OBSERVING REQUEST
University of Arizona Observatories

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

Planck's Dusty Gems: What is Magnifying the Images of the Brightest Gravitationally-lensed Sub-millimeter Galaxies?

P.I.: Brenda Frye (SO; *bfrye@as.arizona.edu*; (520) 626-1857)

CoI(s): S. Malhotra (ASU), N. Nesvadba (U. Paris–Orsay), R. Canameras (U. Paris–Orsay)

Abstract of Scientific Justification

The Planck all-sky survey has revealed a small set of 11 exceptionally bright, gravitationally lensed sub-mm galaxies at secure spectroscopic redshifts $z > 2$ with fluxes up to 1050 mJy at 350 microns. Morphologies and several empirical constraints clearly show that these are strongly lensed galaxies magnified by unusually large factors $\geq$20, including several giant arcs. These are outstanding sources allowing to study the intense star-formation in high-redshift galaxies on small spatial scales which are otherwise not observable at high redshifts. We have already obtained large data sets in the IR and millimeter to study their gas and star formation, but need to know their lensing configuration very well in order to translate several of their key properties (sizes, gas and stellar masses, morphologies) from observed values into intrinsic source properties. The success of our overall follow-up depends on this step, which requires relatively careful observations in this case. Our sources do not fall behind massive galaxy clusters like most giant arcs known, but are either behind dynamically unrelaxed clusters, or perhaps multiple galaxy groups at similar or different redshifts. This means we cannot rely on empirical scaling relationships to constrain the underlying dark-matter distribution, but need direct kinematic constraints from spectroscopy. Based on existing deep rzJK imaging, we will choose about 250 bright red-sequence galaxies and lensed arcs in each field to measure their redshifts with HECTOSPEC, and constrain the dark-matter distribution along the line of sight to the high-redshift galaxies to obtain robust lensing models. **These strongly-lensed galaxies selected from the Planck all-sky sub-mm survey are new, all identified by our team, and are the brightest sub-mm galaxies at high redshift that are currently known.**

Summary of observing runs requested for this project

Run	Telescope	Cage	Instrument	PI	AO	Nights	Moon	Scheduling Optimal	Scheduling Acceptable	Sharing Poss.	Sharing Adv.
1	MMT	f/5	Hectospec			1	dark	Mar-Apr	Mar-May	no	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	PLCK G145.2+50.9	10 53 22.6	60 51 49	We will study the galaxy overdensities
2	PLCK G165.7+67.0	11 27 14.6	42 28 25	towards these 3 sources
3	PLCK G138.6+62.0	12 02 07.7	53 34 40	down to r$\sim$21 mag

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

Scientific Justification

The brightest, most strongly gravitationally lensed high-redshift sub-mm galaxies are veritable gems to study galaxy evolution and structure formation across cosmic time. Massive galaxies at high redshift are known to have formed their stars very rapidly through intense star-formation forming up to $\sim$1000 $M_\odot$ yr^{-1}, and are characterized by their high gas turbulence (Forster Schreiber et al. 2006, ApJ 645, 1062; Swinbank et al. 2011, ApJ 742, 11), powerful winds (Nesvadba et al. 2007, ApJ 657,725), high gas and stellar mass surface densities (e.g., Tacconi et al. 2008, Nature, 461, 781; 2010, ApJ 680, 246), intense radiation fields (Stacey et al. 2010,ApJ 724, 957), high cosmic-ray fluxes (Papadopoulos et al. 2010, ApJ 720,226), and probably often also feedback from powerful AGN. How did these processes contribute to regulate star formation in these galaxies? Because such galaxies have no peer in the local Universe, most of what we know about their intense star formation relies on observations on galaxy-wide scales of several kpc. On these scales, large-scale rotational support keeps the gas from collapsing into clouds and forming stars (e.g., Toomre 1964,ApJ 139,1217 Escala & Larson 2008, ApJL 638, 31). At redshifts z$\gtrsim$2, only the most strongly gravitationally lensed galaxies with magnification factors $\gg$10 allow us to probe individual star-forming regions directly, with sizes of-order 100 pc, where rotational support no longer dominates, and where the local gas and stellar mass surface densities, turbulence, winds, and gas heating together set the stage for the intense star formation. The Hubble frontier fields contain no similar sources; only a single spatially-resolved source is so far known to the literature that enables such detailed studies (the "Cosmic Eyelash",Swinbank et al. 2010, Nature, 454, 733 11, ApJ 742, 11).

