Proxies for stellar mass and star formation rate from galaxy clustering

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We study the environmental dependence of galaxy properties at the redshift range $0.07 \leq z < 0.15$ using galaxies from Galaxy and Mass Assembly (GAMA) survey and making use of their mid infrared *WISE* observations. We measure marked correlation functions for a W1 (3.4 μm) absolute magnitude selected sample using luminosities in u, K, W1, W2, W3, W4 bands, stellar mass and star formation rate as marks. We then compare their amplitude to see which photometric bands are better proxies for stellar mass and SFR in the context of galaxy clustering.

1 Introduction

From an almost uniform mass distribution at high redshifts, the Universe has evolved to form the large-scale structure (LSS) that we observe today (Springel et al., 2005). The distribution of galaxies in the LSS forms a rich network of structures containing knots, filaments, and voids. This makes the LSS an excellent laboratory to study the formation and evolution of galaxies as a function of their environments. In the hierarchical structure formation paradigm, we assume that galaxies reside in dark matter haloes and the properties of the haloes such as their masses and assembly history play an important role in defining the properties of the galaxies. Hence the environmental dependence of halo properties prompts an environmental dependence of galaxy properties. This is evident from the clustering studies using galaxy two-point correlation function (2pCF). It is generally observed that luminous, massive, and redder galaxies tend to be more clustered than fainter, less massive, and bluer galaxies (Zehavi et al., 2011). The environmental dependence of galaxy properties can be even more efficiently probed using marked correlation function (MCF; Sheth & Tormen, 2004, see Sect. 3 for details).

In Sureshkumar et al. (2021), we explored the environmental dependence of optical and near-infrared luminosities, stellar mass, and star formation rate (SFR) of galaxies in the Galaxy and Mass Assembly (GAMA) survey using MCFs. We observed that different properties trace the environment differently with stellar mass being the most strongly correlated between nearby galaxies. Moreover, the MCF using different luminosities expressed a "hierarchy" from the reddest (K) to the bluest (u) band, with the photometric K band (2.2 μm) following the closest the stellar mass and u band (0.4 μm) following the SFR in tracing the environment.

The near and certain mid-infrared band luminosities are often used as tracers of stellar mass (Kauffmann & Charlot, 1998). Lacey et al. (2008) found that luminosity in 2.2 μm is a more robust tracer of stellar mass than 3.6 μm using galaxy stellar mass function. Similarly, u band, mid-IR and far-IR band luminosities are widely used as tracers of SFR. Using galaxy SFR distribution, Lacey et al. (2008) studied how well do single IR wavelength luminosities constrain SFR.

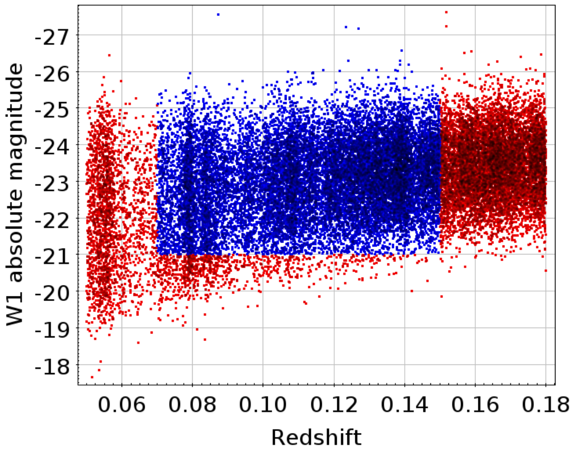

Fig. 1: The selection of W1 absolute magnitude limited sample (blue dots) used in this work.

In this work, we present such a comparative study in the context of galaxy clustering. For that purpose we use a *WISE* W1 absolute magnitude (3.4 μm) selected sample of galaxies from the GAMA-*WISE* catalogue (Cluver et al., 2014) in the redshift range $0.07 \leq z < 0.15$.

2 Data

The Galaxy and Mass Assembly (GAMA)[1] is a multiwavelength spectroscopic survey that provides a sample of around 300000 galaxies down to $r < 19.8$ (Driver et al., 2009). Reliable measurements of galaxy properties such as luminosity, stellar mass, and SFR make GAMA a suitable survey to study the environmental dependence of galaxy properties. Together with auxiliary data GAMA covers UV to far-IR range of wavelengths (0.15 – 500 μm) through 21 broad-band filters. In the work presented here, we utilise the GAMA-*WISE* catalogue built by by Cluver et al. (2014) which contains the luminosities in W1 (3.4 μm), W2 (4.6 μm), W3 (12 μm), and W4 (22 μm) bands from the Wide-field Infrared Survey Explorer (*WISE*) satellite, and corresponding derived absolute luminosities. The stellar mass is taken from the GAMA DMU StellarMassesLambdarv20 (Taylor et al., 2011; Wright et al., 2016) and SFR is taken from the MagPhysv06 DMU (da Cunha et al., 2008).

