Probing the Universe Using a Mostly Virtual Survey: The Garching-Bonn Deep Survey

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We have entered a new era of powerful instruments, enabling high-precision cosmological observations. The Wide-Field-Imager (WFI) at the ESO/MPG 2.2-m telescope is a precursor of them since its field of view is large and of superb image quality. We employed the WFI to compile the *Garching-Bonn Deep Survey* (GaBoDS), where most of the high-quality images are obtained via data mining the ESO archive. This large *virtual* survey is used to determine some of the statistical properties of the Universe utilising weak gravitational lensing.

Gravitational lensing describes the deflection of light from distant objects by intervening mass concentrations in the Universe. Galaxy images which are affected by lensing change their apparent position and flux, but the main observable is a systematic distortion of their shape. Amongst the most prominent examples of gravitational lensing are strongly deformed images of objects behind massive galaxy clusters. They can appear as very elongated, arc-like structures or even as multiple images from a single source as shown in Figure 1.

During the last decade large-format CCD mosaic cameras have been developed which can map up to one square degree of the sky with a single exposure. Furthermore, significant improvements in the image quality of optical observations have been achieved. With these technical developments and expanding data sets, lensing studies have increasingly concentrated on the *weak lensing regime* of field galaxies. Here, the coherent gravitational light deflection of distant galaxies by the tidal gravitational field of the large-scale structure (LSS) in the Universe induces only weak shape distortions of galaxy images. This weak gravitational lensing effect by the LSS is called *cosmic shear* and can only be measured statistically by averaging the distortion signal of many background galaxies.

After its first detection in 2000, cosmic shear has become one of the pillars of our cosmological model. Gravitational light deflection is independent of any assumptions on the relation between dark and luminous matter. It can therefore explore the statistical properties of the LSS and constrain cosmological parameters. Furthermore, the cosmic shear signal can be used to reconstruct maps of the projected mass density field of the LSS. By cross-correlating these maps with galaxy surveys, one can study galaxy biasing as a function of redshift and angular scale. Here we present a report on our cosmic shear and galaxy biasing analysis of the GaBoDS.

GaBoDS – a mostly virtual survey

In 2002, our group started a weak lensing survey with the WFI at the ESO/MPG 2.2-m telescope. The WFI mosaic camera turned out to be an excellent instrument for weak lensing studies because it has a very well-behaved point spread function (PSF) over the whole field of view (FOV; see Figure 2).

The shape distortion of distant galaxy images induced by the LSS is weak and its measurement very noisy since the images of faint distant galaxies typically comprise only a few CCD pixels. Hence, besides the necessary analysis tech-

Figure 1: The rich lensing cluster RXJ1347-1145 at a redshift $z = 0.45$. It was observed with the ACS on board the HST for a total of nine orbits in the three broad-band colours *g*, *i* and *z*. Image by Thomas Erben and Tim Schrabback.

niques to extract a reliable source catalogue, we need high-quality data to perform a successful cosmic shear analysis:
– The data must be observed under superb seeing conditions in clear, dark nights. This ensures a sufficiently high number density of faint background sources to obtain statistically significant results.
– Weak lensing surveys of at least 10–20 square degrees are necessary to obtain significant cosmological constraints. The fields should be spread over a large fraction of the sky in order to have a statistically representative sample.
– A quantitative analysis of lensing signals requires knowledge of the redshift distribution of the galaxy population which is best obtained from the cosmic shear data itself, for instance in the form of photometric redshifts.

