OBSERVING REQUEST
University of Arizona Observatories

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

CLJ1226.9+3332: $z = 0.9$ Massive Galaxy Cluster with an Exceptionally Bright Lensed *Herschel* Source at $z = 2.3$

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Abstract of Scientific Justification

We have recently discovered a bright ($S_{\rm peak}$ ∼100 mJy) cluster-lensed dusty star-forming galaxy (DSFG) with a spectacular morphology in the field of the high-redshift massive galaxy cluster CLJ1226.9+3332 at $z = 0.89$. The HST optical/near-infrared images show three optically-faint red components (an arc elongated over 10", three bright knots with 1-2" separations, and a diffuse extended clump), and our LBT/LUCI spectroscopy determined the redshift of the knots to be $z = 2.26$. Our IRAM30m/EMIR spectroscopy has detected multiple CO and CI(1-0) lines at the same redshift, but the spectra show complex line profiles, likely reflecting the complicated internal structure of this system. What is unique about this system is its unusually large magnification factor (∼50x), but our preliminary lens model is highly uncertain because of a lack of spectroscopic redshifts for multiply lensed images in this cluster field.

Here, we propose to conduct optical multi-object spectroscopy in this cluster field using LBT/MODS. The goal is twofold: (1) obtain spectroscopic redshifts for a number of multiply lensed background galaxies and construct a accurate lens model, which is necessary to study the intrinsic properties of this spectacular lensed DSFG at $z = 2.26$ we have discovered; (2) examine the cluster membership for a number of *Herschel* sources in the field, and study the infrared activities of galaxies in this high-redshift cluster. Lensed DSFGs with such a large magnification factor are rare, and therefore this galaxy deserves a special attention because it provides a window to a luminosity range that is inaccessible otherwise. The redshift of the lensing cluster is also uniquely high in our sample, allowing us to probe the star-forming properties of high-redshift cluster members as well as the cluster mass distribution simultaneously.

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	LBT	f/15	MODS			2	dark	Feb-Mar	Feb–May	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	CLJ1226.9+3332	12:26:58.4	+33:32:47	$z = 0.89$; HST/MST CLASH (Primary target)
2	MACSJ0717.5+3745	07:17:31.7	+37:45:19	$z = 0.55$; HST/MST CLASH & Frontier Field
3	MACSJ1720.3+3536	17:20:17.0	+35:36:24	$z = 0.39$; HST/MST CLASH
4	Abell 2261	17:22:27.3	+32:07;59	$z = 0.39$; HST/MST CLASH

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
G. Walth	E. Egami		no	no

Scientific Justification

Background: Gravitationally Lensed Dusty Star-Forming Galaxies (DSFG)

Over the last few years, discoveries of exceptionally bright (observed $S_{\rm peak} > 100$ mJy in the far-infrared) gravitationally lensed dusty star-forming galaxies (DSFGs) have generated great excitement. This is because these gravitationally lensed DSFGs are so bright that they enable us to perform a variety of follow-up observations using a suite of observing facilities in the submilllimeter, millimeter, and radio now available on the ground. This allows us to study the population of heavily dust-obscured vigorously star-forming galaxies at high redshift ($z > 1$), which is thought to play an important role in the cosmic star-formation history of the Universe and yet has been difficult to study due to heavy dust extinction. Although finding these bright lensed DSFGs had been challenging due to their small surface density ($\sim$1 deg^{-2}), recent large-area submillimeter/millimeter surveys (e.g., Herschel, SPT) covering many hundreds (or even thousands) of square degrees are finding such bright lensed DSFGs with a great efficiency (e.g., Negrello et al. 2010; Vieira et al. 2010, 2013; Weiß et al. 2013).

Scientifically, what is particularly exciting about these lensed DSFGs is that they will allow us to study individual star-forming regions with a spatial scale of local giant molecular clouds (GMCs; $\sim$100 pc). Because of the lensing effect, a higher physical resolution can be achieved when the image of the background galaxy is reconstructed in the source plane with an accurately constructed lens model. And when this gravitational lensing effect is combined with the high spatial resolution offered by submillimeter/millimeter interferometers like SMA, PdB, and ALMA ($\lesssim$0.2"), the resultant map could achieve an unprecedented spatial resolution ($\lesssim$100 pc in the source plane), revealing spectacular morphologies and structures of lensed galaxies.

