OBSERVING REQUEST
University of Arizona Observatories

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

Spectroscopic measurements of concentrated GAMA clusters as optimized gravitational lenses at z∼0.4

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CoI(s): Mehmet Alpaslan (NASA Ames Research Centre), Rogier Windhorst (ASU), Brenda Frye (SO), Iraklis Konstantopoulos (AAO), Seth Cohen (ASU), Rolf Jansen (ASU), Tae-hyeon Shin⋆ (ASU), Aaron Robotham (UWA/ICRAR), Michael Rutkowski (U. of Minnesota), Simon Driver (UWA/ICRAR)

Abstract of Scientific Justification

We propose to use MMT/Hectospec to conduct redshift surveys of concentrated clusters of galaxies at z ∼ 0.4 in order to build detailed models of their projected mass distributions, and identify the lensed sources.. At $z > 8$, observations of high redshift galaxies are crucial in expanding our understanding of the processes of mass assembly and reionization in the early Universe. Direct imaging of $z > 8$ objects, however, is a challenge. Concentrated clusters present an attractive, far more abundant alternative to massive galaxy clusters for lensing $z > 8$ galaxies. We have identified a sample of the 8 most concentrated clusters from the Galaxy And Mass Assembly (GAMA) group catalog, and wish to conduct deep redshift surveys of two (including one cluster confirmed by HST to be lensing) in order to thoroughly determine their galaxy membership to $m_r = 21.5$ mag. ***These objects are the very best lensing clusters at*** $z \sim 0.4$***, selected from amongst 2400 GAMA clusters through lensing modeling using their estimated cluster masses and concentrations.*** We estimate that these lenses will magnify upwards of 500 galaxies at $2 < z < 9$ and several tens of First Light objects at $z \gtrsim 10$.

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			1	dark	Sep–Dec	Dec	yes	no

Scheduling constraints and unusable dates *(up to 4 lines)*: Given RA-range, we prefer two last-half nights in Dec.

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	GAMA cluster 100045	09:16:17.57	-00:24:05.69	z=0.318 concentrated cluster, $\geq$35 members
2	GAMA cluster 100139	08:39:00.82	02:00:55.42	z=0.358 concentrated cluster, $\geq$10 members

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
Tae-hyeon Shin	Rogier Windhorst	RAWindhorst	no	yes
Bhavin Joshi	Rogier Windhorst	RAWindhorst	no	yes

Scientific Justification

1. Introduction

The study of high redshift ($z > 8$) galaxies is fundamental for understanding the processes of mass assembly in the early Universe, as well as shining a light on primordial galaxy evolution, and the epoch of reionization. However, it is difficult for ground-based facilities to observe galaxies at $z > 8$ as barely anything beyond point sources. An alternative approach to visualizing these systems has been to magnify them with gravitational lenses, which enables the detection of lower luminosity high redshift targets, along with the ability to spatially resolve them. ***Successful lensing of high redshift galaxies depends crucially on the full understanding of the mass profile of the lens (and therefore its dark matter halo), which in turn requires deep spectroscopic data on as many galaxies in the cluster as possible.*** A different approach might be to attempt a direct observation of lensed systems before polishing the lenses through photometric/spectroscopic redshifts. However, this is beyond the capability of current ground-based facilities; we rely on HST and JWST to reach 28 and 30 mag arcsec^{-2}, but given the cost of JWST time, we need an excellent lens model before committing that time.

Traditionally, massive galaxy clusters ($\approx 10^{15}$ h^{-1} $M_\odot$; Postman et al. 2012) have been the preferred lenses for detecting high z galaxies. While ideal as lenses, massive clusters are not only relatively rare, but also tend to contain a large amount of intracluster light. The latter can make it difficult, or even impossible to detect faint background lensed galaxies. Concentrated clusters (CCs) offer an equally suitable and attractive alternative as lenses, particularly because their mass profiles are very centrally concentrated, like massive clusters (Oliveira & Giraud 1994). Recently the Galaxy and Mass Assembly survey (GAMA; Driver et al. 2011) has provided a high fidelity group catalog (Robotham et al. 2011), from which we have selected a sample of eight CCs. ***We propose to use MMT/Hectospec to conduct deep spectroscopic observations of two of these CCs that are visible in the Fall (one of which is confirmed by HST observations to be lensing) in order to characterize the membership of these clusters as precisely as possible,*** data we will then use to constrain the surface density profiles of each cluster. We will apply for HST time to image these lensed objects; and in the future, Co-I Windhorst will allocate up to 100 hours of guaranteed JWST GTO time to image these lenses and search for high redshift galaxies.

