Chasing high-redshift clusters around AGN using *Spitzer* data

1. Scientific Justification

1.1. Galaxy clusters at high-z

Clusters of galaxies are the most massive and extended gravitationally bound systems in the universe with typical masses of 10^{14-15} $M_{\odot}$ and contain hundreds of galaxies over regions of several Mpc. According to the current hierarchical models e.g., the Cold Dark Matter ('ΛCDM') model, the smallest and primordial components such as stars appear through the gravitational merging of gas in large CDM halos (White & Rees 1978). As these halos collapse, matter gets distributed along filaments composed of a mixture of gas, young galaxies and other stellar systems. The galaxy clusters are found in the regions of highest galaxy density, at the intersection of these filaments. Clusters contain a large number of galaxies at the same cosmic time making them a unique laboratory to study the formation and evolution of galaxies. In particular, studies of clusters show that their galaxy populations strongly differ at high and low redshift.

One efficient method to find galaxy clusters at high-z has been to observe the extended X-ray emission of the intracluster medium (ICM). Compression and shocks, occurring when the cluster gravitational potential becomes settled, warm up the gas present in the intra-cluster environment. Observations of galaxy clusters in X-rays have revealed that about 15 – 20% of the cluster mass is in the form of hot diffuse gas (while about 4% of the mass is coming from stars and galaxies and the rest from dark matter). This gas, reaching temperature of several 10^7K for typical cluster mass of 10^{14-15} $M_{\odot}$, becomes fully ionized and emits in X-rays. Observations conducted by the *ROSAT* satellite and later by *XMM-Newton* have detected galaxy clusters up to $z \sim 1.5$ with two clusters at $z > 1.3$ to date. However, searching for higher redshift clusters rapidly becomes difficult as the surface brightness of the X-ray emission fades as $(1 + z)^4$.

One other efficient method to look for galaxy clusters has been to look at overdensities of red sources in optical imaging data using the 'red sequence algorithms' (Gladders & Yee 2000). The colours of galaxies are strongly related to a strong break in their spectrum: the 4000Å break. As the 4000Å break shifts towards the near-infrared at $z > 1.5$, the cluster selection using the red sequence algorithms in optical becomes more and more challenging. To chase even higher-z structures, one therefore needs to develop new selection techniques at redder wavelengths e.g., the use of mid-infrared data.

1.2. The power of mid-infrared (*Spitzer*) observations to find high-z galaxy structures

The launch of the *Spitzer Space Telescope* and its Infrared Array Camera (IRAC) in 2003 has dramatically changed the field of high-redshift cluster research. Fields surveys (e.g. the IRAC Shallow Survey; Eisenhardt et al. 2008) have expanded the sample of galaxy clusters known at $z \geq 0.8$. Fig. 1 presents three of these high-z clusters as seen through composite 3-colour images. In each case, the cluster is clearly seen as a clump of red sources in contrast to the bluer field sources. IRAC is an extremely sensitive tool for finding massive galaxies at high-redshift since their 3.6μm and 4.5μm flux densities remain nearly constant at $0.7 < z < 2.5$ due to a negative and favorable k-correction. These IRAC surveys have the strong advantage of providing uniformly selected galaxy cluster samples which are beneficial for a range of studies, including statistically probing cosmological parameters. Indeed, one of the highest redshift clusters known to date, ClG J0218-0510 at $z = 1.62$, in the XMM-LSS field, was originally detected as an overdensity of red IRAC-selected sources (Papovich 2008). Spectroscopic follow-up confirmed 15 members to date (Papovich et al. 2010; Tanaka et al. 2010).

However, clusters are rare objects and finding large samples of massive high-redshift galaxy clusters require field surveys even wider than the several tens of square-degrees which is the current state-of-the-art.

1.3. Chasing high-z clusters in the environment of AGN

Work has been done using targeted clusters searches, i.e., focusing on regions of the sky suspected to host overdensities of galaxies. For exemple, numerous searches for high redshift galaxy clusters have been conducted in the surroundings of powerful radio galaxies and radio-loud quasars at high redshifts ($z > 1.5$) that are known to inhabit rich environments. Best et al. (2003) studied the environments of six radio loud AGN at $z \sim 1.6$. Excesses of red galaxies were detected in most of the fields on two different scales: a central concentration on radial scales within $\sim$ 150 kpc and weaker large scale excesses detected between 1 and 1.5 Mpc radius. They see a large diversity in the concentrations found in different fields, some presenting excesses on both the smaller and larger scales, some showing excesses on only the smaller or larger scale, and in one case, no excess was detected. They deduced from the angular cross-correlation function that on average, the environment of the targeted AGN was consistent with Abell cluster richness classes 0 and 1.

