X-ray and weak lensing measurements of galaxy groups and clusters

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ACADEMIC DISSERTATION

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Abstract

As galaxy clusters are the most massive bound objects in the Universe, their number and evolution is sensitive to the underlying cosmology. The use of clusters for constraining cosmological parameters requires the knowledge of cluster masses. This is typically achieved through calibrating scaling relations, where an observable is used as a mass proxy. Clusters can be efficiently detected through the X-ray emission of the hot intracluster gas, whereas weak gravitational lensing provides the most accurate mass measurements. This thesis studies the X-ray emission of galaxy clusters, the cross-calibration of X-ray instruments and the scaling between X-ray observables and weak lensing mass. It consists of five refereed journal articles.

Two of the articles study solely the X-ray properties of clusters. We characterise the thermal Bremsstrahlung X-ray emission of the Ophiuchus cluster with XMM-Newton and use INTEGRAL to detect non-thermal hard X-ray excess emission. We model the excess emission, assuming that it is due to inverse-Compton scatter of Cosmic Microwave Background photons by a population of relativistic electrons, derive the pressure of the relativistic electron population and give limits on the magnetic field strength. We also study the cross-calibration of the XIS detectors onboard the Suzaku satellite and show that discrepancies can be explained by the modelling of the optical blocking filter contaminant. We conclude that XIS0 is more accurately calibrated than XIS1 and XIS3. However, we show that soft band cluster temperatures measured with XIS0 are ∼ 14 % lower than those measured with XMM-Newton/EPIC-pn due to remaining cross-calibration uncertainties.

In two of the articles we study the scaling of X-ray luminosity and temperature of the intracluster gas to weak lensing mass for galaxy groups and low-mass clusters. These samples are combined with high-mass samples from the literature. We correct our data for survey biases and provide the current limitations for $L_X$ and $T_X$ as cluster mass proxies. Studying the residuals, we find the first observational evidence for a mass dependence in the scaling relations using weak lensing masses - galaxy groups are warmer and more luminous for their mass than more massive clusters. We also study hydrostatic mass bias in X-ray mass estimates and find indications for an increased bias in low-mass systems. The final article presents the catalogue of low-mass clusters used in one of the papers studying scaling relations.

Our results on scaling relations are limited by our understanding of sample selection. More observations of low-mass systems are needed to constrain the inferred mass dependence in both scaling relations and hydrostatic mass bias. Calibration against external measurements, e.g. weak lensing, can help to address cross-calibration discrepancies and forthcoming X-ray observatories will significantly improve our understanding of non-thermal phenomena in clusters.
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Helsinki, January 2016

Kimmo Kettula
List of publications


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<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>160SD</td>
<td>160 Square Degree ROSAT Survey</td>
</tr>
<tr>
<td>ACIS</td>
<td>Advanced CCD Imaging Spectrometer</td>
</tr>
<tr>
<td>AGN</td>
<td>Active Galactic Nuclei</td>
</tr>
<tr>
<td>BCG</td>
<td>Brightest Cluster Galaxy</td>
</tr>
<tr>
<td>BOSS DR9</td>
<td>Baryon Oscillation Spectroscopic Survey Data Release 9</td>
</tr>
<tr>
<td>CC</td>
<td>Cool core</td>
</tr>
<tr>
<td>CCCP</td>
<td>Canadian Cluster Comparison Project</td>
</tr>
<tr>
<td>CFHT</td>
<td>Canada-France-Hawaii Telescope</td>
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<tr>
<td>CFHTLenS</td>
<td>Canada-France-Hawaii Telescope Lensing Survey</td>
</tr>
<tr>
<td>CFHTLS</td>
<td>Canada-France-Hawaii Telescope Legacy Survey</td>
</tr>
<tr>
<td>CMB</td>
<td>Cosmic Microwave Background</td>
</tr>
<tr>
<td>COSMOS</td>
<td>Cosmic Evolution Survey</td>
</tr>
<tr>
<td>EPIC</td>
<td>European Photon Imaging Camera</td>
</tr>
<tr>
<td>FOV</td>
<td>Field-of-view</td>
</tr>
<tr>
<td>HSE</td>
<td>Hydrostatic equilibrium</td>
</tr>
<tr>
<td>HST</td>
<td>Hubble Space Telescope</td>
</tr>
<tr>
<td>IACHEC</td>
<td>International Astronomical Consortium for High-Energy Calibration</td>
</tr>
<tr>
<td>IC</td>
<td>Inverse-Compton</td>
</tr>
<tr>
<td>keV</td>
<td>kiloelectron volt</td>
</tr>
<tr>
<td>LoCuSS</td>
<td>Local Cluster Substructure Survey</td>
</tr>
<tr>
<td>LSS</td>
<td>Large-scale structure</td>
</tr>
<tr>
<td>NCC</td>
<td>Non-cool core</td>
</tr>
<tr>
<td>NFW</td>
<td>Navarro-Frenk-White</td>
</tr>
<tr>
<td>NT</td>
<td>Non-thermal</td>
</tr>
<tr>
<td>OBF</td>
<td>Optical blocking filter</td>
</tr>
<tr>
<td>RASS</td>
<td>ROSAT All Sky Survey</td>
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<tr>
<td>SZ</td>
<td>Sunyaev-Zel’dovich</td>
</tr>
<tr>
<td>WtG</td>
<td>Weighing the Giants</td>
</tr>
<tr>
<td>XIS</td>
<td>X-ray Imaging Spectrometer</td>
</tr>
<tr>
<td>XMM-LSS</td>
<td><em>XMM-Newton</em> Large-Scale Structure Survey</td>
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Chapter 1

Introduction

According to the Hot Big Bang model for cosmology, structures in the Universe form through gravitational collapse from primordial density fluctuations. As galaxy groups and clusters are the most massive gravitationally bound objects observed in the Universe\(^1\), they have evolved from the strongest primordial density fluctuations (e.g. review by Kravtsov & Borgani, 2012). As a consequence, the number of clusters in the Universe is sensitive to the strength of the primordial density fluctuations and the contents of the Universe.

As the most massive objects in the Universe, clusters reside in the high-mass end of the cosmic mass function, describing the number density of objects in a part of the Universe as a function of mass. The cosmic mass function can be parametrised by various cosmological parameters, describing e.g. the amplitude of the primordial density fluctuations, the matter contents of the Universe or the equation of state of dark energy. These cosmological parameters may be constrained by fitting a mass function to the observed number density of clusters (recently by e.g. Vikhlinin et al., 2009; Mantz et al., 2010a, 2015; Planck Collaboration et al., 2014, 2015a). However, the outstanding challenge in constraining cosmological parameters this way is to obtain reliable cluster masses (e.g. review by Allen et al., 2011). As mass measurements of individual clusters are observationally demanding, cluster mass calibration is typically achieved through calibrating a scaling relation between an observable and cluster mass. Assuming that only gravity affects cluster evolution, the scaling relations are described by power-laws (the self-similar model of Kaiser, 1986).

The mass contents of clusters are very close to the cosmic average. The main constituent is a dark matter halo, making up approximately 80 – 90 % of the mass, whereas dominant baryonic component is the hot intracluster gas (e.g. Sarazin, 1988). The gas is heated through the gravitational collapse during cluster formation to temperatures of $\sim 10^7 - 10^8$ K, rendering it highly ionised. For the low density gas, this leads to thermal bremsstrahlung X-ray continuum emission with $kT \sim 1 - 10$ keV and line emission due to collisional excitation (e.g. review of Böhringer & Werner, 2010). The X-ray properties of the hot gas are described in more detail in Chapter 2. Galaxies only make up a few per cent of the total cluster mass and they are thus a subdominant baryonic component. Richness, the number of member galaxies in a

\(^1\)For the purposes of this thesis clusters and groups are treated as the same type of astronomical objects and the convention of referring to objects with a mass under $\sim 10^{14} M_\odot$ as groups and mass over $\sim 10^{14} M_\odot$ as clusters is followed here. Groups and clusters collectively will be referred to as clusters.
Chapter 1. Introduction

Figure 1.1: Left panel: A composite image of the relaxed galaxy cluster Abell 1689. The hot intracluster gas detected with the Chandra X-ray observatory is shown in purple, while galaxies seen in optical data from the Hubble space telescope are seen in yellow. The cluster is showing a smooth, approximately spherical appearance. Image credit: X-ray: NASA/CXC/MIT/E.-H Peng et al; Optical: NASA/STScI. Right panel: The Bullet cluster 1E0657-56, with the hot X-ray emitting gas shown in red, the dark matter detected through gravitational lensing shown in blue and galaxies in yellow. The Bullet cluster consists of two clusters undergoing a merger approximately in the plane of the sky, leading to an irregular morphology. In case of the Bullet cluster, the hot gas, making up of the majority of the baryonic matter, has uncoupled from the dark matter. Image credit: X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.; Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.

cluster, ranges from only a few in low mass galaxy groups to several hundred in the most massive clusters. The different components are illustrated in Fig. 1.1.

Cluster mass is typically described through spherical overdensity mass $M_{\Delta}$, i.e. the mass inside $r_{\Delta}$, a radius where the mean mass density is $\Delta$ times the critical density of the Universe or the mean density of the Universe at the redshift of the cluster. Results are commonly quoted for $\Delta = 200$, $\Delta = 500$ or $\Delta = 2500$. $r_{200}$ corresponds approximately to the typical virial radius of a cluster and $M_{200}$ can be taken as a representation of the total mass of the system. $M_{200}$ ranges from under $10^{13} M_{\odot}$ for low mass groups to a few times $10^{15} M_{\odot}$ for the most massive clusters.

Historically, cluster masses have typically been inferred from the X-ray emission of the hot intracluster gas through the assumption of hydrostatic equilibrium (HSE) (e.g. Sarazin, 1988). However, most clusters possess substructure and are at least somewhat triaxial in shape (see Fig. 1.1). Clusters grow and evolve through merging and accretion (Kravtsov & Borgani, 2012). Most of the cluster growth is through minor mergers with systems which have a significantly lower mass than the accreting cluster and thus have only a small effect on the cluster morphology. However, a cluster can also undergo major mergers with systems of approximately equal mass. These violent events disrupt the cluster and lead to various dynamical states over a time scale of gigayears. Increasing evidence is mounting for turbulence (e.g. Schuecker et

\[2\text{In this thesis critical density is used, unless stated otherwise.}\]
al., 2004; Pinto et al., 2015) and non-thermal (NT) relativistic electrons (e.g. Rephaeli et al., 2008, and references therein) in the intracluster gas. These are possibly linked with cluster mergers and create excess NT pressure support that breaks the HSE condition and thus biases mass estimates relying on it (e.g. Nagai et al., 2007; Mahdavi et al., 2013; Planck Collaboration et al., 2014, 2015a; von der Linden et al., 2014; Hoekstra et al., 2015). It is also worth noting that these baryonic processes may drive the scaling relations away from the prediction of the purely gravitational self-similar model.

Gravitational lensing, the bending of light in a gravitational potential well, is sensitive to both dark and baryonic matter. In particular, weak lensing by clusters provides an alternative way for measuring cluster mass (e.g. review by Hoekstra et al., 2013). Weak lensing benefits from being immune from assumptions of baryonic physics, such as the HSE condition and simulations show that weak lensing returns the most reliable mass estimates for clusters (e.g. Meneghetti et al., 2010; Sereno & Ettori, 2015). Weak lensing mass measurements are described in more detail in Chapter 3. Consequently, calibrating an X-ray mass proxy to weak lensing mass has proven to be a very promising method for cluster count cosmology (e.g. Allen et al., 2011, and references therein). Weak lensing calibrated scaling relations are explored further in Chapter 4.

This thesis studies properties of the X-ray emission of the hot gas in clusters and the calibration of X-ray observables to weak lensing masses. As the NT processes in intracluster gas are at the limit of the capabilities of current X-ray instruments, the NT characteristics of clusters are still poorly understood. Consequently, it is difficult to estimate the amount of hydrostatic mass bias from X-ray observations alone. Comparison of X-ray and lensing mass calibration for clusters provides a more promising way for quantifying hydrostatic mass bias. However, even direct comparisons are susceptible to different sample selection. Consequently, no consensus on the exact character of hydrostatic mass bias has been reached.

The picture is complicated further by issues in the calibration of X-ray instruments. Identical measurements performed with different X-ray instruments provide statistically discrepant results, indicating significant cross-calibration uncertainties (e.g. Nevalainen et al., 2010; Schellenberger et al., 2015). This leads to an additional uncertainty in the X-ray observables used as mass proxies with both X-ray and lensing masses and to the X-ray mass estimates themselves (Israel et al., 2015).

Finally, the intracluster gas is affected by feedback from star formation and Active Galactic Nuclei (AGN). As shown through recent X-ray observations, this energy injection can have an effect on the global energetics of the intracluster gas in a cluster (e.g. review by Fabian, 2012). Recent simulations indicate that this energy injection leads to a mass dependence in the mass calibration, with low-mass systems being more strongly affected (Le Brun et al., 2014; Planelles et al., 2014; Pike et al., 2014). As weak lensing mass measurements of low-mass systems are observationally demanding and X-ray masses are susceptible to hydrostatic mass bias which, it is hard to constrain the inferred mass dependence observationally.
CHAPTER 1. INTRODUCTION

1.1 The structure of the thesis

This thesis consists of five original journal articles and an introductory part. The introductory part is structured as follows. The relevant aspects of X-ray observations of galaxy clusters and results related to them are discussed in Chapter 2. Chapter 3 introduces the method for weak lensing mass measurements used in the articles. Chapter 4 discusses weak lensing calibrated scaling relations and their implications. The articles and the author’s contribution to them are summarised in Chapter 5. Finally, concluding remarks are given in Chapter 6.
Chapter 2

X-ray emission from the intracluster gas

The intracluster gas in galaxy clusters heated to $\sim 10^7 - 10^8$ Kelvin (corresponding to $\sim 1 - 10$ keV) during cluster formation. This gas has a low density (typically $10^{-1} - 10^{-4} \text{ cm}^{-3}$) and it is hydrogen dominated, with a metal abundance of $\sim 0.30 - 0.50$ of the solar value. This leads to a highly ionised plasma which emits a bulk of its thermal energy in the soft X-ray band. As clusters typically subtend arcminute scales on the sky, the emission of the hot gas is observed as extended sources with X-ray telescope such as \textit{XMM-Newton}, \textit{Chandra} and \textit{Suzaku}.

