POSSIBLE EVIDENCE OF THE RADIO AGN QUENCHING OF NEIGHBOURING GALAXIES AT $z \sim 1$

Lu Shen$^1$,⋆ Adam R. Tomczak$^1$, Brian C. Lemaux$^1$, Debora Pelliccia$^1$, Lori M. Lubin$^1$, Neal A. Miller$^2$, Serena Perrotta$^3$, Christopher D. Fassnacht$^1$, Robert H. Becker$^1$, Roy R. Gal$^4$, Po-Feng. Wu$^5$, Gordon Squires$^6$,

$^1$Physics Department, University of California, Davis, One Shields Avenue, Davis, CA 95616, USA
$^2$Stevenson University, Department of Mathematics and Physics, 1525 Greenspring Valley Road, Stevenson, MD, 21153, USA
$^3$Department of Physics and Astronomy, University of California, Riverside, 900 University Ave, Riverside, CA 92521
$^4$University of Hawai’i, Institute for Astronomy, 2680 Woodlawn Drive, Honolulu, HI 96822, USA
$^5$Max-Planck Institut für Astronomie, Königstuhl 17, D-69117, Heidelberg, Germany
$^6$Spitzer Science centre, California Institute of Technology, M/S 220-6, 1200 E. California Blvd., Pasadena, CA, 91125, USA

Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT
Using 57 Radio Active Galactic nuclei (RAGN) at $0.55 \leq z \leq 1.3$ drawn from five fields of the Observations of Redshift Evolution in Large Scale Environments (ORELSE) survey, we study the effect of injection of energy from outbursts of RAGN on their spectroscopically-confirmed neighbouring galaxies (SNGs). We observe an elevated fraction of quenched neighbours ($f_q$) within 500 kpc projected radius of RAGN in the most dense local environments compared to those of non-RAGN control samples matched to the RAGN population in colour, stellar mass, and local environment at 2σ significance. Further analyses show that there are offsets at similar significance between $f_q$s of RAGN-SNGs and the appropriate control samples for galaxies specifically in cluster environments and those hosted by the most massive cluster galaxies, which tentatively suggests that some negative feedback from the RAGN is occurring in these dense environments. In addition, we find that the median radio power of RAGN increases with increasing local overdensity, an effect which may lend itself to the quenching of neighbouring galaxies. Furthermore, we find that, in the highest local overdensities, the $f_q$ of the sub-sample of lower stellar mass RAGN-SNGs is larger than that of the higher stellar mass RAGN-SNGs sub-sample, which indicates a more pronounced effect from RAGN on lower stellar mass galaxies. We propose a scenario in which RAGN residing within clusters might heat the intracluster medium (ICM) affecting both in situ star formation and any inflowing gas that remains in their neighbouring galaxies.

Key words: galaxies: active – galaxies: star formation – radio continuum: galaxies – galaxies: clusters: general – galaxies: groups: general – galaxies: evolution

1 INTRODUCTION
On galaxy scales, radio active galactic nuclei (RAGN) deposit most of their energy and momentum into the interstellar, circumgalactic, or intergalactic medium via high-velocity jets, which may be responsible for the quenching of the star formation in the host galaxy or helping to maintain its quiescence (see Fabian 2012 for a review). However, it is not yet clear whether RAGN can have a significant effect on neighbouring galaxies.

In principle, there exist many reasons to suggest that RAGN might affect other galaxies in their vicinity. Radio observations have revealed that powerful radio jets, originating from the center of the RAGN, extend for kiloparsecs or even megaparsecs beyond the host galaxy (see review paper by McNamara & Nulsen 2012). Many X-ray observations have revealed cavities, bubbles and shocks in the hot intracluster medium (ICM) of some clusters, coincident with the lobes of the radio sources (e.g. Boehringer et al. ***Contact e-mail: lushen@ucdavis.edu***
There are several channels that enable RAGN to efficiently interact with the ICM, such as displacing gas, driving shocks, or transporting low entropy gas and heavy elements outward from cluster cores. In the inner region (∼30 kpc) of a cluster, RAGN heating via energetic outbursts released from RAGN drive shocks, which boost the entropy level and lift the temperature along the direction of the outbursts. In the outer region (∼300 kpc and larger), hot and overpressurized bubbles released by RAGN produce a weak shock that heat the surroundings, as observed by Deep Chandra images of Hydra A (Nulsen et al. 2005) and MS0735+7421 (McNamara et al. 2005). Furthermore, studies of hydrodynamical simulations show that multiple cycles of RAGN activity in galaxies both central to and interspersed throughout the cluster act as heating agents of the ICM (e.g. Dalla Vecchia et al. 2004; Brüggen et al. 2005; Nusser et al. 2006). Voit (2005) simulated the RAGN heating based on observed core gas entropy profiles and suggested that multiple cycles of RAGN outbursts incrementally heat and increase entropy by several keV cm⁻² at ∼1 Mpc. These observations and simulations indicate RAGN are important components of the heating in the ICM, leaving open the possibility that such heating might be involved in the prevention of new episodes of star formation in both the host galaxies and its neighbours.

However, observational evidence of such feedback is scarce, as the few studies that have observationally investigated such feedback have found minimal or no affect by RAGN on their surrounding galaxies. Shabala et al. (2011) studied photometrically selected neighbouring galaxies in two subsamples of RAGN in local groups and clusters, classified by radio morphology into ∼70 Fanaroff-Riley class II (FR-II) sources (edge-dominated radio emission) and 21 FR-I sources (core-dominated radio emission). They found that neighbouring galaxies in the projected jet paths of FR-II RAGN are redder than neighbouring galaxies outside the jet path, suggesting the radio jets might be capable of quenching neighbouring galaxies that reside in the jet path, but no such trend was found for the satellites of FR-I RAGN. Later, Pace & Salim (2014) studied neighbouring galaxies within 100 kpc of a larger (∼7000) sample of FR-I and FR-II RAGN selected from the SDSS and NVSS+FIRST surveys at z ≤ 0.3. This population was compared to neighbouring galaxies of a control sample of non-radio emitting galaxies of the same absolute magnitude (+0.3) across five fields in the observationally nearby sample of 18 galaxy clusters in a redshift range of 0.55 ≤ z ≤ 1.3 across five fields in the Observation of Redshift Evolution in Large Scale Environments (ORELSE; Lubin et al. 2009) survey. The ORELSE survey is a systematic search for large-scale structures (LSSs) in ∼0.25-0.5 deg² around an original sample of 18 galaxy clusters in a redshift range of 0.55 ≤ z ≤ 1.3. This survey targets galaxy populations over a wide range of local and global environments. We briefly introduce the observational data and reduction in section 2. In section 3, we describe our method for selecting the RAGN and control sample, as well as their neighbouring galaxies. In Section 4, we show our results on the quiescent fractions of neighbouring galaxies of RAGN and analyses on its potential cause. In Section 5, we then discuss the results and propose a scenario to explain them. Throughout this paper all magnitudes, including those in the infrared (IR), are presented in the AB system (Oke & Gunn 1983; Fukugita et al. 1996). All distances are quoted in proper units. We adopt a concordance ΛCDM cosmology with H₀ = 70 km s⁻¹ Mpc⁻¹, ΩΛ = 0.73, and ΩM = 0.27, and a Chabrier stellar initial mass function (IMF; Chabrier 2003).

2 DATA AND METHODS

In this section, we introduce the observational data and describe the reduction of those data, the method adopted to estimate local and global environment measurements, and the calculation of the quiescent fraction (fQ). In this paper, we use five fields (SC1604, SG0023, SC1324, RXJ1757, RXJ1821) from the ORELSE survey which have fully reduced radio catalogues and accompanying photometric and spectroscopic catalogues. These observations span 7-15 Mpc in the plane of the sky and encompass 11 clusters and 17 groups, spanning a total (dynamical) mass range of 10¹²⁻¹⁵ M☉ to 10⁻¹²⁻¹¹ M☉. See Shen et al. (2017) and Rumbaugh et al. (2012) for more details on these five fields.

