SCIENTIFIC AIM AND RATIONALE

Background

As a galaxy falls into a galaxy cluster, a variety of processes act to dramatically transform it. Tidal stripping by the cluster potential removes a large fraction of the galaxy's dark matter; ram-pressure stripping by the cluster's hot ($T > 10^7$ K, even up to $T > 10^8$ K in the most extreme cases) intracluster medium (ICM) remove the cold gas that the galaxy would have turned into new stars, halting star formation essentially to a complete stop within a few Gyr (e.g., Oman et al. 2021), and close encounters with other galaxies can also heat or remove a galaxy's cold gas supply, while also disturbing the dynamical structure of the galaxy. The cumulative effect of these interactions is that massive ($M > 10^{14}\,\mathrm{M}_\odot$) galaxy clusters are largely dominated by red, passively-evolving elliptical galaxies (Dressler 1980). Furthermore, a surprising fact has been the wealth of observational evidence and theoretical predictions that have shown that these processes begin to take place well before they fall into the massive clusters that host the red ellipticals, at mass scales $M \sim 10^{13}\,\mathrm{M}_\odot$ (e.g., Haines et al. 2015, Bahé et al. 2019).

However, star formation activity *can* also exist in clusters, through several channels. For instance, a star-forming galaxy may have only recently fallen into the cluster and had not yet had enough time for environmental processes to halt star formation to a complete stop. While this is expected to happen well outside a cluster's virial radius (e.g., Haines et al. 2015), such galaxies can appear close to the cluster core due to projection effects. Star formation can also be triggered by shocks from major cluster mergers (e.g., Sobral et al. 2015, Kelkar et al. 2020) or even by less violent phenomena such as gas sloshing due to minor mergers or turbulence left over from past mergers (Stroe et al. 2017). Cluster-scale shocks can also induce AGN activity in cluster galaxies (e.g., van Weeren et al. 2017). Star formation can also be triggered in central cluster galaxies (hereafter BCGs) in particular, for instance by the infall of low-entropy gas due to a high ICM density in the cluster core, as has been observed in the extreme 'Phoenix' cluster (McDonald et al. 2012).

Being the reddest (and therefore less subject to obscuration) of strong optical emission lines, the Hα line at rest-frame $\lambda_0 = 6563$Å is a particularly useful tracer of star formation and AGN activity. The two mechanisms can be disentangled through optical line ratio diagnostics (e.g., Kewley et al. 2006), but spectroscopic observations are usually limited to a small number of galaxies and relatively small fields of view, and are expensive to obtain. For this reason, narrow-band observations tailored to Hα emission at specific redshifts have become a powerful way to probe galactic activity over larger samples of galaxies, both in the field and in clusters (e.g., Iglesias-Páramo et al. 2002; Lee et al. 2012; An et al. 2014). Narrow-band imaging also makes it possible to carry out blind surveys for star formation over large fields of view (e.g., entire clusters), in contrast to spectroscopic observations for which targets must be selected in advance (except for integral field spectroscopy, which is however limited to fields of view $< 1'$).

The largest narrow-band Hα cluster survey to date is that of Stroe et al. (2017), who studied 19 clusters at $z = 0.15 - 0.30$ by combining observations in several narrow-band filters in various facilities. They found indications that mergers trigger star formation due to interactions between gas-rich galaxies (which are more common in 'young', i.e. dynamically-disturbed, clusters) as well as ICM shocks, but could not draw robust conclusions due to the limited number of clusters and the complicated cluster sample definition. Indeed, Stroe et al. built their sample with the specific goal of studying the effects of mergers, and while by design it included clusters in varied dynamical stages and covering almost an order of magnitude in mass, it was limited to well-known clusters identified through various techniques. This can induce unknown selection effects, because the most spectacular systems tend to be preferentially followed up (and the definition of 'the most spectacular' is hard to quantify) . Beyond these potential difficulties, Stroe et al. remains the largest survey of Hα as a tracer for star formation and AGN activity in massive galaxy clusters. Because of the narrow-band filters available, Stroe et al. limited their sample to $z = 0.15 - 0.30$.

