Figure 5.3: Comparison of the SDSS and Megacam filter systems. The plot shows the complete transmission curves for the $u'g'r'i'z'$ filters of both systems as a function of wavelength, including the atmospheric transmissivity (as given for the SDSS site), the CCD quantum efficiency, and the actual effect of the filter, as measured in the laboratory. The solid lines give sensitivities of Megacam filters for photons incident on the optical axis while the dash-dotted lines show the same quantity near the corner of the Megacam array. Over-plotted as dashed lines are the transmission curves defining the SDSS bandpass system. The black, dotted curve shows the Megacam quantum efficiency that we derive from the instrument specifications, scaled by one half to show it conveniently on the plot. Note that we need to interpolate its values from only five points in the range $300 \text{ nm} < \lambda < 1000 \text{ nm}$ and have to extrapolate outside this interval.

The relation between Megacam instrumental magnitudes $m_{\text{inst}}$ and catalogue magnitudes $m_{\text{SDSS}}$ for a filter $f$ can be fitted simultaneously as a linear function of airmass $a$ and a first-order expansion with respect to the colour index,

$$m_{f,\text{inst}} - m_{f,\text{SDSS}} = \beta_{f} c_{\text{SDSS}} + \gamma_{f} a + Z_{f}, \quad (5.3)$$

where $c_{\text{SDSS}}$ is a colour index defined by two SDSS filters, $\beta_f$ the corresponding colour term, and $Z_f$ the photometric zeropoint in which we are mainly interested. For the fit, we select objects of intermediate magnitude that are neither saturated nor exhibit a too large scatter in $m_{\text{inst}}$ given a certain $m_{\text{SDSS}}$. Following the model of Hildebrandt et al. (2006), we account for the variable photometric quality of our data by fitting $\beta_f$, $\gamma_f$, and $Z_f$ simultaneously in optimal conditions, fixing $\gamma_f$ in intermediate, and fixing $\gamma_f$ and $\beta_f$ in even poorer conditions.
Figure 5.4: Accuracy of the photometric calibration: For the different combinations of filters and nights used to calibrate the data sets discussed in this thesis, the scatter $\Delta m'$ around the best-fit solution (solid line) is shown. Each point corresponds to an SDSS standard source for which the abscissae give the separation $\theta_0$ in arc minutes from the centre of the pointing. Note that for each panel a maximum $\Delta m'$ has been determined by iterative 3$\sigma$-clipping.
CHAPTER 5. DATA REDUCTION

5.2. PHOTOMETRIC CALIBRATION

Table 5.2: Coefficients of photometric calibration defined by Eq. (5.3) for all photometric nights in which 400d clusters have been observed with MMT/MEGACAM. Note that nearly all Run C and Run E data are photometric, while there were no photometric nights in neither Run B nor Run J.

<table>
<thead>
<tr>
<th>Filter</th>
<th>Obs. Date</th>
<th>$Z_f$</th>
<th>$\beta_f$</th>
<th>$c_{\text{SDSS}}$</th>
<th>$\gamma_f$</th>
<th>$n_{\text{par}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g'$</td>
<td>2005-10-30</td>
<td>27.277 ± 0.005</td>
<td>0.106 ± 0.007</td>
<td>$g' - r'$ (-0.15)$^\dagger$</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2005-11-01</td>
<td>27.286 ± 0.005</td>
<td>0.116 ± 0.005</td>
<td>$g' - r'$ (-0.15)$^\dagger$</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>$i'$</td>
<td>2005-10-31</td>
<td>26.426 ± 0.002</td>
<td>0.124 ± 0.002</td>
<td>$r' - i'$ (-0.05)$^\dagger$</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2005-11-01</td>
<td>27.408 ± 0.009</td>
<td>0.119 ± 0.002</td>
<td>$r' - i'$ -0.03 ± 0.01</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>$r'$</td>
<td>2005-06-07</td>
<td>26.819 ± 0.001</td>
<td>0.040 ± 0.001</td>
<td>$g' - i'$ (-0.10)$^\dagger$</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2005-06-08</td>
<td>26.834 ± 0.008</td>
<td>0.048 ± 0.001</td>
<td>$g' - i'$ -0.12 ± 0.01</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2005-10-30</td>
<td>26.950 ± 0.018</td>
<td>0.046 ± 0.002</td>
<td>$g' - i'$ -0.10 ± 0.02</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2005-10-31</td>
<td>26.959 ± 0.004</td>
<td>0.042 ± 0.003</td>
<td>$g' - i'$ (-0.10)$^\dagger$</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2005-11-01</td>
<td>26.960 ± 0.008</td>
<td>0.048 ± 0.004</td>
<td>$g' - i'$ (-0.10)$^\dagger$</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2005-11-08</td>
<td>26.807 ± 0.005</td>
<td>0.046 ± 0.003</td>
<td>$g' - i'$ (-0.10)$^\dagger$</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

