OBSERVING REQUEST
University of Arizona Observatories

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

Mapping the Most Powerful Gravitational Lens Telescopes with MMT Hectospec

P.I.: Kenneth C. Wong (ASIAA; *kcwong@asiaa.sinica.edu.tw*; 886-02-2366-5428)

CoI(s): Ann I. Zabludoff (SO), K. Decker French⋆ (SO),
S. Mark Ammons (Lawrence Livermore National Laboratory),
Charles R. Keeton (Rutgers University), Curtis McCully (UC Santa Barbara)

Abstract of Scientific Justification

Detecting the earliest galaxies at $z \gtrsim 7$ and determining their properties is a major challenge in observational cosmology. Past studies have required a large investment of HST time and have only detected a handful of high-z candidates. Gravitational lensing by a foreground galaxy cluster can make these sources easier to detect, but also reduces the volume surveyed, limiting the chance of detection. Thus, the best gravitational telescopes may not be those currently in use, but other lines of sight whose total mass is larger and optimally distributed to produce the highest étendue, or largest area of high magnification. Our work has shown that lines of sight containing multiple halos in projection can increase the lensing cross section, allowing one to probe further down the luminosity function. *We have identified fields in SDSS with the highest total luminosity densities of luminous red galaxies. Galaxy spectroscopy reveals that these lines-of-sight have multiple cluster-scale halos and larger total masses than even known strong lensing clusters, and so are more powerful gravitational lens telescopes.* We have recently published papers on our selection methodology, the modeling of the first two beams, and the frequency of such beams predicted by cosmological simulations. Here, we propose to complete spectroscopy of the remaining three of the sample of ten beams. These three are identified from the SDSS and are likely to be among the very best on the sky. All sample beams have archival, awarded, or proposed Subaru imaging necessary to constrain the magnification maps to the precision required to convert follow-up high-z detections to an intrinsic galaxy luminosity function.

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	*		2	dark	Jan–Jul	Jan–Jul	yes	yes

Scheduling constraints and unusable dates *(up to 4 lines)*: We prefer these targets, but we have other targets available throughout the semester if necessary.

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	0104	01:04:33.2	+12:51:41	
2	2322	23:22:36.9	+09:24:08	
3	1616	16:16:11.9	+06:57:45	

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
K. Decker French	Ann Zabludoff		no	no

Scientific Justification

The Most Powerful Telescopes In the Universe – Detecting very high-redshift ($z \sim 7-10$) galaxies is key to understanding how the first generation of stars and galaxies formed, and to what extent their UV emission is responsible for reionizing the neutral hydrogen during this epoch. However, observing these sources is extremely challenging. Applications of the Lyman-break dropout technique to blank fields (e.g., Bouwens et al. 2011, 2014; Ellis et al. 2013; McLure et al. 2013; Oesch et al. 2013a,b; Schenker et al. 2013) have required a large investment of *HST* time and detected only a handful of $z \sim 10$ candidates. Gravitational lensing by foreground galaxy clusters can help, but only if the volume surveyed for high-z sources remains large despite the magnification. The HST Frontier Fields will target $4-6$ lensing clusters to detect faint high-redshift galaxies that are otherwise unaccessible. While these are very powerful and well-characterized lenses, they may not be the *best* gravitational telescopes in the Universe — there are lines-of-sight (or "beams") whose total mass is larger and optimally distributed to produce the highest étendue, the largest area in the source plane with high magnification.

We have shown that lines of sight containing multiple, projected, cluster-scale halos can boost the lensing cross section by up to $\sim 3\times$ relative to the single-cluster lenses commonly exploited for high-z source detection (Wong et al. 2012). *This improvement can translate into a ∼3-30× increase in $z \sim 10$ detections at the faint end of the galaxy luminosity function (LF)*, depending on the (very uncertain) faint-end slope. Our analysis of cosmological simulations reveals that the beams most successful at lensing $z \sim 10$ galaxies are $10\times$ more likely to contain multiple, cluster-mass halos than single clusters (French et al. 2014).