It turns out that a cosmic shear survey of about 10 square degrees is very difficult to execute with regular observing proposals on a short timescale, even with wide-field imaging and Service mode observations which ensure data of high quality. On the other hand, several observing programmes, such as the multi-colour ESO Deep Public Survey[1] (DPS, Hildebrandt et al. 2006a) or the Capodimonte Deep Field[2], obtained data which are well suited for cosmic shear studies. After a one-year proprietary period (not for the DPS) those data sets became publicly available to the astronomical community via the ESO archive and we could immediately add them to our own observations. Therefore, we initiated a dedicated archive research proposal within the ASTROVIRTEL[3] project (ASTROVIRTEL cycle 2: *Gravitational lensing studies in randomly distributed, high galactic latitude fields; P.I. Thomas Erben*) to systematically search the ESO archive for high-quality WFI observations. Our archive query requirements, which aim at observations with a minimum observing time in a given filter configuration, together with constraints on seeing and galactic latitude, needed a substantial extension of the existing archive interface. To this end, the ASTROVIRTEL team developed the tool *querator*[4] which extends the traditional archive query form for telescope, camera, filter configuration and object position by advanced search possibilities for multi-colour observations and our needs. Whereas we obtained one square degree of usable data with own observations in the first year, the archive search with *querator* provided us, without new observations, with 4.5 square degrees within two months. Together with the previously retrieved archive data, WFI data from the COMBO-17 project (e.g. Wolf et al. 2004) and the EDisCS survey (White et al. 2005), the GaBoDS currently consists of 15 square degrees of high-quality imaging data.

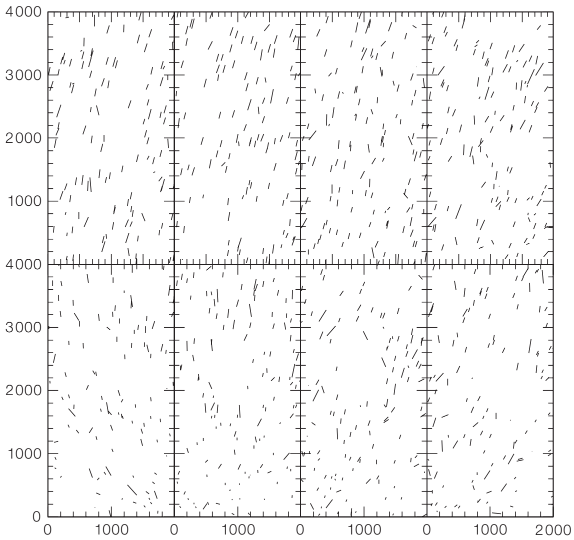


Figure 2: A typical ellipticity distribution of stellar objects for a WFI exposure with a seeing of 1″. WFI is a CCD mosaic camera with 4 × 2 chips each having 2K × 4K image pixels. The total field of view of the camera is 34′ × 33′. The sticks indicate the orientation and length of the stellar ellipticity in the field. No stellar image has an ellipticity larger than 2.5 % (corresponding to an ellipse with an axis ratio of ~ 0.95) and the PSF is smooth over the whole field of view.

All raw science and calibration frames were reduced and analysed in a homogeneous way, employing the THELI pipeline that we developed and released publicly (Erben et al. 2005). THELI is a stand-alone reduction pipeline based on UNIX scripts which uses only open source software, and which makes heavy use of pre-existing software modules. The pipeline has been developed with weak lensing applications in mind: owing to the stringent requirements posed by weak lensing, the relative astrometric accuracy of the dithered individual exposures must be better than about 1/10 of a pixel to not introduce artificial image ellipticities in the coaddition process.

The GaBoDS is a useful cosmic shear survey due to its field depth (*R*-band limiting magnitude between 25.0 mag and 26.5 mag; 5σ sky level measured in a circular aperture of 2″ radius) and seeing (between 0.7″ and 1.2″). This yields a large number of faint galaxies that we finally used for our cosmic shear analysis (almost 10^6 galaxies) and permits a good PSF correction. Furthermore, the images form small patches which are widely separated in the sky, hence they are uncorrelated (Figure 3).

