Galaxy clusters mass measurements: news in X-ray and Weak lensing data analysis

Iacopo Bartalucci¹, Ilaria Formicola¹, Rossella Martino²

¹ Department of Physics, Università di Roma Tor Vergata, 00133 Rome, Italy
² Laboratoire IRFU/Service d’Astrophysique - CEA - CNRS - Bat. 709, CEA-Saclay, F-91191 Gif-sur-Yvette Cedex, France
E-mail: bartalucci@roma2.infn.it, formicola@roma2.infn.it, martino@roma2.infn.it

Abstract.
We describe the recent improvements made on the techniques for the estimates of the total mass of galaxy clusters using the X-ray data, obtained by the Chandra and XMM satellites, and the weak lensing observations, performed by Subaru telescope. Furthermore, we show the current state of X-ray and weak lensing mass comparison obtained by simulations and observational data. In particular, we use a subsample of 21 galaxy clusters of the LOCUSS High-Łx sample, for which we find that X-ray masses overcome weak lensing mass by about 10%.

1. Introduction
Galaxy clusters are the largest and most massive collapsed objects in the Universe. They are directly linked to the primordial density perturbations, therefore they are powerful tools to test the cosmological theories and to constrain cosmological parameters ([1], [2], [3], [4], [5]).

Structures formation on large scale and their time evolution can be investigated using N-body simulations ([6], [7], [8]). Results obtained from N-body simulations need to be compared with observations in order to study hidden biases, quantifying sources of uncertainty in the measure with a good control on systematic errors. This issue can be investigated using both observational data and numerical simulations ([9], [10], [11]). Furthermore, it is very important to perform a multi-wavelength study, comparing results obtained from two different techniques based respectively on X-ray and weak lensing observations ([12], [13], [14]).
The X-ray emission produced by the hot Intracluster Medium (ICM) within galaxy clusters allows to estimate cluster mass profiles analyzing the gas density and temperature structures, assuming the hot ICM to be in hydrostatic equilibrium within the cluster gravitational potential well.
The weak lensing analysis measures weak distortions in the shape of faint distant galaxies, induced by the cluster potential, to derive the mass. Weak gravitational lensing provides a unique tool to study the dark matter content in galaxy clusters since it probes the total matter density with no distinction between ordinary barionic matter and dark matter and without any assumption on the shape and/or on the dynamical state of the cluster. However, halo triaxiality could lead to an overestimation of mass and concentration derived from the NFW halo profile. In fact in this case a measure of the three-dimensional structure of the halo is obtained from a 2-D information, since lensing is sensitive only to the projected mass ([15]).
hand, with respect to the weak lensing analysis, the X-ray method has the advantage to be less sensitive to projection effects due to additional mass concentration along the line of sight. All these reasons make complementary the two techniques. With the aim to derive an accurate mass measure using both techniques we describe the main features of the recent improvements made for each of them. In particular, we develop a new analytical background model for Chandra data, allowing to study in detail galaxy clusters up to their outskirts, and test selection criteria for background lensed sources, in order to avoid dilution in the lensing signal, using lensing simulation and applying these criteria to Subaru data. Furthermore, we show the current state of X-ray and weak lensing mass comparison obtained from simulations and observational data.

2. Weak Lensing Analysis

An accurate cluster mass measure by weak lensing requires a careful selection of background galaxies. Therefore it’s necessary to avoid, in the selected sample, cluster and foreground unlensed sources which dilute the lensing signal. Dilution increases as the cluster-centric distance decreases since the number density of cluster galaxies, which contaminate the background galaxies sample, follows the density profile of the cluster. Without any redshift information, it’s possible to select background sources using photometry or photometric redshifts depending on the number of photometric bands available. Starting from magnitudes in three bands, cluster, background and foreground galaxies can be identified as overdensities in two-colors diagrams as suggested by [16].

In this section we describe our criteria for selection of galaxies in two-colors diagrams, applied to simulations of lensing observations and to a real cluster: Abell 2219. Wide field simulated images of the $g_1$ cluster ([17]) in $B, V, R, I, z$ bands using the SUBARU Suprime-Cam allow us to derive galaxy colors and photometric redshifts. Our selection criteria, based on galaxy colors, use the COSMOS catalog with photometry and photometric redshifts ([18]) to derive where galaxies with photometric redshifts lower or higher than the cluster redshift lie in color-color diagrams, obtained plotting the $V - R$ vs $B - R$ and the $R - I$ vs $B - V$ colors. We apply the same color cuts which identify each population of galaxies in the COSMOS two-colors diagrams to sources belonging to the images of the $g_1$ cluster, deriving in this way the background and the foreground galaxy populations. In order to test our selection we derive galaxy radial density profiles and shear profiles of both tangential and radial components for each identified population. A good selection, indeed, implies tangential shear profiles for cluster and foreground galaxies consistent with zero and almost flat galaxy radial density profiles for background and foreground galaxies, since these galaxies are uniformly distributed across the field of view. The shear signal is obtained averaging on the observed ellipticities, corrected for the observational distortions introduced by seeing and PSF anisotropy. This correction is done following the approach suggested in the work of [19], (KSB method), and performed as described in [20] and [21].

