OBSERVING REQUEST
University of Arizona Observatories

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

Spectroscopic measurements of concentrated GAMA group galaxies 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), Bhavin Joshi⋆ (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 deep spectroscopic observations of concentrated groups of galaxies in order to gain a detailed understanding of their mass profiles and use them to lens high redshift galaxies. 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 not currently possible. Concentrated groups present an attractive, far more abundant alternative to massive galaxy clusters for lensing $z > 8$ galaxies. We have identified a sample of the 10 most concentrated groups from the Galaxy And Mass Assembly (GAMA) group catalog, and wish to conduct deep spectroscopic surveys of each in order to thoroughly determine their galaxy membership to $m_r = 21.5$ mag. **These are the very best 10 lensing groups at $z \sim 0.4$, selected from amongst 2400 GAMA groups through lensing modeling using their known group masses and concentrations.** These observations will in turn lead to a detailed model of the surface density profiles of each concentrated group; a crucial step in lensing studies. We estimate that these lenses will magnify upwards of 500 galaxies at $2 < z < 9$, which we will image with guaranteed JWST GTO time.

Summary of observing runs requested for this project

Run	Telescope	Cage	Instrument	PI	AO	Nights	Moon	Scheduling Optimal	Scheduling Acceptable	Sharing Poss.	Sharing Adv.
1	MMT	f/5	Hectospec			3	dark	Feb–Mar	Jan–Apr	yes	no

Scheduling constraints and unusable dates *(up to 4 lines)*: None.

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 Group 100063	08:54:46.54	-01:21:37.03	z=0.106 concentrated group, $\geq$12 members
2	GAMA Group 100662	08:36:58.92	00:06:39.03	z=0.328 concentrated group, $\geq$6 members
3	GAMA Group 200059	12:17:31.51	00:23:49.84	z=0.372 concentrated group,$\geq$14 members
4	GAMA Group 300715	14:31:21.19	-00:53:44.33	z=0.402 concentrated group, $\geq$5 members
5	GAMA Group 300765	14:18:12.65	-00:08:35.22	z=0.356 concentrated group, $\geq$5 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. These targets, however, are too distant to be barely resolved as anything but point sources. An alternative approach to visualizing these systems has been to magnify them with gravitational lenses, which enables the detection of several 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 mag/sq.arcsec and 30 mag/sq.arcsec, 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 groups (CGs) offer an equally suitable and attractive alternative as lenses, particularly because their mass profiles are very centrally concentrated, like 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 ten CGs. **We therefore propose to use MMT/Hectospec to conduct deep spectroscopic observations of these CGs in order to characterize the membership of these groups as precisely as possible,** data we will then use to constrain the surface density profiles of each group. We will then 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 look for high redshift galaxies.

2. Concentrated groups selected from GAMA

The GAMA survey is highly complete (98%) spectroscopic redshift survey out to $m_r = 19.8$ mag with $\sim$200,000 spectra in three equatorial fields measuring 5×12 sq degrees each; as well as two fields in the southern sky, all of which are shown in Figure 1. One of the primary data products of GAMA is the GAMA Galaxy Group Catalogue (G^{3}C, Robotham et al. 2011, Figure 2), which classifies approximately 40% of the galaxies in the survey as belonging to a group. **We wish to use Hectospec to fully characterize the membership of these groups, past $m_r = 19.8$ mag**. From this catalog, we have identified a sample of 10 concentrated groups 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 group using its dynamical mass and the slope between the 50$^{\rm th}$ and 68$^{\rm th}$ percentile radii. When then estimated the dark matter halo that these CGs 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 10 CGs are expected to lens approximately 500 galaxies at $z > 2$, with 10 or more galaxies at $z > 8$.** Figure 4 displays an HST ACS/WFC3 image of GAMA CG 200011 lensing a background galaxy, demonstrating the feasibility of CGs as lenses.

3. Sample selection

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 group has a measured radius r and velocity dispersion σ_v value associated with it; from these values we derive calculate the dynamical mass of each group ($M \propto r\sigma_v$) using mock galaxy catalogs whose geometry and luminosity function match those of GAMA. We note that we only consider groups with 4 or more members in order to ensure the measured σ_v value is reliable. The concentration parameter 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.

