IC vs. ICM: distinguishing between X-ray emission from RLAGN lobes and their host galaxy groups

Judith Ineson, University of Southampton, UK
Judith Croston, Open University, UK

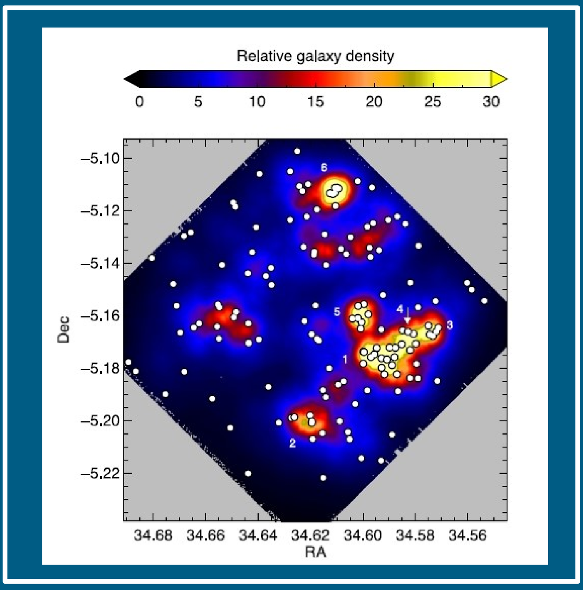

Fig. 1: Cl 0218.3–0510, an example of a protocluster at redshift 1.7, from Hatch et al. (2016). Galaxy group 1 is the most massive system (6×10^{13} $M_\odot$).

Background

Tracing the formation and evolution of galaxy groups and clusters gives information on the formation and growth of cosmic structure, the expansion history of the universe and the quantities of dark energy and matter, and so observations of the birth and growth of clusters are critical for constraining cosmological models (e.g. Voit 2005; Allen et al. 2011; Borgani & Kravtsov 2011). The clusters we see today formed largely during the last 10 billion years by hierarchical structure growth from smaller components - Hatch et al. (2016), for example, describe a protocluster at redshift z≈1.6 which simulations predict will grow into a cluster with mass M_{500}~3×10^{14} $M_\odot$ by z=0 (Fig. 1). The most massive group in the protocluster is ~6×10^{13} $M_\odot$.

We therefore need surveys able to detect large numbers of galaxy groups with masses down to, and preferably lower than $M_{500}=10^{13}$ $M_\odot$ out to z~2. With current technologies, only optical and X-ray observations can detect these relatively small systems. Optical methods give large uncertainties on mass calculations for groups, which may have only a handful of members, and X-ray observations for distant systems are too long to be used for surveys, so measurements of galaxy groups beyond z~0.5 are in short supply.

Matz (2019) discusses some upcoming cluster surveys. As can be seen in Fig. 2, the Athena X-ray telescope has the only survey planned that will capture these systems. The survey flux limit should allow detection and characterisation of systems below 10^{13} $M_\odot$ to beyond z~1, rising to ~6×10^{13} by z=2. Optical/NIR coverage by Euclid and LSST will give information on the systems' components, including the redshift.

