The Zeldovich Universe:
Genesis and Growth of the Cosmic Web
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The intergalactic medium in the cosmic web

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Abstract. The intergalactic medium (IGM) accounts for $\gtrsim 90\%$ of baryons at all epochs and yet its three dimensional distribution in the cosmic web remains mostly unknown. This is so because the only feasible way to observe the bulk of the IGM is through intervening absorption line systems in the spectra of bright background sources, which limits its characterization to being one-dimensional. Still, an averaged three dimensional picture can be obtained by combining and cross-matching multiple one-dimensional IGM information with three-dimensional galaxy surveys. Here, we present our recent and current efforts to map and characterize the IGM in the cosmic web using galaxies as tracers of the underlying mass distribution. In particular, we summarize our results on: (i) IGM around star-forming and non-star-forming galaxies; (ii) IGM within and around galaxy voids; and (iii) IGM in intercluster filaments. With these datasets, we can directly test the modern paradigm of structure formation and evolution of baryonic matter in the Universe.

Keywords. intergalactic medium; cosmology: large scale structure of the Universe; galaxies: formation; quasars: absorption lines

1. Introduction

The physics of the intergalactic medium (IGM) and its connection with galaxies are key to understanding the evolution of baryonic matter in the Universe. The IGM is the main reservoir of baryons at all epochs (e.g. Fukugita *et al.* 1998; Shull *et al.* 2012), and provides the primordial material for forming galaxies. Once galaxies are formed, supernovae (SNe) and active-galactic nuclei (AGN) feedback inject energy in the interstellar medium, some of which escapes the galaxies as winds, enriching the IGM with metals (e.g. Wiersma *et al.* 2011; Ford *et al.* 2014). Because of the continuous interplay between the IGM and galaxies, it is sensible (if not necessary) to study these two concepts simultaneously (e.g. Morris *et al.* 1993; Lanzetta *et al.* 1995; Tripp *et al.* 1998; Chen & Mulchaey 2009; Prochaska *et al.* 2011; Tumlinson *et al.* 2011; Tejos *et al.* 2014; Werk *et al.* 2014).

The large scale environment in which matter resides also plays an important role. Given that baryonic matter is expected to fall into the considerably deeper gravitational potentials of dark matter, the IGM gas and galaxies should be predominantly found at such locations, forming the so-called 'cosmic web' (Bond *et al.* 1996). Galaxies appear to follow the filamentary structure which simulations predict (e.g. Springel *et al.* 2006), and their properties are partly shaped by environmental effects (e.g. Dressler 1980; Skibba *et al.* 2009). However, much less is known about the *actual* properties and distribution of the IGM in different cosmological environments. This is so because the only feasible way to observe the bulk of the IGM is through intervening absorption line systems in the spectra of bright background sources (e.g. quasi-stellar objects, gamma-ray bursts, galaxies), which limits its characterization to being one-dimensional.

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† On behalf of our full collaboration.