2.1 Imaging and Photometry

Comprehensive photometric catalogues are constructed for all five fields. We summarize the available optical and near-infrared (NIR) observations and the reduction process here. See Tomczak et al. (2017) and Tomczak et al. (submitted) for specific details and additional information regarding the photometry used in this study. Optical imaging was taken with the Large Format Camera (LFC; Simcoe et al. 2000) on the Palomar 5-m telescope, using Sloan Digital Sky Survey (SDSS, Doi et al. 2010)-like r′, i′ and z′ filters, reduced in the Image Reduction and Analysis Facility (IRAF, Tody 1993), following the method in Gal et al. (2008). We also use R*, R′, I*, L*, Z* and Y band optical imaging from Suprime-Cam (Miyaizaki et al. 2002) on the Subaru 8-m telescope, reduced with the SD-FRED2 pipeline (Ouchi et al. 2004) supplemented by several routines from Traitement Élémentaire Réduction et Analyse des PIxels (TERAPIX)¹. Some J and K band data were taken with the United Kingdom Infra-Red Telescope

¹ http://terapix.iap.fr
Table 1. Number of Spectroscopic objects, radio galaxies, RAGN and SNGs in each field

| Field   | R.A.\(^1\) | Decl.\(^1\) | Num. of Clusters/Groups\(^4\) | Spec\(^2\) | Radio-spec\(^3\) | Num. of RAGN | Num. of RAGN-SNG\(^5\) | RAGN Size\(^6\) |
|---------|------------|------------|-------------------------------|------------|----------------|--------------|------------------------|-----------------|
| SC1604  | 16:04:15   | +43:21:37  | 6(4)                          | 960(583)   | 108            | 27           | 72                     | 4.3^{+1.4}_{-0.3} |
| SG0023  | 00:23:52   | +04:22:51  | 9(6)                          | 655(420)   | 46             | 9            | 12                     | 5.5^{+2.0}_{-1.0} |
| SC1324  | 13:24:35   | +30:18:57  | 3(5)                          | 673(530)   | 38             | 8            | 20                     | 6.8^{+1.7}_{-0.6} |
| RXJ1757 | 17:57:19.4 | +66:31:29  | 1(1)                          | 257(186)   | 26             | 4            | 5                      | 5.5^{+0.8}_{-0.7} |
| RXJ1821 | 18:21:32.4 | +68:27:56  | 2(0)                          | 231(200)   | 32             | 9            | 39                     | 5.2^{+0.6}_{-0.3} |

1 Coordinates for SC1604, SG0023, SC1324 are the median of central positions of clusters/groups, while RXJ1757 and RXJ1821 are given as the centroid of the peak of diffuse X-ray emission associated with the respective cluster.

2 Number of secure spectroscopically confirmed galaxies in the redshift range 0.55 ≤ z ≤ 1.3, with 18.5 ≤ i′/z ≤ 24.5 (for more details see Section 2.2). The number in parentheses denotes the subset of these galaxies with M_{i} ≥ 10^{10}M_⊙ and M_{SIV} - M_{r} ≥ 2 limit. (for more details see Section 3.3).

3 Number of radio sources matched to all spectroscopic confirmed galaxies.

4 Number of clusters (groups) in each field.

5 Number of spectroscopically-confirmed neighbouring galaxies (SNGs) around RAGN sample in each field. See Section 3.3 for details on SNG selection criteria.

6 The median value of RAGN size and the 1σ scatter (i.e. 16% and 84% values) in each field.

Wide-Field Camera (WFCAM; Hewett et al. 2006) mounted on the United Kingdom Infrared Telescope (UKIRT) and was reduced using the standard UKIRT processing pipeline courtesy of the Cambridge Astronomy Survey Unit. Additionally, J and Ks band imaging was taken using the Canada-France-Hawaii Telescope Wide-field InfraRed Camera (WIRCam; Puget et al. 2004) mounted on the Canada-France-Hawai’i Telescope (CFHT) and was reduced through the I’iwi preprocessing routines and TERAPIX. Infrared imaging at 3.6, 4.5, 5.8, and 8.0 µm (5.8 and 8.0 µm only available for SC1604) was taken using the Spitzer telescope Infrared Array Camera (IRAC; Fazio et al. 2004). The basic calibrated data (cBCD) images provided by the Spitzer Heritage Archive were reduced using the MOsaicker and Point source EXtractor (MOPEX; Makarov & Marleau 2005) package augmented by several custom Interactive Data Language (IDL) scripts written by J. Surace.

Photometry was obtained by running Source Extractor (SExtractor; Bertin & Arnouts 1996) on point spread function (PSF)-matched images convolved to the image with the worst seeing. Magnitudes were extracted in fixed circular apertures to ensure that the measured colours of galaxies are unbiased by different image quality from image to image. Also, the package T-PHOT (Merlin et al. 2015) was used for Spitzer/IRAC images, due to the large point spread function of these data that can blend profiles of nearby sources together and contaminate simple aperture flux measurements.

Spectral Energy Distribution (SED) fitting is performed in a two-stage process. First, we used the Easy and Accurate Redshifts from Yale (EAZY; Brammer et al. 2008) code to estimate photometric redshifts (z_{phot}) for galaxies that lacked spectroscopic redshifts. Rest-frame colours are also derived in this step using the best-fit z_{phot} (z_{spec} when available) which are used to classify galaxies as star-forming or quiescent (see Section 2.5). In the second step, we used the Fitting and Assessment of Synthetic Templates (FAST; Kriek et al. 2009) code to estimate stellar masses as well as other properties of the stellar populations of galaxies.

In brief, FAST creates a multi-dimensional cube of model fluxes from a provided stellar population synthesis (SPS) library. Each object in the photometric catalogue is fit by every model in this cube by minimizing \( \chi^2 \) for each model and adopted the model of the lowest minimum \( \chi^2 \) as the best-fit. For this we made use of the SPS library presented by Bruzual & Charlot (2003), assuming a Chabrier (2003) stellar initial mass function, allowing for dust attenuation following the Calzetti et al. (2000) extinction law. See Section 2.3 of Tomczak et al. (2017) for a more thorough description of these procedures and assumptions. It is important to note that we have tested our analysis using stellar masses derived from a smaller stellar population synthesis (SPS) modeling parameter space and find that our results of RAGN classification and stellar mass distributions are unaffected (see Shen et al. 2017 for a description of this parameter space). Based on a visual inspection of the best-fit SEDs of all RAGN, we find a good agreement between the models and the observed photometry, which gives us confidence that the reported stellar masses and dust extinctions are representative of host galaxies despite the presence of non-stellar emission. To further underscore this point, the median \( \chi^2 \) of the best-fit SEDs of all RAGN is 1.19 compared to 0.97 for the median \( \chi^2 \) value of the full photometric catalogue (with good use flag).

The precision of the photometric redshifts were estimated from fitting a Gaussian to the distribution of \( z_{spec} - z_{phot} / (1 + z_{spec}) \) measurements in the range 0.5 ≤ z ≤ 1.2. We find values of \( \sigma_{\Delta z}/(1+z) \) ranging from 2.9 - 3.2% for all five fields to a limit of i′ ≤ 24.5 and a catastrophic outlier rate (\( \Delta z/(1+z) > 0.15 \)) of 4.8-9.5%. Additionally, photometric sources are limited to 18.5 ≤ i′ ≤ 24.5. These are the same limits that we will apply to the spectroscopic sample (see Section 2.2) as a compromise between maximizing the sample size and the spectroscopic completeness. For structures at z>0.95 the Z band was used instead with the same limits.

2 http://casu.ast.cam.ac.uk/surveys-projects/wfcam/technical
2.2 Spectroscopy

Spectroscopic targets were selected based on the optical imaging in the $r'$, $i'$, and $z'$ from LFC imaging following the methods in Lubin et al. (2009). In brief, the spectroscopic targeting scheme employed a series of colour and magnitude cuts that are applied to maximize the number of targets with a high likelihood of being on the cluster/group red sequence at the presumed redshift of the LSS in each field (i.e., priority 1 targets). However, the fraction of priority 1 targets which entered into our final sample ranged from 10% to 45% across all ORELSE fields, a fraction which tended to vary strongly with the density of spectroscopic sampling per field (see Tomczak et al. 2017 for more discussion). In addition, for certain masks we prioritized X-ray and radio detected objects. The optical spectroscopy was primarily taken with the Deep Imaging and Multi-Object Spectrograph (DEIMOS; Faber et al. 2003) on the Keck II 10m telescope and reduced using a modified version of the Deep Exploratory Probe 2 (DEEP2; Davis et al. 2003; Newman et al. 2013) pipeline. See Lemaux et al. (submitted) for details on the modifications to the pipeline. A few additional redshifts from the Low Resolution Imaging Spectrometer (LRIS; Oke et al. 1995) were added for SC1604, SG0023 and RXJ1821 (see Oke et al. 1998; Gal & Lubin 2004; Gioia et al. 2004). For more details on the spectroscopic observations in these fields see Lemaux et al. (2012, 2017) and Rumbaugh et al. (2017).

