OBSERVING REQUEST
University of Arizona Observatories

Year: 2017 **Term:** Jul–Dec **Proposal type:** short-term*

Surveying Galaxy Cluster Physics and Cosmology from the Cluster Outskirts

P.I.: Anna Patej (SO; *apatej@email.arizona.edu*; (714) 290-9075)

CoI(s): Xiaohui Fan (SO), Eduardo Rozo (UA Physics), Abraham Loeb (Harvard), Arjun Dey (NOAO)

Abstract of Scientific Justification

Interest in the physics of galaxy cluster outskirts has been recently revitalized by simulations that have reinforced the long-standing analytical predictions of a steep density jump in the dark matter density profiles of clusters. This feature not only provides a physical length scale for clusters but can also be used as novel test of the physics of dark matter. Observational work following up on these predictions has relied on the assumption that cluster galaxies in the outskirts follow similar collisionless dynamics as the dark matter and has attempted to detect the feature in galaxy density profiles; the results have been discrepant with the predictions for the dark matter. We propose to study the physics behind these discrepancies by examining the outskirts of galaxy clusters via spectroscopy of galaxy cluster members using Hectospec. This work will allow us to place constraints on various processes that may be affecting the outskirts, such as dynamical friction. This spectroscopy will additionally enable us to address the dominant source of systematic uncertainty in using clusters for cosmology, namely the mass calibration, by allowing us to test a new approach to measuring cluster masses using spectroscopic velocities. The proposed observations will target five galaxy clusters in the redshift range of $0.1 < z < 0.3$ out to a radius of about $2 \times R_{vir}$. These clusters are selected from the sample of HeCS clusters (Rines et al., 2013) which have been previously targeted with Hectospec in order to leverage the availability of spectroscopy in the cluster interior and include those clusters with weak lensing measurements from the Canadian Cluster Comparison Project (Hoekstra et al., 2015). The current proposal is an extension of the previously awarded program UAO-S106 in 2017A.

Summary of observing runs requested for this project

								Scheduling		Sharing	
Run	Telescope	Cage	Instrument	PI	AO	Nights	Moon	Optimal	Acceptable	Poss.	Adv.
1	MMT	f/5	Hectospec			3	dark	Jul–Dec	Jul–Dec	yes	yes

Scheduling constraints and unusable dates *(up to 4 lines)*:

no text past this line

A $\star$ appended to the proposal type indicates a continuation proposal; a $\star$ 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	Abell 267	01:52:42.29	+01:00:45.0	Galaxy Cluster; $z = 0.23$
2	Abell 697	08:42:56.69	+36:21:45.0	Galaxy Cluster; $z = 0.28$
3	Abell 773	09:17:50.98	+51:43:29.3	Galaxy Cluster; $z = 0.22$
4	Abell 963	10:17:02.40	+39:02:54.2	Galaxy Cluster; $z = 0.20$
5	RXJ2129	21:29:40.80	+00:05:14.3	Galaxy Cluster; $z = 0.23$

Approval for Instrument Use from PI: N/A

Graduate students *(provide the following information if student is PI on the cover page or if this is a 2nd-year or Thesis program. Send confirmation email to TAC chair in place of signature.)*

Student's Name	Advisor's Name	Advisor's Signature	2nd-yr	Thesis

Scientific Justification

The outskirts of galaxy clusters contain a wealth of information about wide-ranging astrophysical processes, including matter accretion and structure formation (e.g., Bertschinger, 1985), galaxy evolution, (e.g., Haines et al., 2013; Just et al., 2015), and the impact of environment on stellar populations (e.g., Bahcall & Kulier, 2014), among many others. However, the low matter densities in these regions as well as the large areas that they cover on the sky make these regions extremely challenging to probe observationally.

Recent simulations (Diemer & Kravtsov, 2014) have revitalized interest in the physics of cluster outskirts, where both the simulations as well as long-standing analytical models of structure formation (e.g., Fillmore & Goldreich, 1984; Bertschinger, 1985) have predicted the existence of density jumps. The simulations have emphasized that the dark matter halos of massive galaxy clusters should feature a sharp steepening of slope just beyond the virial radius whose location and strength depend on the cluster's mass accretion rate. This feature accordingly introduces a new, physical size scale in galaxy clusters and also provides a novel test of the nature of dark matter.

