ID: S022 **PI: Marie Wingyee Lau** **Inst.: Kast** **Req.: 10 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 ($i \approx 26.5$), weak 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 $z < 0.4$. 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. 2017). 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 $z < 0.45$. 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 $z = 0.4$, which is much larger than the typical size of a dark matter halo ($R_{\mathrm{halo}} \sim 1\,\mathrm{Mpc}$). Hence photometric redshifts are prone to projection effects, and are insufficient for distinguishing between galaxies in the same halo versus those in more distant 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 ($\sigma_{M_{\mathrm{halo}}|\lambda} = 0.16\,\mathrm{dex}$) was thought to be lower than the scatter in halo mass at fixed galaxy mass ($\sigma_{M_{\mathrm{halo}}|M_*} = 0.25\,\mathrm{dex}$).

References

- Busch, P., et al. 2017, MNRAS
- Huang, S., et al. 2017, Submitted to MNRAS
- Rozo, E., et al. 2014, ApJ
- Rykoff, E. S., et al. 2014, ApJ

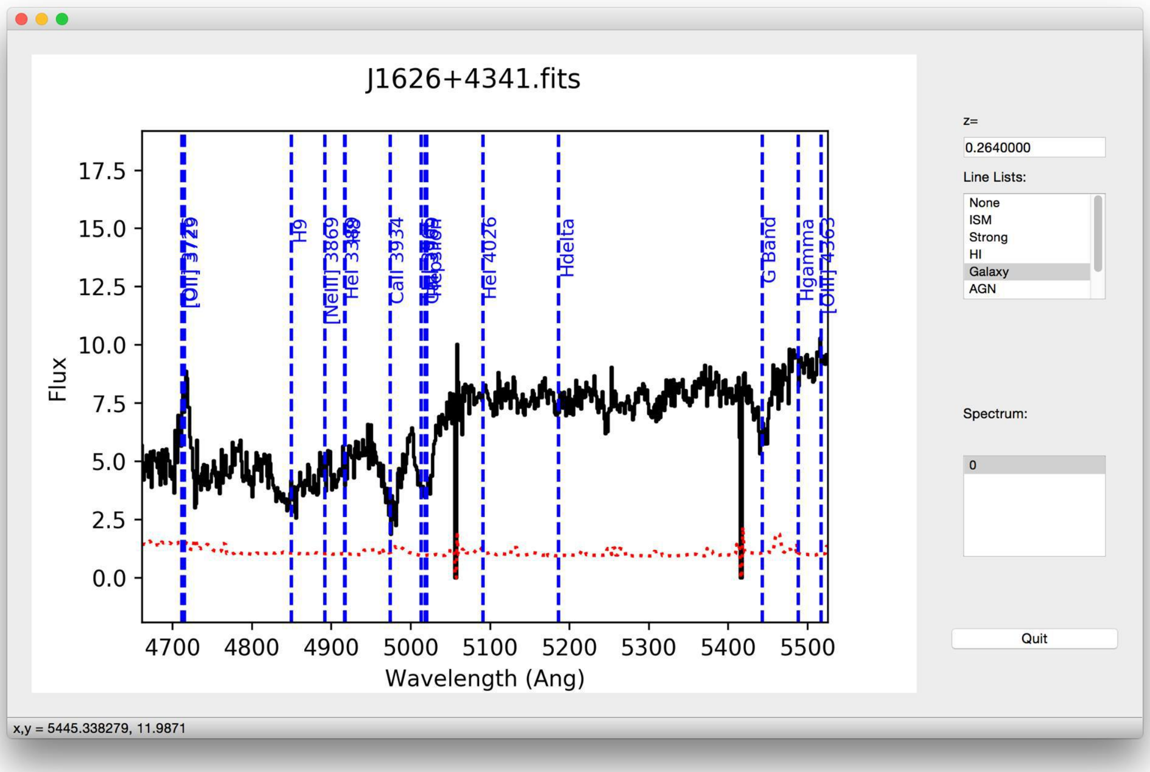

Figure 1: A Kast spectrum of the J1626+4341 galaxy, zoomed into the CaII H+K doublet region. The galaxy has an r-magnitude of 18.3, and a spectroscopic redshift of 0.264. The spectrum is a coadd of three one-hour exposures taken on 2018 Apr 21. We mark locations of several common transitions redshifted to the galaxy's frame. .