The host galaxies of powerful radio sources are some of the most massive galaxies in the Universe (e.g., Seymour et al. 2007) and are likely to be the progenitors of Brightest Cluster Galaxies (see Miley and De Breuck 2008 for a review). Because they are so massive, high redshift radio

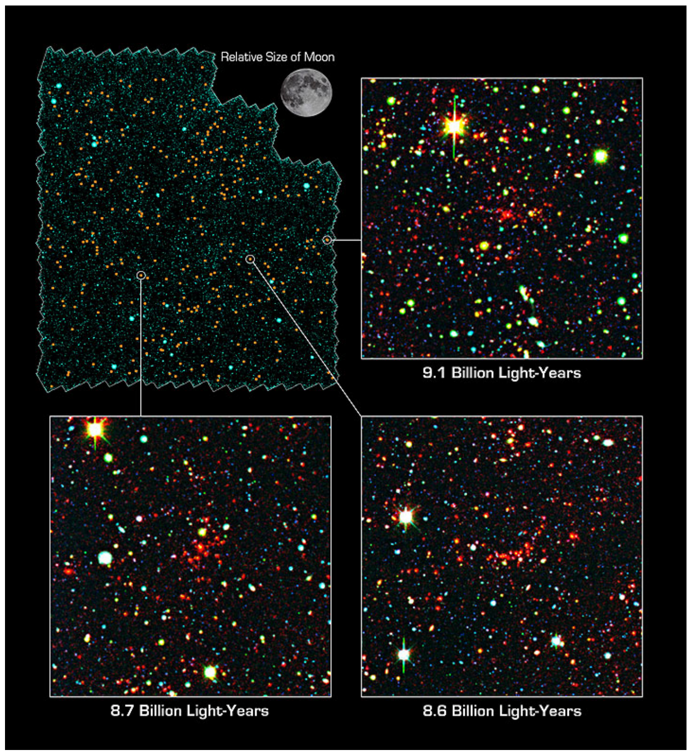

Fig. 1.— Composite 3-colour images (B_w, I, [4.5]; $5' \times 5'$) of three clusters at $z > 1$ presented in Eisenhardt et al. (2008) and their location in the Boötes field (Top Left). *Top Right:* ISCS J1438.1+3414 (z = 1.413). *Bottom Left:* ISCS J1429.3+3437 (z = 1.258). *Bottom Right:* ISCS J1434.5+3427 (z = 1.243). Courtesy of Mark Brodwin.

galaxies (HzRGs hereafter) are excellent signposts to pinpoint the densest regions of the Universe out to very high redshifts and therefore provide a unique tool for studying cluster formation in the early universe. The advantage of searching for clusters associated with radio galaxies is that the redshift of the possible clusters is known. One search technique, extensively used by George Miley's team in Leiden has been to use narrow-band imaging to detect emission line objects around HzRG, in particular using bands that correspond to the redshifted Hα and Lyα emission lines. Two overdense fields of Lyα emitters have even been detected around $z > 4$ HzRGs. Overdensities of Lyα emitters with densities 3 – 5 times larger that the field density have been found by this method (Venemans et al. 2007). A range of complementary studies have made use of optical through mid-infrared observations to isolate candidate cluster members associated with radio galaxies (Kodama et al. 2007; Galametz et al. 2009a, 2010).

2. Proposed project

We propose to identify a new sample of galaxy clusters at $z \sim 1$ using IRAC observations of radio-loud AGN.

2.1. The AGN sample at $z \sim 1$

Falder et al. (2010) studied a large sample of high-redshift active galactic nuclei (AGN) at $z \sim 1$. Their sample, observed in the four IRAC bands, is split into three subsamples, all at the single cosmic epoch of $0.9 < z < 1.1$: 75 radio-loud quasars (RLQs), 71 radio-quiet quasars (RQQs) and 27 radio galaxies (RGs). This mixed sample of both unobscured (type 1) AGN, in the form of quasars, and obscured (type 2) AGN, the RGs, will allow us to test AGN unification schemes.