Other studies before and after Stroe et al. (2017) have looked at star formation in clusters in particular regarding its connection with cluster mergers. However, such studies have been usually limited to one or very few clusters because of the difficulty in measuring emission lines for large numbers of galaxies through multi-object spectroscopy (MOS), because of the very limited redshift range offered by narrow-band filters, or to very low redshifts (usually $z < 0.1$). For example, Cohen et al. (2014) found that clusters with more substructure (traced by the galaxy distribution) tend to have higher star formation in local SDSS clusters. Kelkar et al. (2020) found an excess of blue star-forming near the ICM shocks traced by radio relics and only red, quenched spirals elsewhere. However, without a coherent, well-defined sample of clusters it is difficult to draw conclusions applicable statistically to the population of clusters in the Universe, as these works have also acknowledged. Using radio data from MeerKAT, Kesebonye et al. (2023) have offered independent evidence for both the decline of star formation toward the center as well as the stronger predominance of star formation in disturbed clusters compared to relaxed ones, supporting the above conclusions.

This proposal

We propose to take advantage of the large, homogeneous cluster sample produced by the Atacama Cosmology Telescope (ACT) through the Sunyaev-Zel'dovich (SZ) effect to undertake **the largest and most distant homogeneous Hα survey in galaxy clusters to date**. While the sample of Stroe et al. (2017) included 19 galaxy clusters over $z = 0.15 - 0.30$, we propose to use three narrow-band filters on the Blanco telescope to observe **66 clusters at redshifts** $z = 0.47 - 0.81$. ACT's Data Release 5 (ACT-DR5, Hilton et al. 2021; see Fig. 1) contains 42 clusters with *spectroscopic redshifts* with Hα falling within 0.5 FWHM of the central wavelength of DECam's NB964 filter centered at $\lambda = 964.2$ nm, which corresponds to the redshift range $z = 0.462 - 0.477$; 17 clusters with the same criterion for NEWFIRM's NB1066 centered at $\lambda = 1066$ nm, i.e., $z = 0.621 - 0.627$; and 7 clusters falling within the redshift range where Hα falls in NEWFIRM's NB118 filter at $\lambda = 1.18\,\mu$m, namely $z = 0.799 - 0.817$. Such a large sample, constructed in a blind, homogeneous, well-understood way offers the unique possibility of constraining the relation between star formation and cluster mass and dynamical state while keeping selection effects under control. By comparing our results with Stroe et al. we will extend constraints on the evolution of this relation to a lookback time corresponding to half the current age of the Universe. The large statistics will even allow us to control for 'progenitor bias' and study how galaxies evolve as the clusters they reside in grow over cosmic time.

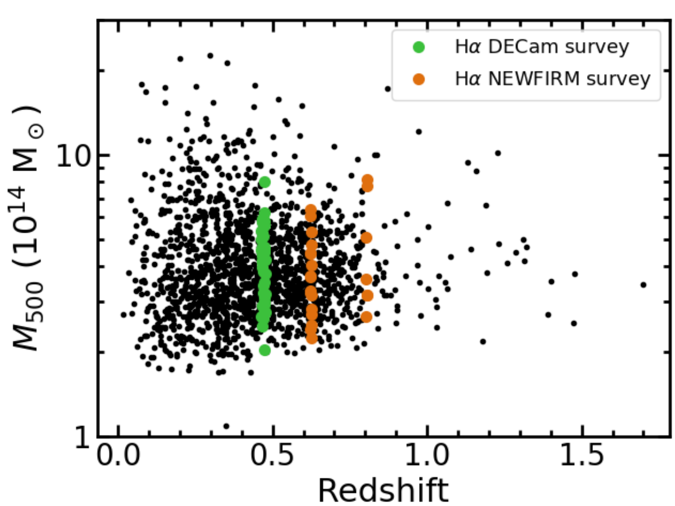

Figure 1: Mass and redshift distribution of ACT-DR5 clusters, with targets of this proposal highlighted in green ($z = 0.47$) and orange ($z = 0.62$ and 0.81).

The large field-of view of DECam, with a radius of 1.1 deg., corresponds to 24 Mpc at $z = 0.47$. Such an aperture will allow us to probe, with a single pointing per cluster, cluster-centric

