The redshift-space two-point correlation function of ELAIS-S1 galaxies

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ABSTRACT
We investigate the clustering properties of galaxies in the recently completed ELAIS-S1 redshift survey through their spatial two-point autocorrelation function. We used a subsample of the ELAIS-S1 catalogue covering approximately 4 deg² and consisting of 148 objects selected at 15 µm with a flux > 0.5 mJy and a redshift z < 0.5. We detected a positive signal in the correlation function that in the range of separations 1–10 h⁻¹ Mpc is well approximated by a power law with a slope γ = 1.4 ± 0.25 and a correlation length s₀ = 5.4 ± 1.2 h⁻¹ Mpc, at the 90 per cent significance level. This result is in good agreement with the redshift-space correlation function measured in more local samples of mid-infrared-selected galaxies such as the IRAS Point Source Catalog (PSCz) redshift survey. This suggests a lack of significant clustering evolution of infrared-selected objects out to z = 0.5 that is further confirmed by the consistency found between the correlation functions measured in a local (z < 0.2) and a distant (0.2 < z < 0.5) subsample of ELAIS-S1 galaxies. We also confirm that optically selected galaxies in the local redshift surveys, especially those of the SDSS sample, are significantly more clustered than infrared objects.

Key words: galaxies: clusters: general – galaxies: evolution – cosmology: observations – large-scale structure of Universe – infrared: galaxies.

1 INTRODUCTION
Investigating the redshift-space distribution of galaxies has long been regarded as a fundamental aspect of observational cosmology. The primary statistical tool for characterizing galaxy clustering is the spatial two-point correlation function ξ(s), since, in the current paradigm of structure formation, the galaxy two-point correlation function is directly related to the initial power spectrum of mass density fluctuations.

This is true as long as galaxies trace the underlying mass density field. However, it is now well established that the clustering of galaxies at low redshift depends on a variety of factors, implying that not all types of galaxies can be regarded as unbiased mass tracers. The clustering of optically selected galaxies has been found to depend on galaxy luminosity (Norberg et al. 2002 and references therein), morphological and spectral type (Hermit et al. 1996; Zehavi et al. 2002; Magdwick et al. 2003). On the other hand, the clustering of infrared- (IR-) selected galaxies seems to depend on their infrared colour (Hawkins et al. 2001) rather than on luminosity (Szapudi et al. 2000).

The evidence that different galaxy populations might give different biased pictures of the mass distribution has complicated but also enriched the interpretation of galaxy clustering. Indeed, the very fact that the spatial clustering of galaxies is related to their physical properties represents an important observational test for all theories of galaxy formation. In particular, strong constraints on galaxy evolution models can be obtained by measuring the relative clustering of different extragalactic objects as a function of redshifts, for which very deep galaxy samples are required.

Several deep redshift surveys of optically selected galaxies, such as the Keck surveys of the GOODS-north (Wirth et al. 2004) and GOODS-south (Vanzella et al. 2004) fields and the DEEP2 redshift survey (Davis et al. 2003), are currently being performed. First, results based on early data look very promising indeed. The analysis of Coil et al. (2004) has shown that the two-point correlation function of DEEP2 galaxies with a median redshift of z = 1.14 is consistent with that measured by Adelberger (2003) in a very deep (z ~ 3) sample of Lyman break galaxies but is significantly smaller than the correlation measured in the local (z ~ 0) 2dF galaxy sample.

