1. Overview

Large-scale structures in the universe form hierarchically. Massive galaxies are formed through mergers of smaller galaxies, groups grow through the accretion of galaxies, and clusters in turn accrete both groups and individual galaxies. Over the same epoch where these structures experience significant growth ($z < 1$), the fraction of star forming galaxies within them decreases, and at a faster rate than for field galaxies (Saintonge et al. 2008; Finn et al. 2010). It is now widely accepted that there must be physical processes at work in dense environments to actively quench star formation (e.g. Lewis et al. 2002; Balogh et al. 2004). Many studies show that galaxy star-formation rates are suppressed at distances up to ∼5 virial radii from cluster centers (see Fig. 1 right panel; Lewis et al. 2002; Gómez et al. 2003; Bahé et al. 2013), which suggests that galaxies are affected by environmental processes before they fall into clusters (e.g. Poggianti et al. 1999; Cortese et al. 2006). However, despite significant effort to understand the quenching processes (e.g. Wetzel et al. 2013), state-of-the-art hydrodynamic (e.g. Davé et al. 2011) and semi-analytic (e.g. Guo et al. 2011; Hirschmann et al. 2014) models significantly overpredict the efficiency of quenching in dense environments. The result of this failure is that we still do not know which mechanisms dominate the environmental suppression of star formation and where these mechanisms are effective.

A major impediment to progress is the simplistic way in which environments have been defined. Galaxy environments have typically been characterized by local density or by distance from the nearest group or cluster. However, this approach is inadequate as the structure around clusters is composed of a rich filamentary network through which galaxies move in their transition from regions of low to high density (Fig. 1 left panel). Increasing evidence that filamentary structures are the first sites of significant environmentally-driven quenching. For example, Cybulski et al. (2014) find that galaxy star-formation rates are altered in filaments. However, they are not able to identify the mechanisms that drive quenching in filaments because they do not measure the spatial distribution of star formation and lack direct measures of the neutral and molecular gas content.

We have embarked on a multi-year program designed to overcome these impediments and thereby significantly improve our understanding of the dominant physical processes that are driving pre-processing in filaments. We propose a comprehensive survey of the warm ionized, neutral, and molecular gas and dust properties in galaxies that reside in four nearby filaments surrounding the Virgo cluster. We will create spatially-resolved maps of the gas and dust for a large sample of filament galaxies. This will allow us to determine the role that filaments play in quenching galaxies. We are well prepared to carry out this analysis as we: **1)** have extensive experience in the analysis of environmental effects on galaxies (Poggianti et al. 2006; Desai et al. 2007; Rudnick et al. 2009; Finn et al. 2010; Cantale et al. 2016), **2)** have already made significant progress on our observing campaign, **3)** have institutional access to facilities necessary to complete our observing program, and **4)** have our own theoretical models with which we will be able to interpret our observational results. The area around the Virgo cluster is ideal for this experiment for two primary reasons. First, Virgo is one of the best studied regions of the sky, and our program directly benefits from the wealth of ancillary data. Second, the galaxies are close enought to allow CO and HI observations of a large sample of galaxies in a reasonable amount of observing time, yet the galaxies are far enough away to avoid significant aperture effect from single-dish HI and CO measurements.

Our novel approach addresses these outstanding problems by accomplishing *three specific aims*:

• **Find the effect of filaments on the molecular and atomic gas content of galaxies:**
→ For 200 filament galaxies surrounding Virgo, we will characterize the content of the ISM, using Hα and WISE for star formation rates, SDSS for stellar masses, HI for the neutral gas mass, and CO for the molecular gas mass. By comparing to field, group, and Virgo cluster core samples, we will determine the environmental density at which the ISM content of galaxies is first modified.

• **Find the effect of filaments on the spatial distribution of star formation and dust:**
→ In addition to measuring the ISM content of galaxies within filaments, we will take a step further and characterize its spatial distribution. We will use SDSS to measure the extent, morphology, and asymmetry of the stellar disk, Hα for the star-forming disk, and WISE for the dust disk. This spatial analysis will give us a richer picture of how large scale structures affect the internal ISM of galaxies. We will compare these data to significant amounts of data taken by our team on the cores of local (but more distant than Virgo) clusters and groups (Finn et al. in prep).

• **Compare our data to theoretical models:**
→ Our team includes a leader in the development of semi-analytic models (SAMs; co-I De Lucia). These make robust predictions for the spatial extent of different gas phases for field galaxies. These models incorporate prescriptions for where and how starvation and ram pressure stripping affect the gas. By comparing our observations to these models we will determine the dominant mechanisms in each environmental regime.

2. Scientific Motivation

Hydrodynamic simulations of cluster infall regions predict that the regions in filaments with the highest density gas can enhance the ram pressure in filaments by up to a factor of ~ 100 (Bahé et al. 2013). This means that freshly infalling galaxies with $\log(M_{\star}) < 9.5$ near a massive cluster can be stripped of their cold gas even well outside the virial radius. For more massive galaxies and at larger distances from the cluster, the ram pressure in filaments is still sufficient to strip off the hot gas that will replenish the dense star-forming gas, although it will likely not affect the densest cold gas. Filaments may therefore be the key sites where galaxies are affected by their environments before they fall into clusters.

The environmental effects thus have different signatures on the relative abundances and spatial distribution of the warm ionized gas, neutral, and molecular gas. By observing both phases, we can distinguish among these processes. AGN and supernova feedback may quench star formation through ejection or heating of the gas without impacting the distribution of existing stars (e.g. Springel et al. 2005; Croton et al. 2006; Dekel & Birnboim 2006). Environmentally-driven processes such as tidal interactions and mergers can affect the distribution of both gas and stars (Springel et al. 2005; Croton et al. 2006; Dekel & Birnboim 2006), whereas pressure-driven interactions, such as starvation (Larson et al. 1980) and ram-pressure stripping (e.g. Gunn & Gott 1972), are expected to act primarily on the gas (see Figure 2). **Studying the relative distribution and amount of gas and stars can help identify the dominant processes that deplete gas in galaxies.**

We have completed a survey of 200 local group and cluster galaxies, using *Spitzer* 24μm imaging to map the spatial distribution of star formation relative to the stellar disk (Finn et al. 2016, in prep; Local Cluster Survey - LCS). We find that the relative size of the star-forming disk is smaller for cluster galaxies than for field galaxies, and the relative size of the star-forming disk

