Mem. S.A.It. Vol. 81, 163

Memorie della

Clusters of galaxies in the Chandra and XMM - Newton Era

Julia Weratschnig

Institute of Astro- and Particle Physics, University of Innsbruck, Technikerstrasse 25, 6020 Innsbruck, Austria, e-mail: `julia.weratschnig@uibk.ac.at`

Abstract. We present new results in the study of clusters of galaxies obtained with modern X-ray satellites like XMM-Newton and Chandra. Over the last ten years, both telescopes have studied these objects in detail and made many new insights into the involved physical processes possible. We present some highlights of the last ten years, like the measurement of the Hubble parameter, a probably detection of warm-hot matter in the filament between two clusters, new constraints on the nature of dark matter and some others. This choice is of course a personal "hit list" of the author, but hopefully contains an interesting overview of recent cluster research.

Key words. Clusters of Galaxies: general – Clusters of Galaxies: X-ray observations – Clusters of Galaxies: new results

1. Introduction

Clusters of galaxies are known to be the largest gravitationally bound structures in the Universe. They are tools to study large scale structure formation, the distribution of matter in space and offer insights into many physical processes which are unique in a cluster environment. Observations and theoretical modelling have shown that clusters of galaxies consist of 80% dark matter, 15-20% intra cluster medium and only (3-5)% of the matter is in the form of galaxies. These percentages are representative for the whole universe.

The intra cluster medium was discovered in the 1960s, when clusters showed to be sources of a diffuse X-ray emission. Soon it became clear that this radiation is emitted from a hot, ionised gas, the intra cluster medium (ICM). Fig. 1 shows the diffuse emission from the ICM as it is detected with XMM-Newton. The cluster shown is MS0451 at a redshift of 0.55. With a flat cosmology and a Hubble parameter of $71 km sec^{-1} Mpc^{-1}$ the emission of the ICM can be seen out to about 890kpc.

The main emission process in the ICM is thermal bremsstrahlung which produces a continuum emission. Additional to the continuum, line emission was detected. This shows that also heavy elements like iron or oxygen are present in the ICM. Since those elements are only produced in stars (which are usually found inside of galaxies), interaction mechanisms have been suggested to transport the metals from the galaxies into the ICM. Fig. 2 shows the spectrum of MS0451, taken with the EPIC cameras aboard XMM-Newton. The continuum which is due to thermal bremsstrahlung is used to determine the temperature of the gas, while the strength of