$^\dagger$ Normalised to an exposure time of 1s and an airmass $a = 0$.

$^\ddagger$ Number of parameters used in the fit.

$^\S$ Fixed to default value.

For each filter, we chose a colour index $c_{\text{SDSS}}$ in Eq. (5.3) that has been proven to provide a reliable transformation during calibration of the Canada-France-Hawaii Telescope Legacy Survey (CFHTLS) data, which also uses a similar filter system$^4$. These colour indices are given in Table 5.2, which shows the results for the fit parameters $Z_f$, $\beta_f$, and $\gamma_f$ for the photometric nights in which MEGACAM observations of 400d clusters were performed.$^5$ We note that while nearly all data in Run C and Run E were taken in photometric conditions, all zeropoints obtained from observations in Run B and Run J are significantly smaller, indicative of non-photometric conditions.

We find the zeropoints $Z_f$ of the photometric nights to agree among the filters $g'r'i'$, with a largest deviation of $\approx 0.15$ mag. The scatter $\Delta m' = m_{\text{inst}} - m_{\text{SDSS}} + \beta_f c_{\text{SDSS}} + \gamma_f a + Z_f$ of the individual SDSS standards about the best-fit solution (Fig. 5.4) has a comparable amplitude. The error of $Z_f$ given in Table 5.2 is the formal fitting error. Figure 5.4 presents the data from which the parameters $Z_f$, $\beta_f$, and $\gamma_f$ have been determined, applying an intervening 3σ-clipping fit of Eq. (5.3).$^6$

Comparing the colour terms $\beta_f$ for the different nights, we find considerable agreement within the values for each of the three bands, although the formal errors underestimate the true uncertainties. In previous MEGACAM studies, Hartman et al. (2008, Table 5) quote $\beta_g = 0.122 \pm 0.002$ and $\beta_i = 0.137 \pm 0.002$, the first in agreement with our results, the latter significantly higher than our value. Furthermore, Walsh et al. (2008) find $\beta_g = 0.091 \pm 0.068$, consistent with our values given the large error. We suspect that the large span in values of $\beta_g$ might be caused by the known dependence of the filter throughput on the distance to the optical axis, which is most pronounced in this band (Fig. 5.3). Plotting the scatter $\Delta m'$ as a function of the separation $\theta_0$ of the source from the optical axis of MEGACAM (Fig. 5.4), given by the pointing position in the flt.fits header, we can confirm trends of $\Delta m'(\theta_0)$ in all filters, most pronounced for the $g'$-band used in 2005 observations.

---


5 Note that photometric solutions given for Run E in Table 5.2 are corrected w.r.t. Table A.1 in Israel et al. (2010). The amount of these corrections is of the order of, and in most cases smaller than, the scatter observed in Fig. 5.4.

6 The number of initial photometric data points for each night and filter strongly depends on whether the observed clusters lie within the SDSS “footprint”.

51
October 30. Further investigation is needed to conclude about this issue, requiring full propagation of errors on instrumental magnitude. Because the radial dependence observed in Fig. 5.4 does not exceed the residual scatter for sources at the same $\theta_0$, the global photometric fits (Eq. 5.3) fulfil the requirements of our analysis.

