It has been known for more than 25 years that in a statistical sense galaxy properties depend on the local environment: there is a clear trend for early-type systems to concentrate in high-density regions (Dressler 1980; Dressler et al. 1997). This dependence on environment must hold important information about the history of galaxy formation, so it is important to study the connection between the properties of the galaxies and local galaxy density in greater detail.

The type-dependent luminosity function (the luminosity function calculated for different galaxy types) is a direct means to quantify how the colours and luminosities of galaxies are influenced by their environment. With the advent of deep redshift surveys it has become feasible to measure the luminosity function for field and cluster galaxies, respectively (e.g. Valotto et al. 1997; Ratcliffe et al. 1998; Trentham 1998; Trentham & Tully 2002; Martinez et al. 2002; Christlein & Zabludoff 2003; Zandivarez et al. 2006); eventually, statistical power reached the stage where the type-dependent luminosity function could be estimated directly in regions of differing density contrast (e.g. Bromley et al. 1998; Gray et al. 2004).

To date, the most comprehensive analysis of this type has been that of Croton et al. (2005), who used the 2dFGRS data (Colless et al. 2003) to investigate luminosity functions split by galaxy colour in different environments. Since the 2dFGRS galaxies have spectroscopic redshifts, it was feasible to calculate the local density contrast in spheres of $sh^{-1}$ Mpc radius, and since the number of galaxies and the observed dynamic range of overdensities is large, the sample could be divided into six bins of density contrast.

If the dependence of galaxy properties on environment reflects the formation history of the galaxies, it is clearly of great interest to carry out a similar investigation at higher redshifts. Ilbert et al. (2006) studied a sample of 6582 galaxies with $z < 1.5$ from the VIMOS-VLT Deep Survey (VVDS); although the VVDS redshifts are spectroscopic, allowing an accurate measurement of the local overdensities, the sample is sufficiently small that only the environmental dependence of the galaxies luminosity function was measured.

Cooper et al. (2006a) used a larger sample of 19,464 DEEP2 (Davis et al. 2003) galaxies in the redshift range $0.4 \leq z \leq 1.35$. They measured the evolution of the colour-density relation and found the fraction of red galaxies to depend strongly on environment out to $z \sim 1$. They also investigated the type-dependent luminosity function, and found a good general agreement between their measurement and the COMBO-17 data from Wolf et al. (2004), but did not split the sample by environment (Faber et al. 2004; Willmer et al. 2006), which is explored in the present paper.

Due to their larger number statistics and completeness to greater depths, multicolour photometric redshift surveys can be used to measure the dependence of the luminosity function on environment at intermediate redshift in greater detail – if the influence of the redshift inaccuracy on the measurement of the overdensities is well understood. Using the COMBO-17 survey (Wolf et al. 2004), we will demonstrate in this paper how local overdensities can be computed and how the influence of the redshift errors can be treated. We will then show how the dependence of the luminosity function on the environment can be investigated, and present the results.

This paper is structured as follows: The dataset used in our study (COMBO-17) is introduced in Section 1. In Section 2 we describe the influence of redshift inaccuracies on the measurement of the local density contrast using a COMBO-17 mock catalogue, which is based on an N-body simulation combined with a semi-analytic model for galaxy evolution (van Kampen et al. 1999; 2003). Following this exercise, we calculate the local density contrast in three COMBO-17 fields and measure the luminosity function for red sequence and blue cloud galaxies in the redshift range $0.25 \leq z \leq 0.4$ (see Section 3). The results are discussed in Section 4 and a brief summary and an outlook is given in Section 5.

We assume a flat cosmological geometry with $\Omega_m = 0.25$; all lengths quoted are in comoving units. Normally, we show explicit dependence on $h$ (which denotes $H_0/100$ km s$^{-1}$ Mpc$^{-1}$); but for absolute magnitudes we suppress this dependence, so that $M_B$ denotes $M_B - 5 \log_{10}h$.