The power of this effect has been dramatically demonstrated by the discovery and subsequent follow-up observations of an exceptionally bright ($S_{870} = 106$ mJy) DSFG at z=2.3, known as the Eyelash galaxy, which is strongly lensed by a massive galaxy cluster at z=0.3 (Swinbank et al. 2010; Danielson et al. 2011; Swinbank et al. 2011). With a resolution of $\sim$0.2", SMA has resolved this source into multiple components, and for the most highly amplified clumps, the source plane resolution reached $\sim$90 pc, only slightly larger than the typical size of GMCs in the Milky Way. From this SMA study, Swinbank et al. (2010) concluded that star-forming regions in this galaxy are similar in size to GMCs in the Milky Way and Local Group galaxies, but their mean luminosity density is comparable to that of the GMC dense cores. In other words, **GMCs in this galaxy look like super-sized dense cores**. This probably suggests that the underlying physics of the star-forming processes is similar to what we see locally in dense cores although the energetics of these star-forming regions are unlike anything found in the present-day Universe. Subsequent results from the high-resolution PdBI CO mapping are even more spectacular, measuring the dynamics and gas surface density, and estimating the mid-plane hydrostatic pressure of the ISM, which has important consequences for star-forming efficiencies (Swinbank et al. 2011). Taken together, these studies point to a great potential for conducting similar studies with a larger sample of lensed DSFGs.

The *Herschel* Lensing Survey (HLS) — Search for Cluster-Lensed DSFGs

Gravitationally lensed galaxies found in field surveys like those with *Herschel* and SPT are mostly produced by galaxy-galaxy strong lensing. On the other hand, the Eyelash galaxy mentioned above is lensed by a massive galaxy cluster. Although both lensing processes produce bright lensed images, cluster-lensed systems provide a number of practical advantages: (1) ease of constructing accurate lensing models due to constraints from multiple lensed images seen in cluster cores; (2) less severe effect of differential magnification due to larger lens sizes; (3) unobstructed view toward the lensed galaxy (in galaxy-galaxy lensing a bright lensing galaxy is always in front of the lensed background galaxy); and (4) capability to produce large ($\sim$100$\times$ or more) magnification factors.

To discover bright *cluster-lensed* DSFGs like the Eyelash, our team has been conducting a large *Herschel* survey of gravitationally lensed galaxies in the fields of massive galaxy clusters, **the *Herschel* Lensing Survey (HLS)** (Egami et al. 2010). HLS obtains deep PACS (100/160 μm) and SPIRE (250/350/500 μm) images of 54 massive galaxy clusters for a total of 366 hours (HLS-deep), as well as shallower (but nearly confusion-limited) SPIRE images of 527 clusters with a total observing time of $\sim$53 hours (HLS-snapshot).

HLS has proved to be a great success, finding a number of exceptionally bright DSFGs. One recent highlight was the discovery of a bright lensed DSFG at $z = 5.24$ (Combes et al. 2012; Rawle et al. 2014). This source is $\sim$5' away from the cluster center and almost coincident with a bright optical source, which is a galaxy at $z = 0.6$ and likely the dominant lens. The extreme brightness of this source allowed us to detect a number of atomic/molecular emission lines with the IRAM 30m telescope, including a strong water line (Figure 1, left). We also obtained high-resolution [CII] maps with SMA and PdBI, which show complicated morphological/dynamical structures of the [CII] emitting regions (Figure 1, right), suggesting that this may be a system of interacting/merging galaxies.

Another HLS Discovery of an Exceptionally Bright Lensed *Herschel* Source at $z = 2.3$

Using the HLS data, we have recently discovered another bright spectacular lensed DSFG at $z = 2.26$ in the CLASH galaxy cluster CLJ1226.9+3332 at $z = 0.89$. The near-UV to near-IR *HST*/ACS+WFC3 photometry provided by the CLASH 16-filter coverage together with our *Spitzer*/MIPS+IRAC, *Herschel*/SPIRE+PACS, and JCMT/SCUBA2 photometry leads to the complete spectral energy distribution (SED) of this galaxy. We have searched for the redshift of this exceptional system with LBT/LUCI (PI: Clement) and IRAM 30m/EMIR (PI: Egami). We have detected Hα and [NII], and strong CO(3-2), CO(4-3), and [CI](1-0) emission lines (Figure 2), measuring a redshift of z = 2.26. At this redshift, the far-IR SED gives an observed LIR = $10^{13.3} L_{\odot}$, which makes the system resemble among the brightest DSFGs known (e.g., Swinbank et al. 2011; Viera et al. 2013). In reality, the far-IR emission has to be deblended and corrected for lensing magnifications. These corrections should unravel LIRG-type galaxies building up the extreme LIR, and we are currently in the process of obtaining a high-resolution millimeter map with PdB.