### 5.2. Photometric Calibration of CL 0809+2811

The situation for CL 0809+2811 is a peculiar case. This cluster has been targeted in the $r'$-band both in Run E and in Run J. Imaging acquired on 2005 November 08 turned out to be photometric – albeit with a large scatter around the photometric solution – while the majority of frames taken on 2008 January 09 was not. Inspection of the PSF anisotropy on the individual frames, however, revealed that all frames taken under photometric conditions had to be removed from the coaddition because of their extremely anisotropic PSF ($|e| > 0.10$). Nevertheless, because the relative zero-points that had already been established for the THELI set of CL.0809+2811 in the $r'$-band are not affected by the choice of frames for coaddition, the coadded $r'$-band image for CL0809+2811, consisting entirely of exposures taken on 2008 January 09, is photometrically calibrated through the cluster data acquired on 2005 November 08.

### 5.2.3 Indirect Photometric Calibration of CL 0030+2618

Comparing the zeropoints for different nights and fields, we conclude that the nights on which the $r'$-band observations of CL 0030+2618 were performed were not entirely photometric but showed a thin, uniform cirrus. Therefore, in the absence of SDSS data in the field, an indirect calibration method is needed. To this end, we fitted the position in the $r' - i'$ versus $g' - r'$ colour-colour-diagram of the stars identified in the CL0030+2618 field to those found in two other, fully calibrated, galaxy cluster fields, CL.0159+0030 and CL.0809+2811. In the left panel of Fig. 5.5, we compare the $g' - r'$ versus $r' - i'$ colours of stars identified in these two fields with those for theoretical spectra of main-sequence stars from the Pickles (1998) spectral library, finding good agreement between both of the two observed sequences and the predicted stellar colours.

Since we have attained reliable absolute photometric calibrations for the $g'$- and $i'$-bands of CL 0030+2618, the location of the stellar main sequence for this field is determined up to a shift along the main diagonal of the $g' - r'$ versus $r' - i'$ diagram, corresponding to the $r'$ zeropoint. We fix this parameter by shifting the main sequence of CL.0030+2618 on top of the other observed main sequences as well as the Pickles (1998) sequence. We go in steps of 0.05 magnitudes, assuming this to be the highest achievable accuracy when adopting this rather qualitative method, and settle for the best-fit test value (see Table 4.2). The dots in Fig. 5.5 show the closest match with the CL.0159+0030 and CL.0809+2811 stellar colours obtained by the indirect calibration of the CL.0030+2618 $r'$-band.

After the photometric calibration, we became aware of a field observed in the SEGUE project (Newberg & Sloan Digital Sky Survey Collaboration 2003) using the SDSS telescope and filter system that became publicly available with the Sixth Data Release of SDSS (Adelman-McCarthy et al. 2008) and has partial overlaps with the CL.0030+2618 MEGACAM observations. Thus, we are able to directly validate the indirect calibration by comparing the colours of stars in the overlapping region. The right panel of Fig. 5.5 shows the good agreement between the two independent photometric measurements and the Pickles (1998) templates from which we conclude that our calibration holds to a high accuracy.

For comparison we also calibrated the $r'$-band of CL.0030+2618 by comparing its source counts to those in the CL.0159+0030 and CL.0809+2811 fields for the same filter, but discard this
Figure 5.5: Indirect photometric calibration by stellar colours: **Left panel:** plotted here are the \( g' - r' \) vs. \( r' - i' \) colours of sources identified as stars in three galaxy cluster fields observed with MEGACAM. For two of these fields, CL 0159+0030 (upward triangles) and CL 0809+2811 (downward triangles), absolute photometric calibration with SDSS standards could be performed. For CL 0030+2618, \( r' \)-band magnitudes based on the indirect calibration are shown (dots; details see main text). The colours in all three fields agree with the colours of main sequence stars from the Pickles (1998) spectral library (diamonds).

**Right panel:** The \( g' - r' \) vs. \( r' - i' \) colours of stars in the MEGACAM images of CL 0030+2618 (dots) which could also be identified in the partially overlapping SEGUE strip (Newberg & Sloan Digital Sky Survey Collaboration 2003) and shown here as squares are both consistent with each other as well as with the Pickles (1998) colours (diamonds). Each pair of measurements of one individual source is connected with a line.