1. Database: The COMBO-17 Survey

To date, COMBO-17 (Classifying Objects with Medium Band Observations in 17 filters) has observed three disjoint $\sim 31' \times 30'$ southern equatorial fields (for their coordinates see Wolf et al. 2003; W03 in the following) to deep limits in 5 broad and 12 medium passbands, covering wavelengths from 400 to 930 nm. A detailed description of the survey along with filter curves can be found in Wolf et al. (2004).

Galaxies were detected on the deep $R$-band images by using SEExtractor (Bertin & Arnouts 1996). The spectral energy distribution (SEDs) for $R$-band detected objects were measured by performing seeing-adaptive, weighted-aperture photometry in all 17 frames at the position of the $R$-band detected object. All magnitudes are quoted with a Vega zero point.

1.1. Photometric redshifts

Using the 17-band photometry, objects are classified using a scheme based on template spectral energy distributions (SEDs) (Wolf et al. 2001b). Each object is also assigned a redshift (if it is not classified as a star). The redshift errors in this process depend on the magnitude and type of the object. The galaxy redshift estimate quality has been tested by comparison with spectroscopic redshifts for almost 1000 objects (see Wolf et al. 2004). At bright limits $R < 20$, the redshifts are accurate to $\epsilon/(1+z) \sim 0.01$, and the error is dominated by mismatches between template and real galaxy spectra. This error can contain a systematic component that is dictated by the exact filter placement, but these ‘redshift focusing’ effects are of the order of magnitude of the random redshift errors for $z < 1$ and are unimportant for the current analysis. At the median apparent magnitude $R \sim 23$, $\epsilon/(1+z) \sim 0.02$. For the faintest galaxies, the redshift accuracy approaches those achievable using traditional broadband photometric surveys, $\epsilon/(1+z) \gtrsim 0.05$. We thus restricted our analysis to galaxies with $R < 23.65$. In order to define a volume limited sample at $z \leq 0.6$, we furthermore select galaxies with restframe $B$-band magnitudes $M_B \leq -18.0$. There is no point in trying to correct for the incompleteness at high redshifts, because any completeness correction requires the knowledge of the luminosity function as a function of galaxy type, which is not determined accurately enough, so we investigate the local density contrast only at $z \lesssim 0.7$.

1.2. Red and blue galaxies

From the COMBO-17 data we know the redshift and the SED for each galaxy, so it is possible to calculate their absolute rest-frame magnitudes and colours. We can use this information to
investigate the properties of different galaxy types, e.g. red sequence and blue cloud galaxies, where we use the prescription of [Bell et al. (2004)](https://doi.org/10.1086/384467) to separate the two populations from each other:

\[
\text{Red sequence: } (U - V) > (U - V)_{\text{lim}} \quad (1)
\]

\[
\text{Blue cloud: } (U - V) < (U - V)_{\text{lim}} \quad (2)
\]

\[
(U - V)_{\text{lim}} = 1.25 - 0.4z - 0.08(M_V - 5 \log_{10} h + 20) , \quad (3)
\]

\((z)\) denotes the redshift of a given galaxy.

### 2. Method

The local density contrast

\[
\delta = \frac{\rho - \overline{\rho}}{\overline{\rho}}, \quad (4)
\]

where \(\rho\) is the local density, and \(\overline{\rho}\) the mean density, is commonly measured in spheres with a radius of e.g. \(r = 8 h^{-1}\) Mpc, as adopted by [Croton et al. (2005)](https://doi.org/10.1086/428073).

Obviously, the redshift errors in our sample are too large to calculate overdensities in such spheres, but it is still possible to measure overdensities, albeit in slightly larger volumes. Instead of counting the number of galaxies in a sphere or a cylinder centred on individual galaxies, or distributed randomly within the survey volume, we calculated the *comoving space densities* \(\rho(z)\) in redshift bins of \(\Delta z = 0.02\) and steps of \(\delta z = 0.005\). At a redshift of \(z = 0.3\), this corresponds to a comoving radial bin size distance of \(\Delta r \approx 53 h^{-1}\) Mpc. The width of one COMBO-17 field at that redshift (30') is approximately 7.4\(h^{-1}\) Mpc.

