

Mapping Dark Matter in Galaxy Clusters: Gravitational Lensing & Numerical Simulations

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The different regimes of gravitational lensing constitutes an interesting tool in order to map the mass distribution in galaxy clusters on different scales. In this proceedings article, I review some work I have performed on this topic. More precisely, I will focus on : (i) galaxy scale substructures, using weak galaxy-galaxy lensing in order to study how does the environment shape their properties; (ii) the mass profile of Abell 1689 as probed combining strong and weak lensing; (iii) the slope of the inner dark matter distribution in Abell 1703 as measured by strong lensing. The lensing results will be compared to the expectations from numerical simulations, when available.

1 Gravitational Lensing by a Galaxy Cluster

In this article, I will assume that the Newtonian dynamics still holds on large scales and will interpret the results within the framework of dark matter, but note that viable alternative theories of gravity do exist.

The emerging picture coming from observational probes and numerical simulations is the following: clusters of galaxies consist of 1-2% stars; 10-20% intracluster gas with a temperature of 1-15 keV emitting in x-ray; 80-90% dark matter. The lensing effect, i.e. the bending of light by matter along the line of sight from the source to the observer, depends only on the mass distribution of the intervening structures, making gravitational lensing an interesting tool for measuring the mass profiles of lensing structures. In particular, no additional assumptions need to be made with regard to the dynamical state (relaxed or not, in hydrostatic equilibrium or not) or the nature (baryonic or not, luminous or dark) of the intervening matter. However, *all* mass distributions along the line of sight contribute to the lensing signal, introducing contamination by foreground or background objects. In the core of massive clusters, the surface mass density is well above the critical value enabling the use of detected strong lensing features to constrain the inner part of the cluster potential. At larger cluster-centric radii, the ellipticities of weakly sheared background galaxies is used to estimate the weak lensing effects induced by the cluster potential. Combining strong and weak lensing techniques allows one to map the mass distribution of a galaxy cluster from the centre to the outskirts. Moreover, galaxy scale substructures induce local modulation of the shear field in their neighbourhood. This weak signal can be statistically detected in order to probe the mass distribution of galaxy scale substructures.

2 Truncation of Galaxy Dark Matter haloes in High Density Environment

Galaxy scale dark matter haloes can be probed via a technique called weak galaxy-galaxy lensing. The idea is the following : observing the shapes of distant background galaxies which have been lensed by foreground galaxies allows us to map the mass distribution of the foreground galaxies. Of course, the lensing effect is small compared to the intrinsic ellipticity distribution of galaxies, thus a statistical approach is needed. Consequently, galaxy-galaxy lensing studies allow to constrain the mean properties of the halo population as a whole, and the reliability of the signal will depend on the number of foreground-background pairs. One advantage of this statistical approach is that it provides a probe of the gravitational potential of the halos of galaxies out to very large radii, where few classical methods are viable, since dynamical and hydrodynamical tracers of the potential cannot be found at this radii.

2.1 Theoretical Approach

My first approach of galaxy-galaxy lensing has been theoretical (Limousin et al., 2005¹): I have been simulating data sets, for different observational configurations and showed that a maximum likelihood method (Schneider & Rix, 1997²) is well adapted to the problem, in the sense that it allows to retrieve the structural parameters that characterize galaxies' dark matter haloes: the central velocity dispersion, σ_0 , which is related to the depth of the potential well, and $r_{1/2}$, the half mass radius, which is related to the spatial extent of the halo. Given this parametrization, the mass of the halo scales as $M \sim \sigma_0 r_{1/2}$. After extensive simulation work, the technique developed theoretically was applied on a sample of five massive galaxy clusters at $z \sim 0.2$.