Using luminous red galaxies (LRGs) to trace massive structures, we have identified the 200 lines-of-sight, or "beams", with the highest total LRG luminosities in the Sloan Digital Sky Survey (Wong et al. 2013). (One highly-ranked beam contains Abell 370, a Frontier Field, confirming the power of our technique.) Our galaxy spectroscopy with 6.5-m telescopes confirms that these beams contain multiple rich structures and have integrated masses up to $\sim 2\times$ those of the best known strong lensing clusters (Ammons et al. 2014). The two best-sampled beams to date include 2-3 cluster-scale halos and have total masses of $> 3 \times 10^{15} M_{\odot}$ (0850 and 1306; Ammons et al. 2014). Archival imaging data from Subaru/Suprime-Cam reveals new lensed arcs in these beams — *including a unique, multiply-imaged, sub-L^* candidate at $z = 5.03$* — confirming their power as lenses (Figure 2).

We have modeled the spectroscopically-derived mass in each beam, producing the first 2-D magnification maps in these unique fields (Ammons et al. 2014). These maps may have significantly more étendue than known lensing clusters, establishing our beams as some of the best gravitational lens telescopes known (Figure 2, right panel). *Their extreme lensing strengths make them legacy-class fields important to many branches of astronomy, including the vastly improved detection of distant sources at all wavelengths.*

The Problem – What are the characteristics of beams that will maximize the efficiency of detecting the highest redshift galaxies? Known lensing clusters do not necessarily represent the highest mass density lines-of-sight. They are also inferior to fields with multiple projected structures, which work to maximize the areas of ideal magnification needed for optimal source detection. Using Monte Carlo simulations, we have generated magnification maps for $z = 10$ sources lensed by various mass configurations. Beams that contain multiple cluster-scale halos offset on the sky and in redshift can increase the number of detections possible with single cluster lenses (Wong et al. 2012). Lensing techniques maximize the source counts at a given redshift when the sensitivities of current instruments cannot penetrate below L^* (Bouwens et al. 2009), as is the case with J-band dropout surveys at $z \sim 10$ with HST WFC3 (Bouwens et al. 2011).

The Solution – We have identified the 200 beams with the largest projected LRG luminosity (∼mass) densities in the SDSS DR9 (Wong et al. 2013). Structures traced by the LRGs in these beams lie between $0.1 \lesssim z \lesssim 0.7$, optimal lensing planes for this program. These beams represent the best chances for making 1) $z \gtrsim 7$ galaxies detectable with the dropout technique and 2) IR spectroscopic follow-up possible. Our beams have higher total LRG luminosities and magnification area than even the most spectacular single lensing clusters. The legacy of these beams may also include vastly improved detection of γ-ray sources and supernovae at cosmological distances, as well as multi-wavelength investigations of the detailed properties of strongly-lensed sources with future space and large ground-based telescopes.

Progress to Date – MMT/Hectospec and Magellan/LDSS3 spectroscopy in 2011-2014 confirms that the lensing power of these beams may exceed those of the best known lensing clusters. We have obtained **2627** reliable redshifts in the seven beams with a mean redshift success rate of 85%. All Hectospec spectra have been reduced using the HSRED reduction package (R. Cool, priv. communication) and LDSS3 spectra have been reduced with the LCO COSMOS package (Oemler 2011). Twenty-five large galaxy overdensities are obvious in the five beams with mass models, with LOS velocity dispersions ranging from $\sigma \sim 300$ km s^{-1} to 1275 km s^{-1}.

This spectroscopy has confirmed that many galaxy overdensities are associated with LRGs and that LRGs are a sensitive tracer of mass. Redshift histograms are shown in Figure 1 for the two best-sampled of our beams (Ammons et al. 2014). 84% of the LRGs are associated with density peaks in the line-of-sight galaxies. Multiple massive structures are seen at $0.4 < z < 0.8$ in these beams. However, three other similarly promising fields are currently not sampled sufficiently to determine their contribution to the magnification maps. We propose to use MMT/Hectospec to perform deeper spectroscopy in these beams.