Through a unique synergy of the Planck and Herschel satellites, and a large set of already existing follow-up observations from the optical to the radio, we have collected a small sample of 11 of the brightest gravitationally lensed galaxies on the sub-mm sky (Canameras et al. 2014, A&A sub'ed). We used a color selection probing the slope of the FIR spectral energy distribution of dust heated by star formation (Fig. 1) to identify the 230 most likely high-redshift candidates from the Planck all-sky survey, the first with the depth necessary to probe the brightest, rarest high-z sources (Planck Collaboration 2014, A&A sub'ed.), which we subsequently confirmed with Herschel/SPIRE FIR photometry and ground-based follow-up to be indeed high-redshift galaxies. The resulting set of "Planck's Dusty GEMS" (Gravitationally Enhanced subMillimeter Sources) extend the exquisite samples of lensed high-z galaxies discovered by wide-field surveys with the South Pole Telescope (e.g., Viera et al. 2013, Nature 435,994) and Herschel (e.g., Wardlow et al. 2013, ApJ 762, 59) with typically S_{350} =100$-$200 mJy at 350μm, towards even brighter sources, with S_{350} =300$-$1050 mJy, which can only be systematically identified with a genuine all-sky survey (Figs. 2&3). All are near and above the 90% completeness limit of Planck ($\sim$600 mJy, i.e., L_{FIR} 10^{13} $L_\odot$ at z$\sim$2, Planck Collaboration 2014, A&A sub'd), suggesting that these might literally be the brightest gravitationally lensed high-redshift galaxies on the sub-mm sky.

Deep SMA dust and IRAM CO millimeter interferometry confirms that all GEMS are indeed strongly gravitationally lensed galaxies, with several having giant arcs (e.g., Fig. 4&6). Dust and CO interferometry, and line fluxes of 60 bright mm emission lines already allow us to characterize their gas and star-formation properties, and to provide constraints on the physical processes that may contribute to regulating their star formation. All have secure spectroscopic redshifts z= $2.2-3.6$ (from $3-8$ lines per source), and show a range of star-formation and gas mass surface densities, star-formation intensities, atomic-to-molecular mass ratios, turbulent motion, and gas excitation, ranging from more gradually, but still intensely star-forming galaxies on the main sequence (e.g., Brinchmann 2008, MNRAS 386, 769, Elbaz et al. 2011, A&A 533, 119) to the most vigorous starbursts known. None hosts a powerful AGN. We believe that the extraordinary brightness of our sources will make them interesting benchmarks for detailed studies of intense star-formation in dusty starbursts in the high-redshift Universe for years to come.

The present proposal

Interpreting these rich data sets without a detailed lens model is simply impossible. Constraining their intrinsic sizes and morphologies is mandatory, e.g., to obtain robust dynamical mass estimates, total star-formation rates, and stellar and gas masses, the intrinsic sizes of star-forming clumps, etc. This is why we propose here to use MMT/HECTOSPEC to obtain detailed kinematic constraints on the intervening lensing structures of the first three GEMS. A companion proposal has been submitted to the VLT to obtain similar observations for our 4 equatorial sources. We will request another 2 nights to observe 4 sources in the summer semester, which will complete this program.