2.2 Application to a Sample of Cluster Lenses at $z \sim 0.2$

Data were taken at the CFHT with the CFH12K camera through the B, R and I filters (Czoske et al., 2002³). The object detection is described in Bardeau et al. (2005)⁴. We selected the elliptical cluster galaxies as lenses. We used only objects detected in all three bands and with reliable shape information, and we undertook a Bayesian photometric study to derive a redshift estimation for each background galaxy. Comparison to the colour-cut adopted in the DEEP2 redshift survey (Coil et al., 2004⁵) to select galaxies at $z > 0.7$ showed that our procedure allowed to reliably discriminate background galaxies.

The smooth component corresponding to the cluster itself was also considered. The maximum likelihood method was applied on the galaxy catalogs with the goal to derive some constraints averaged on the cluster galaxy population. The main result of this analysis (Limousin et al., 2007a⁶, Fig. 1) is to find galactic dark matter haloes to be very compact compared to field galaxies of equivalent luminosity: an upper limit on the half mass radius is set at 50 kpc, when similar studies performed on field galaxies inferred half mass radius larger than 200 kpc. The mean total mass for the galaxy sample is found of order $0.2 \cdot 10^{12} M_\odot$. These results are in good agreement with former galaxy-galaxy lensing studies through cluster core based on HST data (Natarajan et al., 1998⁷; Geiger & Schneider, 1999⁸; Natarajan et al., 2002a,b^{9,10}; Natarajan et al., 2008¹¹).

This observational results is interpreted within the tidal stripping scenario. The theoretical expectation is that the global tidal field of a massive, dense cluster potential well should be strong enough to truncate the dark matter halos of galaxies that traverse the cluster core (Avila-Reese et al., 2005¹²; Ghigna et al., 2000¹³; Bullock et al., 2001¹⁴). In other words, when a galaxy is falling into a cluster, it will experiment strong tidal forces that will strip their dark matter haloes, feeding the cluster dark matter halo itself.

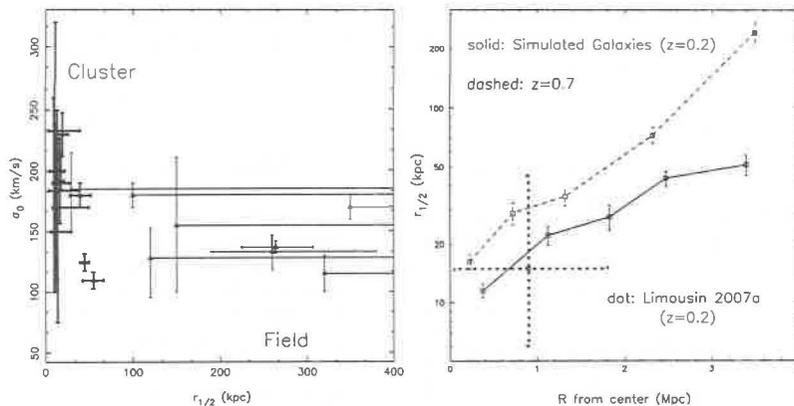


Figure 1: Left: Comparison between galaxy-galaxy lensing results on cluster galaxies (thick black) and galaxy-galaxy lensing results on field galaxies (thin grey): cluster galaxies appear to be significantly more compact than field galaxies. References are given in Limousin et al., 2007a. Right: Evolution of the half mass radius as a function of cluster centric distance for the simulated galaxies at $z = 0.2$ (solid line) and $z = 0.7$ (dashed line). Dotted data point correspond to the galaxy-galaxy lensing constraints derived in Limousin et al., 2007a.