Spectroscopic redshifts of these targets were extracted and assessed using the methods of Newman et al. (2013), while serendipitous detections were following the method described in Lemaux et al. (2009). Only galaxies with high quality redshifts ($Q$=3.4; see Gal et al. 2008; Newman et al. 2013 for the meaning of these values) are used in this study. Spectroscopic samples are limited to the same $i'/z'$ band limits ($18.5 \leq i'/z' \leq 24.5$) as applied to the photometric catalogues to keep these two catalogues consistent. We additionally apply $M_\star \geq 10^{10} M_\odot$ and $M_{\text{NUV}} - M_\star \geq 2$ cuts to the spectroscopically confirmed galaxy sample. These stellar mass and colour limits define where our spectroscopic sample is representative of the underlying photometric sample at $0.55 \leq z \leq 1.3$ subject to the magnitude cuts above (see Shen et al. 2017, Tomczak et al. 2017 and Lemaux et al. submitted, for more details). This final spectroscopic sample consists of 1919 galaxies out of ~2500 galaxies with secure spectral redshift (i.e., $Q=3.4$), reliable photometry, and within the adopted rest-frame colour $M_{\text{NUV}} - M_\star$ and stellar mass range. The numbers in the samples for each field are listed in Table 1. In the reminder of this paper, we use this spectroscopic catalogue to construct the RAGN, control and their neighbouring galaxy samples.

2.3 Radio Observations

All five fields studied here were observed using the Very Large Array (VLA) 1.4GHz imaging in its B configuration, where the resulting FWHM resolution of the synthesized beam is about 5" and has a circular field of view of ~31' diameter centered on the optical images (i.e., the FWHM of the primary beam). Net integration times were chosen to result in final 1σ sensitivities of about 10µJy per beam for each field, a value which was approximately achieved for all five fields. The final images were then used to generate source catalogues. The NRAO’s Astronomical Image Processing System (AIPS) task SAD created the initial catalogues by examining all possible sources having peak flux density greater than three times the local RMS noise. Peak flux density, integrated flux density, their associated flux density errors ($\sigma$), and size are measured. We then instructed it to reject all structures for which the Gaussian fitted result has a peak below four times the local RMS noise.

In the last step, we added those extended sources poorly fitted by Gaussians. We use the peak flux density unless the integrated flux is larger by more than 3σ compared to the peak flux for each individual source. The final radio catalogues contain sources above 4σ and down to a flux density limit of about 30µJy. For more details on the VLA reduction see Shen et al. (2017).

2.4 Environmental Measurements

There are two environment regimes: local environment which probes the current density field to which a galaxy is subject, and global environment which probes the time-averaged galaxy density to a galaxy has been exposed.

2.4.1 Local Environmental Density

We adopt a local environment measurement using a Voronoi Monte-Carlo (VMC) algorithm which is described in full detail in Lemaux et al. (2017) and Tomczak et al. (2017). In brief, 78 thin redshift slices ($\Delta z = \pm 1500$ km/s) are constructed across the broad redshift range of $0.55 \leq z \leq 1.3$, with adjacent slices overlapping by half depth of the slice. Spectroscopically-confirmed galaxies are then placed into these thin redshift slices. For each slice, photometric galaxies without a high quality $z_{\text{spec}}$ (with a good use flag) have their original $z_{\text{phot}}$ perturbed by an asymmetric Gaussian with a mean and dispersion set to the original $z_{\text{phot}}$ and ±1σ uncertainty, respectively, and the objects whose new $z_{\text{phot}}$ fall in the redshift slice are determined. Then a Voronoi tessellation is performed on the slice and is sampled by a two dimensional grid of 75 × 75 proper kpc pixels. Local density is defined as the inverse of the cell area multiplied by the square of the angular diameter distance. The final density map of the slice is computed by median combining the density values at for each pixel from 100 VMC realizations. The local overdensity value for each pixel point $(i, j)$ is then computed as $\log(1 + \delta_{\text{proj}}) = \log(1 + (\tilde{\Sigma}_{\text{VMC}} - \Sigma_{\text{VMC}})/\Sigma_{\text{VMC}})$, where $\Sigma_{\text{VMC}}$ is the median $\tilde{\Sigma}_{\text{VMC}}$ for all grid points over which the map is defined. Local overdensity rather than local density are adopted for mitigating issues of sample selection and differential bias on redshift.

2.4.2 Global Environmental Density

To quantify the global environment, we adopt $R_{\text{proj}}/R_{200}$ versus $|\Delta z|/\sigma_{\text{z}}$ (Carlberg et al. 1997; Balogh et al. 1999; Biviano et al. 2002; Haines et al. 2012; Noble et al. 2013, 2016), defined by $\eta$ from Shen et al. (2017) as:

$$
\eta = (R_{\text{proj}}/R_{200}) \times (|\Delta z|/\sigma_{\text{z}}) \tag{1}
$$

where $R_{\text{proj}}$ is the distance of each galaxy to each group/cluster center, $R_{200}$ is the radius at which the cluster

MNRA000, 1–15 (2018)
density is 200 times the critical density, $\Delta v$ is the difference between each galaxy velocity and the systemic velocity of the cluster, and $\sigma_v$ is the line-of-sight (LOS) velocity dispersion of the cluster member galaxies (see Lemaux et al. 2012 for the computation of $\Delta v$ and $\sigma_v$). The cluster centers are obtained from the $i'$-luminosity-weighted center of the members galaxies as described in Ascaso et al. (2014). The value of $\eta$ for each galaxy is measured with respect to the closest cluster/group. To determine it, we first find all the clusters/groups that are within $\pm 6000$ km s$^{-1}$ in velocity space of a given galaxy, then we compute $R_{proj}/R_{200}$ for the computation of $\Delta v$ and $\sigma_v$.

The value of $\eta$ for each galaxy is measured with respect to the closest cluster/group. If for a given galaxy no clusters/groups within $\pm 6000$ km s$^{-1}$ are found, $\eta$ is computed with respect to all of those clusters/groups in the field and the one with the smallest value is associated with that galaxy. See Pelliccia et al. (2018) for more detail on this calculation. In this paper, when necessary we use $\eta \leq 2$ as the restriction for galaxies in cluster/group environments (see Section 4.4). Note that while most massive clusters/groups are detected in our fields, many lower mass systems are missed (Hung et al. in prep.). For this reason, the $\eta$ values calculated here are necessarily upper limits.

2.5 Classification of Star-forming and Quiescent Galaxies
We adopt the rest-frame $M_{NUV} - M_r$ versus $M_r - M_J$ colour-colour diagram separations from Lemaux et al. (2014), based on the two-colour selection technique proposed by Ilbert et al. (2010), to divide galaxies into two categories: quiescent and star-forming (SF). Specifically, galaxies at $0.55 \leq z \leq 1.0$ with $M_{NUV} - M_r > 2.8(M_r - M_J) + 1.51$ and $M_{NUV} - M_r > 3.75$ and galaxies at $1.0 < z < 1.3$ with $M_{NUV} - M_r > 2.8(M_r - M_J) + 1.36$ and $M_{NUV} - M_r > 3.6$ are considered quiescent. The fraction of quiescent galaxies ($f_q$) for a galaxy population is calculated as the number of quiescent galaxies over the total number in full sample. Uncertainties in $f_q$ are derived from Poissonian statistics. As a reminder, we additionally applied stellar mass $M_* \geq 10^{10}\, M_{\odot}$ and colour $M_{NUV} - M_r \geq 2$ cuts to our entire secure spectroscopically confirmed galaxy sample (see Section 2.2).

3 CONSTRUCTION OF SAMPLES
To search for possible evidence of RAGN influencing the star-forming properties of neighbouring galaxies, we first identify RAGN in our survey and construct a comparison sample of galaxies that are matched in nearly every relevant property (stellar mass, local environment, colour) as control samples. For the remainder of the paper, we refer to the RAGN and controls as “central” galaxies. Then, we select the Spectroscopically-confirmed Neighbouring Galaxy (SNG) sample around the RAGN (RAGN-SNG) and control samples (control-SNG). We describe these selections below.