2. Concentrated clusters selected from GAMA

The GAMA survey is a highly complete (98%) spectroscopic redshift survey down to $m_r = 19.8$ mag with $\sim$200,000 spectra in three equatorial fields measuring 5×12 sq degrees each; and two southern fields of similar size, all of which are shown in Fig. 1a. One of the primary data products of GAMA is the GAMA Galaxy Group Catalogue (G^{3}C, Robotham et al. 2011, Figs. 1b and 2a), which classifies approximately 40% of the galaxies in the survey as belonging to a group or cluster. ***We wish to use Hectospec to fully characterize the membership of these clusters, to $m_r = 21.5$ mag***. The GAMA survey is much deeper than the SDSS, wider than zCOSMOS, and has an extensive ancillary but shallow dataset, thereby making this one of the best samples that exists to perform our selection of clusters at relatively high redshift ($z = 0.4 - 0.5$). From this catalog, we have identified a sample of 8 concentrated clusters at $z = 0.35 \pm 0.05$. Our selection process is described in greater detail in the next section. Briefly, we calculated concentration parameters for each cluster using its dynamical mass and the slope between the 50$^{\rm th}$ and 68$^{\rm th}$ percentile radii. We then estimated the dark matter halo that these CCs would be embedded in, and the luminosity function of the high z galaxies in order to estimate the number of lensed systems that can be detected down to ≈ 30.5 mag, which will be the limit for future space-based observations from JWST NIRSpec. ***These 8 CCs are expected to lens approximately 500 galaxies at $z > 2$, with 8 or more galaxies at $z > 8$.*** Fig. 1c displays an HST ACS/WFC3 image of GAMA CG 100045 lensing a background galaxy, demonstrating the feasibility of CCs as lenses.

3. Selecting the very best concentrated clusters

Surface density is one of the key criteria for gravitational lensing, and we are able to calculate this readily using data in the GAMA Group Catalogue. Each cluster has a measured radius r and velocity dispersion σ_v associated with it; from these we derive the dynamical mass of each cluster ($M \propto r\sigma_v$) using mock galaxy catalogs whose geometry and luminosity function match those of GAMA. We note that we only consider

clusters with 4 or more spectroscopically members in order to ensure the measured σ_v is reliable. We further constrain our sample by considering clusters of high mass (10^{14-15} $M_\odot$) and intermediate redshifts ($z \approx 0.3$–0.7). The concentration parameter for these clusters is then calculated by comparing the radii at $50^{\rm th}$ and $68^{\rm th}$ percentiles. The mass and concentration values are then used to constrain the scale density and scale radius of an NFW profile (Navarro, Frenk & White, 1996). ***Based on this, we pick 8 CCs with the highest mass and concentration, shown in Fig. 2b overlaid on the distribution of GAMA clusters with $n \geq 4$ members.*** While uncertainties exist, the lensing capability of a cluster is primarily set by the concentration parameter of the cluster. Our calculated concentrations, combined with the masses and memberships of each cluster mark these 8 as the strongest lenses in the GAMA catalog.

