OBSERVING REQUEST
University of Arizona Observatories

Year: 2015 **Term:** Aug–Dec **Proposal type:** short-term

The first systematic search for protoclusters at z>3 to study galaxy evolution in dense environments

P.I.: Christina C. Williams (SO; *ccwilliams@email.arizona.edu*;)

CoI(s): Kyoung-Soo Lee (Purdue University), Arjun Dey (NOAO),
Mauro Giavalisco (University of Massachusetts-Amherst), Rui Xue (Purdue University),
Ke Shi⋆ (Purdue University)

Abstract of Scientific Justification

In the theory of hierarchical structure formation, high-density regions are the sites of earliest galaxy formation and give rise to massive galaxy clusters in the local Universe. Early protoclusters therefore represent an important window into the physics of how environmental processes affect the evolution of galaxies. However, dense structures are rare, and current samples of protoclusters at z>3 are insufficiently small to gain a comprehensive understanding of how environment affects galaxies at early times. We propose a wide-field ($\sim$1 deg^2) spectroscopic survey with MMT/Hectospec to measure redshifts for $\sim$1500 Lyman-break galaxies at z$\sim$3-4. We will primarily target galaxy overdensities to spectroscopically confirm a large sample of protoclusters via detecting Lyman alpha line-emitting galaxies. We will also target rare, massive and luminous field galaxies at the same cosmic epoch. The proposed observations will allow detailed studies of the spectroscopic properties (Lyman alpha and interstellar absorption features) for galaxies in a wide range of local environments, thereby quantifying how galaxy formation and evolution has proceeded in different environments. This unique dataset will provide critical information on the evolution of both cluster galaxies and massive field galaxies, allow a detailed comparison of the physical conditions in galaxies in different environments, and finally allow efficient selection of protoclusters in the future surveys.

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	f/5	Hectospec			3	dark	Oct–Nov	Sept–Dec	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	CFHTLS - Deep Field 1	02:25:59	-04:29:40	$\sim$1500 LBGs at z$\sim$3-4 (i_{AB} <26.3)

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

In the present-day Universe, galaxy clusters serve as the main laboratories to study galaxy formation and cosmology. In the hierarchical theory of galaxy formation, these high-density regions are the sites of the earliest galaxy formation. Indeed, recent evidence suggests that high-redshift galaxies in dense environments experience an accelerated path in their evolution (e.g., Steidel+05, Koyama+13). Stellar population studies suggest that they completed their star formation at z>3, and have evolved passively since then (Thomas+05). Observational evidence from known protoclusters at high-redshift support this scenario, as they are found to contain a larger number of massive galaxies as well as bright, high star-formation rate galaxies relative to the field population; there is also evidence that some galaxies are being quenched as early as z$\sim$3 (Lemaux+14). Hence, it appears that the same massive halos also mark the earliest sites of quenching.

Nevertheless, little is known about the early stages of cluster formation, when the members of massive clusters assembled their masses, and subsequently quenched their star-formation. The main limitation to studying their evolution has been the fact that the often-used techniques to identify z$\sim$0-2 clusters, such as extended X-ray emission and the galaxy red sequence (e.g. Papovich+09, Gobat+11, Strazzullo+13) do not apply in the early stages of cluster formation, when systems were not yet virialized, and cluster members were still actively forming their stellar mass. As a result, the currently known protoclusters are not only small in number, but also a heterogeneous mix; some are found serendipitously from blind spectroscopic followup within a handful of deep surveys (e.g., Steidel+98, 2005, Daddi+09, Lemaux+14, Toshikawa+12, Yuan+14), while others are discovered as a result of targeted searches around extremely energetic sources such as quasars or radio galaxies (Venemans+07, Miley+04, Palunas+04, Prescott+08). While some of these sources indeed show a high level of galaxy overdensities nearby, such phenomena are generally thought to be short-lived and therefore a large fraction of high-redshift protoclusters may not be in proximity of such sources. There is some evidence suggesting that these extreme sources greatly influence galaxy formation in their vicinity (e.g., Kashikawa+07), and our lack of knowledge on the physical association and the influence of extreme sources on adjacent galaxies may introduce unknown biases to the study of galaxy formation in protocluster environments.

