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COSMIC SHEAR AND CLUSTERS OF GALAXIES

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The first detections of cosmic shear signal reported recently by 4 independent groups cover angular scales between one and 10 arcmin. On those scales, the cosmic shear is a signature of non-linear perturbations, like groups and clusters of galaxies. I present the results obtained by our team on CFHT and on the VLT and discuss its impact for the analysis of cluster abundances and cosmology

1 Introduction

The effects of gravitational lensing induced by large-scale structures of the universe accumulate along the lines of sight and manifest as a weak distortion on lensed galaxies (the cosmic shear). Theoretical predictions done over the last decade reveal that the statistical properties of cosmic shear contain invaluable clues on the cosmological parameters, the power spectrum of density fluctuation and the biasing. The cosmic shear is therefore an interesting way to probe the properties of the universe on large-scale.
The amplitude of the weak cosmological distortion only reaches few percents and is contaminated by artificial distortions of similar amplitude making its measurement a challenging task. In contrast to arc(let)s analysis, its observational signature can only be recovered statistically from a large sample of galaxies covering several degrees of the sky. Despite difficulties, four teams challenged in order to measure the cosmic shear and get very first constraints on cosmological models from this new technique.
Regarding the topic of this conference, the cosmic shear looks somewhat marginal. However,

on small scales the cosmic shear signal is dominated by distortion produced by non-linear gravitational systems, like groups and clusters of galaxies. It is therefore interesting to present and discuss these important results in a broader context including cluster formation.

2 Theoretical expectations

Most of the mass condensations crossed by photons correspond to large-scale systems with very low mass density contrasts, δ. The perturbation theory is therefore a valid approximation to compute the expected weak lensing signal. By using the Born approximation, one can express the deflection angle, $\boldsymbol{\alpha}(\boldsymbol{\theta}, w)$, at angular distance $f_K(w)$ (w is the radial coordinate) produced by the cumulative effect of the deflectors up to that distance:

$$\boldsymbol{\alpha}(\boldsymbol{\theta}, w) = \frac{2}{c^2} \int_0^w \frac{f_K(w-w')}{f_K(w)} \ \boldsymbol{\nabla}_\perp \Phi(f_K(w-w')\boldsymbol{\theta}, w') \ \mathrm{d}w' \ , \tag{1}$$

where $\boldsymbol{\nabla}_\perp \Phi$ is the perpendicular gradient of the Newtonian potential. Since the gravitational convergence, $\kappa(\boldsymbol{\theta})$, produced by the projected mass density depends on the deflection angle,

$$\kappa(\boldsymbol{\theta}) = \boldsymbol{\nabla}_{\boldsymbol{\theta}} . \boldsymbol{\alpha}(\boldsymbol{\theta}) \ , \tag{2}$$

one can express this "cosmological convergence" as function of the symmetric components of the second derivatives of Φ, that is the mass density $\rho = \Omega_m \ \delta$. For small perturbations, the first order terms of perturbative expansion of Φ provide a good estimate of κ.
In the simple case of a single lens plane and assuming the shape of the power spectrum of density fluctuations is a power law (ie $P(k) \propto k^n$), perturbation theory applied to weak cosmological lensing enables us to make important statements about the use of weak lensing statistics for cosmology:

- To first order, the variance of the convergence averaged over an angular scale θ, $\langle \kappa(\theta)^2 \rangle$ writes:

  $$\langle \kappa(\theta)^2 \rangle^{1/2} \approx 0.01 \sigma_8 \Omega_m^{0.75} z_s^{0.8} \left(\frac{\theta}{1^o} \right)^{-(n+2)/3} \ , \tag{3}$$

  where σ_8 is the normalization of the power spectrum, z_s the redshift of sources.

- Likewise, the skewness of the convergence on angular scale θ, $s_3(\theta)$, can also be expressed as function of the same quantities:

  $$s_3(\theta) \approx 40 \Omega_m^{-0.8} z_s^{-1.35} \ . \tag{4}$$

  Bernardeau et al [?] (1997) first expressed the skewness of the convergence for various cosmologies. They pointed out that it can be used jointly with the variance to provide independently Ω_m and σ_8.

- Finally, the gravitational convergence can be easily related to the the gravitational shear, γ:

  $$\langle \kappa(\theta)^2 \rangle = \langle \gamma(\theta)^2 \rangle \ . \tag{5}$$

  Since in the weak lensing regime γ is measured directly from the gravity-induced ellipticity of galaxies, it is in principle possible to measure the cosmic shear and to get informations about properties of our universe from the measurement of galaxy ellitpicities.

