

Proposal for an ISSI International Team
COSWEB: The Cosmic Web and Galaxy Evolution
Coordinator: Gregory Rudnick

We have assembled the COSWEB team to study the interplay between the cosmic web and galaxy evolution. COSWEB is an outgrowth of a previous ISSI project that focused specifically on how the gas content of galaxies is affected by galaxy clusters. We propose to continue our studies of the gas content of clusters as well as exploit a breakthrough our team has made in characterizing the filamentary structure around clusters.

Starting over thirty years ago, astronomers began to suspect that a galaxy's environment affects its evolution. Compared to the average galaxy, those residing in high density areas have systematically older stellar populations, lower rates of star formation (SF), and different morphologies. In the past decade, large surveys of galaxies with ground-based telescopes have cemented the existence of these environmentally-dependent differences. However, the physical mechanisms by which galaxies are altered as they enter dense environments have not yet been conclusively identified and we do not know where different processes dominate.

Two elements are largely missing from current analyses: 1) information about the gaseous fuel for SF and 2) a proper treatment of dense filamentary environments, rather than a simplistic focus on clusters, groups, and field populations. Our team will address these shortcomings by both characterizing the stellar and gaseous contents of galaxies over a large range in lookback time and by focusing much of our effort on studying galaxies in filaments, the site where many galaxies first encounter a dense environment.

We have assembled a team that can address both of these concerns to bring fresh insights to understanding the environmental dependence of galaxy properties. Our team is composed of 15 individuals from seven countries whose research expertise are as follows:

- *Molecular tracers of star-forming gas:* F. Combes (F), P. Jablonka (CH), G. Rudnick (USA), A. Noble (USA), E. van Kampen (DE), J. Hodge (NL), C. Papovich (USA), M. Cooper (USA)
- *Ionized tracers of star-forming gas:* B. Weiner (USA), G. Rudnick (USA) R. Finn (USA), Y. Jaffe (Chile)
- *Dust-obscured star formation:* R. Finn (USA), V. Desai (USA), G. Rudnick (USA), C. Papovich
- *Galaxy environment:* D. Zaritsky (USA), G. Castignani (F), V. Desai (USA), P. Jablonka (CH), M. Cooper (USA), D. Norman (USA), Y. Jaffe (Chile)
- *Very distant clusters:* G. Rudnick (USA), B. Weiner (USA), A. Noble (USA), E. van Kampen (D), C. Papovich (USA), G. Castignani (F)
- *Theoretical modeling:* G. De Lucia (IT), M. Cooper (USA), F. Combes (F)

These individuals are using the largest ground-based telescopes, the best space facilities, and the largest and newest radio/mm interferometers on the planet. Together they account for much of the data on gas in dense environments, and over a large baseline in cosmic time.

The immediate goals of our team are to:

- Determine the response of the ionized gas to the environments by combining results of HST spectroscopic observations of intermediate redshift clusters with $H\alpha$ narrow-banding imaging of Virgo cluster.
- Determine how the SF rate and dust content are affected by environment through the use of *Spitzer*, *WISE*, and *Herschel* observations of dust emission and interferometric observations of the molecular gas and dust continuum in filaments and galaxy clusters spanning 10 Gyr of cosmic time.
- Compare the state of the gas to that of the stars to constrain the transformative mechanism.
- Initiate new observational programs to measure the spatial distribution of the molecular gas and compare it to the state of the ionized gas.
- Make powerful new constraints on the implementation of gas depletion in galaxy formation models.

The Role of Environment in Galaxy Evolution: our past and future activities

This is an extension proposal for our previous ISSI team “The Effect of Dense Environments on Gas in Galaxies over 10 Billion Years of Cosmic Time,” which produced eight papers and 10 accepted telescope proposals. In this renewal proposal we describe the continuation of our efforts as well as a new research area that grew out of the initial ISSI work, but requires the expertise of six new members.

Filaments as the place where galaxies begin to die? Galaxies in dense environments have lower average SF rates than field galaxies out to at least $z \sim 1$ (e.g. Poggianti et al. 1999; Lewis et al. 2002; Gómez et al. 2003; Postman et al. 2005). However, it is still not clear whether the clusters actively alter the gas content of infalling galaxies or whether they are the final resting place of dead galaxies whose gas was depleted before entering the cluster environment.