Send offprint requests to: J. Weratschnig

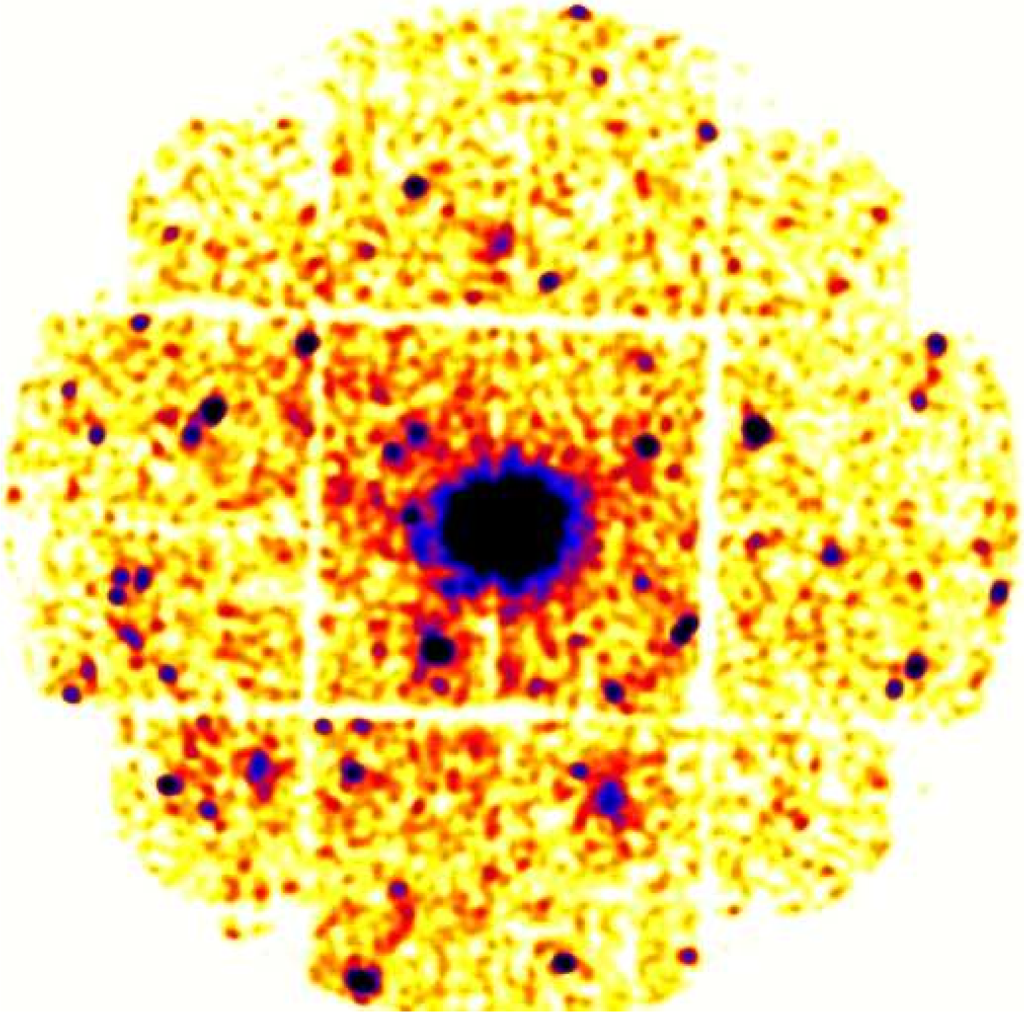

Fig. 1. An XMM-Newton image of the cluster of galaxies MS0451. The size of the cluster in this image is about 3 arcminutes. At a redshift of 0.55 this corresponds to a size of roughly 890kpc (using a flat cosmology and an H_0 of $71 km sec^{-1} Mpc^{-1}$).

the metal lines is a measurement for the metallicity of the ICM.

The ICM offers a unique environment for galaxies: cluster galaxies differ from galaxies in the field. Interaction processes take place between galaxies, but also between galaxies and the ICM. Thanks to these interactions, the ICM gets enriched with high metallicity gas from the galaxies.

2. X-ray telescopes: Chandra and XMM-Newton

Both Chandra and XMM-Newton were launched in 1999, XMM-Newton by the European Space Agency (ESA) and Chandra by the National Association for Space And Aeronautics (NASA). They use Wolter type mirrors (based on total reflection of X-rays on a metallic surface) to focus the X-rays onto the detectors. XMM-Newton consists of

