1. Overview

We propose to combine multi-wavelength data to probe the gas and dust in galaxies in two nearby filaments to constrain the physical mechanisms that cause galaxies to evolve from blue, actively star-forming galaxies to red, passive galaxies. We will focus on where and how passage into a filamentary structure affects a galaxy's gas supply. Specifically, we will measure the spatial extent of the dust and star-forming disks relative to the stellar disk for ∼200 galaxies that reside in the large-scale filaments surrounding the Virgo cluster. We will combine this information with measurements of molecular gas and atomic hydrogen to create a complete census of the interstellar medium for a large sample of galaxies in this dynamic environment.

Virgo is one of the best studied clusters, period. We will combine our gas and dust properties of filament galaxies with existing measurements of Virgo cluster galaxies and isolated field galaxies. We will compare these results to simulations of cluster growth and semi-analytic models of gas consumption to help identify the physical mechanisms that deplete galactic gas in dense environments, a key aspect required to understand galaxy evolution.

Most previous studies that look at the influence of environment on galaxy gas and star formation properties classify environment in terms of either cluster-centric radius or local density. However, the distribution of galaxies is not smooth, even near clusters. In this proposal, we move beyond to look as galaxies along two filaments that are feeding a group and cluster.

2. Scientific Motivation

A wealth of previous work has established that the fraction of quiescent (non star-forming) galaxies increases with stellar mass and environmental density (e.g. Dale et al. 2001; Kauffmann et al. 2004; Peng et al. 2010). However, the physical processes that deplete a galaxy's gas content and thus star formation remain unclear. In this proposal, we are focusing on where and how environment affects galaxies. While interactions with the intracluster medium clearly strip gas from some infalling cluster galaxies (e.g. Chung et al. 2007), there is ample evidence that galaxy star-formation rates are suppressed at distances up to ∼5 virial radii from cluster centers (see Fig 1, left panel; Lewis et al. 2002; Gómez et al. 2003; Bahé et al. 2013). This suggests that galaxies are being processed by dense environments before they fall into clusters (e.g. Poggianti et al. 1999; Cortese et al. 2006).

Studying the relative distribution and amount of gas and stars can help identify the dominant processes that deplete gas in galaxies. Intrinsic processes 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). External or 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 are expected to act primarily on the gas. For example, starvation, which results from a galaxy being cutoff from its supply of cold gas (Larson et al. 1980), is expected to result in truncated gas disks while the spatial distribution of the remaining disk gas is circularly symmetric and the stellar disk is unaffected (e.g. Kawata & Mulchaey 2008). The interaction of galactic disk gas with the intracluster medium via ram-pressure stripping can remove the gas and produce asymmetries in the remaining disk gas (e.g. Quilis et al. 2000; Crowl et al. 2005). The environmental effects thus have different signatures on the relative abundances and spatial distribution of the warm ionized gas and molecular gas. By observing both phases, we can distinguish among these processes.

Large galaxy redshift surveys have revealed that galaxies are distributed in a complex network of matter with a large dynamic range of local density, called the cosmic web or filamentary structures (Kitaura et al. 2009; Darvish et al. 2014). These structures are seen in striking clarity in both simulations (left panel Fig 1) and around the Virgo cluster as shown in Figure 2. Our goal is to understand how galaxies are altered as they move through the cosmic web of filaments and enter the densest regions. We are therefore in the midst of a multi-wavelength study of galaxies at a variety of positions in the cosmic web surrounding the Virgo cluster, one of the best studied regions of high density in the Universe.

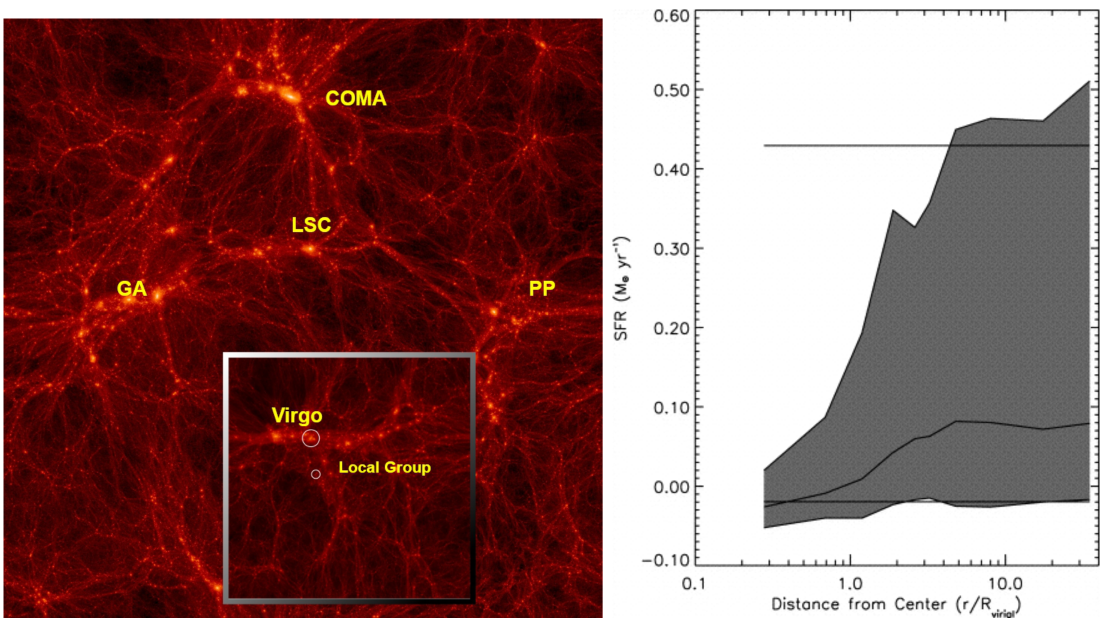


Fig. 1.— *(Left)* Simulation from CLUES showing filamentary structure surrounding clusters in the nearby Universe. Galaxies stream along filamentary structures and into clusters. *(Right)* Figure 6 from Gómez et al. (2003) showing that the upper envelope of star formation rates begins to drop at $4R_{vir}$; there is a very large scatter which complicates the interpretation of this trend. Much of the scatter may come from the large range in local densities at a given projecte radius due to the filamentary structure surrounding clusters. Understanding the impact of environmental processes requires studying galaxies along filaments and not just as a function of projected radius - this is the goal of this proposal.