#### 2.1. Determination of the mean density

The mean density \(\overline{\rho}\) was estimated in the range \(0.25 \leq z \leq 0.7\): This avoids contamination from faint galaxies in the pre-selected cluster Abell 901 at \(z = 0.165\), which could be scattered in redshift due to large photometric redshift errors. Also, with a total field size of 0.78\(h^{-1}\) and the correspondingly small survey volume at \(z < 0.25\), a measurement of the mean number density is always dominated by cosmic variance. Redshifts larger than \(z = 0.7\) are excluded, because the sample then starts to become incomplete and noisy.

Fig. 1 shows the mean comoving number density (the average of the three fields), for the blue and red subsamples. While the number of red galaxies remains roughly constant with redshift, the comoving number of blue galaxies tends to increase. We fit the trend (again over the redshift range \(0.25 \leq z \leq 0.7\)) with a straight line, and use this empirical evolutionary fit instead of the constant mean in the calculation of the overdensities,

\[
\rho(z) = 1.72 \times 10^{-3} + 3.42 \times 10^{-3} z \, h^3\text{Mpc}^{-3} . \quad (5)
\]

This fit certainly overpredicts the number density at \(z \geq 0.8\), so we restrict this analysis to lower redshifts. We will mainly be interested in practice in \(z \simeq 0.3\), where the results have little dependence on the strength of the assumed evolution.

#### 2.2. Redshift errors

Photometric redshift estimates have significant errors, and we need to understand how these affect our estimates of the density contrast. The redshift accuracy depends on observed magnitude; statistically, blue galaxies are fainter than red ones and thus tend to have slightly larger errors. Therefore, when comparing the properties of red sequence with those of the blue cloud galaxies, we have to test which effect the different error distributions have on the measured overdensities of our two subsamples.

In order to simulate the influence of redshift errors on the measurement of local densities in different volumes, we use a mock galaxy survey based on a set of simulations by [van Kampen et al. (1999, 2005)](https://doi.org/10.1093/mnras/294.1.125). The phenomenological model predicts positions on the sky, redshifts including peculiar velocities, magnitudes that would be measured in the COMBO-17 filters, and absolute rest-frame luminosities and colours in the same bands that we use for the analysis of the observations.

Four different simulation volumes are used to produce 80 different lightcones representing individual COMBO-17 fields, for which we also calculate the overdensities (Eq. 4). Each of these COMBO-17 mock samples is selected in the same way as the observed data \((R \leq 23.65, M_B \leq -18.)\). Their number counts and overall redshift distribution have the same expectation, but they differ in detail – thus allowing us to assess the significance of ‘cosmic variance’.

For each galaxy in the COMBO-17 catalogue the rms error of its estimated redshift is provided by the classification scheme, and we use these errors to convolve the ‘spectroscopic’ redshifts in our mock sample with the error distribution. For each galaxy in the mock catalogue we randomly pick out a value \(\epsilon\) from the COMBO-17 data, then draw an error \(\delta z\) from a Gaussian distribution with \(\sigma = \epsilon\), and add this error to the given redshift. Using these new, ‘multicolour’ redshifts, we can repeat the calculation of the galaxy properties (e.g. K-corrections and rest-frame magnitudes), and of the overdensities.

Fig. 2 shows the overdensities calculated for ‘spectroscopic’ against the measurement for ‘multicolour’ redshifts in the same redshift bins. The scatter is small enough to facilitate a measurement of overdensities in a multicolour survey such as COMBO-17. However, the small tilt of the relation shows that high overdensities become slightly lower, and deep underdensities slightly shallower – the dynamic range shrinks and the convolution with the redshift error distribution washes out the measured structures.