A first characterization of our foreground lensing structures based on our already existing deep CFHT and VLT optical/NIR imaging (down to, e.g., r=26.0 mag, $K_{AB} = 24.2$ mag, both at 3σ) is on-going. It already shows that, although none of our sources were *selected* to be along the line of sight to a dense foreground structure, all are behind overdense regions at intermediate redshifts (Figs. 4-6). This is in stark contrast to the larger, but fainter samples of gravitational lenses identified with the wide Herschel surveys and the SPT, which are in most cases small ($\approx$1-2$''$) Einstein rings around individual massive galaxies. It is also in contrast to most other studies of strongly gravitationally lensed galaxies, which often deliberately target regions behind known strong lensing clusters (e.g., the Hubble Frontier Fields). Although photometric redshifts suggest that most of the intervening lensing structures are at rather low redshifts z$\sim$0.1-0.5, they are not the typical massive, strong lensing galaxy clusters. None of them are in the ROSAT (X-ray) or PLANCK (SZ-effect) all-sky catalogs, nor optically selected cluster or group samples, e.g., from the SDSS and 2MASS. They may either be massive dark-matter environments without hot X-ray halo gas, or gravitationally bound lower-mass groups, or clumps in multiple unbound dense regions along cosmic filaments.

We are currently using our existing imaging to determine detailed lens models with LENSTOOL (Kneib et al. 2011). However, with imaging alone, this requires us to make strong assumptions, e.g., for the total mass of the underlying dark-matter environment, its size, cluster/group membership of individual galaxies near the line of sight to the GEMS, and the overall nature of the structure (bound or unbound). The absence of bright X-ray emission suggests that the dark-matter environment may not be dynamically relaxed, which makes using empirical calibrations unreliable, e.g., between the number of galaxies in the structure and the mass of the underlying dark-matter halo. We are currently investigating whether inferring global parameters, e.g., the total mass or concentration parameter, from weak lensing may be possible in some cases, but this alone will not allow us to search for local mass concentrations towards our GEMS, or to constrain the total size of the structure along the line of sight. For example, do the multiple clumps in Fig. 6 represent several groups, or substructure within a common dark-matter halo? Photometry alone cannot provide a conclusive answer, but it will become immediately clear with spectroscopic observations as requested here.

We propose to use MMT/HECTOSPEC with the 270 lpmm grating to obtain spectroscopic redshifts and characterize the lensing potential of 3 of our GEMS that are at RAs most suitable for observations in spring. Our main goals are:

• Prioritize galaxies that fall on or near the red sequence of the main lensing structure, to measure their redshifts using the 4000Å break, absorption lines, e.g., Hβ, Hγ, Hδ, Na D, or MgIλ3832, or emission lines like Hα, [OIII]$\lambda\lambda$4959,5007, or [OII]λ3727. With the 30$'$ field of view and up to 300 fibers, we will be able to probe the surrounding environment out to the typical virial radii of massive clusters. We will use the ensemble of their redshifts also to search for kinematic sub-structure. The red sequence associated with one of our GEMS is shown in Fig. 5.

• Confirm additional bright, potentially lensed high-z candidates and multiple images selected through their red optical/NIR/Spitzer colors (e.g., distant red galaxies with J-K>2.4 mag, following Forster Schreiber et al. 2004, ApJ 616, 40 or red 3.6μm-4.5μm colors in our existing IRAC imaging following Papovich et al. 2008, ApJ, 676, 206), to search for bright line emission, e.g., from Lyα (for z$\geq$2.7), CIVλ1550, [OII]λ3727, or MgIIλ2800, which will provide valuable additional constraints on the overall lensing potential by probing further lines of sight.

• Target additional galaxies, in particular very near the GEMS, to constrain the overall dark-matter distribution along the line of sight to our high-z galaxies. This is particularly important for constraining the additional boost from multiple dark-matter halos. Bayliss et al. (2014), ApJ 783, 41 found several intervening redshift spikes towards strongly lensed galaxies from the Sloan Giant Arcs Survey (SGAS), suggesting that strong lensing clusters may generally be biased towards lines of sight with particularly rich sub-structure of the Cosmic Web. Given that the GEMS are the brightest individual high-redshift galaxies on the sub-mm sky, with no further prior on their line-of-sight dark-matter distribution, then even rather unlikely lensing configurations, like multiple superimposed groups or clusters, cannot be ruled out a priori.