From several deep photometric/spectrsocopic surveys, some protoclusters are identified as galaxy overdensities (Shimasaku+03, Matsuda+05, Ouchi+05), the hallmark of galaxy clusters expected from hierarchical structure formation, and thus are likely representative of the protocluster population. Unfortunately, these deep surveys typically cover between 0.1-1 deg^2, thus sampling an inadequately small volume to find a statistical sample of protoclusters. Small sample size is not only a direct result of the lack of observational signature of protoclusters but is also due to the lack of systematic effort to search for likely candidates. In order to significantly improve our understanding of the early phase of cluster formation, as well as the early evolution of massive cluster members, we need a large representative sample of uniformly selected protoclusters, with spectroscopically confirmed member galaxies.

We propose to carry out the first systematic search for z$\sim 3-4$ protoclusters in an unprecedentedly large cosmic volume. We will target Lyman-break galaxies (LBG) selected in three fields from the Canada France Hawaii Telescope Legacy Survey (CFHTLS; $\sim$3 deg^2 total area). We propose here to begin in 2015B with the Deep 1 (D1) field, a 1 deg^2 area in which we have identified protocluster candidates from overdensities in LBGs (Fig. 1). Using Hectospec on the 6.5-m MMT, we will conduct a spectroscopic survey to confirm redshifts of a large sample of LBGs (u- and g-dropouts at z$\sim$3 and 4, respectively; Lee+11, Hildebrandt+09) via their Lyα emission. Our protocluster search strategy is based on a pilot study of LBGs with Hectospec which resulted in two protoclusters at z=3.78 and z=3.55 (Fig. 2; Lee+14, Dey+15, Xue+in prep.) and revealed that the members of forming clusters show intriguing characteristics that are different from their field counterparts; namely that *i) protoclusters have cores with a high concentration of strong Lyα-emitting members; ii) LAEs trace the same large-scale structure traced by other galaxies.* These characteristics can potentially enable a systematic search for high-redshift protoclusters, in which candidates are identified as overdensities in color-selected galaxies, and spectroscopically confirmed from their Lyα emission. Additionally, we will use the Hectospec spectroscopy to carry out detailed investigations on the physical properties of the member galaxies in direct comparison with rare, massive and luminous (L_{UV} >L*) galaxies in the field, thereby quantifying how galaxy formation has proceeded in different environments, as outlined below.

Protocluster science and the evolution of massive galaxies

1) *We will identify statistically significant samples of protoclusters and characterize their selection function.* This sample will enable the first detailed study of early cluster formation at the peak formation epoch of the member galaxies through the analysis of their spectroscopy and modeling of their stellar populations. The characterization of our selection strategy is essential to calibrating the selection of protoclusters from future large-area surveys (e.g. LSST).

2) *We will identify statistically significant samples of rare, massive and rapidly star-forming field galaxies.* Deep surveys continue to reveal evidence that the most massive field galaxies ($\log M^* \gtrsim 10.5$), like cluster galaxies, also experience an accelerated evolution, forming stars rapidly at high-redshift (Lee+13, Dey+15) and likely also quenching their star-formation early in cosmic time (e.g. Franx+03, Daddi+05, Cimatti+08). How the early evolution and quenching of these massive, highly-star-forming field galaxies compares to that of high-redshift galaxies in dense environments, is a critical comparison for our understanding of galaxy evolution. Our proposed wide-area survey will be ideal for amassing large spectroscopic samples of these rare galaxies both within protoclusters and in the field. We further elaborate in the science goals below.

3) *We will unambiguously determine how Lyα luminosities and equivalent widths change as a function of cluster-centric distance, as well as over a wide dynamic range in local density; from cluster core, filaments, to voids.* It is still unclear why denser environments change the physical properties of galaxies, and a complete understanding of the relevant physics is crucial to our theories of galaxy evolution. The physical mechanism behind the enhanced Lyα-emitting population in protoclusters is unclear (Lee+14, Dey+15). One possibility is that the matter (and galaxy) overdensity leads to a higher normalization of the luminosity function, i.e., there are simply more luminous galaxies in protoclusters than in the field. Another possibility is that galaxy formation in the protocluster core is somehow more efficient than in the field. A lower covering fraction of neutral hydrogen surrounding galaxies in denser environments may also be a plausible explanation. Data from multiple protoclusters are critically needed to address these questions by refining these measurements.