This Chapter introduces the properties of the X-ray emission relevant for this thesis and the observational methods used to measure them. Results on NT emission in the Ophiuchus cluster and cross-calibration of \textit{Suzaku} XIS and \textit{XMM-Newton} EPIC instruments are also discussed. The review of Böhringer & Werner (2010) and book of Sarazin (1988) provide more in-depth introductions to X-ray emission from galaxy clusters for an interested reader.

2.1 X-ray observatories

As the Earth’s atmosphere is not transparent to X-ray radiation originating from space, X-ray observations of astronomical objects have to be performed with space based observatories. The X-ray observatories used in this thesis are satellites. They produce X-ray images of objects within their Field-of-view (FOV) using gracing incidence mirrors and the detectors are X-ray sensitive CCD cameras, providing both imaging and spectroscopic capabilities.

Data from three X-ray observatories are analysed within the context of this thesis. \textit{XMM-Newton} observatory consists of three coaligned X-ray telescopes, which all operate simultaneously. Each of the telescopes has a European Photon Imaging Camera (EPIC) in its focus, two of which are MOS type and one pn type. The telescopes with MOS type camera have additional grating spectrometers, which are not utilised in this thesis. The \textit{Suzaku} observatory was originally equipped with four X-ray Imaging Spectrometers (XIS), providing simultaneous operation. However, as one was lost early in the mission, data from only three were used for this thesis. \textit{Suzaku} also included a hard X-ray detector, which was not utilised in this thesis. Finally, measurements obtained with the Advanced CCD Imaging Spectrometer (ACIS) instrument onboard
the Chandra observatory is used for this thesis. For a more technical description of the observatories and their capabilities the reader is referred to the XMM-Newton Users’ Handbook\(^1\), Suzaku Technical Description\(^2\) and Chandra Proposers’ Observatory Guide\(^3\). It is also worth noting that the Suzaku mission was declared complete in June 2015, while XMM-Newton and Chandra are still operational at the time of writing.

For X-ray observatories, the properties of the telescope are described by the effective area of the mirror \(A_{\text{eff}}\) and the point-spread-function, whereas the efficiency of filters and the detector are described by the transmission function \(T\) and quantum efficiency \(QE\), respectively. These properties are typically a function of energy and also location on the detector for position sensitive instruments. A combination of the above quantities determines the spectral and spatial resolution of the observatory.

\subsection*{2.1.1 Spectral modelling}

The properties of each X-ray telescope are encoded in the response matrix \(R = (A_{\text{eff}} \times T \times QE) \ast R_0\) (where \(R_0\) is a response function normalised to unity), which describes the total effective area or the combined instrumental effects affecting a photon on the path to the detector. The response matrix thus relates the original spectrum of the source \(f(E)\) with the measured data \(D(I)\). Mathematically this can be expressed as

\[
D(I) = \int_0^\infty f(E) \otimes R(I,E) \, dE + B(I),
\]

where \(B(I)\) is a particle background signal, which is not coming through the telescope.

It is typically not possible to invert the equation and to determine source spectrum \(f(E)\) from the observed data \(D(I)\). Instead the forward fitting method of assuming a model spectrum for the source that can be parametrised \(f(E,p_1,p_2,..)\) using specialised X-ray spectroscopy software, such as Xspec\(^4\), is used. The software contains various spectral models which can be physically motivated or phenomenological. The parameters of the selected source model are varied in order to obtain a best fit to the measured spectrum of the source, leading to an optimisation problem. A fit statistic (e.g. \(\chi^2\)) can thus be computed to determine whether the model spectrum fits the observed data and the model parameters corresponding to the most desirable fit statistic give the best-fit value. For physically motivated models, the best-fit parameters give information about the physical properties of the source.

\subsection*{2.2 Thermal emission}

The thermal emission from clusters involves three emission processes. Bremsstrahlung, the deflection of an electron by the charge of an ion, or free-free emission is the dominant process giving rise to continuum emission. Recombination radiation caused by the capture of a free electron or free-bound emission is a subdominant process giving rise to continuum emission. Finally, collisional excitation or bound-bound radiation, arising from the deexcitation of an electron in an ion,

\footnotesize\(^1\)http://xmm.esac.esa.int/external/xmm_user_support/documentation/uhb_2.1/XMM_UHB.html
\footnotesize\(^2\)http://heasarc.nasa.gov/docs/suzaku/prop_tools/suzaku_td/
\footnotesize\(^3\)http://cxc.harvard.edu/proposer/POG/
\footnotesize\(^4\)https://heasarc.gsfc.nasa.gov/xanadu/xspec/
gives rise to line emission. Below, we will review thermal emission processes, and describe relevant aspects of spectral modelling and thermal structure of clusters for the thesis.

### 2.2.1 Bremsstrahlung continuum

In the case of an ion with a charge $Z$ and an electron temperature $T_X^5$ the Bremsstrahlung emissivity at frequency $\nu$ is given by

$$\epsilon_{\nu}^{ff} = \frac{2^5\pi e^6}{3m_e c^3} \left( \frac{2\pi}{3m_e k} \right)^{1/2} Z^2 n_e n_{ii} g_{ff}(Z, T, \nu) T^{-1/2} \exp(-h\nu/kT). \quad (2.2)$$

Here $n_i$ and $n_e$ are the number densities of ions and electrons, whereas $g_{ff}(Z, T, \nu)$ is the Gaunt factor, a quantum mechanical correction with a value close to unity (e.g. Sarazin, 1988). The emissivity is defined here as the emitted energy per unit time, frequency and volume.

For a single temperature gas Equation (2.2) indicates that the spectral shape should be close to an exponential as a function of frequency. As frequency of the exponential cut-off depends on the temperature, it is a powerful temperature diagnostic. The normalisation of the spectra is proportional to the product of the electron and ion densities.

### 2.2.2 Recombination and line emission

For ionization equilibrium, the ionisation structure of an ion $i$ is determined by the balance of the processes that produce and destroy each ion. The ionisation structure giving the ionisation and recombination rates that describe the production and destruction of ion species, can be calculated from a complete list of all important ions and elements. These and resulting ionisation fractions are tabulated in e.g. (Arnaud & Raymond, 1992; Mazzotta et al., 1998).

All collision rates that lead to emission by an ion $i$ follow the form

$$R = n_e n_i C_{i,x} = n_e^2 \left[ \frac{n_i}{n_E} \right] \left[ \frac{n_E}{n_H} \right] \left[ \frac{n_H}{n_e} \right] C_{i,x}(T), \quad (2.3)$$

where $n_E$ and $n_H$ are the element and hydrogen number densities and $C_{i,x}$ are the relevant collision rate coefficients. $\left[ \frac{n_i}{n_E} \right]$ is the fractional abundance of $i$, $\left[ \frac{n_E}{n_H} \right]$ the relative elemental abundance and $\left[ \frac{n_H}{n_e} \right]$ the hydrogen nuclei to electron ratio.

The collisional rate coefficients and resulting ionisation fractions of a single ion species depends on the temperature of the gas and the radiation contribution of a specific ion depends on the density of this species in the plasma. However, as shown by Equation (2.3) all rates are proportional to the square of the electron density $n_e^2$.

### 2.2.3 Thermal spectra

As all emission and ionisation results primarily from collisions (or close fly-bys) of an electron and ion, some assumptions can be made while modelling the emission from

---

$^5$In this thesis $T_X$ is used to distinguish cluster temperature measured through X-ray spectroscopy from $T$, denoting cluster temperature in theoretical context.
Figure 2.1: The relative spectral energy distributions of APEC models with temperatures 1 keV (blue line), 3 keV (black line) and 10 keV (red line), demonstrating the typical spectrum of a low-mass galaxy group, an intermediate size low-mass cluster and a massive cluster respectively. All three models are at zero redshift, have their emission measure set to unity and metal abundance set to 0.3 of the solar value.

The hot low density plasma. Firstly, due to the low density, collisional excitation is much slower than the radiative decay and thus all ions are assumed to decay to the ground state before re-ionisation. Consequently all ionisation processes are initiated from the ground state. Secondly, as the elastic Coulomb collision time scale of particles is much shorter than the age or cooling time of the plasma, a Maxwell-Boltzmann distribution with the temperature $T_X$ for particles in the plasma is assumed. The ionisation and recombination time scales are also generally much smaller than the age of the cluster or any relevant hydrodynamic time scale and the plasma is thus assumed to be in collisional ionisation equilibrium. Finally, as the plasma is optically thin, radiative transfer calculations can be ignored and all photons created in the plasma are assumed to leave the cluster.

These assumptions amount to the thin plasma or coronal limit. This simplifies the modelling, which becomes a book keeping exercise of all relevant electron ion collision rates and their branching ratios. In practise, these are tabulated in plasma codes, such as APEC (Smith et al., 2001) and MEKAL (Mewe et al., 1995). These plasma models can be fitted to the observed cluster data using the method described in Section 2.1.1.

As all photons are assumed to leave the gas, the observed spectrum provides an account of the emission of the total plasma in the cluster. This can be contrasted with e.g. stars, where the emission only originates from a thin skin on the surface. As shown in Equations (2.2) and (2.3) above, the Bremsstrahlung emissivity and collision rates are proportional to the product of the electron and ion densities. Thus, the normalisation of the total thermal spectrum of a cluster is given by the emission measure, defined as

$$E = \int n_e n_i dV.$$  \hspace{1cm} (2.4)

For hot massive clusters Bremsstrahlung is the dominant radiation process and temperature is determined by the exponential cutoff of the Bremsstrahlung continuum.
For groups and low mass clusters with $T \lesssim 2$ keV line emission starts to dominate over the continuum and the temperature dependence of the emission lines becomes a more powerful temperature diagnostic. The temperature dependence of the thermal emission is demonstrated in Fig. 2.1.

Finally, the relative strength of the Fe XXV (helium like) at 6.7 keV and XXVI (hydrogen like) at 7.0 keV emission lines provides an additional temperature diagnostic for bright hot clusters, which is independent of the shape of the Bremsstrahlung spectra (Nevalainen et al., 2003, 2010). The Fe XXV/XXVI line ratio temperature diagnostic is used in Paper IV.

### 2.2.4 Temperature structure

As galaxy clusters form through gravitational collapse of matter around overdense regions, the potential energy of the infalling matter is converted to internal heat. Analogously to the virial equilibrium of galaxies and dark matter particles in the cluster gravitational field, the intracluster gas also reaches a characteristic virial temperature which is proportional to the depth of the cluster gravitational potential. The scaling of temperature and cluster mass are discussed in more detail in Chapter 4.

The imaging spectrometers on board latest generation of X-ray observatories have opened up the possibilities of localised temperature measurements of galaxy clusters (the observatories and instruments are described in Section 2.1). Thus the temperature structure of clusters can be studied. The temperature profiles of a sample of clusters scaled with overdensity radii are shown in Fig. 2.2. The profiles are decreasing outside $\sim 0.2 \ r_{500}$, whereas a two types of behaviour are seen in the cluster core. Cool core (CC) clusters with dense cores show temperature profiles decreasing towards the center of the core, whereas non-cool core (NCC) clusters with smaller central densities show flat temperature profiles or even slightly increasing temperatures towards...
the center of the core. The physical differences between these two populations are discussed in Section 2.4.

As shown in the left panel of Fig. 2.2, most of the cluster volume is located in the region outside the core, where cluster temperature profiles become very similar. Indeed, cluster temperature measured in a radial region of \( r \approx 0.15 - 1.0r_{500} \) can be viewed as a representative self-similar virial temperature. As we show in Paper I and Paper II the temperature measured this way is a low scatter mass proxy.

### 2.3 Hydrostatic mass estimates

A direct application of the knowledge of the temperature structure in galaxy clusters is to use it to determine the mass of clusters under the assumption of HSE (e.g. Sarazin, 1988). The thermal pressure in the intracluster gas is directed outwards from the cluster core. In HSE the thermal pressure is equated to the cluster potential. Assuming that the cluster is spherically symmetric, the total mass is thus given by the temperature and density profiles:

\[
M(r) = -\frac{kT_X(r) r}{\mu m_p G} \left( \frac{d \ln n_e}{d \ln r} + \frac{d \ln T_X}{d \ln r} \right). \tag{2.5}
\]

Here \( G \) is the gravitational constant, \( k \) Boltzmann’s constant, \( \mu \) the mean particle mass and \( m_p \) the mass of the proton.

#### 2.3.1 Hydrostatic mass bias

The accuracy of X-ray hydrostatic mass estimates have been tested both through simulations (e.g. Nagai et al., 2007; Shaw et al., 2010; Rasia et al., 2012) and through comparison of X-ray mass estimates and masses inferred through gravitational lensing (e.g. Mahdavi et al., 2008, 2013; Donahue et al., 2014; Israel et al., 2014, 2015; von der Linden et al., 2014; Hoekstra et al., 2015). The consensus from the simulations is that X-ray mass estimates underestimate the true mass. This is known as HSE or hydrostatic mass bias. Currently, there is strong disagreement in the observations of the amount HSE mass bias. The estimates range from zero up to \( \sim 40 \% \) in the above studies. In particular, *Chandra* tends to find higher X-ray masses with a smaller HSE mass bias than *XMM-Newton* based measurements, which result in smaller masses. These measurements reflect the cross-calibration status of the observatories discussed in Section 2.6. In some cases a trend for mass dependence in the HSE mass bias is reported (e.g. Israel et al., 2014, 2015; von der Linden et al., 2014).

