OBSERVING REQUEST
University of Arizona Observatories

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

A New Approach to Spatially Resolving the Circumgalactic Medium at z = 0.2 - 0.9

P.I.: Michelle L. Wilson⋆ (SO; *mwilson5@email.arizona.edu*; 503-559-1467)

CoI(s): Hsiao-Wen Chen (UChicago), Ann Zabludoff (SO), Fakhri Zahedy⋆ (UChicago)

Abstract of Scientific Justification

Our understanding of gas accretion and expulsion, which govern galaxy mass growth and metal distribution throughout the Universe, is limited by difficulties in observing gas around distant galaxies. Metal absorption lines in a QSO's spectrum offer an effective means of characterizing chemically-enriched gas around foreground galaxies, but the single sightline limits constraints on the small-scale structure and radial distribution of the halo gas. We propose a new approach: using lensed, multiply-imaged QSOs to survey the Mg II, Mg I, and Fe II gas around galaxies at $0.2 < z < 0.9$. We have identified eight gravitational lens systems, each with two to four close-packed images, sampling a total of 23 different sightlines through 38 galaxy halos. We match absorption lines in the QSO spectra to foreground galaxies projected within $\sim30''$ of the QSO. When stacked into probes of composite group and field galaxy halos, these sightlines provide comprehensive radial coverage of the halo over 50-200 kpc with resolutions down to <10 kpc and $<10\ \mathrm{km\,s^{-1}}$, dramatically improving on past studies, which typically have only one sightline through each halo. Our pilot study of one system has already revealed inflowing gas streams or tidal material around two galaxies (Chen et al. 2014). Here we propose Magellan/MIKE and MMT/MAESTRO observations to detect foreground absorbing gas in the lensed QSO spectra of two fields (PG1115 and Q0957), in addition to Magellan/LDSS-3C and MMT/Hectospec observations to identify the specific galaxies and environments responsible for such absorption in another five fields (Q0957, SDSS J1004, SDSS J1029, WFI2033, and HE2149).

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	MAG2	f/11	MIKE			1	dark	Feb–Apr	Feb–Apr	yes	yes
2	MMT	f/5	MAESTRO	*		1	dark	Feb–Mar	Jan–Apr	yes	no
3	MAG2	f/11	LDSS3			1	dark	Jul–Jul	May–Jul	yes	no
4	MMT	f/5	Hectospec			1	dark	Feb–Feb	Jan–Apr	yes	no

Scheduling constraints and unusable dates *(up to 4 lines)*: None.

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	PG1115+080A1,A2	11:18:18.40	+07:45:55.9	$F555W$ = 16.90 (A1), 17.62 (A2), QSO sightlines
2	PG1115+080B	11:18:16.66	+07:45:55.7	$F555W$ = 18.95, QSO sightline
3	PG1115+080C	11:18:17.00	+07:45:57.7	$F555W$ = 18.39, QSO sightline
4	Q0957+561A	10:01:20.83	+55:53:49.62	$F555W$ = 17.09, QSO sightline
5	Q0957+561B	10:01:20.69	+55:53:55.65	$F555W$ = 17.11, QSO sightline
6	WFI2033-4723 field center	20:33:42.08	-47:23:43.0	Multislit spectra of potential absorber galaxies
7	HE2149-2745 field center	21:52:07.44	-27:31:50.2	Multislit spectra of potential absorber galaxies
8	Q0957+561 field center	10:01:20.78	+55:53:49.4	Multifiber spectra of potential absorber galaxies
9	SDSSJ1004+4112 field center	10:04:34.91	+41:12:42.8	Multifiber spectra of potential absorber galaxies
10	SDSSJ1029+2623 field center	10:29:13.35	+26:23:31.8	Multifiber spectra of potential absorber galaxies

Approval for Instrument Use from PI: See attached email from Richard Green.

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
Michelle Wilson	Ann Zabludoff		no	yes
Fakhri Zahedy	Hsiao-Wen Chen		no	no

Scientific Justification

How gas enters and exits galaxies, and how that gas is transformed into stars, is poorly understood. Yet the details of inflows and outflows—whether in disks or in jets, smooth or clumpy, driven by or driving the galaxy's environment—are critical to understanding the complex relationships of gas dynamics to star formation, nuclear activity, and the circumgalactic medium. For most galaxies, we do not know whether gas motions occur in a rotating disk, bipolar outflows, or inflowing streams. We know little about how much of the gas is clumped or on what scale, uncertainties that can affect mass flow rates by $\sim$10x (Martin et al. 2013) and alter the quenching of star formation. The generally unmapped, but simulated (i.e., Shen et al. 2012), ionization and metallicity structure of the halo changes how readily gas can inflow, cool, and form stars (i.e., Kereš & Hernquist 2009). The metallicity of gas inflows and outflows, also unexplored for most galaxies, is tied the baryon transport, star formation efficiency, and enrichment history (i.e., Shen et al. 2012, Ford et al. 2014).

Simulations currently cannot provide direct predictions, as the resolved spatial distribution of gas, including any clumps, on small scales in SPH models is mostly spurious (e.g., Sijacki et al. 2012). Yet there are physical reasons to expect complex structure in the circumgalactic gas: Kereš & Hernquist (2009) find that cool, $\sim$20 kpc wide filaments moving through hotter, diffuse halo gas fragment on scales of $\sim$5 kpc due to thermal instabilities. Dekel et al. (2009), using SPH, find cool filaments with $20^{\circ} - 30^{\circ}$ opening angles, implying $\sim$5-25 kpc widths at impact parameters of 50-100 kpc; the moving mesh code AREPO produces wider, more diffuse, warmer filaments (Nelson et al. 2013). The temperature structure and gas inflow rates in simulations also vary widely; AREPO has half as much accretion of cool clumps and about an order of magnitude more hot accretion than comparable SPH simulations (Nelson et al. 2013).

The complex connection of gas flows and the circumgalactic medium is tied also to the intergalactic medium on even larger scales (100s of kpc). Most galaxies reside in groups, which may have their own extended, gaseous ("intragroup") halos, potential havens for "missing" baryons. Some previous work suggests that group gas is apportioned mostly in individual galaxy halos (Bordoloi et al. 2011 from Mg II absorption). Yet others find evidence for a significant, common group halo (Johnson et al. 2013 from O VI absorption).