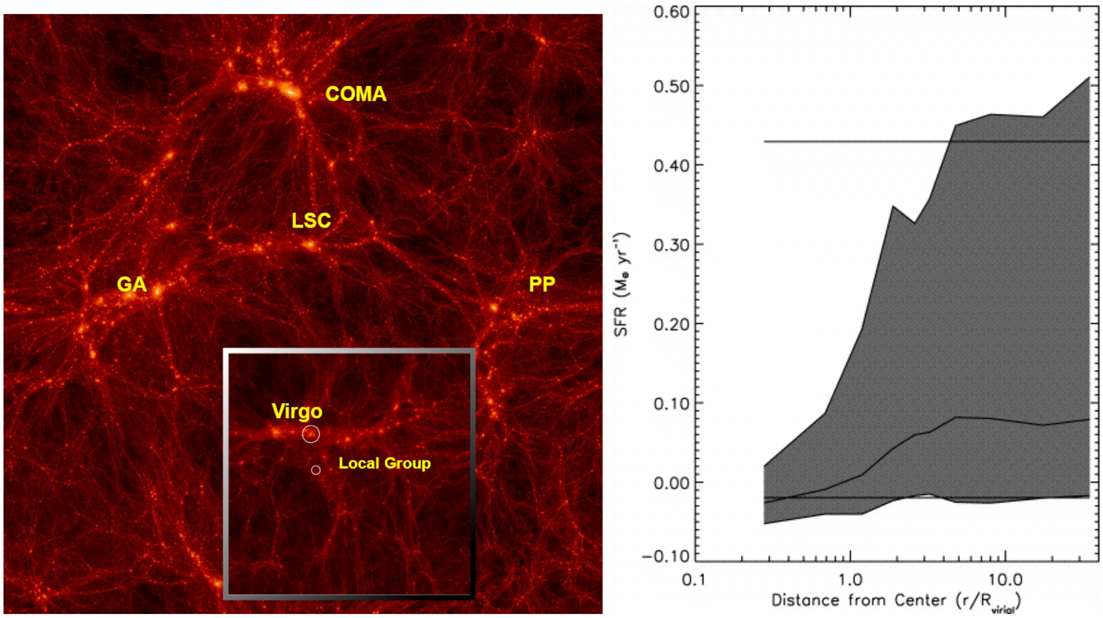

Fig. 1.— *(Left)* Simulation from CLUES showing filamentary structure surrounding clusters in the nearby Universe. *Galaxies stream along these filamentary structures, likely sites of preprocessing.* *(Right)* Figure 6 from Gómez et al. (2003) showing that the upper envelope of star formation rates begins to drop at $4R_{vir}$ from clusters. There is a very large scatter which complicates the interpretation of this trend. *The large scatter in SFRs complicates the interpretation of this trend, and can be alleviated by studying galaxies along filaments rather than just as a function of projected radius - this is the goal of this proposal.*

correlates with HI deficiency. Current semi-analytic that include starvation drastically overpredict the quenched fraction of satellite galaxies, implying significant problems with the implementation of environmental quenching (left panel Figure 3). Unfortunately, the LCS data data do not probe beyond the clusters cores, making it impossible to understand quenching in filaments. Furthermore, due to the depth of the *Spitzer* imaging, we are not able to probe star formation in galaxies with $log_{10}(M_\star/M_\odot) < 9$, where the predictions of semi-analytic models diverge most significantly from observations.

3. Our Survey of Gas in Filament Galaxies

This proposal builds on an existing collaboration, whose stated goal is to understand the environmental effect on gas in galaxies. Using new and archival data, we will explore the physical properties of galaxies in the filaments around the Virgo cluster. While numerous studies have characterized galaxy populations within the core of Virgo, galaxies in the surrounding regions have received relatively little attention. We have successfully completed the first of two awarded CO observing campaigns to directly measure the molecular gas content of galaxies within these filaments. *This proposal* requests funds to: **1)** obtain Hα observations, from which we will derive spatially resolved star formation rates of filament galaxies; **2)** produce spatially resolved dust maps with WISE 12μm imaging; **3)** combine this new data set with publicly available GALEX UV fluxes, and ALFALFA HI gas masses to characterize filament galaxies in a way that is on par with galaxies in the Virgo core. In particular, our core comparison data set will include VLA HI gas masses (Chung et al. 2009), and Herschel and WISE infrared imaging (Davies et al. 2010) for SFRs and stellar masses.

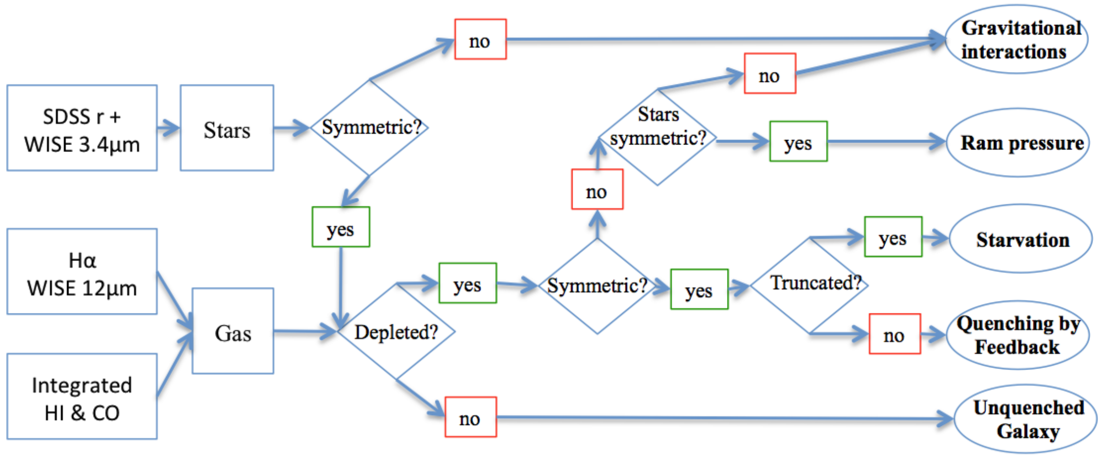

Fig. 2.— Our observations will test quenching prescriptions that are currently implemented in SAMs. Current comparisons suggest that the prescriptions are incomplete (see Figure 3). The above schematic illustrates how we can use our observational results to constrain the SAMs. This simplified schematic does not treat the separate depletion of atomic and molecular gas and assumes that one process is dominating over the others in each galaxy.