4) *We will study how the diagnostics of conditions in the ISM vary as a function of environment.* Extensive study of galaxies in field environments have determined that the presence and strength of Lyα emission is correlated with other galaxy properties (low stellar mass, small dust contents, compact morphologies, and weak interstellar absorption lines; Shapley+03, Jones+12, Lee+13). Energetic forms of feedback may facilitate the escape of Lyα in special cases such as compact starbursts (Williams+15), however in the population as a whole, outflow velocity in the ISM of LBGs tends to be anti-correlated with the strength of Lyα (e.g. Shapley+03). It appears contradictory that LAEs overall tend to be low mass, while galaxies residing in massive halos such as protoclusters have enhanced fractions of LAEs. Environment may therefore be another parameter determining Lyα emission in galaxies, a factor which has previously not been explored. Studying a large sample of Lya-emitting galaxies in field and protocluster environments may help understand this. For the brightest cases, our Hectospec observations will likely detect continuum and interstellar absorption lines (Fig. 2). For fainter galaxies, stacked spectra will yield high S/N composites which can be used to study both Lyα and ISM absorption in bins of mass, UV luminosity, dust reddening, and now, environment. The stacks may also reveal significant detections of HeII, CIV or CIII] emission if present, where the latter has been shown to correlate significantly with the presence of Lyα (Shapley+03, Stark+14).

This unique dataset will provide critical information on the evolution of both cluster galaxies and massive field galaxies, allow a detailed comparison of the physical conditions in galaxies in different environments, and finally allow efficient selection of protoclusters in future surveys.

References Daddi+2009 ApJ 694 • Gobat+2011 A&A 526 • Hildebrandt+2009 A&A 498 • Hong+2014 PASP 126 • Jones+2012 ApJ 751• Kashikawa+2007 ApJ 663 • Koyama+2013 • Lee+2014 ApJ 796 • Lee+2013 ApJ 771 • Lee+2011 ApJ 733 • Lemaux+2014 A&A 572 • Matsuda+2005 ApJ 634 • Miley+2004 Nature 427 • Ouchi+2005 ApJ 635 • Palunas+2004 ApJ 602 • Papovich+2010 ApJ 716 • Prescott+2008 ApJ 678 • Shapley+2003 • Shimasaku+2003 ApJ 586 • Stark+2010 • Stark+2014 MNRAS 445 • Steidel+1998 • Steidel+2005 ApJ 626 • Strazzullo+2013 ApJ 722 • Thomas+2005 ApJ 621 • Toshikawa+2012 ApJ 750 • Venemans+2007 A&A 461 • Williams+2015 ApJ 800

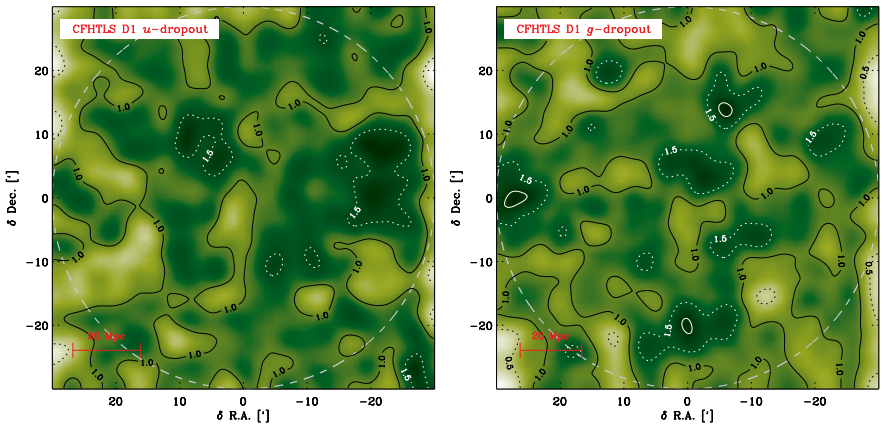

Figure 1: Smoothed density maps of LBGs in D1; u-dropouts at z∼3 (left) and g-dropouts at z∼4 (right). White circle indicates Hectospec FOV. Regions with enhanced surface density of galaxies (green shades) are outlined by white dashed contours. This density map will be used in combination with the Hectospec observations to identify the sites of the most massive protoclusters.