In order to facilitate a direct comparison between red sequence and blue cloud galaxies, we have to understand what effect their slightly different redshift error distributions have on
We now simulate redshift errors by drawing appropriate rms errors from the red sequence and blue cloud galaxy catalogues separately, and then calculate the colour-dependent overdensities for the mock sample. As can be seen from Fig. 2 in the presence of redshift inaccuracies the existing small scale density fluctuations are washed out, and the amplitudes of the overdensities are suppressed. Due to the statistically slightly larger errors of the blue galaxies, the signal is more strongly suppressed than when the errors of the red galaxies are applied. Thus, if we were to measure exactly the same structure using a sample of red and blue galaxies as tracers, the different redshift accuracies would cause us to infer a larger overdensity (or smaller underdensity) from the red sample than from the blue one.

To account for this, we convolve the redshift distribution of the red galaxies with a blurring function, which broadens their redshift error distribution to make it resemble the redshift error distribution of the blue galaxies. Of course the same procedure has to be applied to the bright galaxies as well, in order to make them comparable to the faint ones. In general, for each comparison we have to make sure that the redshift distribution of the sample with the smaller redshift errors has to be blurred in order to make its error distribution resemble the one with the lower accuracy.

The blurring function can be found via the convolution theorem. Denote the redshift error by \( \epsilon \), and let \( f \) and \( g \) be the redshift error distributions of red and blue galaxies respectively. We now seek a blurring function that makes them compatible:

\[
\hat{f}(\epsilon) = \hat{g}(\epsilon) * \hat{b}(\epsilon),
\]

which is simply solved in Fourier terms: \( B(k) = F(k)/G(k) \), where \( k \) is a wavenumber in redshift space.

In order to evaluate the error distributions and account for its redshift dependence, we calculate in each redshift bin of size \( \Delta z = 0.1 \) between \( z = 0 \) and \( z = 1 \) the sum of Gaussians

\[
f(\epsilon) = \frac{1}{N_{\text{gal}}} \sum_{i=1}^{N_{\text{gal}}} \frac{1}{2\pi \sigma_i^2} \exp \left( -\frac{\epsilon^2}{2\sigma_i^2} \right),
\]

for all colour and luminosity samples under consideration. The resulting functions can be closely approximated by a Breit-Wigner or Lorentz curve, and it is convenient to treat this as the exact form:

\[
f(\epsilon) = \frac{W}{2\pi} \frac{1}{\epsilon^2 + \frac{W}{4}},
\]

where \( W \) is the full width at half maximum. We parameterize the evolution with redshift (in the redshift range \( 0.25 < z < 0.7 \)) of the full width at half maximum \( W \) with a second order polynomial:

\[
W(z) = a_0 + a_1(1 + z) + a_2(1 + z)^2,
\]

with the following coefficients for our red and blue, and bright and faint subsamples. Red sequence: \( a_0 = 0.015, a_1 = 0.033, a_2 = 0.026 \). Blue cloud: \( a_0 = 0.090, a_1 = 0.142, a_2 = 0.068 \). Bright galaxies: \( a_0 = 0.124, a_1 = 0.200, a_2 = 0.087 \). Faint galaxies: \( a_0 = 0.094, a_1 = 0.164, a_2 = 0.082 \).

The Fourier transform of a Lorentzian is

\[
F(k) = \exp \left( -W |k|/2 \right),
\]

from which is is readily seen that the required blurring function is

\[
b(\epsilon) = \frac{\Delta W}{2\pi} \frac{1}{\epsilon^2 + \frac{(\Delta W)^2}{4}},
\]

where \( \Delta W \) is the difference in widths of the two populations. We can now use this probability distribution to degrade the redshift accuracy of a given sample in order to be comparable to another sample with larger redshift errors: a redshift offset is drawn randomly from the blurring probability distribution, and added to the true data.

Fig. 3 also shows the overdensity of the mock galaxies, which have first been convolved with the red error distribution, and then further blurred in order to make their redshift inaccuracy comparable to the ones that have been convolved with the blue error distribution. Since the photometric redshift accuracies of the sub-samples are now equal by construction, we can now start to look for differences in the overdensity patterns as a function of colour or luminosity.