3.1 Radio AGN Sample
We perform a maximum likelihood ratio (LR) technique, following the procedures in Section 3.4 in Rumbaugh et al. (2012), to search for optical counterparts to radio sources. In brief, a likelihood ratio is a quantity that estimates the excess likelihood that a given optical source is the genuine match to a given radio source relative to its arrangement arising by chance. The LR is given by the equation

$$LR_{ij} = \frac{w_i \exp(-r_{ij}^2/2\sigma_j^2)}{\sigma_j^2}$$

(2)

Here, $r_{ij}$ is the separation between objects $i$ and $j$, $\sigma_j$ is the positional error of object $j$, where we use $1''$ as the positional error of all radio sources (Condon 1997), and $w_i = n(< m_i)^{-1/2}$ is the square root of the inverse of the number density of optical sources with magnitudes fainter than the observed $i'$ band magnitude. We then carried out a Monte Carlo (MC) simulation to estimate the probability that each optical counterpart is the true match using the LRs. The threshold for matching to a single or double objects is the same as that used in Rumbaugh et al. (2012), though in practice in this paper, only the highest probability matched optical counterpart was considered for each radio source. The optical matching is done to the overall photometric catalogues. We use a search radius of $1''$, aimed at being inclusive, i.e., not to miss any genuine matches due to instrumental/astrometric/astrophysical effects. We then search for extended morphology radio sources and radio doubles using a larger search radius following the same method used in Section 3.4 in Shen et al. (2017). We add in one radio double in SC1324 in this step. In this paper, we focus on radio objects which have photometric counterparts with secure spectroscopically-confirmed redshifts and within the redshift range $0.55 \leq z \leq 1.3$. We refer to these galaxies as radio galaxies. The number of radio galaxies is listed in Table 1.

RAGN were then selected from this pool of radio galaxies following the two-stage radio classification presented in Shen et al. (2017). First, all radio galaxies with $\log(L_{1.4GHz}) \geq 23.8$ are immediately classified as RAGN. Some radio galaxies below this luminosity threshold are also classified as RAGN if they are in the AGN region in the rest-frame $M_U - M_B$ versus stellar mass normalized radio luminosity $L_{1.4GHz}/M_* (M_{\odot})$ (colour-SRL) diagram, as defined below:

$$\begin{align*}
M_U - M_B &> 1.24 & \text{if SRL < 12.3} \\
M_U - M_B &> -0.75R + 9.85 & \text{if 12.3 \leq SRL < 13.5} \\
M_U - M_B &> 0.4 & \text{if SRL \leq 13.5}
\end{align*}$$

(3)

where $M_U - M_B$ is the dust corrected colour. In order to correct for dust we use the value of the colour excess, $E(B-V)$, as estimated for each galaxy from our SED fitting and apply a correction to each rest-frame absolute magnitude following the Calzetti et al. (2000) reddening law. We note that the colour-SRL diagram is calibrated using radio galaxies at all redshifts, and no redshift dependence was found for the classification regions in this diagram. We obtain a total of 57 RAGN in the redshift range of $0.55 \leq z \leq 1.3$.

We manually examine the size of RAGN measured from the task SAD (see Section 2.3). We found that only two
sources out of a total of 57 sources in the RAGN sample that were not well fit by this process. The rest of RAGN are well fit as point sources on the order of the beam size. For those two sources not well-fit by SAD, we estimate the circu-
scopic sample" ). This comparison sample is identified using
cludes RAGN and their neighbouring galaxies within 1
errors of each property of control samples were calculated as
as quiescent or star forming.

In figure 2, we show the comparison of RAGN and con-
control samples. SNGs are selected in cylindrical volumes cen-
large radii of 500 kpc and depths of Δz = ±1000 km/s, as shown in Figure 3. The
projected distance threshold was chosen to include all possible nearby galaxies that might reasonably be affected by proximity to the radio activity (e.g., Tremblay et al. 2010). The velocity requirement was chosen to maximize the purity and completeness of neighbouring galaxies, based on the typical
galaxy velocity dispersion (σ_v ∼ 500 – 1000 km s\(^{-1}\)) along the line of sight of clusters/groups in these five fields (see Lemaux et al. 2012 on how σ_v is calculated). In section 4.2, we will further discuss how varying the radial cut affects the results. For cases where SNGs are selected around two

3.2 Control sample

To isolate the effect of RAGN on their neighbouring galaxies, we also select galaxies as a comparison sample from the spectroscopically confirmed galaxy samples which excludes RAGN and their neighbouring galaxies within 1 Mpc (see section 3.3, referred to as “non-RAGN spectroscopic sample”). This comparison sample is identified using a 3D matching algorithm, following the Shen et al. (2017) method, which ensures that the distributions of M_*, rest-frame colour, and local environment of the control sample match closely to those of the RAGN sample. In brief, we split a 3D phase space (M_{\text{UV}} - M_*, log(M_*/M_\odot), log(1 + \delta_{\text{gal}})) into 4 × 4 × 4 boxes and calculate a 3D probability density map by taking a ratio of the number of galaxies from the

3.3 Neighbouring galaxies

In the final step, we selected the spectroscopically-confirmed neighbouring galaxies (SNGs) around the RAGN and control samples. SNGs are selected in cylindrical volumes centered on each centre having radii of R_{proj} = 500 kpc and depths of Δz = ±1000 km/s, as shown in Figure 3. The

![Figure 1. A cutout of the Y band image taken from the Suprime-
Cam on the Subaru 8-m telescope centered on an extended radio
active galactic nucleus (RAGN) in one of the ORELSE clusters
in the RXJ1821 field. The image is displayed in color rather than
greyscale purely for presentation purposes. Overlaid on the near
infrared cutout are radio contours of three different levels: 3, 5,
and 15 times the 9.33\mu Jy RMS of the radio image. The RAGN,
which is also one of the MMCG is marked with a blue cross. The
cutout is 1" on each side, which translates to 474 kpc at z = 0.9.
This is only one source having extended radio profile and being
hosted by an MMCG.](image-url)
or more RAGN/control galaxies, we assigned these SNGs to the nearest projected RAGN/control galaxy.

4 RESULTS

We calculate the fractions of quiescent galaxies (f_q) for RAGN-SNGs and control-SNGs by binning the two samples into four local overdensity bins, adopting the log(1 + δ_{gal}) values of the RAGN hosts and control galaxies in all cases. For control samples, we obtain the f_q of SNGs binned by log(1 + δ_{gal}) of their centers in each control sample and use the median value of the true value of f_q for the overall control samples. The asymmetric errors of control sample are calculated as the 16% and 84% values on the 100 samples, which represent the variation of the control population. Uncertainties on the median log(1 + δ_{gal}) of RAGN-SNGs are given by σ_{NMAD}/√n − 1 where σ_{NMAD} is the normalized median of the absolute deviations (Hoaglin et al. 1983) and n is the number of the sample (see Müller 2000 for a discussion on adopting this type of estimate on the uncertainty on the median). Throughout the paper we conservatively adopt the σ_{NMAD}/√n − 1 as the formal uncertainty on log(M_*/M_☉), log(1 + δ_{gal}), log(q) and z of RAGN/RAGN-SNGs, and 16% and 84% values of median values of the 100 re-samplings as the asymmetric error on those of control/control-SNGs.

As shown in Figure 4, we find that the f_q of RAGN-SNGs (0.81±0.04) is marginally higher than that of control-SNGs (0.78±0.04).
control-SNGs (0.67\pm0.06) only in the highest overdensity bin (1.2 \leq \log(1 + \delta_{\text{gal}}) \leq 2.1). The difference between the two $f_q$s is 0.14, a discrepancy significant at a 2\sigma level. This significance persists even if we match the median of $\log(1 + \delta_{\text{gal}})$ of control-SNGs samples to that of the RAGN-SNGs sample, by removing the lowest local overdensity control-SNG in the highest overdensity bin. Additionally, this difference persists at the same level if we change the framework of our analysis to include different SED fitting parameters, binning, or colour/stellar mass cuts. To study the possible cause of this potential difference, we perform several diagnostic tests described below.