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Since 2dF $b_1$-selected galaxies are known to trace the underlying mass density field in an unbiased way (Lahav et al. 2002; Verde et al. 2002), the smaller correlation measured in the DEEP2 survey implies that this is not a strongly biased sample of objects either, since the clustering of the dark mass is expected to decrease with redshift in a similar way (Coil et al. 2004). Mid-infrared-selected galaxies also constitute a very interesting population of objects since they are also known to trace the underlying mass distribution in the local Universe in an almost unbiased fashion. More precisely, it has been found that the fluctuations in their number density, $\delta$, is related to the underlying mass overdensity field $\delta_m$ through a simple, linear biasing relation $\delta_g \sim 1.2 \delta_m$ (Tegmark, Zaldarriaga & Hamilton 2001; Taylor et al. 2002). Another reason why mid-infrared selection is interesting is that luminosity in this band is approximately proportional to the star formation rate (independent of dust), thus a mid-infrared sample of galaxies will highlight the distribution of star formation activity at a particular epoch. Clearly, it would be very important to quantify the clustering evolution of mid-infrared-selected objects and compare it with that of optically selected galaxies. This is indeed the main goal of this work in which we analyse the clustering properties of a sample of mid-infrared-selected galaxies extracted from the ELAIS redshift survey (Oliver et al. 2000) and extending out to a redshift of $z = 0.5$. According to La Franca et al. (2004), two main spectroscopic classes have been found to dominate the extragalactic population of these objects: star-forming galaxies [from absorbed to extreme star-bursts: $\nu L_\nu (15 \, \mu m) \sim 10^{8} - 10^{11} \, L_\odot$], which account for 75 per cent of the sources, and active galactic nuclei (excluded from this analysis) which account for 25 per cent of the sources. About 20 per cent of the extragalactic ELAIS sources are dust-enshrouded starburst galaxies, while passive galaxies are essentially absent from the sample.

Our analysis is performed in redshift space and thus complements the previous work of Gonzalez-Solares et al. (2004) who measured the angular correlation properties of a similar sample of ELAIS galaxies from which they have inferred their spatial correlation properties.

The outline of this paper is as follows. In Section 2 we describe the ELAIS-S1 galaxy redshift survey that we analyse in this work. In Section 3 we discuss our method of estimating the two-point correlation function, assess its robustness and evaluate its statistical uncertainties. The main results are presented in Section 4, and discussed in Section 5, in which we also draw our main conclusions.

## 2 THE ELAIS-S1 SAMPLE

The European Large-Area ISO survey (ELAIS, Oliver et al. 2000; Rowan-Robinson et al. 2004) is the largest Open Time programme conducted by the ISO satellite (Kessler et al. 1996). It covers an area of 12 deg$^2$, divided in four fields (N1–N3 in the northern hemisphere and S1 in the southern one) distributed across the sky in order to decrease the biases due to cosmic variance. The survey bands are at 6.7, 15, 90 and 170 $\mu$m; the 15 $\mu$m one presents the highest density of galaxies (Serjeant et al. 2000; Gruppioni et al. 2002; La Franca et al. 2004), making it the best choice for a study of their clustering properties. In this work we concentrate on the southern area, S1.

This survey is made of nine raster observations, each covering $40 \times 40$ arcmin$^2$. The final analysis catalogue at 15 $\mu$m in the S1 field has been released by Lari et al. (2001) covering an area of $2 \times 2$ deg$^2$ centred at $\alpha(2000) = 00^h 34^m 44^s.4, \delta (2000) = -43^\circ 28^\prime 12^\prime\prime$. It includes 462 mid-infrared sources down to a flux limit of 0.5 mJy.

![Figure 1](http://www.nstitroma3.it/~ELAIS_S/)

Figure 1. The angular distribution of ELAIS-S1 sources. The solid square is the central raster S1-R5, observed three times.

We have restricted our analysis to a highly reliable subsample of 406 objects (La Franca et al. 2004).

A detailed description of the optical classification of the ELAIS-S1 sources, size and completeness function of the areas used in our study, and the observed counts for each class of sources (normal galaxies, starburst galaxies and active galactic nuclei (AGN)) are presented by La Franca et al. (2004). The measure of the evolution of star-forming galaxies has been investigated by Pozzi et al. (2004) and Gruppioni et al. (2005), while a first estimate of the luminosity function for type-1 AGN has been presented by Matute et al. (2002).

The central rarer, S1-R5, has been observed three times and thus represents the deepest part of the sample. Consequently, the ELAIS-S1 area has been divided into two regions: (a) the central and deepest part (S1-R5) which covers 0.55 deg$^2$ and reaches 20 per cent completeness at fluxes of 0.7 mJy and (b) the remaining area (S1-Rest) which covers 3.65 deg$^2$ and reaches 20 per cent completeness at fluxes of 1.1 mJy.