Identifying Gravitational Lensing in Subaru Imaging – Subaru/Suprime-Cam imaging is available for five of the beams that we have mapped spectroscopically, exceeding three hours total depth in five bands for three of the beams. We have been awarded or recently proposed for Subaru/Suprime-Cam time for the remainder. So far, imaging of the first field, 0850, has revealed a multiply-imaged V-dropout galaxy ($V - i > 2$ for both components, see Figure 2, left panel). The similarity of SEDs, morphologies, and positions of the components, their elongation perpendicular to the radial vector, and high length-to-width ratio all suggest that they are multiple images of a single galaxy. The maximum-likelihood photometric redshift solution is $z \approx 5.03$, corresponding to a redshifted Lyman Break at ~ 6000 Å. The position of these arcs $55''$ away from the center of the cluster implies a significant critical curve radius for a $z \sim 5$ source plane and an extended field of high magnification. The position of these arcs also agrees with the critical curves as predicted by a mass model constrained by Hectospec spectroscopy (Figure 2, left panel), independently confirming our mass modeling technique (Ammons et al. 2014). The beam hosting this multiply-imaged set is 80% spectroscopically complete to $i = 21.1$ and we do not request further Hectospec time for this target.

These data also contain a large population of background galaxies that can be used for complementary weak lensing analyses of these beams, which we have begun to explore using the existing archival imaging data. We can define a robust sample of background galaxies through a well-tested color-color selection (Medezinski et al. 2010, 2013; Umetsu et al. 2012), allowing us to measure the shear profile around the clusters. We now have the ability to perform full joint modeling with constraints from spectroscopy, strong lensing, and weak lensing (Tagore & Keeton 2014).

Sample Size for Spectroscopic Follow-Up – Of the beams originally selected for their high integrated LRG luminosities, we have been mapping seven spectroscopically. The required sample size of ~ 10 is set to equate the cosmic variance and Poisson errors on n^* at $z \sim 7$ in a hypothetical deep imaging survey with HST to detect $z \gtrsim 7$ dropouts. Assuming the Bouwens et al. (2010, 2011) and Hall et al. (2011) constraints on the $z \sim 7$ - 10 LFs, were we to follow-up our beams with an ultra-deep ($\sim$ 200 orbits) $izJH$ dropout survey, we would detect 48-70 sources at $z \sim 7$ and 4-6 sources at $z \sim 10$ with 5σ confidence. With these numbers of detections, the uncertainties on n^* at $z \sim 7$ due to Poisson error (14.4% for 48 sources) and cosmic variance (14.8%, Trenti & Stiavelli 2008) are comparable for $\sim$ 5-10 widely separated beams.

Why We Need Hectospec Spectroscopy – Finding the regions of ideal magnification requires a map of the magnification to $z \gtrsim 7$. This can be generated from a lens model of the LOS mass distribution using spectroscopic redshifts and positions of field galaxies as constraints (see *Experimental Design*). The resulting magnification map, in concert with the Subaru (and possible *HST*) lensing constraints, will ultimately be used to convert measured photometry of magnified sources at $z > 7$ into intrinsic luminosities. In recent work (Ammons et al 2014), we confirm that our spectroscopic approach produces magnification maps consistent with those determined independently from deep *HST* imaging of lensed galaxies.

