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 star formation rates (SFR), 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 and bring fresh insights to understanding the environmental dependence of galaxy properties. Our team is composed of 12 individuals from six countries whose research expertise as follows (five new members indicated with a '$^*$'):

- *Molecular tracers of star-forming gas:* F. Combes (F), P. Jablonka (CH), G. Rudnick (USA), A. Noble$^*$ (USA), E. van Kampen$^*$ (DE), 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), , G. Rudnick (USA), P. Jablonka (CH)
- *Galaxy environment:* D. Zaritsky (USA), G. Castignani$^*$ (F), 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$^*$ (DE), G. Castignani$^*$ (F)
- *Theoretical modeling:* G. De Lucia (IT), M. Cooper (USA), F. Combes (F), van Kampen$^*$ (DE)

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:

- Use HST spectroscopic observations at intermediate redshift and H$\alpha$ narrow-band imaging of the nearby Virgo cluster to determine the response of the ionized gas to the environmental effects.
- Determine how the SFR and dust content are affected by environment through the use of *Spitzer*, WISE, and *Herschel* observations of dust emission in addition to interferometric observations of the molecular gas content in filaments and galaxy clusters spanning 10 Gyr of cosmic time.
- Compare the spatial distribution of the different gas phases to that of the stars to constrain the environmental mechanisms that suppress star formation and change galaxy morphology.
- Initiate new observational programs using JWST and millimeter interferometers to measure the detailed spatial distribution of the ionized and molecular gas of distant filament and cluster galaxies and compare how each phase responds to galaxy environment.
- Constrain models of environmental gas depletion in simulated galaxies that are evolving in a universe characterized by hierarchical structure growth.

## 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" (PI Rudnick) which produced eight papers, 10 accepted telescope proposals, and one accepted NASA funding proposal. In addition to our significant success in gathering new data and funding resources we also started a new research area that grew out of the initial ISSI work. Exploiting these new data, bringing the new research area to fruition, and synthesizing all the results requires support from ISSI in the form of a renewal proposal. Our new team requires the expertise of five new members.

**A new focus on how the gas within galaxies is altered within Filaments:** 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 core show evidence of cold gas stripping and truncated gas disks (Koopmann & Kenney 1998, 2004; Dale et al. 2001; Crowl 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 and where it occurs it is important to **1)** study the fuel of SF itself and **2)** probe a large sample of galaxies in the filaments surrounding clusters, as these galaxies are experiencing environmental effects for the first time. The first goal was the focus of our last ISSI proposal, which we now propose to extend both to synthesize our results and to begin projects with new facilities. The second goal has been largely accomplished by our team, but needs to be folded into our analysis of the gas properties of galaxies.

**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 have moved 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 $\sim 16$ 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 $\sim 5000\mathrm{deg}^2$, Kim et al. (2016) have identified seven well-defined filaments around the Virgo cluster (Fig. 1, left panel), which we now target.

We have also made breakthroughs in our understanding of the filaments feeding distant galaxy clusters at $z > 0.4$ thanks to our concerted Spatially Extended ESO Distant Cluster Survey (SEEDisCS) program. 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, right panel; 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.

## Our proposed activities

**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). Fortunately, we are in an age of possibility in our ability to study how gas is affected by dense environments, thanks to