Given a certain mass and concentration, one can calculate the magnification bias for strong lensing (Wyithe et al. 2003), which is defined as:

$$B(f) = \frac{\int_{\mu_{\rm lim}}^{\infty} N(> f_{\rm lim}/\mu) \times (dP/d\mu) \times d\mu}{N(> f_{\rm lim})} \tag{1}$$

where $P(>\mu)$ is the probability of getting a magnification greater than surface brightness μ; $f_{\rm lim}$ and $\mu_{\rm lim}$ are the limiting flux and brightness (28 mag in our case); and $N(> f)$ is the expected number of sources within the strong lensing area of the source above a flux f. For sources at $z \sim 8$, assuming a Bouwens et al. (2001) luminosity function, with $\alpha = -1.91$ and $M_* = -20.1$ mag. The lensing bias is therefore the ratio between the number of objects that may be observed via lensing and the number of objects observed in the absence of lensing. **Based on this, we pick 10 CGs with the highest bias parameter** and list their basic properties and the predicted number of objected lensed by each in Table 1, and we show a wider distribution of GAMA groups at $z \geq 0.35$ and the number of predicted lensed systems in Figure 3. While uncertainties exist, the lensing capability of a group is primarily set by the surface density of galaxies along our line of sight. Our calculated surface densities mark these ten groups as the strongest lenses in the GAMA catalog.

4. CGs and weak lensing

While a strong-lensing study reproduces mass profiles of the group centers, a weak-lensing study can extend the mass profiles to the far-outskirts of the groups (see Limousin et al. 2007 for a combined study of strong and weak lensing). As we already have good seeing images from the GAMA survey and previous HST observations, MMT spectra out to $m_r = 21.5$ mag will make it possible to outline the mass profile of each CG to well beyond the virial radius. We expect to obtain the redshifts for the group and its surrounding large scale structure, all of which contribute to the weak lensing signal, from Hectospec observations.

When it comes to a weak-lensing study of clusters, obtaining photometric redshifts (photo-z) from multi-band imaging is usually enough, because the lensing kernel is broad, spanned over a large distance so that the overall result is not very sensitive to the source redshifts (Hoekstra 2013). However, we are dealing with CGs which have much smaller mass and much fewer background galaxies, resulting in a weaker weak lensing signal cf. clusters. This requires spectroscopic level accuracy for the redshift distribution. Even if photometric redshifts suffice, it is still important to know the exact redshifts for the foreground lenses for better photo-z estimation; particularly as it allows for a better Bayesian estimation of photo-z values, acting as an additional constraint.

Hectospec gives us an exceptional opportunity for our spectroscopic study in that it can obtain 300 spectra simultaneously. It will give valuable information on source and lens redshifts for constructing mass profile fully from the centers to far beyond the outskirts of the groups we study.

5. CGs in large scale structure

With its high spectroscopic completeness, GAMA lends itself very well to studies of structure, from the group regime to large scale structure (see Alpaslan et al. 2014a, b for recent results). Groups 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 (Alpaslan et al. 2014a). Given the very wield field of view that Hectospec has, fibers placed on galaxies on the outskirt of each group will give us a unique, first-time glimpse of the dynamics of galaxies infalling from filaments onto groups, and the mass profiles of concentrated groups in filaments.

Recent work by Lopes et al. 2014 and Lacerna et al. 2014 indicates that local density plays a more important role in galaxy evolution as opposed to the mass of the group in which the galaxy resides, particularly with respect to its color, morphology, and concentration. They suggest instead that the role of a group is to trigger changes in the stellar population of a galaxy as it falls into the group, as opposed to once it is inside it. Our Hectospec observations would give us a unique perspective into precisely these dynamics; and when combined with existing robust GAMA catalogs of galaxy properties, provide for a more detailed analysis of the changes in a galaxy as it falls into a group.