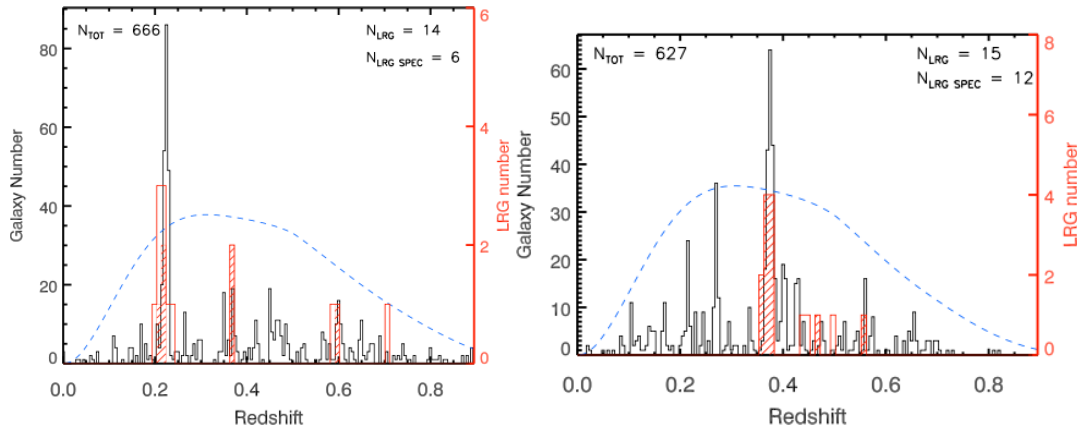

Figure 1: Redshift histograms for two of the beams for which we have acquired spectra over $10.'0$ diameter fields of view from Hectospec and performed reductions. The galaxies in the SDSS DR9 LRG catalog that overlap with our targets (~40% of all LRGs in these fields) are overplotted in red, with our spectroscopic redshift used in place of the original photometric redshift. 84% of the LRGs lie in clear galaxy overdensities, and thus are tracers of the overall mass distribution. Based on their LRG statistics, we expect that the three beams we propose here to finish have even more mass projected along the LOS.

