**OBSERVING REQUEST**
**University of Arizona Observatories**

**Year:** **Term:** – **Proposal type:** short-term

# The GOGREEN Survey of dense galaxy environments at 1<z<1.5

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**Abstract of Scientific Justification**

The GOGREEN survey is designed to monumentally advance our understanding of how environment influences galaxy evolution. GOGREEN studies 21 galaxy clusters in the redshift range 1<z<1.5, selected to be the progenitors of today's massive clusters. The survey includes spectroscopy from an ongoing Gemini Large Program, and multi-band photometry from a range of different observatories. Both imaging and spectroscopy are complete to unprecedentedly low stellar masses at this redshift. This provides the first look at environmental effects on galaxy evolution at a time when galaxies are growing in a fundamentally different way from today, and at stellar masses where environmental effects are thought to dominate. Here we propose to use MMIRS to complete the J- and K-band imaging for one of the "Virgo progenitor" clusters in our sample. As a progenitor of normal mass low-z clusters, this object helps to form the backbone of our evolutionary sample. The proposed imaging is essential to photometrically classify galaxies as passive or star-forming and to compute membership using accurate photometric redshifts that will be well calibrated with our spectroscopy. With these data and our own lower-redshift descendant data, we will measure 1) the evolution of the quenched fraction and its dependence on distance from the cluster centre and 2) the relation between stellar and halo mass and its evolution. This will provide unique constraints to our in-house theoretical models at an epoch where there are currently almost none available.

**Summary of observing runs requested for this project**

| | | | | | | | | Scheduling | | Sharing | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Run | Telescope | Cage | Instrument | PI | AO | Nights | Moon | Optimal | Acceptable | Poss. | Adv. |
| 1 | MMT | | MMIRS | | | 2 | bright | Jan | Dec–Jan | yes | 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 | SpARCS1033 | 10:33:25.6 | 57:53:24 | Galaxy Cluster, depths: $J$=24.0, $K$=23.5 (AB) |

**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 if student is PI on the cover page or if this is a 2nd-year or Thesis program. Send confirmation email to TAC chair in place of signature.)*

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

## Scientific Justification

**Background:** Galaxy clusters are extraordinarily valuable as laboratories for a wide range of tests and experiments. They play a central role in studies of galaxy evolution and structure formation, supermassive black hole growth, feedback, and in characterizing dark matter and dark energy. With their enormous gravitational potentials they act as cosmic "calorimeters", preserving an observable record of the energy inputs and outputs associated with galaxy formation over cosmic time.

Extensive study of galaxy groups and clusters in the local Universe ($z < 1$) has now led to a good empirical picture of how galaxies evolve during the latest stages of structure formation (e.g. Peng et al. 2010, Wetzel et al. 2012), the two key variables being a galaxy's *stellar mass* and the *environment* in which it resides. However, the possible physical mechanisms that drive galaxy evolution differ in their expected timescales and redshift evolution and can be strongly constrained by pushing to high redshift (Balogh et al. 2016). For example, at $z > 1$ the interactions between galaxies and their environment are also expected to have been very different as the expansion of the Universe was not yet accelerating, the Universe was more than eight times denser, and the gas accretion rates, relative gas mass, and star-formation rates (SFRs) of galaxies were so much higher than they are today (McGee et al. 2014).

Despite significant effort, however, existing cluster studies at $z > 1$ remain primarily in the "cluster confirmation" stage, where samples are heterogeneous and spectroscopy is shallow and systematically incomplete. Indeed, most studies have focused on only the most massive clusters, as these are the easiest to find. However, since structures grow hierarchically, one must consider an "evolutionary sequence" in which lower mass clusters are studied in the earlier Universe (at higher redshift) and compared with their more massive descendants in the more local Universe.

