Large-Scale Structure from Wide-Field Surveys

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Abstract. In this introductory talk I give an elementary overview of the development, current status, and near term outlook for three probes of large scale structure; galaxy clustering, bulk flows and weak lensing observations.

1 The Paradigm for Structure Formation

This meeting is largely concerned with the major observational expansion occurring in the field of wide-field cosmological surveys. These advances are taking place on a number of fronts, and promise to provide clear answers to a number of outstanding cosmological questions. The fertility of this field owes much to the fact there has long been a strong paradigm for structure formation; that the structure we see in the Universe traces its roots back to small random fluctuations in the early Universe which have evolved to the present by relatively well understood physics. While this picture may be wrong, and has certainly undergone considerable evolution over time, it has provided an important and influential framework for the interpretation of cosmological observations.

The roots of this paradigm go back to Harrison [1] and Zel'dovich [2] who first seriously discussed the implications of the assumption that structure originated in the big-bang; pioneering advances were made by Peebles and others [3] in quantitative calculation of the evolution of fluctuations from the radiation dominated era to the present, and this 'hierarchical clustering scenario' was developed to a refined state by Gott and Rees [4] who painted a picture for the fluctuation spectrum very similar in fact to the predictions from currently popular models. Their 'phenomenological' approach, working backwards from the observed state of structure, was followed by the development of inflationary scenario [5] in which the Universe passes through a phase of accelerated expansion which leaves the Universe in a state close to critical density. This is terminated by re-heating [6] and followed by the radiation era and finally matter domination.

On this background cosmology one can compute the evolution of linearized fluctuations. It is a remarkable achievement that this analysis allows one to follow a fluctuation with present scale equal to that of a galaxy or cluster or supercluster from when it was not much larger than the Planck scale. In models like 'chaotic inflation' these fluctuations start off as essentially massless zero-point fluctuations of the 'inflaton' field which, when they reach the horizon scale, get frozen in as fossilized ripples in the spatial curvature [7, 8, 9, 10], destined to re-enter the horizon at much later times as classical density perturbations with the so-called 'Harrison-Zeldovich' spectrum. The evolution from the radiation to matter dominated eras and through decoupling is solvable by integrating the Boltzmann equation [11, 12]. At later time the evolution of fluctuations proceed through the linear, quasi-linear ($\Delta\rho/\rho \sim 1$), and into the non-linear regime. If the universe is dominated by collisionless dark matter then the non-linear evolution can be calculated by a variety of techniques, from direct N-body to analytic approximations. The culmination of this evolution is shown by the Virgo consortium simulation [13].

Much of our knowledge of the large-scale structure comes from the distribution of galaxies. Here the otherwise clean theoretical predictions for the matter distribution become murky due to the possibility that the galaxy distribution may be 'biased' in some way. There are various types of bias that can arise. One is the statistical 'high peaks' bias. This mechanism explains the anomalously strong clustering of clusters of galaxies [14], and has been explored by analytic [15] and numerical [16] methods. The idea that galaxies may be biased in this way is attractive, since it might provide a way to reconcile dynamical estimates of Ω with a closed Universe. The applicability of these results to real galaxies however remains unclear, and there is the possibility of competing effects from astrophysical biases such as ram pressure stripping of gas from disk galaxies as they fall into clusters which would tend to counteract the statistical bias effect. In the face of these uncertainties, the common approach is simply to parameterize the effect by a bias factor b, which gives the ratio of density contrast of galaxies to that of the matter, and treat this as a phenomenological parameter to be fixed by observations.

This dark-matter dominated hierarchical clustering paradigm has lasted well and accounts, quantitatively at least for much of structure we see in the distribution of galaxies today and at smaller scales at higher redshift in absorption systems. The simplest version of the theory ($\Omega_m = 1$, CDM) is now disfavored both from large-scale structure observations and on other grounds [17, 18], but there are various avenues for modification that have been fruitfully explored; one can modify the early-universe physics and there have been a plethora of inflationary models proposed, and one can modify the matter content by incorporating hot dark matter for instance. Defects offer another possibility, and the consequences of non-trivial self-interaction of the dark matter have barely been explored. The upshot of these models are predictions for the power spectrum of mass density fluctuation $P(k)$ that can be tested against observations in a number of ways.