3. Results

3.1. Overdensities in the COMBO-17 survey

Fig. 4 shows the overdensities measured in the three COMBO-17 fields, which we calculated in relatively large bins of \( \Delta z = 0.05 \), in steps of \( \delta z = 0.01 \). Later we will decrease the size of our bins, but here we want to compare the large-scale properties of the three fields.

The error bars plotted for the CDFS are the variances of the overdensities calculated in 80 mock COMBO-17 fields and should thus include not only Poisson noise, but also cosmic variance. However, since the data points are highly correlated (the spacing of the bins being smaller than the binsize), it should be noted that the errors are also correlated.

Of particular interest is the range \( 0.25 < z < 0.4 \). Here one of our three fields, the Chandra Deep Field South (CDFS), is underdense with respect to the others. The mean overdensity in the CDFS is \( \delta = -0.36 \pm 0.08 \), whereas in the A901 field it is \( \delta = 0.16 \pm 0.21 \), and in the S11 field we find \( \delta = 0.11 \pm 0.24 \), respectively. So in both A901 and S11 the overdensity fluctuates about the mean, whereas the CDFS is clearly underdense in this redshift range.
Fig. 3. Overdensity of the mock galaxies in one ‘COMBO-17 field’. The solid line is the overdensity of the galaxies with ‘spectroscopic’ redshifts, the dotted line is the measurement using the same galaxies, but convolved with the error distribution of the red COMBO-17 galaxies, the dashed line is the overdensity of the mock galaxies, which have first been convolved with the red error distribution, and then further blurred in order to make their redshift inaccuracy comparable to the ones that have been convolved with the blue error distribution.

Table 1. The numbers of galaxies in the different subsamples, per COMBO-17 field. All galaxies are preselected to have $R \leq 23.65$, $M_{B_J} \leq -18$, and $0.25 \leq z \leq 0.4$. ‘Bright’ means $M_{B_J} < 19.5$, and ‘faint’ $M_{B_J} \geq 19.5$.

<table>
<thead>
<tr>
<th>COMBO-17 field</th>
<th>$N_{\text{tot}}$</th>
<th>$N_{\text{red}}$</th>
<th>$N_{\text{blue}}$</th>
<th>$N_{\text{bright}}$</th>
<th>$N_{\text{faint}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDFS</td>
<td>301</td>
<td>56</td>
<td>245</td>
<td>63</td>
<td>238</td>
</tr>
<tr>
<td>A901</td>
<td>594</td>
<td>162</td>
<td>432</td>
<td>165</td>
<td>429</td>
</tr>
<tr>
<td>S11</td>
<td>543</td>
<td>178</td>
<td>365</td>
<td>141</td>
<td>402</td>
</tr>
</tbody>
</table>

Unfortunately the mock COMBO-17 catalogues we used to calculate the rms errors of the overdensities can currently not be used to calculate errors for red and blue (or bright and faint) subsamples as well, since the mock galaxies do not exhibit the same dependencies of colour and luminosity on the local density contrast as the observed galaxies. A thorough error analysis has thus to be postponed to a future paper, when improved mocks are available.

Fig. 4. The overdensities in the three COMBO-17 fields, calculated in bins of $\Delta z = 0.05$ and steps of $\delta z = 0.01$, versus redshift. The vertical lines indicate the range in which the luminosity function will be estimated. The errors are rms errors calculated from 80 COMBO-17 mock catalogues, but in order to avoid confusion error bars are only plotted for every second data point.

This is a fortunate coincidence: owing to the smaller number of galaxies and the dynamic range of overdensities observed by COMBO-17 we can not split our sample into overdensity bins in the way e.g. [Croton et al. 2005] did – but we can compare the statistical properties of the galaxies in this specific underdense region with those in ‘normal’ dense regions at the same redshift.