Several lines of reasoning suggest that the best lenses for detecting the faint, background-limited lensed sources must be at $z < 1$. For galaxy clusters at higher redshifts, the mass assembly by hierarchical growth is still in progress. Galaxies are infalling into the cluster gravitational potential wells, and the cluster halos are merging and growing into massive clusters at later cosmic times. There are indeed some cases of hypothetical high lens redshifts that come out of the modeling, but actual cluster lenses at $z > 1$ are necessarily young systems that have yet to settle down into virialized systems and thus are also less massive and less compact (Fig. 2a). Further, for the idealised case of an extended isothermal mass, the parameter that most influences the lensing strength is the lens-source distance (Kaiser 1995). Additionally, from a purely practical standpoint, lower redshift lenses are useful for also being brighter and easier to follow-up and characterize in detail.

4. CCs in large scale structure

With its high spectroscopic completeness, GAMA lends itself very well to studies of structure, from the group/cluster regime to filaments and voids (see Alpaslan et al. 2014a, b for recent results). Groups and clusters are very clearly embedded within filaments, and are often surrounded by galaxies that are associated with the filament, but do not belong to any group or cluster (Alpaslan et al. 2014a). Galaxies are tightly linked to their environment - the presence of other galaxies has a strong impact on morphology and baryonic content. This relationship is well understood at local scales; however, there is little existing work to quantify the role of filaments in galaxy evolution, particularly when it comes to mass transport along the Cosmic Web.

Similarly, our current understanding of mass flow along the Cosmic Web is patchy at best. The generally accepted picture is that galaxies accrete gas through filaments at $z \sim 3$ (Keres et al. 2005, Snedden et al. 2014), which are thought to be abundant in baryons (Davé et al. 2001); and recent observational work has detected an abundance of Hα emitters and starburst galaxies in filaments (Darvish et al. 2014 and Fadda et al. 2008). ***There is, however, scant direct evidence for the effects of mass flow in the Cosmic Web in the nearby ($z < 0.5$) Universe. Existing galaxy survey data are neither deep nor sufficiently complete at $z > 0.2$ to reliably characterise large scale structure.*** Hectospec therefore is an ideal facility to study filamentary structure at higher redshifts, as the 1-degree field of view afforded by the facility, together with its 300 fibres and deep magnitude limit, mean that with one pointing we can cover both the cluster at the centre of the field, as well as the surrounding filaments and void galaxies. **This data will not only allow us to give a detailed description of the large scale structure of these galaxies (as in Alpaslan et al. 2014a, b), but also link their star formation activity with said structure. Studies of SF and environment are only able to go as far as the edges of clusters (e.g. Mahajan et al. 2012), meaning that this data would represent a significant step forward in understanding the effects of large scale structure on galaxy evolution.**

Our Hectospec observations will shed light on the faint population of galaxies that have been both predicted (van de Weygaert et al. 1993, Gottlöber et al. 2003) and observed (Alpaslan et al. 2014a, b) in voids. These galaxies are found to lie in coherent structures called tendrils, which resemble filaments on smaller scales. The overall low luminosity of tendril galaxies means that they are impossible to detect with shallow surveys, meaning that many galaxies that were previously thought to be in voids actually reside in such structures (Alpaslan et al. 2014b). Hectospec will allow us to peer deeper into voids that ever before (at least ~ 2 magnitudes deeper than GAMA) and determine if there are void substructures beyond voids, or if indeed these structures are simply the brightest galaxies in faint clusters existing within voids.