A study based on 3.6μm number counts shows excesses of 3.6μm sources within 300 kpc of the AGN, as well as evidence for a positive correlation between source density and radio power. We propose here to refine the analysis of this unique dataset combining the power of the four IRAC bands in order to isolate high-z galaxy clusters associated with this large sample of AGN.

2.2. IRAC selection criterion

We present in this section, examples of simple and robustly tested IRAC color criteria that will be used in order to isolate high-redshift galaxy cluster candidates.

Selection of high-z galaxies

One of the main spectral features in the spectral energy distribution (SEDs) of galaxies is the 1.6μm bump, caused by a minimum in the opacity of the H^- ion which is present in the atmospheres of cool stars. This bump, seen in the SEDs of all normal galaxies, has often been used as an efficient photometric redshift indicator. Fig. 2 (top panel) shows the position of the 1.6μm bump for galaxies at $z = 1$ and $z = 1.2$ relative to the IRAC 3.6 and 4.5μm bands. The bump enters the IRAC bands at $z \sim 1$ and shifts beyond 3.6μm at $z \sim 1.2$ resulting in red [3.6] − [4.5] colors.

Fig. 2 (bottom left panel; Papovich et al. 2008) shows the expected behavior of the [3.6]−[4.5] color as a function of redshift for various stellar population models. The curves in the figure correspond to a wide range of composite model stellar populations. These models include purely passive, old stellar populations formed in an instantaneous burst, models with exponentially declining star formation rates, and models with constant star formation rates and various dust attenuation. Even though the models are diverse, they span a tight locus in [3.6] − [4.5] color, showing a characteristic S shape with a local maximum at $z \sim 0.3$, a local minimum at $z \sim 0.7$, and a rise to red colors for $z \geq 1$. They showed that selecting galaxies with red [3.6] − [4.5] color is a very efficient method to isolate high-z galaxies.

Selection of AGN

Recent studies suggest that AGN companions are often found around radio galaxies. Croft et al. (2005) spectroscopically confirmed three QSOs in the surroundings of PKS 1138-262 at $z = 2.16$ and suggested that the QSOs were triggered by the protocluster formation. Venemans et al. (2007) also detected QSOs near radio-galaxies at $z > 3$. Recently, Galametz et al. (2009b) studied the AGN population in a large sample of galaxy clusters at $z < 1.5$ and found an excess of AGN within 0.5 Mpc of the cluster centers, with the number of AGN in clusters increasing with redshift. Powerful AGN provide an alternative way to look for relatively massive host galaxies in a complementary technique to the near-IR color selection.

Stern et al. (2005) presents a robust technique for identifying active galaxies from mid-infrared color criteria. While the continuum emission of stellar populations peaks at approximately 1.6μm, the continuum of AGN is dominated by a power law throughout the mid-infrared. Stern et al. (2005) adopt the following (Vega system) criteria to isolate AGN from other sources: $([5.8]-[8.0]) > 0.6 \cap ([3.6]-[4.5]) > 0.2\times([5.8]-[8.0])+0.18 \cap ([3.6]-[4.5]) > 2.5\times([5.8]-[8.0])-3.5$ (see Fig. 2, bottom right panel; red line). Since the criterion is designed to identify power-law spectra, they do not preferentially select AGN in any specific redshift range.

