LeMoMaF: Lensed Mock Map Facility

Jaime E. Forero-Romero\textsuperscript{1}, Jérémie Blaizot\textsuperscript{2}, Julien Devriendt\textsuperscript{1}, Ludovic Van Waerbeke\textsuperscript{3}, Bruno Guiderdoni\textsuperscript{1}

\textsuperscript{1}Université Claude Bernard Lyon 1, CNRS UMR 5574, ENS Lyon, Centre de Recherche Astronomique de Lyon, Observatoire de Lyon, 9 Avenue Charles André, 69561 St-Genis-Laval Cedex, France
\textsuperscript{2}Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Str. 1, 85741 Garching, Germany
\textsuperscript{3}University of British Columbia, 6224 Agricultural Road, Vancouver, V6T1Z1, B.C., Canada

ABSTRACT

We present the \textit{Lensed Mock Map Facility} (LeMoMaF), a tool designed to perform mock weak lensing measurements on numerically simulated chunks of the universe. Coupling N-body simulations to a semi-analytical model of galaxy formation, LeMoMaF can create realistic lensed images and mock catalogues of galaxies, at wavelengths ranging from the UV to the submm. To demonstrate the power of such a tool we compute predictions of the source-lens clustering effect on the convergence statistics, and quantify the impact of weak lensing on galaxy counts in two different filters. We find that the source-lens clustering effect skews the probability density function of the convergence towards low values, with an intensity which strongly depends on the redshift distribution of galaxies. On the other hand, the degree of enhancement or depletion in galaxy counts due to weak lensing is independent of the source-lens clustering effect. We discuss the impact on the two-points shear statistics to be measured by future missions like SNAP and LSST. The source-lens clustering effect would bias the estimation of $\sigma_8$ from two point statistics by $2\% - 5\%$. We conclude that accurate photometric redshifts for individual galaxies are necessary in order to quantify and isolate the source-lens clustering effect.

Key words: cosmology: gravitational lensing - large-scale structure - methods: numerical

1 INTRODUCTION

One of the key goals of modern astrophysical and astronomical research is to map out the spatial distribution of the various matter components of the Universe. In the actual concordance cosmological model, about 85\% of the matter in the universe is thought to be non-baryonic and non-interacting dark matter, the other 15\% being composed of baryons (Spergel et al. 2006).

One of the most promising tools to track the distribution of dark matter on cosmological scales is weak gravitational lensing, which has already proven to be well suited for other purposes, such as precision cosmology (Hu 2002; Huterer 2002; Benabed & Van Waerbeke 2004; Bernstein & Jain 2004; Tereno et al. 2005).

Weak gravitational lensing affects the observed galaxy properties such as ellipticities, magnitudes and apparent positions in the sky. In the weak lensing regime, these effects can only be measured in a statistical sense. Indeed, the first detections of the weak lensing signal (Bacon et al. 2000; Kaiser et al. 2000; Maoli et al. 2001; Van Waerbeke et al. 2002, 2004; Brown et al. 2003; Jarvis et al. 2003), are based on an analysis of the spatial correlation between ellipticities of galaxies. The study of weak lensing through the changes in magnitudes and apparent position in the sky that is causes is an even more challenging measurement (Scranton et al. 2003; Zhang & Perl 2005).

Most of the difficulties in measuring the weak lensing signal come from observational systematics such as uncertainties in the determination of the point-spread function (PSF) and selection biases (Kaiser 2000; Erben et al. 2001; Vale et al. 2004). There also exist astrophysical errors related to uncertainties in photometric redshift calibration (Ishak & Hirata 2003; Van Waerbeke et al. 2003), intrinsic alignments due to physically associated lens-source pairs (Mandelbaum et al. 2006) or even distant lens-source pairs (Hirata & Seljak 2004). Most of the methods used to assess the importance of all these effects are theoretical or numeri-
cal. For the latter, one should also account, in principle, for uncertainties associated with numerical errors inherent to N-body simulations, neglected baryonic cooling effects and to a larger extent a poor understanding of the theory of galaxy formation.

The most realistic simulations of weak gravitational lensing performed so far rely on a dark matter distribution taken from an N-body simulation and galaxies drawn from a Halo Occupation Model (HOD) parameterized by halo mass alone (Hézou et al. 2003; Van Waerbeke et al. 2005), without any information about apparent magnitudes or galaxy colors. Even if this information was available from such models, the mere fact that properties of dark matter halos depend not only on their masses, but also on their assembly histories — and that these latter have significant effects on galaxy clustering (Croton, Gao & White 2006) — rules out HOD models based on halo mass as precision tools to model effects that rely heavily on a realistic description of the correlations between galaxy and dark matter distributions. The consensus is that an analysis which includes more realistic galaxy populations at various wavelengths are needed.

This paper presents an approach which is a first step to fill this gap and perform more realistic weak lensing simulations thanks to a more realistic description of galaxy populations. It consists in building a tool which we call Lensed Mock Map Facility (LEMMOAF) hereafter, to link together three well established numerical techniques, each one tackling a different aspect of the problem. More specifically, a state-of-the-art semi-analytic model (SAM) tracks the properties of galaxies within a high resolution N-body simulation as they evolve in time. Then a light cone is assembled from the outputs of the simulations to convert “theoretical” quantities into observables. Finally, a ray tracing algorithm extracts the weak lensing signal from the cone. The SAM of galaxy formation that we use in this work is GALICS (GALaxies In Cosmological Simulations, Hatton et al. 2003), and mock galaxy maps along with dark matter cones are obtained through a random tiling technique of simulation snapshots, using the moment (Mock Map Facility, Blaizot et al. 2005) pipeline.

This paper is organised as follows. In Sec. 2 we review the characteristics of GALICS and MOMAF which are relevant to the present study. In Sec. 3 we explain the weak lensing formalism and its implementation in LEMMAF. In Sec. 4 we present the statistics of the weak lensing convergence and the effect of weak lensing on differential galaxy counts. Finally, we discuss our results and outline prospective in Sec. 5.