Understanding the detailed gas distribution and morphology, as well as its kinematic, ionization, and metallicity structure, requires resolving spatial and velocity differences on galactic scales ($\sim$10 kpc), and at circum- and intergalactic distances (10s to 100s of kpc), for galaxies in the field and in groups. We propose to do so here with a new approach and a unique sample of lensed, multiply-imaged, close QSO sight-lines.

The Problem. Absorption lines in QSO spectra have constrained the metallicity and velocity of gas projected $>$100 kpc from galaxies, and emission line measurements have detected galaxy-scale outflows. However, fine-scale structure in this gas remains unexplored due to the lack of spatially resolved kinematics on scales of $<$10 kpc at radii from 10s to 100s of kpc.

One common tracer of cool, T$\sim10^4$ K gas in and around galaxies is the Mg II 2796, 2803 Å absorption doublet. This feature is seen routinely in QSO spectra and traces H I clouds with N(HI) $\approx 10^{18} - 10^{22}$ cm^{-2} (Bergeron & Stasńska 1986). Only gas at one radius from the galaxy's center can be measured for most galaxies, as it is unlikely for several QSOs to be projected near each other. Interpreting absorption measurements has proved impossible due to generally having only one QSO sightline to probe the gas in each halo (see, though, Keeney et al. 2013, who use three separate QSOs to probe one low-redshift galaxy). Others have explored using multiple sightlines of lensed QSOs (i.e., Ellison et al. 2007, Hamano et al. 2012, Misawa et al. 2013), but not to constrain z$<$1 halo gas structure.

The Solution. We propose to use multiple, close sightlines of gravitationally lensed QSOs to resolve the morphology, kinematics, and metallicity and ionization structure of circumgalactic gas of galaxies in groups and the field on unprecedented scales. When stacked into composite group and field galaxy halos to probe environmental differences, these sightlines will provide comprehensive radial coverage over 50-200 kpc with resolutions down to $<$10 kpc and $<$10 km s^{-1} (see Figure 1, left). We have already used morphologies and galaxy orientations measured from archival *HST* images to compare velocity gradients of absorption components among close sightlines to theoretical gas distributions to constrain the detailed halo gas structure (Chen et al. 2014). We also are employing Mg I 2852 Å and Fe II 2382 Å absorption to determine the ionization fraction in each sightline and the alpha abundance [Mg/Fe] to determine the metallicity structure. We will compare the scatter in absorber equivalent width with impact parameter to see whether the scatter in larger, single sightline studies (i.e., Nielsen et al. 2013) is best explained by variations within halos due to gas structure or by halo to halo variation. *Our rich dataset is uniquely able to characterize the absorption systems' host galaxies' halo structure and to look for environmental effects.* We propose to use Magellan/MIKE and MMT/MAESTRO to look for absorption lines in QSOs due to foreground circumgalactic gas and Magellan/LDSS-3C and MMT/Hectospec to identify the absorber hosts and characterize their environments.

The Sample. We have identified eight lensed QSO systems from CASTLES (Muñoz et al. 1998) in which the QSO image separations, QSO brightnesses, and known foreground galaxies and environments are ideal for probing 23 sightlines through at least 38 galaxy halos. Our unique sample allows us to look for differences in the velocity and ionization structure of foreground Mg II, Mg I, and Fe II on scales $\sim$10 km s^{-1} at two to four physical locations separated by $\sim$5-140 kpc around each field or group galaxy (see Figure 1, left). This study reaches finer gas spatial resolution per galaxy than most and benefits from the statistics of sightlines though many known field and group galaxies. While our technique has already provided valuable results for one system (HE0435; see below and Chen et al. 2014) and we are analyzing data for another (HE2149), we must complete the larger survey to explore the full range of galaxy environments and variations among galaxy halos. Archival Subaru/HDS spectra are available for the QSO images in SDSS J1029. We lack high-quality QSO spectra for the five remaining fields. We have redshifts for 34 of 83 potential absorber galaxies in these eight fields. *We here propose to obtain QSO spectra in the fields PG1115 and Q0957 and to conduct redshift surveys for additional potential absorbers projected within $\sim$ 30$''$ of the lensed systems in the fields Q0957, SDSS J1004, SDSS J1029, WFI2033, and HE2149.*

Results So Far. Our Magellan/MIKE spectra for the four sightlines of QSO HE0435 reveal a high incidence and moderate velocity gradient of Mg II absorbing gas on scales of $\sim$10 kpc at projected distances $\sim$30 kpc from the starforming disk of a foreground galaxy at z = 0.4188 (see Figure 1, right). We compare the absorbers' velocity components and spatial separations to models to constrain the gas distribution. The Mg II absorbers have a velocity gradient between sightlines that is inconsistent with the expected flat rotation curve at these radii for a disk, a deprojected outflow speed ($\sim$100 km s^{-1}) significantly smaller than for a biconical outflow at that height (e.g., Steidel et al. 2010), and 160-180 km s^{-1} velocity widths in the four sightlines consistent with the expected circular velocity of $\sim$170 km s^{-1} for a galaxy at this mass ($\approx 10^{12} M_\odot$) and redshift. Therefore, the Mg II absorption is well explained by infalling gas from the intergalactic medium or tidal streams (Chen et al. 2014). Spatial coherence among the sightlines suggests that the gas follows organized motion. However, in a second foreground galaxy (z = 0.7818), large variations in the mean velocity offsets and widths in sightlines separated by <10 kpc may indicate turbulence and inhomogeneity in the circumgalactic gas (Chen et al. 2014). *These differences between the two foreground galaxies motivate us to explore here the diversity of gas geometries and ionization structure around galaxies in various environments, justifying the larger sample provided by our full eight field survey.*

