ID: S000 **PI: Marie Wingyee Lau** **Inst.: Kast** **Req.: 17 nights**

A Potentially Transformative Approach to Cluster Cosmology

1 Scientific Justification

Pinning down the nature of dark energy is one of the most pressing questions in modern physics. Dark energy is thought to be either a cosmological constant with an equation of state that remains constant at all times ($w = P/\rho = -1$), a new type of fluid with an equation of state that varies with time ($w \neq$ constant), or dark energy might indicate a breakdown of Einstein's Theory of General Relativity. It is of critical importance to distinguish between these three scenarios. This can only be accomplished by ambitious and demanding measurements of both the expansion rate of the universe (to track the time evolution of dark energy) together with measurements of the rate at which cosmic structures, such as galaxies and clusters of galaxies, grow with time (the growth rate). The redshift evolution of the abundance of massive clusters is a direct probe of the growth of large scale structures.

The Hyper Suprime Cam survey is a large (1400 deg^2), deep ($i \approx 26.5$), lensing survey conducted on the Subaru telescope between 2014 to 2019. One of the goals of the HSC survey is to identify galaxy clusters and to constrain the growth of large scale structure in the redshift range where the effects are dark energy are the largest, namely $z < 0.5$. The default plan in HSC is to identify clusters via the "red-sequence" method. In recent years, the quality of optical red-sequence clusters finders has much improved, with the state-of-the-art being the redMaPPer cluster finder (Rykoff et al. 2014; Rozo et al. 2014). However, as the volume of data increases, imposing correspondingly stricter requirements on systematic errors, three aspects are becoming serious limiting factors:

1. It is not straightforward to identify the galaxy at the center of the cluster, or the central galaxy. This creates mis-centering errors which directly propagate into errors on halo masses from weak lensing.

2. Red-sequence cluster finders are prone to projection effects and some "massive clusters" are actually two smaller systems projected along the line-of-sight (e.g. Busch et al. 2017). Conversely, red-sequence cluster finders also sometimes accidentally break up massive clusters into two smaller systems, known as "fragmentation".

3. The solution to (1.) and (2.) is to forward model the cluster finding process by running red-sequence cluster finders on mock observations. However, building mock catalogs that are reliable enough to completely forward model this process is a long standing issue in this field to which there is no immediate solution at hand.

With these challenges in mind, our group has been using HSC data to explore some exciting and potentially transformative new ideas about optical cluster finding. The basic idea, while exceedingly simple, appears to be performing amazingly well. Our approach is based on the idea that galaxies that live at the very centers of clusters (BCGs; Brightest Cluster Galaxies) have extended light profiles which distinguish them from other galaxies (Huang et al. in preparation). With deep enough data, we are finding that BCGs can be identified directly based on their extended light profiles and their luminosities. So why has this method not been used previously? It is largely because of a prevailing consensus that the luminosities of central galaxies do not correlate with halo mass as well as "richness" estimators such as the redMaPPer λ parameter[1]. With more in-depth investigation, however, we are finding that these ideas stem from the use of shallow imaging data (such as SDSS) and poorly estimated luminosities. Instead, with deeper data, and using more carefully extracted luminosities (Huang et al. 2017), our weak lensing tests are showing that the luminosities of central galaxies trace halos as well as λ, and possibly even better!

Our new approach has advantages over red-sequence based methods for all three key points (1.), (2.), and (3.). Our method identifies BCGs directly via their extended light profiles, and projection effects should be minimal. Furthermore, the simplicity of this method imposes less stringent requirements on mock catalogs. Mocks for this cluster finder would only need to model the connection between massive central galaxies and their halos, a more simple task than modeling the full red-sequence population.