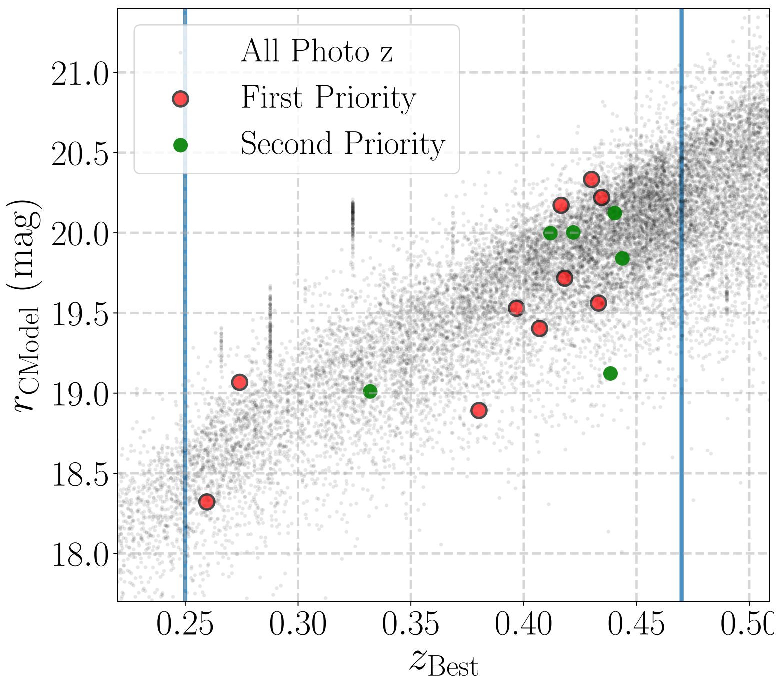

Figure 2: Distribution of our 2018B targets, as well as the parent HSC survey sample, as a function of redshift and r-magnitude.

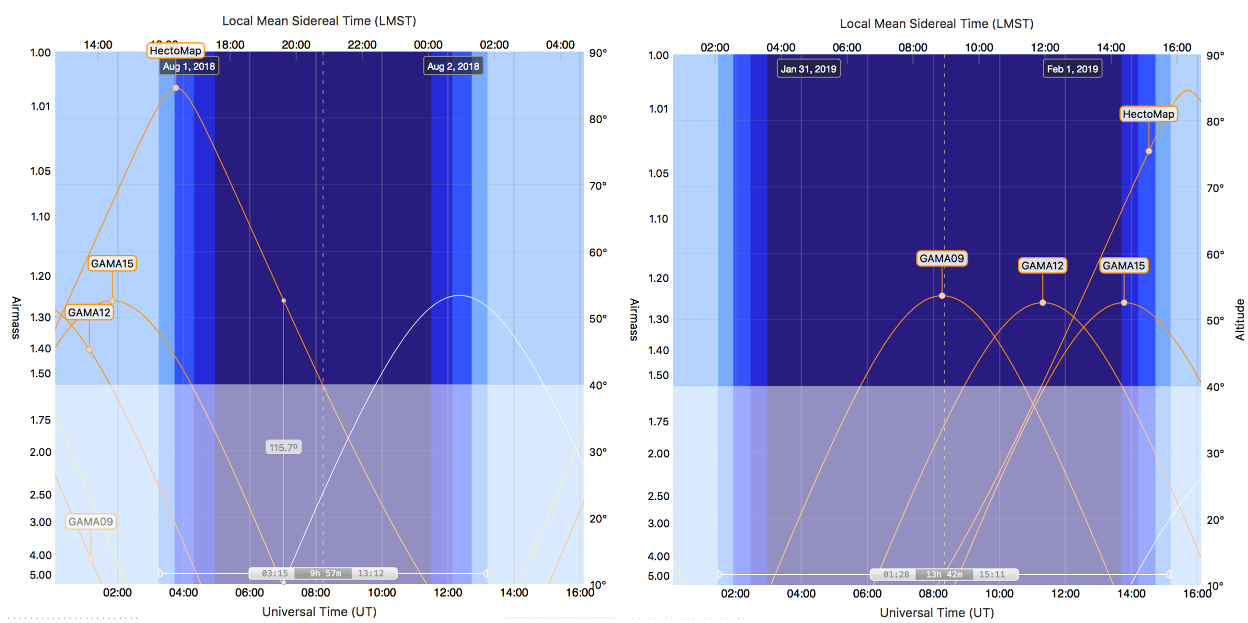

Figure 3: (Left) Visibility curves of our four targeted fields on 2018 August 1. (Right) Visibility curves on 2019 January 31. We request first-half-nights in August, and second-half-nights in January. Our targets will not be visible for more than half of the nights in other months.

2 Targets and Exposures

For this current semester, With Kast observations, we aim at acquiring spectroscopic redshifts of 8 to 14 galaxies in four different fields in the sky. Our sample is selected from our HSC catalogs with $0.25 < z_{\rm photo} < 0.45$ (our redshift range of interest). We will use the *RedRock* software to cross-correlate Kast spectra with galaxy templates. The distribution of our 2018B targets as well as the parent HSC survey sample in redshift and magnitude are shown in Figure 2.