2 Galaxy Clustering

Galaxy clustering is the most mature of the probes of LSS and, for redshift surveys at least, gives a very direct way to probe the power spectrum. One can, for instance, compute the variance of galaxy fluctuations counts in cells σ^2 as a function of cell, or smoothing, scale, and this is then related to the power spectrum by

$$\sigma^2 = b^2 \int d^3k\, W^2(k) P(k) \tag{1}$$

where $W(k)$ is the transform of the smoothing volume. This is only illustrative, and more sophisticated techniques are actually used to measure $P(k)$ and estimate the measurement errors.

Low-redshift, large solid angle, redshift surveys such as the CfA, IRAS, LCRS and SSRS surveys [19, 20, 21, 22, 23] have established a number of facts: The power-law form for the 2-point function $\xi_{\rm gg}(r) \propto r^{-\gamma}$ with $\gamma \simeq 1.8$ [24, 25, 26] corresponding to $P(k) \propto k^n$ with $n \simeq -1.2$, and the scaling of the 3- and 4-point functions ζ, η. The 'cosmic virial theorem' [24] result that if galaxies trace the mass then $\Omega_m \simeq 0.2 - 0.3$. The strong relative bias as a function of morphological type [27, 28, 29]. The large-scale filamentary or web-like inter-cluster structure, which resonates with the theoretical picture [30]. The power spectrum has been measured [31, 32, 33, 34] and seems to continue rising with wavelength to $\lambda \sim 200h^{-1}$Mpc, in conflict with standard CDM predictions, beyond which the data give out. There have been attempts to measure the redshift-space distortion effect [35, 36] but these have been somewhat noisy to date.

Deeper pencil beam surveys show a remarkable regularity of the distribution of clumps of galaxies [37], and there have been suggestions that the large scale structure in the LCRS [38] also appears non-Gaussian, though see [39]. The CFRS survey [40] shows strong negative evolution of the clustering strength going back to $z \simeq 1$, which has been compared to theoretical predictions by Peacock [41], though this to be contrasted with the strong clustering found by Steidel and colleagues [42, 43] in their $z \sim 3$ color selected survey where we are perhaps seeing statistical 'high-peaks' biasing of galaxies in action.

Angular surveys provide an important complement to z-surveys; the clustering is smeared out somewhat in projection, but the great volume of these surveys makes them potentially valuable probes of $P(k)$ beyond the expected peak in $P(k)$. The 2-D power spectrum is simply related to the 3-D spectrum by a convolution in log frequency space [44], and deconvolution of the measured angular power spectrum [45] suggests that we are already seeing the turnover.

In the near term future the big developments in relatively low redshift, large solid angle surveys will be the Sloan SDSS [46, 47] and Anglo-Australian 2dF [48, 49] surveys. These should probe the power spectrum to lower k and should convincingly reveal the turnover in $P(k)$ if it exists. They should give the signal to noise required to measure the z-space distortion effect. It should be possible to better quantify the dependence of galaxy clustering on galaxy type, and the higher precision for higher order statistics open up the possibility of testing for dynamical and bias associated non-gaussianity [50], and may also provide constraints on non-gaussianity of the primordial fluctuations [51]. The successor to the LCRS survey will be the DEEP survey, which will explore a slice of the Universe at $z \sim 1$, allowing detailed study of the evolution of clustering, and z-space distortion effect [52], including the asphericity due to the cosmological background [53, 54]. State of the art high redshift surveys [55] extend to magnitudes $m_I \sim 23$, at which point spectra take several hours on a 10m class telescope to obtain and there are severe problems in getting firm redshifts for many faint galaxies at $z \sim 2$. The VIRMOS survey, with its 120 VLT nights, should however make a significant impact here. Clustering studies from angular surveys will benefit from the development of wide format CCD cameras [56, 57] and will further benefit from photometric redshift estimation [58, 59, 60] which will help the deprojection. Many of the talks in this volume expand on these points.

3 Bulk-Flows

Bulk-flow studies developed somewhat later. The idea here is that there should be distortion of the cosmic expansion field associated with the growth of structure, so if one can determine accurate redshift independent distances to galaxies then one can measure this 'peculiar velocity field' (for reviews see [61, 62, 63, 64]). This provides a probe of $P(k)$ with the variance in velocity smoothed on some scale being

$$\sigma_v^2 = \int d^3k \; (H/k)^2 W^2(k) P(k) \tag{2}$$

Advantages of this technique are that it provides a direct probe of the mass fluctuations independent of bias, and also (essentially due to the $1/k^2$ weighting in the integral here) provides a nice probe of fluctuations in the linear and quasi-linear regimes. The disadvantage is that the technique is limited to the fairly nearby Universe because of the nature of the distance errors. Bulk flow $P(k)$ measurements [65, 66] are therefore subject to substantial sampling, or 'cosmic', variance. These observations can however also be profitably used to compare the inferred mass fluctuations with the galaxy distribution (by POTENT or other techniques [67, 68]), and in this way test the gravitational instability picture.

