have estimated masses $M > 10^{14} M_{\odot}$ and up to a few times $10^{14} M_{\odot}$, consistent with the XXL high mass subsample. Nevertheless, their low-redshift sample at $z \sim 0.3$ is much more massive, being the compilation of the sample of Haines *et al.* (2012) and Martini *et al.* (2009). On the other hand, the mass of the proto-cluster at $z = 1.6$ has an estimated mass of $5.7 \times 10^{13} M_{\odot}$, within the range of the XXL low-mass subsample. Evidently, at redshifts above $z = 1$ the AGN fraction in clusters is not dissimilar to the AGN fraction in our sample, but this probably correlates with cluster mass and not evolution. We note however, that the cluster AGN fraction does evolve, but at the same rate as the field AGN fraction.

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