At low and intermediate redshifts, the suppression of SF starts at large distances from cluster cores, within groups and filaments (Lewis et al. 2002; Gómez et al. 2003; Laigle et al. 2017). This is consistent with simulations that show a boosting of ram pressure within filaments (Bahé et al. 2013), through which the bulk of the mass flows into the cluster (Ramachandra & Shandarin 2015). In contrast, spiral galaxies in the Virgo cluster show evidence of cold gas stripping and truncated gas disks (Koopmann & Kenney 1998, 2004; Dale et al. 2001; Crawl et al. 2005; Chung et al. 2007). This demonstrates that the cluster environment is actively altering the star-formation properties of at least some of the infalling galaxies.

To conclusively determine the cause for the end of SF in dense environments it is important to **1)** study the fuel of SF itself and **2)** probe a large sample of galaxies in the filaments surrounding clusters, which are experiencing environmental effects for the first time.

A revolution in our characterization of filaments: Galaxy environment studies in the past 25 years have focused on a simple trilogy of field, group, and cluster environments. We propose to move beyond these categories by characterizing galaxies within filaments out to lookback times of 6 billion years.

The region around the Virgo cluster is ideal because at ~ 16 Mpc, it is near enough to allow spatially resolved studies, and to benefit from existing shallow, wide surveys. Taking advantage of the massive investment of SDSS spectroscopy over $\sim 5000\text{deg}^2$, Kim et al. (2016) have identified seven well-defined filaments around the Virgo cluster (Fig. 1).

We have also made breakthroughs in our understanding of the filaments feeding distant galaxy clusters at $z > 0.4$. These advances have come thanks to the availability of 1 deg^2 field of view imagers on 4-meter telescopes that have enabled distant filaments to be identified via accurate photometric redshifts and subsequently be confirmed with multi-object spectroscopy on 6–8-meter class telescopes (Fig. 1; Rerat et al. in prep). It has taken years to amass this data but we now have the first ability to study highly pure samples of filament galaxies many virial radii away from clusters, in the regions where they may experience environmental affects for the first time.

A revolution in our knowledge of the gas: To understand how SFRs are altered, we require direct probes of the content and spatial distribution of the gas, which depending on its phase either traces active sites of SF or its fuel supply (e.g. Kennicutt 1998; Bigiel et al. 2008; Leroy et al. 2008).

We are entering a new age of possibility in our ability to study how gas is affected by dense environments thanks to space-based (*Spitzer*, *Herschel*, WISE, HST, JWST) and ground-based (ALMA, IRAM, NOEMA, JVLA, VLT, Nancay) observatories. With slitless spectroscopy observations with HST we are obtaining detailed spatial maps of SF in clusters and their infall regions for systems at $z < 0.6$. HST grism spectroscopy is allowing us to probe the ionized gas and stellar populations of a sample of the most distant clusters at redshifts $z > 1.5$. *Spitzer*, WISE, and *Herschel* have also given us views of the obscured SF of galaxies back to the early epochs of time. Locally they allow us to map the relative spatial distribution of the dust and the stars, thus tracing the stripping of the cold gas. CO observations at the JVLA, IRAM, NOEMA, and ALMA are enabling us to directly measure the content of molecular gas in filament galaxies