2 GALICS AND MOMAF

2.1 GALICS

GALICS is a hybrid model of galaxy formation which combines cosmological dark matter N-body simulations with a semi-analytic description of baryonic processes. The model is fully described in Hatton et al. (2003), and the version we use here is the same as that used in the previous papers of the GALICS series (Hatton et al. 2002; Devriendt et al. 2005; Blaizot et al. 2004). We briefly recall what are the main ingredients in Appendix A and B. Eventually, GALICS outputs are turned into mock catalogues using MOMAF. The following section summarizes how this is achieved.

2.2 MOMAF

MOMAF (Blaizot et al. 2005) is a tool which converts theoretical outputs of hierarchical galaxy formation models into catalogues of virtual observations. The general principle is simple: mock light cones are generated using semi-analytically post-processed snapshots of cosmological N-body simulations. These cones can then be projected to synthesise mock sky images.

MOMAF uses a random tiling technique described in Blaizot et al. (2005) to build mock observations from the redshift outputs of GALICS. As explained in Blaizot et al. (2005), several different observing cones can be generated from the same set of outputs of GALICS, by changing either the line of sight or the seed for the random tiling. Blaizot et al. (2005) also discuss the bias induced by this random tiling approach on the clustering signal of the final maps.

In this paper, we build 25 cones of galaxies and 25 corresponding cones of dark matter with seeds and lines-of-sight randomly chosen for each observer position, using the same seed for every matching pair of galaxy and dark matter cone. These 25 cones allow us to infer an estimate of the dispersion of clustering measurements, that is to say, an estimate of the cosmic variance associated with our mock catalogues. We use galaxy magnitudes in two filters: SDSS r and JOHNSON K, because the results in these bands have already been thoroughly examined by Blaizot et al. (2003) and Blaizot et al. (2008). The results of the galaxy counts from GALICS-MOMAF and its comparison to observations are shown in Fig. 1 and galaxy redshift distributions for different cuts in magnitude are shown in Fig. 2. In order to make semi-analytic predictions of the weak lensing statistics (Van Waerbeke et al. 2001) for this broad distribution we describe it with the following functional form:

\[
n(z) = \frac{\beta}{z_0 \Gamma(\alpha + \beta)} \left( \frac{z}{z_0} \right)^\alpha \exp \left[ - \left( \frac{z}{z_0} \right)^\beta \right]
\]

where \(\Gamma(x)\) is the Gamma function and \(\alpha, \beta\) and \(z_0\) are free parameters to determine for each distribution.

However, we note that given the rather small size of the original N-body simulation box (100 h\(^{-1}\) Mpc on a side) that was used to run GALICS on, our estimate of the cosmic variance is likely to be biased and has to be taken as a lower boundary on the true cosmic errors. Finally, the mock catalogues we will use in the following are 4400 h\(^{-1}\) Mpc in depth, and 1.4° × 1.4° in angular size.

3 LENSED MOMAF

3.1 Weak Lensing Formalism

In this section we provide a summary of the weak lensing equations relevant for building LEMMAF and refer the reader interested in a more detailed treatment to Jain et al. (2000).

We use comoving coordinates and place ourselves in the framework of an isotropic and homogeneous universe that
Figure 1. Galaxy counts in the filters SDSS r (Yasuda et al. 2001) and JOHNSON K (Djorgovski et al. 1995; Gardner et al. 1996; Moustakas et al. 1997) obtained through the GALICS-MOMAF pipeline. Squares are the observational points, and lines the results of the analysis of several virtual light cones built with the simulation. On the right hand side panel one can clearly see when the incompleteness in the number of low luminosity mock galaxies kicks in due to the finite mass resolution of the simulations.

Figure 2. Distributions in redshift for different cuts in r and K magnitude of the galaxy cones. The dots show the mean value of $n_s(z)$ obtained by averaging over the 25 cones, and the error bars show the 1-$\sigma$ error on this mean value. The continuous line is the fit to the function in Eq. 1.

can be described by the Robertson-Walker metric, where in the presence of a perturbative gravitational potential the change in a photon’s direction can be written as:

$$d\vec{\alpha} = -2\vec{\nabla}_\perp \phi d\chi$$

(2)

where $d\vec{\alpha}$ is the photon’s deviation, $\phi$ is the gravitational potential, $\vec{\nabla}_\perp$ is the gradient in the direction perpendicular to the photon line of propagation and $\chi$ is the radial comoving coordinate. A deflection at $\chi'$ produces in a plane

located at coordinate $\chi$, perpendicular to the line of sight, a deflection of

$$d\vec{x} = r(\chi - \chi')d\vec{\alpha}(\chi')$$

(3)

where $r(\chi)$ is the comoving angular distance, that in a plane universe ($\Omega_\Lambda + \Omega_m = 1$) is equal to $\chi$. Integrating along the perturbed trajectory of the photon, and then dividing by $r(\chi)$ we obtain the angular position at position $\chi$.
\[ \bar{\theta}(\chi) = \bar{\theta}(0) - \frac{2}{r(\chi)} \int_0^\chi d\chi' r(\chi') \nabla_r \phi \]  

(4)

This treatment holds for a single photon. To obtain the effect on an extended object we calculate the Jacobian of the transformation \((\partial \theta_i(\chi)/\partial \theta_j(0))\), which we call \(A_{ij}\) where \(i\) and \(j\) denote perpendicular directions in the plane perpendicular to the line of sight, in which \(\bar{\theta}\) is also located:

\[ A_{ij} = -2 \int_0^\chi d\chi' \frac{r(\chi')}{r(\chi)} \nabla_r \theta_i \nabla_r \phi + \delta_{ij} \]  

(5)

the Jacobian matrix is usually decomposed as follows:

\[ A = \begin{pmatrix} 1 - \kappa - \gamma_1 & -\gamma_2 - \omega \\ -\gamma_2 + \omega & 1 - \kappa + \gamma_1 \end{pmatrix} \]  

(6)

where \(\kappa\) is the convergence, \(\gamma\) is the shear and \(\omega\) the rotation.