The optical analysis of the 406 objects brings 332 (80 per cent) optical identifications on CCD exposures down to $\sim 23$, and 290 spectroscopic classifications (90 per cent of the optically identified sample). Of these, 93 were found to be stars and 199 extragalactic sources. Among these, we kept only the galaxies with $z < 0.5$, because according to analyses based on the mean optical/mid-IR ratios of the sources, the sample is virtually 100 per cent spectroscopically complete down to this redshift (La Franca et al. 2004). We have excluded all the AGN-type sources. This left us with 148 redshift-determined galaxies, 48 belonging to the deeper S1-R5 raser and the remaining 100 galaxies belonging to the surrounding areas, S1_Rest.

The angular distribution of ELAIS-S1 galaxies in our sample is displayed in Fig. 1 (filled dots). The galaxy surface density is higher in the central region corresponding to the deeper S1-R5 raser.

The continuous line histograms in both panels of Fig. 2 show the redshift distribution of the ELAIS-S1 galaxies in the S1-R5 (top) and S1-Rest (bottom) rasters. Gonzalez-Solares et al. (2004) have shown that the redshift distribution of ELAIS objects obtained from

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1 Data and related papers concerning the ELAIS southern survey are available at [http://www.nstitroma3.it/~ELAIS_S/](http://www.nstitroma3.it/~ELAIS_S/).
follow-up spectroscopic observations and photometric redshifts is consistent with that predicted from the ELAIS luminosity function of Pozzi et al. (2004). This redshift distribution will be used in the next section to estimate the galaxy correlation function and to construct the mock ELAIS-S1 catalogues.

3 MEASURING THE REDSHIFT-SPACE CORRELATION FUNCTION $\xi(s)$

Our purpose is to estimate the redshift-space two-point correlation function of ELAIS-S1 galaxies and its uncertainties. It is worth stressing here that clustering in redshift space is systematically different from the true one in real space. On small scales, velocity dispersion in virialized systems smears out structure along the line of sight and thus increase the amplitude of $\xi(s)$ on the corresponding scales. Here we make no attempt to correct for redshift-space distortions. Therefore, direct comparisons will only be made with similar measurements of the redshift-space two-point correlation function of other galaxy redshift catalogues.

3.1 Estimate of $\xi(s)$

Several different methods have been proposed to estimate the two-point correlation function. In this work we use the (Landy & Szalay 1993, hereafter LS) estimator that, according to extensive numerical tests, turned out to be the best suited for astrophysical applications (Kerscher, Szapudi & Szalay 2000).

With the LS estimator a reliable and unbiased estimate of $\xi(s)$ is obtained by cross-correlating the real data set with a sample of fake objects lacking any spatial correlation which, however, suffers from the same selection effects and incompleteness as the real catalogue. To obtain a sample of synthetic objects we first create a random sample of points uniformly distributed over the same area as the real data set, and then we generate their redshift distribution constrained to match that of the real objects determined by Pozzi et al. (2004). For each random catalogue we generate 10 times the number of fake objects as real galaxies.

The LS estimator is

$$\xi(s) = \frac{N_{DD}(s)}{N_{RR}(s)} \left( \frac{n_R}{n_D} \right)^2 - 2 \frac{N_{DR}(s)}{N_{RR}(s)} \left( \frac{n_R}{n_D} \right) + 1,$$

where $N_{DD}$, $N_{DR}$ and $N_{RR}$ are the weighted data–data, data–random and random–random pair counts with redshift-space separation $s$. $n_D$ and $n_R$ are the mean densities of galaxies and random objects, respectively.

The flux-limited nature of our data set is accounted for by weighting each galaxy by

$$w_i = \frac{1}{1 + 4\pi n(z_i) J_3(s)},$$

where $n(z_i)$ is the observed space density of galaxies at redshift $z_i$ and $J_3(s) = \int_0^s \xi(r)r^2 dr$ (Efstathiou 1988). To implement this weighting scheme, which requires prior knowledge of $\xi(s)$, we have adopted an iterative procedure in which we first compute $\xi(s)$ using $w_i = 1$ and then we fit a power law to the results in the range $1-10 h^{-1}$ Mpc. Then we compute the new weights $w_i$ by truncating the maximum value of $J_3$ to 1500. Only one iteration was needed to obtain a stable result.

To check the robustness of our results we have varied both the estimator of $\xi(s)$ and the weighting scheme. More precisely, we have also used the estimators of Hewett (1982), Davis & Peebles (1983) and Hamilton (1993). Moreover, for the case of the LS estimator only, we have implemented two alternative weighting schemes: the case of no weight (i.e. $w_i = 1$) and the case in which we weight by the inverse of the selection function [i.e. $w_i = n_D/n(z_i)$]. In all cases explored we have found that the various estimates of $\xi(s)$ were consistent, within the errors, in the range $1-10 h^{-1}$ Mpc.