Before measuring and comparing luminosity functions, we calculate the overdensities in this field again for different subsamples (this time in bins of size $\Delta z = 0.02$ and $\delta z = 0.005$): a sample of red sequence and blue cloud galaxies (see Sect. 1.2), and a sample of bright ($M_{B_J} < 19.5$), and faint ($M_{B_J} \geq 19.5$) galaxies, respectively, see Fig. 5. The numbers of galaxies in the different subsamples are given in Table 1.

Fig. 5. The overdensities in the CDFS, calculated in bins of $\Delta z = 0.02$, for bright ($M_{B_J} < 19.5$), and faint ($M_{B_J} \geq 19.5$) galaxies (upper panel), and red sequence and blue cloud galaxies (lower panel). For both the bright and red sequence subsamples, the redshifts have been blurred, in order to make their redshift inaccuracies similar and thus the measurement of the overdensities comparable to the faint and blue cloud subsamples, respectively.

From Fig. 5, it is evident that although the redshifts of the red and bright samples have been further smoothed in the way explained in Section 2, the structures are more distinct in the red/bright samples than in the blue/faint ones, respectively.
The different samples trace the underlying dark matter density field differently. Bright galaxies are generally found to be more strongly clustered than the faint ones, because they are thought to reside in massive dark matter haloes, which are generally believed to be more strongly clustered than small ones (e.g. Cole & Kaiser 1999; Mo & White 1996; Sheth & Tormen 1999). At the same time, red galaxies are observed to be more strongly clustered than the blue galaxies (e.g. Davis & Geller 1976; Norberg et al. 2002; Zehavi et al. 2005; Phleps & Meisenheimer 2003; Phleps et al. 2006). However, it is presently not clear whether luminosity or colour is the determining property (see e.g. Norberg et al. 2003).

As can be seen in Fig. 5, the underdensity in the CDFS at $0.25 \leq z \leq 0.4$ is particularly pronounced when calculated using only red galaxies for the determination – this region is mainly deficient in red galaxies. We will see in the next section that this deficiency reflects mainly a reduction in the number of faint red galaxies.

3.2. Luminosity functions

In order to investigate which galaxies are most deficient in the underdense region in the CDFS, we have calculated rest-frame $B$-band luminosity functions for the galaxies in the redshift bin $0.25 \leq z \leq 0.40$ in all three fields, split by colour according to Eqn. 3.

At redshift $z = 0.4$, a luminosity of $M_B = -17$ corresponds to an observed-frame apparent magnitude of $R_{\text{tot}} = 23.2$ or $R_{\text{aper}} = 23.5$ in the COMBO-17 apertures. The aperture magnitudes and colours determine the completeness, which we estimate as $> 90\%$ at every point in the redshift-luminosity data cube. Nevertheless, the calculation of the luminosity functions including completeness correction has been implemented exactly as described in W03 and later COMBO-17 papers.

Fig. 6 shows the luminosity functions of the red sequence and blue cloud galaxies in the redshift bin $0.25 \leq z \leq 0.4$ for the three COMBO-17 fields. Parameters for the Schechter fits (as plotted in Fig. 6) are given in Table 2. We present the luminosity functions separately for our three fields in order to investigate their differences. In W03 it was already reported that the CDFS is underdense in the ‘semi-local’ redshift bin $z = 0.2, 0.4$ (see their Fig. 12). However, W03 investigated luminosity functions either split by field or split by spectral type. In contrast, here we present the LF split both by field and by rest-frame colour.

As can be seen from Fig. 6 and Table 2, the luminosity function of the blue cloud galaxies does not differ from field to field (apart from the normalisation $\phi^*$, which unsurprisingly is lower in a low density region). In contrast to that, the luminosity function of the red sequence galaxies in the CDFS (the underdense region) is indeed clearly distinct from the one measured in the two other fields, which have about mean density. Not only is the normalisation slightly lower, but also the slope $\alpha$ is clearly more positive: the underdensity in the CDFS is mainly due to a deficiency of faint red galaxies.