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.

3. Gas and Dust Content of Virgo Filament Galaxies

We propose to explore the physical properties of galaxies in the filaments around the Virgo cluster. Our approach differs from and complements previous works, as it moves away from the simple field/group/cluster trilogy. We follow instead the complex network of galaxies around a well studied cluster. Virgo is an ideal target as it is one of the best studied clusters. However, there is only sparse data on galaxies in the well-defined filaments leading into Virgo from large radii, making our project especially timely. The study of these filaments will benefit from the comparison with the rich ensemble of data already obtained for the center of Virgo: the atomic gas with the VLA by Chung et al (2009), and also at large scale with ALFALFA (Giovanelli et al. 2005); the dust content with the Herschel Virgo Cluster Survey (Davies et al. 2010); the stellar mass with WISE (Ferrarese et al. 2012); and recent star formation from UV data with GALEX (Boselli et al. 2011).

3.1. The Filament Galaxy Sample

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, some that lead directly into the cluster and others that are nearby but not falling into Virgo (see right panel of Figure 2). This proposal focuses on two of the filaments identified by Kim et al. (2016), and we highlight these in the left panel of Figure 2. The NGC5353 filament, the first in our study, feeds the NGC5353 group and extends over 20 Mpc, passing close to but not into the Virgo cluster (Kim et al. 2016). The second filament that we will study is the Leo filament. Kim et al. (2016) show that once you project galaxies into a Virgo-centric coordinate system (see right panel of Figure 2), galaxies in this region exist in three distinct filaments. We will target all of these. 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 of the Virgo filaments and thus the galaxies have smaller apparent size. This helps to minimize the aperture correction that we need to apply to CO observations when the galaxy size extends beyond the beam size.

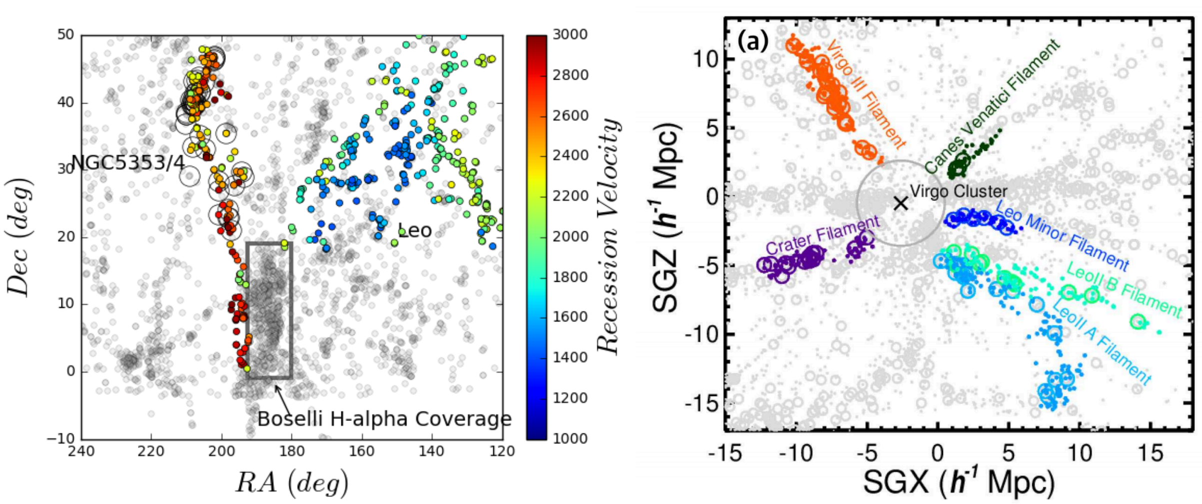


Fig. 2.— *(Left)* Figure 1(a) from Kim et al. (2016) showing filaments surrounding Virgo Cluster as observed on the plane of the sky in RA and Dec. *(Right)* Figure 2(a) from Kim et al. (2016) showing the same galaxies but projected into Virgo-centric coordinates. The Leo filaments can now be seen as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

The two filaments contain over 600 galaxies, and we show the $NUV - r$ color versus stellar mass for these galaxies in Figure 3. The grey circles show all the filament galaxies that are in the NASA-Sloan Atlas (Blanton et al. 2005), which we use as our primary galaxy catalog. The green points show the 120 galaxies we will target with CO observations. We have restricted the mass range for the CO sample to $9 < \log_{10}(M_\star/M_\odot) < 10$. 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). We set the upper limit to the mass range because we expect that galaxies with $\log(M_\star/M_\odot) < 10$ will be most affected by the environment. We will push above this mass limit as telescope time permits. The blue circles in Figure 3 show galaxies that we will target with $H\alpha$ imaging. The $H\alpha$ subsample includes all galaxies with $8.5 < \log_{10}(M_\star/M_\odot) < 10$. A total of 95 of these are in the NGC5353 filament and the remaining 126 are associated with the Leo filaments. The open red circles in Figure 3 show 184 galaxies that are detected at 12μm by WISE with a signal-to-noise ratio above 10. We set this as the lower SNR limit so that we have sufficient signal for fitting a two-dimensional *Sérsic* model, and we discuss the details of our image fitting in Section 3.2.3. **The acquisition, data reduction, and analysis of the $H\alpha$ imaging comprise one main thrust of this proposal. The second main goal of this project is to map the spatial distribution of dust within the filament galaxies using WISE 12μm imaging.**