Group ID	Term	RA	Dec	$\log\left(\frac{M}{M_\odot}\right)$	$\langle z \rangle$	Concentr.	N(lensed)
100662	2015A	129.2455	+0.1108	13.63	0.33	25	$\geq$1, 2, 20
100965	2014B	130.4616	+2.9932	13.61	0.42	21	$\geq$1, 4, 40
101258	2014B	133.2719	+0.1268	13.59	0.38	20	$\geq$1, 3, 30
101744	2014B	131.2552	+1.4600	13.61	0.41	27	$\geq$1, 7, 70
200059	2015A	184.3813	+0.3972	14.16	0.37	12	$\geq$1, 5, 50
200245	2015B	185.2105	+0.1359	14.95	0.40	5	$\geq$1, 2, 20
200315	2015B	174.9247	+0.7624	13.58	0.35	18	$\geq$1, 2, 20
201041	2015B	175.7007	+0.5193	13.64	0.41	20	$\geq$1, 4, 40
300715	2015A	217.8383	−0.8956	13.88	0.40	15	$\geq$1, 3, 30
300765	2015A	214.5527	−0.1431	14.17	0.36	13	$\geq$1, 5, 50

Table 1: The ten best concentrated group galaxies for lensing in GAMA. N(lensed) gives the expected number of lensed objects observable with HST at $z > 8$ and at $z > 2$, and with JWST at $z > 2$.

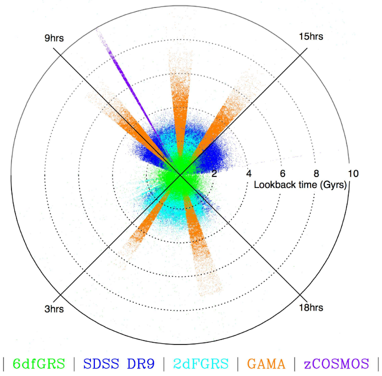

Figure 1: An 'overhead' view of the distribution of galaxies in the GAMA, SDSS DR9, 2dFGRS, 6dfGRS, and zCOSMOS surveys. *GAMA's three equatorial fields (shown in orange) are spectroscopically 98% complete and* **provide the best existing data set for identifying concentrated groups at** $0.1 \leq z \leq 0.4$ **or a lookback time of 4 Gyrs.**

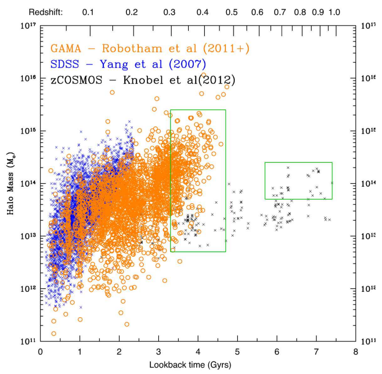

Figure 2: Mass and redshift distributions for groups in different surveys. At $\sim$4 Gyrs lookback time, GAMA groups (Robotham et al. 2011; green box) cover higher redshifts than SDSS groups, and higher masses than COSMOS groups, despite that these extend to somewhat higher redshifts. Fewer than 10% of galaxy groups with $\gtrsim$4 known members are concentrated (Konstantopoulos et al., in prep) **We propose to observe the 10 most concentrated GAMA groups with MMT/Hectospec**.