Cosmic shear analysis with GaBoDS

In the weak lensing regime, shape distortions are characterised by a quantity called shear. It quantifies the anisotropic stretching of a source image, where, for example, an intrinsically round object is deformed into an ellipse. The shear can be estimated from the galaxy ellipticity which is directly related to its observable light distribution. Correlations in the *cosmic shear field* (the coherent shear pattern) are connected to the matter density power spectrum and its underlying cosmology. We calculated from the measured correlations the aperture mass dispersion. The aperture mass measures the tangential alignment of galaxy images relative to a chosen reference point, and thus quantifies the local strength of the coherent shear field (just like the tangential stretching of arcs measures the lensing strength of a cluster; see Figure 1). Its dispersion is a powerful cosmic shear

[1] *http://www.eso.org/eis*
[2] ESO Press Photos 15a-f/01
[3] *http://www.euro-vo.org/astrovirtel/*

[4] *http://archive.eso.org/querator/*

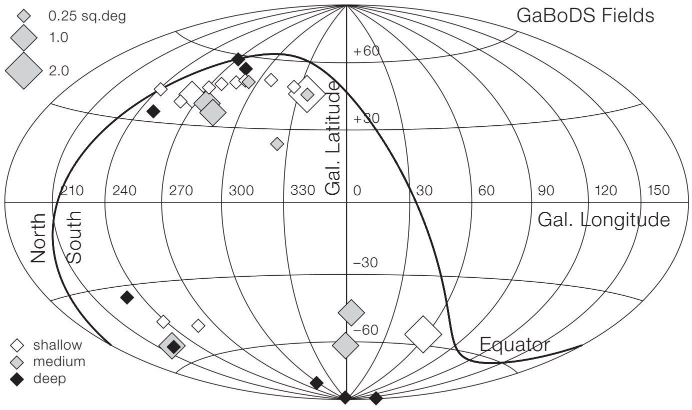


Figure 3: Sky distribution of the GaBoDS fields. The survey has a total area of 15 square degrees and contains 29 different lines of sight, all at high galactic latitude. The different patches comprise areas from 0.25 up to 2 square degrees.

measure since it is a very local measure of the power spectrum of the line-of-sight projected mass density. Moreover, it is a sensitive tool to reveal possible systematic errors in the data.

PSF correction

Cosmic shear induces per-cent level correlations in the ellipticities of distant galaxy images which can be an order of magnitude lower than correlations induced by systematic effects, like the anisotropic PSF. The correction of these systematics is challenging and has to be tested and applied carefully. Therefore, we performed a precise PSF correction method to obtain reliable shear estimates. The correction is done in two steps. One first has to correct the galaxy ellipticities for the effect of an *anisotropic* PSF using a sample of bright, unsaturated stars which are point-like and unaffected by lensing. Measuring their ellipticity yields the PSF anisotropy pattern of the field. Since the PSF anisotropy of the coadded images from the WFI is rather small and varies smoothly over the total FOV, we perform an *interpolation* of the stellar anisotropy over the entire FOV (Figure 4) to estimate the PSF anisotropy at the position of the galaxies. Second, the *isotropic* smearing caused by seeing has to be accounted for. Specialised software for these tasks has been developed independently and thoroughly tested, most recently in a world-wide blind test: the STEP project (Heymans et al. 2006).