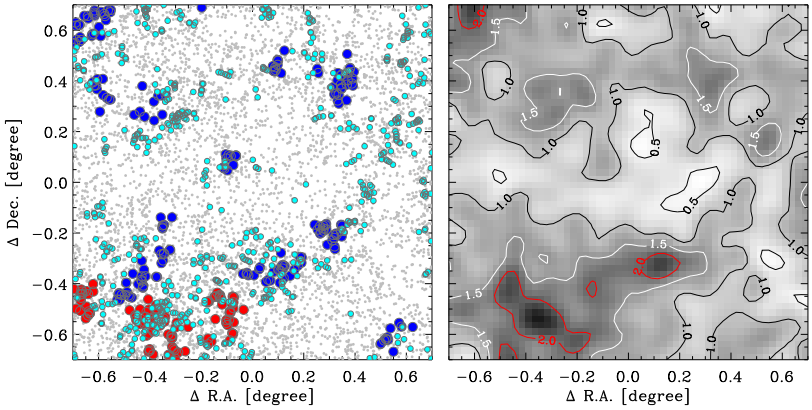

Figure 2: Left: Distribution of protocluster members with i_{AB}<26 from simulations. Members of $>10^{15}M_\odot$ protoclusters are in red, (3-10)x10^{14} $M_\odot$ in blue, (1-3)x10^{14} $M_\odot$ in cyan. Grey points are field galaxies not associated with these structures. Right: Smoothed density map of all galaxies in the same simulated field. It is clear that the largest structures stand out in the density map. This demonstrates that our procedure will be an efficient way to find protoclusters.

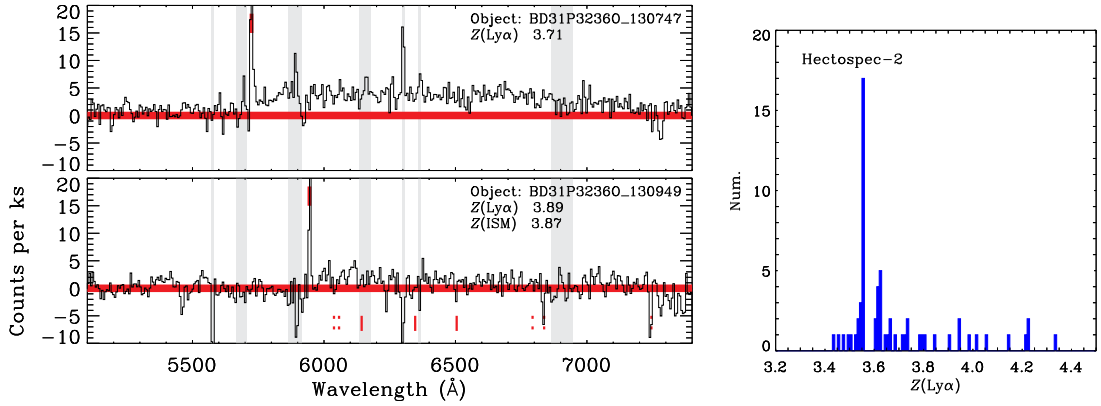

Figure 3: Sample Hectospec spectra from our pilot program (PI: Dey). Most galaxies showed Lyα emission except for <20 UV-luminous galaxies detected with clear continuum. Grey columns mark sky lines, red vertical lines mark emission/absorption line features identified in the spectra. Many show low level absorption features which can corroborate Lyα identification. Right: Redshift histogram for one Hectospec pointing from our pilot program. One field contains a clear redshift spike at z = 3.55, demonstrating that the proposed method will be extremely effective in identifying protoclusters.

Experimental Design & Technical Description

The main goal of this proposal is to build a large *spectroscopic* sample of galaxies, including both those in dense protocluster environments, and also the most massive star-forming galaxies in the field. Both populations have eluded detailed investigations due to their extremely low space densities. The proposed program is designed to efficiently identify both targets, thereby enabling detailed investigations on the stellar population properties of these galaxies. By comparing with those of field galaxies, we will determine how galaxy formation proceeded in different environments (defined as galaxy overdensity or halo mass).

Field for 2015B: For semester 2015B we are proposing to observe the CFHTLS D1 field, and plan to expand our spectroscopic survey with future proposals for the D2 and D3 fields (total area $\sim$3 deg^2). All CFHTLS fields have deep imaging ($ugriz$). The D1 field is the only CFHTLS Deep field observable in a B semester from the northern hemisphere. D1 is the target of two of the largest spectroscopic surveys, namely, the VLT VMOS Deep Survey fields and VIMOS Ultra Deep Survey (PI: Le Fevre), and has a dedicated deep near-infrared survey (WIRCAM Deep Survey: Bielby+12). We have access to the existing spectroscopy, which are used to calibrate the photometric selection of LBGs.

