OBSERVING REQUEST
University of Arizona Observatories

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

Near-infrared spectroscopy of exceptionally bright Herschel Lensing Survey galaxies at redshifts z = 1.2 - 5.2

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Abstract of Scientific Justification

56 of the most exceptionally Infrared bright galaxies ($>$ 90 mJy in either 250/350/500 μm) detected with the Herschel Lensing Survey (HLS) were imaged with IRAC 3.6 and 4.5 μm. Of these 56 sources, 12 of them have been spectroscopically confirmed (z = 1.2 – 5.2) in the radio by detecting multiple CO line transitions. Since they are so exceptionally bright in the Far-IR, we can infer that these galaxies are being gravitationally lensed by massive galaxy clusters with magnifications as high as 50-100x. We have the unique opportunity to probe the ISM within these galaxies, up to high redshifts, due to their magnified brightness. Dusty star forming galaxies, in the field, at these redshifts are much more difficult to observe. Due to their dust extinction and redshift, the only way to detect emission lines is by stacking several sources. This obviously biases emission line studies of dusty galaxies towards more luminous sources. Studying the ISM of dusty star forming galaxies provides us useful information about their metallicity, instantaneous star formation, ionization, dust attenuation and if they host an AGN. As follow-up to the spectroscopic survey of lensed Herschel selected galaxies around massive galaxy clusters, we propose to use LBT/LUCI and Magellan/FIRE to observe multiple redshifted optical emission lines for galaxies with redshifts z $>$ 1.2 in the NIR. For the 44 gravitationally lensed Herschel galaxies without redshifts, by using the spatial information from IRAC, we can correctly identify the Herschel counterpart, now making it possible to go after their redshifts. These galaxies are typically extremely faint in the optical but bright in the near-IR and Far-IR; from their inferred Far-IR luminosity, suggests bright nebular emission lines which we can target to determine redshifts.

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	LUCI			2	bright	Jan–Apr	Jan–Apr	yes	no
2	MAG1	f/11	FIRE			2	bright	Jun–Jul	Mar–Jul	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	MACSJ0032.1	00:32:07.965	+18:06:46.80	z=3.628; LUCI
2	Abell 611	08:00:57.900	+36:14:14.00	z=1.885; LUCI
3	CODEX 16559	08:50:58.797	+48:29:41.64	z=1.19; LUCI
4	Abell 773	09:18:28.436	+51:42:24.33	z=5.24; LUCI
5	Abell 851(b)	09:42:03.840	+47:00:34.40	z=3.7; LUCI
6	Abell 851	09:43:03.640	+47:00:57.23	z=1.650; LUCI
7	CODEX 39326	11:24:02.220	+24:04:38.40	z=1.801; LUCI
8	CLJ1226	12:26:59.991	+33:32:41.77	z=2.266; LUCI
9	MACSJ0111.5	01:11:27.733	+08:55:28.63	LUCI
10	MACSJ1115.8	11:15:50.677	+01:30:35.37	LUCI
11	CODEX 52909	11:53:18.934	+07:55:38.33	LUCI
12	MACSJ0257	02:57:41.627	-22:09:07.73	z=4.69; FIRE
13	MACSJ1314.3	13:14:21.438	-25:15:47.64	z=1.447; FIRE
14	RXCJ2043	20:43:14.202	-21:44:38.52	z=2.04; FIRE
15	Abell 2813	00:43:25.100	-20:37:01.00	FIRE
16	MACSJ0206.4	02:06:30.510	-14:54:07.70	FIRE
17	Abell 368	02:37:18.228	-26:25:56.39	FIRE
18	Abell 3088	03:07:09.943	-28:34:58.57	FIRE
19	MACSJ0359.1	03:59:08.100	-72:07:24.60	FIRE
20	MACSJ0510.7	05:10:44.400	-08:01:13.50	FIRE
21	MACSJ0637.3	06:37:16.530	-48:26:40.70	FIRE
22	MACSJ1105.7	11:05:40.680	-10:14:44.70	FIRE
23	MACSJ1617.5	16:17:33.500	-07:16:01.00	FIRE
24	MACSJ2003.4	20:03:33.200	-23:24:23.00	FIRE
25	MACSJ2254.0	22:54:00.500	-63:15:00.50	FIRE