The relation between the gravitational potential and the mass density perturbation \(\delta = \rho/\bar{\rho} - 1\) is given by:

\[ \nabla^2 \phi = \frac{3}{2} \frac{H_0}{c}^2 \Omega_m \frac{\delta}{a} \]  

(7)

where \(H_0\) is the Hubble constant at the present, \(c\) is the speed of light and \(a\) is the expansion factor.

3.2 Multiple plane formalism

The multiple plane formalism consists in dividing the space between the source and the observers into \(N\) equidistant (in comoving coordinates) planes perpendicular to the line of sight. Following the convention of Hamana & Mellier [2001] we place ourselves in a cartesian coordinate system noted by \((x_1, x_2, y)\) where the origin is the observer and \(y\) indicates the direction of observation. For small angular size fields of view, \(y\) can be identified with the radial comoving distance \(\chi\). The inter-plane comoving distance will be called \(\Delta y\). The projected density contrast on the \(i\)-th plane located at \(y_i\) is given by:

\[ \Sigma_i(x_1, x_2) = \int_{y_{i-1}}^{y_i} dy \bar{\delta}(x_1, x_2, y) \]  

(8)

which defines a corresponding two dimensional potential \(\Psi = 2 \int dy \bar{\delta}\phi\). The position of a light ray in the \(n\)-th plane can then be found using the multiple plan lens equation:

\[ \bar{\theta}_n = \bar{\theta}_1 - \sum_{i=1}^{n-1} \frac{r(\chi_n - \chi_i)}{r(\chi_i)} \nabla \Psi_i \]  

(9)

\[ A_n = I - \sum_{i=1}^{n-1} \frac{r(\chi_n - \chi_i)r(\chi_i)}{r(\chi_n)} U_i A_i \]  

(10)

where \(I\) is the identity matrix and \(U_i\) is defined by:

\[ U_i = \begin{pmatrix} \partial_1 \Psi_i & \partial_2 \Psi_i \\ \partial_1 \Psi_i & \partial_2 \Psi_i \end{pmatrix} \]  

(11)

where \(\partial_{ij}\) symbols stand for partial differentiation.

3.3 Ray Tracing Algorithm

The algorithm can be divided in three steps. First, the projection of the dark matter distribution onto the planes. Second, the calculation of the potential and its first and second derivatives in these planes and finally the ray tracing from the observer to the last plane. In practice, things proceed as follows:

1. Once we have the dark matter particles of the simulation positioned inside an light cone build with MOMAF, we define an orthogonal coordinate system \((x_1, x_2, y)\) at the origin of the cone, where the \(y\) axis is directed from the observer along the symmetry axis of the cone. We then project (along the \(y\) axis) all the particles onto \(N\) equidistant planes parallel to the one located at the origin of the cone, which means for example that particles originally between \((x_1, x_2, y)\) and \((x_1, x_2, y + \Delta y)\) now sit at \((x_1, x_2, y + \Delta y)\).

2. In each plane we interpolate the overdensity \(\delta\) in equation (5), using a cloud-in-cell (CIC) algorithm, over an uniform square grid, \(G\), of \(N_g\) cells on a side of comoving size \(L_{side}\). \(N_g\) and \(L_{side}\) are kept identical for all planes. In order to solve the Poisson equation we pad with zeroes around the grid \(G\), thus creating a grid of size \(2 \times N_g\) in side. We then perform a fast Fourier transform (FFT) of the overdensity grid, and in Fourier space we divide by \(-1/k^2\) to inverse transform and obtain the gravitational potential \(\Psi\) on the grid. Finally, using finite differences methods we obtain the first and second derivatives of the potential along the \(x_1\) and \(x_2\) directions. This allows us to construct the matrix \(U\) in Eq. (11) for each point in the plane. A detailed numerical implementation for this step can be found in Premadi et al. [1998].

3. We initialize the ray positions over a uniform grid on the nearest plane to the observer. For each ray we interpolate the values of \(\bar{\alpha}\) and the elements of \(U\) using their tabulated values on the CIC grid. Applying equation (5) we then figure out the position of each ray on the next plane, and again interpolate the values of \(\bar{\alpha}\) and \(U\) at this new position to calculate \(A\), and so on and so forth until we reach the final plane. We store all these values, for each ray on every plane.

3.4 Shearing of galaxies

The galaxies in GALICS are represented by three components: disk, bulge and burst. Geometrically speaking, on a mock image, the disk is seen as an ellipse, and the bulge and the burst as circles. The burst is treated as a punctual source and only its magnitude will be modified by weak lensing. The circle and the ellipse can both be parametrised by their circle and the ellipse can both be parametrised by their

\[ Q = \frac{1}{\pi ab} \left( a^2 \cos^2 \beta + b^2 \sin^2 \beta \right) \left( a^2 - b^2 \right) \sin \beta \cos \beta \left( a^2 \sin^2 \beta + b^2 \cos^2 \beta \right) \]  

(12)

The case of the circle is recovered by setting \(a = b\) and \(\beta = 0\). Supposing that the Jacobian matrix does not vary much along the corresponding surface of the galaxy (which is a good approximation in the case of weak lensing caused
by large scale structure) the lensed shape matrix $Q'$ can be written as:

$$Q' = A^{-1}QA^{-1}$$

In this way the lensed properties of the disk and the bulge can be easily found if one knows the Jacobian matrix. In LEMOMAF the A matrix used to lens a galaxy is the average of four matrices, located at the point of impact of the four closest rays on the nearest plane to this galaxy. We lens bulge and disks separately.

This is used to produce mock lensed images useful for a more realistic treatment of the detection in simulations of the lensing signal through cosmic shear. In this paper we won’t use this capability. We will infer the measurements of $\kappa$ directly from the numerical values used to modify the galaxy’s properties.