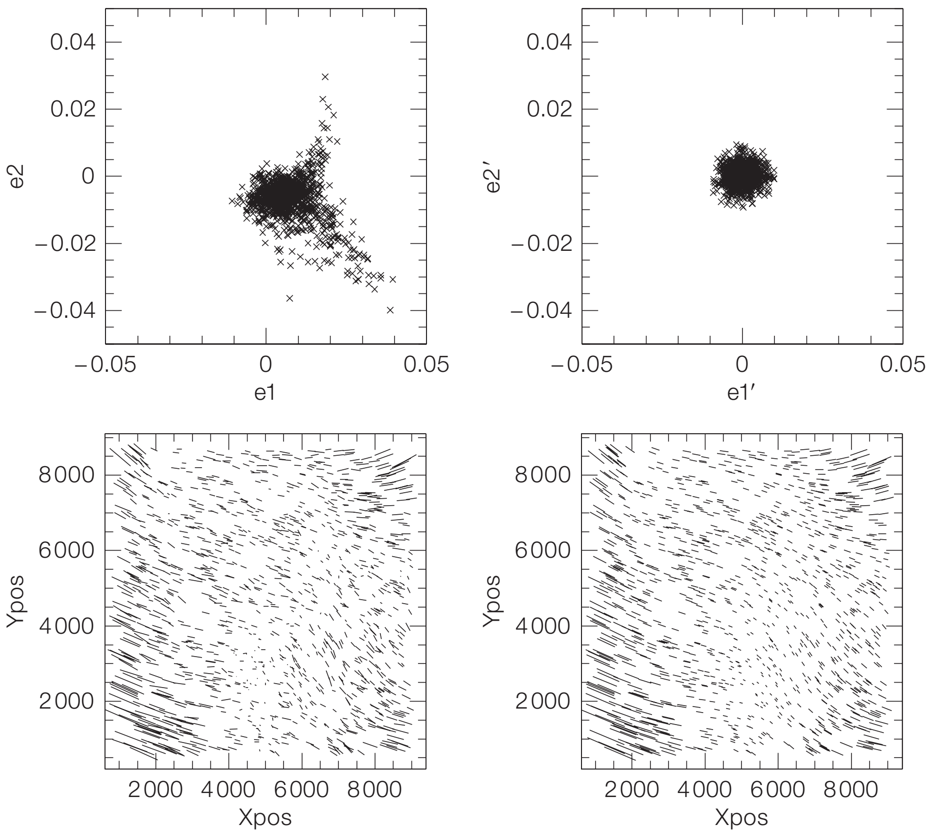
Redshift distribution of galaxies

For quantitative cosmic shear analyses not only the observed shape of source galaxies but also their redshift distribution has to be known. This distribution is directly estimated from galaxies of seven statistically independent DPS fields observed in *UBVRI*. In this way, the total error estimate of our redshift distribution includes sampling variance. This is an advantage of the GaBoDS since we do not have to rely on redshift distributions estimated from external redshift surveys covering only a small area in the sky. These DPS fields yield accurate photometric redshift information for about 10 % of the galaxies considered for the cosmic shear analysis. To acquire a smooth redshift distribution for all galaxies of the GaBoDS galaxy lensing catalogue, we perform a five-parameter fit to the measured redshift distribution.

Cosmological parameters from cosmic shear

For our cosmic shear analysis of the GaBoDS we calculated the aperture mass dispersion and found no significant systematic errors resulting from the data treatment (e.g. an imperfect PSF-anisotropy correction), see Figure 5. This en-

Figure 4: Example of a PSF anisotropy correction. **Upper panels:** the uncorrected (e1, e2, left) and PSF-corrected (e1′, e2′, right) stellar ellipticity components. **Lower panels:** the uncorrected stellar ellipticity (left) and the ellipticity of the interpolation (right) as a function of position. Here, the interpolation is a low-order 2D polynomial fit to the stellar ellipticities.



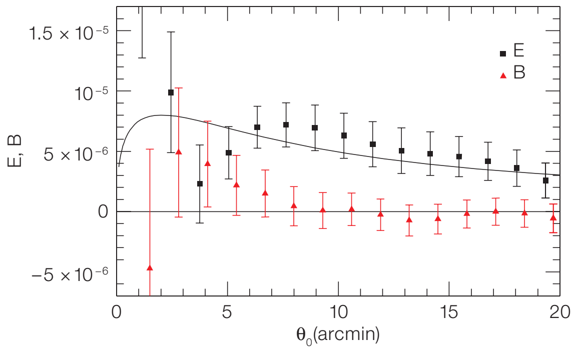


Figure 5: The decomposition of the aperture mass dispersion signal into E- and B-modes of the GaBoDS fields. The E-modes carry the cosmic shear signal, whereas 'curl-like' B-modes are not expected from lensing and would indicate remaining systematics. The line is a CDM prediction assuming a flat Universe with $\Omega_m = 0.3$ and $\sigma_8 = 0.9$.