References: Bergeron, J., & Stasińska, G. 1986, A&A, 169, 1; Bordoloi, R., Lilly, S. J., Knobel, C., et al. 2011, ApJ, 743, 10; Chen, H.-W., Gauthier, J.-R., Sharon, K., et al. 2014, MNRAS, 9; Dekel, A., Birnboim, Y., Engel, G., et al. 2009, Nature, 457, 451; Ellison, S. L., Hennawi, J. F., Martin, C. L., & Sommer-Larsen, J. 2007, MNRAS, 378, 801; Ford, A. B., Davé, R., Oppenheimer, B. D., et al. 2014, MNRAS , 444, 1260; Hamano, S., Kobayashi, N., Kondo, S., et al. 2012, ApJ, 754, 88; Johnson, S. D., Chen, H.-W., & Mulchaey, J. S. 2013, MNRAS, 434, 1765; Keeney, B. A., Stocke, J. T., Rosenberg, J. L., et al. 2013, ApJ, 765, 27; Kereš, D., & Hernquist, L. 2009, ApJ, 700, L1; Martin, C. L., Shapley, A. E., Coil, A. L., et al. 2013, ApJ , 770, 41; Misawa, T., Inada, N., Ohsuga, K., et al. 2013, AJ, 145, 48; Muñoz, J. A., Falco, E. E., Kochanek, C. S., et al. 1998, Ap&SS, 263, 51; Nelson, D., Vogelsberger, M., Genel, S., et al. 2013, MNRAS, 429, 3353; Nielsen, N. M., Churchill, C. W., Kacprzak, G. G., & Murphy, M. T. 2013, ApJ, 776, 114; Shen, S., Madau, P., Aguirre, A., et al. 2012, ApJ , 760, 50; Sijacki, D., Vogelsberger, M., Kereš, D., Springel, V., & Hernquist, L. 2012, MNRAS, 424, 2999; Steidel, C. C., Erb, D. K., Shapley, A. E., et al. 2010, ApJ, 717, 289

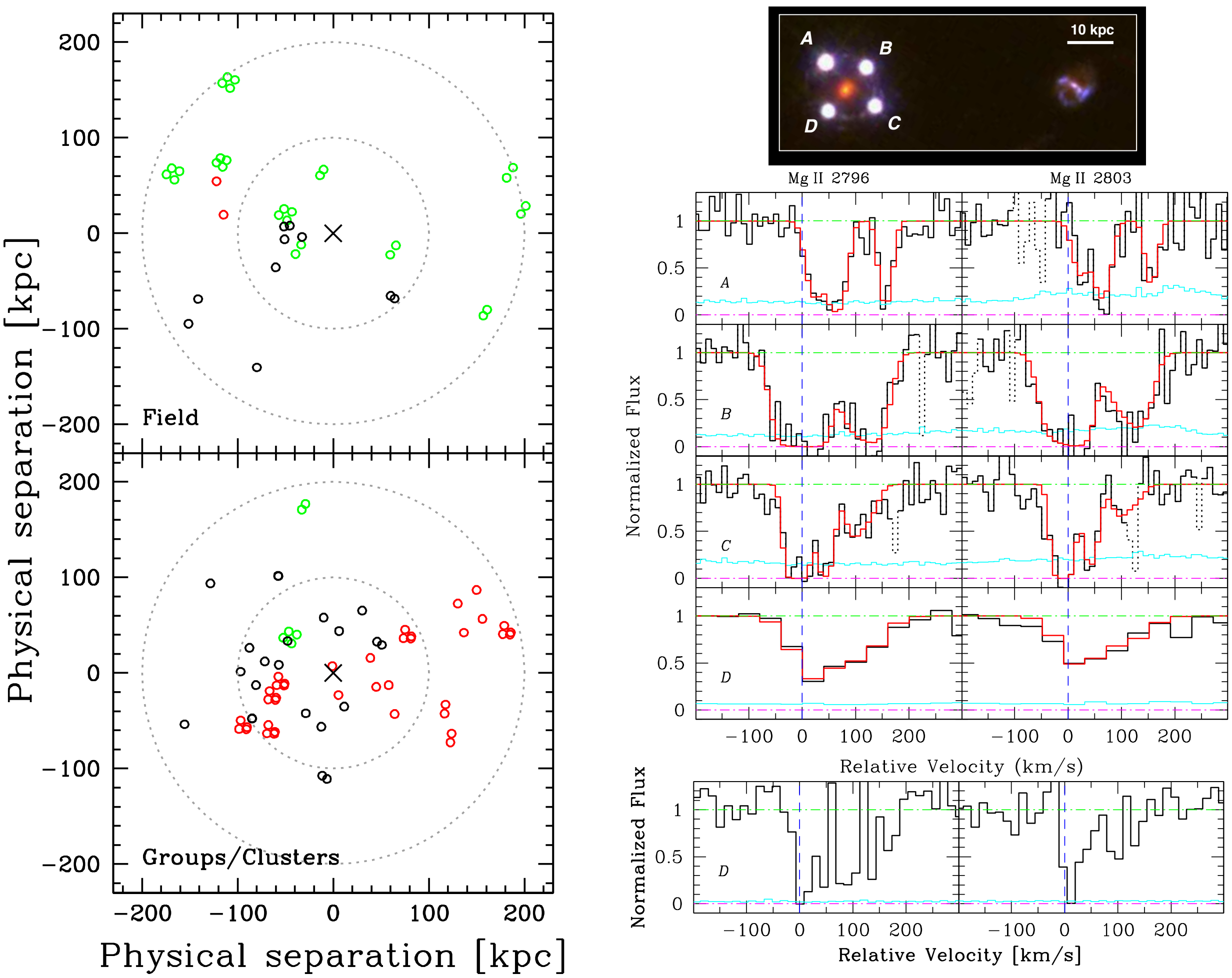

Figure 1: *Left column:* Composite spatial distribution of 23 sightlines probing 38 foreground field (top) and group and cluster (bottom) galaxies in our spectroscopic sample. The crosses mark the center of the composites. The open circles mark the sightlines probed with the QSOs HE0435 and HE2149 (green, which we have observed); SDSS J1004, SDSS J1029, FBQ0951, and WFI2033 (black, which we will observe later or have archival observations for, in the case of SDSS J1029); and Q0957 and PG1115 (red, which we propose to observe here). The dotted circles mark projected distances of 100 and 200 kpc. **The QSO images probe a range of impact parameters for both composites, and their multiple images give us spatial resolution on scales of ∼10 kpc.** We expect to find Mg II at <100 kpc for field galaxies but at up to ∼200 kpc for group and cluster galaxies. These observations will provide new constraints on the halo properties versus galaxy environment. *Right column: Top: HST* image of the HE0435 multiply imaged QSO (left) and a foreground galaxy at z = 0.4188 (right) from Chen et al. (2014). *Middle:* Mg II $\lambda\lambda$ 2796, 2803 Å absorption profiles along four QSO sightlines through this galaxy's halo, also from Chen at al. (2014). Shown are the continuum normalized spectrum (black, with contaminating features dotted out), the error spectrum (cyan), and the best fit model spectrum (red). The spectra for A, B, and C are from Magellan's MIKE spectrograph while that with worse resolution (D), is from Magellan's MagE spectrograph. *Bottom:* Reduction of our October 2013 Magellan/MIKE observations of image D. There are dominant absorption components near the systemic velocity and secondary components to the red in all sightlines with small ($\approx$ 20 km s^{-1}) velocity offsets. **The differences in the absorber velocities between sightlines, when compared to model expectations, suggest inflowing gas streams or tidal material.**

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)***

Halo Gas along the Sightlines of Lensed, Multiply Imaged QSOs. To probe the velocity structure of halo gas at 0.2<z<0.9, we propose here to obtain echelle spectra of lensed QSO images for two systems. These high resolution spectra allow for the possibility of mapping slightly different velocities for an absorber sampled by multiple, closely-spaced, lensed QSO images. The S/N and spectral resolution required for our study are estimated based on a series of Monte Carlo simulations as well as observing experience with QSO HE0435. We find that $S/N \approx 10$ per spectral resolution element of dv $\approx$ 20 km s^{-1} is necessary.