### 4.1 Assessing the Representativeness of the Control Sample

First, we want to investigate whether this is a real physical effect caused by the RAGN or just systematic differences between the RAGN-SNGs and control-SNGs. Studies have shown that the quiescent fraction depends on galaxy stellar mass, redshift (e.g. Muzzin et al. 2013, 2014; Tomczak et al. 2014 and Lemaux et al. submitted), and its presence in a cluster/group or field environment (e.g. Hansen et al. 2009; Cooke et al. 2016). To exclude these factors, we run comparisons between these parameters of the RAGN-SNGs and control-SNGs.

As shown in panel A of Figure 5, the binned median $\log(M_*/M_\odot)$ values of RAGN-SNGs versus control-SNGs overlap across the three overdensity bins, indicating no stellar mass dependence in the neighbouring galaxies driving the $f_q$. We also perform a K-S test on the $\log(M_*/M_\odot)$ distributions of these two samples. The p-value (\sim 0.2) is not sufficiently small to confirm that two distribution are drawn from different underlying distributions. We also show the binned median $\log(M_*/M_\odot)$ values of RAGN and the control samples in panel A, which confirms that the control samples are well matched to RAGN. This consistency discounts a possible halo mass effect on their neighbouring galaxies ("Galactic conformity", e.g. Phillips et al. 2014; Kawa\textit{in}wanich\textit{akj}i et al. 2016), assuming a relation between stellar and halo mass.

As shown in panel B of Figure 5, the two SNG populations reside in the same global environments across the three overdensity bins. We also perform a K-S test on the $\eta$ distributions of these two samples. We obtain a p-value of \sim 0.1, which is larger than the threshold of rejecting the null hypothesis that the distributions of the two samples are the same. The median $\log(\eta)$ values of the two center samples are comparable across the four overdensity bins. The two cumulative distributions are shown in the Figure 2 with a p-value of 0.32 from the K-S test which is not sufficiently small to confirm that the two distribution are drawn from different distributions. These tests eliminate the possibility of a global environmental effect on the $f_q$ of the SNG samples.

Lastly, we compare the redshift distributions of the two SNG populations as shown in panel C of Figure 5, the binned median z values of RAGN-SNGs versus control-SNGs in each of the three overdensity bins. The K-S test of the redshift distributions of all RAGN-SNGs and control-SNGs samples gives a small p-value of \sim 0.01, indicating that they are likely drawn from different distributions. The K-S test of the redshift distributions of the two SNGs samples in the highest overdensity bin also gives a small p-value (\sim 0.01). However, in the highest overdensity bin, the median z value of RAGN-SNGs and control-SNGs are 0.823\pm0.005 and 0.813\pm0.007, respectively. The two median z values are within 1\sigma difference, which suggests that, at least in the highest overdensity bin, the $f_q$ of neighbouring galaxies is not driven by redshift evolution.

We have analyzed the representativeness of the control sample and attempted to eliminate all possible factors that might cause the comparisons between the quiescent fraction of RAGN-SNGs and control-SNGs to be biased. Nevertheless, the number of galaxies in these two SNGs sample are small. The control samples are constructed from a limited number of galaxies in the five fields studied here as their stellar mass is, in general, high and such galaxies are relatively rare especially after removing all RAGN hosts from consideration. In order to compensate for this relative lack of galaxies in our primary control samples, we introduce a second control method. This method is based on analysis from Lemaux et al. (submitted) using 4552 galaxies in 15 ORELSE fields with secure spectroscopic redshifts between 0.55 \leq z \leq 1.40 and with the same stellar mass and colour limits as are applied in this paper. Lemaux et al. derived the quiescent fraction relation as a function of redshift, stellar mass, environment $f_q(z, \log(M_*/M_\odot), \log(1 + \delta_{\text{gal}}))$ as following the form:

\begin{equation}
\begin{split}
f_q = (1.8544 \pm 0.0002) \times z^{0.1422 \pm 0.0007} \\
+ (8.3876 \pm 0.0001) \times \log(M_*/M_\odot)^{0.2224 \pm 0.0007} \\
+ (-11.8321 \pm 0.0002) \times \log(1 + \delta_{\text{gal}})^{0.0075 \pm 0.0002}
\end{split}
\end{equation}
Figure 5. Panel A: Stellar mass of RAGN (orange), control (cyan), RAGN-SNGs (red) and control-SNGs (green) as a function of the median \(\log(1 + \delta_{\text{gal}})\) of the centre RAGN/control sample. Panel B: \(\log(\eta)\) of RAGN, control, RAGN-SNGs and control-SNGs as a function of the median \(\log(1 + \delta_{\text{gal}})\) of the centre RAGN/control sample. Panel C: redshift of RAGN, control, RAGN-SNGs and control-SNGs as a function of the median \(\log(1 + \delta_{\text{gal}})\) of the centre RAGN/control sample. Panel D: Radio luminosity at 1.4GHz of RAGN, binning by \(\log(1 + \delta_{\text{gal}})\). The median value (log(L1.4GHz) = 23.98 ± 0.11) of the full RAGN sample is shown by the black dashed line. Uncertainties on \(\log(1 + \delta_{\text{gal}}), \log(M/M_\odot), \log(\eta)\) and \(z\) of RAGN/RAGN-SNGs are the \(\text{NMAD}/\sqrt{n - 1}\) (see Section 4.1). The error bars on \(\log(1 + \delta_{\text{gal}}), \log(M/M_\odot), \log(\eta)\) and \(z\) of control/control-SNGs are the asymmetric errors (i.e., 16% and 84% values of the median values of 100 re-samplings).

4.2 Effect of Varying \(R_{\text{proj}}\)

In this section, we examine the effect of choosing different radii on the result. This analysis is motivated by the fact that previous studies looked at the effect of RAGN on neighbouring galaxies selected within smaller radii (e.g., 100 kpc in Pace & Salim 2014). If we use 250 kpc as the radius threshold, there are only 37 galaxies left in the RAGN-SNGs sample in the highest overdensity bin, reduced by ~38.5%. The quiescent fraction is 0.86 ± 0.06 for RAGN-SNGs, compared to (0.75±0.07) for the control-SNGs using the same radius threshold. The difference is ~1σ, which is not as significant as using 500 kpc as the radius threshold. This result could be due to either the large uncertainty derived from the small number of galaxies in these two SNG samples that wash out the signal or the signal does not come mainly from the inner region. We slightly vary this radial cut to 450 and 550 kpc. The total number of RAGN-SNG is decreased by 12.9% and the signal seen in the most dense environment vanishes. Regardless, both control methods have measured or global \(f_q\) values that are consistent at the < 1σ level.
This result may indicate that the injection of energy from an RAGN does not affect galaxies on scales larger than 500 kpc. Therefore, we feel confident in our choice to use 500 kpc as the transverse radial search range for neighbouring galaxies.

We note that the vast majority of RAGN are compact, beam-size-scale sources, and none of the RAGN extends to the radius we tested, which minimizes the possibility that the neighboring galaxies are directly affected by RAGN radio lobes and the bow shocks driven by the radio lobes on similar scales (Shabala et al. 2011). However, it is possible that the heating through one or multiple cycles of RAGN outbursts could incrementally heat the cluster gas and as gas propagating out to 500 kpc, although we are not able to determine based on the current analysis how many cycles of RAGN activity are needed, or if, indeed, more than a single outburst is necessary to heat the ICM gas up to 500 kpc.

4.3 Effect of Radio Luminosity

In panel C of Figure 5, we show that the median radio luminosity of RAGN studied here increases by 0.48 dex across the three overdensity bins, which indicates a possible correlation between these two properties. We apply the Spearman test to assess the correlation between them. The correlation coefficient is 0.36, and the p-value for non-correlation is 0.028. We further test this result adopting a Monte-Carlo simulation where in each iteration we allow the value of luminosity for an individual RAGN to vary based on a Gaussian with a mean and dispersion set to the original $L_{1.4GHz}$ and its error, respectively. 88% of Monte-Carlo realizations suggest that there is a correlation (i.e., the Spearman p-value is <0.05). All these tests suggest a real positive correlation between local overdensity and luminosity. This agrees with the general picture where the relative number of massive galaxies increases with environmental density, especially for quiescent galaxies (see Figure 6 in Tomczak et al. 2017). Thus, at fixed accretion mode and accretion rate, massive galaxies which harbor massive black holes would have higher jet power and hence higher radio luminosity. The presence of this correlation leaves open the intriguing possibility that the increasing power of RAGN seen in higher density environments lends itself to the quenching of neighbouring galaxies. We will further discuss this potential additive quenching effect in Section 5.1.