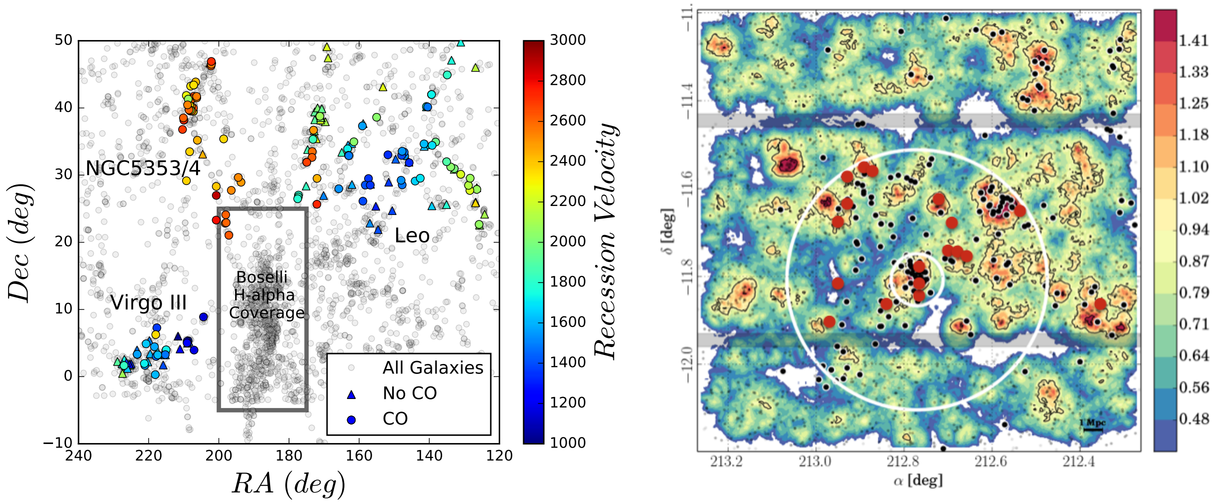


Figure 1: *Left panel* - Our sample of filaments around the Virgo cluster. Galaxies we have already observed in CO are shown color-coded by their velocity and split into sources with (circles) and without (triangles) CO detections. All of these sources have HI observations and will have H$\alpha$ images taken during the timeframe of our ISSI team through already approved programs. We are also beginning spatially resolved mapping of the CO for a subset of our CO detections. Other galaxies around the Virgo cluster from Kim et al. (2016) are shown in gray. The Leo filaments are made up of multiple distinct filaments. 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 drawn from the SEEDisCS sample. 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.*

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space-based (*Spitzer*, *Herschel*, WISE, HST, JWST) and ground-based (ALMA, IRAM, NOEMA, JVLA, VLT, Nancay) observatories and large observational efforts using these facilities, many of which have been executed by our team members.

We have largely characterized the environments of our galaxies and our immediate work is now to study specific phases of the gas through a set of well-defined programs, described below. Each of our proposed team members is leading 1–2 of these efforts. 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?

*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; Crowl 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$\alpha$ emission ($\lambda = 1.875\mu$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$\mu$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 our *Spitzer* 24$\mu$m observations of 9 local groups and clusters (PI Finn; Finn et al. 2017) and WISE 12 and 22$\mu$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 team 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 medium, 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 $\sim 5$ Gyr of cosmic time while our cluster sample spans $\sim 10$ 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 12 experts in various areas of galaxy evolution studies and represents 6 countries (USA, F, CH, IT, Chile, DE). They are playing key roles or are leading projects in one or more of the areas mentioned above. This group has five new members (indicated with a '*'), who bring essential expertise to our collaboration. • *Molecular tracers of star-forming gas:* Combes, Jablonka, Rudnick, Noble*, van Kampen*, Cooper • *Ionized tracers of star-forming gas:* Weiner, Rudnick, Finn, Jaffe* • *Dust-obscured star formation:* Finn, Rudnick, Jablonka • *Galaxy environment:* Zaritsky, Castignani*, Jablonka, Cooper, Norman*, Jaffe* • *Very distant clusters:* Rudnick, Weiner, Noble*, van Kampen*, Castigiani* • *Theoretical modeling:* De Lucia, Cooper, Combes, van Kampen*. In addition to our 12 member team, we also have three experts who are in close contact with our group and will consult with the team on an as-needed basis throughout the ISSI process: V. Desai (USA), C. Papovich (USA), and J. Hodge (NL).

**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 next flagship space telescope.

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 proposal[1]. The ISSI 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.

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[1] `http://www.issibern.ch/teams/gasingalaxies/`

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