**The GOGREEN survey:** In order to address these shortcomings of earlier works, our survey (GOGREEN, PI: M. Balogh) aims to be the definitive survey of overdense environments at $1 < z < 1.5$. A key component of this is the careful mass selection of 21 groups and clusters which matches progenitors and descendants across most of the age of the Universe (see Fig. 1). (Note in particular that previous studies selecting only the highest mass systems at $z \sim 1$ would implicitly be matching to systems which would be so massive as to be extremely rare or even entirely absent in the local Universe.) The main goals of this project are to measure correlations between stellar mass (extending down to $\mathcal{M}_\star > 10^{10}\mathcal{M}_\odot$), host halo mass and stellar populations at this important but poorly explored epoch. We will compare these measurements to our own state-of-the-art models to constrain the timescale of quenching, its redshift evolution, and where it occurs. GOGREEN has two main observational components: an approved Gemini Large program (PI: Balogh), comprising 438 guaranteed hours of $z$-band imaging and deep spectroscopy on galaxy targets selected from deep IRAC [3.6] images; and a deep multi-band imaging survey (described below).

**Photometry is Critical:** The imaging plays a central and critical role in the project in two key areas: **1)** accurate rest-frame UV-to-NIR SEDs to separate dusty and passive galaxies and measure stellar masses (Fig. 1) and **2)** accurate and precise photometric redshifts to select cluster members over a range in cluster-centric radius and down to the stellar mass limit. As we outlined in our accepted Gemini LP proposal[1] "... *to classify galaxies is from the UVJ colour-colour diagram, which does an excellent job of separating dusty star-forming galaxies from truly passive galaxies (e.g. Muzzin et al. 2013b, Mok et al. 2013, 2014). This requires deep R/I/J/K imaging, which we have for most clusters in our sample. For the remainder we are applying to CFHT, Subaru, VLT and Magellan...we are committed to completing this coverage for the entire sample."*

With our unparalleled spectroscopy, we will characterize the host halos. As shown in van der Burg et al. (2013), spectroscopy is also very helpful when combined with well-calibrated photometry to calibrate photometric redshifts near our stellar mass limit, specifically for the task of deciding how to best establish cluster membership based on photometry only. The spectroscopy alone, however, is insufficient for these tasks as the incompleteness near the mass limit is large and the spatial coverage in the cluster is very limited.

This is an ambitious project which requires a significant investment of telescope time. For the southern

[1] http://saguaro.phsx.ku.edu/ grudnick/GOGREEN/GOGREEN_complete.pdf

clusters we have obtained $UBVRIzYJK_s$ imaging through approved allocations at the VLT (42h) and Magellan (3 nights). For the northern clusters we have received Subaru observations in 16A and 16B in the $grizY$ bands of most clusters (PI: Cooper). In the current semester (17A) we will obtain the remaining $zY$ imaging. Observations are also being undertaken on WIRCam@CFHT for the northern sample, but in order to complete the sample we require J and K imaging of one final cluster, for which we request time on MMIRS-MMT. Its large field of view make MMIRS one of the best instruments for NIR imaging of low mass galaxies out to multiple virial radii around distant clusters. These data are not only critical to constrain photometric redshifts, but also for modelling the SEDs of our objects.

With the full sample we will accomplish many science goals. Below we outline just two:

**Environment-quenching of low-mass galaxies:** Despite great efforts, physically motivated models of galaxy formation have consistently failed to reproduce the observed properties of the satellite galaxy population (Weinmann et al. 2006, Hirschmann et al. 2014). Simply 'turning the knobs' on cluster specific processes, like the effectiveness of ram-pressure stripping, does not result in the satellite properties we observe (Font et al. 2008). While it is clear that internal gas accretion, ejection and heating processes are intimately linked to the properties of these satellite galaxies (Weinmann et al. 2010, Bahe & McCarthy 2015), a failure to correctly reproduce properties indicates a failure in our understanding of these key processes. A powerful test to advance our understanding of galaxy formation is the abundance of low-mass, passively evolving cluster members (e.g. see Fig. 2; McGee et al. 2014, Balogh et al. 2016). At $1 < z < 1.5$ this measurement requires rest-frame $UVJ$ data to identify passive galaxies and accurate photometric redshifts to characterize the spectroscopic completeness.