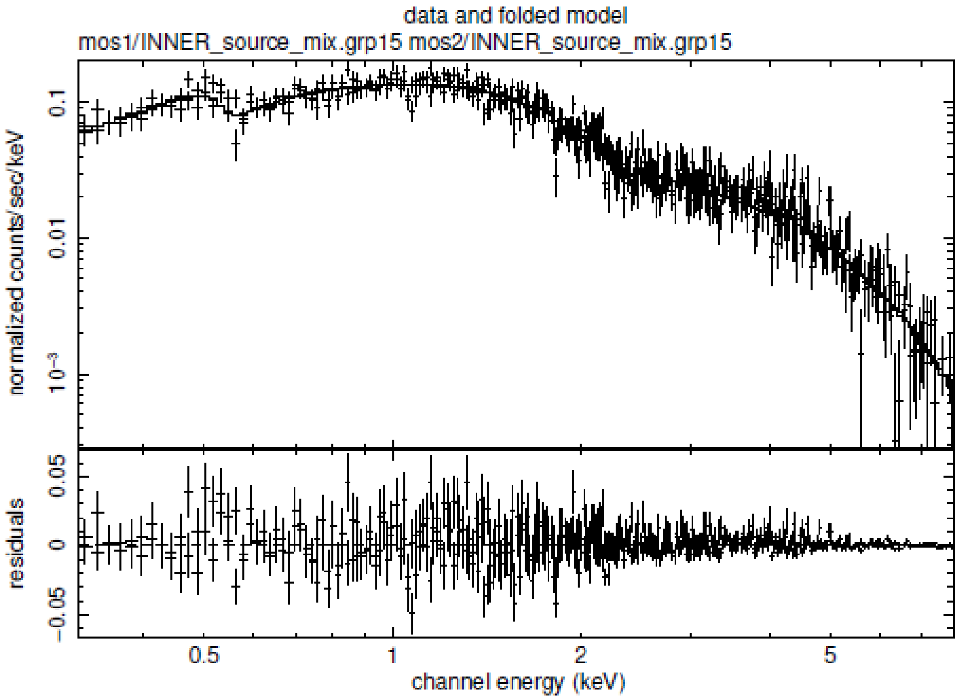

Fig. 2. An XMM-Newton EPIC spectrum of MS0451. The continuum is due to thermal bremsstrahlung of the ICM, with line radiation visible from metals.

three different telescopes, each of which has 58 nested mirrors. Chandra consists of one telescope with 4 nested mirrors. The collecting area of XMM-Newton is about 10 times larger than the one of Chandra. The specifications of the two satellites are given in Table 1.

For further and more detailed information on the two telescopes and the necessary data reduction, we refer the interested reader to the manuals and papers dealing with the calibration of the data reduction, see Table 2.

3. Results obtained with Chandra and/or XMM-Newton

In the following sections, I present some recent results which have given new insights into clusters of galaxies, confirmed theoretical predictions or raised new questions which will have to be addressed in the future. Most of the presented results use either Chandra or XMM-Newton data (or both) to gain information on properties of the ICM.

3.1. SN - Independent measurement of the Hubble parameter

The Hubble parameter is one of the most important parameters in astrophysics, and its correct measurement is crucial. It is needed to obtain correct distances and therefore crucial when deciding on correct cosmological models. With observations using both Chandra data and radio observations from a sample of clusters of galaxise, Bonamente et al. (2006) determine the value of the Hubble parameter. Their method is based on the Sunyaev Zel'dovich (SZ) effect and is independent of distances measured with supernovae.

They use a sample of 38 clusters of galaxies in a redshift range between 0.14 and

Table 1. Technical data for Chandra and XMM-Newton

Telescope	Focal length	mirror	Collecting area	number of detectors	Spatial resolution	Spectral resolution
Chandra	10m	1.2m	0.04m^2	4 (ACIS, HRC, LETG, HETG)	0.5 arcseconds	$\frac{d}{dE}$ 20-50 (ACIS) or 60-1000 (HETG)
XMM-Newton	7.5m	0.7m	0.43m^2	3 (EPIC, RGS, OM)	20 arcseconds	$\frac{d}{dE}$ 20-50 (EPIC) or 200-800 (RGS)

Table 2. Manuals and data reduction for XMM-Newton and Chandra

Telescope	Manuals	Information concerning data reduction
Chandra	`http://cxc.harvard.edu/ciao/`	background spectra: Markevitch et al. (2003), `http://cxc.harvard.edu/contrib/maxim/bg/index.html`, `http://asc.harvard.edu/cal/Acis/Cal_prods/vfbkgrnd/index.html`
XMM-Newton	`http://xmm2.esac.esa.int/external/xmm_user_support/documentation/`	vignetting correction: Arnaud et al. (2001), double background subtraction: Arnaud et al. (2002), background files working group: `http://xmm2.esac.esa.int/external/xmm_sw_cal/background/index.shtml`

