

Studying Galaxy and Structure Formation with Complete Redshift Surveys

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Abstract

We briefly review the history of “complete” wide-angle redshift surveys of galaxies, highlighting the contribution of each survey to our current understanding of the nature of the galaxy distribution. We also review and discuss the constraints imposed on theories of galaxy and structure formation by the results of analyzes carried out with the CfA2 and SSRS2 surveys, currently the largest samples available for these kinds of studies.

1 Introduction

Among the several tools available to study the large-scale structure of the Universe, redshift surveys have played a pivotal role over the past two decades. If galaxies trace matter redshift surveys are a direct probe of the underlying mass distribution. If not, they contain important information about the way galaxies form. Either way, they represent the benchmark against which the success of any given theory of LSS formation has to be assessed. This has motivated the continuous effort of carrying out complete surveys to greater depths and of refining N-body simulations, most notably by investigating hydrodynamical effects to allow for more realistic galaxy formation.

Beginning in the mid 70s, several surveys covering large areas of the sky have been conducted probing the galaxy distribution to ever increasing depths. Complete optical and radio surveys like the RSA, CfA1, Arecibo, SSRS, CfA2 and SSRS2 have over the years revolutionized our ideas regarding the distribution of luminous matter. The CfA1 survey [18], the first three-dimensional survey to probe distances beyond Virgo, gave us the first hints that the Universe was rather inhomogeneous with the existence of large empty regions, while the Arecibo survey [17] showed the existence of large coherent structures extending over scales $\gtrsim 50$ Mpc. The existence of voids and large coherent structures were confirmed by the diameter-limited SSRS

[6], with an effective magnitude-limit roughly 0.5 mag fainter than that of CfA1. The fainter magnitude limit produced much sharper maps which allowed the identification of wall-like structures bounding large empty regions. The existence of such structures had already been predicted from the results of the first 6° slice of the CfA2 survey extending the magnitude limit to $m_{B(0)} = 15.5$ [11]. The extension of the CfA2 survey eventually uncovered the remarkable Great Wall [15] within which several clusters are embedded. The SSRS2 [7], with the same magnitude-limit of the CfA2, showed by probing a different region of the sky that wall-like structures and large voids are common features of the galaxy distribution. Their frequency and size may still prove to be important constraints for theoretical models (see section III). Finally, the Las Campanas Survey [23], the first of the new generation of multifiber redshift surveys, has shown that the picture that emerged from the nearby surveys seems to extend to large distances, strongly suggesting that we may have identified the largest scale of inhomogeneities. The activity in the area is still intense with several probe- or slice-like surveys probing greater depths being now near completion [1],[16],[36], [37]. It is important to emphasize that with only sparse or dilute surveys it would have been difficult to uncover the sharp, coherent features observed with dense surveys.

The net result of the effort of the past two decades has been to produce complete surveys of optically and infrared selected galaxies covering large areas of the sky. To a magnitude limit of $m_{B(0)} = 14.5$ the sample consists of about 6000 galaxies covering about 1/2 the sky [31]. A similar sample extending to lower galactic latitudes is also currently available [34]. To $m_{B(0)} = 15.5$ the combined CfA2+SSRS2 sample consists of over 15,000 galaxies with a sky coverage approaching 1/3 of the sky. Complementing these dense optical surveys, we also have the more dilute *IRAS* 1.2 Jy survey of ≈ 5000 infrared-selected galaxies [14], covering about 95% of the sky to an effective depth comparable to the CfA2+SSRS2 ($\gtrsim 120 h^{-1}$ Mpc). In addition, there are the sparsely-sampled surveys like the Stromlo-APM survey of optical galaxies [25] and the QDOT survey [33] of infrared selected galaxies probing larger volumes. Although an impressive achievement much remains to be done at large distances and a new generation of wide-angle surveys is about to start with the 2dF and the Sloan Digital Sky Survey.

Below we review some of the results that have been obtained from analyzes of CfA2 and SSRS2 surveys. These analyzes take advantage of the wide-angle coverage and the large number of galaxies in each sample. The wide-angle coverage allows to probe larger pair separations in three-dimensions and to extract information over a wide range of scales. We also use the samples individually and examine the sample-to-sample variations to evaluate the cosmic variance of the results. The large number of galaxies is important because the sample can be sub-divided by different criteria like luminosity, morphological type and colors to investigate the dependence of the the clustering properties on the class of objects considered.

