Probing cosmic velocity-density correlations with galaxy luminosity modulations

Martin Feix\textsuperscript{1,2}\textsuperscript{*}

\textsuperscript{1} Zentrum für Astronomie der Universität Heidelberg, Institut für Theoretische Astrophysik, 69120 Heidelberg, Germany
\textsuperscript{2} Institut für Kernphysik, Karlsruher Institut für Technologie, 76344 Eggenstein-Leopoldshafen, Germany

\textsuperscript{*} E-mail: feix@uni-heidelberg.de

ABSTRACT

We study the possibility of using correlations between spatial modulations in the observed luminosity distribution of galaxies and the underlying density field as a cosmological probe. Considering redshift ranges, where magnification effects due to gravitational lensing may be neglected, we argue that the dipole part of such luminosity-density correlations traces the corresponding velocity-density signal which may thus be measured from a given galaxy redshift catalogue. Assuming an SDSS-like survey with mean density $\bar{n} = 0.01 (h^{-1} \text{Mpc})^{-3}$ and effective volume $V_{\text{eff}} = 0.2 (h^{-1} \text{Gpc})^3$ at a fiducial redshift $z = 0.1$, we estimate that the velocity-density correlation function can be constrained with high signal-to-noise ratio $\gtrsim 10$ on scales 10–100 Mpc. Similar conclusions apply to the monopole which is sensitive to the environmental dependence of galaxy luminosities and relevant to models of galaxy formation.

Key words: cosmology: large-scale structure of the Universe – methods: statistical – methods: data analysis – surveys

1 INTRODUCTION

Within the standard cosmological paradigm, the process of structure formation is connected to matter flows that exhibit a coherent pattern on large scales. Since the motions of astronomical objects such as galaxies are believed to reliably trace these matter flows, their peculiar velocities, defined relative to the uniform expansion of the cosmic background, provide a sensitive probe of the underlying cosmological model (e.g., Strauss & Willick 1995).

At cosmologically relevant distances, however, observations can only probe total velocity components along the line of sight that are difficult to measure because surveys only provide redshifts, but not actual distances. Typically, these are estimated by resorting to empirical, redshift-independent distance indicators that exploit established relations between observable intrinsic properties of galaxies or other astronomical objects (Tully & Fisher 1977; Djorgovski & Davis 1987). Combining the inferred distances with redshift data then yields estimates of the radial peculiar velocity field sampled at the corresponding object positions.

Traditionally, peculiar velocity surveys of this kind have been recognized as a valuable asset since they offer direct constraints on the peculiar velocity field of galaxies. Most notably, this includes measurements of the cosmic bulk flow, i.e. the volume average of the peculiar velocity field, that can be tested against expectations of different cosmological models (e.g., Nusser et al. 2011; Turnbull et al. 2012). The inferred peculiar velocities may also be compared to the large-scale velocity field independently predicted from the observed galaxy distribution using gravitational instability theory, allowing for estimates of the growth rate of density fluctuations (e.g., Erdoğdu et al. 2006; Davis et al. 2011; Hudson & Turnbull 2012). Unlike the clustering analysis of redshift-space distortions (RSDs; Kaiser 1987; Percival & White 2009), this latter approach is less affected by cosmic variance as it involves the ratio of correlated fields. The uncertainties mainly arise from the precision of the peculiar velocity estimates themselves. In particular, peculiar velocity surveys allow for a simultaneous analysis of multiple tracers, i.e. the galaxy density and the peculiar velocity fields, whose cross-correlations add independent information that leads to tighter cosmological constraints (Nusser 2017; Adams & Blake 2017) and is also important to the modelling of RSDs (Koda et al. 2014).

Due to observational challenges, however, peculiar velocity surveys suffer from complicated selection functions, sparseness, relatively small galaxy numbers in comparison to galaxy redshift catalogues, and errors that increase rapidly with redshift. This limits its reliable studies of the cosmic peculiar velocity field to the local Universe (but also see Hellwing et al. 2017; Hellwing et al. 2018). Current datasets like Cosmicflows-3 (Tully et al. 2016) contain on the order of $10^4$ objects out to distances of about 100–150 Mpc. Next-generation surveys such as TAIPAN (da Cunha et al. 2017) and all-sky HI radio observations (e.g., WALLABY; Duffy et al. 2012) will extend to around twice larger distances, increasing the number of objects by roughly an order of magnitude.