couraged us to perform a cosmological parameter estimate (Hetterscheidt et al. 2006). For this purpose we combine the fit of the redshift distribution with the cosmic shear signal and estimate the total noise covariance matrix in an unbiased way *directly from the data without any further assumptions,* since the observed fields are statistically independent. Our analysis is basically concentrated on the mass power spectrum normalisation, σ_8, and the total matter density, Ω_m. For this estimate we assume a flat ΛCDM Universe with negligible baryon content. We derive σ_8 and Ω_m while marginalising over the HST Key Project uncertainties in the Hubble parameter and the source redshift distribution. We employ the so-called Monte Carlo Markov Chain, an efficient method to estimate the posterior likelihood in our *eight*-dimensional parameter space (Ω_m, σ_8, *h*, and the five fit parameters of the redshift distribution).

As a result we obtain the joint constraints on Ω_m and σ_8 (Figure 6). The confidence contours reveal the typical 'banana'-like shape reflecting the strong degeneracy between these two parameters, hence they are poorly constrained without further priors: $\sigma_8 = 0.61^{+0.31}_{-0.20}$ and $\Omega_m = 0.46^{+0.30}_{-0.22}$. Measurements of the CMB, however, yield a degeneracy in the Ω_m-σ_8 plane that is almost perpendicular to that of cosmic shear (Figure 6). Combining them would therefore substantially improve the Ω_m, σ_8 estimate.

The GaBoDS data set alone yields a normalisation of $\sigma_8 = 0.80 \pm 0.10$ (1σ statistical error) for a fixed total matter density of $\Omega_m = 0.3$, which is of similar accuracy to those obtained from measurements of the CMB and galaxy clusters.

Probing galaxy bias with GaBoDS

The relation between the spatial distribution of galaxies and the distribution of dark matter is expressed *statistically* by galaxy biasing parameters. Weak gravitational lensing provides a unique method to study the dark-matter distribution independently from the galaxy distribution, and to compare the two in order to measure the galaxy bias. Moreover with lensing, also the smaller, highly non-linear scales can be assessed which is not possible with other methods relying on linear perturbation theory.

In Figure 7 the basic concept of galaxy biasing and its measurement is illustrated. From the statistical point of view, *bias parameters* quantify the auto- and cross-correlation of the matter and galaxy distribution. Observationally, the projected mass distribution is measured in terms of the shear, whereas the projected galaxy distribution is seen as their distribution in the sky. The bias parameter *b* is the ratio of rms fluctuations of galaxies and matter, whereas the correlation coefficient *r* quantifies the correlation of galaxies and matter. Unbiased fields have *b = r = 1*.

Our primary interest is in the *spatial values* of *b* and *r* and not their projections in the sky. Therefore, we perform a deprojection of the measurements based on a fiducial cosmology, and the redshift distribution of foreground and background galaxies.

In Simon et al. (2006), we measured the spatial bias parameters *b* and *r* on *different scales*. The fluctuations in the projected matter distribution are smoothed using the already mentioned aperture mass; the filter radius determines the scale we are looking at. The aperture mass fluctuations are then compared to the projected number density of (foreground) galaxies, smoothed by using the same aperture filter as the one used for the aperture mass.