Indirect photometric calibration as we find a discrepancy of the resulting main sequence in \( g' - r' \) versus \( r' - i' \) with the theoretical Pickles (1998) models mentioned earlier.

### 5.2.4 Indirect Photometric Calibration of CL 0230+1836

Based on the experiences with the CL 0030+2618 \( r' \)-band, we perform the photometric calibration of CL 0230+1836, for which both the \( r' \)- and the \( g' \)-band were observed in non-photometric conditions, and no SDSS data of the field are available. Because the stellar sequence in \( g' - r' \) versus \( r' - i' \) colours consists of two "legs" joined at a distinct "knee" where its slope changes, this poses only a slightly more complicated problem. First, we fix \( Z_{g'} \) for CL 0230+1836 by shifting the corresponding sequence such that one of the two coordinates of the turning point coincides with the Pickles (1998) templates. Second, we can then determine \( Z_{r'} \) in the same way we did for
5.3. FRAME SELECTION

CHAPTER 5. DATA REDUCTION

Figure 5.6: Indirect photometric calibration by stellar colours: Same as the left panel of Fig. 5.5, but for CL 0230+1836 (blue squares).

CL 0030+2618. Figure 5.6 shows that a consistent stellar sequence with the CL 0159+0030 and CL 0809+2811 fields is also achieved for the CL 0230+1836 zeropoints.

5.3 Frame Selection

The success of a lensing analysis depends crucially on the data quality. Because we follow the usual approach in weak lensing to rebin the frames to a common image coordinate system and stack them, the stacking process is a potential source of biases to the shape information. It is evident that the decision which frames should contribute to the shape measurement is of great importance. Apart from seeing and photometric quality, which can be easily assessed while the observation takes place, PSF anisotropy is a key factor as it can only be corrected up to a certain degree.

5.3.1 Measuring the PSF Anisotropy

In the following, we describe how star catalogues that allow us to investigate the PSF anisotropy are created from the individual exposures. To this end, we apply modified versions of the catalogue creation routines in our KSB pipeline we describe in Sect. 5.4.
Figure 5.7: The distribution of sources in apparent size – magnitude – space in the eight MEGACAM 400d cluster fields. Plotted are SExtractor magnitudes $r'_{\text{AUTO}}$ against half-light radii $\theta$ of all sources in the respective KSB catalogues. The stellar loci are prominent. We categorise as stars all sources within the light-grey shaded areas defined by $\theta^*_{\text{min}} < \theta < \theta^*_{\text{max}}$ and $r^*_{\text{min}} < r'_{\text{AUTO}} < r^*_{\text{max}}$. All sources to the right and lower sides of the thick grey lines, i.e. those with $\theta > \theta^*_{\text{max}}$ for $r^*_{\text{min}} < r'_{\text{AUTO}} < r^*_{\text{max}}$ and $\theta > \theta^*_{\text{ana}}$ for $r'_{\text{AUTO}} > r^*_{\text{max}}$ are categorised as unsaturated galaxies. The values of $\theta^*_{\text{min}}, \theta^*_{\text{max}}, r^*_{\text{min}},$ and $r^*_{\text{max}}$ for the individual fields are listed in Table 5.3.
Using the background-subtracted exposures produced by THELI directly before the coaddition as input to SExtractor and the corresponding weight files as noise maps, we draw a catalogue of detected sources for each chip in all frames having passed the seeing and relative zero-point selection criteria. In the source detection, our default criteria DETECT_MINAREA = 4 and DETECT_THRESH = 1.5 are applied. Next, extended sources exceeding a flux radius of \( r_{\text{g}} = 10 \) px and sources that are flagged by SExtractor are removed from the catalogue because the shape measurement does not work reliably in these cases. The main reasons for a source getting flagged are blending with another detection and missing data points, e.g., near the image borders.

For the sources in the resulting “pre-KSB” catalogue, we determine the second-order brightness moments \( Q_{ij} \), defined in Eq. (3.18), within an aperture with radius \( \ell_{\text{SIL}} \times r_{\text{g}} \) and using a Gaussian window function \( W_{G}(\theta) \) with standard deviation \( \sigma_{g} = r_{g} \). Here, we apply the default aperture radius of \( \ell_{\text{SIL}} = 3 \) flux radii. The KSB catalogue consists of all sources for which the routine \texttt{analyse1dac} (Erben et al. 2001) returns a successful shape measurement.