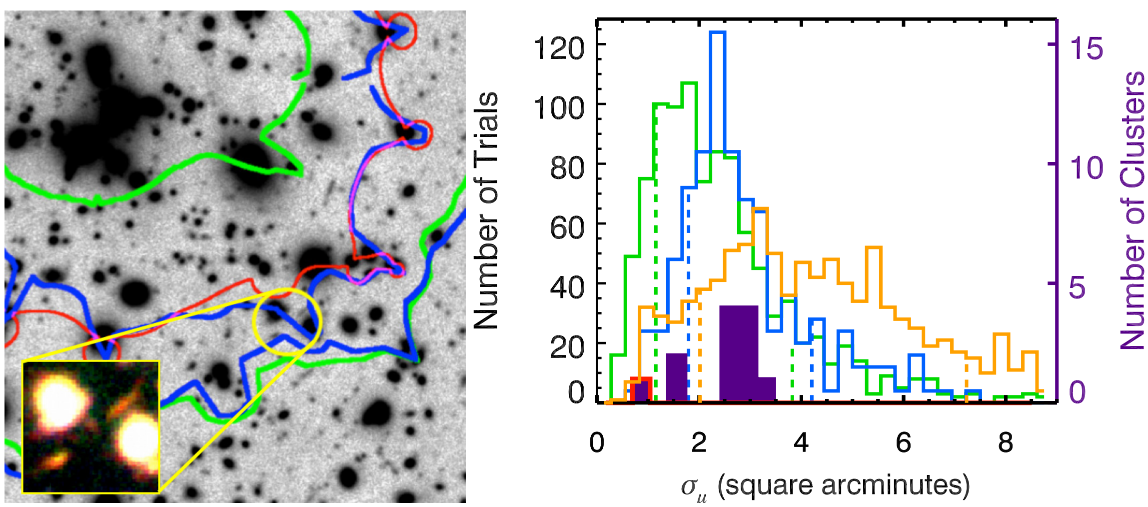

Figure 2: **Left:** Subaru/Suprime-Cam image ($1.0' \times 1.0'$) containing the multiply-imaged candidate in beam 0850 (yellow circle). Both components are V-dropouts with a maximum-likelihood photo-z of $z = 5.03$. Predicted critical curves for a $z_s = 5.03$ source plane, as determined by our mass model derived from Hectospec spectroscopy alone, are shown in red and are consistent with the candidate. The 1-σ range of predicted critical curves with no lensing constraints is shown in green, while the range when using the multiply-imaged source as a constraint is shown in blue. The constraints are greatly improved by just this single lensed source. **Right:** Probability distributions of $\sigma_{\mu>10}$ (area in the lens plane with magnification $\mu > 10$) with a $z_s = 10$ source plane for beams 0850 (green) and 1306 (orange) determined by marginalizing about known observational errors and uncertainties in constraining cluster properties. The blue curve shows the distribution for 0850 when using the multiply-imaged $z_s = 5.03$ candidate as a lensing constraint. The dashed lines show the 68% confidence intervals. Note that the addition of the strong-lensing information has restricted the range of $\sigma_{\mu>10}$ and increased the median value of the distribution. For comparison, we include a histogram of $\sigma_{\mu>10}$ values for 12 massive clusters in the MACS survey (violet histogram; Zitrin et al. 2011), as well as for ACT-CL J0102-4915 ("El Gordo", red histogram, Zitrin et al. 2013). The median of the $\sigma_{\mu>10}$ range for 0850 is comparable to the values for the known massive clusters when including the strong lensing constraint, and the range for 1306 surpasses these 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**)*

We propose to complete our MMT/Hectospec spectroscopy of $200 - 400$ field galaxies per beam in three of the most luminous of the ultra-high density beams we have selected from the SDSS DR9 LRG catalog (Wong et al. 2013). In the case of individual LOS galaxies, we will convert their absolute magnitudes into masses. For more massive, bound structures including ten or more galaxies, we will use the galaxy kinematics to estimate the group or cluster velocity dispersion and virial mass (Ammons et al. 2014). We are identifying large, lensed arcs in these fields with past optical imaging data from NOT and WIYN (M. Gladders, priv. comm.), archival and upcoming optical data from Subaru/Suprime-Cam, and NIR data from LBT/LUCI.

Hennawi et al. (2007) found that structures at redshifts z ~0.2-1 are most likely to lens high-redshift ($z > 4$) sources into detectability, with the peak in likelihood at $z \sim 0.5 - 0.6$. We thus need considerable wavelength coverage. We will obtain low resolution ($\sim 6 - 10$ Å) spectra covering $\sim 5000 - 9000$ Å, which will span [OII] to Hβ for galaxies out to $z \sim 0.8$ and will include at least [OII] and Ca II H + K for more distant galaxies. We design the spectroscopic program to constrain the masses of all galaxy structures with $\sigma > 300$ km s^{-1} out to $z = 0.8$, fully sampling the redshift range over which the LRGs are seen (Figure 1). The LRGs are observed to reside in groups with velocity dispersions as low as $\sigma \sim 300$ km s^{-1} in our beams, so we must be complete to at most this mass to avoid missing a significant contributor to the lensing magnification. Groups with velocity dispersions > 300 km s^{-1} are likely to have ten or more $0.7L^*$ or brighter galaxies (Zabludoff & Mulchaey 1998) whose redshifts can be used to securely constrain the velocity dispersion and virial mass of the system. Thus, we choose our spectroscopic depth ($I_{AB} \sim 21.1$) to sample quiescent $0.7L^*$ galaxies out to $z \sim 0.8$. Redshifts (and thus rough mass estimates) for individual quiescent galaxies a magnitude brighter than L^* and for star forming L^* galaxies can be obtained out to $z \sim 1$, necessitating good wavelength coverage in the red. *Our analysis of beams in the Millennium and Millennium XXL simulations indicates that unseen mass below our sensitivity limits or beyond $z \sim 1$ is unlikely to perturb our magnification maps by more than a few percent* (French et al. 2014).

Target Selection and Exposures – We propose to use MMT/Hectospec to complete our mapping in three of the densest beams in our sample. These beams are selected for their clear overdensity of bright, red sources in SDSS imaging and correspondingly high projected luminosity density relative to well-known lensing clusters. To increase efficiency over the targeted redshift range ($0.4 < z < 0.8$), we include a simple color cut ($i - z > 0.3$) to de-prioritize $z < 0.4$ structures, which have been well-sampled in previous Hectospec runs. Each beam has between 42 and 149 SDSS-identified galaxies with $I_{AB} < 21.1$ and $i - z > 0.3$ that are projected within $3\overset{'}{.}5$ of the beam center and have no measured redshift.