As revealed by HST images (Figure 2), this source is composed of three lensed galaxies with spectacular morphologies: an optically faint red arc elongated over 10" (labeled C), three bright knots on its southern end separated by 1.2" and 2" each (labeled A), and an extended clump at 10" south of these knots (labeled B). Both galaxies A and B seem to contribute to the extreme emission in the *Spitzer*/MIPS and *Herschel*/SPIRE bands (see the elongated emission in the MIPS and SPIRE images shown in Figure 2). This complex background system of galaxies is lensed by not only the cluster but also locally by a foreground galaxy. Our preliminary lensing model shows that the bright knots are three multiple images of the same galaxy, while the arc and the southern clump are single images highly distorted/magnified of two other galaxies, all lying at close redshifts. This specific alignment of objects on the sky would lead to an unusually high magnification factor of $\sim$50 in total. However, this number is highly uncertain because we do not have many spectroscopic redshifts of background lensed galaxies to constrain the cluster mass model well.

Proposed Observation

We propose here to conduct optical multi-object spectroscopy in the field of the $z = 0.89$ massive cluster CLJ1226.9+3332 using LBT/MODS. The goal is twofold: (1) obtain spectroscopic redshifts for a number of multiply lensed background galaxies in this cluster field (as well as for the lensing galaxy in front of the galaxy A) and construct an accurate lens model, which is necessary to study the intrinsic properties of the spectacular lensed galaxy at $z = 2.26$ we have discovered; (2) Examine the cluster membership for a number of *Herschel* sources in the field, and study the infrared activities of galaxies in this high-redshift cluster.

Lensed DSFGs with such a large magnification factor are rare, and therefore this galaxy deserves a special attention because it provides a window to a luminosity range that is inaccessible otherwise. We will also try to see if we can detect Lyα emission from this DSFG. The redshift of the lensing cluster is also uniquely high, allowing us to probe the star-forming properties of high-redshift cluster members simultaneously. In fact, such a high-redshift massive cluster is rare enough that the mass distribution we will map out through our lensing analysis will be of great interest by itself.

Reference: Combes, F., et al. 2012, A&A, 538, L4; Danielson, A. L. R., et al. 2011, MNRAS, 410, 1687; Egami, E., et al. 2010, A&A, 518, L12; Negrello, M., et al. 2010, Science, 330, 800; Rawle, T. D., et al., 2014, ApJ, 783, 59; Swinbank, A. M., et al. 2010, Nature, 464, 733 ; Swinbank, A. M., et al. 2011, ApJ, 742, 11; Vieira, J. D., et al. 2010, ApJ, 719, 763; Vieira, J. D., et al. 2013, Nature, 495, 344; Weiß, A., et al. 2013, ApJ, 767, 88