In this work, we use an absolute W1 magnitude selected sample of galaxies from the GAMA-*WISE* catalogue in the redshift range $0.07 \leq z < 0.15$. The sample has a flux limit of $r < 19.8$ and a W1 magnitude limit of $M_{\rm W1}^{\rm lim} \leq -21$. In the following, we consider only those galaxies that have absolute luminosities computed in all four *WISE* bands and this condition gives a set of 16800 galaxies (Fig. 1). Possible biases introduced by sample incompleteness introduced by such a selection is addressed in Sureshkumar et al. (2022).

[1] `http://www.gama-survey.org/`

3 Measurement methods

The galaxy two point correlation function (2pCF) $\xi(r)$, is a statistical tool to quantify galaxy clustering. It is a function of the separation scale r and is defined as the excess probability of finding galaxy pairs with a given separation r over a random distribution. It has been widely used to study the galaxy clustering and its dependence on galaxy properties. At intermediate separation scales, $\xi(r)$ usually can be well fitted by a power law given by $\xi(r) = (r/r_0)^{-\gamma}$ with r_0 and γ being the correlation length and slope, respectively. Deviations from this trend observed at small separation scales are mostly attributed to different behaviour of galaxies residing in the same dark matter halo (so-called one halo term). These features are expected to give us some insight into the interplay between galaxy properties and clustering in small scale (one-halo) environment.

In the traditional 2pCF analysis, galaxy samples are often divided into different bins based on the galaxy property of interest. Then, the 2pCF is measured and modelled in each bin and the correlation lengths or, in a more advanced formalism, properties derived through the halo occupation distribution (HOD) model fitting, are being compared among the bins (e.g. Zehavi et al., 2011). In such an approach, the galaxy property of interest is used only to define the sample and not during the computation of $\xi(r)$.

A more efficient tool to study the environmental dependence of galaxy properties, including small scales corresponding to one halo term in the CF, is marked correlation function (MCF; Sheth & Tormen, 2004). The MCF takes into account the properties (called *marks*) of each galaxy in the sample and uses them as weights while computing the correlation function. Such a weight enhances the significance of those galaxy pairs in which both galaxies are stronger in the given property with respect to the rest of the sample. So, by comparing the amplitudes of MCF computed using different properties as marks, we can find which galaxy property most strongly correlates (or anti-correlates) with environment.

More specifically, the two-point marked correlation function is defined as,

$$M(r) = \frac{1 + W(r)}{1 + \xi(r)}, \tag{1}$$

where $\xi(r)$ is the galaxy two-point CF and $W(r)$ is the weighted CF computed by weighting each real galaxy in the pair.

In practice, to reduce the effect of the redshift-space distortions, we measure the two-dimensional 2pCF using Landy-Szalay estimator (Landy & Szalay, 1993) and integrate it along the line of sight to obtain projected 2pCF $\omega_\mathrm{p}(r_\mathrm{p})$ (Davis & Peebles, 1983). Then the projected marked correlation function is given by,

$$M_\mathrm{p}(r_\mathrm{p}) = \frac{1 + W_\mathrm{p}(r_\mathrm{p})/r_\mathrm{p}}{1 + \omega_\mathrm{p}(r_\mathrm{p})/r_\mathrm{p}}. \tag{2}$$

Following Skibba et al. (2006), the errors in $M_\mathrm{p}(r_\mathrm{p})$ can be estimated by randomly scrambling the marks among the galaxies in the sample and remeasuring the MCF 100 times. We refer the reader to Sect. 3 of Sureshkumar et al. (2021) for a detailed explanation of the methodology involved in computing 2pCF and MCF.

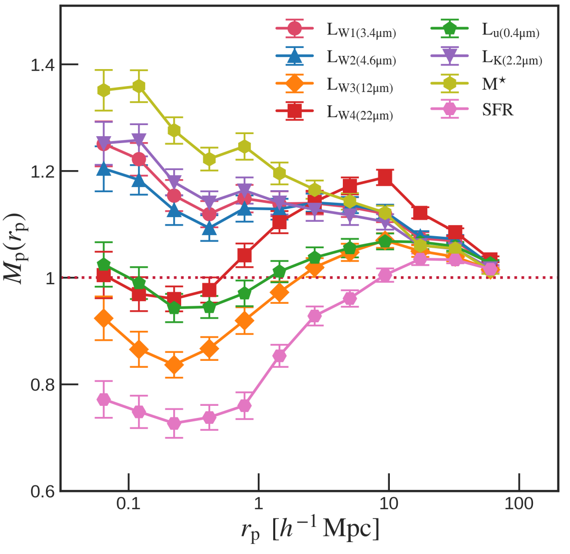

Fig. 2: Projected MCFs obtained using luminosities in u, K, W1, W2, W3, W4 bands, stellar mass and SFR in the sample shown as blue dots in Fig. 1.

4 Results

The strength of deviation of a MCF from unity implies the strength of the correlation between the corresponding property and the environment. In Fig. 2, we present the measurements of MCFs obtained using galaxy luminosities in u, K, W1, W2, W3, W4 bands, stellar mass and SFR as marks. All the MCFs deviate from unity at small scales and approach unity at larger scales. For the same population of galaxies, different properties provide different amplitudes for the MCF. That shows that different properties correlate with environment differently.