Real redshift and ellipticities, available for each source in the images of the $g_1$ cluster, allow us to quantify the contamination due to unlensed sources both in the case of a selection based on colors and in the case of a selection based on photometric redshifts, derived using the photometry in five bands.

We find that less than the 10% of foreground galaxies contaminate the background color-selected sample and the background sample selected with photometric redshifts. In addition, as described in [22], the KSB approach underestimates measured ellipticities: for these simulations measured ellipticities are underestimated of about 20% with respect to true ellipticities.

On the basis of results obtained from simulations we apply the described selection methods to a real cluster, Abell 2219, in order to derive an accurate mass estimation by weak lensing. Abell 2219 is a massive X-ray luminous cluster at $z = 0.22$. Cluster observations were performed with the SUPRIME cam at the SUBARU telescope in $B, V, R_c$ bands and with the Large Binocular
Camera at the LBT in $I$ band. Subaru images were reduced with VST-Tube imaging pipeline ([23]) using ASTROMC ([24]) to remove distortions introduced by optics. The observed shear of background galaxies, selected as described above, is used to derive an estimate of the cluster mass following the aperture densitometry technique ([25]) and fitting the expected shear profile described by SIS and NFW models to data ([26]). More details on described methods and obtained results will be found in [27].

3. X-Ray Technique

In this section we explain the main features for the mass estimates using the X-ray data, focusing on the news in our technique. We use data obtained from the X-ray Chandra and XMM-Newton satellites, with the ACIS-I (Advanced CCD Imaging Spectrometer)\(^1\) and EPIC (European Photon Imaging Camera)\(^2\) cameras respectively. The imaging and the spectral analysis for Chandra ACIS-I and XMM-Newton EPIC observations are performed following the procedure described in [28] and [14], where all event-lists are merged in a single energy position photon cube. The brightness and temperature profiles are extracted in concentric annuli centered on the centroid of the cluster and then are used to derive the density and 3-D temperature profiles following the “forward” method described e.g. in [10]. In particular we assume a modified $\beta$-model profile for the density distribution and a power-law for the temperature profile as described in [29] and [14]. These profiles are then projected along the line of sight, in concentric shells. For XMM-Newton data, the projection of density includes a convolution by the instrument PSF. The density and 3-D temperature profiles are used to estimate the total gravitating mass assuming the hydrostatic equilibrium condition:

$$-G\mu m_p n_{gas} M_{tot}(<r)/r^2 = dP/dr = d(n_{gas} \times T)/dr,$$

where $G$ is the gravitational constant, $\mu = 0.59$ the mean molecular weight in a.m.u., $m_p$ the proton mass, $k$ the Boltzmann constant, and $n_{gas}$ and $T$ are the 3D gas density and temperature profiles respectively.

In this technique to measure projected temperature we need to separate adequately the background components spectra from the thermal emission spectra of the ICM. When we refer to background we mean the sum of two components: the physical background, produced by X-ray sources, and an instrumental background, produced by the high energy particles which hit detectors and cause instruments to glow. The first component is well known and analytically modeled ([30], [31]). The second component is modeled only for XMM-Newton observations ([31], [32]). In our work we focus on the analysis of Chandra ACIS-I particle background. The Chandra standard analysis tools provide background datasets that are subsequently subtracted from the observation of interest causing the eventual mixing of systematic and measure errors. For instance we know that instrumental background has a spatial variation gradient ([33]) which introduces systematic errors in the normalization of the background components. In the central regions the signal level is typically $2-3$ order of magnitude greater than the background signal so the mixing effect is negligible, while it becomes important in the outskirts where the ICM emission is faint and the signal level is of the same level of background. Studying galaxy cluster outskirts is crucial to fully understand evolution and formation of these structures. For the first time we produce an analytical model for Chandra ACIS-I instrument which allows us to predict particle background, minimizing systematic error, with a precision up to 2% in the continuum and 5% in the lines.