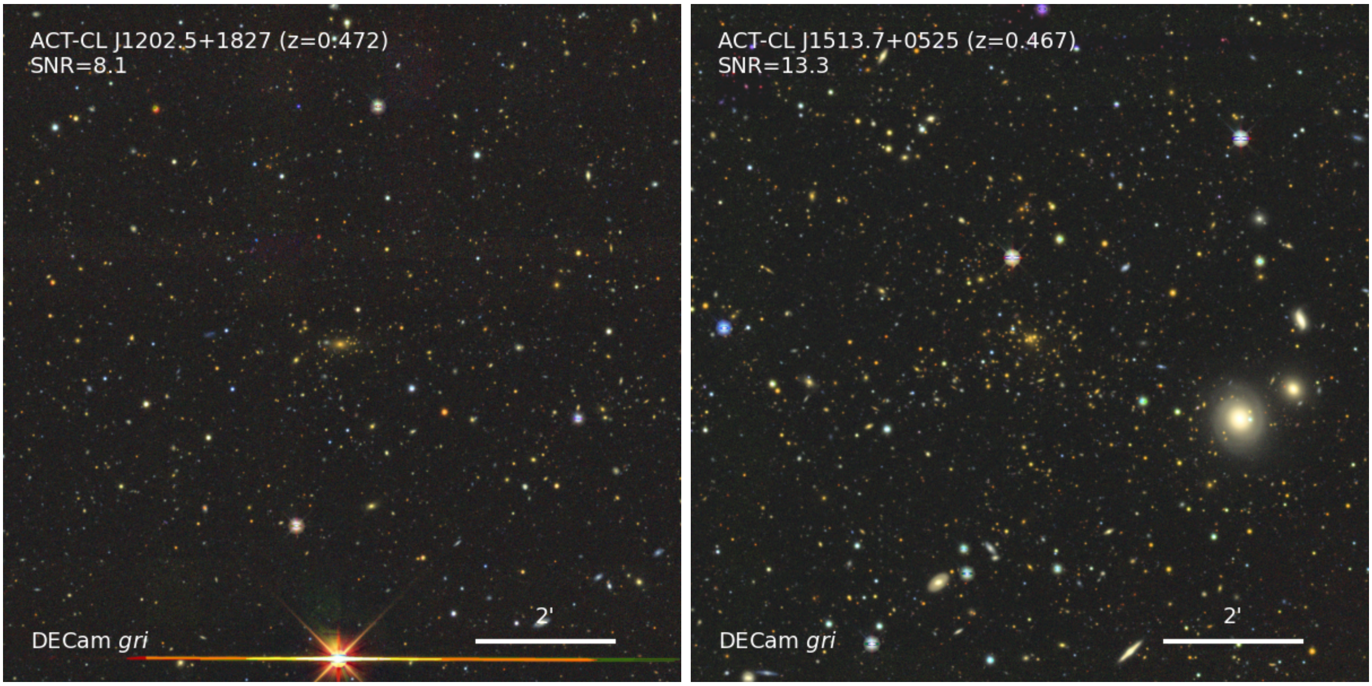

Figure 2: DECam gri optical images of two example clusters at $z = 0.47$. ACT-CL J1202.5+1827 quite centrally concentrated with a dominant brightest cluster galaxy and not many more red-sequence galaxies easily identifiable, while ACT-CL J1513.7+0525 is extremely rich and extended on the sky. Each image is $10'$ on a side, corresponding to 3.6 Mpc at $z = 0.47$.

distances $r \gtrsim 10r_{200}$. Therefore the proposed observations allow us not only to study star formation and AGN activity near the cluster cores but all the way to the large-scale structure from which the cluster is growing. For comparison, the recently-approved 4MOST-CHANCES project (Haines et al. 2023), which was specifically designed to study the transformation of galaxies falling into clusters, will reach radii $r = 5r_{200}$ for 150 clusters at $z < 0.4$ over 5 years of 4MOST observations. The proposed observations will offer a uniquely wide view of the quenching processes around galaxy clusters. Similarly, the NEWFIRM half-side of 13.8 arcmin corresponds to 5.8 Mpc at $z = 0.62$ and 6.4 Mpc at $z = 0.81$, which means we will cover radii $r > 3r_{200}$ for the high-redshift NEWFIRM samples, i.e., well into the preprocessing regime as well.

We will use these data to measure star formation rates and AGN activity by combining the narrow-band images with DECaLS $griz$ and WISE 3.4 and 4.5 μm data (and NEWFIRM J at high redshift) to fit spectral energy distributions for all sources found in the narrow-band images. DECam images are large enough to provide measurements of field levels for each individual clusters, while for NEWFIRM data we will use the DAWN (Harish et al. 2020) and LAGER (Khostovan et al. 2020) surveys as benchmarks. We will follow the corrections for line contamination and photometric calibration by those same works. SZ data from ACT, as well as X-ray data, will allow us to relate galactic activity to ICM properties. We will perform an initial comparative analysis with archival MeerKAT data (seven of our targets have such data) and propose more observations as needed.