MIKE Observations. MIKE with a 1$''$ slit delivers a spectral resolution of $\approx$ 12 km s^{-1} over 3300 - 5000 Å and is the best instrument available for the proposed study (see Figure 1, right). Experience with HE0435 showed us that three hours of observation using 2x4 (spatial $\times$ spectral) binning results in S/N $\gtrsim$ 10-20 per resolution element at $\lambda \gtrsim$ 3800 Å for an object with F555W = 19.17 (HE0435B). At this pixel resolution, the line spread function is slightly under-sampled, but it will be sufficient to constrain the velocity centroids of individual components on scales of $\sim$10 km s^{-1}. We require three hours per image to observe QSO PG1115 images B and C. Images $A1$ and $A2$ are closely spaced ($\sim 0.''5$), so they will be blended, resulting in effectively one sightline. We require one hour for these two combined images. *We request 8.4 hours, including 20% overhead, (two half nights, due to this object's position) of Magellan/MIKE time to observe three sightlines of QSO PG1115. We know this instrument is capable of these observations, which are needed for M. Wilson's thesis, so we prioritize these MIKE observations over the MAESTRO ones.*

MAESTRO Observations. MAESTRO with a $1.''1$ slit delivers a spectral resolution of 11.7 km s^{-1}, and 2×4 (spatial $\times$ spectral) binning results in an instrument dispersion of 12.8 km s^{-1}, over the wavelength range of 3150 - 9850 Å. The QSO Q0957 has two images ($F555W$ = 17.09 and 17.11) separated by $6.''3$. Since the instrument is still being perfected, the exposure time required for our observations is uncertain. Based on MAESTRO's recent performance, which suggests a throughput 1/4-1/3 of MIKE (R. Green, private communication), we estimate needing four hours for each image of Q0957. Thus, *we ask for 9.6 hours (one night) including 20% overhead of MMT/MAESTRO time to push to the instrument's full capability.*

Identifying the Absorbers with Galaxy Spectroscopy. To identify all possible absorbers, we must measure redshifts for galaxies projected within $\sim$30$''$ of the lensed QSOs. We will utilize the multiplexing capabilities of LDSS-3C and Hectospec to observe additional galaxies to constrain the large-scale structures in which the confirmed absorbers reside, some of which we already know are in groups or clusters. LDSS-3C's VPH All grism delivers 1.89 Å/pixel resolution from 4650-8800 Å, and Hectospec's 270 l/mm grating delivers 1.21 Å/pixel from 3650-9200 Å, which will allow us to measure redshifts of galaxies from 0.2 < z <0.9.

Within 30$''$ of the lensed QSO in WFI2033, there are four galaxies with $I_C < 21.5$ mag (the star-galaxy separation limit for our photometry), for which we need two LDSS-3C masks due to their positions. We have redshifts for most candidate absorbers in HE2149, but we still lack a spectrum for one since all but 80 minutes of our last LDSS-3C run was lost to weather. We require one mask to observe this object; the additional galaxies from this mask will be valuable, since this field has one of the lowest spectroscopic completenesses in our redshift survey. Our Hectospec fields (Q0957, SDSS J1004, and SDSS J1029) are not in our previous redshift survey and so have only a few redshifts available from the literature. SDSS photometric redshifts indicate that there are 37 absorber candidates within $\sim$30$''$ of the lensed QSOs. Hectospec's large multiplexing ability is therefore very useful for these fields, as it allows us to better characterize these absorber candidates' environments, some of which are in the lensing clusters. We need one fiber configuration for each field to observe 11 absorber candidates and $\sim$ 750 additional galaxies. Based on previous experience, we need 120 minutes of integration for galaxies down to $I_C \sim$21.5 mag, $i \sim$22 mag using either instrument (156 minutes with overhead). *We request 7.8 hours (one night) of Magellan/LDSS-3C and 7.8 hours (one night) of MMT/Hectospec to complete the proposed multiplexed spectroscopy of these >750 galaxies.*

These observations, while complementary, can be conducted independently of each other. For all four observing runs, we require dark time because we are observing relatively faint objects at optical wavelengths.

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**)*

Project Scope. Our ultimate goal is to collect high resolution spectra of eight lensed QSO systems (HE0435, Q0957, FBQ0951, SDSS J1004, SDSS J1029, PG1115, HE2149, and WFI2033) to gain a total of 23 sightlines with a spatial resolution of $\sim$ 5-10 kpc through the innermost 200 kpc of at least 38 foreground galaxy halos in groups and the field (see Figure 1, left). This sample is large enough to make the comparison of these two galaxy environments statistically meaningful. With lower resolution spectra, we will obtain redshifts for all the galaxies with $I_C < 21.5$ mag projected within 30$''$ of the lensed QSOs to include other possible absorbers and to better define the confirmed absorber environments.

We were awarded a half night of UAO time in October 2013 to observe image D using Magellan/MIKE. The spectrum is reduced and is being analyzed. In August-September 2014, we were awarded 1.5 nights of Magellan/LDSS-3C time to collect spectra of foreground galaxies in the fields HE0435 and HE2149. However, we lost all but 80 minutes due to weather. Even so, we were able to observe one of our masks for 2/3 as much time we planned, which allowed us to collect spectra sufficient to measure redshifts for the brighter galaxies in the mask. One of those was a galaxy within 30$''$ of the lensed QSO; we have measured a preliminary redshift that corresponds to absorption found in the QSO spectrum.