### 3.5 Limits of the method

Most of the limitations of our ray tracing implementation are resolution issues that come from the use of N-body simulations and the interpolation grids used to trace the light rays. These errors in the calculation of the weak lensing signal from numerical simulations have been thoroughly quantified before (Jain et al. 2000; Vale&White 2003). We recall these results here, explicitly pointing out the place where the parameters that we use limit the approach the most.

Two relevant scales can be defined to assess the quality of the weak lensing signal in the simulation. The first one, $\sigma_g$, relates to the size of the Fourier grid where the lensing signal is obtained, and the second, $\sigma_n$, to the finite resolution of the N-body simulation. We define these quantities as: $\sigma_g = L_{\text{side}}/N_g$, $\sigma_n = L_{\text{box}}/N_{\text{part}}^{1/3}$, where $L_{\text{side}}$ is the size of the grid in the plane where we interpolate, $N_g$ its number of cells in one dimension, $L_{\text{box}}$ is the size of the simulation box and $N_{\text{part}}$ is the number of particles inside this box.

If $\sigma_g$ is larger than $\sigma_n$, the power of the signal on small scales will be dominated by the Fourier grid cut-off. If it is smaller, the power of the signal is dominated by noise in the N-body simulation. Moreover, if $\sigma_g$ is not only larger than $\sigma_n$ but also larger than any significant physical scale in the simulation, the features of the overdensity field that produce the deflection of the rays on that scale are wiped out, and no weak lensing signal is measured by the ray tracing method.

We choose a value of $\sigma_g/\sigma_n \sim 1$, guided by the results of previous studies. In our case, since we use a simulation with $L_{\text{box}} = 100 \ h^{-1} \ Mpc$ and $N_p = 256^3$, this translates into a resolution of $\sigma_n = 390 \ h^{-1} \ kpc$. Our ray tracing simulation uses a grid with $L_{\text{side}} = 200 \ h^{-1} \ Mpc$ and $N_g = 800$, which translates into $\sigma_g = 250 \ h^{-1} \ kpc$.

For a source at a given redshift, the weak lensing signal probes structures at intermediate redshifts between source and observer. This can be seen from the equation \[ (12) \] where the distance combination $r(\chi_n - \chi_i)r(\chi_i)/r(\chi_n)$ plays the role of an efficiency function for the lensing convergence. This distance combination peaks at an intermediate redshift between the observer and the source as shown in the upper panel of Fig. 3 where it is plotted normalized to the plane distance for three different source positions.

When one takes into account the redshift distribution of the sources used to measure the weak lensing signal, $n_s(z)$, one realizes that each redshift contributes a different amount to each plane. In order to estimate the joint contribution from the lens efficiency and the redshift distribution of the sources, we consider that each efficiency curve is multiplied by the value of $n_s(z)$ where $z_i$ is the redshift at which the efficiency curve is calculated, and then we add all the different efficiency curves together. In the middle panel of Fig. 3 we show the results of this calculation for a uniform $n_s(z)$ as well as for the six source distributions presented in Fig. 2.

From the middle panel of Fig. 3 one can see that the distances probed by galaxy populations measured in the SDSS $r$ filter are comprised between $0 - 1000 \ h^{-1} \ Mpc$ (redshifts 0 to 0.5), while for the Johnson $K$ filter this distance interval lies between $1000 - 3000 \ h^{-1} \ Mpc$ (redshifts from 0.5 to 2.0), with a broad peak around $1500 \ h^{-1} \ Mpc$.

Once the value of $\sigma_g$ is fixed, we can determine the angular resolution as a function of the distance from the
observer, as shown in the lower panel of Fig. 3 for our chosen value of $\sigma_g$. From this figure, one can check that in the redshift range probed by galaxies seen in the SDSS r filter this angular resolution is on the order of $\sim 1.5$ arcmin, and for that probed by galaxies in the JOHNSON R filter of about $\sim 0.5$ arcmin.

Discontinuities induced by the random rotations and origin shifts of the tiled boxes in the construction of the cone, using planes that are not perpendicular to the path of the light rays produce artifacts that were also analyzed by Vale&White (2003), concluding that their effects on the lensing signal are negligible. Finally, other errors arise from the translation of dark halo mass resolution into completeness limits at a given magnitude in a given waveband at a given redshift for the galaxy population, or from reduced spatial correlations caused by the random tiling technique. All this limitations have been studied in detail Hatton et al. (2003), Blaizot et al. (2004), Blaizot et al. (2005) and Blaizot et al. (2006). In this paper we remain inside these limits to draw our conclusions, but explicitly indicate when they are reached.

4 RESULTS

In this study, we make two kinds of numerical experiments with LEMOMAF: (i) we measure the weak lensing signal induced by the dark matter cone at galaxy positions, and (ii) we study the change in galaxy counts caused by weak lensing effects. Before exploring the results of these experiments we briefly discuss the behaviour of the LEMOMAF ray tracing module.

4.1 Ray Tracing Results

In this section, we focus on the measurements of the moments of convergence ($\kappa$) to present the results of the ray-tracing module of LEMOMAF.

The dark matter cones we use to make these measurements are $1.4^\circ$ on a side, and have a depth of 4400 $h^{-1}$ Mpc, with a distance of 100 $h^{-1}$ Mpc between lensing planes. In each of these planes, we use a grid with size $L_{\text{side}} = 200$ $h^{-1}$ Mpc which is split in $N_\theta = 800$ cells. Weak lensing properties and galaxy counts are measured only in a central field of 1.0$^\circ$ on a side. We characterize $\kappa$ through moments of its distribution function such as its variance $\langle \kappa^2 \rangle$, its skewness

$$S_3(\theta) = \frac{\langle \kappa^3 \rangle}{\langle \kappa^2 \rangle^{3/2}}$$

and kurtosis

$$S_4(\theta) = \frac{\langle \kappa^4 \rangle - 3(\langle \kappa^2 \rangle)^2}{(\langle \kappa^2 \rangle)^2}$$

We calculate these moments after smoothing the convergence maps with a circular top-hat filter of angular scale $\theta$.