4.4 Effect of cluster environments

The larger quiescent fraction in galaxies surrounding RAGN is only marginally seen in the highest local density region. 10 out of 11 RAGN in that density bin are within the cluster environments as defined in Section 2.4, while 6 RAGN are in the virialized core of clusters\footnote{Though it is possible for a group galaxy to exist at these log$(1 + \delta_{gal})$ and $\eta$ values, we confirmed that none of these RAGN lie within the known group sample in these fields.}. One question raised from this result is whether the energy transfer mechanism from the RAGN to its neighbouring galaxies is more efficient in clusters (relative to field or group environments) because the RAGN jet can interact with the ICM, a channel not possible to field/group RAGN. There are 24 RAGN that reside in cluster environments and 3 RAGN associated with group environments (i.e., $\eta \leq 2$; see Section 2.4). Because of the small number of RAGN in group environments, with none of them hosted by the most massive group galaxy, we test the hypothesis using only cluster RAGN. There are 106 RAGN-SNGs in the cluster RAGN sub-sample comprising 72% of the total RAGN-SNGs sample. 68 of these galaxies (96%) are in the highest overdensity bin. We select control samples from a pool of cluster galaxies having $\eta \leq 2$, using the same matching algorithm as described in Section 3.2. The median number of control-SNGs is ~65% of the total control-SNGs sample. The number of centers in the cluster and their SNGs are shown in the Table 2.

We then compare the $f_q$ of neighbouring galaxies of this RAGN sample with that of the control samples. We obtain the $f_q$ of 0.73±0.04 for RAGN versus 0.60±0.06 for the control samples as shown in the left panel of Figure 6, labeled as “Cluster sample”. The error on the control sample value is derived from the variation of 100 control resamplings. The offset between the RAGN-SNGs and control-SNGs at 1.8σ significant level is consistent with our result in the highest local overdensity bin. However, in the cluster RAGN sample, the RAGN are spread across all three overdensity bins. As a comparison, we calculate the global $f_q$ based on the global relation described in Section 4.1 given their median values of stellar mass, redshift and local overdensity. The global $f_q$ is also shown in the left panel of Figure 6. The quiescent fraction of the control-SNGs is $\sim 1\sigma$ higher than its global $f_q$, whereas the quiescent fraction of RAGN-SNGs is 4$\sigma$ higher than its global $f_q$. We note that both measured $f_q$s are higher than their global $f_q$s; nevertheless, as mentioned earlier, the differences between the controls and their corresponding global $f_q$s are within the 1$\sigma$ uncertainty. The 4$\sigma$ offset between the $f_q$ of RAGN-SNGs in the cluster and its global $f_q$ tentatively suggests that RAGN within cluster environments might have a larger effect on their neighbouring galaxies, relative to the field or group environment. This large offset may imply that at least some physical mechanism special to the interaction between the RAGN and the cluster environment is capable of affecting the star formation of neighbouring galaxies (see discussion in Section 5).

Along this line, studies have suggested that RAGN hosted by the brightest cluster galaxies act as heating agents powerful enough to prevent further cooling of the ICM and regulate density and entropy of the ICM in the cluster environments (e.g., Mittal et al. 2009; McNamara & Nulsen 2007; Best et al. 2007). Moreover, other studies suggested that the heating effects of AGN activity from any cluster galaxies, not only those hosted by the Most Massive Cluster Galaxies (MMCGs), might be sufficient to heat the surrounding ICM at larger radii (Nusser et al. 2006; Fabian et al. 2006). We use MMCGs to represent the brightest cluster galaxy population in this paper, since there is an enormous overlap between these two types of galaxies in our sample (Rumbaugh et al. 2018). To determine whether RAGN hosted by MMCGs have a larger effect on their neighbouring galaxies than MMCGs without RAGN, we implement a comparison of RAGN that are hosted by MMCGs with a control sample. There are 5 RAGN hosted by the...
MMCGs. Here we define the criteria of MMCGs as \( \eta \leq 2 \), \( \leq R_{200} \), and the galaxy being among the top 3 most massive galaxies in a cluster. Three of these RAGN have 6 companion RAGN within \( R_{\text{proj}} \leq 500 \) kpc. Therefore, to consider their feedback together, we categorize these 11 RAGN as the overall RAGN-MMCGs sample. Because RAGN-MMCGs are always the 1st or 2nd mass-ranked MMCGs, we use the rest of the 1st and 2nd mass-ranked MMCG candidates as the control-MMCGs. The number of RAGN/control-MMCGs and their SNGs are shown in the Table 2. The \( f_q \) are 0.83\( \pm \)0.03 for RAGN-SNGs and 0.70\( \pm \)0.05 for the control-SNGs and are shown as “MMCGs sample” in the left panel of Figure 6. The offset is at a 2.2\( \sigma \) significant level, consistent with the offset seen in the cluster comparison and in the highest overdensity bin. In addition, we calculate the corresponding global \( f_q \) of RAGN- and control-MMCGs using the relation described in Section 4.1. These values are shown in the Figure 6. The quiescent fractions of SNGs of the RAGN-/control-MMCGs are both much higher than their corresponding global \( f_q \). However, MMCGs are a special type of galaxy whose effects are not considered in the global \( f_q \) relation. Although we present the global values for completeness, we do not think that a comparison to our second control method is valid in this case.

Since the MMCG sample is small, to preclude a single MMCG or cluster from dominating the signal, we apply a modified jackknife method. In each iteration, we select 10 out of total 11 galaxies from the MMCG-RAGN/control sample and calculate the \( f_q \) of neighbouring galaxies of the selected centers. The standard deviation on the median \( f_q \) of jackknife re-samplings are 0.001 and 0.004, respectively. The small deviations indicate that the results are not dominated by a single centre galaxy. We notice that 4 out of 11 RAGN and 32 out of total 67 RAGN-SNGs are associated with the most massive cluster in RXJ1821. Additionally, the RXJ1821 cluster is unique in the sample studied here in terms of its mass and compactness (Rumbaugh et al. 2012; Shen et al. 2017). We attempted an analysis that excludes all SNGs in this cluster, finding no significant difference between quiescent fractions of SNGs of MMCG-RAGN and that of MMCG-control. However, the small sample size of the remaining galaxy population essentially precludes a significant result. Furthermore, we attempted to compare these 4 RAGN and their associated RAGN-SNGs in the RXJ1821 cluster to the rest of its cluster members. The \( f_q \) of the RAGN-SNGs sub-sample is higher than that of the other cluster members at \( \geq 3\sigma \), even when we match the median \( \eta \) value of the two sub-samples. However, we only have this one cluster that has multiple RAGN in the cluster centre so we cannot draw any firm conclusions. We will explore in future work, using the power of the full ORELSE sample, whether such clusters are primarily responsible for driving the elevated \( f_q \) seen here. As we mentioned in Section 3.1 and shown in Figure 1, there is one extended RAGN source hosted by the MMCG in the main RXJ1821 cluster. This RAGN is not coincident with the X-ray center, but is actually \( \sim 700 \) kpc away. We test the impact of this special case by removing the 9 SNGs of this RAGN from the RAGN-SNGs sample and re-calculating the \( f_q \). None of the results change meaningfully.

Radio AGN in clusters are known to be associated with strong cool-core clusters, clusters which are typically in a relaxed state (e.g. Mittal et al. 2009, Cavaliere et al. 2016). Relaxed clusters, in general, might be expected to have higher quiescent fractions (e.g. Lemaux et al. 2012). These cool-core clusters, however, are probably not prevalent in our sample and, regardless, our data do not have the ability to discern such phenomenon. In addition, although RAGN are preferentially found in regions of higher global density (Shen et al. 2017), they are not typically found in the centre of the clusters that are studied here. Therefore, they are likely not the type of RAGN seen in cool-core clusters. However, a concern still remains that, if our RAGN sample reside in the clusters that have a higher average \( f_q \) than that of clusters which host the control samples, then our result could be biased in exactly the direction we are claiming a potential signal. As we show here, however, this bias is almost certainly not present in our sample. From the analysis presented in Rumbaugh et al. 2018, we confirm that RAGN in the cluster and MMCGs sub-samples reside in clusters having various \( f_q \) spanning from 0.38 to 0.78. Furthermore, we see no evidence of correlation between the number of RAGN and the fraction of quiescent members in the same cluster. These results imply that the elevated \( f_q \) seen in the cluster and MMCG comparisons are not driven by other unrelated processes in their host clusters. As emphasized in the left panel of Figure 6, no matter what comparison we made, we have \( \sim 2\sigma \) significant between \( f_q \) for RAGN-SNG and that for all other control-SNG samples. We will further discuss the quenching effect of RAGN in clusters and those being hosted by MMCGs in Section 5.1.