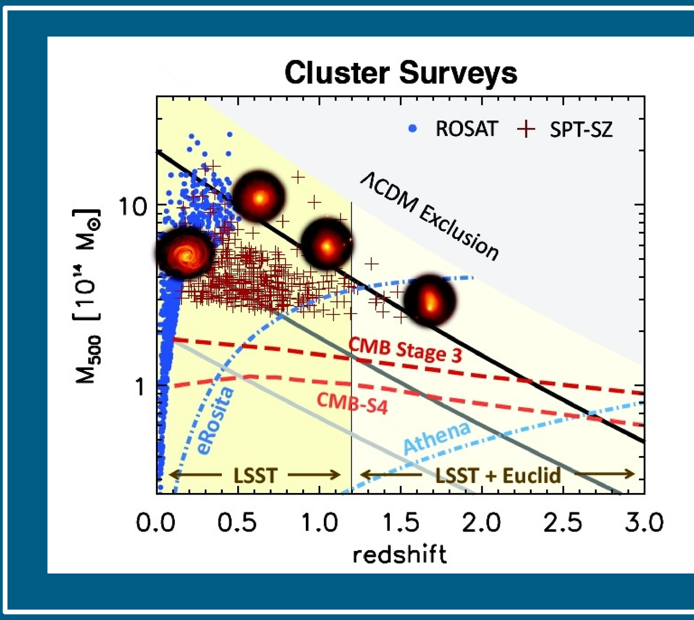

Fig. 2. Some existing and future cluster surveys, from Mantz et al. (2019). The only surveys that will detect galaxy groups between redshifts 0.5 and 2 are Athena (X-ray) and Euclid and LSST (optical/NIR).

A source of pollution of the ICM emission?

Some of these galaxy groups will host radio-loud AGN (RLAGN) – Williams et al. (2018) found 641 RLAGN with a 150 MHz luminosity greater than 10^{24} WHz^{-1} in a field of 19 deg^2. The relativistic leptons in the lobes of RLAGN interact with the CMB to produce inverse Compton (IC) emission at similar X-ray frequencies to the thermal bremsstrahlung from the ICM, and this is often seen in the lobes of FRII morphology RLAGN (Fig. 3). The CMB energy density increases with redshift, so the IC flux density remains much the same between z=0.5 and 2, and Erlund et al. (2016) observed IC emission from radio galaxies out to redshift ~2. FRI sources will also produce IC emission, but they contain a significant proportion of non-relativistic particle and so their emission will be less.

These group/RLAGN sources will have higher X-ray flux than similar galaxy groups without RLAGN, and so the IC contribution needs to be accounted for when calculating the properties of the groups. Also the CMB IC is produced by lower energy electrons than those responsible for the synchrotron radiation in the lobes and so the IC persists for a while after the synchrotron emission has stopped. Mocz (2011) estimated that 10 to 30% of double-lobed X-ray sources at redshifts 1 to 2 could be inverse Compton ghosts. These will also contribute to the X-ray flux in the region of the host group but they will not be catalogued so they will all have to be identified from the X-ray spectra.