The strength of the bias reflects the uncertainties in temperature measurements and unaccounted pressure support in the intracluster gas. Different mechanisms such as turbulence, bulk motion and NT electrons could result in excess pressure support in the intracluster gas. However, these are all currently poorly understood, but evidence for NT electrons are discussed in Section 2.5. Furthermore, temperature measurements of hot clusters suffer from a systematic uncertainty of \( \sim 10 \% \) level due to uncertainties in the calibration of X-ray instruments (see Section 2.6). Finally, the assumption of spherical symmetry for clusters required for deriving hydrostatic mass estimates is not always valid. Consequently, cluster selection can have an effect on the amount of HSE bias. The bias in a subset of relaxed system is expected
to be smaller than for a representative sample of the cluster population as a whole, including disrupted clusters undergoing major mergers.

The impact of the hydrostatic mass bias is demonstrated by the Planck cosmological constraints using cluster counts, where the strength of the bias is the main source of uncertainty (Planck Collaboration et al., 2014, 2015a). In the context of this thesis, hydrostatic mass bias is explored through comparison of scaling relations using X-ray and lensing masses in Paper II and the discussion is developed further in Paper I. The implications are discussed in Section 4.4.2.

2.4 AGN feedback

As discussed above in Section 2.2.4 and shown in Fig. 2.2, cluster temperature profiles show two types of behaviour when approaching the cluster core. Physically, CC clusters typically have higher central densities than NCC clusters, which usually have central densities below $10^{-2}$ cm$^{-3}$. As the emission of the intracluster gas is proportional to the square of the gas density (see Equation 2.4), the high central density of CC clusters results in very strong central luminosity peaks. Consequently, the high central luminosity results in radiative cooling times below $10^9$ yr. In absence of any heat source which could balance the cooling, the gas should consequently cool, leading to much stronger star formation in the central galaxies of CC clusters than observed. Different mechanisms to offset the cooling such as cooling flows (e.g. Fabian & Nulsen, 1977; Fabian, 1994) and feedback from the AGN in the Brightest Cluster Galaxy (BCG) located at the center of the cluster (e.g. Peterson & Fabian, 2006; McNamara & Nulsen, 2007; Fabian, 2012; Kirkpatrick & McNamara, 2015) have been proposed.

The high quality data provided by the latest generation of X-ray observatories convincingly provide a picture of balancing the energy losses by the energy injection of the central AGN (e.g. McNamara & Nulsen, 2007; Fabian, 2012, and references therein). Powerful jets created by the accretion onto the black hole powering the AGN inflates bubbles of relativistic plasma visible in radio on both sides of the black hole. These bubbles separate and rise buoyantly in the intracluster gas as new bubbles form. The power of the AGN inflating the bubbles can be estimated from the volume of the bubbles and the surrounding pressure. Generally, good agreement is found between the AGN power and the energy loss through cooling in the CC.

The power injected by the AGN can affect the global energetics of the cluster. Recent simulations show that the feedback from the central AGN can affect scaling relations of galaxy groups and low mass clusters (Le Brun et al., 2014; Planelles et al., 2014; Pike et al., 2014). We study this effect observationally in Paper I and the implications are discussed in Section 4.4.1.

2.5 Non-thermal emission

Diffuse extended radio emission has been detected in over 50 clusters (e.g. reviews by Feretti & Giovannini, 2008; Ferrari et al., 2008). This emission is present in the forms of halos or relics and it is directly associated with the intracluster gas, without any connection to member galaxies. The origin of the emission is synchrotron radiation by a population of relativistic electrons in the intracluster gas. A population of
relativistic electrons in the intracluster gas will lose energy through inverse-Compton (IC) scattering of Cosmic Microwave Background (CMB) photons, resulting in power-law shaped X-ray continuum emission (Rephaeli, 1977). As the temperature of CMB radiation is known, the ratio of radio and IC emission depends on the intra-cluster magnetic field strength, with a weaker magnetic field resulting in a higher NT X-ray flux for a given radio flux. For the observed radio fluxes, volume averaged magnetic fields below the order of $0.1 \mu G$ would result in detectable NT X-ray emission.

There have been several reports claiming detection of NT excess X-ray emission in both soft ($\lesssim 1$ keV, see Durret et al., 2008, for a review) and hard ($\gtrsim 20$ keV, see Rephaeli et al., 2008, for a review) X-rays. However, as the reported NT fluxes are at the limits of the current instruments and thus heavily affected by systematic uncertainties, these reports are controversial. Several factors affect the reliability of the claimed detections - with the primary being the ability to detect an intrinsically weak excess component below the much stronger thermal emission. For hard excess, lack of spatial information and source confusion also comes into play. *NuSTAR*, which is currently the only observatory with imaging hard X-ray optics, has detected no NT emission in the Bullet (Wik et al., 2014) or Coma (Gastaldello et al., 2015) clusters. Both clusters house powerful radio halos (e.g. Liang et al., 2000; Thierbach et al., 2003, for Bullet and Coma respectively).

As the ratio of radio to IC X-ray emission depends on the strength of the cluster magnetic field, the lack of unequivocal detections of IC emission gives a lower limit for the magnetic field strength of $\sim 0.1 \mu G$. Indeed, Faraday rotation measurements of clusters indicate magnetic field strengths of the order of $1 – 10 \mu G$, approximately one to two orders of magnitude stronger than the lower limit derived from the non-detection of NT X-ray emission. However, the volume averaged magnetic field might be weaker than the magnetic field measured by Faraday rotation along the line of sight.

In primary models, the relativistic electrons are accelerated by shocks and/or turbulence induced by cluster mergers. While hadronic collisions have also been proposed for the origin of the relativistic electrons, these secondary models are expected to produce gamma ray emission. However, the secondary models are unlikely due to much lower than predicted gamma ray fluxes of galaxy clusters observed with *Fermi-LAT* (Zimmer & Fermi-LAT Collaboration, 2015, and references therein). NT relativistic electrons and turbulence accelerating the electrons leads to pressure support in addition of the thermal pressure of the intracluster gas. The NT emission of clusters is thus directly linked to the hydrostatic mass bias discussed above.

### 2.5.1 The Ophiuchus cluster

Within the context of this thesis, we study the relativistic electron population in the Ophiuchus cluster in Paper IV. We characterise the thermal emission within the central 7 arcmin region using *XMM-Newton* EPIC-pn, confirming the existence of a cool core with a relatively long cooling time. Including hard X-ray data from the ISGRI instrument onboard *INTEGRAL* yields a $5.7\sigma$ detection of excess emission over the thermal prediction in a $20 – 120$ keV band. As Govoni et al. (2009) detected a radio mini-halo in Ophiuchus, we model the X-ray excess as IC emission assuming that the same population of relativistic electrons produces both the radio and NT X-ray emission. The NT component produces $\sim 10 \%$ of the total flux in a $1 – 10$
keV band and the pressure support of the relativistic electrons is $\sim 1\%$ of that of the thermal electrons. We find that the photon index of the IC emission is consistent with the constraints from the radio emission and use the ratio of radio to NT X-ray flux to derive a magnetic field strength of $0.05 - 0.15\mu G$.

As discussed in Paper IV, the existence of a cool core and the lack of major merger signs indicates that the electron population is due to a primary old merger and subsequent re-acceleration due to turbulence, or that the population is produced by secondary hadronic collisions. As the derived slope of the power-law spectrum in Ophiuchus is flatter than predicted for secondary models (Colafrancesco & Marchegiani, 2009) and secondary models are unlikely given the recent findings with Fermi-LAT discussed above, the old merger and re-acceleration due to turbulence is the likely scenario. In this case, the time since the merger must at least correspond to the cooling time of the cool core $3 \times 10^9$ years. This relatively long cooling time indicates that most merger signatures have disappeared.

The steep radio index implied by the IC spectra is also consistent with a significantly aged relativistic electron population. Giant radio halos tend to be associated with clusters undergoing major mergers, whereas mini-halos are mainly detected in relaxed CC clusters (Ferrari et al., 2008). As the magnetic field is amplified by strong shocks associated with major mergers, the amplified magnetic field would render NT X-ray emission levels very low while powering a giant radio halo in these clusters. However, the magnetic field decays with time and the magnetic field strength is consequently expected to be lower in clusters displaying signs of ageing in the radio emission. The weaker magnetic field results in higher NT X-ray emission in relation to the radio emission. The relatively low magnetic field strength derived for Ophiuchus combined with the radio mini-halo could thus imply that Ophiuchus is in a "sweet spot", where the magnetic field has decayed, boosting NT X-ray emission enough to be detected, while still hosting a sufficient reservoir of relativistic electrons to drive the emission. Assuming this scenario is representative for mini-halo clusters, targeting these in future searches of NT X-ray emission could prove more fruitful than clusters housing giant radio halos, such as Coma and Bullet recently targeted by NuSTAR (Wik et al., 2014; Gastaldello et al., 2015).

2.6 X-ray cross-calibration

Assuming that all instruments are correctly calibrated, identical measurements performed with different instruments and telescopes should give identical results. However, recent measurements of galaxy clusters show statistically significant discrepancies due to calibration uncertainties. This has been shown within the context of the International Astronomical Consortium for High Energy Calibration IACHEC\textsuperscript{6} in Paper III and by Nevalainen et al. (2010), Schellenberger et al. (2015) and Israel et al. (2015), and independently by e.g. Snowden et al. (2008), Mahdavi et al. (2013) and Donahue et al. (2014). The calibration uncertainties are also observed with other types of objects than clusters (Read et al., 2014).

\textsuperscript{6}http://web.mit.edu/iachec/
2.6.1 Temperature discrepancies

The above studies show that galaxy cluster temperatures measured with XMM-Newton/EPIC are systematically lower than temperatures measured with Chandra/ACIS. For temperatures fitted using a wide energy band (approximately 0.5 – 7.0 keV), the average difference is 10 – 15 %, whereas luminosities agree to a few per cent. However, the temperature difference due to calibration problems shows a strong energy dependence - it is negligible for $T_X \lesssim 4$ keV, but increases to over 20 % for $T_X = 10$ keV. For temperatures measured using a soft (approximately 0.5 – 2.0 keV) and hard (approximately 2.0 – 7.0 keV) energy band, the hard band leads to agreement within $\sim 5$ % whereas the soft band leads to significant discrepancies. In Paper III we extend previous cross-calibration studies to include Suzaku/XIS (see Section 2.6.3).

The temperatures of hot clusters are determined by the shape of the Bremsstrahlung continuum (Section 2.2.3). However, if the shape of the effective area (i.e. energy dependence of $A_{\text{eff}}$, see Section 2.1.1) implemented in the instrument calibration through the response is inaccurate, the derived temperature will be inaccurate. As temperature measurements of cool low mass systems are driven by the relative strength of the emission lines of ions instead of continuum shape, the effect of the energy dependence of the effective area is diminished in this case, as indicated by the observed energy dependence of the temperature discrepancies. The continuum based temperature measurements of hot systems can also be calibrated against ionisation temperatures using the Fe XXV/XXVI line ratio method described above, as done by Nevalainen et al. (2010). Here the emission lines are in a narrow energy band and the effect of the energy dependence of the effective area is thus negligible. The Fe XXV/XXVI temperatures show good agreement with hard band continuum temperatures.

2.6.2 Stacked residuals

The energy dependence of the cross-calibration accuracy of the effective area of an instrument $i$ can be studied against a reference instrument $\text{ref}$ through the stacked residuals method (Longinotti et al. (2008) and Paper III). Assuming a spectral model fitted to a cluster observation obtained with the reference instrument $f_{\text{ref}}$, a model prediction for $i$ assuming $f_{\text{ref}}$ is obtained by folding this model through the response of $\text{ref}$. Dividing the data of the same cluster from $i$ with this prediction gives an estimate of the energy dependent bias in the effective area of $i$, assuming that $f_{\text{ref}}$ is a perfect description of the data from the reference instrument. Thus the residual between $f_{\text{ref}}$ and the data from the reference instrument have to be removed from the ratio. Using the notation of Section 2.1.1, this useful measure for effective area cross-calibration is given by

$$r_{i/\text{ref}}(E) = \frac{D_i(E)}{f_{\text{ref}}(E) \otimes R_i(E)} \times \frac{f_{\text{ref}}(E) \otimes R_{\text{ref}}(E)}{D_{\text{ref}}(E)},$$

(2.6)

If the shape calibration of the effective areas of both instruments is consistent, the residual is consistent with unity. Note that the above method requires that the data from both instruments use the same binning.

By calculating the median and median absolute deviation of $r_{i/\text{ref}}$ for a sample of clusters, systematic differences in the calibration can be characterised. Furthermore,
if the shape of the effective area implemented in the response file of an instrument is modified by the amount suggested by the stacked residual, consistent temperatures are measured with both instruments (Read et al., 2014; Schellenberger et al., 2015; Israel et al., 2015).

### 2.6.3 Cross-calibration of Suzaku/XIS and XMM-Newton/EPIC-pn

Within the context of this thesis, we study the calibration of Suzaku X10, XIS1 and XIS3 instruments by comparing them to XMM-Newton/EPIC-pn in Paper III. In the hard 2.0 – 7.0 keV band all studied instruments result in temperatures consistent within $\sim 5 \%$, indicating that Suzaku, XMM-Newton and Chandra calibration is consistent in the hard band. For the soft 0.5 – 2.0 keV band, we find that XIS1 and XIS3 data result in consistent temperatures, while XIS0 data results in lower temperatures by 20 – 30 %. Stacked residuals indicate a systematic difference in the soft band, where XIS0 effective area is underestimated or XIS1 and XIS3 overestimated below 1 keV by up to $\sim 20 \%$.