The predictions of the density jump can in principle be tested with weak gravitational lensing, but the challenge of extracting a significant weak lensing signal with existing datasets at such large radii has led to the development of other strategies. One promising approach to probing the physics of the outskirts of galaxy clusters is to use the cluster galaxies themselves as luminous tracers of the matter distribution. This requires a means of identifying cluster members; the most secure method is by spectroscopy. Spectroscopy of cluster members is also an important method of empowering galaxy cluster cosmology. The dominant source of systematic uncertainty in using clusters for cosmology is the mass calibration; with cluster member galaxy redshift estimates, we can obtain estimates of cluster masses via the caustic method (Diaferio & Geller, 1997; Diaferio, 1999) and the virial theorem (e.g. Rines et al., 2013; Ruel et al., 2014).

The largest spectroscopic samples of cluster members come from the Hectospec Cluster Survey (Rines et al., 2013), which observed a sample of 58 galaxy clusters at $0.1 < z < 0.3$ and identified hundreds of cluster members per cluster out to roughly the virial radius, with sparse coverage beyond (see Figure 1). We propose to extend the range of spectroscopically-identified cluster members out to at least $2 \times R_{\rm vir}$ for five of these clusters, leveraging the availability of spectroscopy in the inner regions of the clusters to minimize our time request. We aim to use this sample of clusters to address three primary questions in galaxy cluster astrophysics and cosmology: first, we intend to constrain a key systematic in measuring density jumps in galaxy clusters from the galaxy distribution, which is understanding how the target galaxies trace the underlying matter distribution; second, we aim to improve spectroscopic mass estimates; and, lastly, we will examine the nearby filamentary regions of clusters to study the behaviors of their galactic populations.

Galaxies as Tracers of the Cluster Potential

Under the assumption that the galaxies follow similar collisionless dynamics as the dark matter, the galaxy density profiles should show a steep density jump as well. Several recent works have provided observational evidence for the density jump using the galaxy density profiles of clusters (Tully, 2010; Patej & Loeb, 2016; More et al., 2016). However, there are discrepancies between the observations and the predictions of the simulations of Diemer & Kravtsov (2014), which may indicate that the commonly assumed similarity of dark matter and galaxy dynamics in cluster outskirts does not hold and can provide a key observational test of processes like dynamical friction in cluster-size halos (e.g, Adhikari et al., 2016).

One crucial feature in the observational approaches is the reliance on primarily red sequence galaxies to characterize the galaxy density profile. While red sequence galaxies do in fact tend to comprise a majority of cluster members well within the virial radius, it has been well-established that the fraction of such galaxies decreases in the outskirts, transitioning into the bluer field galaxy distribution (e.g., Dressler, 1980). Accordingly, a possible source of the discrepancy between the observed and predicted behaviors may be that this target population of galaxies does not accurately trace the cluster potential in the outskirts.

We intend to address this question in a more general framework that has analogues in studies of the large-scale structure (LSS) of the universe; galaxy redshift surveys target specific populations of galaxies (e.g. luminous red galaxies for SDSS/BOSS) to use as tracers of LSS, and it is accordingly necessary to understand the extent to which the observed subset of galaxies probes LSS. Patej & Eisenstein (2016) already considered this question in the context of the color of BOSS galaxies, finding that on intermediate scales of $20 \lesssim R \lesssim 100\ h^{-1}\mathrm{Mpc}$, red and blue galaxies do roughly trace the same large-scale structure.

We will pursue this question on cluster scales, using a modified galaxy bias framework. The spectroscopic observations requested herein will be key to precisely establishing cluster membership for galaxies of various types near the cluster outskirts. This sample of cluster members can then be split up into subsamples whose profiles we will analyze in relation to the underlying mass profiles of the clusters obtained from the weak lensing results of the *Canadian Cluster Comparison Project* (Hoekstra et al., 2015), which has some overlap with the Rines et al. (2013) sample of clusters. The results of this work will establish how well member galaxies of different types trace the cluster potential and provide novel insights into the processes affecting the dynamics of galaxies in dense cluster environments.