We are especially interested in two results to validate our ray tracing code:

1) The dependence of $\langle \kappa^2 \rangle^{1/2}$ and $S_3$ as function of the redshift of the source, for which analytic expressions can be derived.

2) The dependence of $\langle \kappa^2 \rangle^{1/2}$, $S_3$ and $S_4$ on the smoothing scale $\theta$, for a given redshift of the source, for which published values exist in the literature.

In Fig. 4 we show our measurements for $\langle \kappa^2 \rangle^{1/2}$ and $S_3$ as a function of redshift, for nine different smoothing angles $\theta$ spaced every arcminute from $1^\circ$ to $9^\circ$. From this figure we can see that our computational values follow fairly well the expected theoretical trend. The agreement is better when the source plane is located at redshifts larger than $z = 1$. For closer source planes, located at $z < 1$, the slope of our numerical relation is steeper by than a factor of two.

In Fig. 5 we plot our results for $\langle \kappa^2 \rangle^{1/2}$, $S_3$ and $S_4$ as a function of the smoothing angle $\theta$, for sources located in a single plane at $z = 1$ and a field of view of $1^\circ \times 1^\circ$. The order of magnitude of $S_3$ and $S_4$ is consistent with a compilation of results for these moments made by Vale&White (2003) for smoothing scales of $4^\circ$. These authors quote an average of $S_3 \sim 135 \pm 10$ and $S_4 \sim (3.5 \pm 0.5) \times 10^4$ for measures obtained using different methods, with error bars reflecting the dispersion amongst reported values. For the same smoothing scale we find $S_3 = 115 \pm 5$, and $S_4 = (2.5 \pm 0.3) \times 10^4$.
keeping in mind that uncertainties coming from the numerical simulations themselves can contribute for an extra 10% error in our case, and that theoretical methods compiled in Vale&White (2003) suffer from a similar underestimate.

Being reasonably confident that we are able to produce reliable weak lensing measurements, we can now couple our ray tracing code to the outputs of a hybrid model of galaxy formation to study the source-lens clustering effect on the convergence statistics, and the effect of weak lensing on galaxy counts.

### 4.2 Source Lens Clustering

In the previous section we measured the statistics of the convergence of rays that uniformly covered a fraction of the sky. In reality, we only have access to the convergence signal measured for galaxies that have specific clustering properties and, even more important, are correlated to the lensing potential. This is known in the literature as the Source-Lens Clustering (SLC) effect.

Theoretical studies of the SLC effect predict that it alters the higher order statistics of the convergence. More precisely, while $\langle \kappa^2 \rangle^{1/2}$ should remain unchanged according to theory, $S_3$ should have a lower value. As a matter of fact, $S_3$ is known to be sensitive to $\Omega_m$ almost independently of $\sigma_8$, and a combined analysis of the skewness and the variance of the convergence could in principle provide new constraints on the values of $\Omega_m$ and $\sigma_8$.

Figure 5 shows convergence statistics as a function of smoothing scale. Sources are all located in a single plane at $z = 1$. Top panel: variance (divided by $10^{-2}$). Middle panel: skewness (divided by 10). Bottom panel: kurtosis (divided by 10^4). Error bars indicate the 1-σ dispersion measured around the mean for the 25 cone realisations.

Previous numerical work on the SLC effect (Hamana et al. 2002) has focused on its impact on $S_3$ estimations. This work was carried out using a simple bias model to paint a population of galaxies on top of the dark matter density field. To our knowledge, our work is the first attempt to use a galaxy population self-consistently derived from a N-body simulation to estimate of the impact of the SLC effect. More specifically, with MOMAF, we obtain both a dark matter distribution and its matching galaxy distribution in a light cone, this latter being derived by post-processing the dark matter simulation with the GALICS semi-analytic model. We then calculate the weak lensing signal over all the field at all the planes used in the ray tracing simulation with MOMAF, and use this information to shear the properties of galaxies which are in the cone, while storing the value of the convergence computed at each galaxy position. In this section, we therefore return to the analysis of the convergence statistics, but only for the subset of values measured at each galaxy position by interpolation of the values at the neighboring rays.

To quantify the impact of using a self-consistent modelling of the galaxy population on our results, we couple the dark matter and galaxy cones in three different ways.

In the first way, that we call MATCH, we shear the galaxies according to their true underlying dark matter distribution. In the second way, called RANDOM, we keep the same pair of galaxy cone/DM cone as in the MATCH case, but erase some of the spatial clustering information by randomizing the positions of galaxies over the sky plane while keeping their distance to the observer constant (i.e. we preserve the galaxy redshift distribution). Finally, in the third case, called NO MATCH, we use the full spatial clustering information for galaxies, but shear them using a different underlying dark matter distribution from the one with which their properties were derived. The idea behind these “tricks” is that cross-comparisons between the MATCH, NO MATCH and RANDOM methods should provide us with a better understanding of where the impact of the source-lens clustering effect on the convergence statistics comes from.

We use two broad band luminosities for each galaxy, those measured in the SDSS r, and JOHNSON K filters. We build 25 different light cones in order to minimize the bias effects induced by the random tiling technique, and maximize the accuracy of the statistics (Blaizot et al. 2003). For each light cone we output both the galaxies and the dark matter distribution. To mimic observational effects as best as we can, we select galaxies on which the lensing signal is to be measured based on their apparent magnitude. The resulting redshift distributions are shown in Fig. 2 where we
Figure 6. Comparison of the convergence statistics for three different magnitude ranges in the SDSS r filter, and for three different methods of measuring the convergence at each galaxy position. The solid line indicates results obtained with the RAND method, the dashed line with the NO MATCH method, and the dotted line with the MATCH method. $\langle \kappa^2 \rangle$ has been divided by $10^{-4}$, $S_4$ by $10^4$. Overplotted diamonds show values computed with the semi-analytic model described in Van Waerbeke et al. 2001.

