OBSERVING REQUEST
University of Arizona Observatories

Year: 2015 **Term:** Jan–Jul **Proposal type:** short-term

Search for Galaxy Clusters around Extremely Massive Black Holes

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Abstract of Scientific Justification

Extremely massive black holes (EMBHs) are the most massive black holes (BHs) in the universe with $M_{\rm BH}\gtrsim10^{9.5}\,M_\odot$. The local $M_{\rm BH}$-host galaxy correlation suggests that EMBHs are in the most massive galaxies ($M_* \sim 10^{12}\,M_\odot$), which are commonly found in dense cluster environments. Therefore, one can expect that there is a close connection between active EMBHs (AGNs with EMBHs) and dense environments which could make active EMBHs attractive signposts to discover high redshift clusters of galaxies. However, the link between active EMBHs and the dense environment has been poorly studied and is uncertain yet since the $M_{\rm BH}$ scaling relations could break down at the most massive end and the formation of the most massive galaxies may not coincide with the environment where they end up eventually. In order to examine where active EMBHs reside, we will perform Hectospec spectroscopy of cluster candidates around six active EMBHs at $z < 0.4$, to determine the membership of galaxies associated with the active EMBHs and $M_{\rm halo}$ of the clusters. This study will be a first step to reveal how active EMBHs, the likely seeds of the most massive galaxies, are inter-related with large scale structures and to possibly test the $M_{\rm BH}$ scaling relations at the massive end. The results of this study will also serve as an important step-stone for future studies of this kind to establish the correlation between the active EMBHs and their environment at low to high redshift.

Summary of observing runs requested for this project

Run	Telescope	Cage	Instrument	PI	AO	Nights	Moon	Scheduling Optimal	Scheduling Acceptable	Sharing Poss.	Sharing Adv.
1	MMT		Hectospec			1	grey	Apr–May	Mar–Jun	no	no

Scheduling constraints and unusable dates *(up to 4 lines)*:

no text past this line

A ⋆ appended to the proposal type indicates a continuation proposal; a ⋆ appended to the name of a proposer indicates the proposer is a (graduate) student; a proposer whose name is underlined is certified on the proposed telescope/instrument combination; if a ∗ appears within the PI or AO box in the observations summary table, the instrument is a PI instrument and/or Adaptive Optics are requested – signatures are required on the next page.

Target list (attach list if longer than 26 objects)

#	Object	RA	Dec	mag / color / type / redshift / comment / etc.
1	Q0806+484	08:06:44.42	+48:41:49.2	$z = 0.3701$, log(MBH)=9.7, $R < 21.5$
2	Q1012+261	10:12:26.85	+26:13:27.2	$z = 0.3783$, log(MBH)=10.26, $R < 21.5$
3	Q1048+302	10:48:20.12	+30:26:27.5	$z = 0.3876$, log(MBH)=9.73, $R < 21.5$
4	Q1353+134	13:53:54.89	+13:42:28.5	$z = 0.3722$, log(MBH)=10.09, $R < 21.5$
5	Q1558+223	15:58:46.72	+22:35:49.6	$z = 0.3992$, log(MBH)=9.78, $R < 21.5$
6	Q1704+604	17:04:41.38	+60:44:30.5	$z = 0.3716$, log(MBH)=9.81, $R < 21.5$

Approval for Instrument Use from PI: ____________________

(have instrument PI signature appear on, or attach PI e-mail to, ***all*** *copies)*

Graduate students *(provide the following information for* ***each*** *student named as PI or CoI on the cover page. Have the advisor's signature(s) appear on* ***all*** *submitted copies)*

Student's Name	Advisor's Name	Advisor's Signature	2nd-yr	Thesis

Scientific Justification

Extremely massive black holes (EMBHs) are the most massive black holes in the universe with $M \sim 10^{10}\,M_{\odot}$. The discovery of $\sim 10^{10}\,M_{\odot}$ BHs in several nearby early-type galaxies (McConnell et al. 2011; van den Bosch et al. 2012) shows that EMBHs do exist, as previously speculated from the heaviest black hole masses of distant quasars. However, questions still remain as to how abundant such EMBHs are and whether they obey the scaling relations such as the local $M_{\rm BH}$–σ_* relation and the virial $M_{\rm BH}$ estimators from the spectra taken at a single epoch.