Improving Spectroscopic Cluster Mass Estimation

It is essential to have accurate galaxy cluster masses in order to use clusters as cosmological probes; the mass calibration is the dominant source of systematic uncertainty in galaxy cluster cosmology. There are currently several complementary methods of determining galaxy cluster masses, each with its own possibly inaccurate assumptions on cluster structure and dynamics; these include gravitational lensing, gas-based mass measures from X-rays/Sunyaev-Zel'dovich effect, and spectroscopic velocities (caustic and virial masses). Recent work by Hoekstra et al. (2015) compared weak lensing measurements to masses determined via X-rays and optical/IR spectroscopy, finding that there is substantial scatter between the weak lensing and caustic masses, with the weak lensing masses typically about 1.22 times larger.

One of the drawbacks of the caustic method, however, is that the mass is determined up to a multiplicative factor that needs to be calibrated using simulations; this multiplicative factor is often taken to be constant even though it may in fact have a radial dependence (see Rines et al., 2013, and references therein), which can introduce additional uncertainty into the mass measurement. We have developed an alternative method of determining galaxy cluster masses (Patej & Loeb in prep.) using spectroscopy of the outskirts that is similar in spirit to the caustic technique but uses inferences from the large-scale structure surrounding the cluster to eliminate the reliance on simulations to calibrate the method. With the observations proposed herein, we will test this method with on-sky data and compare to existing mass measurements, particularly the weak lensing results of Hoekstra et al. (2015), to establish whether we can make sufficient improvement on spectroscopic mass with this method, particularly with an eye towards using data from the upcoming Dark Energy Spectroscopic Instrument (DESI) to empower galaxy cluster cosmology.

Galaxies in Filamentary Regions

The outer regions of galaxy clusters contain environments of varying density; that is, at some points in the outskirts the galaxies reside in denser, filamentary regions, while at others the galaxy distribution tapers off into voids. The most recent, deep *Chandra* imaging of galaxy cluster outskirts has revealed that the behavior of the gas in the filamentary regions differs from the gas in the less dense regions (B. Forman, *private communication*; Vikhlinin et al., in prep). Spectroscopy of the cluster outskirts will allow us to examine this question for the galaxy distribution and to investigate the transformation of galaxies as they accrete onto clusters in various environments, e.g., by comparison to the optical imaging, which will allow the study of the morphological changes the member galaxies undergo in the outskirts. Additionally, probing the distribution of cluster members into the filamentary regions will allow for testing the effects of cluster member contamination on weak lensing measurements, particularly at large radii (e.g., Hwang et al., 2014).

Composition of the Sample and Observational Parameters

We will be targeting a sample of five clusters, which have been selected from the sample of Rines et al. (2013) in order to leverage their extensive spectroscopic observations of the interior cluster regions and to overlap with the clusters from (Hoekstra et al., 2015). The target galaxies will be selected from SDSS photometry with $r = 16 - 21.5$ (similar to HeCS but extended to roughly reach the completeness magnitude of SDSS in these cluster fields); we will start by including target galaxies along the red sequence that do not already have spectra and move blueward using the guidance of SDSS photo-zs. More detailed discussion regarding the observing strategy can be found in the Experimental Design section.