From an observational point of view, these statements establish the scientific potential of cosmic shear statistics. However, the key question one needs to address is the feasibility. Further theoretical studies done by Jain & Seljak [?] (1997) or van Waerbeke et al et al [?] (2000b) focussed

Table 1: Expected signal-to-noise ratio on the measurement of the variance and the skewness of the convergence for two extreme realistic cosmological models. In the first column, the size of the field if view (FOV) is given. The signal-to-noise ratio is computed from the simulations done by van Waerbeke et al (1999). The top line of this table describes shortly some details of the analysis. The redshift of the sources and the galaxy number density correspond to a typical 2-hours exposure on a 4-meter telescope.

$z_s = 1$, Top Hat Filter , $n = 30$ gal.arcmin^{-2}				
FOV	S/N Variance		S/N Skewness	
(deg.×deg.)	$\Omega_m = 1$	$\Omega_m = 0.3$	$\Omega_m = 1$	$\Omega_m = 0.3$
1.25×1.25	7	5	1.7	2
2.5×2.5	11	10	2.9	4
5×5	20	20	5	8
10×10	35	42	8	17

on the non-linear regime of mass density fluctuations. On small scales, the theoretical expectations of first order perturbations are no-longer valid and the non-linear evolution of the power spectrum has to be taken into account (following the Hamilton et al [?] 1991 and Peacok & Dodds [?] 1996 approximations). It turns out that, on angular scale below 10 arcmin, the amplitude of the cosmic shear variance is twice the linear prediction and ranges between 4 and 8 percents, according to cosmological models. Therefore, in principle it should be detectable, even with present-day ground-based telescopes.

3 Conditions for cosmic shear detection

The design of the survey and the accuracy of PSF-anisotropy correction control the successful outcome of any cosmic shear survey.
The size of the survey is critical. In order to constrain cosmological scenarios, it must at least cover an angular scale which provides a cosmic shear signal-to-noise ratio higher than 3 for any model one could reasonably expect. Van Waerbeke et al [?] (1999) addressed this issue and used extensive simulations to infer the best strategy. Their main results are listed in Table **??**. It shows that one needs to survey about one deg^2 to get a significant estimate of the variance of κ, whereas about 10 deg^2 are needed to probe its skewness. These predictions may be somewhat pessimistics and the size of the survey could be lower than the van Waerbeke et al simulations, because the enhancement of the shear produced by non-linear effects on small scales were not taken into account. In practice, since many ongoing surveys do have already covered one deg^2, at least the variance can be measured easily right now.

The feasibility of the detection of cosmic shear critically depends on the accuracy of the PSF anisotropy correction. These anisotropies result of atmospheric distortion (atmospheric dispersion), technical or optical problems (bad telescope tracking, telescope flexures, charge transfer inefficiency, optical distortions) or astronomical artifacts (saturated stars or diffusion halos produced by multiple reflexions from bright objects). The correction of PSF anisotropy in weak lensing analysis has been addressed by many groups over the last years (see Mellier [?] 1999 and Bartelmann & Schneider [?] 2000 for reviews). The technique developed by Kaiser, Squires & Broadhurst [?] (1996, hereafter KSB) is now widely used and recent extensive simulations show that, by using the KSB correction, weak lensing signals can be recovered without biases (Hoekstra et al [?] 1998, Erben et al [?] 2000, Bacon et al [?] 2000). Erben et al (2000) have processed thousands of simulated images containing a wide variety of PSFs with most of the optical distortions one could expect. They are listed in Fig. **??**. They conclude that any shear amplitude in the range $0.012 < |\gamma| < 0.300$ can be recovered with a 10% relative accuracy. This important result implies that the cosmic shear should be detected even in usual ground-based images,