Two of the three targeted beams have been partially mapped with previous MMT/Hectospec observations. The proposed observations are necessary to reach ~80% redshift completeness in these three beams for $I_{AB} \leq 21.1$, $i - z > 0.3$, and $r < 3\overset{'}{.}5$. For quiescent galaxies, using absorption lines such as Ca II H + K, a signal-to-noise ratio of 3 per resolution element is required to obtain a reliable redshift. The *xfitfibs* software indicates that we can observe ~35 of our 42-149 central galaxies in a single pointing. We require one to four configs each to obtain redshifts for sources with $I_{AB} < 21.1$ and $i - z > 0.3$. In our experience with Hectospec, 120 minutes per slitmask will reach this depth. Including 30 minutes of overhead per config and 1-4 configs per beam, we require 20 hours to complete the three targets with Hectospec, or 2 nights.

The Need for Hectospec – MMT/Hectospec's large field of view is preferred for obtaining galaxy redshifts beyond the selection radius of these beams ($3\overset{'}{.}5$), some of which will be bound to central structures and will be helpful for constraining their centroids and velocity dispersions. Slitted multi-object spectrographs on telescopes of comparable size deliver roughly similar numbers of centralized objects per pointing (~ 50), but do not sample beyond the selection radius due to limited field size. Each Hectospec configuration will deliver spectra for hundreds of additional galaxies beyond the $3\overset{'}{.}5$ selection radius.

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**)*

Overall Project Scope and Complementary Observations – Our ultimate goal is to use powerful lensing beams as gravitational telescopes to magnify high-redshift sources ($z \gtrsim 7$) into observability. Constraining the mass model in these beams is a necessary first step to localizing the areas of ideal magnification on the sky. These data can be used in conjunction with strong lensing constraints from ongoing deep imaging of arcs in these beams (see below) in order to determine a more accurate mass model.

As part of this program, we have been awarded 155 hours of observing time with MMT Hectospec (90 hours actually dispersed) through UAO and NOAO and 2 nights with Magellan/LDSS3. We have used this time to survey seven of our densest beams (with six completed) and have constructed mass models for five. These data have confirmed that our beams are exceptionally massive, but we require better completeness on the line-of-sight structures to construct a magnification map of the precision necessary to infer intrinsic luminosities of high-redshift lensed sources. All three of the proposed targets are highly ranked in our list sorted by integrated LRG luminosity density, and have no existing spectroscopic coverage. The proposed 2 nights with Hectospec will complete the spectroscopic coverage in all three beams.

We have been awarded optical broadband photometry time with Subaru/Suprime-Cam 2013A-2014B through NOAO and NAOJ to obtain deep multi-color imaging of these beams, comparable to archival data available for beam 0850 in which we identified the multiply-imaged $z \approx 5.03$ candidate. This imaging will reach ~ 27 AB depths in $BVRiz$ for beams in which we have spectroscopic data. This data, along with complementary J-band observations from LBT/LUCI, will be used to identify multiply-imaged galaxies at $z \sim 1 - 3$ through their similar colors and morphologies. The photometric observations will also be used to calculate photometric redshifts, which are crucial for lens modeling of these beams. Strong lensing constraints provide more accurate constraints on critical curve locations, but only for a few field positions; galaxy redshifts provide better field sampling. We have demonstrated our methods with the first two beams (0850 and 1306), and are proposing to target the remaining three required for high-z source detection statistics in subsequent semesters. The larger collaboration is centered at the University of Arizona, but includes Anthony Gonzalez (U Florida), David Hogg (NYU), and Keiichi Umetsu (ASIAA).