The early history of bulk-flow measurements was at times confusing and contradictory, but by the late 80's a fairly coherent picture emerged [69, 70] from samples of typically several hundreds of galaxies, of substantial flows on fairly large-scales, and that the 600 km/s motion of the local group with respect to the microwave background radiation is neither atypical nor a small-scale local fluctuation. The divergence of these flows seems to (anti) correlate with the galaxy distribution [71, 72] as expected in the gravitational instability picture. Most of these comparative studies have concentrated on IRAS galaxies, and seem to indicate a rather high value of Ω [64], subject to the question of bias, though see [73]. This result is supported by the 'dipoles' analysis [74] which seems to suggest that the acceleration of the local group agrees in direction with the observed motion, and, if the acceleration has converged, that Ω is high. One should not discount here the possibility of additional attraction from large scales [75]. The '7-samurai' study [70] led famously to the discovery of the Great Attractor [76, 77, 78]; which we take to be the conclusion that there is a large mass concentration lying behind Centaurus cluster – this cluster's large apparent motion with respect to to the MBR not being predicted from the distribution of IRAS galaxies at least [71].

More recently, and with much effort, the sample sizes have been increased to thousands of galaxies [79, 80]. The comparison [81] of the MkIII velocities with the IRAS galaxy distribution revealed some rather worrying systematic discrepancies, including flow patterns of a form hard to reconcile with gravitational instability, but the comparison of the IRAS galaxy distribution with the SFI velocity dataset [82] seem to show better agreement, and seem to further support a high density Universe $\beta \equiv \Omega^{0.6}/b \simeq 0.6$ in line with other studies above. Brightest cluster galaxies [83] provide an attractive way to increase the sample depth, but the results remain somewhat controversial. An important development taking place is the augmentation of the conventional Tully-Fisher, Faber-Jackson, $D_n - \sigma$ techniques with distances from surface-brightness fluctuations [84] which give greatly reduced statistical uncertainty, and 1a supernovae distances [17] may also provide a useful check on the other techniques.

In contrast to the apparent strong flows on large-scales the small scale flow field is remarkably cold [85, 86]. This has been characterized as the 'cosmic Mach number problem' [87] and remains a challenge to cold-collisionless dark matter models.

4 Weak Lensing

Weak lensing, in the sense of the statistical distortion of the shapes of faint background galaxies, has now been measured for quite a number of clusters: [88, 89, 90, 91, 92, 93, 94, 95, 96, 97, 98, 99, 100, 101, 102], and provides a direct measurement of the total mass distribution in clusters. Following the pioneering attempt of Tyson and colleagues [103] using photographic plates, several groups [104, 105, 106, 107]) have reported CCD measurements of the 'galaxy-galaxy lensing' effect due to dark halos around galaxies, and there have also been estimates of the shear due to large-scale structure [108, 109, 110], the shear variance being related to the power spectrum by

$$\sigma_\gamma^2 \sim (H_0 D/c)^3 \int d^3k \; (H/k) P(k) \tag{3}$$

and there has been much theoretical activity in prediction of large-scale shear [111, 112, 113, 114, 115, 44, 116, 117] and in reconstruction techniques [118, 119, 120, 121, 122]. Most of the observational studies have been made with fairly small CCD detectors; this severely limits the distance out to which one can probe the cluster mass distribution and also limits the precision of galaxy-galaxy lensing and large-scale shear studies.

Recently we have presented a weak lensing analysis [123] of deep I and V photometry of the field containing the $z \simeq 0.42$ supercluster MS0302+17 taken with a large 8192×8192 pixel CCD mosaic camera, the UH8K [56], mounted behind the prime focus wide field corrector on the CFHT. The field of view of this camera on this telescope measures $0^\circ.5$ on a side, and greatly increases the range of accessible scales.

We assembled the $\sim$ 5hrs of multiple exposure into a composite image on which we detected $\sim 40,000$ faint galaxies whose shapes we measured to obtain estimates of the weak lensing shear field $\gamma(r)$ and thereby the dimensionless surface density $\kappa(r)$, the ratio of the physical surface density to the critical density, as shown in the left panel of figure 1.