2.3 Comparison with N -body hydrodynamical simulations

In order to get more insight into the tidal stripping scenario and to interpret the observational results within a theoretical framework, I have been analyzing high resolution, N -body hydrodynamical simulations of two fiducial galaxy clusters (Limousin et al., 2008¹⁵). These simulations include dark matter and baryonic particles (Sommer-Larsen et al., 2005¹⁶). The effect of tidal stripping on cluster galaxies hosted in these dark matter subhalos as a function of cluster-centric radius is investigated. To quantify the extent of the dark matter halos of cluster galaxies, we introduce the half mass radius $r_{1/2}$ as a diagnostic, and study its evolution with projected cluster-centric distance R as a function of redshift. We find a well defined trend for $(r_{1/2}, R)$: the closer the galaxies are to the center of the cluster, the smaller the half mass radius. Interestingly, this trend is inferred in *all* redshift frames examined in this work ranging from $z = 0$ to $z = 0.7$. At $z = 0$, galaxy halos in the central regions of clusters are found to be highly truncated, with the most compact half mass radius of 10 kpc (Fig. 1). We compare these results with galaxy-galaxy lensing probes of $r_{1/2}$ and find qualitative agreement. We make predictions concerning the evolution of $r_{1/2}$ with cluster-centric radius that will be possible to probe with future surveys using space based telescopes such as SNAP, that combine wide field and high resolution imaging.

3 Combining Strong and Weak Gravitational Lensing in Abell 1689

3.1 Strong Lensing Analysis

Deep HST ACS images have provided an unprecedented wealth of arcs in Abell 1689. 34 multiply imaged systems have been reported and used in Limousin et al., 2007b¹⁵. 24 systems have been confirmed spectroscopically. Using these observational constraints, I built a mass model using the LENSTOOL software (Jullo et al., 2007¹⁷). Thanks to the large number of multiple images, the projected mass distribution is very well constrained, at the percent level accuracy. This mass model has been used by Stark et al., (2007)¹⁸ to detect very high redshift candidates beyond redshift 8, thanks to the natural amplification provided by the cluster. I also report the finding

of five strong galaxy-galaxy lenses located at ~ 300 kpc from the cluster center, i.e. *outside* the critical region of the cluster. These events have been used as an independent probe of the cluster potential in Tu et al., (2008)¹⁹.

3.2 Weak Lensing Analysis

Strong lensing allows us to constrain the projected mass distribution in the cluster core (typically $50''$ from the cluster centre). To probe the cluster potential at larger cluster-centric radii (up to $1000''$), I have been using wide field multi-color data from the CFH12K camera. From a background galaxy catalog, it is straightforward to construct a shear profile, but a difficult issue is to reliably know who has been lensed by the cluster, since any contamination of the background galaxy catalog with non lensed cluster galaxies will dilute the shear signal and bias the derived parameters (Fig. 2). Using Bayesian photometric redshift, I have selected a background galaxy population. The strong lensing and the weak lensing regimes are found to agree for the first time in this extensively studied cluster. The global concentration parameter is found to be around 8, a value which is rather high but compatible with Λ CDM predictions (Neto et al., 2007²⁰). Former analysis based on Subaru data on the other hand have reported concentration parameters larger than 20 (see, for example, Medezinsky et al., 2007²¹), which is problematic for the Λ CDM scenario. Since it is important to discriminate between these values, we have been revisiting the weak lensing analysis from a mosaic of 16 HST pointings (Dahle, Limousin et al. in prep.). This independent analysis leads to a concentration parameter around 10. We thus conclude that there is no concentration problem in Abell 1689. There remain some discrepancies between the lensing and the X-ray masses. However, analysis of new very deep CHANDRA data (see contribution by Signe Riemer-Sørensen) reveal a complicated structure which is likely not to be in hydrostatic equilibrium and elongated along the line of sight, which could explain the mass disagreement. Moreover, this elongation along the line of sight (which is clearly supported by the spectroscopy of bright cluster members) can also explain the large Einstein radius observed in this cluster and which have been recently claimed to be problematic for Λ CDM (Broadhurst & Barkana, 2008²²).