Table 1: Description of Filament Galaxy Samples

Gas Probe	**Telescope**	N_{gal}	**Mass Range**	**Rationale**
Hα	WIYN 0.9m, Mt Laguna	100, 120	$8.5 < \log(M_\star/M_\odot) < 10$	mass range where environmental effects are expected and where SAMs deviate most from observations
IR	WISE	184	$8.5 < \log(M_\star/M_\odot) < 11.5$	all detections with $SNR(12\mu m) > 10$ for reliable image fitting
CO	IRAM	120	$9 < \log(M_\star/M_\odot) < 10$	CO obs. are difficult for $\log(M_\star/M_\odot) < 9$ due to low metallicity
HI	Nançay	300	$8.5 < \log(M_\star/M_\odot) < 10$	Same as Hα rationale; 75% of sample already has HI observations from literature

Tully (1982) first studied the large-scale structure around the Virgo cluster and identified several concentrations of galaxies that he termed clouds. More recently, Kim et al. (2016) repeat this analysis with a much larger spectroscopic dataset that probes to lower luminosities, and they are able to identify multiple filaments around Virgo (see right panel of Figure 4). This proposal focuses on selected filaments identified by Kim et al. (2016), and we highlight these in the left panel of Figure 4. The NGC5353 filament feeds the NGC5353 group and extends over 20 Mpc, passing close to but not into the Virgo cluster (Kim et al. 2016). The other filaments that we will study feed the Virgo cluster directly. We will therefore be able to examine galaxies feeding halos of very different masses. We focus on the NGC5353 and Leo filaments for two practical reasons: (1) these filaments extend the furthest north on the plane of the sky, and this allows for a longer observing window from northern-hemisphere telescopes, (2) these filaments are among the most distant in the region and thus the galaxies have smaller apparent size, minimizing the required CO aperture corrections.

The two filaments contain over 600 galaxies with a range in specific SFR and stellar mass (Figure

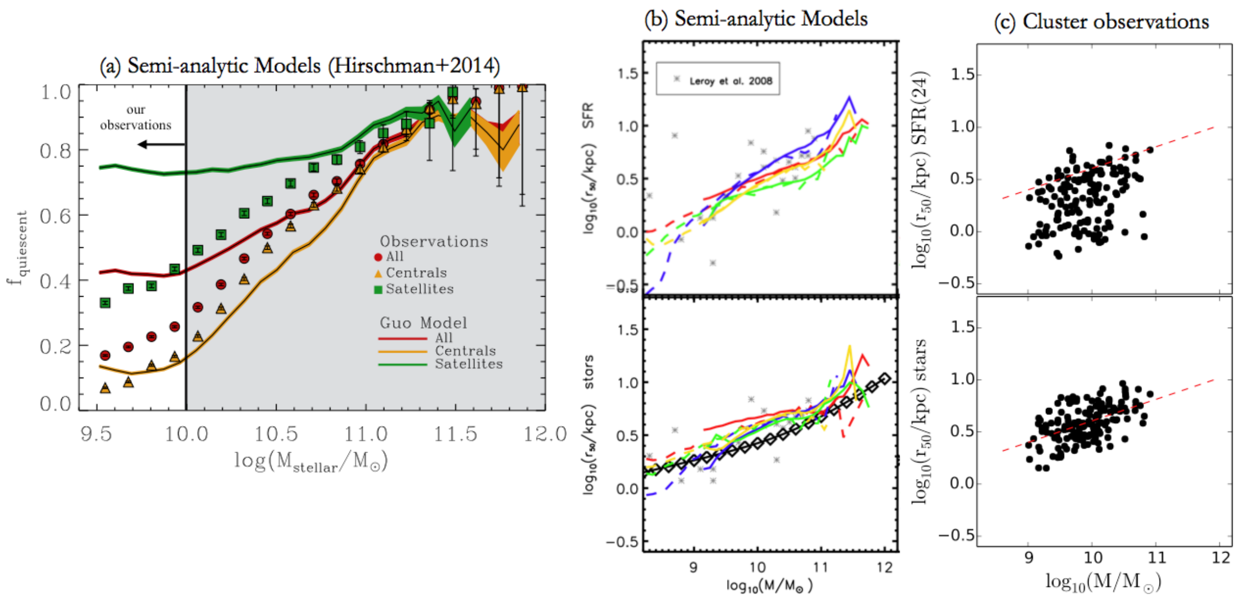

Fig. 3.— (a) **The "satellite overquenching problem":** Comparison between $z = 0$ quenched fraction observations (points) and state-of-the-art semi-analytic model predictions (lines) from Guo et al. 2011 (adapted from Hirschmann et al. 2014). This model, like many others (e.g. Somerville et al. 2008; Kimm et al. 2009), reproduces the quiescent fraction of central galaxies fairly well (yellow), but greatly overproduces the quiescent fraction of satellite galaxies (green). (b) **Predicted** half-light radius of stars (bottom) and star formation (top) versus stellar mass for $z = 0$ field galaxies (Xie et al. 2016, in prep). The different color lines represent different models for partitioning atomic and molecular hydrogen, which agree with field galaxies observations, indicated by grey points. (c) **Measured** half-light radius of stars (bottom) and star formation (top) versus stellar mass for galaxies in the *Local Cluster Sample* (Finn et al. 2016, in prep). The red dashed line is a linear fit to the stellar half-light radius and is shown in the top panel for comparison. Clearly as seen in panel a, the starvation recipes included in semi-analytic models are too efficient at quenching galaxies, but the reason is not clear. *Our observations of the relative sizes of stars and gas in dense environments will provide valuable constraints for the next generation of semi-analytic models that treat environmental suppression of star formation.*

5.) We define four subsamples of filament galaxies and describe the mass limits and rationale for the selection of each sub-sample in Table 1.

4. Proposed Work

We will use Hα and WISE 12μm images to measure the spatial distribution of ongoing star formation. We will make direct measurements of the atomic and molecular gas using HI and CO data. Finally, we will compare our observations to theoretical models. Below we describe our proposed work and the division of labor among the co-PIs.

4.1. Spatially Resolved Star Formation from Hα

Hα is the standard for measuring star-formation in local galaxies (e.g. Kennicutt 1998), and the combination of Hα, UV, and mid-infrared imaging provides a powerful measure of star-formation rates that is independent of extinction. The combination of star-formation rates and CO observations will allow us to calculate gas consumption timescales and characterize multiple phases of the galactic gas. Equally important, the spatial extent of Hα, when compared to the radial distribution