We investigate if the discrepancies can be due to uncertainties in the time dependence of the implemented column density of the optical blocking filter (OBF) contaminant by forcing soft band temperatures and metal abundances of all three XIS instruments consistent, while letting the column density of the OBF contaminant vary freely for each instrument in the spectral fits. This significantly improved the statistical quality of the spectral fits compared to the unmodified calibration. We found that the OBF contaminant of XIS0 is accurately calibrated, whereas our modelling brought significant modifications to the column density of the OBF contaminant for XIS1 and XIS3. The modified calibration resulted in temperatures consistent with XIS0 and no residuals in the effective area between the instruments.

The conclusion is thus that XIS0 is most accurately calibrated of the XIS instruments and that the combined fit can not be driven by the data, as the back illuminated XIS1 collects more photons than the front illuminated XIS0 or XIS3. Using XIS0 for comparison with XMM-Newton/EPIC-pn in the soft band, we find that XMM-Newton results in $\sim 14 \%$ higher temperatures. In the full 0.5 – 7.0 keV band, XIS0 temperatures are $\sim 5 \%$ lower than XMM-Newton/EPIC-pn temperatures. This implies that Suzaku based HSE masses are lower than those obtained with XMM-Newton and Chandra. As the difference in XMM-Newton and Chandra based mass estimates closely mirrors the temperature discrepancies (with XMM-Newton resulting in $\sim 15 \%$ lower than Chandra, e.g. Schellenberger et al., 2015), the results in Paper III imply that Suzaku/XIS0 based mass estimates would be $\sim 5 \%$ and $\sim 18 \%$ below those obtained with XMM-Newton and Chandra, respectively.

As it is unlikely that these discrepancies in cluster mass measurement can be solved with X-ray measurements alone, alternative methods for calibration needs to be explored. Weak lensing has proven to be a very useful way of obtaining cluster masses independent of X-ray calibration and assumptions about the physical state of the intracluster gas, addressing the main shortcomings in X-ray mass measurements. Indeed, as demonstrated by Israel et al. (2015), weak lensing mass measurements can even be used as an external calibration source for X-ray instruments.
Chapter 3

Weak lensing mass determination

The paths of photons emitted by background sources are perturbed by the gravitational field of foreground objects, distorting the images of the background sources. This phenomena is known as gravitational lensing. As the amplitude of the distortion provides a measure of the tidal gravitational field causing the distortion, it is possible to determine the projected foreground mass (for e.g. a galaxy cluster) by measuring the lensing induced distortion of distant background galaxies. Gravitational lensing mass measurements benefit from the fact that it is independent of the physical composition and dynamical state of the foreground object.

As originally discussed by Zwicky (1937), if the gravitational deflection is strong enough, multiple images of the same source can be seen in a strong lensing event. Strong lensing provides precise constraints on the mass enclosed by the images. Since first reported in clusters of galaxies by Lynds & Petrosian (1986) and Soucail et al. (1987), strongly lensed galaxies are routinely observed behind massive clusters. Unfortunately strong lensing is limited to the inner regions of clusters, where the mass concentration is high. On larger radii the gravitational field causes a small change in the shapes of background galaxies, leading to a statistical alignment of an ensemble of source galaxies, known as weak lensing. Since first observed by Tyson et al. (1990), weak lensing has matured into the leading method to provide accurate masses for samples of galaxy clusters (e.g. Okabe et al., 2010; Applegate et al., 2014; Umetsu et al., 2014; Hoekstra et al., 2015).

This Chapter introduces the methods for measuring cluster masses by weak lensing used in this thesis, discusses both the systematics affecting the mass measurements and practical aspects of measuring the signal. For a more thorough introduction to gravitational lensing formalism, the interested reader is referred to Bartelmann & Schneider (2001), Schneider (2006) or Kneib & Natarajan (2011), while Hoekstra et al. (2013) gives a recent review on the subject of cluster mass measurements using gravitational lensing.

3.1 Weak lensing signal

In gravitational lensing inhomogeneities in the matter distribution along the line-of-sight deflect photons emitted by distant source galaxies. Thus a source with the true position $\beta$ is observed at $x$. These are related by the lens equation

$$\beta = x - \alpha(x), \quad (3.1)$$
where $\alpha$ is the deflection angle. If the lens equation can have multiple solutions for $x$, a multiply imaged strongly lensed object is present. The effect of a gravitational lensing event is a mapping of a source with a true surface brightness distribution $f_S(x)$ to the observed surface brightness distribution

$$f_{\text{obs}}(x) = f_S(\beta(x)).$$

(3.2)

A useful result of this is that gravitational lensing preserves surface brightness. In the weak lensing limit where the deflection angles and its spatial variation are small compared to the angular extent of the sources, this mapping can be linearised.

Using the linearised mapping, Kaiser & Squires (1993) first showed that it is possible to express the surface mass density in the lens plane in terms of an observable known as shear. The complex shear, defined as $\gamma \equiv \gamma_1 + i\gamma_2$, describes the anisotropic distortion of a source galaxy. As galaxy shapes are quantified through ellipticity $\epsilon = (a - b)/(a + b)$ (where $a$ is the semi-major axis and $b$ the semi-minor axis), shear thus relates the intrinsic (unlensed) ellipticity of a galaxy to the observed ellipticity

$$\epsilon_{\text{obs}} = \epsilon_{\text{int}} + \gamma.$$  

(3.3)

The observed ellipticity of a single source galaxy would provide a useful estimate for the shear in the case that the intrinsic ellipticity is significantly larger than the shear or the intrinsic ellipticity is known a priori (see Fig. 3.1). In practice, the assumption that galaxy ellipticity is randomly distributed has to be made and the width of the ellipticity distribution $\sigma_{\gamma} = \sqrt{\langle \epsilon_{\text{int}}^2 \rangle}$, known as shape noise, provides an intrinsic limitation to weak lensing measurements. As the typical shape noise of $\sim 0.25$ (Hoekstra et al., 2000; Leauthaud et al., 2007) is larger than the typical shear induced by a galaxy cluster ($\sim 0.05$ Leauthaud et al., 2010), shear must be estimated by averaging over a large number of source galaxies. In this case the statistical uncertainty of a shear component $\gamma_i$ is given by

$$\sigma_{\gamma,i} = \sqrt{\langle \epsilon_{\text{int}}^2 \rangle / N},$$

(3.4)

where $N$ is the number of galaxies used to measure the lensing signal.

The net lensing signal induced by an isolated lensing object is a systematic tangential alignment of source galaxies with respect to the lens, resulting in a positive azimuthally averaged tangential shear, or $E$ mode signal. The tangential shear is given by

$$\gamma_t = -(\gamma_1 \cos 2\phi + \gamma_2 \sin 2\phi),$$

(3.5)

where $\phi$ is the azimuthal angle. The cross-component shear, or $B$ mode signal, is given by

$$\gamma_x = -(\gamma_1 \sin 2\phi - \gamma_2 \cos 2\phi).$$

(3.6)

It is angled at 45° from the tangential shear and the azimuthally averaged cross-component is expected to be consistent with zero for a perfect lensing signal.

The tangential shear signal as a function of radius from the cluster can be interpreted as surface mass density contrast $\Delta \Sigma$ (Miralda-Escude, 1991). If the redshifts of the sources and lens are known, the azimuthally averaged surface mass density contrast can be expressed as

$$\Delta \Sigma(r) = \Sigma(< r) - \Sigma(r) = \Sigma_{\text{crit}} \times \gamma_t(r),$$

(3.7)
Figure 3.1: The gravitational lensing induced tangential alignment on a population of intrinsically round source galaxies (upper panels), in which case the ellipticity of source galaxies is only due to the lensing mass (located at the centre of each panel). Lower panels demonstrate the tangential alignment of a population of source galaxies with intrinsic randomly distributed ellipticities (shape noise), which provides an intrinsic limitation to the lensing measurements. The lensing induced distortions are exaggerated for plot clarity. ©User:TallJimbo / Wikimedia Commons / CC-BY-SA-3.0
where $\Sigma(< r)$ is the mean surface mass density within $r$, $\Sigma(r)$ is the azimuthally averaged surface mass density at $r$ and $\Sigma_{\text{crit}}$ is the critical surface mass density of the lensing system. The critical surface mass density depends on the geometry of the lens-source system and is given by

$$\Sigma_{\text{crit}} = \frac{c^2}{4\pi G D_{\text{OS}} D_{\text{OL}} D_{\text{LS}}}.$$  \hspace{1cm} (3.8)

Here $c$ is the speed of light, $G$ is the gravitational constant and $D_{\text{OS}}, D_{\text{OL}}$ and $D_{\text{LS}}$ are the angular diameter distances between observer and source, observer and lens and lens and source, respectively.

In practice, the total lensing signal is estimated by summing over individual source galaxies with tangential shear $\gamma_{\text{t},i}$ located within a circular region in the lensing plane. Using an inverse variance weighting in the sum, the total lensing signal is given by

$$\Delta \Sigma = \frac{\sum_{i=1}^{N_{\text{Source}}} w_i \times \gamma_{\text{t},i} \times \Sigma_{\text{crit},i}}{\sum_{i=1}^{N_{\text{Source}}} w_i}.$$  \hspace{1cm} (3.9)

where $w_i$ is the weight given by

$$w_i = \frac{1}{(\Sigma_{\text{crit},i} \times \sigma_{\gamma,i})^2}.$$  \hspace{1cm} (3.10)

If the signal to noise for a single lens is not high enough to measure $\Delta \Sigma$, it is possible to increase the signal by stacking $\Delta \Sigma$ of several sources by summing over every lens-source pair included in the stack (see Fig. 3.2).

### 3.2 Cluster mass determination

A convenient method for measuring cluster masses using weak lensing is to fit a parametric model to the lensing signal given by Equation (3.9). An alternative to
this is aperture mass, which directly relates the lensing signal with projected mass within an aperture. The benefit of assuming a parametric model is that it recovers the density profile of the lensing object and thus both breaks mass-sheet degeneracy, i.e. that a constant mass layer leaves the shear unchanged and shear thus only maps the relative surface mass density, and deprojects the mass distribution.

The method of fitting a Navarro-Frenk-White (NFW) density profile (Navarro et al., 1997) to the surface mass density contrast is employed in Paper I and Paper II. The NFW profile based weak lensing mass estimates and the effect of the choice of cluster center and large-scale structure (LSS) are described below.

### 3.2.1 NFW profile

Numerical simulations show that the dark matter halos over a wide mass range, including those of galaxy groups and clusters, follow the NFW profile given by

$$
\rho(r) = \frac{\delta_c \rho_{cr}}{(r/r_s) \left(1 + r/r_s\right)^2}, \quad (3.11)
$$

where $\rho_{cr}$ is the critical density of the Universe at the redshift of the halo (Navarro et al., 1997). The profile depends on two parameters, halo mass (denote here by $M_{200}$) and concentration. The concentration parameter $c_{200} = r_{200}/r_s$ is related to the characteristic scale radius $r_s$ of the halo. The density contrast in Equation (3.11) is given by

$$
\delta_{c_{200}} = \frac{200}{3} \frac{c_{200}^3}{\ln(1+c_{200}) - \frac{c_{200}}{1+c_{200}}}. \quad (3.12)
$$

The analytic expression for the projected surface mass density signal corresponding to an NFW profile $\Delta \Sigma_{NFW}$ have been derived by Bartelmann (1996) and Wright & Brainerd (2000):

$$
\Sigma_{NFW}(x) = \begin{cases} 
\frac{2r_s \delta_c \rho_{cr}}{x (x^2-1)} \left[1 - \frac{2}{\sqrt{1-x^2}} \text{artanh} \sqrt{\frac{1-x}{1+x}} \right], & x < 1 \\
\frac{2r_s \delta_c \rho_{cr}}{3}, & x = 1 \\
\frac{2r_s \delta_c \rho_{cr}}{x (x^2-1)} \left[1 - \frac{2}{\sqrt{1-x^2}} \text{arctan} \sqrt{\frac{x-1}{x+1}} \right], & x > 1 
\end{cases} \quad (3.13)
$$

where $x = r/r_s$.

The problem of measuring lensing mass thus reduces to fitting $\Delta \Sigma_{NFW}$ to the measured lensing signal given by Equation (3.9). As the NFW density profile depends on two parameters - mass and concentration - there are two free parameters in the model fit. Unfortunately, typical weak lensing data does not allow to constrain both parameters well for individual clusters. As numerical simulations indicate that the two parameters are correlated (e.g. Duffy et al., 2008; Dutton & Macciò, 2014), this problem can be circumvented by assuming a mass - concentration relation based on the simulations.

As lensing is sensitive to both baryonic and dark matter, the baryonic contribution should in principle be included in the density profile. The impact of baryonic physics is most prominent in cluster cores, but the effect on mass measurements is unclear (Duffy et al., 2010). However, the impact of baryonic physics can be minimised by excluding cluster cores from the density profile fit used to determine the weak lensing mass.
3.2.2 Cluster centring

The choice of cluster center is important as miscentring the dark matter halo reduces the surface mass density contrast low, consequently biasing the lensing mass (e.g. Hoekstra et al., 2011; George et al., 2012). The size of the bias depends on the radial range used in the lensing mass fit - if the fit is extended to large radii, the effect is reduced. While it is possible to account for possible miscentring in the profile fit, it might bias the lensing mass high. Thus, external constraints such as adopting the location of the BCG or peak of the X-ray emission are generally preferable. However, this might lead to complications due to e.g. uneven X-ray coverage of a sample. Also, for clusters displaying strong merger signs the location of the X-ray peak might not coincide with the main cluster halo.

3.2.3 Large-scale structure

As clusters are located in the intersections of filaments in the cosmic web, some of the surrounding LSS can be physically associated with the cluster complicating the interpretation of lensing measurements. This correlated LSS has been studied in numerical simulations by e.g. Marian et al. (2010), Becker & Kravtsov (2011) and Bahé et al. (2012). Becker & Kravtsov (2011) shows that correlated LSS introduces a non-negligible contribution to the scatter in mass estimates (∼ 20 % of the total scatter). Only if the lensing signal is integrated beyond the typical virial radii (> 6h^{-1} Mpc), a bias might be introduced as the NFW profile is not be a good description of the cluster signal at large radii. However, Becker & Kravtsov (2011) concludes that correlated LSS is not a major source of uncertainty.