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
Gregory Walth	Eiichi Egami		no	yes

Scientific Justification

Dusty star forming galaxies contribute to the majority of star formation seen in the Universe, between redshifts *z = 1 – 4*. Being able to determine the physical conditions in which these galaxies form and evolve is key to their understanding. Typical rest-frame UV selection techniques, such as BzK, Lyman break and narrow-band Lyα imaging may be missing a more dust extincted star forming population. Selecting galaxies in the Far-IR (FIR) may be a better way to select dusty star forming galaxies, where the FIR probes the thermal dust emission, which is re-radiated light from young stars. With the *Herschel Space Observatory* it is possible for the first time to measure the full FIR emission from dusty star forming galaxies at redshifts *z = 1 – 4*. *Herschel* reaches the confusion limit quickly, and only the brightest galaxies are accessible to study. Utilizing the gravitational lensing power of clusters it is possible to surpass the confusion limit and detect lower luminosity galaxies and galaxies at higher redshift.

In order to get at the physical conditions of dusty star forming galaxies it is necessary to observe nebular emission lines. At the epoch of peak star formation in the Universe, the emission lines from the galaxies during this period have redshifted into the near-IR (NIR). Detecting [OII], Hβ, [OIII] and Hα reveal conditions of a galaxy's ISM; specifically, ionization ([OIII]/[OII]), star formation (Hα, [OII]) (Kennicutt et al. 1998, Kewley & Dopita 2002), metallicity (R23, N2) (Pettini & Pagel 2004) and whether the galaxy is an AGN (Kewley et al. 2002). Most deep field surveys require several hours of integration on large aperture telescopes in order to obtain NIR spectroscopy, which are only feasible for the brightest galaxies. Gravitational lensing by massive galaxy clusters typically produce magnifications on the order of 2-3$\times$ and as high as 50-100$\times$, if a galaxy is near a critical line. With gravitational lensing it is possible to detect nebular emission lines of fainter galaxies within a few hours of integration.

The "Herschel Lensing Survey" (HLS; E. Egami et al. 2010) is a survey of massive galaxy clusters in the Far-IR used to detect lensed galaxies in the submillimeter. HLS consists of two surveys, a deep survey (HLS-deep; 290 hrs) of 44 clusters utilizing PACS (100, 160 μm) and SPIRE (250, 350, 500 μm) and snapshot survey (HLS-snapshot; 52 hrs) of 527 clusters with SPIRE only bands. In addition to this sample, we are also targeting GT Herschel clusters (76 hrs) which are 10 most well studied galaxy clusters that were imaged with Herschel, such as Abell 1689. These clusters have multi-band ACS/WFC3 HST imaging as well as spectroscopic redshifts for many of the galaxies. A rich data set yet to be exploited for NIR spectroscopy. With the Herschel it is possible to measure the FIR luminosity of these galaxies and get an accurate view of their obscured star formation. In combination of with Hα we will have a coherent picture of the ongoing star formation within each galaxy within this epoch of star formation.

From HLS, as many as 85 sources were detected $>$90 mJy in either 250/350/500 μm out of 591 massive clusters. Of these bright sources, 56 were imaged with IRAC 3.6/4.5 μm. From this sample, 12 exceptionally bright sources have been followed up with with several radio observatories (Carma, GBT, JCMT, SMA and VLA). By detecting multiple CO lines, we were able to determine their redshifts, which range from z = 1.2 – 5.2. From the apparent luminosities inferred from the L_{FIR}, all the sources must be lensed. In one case, an HLS bright galaxy at redshift z = 4.69 galaxy with an apparent L_{FIR} of 5×10^{13} $L_{\odot}$, the lensing models (determined from HST imaging and redshifts of multiple images) suggests a magnification of $>$50x.

Submm galaxies are typically extincted by dust in the rest frame optical. This is a serious concern for detecting emission lines in the NIR. Since these galaxies are exceptionally bright in the Far-IR, their inferred star formation rates (SFRs) suggest that their expected line emission from the Balmer (Hα, Hβ) and [OII] lines would also be bright. Based on the performance of LUCI and FIRE and assuming a Calzetti extinction law, we can determine the line detection limits for Hα, Hβ and [OII]. We can confidently go after galaxies with extinctions as high as A_v up to 4.