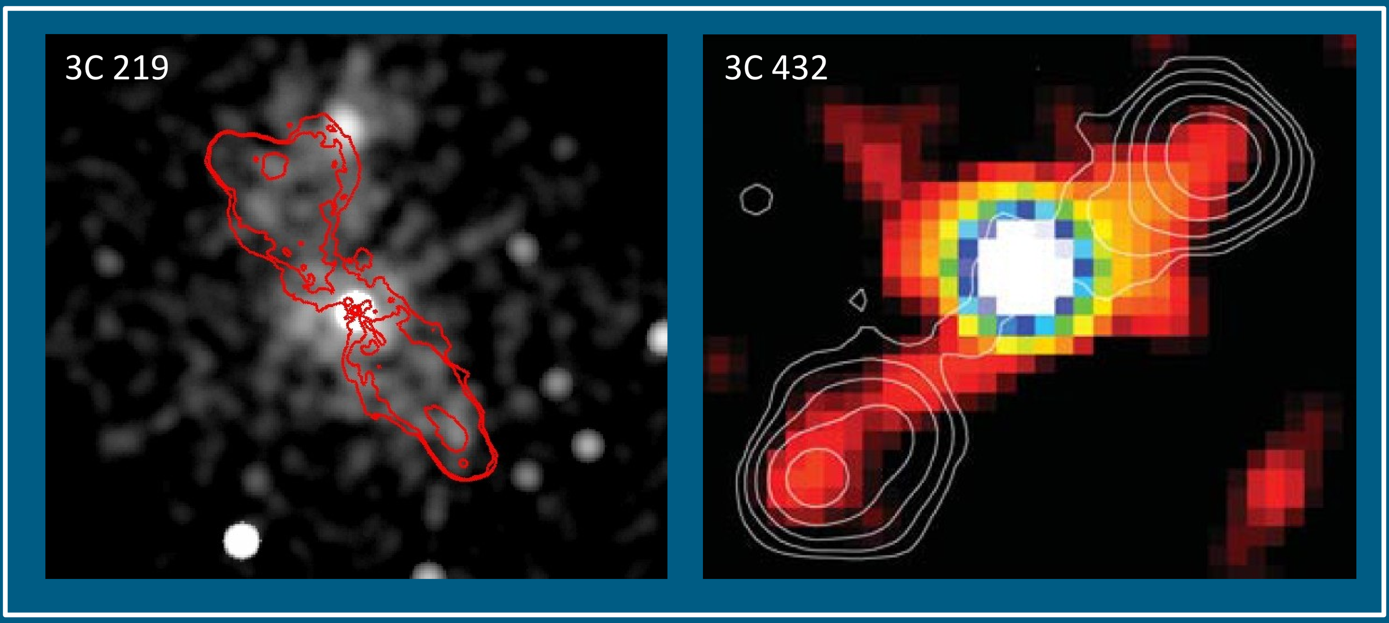

Fig. 3: Examples of inverse Compton emission from radio galaxy lobes: 3C 219 (z=0.17, J. Ineson) and 3C 432 (z=1.79, Erlund et al. 2016) . The contours overlaying the X-ray images show the radio emission.

Flux densities expected from FRII radio lobes and their host galaxy groups

Croston et al. (2018) found that the properties of a galaxy group housing a symmetric, mature FRII RLAGN can be predicted from the properties of the RLAGN alone. We used this to predict the hosts of a series of RLAGN of different luminosities and of lengths from 25 kpc to 3 Mpc.

Traditionally, the majority of FRII RLAGN lie above $L_{150}=10^{26}$ WHz^{-1}, but recent, more sensitive surveys have found RLAGN with FRII morphology up to three orders of magnitude below this (e.g. Capetti et al. 2017, Mingo et al. 2019). We therefore estimated the host properties of FRIIs with luminosities of $L_{150}=10^{24}$, 10^{26} and 10^{28} WHz^{-1}. The fluxes for the ICM and IC for the range of lengths and luminosities were estimated for z=0.5 and z=2.0, and are shown in Fig. 4. For the z=0.5 results, the rectangles show the range of ICM environments found for sources of 10^{26} and 10^{28} WHz^{-1} in the samples in Ineson et al. 2013 and 2015.

At z=0.5, the predicted ICM flux is above the Athena survey flux limit for all the RLAGN and the IC exceeds the flux limit for all but the shortest radio lobes, but it is of concern that the IC flux is higher than the predicted ICM flux for the longer lobes.

The ICM flux reduces as redshift increases but the IC flux stays much the same, is still detectable for all but the shortest, low luminosity sources at z=2, and is higher than the predicted ICM flux for all sources.

Thus the IC emission is likely to dominate over that of the host galaxy group for the majority of FRII sources in the redshift range 0.5 to 2, and will need to be accounted for when processing X-ray survey data.