**Hierarchical assembly of baryons:** In the low-redshift Universe, several studies indicate that the fraction of a system's baryons contained in stellar mass is a strong function of halo mass above $10^{13.5}\mathcal{M}_{\odot}$, with groups containing a higher fraction than more massive clusters (Gonzalez et al. 2007; Giodini et al. 2009; Andreon 2010). These observations are difficult to reconcile with hierarchical structure formation in which clusters are built through the accretion of groups, and can only be explained if today's groups are not representative of the systems which formed today's clusters (Balogh et al. 2008). To understand this cosmic conundrum, we need a precise, system-by-system determination of the stellar mass content of groups and clusters at $z > 1$. Obtaining such a precise measurement requires accurate photometric redshifts tested with very deep spectroscopy to the same stellar mass limit.

The GOGREEN sample was carefully designed to include an equal number of clusters in each of three different halo mass ranges: groups ($\sim 5 \times 10^{13}\mathcal{M}_{\odot}$), Virgo cluster progenitors ($\sim 2 \times 10^{14}\mathcal{M}_{\odot}$), and Coma cluster progenitors ($\sim 10^{15}\mathcal{M}_{\odot}$). Within each halo mass bin, the systems are chosen to span and fully sample the redshift range $1 < z < 1.5$. In addition, GOGREEN is designed to reach stellar masses of $10^{10}\mathcal{M}_{\odot}$ as environmental quenching is most readily detected in low stellar mass galaxies. It is this deliberate cluster selection and stellar mass-limited selection that gives GOGREEN the unique power to separate the roles of halo mass, stellar mass, and redshift. Without the proposed photometry we will not be able to accomplish these key GOGREEN science goals.

**References:** Andreon 2010, MNRAS, 407, 263 • Bahe & McCarthy, 2015, MNRAS, 447, 969 • Balogh et al. 2008, MNRAS, 285, 1003 • Balogh et al. 2016, MNRAS, 456, 4364 • de Lucia et al. 2012 MNRAS, 423, 1277 • Font et al. 2008, MNRAS, 389, 1619 • Giodini et al. 2009, ApJ, 703, 982 • Gonzalez et al. 2007, ApJ, 666, 147 • Hirschmann et al. 2014, MNRAS, 444, 2938 • McCracken et al. 2012, A&A, 544, 156 • McGee et al. 2014, MNRAS, 442L, 105 • Mok et al. 2013, MNRAS, 431, 1090 • Mok et al. 2014, MNRAS, 438, 3070 • Muzzin et al. 2013a, ApJS, 206, 8 • Muzzin et al. 2013b, ApJ, 777, 18M • Peng et al. 2010, ApJ, 721, 193 • Taniguchi et al. 2007, ApJS, 172, 9 • van der Burg et al. 2013, A&A, 557, A15 • van der Wel et al. 2014, ApJ, 788, 28 • Weinmann et al. 2006, MNRAS, 366, 2 • Weinmann et al. 2010, MNRAS, 406, 2249 • Wetzel et al. 2012, MNRAS, 424, 232 • Wetzel et al. 2013, MNRAS, 432, 336 • Williams et al., 2009, ApJ, 691, 1879