The extension of the currently known $M_{\rm BH}$ - host galaxy relation suggests that EMBHs live in the most massive early-type galaxies in the local universe. Since the most massive galaxies predominantly live in dense cluster environments with $M_{\rm halo} > 10^{14}\,M_{\odot}$ (Figure 1), we can expect that active EMBHs (EMBHs in active galactic nuclei, AGNs) also lie in dense cluster environments as long as the following conditions are met: (i) the extrapolation of the $M_{\rm BH}$ - host galaxy relation is valid at the most massive end; (ii) the currently existing AGN $M_{\rm BH}$ estimators are valid at the most massive end; and (iii) the formation of EMBHs coincides with the environment where they are located after the active phase.

This makes the study of the environment of EMBHs in AGNs at moderate redshift an intriguing subject to study. If EMBHs are found to live in the dense cluster environment as argued above, it would validate the three assumptions we made to connect EMBHs and the dense environment. Also, it would provide a strong justification for using active EMBHs to identify clusters at high redshift that are being pursued by many groups to constrain cosmological parameters and galaxy evolution models. Alternatively, active EMBHs may turn out NOT to be in dense environment, which would open up other interesting possibilities such as the breakdown of the $M_{\rm BH}$ scaling relations. It could also indicate that the most massive galaxies originally form at a group environment, and later get incorporated into a much larger structure (e.g., Yi et al. 2013). If so, active EMBHs may be found near, but not at the centers of clusters of galaxies.

Previous searches of overdense areas around AGNs have found that some AGNs (10 – 30 %) are associated with galaxy clusters, but not all. The general trend is such that more luminous AGNs tend to be more frequently associated with modest galaxy overdensities of the Abell cluster rank of only 0 – 2 (Hall & Greene 1998), but the AGN-environment relation needs further studies with several studies showing mixed results (Boyle & Couch 1993; Sanchez & Gonzalez-Serrano 1999). Furthermore, previous studies were limited mostly to the investigation of overdense areas around radio-loud/quiet AGNs (e.g, Falder et al. 2010), not on the basis of the mass of the host galaxies or $M_{\rm BH}$. The investigation of overdensity around active EMBHs is even more scarce, since the number of EMBHs is not large (tens of such objects over the entire SDSS coverage at $z < 0.4$).

In order to investigate the connection between active EMBHs and galaxy clusters, we have searched for galaxy overdensities around active EMBHs at $z < 0.4$, chosen from the SDSS quasar catalog of Shen et al. (2011) with $M_{\rm BH} > 10^{9.5}\,M_{\odot}$. Figure 2 shows the galaxy number density maps within 30′ radius (i.e., Hectospec field of view) of six active EMBHs. We constructed the number density maps using galaxies with $R < 22$ mag that have photometric redshifts within ± 0.1 of the quasar redshift. Some active EMBHs (30%) are in overdense areas, and other active EMBHs (50%) are NOT in the densest areas but only several Mpc away from galaxy cluster candidates or superclusters. The large scale field of view also reveals structures resembling filaments.

Here, we propose to perform multi-object spectroscopy of active EMBH fields at $z < 0.4$ using Hectospec on MMT. The large field of view of Hectospec ($1\,\rm deg$ diameter) allows us to search structures as large as 27 Mpc across in comving scale and overcome shortcomings of previous studies that have been limited to 10′ scale. It also allows us to use galaxies in the outer-rim of the Hectospec field of view as control samples. The low redshift of the sample minimizes the effects possibly arising from cosmological evolution of AGNs. Through this observation, we will determine: (i) the association of cluster candidates and active EMBHs by identifying spectroscopic redshifts of member galaxies; (ii) the velocity dispersion of the overdense area thus dynamical $M_{\rm halo}$ of the structures associated with active EMBHs; and (iii) galaxy properties in such environments. This study will possibly provide a powerful means to uncover galaxy clusters at high redshift and a unique insight on the properties of EMBHs and their host galaxies. The results will serve as a solid footstep for future studies of similar objects at higher redshift with GMT, with the projected distance of the Hectospec field size and the depth for $z < 0.4$ universe that matches the GMT GMACS field size and the depth to study the high redshift universe ($z > 1$).