\(^1\) for more details see http://cda.harvard.edu/chaser/

\(^2\) for more details see http://xmm.esac.esa.int/xsa/
4. Results and Comparisons
We apply our X-ray technique to derive the total hydrostatic mass for the 51 clusters of galaxies of the LOCUSS High-$L_X$ volume limited sample. We analyze all the available Chandra and XMM-Newton observations for this sample. As it will be shown in details in [14], using a subsample of 22 clusters observed with both instruments, the total cluster masses are totally consistent with an accuracy of the 5%. Therefore, for a subsample of 21 clusters we compare our X-ray hydrostatical masses with the most recent observational results of weak lensing mass estimates, presented in [34], at $r = r_\Delta$, where $\Delta = 2500, 1000, 500$ is defined as the ratio of cluster matter density over the critical density to have a flat Universe. The average X-ray to weak lensing mass ratios are calculated taking into account the errors in the X-ray and weak lensing mass estimates, following the method described in [35]. We find that the mass ratios $M_X/M_{WL}$ are equal to $1.12 \pm 0.06$, $1.12 \pm 0.06$ and $1.09 \pm 0.07$ at $\Delta = 2500, 1000$ and 500, respectively. We find that X-ray masses are higher of a 10\% than weak lensing masses at all overdensities. In Fig 1 we plot our X-ray hydrostatic to weak lensing mass ratios as a function of density contrast as black squares. Therefore, we compare our results with previous ones and numerical simulations. In Fig 1 previous observational results obtained by [12] are plotted as blue triangles: in this work, the X-ray and weak lensing masses are in agreement, with a mass ratio equal to the unity for all overdensities. We also overplot the recent results obtained by Pratt et al. 2012 at $r_{500}$ with green squares. In this last work, they find that the hydrostatic X-ray masses are on average $22 \pm 8\%$ larger than the corresponding weak lensing masses. They show how this results seem to be due to the offset of the centre of the cluster used in the analysis, equal to X-ray peak and BCG position for x-ray and weak lensing techniques respectively. We also plot the previous numerical simulations results obtained by [10] sample with forward method (yellow stars) and backward method (orange stars) and values obtained by [11] (magenta upside triangles). Simulations find that X-ray masses are low-biased compared to lensing masses by 10-20\% at all overdensities. These results have an opposite trend with respect to our measurements, for which X-ray hydrostatical masses are, on average, higher than weak lensing masses of 10\%.
Therefore, the current comprehension of the differences between X-ray and weak lensing masses is yet puzzling. This is mostly due to the non-availability of large samples with both high-quality X-ray and weak lensing mass estimates. This is one of the main aims of the Locuss project, and new results should be obtained in few years.

5. References

[1] Press and Schechter 1974 Astrophys. J. 187 425-438
[2] S. White, F. Navarro, E. Evrard and C. Frenk 1993 Nature 366 429-433
[3] V. R. Eke, and S. Cole, and C. S Frenk, and J. Patrick Henry, 1998 Mon. Not. R. Astron. Soc 298 1145-1158
[4] S. W. Allen, and R. W. Schmidt, and A. C. Fabian, 2002 Mon. Not. R. Astron. Soc 334 L11-L15
[5] A. Vikhlinin, and A. V Kravtsov, and R. A. Burenin, and H. Ebeling, and W. R. Forman, and A. Hornstrup, and C. Jones, and S. S. Murray, and D. Nagai, and H. Quintana, and A. Voevodkin, 2009 Astrophys. J. 692 1060-1074
[6] R. K. Sheth, and G. Tormen, 1999 Mon. Not. R. Astron. Soc 308 119-126
[7] A. Jenkins, and C. S. Frenk, and S. D. M. White, and J. M. Colberg, and S. Cole, and A. E. Evrard, and H. M. P. Couchman, and N. Yoshida, 2001 Mon. Not. R. Astron. Soc 321 372-384
[8] C. Giocoli, and G. Tormen, and F. C. van den Bosch, 2008 Mon. Not. R. Astron. Soc 386 2135-2144
[9] E. Rasia, and S. Ettori, and L. Moscardini, and P. Mazzotta, and S. Borgani, and K. Dolag, and G. Tormen, and L. M. Cheng, and A. Diaferio, 2001 Mon. Not. R. Astron. Soc 321 372-384
[10] M. Meneghetti, and E. Rasia, and J. Merten, and F. Bellagamba, and S. Ettori, and P. Mazzotta, and K. Dolag, and S. Marri, 2010 Astron. & Astrophys 514 A93
[11] D. Nagai, and A. Vikhlinin, and A. V Kravtsov, 2007 Astrophys. J. 655 98-108
[12] Y.-Y. Zhang, and N. Okabe, and A. Finoguenov, and G. P. Smith, and R. Piaretti, and R. Valdarnini, and A. Babul, and A. E. Evrard, and P. Mazzotta, and A. J. R. Sanderson, and D. P. Marrone, 2010 Astrophys. J. 711 1033-1043