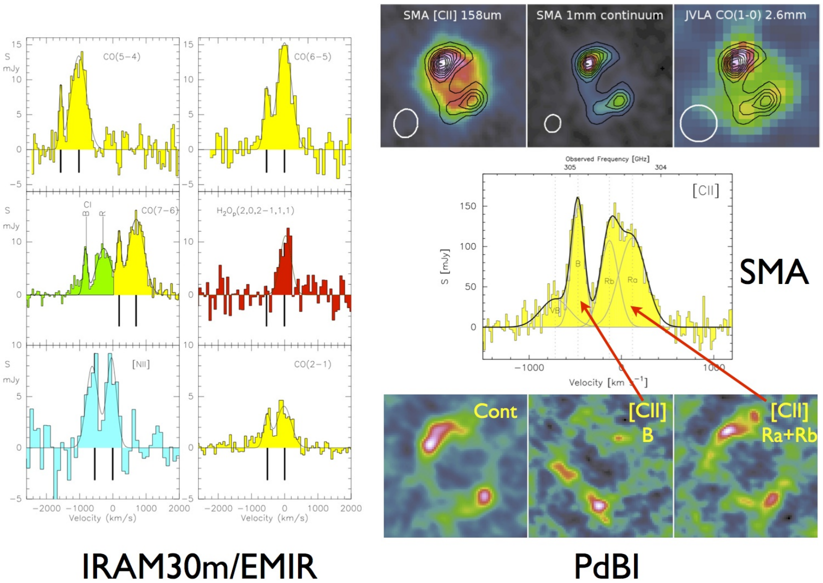

Figure 1: Strongly lensed SMG at z=5.24 discovered by the HLS: (Left) Millimeter line spectra obtained with IRAM 30m/EMIR (Combes et al. 2012); (Right) [CII] 158 μm spectrum obtained with SMA (middle panel). High-resolution SMA [CII] and JVLA CO(1-0) maps revealed a complex morphology (upper panel). Higher-resolution PdBI maps have identified the two velocity components (B and Ra+Rb) spatially (bottom panel), which may be interacting galaxies (Rawle et al. 2014; Boone et al. 2015, in prep).

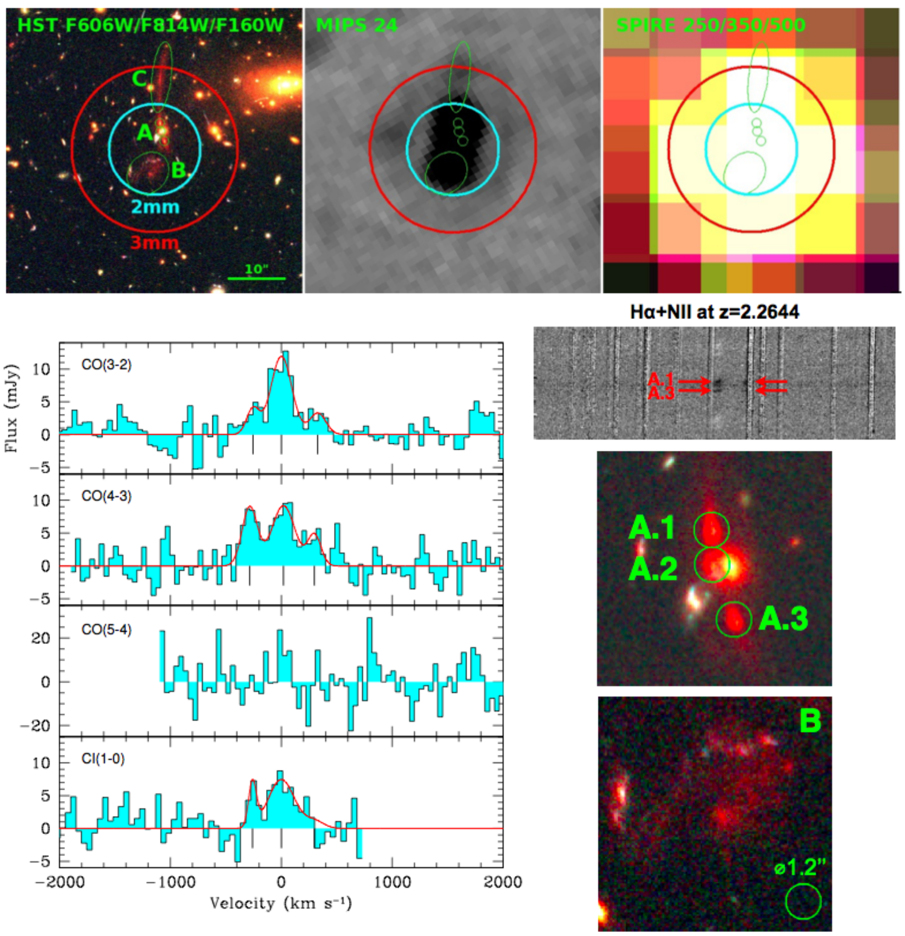

Figure 2: Exceptionally bright lensed *Herschel* source discovered in the field of CLJ1226.9+3332 at z = 0.89: (Top) HST, *Spitzer*/MIPS 24 μm, and *Herschel*/SPIRE images with the IRAM30m beams overlaid; (Lower left) IRAM30m/EMIR line spectra showing complex line profiles similar to those shown in Figure 1; (Lower right) LBT/LUCI detecting Hα+[NII] lines from A.1 and A.3. A.2 is likely off the slit.