2 Mapping the Galaxy Distribution

The CfA2+SSRS2 sample currently provides the best three-dimensional maps of the present-day galaxy distribution. Confirming growing evidence accumulated over the years there seems to be little doubt that galaxies lie preferentially along thin, coherent wall-like features that define large empty regions devoid of galaxies. While high-density regions can be traced to scales of $\approx 100 h^{-1}$ Mpc, it is thought that the relevant scale may be the linear extent of voids, typically $\approx 50 h^{-1}$ Mpc. Inspection of maps like that depicted in the poster of this meeting [7] strongly suggests that the distribution of galaxies consists of a closely-packed, volume-filling network of voids. This picture of the LSS is qualitatively consistent with the redshift maps of

the Las Campanas Survey [23] and the interpretation given to the redshift distribution observed by deep probes [4], while advocating the existence of much larger voids.

Unfortunately, even for the combined sample the surveyed volume is relatively small compared to the scale of voids. Not enough voids are fully contained within the survey volume to adequately test the hypothesis of a void-filled Universe. All we know with some degree of confidence is that a significant fraction of the volume is empty of galaxies and that large walls exist and are common. Whether we chose to think in terms of walls or of voids the relevant point is to determine whether there is a characteristic scale imprinted in the galaxy distribution and if so what it is. These informations are crucial since they may be clues to the process of formation of LSS and they may impose constraints on the amount of power required on large scales to give rise to the observed structures. Equally important is to ask whether small amplitude Gaussian random fluctuations can produce non-linear features with sizes and frequency of the observed walls. Even if galaxies are “painted” and do not delineate real voids in the underlying mass distribution, the existence of a characteristic scale would be important to constrain the biasing mechanism.

We point out that even if the observed distribution is adequately described by a void network, it is not trivial to have a proper definition of what a void should be in a distribution with power on different scales and to define a suitable algorithm to identify voids and to determine their size distribution which will depend on the definition of a void (see [20], [24]). The same difficulties are present in the case of numerical simulations. Claims that current models can produce redshift distributions similar to the observations, having no difficulty producing walls and voids similar to those observed, are as subjective as our claims of a void-filled Universe, leaving open the questions posed above.

It should be pointed out that if one assumes that the distribution is in fact void-filled one can in principle constrain the characteristic scale of the voids. One way of estimating the typical size of voids is by using the zero-crossing of the two-point correlation function, which in the case of a cellular-like distribution should occur at half the size of the cell. Monte-Carlo tests using mock surveys, drawn from a Voronoi tessellation with the same selection and observational mask as real surveys, indicate that current surveys like the combined CfA2+SSRS2 and Stromlo-APM may be large enough to provide a reasonable constraint on the typical size of voids [19] or at least distinguish between the scale seen nearby from that observed with the deep probes.

3 Voids as Constraints to Models

Since the discovery of the Bootes void [21] it has been recognized that the existence of large voids could pose a serious challenge to models of LSS. However, little work has been done in trying to quantify what these constraints would be despite the fact that since this first discovery dense surveys have shown that the voids are not only large but also frequent. They are seen in every direction we have surveyed.

Recently this question has been re-examined under the assumptions that we have a void-filled distribution, that galaxies trace the underlying matter distribution and that structures grow gravitationally [3], [32]. In the scenario advocated by these authors the present-day voids, those surrounded by high-density walls, result from the evolution of small underdense regions reaching shell-crossing today. By analysis of the evolution of inverted top-hat density fluctuations and statistical arguments it can be shown that at any epoch voids reaching shell-crossing are the largest defining a characteristic scale and roughly filling the volume.

From the inverted top-hat model one can also derive the amplitude required at horizon-crossing for the matter fluctuations to form a void of a given size at the present epoch. Equating

this value to the rms density fluctuation on a given scale constrains the amplitude of the linear power-spectrum. Using a generic power-spectrum $P(k) \propto k^n$ we can determine n by requiring the mass power-spectrum to also satisfy the normalization imposed by COBE on large scales, thus relating the value of n to the assumed scale of voids. The main results of this analysis [32] are that the formation of $50 h^{-1}$ Mpc voids in diameter in an $\Omega = 1$ universe can only be achieved if $n \sim 1.25$, violating the inflationary paradigm. On the other hand smaller voids, $35 h^{-1}$ Mpc in diameter, would be consistent with $n = 1$. Despite uncertainties in the theoretical calculation the work illustrates how the presence of large voids in the galaxy distribution can provide quantitative constraints to models of structure formation and should stimulate work in methods of extracting information on voids from redshift surveys.