Recently, an alternative methodology towards constraining the large-scale peculiar velocity field from galaxy redshift surveys has been proposed. In contrast to the analysis of peculiar velocity cat-
alogues, this approach is not limited to small redshifts and does not rely on the use of traditional distance indicators. The method uses the fact that galaxy peculiar motions affect luminosity estimates derived from measured redshifts which are used as distance proxies. Therefore, spatial modulations in the observed distribution of galaxy luminosities can be exploited to place bounds on the underlying large-scale galaxy velocity field. Dating back to the work of Tamman et al. (1979), key to this luminosity-based approach is that peculiar velocities increase the scatter of (absolute) galaxy magnitude estimates about their true values, i.e. galaxies generally appear brighter or dimmer than they would be if their redshifts accurately reflected the correct distances. In the case of spatially coherent motions, the effect is systematic and depends on the position of galaxies in the observed survey volume. With the advent of larger galaxy samples and improved photometry in current survey data, this method has started to become interesting for cosmological applications. For example, it has been adopted to independently measure bulk flows (Nusser et al. 2011; Branchini et al. 2012; Feix et al. 2014) and the cosmic growth rate (Nusser et al. 2012; Feix et al. 2015, 2017) out to redshifts $z \sim 0.1$.

Applications using galaxy luminosity modulations are not limited to one-point statistics associated with the luminosity distribution of galaxies. Tracing the radial peculiar velocity field of galaxies, these modulations may also be studied in terms of spatial correlations that can be easily computed from the data and do not require any smoothing or pre-modelling of the signal. Previous analyses have mostly focused on the correlation function of luminosity distances (e.g., Bonvin et al. 2006; Hui & Greene 2006; Nusser et al. 2013; Biern & Yoo 2017). The main purpose of this work is to motivate measurements of luminosity-density correlations as a probe of cosmic large-scale velocity-density correlations beyond redshifts $z \sim 0$, and to provide a first assessment of such an approach.

The paper is structured as follows: in section 2.1, we consider the various contributions to the large-scale luminosity signal and its correlation with the underlying density field. Assuming Gaussian statistics and the distant observer approximation, we then discuss how well the sought cosmological signal could be extracted and provide a first quantification of its statistical significance in sections 2.2 and 2.3. Finally, we conclude in section 3.

2 METHODOLOGY

2.1 Basic considerations

Consider a galaxy redshift catalogue with measured apparent magnitudes $m_j$, angular positions $\vec{r}_j$, and spectroscopic redshifts $z_j$, centred around an effective redshift $z_{\text{eff}}$. For each galaxy in the sample, we may estimate the luminosity modulation

$$\Delta M_j = M_j - \overline{M},$$

where $M_j$ is the observed absolute magnitude of galaxy $j$ derived from the redshift $z_j$ (taken as a distance proxy within an assumed background cosmology) and $\overline{M}$ is the mean over all galaxies in the sample. Since $\overline{M}$ depends on $z_{\text{eff}}$, we envisage two possibilities of determining it from the data. The first one is to divide the sample into multiple redshift bins which are then used to compute individual estimates of $\overline{M}$. Alternatively, $\overline{M}$ can be obtained through the global luminosity function at $z_{\text{eff}}$ if one accounts for an effective luminosity evolution term in the distance-magnitude relation.

In what follows, we shall restrict ourselves to galaxy redshifts $z < 0.4$–$0.5$ such that any magnification effects in $\Delta M$ due to gravitational lensing may be safely neglected (e.g., Yoo 2009). In this case, the large-scale luminosity modulation signal separates to lowest order in perturbation theory into two main contributions. The first one traces the radial peculiar velocity field whereas the second component arises from environmental dependencies of the galaxy luminosity distribution and reflects the fact that more luminous galaxies tend to populate higher-density regions (Mo et al. 2004). Additional scatter due to the natural spread in galaxy luminosities is not expected to be correlated with any of these components and will only contribute Poissonian noise.