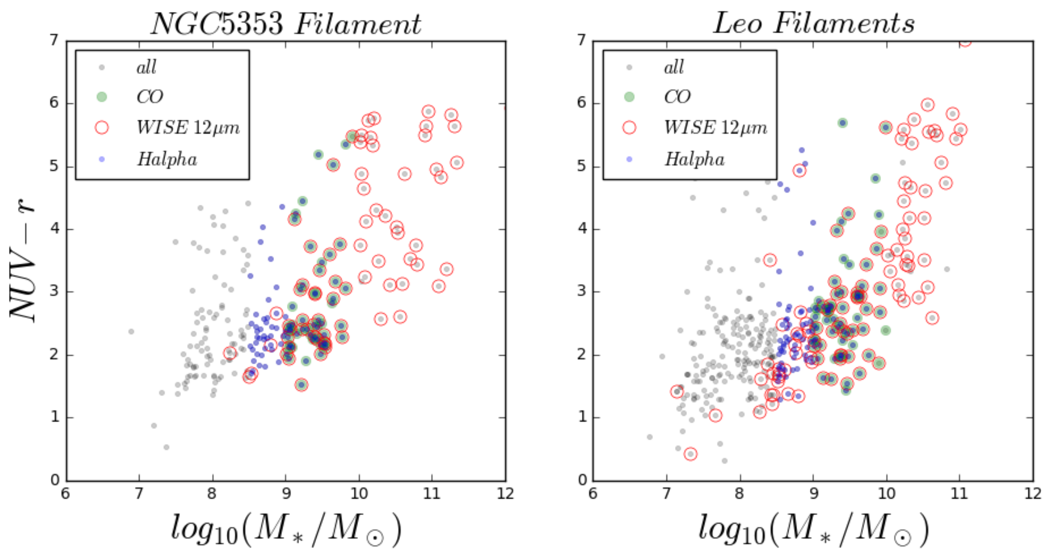


Fig. 3.— $NUV - r$ color versus stellar mass for galaxies in the (left) NGC5353 filament and the (right) Leo filaments. The grey circles show all the filament galaxies that are in the NASA-Sloan Atlas, and the red circles show all galaxies that are detected at 12μm by WISE with a signal-to-noise ratio above 10. The blue dots show galaxies that we will observe in $H\alpha$, and the green dots show the galaxies that we will observe in CO. We apply the upper-mass limit for both the CO and $H\alpha$ samples because $\log_{10}(M_\star/M_\odot) < 10$ are expected to be most affected by environment. We apply the lower mass limit to the CO sample because CO becomes difficult to detect in galaxies with $\log_{10}(M_\star/M_\odot) < 9$ due to lower metallicity.

3.2. Methodology

Several groups have shown the power of panchromatic galaxy surveys - SINGS, THINGS, LITTLE THINGS - for understanding the complicated interplay between warm and cold interstellar medium.

We take a similar approach, providing a complete census of cold gas and dust, and look at how the filament environment affects the many components a galaxy's gas reservoir.

Describe what each wavelength gives us

We will quantify the stellar and dust components using SDSS imaging, optical spectroscopy, and far infrared (WISE) fluxes. Cutting off the hot gas supply or stripping the diffuse molecular gas is a likely precursor to the suppression of star formation as the galaxy will use up its cold gas on a timescale of ~ 2.3 Gyr (Bigiel et al. 2011). Likewise, direct stripping of the cold gas will result in a suppression of the CO and infrared luminosity and truncated $H\alpha$ emission (e.g. Koopmann et al. 2004). Therefore, we expect a variety of gas effects to be observable by observing a sample of galaxies in both $H\alpha$ and CO. Note that Virgo is the closest relatively massive cluster. There is no counterpart in which the major question of the origin of star formation quenching could be addressed in such exquisite details.

3.2.1. Molecular and Atomic Gas

Why is CO important?

Team members Jablonka and Combes are leading the observing campaign to measure CO(2-1) and (1-0) for all filament galaxies with $9 < \log_{10}(M_\star/M_\odot) < 10$ using the IRAM 30-m telescope. During October 2016, they succesfully observed 40 galaxies in the NGC5353 filament, and 38 of these were detected. We show the CO spectra for three of these detections in the right panel of Figure 4. 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.

Why is HI important?

The area surrounding Virgo is incredibly well-studied, and 75% of our target galaxies already have HI observations.

Combes is leading the effort to observe all of the filament galaxies in HI that don't already have existing observations. She has submitted a proposal to use the Nancay 200×35 m^2 telescope. She will contine to request time on this telescope until the HI observations are complete. This will provide HI masses.

The specific HI and CO observations of our targets will serve the following immediate goals: (1) determine their total cold gas content. (2) Get insight in the molecular to atomic gas ratio. (3) Compare the atomic and molecular content to the star formation rate, obtained from both infrared and $H\alpha$ fluxes (sdss spectra), and hence determine the star formation efficiency. This will serve direct comparison with the Virgo cluster and the field, using published analogous studies.