By analysing the distribution of the KSB catalogue sources in the space spanned by their \( r'_{\text{AUTO}} \) magnitude\(^7\) measured by SExtractor and the half-light radius \( \vartheta \) resulting from \texttt{analyse1dac}, we now select the unsaturated stars which we will use as PSF tracers. Apart from containing far fewer sources, the resulting diagrams look very similar to the \( \vartheta-r'_{\text{AUTO}} \)-distributions for the final coadded images presented in Fig. 5.7. The half-light radius of an unsaturated star observed in a CCD image does not depend on its magnitude, its brightness distribution being determined by the PSF scaled by a magnitude-dependent amplitude and the photon noise. We observe a stellar locus of small extent in \( \vartheta \), blending into the “cloud” of extended sources for faint \( r'_{\text{AUTO}} \approx 22.5 \) magnitudes, while saturated stars appear larger than the PSF\(^5\). The prominent stellar locus enables us to define a sample of stars by applying thresholds \( \vartheta_{\text{min}}^\star < \vartheta < \vartheta_{\text{max}}^\star \) and \( r'_{\text{min}}^\star < r'_{\text{AUTO}} < r'_{\text{max}}^\star \) defined for the individual frame (by concatenating the catalogues of all 36 chips). Affected by neither intrinsic ellipticity nor lensing shear, the stars as tracers of the PSF play an eminent role in the KSB algorithm (Sect. 5.4).

Thus having defined a sample of 500–1000 sources probing the PSF at different positions of the MEGACAM array, we repeat the shape measurement for these stars, now with a Gaussian window function of \( \sigma_{g} = 2.6 \) px, i.e. similar to the half-light radius \( \vartheta \) of a star observed with MEGACAM under typical seeing conditions. Calculating the ellipticity components \( e_{1,2} := \chi_{1,2} \) of each star by applying Eq. (3.19), we obtain a list of PSF anisotropy measurements for each exposure.

### 5.3.2 Selection for the 400d Cluster Fields

Although, generally, the MEGACAM PSF is quite isotropic such that isophotes of stars can to a good degree be considered as circles, there are some frames in our data set that show a highly anisotropic PSF. These images appear in all runs and filters and have not necessarily been taken in the poorest seeing conditions. Figure 5.8 shows the spatial distribution of the anisotropy in stellar images for a typical frame with high (top panel) and low (bottom panel) average PSF anisotropy \(| \langle e \rangle | \), both of them \( r'\)-band observations of CL 0030+2618. In contrast to other telescope–camera systems, there is no stable pattern of low and high anisotropy as a function of position in the focal plane of MEGACAM, but the place where the most circular PSF is found can change significantly in a short

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\(^7\)The index “AUTO” refers to the default aperture applied by SExtractor, for which an elliptical aperture is fitted to the source brightness distribution. To measure colours, we use the preferred isophotal “ISO” apertures instead – including all pixels within a given isophote – but find the differences between both to be usually small.

\(^5\)Note that saturated stars are absent from Fig. 5.7 because they are masked out during the “coaddition post production” stage (Sect. 5.1.3).
Figure 5.8: Spatial distribution of stellar anisotropies for an example exposure of high overall PSF anisotropy. Shown are the magnitudes and orientations of the raw ellipticity $e$ for stars identified in the MMT/Megacam exposures of CL 0030+2618 labelled $\Theta 936$ (upper panel) and $\Theta 952$ (lower panel) in Fig. 5.9. While within each chip the $x$ and $y$ axes are to scale, the array layout is only schematic. Note that, due to the 2×2-binning (Sect. 4.2.3), each chip has 1024×2304 image pixels.
Figure 5.9: Anisotropy of stellar images in the MEGACAM cluster fields. Shown are the average ellipticity components $\langle e_1^* \rangle$ and $\langle e_2^* \rangle$ in the frames considered suitable for coaddition after the data reduction has otherwise been completed. Each symbol corresponds to a $r'$-band frame observed in the CL 0030+2618, CL 0159+0030, CL 0230+1836, or CL 0809+2811 fields (four panels from top left to bottom right). Frames marked with filled symbols contribute to the final stacked image while open symbols denote frames that were rejected for their highly anisotropic PSFs. The positions of a few extreme outliers far outside the plotting range are indicated by arrows. Special plotting symbols highlight the two cases shown in Fig. 5.8. As a visual aid, dotted circles indicate average anisotropies of $|\langle e \rangle| = 0.05$ and $|\langle e \rangle| = 0.10$. 
Figure 5.10: Anisotropy of stellar images in the Megacam cluster fields. The same as Fig. 5.9, but for the CL 1357+6232, CL 1416+4446, CL 1641+4001, and CL 1701+6414 fields.