References

Boyle, B. J., and Couch, W. J. 1993, MNRAS, 264, 604
Falder, J. T., et al. 2010, MNRAS, 405, 347
Hall, P. B., & Green, R. F. 1998, 507, 558
McConnell, N. J., et al. 2011, Nature, 480, 215
Muldrew, S. I., et al. 2012, MNRAS, 419, 2670
Sanchez, S. F., & Gonazlez-Serrano, J. J. 1999, A&A, 352, 383
Shim, H., et al. 2013, ApJS, 207, 37
van den Bosch, R. C. E., et al. 2012, Nature 491, 729
Yi, S. K., et al. 2013, A&A, 554, 122

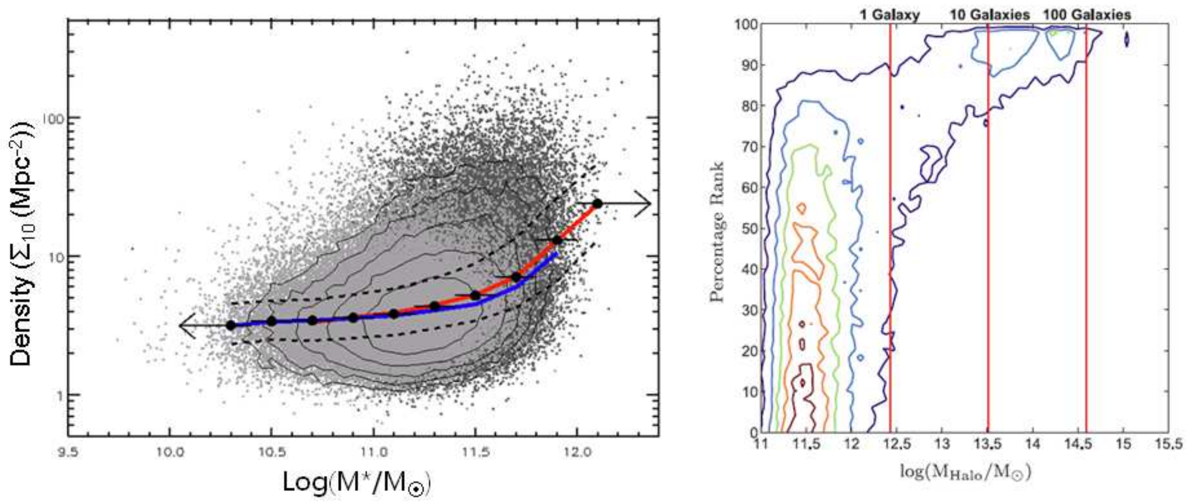

Figure 1: (Left) The galaxy surface density (Σ_{10}, the number of galaxies within a projected distance to the 10th nearest neighbor) versus the stellar mass of galaxies (Yoon, Im, et al. 2014, in prep.). The Σ_{10} values are derived by using galaxies with $M_R < -19.5$ mag, and within $\pm$6500 km s^{-1} from the galaxy in consideration. We see that only the most massive galaxies are dominantly found at high density regions on average. (Right) The percentage rank of galaxy overdensities versus $M_{\rm halo}$ from Muldrew et al. (2012), which is a result based on numerical simulations. The most massive galaxies in the left figure are within top 10% percentile of galaxy overdensities with tens of member galaxies. This figure shows that such overdensities correspond to the halos with $M_{\rm halo} > 10^{14} M_{\odot}$.