3.2.2. Ionized Gas and Current Star Formation Rates

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

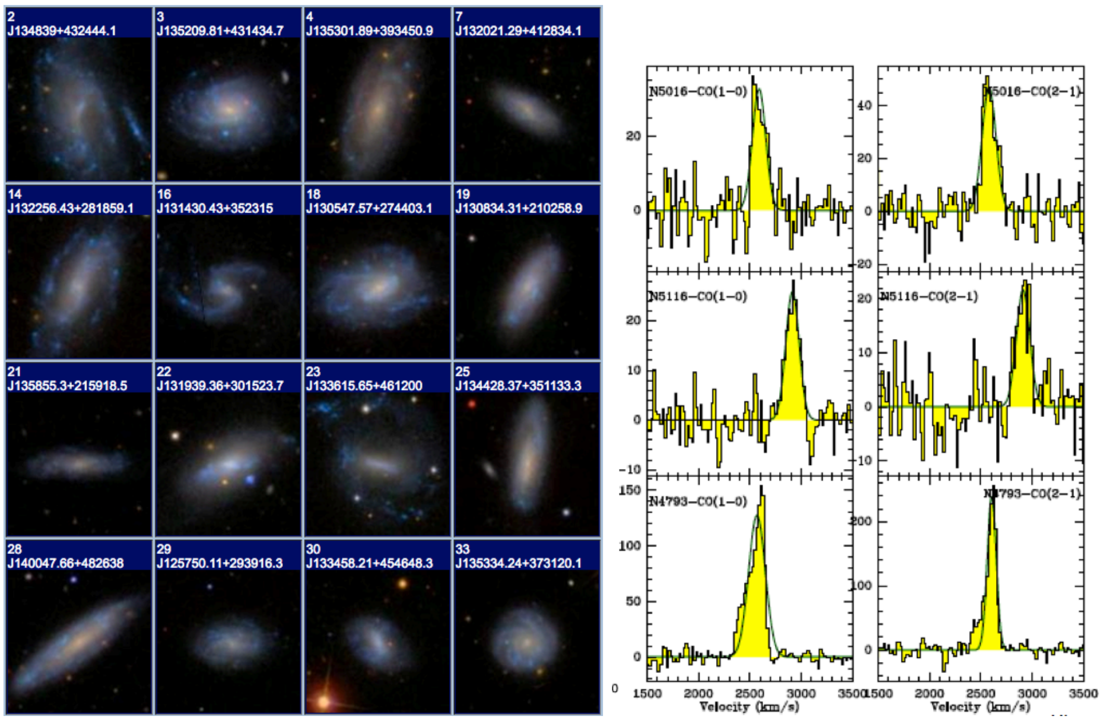


Fig. 4.— *(Left)* SDSS color images showing 16 randomly selected galaxies in NGC5353 filament. *(Right)* Newly acquired CO (1-0) and (2-1) spectra from IRAM 30-m telescope for galaxies in the NGC5353 filament taken during October 2016. Of the 40 galaxies that were observed, 38 were detected in CO. Collaborator Jablonka will observe an additional 40 galaxies in December 2016, and she will continue observations until the CO sample is complete.

distribution of the underlying stellar population, 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 show evidence of cold gas stripping (e.g. Koopmann & Kenney 1998, 2004; Dale et al. 2001; Crowl et al. 2005; Chung et al. 2007; Corbelli et al. 2012; Gavazzi et al. 2012; Boselli et al. 2015), including truncated Hα 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 $H\alpha$ imaging has been done in groups, clusters, and the field, little has been done to map the spatial extent of $H\alpha$ in filament galaxies. The goal of our program is to obtain spatially resolved $H\alpha$ maps for 222 star-forming galaxies in the NGC5353 and Leo filaments. These maps will allow us to test specific quenching mechanisms that involve the removal or rapid consumption of gas from galaxies. Key to accomplishing these goals are that we are able to measure $H\alpha$ 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 must detect galaxies with star-formation rates below the star-forming main sequence. Elbaz et al. (2011) find that a $\log_{10}(M_\star/M_\odot) = 9$ galaxy has a SFR of 0.25 $M_\odot$/yr at $z = 0$. The detection limits of our $H\alpha$ imaging will allow us to detect galaxies with star-formation rates a factor of ten below the star-forming main sequence.