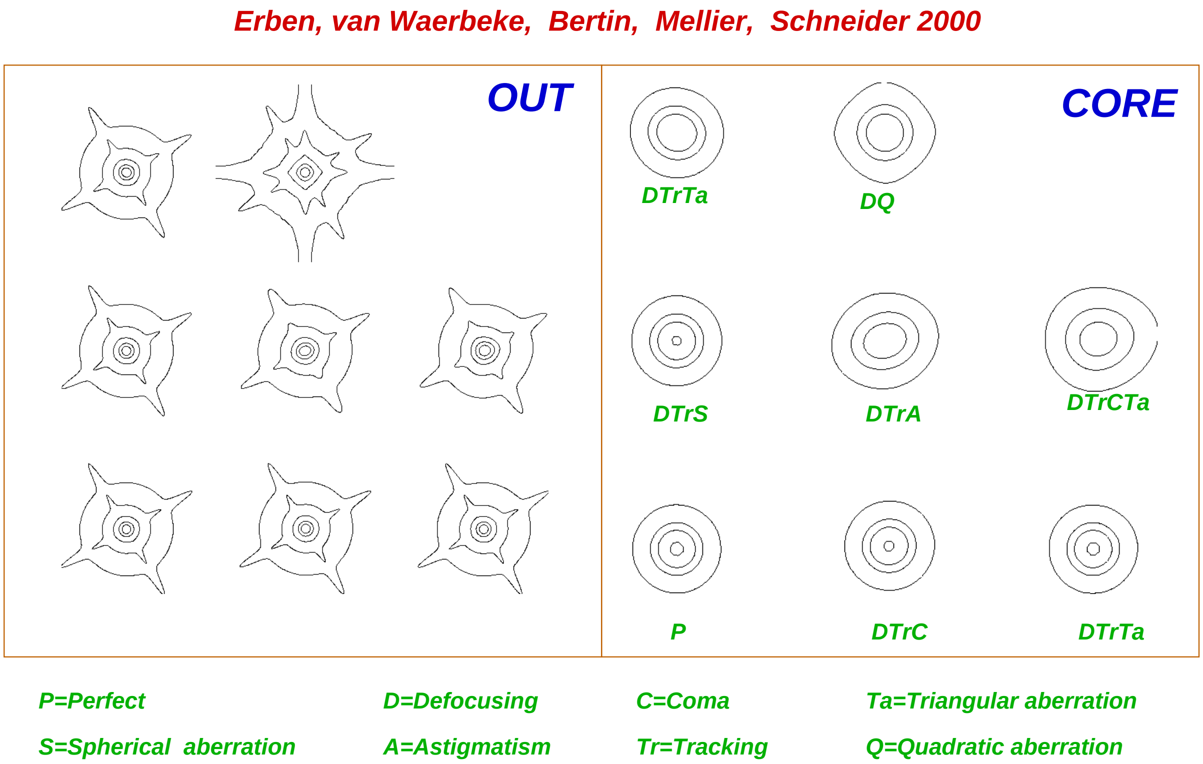

Figure 1: The various optical distortions simulated by Erben et al (2000) in order to evaluate the limiting performances of KSB. The left panel shows the external shapes of the PSF for each set of parameters listed below the stars. On the right panel, the central part of the PSF has been zoomed in order to show details of internal shapes. For all these models the shear can be recovered down to 0.01 with 10% relative accuracy.

provided the seeing is smaller than 1 arcsecond.

4 First detection of cosmic shear

Thanks to the optimistic conclusions on the feasibility of a cosmic shear survey and reliability of PSF corrections, four teams carried out a wide field survey of galaxies in order to detect cosmic shear signatures on scales ranging from one to ten arcminutes:

1. Van Waerbeke et al [?] (2000) covered 1.7 deg^2 up to $I = 24$ over 5 uncorrelated fields obtained at CFHT,
2. Bacon et al [?] (2000) investigated 14 fields up to $R = 24$ obtained at WHT over 0.5 deg^2,
3. Wittman et al (2000) observed 1.5 deg^2 up to $R = 26$ over 3 uncorrelated fields at CTIO,
4. Kaiser et al [?] (2000) analysed 6 fields up to $I = 24$ at CFHT, covering 1. deg^2, and finally
5. Maoli et al [?] (2000) used 45 VLT fields covering 0.5 deg^2 up to $I = 24$.

The teams used different instruments, observed different fields of view and used different techniques to analyze the data and correct for the PSF anisotropy which enables to check the reliability and the confidence level of the results. This is indeed a chance to get these works published almost simultaneously.
Our CFHT and VLT surveys are reported in van Waerbeke et al (2000) and Maoli et al (2000) respectively (see Fig. **??**). Thanks to these independent data set, we were able to cross-check our results and investigate the reliability of our corrections of systematics. Details can be found