As gravitational lensing is sensitive to all structures along the line of sight, uncorrelated randomly distributed inhomogeneities in the matter distribution along the line-of-sight can also contribute to the lensing signal. The uncorrelated LSS introduces excess correlations in the shapes of galaxies, which acts as an additional source of noise in cluster weak lensing studies (Hoekstra, 2001, 2003). This noise arises as it is inherently impossible to distinguish the LSS contribution from the cluster signal. Fortunately, the uncorrelated LSS contribution vanishes on average and thus does not bias the masses. As with the correlated LSS, the impact of uncorrelated LSS also increases with integration radii far beyond the virial radius (Becker & Kravtsov, 2011).

3.3 Accuracy of weak lensing masses

The robustness of weak lensing mass measurements can be assessed through comparison to cosmological numerical simulations. This is possible as lensing masses are insensitive to the dynamical and thermodynamical state of the cluster.

The main complication in weak lensing mass measurements is that clusters generally are triaxial objects, and the mass estimates require assumptions about the detailed geometry of the cluster. As shown by e.g. Meneghetti et al. (2010) and Becker & Kravtsov (2011) cluster triaxiality severely limits the usefulness of weak lensing measurements of individual clusters under the assumption of spherical symmetry, as the mass estimate may be biased high or low depending on the orientation
of the cluster. However, for a sample of clusters, used e.g. for calibrating a scaling relation, the bias cancels out but leads to an irreversible scatter in mass.

Becker & Kravtsov (2011) estimated that the total scatter in a sample of NFW profile based weak lensing mass measurements due to the combined effect of triaxiality and LSS discussed above is at the level of 20 – 30 %, depending on cluster mass. The scatter is expected to be stronger for low-mass systems. They also show that the average mass is biased low by $\sim 6 \%$ if the lensing signal is integrated beyond $\sim 10$ arcmin, but that the bias is diminished if the fit radius is limited to 1 – 2 times the virial radius. However, shape noise of source galaxies used to measure shear is still the dominant source of scatter for ground based measurements.

### 3.4 Measuring the weak lensing signal

For the practical aspects of weak lensing mass measurements of clusters, a large number of source galaxies have to be identified and their shape has to be measured. The mass measurement method described above also requires the knowledge of the source redshift distribution both to measure the strength of the lensing signal and to distinguish source galaxies from cluster members.

The amplitude of the lensing signal as a function of redshift can be quantified by $\beta = \langle D_{LS}/D_{OS} \rangle$, the average ratio of the angular diameter distance between the lens and sources and the angular diameter distance between the observer and the lens, as illustrated in Fig. 3.3. For a typical density of resolved sources in deep ground based observations of $10 – 20$ arcmin$^2$, e.g. in Paper I we resolve 11 sources arcmin$^2$ using Canada-France-Hawaii Telescope Lensing Survey (CFHTLenS) data. The masses of massive and intermediate mass clusters at intermediate cluster redshift (corresponding to $\beta \sim 0.7$) can be determined individually. However, low-mass systems require stacking of the data from several clusters or a larger number of source galaxies only available through deep space based data. In Paper II we measure weak lensing masses of individual low-mass galaxy groups in the Cosmic Evolution Survey (COSMOS) using deep HST observations which resolve 46 sources per arcmin$^2$. Similarly, as $\beta$ decreases for high redshift clusters (Fig. 3.3), weak lensing measurements of high redshift clusters require space based data.

The sensitivity of the lensing signal to source redshift distribution is quantified by the slope $\partial \beta / \partial z$. The number of sources for ground based surveys typically peak around $z \sim 0.7 – 0.8$ (e.g. Fig. 3.4 and Applegate et al., 2014). For the $z = 0.5$ cluster in Fig. 3.3 this is a redshift range where $\beta$ rises with a significant slope, demonstrating that lensing mass measurements for intermediate and high redshift clusters are very sensitive to uncertainties in source redshifts. As seen in Fig. 3.3, the effect is less relevant for low redshift clusters.

Targeted spectroscopic redshift measurements of the large number of faint galaxies required for weak lensing measurements is not feasible due to the high cost of telescope time. Fortunately the precision of photometric redshift estimates using five or more bands are high enough for measurements of high and intermediate mass clusters up to intermediate redshifts. As cluster mass scales linearly with $\beta$, a systematic error in redshift measurements will translate directly to a corresponding bias in mass, making corrections for source redshift uncertainties simple. It is possible to relate a source galaxy catalogue with incomplete redshift information to the photometric catalogues.
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Figure 3.3: Average $\beta = \langle D_{LS}/D_{OS} \rangle$, the ratio of the angular diameter distance between the lens and the source and the angular diameter distance between the observer and the lens, as a function of source redshift for a cluster at $z = 0.2$ (solid line), $z = 0.5$ (dashed line) and $z = 0.9$ (dotted line). The value of $\beta$ quantifies the amplitude of the lensing signal, whereas the slope of $\beta$ describes the sensitivity to errors in the source redshifts.

Figure 3.4: The photometric redshift distribution for galaxies with $i$ band magnitude below 24 from CFHTLenS. Dashed lines show stacked probability density functions and solid histograms distributions of most probable photometric redshift. Data from the whole CFHTLS-Wide survey are shown in black, W1 field in red, W2 field in green, W3 field in blue and W4 field in cyan. Figure credit: Hildebrandt et al., MNRAS, 421, 2355, 2012, CFHTLenS: improving the quality of photometric redshifts with precision photometry, Figure 10.
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from e.g COSMOS (Ilbert et al., 2009) and to assume the literature redshift distributions as representative. However, the lack of redshift information for individual galaxies leads to problems with contamination by unlensed cluster member and foreground galaxies. Cluster members and foreground galaxies dilute the lensing signal, biasing the cluster mass low. For photometric measurements with known uncertainties, the contamination of the source catalogue can be modelled and a correction applied to the lensing signal. If redshift information on source galaxies is incomplete, it is possible to identify cluster members using a color-magnitude diagram.

For the weak lensing mass measurements included in this thesis, in Paper II we have photometric redshifts for all source galaxies measured using more than 30 bands (Ilbert et al., 2009) and spectroscopic follow up of ~10% of the sources. In Paper I we have photometric redshifts for the full source catalogue based on five optical bands (Hildebrandt et al., 2012). The quality of the photometric data and the number of source galaxies allows us to calibrate scaling relations to mass measurements of individual clusters.
Chapter 4
Scaling relations

Constraints on cosmological parameters through cluster counts requires the knowledge of masses of galaxy clusters. As weak lensing and X-ray hydrostatic mass measurements of individual clusters, described in previous chapters, are observationally expensive, it is generally not feasible to obtain individual mass measurements for a large number of systems. Instead, mass proxies calibrated through a scaling relation between observable and mass are used. The scaling relations are generally described as power-laws based on the self-similar model of Kaiser (1986), with points scattering around the relation following a lognormal distribution. As the relations describe positive correlations - more massive clusters are expected to be hotter and more luminous - scaling relations are also useful for studying the thermodynamic properties of clusters.

In this thesis, the scaling between weak lensing mass and X-ray observables of low- and intermediate-mass systems are studied in Paper I and Paper II. This Chapter introduces the self-similar model of Kaiser (1986), presents the cluster sample construction, scaling relations and survey biases affecting the relations. Finally, the physical implications of the results from scaling relations in this thesis are discussed. For the interested reader, Giodini et al. (2013) gives a recent review of cluster scaling relations.

4.1 The self-similar model

Kaiser (1986) considered the simple case, where gravity is the only important force affecting cluster evolution in a flat Universe (i.e. where the average density is equal to the critical density or $\Omega = 1$). Under this assumption the initial spectrum of density fluctuations is a power-law as a function of wave-number, and the amplitude of the fluctuations is a power-law function of scale or mass. In this case the mass-scale characterising the transition from linear to non-linear evolution $M_{NL}$ is the only scale introduced. In this case the mass ratio of the density fluctuations to $M_{NL}$ describes all properties of the evolved fluctuation field (e.g. number density of halos with a given mass as a function of time) as $M_{NL}$ fully describes the dependence on the matter spectrum.

Using the definition of Mandelbrot (1967) an object is self-similar when each portion of itself can be considered a reduced scale image of itself. For physical systems, the definition of self-similarity is invariance of dimensionless statistics under rescaling
over a limited range of scales. For the Kaiser (1986) model, the growth of structures is self-similar with respect to time, leading to a hierarchical scenario where small structures form first and function as building blocks for larger ones. In this case small structures are scaled down versions of the big ones. However, Kaiser (1986) argues that self-similarity predicted by the power-law shape can not be expected on all scales, but that it is a good approximation on the scales of galaxy groups and clusters. Numerical simulations by Navarro et al. (1995) show that self-similarity also holds for gas in clusters with gravity and shock heating included, if all other non-thermal dissipative processes are excluded.

Using the self-similar model, relations between cluster mass and X-ray properties of the gas in clusters can be predicted. Three important scaling relations are investigated within the context of this thesis, that between soft band X-ray luminosity and the temperature of the intracluster gas, cluster mass to soft band X-ray luminosity and cluster mass to temperature. Predictions of relations using other observables, such as gas mass $M_{\text{gas}}$ and $Y_X = M_{\text{gas}} \times T_X$, can also be derived. However, these relations are not studied here and the interested reader is referred to e.g. Kravtsov & Borgani (2012) or Giodini et al. (2013).

In the self-similar case, two haloes that have formed at the same time will have the same mean density and

$$\frac{M_{\Delta}}{R_{\Delta}^3} = \text{constant}. \quad (4.1)$$

Assuming that a cluster is in hydrostatic equilibrium, temperature of the gas is a direct measure of the depth of the potential well and thus of the virial mass

$$T \propto \frac{GM}{R} \propto R_{\text{vir}}^2, \quad (4.2)$$

where $R_{\text{vir}}$ is the virial radius. Substituting Equation (4.1) into Equation (4.2) results in the scaling of mass to temperature:

$$M_{\Delta} \propto E(z)^{-1} T_{\Delta}^3. \quad (4.3)$$

Here

$$E(z) = \frac{H(z)}{H_0} = \sqrt{\Omega_M (1 + z)^3 + \Omega_{\Lambda}} \quad (4.4)$$

describes the redshift evolution of the Hubble parameter. Assuming pure thermal Bremsstrahlung emission described in Section 2.2.1, it is possible to relate the temperature of the gas with bolometric X-ray luminosity $L$. This yields that $L \approx f_{\text{gas}}^2 T^2$, where $f_{\text{gas}}$ is the mass fraction of the X-ray emitting intracluster gas. As the gas fraction is expected to be constant in the self-similar model, the scaling relation between luminosity and temperature is given by

$$L \propto E(z) T^2. \quad (4.5)$$

Finally, the scaling relation between mass and luminosity is given by combining Equations (4.3) and (4.5), resulting in

$$M_{\Delta} \propto E(z)^{-2} L_{\Delta}^3. \quad (4.6)$$

The self-similar relations are only valid in case no other processes than gravity and shock heating are significant and the condition of hydrostatic equilibrium holds. The
above conditions may break down for disturbed clusters undergoing mergers (Poole et al., 2007), leading to scaling relations differing from the self-similar prediction. However, as the self-similar model assumes that all clusters are scaled versions of each other, it might not be accurate for strongly disturbed clusters. It is also important to note that Equations (4.5) and (4.6) are derived assuming bolometric X-ray luminosity and only Bremsstrahlung emission, whereas X-ray luminosity measurements are typically done in some discrete energy band and clusters also emit X-ray line emission\(^1\), which shows a strong temperature dependence (see Fig. 2.1).

4.2 Cluster sample construction

A good understanding of the physics of individual galaxy clusters is not enough for the calibration of a robust mass proxy. The properties of the cluster population as a whole need to be considered in order to achieve representative samples to understand the shape, and intrinsic scatter of the scaling relations.

Clusters studied in this thesis are selected based on their X-ray emission. X-ray selection is probably the most efficient and complete method for identifying clusters over a wide mass and redshift range. As the X-ray emission depends on the square of the gas density, it picks up dense structures, such as X-ray bright CCs (see Section 2.2.4) more efficiently than other methods, such as selection using the Sunyaev-Zel’dovich (SZ) effect or galaxy properties. Thus, CC clusters might be overrepresented in X-ray selected samples. The construction of the samples analysed in Paper I and Paper II are described below in Sections 4.2.2 and 4.2.1 respectively.

4.2.1 COSMOS

As deep, contiguous X-ray coverage of the 2 square degree COSMOS field is available, galaxy groups can be identified directly through extended X-ray emission (see Scoville et al., 2007, for an overview of the COSMOS survey). The George et al. (2011) COSMOS X-ray group catalogue is constructed through a search for extended X-ray emission in all XMM-Newton and Chandra observations of the COSMOS field performed prior to 2010, excluding group core regions. XMM-Newton and Chandra data are filtered separately for point sources. Excising group cores from the analysis means that the COSMOS sample is not biased towards systems with bright CCs. After detection of extended X-ray emission groups are verified optically through a red-sequence, where group member galaxies are identified in colour-magnitude space. The full George et al. (2011) catalogue contains 189 groups out to \(z = 1\) in the \(10^{13} - 10^{14} M_\odot\) range. Spectroscopic coverage of the COSMOS field allows for a spectroscopic identification of 90% of the groups in the George et al. (2011) catalogue.

In Paper II we select sources with a detection significance over \(10\sigma\) in the George et al. (2011) catalogue, corresponding to \(> 100\) X-ray counts. After excluding two sources at the edge of the COSMOS field falling outside the coverage of HST observations and one source with shallow X-ray coverage, we end up with a sample of 10 systems. These systems all have a clear X-ray peak with a single optical counterpart. As shown by Leauthaud et al. (2010), X-ray emission and lensing signal have a strong correlation for the COSMOS data. The adopted detection significance threshold al-

\(^1\)In this thesis \(L_X\) is used for observed X-ray luminosity.
allows us to measure lensing masses of individual systems (instead of stacking several systems, such as in Leauthaud et al., 2010) and to have a sufficient number of counts to measure spectroscopic X-ray temperatures, excluding cluster cores. In Paper I we also present core-excised soft band X-ray luminosities of the COSMOS systems.