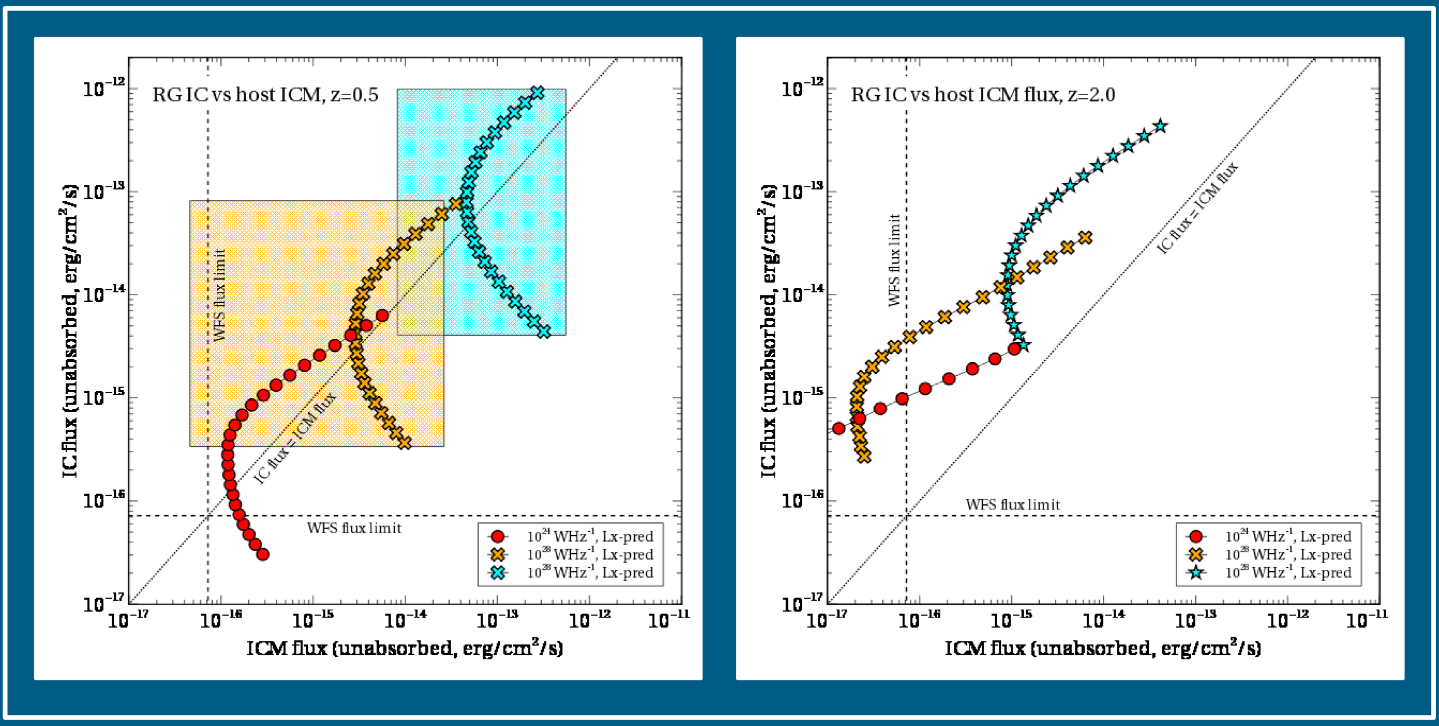

Fig. 4: Flux densities of FRII IC emission vs the predicted ICM emission of their host galaxy groups, for redshifts 0.5 (left) and 2.0 (right). Red circles, orange crosses and cyan stars are RLAGN with $L_{150}=10^{24}$, 10^{26} and 10^{28} WHz^{-1} respectively, and the dashed lines show the expected flux limit of the Athena survey.
The orange and cyan rectangles show the range of galaxy groups for the 10^{26} and 10^{28} WHz^{-1} FRIIs in the samples in Ineson et al. 2013 and 2015.

The size of the problem

We modelled a sample of the RLAGN sources expected in the area of the Athena survey using the source numbers and sizes in the LOFAR surveys reported in Hardcastle et al. (2018) and Williams et al. (2018). This gave a total of 614 mature sources up to 3 Mpc in length, with 150 MHz luminosity above 10^{24} WHz^{-1} and redshifts from 0.5 to 2. We used the SYNCH code (Hardcastle et al. 1998) to obtain the IC emission expected from each source (assuming FRII morphology), and XSPEC with the Athena WFI response files to simulate their spectra and obtain the photon counts during 80 ks observations, assuming Galactic absorption of 3×10^{20} cm^{-2}.

We again used the Croston et al. method to predict the properties of the galaxy groups hosting the RLAGN sample, simulated the spectra and estimated numbers of detected photons from the ICM.

Fig.5 shows the results for the sample at redshifts 0.5-1.0 and 1.5-2.0, illustrating the potential numbers of RLAGN with IC emission detectable by the Athena survey, and in particular how few of their host galaxy groups will be detectable at higher redshifts. At low redshifts, ~80% of the RLAGN and ~50% of their host groups are detected; at redshift 2, however, ~95% of the sample RLAGN are detected, but only ~15% of their hosts. If follow-up spectroscopy can identify the emission as IC rather than thermal bremsstrahlung, it will be useful in indicating the likely presence of a galaxy group and will put an upper limit on its flux.