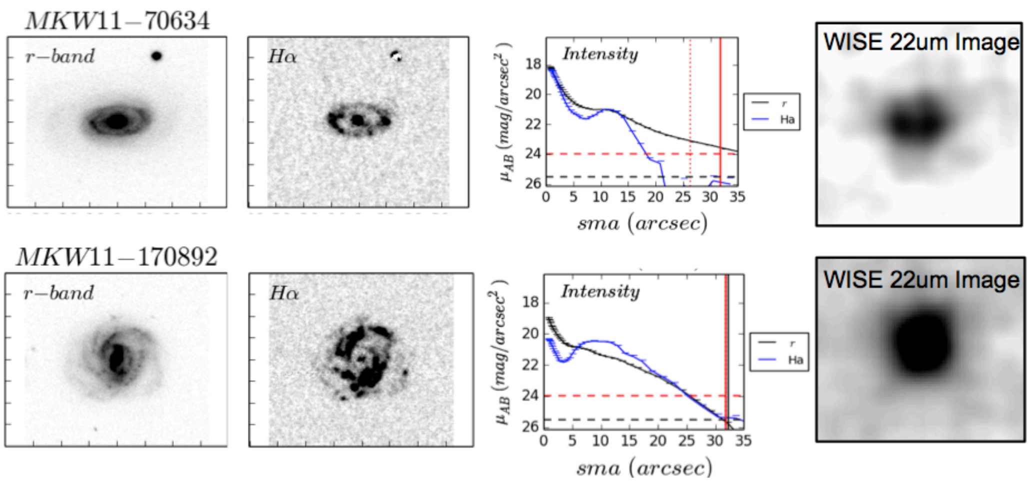


Fig. 5.— To illustrate our proposed $H\alpha$ analysis, we show imaging taken with the KPNO 0.9-m+HDI of two galaxies within the nearby group MKW11 (v_r = 6900 km/s). The left column shows a galaxy for which the star-forming disk probed by $H\alpha$ is truncated along the semi-major axis (sma) relative to the stellar disk as probed in the r-band. The right column shows an example that is not truncated. The SFR is resolved at about 1/10 of a kpc in $H\alpha$. In contrast, the WISE PSF 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 extent and morphology of the star formation. Indeed, the WISE photometry may underestimate the SFR for the lowest mass galaxies in our sample because of their low metallicity. As these galaxies are likely the most susceptible to stripping, $H\alpha$ imaging is necessary to understand how environment affects their gas.

We will complete the $H\alpha$ observations at the WIYN 0.9 and 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 $H\alpha$ 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 $0.5^\circ \times 0.5^\circ$ field of view. Thus we expect to complete $H\alpha$ imaging for ~ 100 galaxies at the WIYN 0.9m.

We will observe the remaining 120 galaxies in the $H\alpha$ sample using the XX telescope at the Mount Laguna observatory. ***** Background from Greg - commissioning, camera**** $22 \times 22'^2$ field of view. Ready for operation in Spring 2017. We have included funds to purchase an identical $H\alpha + 4$ nm filter for this telescope.

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

3.2.3. Dust Masses and Spatially-resolved Dust Maps

WISE 12-micron images are sensitive to emission from polycyclic aromatic hydrocarbons, 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 6). Along with SDSS fiber spectroscopy, the WISE colors will be used to eliminate galaxies with infrared size measurements that are likely to be affected by an AGN.

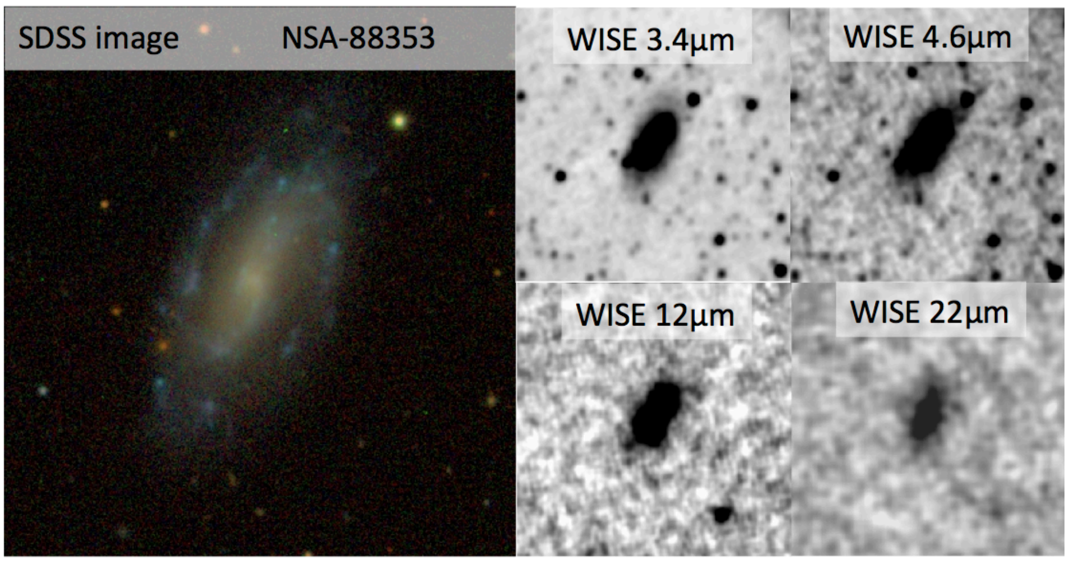


Fig. 6.— Multi-wavelength images of spiral galaxy NSA-88353. The 4 panels on the right are the WISE images. The resolution of WISE is sufficient to measure the spatial extent of dust emission using the 12μm images. The 22μm fluxes indicate the amount of dust-obscured star formation and thus provide an important complement to the $H\alpha$-derived star-formation rates.

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. Finn has completed a similar analysis using GALFIT to analyze MIPS 24μm images for galaxies in 9 nearby galaxy clusters (**?**). 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 MIPS. We are thus confident in our ability to measure sizes at 12μm.

We will use *unWISE* image products and PSFs (Lang 2014) because they are optimized for extended sources whereas the WISE image image products have been optimized for point sources.. We will use the best-fit parameters from the r-band as the initial guess for the 12μm fits. To test the sensitivity of our results to these initial conditions, we will stochastically vary the intial conditions to provide more robust estimates of range of acceptable fit parameters. This process is described in more detail below. The WISE data have lower resolution and lower signal-to-noise ratios than the optical imaging that GALFIT is typically used with. We will use simulated galaxies to test the reliability of our GALFIT model parameters.