We were awarded nine nights in 2018A. However, we almost lost our entire program to weather. We have only secured spectroscopic redshift for one galaxy, with somewhat uncertain spectroscopic redshift for another galaxy. Figure 1 shows our Kast spectrum of the galaxy with secure redshift, J1626+4341. We reduced the data using the PYPIT software. This is the brightest target on our list, with r-magnitude of 18.3. We attempted observing other galaxies on our list, e.g. J0857+0131 of r-magnitude 19.8, and estimated the brightness limit of Kast. We find that, for galaxies of $r \sim 20$, the object trace *cannot* be identified on a one-hour Kast red frame at wavelengths $< 5000\,$Å, even under good weather conditions. In our 2017 trial run that was director's discretionary time, we observed four galaxies that have spectroscopic redshifts already determined from SDSS, to determine the signal-to-noise required for deriving reliable spectroscopic redshifts. We find that a signal-to-noise of > 5 per angstrom is necessary for measuring a redshift. A minimum of $3 \times 2\,$hours $= 6\,$hours exposure is necessary for faint galaxies of $r \sim 20$. As the key features to be detected—the CaII H+K doublet and the 4000 Åbreak, lie on a steep slope in flux and on the blue end of the Kast red side which has lower efficiency, long exposures are required. As the exposure time per frame is long, three frames are necessary for cleaning cosmic rays and alpha particles from the dewar.

Among our four targeted fields, the HectoMap field is visible from dusk until midnight in 2018 August, while the GAMA-09, GAMA-12, and GAMA-15 fields are visible from midnight until dawn in 2019 January. Our fields will not be visible in other months in 2018B. Therefore, we request first-half-nights in 2018 August and second-half-nights in 2019 January. If we are awarded full nights instead, we will supplement the other half of the nights with targets from the J. X. Prochaska research group. Figure 3 shows the visibility curves of the four targeted fields on 2018 August 1 and 2019 January 31. While dark time is preferred due to the faintness of our targets, our time constraints are more critical than dark time.

We will use the $3''$ slit and the 600/5000 grating on the Kast red side. We will not use the blue side and will take out the dichroic beamsplitter. This wide slit will allow more light from our massive, extended galaxies. Our setup will resolve and cover the 4000 Å break, the CaII H and K lines, and the G-band features for a sufficiently wide redshift range. Our science goal will require 2 hours to 10 hours of exposure per object to obtain sufficient signal-to-noise. These long exposures will be broken into one-hour to two-hour exposures, depending on the minimum exposure time required to identify the object trace. With overhead, we can observe on average 2 targets per night. Accounting for poor weather conditions and Target

Table 1: List of targets.

Name	RA (J2000)	Dec (J2000)	SDSS r-mag	photo-z	Exposure (s)	Priority
J0857+0131	08:57:06.37	+01:31:30.7	19.8	0.42	21600	1
J1149-0021	11:49:48.12	-00:21:53.6	20.4	0.43	21600	1
J1203-0006	12:03:46.51	-00:06:28.2	20.2	0.42	21600	1
J1431-0045	14:31:33.58	-00:45:11.2	20.3	0.43	21600	1
J1616+4234	16:16:49.60	+42:34:08.9	19.6	0.43	14400	1
J1625+4338	16:25:24.37	+43:38:11.0	19.6	0.40	14400	1
J1627+4357	16:27:36.12	+43:57:07.4	19.5	0.41	14000	1
J1628+4314	16:28:29.55	+43:14:55.7	18.9	0.38	7200	1
J0852+0137	08:52:57.98	+01:37:05.6	19.9	0.44	21600	2
J0904+0000	09:04:08.14	+00:00:34.1	20.1	0.42	21600	2
J1155-0031	11:55:11.12	-00:31:26.6	19.1	0.33	10800	2
J1621+4312	16:21:59.10	+43:12:44.8	20.2	0.44	21600	2
J1627+4310	16:27:38.23	+43:10:24.0	19.2	0.44	10800	2

of Opportunity interrupts, **we request 6 first-half-nights in (early) August and 14 second-half-nights in (late) January.**

Table 1 lists our galaxies to be observed in 2018B. We will observe the second priority targets if we are granted additional observing time. In poor observing conditions we will increase the exposure time and give preference to brighter targets.

3 Supplementary Observations Required from other Observatories

Our full cluster catalogs include spectroscopic redshift catalogs from the GAMA team. We will request observing time from Gemini Observatory for targets that are fainter than r-magnitude of 20.

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, and nine regular nights in 2018B. We lost eight out of the nine nights our 2018B program to weather.

PI Lau is a postdoctoral at UCSC, who has been awarded a total of 32 nights on Shane and has been the lead observer of 60 nights on Shane using Kast and ShARCS.

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

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