### 4.2.2 CFHTLS

The XMM-CFHTLS survey, presented in Paper V, consists of pointed XMM-Newton follow up of clusters selected from ∼ 90 deg² in Canada-France-Hawaii Telescope Legacy Survey (CFHTLS) W2, W4 fields and half of the W1 field (PI: Finoguenov). As no deep contiguous X-ray coverage of the CFHTLS-Wide fields is available, we identify cluster candidates through extended emission in ROSAT All Sky Survey (RASS, Voges et al., 1999). The cluster candidates are filtered using a multicolour red sequence finder using five band CFHTLS optical data. We also perform spectroscopic follow up of some systems using Hectospec in combination with Baryon Oscillation Spectroscopic Survey Data Release 9 (BOSS DR9) data. The full XMM-CFHTLS catalog contains 196 systems, covering mainly an intermediate mass range between groups and clusters at intermediate redshifts. We are currently expanding the catalogue by performing XMM-Newton follow up of RASS sources without XMM-Newton coverage in the full 180 square degree CFHTLS wide footprint (PI: Kettula).

In Paper I we analyse 11 XMM-CFHTLS systems which are detected with a signal-to-noise ratio of over 20 (corresponding to over 400 X-ray counts from the whole cluster, including core) and include one system from the 3 deg² overlap between XMM-Newton Large Scale Structure Survey (XMM-LSS) and CFHTLS presented in Gozaliasl et al. (2014). We measure core-excised X-ray temperature and luminosity using the XMM-CFHTLS data and measure lensing masses using data from CFHTLenS (Heymans et al., 2012).

### 4.3 Scaling relations

Most of the recent efforts for calibrating X-ray scaling relations have concentrated on cluster-mass objects, with higher signal-to-noise ratio than groups and which reside in a mass range where the mass function is more sensitive to cosmological parameters. These rely on both X-ray HSE (e.g. Vikhlinin et al., 2009; Pratt et al., 2009; Mantz et al., 2010b) and weak lensing masses (e.g. Smith et al., 2005; Hoekstra, 2007; Mahdavi et al., 2013).

In addition to recovering the scaling relation, an understanding of the scatter of the data around the mean relation is needed to achieve a well calibrated mass proxy. Unfortunately, the definition of the scatter is not always unambiguous in the literature. It is important to distinguish if the scatter is quoted about the best-fit relation (i.e. perpendicular to the relation) or as scatter in mass at a fixed value of the proxy. Furthermore, as the power-law scaling relations are typically fitted to linearised relations, the scatter can be quoted as scatter in mass or log-mass.

Cluster luminosity and temperature can be measured independently from X-ray data: whereas the temperature is determined from the X-ray spectra (see Section 2.2.3), luminosity is measured from imaging data by integrating the surface brightness profile. These measurements show that the scaling of luminosity to temperature tends
to be steeper than expected from the purely gravitational case, the slope of the power-law is typically closer to 3 than predicted 2 (e.g. review by Giodini et al., 2013, and references therein). Relations that include the cluster core tend to have a large scatter, dominated by the presence of CCs, which have very strong surface brightness peaks in the cluster center with corresponding temperature drops. The effect is demonstrated in Fig. 4.1 using the online Data Visualiser for the Jaco/CCCP Sample2 (Hoekstra et al., 2012; Mahdavi et al., 2013), where the scatter in $L_X$ at fixed $T_X$ decreases from $50 \pm 8\%$ to $30 \pm 6\%$ by excluding cluster cores. As the cores are very bright, the core-inclusion also leads to a shallower relation corresponding to a larger luminosity for a given temperature for the Mahdavi et al. (2013) sample.

The scatter in the mass – temperature relation is typically smaller than in other relations studied in this thesis (e.g. 17 ± 8\% in lensing mass at fixed core-excised $T_X$, Mahdavi et al., 2013), rendering the $M – T_X$ relation attractive for cosmological applications. For massive clusters, the slope of the $M – T_X$ relation tends to be consistent with the self-similar prediction (Giodini et al., 2013). Uncertainties in the relation are mainly associated with uncertainties in the measurements, e.g. the HSE assumption might be broken biasing X-ray mass measurements (Section 4.4.2), weak lensing mass measurements of a sample of clusters are subject to an irreversible scatter (see Section 3.3) and temperature measurement are subject to calibration uncertainties of X-ray detectors (see Section 2.6).

As luminosity measurements require only the knowledge of cluster flux and redshift, they are generally available even if the data is too shallow to measure temperature or other mass proxies. The $M – L_X$ relation is therefore very useful in surveys with shallow cluster observations. The slope of the relation is typically somewhat shallower than expected from the self-similar case (Giodini et al., 2013), whereas the scatter is typically larger than for the $M – T_X$ relation. As an example, the Mahdavi et al. (2013) sample results in 26 ± 5\% for mass at fixed core-excised $L_X$.

### 4.3.1 Low-mass systems

If cosmological constraints are derived covering a large mass range, the degeneracy between the cosmological parameters $\Omega_M$ (describing the mass content of the Universe) and $\sigma_8$ (the amplitude of the power spectrum of initial density perturbations on $8h^{-1}$ Mpc scales) can be broken (Reiprich & Böhringer, 2002; Pillepich et al., 2012). Low-mass systems are also more numerous than rare massive clusters and they will consequently dominate the samples in upcoming cosmological surveys. Thus there is a strong incentive to extend scaling relations to group-mass objects, regardless of the observational difficulties in measuring masses of representative group samples.

X-ray surveys of galaxy groups have provided scaling relations for samples of very nearby low-mass systems under the assumption of HSE (Nevalainen et al., 2000; Finoguenov et al., 2001; Sun et al., 2009; Eckmiller et al., 2011; Lovisari et al., 2015). These reported stronger deviations from self-similarity when groups are included. Maughan et al. (2012) also finds a break in the core-excised $L_X – T_X$ relation below 3.5 keV. Relations including galaxy groups also generally show stronger intrinsic scatter in mass than relations using clusters only. This indicates that non-gravitational processes may have a significant effect on the energy budget for low-mass systems. A consequence of the non-gravitational processes is that they may lead to significant

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2http://sfstar.sfsu.edu/ccc/
Figure 4.1: $L_X - T_X$ relation including cluster core (left panel) and excluding cluster core (right panel) using the CCCP sample and demonstrating the effect of the cluster core on intrinsic scatter. The scatters quoted in the Figure are in $L_X$ at fixed $T_X$. Figure credit: Hoekstra et al. (2012); Mahdavi et al. (2013) and the online Data Visualizer for the JACO/CCCP sample.

Figure 4.2: The weak lensing signal-to-noise and relative importance of AGN feedback as function of mass, with the approximate mass range of the sample analysed in Paper I overlaid. The magenta band shows how the ability determine weak lensing mass increases with mass based on Hamana et al. (2004). The orange band shows how the mechanical output of radio AGN increases in systems with lower mass in relation to gravitational binding energy of the cluster, illustrating the importance of AGN feedback (Giodini et al., 2010). The approximative mass ranges of the COSMOS, CFHTLS and CCCP samples are also shown. Figure adapted from Paper I.
breaks in the HSE condition and that X-ray HSE masses of galaxy groups may thus be strongly biased. Consequently lensing mass calibration of low mass systems is of high interest. Unfortunately, as shown by Fig. 4.2, lensing measurements of individual galaxy groups are observationally very demanding and previous work has thus relied X-ray mass measurements or stacking analysis lensing analysis (e.g. Leauthaud et al., 2010).

Connor et al. (2014) presents lensing calibrated $M - T_X$ and $M - L_X$ relations for a sample of groups and low-mass clusters from the 160SD field. However, Connor et al. (2014) use a different aperture to extract quantities than Paper I and Paper II and include the cluster core in their choice of aperture. Thus the relations presented by Connor et al. (2014) are not compatible with those included in this thesis.

### 4.3.2 COSMOS and CFHTLS

Paper II provides the first lensing calibrated $M - T_X$ relation for galaxy groups using individual systems. The sample, selected from the COSMOS field (see Section 4.2.1), is combined with five more massive systems from the 160 Square Degree ROSAT Survey (160SD) field (Hoekstra et al., 2011) and 50 systems from the Canadian Cluster Comparison Project (CCCP) catalogue of massive clusters with the lensing analysis of Hoekstra et al. (2012) and X-ray analysis of Mahdavi et al. (2013).

In Paper I the COSMOS sample is extended with intermediate-mass systems (low-mass clusters) from CFHTLS (Section 4.2.2). The COSMOS and CFHTLS systems are combined with the massive CCCP clusters, using revised lensing analysis presented in Hoekstra et al. (2015), to provide a sample of 75 systems. The sample spans over two orders of magnitude in mass (see Fig. 4.2), three orders of magnitude in luminosity and approximately one order of magnitude in temperature. We use the sample to present reference $M - T_X$, $M - L_X$ and $L_X - T_X$ relations and include corrections for observational biases discussed below.

We find that the core-excluded $L_X - T_X$ relation has a slope of $2.52^{+0.17}_{-0.16}$ and a scatter of $0.10^{+0.04}_{-0.04}$ in log-$L_X$ at fixed $T_X$. The slopes of the $M - L_X$ and $M - T_X$ relations are consistent with the self-similar prediction at $0.74^{+0.09}_{-0.08}$ and $1.52^{+0.17}_{-0.16}$ respectively. The scatter in log-mass are $0.10^{+0.04}_{-0.04}$ and $0.07^{+0.04}_{-0.05}$ at fixed $L_X$ and $T_X$ respectively, showing that $T_X$ is a lower scatter mass proxy than $L_X$.

We divide our sample to 55 relaxed and 15 non-relaxed systems based on the offset between BCG and X-ray peak. Cluster triaxiality and substructure are the dominant sources of scatter for lensing mass (see Section 3.3) and as these are more pronounced in non-relaxed, merging clusters. We find an indication for increased scatter in mass for the non-relaxed systems, most likely due to enhanced triaxiality. Overall, non-relaxed systems contribute little to our X-ray selected samples. Cluster samples with a different selection leading to a higher fraction of non-relaxed systems may have a larger scatter.

The other main physical implications of the scaling relations presented in Paper I and Paper II are discussed in Section 4.4.

### 4.3.3 Survey biases

The scaling relations investigated in this thesis are subject to two kinds of selection biases, Malmquist and Eddington bias. Malmquist bias arises as intrinsically brighter
Figure 4.3: Illustration of the effect of Malmquist and Eddington bias on scaling relations using simulated data indicated by crosses. The solid lines show a luminosity – mass relation fitted to the full simulated cluster population, which follows an exponential log-mass distribution and is shown in the left panel. The right panel shows only clusters with luminosity greater than a threshold value, indicated by the dashed line, and the scaling relation fitted to the full sample. Figure credit: Mantz et al., MNRAS, 406, 1773, 2010, *The observed growth of massive galaxy clusters - II. X-ray scaling relations*, Figure A1.

Sources are detected out to a larger distance than less bright sources (Malmquist, 1922) and it affects any flux limited survey if the intrinsic brightness varies within the sample. Eddington bias arises in case of a fluctuation in survey observable and different number of objects at different values of the observable. Given the intrinsic scatter in galaxy cluster scaling relations, it is more likely that a lower mass system upscatters to a higher mass than for a massive systems to downscatter to a lower mass due to the steep decline of the mass function at high masses. At the flux limit of a survey, a part of the population is scattered over the detection limit.

The effect of these survey biases can be demonstrated using an illustrative example from Mantz et al. (2010b) in Fig. 4.3. The left panel shows a simulated population of clusters follow an exponential distribution in log-mass and the associated luminosity – mass relation, with a lognormal scatter in luminosity. The right panel shows the effect of the survey biases – in this case only systems above a threshold luminosity shown by the dashed line are detected. In this case the observed population does not follow the same scaling as the true underlying population and the observed data can not be used to be used to recover the underlying relation if the biases are unaccounted for. It is also important to note that the survey biases described here can not be circumvented by targeted follow up observations as the follow up observations themselves are subject to the same bias related to the original sample.

The strength of Malmquist and Eddington bias depends on the covariance between total scatters (intrinsic and statistical) of the survey observable used to select clusters and the parameter of interest. In the example using simulated data above there is a strong covariance and the relation is thus heavily affected. Unfortunately, the covariance of the scatters in real data are not known. Consequently the usual approach is not to include any correction. We employ this approach in Paper II. In Paper I, we...
improve the earlier modelling and present a bracketing solution by both measuring scaling relations employing a correction assuming a covariance of one and without the correction, corresponding to zero covariance. The true value of the correction is somewhere between those two extremes, depending on the covariance.

The Malmquist bias correction is included in the fitting routine of Kelly (2007) used in Paper I. The correction term for Eddington bias, given by

\[ r\sigma^2 \ln(10) \frac{d\alpha}{d\ln(M)} \ln(M) \]

where \( r \) is the covariance of the scatters, \( \sigma \) the scatter in the parameter of interest and \( \alpha \) the slope of the mass function. The correction term is computed individually for log-mass, log-\( L_X \) and log-\( T_X \) for each system and subtracted from the corresponding measurement. The corrections are particularly sizeable for the high-mass CCCP sample, which contains a large number of massive systems at relatively high redshifts (see Fig. 4.4).

Our results demonstrate the importance of the covariance – in addition to affecting the slope and normalisation of the relations the correction in Paper I leads to a decrease in scatter in mass, which would indicate both a strong covariance between X-ray selection and lensing mass and that the modelling gets improved. It is also important to note that the selection biases will also affect simulations with a realistic treatment of cluster selection and scatter. We verify our findings in Paper I by using a different high-mass sample constructed from the literature and show that sample variance is the dominant effect leading to discrepant scaling. Thus, our results are limited by our ability to understand the cluster selection.