References: An et al. 2014, ApJ, 784, 152 • Bahé et al. 2019, MNRAS, 485, 2287 • Haines et al. 2015, ApJ, 806, 101 • Haines et al. 2023, The Messenger, 190, 31 • Hilton et al. 2021, ApJS, 253, 3 • Iglesias-Páramo et al. 2002, A&A, 384, 383 • Kelkar et al. 2020, MNRAS, 496, 442 • Kesebonye et al. 2023, MNRAS, 518, 3004 • Kewley et al. 2006, MNRAS, 372, 961 • Lee et al. 2012, PASP, 917, 782 • McDonald et al. 2012, Nature, 488, 349 • Oman et al. 2021, MNRAS, 501, 5073 • Sobral et al. 2015, MNRAS, 450, 630 • Stroe et al. 2017, MNRAS, 465, 2916 • van Weeren et al. 2017, Nature Astronomy, 1, 5

TECHNICAL DESCRIPTION

DECam observations

We base our exposure time calculations for the DECam survey at $z = 0.47$ on the NB964 survey of emission lines by Khostovan et al. (2020). We will perform photometric calibration taking advantage of the DECaLS well-calibrated broad band data as discussed in Hu et al. (2019). We aim to determine the Hα down to a reference sSFR of $10^{-11}\,\mathrm{yr}^{-1}$ at 5σ, corresponding to the typical threshold used to separate star-forming and quiescent galaxies. For a typical galaxy of $M_\star = 10^{10}\,\mathrm{M}_\odot$ and using the commonly-used Kennicutt (1998) relation between SFR and Hα luminosity, we find we require a flux limit $F_{\mathrm{H}\alpha}^{\mathrm{limit}} = 6.7 \times 10^{-17}\,\mathrm{erg\,s^{-1}\,cm^{-2}}$. Scaling from the exposure time and flux limit of Khostovan et al. (2020), we derive an exposure time of 42 minutes per cluster. Note that by scaling their exposure time and their Hα flux limit we account for all the corrections to go from observed narrow-band flux to Hα flux alone. Considering exposures of 120 s each (on average) to minimize artifacts from bright stars will require 21 exposures per cluster, which we will also use to cover the chip gaps by dithering. Since the read-out time is 20 s, this implies a read-out overhead per cluster of seven minutes. Rounding up to ten minutes to include slewing and other overheads, we estimate a total observing time of 52 minutes per cluster. Therefore to observe 42 clusters with DECam we require a total 37 hours.

NEWFIRM observations

In order to be more realistic about the exposure times for the high redshift NEWFIRM sample, considering we also need to observe in J-band, we aim to reach a sSFR limit of $10^{-11}\,\mathrm{yr}^{-1}$ under the Kennicutt (1998) relation at 3σ (instead of 5σ used for the $z = 0.47$ sample). Scaling from the exposure time and depth of the NB1066 observations by Harish et al. (2020) implies a narrow-band exposure time of 41 minutes per cluster. Assuming a standard 50% overhead for NIR observations, we require 62 minutes per cluster with the narrow-band filter, totalling 18 hours.

We also scale the NEWFIRM J-band observations of Ly et al. (2011) needed to determine the Hα continuum emission. In order to be able to confidently (i.e., at 3σ) isolate galaxies with significant Hα line emission using the criteria of Harish et al. (2020), we require 19 minutes of exposure per cluster in the J-band. With an assumed 50% overhead, this results in total observing time of 29 minutes per cluster, or 8 hours for the 17 clusters.

Similar considerations for the $z = 0.81$ sample of 7 clusters lead us to request a total 18 hr (104 min of exposure per cluster) with NEWFIRM's NB118 and 5 hr with J-band (29 min per cluster).

Summary

In summary, we request (i) 37 hours with DECam NB964, (ii) 18 hours with NEWFIRM NB1066, (iii) 18 hours with NEWFIRM NB118, and (iv) 13 hours with NEWFIRM J-band. **Our total request is therefore 86 hours, or 10 nights.** As detailed in the next section, we split this request into **6 nights in 2024A and 4 nights in 2024B**. In order to optimize exposure times (e.g., according to the existence of bright stars in the field), we request Visitor Mode Observations.

Our minimum request of 7 nights would allow us to carry out the majority of the DECam survey and about half the high-redshift observations but essentially exclude the $z = 0.81$ sample, which will enable a limited study of the evolution of galaxy activity in clusters at intermediate redshifts. We therefore argue that the total time requested is justified as it will allow us to push the evolutionary analysis significantly further back in time, taking advantage of the well-defined selection function of both samples.