4.5 Effect on low stellar mass SNGs

Previous studies suggested that both RAGN feedback and cluster physical mechanisms, such as ram pressure stripping, might have larger effects on low stellar mass galaxies (e.g., Shabala et al. 2011; Bahé & McCarthy 2015). Therefore, we separate RAGN-SNGs in the highest density bin, as shown in Figure 4, into two sub-samples: low stellar mass (\( M_\star \leq 10^{9.5} M_\odot \)) and high stellar mass (\( M_\star \geq 10^{10.5} M_\odot \)) galaxies. We find that the low stellar mass sub-sample has a higher quiescent fraction (\( f_q = 0.87 \pm 0.06 \)) than the high stellar mass sub-sample (\( f_q = 0.79 \pm 0.05 \)), as shown in the right panel of Figure 6.

As discussed in Section 4.1, studies have found that the quiescent fraction of galaxies depends on various parameters, e.g., stellar mass, environment, and redshift (Muzzin et al. 2013; Tomczak et al. 2014; Cooke et al. 2016). Thus, to make a fair comparison between the two stellar mass sub-samples, we should apply corrections to their quiescent fraction based on the expected values at their respective average \( M_\star \), \( z \), and \( \log(1 + \delta_{\text{gal}}) \) values. Specifically, the quiescent fraction has been found to be strongly tied to each of these three parameters using \( \sim 4500 \) spectroscopically confirmed galaxies across 15 ORELSE fields (see Lemaux et al. submitted). Lemaux et al. found that the quiescent fraction, on average, smoothly decreases with decreasing stellar mass at all redshifts for galaxies residing in all environments. Based on the global relation presented in Section 4.1, the global \( f_q \) of the lower and higher stellar mass sub-samples are 0.48 \( \pm \) 0.02 and 0.61 \( \pm \) 0.02, respectively, given the median stellar masses (10.32 vs 10.79), redshifts (0.821 vs 0.859) and local overdensity (1.22 vs 1.33) of these RAGN-SNG sub-samples.
Numerous studies have shown that feedback from RAGN can affect the star formation of their host galaxies. We searched for the signature of this effect to larger radius and across a wider dynamical range of environments, using 57 RAGN and their neighbouring galaxies ($R_{\text{proj}} \leq 500$ kpc) at intermediate redshifts ($0.55 \leq z \leq 1.3$) selected from five fields in the ORELSE survey. To isolate the effect of RAGN, we selected 100 control galaxies which match the colour, stellar mass and local overdensity of RAGN (see Section 3.2) and obtained neighbouring galaxies of the control sample (see Section 3.3). We calculated the fractions of quiescent galaxies for RAGN-SNGs and control-SNGs by binning the two samples into four local overdensity bins and found a marginal ($2\sigma$) increase in $f_q$ of RAGN-SNGs compared to control-SNGs at the highest densities of $\log(1 + \delta_{\text{gal}}) \geq 1.2$, but in no other local environments.

To confirm the validity of the comparisons made, we ran diagnostic tests in Section 4.1 and Section 4.2. We first examined whether this possible difference is due to the intrinsic differences between RAGN-SNGs and control-SNGs which may bias the $f_q$ based on the stellar mass, environment, and/or redshift. We exclude these possible effects on $f_q$ of the two SNG samples and even the RAGN and control samples. We then use different radii to select neighbouring galaxies and found that the largest difference between the RAGN-SNG and control-SNG samples is seen using 500 kpc as $R_{\text{proj}}$. Using smaller radial range reduces the sample size of SNGs, which increases the uncertainty of $f_q$. In addition, small variations on the radius cut ($\pm 50$ kpc) do not affect our result. Further, we found the signal vanished using a larger radial range, which could be explained by the fact that RAGN might not be capable of affecting their neighbouring galaxies to such large distances.

After eliminating possible effects from factors other...
than the RAGN, we searched for the origin of this difference from radio power in Section 4.3 and cluster environments in Section 4.4. We found that the median values of radio power of RAGN increases with increasing local overdensity, which suggests that the increased radio power of RAGN in high-density environments might be one of the potential factors that enhances the quenching of RAGN-SNGs. Because the observed difference in \( f_q \) occurs at very low \( \log(\eta) \) and because \( \sim 50\% \) of RAGN and \( 62\% \) of SNGs in our sample are within the cluster environments, we examined whether RAGN combined with the cluster environment may cause the larger quenching effect in the highest overdensity bin. We performed a comparison of RAGN in clusters and those hosted by MMCGs with a matched cluster/MMCG control sample and found a 2\( \sigma \) increase as in our previous result. When comparing \( f_q \) for RAGN- and control-SNGs in clusters and the highest overdensity bin to their \( f_q \) from the derived global relation between quiescent fraction and stellar mass, redshift, and local overdensity from Lemaux et al. (submitted), a more significant offset is observed between RAGN-SNGs and its global \( f_q \), compared to the \( f_q \) of the primary control-SNGs and its global \( f_q \). In addition, we find a 6\( \sigma \) offset relative to its global \( f_q \) for the lower stellar mass RAGN-SNGs versus a 3\( \sigma \) offset for the higher stellar mass subsample, as well as the inverse relation of \( f_q \) for RAGN-SNGs depending on stellar mass compared to the global values was found. Both of these results imply that the RAGN have a larger effect on low mass galaxies, as might be expected.

5.1 Possible Interpretations for RAGN Induced Quenching of Neighbouring Galaxies

Emboldened by the observation of a significantly higher incidence of quiescence of galaxies in close proximity of a RAGN, we propose here possible interpretations of why RAGN residing in clusters might act to decrease the capability of surrounding galaxies to form stars. Because of their location within an overarching diffuse medium where RAGN are thought to be able to heat the surrounding ICM and to potentially enhance the physical mechanisms which remove galaxy gas, RAGN could have the consequence of quenching star formation in neighbouring galaxies.

Many studies of clusters at low redshift using both X-ray and radio observations have revealed that AGN deposit energy via jets and bubbles and moves ICM gas to outer cluster regions via weak shocks, with the latter mechanism acting on a larger scale (\( \sim 300 \) kpc). Recent observations of very large-scale and diffuse radio structures around 3C 31 and earlier observations of M87 suggest that a large-scale (\( \sim 200 \) kpc) heat deposition may be taking place (Hardcastle et al. 2002; Owen et al. 2000). Ma et al. (2011) studied ICM atmospheric heating via RAGN jets in the redshift range 0.1 \( \leq z \leq 0.6 \). They found that those RAGN residing within a projected radius of 250 kpc from the cluster center are able to heat gas in the ICM on order of \( \sim 0.2 \) keV per particle within \( R_{500} \), which corresponds to \( \sim 700 \) kpc for clusters in these five fields. In our sample, the average radio power \( P_{\text{radio}} \) at 1.4GHz is \( 10^{24.2} \) W Hz\(^{-1} \) in the highest overdensity bin. Following the \( P_{\text{jet}} \sim P_{\text{radio}} \) scaling relations in Cavagnolo et al. (2010), we obtain a jet power (\( P_{\text{jet}} \)) of \( \sim 10^{44} \) erg/s, similar to the average RAGN jet power studied in Ma et al. (2011). We assume this \( \sim 0.2 \) keV increase of \( T_{\text{ICM}} \) up to \( R_{500} \) in our clusters. Given that the median \( T_{\text{ICM}} \) of our cluster sample is 3.7 KeV, as measured within core radii of 180 kpc from Chandra observations (see more details in Rumbaugh et al. 2018), the corresponding increase in the median value of \( T_{\text{ICM}} \) is 5% with a range from 2% to 25%. The estimated mass loss rate due to hydrodynamic interactions (i.e., viscous stripping and thermal evaporation) taking place between the galaxy’s ISM and the ICM is \( M \propto T_{\text{ICM}}^2 \) (see Boselli & Gavazzi 2006 for reference). Therefore, given the estimated \( T_{\text{ICM}} \) increase, \( M \) could increase by \( \sim 15\% \), with the range of 6% to 75%. In summary, this simplified estimation of the temperature change and its consequence on mass loss rate supports our scenario that the heating mechanism of RAGN could remove gas from a galaxy that would be available for star formation and consequently of quench star formation in neighbouring galaxies. To this end, some simulations of RAGN shown that multiple duty cycles lead to the depositing of considerable energy to the ICM (e.g., Voit & Donahue 2005), though it is unclear if any of the RAGN in our sample are comparable to the phenomenon simulated (see discussion in Section 4.4).