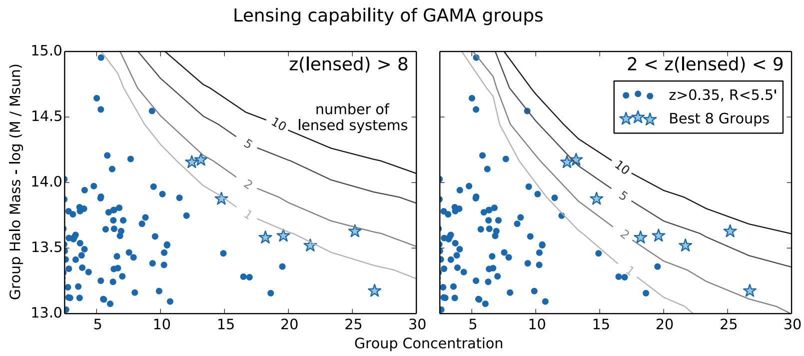

Figure 3: [*Left*] Distribution of mass and concentration for GAMA groups at $z \geq 0.35$. The concentration parameter is estimated from the 50 and 68% group mass radii. Contours are the number of predicted lensed sources, assuming NFW DM halo profiles. This prediction assumes a limiting magnitude of $AB \approx 28$ mag (for HST observations). *Guaranteed JWST Time will yield 50 times more lensed objects*. [*Right*] Same for lensed objects with $2<z<9$. JWST's 2 mag depth increase over HST will provide 6$\times$ more sources, and its wider redshift range another 2$\times$more sources. **These best lensing GAMA groups will yield in total 40 lensed objects detectable with HST, and 400–500 for JWST**.

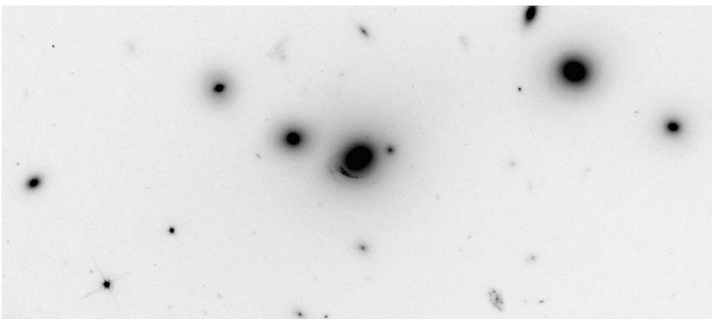

Figure 4: GAMA CGs are feasible lenses, as shown by this HST ACS/WFC3 image of a background galaxy being lensed by GAMA group 200011.

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 groups down to $m_r < 21.5$ mag, in order to better define their mass profiles. For this purpose, we wish to observe 4 of the 10 most concentrated groups we have identified from the GAMA survey over the course of 3 nights, as well as one additional group for which HST ACS/WFC3 imaging has already detected lensing. **The time required to measure redshifts down to $m_r = 21.5$ mag is 3 hours per concentrated group.**

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 groups per 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 3 nights to observe the 4 CGs and 1 lensing group. 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 groups will be placed on outlier galaxies around each group; each concentrated group is selected to easily fit into the 1 degree diameter FOV of Hectospec (all our CGs 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 4 GAMA groups were chosen from amongst 24,000 GAMA groups 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 group redshifts. Hence, we have used one of the best samples that exists to select these highly concentrated groups at relatively high redshift ($z < 0.45$). The proposed set of 4 GAMA groups 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 groups 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 3 nights for this proposal. This will allow us to observe the 4 best of our 10 target groups. In order to observe the remainder of our groups, we will request further Hectospec time of the order of 4 additional nights after this pilot program is completed.

2) The targets for this project are chosen from the GAMA survey. Each group 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 group, thus requiring deeper observations with Hectospec.

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

References

Postman et al. 2012, ApJS 199, 25
Driver et al. 2011, MNRAS 413, 971
Wyithe, Winn & Rusin, 2003, ApJ 583, 58
Yang et al., 2007, ApJ, 671, 153
Limousin, M. et al., 2007, ApJ, 668 (2007) 643L
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Lopes, P. A. A. et al., 2014, MNRAS, 437, 2430
Wong, K. et al., 2013, ApJ, 769, 52
Oliveira & Giraud 1994, ApJL 437, L103
Robotham et al. 2011, MNRAS 416, 2640
Bouwens et al., 2011, ApJ, 737, 90
Knobel et al., 2012, ApJ, 753, 121
Hoekstra, H., arXiv:1312.5981v1
Alpaslan, M. et al., 2014, MNRAS, 440L, 106
Lacerna, I. et al., 2014, ApJ, 788, 29

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 three 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."

  • The other paper will be submitted by P. Nguyen et al. to AJ on "Resolved Stellar Population Studies of Galaxies at z$\simeq$1–3 by Combining HST CANDELS UV and BVizYJH Images with Deep High-Resolution LBT U-band Images."

  • A third paper is led by our Italian LBT Collaborators, by A. Grazian, A. Fontana et al. (incl. T. Ashcraft, P. Nguyen, 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."