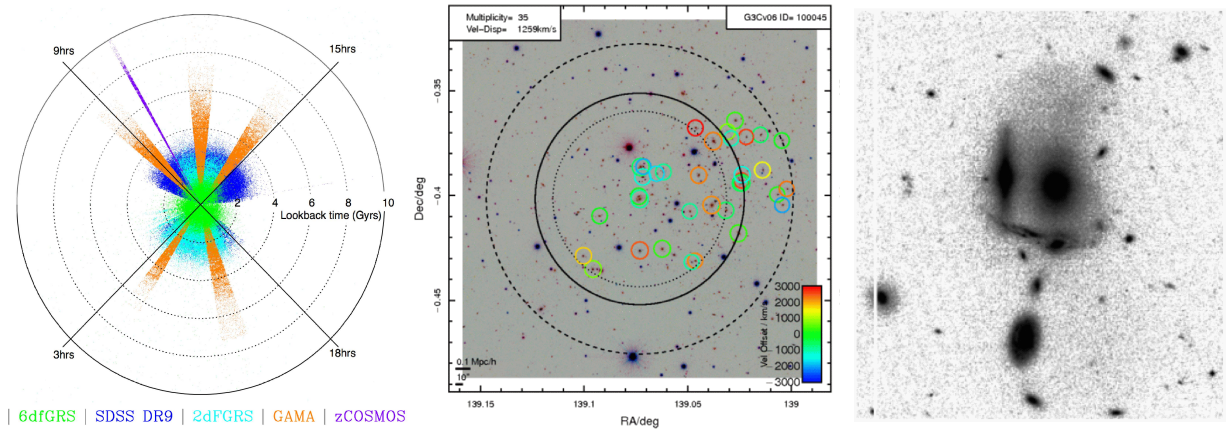

Fig. 1 *Left:* The spatial distributions of galaxies from large surveys. *Middle:* GAMA cluster 100045 imaged with SDSS data. Spectroscopically confirmed members of the cluster are circled. *Right:* HST r-band imaging of an arc on GAMA cluster 100045, demonstrating the evidence for strong lensing of such clusters.

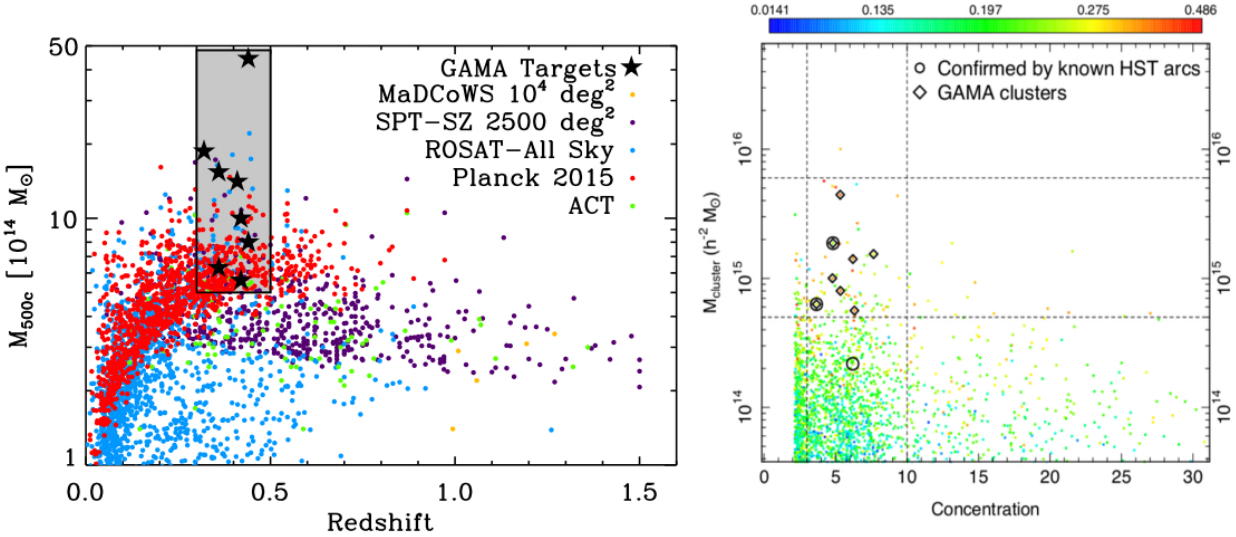

Fig. 2 *Left:* Masses for known clusters as a function of redshift. GAMA sources are indicated in the upper left. Note the trend of lower masses seen at $z > 1$, indicating the undergoing mass assembly of such systems. *Right:* Distribution of mass and concentration for GAMA clusters with $N >= 4$ members, coloured according to their redshift. Circles mark clusters whose lensing has been confirmed by HST observations, and the diamonds mark our target clusters.