So far calculations have been restricted to generic power-spectra and for a flat Universe with $\Omega = 1$. Extensions of these calculations are currently underway to consider open universes, with or without a cosmological constant, and more realistic power-spectra using the information extracted from redshift surveys as discussed below.

4 Galaxy Power-Spectrum

If galaxies trace matter the galaxy power-spectrum provides important information on the fluctuations of the mass distribution. We have used the CfA2+SSRS2 sample to estimate the redshift space power-spectrum [8]. The main results of this analysis are: 1) that on large scales the PS continues to rise ($n \sim -1.1$) showing only weak signs for a turnover on scales $\gtrsim 200 h^{-1}$ Mpc; 2) the differences between the PS computed from different samples are consistent with the error estimates based on mock surveys drawn from N-body simulations adopting the same selection criteria as the data; 3) the systematic differences between the PS can be accounted, at least in part, by different amounts of redshift distortions; 4) tests indicate that the results are not sensitive to the magnitude-limit adopted for the CfA2 sample; 5) that the feature on scales $30\text{-}50 h^{-1}$ Mpc [30] are clearly seen in 2 out of 3 samples considered and it is not an artifact of our method since the PS of mock surveys do not show a systematic occurrence of this feature; 6) evidence for the dependence of the amplitude of the PS on the luminosity of the galaxies, suggesting a relative bias between luminous and less-luminous galaxies [35].

A comparison of the PS of galaxies as determined from the combined CfA2+SSRS2 sample and that predicted by CDM models, both in redshift space, is shown in figure 1. The upper solid line represents the PS of a CDM model with $\Omega h = 0.2$ in a flat Universe with cosmological constant. The lower curve is a CDM model with $\Omega h = 0.5$. Both models are unbiased and normalized to $\sigma_8 = 1$. The excess power on scales $\sim 100 h^{-1}$ Mpc favors a CDM model with minimal bias and $\Omega h = 0.2$. Note that both cases are consistent with the constraints imposed by COBE on large scales. The feature at the $\sim 30 h^{-1}$ Mpc scale is also clearly seen and it may be a signature of the observed voids. We should point out that our the shape of our PS is consistent with other estimates based on infrared-selected galaxies [12] apart from a shift in the amplitude which reflects the relative bias between the two populations of galaxies.

5 Small Scales Peculiar Velocities

An important constraint on models of structure formation comes from the measurement of peculiar velocities of galaxies on small scales. As it is well known, the prediction of large peculiar velocities on small scale inconsistent with much lower observational estimates [10] is a major drawback of the unbiased $\Omega = 1$ CDM model. Before the COBE era it was possible

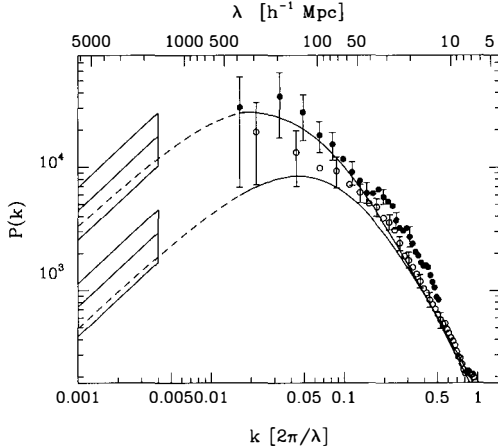


Figure 1: Comparison of the observed power-spectrum of galaxies and that predicted by different CDM models, both represented in redshift space.

to circumvent this problem by arguing that galaxies were biased relative to the mass which allowed some freedom in the normalization of the mass power-spectrum. However, this is no longer possible and demands a new examination of the problem both theoretically and observationally.

On the theoretical side, recent results from high-resolution N-body simulations [38] have shown that simulations with not sufficient mass resolution can significantly overestimate the value of the pairwise radial velocity dispersion used in the comparison to the data. On the observational side, we have used the CfA2+SSRS2 sample to determine the small scale peculiar velocities as measured by the pairwise velocity dispersion σ_{12} [26].