4. Discussion

Our detection of a lack of faint red galaxies in voids is in qualitative agreement with the work of Croton et al. (2005), who investigated the influence of the environment on galaxy properties in the local universe using 2dFGRS data (Colless et al. 2001). Croton et al. were able to measure the type-dependent luminosity functions in six different overdensity regimes from voids to clusters of galaxies. They found that late-type galaxies display a consistent luminosity function across all density environments, with a weak dimming of $M^*$ in the underdense regions and an almost constant faint-end slope. In contrast the luminosity function of the red galaxies differs sharply between the extremes in environment: $M^*$ brightens by approximately 1.5 mag going from voids to clusters, while the faint-end slope moves from $\alpha \simeq -0.3$ in underdense regions to $\alpha \simeq -1.0$ in the densest part of the survey.

A similar analysis has been undertaken by Zandivarez et al. (2006), who investigated the dependence of the galaxy luminosity function on system masses of galaxy groups identified in the Fourth Data Release of the Sloan Digital Sky Survey (Adelman-McCarthy et al. 2006), and found a continuous brightening of the characteristic magnitude, and a steepening of the faint end slope as the system mass increases. When they split their sample by $u - r$ colour into red and blue galaxies, they found that the changes observed as a function of the system mass are mainly seen in the red, passively evolving, galaxy population, while the luminosities of blue galaxies remain almost unchanged with mass. When we take the system mass as equivalent to the local density, then this result is consistent with the result of both Croton et al. (2005), and with our own.

Therefore we conclude that the same dependency of the luminosity function on environment – a lack of faint red galaxies in underdense regions and a dominant population of bright red galaxies in overdense environments – was already in place at $z \leq 0.4$.

Results from the DEEP2 Galaxy Redshift Survey (Davis et al. 2003) show that the colour segregation observed between local group and field galaxies is even seen at $z \sim 1$ (Cooper et al. 2006a,b; Gerke et al. 2006). DEEP2 is a spectroscopic survey of galaxies at redshifts around unity ($0.7 \leq z \leq 1.4$), to a limiting magnitude of $R_{AB} = 24.1$. The unprecedented combination of depth and redshift accuracy allows for an examination of the influence of the environment on the galaxies’ properties at $z \sim 1$. Cooper et al. (2006b) use a sample of 19,464 galaxies drawn from the DEEP2 survey to show how the density-luminosity relation evolves continuously, with red galaxies more strongly favouring overdense regions at lower redshift as compared to their high-redshift counterparts, with the fraction of blue galaxies (which is lower in groups than in the field) staying roughly constant with redshift. However, at $z \sim 1.3$, the red fraction starts to correlate only weakly with overdensity (Cooper et al. 2006a), and the group and field blue fractions become indistinguishable (Cooper et al. 2006b).

This observed trend – the growing fraction of red galaxies in overdense regions, while the overall fraction of blue galaxies evolves slowly up to $z \sim 1$ – suggests that the strong dependence of the galaxy properties on the environment at lower redshifts is a result of environment-driven mechanisms. The build-up of the red sequence appears to have occurred preferentially in overdense regions. One further piece of evidence in this direction comes from Gerke et al. (2004), who find that at $z \geq 0.7$ red galaxies already tend to be bright, and bright galaxies in general tend to live in dense environments, even at redshifts around unity. Our results complement and reinforce this general picture.

However, these results are in clear contrast to those of Hubble et al. (2006). They claim to have found a steepening of the slope of the luminosity function in underdense environments at higher redshifts and hence an excess of faint red galaxies in underdense regions. An explanation for their interpretation of their data as steepening of the slope could be found in the difficulty of estimating $\alpha$ when the data are only complete to $B \leq -19$, as is the case in their higher redshift samples. Their conclusion
is also mainly based on luminosity functions split by environment and redshift bin, but not by colour. In that case, the excess of luminous red galaxies in overdense regions manifests itself in a bump at the bright end of the total luminosity function, and thus can feign a flatter faint-end slope when compared to the luminosity function in underdense regions, where the bright red galaxies are rare. This is demonstrated in Fig. 7 where we show the luminosity function of all galaxies in the underdense CDFS (black line) in comparison with the A901 (blue line), with a change in plot style fainter than $M_B = -19$. Thus, if no data are available at the faint end, the slope of the luminosity function of the underdense region can seem as if it continues to rise quite steeply, when in fact the slopes of both luminosity functions are the same, and the difference is rather at the bright end. Only when the luminosity function is estimated for blue and red galaxies separately, does a dependence of the slope (of the red galaxies) on environment become measurable.