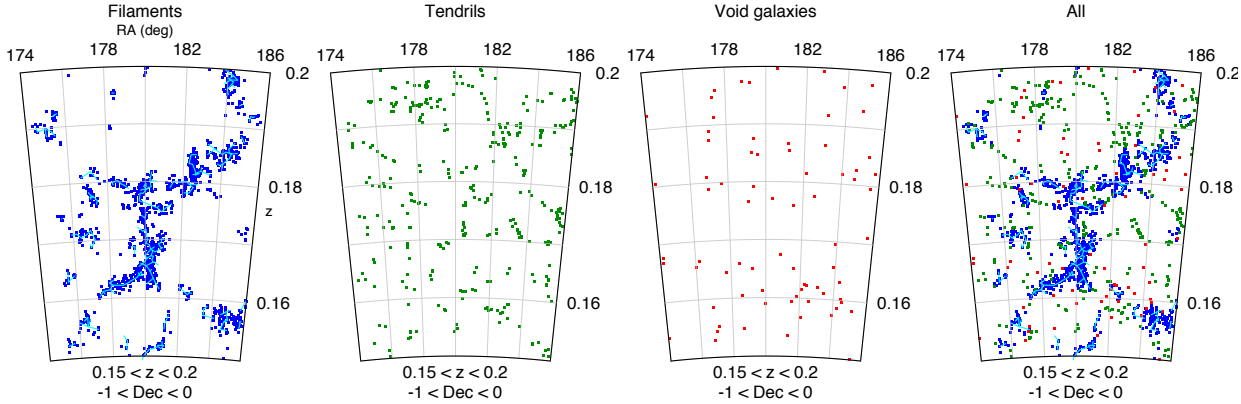

Fig. 3 Large scale structure in a cluster complex in the GAMA survey. Blue points represent galaxies in filaments, which are themselves formed by groups and clusters (whose links are shown in cyan). Red points represent isolated voids in galaxies, and green points mark galaxies in tendrils. We will construct an equally detailed map around each of our target clusters.

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**)*

Our goal is to obtain spectroscopic measurements with Hectospec of galaxies in concentrated clusters down to $m_r < 21.5$ mag, in order to better define their mass profiles. For this purpose, we wish to observe 2 of the 8 most concentrated clusters we have identified from the GAMA survey over the course of 1 night. One of these clusters, 100045, already has HST ACS/WFC3 imaging that confirms its lensing ability. ***The time required to measure redshifts down to $m_r = 21.5$ mag is 3 hours per concentrated cluster.***

We arrived at this number by following the analysis of the SHELS survey (Geller et al. 2012), which used 2 hour integrations with Hectospec to obtain redshifts with $m_r \leq 20.8$ mag. Given the mean exposure time for SHELS of one hour, we therefore request 3 hours to reach our limit of $m_r \leq 21.5$ mag. Adding overheads, we will be able to observe two concentrated clusters in one evening. ***Given that our aims are to measure redshifts, we do not require a very high S/N ratio (i.e. S/N $\geq$ 5)***, so this time is sufficient. We therefore request 1 night to observe the 2 CCs (which includes the lensing CC). For comparison, spectroscopic observations conducted as part of the GAMA survey on the Anglo-Australian telescope generated spectra with an average S/N of ~ 4.8, that were reliably used to measure redshifts out to $z = 0.5$ and $m_r = 19.8$ mag. Any fibers that are not allocated to galaxy clusters will be placed on outlier galaxies around each cluster; each concentrated cluster is selected to easily fit into the 1 degree diameter FOV of Hectospec (all our CCs have a radius ≤ 5.5'), and our target galaxies are sufficiently separated such that fiber collisions will be mitigated (given Hectospec's minimum fiber separation of 20 arcseconds).