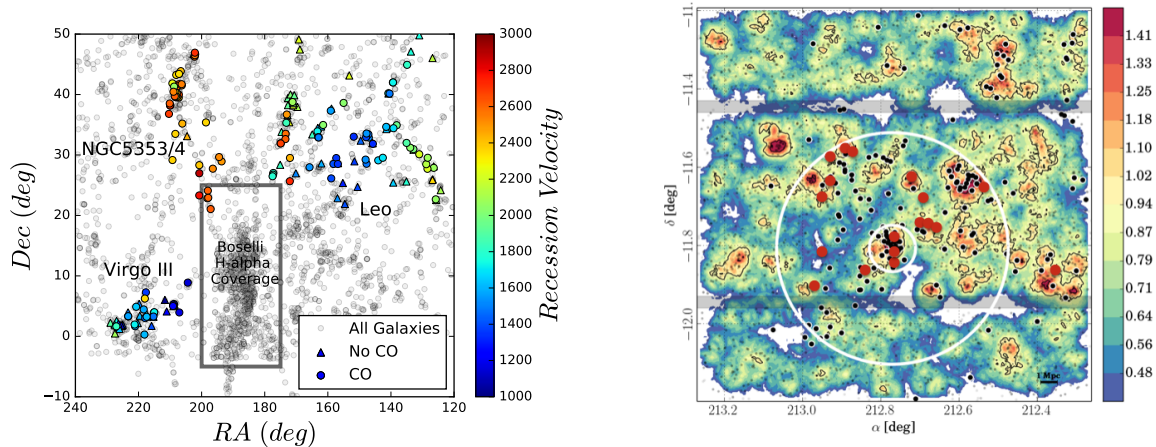


Figure 1: *Left panel* - Our sample of filaments around the Virgo cluster. Galaxies we have already observed in CO are shown color-coded by their velocity and split into sources with (circles) and without (triangles) CO detections. All of these sources have HI observations and will have H α images taken during the timeframe of our ISSI team. Other galaxies around the Virgo cluster from Kim et al. (2016) are shown in gray. Our data will complement the wealth of data available in the Virgo core (gray rectangle). *Right panel* - Filamentary structure around a well-studied cluster at $z=0.52$. The color-scale shows the density of sources as measured from photometric redshifts. The black dots are spectroscopically confirmed members and the red dots show sources with ALMA CO observations. *By combining observations of multiple gas phases our ISSI team will gain a unique view of how filaments affect the gas in galaxies over 5 billion years of cosmic time.*

and we can access HI with JVLA and the Nancay telescope. Finally, with ALMA and NOEMA we will measure the spatial distribution of molecular gas in galaxies, thus directly probing the physical conditions of star formation as they interact with dense environments.

Each of our proposed team members is leading 1–2 of the efforts described above. We will bring together these resources to address the following questions: In what environment moving from the field, into filaments and groups, and into cluster cores is the gas of galaxies first affected? How are the content, distribution, density, and temperature of the gas altered? Over what timescales does the depletion occur? What are the responsible mechanisms for the gas removal and how do they operate in different environments?

Our proposed activities

We have largely characterized the environments of our galaxies and our immediate work is now to study specific phases of the gas. The analysis of individual datasets, which usually focus on an individual environment, redshift, or gas phase, will be primarily done by the PIs of those programs. A main goal of our proposed ISSI team is to bring all of these results together to form coherent and broad-reaching conclusions with the data that have been provided by the new facilities.

Ionized gas: We will determine the effect of environment on the dense ionized gas by combining an HST/WFC3 grism Cycle 20 program (PI: Rudnick) on the infall regions of 4 intermediate redshift clusters with a narrow-band imaging survey of Virgo filament galaxies (PI: Finn). With these programs we will distinguish between different methods of gas depletion by determining relative structure of the star-forming and stellar disks. For example, ram-pressure stripping makes the prediction that the gas disks will be asymmetric (e.g. Quilis et al. 2000; Crawl et al. 2005) with respect to the stars and that the SFRs in the inner parts of the galaxy should be the same as or even enhanced with respect to field galaxies (Koopmann & Kenney 2004; Weinmann et al. 2010). Galaxy-galaxy interactions, however, will result in both the gas and stars being asymmetric. Finally, starvation, which describes a weaker version of ram-pressure stripping (e.g. Larson et al. 1980), may only affect the relative sizes of the gas and stellar disks. Our team will propose with JWST grism spectroscopy to obtain spatially resolved maps of Pa α emission ($\lambda = 1.875\mu\text{m}$), which provides an extinction-free measure of the instantaneous SF and which is only available through JWST.

Obscured star formation: Infrared observations from *Spitzer*, *WISE*, and *Herschel* probe the emission by dust grains that have been heated by young stars and can be used to infer the total infrared luminosity L_{IR}

and SFR. To isolate the density at which the SFR is first modified in the cosmic web we will use completed wide-field *Spitzer* 24 μ m observations around 11 clusters at $0.6 < z < 0.8$ (PI Rudnick) to measure whether there is a location at which the fraction of vigorously star-forming galaxies drops. We will also use *Spitzer* 24 μ m observations of 9 local groups and clusters (PI Finn; Finn et al. 2017) and WISE 12 and 22 μ m observations of Virgo filament galaxies (PI Finn) to compare the spatial distribution of the dust emission in galaxies to that of their stars. Active stripping of the dust, which is usually co-spatial with the cold gas, will result in a spatial offset of the dust emission from the stellar light, while a mere decoupling of the galaxy from its gas supply will result in a lower mean intensity and smaller size of the dust emitting region.

The fuel for star formation. To truly understand the modulation of SF by reduction in the H_2 fuel supply requires that we observe the cold gas, or at least a good tracer like CO. As part of the efforts initiated by our previous ISSI team we have embarked on an ambitious observational campaign to search for stripping by imaging Virgo filament galaxies in CO, both with the IRAM 30m dish and with the NOEMA interferometer. We have also made excellent progress on increasing the number of CO detections in intermediate redshift clusters and their surrounding filaments using NOEMA (Jablonka et al. 2013) and ALMA observations (Jablonka in prep.) and our ISSI team will follow these detections up with spatially resolved observations in future ALMA cycles. We will also apply for JWST observations to measure H_2 directly.