Sample/Targets: Within the 1$\sim$deg^2 D1 field, we have identified 11,065 $z \sim 3$ galaxies, 5,208 $z \sim 4$ galaxies selected as Lyman-break galaxies. The Lyman break technique isolates galaxies in the predetermined range of redshift by measuring colors produced by the Lyman limit (912Å) and Lyα forest (Steidel & Hamilton 1996). The CFHTLS Deep survey imaging is deep enough for us to select galaxies at $i \approx 26.3$ AB, sampling 1.5 mag below the characteristic luminosity at these redshifts. Assuming a typical LBG redshift selection function of $\Delta z = \pm 0.3$, the volume sampled by these galaxies is 7.9 (7.4) $\times 10^6$ (Mpc)^3 comoving at $z \sim 3$ (4). This volume is large enough to contain multiple massive protoclusters (scaling from the space density of local clusters) as demonstrated in Fig. 2.

Search Method: Our targets consist of (1) LBG candidates within protocluster regions; and (2) candidates for very massive, luminous LBGs, both in the field and in the protoclusters. Our protocluster targets are galaxies residing in regions of enhanced (surface) overdensities, $\Sigma \geq 1.5\bar{\Sigma}$ (50% or more overdense than the average), consisting of ≈ 800 galaxies (Fig. 1). Independently, we identified candidates for galaxies already massive at $z \sim$ 3-4. The candidates are a subset of our parent LBG sample with $K_S < 23$ corresponding to $M_{\rm star} \geq (1.5 - 2.5) \times 10^{10} M_\odot$ at this redshift assuming a realistic range of other parameters (age, metallicities, extinction). The latter targets consist of 447 galaxies.

Proposed Observations and Need for Hectospec: Hectospec's multiplexing capability and large FOV (1 deg diameter) are well matched to efficiently follow up a large number of our targets. Each pointing will allow us to observe up to 200 $i < 25$ galaxies as primary targets and additional 20-50 fainter galaxies as secondary targets. We will place the remaining fibers on blank sky for robust sky subtraction. Six Hectospec pointing will result in spectra for 1200 primary targets and 100-300 secondary targets. The actual success rate will sensitively depend on Lyα-emitting fraction of protocluster galaxies (one of the main science goals of this proposal) and that of low-luminosity secondary targets. For the latter, recent studies suggest that low-luminosity galaxies are more efficient Lyα emitters (Stark+11). Our pilot program in 2012 demonstrated the efficiency of using Hectospec for detection of Lyα emission in high-redshift galaxies (Hong+14, Dey+15). Conservatively assuming a 30% success rate, we will determine a total of 400-450 redshifts.

Exposure Time and Time Request: We will use Hectospec with 2700 l/mm grating to cover the spectral range of 3650-9200Å. The LBGs are likely to have their breaks and spectral lines in the blue (<5577Å) and therefore sky subtraction is not the limiting factor. Considering the large number of targets and the fact that Hectospec fibers cannot be closer than 20$''$ at a given time, we request 6 independent configurations of 4 hours each (each split into four 1-hour exposures). This will be particularly helpful for observing galaxies in protocluster candidate sites. We have demonstrated this is possible with our pilot program (Hong+ 14, Xue+, in prep), where we were able to measure redshifts with Hectospec for galaxies brighter than $I \approx 24.7$ AB. Including time estimates for the additional overhead including pointing, fiber positioning/realignment, and zenith passage of the field (1 hour/night), we can observe 2 configurations per night. We request a total of three nights for this project. Since the success of this program depends on measuring redshifts of faint galaxies with emission lines near 4600-5800Å, we request dark time no more than 4 days from new moon.

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**)*

In the current semester (2015B) we are requesting three nights to observe in the 1$\sim$deg^2 CFHTLS D1 field. In future semesters we plan to propose for two more fields of similar size (CFHTLS D2 and D3) in a similar configuration on Hectospec through Steward in the following semester(s), and so we estimate that in total, the project will require nine nights on the MMT to complete.

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**)*

⋆ This project has not made use of UAO telescope allocation in the last two years.

⋆ The pilot study mentioned in this proposal was the result of an accepted proposal through UAO in the May-July semester of 2012 (PI: A. Dey), which used Hectospec to study rare ultra-luminous B*w*-dropouts at z∼3.7 in the NOAO Deep Wide Field Survey Bootes field. The survey was successful and the results, which included the identification of two new protoclusters at z=3.78 and z=3.55, are published in Lee et al. 2014, Hong et al. 2014, Dey et al. 2015, Xue et al. (in prep).

The PI has an accepted program for a different project through UAO with LUCI/LBT from semester 2015A, and the first data for this program is scheduled to be taken on April 6, 2015.