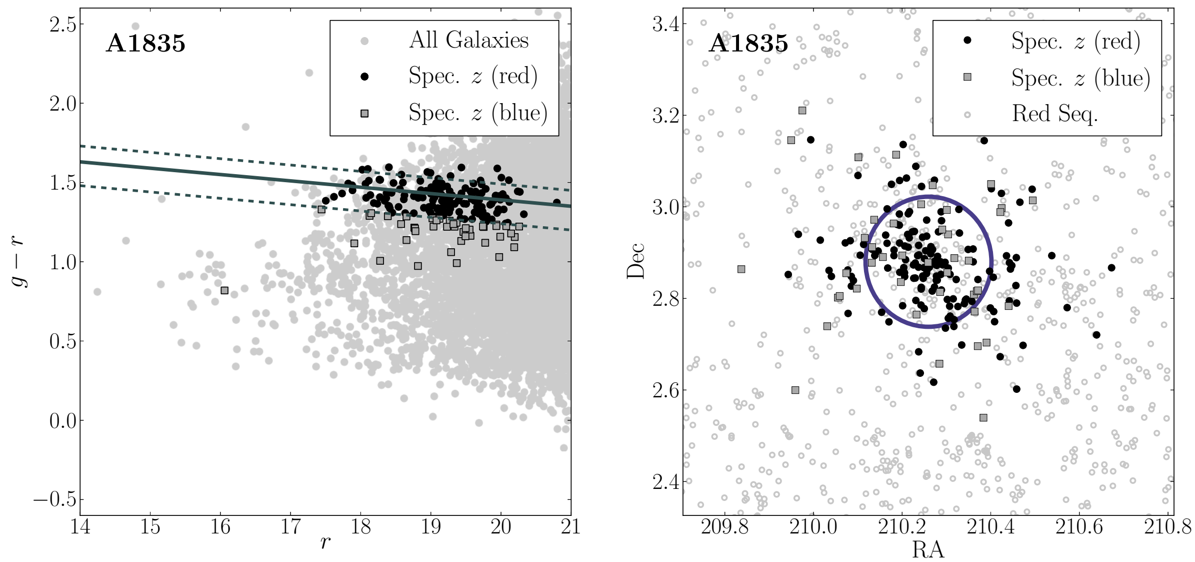

Figure 1: These panels show the distributions of cluster members identified via the publicly available spectroscopy of Rines et al. (2013) in color-magnitude space (left) and on the sky (right) for one of our targeted clusters. The color-magnitude diagram is constructed from SDSS photometry; we denote the red sequence by enclosing the region within dashed lines. Red galaxies are labelled as black points while galaxies blueward of the red sequence are indicated by gray squares. The righthand plots show the spatial distributions of these populations of galaxies; the circle indicates the R_{200c} ($< R_{vir}$) radius of the cluster. The proposed observations will probe fainter galaxies down to roughly the completeness limit of SDSS and out to over twice R_{vir} to trace out the galaxy distribution into the filamentary regions. Significantly, we will extend the target selection further blueward of the red sequence in order to capture the behaviors of these populations of galaxies in cluster outskirts.

References

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Tully, 2010, arXiv: 1010.3787
Vikhlinin et al. (in prep)

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 propose to observe five clusters originally observed in the Hectospec Cluster Survey (HeCS; Rines et al., 2013) out to larger radii of about $2 \times R_{vir}$ and to fainter magnitudes (to $r = 21.5$) using a similar observing strategy to HeCS in the outskirts in order to essentially fill in the missing galaxies. The five clusters that have been chosen from that survey to be observed in this program were selected primarily due to their overlap with the weak lensing sample of Hoekstra et al. (2015) and secondarily in order to span a representative range of parameters (including redshift, mass, X-ray luminosity) that may correlate with our results. This sample extends our sample from 2017A (which is not yet fully observed but due to a modification of the observing strategy is set to observe a smaller number of clusters than originally proposed) to include more higher redshift clusters and better mass range coverage, providing a more representative total sample.

Although the HeCS clusters span the redshift range of $0.1 < z < 0.3$, our clusters are selected in the narrower range of $0.19 \leq z \leq 0.28$, where the radius of a Hectospec pointing is between 4.0-5.4 h^{-1}Mpc, and the clusters selected here have $R_{200c} \sim 1.2\ h^{-1}\mathrm{Mpc}$. The field-of-view of Hectospec is sufficiently large that a single configuration will attain the range of $2\times R_{vir}$ even for the lowest redshift clusters. The goal of reaching roughly $2 \times R_{vir}$ is set by the fact that we are interested in determining how the galaxies trace the underlying matter distribution into the region where the density jumps are predicted. The simulations of Diemer & Kravtsov (2014) suggest that, in projected profiles, the gradual steepening of slope extends over a range of radii, which for a high mass accretion rate can be about $(0.5 - 2) \times R_{200m}$ (see Figure 13 of Diemer & Kravtsov (2014)). Since $R_{200m} \sim 1.4R_{200c} \sim 1.2R_{vir}$ for clusters in the redshift range of the HeCS sample, this means that we need to probe galaxies within the range of roughly $0.6 - 2.4R_{vir}$.