0.89 and determine the angular distance to each of these clusters. The angular distance to the cluster can be calculated, if its real size together with the angular size is known. Bonamente et al. (2006) used two different models together with measurements of the SZ effect to determine the size of the observed clusters:

1. **A hydrostatic equilibrium model:** This models takes radial variations in temperature, density and abundance into account.
2. **An isothermal single β-model** without the assumption of equilibrium

The value for the Hubble parameter which is obtained in this work is $H_0 = 76.9^{+3.9}_{-3.4} kms^{-1}Mpc^{-1}$ using **model 1**, and $H_0 = 73.7^{+4.6}_{-3.8} kms^{-1}Mpc^{-1}$ for **model 2** (both times using a cosmology with $\Omega_M = 0.3$ and $\Omega_\Lambda = 0.7$). If the cool cores of clusters are rejected from the analysis to avoid any influences from this region, $H_0 = 77.6^{+4.8}_{-4.3} kms^{-1}Mpc^{-1}$. The result is very robust and does not depend much on the chosen model, it is also in good agreement with the value for H_0 obtained using supernova observations with the Hubble Space Telescope ($H_0 = 72 \pm 8 kms^{-1}Mpc^{-1}$). For details on the data analysis and the methods we refer the reader to the original paper of Bonamente et al. (2006).

3.2. Cold fronts, shocks and AGN cavities

Since X-ray emission is proportional to the density squared of the ICM, X-ray observations are a good method to study the structure of the ICM. With the unrivalled imaging possibilities offered by Chandra and XMM-Newton, the study of small scale phenomena in the morphology of clusters of galaxies is possible for the first time. Those observations offer a new insight into physics. A complete review on the topic of cold fronts and shocks can be found in Markevitch & Vikhlinin (2007), in the following sections I will shortly summarise the main points of their paper.

3.2.1. Cold fronts

A strong jump in ICM density was observed with Chandra for Abell 2142 (Markevitch et al. 2000) and Abell 3667 (Vikhlinin et al. 2001), which turned out to be the first observations of cold fronts in clusters of galaxies. Thanks to the high resolution of Chandra, it was possible to determine the temperature inside and outside of the density jump. The temperature inside is lower than outside, while the density is higher on the inside of the front. These values show that this feature is not a common merger shock. These dense, cool clouds are thought to be - among some other explanations - the surviving cool cores of a merged cluster. The outer part of the region is shock heated.

Apart from the study of the cold front itself, those phenomena can be used to gather information of ICM properties. They allow to determine the gas bulk motion perpendicular to the line of sight (by measuring the differences in the thermal pressure), offer the possibility to study the growth of instabilities, the thermal conductivity and the viscosity in the ICM. They also allow to determine whether magnetic fields are strong enough to suppress the conductivity of the ICM.

3.2.2. Merger shocks and AGN cavities

Shocks in the ICM have been predicted in simulations of clusters of galaxies, but the observation of these phenomena became only possible using the high quality imaging from Chandra and XMM-Newton. Two possible causes for a shock can be observed and studied with those satellites:

1. Cavities produced by a powerful AGN
2. Shocks due to a merger

AGN cavities have been observed by e.g. Gitti et al. (2007) in the cluster of galaxies MS0735+7421. They report the existence of a cavity visible in the X-ray image, which coincides with the radio lobe of a powerful AGN. Further studies of these objects still need to be done to confirm a jump in temperature or to determine what type of material fills these bubbles.

Merger shocks are caused by an infalling subcluster. Since the Mach numbers of the gas are different, the gas gets heated and we observe a jump in temperature and density - with the higher temperature on the ”inside” of the density jump. Several conditions need to be fulfilled for a shock to be observed: It has to happen perpendicular to the line of sight, the subclusters have to be of different mass and we must look at the shock front when it still resides in a high density region. The most famous example for a prominent merger shock is probably the cluster of galaxies 1E 0657-558 (also known as the ”Bullet Cluster”) which was studied by Clowe et al. (2006). Another example for a cluster containing a merger shock is Abell 514 (Weratschnig et al. 2008).