We perform the galaxy bias analysis for three different foreground galaxy samples that are selected by *R*-band magnitude. The redshift distributions of galaxies in the various samples are estimated from the COMBO-17 survey which provides

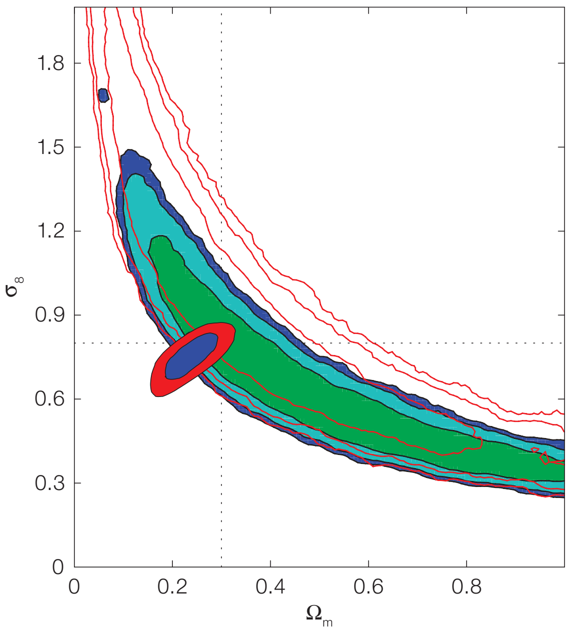


Figure 6: Joint marginalised constraints on σ_8 and Ω_m from our cosmic shear analysis of the GaBoDS data set. The shaded regions and the red contours show 1,2,3σ significance regions, obtained with two different cosmic shear statistical measures. Overlaid is a sketch of the joint constraint for WMAP only (Spergel et al. 2006, 1σ and 2σ contours in blue and red, respectively).

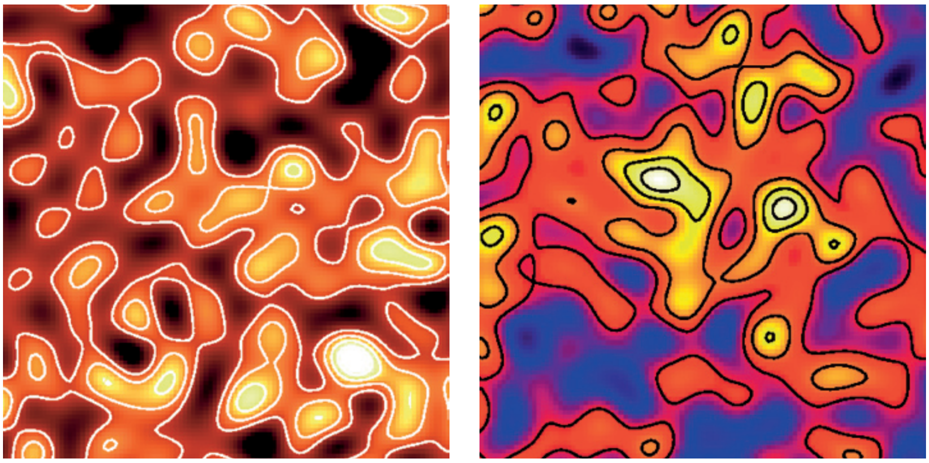


Figure 7: **Left:** smoothed fluctuations in the number density distribution of 'foreground' galaxies in the sky ($21.0 \le R \le 23.0$) as observed in the A901 field. **Right:** projected and smoothed fluctuations in the total matter density obtained from image ellipticities of faint 'background' galaxies ($21.5 \le R \le 24.0$) within the same field of view. Comparing, in a statistical sense, both maps allows a measurement of (projected) galaxy bias, thus the relation between the distribution of matter and galaxies. Although galaxies are almost unbiased tracers of the matter distribution at low redshift, both maps appear quite different. This is partly due to overlaid shot-noise patterns, but also partly due to different redshift sensitivities of the projections. We accounted for both in the final analysis.

accurate photometric redshifts for three of the GaBoDS fields that are thought to represent the whole survey. The samples have a relatively wide distribution with means of $\bar{z} = 0.34 \pm 0.18$, 0.47 ± 0.22, 0.62 ± 0.27 ('foreground') and $\bar{z} = 0.67 \pm 0.29$ for the mean redshift of galaxies inside the lensing catalogue ('background'); the 1σ-widths of the distributions are also given. Therefore, the three foreground samples represent galaxies at different redshifts, albeit as averages over a quite large range.