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. We estimate the computational complexity for analyzing the WISE images for ~ 200 galaxies with GALFIT in a systematic fashion. We would scan over the five-dimensional parameter space p=(x, y, radius, concentration, brightness), by discretizing each dimension between a minimum and a maximum value. Assuming an average of 10 points per search direction, the discrete lattices has 10^5 points. Preliminary analyses show that the average time GALFIT takes to fit each WISE image is about 20 seconds. That corresponds to a total estimated computational time of the order 4×10^8 seconds to scan the entire parameter space, which can be managed by the High Performance Computer Cluster (HPCC, see Facilities section of this proposal) available at Siena College (in about a couple of weeks of computational time). However, additional fine tuning of the parameters (e.g. by doubling the number of lattice points per parameter dimension) can quickly lead to a system that is beyond to Siena Colleges current computational capabilities. For that reason we plan to perform a stochastic sampling of the parameter space, with GALFIT. In fact, since GALFITs minimization algorithm is based on a quadratic function (by means of the Levenberg-Marquardt algorithm), we can estimate the Hessian numerically around randomly chosen starting points $\{p\}$ from which we can extrapolate the size of the basin of attraction (the *Sérsic* model requires an initial guess for the center (x,y), effective radius, *Sérsic* index, and magnitude) . A similar strategy has been successfully adopted in (Pardo et al. 2011) where Monte Carlo sampling alternates with gradient minimization algorithm. By running it on Siena Colleges HPCC, we estimate it would take less than 2 days of computational time. The test and exploratory runs are anticipated to take an additional 50 CPU hours (Sala et al. 2012, for a recent application of this method see,). The two computational techniques described above are sufficient to create a map of the full phase diagram accurately. In addition, 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).

3.3. Comparison with Theory

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 left panel of Figure 7, 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 explicity include environmental processes such as ram-pressure stripping. In the right panel of Figure 7, we show the *measured* size of the star-forming and stellar disks versus stellar mass for the *Local Cluster Survey* galaxies. While the size of the stellar disks are consistent with the model predictions, the size of the star-forming regions fall systematically below the model predictions. This indicates that additional environmental processes must be included to explain the small observed size of the star-forming region in these galaxies. However, the *Local Cluster Survey* sample is small and contains very few isolated/field galaxies. We need (1) a larger sample of cluster galaxies to confirm the inconsistency between model and obervations, (2) a larger field sample to serve as a controlled comparison with the models, and (3) a more robust determination of the size of the star-forming region that includes a formal analysis of uncertainty.

Theoretical models of ram-pressure stripping provide predictions that we can compare directly to

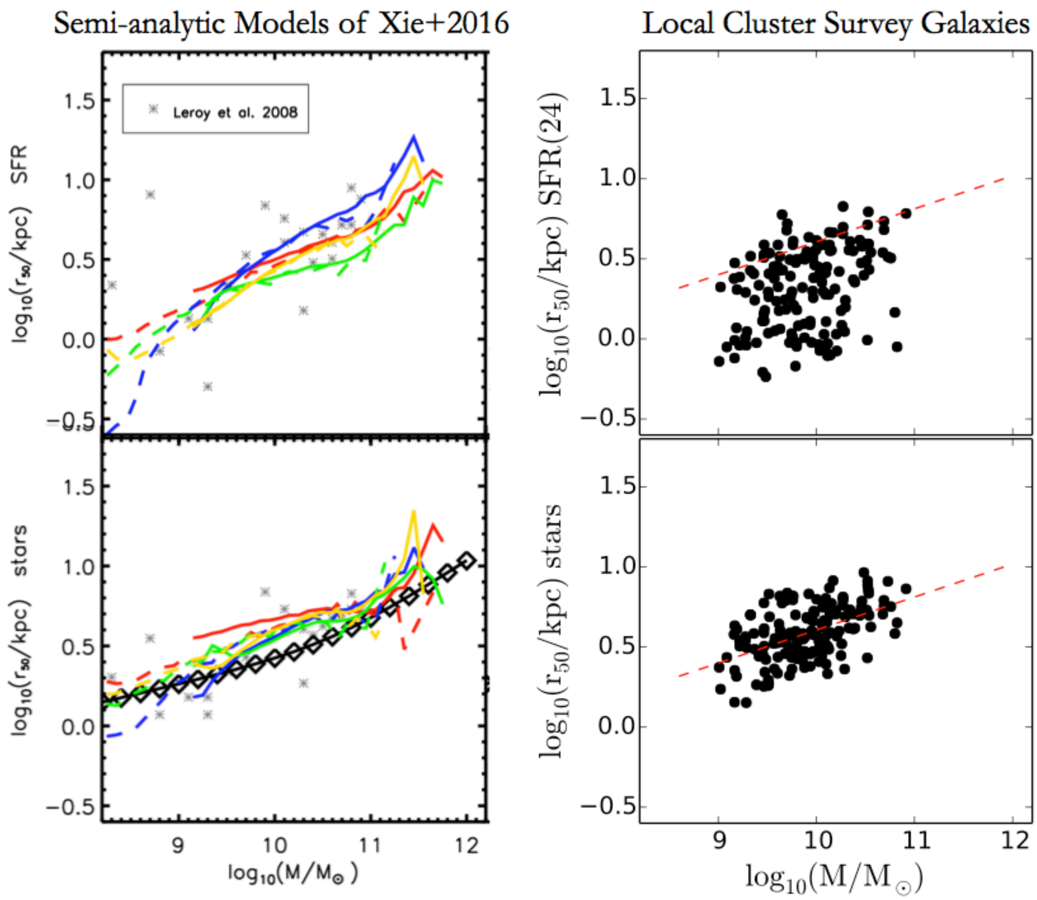


Fig. 7.— (left) **Predicted** half-light radius of stars (bottom) and star formation (top) versus stellar mass for $z = 0$ galaxies (Xie et al. 2016, in prep). The different color lines represent different models for partitioning atomic and molecular hydrogen, and the grey points show comparison with some existing observations. (right) **Measured** half-light radius of stars (bottom) and star formation (top) versus stellar mass for galaxies in the *Local Cluster Sample*. The red dashed line is a linear fit to the stellar half-light radius and is shown in the top panel for comparison. The size of the star forming region is smaller than predicted by semi-analytic models, suggesting that starvation is not sufficient to explain the observed size of the SF region in these galaxies. A larger sample of galaxies with more robust size measurements is needed to confirm this result.