Merger shocks allow to derive the Mach number of the infalling gas. The width of a merger front gives constraints on the number of AGN bubbles in this region and allows tests of the matter and physics involved (electron-ion equilibrium, timescales of astrophysical plasmas, non thermal phenomena). For more details, we refer to Markevitch & Vikhlinin (2007) and references therein.

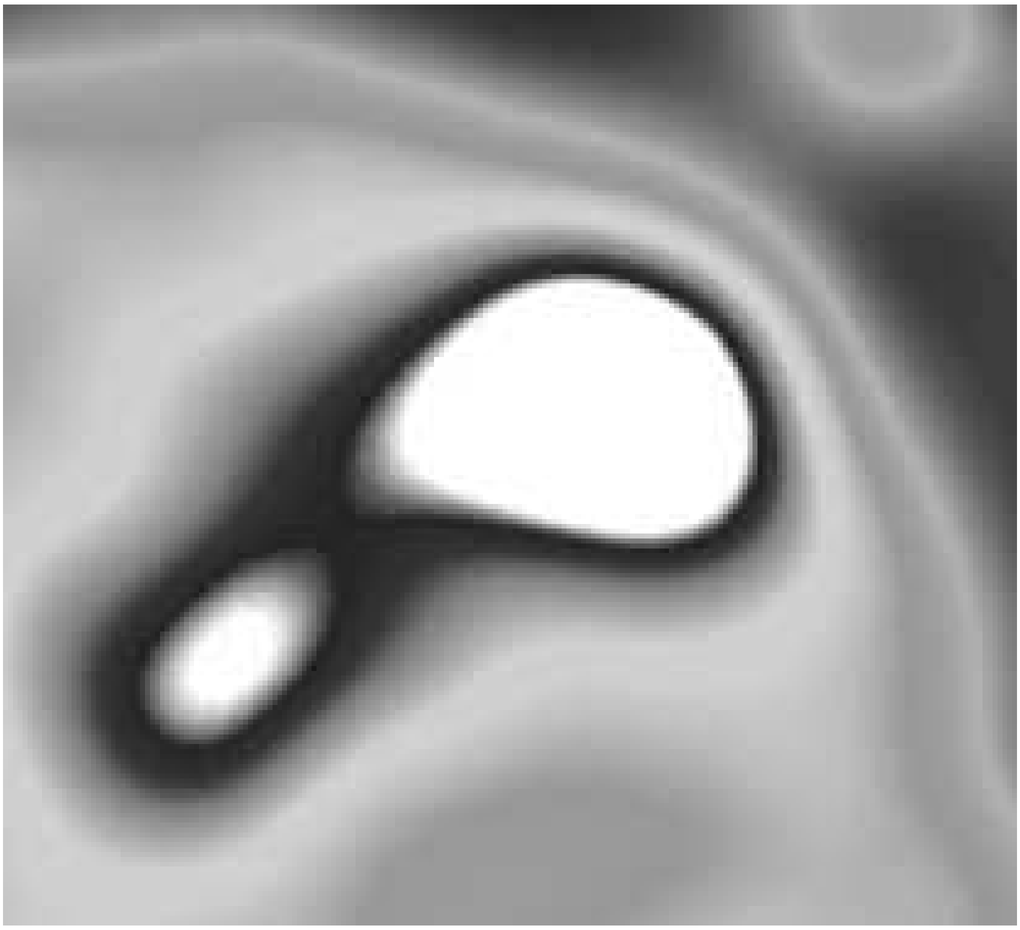

Fig. 3. The cluster of galaxies Abell 514. In the upper subclump, the steep decline in surface brightness is a sign for a merger shock.