The main goals of our program are the following:

(1) Detect nebular emission lines in the NIR for exceptionally bright galaxies with spectroscopic redshifts z $>$ 1.2

Additional parameters are needed to develop a better understanding of the mechanisms at work in a galaxy. Optical spectroscopy of nebular emission lines is another way to get at the physical properties of a galaxy (e.g. dust extinction, star formation rates, metallicity and ionization state). Once galaxies are at redshifts z

>0.5, nebular emission lines redshift out of the optical into the NIR. In order to get complete information on the emission from galaxies, one has to utilize NIR spectroscopy. As one example, lines such as Hα are used for measuring star formation, and in combination with Hβ can determine the dust extinction.

The HLS bright sources are all comparable in apparent luminosity (10^{13} – 10^{14} $L_{\odot}$) as the Cosmic Eyelash (Swinbank 2010), one of the brightest Infrared galaxies at redshift z$\sim$2 detected with Herschel. It is inferred from the exceptional brightness (>90 mJy in either 250/350/500 μm) that these sources are gravitationally lensed and are being magnified by a large magnification ($\sim$50x). This enables us to detect relatively faint emission lines at high redshift. Even with the possibility of high extinction, a non-detection would provide a useful limit of the extinction caused by the dust in these galaxies.

An example of a galaxy faint in the optical yet bright in the NIR is a source found behind RXCJ2043 (figure 1). One of the brightest HLS sources ($\sim$324 mJy in 350 μm, magnification of 39$\times$), the redshift determination came from multiple CO lines (z=2.04) measured with IRAM 30m. VLT/SINFONI observations in the NIR yielded a Hα detection, yet optical follow-up with VLT/FORS2 failed to detect Lyα, with only faint continuum detected after 3 hrs of integration. This may be typically of dusty galaxies in which the extinction is high enough for Lyα to never escape, but not so dusty that Hα can be detected.

Figure 2 shows [OIII]λ4959,5007 and Hβ detected for HLSJ0032, a source at redshift z=3.628, in the K-band on LBT/LUCI in ideal conditions (0.3" seeing). With these lines, we can put a strong constraint on metallicity and estimate Hα flux from Case B recombination. This system benefits from multiple images (4 multiples) with one of the images having a magnification of 20$\times$.

Figure 3 shows a spectacular example of FIR bright (>100mJy) lensed galaxy detected behind the CLASH cluster CLJ1226. This system has a large arc (>18") which appears to be associated with 3 bright knots, that are triply imaged around a cluster member. This sources are all detected in HST/WFC3 but extremely faint in the optical HST/ACS. It is strongly suggestive that this is a extremely dusty star forming galaxy from the FIR brightness and optical faintness. Hα for the knots was detected within 20 minutes on LBT/LUCI, with a redshift z=2.266. Based on the spectral slope, we anticipate a 3 hour integration in order to detect Hβ.

(2) Determine redshifts for bright Herschel galaxies with Spitzer/IRAC imaging – We recently completed a survey of 56 HLS bright sources with Spitzer/IRAC, in which redshifts for 44 are unknown. The Herschel/SPIRE PSF is not sufficient resolution to determine the position of the sources, multiple sources may contribute to the SPIRE flux. IRAC imaging enables the proper selection of Herschel counterparts and provides the spatial resolution needed to follow up these sources. A subsample of these sources have radio (SMA, VLA) emission and continuum imaging, also aiding in the positioning of the slit (Figure 1 and 2).

The SEDs of these sources are steeply declining in the optical, due to large dust extinction, and suggest a photometric redshift $z > 1$. In the optical, for star forming dusty galaxies at redshifts $z = 1 – 2$, [OII] and would be the only line available, and it would be difficult to go after due high dust extinction. At redshifts $z > 2$, in the UV, Lyα may not be seen at all, as UV light is more heavily affected by dust extinction than optical light. Since these galaxies are detected in Herschel and highly amplified, it is expected from their inferred SFRs that they should have strong detectable nebular line emission. The best option is to go after these sources in the NIR where their rest-frame optical nebular lines are least affected by the dust extinction. Magellan/FIRE is ideal for these type of sources without redshifts, with the ability to go after them in several bands (Y through K) simultaneously using the echellette.