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**)*

The main goal of our observations is to obtain redshifts from massive galaxies at intermediate redshifts, in order to (1) characterize the dynamical structure and substructure of overdense regions along the line of sight, (2) identify additional overdensities of galaxies at different redshifts, and (3) search for bright line emission from other gravitationally lensed high-redshift galaxies.

We will select our targets from already existing CFHT Megacam and WIRCAM imaging. Both are wide-field imagers, covering 1 square-degree and 20 square-arcmin, respectively, well matched to the 30′ field of view of HECTOSPEC. The wide fields-of-view are in good correspondence to the expected sizes of massive intermediate-redshift galaxy clusters at $z \sim 0.1 - 0.5$, and will allow us to probe out to the virial radii of potential foreground clusters (∼1.5 Mpc), requiring at least a 10−20′ FOV at these redshifts. From our existing imaging we expect that we will obtain about 250 redshifts per observation.

As already stated in the previous section, we will select member galaxies of the primary lensing structures by using their position in our optical/NIR color-magnitude diagrams ('red sequence', a primary characterstics of the galaxy population in dense regions of the Universe). An example is shown in Fig. 6. For the expected mass range of our foreground structures, we expect to find redshift offsets of few 100 km s^{-1} at least, and up to about 1000 km s^{-1} for massive clusters, potentially more if we are seeing multiple galaxy groups that are not gravitationally bound. Biviano et al. (2006, A&A 456, 23) studied the expected biases from scarce sampling of dark-matter halos in surveys like those we propose here, finding that adequate approximations on the velocity dispersion of the dark-matter halo can be found with 20 galaxies, which we will greatly exceed. We will therefore also be able to reliably probe kinematic substructure in the main lensing halos.

We will also search for additional massive galaxies along or near the line of sight, or additional rich dark-matter environments, which should appear as individual bright galaxies at different redshifts or spikes in the redshift distribution of galaxies in our HECTOSPEC data. Such structures can be at greater redshifts than those of the primary lense, out to z∼1 in extreme cases. The large wavelength coverage of HECTOSPEC will therefore be ideal to obtain a robust census of dark-matter halos along the line of sight. We note that individual lensing galaxies will be massive, with stellar masses of few 10^{11} $M_\odot$ or more, and can be traced out to large distances with data sets like what we request here. For particularly massive individual galaxies, we may even be able to infer dynamical masses from our spectra, if their velocity dispersions are large enough. Alternatively, we will use our photometric constraints that will be tightened by accurate spectroscopic redshifts.

We will use the standard tools to reduce and analyze HECTOSPEC spectra and to measure redshifts from hese data. We will then use all of these redshifts and the derived properties of dark-matter halos towards our galaxies to constrain our lens models with LENSTOOL (Kneib et al. 2011). This is the most widely used software package today to model gravitationally lensed galaxies behind complex foreground structures like groups or lenses, and we are already experienced users of LENSTOOL, already collaborating with the group that developed and maintains LENSTOOL in Marseille.

For the galaxies in our target fields, 3 h integrations are requested using the 270 grooves/mm grating to make use of the extended wavelength range to measure redshifts for the faint galaxies which typically have less secure photometric redshifts . We arrive at this number as follows: the SHELS Survey (Geller et al. 2012) used 0.75-2.0 h integrations to obtain 96% redshift completeness to $R(Vega)$<20.6 mag. This corresponds to R_{AB}=20.8 mag, or i_{AB}=20.5 mag, assuming a mean $(R - i_{AB})$=0.3 mag. Since the mean exposure time for SHELS was 1 h, we are requesting 3 h to reach our limit of i_{AB}<21 mag. In sum, observing the three target fields amounts to 9 h, or one night in our required timeframe of Mar-Apr.