We intend to apply this method to HSC data of a massive galaxy catalog that comprises super massive galaxies with $\log(M_*/M_\odot) > 11.5$ and $z < 0.5$. The majority of galaxies in our sample have spectroscopic redshifts from either the GAMA survey or the BOSS survey. However, there is still a small number of galaxies in our sample for which we are lacking spectroscopic redshifts. The typical photometric redshift precision $\sigma(z) \approx 0.05$ corresponds to a co-moving distance of $\approx 120\,h^{-1}\,\mathrm{Mpc}$ at $z = 0.5$, which is much larger than the typical size of a dark matter halo $\sim 1\,\mathrm{Mpc}$. Hence photometric redshifts are prone to projection effects, and are insufficient for distinguishing between galaxies in the same halo versus those in more distance halos. On the other hand, the minimum resolvable distance is limited by the finger-of-god effect. The typical halos of our study have velocity dispersions $\sigma(v) \approx 600\,\mathrm{km\,s^{-1}}$ and this sets our desired redshift precision.

The goal of this proposal is to acquire spectroscopic redshift for galaxies in our sample that currently only have a photometric redshift. This is critical to our science as it enables us to confirm the redshifts of the clusters, to disentangle projection effects, and to remove a small number of satellite galaxies. The number density of galaxies for which we do not already have a redshift is very low (less than one per square degree). Therefore, redshift acquirement cannot benefit from any multiplexing advantages and so our targets are well-suited for single-slit spectroscopy with KAST. The spectroscopically complete sample that we will compile will be similar to the DESI Bright Galaxy Survey. Thus, our sample will also be of tremendous values for the preparation of DESI.

[1]The logarithmic scatter in halo mass at fixed λ ($\sigma_{M_{\rm halo}|\lambda} = 0.16\,\mathrm{dex}$) was thought to be lower than the scatter in halo mass at fixed galaxy mass ($\sigma_{M_{\rm halo}|M_*} = 0.25\,\mathrm{dex}$).

References

- Busch, P., et al. 2017, MNRAS
- Huang, S., et al. 2017, accepted to PASJ special issue for HSC Subaru Strategic Program
- Hutchinson, T. A., et al. 2016, AJ
- Rozo, E., et al. 2014, ApJ
- Rykoff, E. S., et al. 2014, ApJ