3.3. Constraints on dark matter

The observation of merger clusters also offers new insights and constraints on the nature of dark matter. Studies addressing this topic are mostly done as a combination of a lensing analysis with X-ray observations. In this way, discrepancies in the distribution of dark matter versus the distribution of the ICM can be seen. Depending on these discrepancies, conclusions about the cross section for interaction of the dark matter particles can be drawn. Clowe et al. (2006) report a very low cross section of dark matter for the observation of the bullet cluster, which is also in good agreement with results reported by Bradač et al. (2008). However, Mahdavi et al. (2007) show that in the merger cluster Abell 520 the case is different, and they need a higher cross section for the dark matter interactions than the other two suggest. While in both MACS J20025.4 (Bradač et al. 2008) and the Bullet Cluster (Clowe et al. 2006) the dark matter is clearly in front of the ICM and correlates in position with the cluster galaxies (which can be described as non-interacting particles), in Abell 520 Mahdavi et al. (2007) report a dark core which coincides with the the position of an ICM subclump. While a lot of observations show the presence of a dark matter component, the true nature of it remains unknown and needs to be studied in the future.

3.4. First detection of warm hot gas in filaments?

The large scale structure of the universe is thought to be in the form of a cosmic web, which consists of filaments and clusters of galaxies where the filaments intersect. While the filaments have been observed in optical surveys (Joeveer et al. 1978; Tegmark et al. 2004), it is assumed from simulations that a lot of the baryons in the filaments are in the form of a low-density, warm gas (Cen & Ostriker 1999; Davé et al. 2001). Werner et al. (2008) present the possible first detection of the baryonic matter in a filament in X-rays. They use a deep observation from XMM-Newton to study the neighboring clusters of galaxies Abell 222 and Abell 223. By using a wavelet decomposition of the image in the soft X-ray band, a filament connecting these two clusters is seen. Follow up observations (e.g. using a lensing analysis to detect the filament) are still needed to confirm this finding.

3.5. Conclusions from comparison with simulations

With simulations temperature and metallicity maps of clusters of galaxies can be produced to study different enrichment processes as well as the dynamical state of a cluster (pre- or post merger). With XMM-Newton and also Chandra it is now possible to create such maps also for deep observations of clusters of galaxies. Lovisari et al. (2009) have shown that simulations and observations can be used to draw conclusions on the nature of a cluster of galaxies. In a follow up paper (Lovisari et al. 2009) they study the metallicity map of Abell 3667 together with results from simulations to determine the dynamical state and enrichment of the ICM.

3.6. New results from magnetic fields

Dolag et al. (2001) have studied the correlation between cluster magnetic field strength and ICM density. Both values are obtainable with observations: Faraday Rotation Measures (FRM) allow to study the distribution of magnetic field strength in a cluster of galaxies, while the ICM density is proportional to the X-ray surface brightness. Both parameters are line of sight integrals depending on ICM properties. The relation between them ($\sigma_{RM} - L_X$ relation) gives insight into the nature of the magnetic fields present in a cluster of galaxies. Weratschnig et al. (2008) have studied XMM-Newton observations of Abell 514 to study this correlation with new data. For a sample of other clusters (Abell 119, Coma, Abell 401 and 3C 129) where both XMM-Newton archive data and FRM are available, Weratschnig (2009) has measured a new value for the slope parameter of the $\sigma_{RM} - L_X$ relation. The value of $\alpha = 0.95$ is in agreement with theoretical predictions that the cluster magnetic fields are frozen into the ICM.

3.7. High redshift clusters - Study of evolution of clusters

To study the evolution of clusters of galaxies, large samples over a large range of redshift are needed. The search for high redshift clusters with both XMM-Newton and Chandra is still going on, and several groups are involved, like shown by Fassbender (2007).

3.8. Results from Suzaku

Additional to from XMM-Newton and Chandra, the Japanese satellite Suzaku is in service since 2005. It has a very high energy resolution and a very low background, which make this instrument ideal to study cluster spectra, allows the determination of abundance profiles and also the determination of the bulk velocity along the line of sight (thanks to highly sensitive X-ray spectroscopy, especially of the Fe line at 6.7 keV).