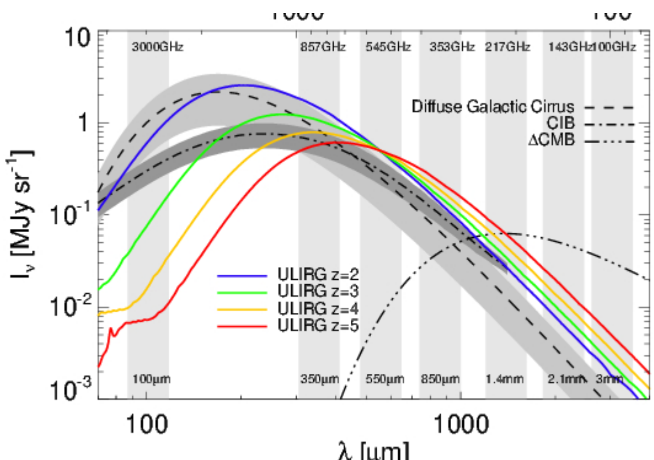


Fig. 1: We use a FIR color selection tmatched to the FIR dust SED of high-z galaxies in the high-frequency bands of Planck to identify our sources.

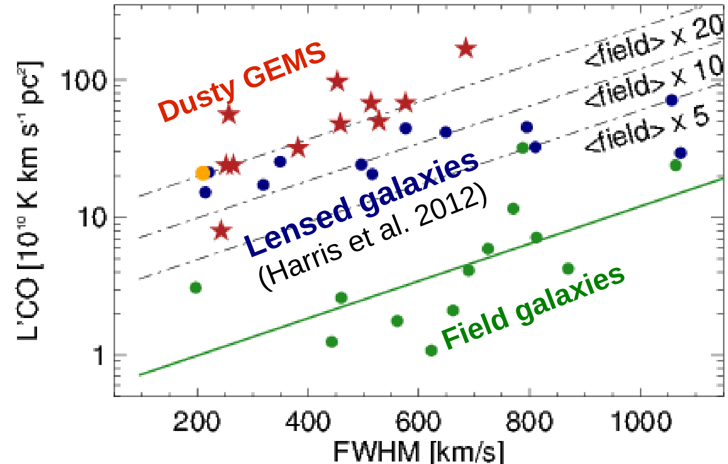


Fig. 2: Empirical constraints, e.g.,from CO line widths and luminosities (Harris et al. 2012), point towards high magnification factors for all GEMS. Blue symbols are gravitationally lensed galaxies from H-ATLAS (Harris et al. 2012).

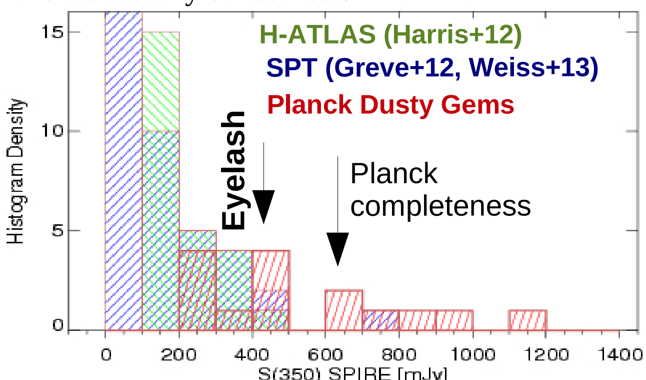
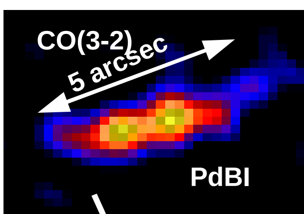


Fig. 3: SPIRE S_{350} fluxes of the HATLAS lenses of Harris et al. (2012, green), SPT lenses of Greve et al. (2012, blue), and Weiss et al. (2013), and our brightest Planck targets (red).