Most likely, the cases of an anisotropic PSF in the whole field-of-view can be attributed to problems with either the tracking or the focusing of the telescope.

As we elaborate in Sect. 5.4.1, the KSB algorithm needs to correct for PSF anisotropy which mimics and superposes the shear signal. This correction performs best in terms of recovered shear if the PSF is close to circular in the first place. Consequently, because the PSF anisotropy in every individual frame propagates into the stacked image via resampling with SWarp, we reject the frames showing the largest $|\langle e \rangle|$ from the coaddition.

We show the average anisotropies $|\langle e \rangle|$ for the lensing band frames of all eight clusters, which we otherwise consider usable for coaddition, in Figs. 5.9 and 5.10. Each plotting symbol denotes a 300 s $r'$-band exposure where filled symbols mark frames used in the final coaddition and open

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9Dietrich et al. (2009) show a corresponding diagram for WFI for which the largest anisotropies were consistently observed at the same edge of the array with a given setup. Gavazzi & Soucail (2007) present very similar stellar anisotropy patterns for the four CHFTLS Deep fields.
symbols stand for rejected frames. The frames with the most anisotropic PSFs, far outside the plotting range, are indicated by arrows. In all cases, we include frames with average anisotropies \(|\langle e \rangle\) \leq 0.05 and always exclude exposures with \(|\langle e \rangle| > 0.10\) (inner and outer circles in Figs. 5.9 and 5.10). We note that only for CL 1641+4001, all analysed \(r^\prime\)-frames fulfill \(|\langle e \rangle| \leq 0.05\). Concerning the intermediately anisotropic (0.05 < \(|\langle e \rangle| \leq 0.10\) PSFs, our approach depends on their distributions in the \((e_1) - (e_2)\)-plane and the number of available frames with \(|\langle e |\) \leq 0.05.

If there is almost no (CL 1357+6232) or a significant gap (CL 0809+2811) in the \(|\langle e \rangle|\)-distribution around 0.05, the decision is relatively easy. For CL 0030+2618, with a large total number of frames, exposures in the 0.05 < \(|\langle e \rangle| < 0.06\) interval were included in a case-to-case decision based on the inspection of diagrams analogous to Fig. 5.8. We then included frames in which a place in the focal area exists where the PSF is almost circular, i.e. the “tracking error-like” anisotropy does not dominate. We conclude that a more quantitative selection scheme would be desirable in terms of consistency, but we stress that our frame selection is motivated by the few available data with both good seeing and small PSF anisotropy.

## 5.4 KSB Analysis

The shape measurement analysis (cf. Sect. 3.2) we apply is based on the Kaiser et al. (1995, KSB) algorithm, following the ideas introduced in Erben et al. (2001). Our reduction pipeline was adapted from the “TS” implementation presented in Heymans et al. (2006) and explored in Schrabback et al. (2007) and Hartlap et al. (2009).

### 5.4.1 The KSB Algorithm

The KSB algorithm confronts the problem of reconstructing the shear signal from measured galactic ellipticities by separating the reduced shear \(g\) from both the intrinsic ellipticities of the galaxies and PSF effects. The effects of shear dilution by the PSF and the convolution of the intrinsic ellipticity of the detected galaxies with the anisotropic PSF component can be isolated by measuring the PSF from the stars, as already mentioned.