As the HeCS survey has already successfully observed these clusters near our required limits, our observing strategy will be mostly borrowed from their techniques. However, the results from the data we obtained in 2017A (currently only 1 configuration has been observed out of 8 scheduled), suggest that our observing strategy needs to be modified to include more configurations per cluster. In 2017A, we submitted two configurations per cluster, whereas this semester, we will obtain three configurations, with three 25-minute exposures per pointing, which both our previous observations and Rines et al. (2013) found to be sufficient for clusters in this redshift range even under poor conditions. This means 5 clusters, with 3 pointings each, and 3 exposures of 25 minutes per pointing, yields observing time+overheads of about 3 nights.

The clusters selected for this program are in the SDSS footprint, so SDSS photometry will be used to select target galaxies with $r = 16 - 21.5$ (following and expanding the HeCS selection). Towards the faint end, we can also make additional gains by adding in deeper DECaLS/BASS/MzLS photometry. This magnitude range means that this program will be observing galaxies fainter than the sky brightness and thus requires dark time for efficient observing. Galaxies that already have spectra from HeCS or SDSS will be removed from the targeting. However, as their program highly prioritized galaxies near the X-ray center of the cluster, most of the potential cluster members in the outskirts were not observed.

The red sequence method will be used to make a preliminary target list of galaxies within limits of 0.1 (above) and 0.15 (below) the red sequence; these limits have been calibrated based on the existing spectroscopy from HeCS (see Figure 1). Additional targets blueward of the red sequence will be selected with the guidance of SDSS photometric redshifts. Bluer galaxies are expected to have emission lines from star formation and so we expect to be able to obtain accurate redshifts from them. Targets will be assigned priority so as to emphasize radial continuity with the previously obtained spectra.

While red cluster members can be reliably targeted from photometry, the situation for bluer galaxies (even using the aid of photo-z's) is more challenging. In our only configuration observed thus far using our targeting strategy, the likely cluster member fraction is about 30% (out of all targeted objects; see Figure 2). The final 2017A strategy included two configurations per cluster for four clusters, which is expected to yield $\sim 60 - 70$ new cluster members per cluster. Accordingly, for this proposal we modify the strategy to include 3 configurations per cluster so that we can expect to obtain ~ 100 new cluster members per cluster.

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**)*

In 2017A, we were awarded 1.5 nights on Hectospec for this project, and submitted four cluster fields with two configurations each to the Hectospec scheduler. Of these, only a little under two or so hours have been used so far to observe 1 configuration. Because that observation has indicated that we definitely require more than 1 configuration per cluster, we have upped the request to 3 configurations per cluster. The current state of our data and observations is shown in Figure 2 in the following section on Past Use of Steward Facilities, and also discussed in the preceding section on Experimental Design.

Accordingly, we are asking for roughly 3 nights of dark time to complete observations of five clusters that not only are critical for several compelling investigations outlined in the Scientific Justification, but also leverage several powerful existing datasets. The PI is not requesting time on any other UAO instruments for 2017B.

Because of the change in observing strategy, we anticipate a request of about ~ 1 night to get an additional configuration for A semester clusters in 2018A (the request may be slightly increased if some of the clusters that we selected for 2017A end up not being observed at all in 2017A). It is possible that there will be requests to extend this project to, e.g., lower mass clusters or higher/lower redshift clusters in future semesters beyond 2018A if the analyses of this sample suggest it would be worthwhile. It is not possible at this time to foresee how many nights would be requested in those future semesters.

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)***

⋆ We were awarded 1.5 nights of dark time for this project in 2017A. To date, only one of eight configurations has been observed. The data collected thus far have been studied to inform the strategy for the 2017B semester as discussed above. Figure 2 shows the status of the observations obtained thus far, and indicates that our targeting strategy, while necessarily including some targets within R_{200c} to emphasize radial continuity with existing spectroscopy, is probing well into the infall regions beyond for a fairly low-redshift cluster ($z \approx 0.18$) in the Rines et al. (2013) sample.