Figure 7. The $R(S)$ factor as defined in Eq. [10] for $\langle \kappa^2 \rangle$ and $S_3$, for the three different magnitude ranges in the SDSS r filter. The solid line compares the methods MATCH and RAND. The dashed line compares the methods MATCH and NO MATCH.
Figure 8. Comparison of the convergence statistics for three different magnitude ranges in the JOHNSON K filter, and for three different methods of measuring the convergence at each galaxy position. The solid line indicates results obtained with the RAND method, the dashed line with the NO MATCH method, and the dotted line with the MATCH method. $\langle \kappa^2 \rangle$ has been divided by $10^{-4}$, $S_4$ by $10^4$. Overplotted diamonds show values computed with the semi-analytic model described in Van Waerbeke et al. 2001.

Figure 9. The $R(S)$ factor as defined in Eq. [16] for $\langle \kappa^2 \rangle$ and $S_4$, for the three different magnitude ranges in the JOHNSON K filter. The solid line compares the methods MATCH and RAND. The dashed line compares the methods MATCH and NO MATCH.
have arbitrarily split magnitudes in three bins: \(20 < m < 21\), \(21 < m < 22\) and \(20 < m < 22\). Once again, we recall that each light cone is \(1.4^\circ\) on a side, and has a depth of 4400 \(h^{-1}\) Mpc, with a distance between lensing planes of 100 \(h^{-1}\) Mpc. In each of these planes we use a grid of size \(L_{\text{side}} = 200\) \(h^{-1}\) Mpc split into \(N_p = 800\) cells. Weak lensing properties and galaxy counts are measured in a centered field of 1.0\(^\circ\) on a side.

Fig. 6 and 7 show the results for the higher order moments of the convergence and the six redshift distributions plotted in Fig. 2. Each linetype corresponds to a different method to construct the maps; RANDOM, NO MATCH and MATCH. We also compare our numerical results to the semi-analytic calculations of Van Waerbeke et al. (2001). Overall, the semi-analytical predictions of these authors show very good agreement with the lensing signal measured in our mock catalogues. Moreover, the better agreement with the RANDOM mocks is somewhat expected: out of the three methods we presented here, this is the one which follows the most closely the assumptions made in Van Waerbeke et al. (2001). Most of the small scale deviations from the semi-analytic trend in the variance plots can be attributed to the finite spatial resolution of our simulation (see Section 3.5).

We introduce the parameter \(R\) as done by Hamana et al. (2002) to quantify the amplitude of the SLC effects:

\[
R(S) = \frac{S_{\text{NO SLC}} - S_{\text{MATCH}}}{S_{\text{NO SLC}}} \tag{16}
\]

where \(S\) can be \((\kappa^2)\) or \(S_3\), and NO SLC is one of the methods RANDOM or NO MATCH. Fig. 7 and 9 show the results for this expression.

From these figures, it is clear that the results for \((\kappa^2)\), \(S_3\) and \(S_4\) in both filters, and in the three different magnitude bins show the same trend: these statistics are systematically lower for the MATCH case than for the NO MATCH and RANDOM cases, with these latter being remarkably similar. Furthermore, we clearly see that the effect is more pronounced for the narrower redshift distribution of sources (i.e. SDSS r band). These results, which are obtained using a fairly realistic galaxy distribution, are in broad agreement with the simpler approach advocated by Bernardes (1998) and Hamana et al. (2002). However, we also find a significant SLC effect on the two point statistics (\(R \sim 20\%\) for the SDSS r distributions, \(R \sim 5\%\) for the JOHNSON k distributions), which is not expected from perturbation theory alone. We suspect that it arises because our simulation probes the highly non-linear regime. A comparison of the MATCH to the NO MATCH run — where the clustering of sources is preserved albeit galaxies positions are not correlated with that of the underlying dark matter distribution — strongly suggests that the signal comes from the adequation of the intra halo galaxy population with the depth of its host potential well.

Finally, we would like to emphasize that such a mock catalogue approach should allow a fast calculation of the SLC effect for future weak lensing surveys intending to use cosmic shear as a precision cosmology tool.

### 4.3 Galaxy counts

Weak lensing enlarges the area of the sky which is observed, thus lowering the number density of objects which are detected. In the same time, it causes galaxies to appear brighter, thus increasing their number density for a given apparent magnitude. The net effect depends on the slope \(s(m)\) of the number counts of galaxies. Let us write \(N_0(m)dm\) as the number of galaxies with magnitudes between \(m\) and \(m + dm\), and \(s(m) = d\log N_0(m)/dm\). If the sources undergo a magnification \(\mu = 1/\det A\) (see section 3.1 for a definition of the matrix \(A\)), and \(N'(m)\) is the magnified number of sources corresponding to \(N_0(m)\), we can write \(N'(m) = \mu^{2s-1}N_0(m)\) (Broadhurst et. al. 1995; Jain 2002; Scranton et al. 2003).

The effect of the magnification on the solid angle, which is responsible for a factor \(\mu^{-1}\) can only be detected if we use a grid that allows us to have a resolution in the order of 0.1 arcmin to make a proper estimation of the deflection angle for a given galaxy. The angular resolution of our simulations is roughly 1 arcmin, which is clearly not enough. Therefore we expect that only the lensing effects on galaxy magnitudes (which does not require high angular resolution to be seen) will be perceptible. This simplifies the expression of magnified number of sources to \(N'(m) = \mu^{2s-1}N_0(m)\), which in turn reduces, in the weak lensing regime (\(\mu = 1 + 2\kappa\)), to:

\[
\frac{N'(m)}{N_0(m)} - 1 = 5.0\ \kappa \ s \tag{17}
\]

The numerical experiments we carry out with LEMOMAF are meant to explore the effect of weak lensing on galaxy counts via the estimate of this ratio, as we vary the size of the field in which the measurement of the counts are performed.