On non-UAO time, we were allocated one night in Fall 2012 to observe HE0435 with MIKE, but we only obtained spectra for images A-C. We have completed reduction and analysis of these spectra and have published a paper (Chen et al. 2014). We also used some of two non-UAO nights of MIKE time in November 2013 to observe the two images of HE2149 and make additional observations of HE0435; these spectra are being reduced.

We request one night of Magellan/LDSS-3C time to observe the four images (three effective sightlines) of the lensed QSO PG1115, one night MMT/MAESTRO to observe the two images of Q0957, one night of Magellan/LDSS-3C time to collect redshifts for the five absorber candidates in the fields WFI2033 and HE2149 and $\sim$ 45 additional galaxies to further investigate their environments, and one night to collect redshifts of 12 absorber candidates and $\sim$750 galaxies to characterize the absorbers' environments in the fields Q0957, SDSS J1004, and SDSS J1029.

To complete this project, we will need at least 18 more hours of MMT/MAESTRO time to get high resolution spectra of the four images of SDSS J1004 two images of SDSS J1029 and 14 hours of Magellan/MIKE time to get high resolution spectra of the four images of WFI2033. We will also need five hours of Hectospec time to get the remaining redshifts in the fields FBQ0951.

No other telescopes currently are being used for this project.

This project is led by Michelle Wilson and will be a significant component of her thesis. UAO time consists of $\sim$ 80% of the time for this project; the remaining $\sim$ 20% was University of Chicago time used for the observations of HE0435 presented in Figure 1 (right) and the spectroscopy of the QSO images of HE2149.

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)***

PI Wilson: Status of data from Magellan UAO time for this project:

⋆ **October 9 - 11, 2013: Half night of Magellan/MIKE time utilized to observe image D of HE0435. The spectrum is reduced and is being analyzed.**

⋆ **August 30 - September 1, 2014: Lost all but 80 minutes of our 1.5 nights due to weather. However, the one mask we observed for 2/3 the time we needed has produced a preliminary redshift for one of our absorber candidates that matches absorption in the QSO spectrum.**

Co-I Zabludoff: Papers that have been published or are being prepared including data from previous allocations of MMT/Hectospec or Magellan/IMACS/LDSS-3C time for lensing projects:

- **Momcheva, I.G., Williams, K.A., Cool, R.J., Keeton, C.R. & Zabludoff, A.I. 2014, ApJ, A Spectroscopic Survey of the Fields of 28 Strong Gravitational Lenses: The Redshift Catalog, submitted.**
- **Ammons, S.M., Wong, K.C., Zabludoff, A.I., & Keeton, C. R. (2014, ApJ, 781, 2)**
- **Wong, K.C., Keeton, C.R., Williams, K.A., Momcheva, I., & Zabludoff, A.I. (2011, ApJ, 726, 84)**
- **Momcheva, I., Williams, K.A., Keeton, C.R. & Zabludoff, A.I. (2006, ApJ, 641, 169)**

Other lensing publications have resulted from or are related to UAO time:

- **McCully, C., Keeton, C.R., Wong, K.C., & Zabludoff, A.I. 2014, MNRAS, A New Hybrid Framework to Efficiently Model Lines of Sight to Gravitational Lenses, 443, 3631.**
- **French, K.D., Zabludoff, A.I., Wong, K.C., Ammons, S.M., & Keeton, C.R. (2014, ApJ, 785, 59)**
- **Wong, Kenneth C., Zabludoff, Ann I., Ammons, S. Mark, Keeton, Charles R., Hogg, David W., Gonzalez, Anthony H. (2013, ApJ, 769, 52)**
- **Wong, K.C., Ammons, S.M., Keeton, C.R., & Zabludoff, A.I. (2013, ApJ, 767, 97)**
- **Wong, K.C., Ammons, S.M., Keeton, C.R., & Zabludoff, A.I. (2012, ApJ, 752, 104)**
- **Williams, K.A., Momcheva, I., Keeton, C.R., Zabludoff, A.I., & Lehar, J. (2006, ApJ, 646, 85)**
- **Keeton, C.R. & Zabludoff, A.I. 2004, ApJ, 612, 660**

LaTeX 2_ε UAO Observing Proposal class, 'soprop.cls' v1.3 (2007 Aug 01 [RAJ]).

From: **Richard Green** rgreen@email.arizona.edu
Subject: Re: Maestro for 2015A?
Date: September 29, 2014 at 11:20 AM
To: Michelle Wilson mwilson5@email.arizona.edu

Hi Michelle,

Yes, the plan is to offer MAESTRO as shared risk, and I'm happy to give permission (and encouragement!) for your application.

All the best,
Richard

On Sep 26, 2014, at 3:24 PM, Michelle Wilson <mwilson5@email.arizona.edu> wrote:

> Hi Richard,
>
> We're hoping to propose again to use Maestro in 2015A, since our chat the other day sounded like our program should still be possible with it. Will it still be offered under shared risk? If so, may we have permission to apply for it?
>
> Thanks,
> Michelle

Richard Green
Assistant Director for Government Relations
Steward Observatory
University of Arizona
933 N. Cherry
Tucson, AZ 85721-0065
520-626-7088

Thesis Plan: The Environment-Galaxy Connection in a Unique Survey of Gravitational Lens Fields

Michelle Wilson

The Importance of Environment

Groups are the most common environment for galaxies in the universe, but we still do not understand how or to what extent these environments affect galaxy evolution or, conversely, how galaxies affect their environments. By looking for differences in properties of galaxies in varying environments, we can begin to isolate what physics is important for the accretion histories that shape galaxies. Gas structure (clumpiness, whether it is in a rotating gas disk, biconical outflows, or inflowing streams) affects mass flow rates and thus how efficiently metals can escape galaxies or gas can enter to fuel future star formation or AGN; however, gas detection techniques have limited how well structure can be measured. Brightest cluster galaxies have been well studied, and have been found to be uniform in their properties, generally being red, non-star forming elliptical galaxies. However, brightest group galaxies at intermediate redshifts, the most massive objects in the more common group environment, have not been similarly well studied, so we still do not know how these galaxies formed. Environmental effects, such as tidal stripping of gas, or processes governed by host galaxy properties, such as halo mass, might dominate AGN evolution, but so far investigations of such effects have yielded contradictory results.