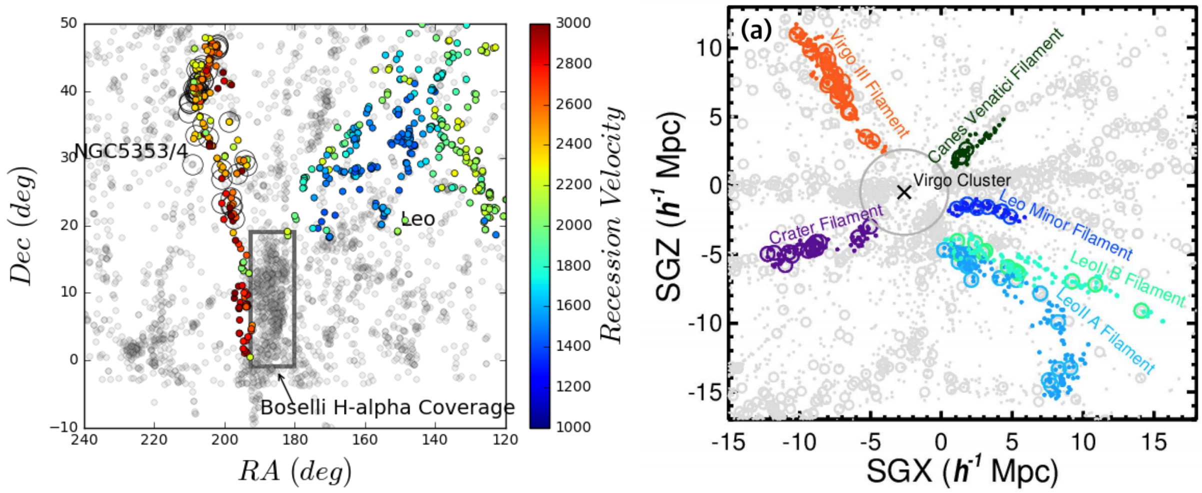

Fig. 4.— *(Left)* Filaments as identified in Figure 1(a) of Kim et al. (2016) showing filaments surrounding Virgo Cluster as observed on the plane of the sky in RA and Dec and coded by recessional velocity. *(Right)* Figure 2(a) from Kim et al. (2016) showing the same galaxies but projected into Virgo-centric coordinates. The Leo filaments can now be seen as three distinct filaments. The NGC5353 filament, which does not intersect the Virgo Cluster, is not shown in the right panel.

of the underlying stellar population and the dust (§4.2), provides a powerful means to identify the physical processes that affect a galaxy's gas supply (e.g. Hodge & Kennicutt 1983; Dale et al. 2001; Gavazzi et al. 2012; Boselli et al. 2015). Studies of the Virgo cluster core show evidence of cold gas stripping (e.g. Crowl et al. 2005; Chung et al. 2007; Corbelli et al. 2012; Gavazzi et al. 2012; Boselli et al. 2015), including truncated $H\alpha$ emission of Virgo spirals compared with their field counterparts (Koopmann & Kenney 2004). We will be able to determine if environmental transformation starts in the filaments, before galaxies are accreted into the densest environments.

While extensive Hα imaging has been done in groups, clusters, and the field, little has been done to map the spatial extent of Hα in filament galaxies. The goal of our program is to obtain spatially resolved Hα maps for 222 star-forming galaxies in the NGC5353 and Leo filaments. Key to testing quenching mechanisms are that we are able to measure Hα profiles to low surface brightness and that we can probe galaxies at different positions along the filament out to large distances from Virgo. To properly probe any environmentally-driven quenching, we will detect galaxies with star-formation rates 10 times lower than the star-forming main sequence.

We will complete the Hα observations at the WIYN 0.9 and the Phillips Claud Telescope (PCT) at the Mt. Laguna Observatory. For the WIYN 0.9 m, we will apply for time through NOAO (already submitted a proposal for Spring 2017 semester), requesting approximately 6 nights each spring for the three years covered by this proposal. Based on past Hα imaging experience with the WIYN 0.9 m, we need about 2 hours per target, and so we expect to be able to complete 4 objects per night and 24 pointings per run. Our yield will be slightly higher (~ 30) because we will be able to place multiple objects within the $0.5° \times 0.5°$ field of view. Thus we expect to complete Hα imaging for ~ 100 galaxies at the WIYN 0.9m.

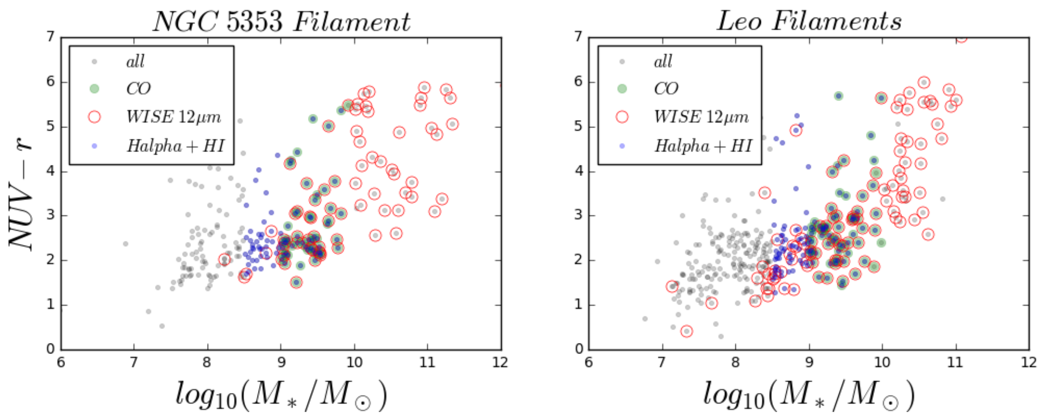

Fig. 5.— $NUV - r$ color versus stellar mass for galaxies in the (*left*) NGC5353 filament and the (*right*) Leo filaments. Grey circles show NASA-Sloan Atlas galaxies, red circles show WISE 12μm detections with $SNR > 10$, blue dots show galaxies that we will observe in Hα and HI (if HI observations do not already exist), and green dots show those that we will observe in CO. The sub-samples are described in Table 1.

We will observe the remaining 120 galaxies in the Hα sample using the PCT. This 1.25m telescope has a 4k×4k detector with a $22' \times 22'$ field of view. It is in the final phase of commissioning and should be ready for operation in Spring 2017. The University of Kansas is a partner on this telescope with a 15% share of the total time, of which co-PI Rudnick is entitled to a significant share. This telescope can be remotely controlled and so will allow for observing either from KU or from Siena College; remote observing will save substantially on travel costs for such a large observing program. We have included funds to purchase a narrow-band filter suitable for observing $H\alpha$ at the redshift of our filaments.

Co-PI Finn is involved in an Hα imaging survey of nearby galaxy groups as part of the Undergraduate ALFALFA Team. She and her undergraduate students have developed code to reduce Hα imaging taken with the HDI camera on the WIYN 0.9 m telescope. These programs will be used to reduce the Hα imaging for this proposal, and we will adapt the code to accomodate the imaging data from Mount Laguna observatory.

4.2. Spatially-resolved Dust Emission as a Tracer of Obscured Star Formation

WISE 12-micron images are sensitive to emission from polycyclic aromatic hydrocarbons that are heated by young stars, and we will thus use these images to trace the spatial extent of dust in the filament galaxies. While the WISE PSF is rather large ($6.5''$ at 12μm), it still probes down to kiloparsec scales for galaxies in our filaments, and is sufficient for this study (see Figure 7). Along with SDSS fiber spectroscopy, the WISE colors will be used to identify galaxies with an AGN.