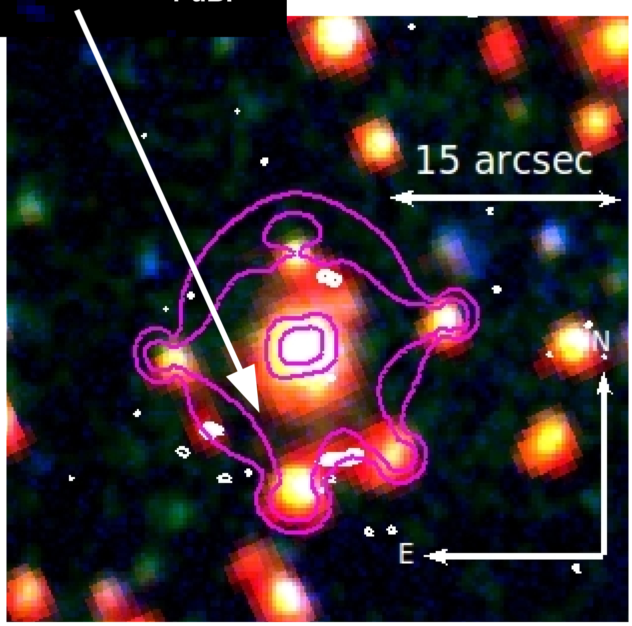


Fig 4: CFHT rJ, Spitzer 3.6um morphologies and PdBI CO contours (white). Magenta lines (best seen in the electronic version) show magnification factors >20

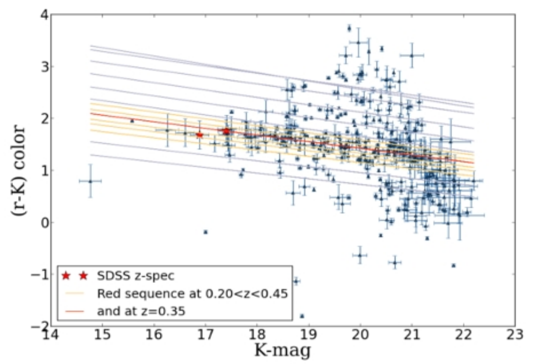


Fig. 5: Color magnitude diagram of the GEM shown below in Fig. 4, highlighting the need for spectroscopic redshifts. Although we clearly see the red sequence in a diagram, only the (accidental) 2 spectroscopic redshifts from the SDSS allow us to infer that the two dense groups of 3-5 galaxies are within <1000 km/s from each other. We currently have no constraints on the remaining structures, our only redshifts are from CO (i.e., only the Western arc).