It is useful to express luminosity modulations in terms of an associated radial velocity $u_{M,j}$,

$$u_{M,j} = u_j + u_{\text{env},j} + \epsilon_j,$$

where $u_j$ and $u_{\text{env},j}$ are the radial peculiar velocity component and the environmental luminosity dependence, respectively, and $\epsilon_j$ is assumed to be an uncorrelated error corresponding to the intrinsic scatter of galaxy magnitudes. To translate a magnitude shift, $\Delta M_j$, into its associated radial peculiar velocity, $u_{M,j}$, we will adopt a linear relation for simplicity. The relation is obtained from expanding the distance modulus $DM$ at $z_j$ in terms of a small redshift perturbation, where

$$DM(z) = 25 + 5 \log_{10}[D_L(z)/\text{Mpc}]$$

and $D_L$ denotes the cosmological luminosity distance in units of Mpc. Since the variance of $u_{M,j}$ is dominated by the error $\epsilon_j$, we approximately have

$$\sigma_u^2 \approx \langle \epsilon^2 \rangle = \frac{1}{N} \sum_j \sigma_{u,j}^2,$$

where $N$ is the number of available galaxies in the sample. Again, this quantity (used to quantify shot noise contributions) may be estimated from the data through the observed scatter of magnitudes, $\sigma_u^2 = \sum_j \sigma_{u,j}^2/N$, where $\sigma_{M,j}^2 = \Delta M_j^2$ (cf. Nusser et al. 2013).

The above will form the basis for our study of luminosity-density correlations in the next sections. Despite its simplicity, our approach will suffice to get a first assessment of how well measurements of such correlations on scales $\gtrsim 10h^{-1}$ Mpc ($h$ is the dimensionless Hubble constant) can be used as a cosmological probe.

2.2 Luminosity-density correlations

Focusing on large scales, where linear perturbation theory is applicable, the density contrast of galaxies, $\delta_g$, is related to that of matter, $\delta$, through the linear local bias factor $b$, i.e. $\delta_g = b \delta$. Expressing all quantities in terms of their Fourier transforms and neglecting the effects of RSDs and shot noise for the moment, we will be interested in correlations of the form

$$\langle u_{M} \delta_g^2 \rangle = V P_{M,\delta} \approx \langle u^2 \rangle + \langle u_{\text{env}}^2 \rangle,$$

and

$$\langle u_{M} u_{M}^* \rangle = V P_{M M} \approx \langle u^2 \rangle + \langle u_{\text{env}}^2 \rangle + \langle u_{\text{env}}^2 \rangle + \langle u_{\text{env}}^2 \rangle,$$

where $P_{M,\delta}$ and $P_{M M}$ denote the corresponding power spectra, and $V$ is the sample volume. The large-scale dependence of galaxy...
luminosities on their environment is strongly supported by several studies (e.g., Balogh et al. 2001; Mo et al. 2004; Croton et al. 2005; Park et al. 2007; Merluzzi et al. 2010; Faltenbacher et al. 2010; Zehavi et al. 2011), pointing towards the large-scale environment’s overdensity as the most important factor on scales of a few Mpc. Lacking observational constraints on the large scales relevant to this work, we will assume that the observed environmental dependence can be extrapolated to scales of 10–100h−1 Mpc.

The distinct angular dependence of contributions due to the peculiar velocity field allows for separating these two effects, making it possible to extract them from the measured luminosity-based signal. To illustrate this point, let us simplify the problem by considering the above correlations in the distant observer approximation. Further, we will model effects due to environment by assuming that \( u_{\text{env}} \) only depends on the local density contrast, irrespective of the adopted smoothing scale (Mo et al. 2004; Faltenbacher et al. 2010; Yan et al. 2013). Setting \( u_{\text{env}} = \alpha \delta \) and using the linear velocity-density relation

\[
u = -i \mu \frac{aHf}{k} \delta,
\]

where \( \alpha \) denotes the cosmic scale factor, \( H \) is the Hubble constant, \( f = d \log D/d \log a \) is the linear growth rate of density perturbations, and \( \mu \) is the cosine of the angle between the wave vector \( k \) and the line of sight (\( \mu = k_z/k \)), \( k_z \) denotes the line-of-sight component, and \( k = |k| \), the spectra in Eqs. (5) and (6) take the form

\[
P_{M\delta} = \mu b_{\gamma} P_{\delta\delta} + \alpha b P_{\delta\delta},
\]

\[
P_{MM} = \mu^2 P_{uu} + \alpha^2 P_{\delta\delta}.
\]

where we have introduced the galaxy correlation coefficient \( r_{g} \) and

\[
P_{\delta\delta} = i \frac{aHf}{k} P_{\delta\delta}, \quad P_{uu} = \left( \frac{aHf}{k} \right)^2 P_{\delta\delta}.
\]

Note that the coefficient \( r_{g} \) may take values smaller than unity in the case of stochastic biasing (Dekel & Lahav 1999) and that the velocity-density spectrum is purely imaginary, which leads to a vanishing cross term in the expression for \( P_{MM} \).