To quantify the extent of the WISE 12μm images, we will use *GALFIT* software (Peng et al. 2002) to fit two-dimensional *Sérsic* models to the galaxy images. We will use *unWISE* image products and PSFs (Lang 2014) because they are optimized for extended sources whereas the WISE image products have been optimized for point sources. Co-PI Finn has completed a similar analysis using GALFIT to analyze MIPS 24μm images for galaxies in 9 nearby galaxy clusters (Finn et al. 2016, in prep). The spatial resolution of the MIPS 24μm images is comparable to the resolution of WISE at 12μm, yet the filament galaxies are significantly closer than the galaxies that we analyzed with

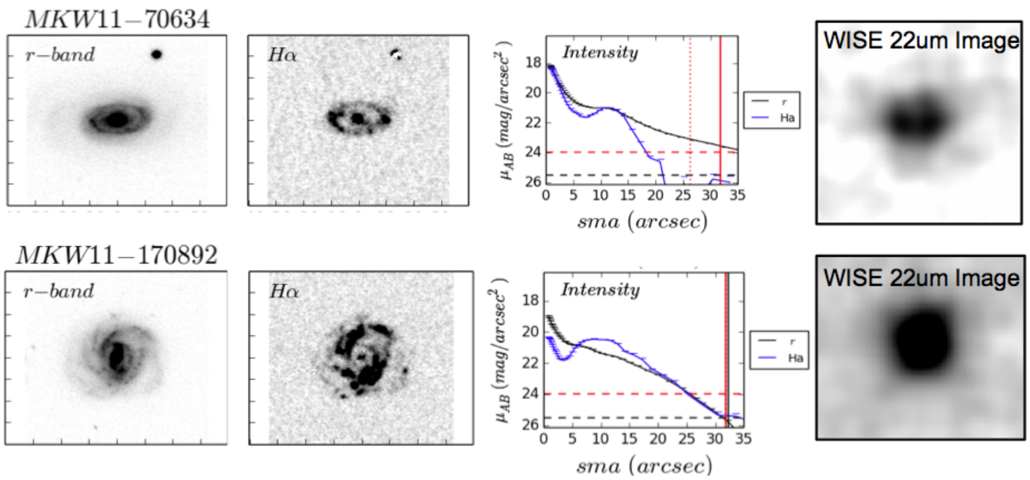

Fig. 6.— To illustrate our proposed Hα analysis, we show imaging taken with the KPNO 0.9-m+HDI of two galaxies within the nearby group MKW11 (v_r = 6900 km/s). The top row shows a galaxy whose Hα is truncated relative to the stellar disk as probed in the r-band. This is clearly seen in the radial profiles (third column from left.) The bottom row shows a galaxy with extended Hα emission. The SFR is resolved at about 1/10 of a kpc in Hα. In contrast, the WISE PSF at 22μm is 12 arcsec, corresponding to about 1 kpc. The image thumbnails in each row are the same size, demonstrating that the WISE data are not sufficient to measure the morphology of the star formation. The WISE 22μm data will be useful for a global SFR estimate when combined with GALEX UV and Hα imaging, and the 12μm data (FWHM = 1/2 kpc) will probe the radial profile of obscured star formation. While the WISE photometry may underestimate the SFR for the lowest mass galaxies in our sample because of their low metallicity, the combination of WISE, UV, and Hα imaging will allow us to understand how environment affects the distribution of star-formation.

MIPS. We have also performed extensive simulations to show that we can recover sizes for galaxies with WISE 12μm SNR$>$ 10. We are thus confident in our ability to measure robust sizes at 12μm.

The analysis of the WISE imaging will be the most computationally intensive part of the proposed work because we plan to run multiple models for each galaxy to assess the impact of our initial conditions on the resulting size measurements. For each galaxy, we will stochastically sample across the parameter space of initial conditions, and each model has five free parameters. Nonetheless, using extensive testing, we estimate that it would take less than 2 days of computational time on the Siena College High Performance Computer Cluster (HPCC, see Facilities section of this proposal). Co-I Vernizzi will be responsible for this piece of the project. We will compare the GALFIT results to those generated by other independent fitting programs such as GALPHAT (Yoon et al. 2011) and The Tractor (Lang et al. 2016).

4.3. Molecular and Atomic Gas

The CO luminosity can be used to estimate the molecular Hydrogen mass that is the direct fuel for star formation. The conversion from CO luminosity to to H_2 mass depends on metallicity, which in turn depends on stellar mass, as well as on parameters such as cloud size, which scale with the SFR density. This conversion has been calibrated both observationally and theoretically (see Bolatto et al. (2013) and references therein), and we will use it to estimate the molecular gas mass of our galaxies. This is crucial to understand how the moderately dense gas is affected by environmental gas processes.

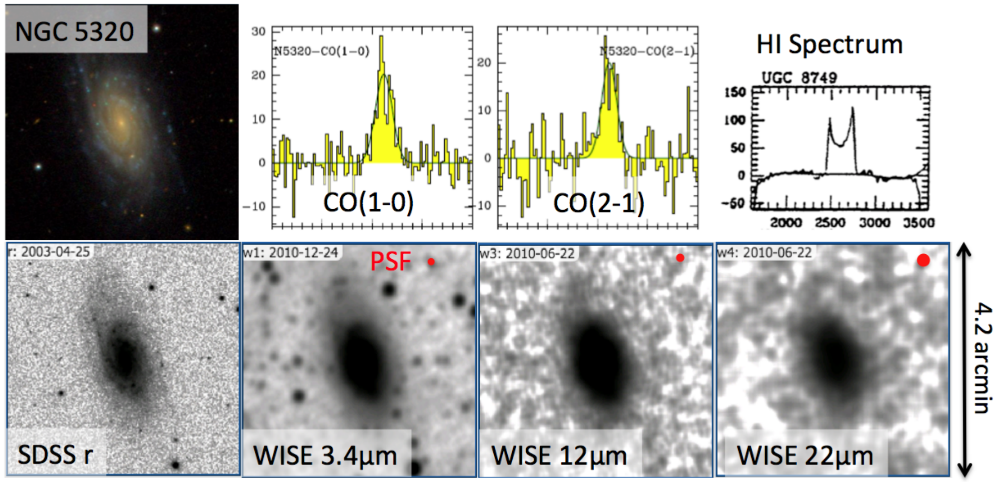

Fig. 7.— Multi-wavelength images of spiral galaxy NGC 5320. The top row shows the SDSS color image, the newly acquired CO(1-0) and (2-1) spectra, and the HI archival spectrum. The bottom row shows the SDSS r-band imaging and the WISE 3.4, 12 and 22μm images. The resolution of WISE at 12μm is sufficient to measure the spatial extent of dust emission. The 22μm fluxes indicate the amount of dust-obscured star formation and thus provide an important complement to the Hα-derived star-formation rates.

Team members Jablonka and Combes are leading the observing campaign to measure CO(1-0) and CO(2-1) for all filament galaxies with $9 < \log_{10}(M_\star/M_\odot) < 10$ using the IRAM 30-m telescope. Galaxies below this mass limit are difficult to detect in CO due to lower metallicity and photodissociation of CO (e.g. Cormier et al. 2014). During October 2016, they succesfully observed 40 galaxies in the NGC5353 filament, and 38 of these were detected. We show the CO spectra for one of these detections in Figure 7. The team has an additional block of time in December 2016, and we expect to double the number of CO detections. Jablonka and Combes will continue to apply for IRAM time to complete the CO observations for the subsample described in Table 1 (see letter of collaboration).