Here, we further discuss three factors which might affect our scenario: radio power, stellar mass of neighbouring galaxies, and effects related to RAGN being hosted by MMCGs. The radio power \( P_{\text{radio}} \) at 1.4GHz of our RAGN sample spans \( 10^{23.22} \sim 10^{35.15} \) W Hz\(^{-1} \) and, as shown in the panel C of Figure 4, the median values of radio power increase by 0.48 dex across the three overdensity bins. Assuming the same \( P_{\text{jet}} \sim P_{\text{radio}} \) scaling relation as above, the corresponding \( P_{\text{jet}} \) range across these bins is \( 10^{43.33} \sim 10^{45.75} \) erg/s. This estimated range results in a \( \sim 2.5 \) dex change from the low- to the high-density environments in \( P_{\text{jet}} \). However, there is an extremely large scatter in this scaling relation (\( \sim 3.5 \) dex). As such, we are not able to definitively claim that the increase in radio power observed from low- to high-density environments contributes to the possible quenching effect.

In Section 4.5, the lower stellar mass RAGN-SNGs were shown to have a higher quiescent fraction both relative to their higher stellar mass RAGN-SNGs and relative to the global value derived from the full OREFLE sample. This increased \( f_q \) for lower stellar mass galaxies in the densest regions of massive clusters evokes thoughts of ram pressure stripping, which is more efficient in stripping gas in the lower stellar mass galaxies mostly due to their shallower potential well (Boselli & Gavazzi 2000). Therefore, the more pronounced effect for lower stellar mass neighbouring galaxies seen here could be explained by the additive effect of heating by RAGN, which would further weaken an already shallow potential well, so that ram pressure stripping effects could excise most of the in situ gas. In galaxies with a steeper potential well, i.e., higher stellar mass galaxies, the difference in temperature induced by the RAGN may not be enough to make an appreciable difference in ram pressure stripping effectiveness.

In case of RAGN hosted by MMCGs, we found an offset between RAGN-SNGs and control-SNGs at 2\( \sigma \) level, which is similar to the offset seen in the cluster comparison and in the highest overdensity bin. Many studies have demonstrated that RAGN within the cooling radius of clus-
ters (i.e. the radius within which the cooling time is less than the Hubble time) could regulate heat, density and entropy of the ICM (e.g., Mittal et al. 2009; McNamara & Nulsen 2007), with such heating exceeding that of all other RAGN in a given cluster combined (Best et al. 2007). However, the fact that the small sample size of the MMCG population essentially precludes a more significant result. In addition, these RAGN typically have nearby RAGN in our sample, which appear to be another factor that can enhance the quenching effect. This result is in line with studies that suggested that the heating effects of AGN activity from all cluster galaxies might be a solution to insufficient heating of the ICM at larger radius ($R_{200}$) of the cluster center (Nusser et al. 2006; Fabian et al. 2006). We will explore in future work, using the power of the full ORELSE sample, whether RAGN being hosted by MMCGs are responsible for driving the elevated $\mathcal{L}_q$ seen here.

As for non-cluster environments, Giodini et al. (2010) studied the mechanical energy output from 16 group RAGN up to $z \sim 1$. They found that the energy released by RAGN is larger than gravitational binding energy of the intragroup medium. They suggested that gas in the group has been re-removed by RAGN. In the Local Group, an additional RAGN feedback mechanism is found via strong shocks by powerful FR-II type radio sources (Worrall et al. 2012), in line with the feedback mechanism suggested by Shabala et al. (2011). Unfortunately, we could not test in group environments, since our current sample only contains 3 RAGN in known galaxy groups, and none of them reside in the center of groups in the ORELSE fields being studied in this paper. On the other hand, RAGN in field environments may not be able to transfer their energy output effectively to neighbouring galaxies. This could be explained due to the lack of a medium necessary to couple the mechanical energy of the RAGN jets. Additionally, in situ HI/HH gas in neighbouring galaxies is transparent to the RAGN jets (i.e. jet are not capable of interacting with galaxies in situ HI/HH gas; McNamara & Nulsen 2012). Therefore, we would not expect significant effects in the field environments as we have found in the cluster environments.

There still remain, however, some caveats in our analyses. Given the size of our total RAGN sample and RAGN-cluster sample, we are not able to definitively confirm our result at least for some aspects of this analysis. In addition, the spatial selection of our spectroscopy could affect our result. Though we attempt to mitigate the effects that such sampling could have on our results by selecting 100 different control samples, it is at least conceivable that some differential bias between the RAGN-SNGs and control-SNGs persists. This is, additionally, a bias which may be compounded for RAGN which emit jets with smaller opening angles. The full ORELSE sample, which is expected to provide a RAGN sample which exceeds the current sample by a factor of approximately three, should be efficient to settle these issues and to definitely determine whether the RAGN-induced quenching suggested here is real or not.

ACKNOWLEDGEMENTS

This material is based upon work supported by the National Science Foundation under Grant No. 1411943. Part of the work presented herein is supported by NASA Grant Number NNX15AK92G. This study is based on data taken with the Karl G. Jansky Very Large Array which is operated by the National Radio Astronomy Observatory. The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. This work is based, in part, on data collected at the Subaru Telescope and obtained from the SMOKA, which is operated by the Astronomy Data centre, National Astronomical Observatory of Japan; observations made with the Spitzer Space Telescope, which is operated by the Jet Propulsion Laboratory, California Institute of Technology under a contract with NASA; and data collected at UKIRT which is supported by NASA and operated under an agreement among the University of Hawaii, the University of Arizona, and Lockheed Martin Advanced Technology centre; operations are enabled through the cooperation of the East Asian Observatory. When the data reported here were acquired, UKIRT was operated by the Joint Astronomy Centre on behalf of the Science and Technology Facilities Council of the U.K. This study is also based, in part, on observations obtained with WIRCam, a joint project of CFHT, Taiwan, Korea, Canada, France, and the Canada-France-Hawaii Telescope which is operated by the National Research Council (NRC) of Canada, the Institut National des Sciences de l’Univers of the Centre National de la Recherche Scientifique de France, and the University of Hawaii. The scientific results reported in this article are based in part on observations made by the Chandra X-ray Observatory and data obtained from the Chandra Data Archive. The spectrographic data presented herein were obtained at the W.M. Keck Observatory, which is operated as a scientific partnership among the California Institute of Technology, the University of California, and the National Aeronautics and Space Administration. The Observatory was made possible by the generous financial support of the W.M. Keck Foundation. We wish to thank the indigenous Hawaiian community for allowing us to be guests on their sacred mountain, a privilege, without with, this work would not have been possible. We are most fortunate to be able to conduct observations from this site.

REFERENCES

Ascaso B., Lemaux B. C., Lubin L. M., Gal R. R., Kocevski D. D., Rumbaugh N., Squires G., 2014, MNRAS, 442, 589
Bahé Y. M., McCarthy I. G., 2015, MNRAS, 447, 969
Balogh M. L., Morris S. L., Yee H. K. C., Carlberg R. G., Ellingson E., 1999, ApJ, 527, 54
Bertin E., Arnouts S., 1996, A&AS, 117, 393
Best P. N., von der Linden A., Kauffmann G., Heckman T. M., Kaiser C. R., 2007, MNRAS, 379, 894
Birzan L., Rafferty D. A., McNamara B. R., Wise M. W., Nulsen P. E. J., 2004, ApJ, 607, 800
Biviano A., Katzerg P., Thomas T., Adami C., 2002, A&A, 387, 8
Boehringer H., Voges W., Fabian A. C., Edge A. C., Neumann D. M., 1993, MNRAS, 264, 529
Boselli A., Gavazzi G., 2006, Publications of the Astronomical Society of the Pacific, 118, 517
Brammer G. B., van Dokkum P. G., Coppi P., 2008, ApJ, 686, 1503
Brüggen M., Ruszkowski M., Hallman E., 2005, ApJ, 630, 740