The final result was obtained by combining the measurements for all individual GaBoDS fields. The result for the bias parameters is very similar for all three galaxy samples and is shown for the brightest sample in Figure 8. This means that over the observed redshift range, and for the range of scales considered, the bias evolution is relatively mild.

The bias factor shows indications for a scale-dependence with an anti-bias, $b < 1$, at about $3\,h^{-1}$ Mpc; towards smaller (and perhaps also larger) scales the bias factor rises again. This behaviour, especially a scale-dependence of b on scales where the structure growth is in the non-linear regime, is expected from cosmological simulations such as in Springel et al. (2005). The average of b between one and eight Mpc/h, weighted by the statistical uncertainty of our mea-surement, is $\bar{b} \approx 0.8 \pm 0.1$.

The correlation between the matter and galaxy distributions is measured with larger uncertainties. Still, we find that there is a decorrelation between both in all three samples with an average (over the same range of scales as for $\bar{b}$) of approximately $\bar{r} \approx 0.6 \pm 0.2$. The fact that this correlation is not perfect, i.e. $r \neq 1$, implies that the biasing of galaxies is either non-linear and/or stochastic. In order to disentangle non-linear and stochastic biasing, a higher-order correlation analysis will be required which is within reach by the upcoming weak lensing surveys.

Outlook

The use of the GaBoDS data is not restricted to lensing analyses, but has already been extended to other projects as well, including Lyman-break galaxies (Hildebrandt et al. 2006b). We have made our reductions and derived products of a large fraction of the GaBoDS data publicly available via the ESO archive, such as the DPS[5,6], which includes the ultra-deep WFI image of the Chandra Deep Field South[7]. With its substantial scientific output, the GaBoDS is a good example for the use of the ESO archive. The upcoming public surveys with the new VST and VISTA telescope will provide an enormous increase of such data products, and we foresee a large scientific harvest from these surveys.

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[6] *http://marvin.astro.uni-bonn.de/DPS*
[7] ESO press release (14.04.2006): *http://www.eso.org/outreach/press-rel/pr-2006/pr-14-06.html*

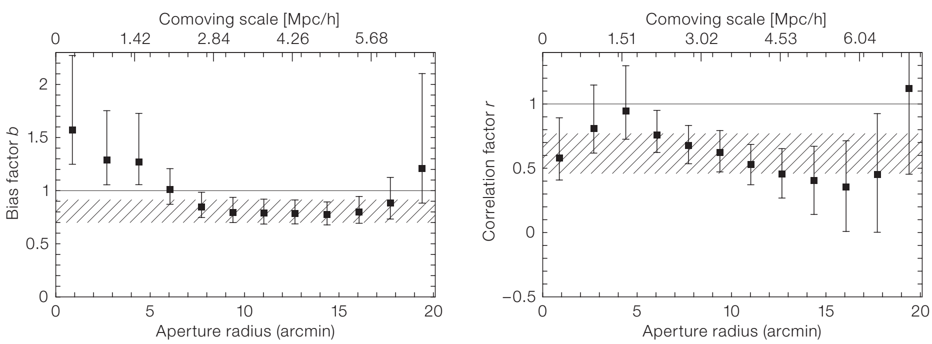

Figure 8: **Left:** Spatial linear bias factor b of the brightest 'foreground' galaxy sample (the effective comoving spatial scale in the top axis is based on the mean redshift of the sample, $\bar{z} \approx 0.34$). **Right:** Spatial linear correlation r between total matter fluctuations and galaxy number density fluctuations. Shaded areas denote the 1σ-confidence of the average b and r for smoothing scales between 2′ and 19′. The results are for a flat Universe with $\Omega_m = 0.3$. Note that the errors of neighbouring bins are strongly correlated.