These 2 GAMA clusters were chosen from amongst 24,000 GAMA groups and clusters over 300 deg sq. with redshifts $z < 0.45$ complete to $m_r = 19.8$ mag, about 2400 of which have $N \geq 4$ spectroscopic cluster redshifts. Hence, we have used one of the best samples that exists to select these highly concentrated clusters at relatively high redshift ($z < 0.45$). The proposed set of 2 GAMA clusters is thus one of the best samples available today at $z < 0.45$ to search for lensed candidates at $2 < z < 10$ which we intend to follow up with HST in the next few Cycles, and with JWST shortly after its launch in fall 2018 in an optimized search for $z > 10$ objects. Therefore, we request here that we can verify these best lensing clusters with the proposed Hectospec data, by obtaining spectra that are 1.5-2 mag deeper that what is currently available. Our work complements that of Wong et al. (2013) in that we provide lensing fields that are optimized for JWST First Light searches at $z > 10$ over the 2x4' JWST FOV, without the added complexity of having a large excess of foreground galaxies or intracluster light, which may complicate the stray-light removal from JWST images.

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**)*

1) As this is a new project, no nights have previously been given. We request 1 night for this proposal. This will allow us to observe the 2 best of our 8 target clusters. In order to observe the remainder of our clusters, we will request further Hectospec time of the order of 3 additional nights after this pilot program is completed.

2) The targets for this project are chosen from the GAMA survey. Each cluster has been identified using AAO 4 meter spectra reaching down to $m_r = 19.8$ mag; however, this depth is not sufficient to fully identify the full membership of each cluster, thus requiring deeper observations with Hectospec.

3) Co-I Windhorst is leading the study of GAMA galaxy clusters as lenses for high redshift galaxies. This UAO time is vital to be able to fully model the mass profile of each cluster; without this information, accurately measuring lensed background galaxies is not possible. Weak lensing measurements made with this data will directly contribute to the Co-I Mr. Tae-hyeon Shin's dissertation.

References

Alpaslan et al., 2014, MNRAS, 438, 117
Bouwens et al., 2014, ApJ, 793, 115
Davé et al., 2001, ApJ, 552, 473
Fadda et al., 2005, ApJL, 672, L9
Gottlöber et al., 2003, MNRAS, 344, 715
Keres et al., 2005, MNRAS, 363, 2
Navarro, Frenk & White, 1996, ApJ, 463 563
Postman et al., 2012, ApJS 199, 25
Snedden et al., arXiv:1412.7050
Wong et al., 2013, ApJ, 769, 52
Alpaslan et al., 2014, MNRAS, 440L, 106
Darvish et al., 2014, ApJ, 796, 51
Driver et al., 2011, MNRAS 413, 971
Geller et al., 2012, AJ, 143, 102
Kaiser et al., 1995, ApJ 439, 1
Mahajan et al., 2012, MNRAS, 427, 1252
Oliveira & Giraud 1994, ApJL 437, L103
Robotham et al., 2011, MNRAS 416, 2640
van de Weygaert et al., 1993, MNRAS, 263, 481

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**)*

• Windhorst, Rutkowski, & Jansen were awarded 3 nights of joint MMT/Blue Channel time in June 2014 for spectroscopic follow-up of emission-line galaxies at $z \simeq 2$. The data has been reduced and analysis of this program is ongoing, with a drafted paper expected by M. Rutkowski et al. by the end of the year.

• Windhorst, Jansen, Rutkowski were awarded 2.0 nights in 2012–2013 to image the four CANDELS field in the U-band plus the rizY+972N filters with the LBT/LBC. About 1.0 night was lost to weather. This is part of a larger project to obtain deep U-band imaging in all five CANDELS fields, with significant LBT time also contributed by our Italian, U-MN and U-VA collaborators. The data has been fully reduced and analysis of this program is ongoing. The first two papers from this project are currently being written, with expected completion by the end of the year:

• One paper will be submitted by T. Ashcraft et al. to PASP on "Improving the FWHM of Deep LBT U-band Image Series by Combining Optimally Weigthed Image Sub-Stacks."

• A second paper is led by our Italian LBT Collaborators, by A. Grazian, A. Fontana et al. (incl. T. Ashcraft, R. Windhorst, R. Jansen, S. Cohen. at ASU and M. Rutkowski, C. Scarlata, R. W. O'Connell) to ApJS on: "The 32-hour Ultradeep LBT U-band Survey of the HST CANDELS Field GOODS-North."