Resources and Publication Timescale – We are committed to prompt reduction and analysis of the Hectospec data. Our team's motivating goals are to (1) quickly confirm and publicize our strong lensing beam selection methodology and (2) use mass-modeling of the redshift distribution to identify regions of ideal lensing magnification for follow-up near-IR spectroscopy. ApJ papers describing our selection method (Wong et al. 2013), presenting spectroscopy of our best two cosmic telescopes (Ammons et al. 2014), and detailing the results of our analysis of lensing beams in the Millennium and Millennium XXL simulations (French et al. 2014) have been published.

CoI Ammons and PI Wong will be responsible for reducing the data from these observations and the complementary LBT imaging observations. CoIs Zabludoff & Keeton's NSF grants (AST-1211874; AST-1211385), PI Wong's EACOA Fellowship grant provide adequate resources for data reduction, analysis, and publication. This project has been and will continue to be primarily run and funded out of Steward Observatory.

Previous Use of Steward Facilities *List **all** allocations of telescope time for the present project and allocations for other projects on facilities available through UAO during the past 2 years, together with the current status of the data (cite publications where appropriate). Mark those allocations related to the present proposal (i.e, precede text with* `\related` *command). (**up to one page**)*

⋆ **PI Wong:** 2014B: Awarded 20 hours of Hectospec time for the same spectroscopic program.

⋆ **PI Wong:** 2014A: Awarded 20 hours of Hectospec time for the same spectroscopic program.

⋆ **PI Wong:** 2013A: Awarded 1 night of LBT/LUCI imaging time for this same imaging program targeting lensing beams with the goal of identifying and constraining the photometric redshifts of multiply-imaged systems in these fields. Data from this imaging program is presented in Ammons et al. (2014).

⋆ **PI Wong:** 2013A: Awarded 20 hours of Hectospec time for the same spectroscopic program.

⋆ **PI Wong:** 2012C: Awarded 20 hours of Hectospec time for the same spectroscopic program.

⋆ **CoI Ammons:** 2011C: Awarded 13 hours of Hectospec time (9 hours actual) for the same spectroscopic program.

⋆ **CoI Ammons:** 2011B: Awarded 24 hours of Hectospec time (17 hours actual) for the same spectroscopic program.

⋆ **CoI Ammons:** 2011A: Awarded 20 hours of Hectospec time (16 hours actual) and 2 nights of Magellan LDSS3 time for a spectroscopic program targeting lensing beams for this project with the goal of determining a preliminary model for the mass distribution along the LOS and confirming the lensing strength of the beams. See "Progress to Date" section in Scientific Justification.

ApJ papers presenting our selection method and presenting our current spectroscopy for the best two beams have been published:

- **Ammons, S.M., Wong, K.C., Zabludoff, A.I., & Keeton, C.R. 2014, ApJ, 781, 2**
- **Wong, K.C., Zabludoff, A.I., Ammons, S.M., Keeton, C.R., Hogg, D. W., & Gonzalez, A. H. 2013, ApJ, 769, 52**

⋆ **CoI Zabludoff:** Papers that have been published or are being prepared including data from previous allocations of MMT/Hectospec time (as well as Magellan/IMACS/LDSS3 time) for lensing projects:

- **Wong, K.C., Keeton, C.R., Williams, K.A., Momcheva, I., & Zabludoff, A.I. 2011, ApJ, 726, 84**
- **Momcheva, I., Williams, K.A., Keeton, C.R. & Zabludoff, A.I. 2006, ApJ, 641, 169**

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

- **McCully, C., Keeton, C.R., Wong, K.C., & Zabludoff, A.I. 2014, MNRAS, 443, 3631**
- **French, K. D., Zabludoff, A.I., Wong, K.C., Ammons, S.M., & Keeton, C.R. 2014, ApJ, 785, 59**
- **Wong, K.C., Ammons, S.M., Keeton, C.R., & Zabludoff, A.I. 2012, ApJ, 752, 104**
- **Williams, K.A., Momcheva, I., Keeton, C.R., Zabludoff, A.I., & Lehar, J. 2006, ApJ, 646, 85**
- **Keeton, C.R. & Zabludoff, A.I. 2004, ApJ, 612, 660**