Expanding the spectra in Eq. (8) in terms of multipoles, one finds that the monopole and dipole of \( P_{M\delta} \) are given by

\[
P_{M\delta}(0) = \alpha b P_{\delta\delta}, \quad P_{M\delta}^{(1)}(1) = b_{\gamma} P_{\delta\delta},
\]

and the monopole of \( P_{MM} \) is

\[
P_{MM}(0) = \frac{1}{3} P_{uu} + \alpha^2 P_{\delta\delta}.
\]

Equation (10) shows that the dipole of \( P_{M\delta} \) probes cosmological velocity-density correlations whereas the monopole isolates the effect due to environment. The monopole of \( P_{MM} \) traces a combination of both contributions and does not depend on \( b \) and \( r_{g} \). In principle, it is also possible to extract the velocity contribution from \( P_{MM} \) by considering its quadrupole. As will become clear below, however, the prospects of measuring its signal are rather dim, and we choose not to discuss this possibility further.

To quantify how well the monopole and dipole of \( P_{M\delta} \) could be constrained from observations, we will assume Gaussian statistics and adopt a standard count-in-cells approach to estimate statistical uncertainties (e.g., Peebles 1980; Smith 2009). Because the calculation closely follows the multipole analysis presented in Feix & Nusser (2013), we will only sketch the derivation here. We start from discrete representations of the fields in Fourier space, i.e.

\[
u_{M}(k) = \frac{1}{N} \sum_{\gamma} u_{M,\gamma} n_{\gamma} \exp(\text{i}kr_{\gamma})
\]

and

\[\delta(k) = \frac{1}{N} \sum_{\gamma} (n_{\gamma} - \langle n_{\gamma} \rangle) \exp(\text{i}kr_{\gamma}),\]

where the index \( \gamma \) runs over infinitesimal cells that sample the volume \( V \) and contain at most a single object (\( \langle n_{\gamma} \rangle \), and \( \Pi \) is the mean number density defined by \( \langle n_{\gamma} \rangle = \Pi \Delta V_{\gamma} \). The product \( u_{M,\gamma} \delta \) is then used to construct estimators of the monopole and the dipole, \( P_{M\delta}^{(0)} \) and \( P_{M\delta}^{(1)} \), respectively. The last step consists of determining the expected variance of these estimators to leading order in \( (\Pi V)^{-1} \). Assuming \( b = r_{g} = 1 \) for simplicity, we arrive at

\[
\Delta P_{M\delta}^{(0)} = \frac{1}{2Nk} \int_{-1}^{1} d\mu \left( P_{MM} + \frac{\sigma_{\delta}^2}{\Pi} \right) \times \left( P_{\delta\delta} + \frac{1}{\Pi} + P_{M\delta}^{(k)} P_{M\delta}^{(-k)} \right)
\]

\[
= \frac{1}{Nk} \left( \frac{1}{3} P_{uu} + \alpha^2 P_{\delta\delta} + \frac{\sigma_{\delta}^2}{\Pi} \right) \times \left( P_{\delta\delta} + \frac{1}{\Pi} + \frac{3}{5} P_{\delta\delta} - \alpha^2 P_{\delta\delta} \right)
\]

and

\[
\Delta P_{M\delta}^{(1)} = \frac{9}{2Nk} \int_{-1}^{1} d\mu \frac{\mu^2}{2} \left( P_{MM} + \frac{\sigma_{\delta}^2}{\Pi} \right) \times \left( P_{\delta\delta} + \frac{1}{\Pi} + P_{M\delta}^{(k)} P_{M\delta}^{(-k)} \right)
\]

\[
= \frac{3}{Nk} \left( \frac{3}{5} P_{uu} + \alpha^2 P_{\delta\delta} + \frac{\sigma_{\delta}^2}{\Pi} \right) \times \left( P_{\delta\delta} + \frac{1}{\Pi} + \frac{3}{3} P_{\delta\delta} - \alpha^2 P_{\delta\delta} \right)
\]

where

\[
Nk = \frac{1}{2\pi^2} k^2 \Delta k V_{\text{eff}}
\]
results in a negligible correction to the dipole of $P_{M\delta}$. For even larger radii $r \gtrsim 250\,h^{-1}\,\mathrm{Mpc}$, we thus do not expect any significant deviations from our findings, suggesting that the expressions derived for $P_{M\delta}$ and $P_{MM}$ may be safely adopted to estimate statistical errors associated with such correlation measurements.

