Proposal for an ISSI International Team

# COSWEB: The Cosmic Web and Galaxy Evolution

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## 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 five 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 five new members.

**Filaments as the place where galaxies begin to die?** Galaxies in dense environments have lower average star-formation rates (SFRs) 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 star formation is at large distances from cluster cores, within groups and filaments (Lewis et al. 2002; Gómez et al. 2003; Laigle et al. 2017; Rerat et al. in prep). This is consistent with simulations showing that strong 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 star forming 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 star formation in dense environments it is important to **1)** study the fuel of star formation 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 characterize 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 $\sim 5000\text{deg}^2$, 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 star formation 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 star formation 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 star formation of galaxies back to the early epochs of time. Locally they allow us to map

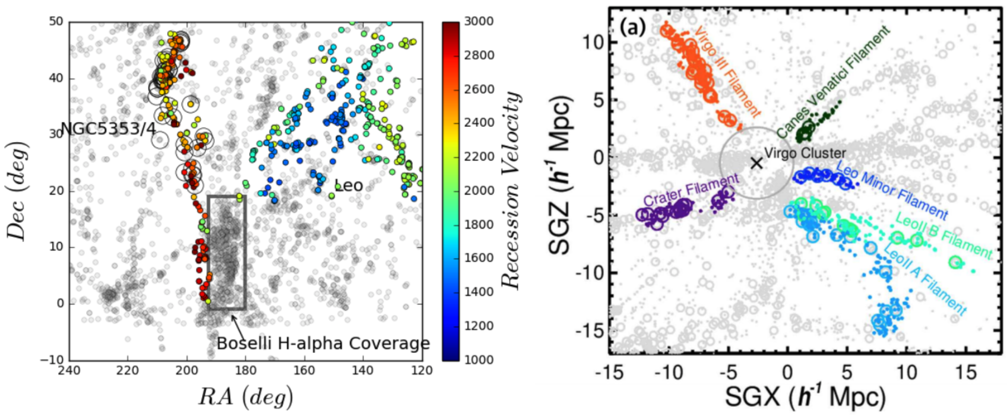


Figure 1: This is a placeholder caption about the Virgo filaments and SEEDisCS filaments.

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 and we can access HI with JVLA and the Nancay telescope. Finally, the fully commissioned ALMA and NOEMA are giving us the ability to 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 ISSI 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, through 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 do they operate differently in different environments?

## Our proposed activities

The environments of our galaxies have been largely characterized and our immediate work is 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. However, until we try to bring all of the results together it will be impossible to form coherent and broad-reaching conclusions with the data that have been provided by the revolutionary new facilities. Performing this synthesis is one of the main goals of our proposed ISSI team.

*Ionized gas:* The effect of environment on the dense ionized gas will be determined 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. By comparing the H$\alpha$ properties of the filament galaxies to those in clusters and infalling groups, we will be able to determine if the filament and group environments are hosting processes that are important in altering star-forming galaxies and how how that role has evolved over the last 5 Gyr.

*Obscured star formation:* Infrared observations from *Spitzer*, WISE, and *Herschel* probe the emission by dust grains that have been heated by star formation and can be used to infer the total infrared luminosity $L_{IR}$ and SFR. At $z < 2$ it is clear that the total SFR in cluster galaxies has declined faster than the field (Finn et al. 2010; Saintonge et al. 2008; Tran et al. 2010; Alberts et al. 2014). It is not clear, however, whether this is because evolution in early clusters is “accelerated” (Papovich et al. 2012) or because the cluster environment speeds up the depletion of gas at late times.

To break this degeneracy 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 *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 star formation by reduction in the $H_2$ fuel supply requires that we observe the cold gas, or at least CO, which is the best tracer possible. Thanks to dramatic technological advances in millimetric interferometry with JVLA, NOEMA, and ALMA and the sensitivity if the IRAM 30m telescope we are now able to study CO over the full redshift range in which clusters are growing.