Our rich dataset makes us uniquely qualified to investigate these issues of galaxy formation. We have collected a large photometric and spectroscopic galaxy sample (9,674 galaxies) with $0 < z < 1$ (80% between 0.1 and 0.7) in 26 strong gravitational lens fields, and we are currently acquiring high resolution spectra of the images of five of the these lensed quasi-stellar objects (QSOs) and three additional lensed QSOs. We are supplementing our redshift catalog with additional redshift observations as well as with additional redshifts from the NASA Extragalactic Database (NED) and the Sloan Digital Sky Survey. Data from NASA missions, such as *WISE, Spitzer*/MIPS, and *HST* further enrich our dataset. We are also creating a galaxy group catalog (~150 groups) with which to characterize these galaxies' environments.

Question 1: How are Gas Inflows and Outflows in Galaxy Halos Affected by Environment?

There are still serious gaps in our knowledge of how gas and metals flow between galaxies and their environs. We know little about how much of the gas is clumped and on what scale. Simulations currently cannot provide direct predictions, as clumps in SPH models are mostly spurious (e.g., Sijacki et al. 2012). Yet there are physical reasons to expect clumpy circumgalactic gas: Kereš & Hernquist (2009) find that cool, ~20 kpc wide filaments moving through hotter, diffuse halo gas fragment on scales of ~5 kpc due to thermal instabilities. Dekel et al. (2009), using SPH, find cool filaments with 20˚-30˚ opening angles, implying ~5-25 kpc widths at impact parameters of 50-100 kpc; AMR simulations produce wider, more diffuse, warmer filaments (Nelson et al. 2013). Progress requires observational constraints on the morphology, kinematics, and metallicity and ionization structure of circumgalactic gas on 10s of kpc scales, measurements that would inform simulations and vastly improve our understanding of galaxy evolution and the circumgalactic medium.

The complex connection of gas flows and the circumgalactic medium is tied also to the intergalactic medium on even bigger scales (100s of kpc). Most galaxies reside in groups, which may also have gaseous halos. Some previous work finds that group galaxy Mg II absorption is consistent with the superposition of individual field galaxy halos (Bordoloi et al. 2011). Yet others find evidence for group halo gas in O VI absorption (Johnson et al. 2013). Understanding complex gas flows requires resolving spatial and velocity differences on galactic scales (~10 kpc), and at circum- and intergalactic distances (10s to 100s of kpc), for groups and in the field.

The Problem. Absorption lines in QSO spectra have constrained the metallicity and velocity of gas projected ~100 kpc from galaxies, and emission line measurements have detected galaxy-scale outflows. However, fine-scale structure in this gas remains unexplored due to the lack of spatially resolved kinematics on scales of ~10 kpc at radii from 10s to 100s of kpc.

One common tracer of cool, T ~ 10^4 K gas in and around galaxies is the Mg II 2796, 2803 Å absorption doublet. This feature is seen routinely in QSO spectra and traces H I clouds with N(H I) ≈ 10^{18} - 10^{22} cm^{-2} (Bergeron & Stasńska 1986). Only gas at one radius from the galaxy's center can be measured for most galaxies, as it is unlikely for several QSOs to be projected near each other. Interpreting absorption measurements has proved impossible due to generally having only one QSO sightline to probe the gas in each halo (see, though, Keeney et al. 2013, who use three separate QSOs to probe one low-redshift galaxy). Others have explored using multiple sightlines of lensed QSOs (i.e., Ellison et al. 2007), but not to constrain z<1 halo gas structure.

The Solution. We propose to use multiple sightlines of gravitationally lensed QSOs (i.e., Figure 1) to resolve the morphology, kinematics, and metallicity and ionization structure of circumgalactic gas of galaxies in groups and the field on unprecedented scales. When stacked into composite group and field galaxy halos to probe environmental differences, these sightlines will provide comprehensive radial coverage over 50-200 kpc with resolutions down to <10 kpc and <10 km s^{-1} (see Figure 2, left). We have already used morphologies and galaxy orientations measured from archival *HST* images (see Figure 1) to compare velocity gradients of absorption components among close sightlines to theoretical gas distributions to constrain the detailed halo gas structure (Chen et al. 2014). We also are employing Mg I 2852 Å and Fe II 2382 Å absorption to determine the ionization fraction in each sightline and the alpha abundance [Mg/Fe] to determine the metallicity structure. We will compare the scatter in absorber equivalent width with impact parameter to see whether the scatter in larger, single sightline studies (i.e., Nielsen et al. 2013) is best explained by variations within halos due to gas structure or by halo to halo variation. *Our rich dataset is uniquely able to characterize the absorption systems' host galaxies' halo structure and to look for environmental effects.*

The Sample. We have identified eight lensed QSO systems from CASTLES (Muñoz et al. 1998) in which the QSO image separations, QSO brightnesses, and known foreground galaxies and environments are ideal for probing 23 sightlines through at least 38 galaxy halos. Our unique sample allows us to look for differences in the velocity and ionization structure of foreground Mg II, Mg I, and Fe II on scales ~10 km s^{-1} at two to four physical locations separated by ~5-140 kpc around galaxies in the field and in groups (see Figure 2, left). This study reaches finer gas spatial resolution than most. While our technique has already provided valuable results for one system (HE0435; see below and Chen et al. 2014) and we are analyzing data for another (HE2149), we must complete the larger survey to explore the full range of galaxy environments and variations among galaxy halos. We have three more fields with lensed multiply-imaged QSOs (Q0957, SDSS J1004, and SDSS J1029) and with some preliminary data from the literature.

Results So Far. Our Magellan/MIKE spectra for the four sightlines of QSO HE0435 reveal a high incidence and moderate velocity gradient of Mg II absorbing gas on scales of ~10 kpc at projected distances ~30 kpc from the starforming disk of a foreground galaxy at z = 0.4188 (see Figure 2, right). We compare the absorbers' velocity components and spatial separations to models to constrain the gas distribution. The Mg II absorbers have a velocity gradient between sightlines that is inconsistent with the expected flat rotation curve at these radii for a disk, a deprojected outflow speed (~100 km s^{-1}) significantly smaller than for a biconical outflow at that height (e.g., Steidel et al. 2010), and 160-180 km s^{-1} velocity widths in the four sightlines consistent with the expected circular velocity of ~170 km s^{-1} for a galaxy at this mass (~ 10^{12} $M_{\odot}$) and redshift. Therefore, the Mg II absorption is well explained by infalling gas from the intergalactic medium or tidal streams (Chen et al. 2014). Spatial coherence among the sightlines suggests that the gas follows organized motion. However, in a second foreground galaxy (z = 0.7818), large variations in the mean velocity offsets and widths in sightlines separated by <10 kpc may indicate turbulence and inhomogeneity in the circumgalactic gas (Chen et al. 2014). *These differences between the two foreground galaxies motivate us to explore here the diversity of gas geometries and ionization structure around galaxies in various environments, justifying the larger sample provided by our full eight field survey.*

Question 2: How did Brightest Group Galaxies Form?