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 larger sample is needed to disentangle these effects. In addition, low mass galaxies should be more vulnerable to having their gas removed because the gas in lower mass galaxies is not as tightly bound (e.g. Kawata & Mulchaey 2008; McCarthy et al. 2007; Bekki 2014). We find some evidence of this in the *Local Cluster Survey*, but a larger sample is needed to strengthen the statistical significance.

Constrained Local UniversE Simulations (CLUES) of local volume[1] includes dark matter, gas and stars. Co-I De Lucia will work to integrate her semi-analytic models with the CLUES dark matter merger trees so that she can predic the spatial distribution of star and star formation for galaxies in the local volume.

3.4. Workplan, Major Milestones, and Timeline for Completion

The division of observing and analysis responsiblities among the team members is outlined in Table **??**. The expertise and roles of individual team members is described below.

Rose Finn, Ph.D., (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 $H\alpha$ imaging survey at KPNO and the analysis of the WISE 12μm imaging, supervise the undergraduate students, and draft the paper.

Vandana Desai, Ph.D., is an astronomer at the NASA/IPAC Infrared Science Archive (IRSA). Vandana has extensive experience in all aspects of infrared astronomy and will lead technical aspects associated with the WISE data. She also is well-versed in best-practices of data sharing and will lead our efforts to disseminate data products over the web.

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.

Gregory Rudnick, Ph.D., is an associate professor at the University of Kansas. He has expertise in 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 $H\alpha$ imaging survey at XX observatory. Will supervise XX students.

Gabriella De Lucia, Ph.D, is a permanent research scientist at INAF - Astronomical Observatory of Trieste. Grabriella provides expertise in semi-analytic modeling of galaxy evolution. She is working on models that predict the spatial extent of the stellar and star-forming disks, and her work is thus extremely pertinent to this proposal. She will lead the theoretical interpretation of our results and the comparison with semi-analytic models of gas consumption.

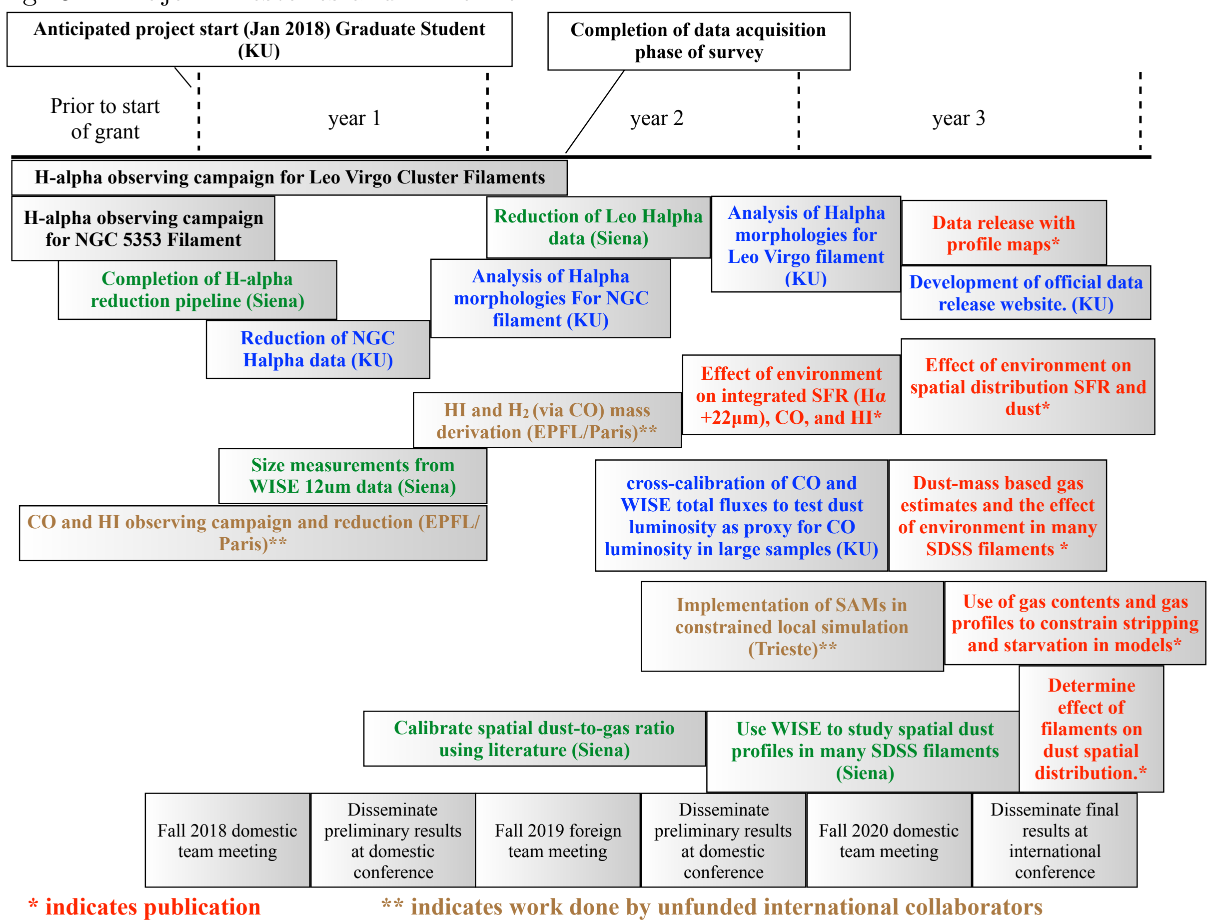
Pascale Jablonka is senior researcher at the Laboratory of Astrophysics of EPFL (Switzerland). She conducts both observations and numerical simulations to gain insights into the formation and evolution of galaxies. Her research focuses on two mains topics related to the present proposal: i) Infering the driving parameters of the galaxy star formation histories. ii) Deciphering the impact of the environment on galaxy evolution. She is leading a CO survey of cluster galaxies at intermediate redshift. She will observe the cold gas content of galaxies in the filamentary structures feeding the Virgo cluster, in atomic (HI) and molecular (CO) forms.