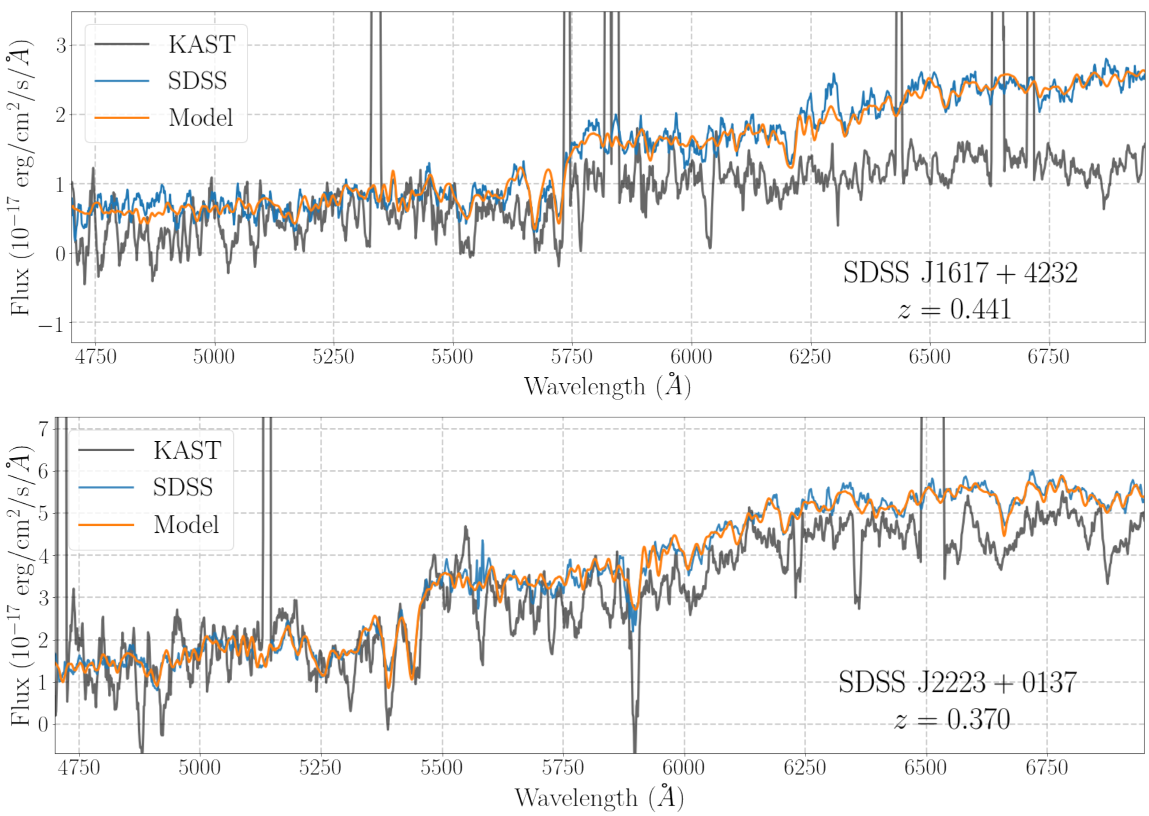

Figure 1: Preliminarily reduced and smoothed Kast spectra of two galaxies taken in our trial run on 2017 July 14, SDSS spectra of the same galaxies, and the SDSS models. The galaxies have $r = 20.0$ and $r = 18.4$ respectively. With signal-to-noise ≈ 5, the 4000 Å-break and the Ca II H+K doublet are marginally identifiable.