References: Harish et al. 2020, ApJ, 892, 30 • Hu et al. 2019, ApJ, 886, 90 • Kennicutt 1998, ARA&A, 36, 189 • Khostovan et al. 2020, MNRAS, 493, 3966 • Ly et al. 2011, ApJ, 726, 109

JUSTIFICATION OF LONG-TERM STATUS

The ACT-DR5 sample offers the unique possibility to perform cluster studies with both high statistical power and low systematic uncertainties in terms of cluster properties. In fact, the number of clusters available from ACT-DR5 to perform studies such as that proposed here—even when we impose stringent constraints, such as redshift constraints in this proposal—is so large that it is unrealistic to observe such a large sample in one semester. Trimming the sample, on the other hand, is not ideal as it will preclude full exploitation of one of the main legacy products of ACT. Furthermore, the cluster sample covers the entire RA range and not all clusters are observable in any given semester. In particular, 6 out of the 7 clusters in the $z = 0.81$ sample are not well suited for observation in the A semester. Therefore limiting our proposal to the 2024A semester would preclude extension of our sample to $z = 0.81$, cutting short our coverage of cosmic time by 30% (from a span of 3 Gyr over $z = 0.47 - 0.81$ to 2 Gyr over $z = 0.47 - 0.62$).

As explained above, 6 out of 7 $z = 0.81$ clusters are observable in 2024B only, which sets a minimum requirement for 2024B of 2 nights. Most of the remaining clusters in our sample are better observed in 2024A although most can also be observed in 2024B thanks to the favorable declinations. We therefore decide to split our request into 6 nights in 2024A and 4 nights in 2024B. Our minimum request of 7 nights is split into 5 nights in 2024A and 2 nights in 2024B.

CURRENT STATUS OF THE PROJECT

This proposal is based on the cluster sample constructed by the team and presented in Hilton et al. (2021). Thanks to its sheer size and well-defined selection function, this sample is ideal for studies of cluster and cluster galaxy evolution. Construction of this catalog relied heavily on data from the Dark Energy Legacy Survey (DECaLS) for optical confirmation, richness measurements and photometric redshifts, and includes a wealth of ancillary data, both targeted and survey-type, from radio to X-rays.

The list of investigators is composed of members of the ACT Clusters working group, in which PI Sifón has played a central role for the past 12 years, leading studies on galaxy dynamics (Sifón et al. 2013, 2016) and high-redshift cluster follow-up (Sifón et al. in prep.) and co-leading most other cluster-centered work, including follow-up of the spectacular 'El Gordo' cluster (Menanteau, Hughes, Sifón et al. 2012), cluster SZ detection and initial characterization (Menanteau, Sifón et al. 2013; Hilton, Hasselfield, Sifón et al. 2018; Hilton, Sifón et al. 2021), stellar mass measurements (Hilton, Hasselfield, Sifón et al. 2013), and gravitational lensing measurements of cluster masses (Madhavacheril, Sifón et al. 2020; Robertson, Sifón et al. 2023).

PI Sifón will lead the data reduction and census of Hα emission and its implications for star formation and AGN activity within and around clusters, including the comparison with literature measurements such as those discussed in the Scientific Rationale. (Should the PI have any graduate students at PUCV during 2024-2025 this project will be offered to them.) Co-Is Hilton, Kesebonye, and Knowles will lead comparison with radio data from GMRT and MeerKAT (e.g., Knowles et al. 2021, 2022; Kesebonye et al. 2023). Co-I Hughes will carry out a comparison with X-ray data from *XMM-Newton* and *Chandra*. Co-Is Mrozckowski, van Marrewijk, and Vargas are leading ALMA and APEX follow-up efforts within ACT and will compare our proposed observations with these high-resolution submm data. In all these cases, the comparisons will consist of analyzing available archival data or proposing new observations on the respective facilities when justified. We therefore argue that while the majority of Co-Is are affiliated to non-Chilean institutions, it is composed of a well-established team with a long track-record of joint collaborative work. Furthermore, the project will be led by the PI as a continuation of these joint efforts by the entire team with the PI having had a critical role for a long time, in particular on the subject of this proposal. The request to the CNTAC is therefore well justified.

References: Hilton et al. 2013, MNRAS, 435, 3469 • Hilton et al. 2018, ApJS, 235, 20 • Hilton et al. 2021, ApJS, 253, 3 • Kesebonye et al. 2023, MNRAS, 518, 3004 • Knowles et al. 2021, MNRAS, 504, 1749 • Knowles et al. 2022, A&A, 657, 56 • Madhavacheril et al. 2020, ApJL, 903, 13 • Menanteau et al. 2012, ApJ, 748, 7 • Menanteau et al. 2013, ApJ, 765, 67 • Robertson et al. 2023, arXiv:2304.10219 • Sifón et al. 2013, ApJ, 772, 25 • Sifón et al. 2016, MNRAS, 461, 248