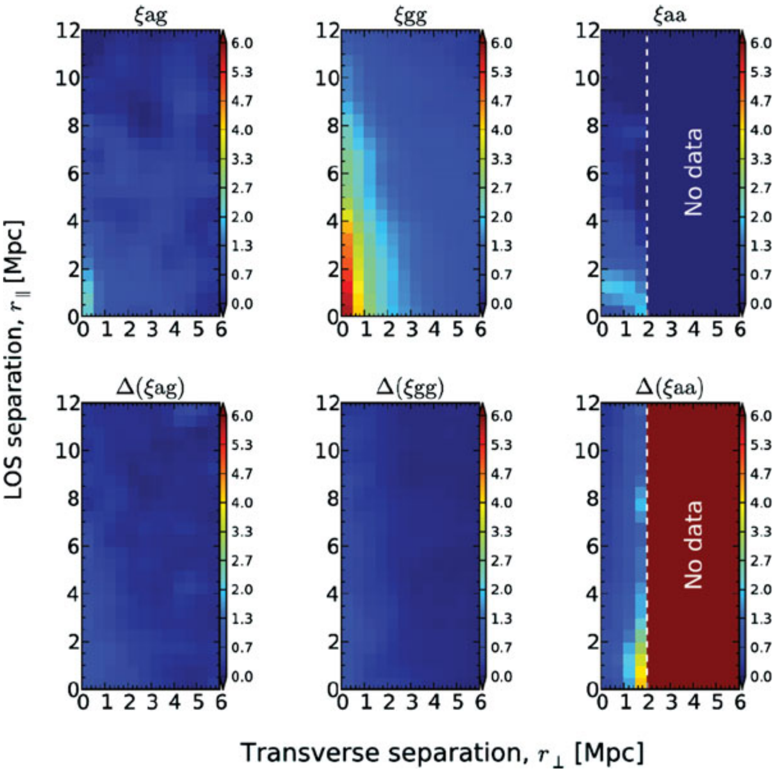

Figure 1. Two-dimensional two-point correlation functions (top panels) at $z \lesssim 1$, and their respective uncertainties (bottom panels). From left to right: H I–galaxy ($\xi_{\rm ag}$), galaxy–galaxy ($\xi_{\rm gg}$) and H I–H I ($\xi_{\rm aa}$) cross-correlations. Figure adapted from Tejos *et al.* (2014).

The advent of big galaxy surveys such as the 2dFGRS (Colless *et al.* 2001) or the SDSS (Abazajian *et al.* 2009), have revolutionized the study of the cosmic web and the large-scale structure (LSS) of the Universe. This is eloquently demonstrated by the plethora of LSS catalogs that are currently available: from galaxy voids (e.g. Pan *et al.* 2012; Sutter *et al.* 2012; Nadathur & Hotchkiss 2014; Way *et al.* 2014), galaxy filaments (e.g. Tempel *et al.* 2014), to galaxy groups and clusters (e.g. Hao *et al.* 2010; Rykoff *et al.* 2014). By combining and cross-matching multiple one-dimensional IGM information with galaxy and LSS surveys, an averaged three dimensional picture can be obtained. Here, we present our recent and current efforts to map and characterize the IGM in the cosmic web using galaxies as tracers of the underlying mass distribution.

2. The IGM-galaxy cross-correlation

The two-point correlation function between neutral hydrogen (H I) and galaxies is a powerful statistical technique to assess the connection between the IGM and galaxies (e.g. Chen *et al.* 2005; Ryan-Weber 2006; Wilman *et al.* 2007; Chen & Mulchaey 2009; Shone *et al.* 2010; Tejos *et al.* 2014).

In Tejos *et al.* (2014), we have recently published observational results on the H I–galaxy two-point cross-correlation at $z \lesssim 1$ ($\xi_{\rm ag}$; see Fig. 1). These results come from the largest sample ever done for such an analysis, comprising about ~ 700 H I absorption line systems in the UV spectra of 8 background QSOs, in 6 different fields observed with the HST, and about ~ 17000 galaxies with spectroscopic redshifts around these QSOs sightlines, coming from our own spectroscopic surveys, and previously published catalogs by the VVDS (Le Fèvre *et al.* 2013) and GDDS (Abraham *et al.* 2004) galaxy surveys.