Proposed Observation

We plan to use LBT/LUCI and Magellan/FIRE to measure nebular emission lines for gravitationally lensed Herschel galaxies and redshifts for bright lensed Herschel galaxies detected in IRAC.

We request four nights of observing time, 2 nights with LBT/LUCI and 2 nights with Magellan/FIRE.

References: Egami et al. 2010, A&A , 518, L17 • Kennicutt, R. C., Jr. 1998, ARA&A , 36, 189 • Kewley, L. J., et al. 2004, AJ , 127, 2002 • Kewley, L. J., & Dopita, M. A. 2002, ApJS , 142, 35 • Livermore, R. C., et al. 2012, MNRAS , 427, 688 • Pettini, M., & Pagel, B. E. J. 2004, MNRAS , 348, L59 • Swinbank, A. M., et al. 2009, MNRAS , 400, 1121

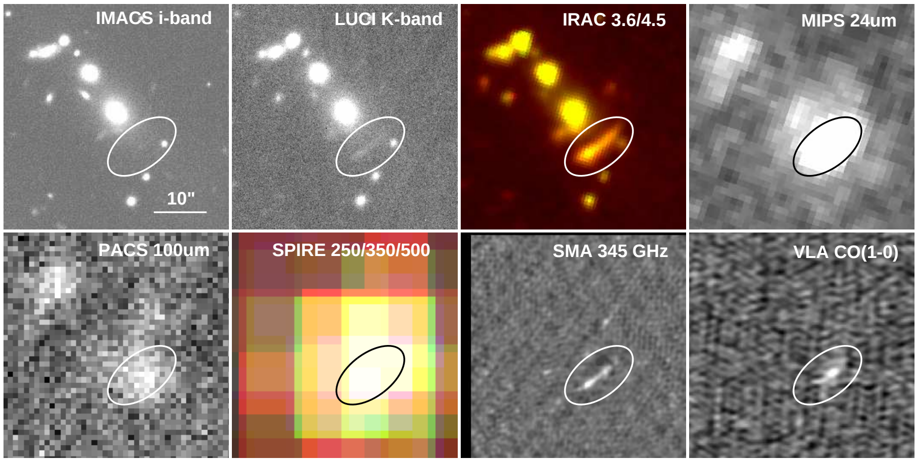

Figure 1: The lensed galaxy HLSJ2043 (z=2.04) is extremely faint in the optical, yet quite bright in NIR bands. Multi-wavelength follow-up is necessary for finding counterparts to Herschel sources and NIR and radio continuum imaging plays a critical role.

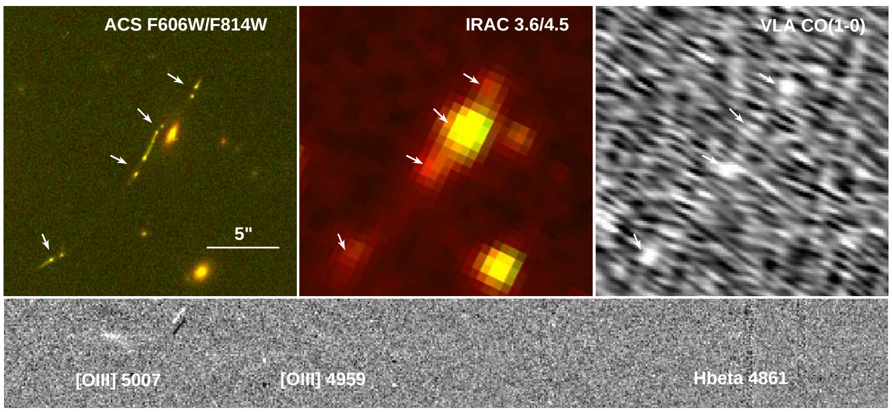

Figure 2: **Top** HLSJ0032 (z=3.628) is multiply-imaged (4 images) system detected with Herschel, the brightest images is magnified by 20×. **Bottom** Hβ and [OIII]λ4959,5007 detected with LBT/LUCI after an hour of 0.3" seeing, this information constrains the metallicity and instantaneous star formation rate.