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**)*

Targets: Our primary target is the $z = 0.89$ cluster CLJ1226.9+3332. We will obtain spectroscopic redshifts of several multiple-image systems at $z \sim 3-5$ identified in this cluster field, and will construct an accurate cluster mass model, which will allow us to study the intrinsic properties of the $z = 2.26$ lensed DSFG we have discovred. Note that because the three multiple images of galaxy A are due to galaxy-galaxy lensing by a foreground galaxy, its spectroscopic redshift does not allow us to constrain the cluster mass distribution at larger scale. We will simultaneously measure the redshifts for a number of *Herschel* sources in the field, identifying infrared-bright cluster members. Since the redshift of this cluster is uniquely high in our HLS sample, it is of great interest to study the star-forming properties of galaxies in this cluster. CLJ1226.9+3332 is one of the CLASH clusters, and therefore has a wealth of ancillary data. Note, however, that this cluster is too north for VLT, and is not included in the CLASH-VLT/VIMOS follow-up program.

As a secondary target, we will observe another northern (DEC$> +30$) CLASH cluster (see the target list for potential targets). MACSJ0717.5+3745 is particularly interesting because it is one of the HST Frontier Field clsuters, and its ultra-deep Frontier-Field coverage will be completed by the end of 2014. Therefore, the optimal period for our observing run is Feb–Mar, when both CLJ1226.9+3332 and MACSJ0717.5+3745 are observable. However, if the run can only be scheduled at a much later time, we will observe either MACSJ1720.3+3536 or A2261 as a secondary target.

Selection of optical counterparts: Multi-wavelength imaging for each cluster consists of Spitzer (IRAC and MIPS 24 μm) and/or near-infrared (J and K) bands, as well as multi-filter optical data (including HST). The majority of the ancillary data coincides with at least the 6'$\times$6' MODS field-of-view, enabling a full construction of the SED for the Herschel sources (Pérez-González et al. 2010), together with identification of the counterpart in high-spatial resolution imaging. Counterparts in at least the shortest IRAC bands (positional accuracy <0.5"), and ideally in optical bands, are important to attain the required precision in spatial coordinate. Photometric redshifts will guide the selection of candidate Herschel-detected cluster members. In the cluster center (covering the highest magnifications, $\mu > 1$ mag, and the strong-lensing region), HST images allow us to identify multiple-images and arcs.

Configuration and exposure time: LBT/MODS provides a 6'$\times$6' field of view, which is well-matched to the Herschel coverage of HLS. On average, accounting for the typical source density, a single mask can accommodate $\sim$20 slits.

A typical lensed source has a redshift $0.3 < z < 5$, with a peak in the redshift distribution at $z \sim$ 1.0–1.5. We therefore target line emission where available, and interstellar absorption features for the brightest objects, including cluster members. The red arm ($550 < \lambda < 1050$ nm) of MODS detects [OII] for $z \lesssim$1.8 and MgII for $z \lesssim 2.5$, and Lyα for $z \gtrsim$3.5. The sensitive, blue-optimized channel ($320 < \lambda < 600$ nm) will enable Lyα detections for sources beyond $z \gtrsim 1.6$ (and certainly for z > 2.0). The near continuous redshift coverage ensures that MODS will be especially powerful for this type of redshift search.

The preferred configuration uses the dual grating spectroscopy mode, which obtains the entire wavelength range (320–1050 nm) in one observation. We do not require particularly high spectral resolution, so we can open the slits up to a width of 1" and improve sensitivity. Since it is not possible to place all the important multiply lensed images on one mask, we will design two masks per cluster. Our previous experience with a range of optical spectrographs (VLT/FORS2, Keck/LRIS, Magellan/IMACS...) suggests a $\sim$4-hour exposure per mask. We estimate that this will be sufficient to detect continuum with a S/N of $\sim$5 at I=22 mag, while for fainter sources, the [OII] and Lyα emission lines should be detectable (under typical assumptions of equivalent widths) for sources as faint as I=25 mag.