Locally, brightest cluster galaxies are red, devoid of star formation, and have similar properties across all dense environments. Their photometric properties are quite uniform (i.e., Postman & Lauer 1995) and show color evolution similar to an old, single burst stellar population (i.e., Whiley et al. 2008). Spectroscopically, brightest cluster galaxies are mostly quiescent, although some have emission lines ascribed to cooling flow fueled star formation (i.e., Crawford et al. 1999). Brightest group galaxies at intermediate redshifts, the most massive objects in the more common group environment, have not been similarly well studied. Studying brightest group galaxies over a range of redshifts can provide insight into the processes that drive their formation and evolution. For example, if these galaxies grew mainly through cooling flow accretion, they should be at rest at the center of their group, whereas if they formed through mergers, they should form on similar orbits to other group galaxies and settle over time into the group centers. Properties such as their morphologies and spectroscopic characteristics could indicate current or recent star formation, as well.

The Problem. The color, spectroscopic properties, and morphological properties of brightest group galaxies have begun to be studied, but how they formed is still unclear. Zabludoff & Mulchaey (1998) found that local brightest group galaxies are consistent with the spatial and kinematic centers within observational errors, suggesting that they formed in the center of their groups. At some redshift, however, these galaxies might have properties that can distinguish between central formation and migration, and they might not yet have become dominant. They could exhibit offsets from the group potential if they did not form there, have signs of recent star formation, or have stellar masses comparable to other group galaxies. Both Mulchaey et al. (2006), who studied a sample of nine X-ray groups at z ~ 0.23 - 0.59, and Jeltema et al. (2007), in their followup sample of seven of the nine, found that not all of their brightest group galaxies are in the center of the X-ray emission, suggesting that a range of brightest group galaxy formation stages could be present at intermediate redshifts. However, the properties of large samples of brightest group galaxies (or their kinematics in any sample size) have not been studied at these redshifts, leaving a blank in our understanding of them potentially when they were young enough to have traces of their formation.

The Solution. We propose to study the kinematic and physical properties of brightest group galaxies at intermediate redshifts. Their kinematics within their groups could reveal where brightest group galaxies are in the group gravitational potential as a function of time, which in turn could constrain how they could have accumulated their relatively large masses.We will calculate their projected physical separation and velocity offset from the center of the group potential, as measured by the other group galaxies, and compare the composite brightest group galaxy distribution to what we would expect if they were all intrinsically at rest in the center of the potentials and were observed with measurement uncertainties. We will see if all our brightest group galaxies are red, non-star forming ellipticals like brightest cluster galaxies or if they show spiral features, emission lines, or strong Balmer absorption indicative of ongoing or recent star formation. Their colors can also be used to infer possible star formation histories. We will compare their colors with what we would expect for old single stellar populations to see if they are consistent with this formation mechanism or if a color offset or large scatter suggests more extended, later, or variable star formation histories.

Results So Far. Preliminary results have indicated that while the majority of brightest group galaxies are red, dead, elliptical galaxies, some are disks, and some are undergoing star formation or have young stellar populations, indicating diversity in star formation histories. The non-star forming brightest group galaxies are well described by an old, single burst stellar population. Brightest group galaxies, on average, are not consistent with being at rest in the center of the group gravitational potential within uncertainties, suggesting that significant growth through central accretion is unlikely (see Figure 2). These results support brightest group galaxies forming mainly through the mergers of old stellar populations, although some have had more recent star formation. However, we must perform the analysis with our final group catalog.

Question 3: Do Environmental Effects on Gas Inflows Affect AGN Evolution?

How environment affects AGN is not well understood. Do environmental effects, such as tidal stripping of gas, dominate AGN evolution, or is it most influenced by processes governed by host galaxy properties, such as halo mass? Such dependencies are important, since AGN feedback could affect gas in the host and its surroundings and thus limit gas supplies for further star formation. Environmental dependencies on the fraction of AGN host galaxies and their spatial distribution within groups can determine if environmental processes are important quenching mechanisms. If they are, the AGN fraction would be smaller in groups than in the field. If AGN are found in the outskirts of groups, interactions with the group as the galaxies fall in might be driving their nuclear activity, whereas if the AGN are evenly distributed, other processes likely dominate. Since host galaxy mass might also affect the likelihood of AGN presence, being able to control for these properties using multivariate analysis is critical.

The Problem. What governs AGN evolution is a persistently puzzling question. Environmental effects have been considered, and evidence both for and against these having an effect have been found (i.e. Martini, Mulchaey & Kelson 2007; Pentericci et al. 2013). However, previous group samples often are small (i.e., < 20 structures, Pentericci et al. 2013) and use X-ray AGN selection criteria, which could miss obscured AGN.

The Solution. We will investigate AGN fraction in groups and the field to test whether environmental interactions, such as mergers and various gas stripping mechanisms, dominate AGN evolution. We will also look at AGN position within their groups to see if they are smoothly distributed or concentrated in either the center or outskirts of their groups.

The Sample. Our large sample provides several improvements over previous group samples at z < 1. It covers a substantial redshift range without combining several redshift catalogs, as has some previous work (i.e., Pentericci et al. 2013), and is significantly larger (~ 150 groups instead of ~ 20). While we will have to consider variations in completeness and sensitivity with redshift, we will apply our analysis in a comprehensive manner. The available infrared data from NASA's *WISE* and *Spitzer* will allow us to select dust obscured AGN that would have been missed in an X-ray selected sample. In addition, our optical spectra and archival X-ray data will be used to test which AGN would be selected using other common selection methods. Our extensive supporting data will also allow us to perform a multivariate analysis to control for host galaxy properties, such as mass (calculated using *WISE* data), that might also be dominating AGN evolution. Thus, we are well-positioned to weigh in on the question of whether host galaxy environment or halo mass is more important for AGN evolution.

Summary

Using our unique photometric and spectroscopic sample of galaxies in fields of strong gravitational lenses and the group catalog we are developing, we will investigate how environment affects galaxy accretion histories in three interrelated ways. We will probe circumgalactic gas to study the gas distributions around individual galaxies and environmental differences, explore the physical and kinematic properties of brightest group galaxies to test possible formation mechanisms, and examine environmental effects on AGN using multivariate analysis.