We will use HI to trace the diffuse neutral gas. As it is optically thin, it is straightforward to convert an HI luminosity to a neutral Hydrogen mass. Finally, HI typically has a much larger radial extent than CO and as a result is more sensitive to environmental effects. 75% of our target galaxies already have HI observations, and collaborators Jablonka and Combes are leading the effort to observe the remaining galaxies. We have submitted a proposal to use the Nançay 200×35 m^2 telescope, which has a low oversubscription rate and to which Combes and Jablonka have preferred access. We will continue to request time on this telescope until the HI observations are complete for that subsample as described in Table 1 (see letter of collaboration).

With the HI and CO observations of our targets we will accomplish the following immediate goals: (1) we will measure their total molecular and neutral gas content; (2) we will compare the atomic and molecular content since different gas depletion mechanisms affect the diffuse and dense gas differently; (3) we will compare this to the galaxy sizes, SFRs, and stellar masses to determine the gas deficiency of filament galaxies (if any) compared to galaxies in the field, group, and clusters with similar data as obtained from the literature (e.g. Ciesla et al. 2012; Davies et al. 2010). Co-PI Rudnick and his student will lead the publication of these results.

4.4. Comparison with Theory

An important aspect of our work is using theoretical models to understand what processes are affecting the gas distribution in our galaxies. Our collaborator De Lucia is an expert in semi-analytic models of galaxy formation and, in addition to her existing models (Zoldan et al. 2016) will produce models directly suited for comparison with our observations. The first scenario we must consider is whether our results are consistent with predictions of gas depletion through starvation and the consumption of the remaining gas rather than more extreme environmental processes such as ram-pressure stripping. In the middle panels of Figure 3, we show the predicted size of the stellar and star-forming components of $z = 0$ galaxies based on the semi-analytic models of Xie et al. (2016, in prep). These models include starvation but do not explicitly include environmental processes such as ram-pressure stripping. However, these models are largely untested in dense environments. In the right panel of Figure 3, we show the *measured* size of the star-forming and stellar disks versus stellar mass for the *Local Cluster Survey* galaxies (Finn et al. 2016, in prep). We will use the measured size of star formation in filament, group, and cluster galaxies to constrain the environmental gas processes included in the models. While providing useful data for this exercise on the cores of clusters, the *Local Cluster Survey* sample is small and does not probe filamentary structures surrounding the clusters.

Theoretical models of ram-pressure stripping provide predictions that we can compare directly to our measurements. For example, numerical simulations of starvation and ram-pressure stripping of cold gas generically predict that star formation in the edges of galaxies will be affected more strongly than star formation near the centers of galaxies; the spatial extent of the star-forming disk should be smaller for galaxies that are undergoing stripping (e.g. Kawata & Mulchaey 2008; Bekki 2014). We find evidence of this in the *Local Cluster Survey*, but we also find a stronger correlation with bulge-to-total ratio. A large sample that extends beyond the virial radius of clusters is needed to disentangle these effects and this sample has to have low stellar mass, as those galaxies should be more vulnerable to having their gas removed because their gas is not as tightly bound (e.g. Kawata & Mulchaey 2008; McCarthy et al. 2007; Bekki 2014).

The SAMS implemented for many clusters in the Millennium simulation and in cluster zoom simulations will give us a statistical view of how galaxies are affected in filaments around clusters and groups of similar mass to Virgo and NGC 5353. However, none of these clusters actually looks like the surroundings of Virgo, which introduces a systematic error in the comparison. We will therefore implement our SAMS in the Constrained Local UniversE Simulations (CLUES) of the local volume (Carlesi et al. 2016). Specifically, Co-I De Lucia will work to integrate her SAMS with the CLUES dark matter merger trees so that she can predict the spatial distribution of star and star formation for galaxies in a simulation designed to look like the local volume.

4.5. Workplan & Personnel

The division of observing and analysis responsibilities among the team members is outlined in Fig. 8. The expertise and roles of individual team members is described below.

Rose Finn, Ph.D., (co-PI) is a professor in the Department of Physics and Astronomy at Siena College (Loudonville, NY). She is the PI of the *Local Cluster Survey* and has extensive experience with running GALFIT on MIPS 24μm imaging. She will lead the Hα imaging survey at KPNO and the analysis of the WISE 12μm imaging, supervise the undergraduate students.

Gregory Rudnick, Ph.D., (co-PI) is an associate professor at the University of Kansas. He has expertise in galaxy evolution and the effects of environment on galaxy evolution, and he is leading an *HST* study to measure the spatial extent of star-formation in intermediate-redshift galaxies. He will lead the Hα imaging survey at the PCT and will supervise the graduate student whose Ph.D. dissertation will be on this project.

Graziano Vernizzi, Ph.D., is an associate professor at the Department of Physics and Astronomy of Siena College (Loudonville, NY). His research interests lie in computational and theoretical physics, biophysics, nanoscale science, soft condensed matter, and random matrix theory. Graziano will the lead the computational aspects of this project.