The method used to extract the information of peculiar velocities from redshift surveys is based on the calculation of the two-dimensional correlation function $\xi(r_p, \pi)$ as function of the projected separations perpendicular r_p and along the line-of-sight π . In figure 2 we show a contour plot of $\xi(r_p, \pi)$ calculated for the combined CfA2+SSRS2 sample. Note the significant elongation of the contours along the π axis at small separations, indicative of strong redshift distortions on small scales and the compression along the r_p axis, extending to scales $\gtrsim 15 h^{-1}$ Mpc, usually attributed to streaming motions.

The correlation function $\xi(r_p, \pi)$ may be expressed as a convolution of the spatial correlation function $\xi(r)$ with the distribution of pairwise peculiar velocities which, under the assumptions of isotropy and slowly varying velocity dispersion, can be expressed in terms of the first two moments, the relative streaming velocity v_{12} and the pairwise velocity dispersion σ_{12} [10]. If one assumes a specific model for the pairwise velocity distribution and for the variation of the streaming motion as a function of the pair separation, fits of $\xi(r_p, \pi)$ at different r_p may be used to derive σ_{12} as a function of r_p .

In the analysis we have assumed that the pairwise velocity distribution is an exponential and that the functional form of v_{12} is given by the self-similar solution of the BBGKY. The derivation of σ_{12} was carried out for different amplitudes of streaming. The main results of the

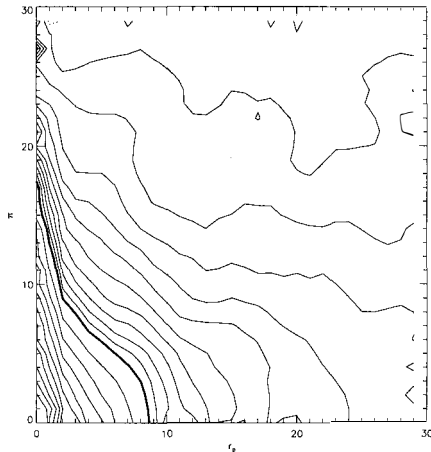


Figure 2: The two-dimensional correlation function $\xi(r_p, \pi)$ of the combined CfA2+ SSRS2 sample from which information on the peculiar velocities of galaxies on small scales is derived.

analysis are the following [26]. We find that our best estimate for the pairwise velocity dispersion is $\sim 540 \text{ km s}^{-1}$ considerably higher than earlier estimates (340 km s^{-1}). However, this value has a large uncertainty which has been estimated from the variation of σ_{12} as determined from the independent analysis of the SSRS2, CfA2S and CfA2N subsamples. Clusters are the main contributors to σ_{12} . When clusters are removed the value of the dispersion drops to $\sim 300 \text{ km s}^{-1}$ in agreement with the results for CfA1 and for the IRAS 1.2 Jy [13]. The dominant source of variance in the estimate of σ_{12} is the shot noise of dense virialized systems. An accurate determination of the dispersion would require probing volumes at least 7 times larger than that of the CfA2+SSRS2 sample as estimated from the observed distribution of velocity dispersions in dense systems or the mass distribution of bound systems expected by the Press-Schechter formalism for a COBE normalized CDM model. The main conclusion is that an $\Omega = 0.2$ CDM model would be consistent with our determination of small scale velocities, consistent with the results obtained with the galaxy power-spectrum.

6 Galaxy Properties

The large number of galaxies and the dense sampling of the galaxy distribution afforded by the CfA2 and SSRS2 surveys make them also suitable to investigate properties of galaxies, their relation with the environment and biasing of different galaxy populations. The use of these surveys for these purposes has so far been limited.

The magnitude limit of the CfA2 and SSRS2 allows the determination of the luminosity function of local galaxies to a relative faint absolute magnitude limit ($M \approx -14$). This function is essential to correct the samples for selection effects and to investigate galaxy evolution. The luminosity function for galaxies of all morphological types has been calculated by for the

CfA2 [27] and the SSRS2[7] samples. The results are somewhat puzzling because there is a significant disagreement between the computed Schechter parameters. While the SSRS2 yields results which are consistent with those computed for the APM survey [25], the value of M_* is considerably fainter as determined from CfA2. Some possible effects that may account for the differences are possible systematic errors in the Zwicky magnitude scale and/or incompleteness of the Zwicky catalog. However, it is important to emphasize that no compelling evidence currently exists to confirm either of these possibilities. Curiously, the peculiar motions in the regions covered by the CfA survey are large, while the volume of space surveyed by the SSRS2 seems to be a particularly quiet region as judged by the small distortions of $\xi(\tau_p, \pi)$, primarily because of the paucity of rich clusters within the volume. This difference may have a bearing on the discrepancy found between the luminosity functions and should be investigated in more detail.