3.2 Error estimation

To quantify the uncertainties in the estimate of $\xi(s)$ we have measured the correlation function in a sets of 30 independent mock galaxy catalogues designed to mimic the properties of the real ELAIS-S1 sample.
These mock catalogues were constructed from the $N$-body numerical experiment labelled L3S performed by Cole et al. (1998). Their simulation assumes a flat $\Lambda$-cold dark matter ($\Lambda$CDM) model cosmology with $\Omega_m = 0.3$, $\Lambda = 0.7$, an rms fluctuation of the mass contained in spheres of radius 8 $h^{-1}$ Mpc, $\sigma_8 = 1.13$ and a CDM power spectrum with shape parameter $\Gamma = 0.25$. The simulation box is of side 345.6 $h^{-1}$ Mpc and has 192$^3$ particles.

To construct each mock catalogue we have used three different outputs from the simulations (corresponding to redshifts of $z = 0$, 0.33 and 0.5) and took advantage of the periodic boundary conditions to obtain different configurations of points in each box by re-centring the coordinate system on a particle chosen at random. We have then stacked six boxes in order of increasing redshift (three of them at $z = 0$, two at $z = 0.33$ and one at $z = 0.5$), placed the observer at the centre of the first box and identified the $X$ coordinate with the direction of stacking. We have then identified the direction of the $X$ axis with the centre of the ELAIS field and considered all particles within an area of $2 \times 2$ deg$^2$ from the field centre. To assign each particle a redshift we have used the distance to redshift relation for a flat, $\Lambda$CDM universe,

$$ r \bigg( \frac{c}{H_0} \bigg) = \int_0^z \frac{dz'}{\sqrt{\Omega_m (1 + z')^3 + \Omega_{\Lambda}}} , $$

where $r$ is the comoving distance, and then added the line-of-sight component of the particle peculiar velocity. Finally, a population of mock galaxies have been extracted from the particles through a Monte Carlo rejection procedure designed to match the observed redshift distribution of real ELAIS galaxies in both the inner 40 $\times$ 40 arcmin$^2$ S1,R5-like, and the outer S1,Rest-like samples. This procedure has been repeated to obtain 30 mock ELAIS-S1 samples, containing $\sim$120 objects each, for which we have evaluated the two-point correlation function. The mean redshift distribution of fake objects in the 30 catalogues is shown in Fig. 2 (dashed line histogram) for the S1,R5 (top panel) and S1,Rest (bottom) rasters.

The filled dots in Fig. 3 show the average $\xi(s)$ in the 30 mock catalogues. The errorbars represent the rms scatter around the mean values. They constitute our estimate of errors in the measurement of the two-point correlation function of the real ELAIS-S1 galaxies. These errors account for cosmic variance and sample noise, which constitutes the main source of uncertainty. The large size of the sample guarantees that the 'integral constraint' correction is only 5 per cent (Gonzalez-Solares et al. 2004) and thus can be neglected in the error budget.

The open dots in Fig. 3 show the ‘true’ $\xi(s)$ of the simulation, measured by considering all particles in one of our ELAIS-like samples. The ‘true’ $\xi(s)$ is consistent with the average $\xi(s)$ of the mocks, indicating that our method for estimating $\xi(s)$ is indeed unbiased.

The mock ELAIS-S1 catalogues mimic the geometry and selection effects of the real sample and account for the spatial clustering and its evolution in a flat $\Lambda$CDM universe. However, they are not guaranteed to reproduce the clustering properties of the ISO galaxies unless, of course, these trace the underlying mass density field out to $z = 0.5$.

As we have verified a posteriori this is indeed the case, in the sense that the ‘true’ $\xi(s)$ in the range 1–10 $h^{-1}$ Mpc is well approximated by a power law where the best-fitting parameters, displayed in Fig. 3, are consistent within the errors with those determined in the analysis of the real ELAIS-S1 sample presented in the following section.