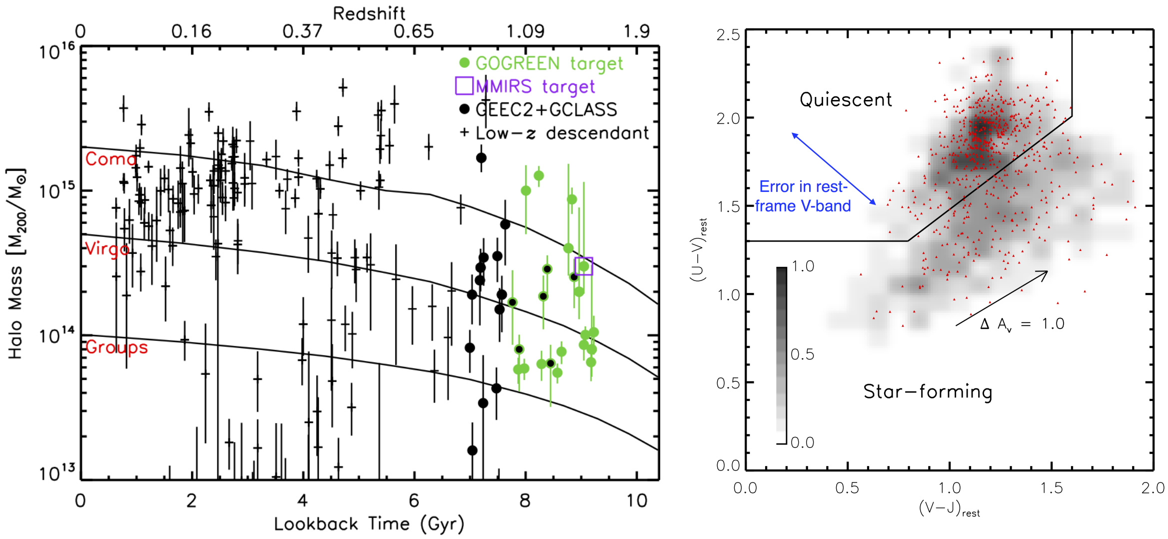


Figure 1: (Left:) The halo masses and redshifts for the clusters in the GOGREEN sample (green circles) alongside those of existing cluster surveys. The GOGREEN sample was chosen to contain progenitors of present-day Coma, Virgo, and Group-mass systems. Black lines show theoretical growth curves from the Millennium simulation. Our target is shown as the purple square and is one of our highest redshift and most massive systems. The MMIRS imaging will enable the key GOGREEN science objectives of classifying galaxies as star-forming or passive via the UVJ diagram (above right) and will allow us to establish membership to large cluster centric radii using accurate and precise photometric redshifts that are tested by our extensive Gemini/GMOS spectroscopy of large numbers of satellites and field galaxies along the line-of-sight. The rest-frame $V$-band at these redshifts corresponds to the proposed $J$-band observations which is therefore necessary for precise SED-based classification.