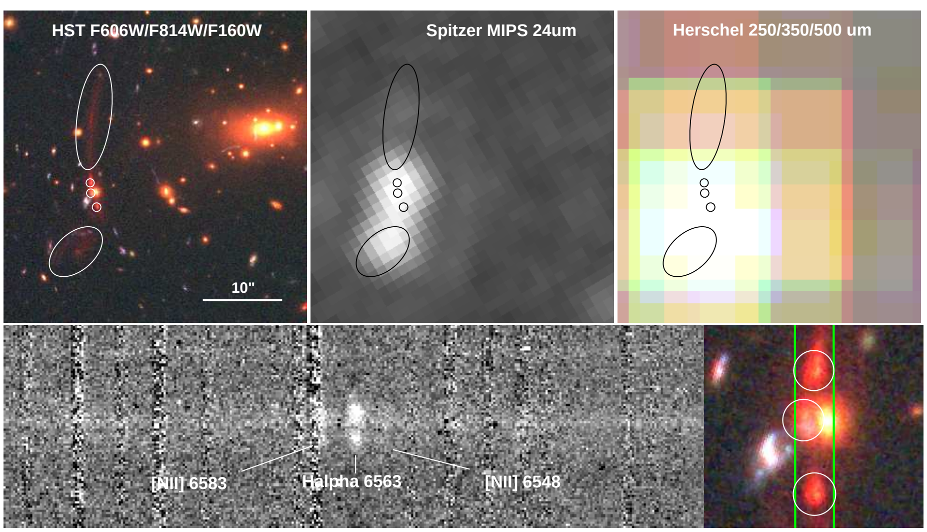

Figure 3: **Top** The large red arc and bright knots are detected with WFC3/F160W and yet optically faint in ACS. Preliminary results suggest that the large arc and bright knots are at the same redshift. **Bottom** All three bright knots are detected in Hα in only 20 minutes with LBT/LUCI at a redshift z=2.226.

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 would like to obtain near-infrared (IR) spectra for (1) exceptionally bright lensed galaxies detected with Herschel with known redshifts $z > 1.2$ in order to obtain key nebular emission lines, (2) determine redshifts for bright (>90 mJy) lensed Herschel galaxies with recent IRAC imaging. Spectroscopic redshifts have been obtained by detecting multiple CO lines in the radio. From SFR measured in the Herschel bands we can estimate the rest-frame optical line flux for these exceptionally bright galaxies. Assuming a Calzetti extinction law and based on the luminosity of the sources, for an hour integration we can detect emission lines with extinctions up to an $A_v \sim 4$ for the range of redshifts in our sample.

Sample Selection: (1) For the observation of bright Herschel galaxies with redshifts, we have selected galaxies for which Hα, Hβ, [OIII], and [OII] have been redshifted into z, J, H and K bands, depending on the redshift. In order to maximize the detection of nebular emission lines in the NIR, we have checked to see that the emission from these galaxies will fall between OH sky emission within the NIR atmospheric windows.

(2) For the observations of the bright Herschel galaxies without redshifts, their FIR luminosity infers that they will have bright nebular emission lines, such as Hα, Hβ and [OIII]λ4959,5007. In these galaxies, they are so dusty that it is difficult to detect [OII] in relatively short exposures, however for a few extreme cases it may be possible (z = *4.9*, Swinbank et al. 2009). While going after [OII] in galaxies at redshifts $z > 2$ may be challenging, we have successfully detected [OII] in a lensed galaxy at redshift z=2.503 which is about 50 mJy at 250 μm. The sources we are targeting at least have 2$\times$ that amount of FIR flux, and are more typically between 100 - 200 mJy at 250 μm. From the atmospheric windows we could target [OII] for redshifts z = 2.14 – 2.53, 3.13 – 3.67, and 4.43–5.31.

Configuration: We plan to use LBT/LUCI and Magellan/FIRE. Each instrument provides a unique advantage and strategy.