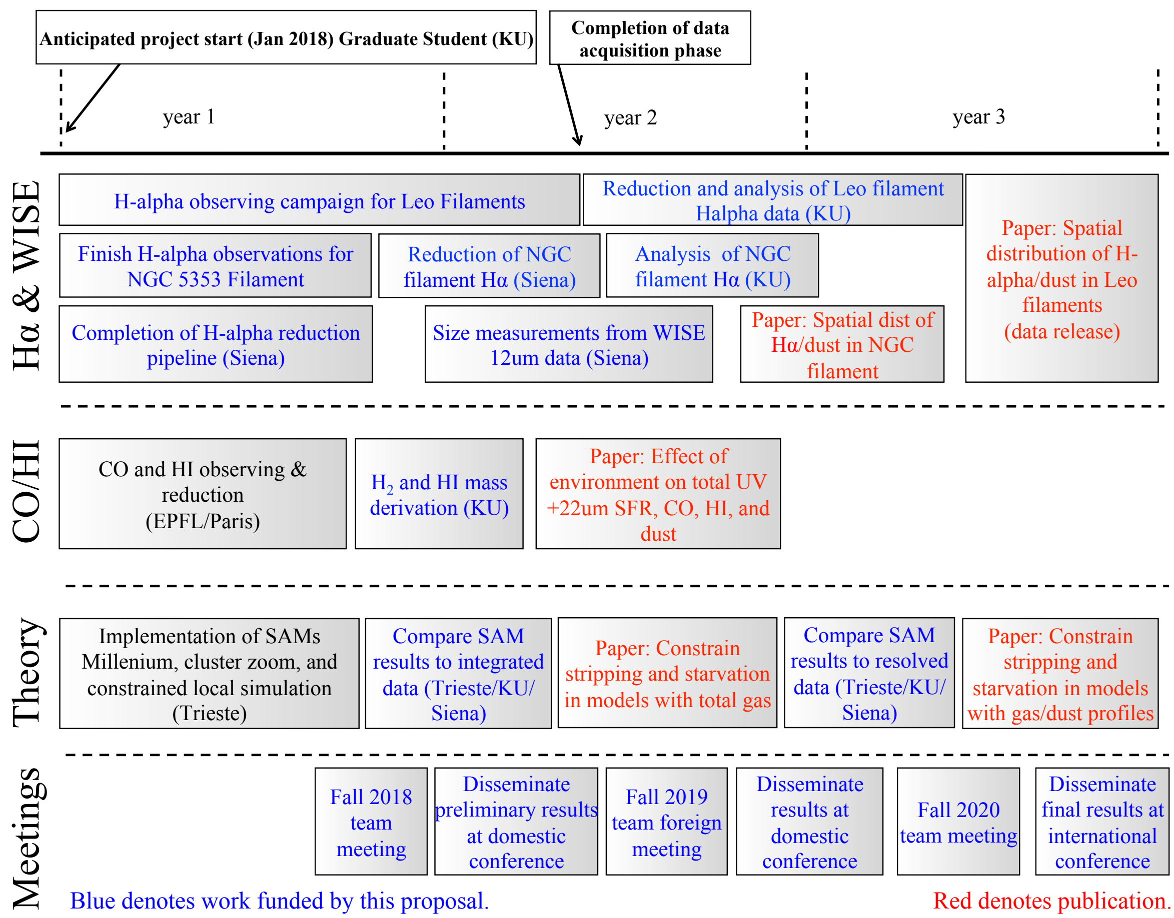

Fig. 8.— Major Milestones and Timeline

4.6. Data Sharing and Further Dissemination of Results

We will release all of our data with our final publication. This will include reduced, calibrated, and astrometrically aligned $H\alpha$ and dust maps, and with integrated CO and HI fluxes. We will produce a catalog of CO, HI, dust, $H\alpha$ properties to be released with our final paper. While this data set of derived information will not be exceptionally large in volume, it will be of value to other observational astronomers and theorists working on galaxy evolution. To facilitate the widespread use of these data, we will publish the full catalog of measured and derived quantities on the web and in the on-line version of Astrophysical Journal Supplement. In addition, we will work with the NASA/IPAC Infrared Science Archive (IRSA) to ensure that our data are discoverable to a larger user base. Co-I Vandana Desai, resident at IPAC, will act as our NED liason to ensure that this gets done in a timely manner.

5. Results from Previous NSF Projects

Co-PI Finn has no prior NSF support to report with a start date in the last 48 months.

5.1. Molecular Gas in Distant Galaxies (PI Rudnick)

Co-PI Rudnick has recently completed his NSF project 1211358 "Characterizing the Molecular Gas Contents of High Redshift Galaxies" ($306,754; 8/1/12-7/31/16).

Intellectual Merit: This study was based on a large body of JVLA data (200 hrs) on a $z = 1.62$ galaxy cluster that was collected between 2012 and October of 2014. The goal of this study was to characterize the molecular gas content of high-z galaxies by observing CO. As a result of the studies of this cluster and of the CO gas content of distant galaxies, Rudnick has authored or co-authored seven papers since 2012 with a total of 185 citations (Papovich et al. 2012; Rudnick et al. 2012; Lotz et al. 2013; Geach et al. 2013; Wong et al. 2014; Geach et al. 2014; Tran et al. 2015) as well an ApJ paper that is in the resubmission process (Rudnick et al.). Since 2012, Rudnick has also given 28 oral presentations on this NSF project. Using the full JVLA data, Rudnick has securely detected CO(1–0) in two massive and gas-rich galaxies in the $z = 1.62$ cluster. These galaxies have surprisingly low star formation efficiencies (SFE) for their high mass and gas fraction (e.g. Genzel et al. 2010). This may indicate the presence of environmental effects on the physical conditions of the molecular gas and on the accretion of gas from the cosmic web in a massive halo. These results appear in a paper that is being resubmitted to ApJ after a favorable referee report. The expected publication date is early 2017. As a direct result of this project Rudnick has also organized a large consortium of scientists who are seeking to use ALMA to make a census of the CO gas in distant cluster galaxies. They will resubmit a significantly sized proposal in April 2017.

Broader Impact: Rudnick has completed the third year (2013-2016) of an outreach program in close collaboration with Andrew Bricker, a Physics teacher at Lawrence High School (LHS). Rudnick developed and executed a year-long program in which the students receive an introductory calculus-based astronomy course and perform a bona fide research project. The goal of the class is to teach high school students research methods, computing skills, the electromagnetic spectrum, the nature of science, and science communication while also giving the teacher new tools to teach research-based activities in the classroom. The project involves using *Spitzer*/MIPS 24μm data to measure L_{IR} and SFRs for the galaxies in the infall regions of intermediate redshift clusters from the ESO Distant Cluster Survey (EDisCS). The students meet every day in a special class period. The teaching assistant funded by the grant performed most of the instructional duties and Rudnick attended class once a week. 30 students have gone through the program during these three years. This total was comprised of $\sim 50\%$ underrepresented student groups: four African American, three Hispanic, one Native American, and 10 female students, two of which were also women of color. As described in §6.2 we employ extensive assessment to understand our success at meeting learning goals. This program is continuing in 2016-2017 funded by another NSF project (see §5.2).

5.2. Galaxy Evolution in Distant Clusters (PI Rudnick)

co-PI Rudnick is in the beginning of his second year for the NSF project 1517815, "Collaborative Research: The GOGREEN Survey - Caring About the Environment" ($347,556; 8/1/15-7/31/18).

Intellectual Merit: This study funds the US analysis efforts for the international Gemini Observations of Galaxies in Rich Early Environments (GOGREEN) project. This project is based on the largest Gemini Long and Large Program (PI: Michael Balogh), which is comprised of 443 hours of Gemini imaging and spectroscopic observations conducted over a 4 year period starting in Fall 2014. The two main components of this project are very deep Gemini optical spectroscopy of a stellar mass ($M > 10^{10} M_{\odot}$) limited sample of galaxies in 21 groups and clusters at $1 < z < 1.5$ and a large multiwavelength imaging program.

The goals of the project are to: **1)** Find the dominant modes of satellite quenching at $z < 1.5$; **2)** Determine how galaxies populate dark matter halos as a function of environment at $z < 1.5$; **3)** Measure the relative timing of morphological transformation and star-formation quenching; **4)** Constrain the dominant driver of size growth in the early-type population at $\boldsymbol{z < 1.5}$.

co-PI Rudnick is in charge of the imaging efforts for the whole collaboration, which involves gathering 11-band photometric data on a broad suite of telescopes including Subaru, CFHT, Magellan, VLT, and ***Spitzer***. The imaging of the southern clusters is 95% complete and the northern clusters only lack their NIR data. We expect the imaging to be completed by the Fall of 2017.