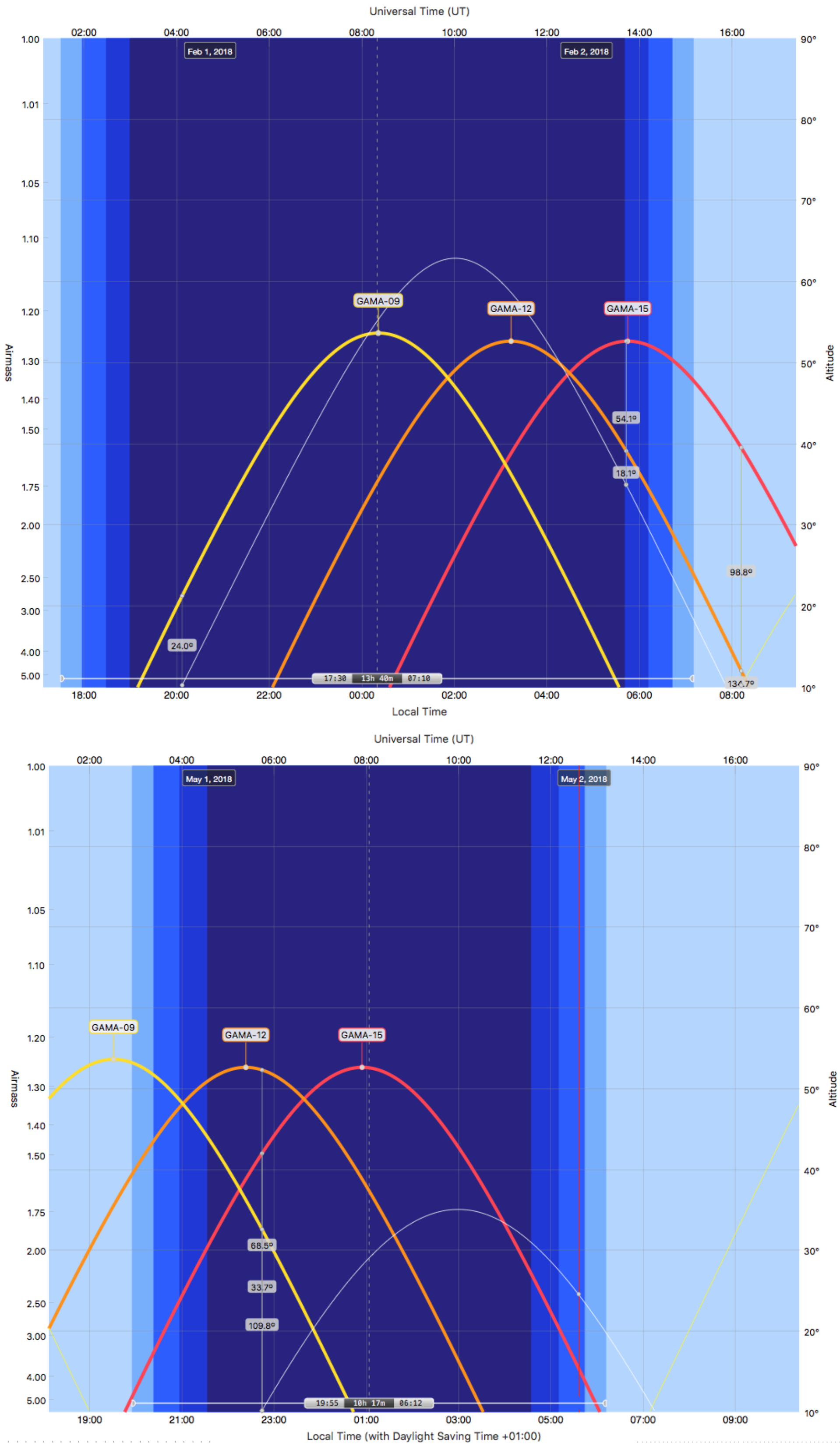

Figure 2: (Top) visibility curves of three of our targeted fields on 2018 February 1. (Bottom) visibility curves on 2018 May 1. March and April will be optimal time for our program.

2 Targets and Exposures

With Kast observations, we will eventually acquire spectroscopic redshifts of 87 galaxies in six different fields in the sky.To ensure that all $0.3 < z < 0.5$ objects are covered, we target objects with $0.25 < z_{\mathrm{photo}} < 0.55$. We will use the *redmonster* software (Hutchinson et al. 2016) to cross-correlate the Kast spectra with galaxy templates. We were granted director discretionary time on 2017 July 14 for a trial run. We observed four galaxies that have spectroscopic redshifts already determined in SDSS, to determine the signal-to-noise required for deriving reliable spectroscopic redshifts, and the brightness limit for Kast observations. We observed four galaxies of SDSS magnitude $r = 20.0$, $r = 19.3$, $r = 18.4$, and $r = 18.8$, each with exposure time 3600—5400 s. We performed preliminary data reduction using PYPIT. Figure 1 shows our Kast spectra of two of the observed galaxies (smoothed for clarity), the SDSS spectra, and the SDSS models. While proper fluxing and cosmic ray rejection are still in progress, we demonstrate that signal-to-noise > 5 is required for spectroscopic redshifts. In turn, this implies our program is feasible for galaxies with $r < 20.0$.

Among our six targeted fields, three fields are observable in 2018A, namely GAMA-09, GAMA-12, and GAMA-15. We will use the Shane 3m telescope and the Kast spectrograph to observe 39 galaxies. Our trial run had 31% dark time. Given the faintness of our targets, dark time is preferred.

Our science goal will require ≈ 7200 s of exposure to obtain sufficient signal-to-noise. These long exposures will be broken into 1800 s exposures as a compromise between CCD read noise and cosmic ray accumulation. With overhead, we can observe 3 targets per night. Accounting for poor weather conditions and Target of Opportunity interrupts, we request 17 nights. Figure 2 shows the visibility curves of the three GAMA fields on 2018 February 1 and 2018 May 1. Because of the low declination, our targets are only observable in a relatively narrow range of time in a semester. We request time allocation in March and April when more of our targets are within the telescope pointing limit.

We will setup to resolve the 4000 Å break and the Ca II H and K lines, while simultaneously cover a sufficiently broad wavelength range for full SED fitting (Figure 1). To this end, we will use the 600/5000 grating on the red side. At 5000 Å a precision of $600\,\mathrm{km\,s^{-1}}$ corresponds to 15 Å, which will be many resolution elements.

Table 1 lists the galaxies in the three targeted GAMA fields to be observed in 2018A. We will observe additional targets in the HSC footprint if we are granted additional observing time.

In poor observing conditions we will increase exposure time and give preference to bright targets.

Table 1: List of targets.