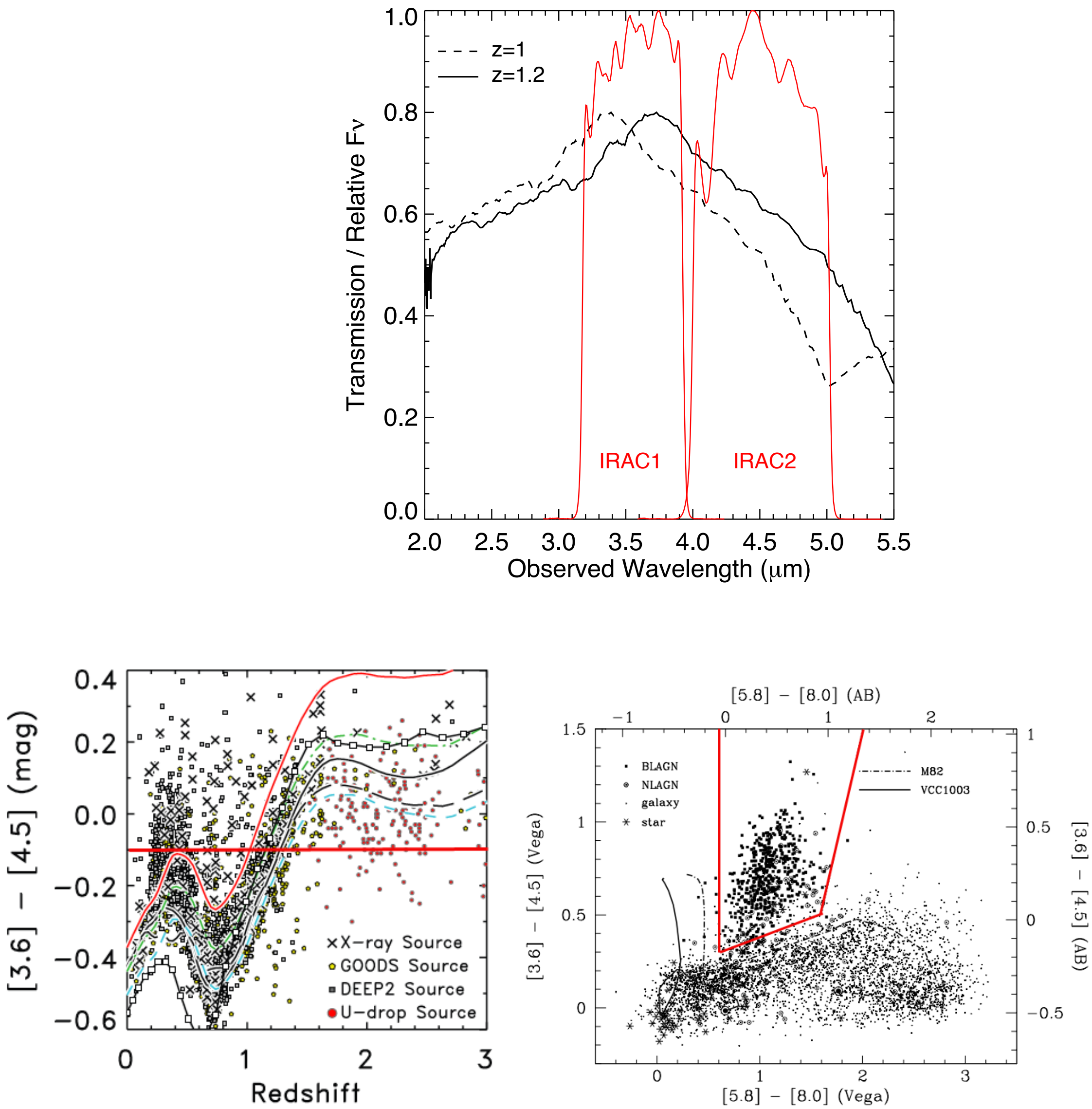

Fig. 2.— *Top:* From Galametz et al. 2011 in prep. Spectral energy distribution of a 2 Gyr-old galaxy redshifted to $z = 1$ (dashed line) and $z = 1.2$ (solid line) assuming a rapid ($\tau = 0.1$ Gyr) exponentially declining star-formation. The strongest feature in this wavelength range is the *rest-frame* 1.6μm stellar bump. Transmission curves for IRAC channel 1 and 2 are overplotted for reference. *Bottom left:* From Papovich et al. 2008. [3.6] – [4.5] color as a function of redshift. *Bottom right:* From Stern et al. 2005. IRAC color distribution ([5.8] – [8.0] vs [3.6] – [4.5]) of spectroscopically identified objects in the AGES survey. The red line empirically separates active galaxies from Galactic stars and normal galaxies.

2.3. Expected results

- We expect to robustly identify a large sample of galaxy clusters at $z \sim 1$ for understanding galaxy cluster formation at this precise epoch.
- We will study how source overdensity depends on radio power. Some work showed that radio power and host galaxy stellar mass are uncorrelatedFalder et al. (2010) shows that radio power and environment are strongly correlated at $z \sim 1$, while other studies suggest a more complicated relationship between radio power and environment at lower redshift. Our project will try to provide an accurate study of the environments of AGN at high redshifts, thereby testing the evolutionary trends hinted at by previous studies.
- We will also study the characteristics of the (mid-IR selected) AGN population in clusters at $z \sim 1$

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