4 RESULTS

The filled dots plotted in Fig. 4 represent the two-point correlation function of the ELAIS-S1 galaxies computed using the LS estimator. The errorbars, evaluated from the 30 ELAIS-S1 mock catalogues, are the same as shown in Fig. 3. Clearly, $\xi(s)$ is well approximated by a power law out to separations of 10 $h^{-1}$ Mpc. In the range 1–10 $h^{-1}$ Mpc the best-fitting power-law model $\xi(s) = (s/s_0)^{-\gamma}$, has a correlation length of $s_0 = 5.4 \pm 1.2$ $h^{-1}$ Mpc and a slope $\gamma = 1.45 \pm 0.25$.
0.25, both determined at the 90 per cent confidence level. Including the correlation of galaxy pairs at separation \( s = 0.6 \, h^{-1} \text{Mpc} \), also shown in the figure, does not modify this result appreciably.

Breaking down the sample by redshift does not change the results significantly either. Indeed, in the local sample composed of 82 objects at \( z < 0.2 \), \( \xi(s) \) is still well approximated by a power law in the range \( 1-10 \, h^{-1} \text{Mpc} \) with best-fitting parameters \( s_0 = 5.4 \pm 1.6 \, h^{-1} \text{Mpc} \) and \( \gamma = 1.6 \pm 0.4 \). These values agree with those found for the distant sample of 66 objects at \( 0.2 \leq z < 0.5 \) for which we have found \( s_0 = 5.1 \pm 1.6 \, h^{-1} \text{Mpc} \) and \( \gamma = 1.4 \pm 0.4 \).

Finally, we have verified that evaluating errors from 100 bootstrap realizations of the ELAIS-S1 sample rather than from the mock catalogues does not change the results significantly as the correlation length only decreases by \( \sim 10 \) per cent and the slope becomes \( \sim 4 \) per cent flatter.

5 DISCUSSION AND CONCLUSIONS

In this work we have evaluated the redshift-space two-point correlation function of mid-infrared-selected galaxies in the deep \( (z \leq 0.5) \) ELAIS-S1 catalogue. We found a significant, positive correlation signal at separations \( \leq 10 \, h^{-1} \text{Mpc} \), where the two-point correlation function is well approximated by a power-law model \( \xi(s) = (s/s_0)^{-\gamma} \) with a correlation length of \( s_0 = 5.4 \pm 1.6 \, h^{-1} \text{Mpc} \) and a slope \( \gamma = 1.45 \pm 0.25 \), with errorbars referring to a 90 per cent confidence level. These results have been obtained using the LS estimator for \( \xi(s) \) and by evaluating the errors from a set of 30 mock ELAIS-S1 catalogues. These results are robust, in the sense that they do not change significantly when varying the method of estimating \( \xi(s) \) (see Section 3.1) or when using different strategies to assess the errors (Sections 3.2 and 4).

It is interesting to compare our results with those obtained from a similar analysis of galaxy clustering in redshift space. Table 1 shows our result together with the corresponding results obtained from some of the major galaxy redshift surveys, characterized by their passband/wavelength of selection (column 2) and the redshift ranges they cover (column 3). It is worth stressing that deviations of the two-point correlation function from a pure power-law shape are more serious in redshift space than in real space, making it difficult to compare results obtained from the analyses of different galaxy samples. To ensure a fair comparison, all best-fitting parameters listed in columns 4 and 5 of Table 1 refer to ranges of separations where all measured \( \xi(s) \) are well approximated by a power law. These ranges turned out to be very close to that of \( [1-10] \, h^{-1} \text{Mpc} \) considered in our analysis, although some of the parameters in the table have been obtained by pushing the estimate of \( \xi(s) \) down to scales as small as \( 0.1 \, h^{-1} \text{Mpc} \) (the 2dFGRS case) or up to separations as large as \( 16.4 \, h^{-1} \text{Mpc} \) (as in the case of the LCRS sample).