Note that not all these RLAGN will be FRIIs; Mingo et al. (2019) found that about 25% of the LOFAR sample were FRIIs so these results are an overestimate. Conversely, the samples used as the basis of this study contained only sources robustly classified as RLAGN (Hardcastle et al. 2018), and so will have underestimated the source numbers, mostly at the higher redshifts, and IC ghosts are not detected in the radio surveys so also need to be taken into account.

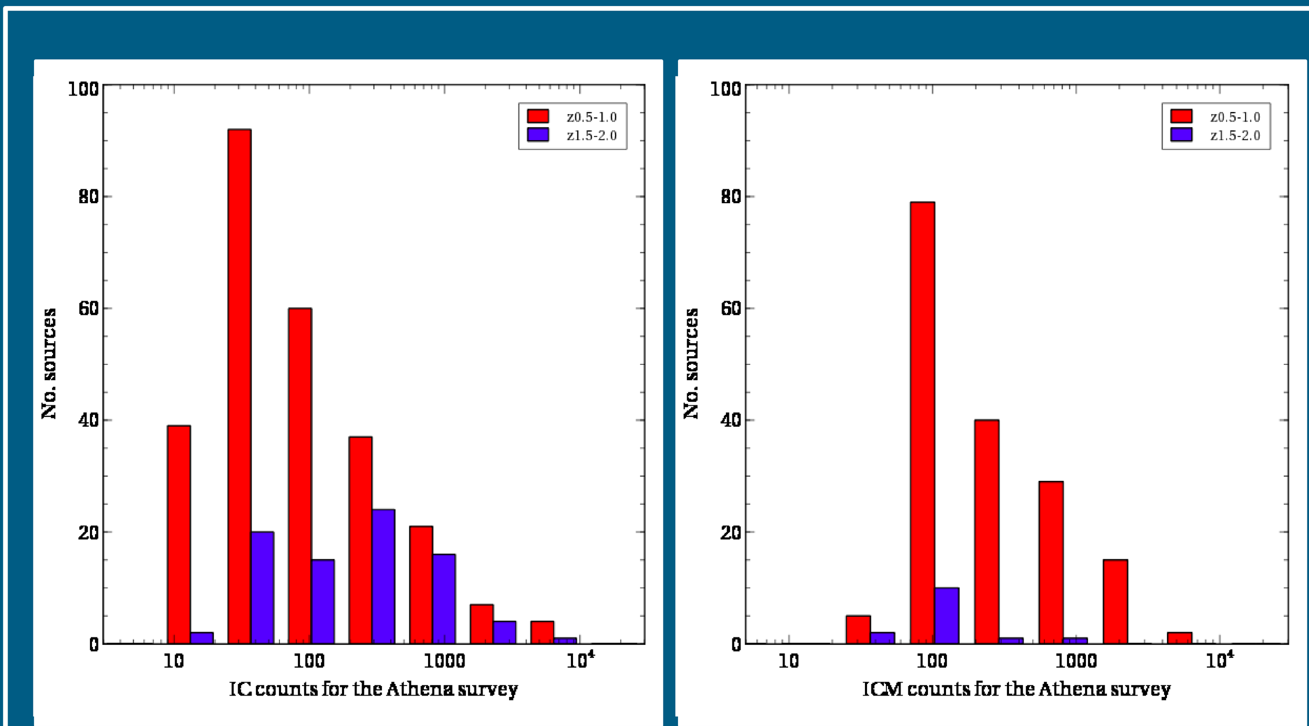

Fig. 5: Estimates of the numbers of RLAGN expected to have photon counts detectable by the Athena survey over the survey area. On the left, the results for the RLAGN IC emission (assuming FRII morphology) and on the right the predicted ICM emission from their host galaxy groups. Redshift 0.5-1.0 is red, redshift 1.5-2.0 is blue.

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Author contact details:
J.Ineson@soton.ac.uk
Judith.Croston@open.ac.uk