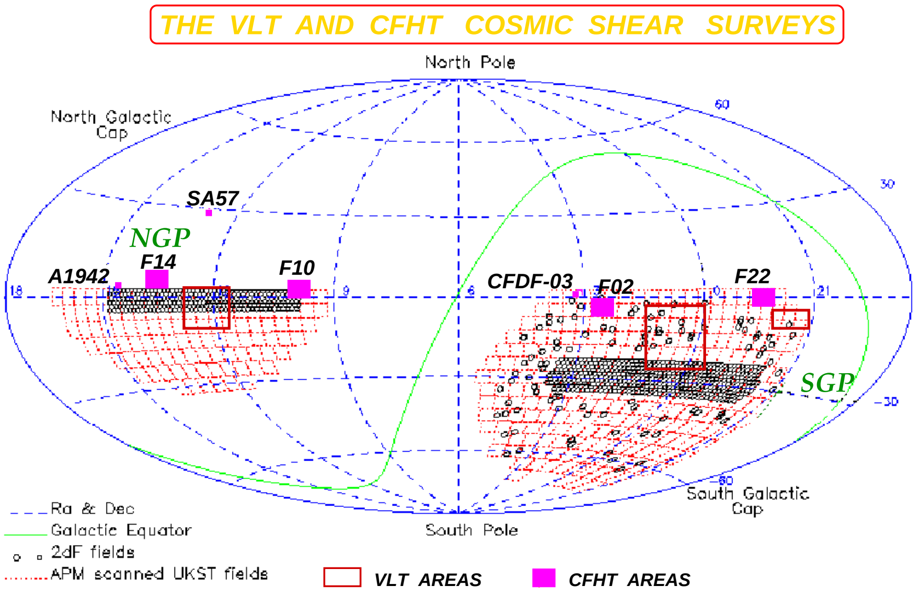

Figure 2: Positions of the areas covered by the CFHT and VLT cosmic shear surveys. The filled areas are the targets covered at CFHT. The open rectangles delineate the areas inside which the 45 VLT targets were selected.

in van Waerbeke et al (2000). The 45 VLT are of special interest because the targets are spread over more than 1000 squares degrees, each of them being separated from the others by at least 5 degrees. These uncorrelated fields provide a direct measurement of the cosmic variance, without need of simulations.

The four teams announced a detection of cosmic shear signal during the first semester 2000. The results are summarized in Fig. **??**. The most striking feature on this plot is the remarkable similarity of the signatures in the range 1' to 10' . This is obviously a crucial point which make us confident that the detection and measurements are reliable and robust, despite concerns about systematics.

5 What do we learn about cosmology and clusters?

The comparison of the measurements with some typical cosmological models displayed in Fig. **??** (the non-linear evolution of the power spectrum is computed with the coeeficient given in Peacock [?] 1999, which seems to provide lower amplitudes of the variance of the shear than previous coefficients) leads to the following conclusions:

- Although the points as function of angular scale are correlated, the simultaneous use of independent data provided by the five groups permits to reject some models with a very high significance. In particular, the SCDM COBE-normalized model is ruled out to at least a 5-σ level.

- In contrast, the popular λ-CDM cluster-normalized model perfectly fit the data, but this is not the only one. The cluster-normalized SCDM as well as a cluster-normalized open universe ($\Omega_m = 0.3$) are also compatible with the observations. This illustrates that error

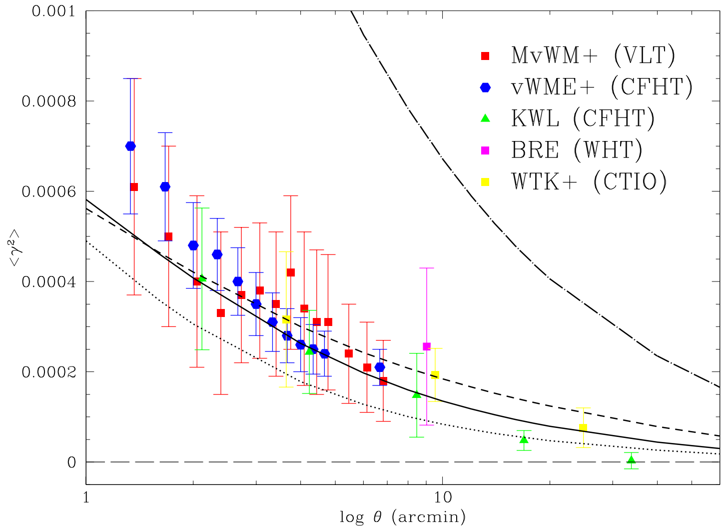

Figure 3: . *The recent results of cosmic shear measurements. The works referred to as Maoli et al 2000 (MvWM+), van Waerbeke et al 2000 (vWME+), Kaiser et al 2000 (KWL), Bacon et al 2000 (BRE) and Wittman et al 2000 (WTK+). Some predictions of cosmological models are also plotted, assuming sources at* $z_{eff} = 1$ *and using the non-linear evolution of power spectrum according to the coefficients given by Peacock (1999). The solid line corresponds to* λ*CDM, with* $\Omega_m = 0.3$, $\lambda = 0.7$, $\Gamma = 0.21$; *the dot-dashed line to COBE-normalized SCDM; the dashed line to cluster-normalized SCDM and the dotted line to cluster-normalized Open CDM with* $\Omega_m = 0.3$.