The large number of galaxies in the samples also allow them to be sub-divided according to different criteria. Taking advantage of this fact, it has been possible to investigate the dependence of the local luminosity function on the morphological types [28]. The results indicate that the LF is similar for all morphological types except for irregular galaxies, which are found to have a much steeper faint-end slope. These results have been confirmed by similar analysis using the SSRS2 [9] which is based in an independent parent catalog and morphological typing. We note that the luminosity functions of early-type galaxies derived from CfA2 and SSRS2 are very similar to those of spirals, in clear disagreement with recent claims that early-type galaxies would have a much flatter faint-end slope.

The overlap which exists between the SSRS2 sample and the ESO-Uppsala Surface Photometry Catalog [22] south of $\delta = -17.5^\circ$ allows colors to be assigned for a significant fraction of galaxies in the SSRS2. We are currently using this color information to examine the dependence of the local luminosity function on color. The distinction between color and morphology is important because although correlated the dispersion in the relation is very large to allow a meaningful morphological classification based on color alone. Preliminary results [29] indicate significant differences in the luminosity function of the two populations with blue galaxies having a very steep faint-end slope $\lesssim -2$, comparable to that obtained for irregular galaxies. This result suggests that a nearby population of blue galaxies may contribute to the faint galaxy counts. Such information is essential to constrain models of galaxy evolution.

Another important application of the large samples available is the study of the relative bias of galaxies of different luminosities and morphological types. This information may be used to place some constraints in the process of galaxy formation. We are currently investigating these effects using the SSRS2. Some preliminary results are reported elsewhere in this volume [2],[5]. For these kind of studies it is critical to be able to examine different classes of objects in the same volume of space in order to distinguish between real clustering differences from effects which may arise when results obtained from different volumes, probing different structures, are compared. This usually requires discarding a significant fraction of the galaxies in the sample. However, with the large samples currently available it is possible to construct suitable volume-limited samples for this kind of analysis. As discussed elsewhere in this volume, preliminary results indicate that galaxies with $L > L_*$ are biased relative to fainter galaxies with the bias depending on the luminosity. Fainter galaxies have clustering properties similar to those of *IRAS* galaxies.

7 Summary

Wide-angle surveys of the nearby Universe have had and will continue to have an enormous impact on studies of LSS providing a wealth of information that one may use to confront and discriminate competing models for the origin of structures.

The CfA2 and SSRS2 surveys have provided dense maps of the distribution of galaxies within a volume $120 h^{-1}$ Mpc in radius. New instrumentation like the 2dF spectrograph at the AAT and the Sloan Digital Sky Survey (SDSS) will allow large angular coverage to much greater depths which will further contribute to our understanding of the way galaxies are distributed not only locally but at different look-back times. Data from these new generation surveys, new measurements of CMB anisotropies on different angular scales and more detailed maps of the peculiar velocity field of galaxies and clusters will keep theorists busy for a long time.