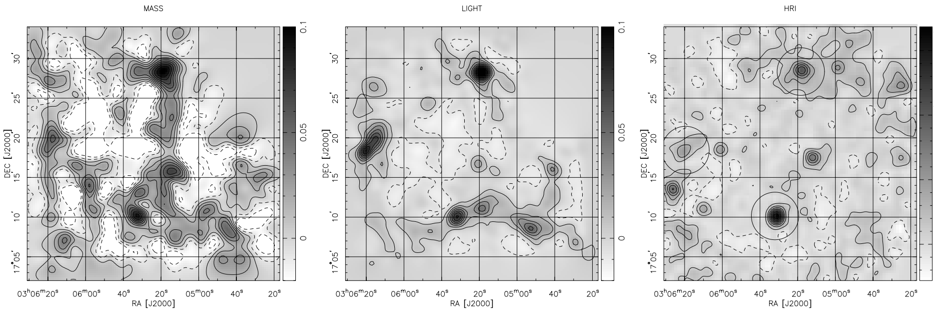

Figure 1: Left hand panel shows the 2-D mass reconstruction. The center panel shows the predicted κ due to structures at $z \sim 0.2 - 0.6$ assuming that early type galaxies trace the mass. Right hand panel shows a smoothed X-ray image from the ROSAT HRI; sources other than those circled appear to be point-like in the unsmoothed image and are most likely unassociated with the supercluster.

Our hope was to compare the mass distribution with the distribution of galaxy light in the supercluster, but measuring the latter proved to be difficult due to the presence of foreground clusters. The elliptical galaxies in the supercluster and other high-z structures are however readily separable from the foreground clutter and we were able to generate a prediction for $\kappa(r)$ assuming that the mass is distributed like these E-galaxies. We did not expect this to agree with the measured mass; E-galaxies are known to be strongly clustered and concentrated in the densest parts of clusters, with the bulk of the population having more extended profiles, and in high density biased models the dark matter would be yet more extended. To our surprise the predicted and observed shear agreed remarkably well (see figure 1). There is considerable noise in the reconstructions, but we can make a fairly precise estimate

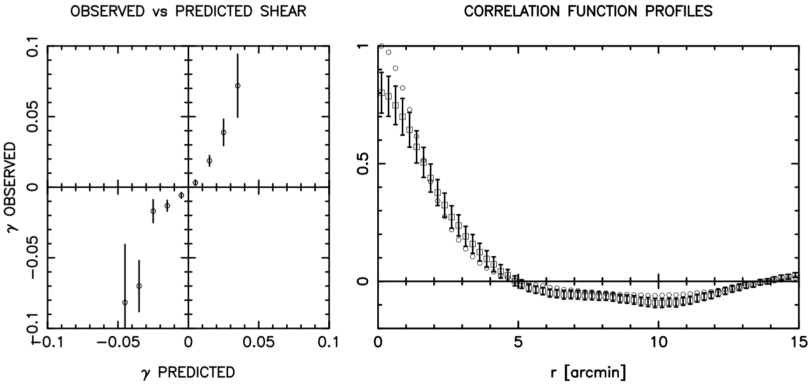

Figure 2: Left panel shows the strong correlation between the measured shear and that predicted, here computed assuming early type galaxies trace the mass with a nominal mass-to-light ratio $M/L = 200h$ and assuming a mean effective redshift for the background galaxies of $z = 1.5$. Fitting for a linear relation gives $M/L \simeq 250h$. Symbols with error bars in the right hand panel shows the cross correlation of the measured surface density with the luminosity density (for $M/L = 280h$) and the circles show the auto-correlation of the luminosity surface density.

of the cross-correlation between the mass and the light as shown in figure 2. The mass-to-light ratio we measure on the largest scales ($\lambda \sim 6h^{-1}$Mpc) is $M/L_B \simeq 280h$, and is very similar to that we find for the centers of the clusters, and is considerably lower than has been found for ultra-massive clusters like A1689 [96]. The clusters in MS0302+17 do not have extended halos, and the mass follows the E-galaxy profile very accurately.

Exactly what these results imply for the cosmological density parameter remains somewhat unclear due to to the possibility of bias, but, at face value, indicate that there is very little mass associated with late type galaxies, that the density parameter is very low $\Omega \simeq 0.05$, and that much or perhaps all of the dark matter is baryonic.

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