As the result of JVLA and ALMA programs, team members have now detected CO in 13 galaxies that reside in four well studied $z \sim 1.6$ proto-clusters (Rudnick et al. submitted to ApJ; Noble et al. in prep.). Taken together with our intermediate redshift measurements, these programs comprise most of the CO detections in dense environments outside the nearby universe. Part of our ISSI program will be to combine these studies to measure how molecular gas and SF relate in dense environments since $z < 2$.

Crucial constraints from observations for theoretical models. Our ISSI includes experts in both semi-analytic models and hydrodynamic simulations. In nearly all of these models, the gas supply to galaxies is cut off upon their entry to another more massive dark matter halo. Our observations will reveal where the gas supply is cut off, i.e. filaments, the virial radius, cluster core, in groups, and how fast it is shut off. Current attempts result in uncomfortably long quenching timescales, which is how quenching is parameterized in the models (McGee et al. 2011; De Lucia et al. 2012). The fundamental problem is that the models don't properly treat the unknown quenching mechanism. Our spatially-resolved study of gas and stellar disks *in filaments as well as in groups and clusters* will help constrain the relative importance of physical processes such as ram-pressure stripping, starvation, or tidal effects, because their effectiveness varies with the density of the intra-cluster, intra-group medium, or intra-filament gas and the velocity of galaxies relative to each other and that gas. We will thus make crucial steps towards understanding the long debated nature of environmental quenching.

Why is our project powerful? Collectively, our team has access to the ideal data to address the questions outlined in our proposal. Our filament sample spans ~ 5 Gyr of cosmic time while our cluster sample spans ~ 10 Gyr and includes the highest redshift cluster with both extremely deep HST grism data (Lee-Brown et al. 2017), along with one of the largest sample of CO detections in distant clusters (Rudnick et al. 2017; Noble et al. in prep.) Importantly, our distant clusters are ideally suited for evolutionary studies as they are all typical progenitors of our local clusters (Milvang-Jensen et al. 2008; Rudnick et al. 2012). At intermediate redshift we probe far enough out in clustercentric radius to identify all of the members that will end up in the cluster at $z = 0$ (Just et al. 2014). At low redshift we use the proximity of Virgo and other local clusters to probe to low stellar masses where environmental quenching is thought to be dominant and we access HI, CO, Ionized gas, dust, and stellar mass in all of our target galaxies.

Our proposed collaboration will also probe nearly all of the phases of the gas that are relevant for SF, from the hot dense gas that traces active SF to the cold molecular gas that is the fuel of SF. We also probe all relevant densities in the cosmic web, from distant filaments to the bottom of deep cluster potential wells. By combining measurements with theoretical models we will gain an improved understanding of how SF

is regulated, and eventually quenched, in dense environments. This synergy of the appropriate data and sample, spanning a large range in redshift, and with accompanying theoretical modeling is unique.

Our proposed team: Our team is composed of 15 experts in various areas of galaxy evolution studies and represents 7 countries (USA, F, CH, IT, Chile, NL, D). They are playing key roles or are leading projects in one or more of the areas mentioned above. • *Molecular tracers of star-forming gas:* Combes, Jablonka, Rudnick, Noble, van Kampen, Hodge, Papovich, Cooper • *Ionized tracers of star-forming gas:* Weiner, Rudnick, Finn, Jaffe • *Dust-obscured star formation:* Finn, Desai, Rudnick, Papovich • *Galaxy environment:* Zaritsky, Castignani, Desai, Jablonka, Cooper, Norman, Jaffe • *Very distant clusters:* Rudnick, Weiner, Noble, van Kampen, Papovich, Castigiani • *Theoretical modeling:* De Lucia, Cooper, Combes. This group has six new members, who bring essential expertise to our collaboration. This group is larger than 12 but some members will self-fund to come to the meetings. The size of our team is necessary to ensure that we have the proper expertise.

The value of ISSI: Making significant progress on understanding environmental effects requires a concerted and multi-wavelength approach that stretches across large swaths of cosmic time and the full range of densities. This is a highly valued endeavor as understanding the gas in galaxies was highlighted in the Astro2010 Decadal report from the U.S. National Academy of Sciences. It is also a main focus of ALMA, the largest Europe-US-Japan project of the decade and of JWST.