Apart from $\xi_{\rm ag}$, we also measured the H I–H I ($\xi_{\rm aa}$) and galaxy-galaxy ($\xi_{\rm gg}$) two-point auto-correlations. Our survey is one of the few in which these three quantities have been measured from the same dataset, and independently from each other. Comparing the results from $\xi_{\rm ag}$, $\xi_{\rm aa}$ and $\xi_{\rm gg}$, we constrained the IGM-galaxy statistical connection, as a function of both H I column density and galaxy star formation activity, on $\sim 0.5-10$ Mpc scales. Our results are consistent with the following conclusions: (i) the bulk of H I systems on $\sim$Mpc scales have little velocity dispersion ($\lesssim 120\,{\rm km\ s^{-1}}$) with respect to the bulk of galaxies (i.e. no strong galaxy outflow/inflow signal is detected); (ii) the vast majority ($\sim 100\%$) of H I systems with $N_{\rm HI} > 10^{14}\,{\rm cm^{-2}}$ and star-forming galaxies are distributed in the same locations, together with $75\pm15\%$ of non-star forming galaxies; (iii) $25\pm15\%$ of non-star-forming galaxies reside in galaxy clusters and are not correlated with H I systems at scales $\lesssim 2$ Mpc; and (iv) $> 50\%$ of H I systems with $N_{\rm HI} < 10^{14}\,{\rm cm^{-2}}$ reside within galaxy voids and hence are not correlated with luminous galaxies.

3. The IGM within and around galaxy voids

In Tejos *et al.* (2012) we have recently measured the properties of H I absorption line systems within and around galaxy voids at $z \leqslant 0.1$, using the galaxy void catalog published by Pan *et al.* (2011) and the low-z H I absorption line catalog published by Danforth & Shull (2008). Our key findings can be summarized as follows: (i) there is a significant excess of IGM gas at the edges of galaxy voids with respect to the random expectation, *consistent* with the overdensity of galaxies defining such voids; and (ii) inside galaxy voids the IGM gas matches the random expectation, *inconsistent* with the underdensity of galaxies defining such voids. In other words, there were no apparent IGM voids detected at the positions of galaxy voids.

We also showed that the column density ($N_{\rm HI}$) and Doppler parameter ($b_{\rm HI}$) distributions of H I lines inside and outside galaxy voids were not remarkably different, with only a $\sim 95\%$ and $\sim 90\%$ probability of rejecting the null-hypothesis of both samples coming from the same parent population, respectively. Still, a trend was present, in which galaxy void absorbers have systematically lower values of both $N_{\rm HI}$ and $b_{\rm HI}$ than those found outside galaxy voids. By performing a similar analysis using a state-of-the-art hydrodynamical cosmological simulation (GIMIC; Crain *et al.* 2009), we showed that these observed trends are qualitatively consistent with current theoretical expectations. However, more quantitative comparisons of the gas properties in galaxy voids between hydrodynamical simulations tuned to explore low density environments (e.g. Ricciardelli *et al.* 2013) and observations (e.g. Tejos *et al.* 2012), are required.

4. The IGM in intercluster filaments

Galaxy clusters represent the densest nodes in the cosmic web (with dark matter halo masses of $M \gtrsim 10^{14} M_\odot$) and as such, N-body numerical simulations predict a high probability of finding intercluster filaments between galaxy cluster pairs when separated by $\lesssim 10-20$ Mpc (e.g. Colberg *et al.* 2005; González & Padilla 2010). Hydrodynamical simulations predict that an important fraction of baryons at low-z are in a diffuse, shock heated gas phase with $T \sim 10^5 - 10^6$ K in these dense filaments, commonly referred to as the warm-hot intergalactic medium (WHIM; Cen & Ostriker 1999; Davé *et al.* 2001). However, this WHIM has been very elusive and difficult to observe (e.g. Richter *et al.* 2006).

Here, we have presented preliminary results on the properties of the IGM in intercluster filaments at $0.1 \leqslant z \leqslant 0.47$ by using a single QSO observed with the HST/COS UV spectrograph, whose sightline intersects 7 independent cluster-pairs at impact parameters < 5 Mpc from the intercluster axes. This technique allowed us to perform, for the first time, a systematic and statistical measurement of the incidence of H I and O VI absorption lines associated to intercluster filaments. We constrained the geometry and physical properties of the IGM gas lying between clusters. Our results are consistent with a filamentary geometry for the gas, and the presence of both broad H I (> 50 km s^{-1}) and O VI hint towards the existence of a WHIM (Tejos *et al.* in prep.).

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