4 Strong Lensing in Abell 1703: Constraints on the Slope of the Inner Mass Distribution

Properties of dark matter haloes are probed observationally and numerically, and comparing both approaches provide constraints on cosmological models. When it comes to the inner part of galaxy cluster scale haloes, interaction between the baryonic and the dark matter component is an important issue which is far to be understood. Efforts are needed on the observational and numerical side in order to understand what is going on in the centre of the most massive virialized structures of the Universe. In a recent article (Limousin et al., 2008²³), we have been trying to measure the slope of the inner dark matter distribution in Abell 1703, using strong lensing techniques. Abell 1703 is a massive X-ray luminous galaxy cluster at $z = 0.28$. The analysis is based on imaging data both from space and ground in 8 bands, complemented with a spectroscopic survey. Abell 1703 looks rather circular from the general shape of its multiply imaged systems and present a dominant giant elliptical cD galaxy in its centre. This cluster exhibits a remarkable bright '*central ring*' formed by 4 bright images at $z_{\text{spec}} = 0.888$ located very close to the cD galaxy, providing observational constraints that are potentially very interesting to probe the central mass distribution (Fig. 2). The stellar contribution from the cD galaxy ($\sim 1.25 \cdot 10^{12} M_{\odot}$ within $7''$) is accounted for in the parametric mass modelling, and the underlying smooth dark matter component distribution is described using a generalized NFW profile parametrized with a central logarithmic slope α . We find that within the range where observa-

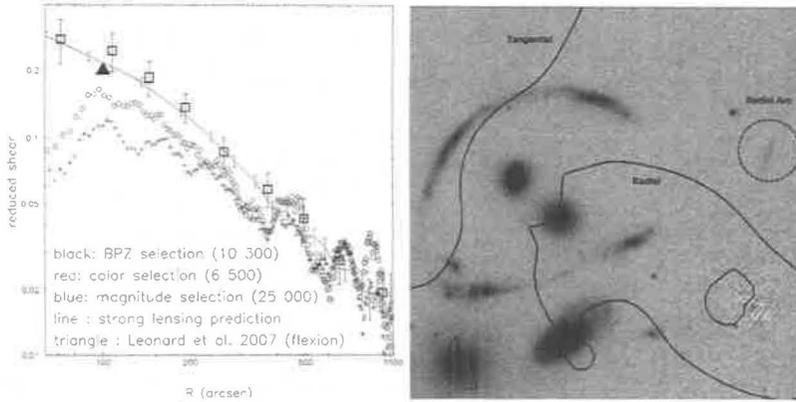


Figure 2: Left: Comparison between shear profiles constructed using different rejection criteria to select background lensed sources: the Bayesian photometric redshift based selection (squares), a color selection (circles), and a magnitude cutoff (plus signs). The number of objects corresponding to each rejection criterion is given in parentheses. The solid line corresponds to the strong-lensing prediction, and the filled triangle comes from the study by Leonard et al., (2007). Right: 'central ring' in Abell 1703, composed of four bright images. F775W image where the light from the cD galaxy has been subtracted (note residuals). We plot the tangential and critical lines at the redshift of this system.

tional constraints are present (from $\sim 5''$ to $\sim 50''$), the slope of the dark matter distribution in Abell 1703 is equal to $1.09^{+0.05}_{-0.11}$ (3σ confidence level). The concentration parameter is equal to $c_{200} \sim 3.5$, and the scale radius is constrained to be larger than the region where observational constraints are available. Within this radius, the 2D mass is equal to $M(50'') = 2.4 \cdot 10^{14} M_{\odot}$. We cannot draw any conclusions on cosmological models at this point since we lack results from realistic numerical simulations containing baryons to make a proper comparison. Such comparison, when possible, may provide an interesting cosmological probe, in particular when it comes to interactions between dark matter and baryons.

Acknowledgments

I thank the organizers for providing me an opportunity to present my work. The work reviewed in this article has been done thanks to the participation of various friends and colleagues: Á. Elíasdóttir, B. Fort, E. Jullo, H. Dahle, H. Tu, J.-P. Kneib, J. Richard, J. Sommer-Larsen, O. Czoske, P. Natarajan, S. Bardeau & T. Verdugo. Marie Curie is acknowledged for the grant that covered my lodging expenses. Funding from the Agence Nationale de la Recherche is acknowledged. The Dark Cosmology Centre is funded by the Danish National Research Foundation.

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