4. Future satellites?

The next large X-ray project is the joint project ”IXO”, the ”International X-ray Explorer”. ESA, NASA and JAXA work together on this project. At the moment, concept studies are made worldwide. The satellite will have wide field imaging, high spectral resolution, grating spectrometers, high timing resolution and also an X-ray polarimeter onboard. The launch is planned to take place in 2020/2021. A 5 year mission which can be extended to a 10 year mission is the goal.

5. Conclusions

Clusters of galaxies are indeed highly interesting objects in observational cosmology. Thanks to modern X-ray satellites like XMM-Newton and Chandra, we know a lot more about clusters now than 10 years ago, but with the new observations also new questions have been posed. Not surprisingly, among the main scientific goals for IXO is also the ”Formation and Evolution of Galaxies, Clusters and Large Scale Structure” which will address many of the questions raised in the last years, like constraints on dark matter and dark energy, the search for missing baryons (filaments) and the detailed study of interaction processes between galaxies and the ICM and their influence on galaxy formation.

6. DISCUSSION

Can you comment on the current status of Symbol X? Symbol X has been cancelled. IXO is still one of the possible large projects of the next years, and will be realized in a cooperation between ESA, NASA and JAXA. The next scheduled missions I know of are e-Rosita (2011) and the Japanese satellite Astro-H, which will be launched 2013 for a five year mission.

Can you describe the observation of the bullet cluster again in more detail? Is there a temperature map available, and what does it tell us in addition to the surface brightness image of the ICM? The famous image of the bullet cluster shows an overlay of the optical image (HST), the X-ray image (Chandra) and the results from a lensing analysis. In the X-ray image, the colour is only depending on the density and does not give any information about the temperature. However, the temperature of the ICM has also been studied. One result was that the weak lensing mass of the smaller clump is in agreement with its X-ray temperature (Clowe et al. 2004). By studying the temperature distribution along the shock front, it can be shown that we see a combination of a cold front and a merger bow shock.

Acknowledgements. I thank the organisers of the conference for giving me the opportunity to present my talk in Vulcano during the Frascati Workshop 2009. Many thanks go to Sabine Schindler, my PhD supervisor, who pointed me towards this highly interesting workshop and gave me the possibility to visit it.

References

Arnaud, M., et al. 2001, A&A, 365, L80
Arnaud, M., et al. 2002, A&A, 390, 27
Bonamente, M., et al. 2006, ApJ, 647, 25
Bradač, M., et al. 2008, ApJ, 687, 959
Cen, R., & Ostriker, J. P. 1999, ApJ, 514, 1
Clowe, D., et al. 2004 ApJ, 604, 596
Clowe, D., et al. 2006, ApJ, 648, L109
Davé, R., et al. 2001, ApJ, 552, 473
Dolag, K., et al. 2001, A&A, 378, 777
Fassbender, R. 2009, PhD Thesis, LMU Munich
Gitti, M., et al. 2007, ApJ, 660, 1118
Joeveer, M., et al. 1978, MNRAS, 185, 357
Lovisari, L., et al. 2009, American Institute of Physics Conference Series, 1126, 290
Lovisari, L., et al. 2009, in prep.
Mahdavi, A., et al. 2007, ApJ, 668, 806
Markevitch, M., et al. 2000, ApJ, 541, 542
Markevitch, M., et al. 2003, ApJ, 583, 70
Markevitch, M., & Vikhlinin, A. 2007, Physrep, 443, 1
Tegmark, M., et al. 2004, ApJ, 606, 702
Vikhlinin, A., et al. 2001, ApJ, 551, 160
Werner, N., et al. 2008, A&A, 482, L29
Weratschnig, J., et al. 2008, A&A, 490, 537
Weratschnig, J., 2009, PhD Thesis, University of Innsbruck, Austria