4.4 Physical implications

4.4.1 Mass dependence

The reports of stronger deviations from self-similarity for relations including low-mass systems are supported by numerical simulations by Le Brun et al. (2014), Planelles et al. (2014) and Pike et al. (2014), which include non-gravitational processes such as radiative cooling and feedback from AGN and star formation. The simulations show that AGN feedback has a strong effect on group scales and that the energy injected to the intracluster gas may lead to a mass dependence in scaling relations. The simulations indicate a break in the relations at \( \sim 10^{14} M_\odot \) and that low-mass systems follow a different relation than high-mass systems.

In Paper I we attempted to measure the mass dependence suggested by simulations by using the three surveys making up the sample as approximative mass bins and providing scaling relations for the low-mass COSMOS, intermediate-mass CFHTLS and high-mass CCCP samples individually. Unfortunately the statistical uncertainties of the parameters are too large to infer any statistically significant results. Instead we study stacked residuals of the bias corrected global relation and show that low mass systems (defined here as \( M_{200} < 2 \times 10^{14} M_\odot \) based on \( L_X \) or \( T_X \) binning) are warmer and more luminous for their mass than high-mass systems (see Fig. 4.5). This implies a steepening at low-masses in the \( M - T_X \) and \( M - L_X \) relation. We also verify this behaviour using a different high-mass sample constructed from the literature.
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Figure 4.4: The ratio of Eddington bias corrected mass to uncorrected mass for the sample included in Paper I, demonstrating the effect of Eddington bias on lensing mass assuming a covariance of one for the scatters. Similar corrections are also performed for $L_X$ and $T_X$, where the size of the correction depends on the scatter in the parameter. Figure adapted from Paper I.

Figure 4.5: Residuals defined as the ratio of data to best fitting model prediction for the bias corrected $M - L_X$ (left panel) and $M - T_X$ (right panel) relations. Large triangles show the median and median standard deviation of stacked residuals in three bins, corresponding to mass ranges of $< 2 \times 10^{14} M_\odot$, $2 - 8 \times 10^{14} M_\odot$ and $> 8 \times 10^{14} M_\odot$. Figure adapted from Paper I.
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The implied low-mass steepening of the $M - T_X$ relation is in tension with Paper II, where we find that groups and clusters follow the same $M - T_X$ relation. However, the data in Paper I is improved by better coverage of intermediate mass systems and updated CCCP lensing measurements. Different low-mass scaling is qualitatively consistent with the predictions from the simulations discussed above and indications for it has been seen in previous work using X-ray HSE masses (e.g. Nevalainen et al., 2000; Finoguenov et al., 2001; Sun et al., 2009; Eckmiller et al., 2011). Thus, Paper I provides the first indication that groups and clusters might follow a more complicated scaling than a single power-law using lensing masses.

Giodini et al. (2010) compared the non-gravitational mechanical energy released by AGNs to the gravitational binding energy of the host cluster. They showed that the energy injected by AGN becomes comparable to the binding energy in cores of galaxy groups (see Fig. 4.2). While clusters can be viewed as closed systems, AGN feedback becomes globally significant at group scales and even mechanical removal of gas is energetically feasible. Indeed, X-ray measurements show that the gas fraction decreases for low mass systems (e.g. Sun et al., 2009; Pratt et al., 2009; Eckmiller et al., 2011).

As $L_X$ is proportional to the square of the gas fraction, removal of gas would make low mass systems less luminous for their mass, which is in apparent tension with the behaviour reported in Paper I. However, this argument (and the self-similar model) considers only bremsstrahlung emission, whereas line emission becomes important for clusters with temperatures below a few keV. The line-emission leads to an additional emission component on top of the continuum, which can produce over 50 % of the total X-ray luminosity in low-mass groups (see e.g. Fig. 2.1), and thus lead to a different dependence on $T_X$. However, our ability to measure this dependence and to better constrain the inferred mass dependence is currently limited by the available data on low-mass systems.

4.4.2 Hydrostatic mass bias

In Paper II, the data indicates that groups and clusters seem to follow the same mass – temperature scaling. This conclusion is also supported by simulations of Borgani et al. (2004) and Nagai et al. (2007) (but contradicted by the later work of Le Brun et al. (2014), Planelles et al. (2014) and Pike et al. (2014)). We compare our relation to $M - T_X$ relations for both groups and clusters in the literature using X-ray HSE masses and show that X-ray masses systematically predict lower masses for groups. We interpret this as a mass dependent HSE mass bias, which increases with decreasing mass and reaches 30 – 50 % at $10^{13} M_\odot$. However, the sample in Paper II does not have good coverage of intermediate mass systems. By inclusion of high-quality intermediate mass CFHTLS data, connecting the low-mass COSMOS and high-mass CCCP samples, and updated CCCP lensing measurements, we are able to infer the mass dependent shape of the $M - T_X$ relation in Paper I (see Fig. 4.5 and Section 4.4.1).

The inferred mass dependent shape of scaling relations makes the interpretation of the HSE mass bias in Paper II more complicated. Recent simulations by Miniati & Beresnyak (2015) show that cluster growth results in turbulence which scales with cluster thermal energy, implying a HSE mass bias which is constant in mass. The simulations of Miniati & Beresnyak (2015) do not consider feedback from AGN, which
becomes energetically significant for galaxy groups, as shown above. The energy injected by AGN could result in excess pressure support in the intracluster gas, in addition to the constant contribution from turbulence predicted by Miniati & Beresnyak (2015). The combination of turbulence and AGN feedback would result in an increased HSE bias for groups in relation to clusters. This is also consistent with the predictions in Paper II. However, discerning the effect of the HSE mass bias from the unknown mass-dependent shape of the scaling relations is not possible with the current data.

The Miniati & Beresnyak (2015) prediction of a constant HSE mass bias at cluster masses is in tension with the mass dependence reported by e.g. Israel et al. (2014, 2015) and von der Linden et al. (2014). They report a trend of increasing HSE mass bias for massive clusters. However, as discussed by Israel et al. (2015), these surveys are subject to Eddington bias. As Eddington bias is proportional to the scatter in mass, which is expected to be larger for weak lensing than X-ray measurements. Thus, lensing mass measurements of massive systems are expected to be more strongly affected by Eddington bias than X-ray masses. Eddington bias is also proportional to the slope of the mass function, increasing with mass (see Fig. 4.4). As the mass function flattens at lower masses, the effect of Eddington bias decreases, which would bring the different mass measurements to closer agreement.

While this thesis was being finished, Smith et al. (2015) became available. Smith et al. (2015) tests the HSE condition in the Local Cluster Substructure Survey (LoCuSS) sample, consisting of 50 X-ray selected clusters in the $z = 0.15 - 0.30$ range. They find a HSE to weak lensing mass ratio of $0.95 \pm 0.05$ within their independently derived $r_{500}$ and report no mass or redshift dependence, suggesting a mean HSE mass bias at a 5 % level. In this case they are comparing a complete sample with uniform X-ray and lensing selection, thus minimising the effects of survey biases. Smith et al. (2015) also compare their lensing masses to X-ray calibrated Planck SZ mass estimates from Planck Collaboration et al. (2015b) in order to determine the amount of HSE mass bias in Planck SZ cluster masses. For the 44 systems in common with Planck and LoCuSS, they find a Planck to lensing mass ratio of $0.95 \pm 0.04$, consistent with LoCuSS X-ray masses. This is inconsistent with the Planck to lensing mass ratios found by CCCP and Weighing the Giants (WtG), who report $0.76 \pm 0.08$ and $0.70 \pm 0.06$ respectively (Hoekstra et al., 2015; von der Linden et al., 2014). However, Smith et al. (2015) finds that these values might depend on redshift. They compare the Planck to CCCP and WtG mass ratios in $z < 0.3$ and $z > 0.3$ redshift bins and find a HSE bias at a 5 – 10 % level in Planck masses in the $z < 0.3$ bin, consistent with LoCuSS, while the $z > 0.3$ bin results in Planck HSE bias at a 30 – 40 % level.

The selection bias corrections applied to CCCP systems in Paper I (see Section 4.3.3) have the strongest effect on the most massive systems, which are also the highest redshift objects in the CCCP catalogue (i.e. in the $z > 0.3$ bin in Smith et al., 2015). As the Planck cluster selection is deep, but not uniform, the cross-match to CCCP is driven by CCCP selection. In such case, only CCCP lensing masses are subject to selection bias in the comparison to Planck masses. The Eddington bias corrections applied to CCCP lensing mass result in a decrease in mass (see Fig. 4.4) and reach a 30 – 40 % level for the highest mass systems, comparable to the HSE bias in the $z > 0.3$ CCCP clusters in the Planck cluster catalogue (Smith et al., 2015). Consequently, the high values for Planck HSE bias reported by von der Linden et al. (2014) and Hoekstra et al. (2015) could be due to WtG and CCCP selection bias.
Chapter 5

Summary of the publications

The thesis consists of five journal publications:


The papers are summarised below. The author’s contribution to the papers is described in Section 5.6.

5.1 Paper I - “CFHTLenS: weak lensing calibrated scaling relations for low-mass clusters of galaxies”

In Paper I, we perform X-ray and weak lensing analysis to a sample of 12 Virgo-like low-mass clusters from CFHTLS. 11 of the clusters are selected based on X-ray counts
from the XMM-CFHTLS survey, presented in Paper V, while one system is from the 3 deg$^2$ overlap between XMM-LSS and CFHTLS presented in Gozaliasl et al. (2014). Weak lensing observations have been performed as a part of CFHTLenS. We combine the CFHTLS sample with 10 low-mass systems from COSMOS (analysed in Paper II) and 48 massive systems from CCCP (analysed by Mahdavi et al., 2013; Hoekstra et al., 2015), to form a sample of 70 systems. We measure core-excised $L_X - T_X$, $M - L_X$ and $M - T_X$ scaling relations and introduce corrections for survey biases. For Eddington bias, we present relations where we assume zero covariance in the scatters of the parameter used for cluster selection and the parameters of interest (corresponding to a zero correction) and a covariance of one (corresponding to a maximum correction).

Using the maximum corrections for Eddington bias, the $M - L_X$ and $M - T_X$ relations calibrated using the full sample have slopes consistent with the prediction from the self-similar model of Kaiser (1986), whereas the $L_X - T_X$ relation is somewhat steeper. We provide the current limitations for core-excised $L_X$ and $T_X$ as mass proxies and show that $T_X$ benefits from a smaller intrinsic scatter in mass. In order to study the sensitivity of our results to the sample, we construct a different high-mass sample from the literature. Even after accounting for cross-calibration of X-ray instruments and survey biases, some tension persists. This demonstrates that variance between samples is the dominant source of uncertainty.

We attempt to study the mass dependence of the scaling relations by using the three surveys making up our sample as approximate mass bins, but these suffer from large statistical uncertainties. Instead we study residuals (defined as data / best-fitting model). Our data indicates that low-mass systems can be more luminous and warmer for their mass than intermediate- and high-mass systems, implying a low-mass steepening in the $M - L_X$ and $M - T_X$ relations. We find consistent steepening using the literature high-mass sample. We also divide our sample into subsamples of 55 relaxed and 15 non-relaxed clusters based on the distance between BCG and X-ray peak. Our data indicates that non-relaxed clusters may have an enhanced scatter in lensing mass, most likely due to pronounced triaxiality and substructure. Overall, we find that non-relaxed clusters contribute little to X-ray selected samples, dominated by relaxed systems. Finally, we study the effects of X-ray cross-calibration on scaling relations by converting our XMM-Newton based measurements to match Chandra calibration. We find that Chandra results in flatter $L_X - T_X$ and $M - T_X$ relations than XMM-Newton.

5.2 Paper II - “Weak Lensing Calibrated M-T Scaling Relation of Galaxy Groups in the COSMOS Field”

In Paper II, we perform X-ray spectroscopy and measure weak lensing masses for a sample of 10 galaxy groups from the COSMOS field in order to provide the first lensing calibrated $M - T_X$ relation for galaxy groups. The galaxy group sample is selected from the COSMOS X-ray group catalogue of George et al. (2011), by requiring a detection significance above $10\sigma$. As the X-ray signal correlates with the lensing signal (Leauthaud et al., 2010), the X-ray cut enables us to measure temperature and mass individually for each system. We measure core-excised temperature using all available XMM-Newton data. We measure lensing mass by fitting NFW density pro-
files to surface mass density profiles using a modified version of the lensing catalogue Leauthaud et al. (2007).

Our sample spans a temperature range of \( \sim 1 - 5 \text{ keV} \) and a mass range of \( \sim 10^{13} - 10^{14} M_\odot \). As the \( M_{500} - T_X \) relation using only the COSMOS systems suffers from large uncertainties, we extend the sample with additional higher-mass systems from the literature. We include five systems from the 160SD survey (Hoekstra et al., 2011) and 50 systems from CCCP (Hoekstra et al., 2012; Mahdavi et al., 2013). The combined sample results in tighter constraints, the slope of \( 1.48^{+0.13}_{-0.09} \) is consistent with the prediction of 1.50 from the self-similar model (Kaiser, 1986). The scatter in mass at fixed temperature is \( 28 \pm 7 \% \).

Comparing our relation to corresponding relations from the literature, we find that relations using clusters only result in consistent slopes regardless if they use X-ray or weak lensing masses. With our data, we conclude that both groups and clusters follow the same scaling. This is in tension with previous work using X-ray mass measurements of galaxy groups (and our later work in Paper I), which indicates that groups follow a steeper scaling. By comparison to our lensing masses, we show that the previous X-ray mass calibrated relations systematically underpredict group masses. We interpret this as evidence for hydrostatic mass bias, which increases with decreasing mass and reaches 30 – 50 % at 1 keV. This conclusion is supported by mock Chandra X-ray mass measurements of simulated clusters by Nagai et al. (2007). We also account for X-ray cross-calibration by converting our XMM-Newton measurements to match Chandra calibration, and demonstrate that the tension between lensing and X-ray calibrated \( M - T_X \) relations cannot be explained by X-ray cross-calibration.