### 2.3 Expectations for SDSS

As a first example, let us consider a galaxy catalogue comparable to the Sloan Digital Sky Survey (SDSS) main galaxy sample (SDSS Collaboration et al. 2000, 2017) at an effective depth $r_{\text{eff}} \approx 300\,h^{-1}\,\mathrm{Mpc}$. To estimate the statistical uncertainty of luminosity-density correlation measurements, we assume that galaxies approximately reside at a fixed redshift $z = 0.1$. The effect of environment is modelled by resorting to the linear relation $\Delta M_{\text{env}} = 0.26$ that follows from observations in the visible band (Croton et al. 2005; Mercurio et al. 2012) and approximately gives $\alpha/c \approx 8.5 \times 10^{-3}$, where $c$ is the speed of light. From SDSS galaxies in the $r$-band, one roughly estimates $\sigma_M \approx 0.5$ which translates into $\sigma_\alpha \approx 0.02c$ at the given redshift (see section 2.1). For the actual computation, we will adopt a flat $\Lambda$CDM cosmology with fixed parameters taken from Calabrese et al. (2013) and the parametrised linear matter power spectrum of Eisenstein & Hu (1998) smoothed on a scale of $10\,h^{-1}\,\mathrm{Mpc}$. Further, we set $\pi = 0.01(\,h^{-1}\,\mathrm{Mpc})^{-3}$ and the effective volume $V_{\text{eff}} = 0.2(\,h^{-1}\,\mathrm{Gpc})^3$ (Percival et al. 2010), and assume a binning width $\Delta k = 0.01\,\mathrm{Mpc}^{-1}$.

Figure 1. Signal-to-noise ratios (S/N) as a function of $k$ for the monopole (black solid line) and the dipole (red dashed line) of $P_{M\delta}$ for an SDSS-like galaxy redshift survey. The estimates assume a binning width $\Delta k = 0.01\,\mathrm{Mpc}^{-1}$ and are based on Eqs. (10), (14), and (15), adopting a linear $\Lambda$CDM power spectrum smoothed on a scale of $10\,h^{-1}\,\mathrm{Mpc}$ and the parameters given in the text. In addition, the figure shows S/N for the monopole of $P_{MM}$ (blue dotted line) for the case of no environmental dependence in the luminosity distribution, i.e. $\alpha = 0$.

The resulting signal-to-noise ratios (S/N) for the monopole and dipole of $P_{M\delta}$ are presented in Fig. 1. Our analysis indicates that both signals can be constrained with relatively high S/N $\gtrsim 10$ on scales of about 10–100 Mpc. In reality, questionable parts of the data and additional cuts might yield slightly lower values of these ratios, but the signals should remain well detectable. As for luminosity autocorrelations, the reduced signal amplitude will probably not allow for a reliable measurement of the velocity signal in current surveys. This is illustrated in the figure by the blue dotted line which shows the expected S/N for the monopole of $P_{MM}$ for $\alpha = 0$. However, tracing a combination of the velocity signal and environmental effects, estimates of this quantity will still be useful to obtain upper limits.

A general concern of luminosity-based techniques is the photometric accuracy of the data. Uncertainties in the photometric calibration might propagate into systematic errors that exhibit a coherent structure on large scales and could mimic spurious flows, leading to biases in the measurements. The precise nature of such systematics depends on the used instruments and survey strategy. Already in current survey such as SDSS, their impact is rather small and amounts to relative deviations at the level of 1% or less (Finkbeiner et al. 2016). It is expected that these will be further reduced in future surveys. Measurements of luminosity-density correlations should be particularly robust to the presence of systematic photometric errors because they are unlikely to be correlated with the underlying density field (Nusser et al. 2012; Feix et al. 2017). In principle, also uncertainties in the radial selection function and the modelling of $K$-corrections (e.g., Blanton & Roweis 2007) and luminosity evolution are potentially problematic, but we believe that any resulting effects should be mitigated due to the fact that luminosity modulations are derived relative to an observed mean distribution. Further complications may arise from partial sky coverage causing a mixing of different multipoles. Clearly, these various issues deserve further study and can be investigated in controlled experiments based on appropriate galaxy mock catalogues or through consistency checks that are directly applied to the data. For example, one possibility would be to consider the analysis for subsamples defined by different mean redshifts or density environments. Another option is to include comparisons to estimates of the full large-scale peculiar velocity field that appear remarkably robust against systematic errors of this kind (Feix et al. 2015, 2017).