bars are still too large and also that the variance of the shear is not enough to break the degeneracy (σ_8, Ω_m). This is only once the skewness of the convergence will be measured that we will be in much better position to constrain cosmological scenarios.

The depth of these surveys corresponds to sources at redshift of about $z \approx 0.8 - 1$. The typical efficiency function, which describes the lensing strength of the lenses as function of the redshift distributions of the lenses and the sources, should therefore peaks at redshift $z \approx 0.4$. On angular scales between 1' and 10', since the non-linear structures dominate the signal, most of the cosmic shear is produced by structures having physical sizes of about $0.2 - 1.0\ h^{-1}$ Mpc. The cosmic shear surveys are therefore mainly probes of weak cosmological lensing produced by clusters of galaxies and compact groups.

The constraints provided by cosmic shear are formally similar to those from cluster abundances obtained from counts of clusters in optical or X-ray surveys (Eke et al [?] 1996, Eke et al [?] 1998; Bridle et al [?] 1999). Depending on the angular scales, the variance of the cosmological convergence writes:

$$\langle\gamma^2\ (\theta < 10')\rangle^{0.5} \propto \sigma_8^{1.3}\Omega_m^{0.65} \quad , \quad \langle\gamma^2\ (\theta > 10')\rangle^{0.5} \propto \sigma_8\Omega_m^{0.8}\ ; \tag{6}$$

whereas, for cluster abundances the constraints have formally the following dependences:

$$\sigma_8\Omega_m^{\approx 0.55} \approx 0.6\ . \tag{7}$$

The cosmic shear has the advantage of being a direct measurement of the lensing effects produced by dark matter. In contrast, the cluster abundances measures the fraction of massive clusters from the light distribution, which implies, either empirical relation between light and mass (like emissivity-temperature relation), or assumptions of the geometry and the physical state of the baryonic and non-baryonic components.

More interesting, in principle, one could break the degeneracy by using cluster abundances and cosmic shear as independent data sets. Up to now, the uncertainties of cosmic shear signal as well as cluster abundances are still too large. But this looks like a very promising approach, which will be feasible soon by using the complete and well-defined X-ray samples provided by XMM, the cluster abundances from the VIRMOS-optically selected sample or even the future SZ-surveys.

6 Future prospects

The first detection of cosmic shear by various groups puts solid grounds on the weak lensing approach as a biased-free cosmological tool. We expect that ongoing surveys will provide soon similar constraints as those from CMB or SNIa projects. Within the next five years, wide field cosmic shear surveys will produce the first measurements of the variance, the skewness of the convergence as well as alternative statistics - like the peak statistics, the genus or the foreground-background correlations - and the properties of the power spectrum of mass density fluctuations up to degree scales. The full mass range of structures will be available then, with very accurate cosmological constrains (van Waerbeke et al 1999).
In parallel, we still have to analyze carefully the effects of systematics and the validity of some approximations which are the main pillars of cosmic shear analysis. Up to now, the investigations carried out in the realm of observations, numerical simulations and perturbation theory lead to detailed studies on the followings issues:

- *Validity of the Born approximation:* The effects of mass density fluctuations on the deformation of the ray bundles are computed assuming that the the deformation can be computed along the unperturbed geodesic.

- *Lens coupling*: When ray bundles eventually cross two lenses, the convergence produced by a lens depends on the lensing effects produced by other structures. Hence, the magnification matrix is not simply the sum of the two convergences but also contains additional coupling terms.

- *Redshift of sources*: Both the variance and the skewness of the convergence strongly depend on the redshift distribution of the lensed sources ($\approx z^{0.7-1.4}$).

- *Source clustering*: Due to galaxy clustering, the amplitude of the gravitational shear may strongly vary from one line-of-sight to another. The average redshift distribution of the sources can therefore be biased by the galaxies located within the massive structure, which bias the value of the convergence in a similar way.