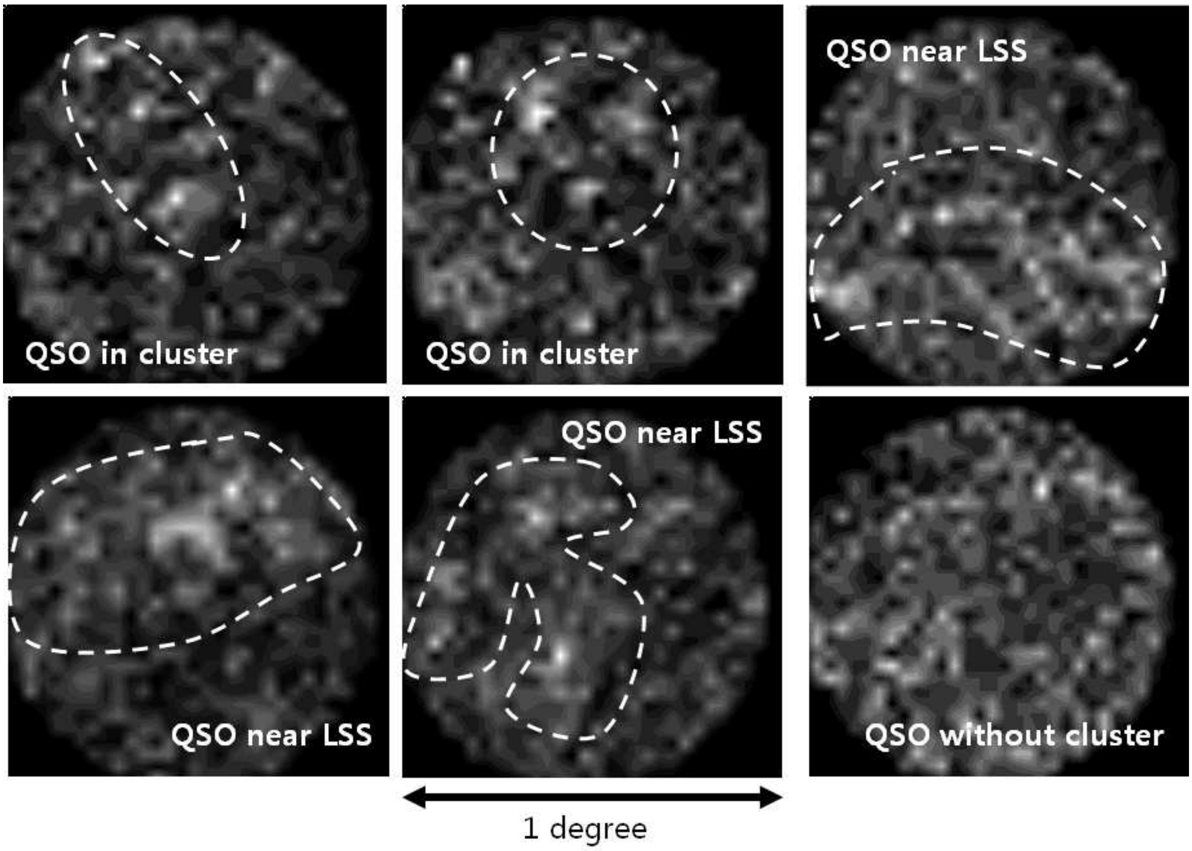

Figure 2: The galaxy number density maps around 6 active EMBHs at $z < 0.4$ in the target table. The active EMBHs are located at center of each image. Each postage stamp image spans 1 degree in size, which corresponds to 27 Mpc in comoving scale at $z = 0.4$. The bright white spots indicate high density regions. The dashed line encircles the location where cluster/supercluster candidates are identified. The outer-rim of the Hectospec field of the last field (lower left) with no obvious overdensities could be used as a control sample.