This is not surprising as different correlation length were measured for galaxy samples selected based on different properties in numerous studies. For e.g., stronger clustering was observed for luminous galaxies when selected based on r band (Zehavi et al., 2005), B band (Marulli et al., 2013), g band (Skibba et al., 2014), and K band (Sobral et al., 2010). At the same time, galaxies luminous in u have an opposite trend, and reside in less dense regions of the LSS (Deng, 2012).

4.1 What is the best proxy for stellar mass?

We observe that at all available scales, MCFs obtained using luminosities K, W1, W2 bands and stellar mass show amplitude greater than unity (left panel of Fig. 3). That means those properties correlate strongly with environment. We observe that stellar mass is the property which displays the strongest correlation with environment (Sureshkumar et al., 2020, 2021). From the comparison of amplitudes of MCFs obtained using those four properties, we see that they trace the environment in a similar fashion. However, none of the luminosities provides an amplitude of MCF as strong as stellar mass itself. The closest to stellar mass are K band and W1 band

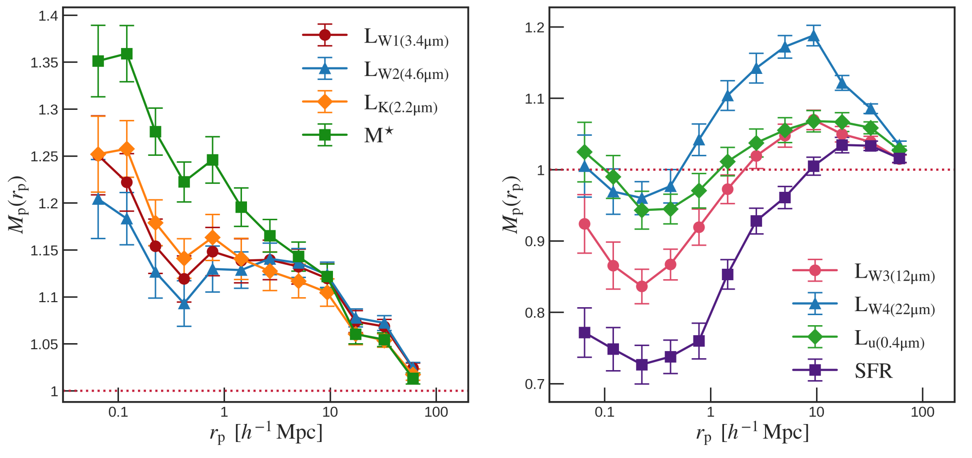

Fig. 3: Luminosities as proxies of stellar mass (*left*) and SFR (*right*).

luminosities, with the K band MCF behaviour being systematically slightly closer but consistent with respect to the error bars. This implies that the K band can be regarded as more robust proxy for stellar mass than mid-infrared bands in terms of galaxy clustering. This can be due to the larger contribution from asymptotic giant branch (AGB) stars relative to those from red giant branch (RGB) stars at the longer wavelength, with AGB stars being more sensitive to star formation than RGB stars (Lacey et al., 2008).

4.2 What is the best proxy for SFR?

In the right panel of Fig. 3, we see a similarity in the behaviour of u, W3, W4 bands, and SFR MCFs. The u band is considered to be a good indicator of SFR because it is sensitive to light from starburst galaxies with young stellar population. Hence it is closely related to the SFR of galaxies (Hopkins et al., 2003).

Whereas, the W3 band at 12 μm is dominated by the stochastically heated 11.3 μm poly-cyclic aromatic hydrocarbon (PAH) which are dominant in actively star forming parts of the galaxy (Sandstrom et al., 2010). So, W3 luminosity also serves as a direct estimate of the global SFR (Calzetti et al., 2007; Treyer et al., 2010). The 22 μm W4 band measures the warm dust continuum which also is believed to serve as a reliable measure of star formation in the absence of active galactic nucleus activity. Because of this mid-IR luminosities often serve as a proxy for SFR, however, the SFRs estimated from mid-IR luminosities represent only a part of the total IR SFR. From our measurement it is clear that none of the single band luminosities we considered (u, W3, and W4) can serve as a perfect proxy for SFR in clustering studies. However, the closest one appears to be the W3 band.

5 Conclusions

In this work, we measured marked correlation functions for a sample of galaxies from the GAMA survey in the redshift range of $0.07 \le z < 0.15$. The MCFs were computed using luminosities in u, K, W1, W2, W3, W4 bands, stellar mass and SFR as marks. We observed that different galaxy properties correlate with environment differently. We conclude that in terms of galaxy clustering studies, K band serves as a better proxy for stellar mass than W1 band. When it comes to SFR, we conclude that W3 band is a better proxy than u band and W4 bands. A detailed analysis on how mid-IR properties and different estimates of stellar mass and SFR trace the galaxy environment is presented in Sureshkumar et al. (2022).

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