This ongoing project has not yet produced any publications. The strategy of the project is to obtain deep spectra over many semesters on the faintest targets, and thus many of the science publications will appear at the end of the proposal period. However, an initial data paper based on the first 30% of the spectroscopic data is in preparation with a Dec. 2016 submission target.

Broader Impact: Rudnick has extended his LHS outreach program into the 2016-2017 academic year and will continue it through the 2017-2018 AY. Changes that we have made this year include a much more agressive targeting of URM students, which we have accomplished by going to more junior students and not having as high of a math prerequisite for entry into the program. As a result we have our highest fraction of URM students yet, with one Native American, three African American, two Hispanic students and three women ,one of which is a women of color. We are currently attempting to expand the program by using seniors who have already completed the program as peer instructors. This will allow us to grow without additional personnel costs.

6. Broader Impact

6.1. Siena College

Modeling Physics for High School Programs: The modeling approach is an innovatve and effective way to teach physics that is fundamentally different from traditional techniques. Students are led through carefully constructed experiments and exercises to clearly develop the conceptual, visual, and mathematical models of how physics works. These models are essential for understanding physics. The modeling approach minimizes lectures, and instead students are actively engaged in collecting and analyzing real-time data that illustrate the fundamental concepts of physics. The students must then construct models to interpret these data.

As a former high school teacher, co-PI Finn knows first-hand the importance of bringing the more effective and engaging techniques to the front line. As part of a previous NSF grant (AST-0847430), we have offered modeling workshop for high school physics teachers for the past 9 summers. We are fortunate to have as an adjunct instructor an area high-school physics teacher who is an expert in using the modeling approach to teach physics, and he will continue to lead these 4-day workshops each summer. We offer continuing education credit to participants that can be used toward teacher recertification. This grant will provide a stipend for Darren Broder to organize and lead the workshops. To assess the impact of the modeling curriculum, participating teachers will administer the force concept inventory and mechanics baseline test.

Undergraduate Research : The importance of undergraduate research is widely recognized in the science community. *Recent studies have shown that undergraduate research may be the pedagogy for the 21st century (e.g., Council on Undergraduate Research Statement and references therein).* Involvement in research projects fosters highly motivated, self-confident students with enhanced analytical and communication skills. co-PI Finn supervised 24 undergraduate students during the tenure of her previous NSF grant (AST-0847430).

Siena College undergraduate students will be involved in all aspects of this proposal. We have budgeted money to bring students on observing trips to Kitt Peak National Observatory, and they will help gather imaging data at PCT through remote observing once the telescope has been commissioned in the Spring of 2017. This grant provides funds for four undergraduates to complete 10 weeks of paid research for each year of the grant. Finn has experience supervising undergraduates on similar projects, and hiring a mix of freshmen through juniors has worked nicely as the older students can help train the freshmen. During the first year, two students will work with Finn to finalize the data reduction pipeline for the KPNO data and to adapt the pipeline for the TCP data. The students will measure radial profiles for the Hα imaging and develop ways to quantify the Hα morphologies. The students will work in collaboration with the graduate student at Kansas to compile the Hα data products.

The other two summer students will work on the analysis of the WISE 12μm images. This part of the project will require more programming skills, and will likely be assigned to the more experienced undergraduate students. The students will work with Finn and Vernizzi to analyze the images with GALFIT and visualize the results of the multiple models that we will fit to each galaxy.

An important part of the research experience is presenting results to the community. I will encourage all students to present their results at the fall meeting of the Astronomical Society of New York and Siena's Academic Celebration, which is held each spring. In addition, seniors will be encouraged to present a poster at the annual winter meeting of the American Astronomical Society.

To assess the impact of this project, I will track participation, papers, presentation, and post-graduate activity of all Siena students who are involved in this project. I will design and implement a survey to assess student plans/goals before, during, and after participation in research.

6.2. University of Kansas

A High School Research Program: Rudnick's broader impact provides for the continuation of a successful research-based outreach component at Lawrence High School (LHS; see §5) that is funded by NSF proposals (1211358 and 1517815). This program is timely, as the Kansas school system is an exemplar of the nationwide debate on the role of science in the classroom. Crucial to increasing and clarifying the role of science is educating students and training teachers. This program is currently funded through the end of the 2017-2018 academic year. The purpose of the current proposal is to: 1) continue the funding of a KU student to work in the classroom, 2) develop the project to the point of sustainability by training the high school teacher in research-based teaching methods, 3) develop a peer instruction model to expand the program to 20 students without additional personnel costs, and 3) expand the program to 20 students. The school district fully supports this program (see letters from McEwen and Bricker.)

Students in this program have carried out a multitude of research tasks, including cross-matching of multi-wavelength catalogs, understanding the relation between catalog and image-level data, measuring SFRs from 24$\boldsymbol{\mu}$m fluxes, computing cluster-averaged properties such as integrated SFRs, comparing results from different groups, assessing the validity of their results, and presenting the results in written and oral form.

Implementation: LHS has a 60% higher percentage of African Americans and a 340% higher percentage of Native Americans, when compared to other Kansas High Schools. Rudnick will continue his successful recruitment of female students and those from underrepresented minorities. The current proposal will extend the ongoing project to measure SFRs of galaxies in the local filaments. The requested funding will be used to continue employment for the current outreach coordinator Brian Schafer, who is an ex-KU Astronomy, Physics, and Chemistry undergrad with extensive teaching training and now four years of experience with our outreach program. This employee will be the main contact person in the classroom and will lead the day-to-day instruction and supervision of the learning teams during the execution of the project. co-PI Rudnick's role is to coordinate the program, decide on the exact curriculum modifications based on our assessment process (see below), attend the class once every week, and ensure that the program becomes sustainable in future years. Through Rudnick's *continuous* support and heavy involvement in the program, the high school teacher is able to devote more of his time to training students to aid in peer instruction, which will allow us to expand in future years without additional personnel costs.

Assessment: The assessment consists of an end of project presentation and paper for each student. Their presentations are made to KU faculty during a mini-conference at KU. All students are given the pre- and post-course Light and Spectra Concept Inventory (Bardar et al. 2006). We also make students give multiple oral presentations throughout the semester and have a rubric to evaluate their improvement over the course of the project. This project satisfies important elements of several of the Kansas state science standards, i.e. "Science as Inquiry" via the process of research and of communicating their results, benchmark 2 and 3 of the Physics standards via learning about the electromagnetic spectrum and how it relates to astronomical phenomena, benchmark 4 of the earth and space sciences standards relating to general astronomy, and benchmark 2 of the "history and nature of science" via the understanding gained of the scientific process.

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