Experimental Design & Technical Description *Describe your overall observational program. How will these observations contribute toward the accomplishment of the goals outlined in the science justification? If you've requested long-term status, justify why this is necessary for successful completion of the science.* ***(up to one page)***

Target selection: The targets for this observation are galaxies with $R < 21.5$ mag around quasars with EMBHs at $z < 0.4$. The EMBH quasars are selected from a SDSS quasar catalog of Shen et al. (2011), and we chose the ones with at the most massive end $M_{\rm BH} > 10^{9.7}\,M_{\odot}$ We also inspected their spectra and cross-checked various $M_{\rm BH}$ estimates to weed out spurious $M_{\rm BH}$ measurements.This leaves six active EMBHs within the visibility during the 2015A semester. Galaxies are searched from the SDSS DR10 database around the active EMBHs,and photometric redshift cuts will be imposed to select galaxies with z_{phot} with ±0.15 from the quasar redshift. The selection process yields 30-60 cluster member candidates within 2 Mpc circle of the quasar and several times more when we consider large scale structures that are possibly linked to the quasar. Note that the radius of 30′ (Hectospec field of view) corresponds to the comoving scale of 13.5 Mpc at $z = 0.4$, and several cluster candidates are also found within the Hetospec field of view. The average distance between member galaxies is 50″ within a 2Mpc radius circle, which is well beyond the minimum allowed distance between fibers of 20 ″. Galaxies in high density areas will be given high priority. Considering that there are about 1000 galaxies within the photometric redshift limited sample, we expect no difficulty filling in all the Hectospec fibers. The galaxies in the outer-rim of the Hectospec field of view will be used as control samples. If it turns out that overdensities extend to the whole Hectospec field of view, we will use the existing redshift survey data (e.g., DEEP3, zCOSMOS, the VLT VIMOS redshift survey) as control samples.

Observing strategy: The Hectospec spectra taken with the 270 l/mm grating will cover wavelengths 3700 Å to 9000 Å, and multiple emission/absorption lines will be used for the redshift identification. The center of the field will be placed at the quasar location. We can accommodate about 250 fibers on science targets in a single fiber position setup and we will give a higher priority for $R < 21$ mag objects which are likely to be absorption line objects like early-type galaxies when they are in high density regions. Remaining fibers will be used to measure the sky background and for spectrophotometric standards (typically F-stars). Based on our previous experience with Hectospec (Shim et al. 2013), we will use on-source 1 hr of exposure per fiber configuration (split into three 20 minute exposures), to achieve highly complete spectroscopic redshift measurements for sources down to $R = 21.5$ mag. We will reduce the data using HSRED, which we have used extensively for our previous Hectospec observations. Our observing time is 1 hrs on-sky + 20 minutes for setup/readout, which gives about 1.33 hrs of time for each field. With 6 fields to observe we expect the total observing time of 8 hrs in total. Therefore, we request 1 night. Because that our sources are faint, it is desirable to observe them in grey/dark time. The targets are observable through out the 2015A semester with a queue mode, although the optimal months to observe all the targets at once is April or May.

Summary of Time Requested and Awarded *The TAC needs to understand the scope of this project — (1) tell us how many UAO nights you've already had for this project, how many you request this time, and (a good guess of) how many you need to complete the project; (2) if a substantial amount of observing for this project comes from non-UAO telescopes, tell us about that observing, and how the UAO part fits in; (3) if you are collaborating with people who have telescopes, especially if you are part of a large collaboration, tell us who is leading the project, and how UAO time and your participation fit in. (**up to one page**)*

N/A

Previous Use of Steward Facilities *List **all** allocations of telescope time for the present project and allocations for other projects on facilities available through UAO during the past 2 years, together with the current status of the data (cite publications where appropriate). Mark those allocations related to the present proposal (i.e, precede text with* `\related` *command). (**up to one page**)*

We used Hectospec/MMT during 2008A and 2008B for two nights to observe infrared sources in the *AKARI* NEP survey field. More than one thousand spectra were obtained and the results of the study were published in a series of papers, and a few more papers are in preparation.

1. Karouzos, M., et al. 2014, ApJ, 784, 137
2. Oi, N., et al. 2014, A&A, 556, 60
3. Shim, H., et al. 2013, ApJS, 207, 37
4. Kim, S. J., et al. 2012, A&A, 548, 29
5. Hanami, H., et al. 2012, PASJ, 64, 70
6. Ko, J., et al. 2012, ApJ, 745, 181
7. Jeon, Y., et al. 2010, ApJS, 190, 166