Index	Name	RA (J2000)	Dec (J2000)	SDSS r-mag	photo-z	Exposure
1	J091751.99+0356	09:17:51.99	+03:56:10.38	19.45	0.30	5400s
2	J145916.60-0103	14:59:16.60	-01:03:17.76	17.97	0.31	5400s
3	J091749.63+0357	09:17:49.63	+03:57:28.21	18.59	0.32	5400s
4	J145813.92+0030	14:58:13.92	+00:30:24.54	19.10	0.33	5400s
5	J115511.15-0031	11:55:11.15	-00:31:26.70	19.18	0.33	5400s
6	J091412.19+0300	09:14:12.19	+03:00:13.36	19.54	0.35	5400s
7	J145842.01+0038	14:58:42.01	+00:38:10.53	18.91	0.35	5400s
8	J090917.11+0403	09:09:17.11	+04:03:19.14	19.09	0.36	5400s
9	J090316.77+0351	09:03:16.77	+03:51:39.93	18.45	0.38	5400s
10	J145415.05-0018	14:54:15.05	-00:18:54.08	19.81	0.39	5400s
11	J091353.38+0353	09:13:53.38	+03:53:15.42	19.34	0.40	5400s
12	J145450.36+0009	14:54:50.36	+00:09:34.02	19.30	0.40	5400s
13	J085706.37+0131	08:57:06.37	+01:31:30.65	19.87	0.41	5400s
14	J150014.41-0032	15:00:14.41	-00:32:23.52	19.62	0.41	5400s
15	J091148.76+0325	09:11:48.76	+03:25:12.36	19.64	0.42	5400s
16	J145400.65-0034	14:54:00.65	-00:34:35.40	19.88	0.42	5400s
17	J090425.96+0035	09:04:25.96	+00:35:48.75	20.19	0.43	7200s
18	J090330.44+0327	09:03:30.44	+03:27:06.66	19.26	0.43	5400s
19	J090223.13+0342	09:02:23.13	+03:42:58.15	19.47	0.43	5400s
20	J144903.56+0026	14:49:03.56	+00:26:52.30	20.11	0.43	7200s
21	J143133.57-0045	14:31:33.57	-00:45:11.20	20.16	0.43	7200s
22	J144341.83-0043	14:43:41.83	-00:43:40.18	19.78	0.43	5400s
23	J090954.01+0152	09:09:54.01	+01:52:29.43	19.86	0.44	5400s
24	J145403.99-0014	14:54:03.99	-00:14:20.33	19.84	0.44	5400s
25	J140316.21-0047	14:03:16.21	-00:47:59.20	19.89	0.44	5400s
26	J090557.49+0212	09:05:57.49	+02:12:33.37	19.62	0.45	5400s
27	J085454.38+0032	08:54:54.38	+00:32:55.72	20.25	0.45	7200s
28	J091720.12+0410	09:17:20.12	+04:10:26.59	19.01	0.45	5400s
29	J091908.04+0325	09:19:08.04	+03:25:27.52	20.07	0.45	7200s
30	J090334.79+0307	09:03:34.79	+03:07:54.48	20.10	0.45	7200s
31	J145154.93+0016	14:51:54.93	+00:16:20.30	19.91	0.45	5400s
32	J140513.07+0017	14:05:13.07	+00:17:39.83	20.02	0.45	7200s
33	J145931.33-0002	14:59:31.33	-00:02:44.57	20.13	0.45	7200s
34	J120422.63-0017	12:04:22.63	-00:17:19.83	19.92	0.45	5400s

3 Supplementary Observations Required from other Observatories

Our full cluster catalogs include spectroscopic redshift catalogs from the GAMA team.

4 Technical Remarks

We have none.

4.1 Status of Previously Approved 3-m Programs

This program obtained director's discretionary time of one night in 2017A.

PI Lau is a graduate student at UCSC, who has been awarded a total of 22 nights in 2015A, 2016A, and 2017A for the program Late-time Optical Spectral Signatures of Tidal Disruption Candidates. The observing program is completed and the path to publication is active.

Co-I Leauthaud and co-I Huang have extensive experience with optical spectroscopy and are experts in assive galaxies.

Co-I Greg Sallaberry is an aspiring undergraduate researcher at UCSC, who will lead the observing and data reduction effort.