We will use Magellan/FIRE in echellette mode (Resolution: 6000-8000) to target the southern hemisphere sources. This would highly benefit our sources with multiple lines expected within multiple bands, making it such that we can go after them in a single shot. Also, it may allow the discovery of other lines that might not be expected at high redshift. In addition, using FIRE would greatly benefit our Herschel sources without redshifts, making such that Y through K bands would be taken simultaneously for a single object, easing the detection of multiple lines and redshift determination. Based on the performance of the instrument, we plan to spend 2 hours per object, roughly spending 3-4 objects per night, we anticipate to observe 6-8 objects for 2 nights.

We will use LBT/LUCI in multi-object mode, with the 210_zJHK grating (Resolution J: 8460, H: 7838, K: 6687) with the J filter (1.17 - 1.32 μm), H filter (1.55 - 1.74 μm) and K filter (2.05 - 2.37 μm) to target the northern hemisphere sources. This resolution allows us to avoid heavy blending of OH lines which are difficult to subtract because of the highly varying NIR sky background. This will enable us to detect galaxy emission lines by spreading the sky emission out for an improved sky-subtraction as well as bracket potential redshift ranges with key emission lines.

LUCI provides a 4' $\times$ 4' field of view and a number of massive galaxy clusters have multiple Herschel sources, it would be possible to fit 10-20 slits of 1" wide and 8" long on a mask. We plan to do 1-2 hr integrations for J, H and K bands. Assuming a 30% overhead we require 2 nights to observe 2-4 clusters.

The combined observations of LBT/LUCI and Magellan/FIRE will be 4 nights in total, 2 nights on LBT/LUCI and 2 nights on Magellan/FIRE. With the northern sources being targeted by LBT/LUCI and the southern sources with Magellan/FIRE.

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**)*

LBT/LUCI (PI: G. Walth): Since 2013A we have been awarded 8 nights on LUCI. Of the 8 nights; 0.5 night was excellent (<0.5" seeing and clear), 0.5 night was good (0.5"< seeing <1.0" and clear), 3.0 nights were lost due to instrument failure, and 2 were lost to weather (wind, 1.5-5" seeing) and 2 are upcoming nights at the end of October.

Magellan/FIRE We have 2 upcoming nights at the end of December.

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**)*

Time allocation over the last two years

- ⋆ LBT/LUCI 2012B (2 nights)
- ⋆ LBT/LUCI 2013A (2 nights)
- ⋆ LBT/LUCI 2013B (2 nights)
- ⋆ LBT/LUCI 2014A (2 nights)
- ⋆ LBT/LUCI 2014B (2 nights awarded)
- ⋆ Magellan/MMIRS 2012A (2 nights)
- ⋆ Magellan/FIRE 2014B (2 nights awarded)

Status of Observations

Magellan/MMIRS: NIR spectroscopic observations of 9 clusters were conducted with 1 hour in J and 1.5 hours in H. From 2011B and 2012A we were able to detect emission lines for 34 galaxies, Hα and Hβ being the primary lines detected spanning redshifts z = 0.5 – 2.5 (Walth et al. 2014c, in prep).

LBT/LUCI: In our recent January run, we were able to detect Hβ and [OIII]λ4959,5007 in an hour at 0.3” seeing for a z=3.628 galaxy (130 mJy at 250 μm) lensed by MACSJ0032 with a magnification of 20$\times$ (Walth et al. 2014d, in prep). In 2013A, under poor conditions (1.5” seeing) we were able to detect Hα and [NII]λ6548,6583 in 2 hours for a z = 1.65 lensed Herschel galaxy. In 2012B, we were able to detect several emission lines ([OII], Hβ, [OIII], Hα and [NII]) for a z = 2.5 galaxy about 1’ from the cluster center of A2631. The galaxy in A2631 is exceptionally bright (50 mJy at 250 μm) and is potentially strongly lensed, with the work ongoing in order to determine the lens model for the cluster. Finally, K band imaging of MACS2043 reveals an extended lensed arc behind the cluster corresponding to our HLS-snapshot survey detection and will be included in Walth et al. 2014b, in preparation.