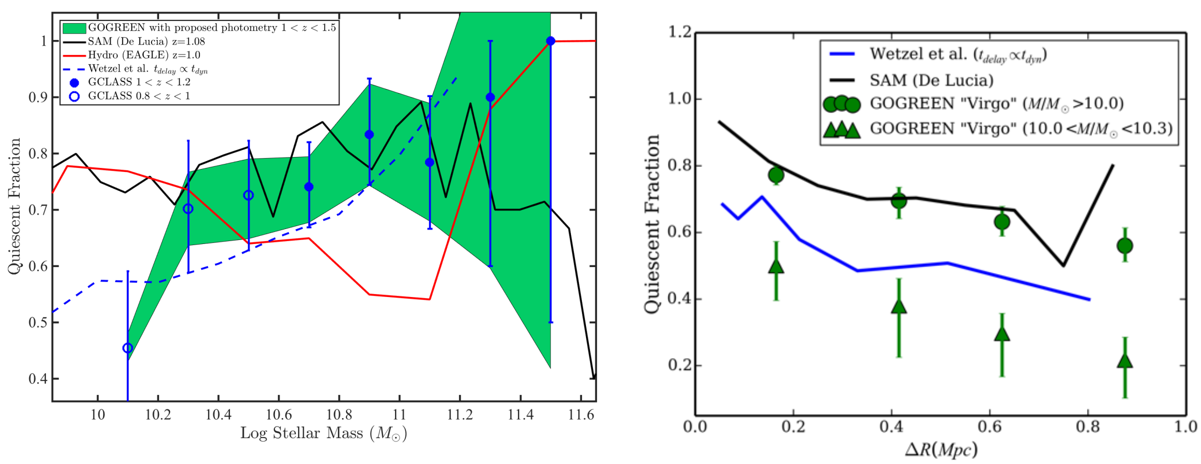


Figure 2: Illustration of GOGREEN's potential for discriminating between quenching models. *Left panel*: The fraction of quiescent galaxies from the shallower $z \sim 1$ GCLASS Survey is compared with our in-house model predictions. The predicted precision for the GOGREEN Virgo progenitors at $1 < z < 1.5$ using our well-calibrated photometric redshifts is shown as the shaded region. With the proposed photometry, the precision for these high-redshift clusters is similar to that of the low redshift GCLASS survey. The shaded region will decrease when we fold in the GOGREEN spectroscopy to identify members. *Right panel:* The radial dependence of the quenched fraction for two models (De Lucia et al. 2012; Wetzel et al. 2013) and the expected size of the GOGREEN uncertainties for the Virgo progenitors. GOGREEN will have the precision to distinguish between these models, which make *fundamentally different assumptions about how galaxies get their gas.*

**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**)*

The proposed Near-IR imaging data allow us to probe the galaxy SED significantly redward of the rest-frame 4000Å-break at the redshifts of the clusters, and thus by using the $K_s$-band as detection band, we perform a galaxy selection that is close to being stellar-mass selected. Note that our deep IRAC/Spitzer data also probe the SED at long wavelengths, but the superior image quality of the $K_s$-band make the latter the ideal band for source detection in the crowded cluster environment. In addition to this critical role of these Near-IR images, the full set of deep multi-colour imaging plays two important roles in our program, described in turn below:

• The spectroscopic sample alone is too sparse at the low-mass end and too geometrically restricted to allow us to robustly correct for spectroscopic completeness and to reconstruct trends with cluster-centric radius. However, the deep spectroscopy will contain $> 1600$ cluster and field galaxies down to the same mass-limit as the photometry. This will allow us to calibrate the photometric redshifts to the level needed for cluster membership determinations, as demonstrated in van der Burg et al. (2013). With the photometric redshifts and our spectroscopy we will be able to distinguish between different quenching models. Key to good photometric redshifts is broad wavelength coverage that samples the 4000Å break at all redshifts of interest. We have used mock observations of model galaxies to verify the redshift performance for different filter combinations and depths. Even the deep $grizY$ photometry from our awarded Subaru time coupled with the deep IRAC data is not enough for accurate photo-z's. Deep $JK_s$ data reduce the contamination by non-cluster members by a quarter and reduce the scatter and number of outliers.

• Rest-frame $UVJ$-band photometry has been shown by many studies to be a very effective discriminator between passive and dusty star-forming galaxies (Fig. 1b; Williams et al. 2009), which have otherwise indistinguishable rest-frame optical colours. As the blue arrow shows, **the proposed J-band data correspond to rest-frame V-band at the cluster redshift. The J-band is thus critical in distinguishing the star-forming from quiescent population, and indeed is indispensable for the key GOGREEN science.**

Our goals require a $5\sigma$ sensitivity of $J = 24.0$, and $K_s = 23.5$ in a $r = 1''$ aperture, which is 0.2 magnitudes shallower than the UltraVISTA/COSMOS survey DR1 (Taniguchi et al. 2007; McCracken et al. 2012). This depth is required to reach 90% detection completeness at galaxy stellar masses of $\mathcal{M}_{\star}$=$10^{10}\mathcal{M}_{\odot}$ in the $K_s$-band (cf. Fig. 2 in Muzzin et al. 2013b) at the redshift of SpARCS-1033. SpARCS-1033 is the cluster we target in this proposal, and it is one of the highest-redshift clusters in the GOGREEN sample ($z = 1.455$). Our extensive SED-fitting and photometric redshift simulations have shown that these are also the minimum depth needed to achieve the science goals at the stellar-mass limit.

**MMIRS request:** We require a depth that is 0.2 magnitudes shallower than UltraVISTA to reach our stellar mass limit of $\mathcal{M}_{\star}$=$10^{10}\mathcal{M}_{\odot}$ at 90% completeness (as outlined above).