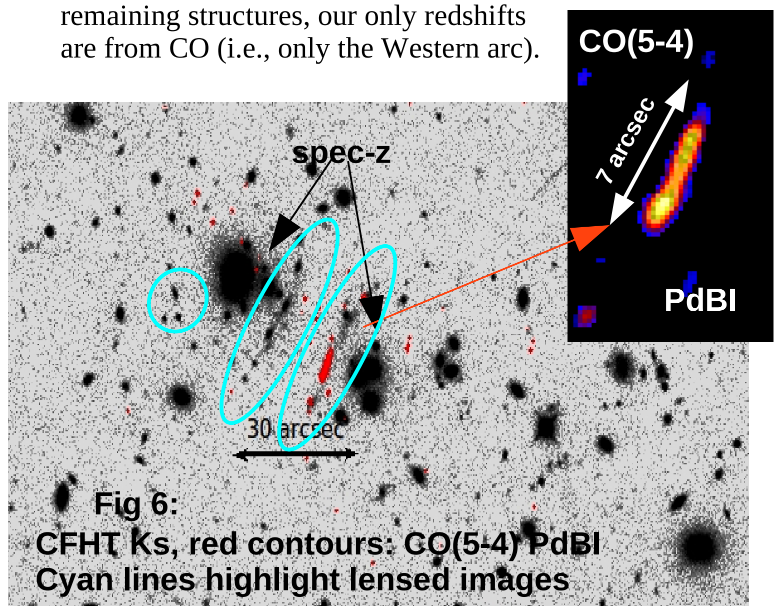


Fig 6: CFHT Ks, red contours: CO(5-4) PdBI Cyan lines highlight lensed images

References: Brinchmann et al. 2008, MNRAS 386, 769 Elbaz et al. 2011, A&A 533, 119 Kneib et al. 2011, ascl.soft/02004 Forster Schreiber et al. 2004, ApJ 616 40 Papovich et al. 2008, ApJ 676, 206 Bayliss et al. 2014, ApJ 783, 41 Harris et al. (2012), ApJ 752, 152 Swinbank et al. (2010), Nature, 464, 733 Swinbank et al. (2011) ApJ 742, 11

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 is a new proposed program and as such there have not yet been any nights awarded for this project. We are requesting one night, which is sufficient to initiate a redshift survey of galaxies and make a significant contribution to the galaxies with known redshifts in this famous cluster. We assigned this proposal as short term as it is a 'stand alone' project, although an additional 3 nights would be required to complete the spectroscopic observations of our entire sample.

(2) The strongly-lensed sub millimeter galaxy targets are supported by an extensive ancillary dataset coming from PI-Frye's *external* collaboration with the PLANCK science team, including Planck/HFI imaging, Herschel/SPIRE imaging, IRAM/PdB imaging and spectroscopy, VLT imaging and spectroscopy, CFHT, and LBT imaging in NIR. Curiously, although we have found giant arcs and their redshifts, there is still very little in the way of spectroscopic redshifts yet known for the *lens*. Thus the UAO time fits in by providing the critical spectroscopic redshifts of the lens members which are necessary to construct the mass map and to measure galaxy properties and physical conditions of our strongly-lensed sub millimeter galaxies. For each bright galaxy, photometric redshift estimates are made as well as more complex derived information, such as multi-color fits to the spectral energy distributions (SEDs).

(3) This part of the Planck Gravitationally Enhanced sub-Millimeter Survey (GEMS) program is designed to produce a spectroscopic catalog of galaxies along the line of sight to i_{AB}<21 mags for the continuum sources, and to i_{AB}<22 mags for the emission line galaxies. All members of this team are experts in the area of the observational study of galaxy formation and evolution and/or gravitational lensing. On collaborators, Co-I Nesvadba is leading the overall GEMS follow-up program. PI-Frye is tasked by the group to lead the ground-based spectroscopic redshift census to map out the line of sight structure out to the far-field. the UAO time will be used to measure redshifts and get basic information on galaxy properties, including identifying the lensing structures which may be in the form compound lenses. The PI plans to present these data and analysis in refereed papers.

We note that the observed galaxy overdensities may also be very interesting targets in their own rights, e.g., to study offsets between the baryonic and dark-matter component in galaxy clusters and groups at different mass scales. This is beyond the goals of the present proposal, but would be an additional benefit of the requested data, and we only add this to highlight that the proposed observations have a high potential of enabling a rich set of subsequent programs. The highly unusual selection of these targets (for being in front of the brightest sub-mm galaxies on the sky, but without additional prior, e.g., on their hot intracluster or intragroup gas) will make them particularly interesting targets for further study. Regardless of this, we highlight that the astrophysical interpretation of our extensive, and already existing IR-to-mm data sets depends critically on having robust lens models. Size scales, morphologies, and total gas and stellar masses are basic quantities that are necesary to study, e.g., the efficiency of feedback, Jeans collapse of giant molecular clouds, turbulent support of these clouds, amongst many other parameters which are key to understanding star formation in the most vigorous star-forming regions we know of.

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 PI took advantage of one TBA observing opportunity using LBT to observe a galaxy protocluster candidate with R. Green on 24-25 Dec, 2012. Both nights of observing were lost due to storms save for a total of $\sim$20 min which was shared between the users present. We did acquire a total of 10 min of NIR imaging in a single band in 2.2-2.5$''$ seeing, which was adequate to identify the cluster members in this submillimeter-selected galaxy protocluster but insufficient to result in a refereed publication.