### 3 CONCLUSIONS

Direct measurements of radial peculiar velocities allow for interesting constraints on cosmic velocity-density correlations, but are limited to rather local volumes due to various observational challenges. Here we propose an alternative route by correlating spatial modulations in the observed galaxy luminosity distribution of a redshift survey with the underlying density field. For redshifts limited to roughly $z < 0.4$–0.5, the monopole part of this signal essentially traces the environmental dependence of galaxy luminosities while the dipole probes large-scale velocity-density correlations. Considering an SDSS-like galaxy survey at $z = 0.1$, we have estimated that both the monopole and the dipole signal could be constrained with relatively high S/N $\gtrsim 10$ on scales of about 10–100 Mpc. Observational constraints on the environmental dependence of galaxy luminosities provide an important test of galaxy formation models that associate galaxies with dark matter halos (Mo et al. 2004). These dependencies are usually studied through the galaxy luminosity function in different density environments or by measuring galaxy clustering properties as a function of luminosity and morphological type (Skiibba et al. 2006; Zehavi et al. 2011; McNaught-Roberts et al. 2014), indicating that local density is the most relevant parameter on the large scales considered here. Probing these effects independently with luminosity-density correla-
tions will provide a valuable addition. Such measurements could also be helpful to quantify the importance of environmental dependencies for previous applications of luminosity-based methods that have been used to constrain bulk flows and the linear growth rate of density perturbations (Nusser et al. 2011, 2012; Branchini et al. 2012; Feix et al. 2014, 2015, 2017).

Similarly, reliably extracting the peculiar velocity signal from these correlations beyond redshifts \( z \sim 0 \) is of great importance for constraining the underlying cosmological model which is sensitive to the nature of dark energy and gravity. Velocity-density correlations play a role in modelling the effects of RSDs on the density autocorrelation function that is determined from redshift surveys (Koda et al. 2014; Okumura et al. 2014; Sugiyama et al. 2016). The analysis of luminosity-density correlations can provide direct observational constraints on this signal and should prove useful in this context. Tracing velocity-density correlations, the dipole of the luminosity-density correlation function is sensitive to the cosmic growth rate and can be used to estimate this quantity as well (Nusser 2017; Adams & Blake 2017). To this end, templates of the velocity-density correlation function that are based on simulated mock catalogues or analytic methods (e.g., Bartelmann et al. 2016) might be expedient tools.

For galaxy data at larger redshifts \( z \gtrsim 0.5 \), one needs to account for magnification due to gravitational lensing caused by the large-scale structure along the line of sight to individual galaxies. Similar to peculiar velocities, the lensing magnification changes the apparent brightness of galaxies and thus contributes to the overall budget of observed luminosity modulations. This effect introduces additional anisotropy in the correlations and is most prominent for separations close to the line of sight, but typically starts to become relevant on very large scales \( \sim 100 \) Mpc (Hui et al. 2007, 2008; Yoo & Miralda-Escudé 2010). Since the magnification may be modelled as part of the cosmological signal, it should also be worthwhile to consider the analysis of angular luminosity-density correlations, which is particularly relevant to photometric redshift catalogues (LSST Dark Energy Science Collaboration 2012; Dark Energy Survey Collaboration et al. 2016). This approach may be considered an extension of Nusser et al. (2013) who proposed a measurement of the angular luminosity modulation power spectrum to probe the signal amplitudes of both peculiar velocities and the gravitational lensing magnification out to \( z \sim 1 \).

We conclude that measurements of luminosity-density correlations constitute an interesting target for probing cosmic physics with current (SDSS Collaboration et al. 2017) and next-generation redshift surveys featuring accurate photometry and large numbers of galaxies (e.g., Laureijs et al. 2011; da Cunha et al. 2017).

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