In the 25 original fields of \(1^\circ \times 1^\circ\) we compute galaxy counts both for unlensed and lensed fields (using the MATCH and NODE, MATCH methods). We then cut each of these fields into smaller square patches of angular size \(12^\prime\), \(15^\prime\), \(20^\prime\), \(30^\prime\) and \(1^\circ\) on a side, and measure the counts in all of these sub-fields. We also calculate for each patch the ratio \(N(m)/N_0(m)\), and organize our results as follows. For a patch of size \(\theta\), taken from a field of original size \(\Theta\) we have \(N_p = (\theta/\Theta)^2\) patches. Labeling subfields as \(\ell = 1, \ldots, N_p\) in every original uncut \(\Theta\) field, we then proceed to stack together the 25 patches which have the same index \(\ell\). For each patch in the stack, we estimate the ratio of lensed to unlensed integrated counts, and compute the mean for each stack.

In Fig. 10 and Fig. 11 we plot these means for our \(N_p\) stacks, for each value of \(\theta\) (column panels) and for both methods, NO MATCH and MATCH (top and middle row panels respectively). In the bottom row of these figures, we show \(\lambda = 5.0\ \kappa s\), in order to facilitate the interpretation of the behaviour of the lensed to unlensed counts ratio in terms of Eq. 17. In this intent, we estimate \(\kappa\) using an average value measured for the galaxies which lie in the magnitude bin of interest in the uncut field of size \(\Theta\). From our ray tracing results (see Fig. 1) we know that we are in the weak lensing regime where \(\kappa < 1\), so Eq. 17 tells us that we can expect a depletion in galaxy counts only when \((\kappa)s\) and \(s\) have different signs.

In the SDSS r band (Fig. 11), \(\lambda\) (in percent) is restricted to the interval \([0, 0.1, 0.0]\). High fluctuations in the counts ratio
Figure 10. Percentile difference between lensed ($N'$) and unlensed ($N_0$) galaxy counts in the SDSS $r$ filter, calculated with the MATCH (upper panel) and NO MATCH (middle panel) methods. The lower panel shows the values of $\lambda = 5.0 \cdot s \cdot \langle \kappa_{\text{gal}} \rangle_{\text{bin}}$, where $s$ is the logarithmic slope of the counts and $\langle \kappa_{\text{gal}} \rangle_{\text{bin}}$ is the average value of $\kappa$ measured from the galaxies in that magnitude bin over the field of size $1^\circ$. Each vertical line splits the plot in panels which contain results for different patches of angular size $\theta$ on a side, cut inside an original field of size $\Theta = 60^\prime$ on a side. Thus the number of curves in each row of panels is $N_p = (\Theta/\theta)^2$, and each curve represents the mean of the measurement over 25 uncorrelated patches. The rightmost upper and middle panel also show the 1-$\sigma$ dispersion between the 25 $\Theta$ fields ($N_p = 1$) as error bars.

Figure 11. Same as Fig. 10 for the JOHNSON $K$ filter. The behaviour for magnitudes $K > 21$ is a numerical resolution artifact which leads to an incompleteness in the number of low luminosity galaxies (see also right panel in Fig. 1). For the low values of the magnitude are due to an ever smaller number of bright galaxies being present in a subfield when the subfield size decreases or the brightness of the source increases. In the magnitude interval $m_K = [19, 22]$ where this effect becomes negligible, we see that galaxy number counts can be enhanced by up to 1%.

In the JOHNSON $K$ filter (Fig. 11), $\lambda$ (in percent) takes values in the interval $[-4.0, 4.0]$, although its change of sign between the magnitudes 21 and 23 is entirely due to the mass resolution of our N-body simulation which translates into an incompleteness for galaxies fainter than $m_K = 21$ (see also Fig. 1). We therefore restrict ourselves to the magnitude interval $m_K = [16, 21]$ for which there exists a good agreement between modeled and observed counts in terms of slope, and the number of bright galaxies per subfield is high enough. In this magnitude interval, the counts can be enhanced up to a 3%, for high values of $m_K$.

In both filters we note that faint galaxies are always more enhanced than bright ones: $\lambda$ as a function of a magnitude is a monotonically increasing function. Of course, this trend has to break down at some point, when the slope of the faint galaxy counts turns over, as shown in Fig. 11 even if in this case it is purely an artifact due to finite mass resolution in our N-body simulation.

Unsurprisingly, the dispersion around the theoretically expected ratio increases when the angular size of the field decreases. Finally, Fig. 10 and 11 show that the source lens clustering effect does not play an significant role in enhanc-
ing galaxy number counts: the NO MATCH and MATCH methods pretty much yield the same quantitative results.

However, from this experiment we confirm our suspicion that the modification of the solid angle is not resolved in our simulations, consequently higher angular resolution must be attained if one hopes to use LEMOMAF in the study of angular correlations induced by cosmic magnification.

5 DISCUSSION AND CONCLUDING REMARKS

In this paper we presented the Lensed Mock Map Facility that combines dark matter N-body simulations and an hybrid model of hierarchical galaxy formation to make mock lensed images and convergence maps, thanks to a ray tracing algorithm. More specifically, the results presented here were obtained using a cosmological N-body simulation performed with a tree-code, the GALICS model of galaxy formation, the MOMAF pipeline which constructs galaxy and dark matter light cones, and a ray tracing algorithm through multiple planes to account for the weak lensing effect. This tool suffers from all the shortcomings inherent to each of these techniques. However, for GALICS and MOMAF these limitations have been carefully identified in a series of papers published over the past four years. As far as the ray tracing algorithm is concerned, its limitations in terms of the N-body simulation parameters have also been discussed quite thoroughly in the literature. To sum up, these shortcomings impose a limitation on the size of the fields that can be constructed, and the angular resolution that can be reached in the construction of the lensed images and the convergence maps.