Francoise Combes, PhD, is a Professor at College de France, and astrophysicist at Paris Observatory. She is an expert in the dynamics of galaxies, their star formation (SF) efficiency and feedback

[1] https://www.clues-project.org

processes, including the action of a super-massive black hole. She has made numerical simulations to test the processes of SF quenching, ram pressure stripping, tidal interaction, or strangulation. She will observe the cold gas content of galaxies in the Virgo filaments, the atomic (HI) or molecular (CO) reservoirs.

Fig. 8.— Major Milestones and Timeline



3.5. 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 HI, Halpha, and SDSS maps with integrated CO fluxes. We will produce a variety of measurements of the gas content of filament galaxies. We will produce a catalog of CO, HI, dust, Halpha 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 Extragalactic Database (NED) 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.

4. Broader Impact

4.1. 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. Experienced physicists already have these mental models, but beginning physics students do not. 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, I know first-hand the importance of bringing the more effective and engaging techniques to the front line. As part of a previous NSF grant (AST-08XX), 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 workshops. We offer 6 hours of 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. The PI supervised 24 undergraduate students during the tenure of her previous NSF grant (AST-0847430).

Previous Siena undergraduate students have worked on $H\alpha$ imaging of nearby galaxy groups. Together we have developed software to streamline the reduction process. Students have presented their preliminary results at Siena's internal academic celebration, the fall meeting of the Astronomical Society of New York, and this January at the winter AAS meeting. The proposed work will benefit directly from the experience of my current undergraduate students and the software they have developed.

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 TCP through remote observing once the telescope has been commissioned. 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 meaure radial profiles for the $H\alpha$ imaing and develop ways to quantify the $H\alpha$ morphologies.

The students will work in collaboration with the graduate student at Kansas to compile the $H\alpha$ 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, so this 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.

Four Siena students began the first stages of their research projects this summer, and I expect all of these students to continue their involvement through the next academic year. Graduating students will be replaced by interested freshman or sophomores to maintain a total of 4 undergraduate researchers at any one time. Specific goals for current and future student researchers are:

- learn how to use python for image reduction and analysis
- learn how to effectively present their results to expert and non-expert audiences
- identify correlations between $H\alpha$, infrared, and cold gas properties of galaxies and look for variations in these correlations as a function of galaxy environment.

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.

4.2. 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 §4.3). 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.)

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 hire a physics or astronomy graduate student interested in education or an employee with similar qualifications. 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. Rudnick's main tasks will be to coordinate the program, decide on the exact curriculum 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.

4.3. co-PI Rudnick

4.3.1. Molecular Gas in Distant Galaxies'

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 §4.2 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 §4.3.2).

4.3.2. Galaxy Evolution in Distant Clusters

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 $\boldsymbol{UBVRIzYJK_S}$[**3.6μ**m][**4.5μ**m] 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.

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.

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5. Summary

Intellectual Merit:

Broader Impact: This proposal resonates with the National Science Foundation's broader impacts criteria on many levels. First, the proposal helps promotes teaching and learning by promoting modeling approach to teaching HS physics, integrating problem-based learning into general physics, and the introduction an astronomy concentrations within the physics major to increase the number of majors. Nationally, astronomy traditionally draws a higher fraction of women than physics, so the introduction of the astronomy concentration should attract more female students, a group that is significantly under-represented in phyiscs. Second, the project provides hands-on training and learning for tens of undergraduate students through research. The Siena undergraduate students will be encouraged to become involved in all aspects of research, including data aquisition at world-class observatories, on-campus data reduction and analysis, and presentation of results at national conferences and through publication in peer-reviewed journals. The computer analysis, data interpretation, and presentation skills the undergraduates learn will be essential for success in the workplace, the classroom, or graduate education in any field of science. Finally, the proposal enhances the infrastructure for research and education at Siena College by formalizing collaborations with the ALFALFA team, several of whom are located in New York State and already serve as an extended network of mentors for Siena undergraduates. The proposal will also enable Siena to conduct remote observing sessions at Arecibo.

Broad Dissemination of Results: The scientific results of will be disseminated broadly through publication in peer-reviewed journals, online database, presentation at regional, national and international meetings. I will provide a full catalog for the scientific community that will include an extensive array of primary and derived data products. This will be a much-needed reference for galaxy evolution modelers, particularly those who model the evolution of galaxies. The pedagogic results will also be disseminated broadly through publication in peer-reviewed journals and presentations at regional and national conferences. Of particular interest is the impact that problem-based learning has on student retention and research readiness. In addition, we will develop a new assessment tool that measures a student's ability to think independently and solve real-world problems. This will be of wide interest to institutions looking to implement similar research-focused curricular changes.

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