Assuming 4 hours per mask (2 masks per cluster), a typical night in 2015A ($\sim$10–11 hours) should be sufficient to observe 2 masks for 2 clusters (assuming $\sim$40% overheads). To complete observations for two clusters, we propose two nights of telescope time.

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) This proposal forms one part of the Steward telescope time supporting our Herschel Program, "The Herschel Lensing Survey" (comprising both the HLS-deep and HLS-snapshot components). Two LBT/MODS nights were awarded in 2013A to target Herschel-selected sub-mm galaxies. High-redshift dropouts were also included in our masks and produced exciting preliminary results which are included in this proposal (Figure 3).

Magellan/IMACS (PI: T Rawle): Our 2010B IMACS run successfully targeted a comprehensive sample of Herschel sources in two HLS clusters. The results have been published in the following papaer:

"Discovery of Warm Dust Galaxies in Clusters at $z \sim 0.3$: Evidence for Stripping of Cool Dust in the Dense Environment?"
Rawle, T. D., et al. 2012, ApJ, 756, 106

LBT/Lucifer (PI: M Rex): Since 2010B, we have been awarded ∼7 nights with the near-infrared spectrograph Lucifer. Although poor weather and instrument misbehavior hampered observations on a few nights, we have obtained spectra for sources behind several HLS clusters to date. We have also obtained a spectacular Lucifer K-band image of a highly lensed FIR-detected arc (z∼2.4) behind MACSJ2043. Our experience with LMS for Lucifer will enable efficient mask design with the similar MODS package.

The two-pronged optical–NIR spectroscopic follow-up campaign allows us to target all Herschel-detected sources efficiently and regardless of the brightness of the optical counterpart. LBT/MODS should make an efficient tool for this type of spectroscopic campaign, and we anticipate further proposals in coming semesters, to complete coverage of the northern HLS clusters.

(2) Twenty-six HLS clusters visible from the southern hemisphere were targeted during two successful programs using ESO VLT/FORS2 (PI: J. Richard). Reduction is currently underway.

Our Arizona team has also used Keck/LRIS to observe a few clusters over three nights in 2012. Since the emphasis of this program is to identify $z > 6$ galaxies by exploiting the excellent red sensitivity of LRIS, the integration time per cluster was much longer. Therefore, the number of observed clusters is small.

(3) The Arizona team play a leading role in the HLS collaboration as a whole, which includes 30+ members in US and Europe, and encompasses a wide range of scientific interests.

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)***

The following is a list Steward time allocations obtained by PI Egami and his student/postdoc:

⋆ Magellan/MMIRS 2012A (PI: G. Walth; 2 nights allocated; ∼1 night usable)

⋆ MMT/SWIRC 2012A (PI: E. Egami; 2 nights allocated; no data due to snow)

⋆ LBT/Lucifer 2012B (PI: M. Rex; 2 nights allocated; 2 nights observable)

⋆ LBT/MODS 2013A (PI: E. Egami; 2 nights allocated; 2 nights observable)

⋆ Magellan/IMACS 2013B (PI: E. Egami; 2 nights allocated; 1 night observable)

Status of the Observations

LBT/Lucifer: Five clusters have been successfully observed to-date, with the reduction currently underway (with a pipeline developed by M. Rex and G. Walth, based on the Carnegie/Magellan COSMOS package). Results from selected sources will be included in Egami et. al. (2014, in prep).

Magellan/IMACS: Observations were very successful in 2010B, with clear weather and no technical difficulties. Two clusters observed with data reduced and redshifts determined. The results have been published in the following papaer:

"Disocvery of Warm Dust Galaxies in Clusters at $z \sim 0.3$: Evidence for Stripping of Cool Dust in the Dense Environment?"
Rawle, T. D., et al. 2012, ApJ, 756, 106

Although the weather was not great for the 2013B run, we did manage to obtain some useful data, including the detection of Lyα line from a $z = 5.66$ galaxy (B. Clement, 2014, in prep).

Magellan/MMIRS: These observations constitute part of G. Walth's Ph.D. thesis project. The data reduction has mostly been done.

LBT/MODS: The data are currently being analyzed. Egami et al. presented these results at the recent STScI workshop (May 2013) on lensing clusters, and B. Clement is currently drafting a paper.