As part of the new efforts initiated by our previous ISSI team we have embarked on an ambitious observational campaign to definitively search for stripping in filaments by imaging Virgo filament galaxies in CO, both with the IRAM 30m dish and with the NOEMA interferometer, the best millimeter interferometer in the northern hemisphere. We are nearly complete with the IRAM program and are proposing for the NOEMA program in Spring 2017 to spatially resolve the gas. 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.

As the result of JVLA and ALMA programs, team members have now detected CO in 13 galaxies that reside in four well characterized $z \sim 1.6$ proto-cluster (Rudnick et al. submitted to ApJ; Noble et al. in prep). Taken together with the intermediate redshift measurements described above, these programs comprise most of the CO detections in cluster and filament galaxies outside the nearby universe. Part of our ISSI program will be to combine these studies to measure how molecular gas and star formation relate in dense environments since $z < 2$. CO measurements for field galaxies are rapidly increasing, promising a perfect field comparison sample. This is a particularly important part of our project as it gets to the heart of what is driving star formation and its cessation, namely the molecular gas and its depletion.

*Providing crucial constraints for theoretical models.* Our ISSI team will use our observations to to place strong constraints on theoretical models of galaxy formation. Our team therefore 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 observational programs will directly constrain these models by revealing 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 and have tried to compensate by relaxing the instantaneous cutoff of gas accretion and by including a treatment of non-instantaneous recycling and a partition of the cold gas into atomic and molecular phases (Xie et al. 2016). 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.

*Elucidating measurements with revolutionary facilities:* ALMA and NOEMA open a new door to spatially resolved studies of the cold gas and JWST will allow the high spatial resolution of the ionized gas for the first time out to high redshift. Our ISSI team has been successful proposing for ALMA to and will build on these efforts with the submission of a proposal to make the first significant census of CO in clusters at $z \sim 1.6$. Thanks to its large wavelength range and 3D spectral capabilities, JWST will allow us to probe the ionized gas in our intermediate and high redshift samples, at wavelengths unencumbered by extinction (Pa$\alpha$, $\lambda = 1.875\mu$m). For our nearby galaxies it will also give us the capability to measure $H_2$ directly, and thus measure the bulk of the cold gas without relying on CO as a proxy. A timely effort in the design of these 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, given ALMA's advanced stage of completion, our ISSI team is in a perfect position to propose large programs to study the cold gas. A priority of this team will be observing filament galaxies and distant clusters with HST, ALMA, and JWST.

**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 star formation, from the hot dense gas that traces active star formation to the cold molecular gas that is the fuel of star formation. We also probe all relevant densities in the cosmic web, from distant filaments to the bottom of deep cluster potential wells. By combining our measurements with theoretical models we will gain a greatly improved understanding of how star formation is regulated, and eventually quenched, in dense environments. This synergy of the appropriate data, in the appropriate sample, spanning a large range in redshift, and with accompanying theoretical modeling is unique.

**Our proposed team:** Our team is composed of 15 highly recognized experts in various areas of galaxy evolution studies and represents 6 countries. They are playing key roles or are leading projects in one or more of the areas mentioned above. • *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) • *Dust-obscured star formation:* R. Finn (USA), V. Desai (USA), Norman, D. (USA), G. Rudnick (USA), C. Papovich • *Galaxy environment:* D. Zaritsky (USA), G. Castignani (F), V. Desai (USA), P. Jablonka (CH), M. Cooper (USA) • *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).

This group has five new members, who bring essential expertise to our collaboration. This group is larger than 12 but we expect that some members will self-fund to come to the meetings. Such a large group is necessary to ensure that we have the proper cross-section of expertise.

**The value of ISSI:** Historically, studies of the cold gas have been carried out independently from those that study the effects of environment. Making significant progress 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.

The funding from ISSI gives us a unique opportunity collaborate over an extended period at the same location. The value of these meetings are high. 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. We have an active ISSI-hosted wiki that serves as an information repository, have already produced five papers together, and have 10 accepted telescope proposals and one successful funding proposal[1]. Extended face-to-face meetings are critical for such undertakings and the ISSI funds make this possible as almost none of the collaborators has the necessary funds from other sources.

**Outcomes:** Our collaboration will result in multiple high impact papers. We will also write a paper that combines the different studies above into a summary and 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 star formation.

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.

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

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