### 5.3 Paper III - “Cross-calibration of Suzaku/XIS and XMM-Newton/EPIC using galaxy clusters”

It is possible to gain information on the cross-calibration of the energy dependence of the effective area by comparing temperatures of the same cluster measured with two different instruments. Similarly, comparison of luminosities tells us about the relative normalisation of the effective area of the instruments. In Paper III we study the cross-calibration of Suzaku/XIS and XMM-Newton/EPIC-pn instruments as a part of the IACHEC Galaxy cluster working group. This paper is an extension to Nevalainen et al. (2010), which compares the calibration of XMM-Newton/EPIC to Chandra/ACIS.

We select clusters from the Highest X-ray Flux Galaxy Cluster Sample (Reiprich & Böhringer, 2002), requiring an off-axis angle less than 1 arcmin, a minimum of 5000 data counts and a total background flux below 10 % of of the cluster flux. We perform our main analysis in two energy bands, soft 0.5 – 2.0 keV and hard 2.0 – 7.0 keV , but also include full 0.5 – 7.0 keV band for reference. We exclude clusters with a galactic absorption column density \( N_H > 6 \times 10^{20} \text{ cm}^{-2} \) from the soft and full band samples. The final soft and full band sample contains 5 systems, whereas the hard band contains 10 systems. In addition to measuring temperatures and fluxes using a 3 – 6 arcmin aperture, we study the effective area cross-calibration through stacked residuals.

We find that hard band temperatures of all studied instruments are consistent within \( \sim 5 \% \) and conclude that the hard band effective area shapes are in good
agreement. However, in the soft band we find significant disagreement. XIS0 results in temperatures 20 – 30% lower than XIS1 and XIS3, with EPIC-pn temperatures approximately in halfway between XIS0 and XIS1/XIS3. Stacked residuals indicate that the discrepancies in the XIS effective area calibration are mainly in the 0.5 – 1.0 keV band. We investigate if the modelling of the XIS OBF contaminant can account for the effective area discrepancies by allowing the column density of the contaminant to vary independently for each instrument, while forcing a consistent emission model. This significantly improves the spectral fits. We find that the standard calibration of XIS0 closely matches the joint XIS modelling and that the joint modelling consequently results in only small modifications to the XIS0 contaminant. For XIS1 and XIS3 the amount of contaminant has to be increased ∼ 1 – 2 × 10^{17} cm⁻², in comparison to the standard calibration. We thus conclude that the XIS0 soft band is more accurately calibrated than XIS1 and XIS3.

We compare fluxes in the hard band, but find the comparison inconclusive due to scatter from cool-cores in Suzaku/XIS. Overall, we conclude that the calibration of Suzaku/XIS is in better agreement with XMM-Newton/EPIC than Chandra/ACIS.

5.4 Paper IV - “XMM-Newton and INTEGRAL analysis of the Ophiuchus cluster of galaxies”

In Paper IV, we model the X-ray emission in the Ophiuchus galaxy cluster using XMM-Newton data and search for NT hard X-ray emission with the IBIS/ISGRI instruments onboard INTEGRAL. Ophiuchus is a hot (T_X ∼ 9 keV) and nearby (z = 0.028) cluster, hosting a radio mini-halo (Govoni et al., 2009).

We map the X-ray brightness distribution using XMM-Newton data and find that the data is well described by a two component surface brightness profile, consisting of a narrow component dominant within 1 arcmin from the brightness peak, corresponding to a cool core, and an extended component, corresponding to the hot intracluster gas. We map the temperature distribution of Ophiuchus with XMM-Newton using both a thermal emission model in a 0.5 – 7.4 keV energy band and Fe XXV / XXVI emission line ratios in a narrow 6.0 – 7.4 keV band. We find that a single thermal model with kT = 9.1 ± 0.1 keV matches the emission in a 1 – 7 arcmin annuli, whereas additional cooler components corresponding to the cool core and BCG are required to describe the data in the central 1 arcmin. We measure a cooling radius of ∼ 30 kpc and cooling time of 3 ×10⁹ years for the cool core.

The thermal model describing the XMM-Newton data underpredicts the INTEGRAL data by 5.7σ in a 20 – 140 keV band. As the detection of a radio mini-halo proves the existence of relativistic electrons in Ophiuchus, we model the hard X-ray excess detected with INTEGRAL as IC scattering of CMB photons. Unfortunately the statistical weight of the INTEGRAL data is low in comparison to the XMM-Newton data, and we are unable to obtain a physical model without significantly constraining the power-law describing the IC emission. We find that adding a power-law with a photon index in the range of 2.2 – 2.5 describing IC emission, while allowing the hot thermal emission component to vary, accurately describes the combined XMM-Newton and INTEGRAL data. This model also results in a significantly better fit for the XMM-Newton data than the thermal model derived using XMM-Newton only.

With the addition of the NT power-law component, the temperature of the hot
CHAPTER 5. SUMMARY OF THE PUBLICATIONS

thermal component increases to \( \sim 10.6 \text{ keV} \). The photon index of the power-law corresponds to a radio spectral index of \( 1.2 - 1.5 \), consistent with the upper limit of 1.7 from radio measurements (Pérez-Torres et al., 2009). The flux of the power-law component in a \( 1 - 10 \text{ keV} \) band is \( \sim 10\% \) of the total flux and the pressure of the non-thermal electrons is \( \sim 1\% \) of that of the thermal electrons. Using the ratio of the radio brightness and power-law flux, we derive a magnetic field strength in the range of \( 0.05 - 0.15 \mu G \).

The long cooling time of the cool core and lack of major merger signatures speak against a recent major merger in Ophiuchus. We thus conclude that the relativistic electron population is produced by turbulence or hadronic collisions.

5.5 Paper V - “Brightest X-Ray Clusters of Galaxies in the CFHTLS Wide Fields: Catalog and Optical Mass Estimator”

Paper V presents the XMM-CFHTLS cluster catalogue from which the sample analysed in Paper I is selected and studies scaling of optical properties with X-ray luminosity. The XMM-CFHTLS catalogue is based on a series of short \textit{XMM-Newton} follow-up observations of faint X-ray sources detected by RASS in CFHTLS W2 and W4 fields and half of the W1 field. We were allocated a total of 220 ks of \textit{XMM-Newton} time. Five band optical data from CFHTLS allows us to construct a multicolour red sequence finder to identify counterparts for extended \textit{XMM-Newton} sources. We are able to assign red sequence redshifts to a total of 196 clusters. Out of these, 81 have spectroscopic redshifts, either from our Hectospec follow up or BOSS DR9.

We derive velocity dispersions for 16 XMM-CFHTLS clusters where we have more than 10 spectroscopic counterparts. We study the scaling of velocity dispersion to soft band X-ray luminosity measured with \textit{XMM-Newton}, and show that our relation is compatible with that of Leauthaud et al. (2010). We also study the scaling of integrated \( z' \) band optical luminosity of red sequence galaxies \( L_S \) to X-ray luminosity. The scatter in \( L_S \) at fixed X-ray luminosity using our multicolour red sequence finder is smaller or equal to that using a single-colour red sequence or a combination of single-colour red sequence and photo-z, regardless of selection radius or fitting method. Thus \( L_S \) measured using our multicolour red sequence finder is a good estimator for X-ray luminosity and consequently cluster mass.

Finally, we apply our red sequence finder to RASS sources without \textit{XMM-Newton} follow up in the full 180 square degree CFHTLS wide footprint. This results in the RASS-CFHTLS catalogue of 32 additional clusters. In comparison to other X-ray cluster samples, XMM-CFHTLS and RASS-CFHTLS clusters are typically in a \( \sim 10^{14} M_\odot \) mass range, covering intermediate masses between less massive groups and more massive clusters.

5.6 Author’s contribution to individual papers

- Paper I: The author had the main responsibility of writing the article. The author wrote all the scripts for fitting and analysing the scaling relations and
prepared most of the plots. The Eddington bias corrections derived by A. Finoguenov were implemented by the author. Furthermore, the author constructed the literature high-mass sample used to verify the results. Co-authors performed the weak lensing and X-ray analysis, commented the manuscript and contributed to the science interpretation and analysis.

- **Paper II**: The author had the main responsibility of writing the article and prepared all of the figures. The author performed both the lensing and X-ray analysis. He wrote the software for measuring lensing masses from the COSMOS lensing catalogue. A. Finoguenov provided original scripts for the X-ray data reduction, which were significantly modified by the author. The author performed the calibration of the $M - T$ relation using scripts written by himself. The co-authors commented the manuscript, contributed to the science interpretation and analysis and developed the shear and X-ray group catalogues used by the author.

- **Paper III**: The author had the main responsibility of writing the article. He reduced both the Suzaku and XMM-Newton data. J. Nevalainen provided scripts for XMM-Newton data reduction and E. Miller for Suzaku data reduction. These scripts were further developed by the author. The spectral analysis was performed by the author under the supervision of J. Nevalainen. The author developed and performed the spectral fitting of the Suzaku OBF contaminant using a spectral model provided by E. Miller. The author prepared all figures in the paper with the exception of Fig. 23. The IACHEC consortium provided comments on the manuscript.

- **Paper IV**: The author performed an initial reduction of the XMM-Newton data and a preliminary analysis of the XMM-Newton data together with the INTEGRAL data. The analysis was finalised by J. Nevalainen, who had the main responsibility of writing the article. The author participated in discussions about the manuscript and provided general comments.

- **Paper V**: This paper presents the sample used in Paper I. The author worked on the role of selection for the scaling relations presented in Section 3 and participated in discussions about the manuscript. He is leading the XMM-Newton X-ray follow up of the RASS-CFHTLS sample presented in this paper. Paper V has been used in the doctoral dissertation of M. Mirkazemi at the Ludwig-Maximilians-Universität in Munich, July 2015.
Chapter 6

Concluding remarks

This thesis studies the X-ray properties of galaxy groups and clusters and the scaling of X-ray observables to weak lensing mass. We have studied the NT properties of the Ophiuchus cluster of galaxies and the cross-calibration of X-ray instruments. We have also studied the scaling of X-ray luminosity, the temperature of the intracluster gas and weak lensing mass for galaxy groups and low-mass clusters. These topics are related through the need to obtain unbiased cluster masses for cosmological constraints using galaxy cluster counts. Scaling relations used for cluster mass calibration are the key source of uncertainty in constraints of cosmological parameters through galaxy cluster counts. Consequently, the topics covered by this thesis are active fields within galaxy cluster studies.

The forthcoming generation of X-ray instruments will significantly improve our understanding of NT phenomena in the intracluster gas by e.g. allowing us to directly measure the amount of turbulence. Understanding the role and energetics of NT phenomena would allow us to directly determine to what degree these affect X-ray mass estimates. Within the context of this thesis, our detection of IC hard X-ray emission in the Ophiuchus cluster hints that targeting mini-halo clusters could be more fruitful than targeting clusters with giant radio halos in searches of IC X-ray emission.

The need for cluster mass calibration has also highlighted the importance of accurate X-ray calibration. We show that XIS0 is likely to be the most accurately calibrated of the XIS instruments onboard the now defunct Suzaku satellite and that the discrepancies between the XIS instruments are attributable to the modelling of the OBF contaminant. However, in general it is evident that obtaining absolute calibration resulting in correct temperatures is very difficult without calibration against external measurements. These could be obtained through weak lensing mass measurements, emission line temperatures or numerical simulations, where an improved understanding of the NT energetics would help to reproduce a more realistic cluster population.

We provide the first lensing calibrated mass – temperature relation for galaxy groups using data from the COSMOS survey, which we combine with more massive systems from the literature. We later include intermediate-mass systems from CFHTLS and measure soft band X-ray luminosities. We also include corrections for survey biases and use the improved data and modelling to provide the current limitations for X-ray luminosity and temperature as cluster mass proxies. Our data shows that temperature, though observationally more expensive, can be a more attractive...
mass proxy than luminosity due to a lower intrinsic scatter in mass and that non-relaxed clusters contribute little to X-ray selected samples. We also show for the first time using lensing masses that low-mass systems seem warmer and more luminous for their mass than massive systems, indicating the need to explore more complicated scaling relations than a single power-law. The mass dependence in scaling relations is also indicated by recent numerical simulations incorporating feedback from AGN and previous observations using X-ray HSE masses. Determining the shape of the scaling relations is very important, given upcoming deep surveys which will detect large numbers of galaxy groups. Currently, our ability to constrain the form of the scaling relations is limited by the available data. However, we have an ongoing program to extend the X-ray coverage of the CFHTLS fields to improve on this issue.

Recent numerical simulations indicate that turbulence due to cluster growth scales with thermal energy, indicating a constant HSE mass bias at cluster masses. As forthcoming instruments will hopefully allow us to directly measure turbulence, this would allow us to observationally verify the scaling of turbulence to thermal energy and possibly use the measurement of turbulence to derive the amount of resulting HSE mass bias. On group scales where AGN feedback becomes significant, our data indicates that the HSE mass bias might be stronger.

Our ability to correct for the survey biases is limited by the unknown covariance of the scatters in the parameter used for cluster selection and the parameter of interest. We are able to demonstrate that it is important for X-ray selected samples, but a better understanding of the covariance would significantly improve the situation. Currently, our results are limited by our ability to understand cluster selection.

To conclude, we are living in very exciting times for X-ray and weak lensing studies of galaxy clusters. Weak lensing has matured into the leading method for obtaining accurate cluster masses. Forthcoming X-ray observatories and X-ray surveys detecting thousands of clusters will likely settle several of the issues presented in this thesis, e.g. the NT energetics of the intracluster medium, the covariance of scatters and the shape of scaling relations.
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