The funding from ISSI gives us a unique opportunity for extended face-to-face meetings. Our experience has shown that the role of these meetings is crucial. For example, during our first workshop as part of the previous proposal we organically decided on pursuing the Virgo filament studies, which now forms a backbone of this proposal. Based on work done at our meetings we have produced eight papers together, and have 10 accepted telescope proposals and one successful funding proposal¹. The SSI funds make these meetings possible as almost none of the collaborators has the necessary funds from other sources. A timely effort in the design of our observing programs is crucial, as JWST has a limited mission lifetime and the first call for proposals is March 2018, right within the timeframe of this proposed team. Likewise, our ISSI team is in a perfect position to propose large programs with ALMA to study the cold gas.

Outcomes: Our collaboration will result in multiple high impact papers. We will also write a paper that combines the different studies above into synthesis of all we know observationally about the gas in galaxies in dense environments. Another paper will combine those observational constraints with our theoretical modeling to constrain the timescales and physical mechanisms for the quenching of SF.

We will submit multiple telescope proposals to ALMA, JVLA, NOEMA, HST, and most importantly JWST, to characterize the gas in much larger samples than is currently possible.

Schedule: We propose to hold an initial full team meeting of five days to kick off the project during the summer of 2017. This would be followed by a final 5 day full team meeting in the summer of 2018.

Financial Support: We request the standard support provided by ISSI of a per diem for the living expenses of Team members while residing in Bern and for the travel expenses of the coordinator (Rudnick). We would also appreciate benefiting from the ISSI Young Scientist scheme for two young researchers.

Required Facilities. We require only meeting facilities and reasonably fast internet access.

Bahé, Y. M. et al. 2013, MNRAS, 430, 3017; Bigiel, F. et al. 2008, AJ, 136, 2846; Chung, A. et al. 2007, ApJ, 659, L115; Crowl, H. H. et al. 2005, AJ, 130, 65; Dale, D. A. et al. 2001, AJ, 121, 1886; De Lucia, G. et al. 2012, MNRAS, 423, 1277; Gómez, P. L. et al. 2003, ApJ, 584, 210; Jablonka, P. et al. 2013, A&A, 557, A103; Kim, S., et al. 2016, ApJ, 833, 207; Kennicutt, Jr., R. C. 1998, ApJ, 498, 541; Koopmann, R. A. et al. 1998, ApJ, 497, L75; —. 2004, ApJ, 613, 866; Laigle, C. et al. 2017, submitted to MNRAS, arXiv:1702.08810 Larson, R. B. et al. 1980, ApJ, 237, 692; Leroy, A. K. et al. 2008, AJ, 136, 2782; Lewis, I. et al. 2002, MNRAS, 334, 673; McGee, S. L. et al. 2011, MNRAS, 413, 996; Poggianti, B. M. et al. 1999, ApJ, 518, 576; Postman, M. et al. 2005, ApJ, 623, 721; Quilis, V. et al. 2000, Science, 288, 1617; Ramachandra, N. & Shandarin, S., 2015, MNRAS, 452, 1643; Rerat, F., Jablonka, P., Rudnick, G., in prep; Weinmann, S. M. et al. 2010, MNRAS, 406, 2249

¹<http://www.issibern.ch/teams/gasingalaxies/>

References

- Bahé, Y. M. et al. 2013, MNRAS, 430, 3017
- Bigiel, F. et al. 2008, AJ, 136, 2846
- Chung, A. et al. 2007, ApJ, 659, L115
- Crowl, H. H. et al. 2005, AJ, 130, 65
- Dale, D. A. et al. 2001, AJ, 121, 1886
- De Lucia, G. et al. 2012, MNRAS, 423, 1277
- Gómez, P. L. et al. 2003, ApJ, 584, 210
- Jablonka, P. et al. 2013, A&A, 557, A103
- Kennicutt, Jr., R. C. 1998, ApJ, 498, 541
- Kim, S. et al. 2016, ApJ, 833, 207
- Koopmann, R. A. et al. 1998, ApJ, 497, L75
- . 2004, ApJ, 613, 866
- Laigle, C. et al. 2017, ArXiv e-prints
- Larson, R. B. et al. 1980, ApJ, 237, 692
- Leroy, A. K. et al. 2008, AJ, 136, 2782
- Lewis, I. et al. 2002, MNRAS, 334, 673
- McGee, S. L. et al. 2011, MNRAS, 413, 996
- Poggianti, B. M. et al. 1999, ApJ, 518, 576
- Postman, M. et al. 2005, ApJ, 623, 721
- Quilis, V. et al. 2000, Science, 288, 1617
- Ramachandra, N. S. et al. 2015, MNRAS, 452, 1643
- Rerat, F. et al. in prep
- Weinmann, S. M. et al. 2010, MNRAS, 406, 2249