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References

- [1] Bellanger, C., de Lapparent, V., Arnouts, S., Mathez, G., Mazure, A. & Mellier, Y. 1995, *Astr. Astrophys. Suppl. Ser.* **110**, 159
- [2] Benoist, C. et. al. 1995, in this volume.
- [3] Blumenthal, G.R., da Costa, L. N., Goldwirth, D. S., Lecar, M. & Piran, T. 1992, *Astrophys. J.* **388**, 234
- [4] Broadhurst, T. J., Ellis, R. S., Koo, D. C., & Szalay, A. S., 1990, *Nature* **343**, 726
- [5] Cappi *et al.* 1995, in this volume
- [6] da Costa, L. N., Pellegrini, P. S., Sargent, W.L.W., Tonry, J., Davis, M., Meiksin, A., Latham, D.W., Menzies, J.W. & Coulson, I. 1988, *Astrophys. J.* **327**, 544
- [7] da Costa, L. N., Geller, M. J., Pellegrini, P. S., Latham, D. W., Fairall, A. P., Marzke, R. O., Willmer, C. N. A., Huchra, J. P., Calderon, J. H., Ramella, M. & Kurtz, M. J., 1994, *Astrophys. J.* **424**, L1
- [8] da Costa, L. N., Vogeley, M., Geller, M. J., Huchra, J. & Park, C., 1994, *Astrophys. J.* **437**, L1
- [9] da Costa, L. N., Marzke, R., Pellegrini, P. S. & Santarosa, G. 1995, in preparation.
- [10] Davis, M. & Peebles, J., 1983, *Astrophys. J.* **267**, 465
- [11] de Lapparent, V., Geller, M.J. & Huchra, J. H., 1986, *Astrophys. J.* **302**, L1
- [12] Fisher, K. B., Davis, M., Strauss, M. A., Yahil, A. & Huchra, J. P. 1993, *Astrophys. J.* **402**, 42
- [13] Fisher, K. B., Davis, M., Strauss, M. A., Yahil, A. & Huchra, J. P. 1994, *Mon. Not. R. Astr. Soc.* **267**, 927
- [14] Fisher, K., Huchra, J. P., Strauss, M., Davis, M., Yahil, A. & Schlegel, D. 1995, preprint

- [15] Geller, M., & Huchra, J. P., 1989, *Science*, **246**, 897
- [16] Geller *et al.* 1995, in preparation
- [17] Haynes, M. P. & Giovanelli 1986, *Astrophys. J.* **306**, L55
- [18] Huchra, J. P., Davis, M., Latham, D.W. & Tonry, J. 1983, *Astrophys. J. Suppl. Ser.* **72**, 433
- [19] Goldwirth, D., da Costa, L. N. & van Weygaert, R. 1995, *Mon. Not. R. astr. Soc.* , in press
- [20] Kauffmann, G. & Fairall, A. 1991, *Mon. Not. R. Astr. Soc.* **248**, 313
- [21] Kirshner, R. P., Oemler, A., Schechter, P. L. & Schectman, S. A. 1981, *Astrophys. J.* **248**, L52
- [22] Lauberts. A. & Valetjin, E. A. 1989, ESO-Uppsala Catalog of Surphace Photometry (Garching:European Southern Observatory)
- [23] Lin, H. 1995. in this volume
- [24] Lindner, U., Einasto, J., Einasto, M., Freudling, W., Fricke, K. & Tago E. 1995, *Astr. Astrophys.* , in press
- [25] Loveday, J., Peterson, B. A., Efstathiou, G., & Maddox, S. J., 1992, *Astrophys. J.* **390**, 338
- [26] Marzke, R., & Geller, M. J., da Costa, L. N. & Huchra, J. P. 1995, *Astron. J.*, in press
- [27] Marzke, R., Huchra, J. P., & Geller, M. J., 1994, *Astrophys. J.* **428**, 43
- [28] Marzke, R., Huchra, J. P., & Geller, M. J., 1994, *Astron. J.* **108**, 437
- [29] Marzke, R. & da Costa, L. N. 1995, in preparation
- [30] Park, C., Vogeley, M., Geller, M. J. & Huchra, J. P. 1992, *Astrophys. J.* **391**, L51
- [31] Pellegrini, P.S, da Costa, L. N., Huchra, J. P., Latham, D. W. & Willmer, C. A. 1990, *Astron. J.* **99**, 751
- [32] Piran, T., Lecar, M., Goldwirth, D. S., da Costa, L. N. & Blumenthal, G. R. 1993, *Mon. Not. R. Astr. Soc.* **265**, 681
- [33] Rowan-Robinson *et al.* , 1990, *Mon. Not. R. Astr. Soc.* **247**, 1
- [34] Santiago, B., Strauss,, M.A., Lahav, O., Davis, M., Dressler, A. & Huchra, J. 1994, preprint
- [35] Vogeley, M., Park, C., Geller, M. J., Huchra, J.P. & Gott, J.R., 1994 *Astrophys. J.* **420**, 525
- [36] Willmer, C.N.A., Koo, D.C., Szalay, A.S. & Kurtz, M.J. 1994, *Astrophys. J.* **437**, 560
- [37] Zucca, E, 1995, in this volume
- [38] Zureck, W., Quinn, P.J., Salmon. T. K. & Warren, M.S. 1994, *Astrophys. J.* **431**, 559