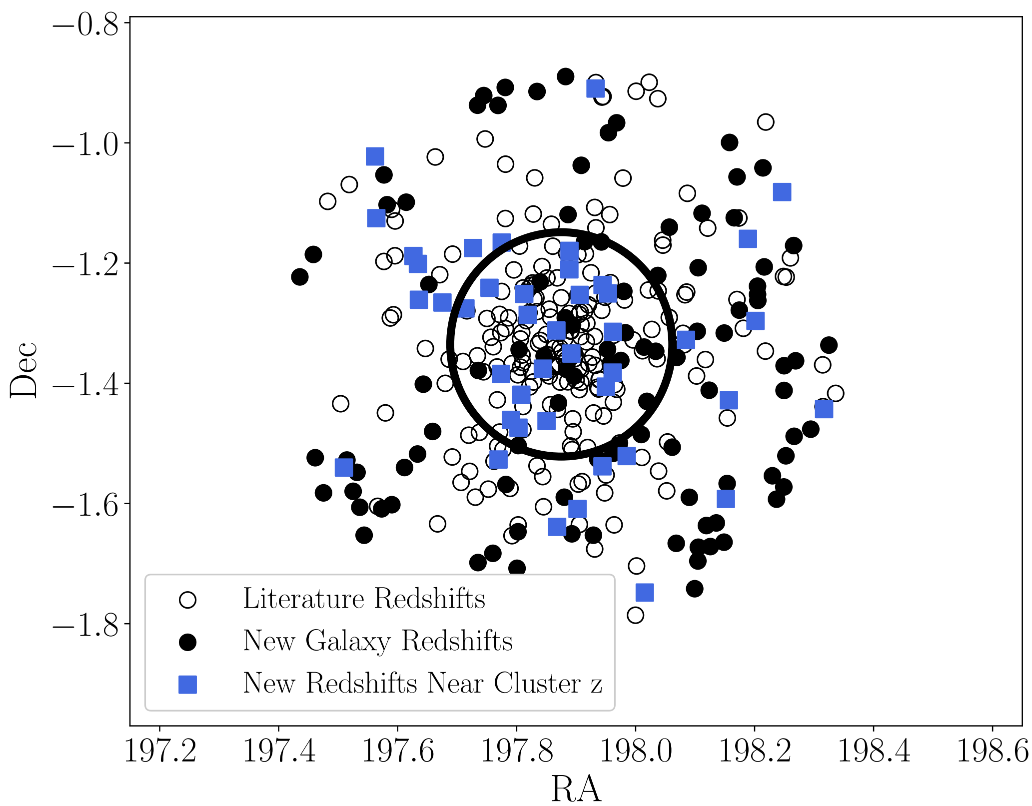

Figure 2: This figure shows galaxies with spectroscopic redshifts in the field of galaxy cluster A1689, the only cluster for which a configuration has been observed so far in 2017A. Some minor quality cuts have been applied to the data that is shown here, and the plot is restricted to objects that were classified as galaxies. The open black circles show galaxy redshifts that were already obtained in this field either by SDSS or Rines et al. (2013). The filled in black circles show new galaxy redshifts observed by our program in 2017A. The blue squares indicate likely cluster members. The large black circle indicates the cluster's R_{200c} radius.

Other Information *Provide any additional program-related information including, for example, relation of current program to externally funded research, to the development of expanded capabilities for UA telescopes, or to individual timescales (e.g. PI is finishing postdoc appointment and this request would complete program). (**up to one page**)*

The PI of this proposal is a NASA Einstein Fellow at Steward Observatory. The proposed observations constitute a substantial portion of her research proposal for the Einstein Fellowship. If not awarded time in 2017B, the analysis could only begin in earnest after 2018A (when additional configurations could be observed for the 2017A clusters), which would be the second semester of the PI's second year of the fellowship.

The PI has two obligations prior to the third year of her fellowship (that is, before the end of the 2018A semester). First, she must justify her research program, its progress over the past two years, and its relation to the objectives of NASA's Physics of Cosmos mission to the Einstein Fellowship committee if she wishes to have the option of extending her fellowship to its third year. Second, she needs to have accrued the bulk of her observations and publications prior to having the possibility of applying for new jobs in the fall of 2018.

Accordingly, the timing of these observations is significant for the PI's career at Steward and beyond.