Our results are fully consistent with those obtained from the analysis of the Point Source Catalog (PSCz) survey (Hawkins et al. 2001), which consists of \( \sim 15 \, 000 \) IRAS galaxies selected at 60 \( \mu \text{m} \), i.e. in a mid-infrared band similar to that of ELAIS galaxies. This sample is, however, much more local than ours and thus the agreement between the two results indicates that the clustering properties of mid-infrared-selected objects do not evolve significantly between \( z = 0 \) and \( 0.3 \). This conclusion is corroborated by the consistency found between the two measurements of \( \xi(s) \) performed in the local \( (z < 0.2) \) and distant \( (0.2 \leq z < 0.5) \) ELAIS-S1 subsamples. Unfortunately, the large uncertainties in our estimate of \( \xi(s) \), that mainly result from the sparseness of the ELAIS-S1 galaxy catalogue, do not allow one to set strong constraints on the clustering evolution.

The lack of significant evolution in the ELAIS galaxy clustering has already been noted by Gonzalez-Solares et al. (2004). In their analysis, which consisted in deprojecting the angular correlation function of ELAIS galaxies via the Limber equation, they have measured a real-space two-point correlation function with a slope \( (\gamma = 2.04 \pm 0.18) \) and a correlation length \( (r_0 = 4.3_{-0.8}^{+0.4} \, h^{-1} \text{Mpc}) \) that are fully consistent with those measured in the PSCz catalogue \( (\gamma = 2.04 \pm 0.18 \text{ and } r_0 \geq 3.7 \, h^{-1} \text{Mpc}; \text{Jing, B¨ orner & Suto 2002}) \). It is worth stressing that the difference between our result and that of Gonzalez-Solares et al. (2004) originates from systematic redshift-space distortions that affect our analysis and result in a shallower slope and a larger correlation length of the two-point correlation function.

Focusing on the mid-infrared objects is of considerable interest since they trace the underlying mass distribution in the local Universe. The consistency that we have found between \( \xi(s) \) in the real sample and that measured in our mock ELAIS-S1 catalogues in which galaxies are identified with the particles of the parent N-body simulation, suggests that mid-infrared-selected galaxies are indeed almost unbiased tracers of the underlying mass density field out to \( z = 0.5 \).

It is interesting to compare our results with those obtained using optically selected galaxy samples, some of which are listed in Table 1. We confirm the well-known fact that infrared-selected objects are significantly less clustered than optical galaxies, although the discrepancy depends on the depth of the sample and (mainly) on the selection band, being larger for SDSS, \( r^* \)-selected objects than for 2dF galaxies selected in the \( b_i \) band.

Investigating how this discrepancy change with redshift, i.e. how the relative clustering of different objects evolve with time, is of fundamental importance since it will allow one to cast light on the galaxy formation and evolution processes. While this work constitutes an early step in this direction, strong observational constraints for theories of galaxy evolution will only be obtained by extending and improving samples such as ELAIS-S1, which implies carrying out larger and deeper infrared redshift surveys such as that already planned in the SWIRE programme (Lonsdale et al. 2003).

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Table 1. Clustering of different galaxy redshift surveys: the parameters of the power-law model.

| Survey        | Selection band | \( \Delta z \)  | \( s_0 (h^{-1} \text{Mpc}) \) | \( \gamma \) |
|---------------|----------------|-----------------|-----------------------------|------------|
| ELAIS-S1\(^a\)| 15 \( \mu \text{m} \) | 0.0–0.5         | 5.40 ± 1.20                 | 1.45 ± 0.25 |
| PSCz\(^b\)    | 60 \( \mu \text{m} \) | 0.004–0.1      | 4.77 ± 0.20                 | 1.30 ± 0.04 |
| CFA2\(^c\)    | \( b_i \)      | 0.0–0.05       | ~7.5                        | ~1.6       |
| ORS\(^d\)     | \( b_i \)      | 0.00–0.027     | 7.60 ± 1.20                 | 1.60 ± 0.10 |
| LCRS\(^e\)    | \( R \)        | 0.033–0.15     | 6.3 ± 0.3                   | 1.86 ± 0.03 |
| SDSS\(^f\)    | \( r^* \)      | 0.019–0.13     | ~8.0                        | ~1.2       |
| 2dFGRS\(^g\)  | \( b_i \)      | 0.01–0.20      | 6.82 ± 0.28                 | 1.57 ± 0.07 |

Notes. \(^a\) This analysis. \(^b\) Hawkins et al. (2001). \(^c\) de Lapparent, Geller & Huchra (1988). \(^d\) Hermit et al. (1996). \(^e\) Tucker et al. (1997). \(^f\) Zehavi et al. (2002). \(^g\) Hawkins et al. (2003).
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