5. Summary and outlook

The dependence of galaxy properties on the environment in which they reside is a clue to the physical processes that led to their formation and present appearance. The means of investigating this correlation of galaxy properties and the local density contrast is the type-dependent luminosity function, calculated in different density regimes. These measures, local overdensities and luminosity functions, make different demands on the data: For a precise determination of overdensities good redshift quality is needed, in the most optimal case spectroscopic. But current spectroscopic redshift surveys are not deep enough to allow for a precise measurement of the luminosity function, especially at intermediate to high redshifts.

In this paper, we have demonstrated that multicolour surveys can overcome this problem. The redshift error distribution has to be well determined, because redshift inaccuracies smooth out the structures. The extent to which the amplitudes are suppressed depends on the size of the redshift errors.

We have used the COMBO-17 survey to calculate overdensities for different samples of galaxies (a red, blue, bright and faint subsample, respectively), in three fields. Instead of calculating the overdensity in small spheres, as is usually done, we do it in very thin redshift slices. We can not divide the data into a full range of overdensity bins, but when calculating the overdensities in the three COMBO-17 fields, we find one of them, the Chandra Deep Field South (CDFS), displays a relatively large underdense region, where the other two fields have overdensities fluctuating about mean density. We use this to compare the luminosity functions of red and blue galaxies in different density regimes (but at the same redshift, $0.25 \leq z \leq 0.4$).

The luminosity function of the blue cloud galaxies is unaffected by the environment: it has the same shape in all three fields. The luminosity function of the red sequence galaxies, on
the other hand, is very different in the underdense region in the CDFS: its faint-end slope $\alpha$ is significantly more positive than in the other two fields at the same redshifts. This finding – that the underdensity is mainly due to a lack of faint red galaxies – is consistent with results at lower redshift (e.g. Croton et al. 2005 or Zandivarez et al. 2006), and fits into the common picture of hierarchical galaxy formation.

Our present analysis is only a preliminary study of how multicolour data can be used to investigate the dependence of galaxy properties on the local environment at redshifts $z \gtrsim 0.2$. By applying a correction for the different redshift accuracies of the subsamples under consideration, it is indeed possible to estimate the galaxy overdensities for red sequence and blue cloud galaxies separately, and calculate luminosity functions for different subsamples in different environments.

However, a full quantification of the effect of the environment on galaxy properties will require much larger surveys. First of all the survey volumes have to be larger: not only will the statistics be better in a bigger survey, but also the dynamic range of observed overdensities. In COMBO-17, the range of overdensities that can be investigated is limited. In a large-area survey, the field can be split into many different smaller subfields (either randomly distributed or deliberately chosen by surface density) and a similar analysis to ours can be carried out, or a count-in-(large)-cells analysis similar to the one by Wild et al. (2005) and Conway et al. (2005), where they counted galaxies in approximately cubical boxes.

Second, a completeness to fainter magnitudes is desirable for a correct and precise determination of the slope $\alpha$ of the luminosity function also at higher redshifts. This is important for the investigation of the evolution of the dependence of galaxy properties on environment.

We can look forward to achieving many of these goals with new generations of deep multicolour or photometric redshift surveys, such as VST-16, KIDS (Kuijken 2006) or Pan-STARRS (Kaiser et al. 2005).

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Fig. 6. The luminosity function of the red sequence (upper panel) and blue cloud (lower panel) galaxies in the redshift range $0.25 \leq z \leq 0.4$, for the three COMBO-17 fields. The STY fit is overplotted in each panel.