- *Intrinsic correlated polarization of galaxies* If the intrinsic orientations of galaxies is not randomly distributed, their coherent alignment may correlate to the geometry of large scale structures in which they are embedded. If this is the case, the coherent alignment produced by weak lensing will be contaminated by the intrinsic alignment of the galaxies and a mass reconstruction based on the shear pattern will be strongly contaminated by spurious weak lensing signal. Recent analyses carried out by Croft & Metzler [?] (2000) and Heavens et al. [?] (2000) conclude that on scale smaller than 10 arcminutes the intrinsic correlation should not contaminate the weak lensing signal, provided the survey is deep enough in order to probe distant lensed galaxies. However, for shallow survey the conclusions are unclear.

In general, it turns out that most of these issues do not have a major negative impact on the cosmic shear. The recent ray tracing analysis done by Hamana et al [?] (2000) shows that neglecting both the full ray tracing and the lens-lens coupling have negligible effects on the results, which is confirmed by semi-analytic computation (Bernardeau et al [?] (1997), van Waerbeke et al [?] (2000b)). The most critical seems to be the source clustering which could change the signal by 20% (Thion et al ? 2000; Hamana et al in preparation). Fortunately, this can be reduced to 1% if one uses sources within a narrow redshift range.

The detection of cosmic shear and the demonstration that reliable results come out from it are one of the most important results in observational cosmology this year. Indeed, we hope it may put cosmic shear projects at the same level as CMB and SNIa experiments. Among those, cosmic shear is the only one which probes directly the distribution of dark matter.

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References

1. Bernardeau, F., van Waerbeke, L., Mellier, Y. 1999, A&A 322, 1.
2. Jain, B., Seljak, U. 1997, ApJ 484, 560.
3. van Waerbeke, L., Hamana, T., Scoccimaro, R., Colombi, S., Bernardeau, F. 2000, submitted (2000b).
4. Hamilton, A.J.S., Kumar, P., Lu, E., Matthews, A. 1991, ApJ 374, L1..
5. Peacock, J.A., Dodds, S.J. 1996 MNRAS 280, L19.
6. van Waerbele, L., Bernardeau, F., Mellier, Y. 1999, A&A 342, 15.
7. Mellier, Y. 1999, ARAA 37, 127.
8. Bartelmann, M. Schneider, P. 2000, Astro-ph/9912508.
9. Kaiser, N., Squires, G., Broadhurst, T. 1995, ApJ 449, 460.
10. Hoekstra, H., Franx, M., Kuijken, K., Squires, G. 1998, ApJ 504, 636.
11. Erben, T., van Waerbeke, L., Bertin, E. 2000, Astro-ph/0007021..
12. Bacon, D., Réfrégier, A., Clowe, D., Ellis, R.S. 2000, Astro-ph/0007023.
13. Van Waerbeke, L., Mellier, Y., Erben, T. et al 2000, A&A 358, 30.
14. Bacon, D., Réfrégier, A., Ellis, R.S. 2000, Astro-ph/0003008.
15. Wittman, D.M., Tyson, A.J.,, Kirkman, D. et al 2000, Nature 405, 143..
16. Kaiser, N., Wilson, G., Luppino, G. 2000, Astro-ph/0003338.
17. Maoli, R., Mellier, Y., Van Waerbeke, L. et al 2000, Astro-ph/0008179.
18. Peacock, J.A. 1999. "Csomological Physics". Cambridge.
19. Eke, V.R., Cole, S., Frenk, C.S. 1996, ApJ 282, 263.
20. Eke, V.R., Cole, S., Frenk, C.S., Henry, P.J. 1998, ApJ 298, 1145.
21. Bridle, S.L., Eke, V.R., Lahav, O. et al 1999, MNRAS 310, 565.
22. Hamana, T., Colombi, S., Mellier, Y. 2000, Proceedings of the XX^{th} Rencontres de Moriond. "Cosmological Physical with Gravitational Lensing". Y. Mellier, J.-P. Kneib, M. Moniez, J. Tran Thanh Van eds. Astro-ph/0009459.
23. Thion, A., Mellier, Y., Bernardeau, F., Bertin, E., Erben, T., van Waerbeke, L. 2000, Proceedings of the XX^{th} Rencontres de Moriond. "Cosmological Physical with Gravitational Lensing". Y. Mellier, J.-P. Kneib, M. Moniez, J. Tran Thanh Van eds. Astro-ph/0008180.
24. Croft, R.A.C., Metzler, C. 2000, Astro-ph/0005384.
25. Heavens, A., Réfrégier, A., Heymans, C. 2000, Astro-ph/0005269.