Using the MMIRS Imaging Exposure Time Calculator, we estimate exposure times by approximating our faintest sources as point sources in 1.0 arcsec seeing and computing the time needed to reach S/N=5 in a 1 arcsec diameter aperture for our limiting magnitudes (J=24.0 and K=23.5 AB), J=23.1, K=21.6 Vega. This gives total integration times of 7020s and 6450s respectively, and is in line with scaling from our observations on other telescopes. From the online observers' manual, the maximum recommended exposure times are 200s in J and 30s in K and we will thus use 2x60s coadds in J and 5x12s coadds in K. Accounting for the 1.475s read time and the maximum 17s dither time, this translates to overheads of 17% and 41% in J and K respectively. With overheads, a single pointing in J and K requires 17.3ks. To tile our $11' \times 11'$ imaging field requires a $2\times2$ grid of MMIRS pointing and so to observe four pointings requires 19.2 hours or 2 nights.

Since we only observe in the near-IR, these observations can be taken at any moon phase. There are ample 2MASS stars in our fields for calibration. We can therefore accommodate slightly varying and non-photometric atmospheric conditions.

**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**)*

The PI of the UAO time (Zaritsky) is part of a large international collaboration comprising ∼30 researchers and a Gemini Large Program (GOGREEN, 440 hours of spectroscopy and $z$-band imaging). Zaritsky is playing an important role in GOGREEN and his role is central to the data acquisition and analysis plans of the larger collaboration. He is specifically interested in looking for ultra-faint dwarf galaxies and their precursors in the GOGREEN clusters, which requires deep multi-band imaging.

The imaging proposed for here is crucial in order to complete the concurrent imaging campaign which provides the only method to address key science questions of GOGREEN (see SJ).

As a whole, the collaboration (∼30 researchers) has obtained significant imaging time (in $ugrizYJK$ for 12 clusters) on multiple instruments (Subaru, VLT, CFHT, and Magellan) to complete this. One night of UAO was already awarded (16B) as part of our Magellan/Fourstar observations of the southern GOGREEN clusters.

This is an ambitious imaging program and thus we are accessing all the resources at our disposal to complete it. The MMIRS time will be especially helpful for this high-z cluster. The use of SO facilities to obtain J and K imaging for some northern clusters plus the night of Magellan already awarded will thus represent a reasonable proportional investment by the PI.

The imaging component of the GOGREEN survey is being coordinated by G. Rudnick (U. Kansas) but the science made possible with the dataset is open to all collaborators, with priority given to those who have so-contributed to the execution of the imaging and spectroscopic surveys. Zaritsky's contributions to GOGREEN will therefore enable him and his students unfettered access to a much larger and comprehensive data set.

**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**)*

Zaritsky et al. - 2 nights of LBT (16A) with MODS to obtain spectra of UDGs in Coma. Published, increased the nunmber of Coma UDGs by a factor of 4 (Kadowaki, Zaritsky, & Donnerstein 2017, ApJ, in press). 2 additional nights (17A). Despite weather and instrumentation problems (glycol lead in MODS), we managed to collect data on about 6 additional UDG candidates. Data being reduced.

⋆ Zaritsky, G. Rudnick (Kansas) and others (16B) - We obtained Magellan FourStar observations of distant clusters (1 night, 2 more from collaborating institutions). Data are in hand.

Zaritsky, G. Rudnick (Kansas) and others (17A) - UKIRT observations of galaxy clusters at $z < 1$. Some observations in hand, more are necessary to complete program.

Halford & Zaritsky were awarded two nights of Magellan time with MIKE to study the IMF in star clusters (16B) as part of a program that has been going on for several years and had three publications so far. The weather was good and we obtained data for 5 additional clusters. The data are reduced. We are re-reducing all of our data to make sure it is homogeneously reduced. We anticipate a publication wihin 6 months. The paper will be part of Halford's PhD thesis.

Zaritsky and collaborators have obtained partial data on a Hectospec program to measure large scale structure around intermediate redshift clusters (16A, 17A). The data are reduced as they come off the telescope and are being used to select targets for ALMA observations and VLT near IR observations. The filamentary structure we were searching for is clear.

**Other Information** *Provide any additional program-related information including, for example, relation of current program to externally funded research, to the development of expanded capabilities for UA telescopes, or to individual timescales (e.g. PI is finishing postdoc appointment and this request would complete program). (**up to one page**)*