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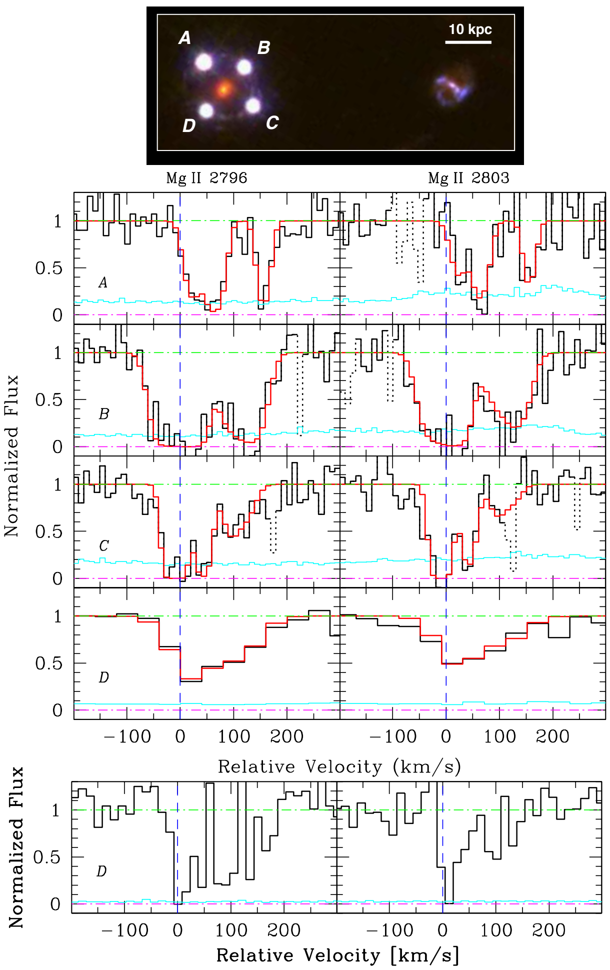

Figure 1: From Chen et al. (2014). Top: *HST* image of the HE0435 multiply imaged QSO (left) and a foreground galaxy at z = 0.4188 (right). Middle: Mg II λλ 2796, 2803 Å absorption profiles from Magellan along four different sightlines through this galaxy's halo. Shown are the continuum normalized spectrum (black, with contaminating features dotted out), the error spectrum (cyan), and the best fit model spectrum (red). The spectra for A, B, and C are from Magellan's MIKE spectrograph, while that with worse resolution (D), is from Magellan's MagE spectrograph. Bottom: Reduction of our October 2013 Magellan/MIKE observations of image D. There are dominant absorption components near the systemic velocity and secondary components to the red in all sightlines with small (~ 20 km s^{-1}) velocity offsets. The differences in the absorber velocities between sightlines, when compared to model expectations, suggest inflowing gas streams or tidal material.

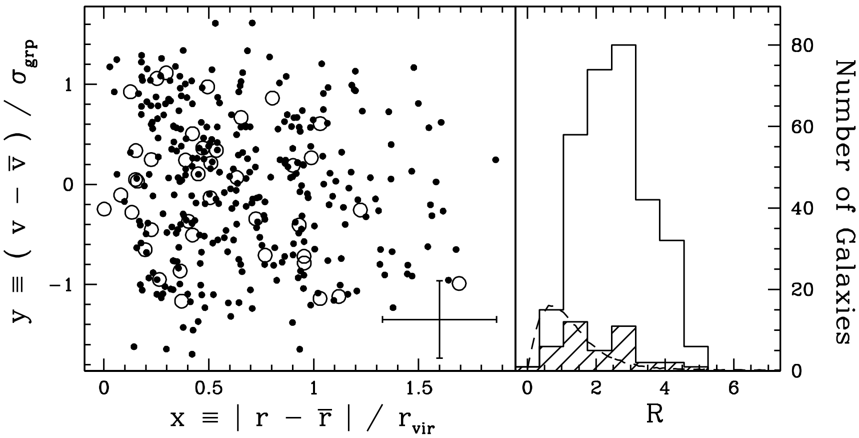

Figure 2: Left: Normalized spatial (x) and kinematic (y) offsets for brightest group galaxies (open points) and other group galaxies (filled points) from the center of the group gravitational potential for our preliminary group sample (40 groups). Error bars in the lower right represent the median 1-σ uncertainties propagated from the measurement errors. Right: R distributions, where R is a combination of the spatial and kinematic offsets of a galaxy from the center of the group potential, for the brightest group galaxies (shaded histogram), other group galaxies (open histogram), and what we would expect if brightest group galaxies were intrinsically at rest in the center of their group potentials (had R = 0) but were observed with measurement uncertainties (dashed curve). The brightest group galaxies are not consistent with being intrinsically in the center of the potential within measurement errors, indicating that major growth through central accretion is unlikely. However, brightest group galaxies are more centralized in the group potential than general group galaxies, so brightest group galaxies might have formed through a merger of normal group galaxies and then have migrated towards the center of the potential.

Project Timeline
Michelle Wilson

Fall 2014
- Finalize group catalog
- Finish and submit group catalog paper
- Perform brightest group galaxy analysis using new group catalog
- Apply for ground based observations of additional QSO sightlines and foreground absorber candidates for absorption line study

Spring 2015
- Finish and submit brightest group galaxy paper
- Analyze resolved gas kinematics, ionization fraction, and [Mg/Fe] of foreground absorbers in HE0435 field
- Analyze QSO and foreground absorbers in HE2149 field and any QSO spectra collected in December 2014.
- Apply for ground based observations of additional QSO sightlines and foreground absorber candidates for absorption line study

Summer 2015
- Submit resolved gas kinematics, ionization fraction, and [Mg/Fe] of foreground absorbers in HE0435 field paper
- Finalize galaxy spectrum fitting
- Determine AGN selection method best for sample and perform the selection
- Analyze environmental dependence on AGN

Fall 2015
- Submit environmental dependence on AGN paper
- Analyze any QSO spectra or foreground absorber candidates collected in spring 2015
- Go on a talk tour to promote these projects
- Analyze full QSO absorption line sample
- Apply for ground-based observations of additional QSO sightlines for absorption line study

Spring 2016
- Finish analysis of full QSO absorption line sample and write paper
- Submit QSO absorption line study paper

Graduate with Ph.D