Working within the proper interval of validity of these methods, we performed two numerical experiments with LEMOMAF. The first one measured the convergence signal induced by the dark matter density field at galaxy positions in a light cone. Different methodologies for this measurement were implemented, in the aim of testing the consequences of the source-clustering effect on the probability density function of the convergence. We found that the SLC effect skews the PDF towards lower values of the convergence and that, in some cases, it makes this PDF look more gaussian than that obtained without including SLC, as expected from theoretical considerations. However, even when probing the same dark matter distribution, the precise trend of the SLC effect depends sensitively on the specific distribution of the galaxies we consider. For instance, we demonstrated that a narrower redshift distribution of the sources is more sensitive to the SLC effect. This could be problematic for future lensing surveys which intend to perform shear measurement in thin redshift slices, a technique called tomography [Hu (1999)]. For the JOHNSON K filter, the SLC effect has an impact at the few percent level (2–5%) on the estimations of $\sigma_8$ from two point statistics. This level of contamination was neglected in previous analysis [Bernardeau (1993) Humana et al. (2002)], because its amplitude was well below the largest weak lensing surveys accuracy at that time (VIRMOS: Van Waerbeke et al. (2000), RCS: Hoekstra et al. (2002)). However, future -nearly full sky- missions like SNAP and LSST will have to reach a precision of $10^{-3}$ on the shear measurement, i.e. roughly 0.1% from on the shear two-points statistics [Van Waerbeke et al. (2006)]. At this level of precision, the SLC will be a major source of systematics, and the only way to tackle this issue is to have photometric redshifts for each individual galaxy, sources and lenses. This strengthen the requirement that future lensing surveys will have to cover a wide range of the optical spectrum, from U band to near infrared, with narrow band filters, similar to the COMBO-17 approach (Heymans et al. (2004)).

The second numerical experiment measured the lensed to unlensed galaxy counts ratio. The value of this ratio was obtained for various angular sizes of observational fields. The general trend of the results in the simulation can be understood using Eq. (17) where only magnitude changes played an important role in enhancing the counts in our simulations. We learnt from this experiment that in order to have a realistic treatment of the magnification effects over the change of galaxy positions in the sky we need to go up in angular resolution.

Among the ideas that remain to be investigated using LEMOMAF are those that take advantage of mock images at multiple wavelengths to identify the best strategies for measuring the shear, as well as those which intend to study the bias introduced by intrinsic alignments or other systematic effects on this measurement. Future prospects with LEMOMAF include the simulation of galaxy-galaxy lensing and cosmic magnification. This kind of signal demands a resolution in our simulations in the order of 0.1 arcmin. With the N-body simulation we used in this paper, and FFT methods we barely achieve a resolution of $1 \sim 2$ arcmin. In order to reach higher resolutions we do not plan to only rely on more resolved N-body simulations but also to switch ray tracing strategy and look in the direction of smooth particle lensing (Aubert et al. 2006), as we have gained confidence from recent studies with GALICS (Blaizot et al. 2006) that the small scale distribution of galaxies produced from an adequate resolution N-body simulation and a new positioning scheme of galaxies inside the halos can be accurate enough to attain this goal. We also plan to use LEMOMAF to help design future lensing surveys, which will need to employ a tool tailored to tackle non-linear effects such as SLC.

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The cosmological N-body simulation (Ninin 1999) we use throughout this paper assumes a flat Cold Dark Matter cosmology with a cosmological constant ($\Omega_m = 0.3$, $\Omega_{\Lambda} = 0.7$), and a Hubble parameter $h = H_0/[100 \text{ km s}^{-1} \text{ Mpc}^{-1}] = 0.667$. The initial power spectrum was taken to be a scale-free ($n_s = 1$) power spectrum evolved as predicted by Bardeen et al. (1984) and normalised to the present-day abundance of rich clusters with $\sigma_8 = 0.88$ (Eke, Cole, & Frenk 1996). The simulated volume is a cubic box of side $L_b = 100h^{-1}\text{ Mpc}$, which contains $256^3$ particles, resulting in a particle mass $m_p = 8.272 \times 10^8 M_\odot$ and a smoothing length of 29.29 kpc. The density field was evolved from $z = 35.59$ to present day, and we out-putted about 100 snapshots spaced logarithmically with the expansion factor.

In each snapshot, we identify halos using a friend-of-friend (FOF) algorithm (Davis et al. 1985) with a linking length parameter $b = 0.2$, only keeping groups with more than 20 particles. At this point, we define the mass $M_{FOF}$ of the group as the sum of the masses of the linked particles, and the radius $R_{FOF}$ as the maximum distance of a constituent particle to the centre of mass of the group. We then fit a tri-axial ellipsoid to each halo, and check that the virial theorem is satisfied within this ellipsoid. If not, we decrement its volume until we reach an inner virialised region.

**APPENDIX A: DARK MATTER**

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virial quantities are the ones we use to compute the cooling of the hot baryonic component. Once all the halos are identified and characterised, we build their merger history trees following all the constituent particles from snapshot to snapshot.

APPENDIX B: LIGHTING UP HALOS

The fate of baryons within the halo merger trees found above is decided according to a series of prescriptions which are either theoretically or phenomenologically motivated. The guideline – which is similar to other SAMs – is the following. Gas is shock-heated to the virial temperature when captured in a halo’s potential well. It can then radiatively cool onto a rotationally supported disc, at the centre of the halo. Cold gas is turned into stars at a rate which depends on the dynamical properties of the disc. Stars then evolve, releasing both metals and energy into the interstellar medium (ISM), and in some cases blowing part of the ISM away back into the halo’s hot phase. When haloes merge, the galaxies they harbour are gathered into the same potential well, and they may in turn merge together, either due to fortuitous collisions or to dynamical friction. When two galaxies merge, a “new” galaxy is formed, the morphological and dynamical properties of which depend on those of its progenitors. Typically, a merger between equal mass galaxies will give birth to an ellipsoidal galaxy, whereas a merger of a massive galaxy with a small galaxy will mainly contribute to developing the massive galaxy’s bulge component. The Hubble sequence then naturally appears as the result of the interplay between cooling – which develops discs – and merging and disc gravitational instabilities – which develop bulges.

Keeping track of the stellar content of each galaxy, as a function of age and metallicity, and knowing the galaxy’s gas content and chemical composition, one can compute the (possibly extincted) spectral energy distribution (SED) of each galaxy. To this end, we use the stardust model (Devriendt et al. 1999) which predicts the SED of an obscured stellar population from the UV to the sub-mm.