Under realistic circumstances, measuring the second-order brightness moments \(Q\) (Eq. 3.18) from discretised images, applying a filter function \(W(\theta)\) that explicitly depends on pixel position, the relations Eq. (3.21) break down in the sense that the transformation \(Q(s) \rightarrow Q\) between unlensed and lensed moments can in general no longer be written as a matrix multiplication. For small reduced shears \(g\) and PSF anisotropies \(q\), however, their effects can be assumed to be linear. Hence, the observed ellipticity \(e\) of a lensed image and its intrinsic ellipticity \(e^{(s)}\) are related by:

\[
e_{\beta} = e_{\beta}^{(s)} + P_{\beta \alpha} g_\alpha + P_{\beta \alpha}^{sm} q_\alpha^* .
\]

(5.4)

Here, small Greek indices denote either of the two components of the complex ellipticity, and the Einstein summation convention has been applied. The 2 \(\times\) 2 matrices \(P^{s}\) and \(P^{sm}\), termed pre-seeing shear polarisability and smear polarisability, provide the transformation of ellipticities under the influences of gravitational shear fields and an (anisotropic) PSF, respectively. Again, asterisks denote quantities measured from stellar sources.

The shear measurement algorithm devised by Kaiser et al. (1995) inverts the relation Eq. 5.4 and infers a direct shear estimator \(e\) from the measured ellipticity \(e_{\beta}\) of each galaxy:

\[
e_{\alpha} = (P^{s})^{-1} e_{\alpha}^{sm} = (P^{s})^{-1} \left[ e_{\beta} - P_{\beta \gamma}^{sm} q_{\gamma}^* \right] ,
\]

(5.5)

where \(e_{\alpha}^{sm} = e_{\alpha} - P_{\alpha \gamma}^{sm} q_{\gamma}^*\) is the anisotropy-corrected ellipticity of a measured source. Deriving Eq. (5.5), we employed the usual assumption for weak lensing that intrinsic source ellipticities

60
cancel out when averaging over a sufficiently large ensemble: \( \langle e(s) \rangle = 0 \). Hence, the respective term drops out in Eq. (5.5) such that averaging over \( e \) directly yields the reduced shear \( g \) and, assuming a convergence \( \kappa \ll 1 \), the shear \( \gamma \):

\[
(\epsilon) = g \approx \gamma .
\] (5.6)

The next step is to insert the observed PSF anisotropy, which can be expressed as \( q_T = (\mathcal{P}_{\text{psm}})^{-1} e_\delta \) using the observed stellar ellipticities \( e_\delta \) and applying Eq. (5.4) for \( g = 0 \) and \( e_\delta^{(s)} = 0 \). Thus we arrive at the complete correction, which provides an estimate of the (reduced) shear \( g \) exerted on a galaxy in our catalogue:

\[
e_a = (\mathcal{P}_g)^{-1}_{\alpha\beta} \left[ e_\beta - \mathcal{P}_{\text{psm}} (\mathcal{P}_{\text{psm}})^{-1} e_\delta \right] .
\] (5.7)

Our description so far leaves open how the polarisability matrices are computed. We remark that because in reality, the isotropic part of the PSF can never be avoided for a sheared image, \( \mathcal{P}_g \) itself is not a “fundamental” quantity, but is expressed internally as

\[
\mathcal{P}_{\text{psm}} = \mathcal{P}_{\text{sh}} - \mathcal{P}_{\text{psm}} \mathcal{P}_{\text{sh}} (\mathcal{P}_{\text{psm}})^{-1} .
\] (5.8)

For the details of the involved calculation of the shear polarisability tensor \( \mathcal{P}_{\text{sh}} \) and \( \mathcal{P}_{\text{psm}} \) from fourth-order brightness moments, we refer to Bartelmann & Schneider (2001).

To reduce uncertainties arising from division by a very noisy measured tensor in Eq. (5.8), we approximate the term in brackets by a smoothly varying quantity. Furthermore, we reduce the noise for small galaxies by approximating \( \mathcal{P}_g \) by half its trace for the division in Eq. (5.7), noticing its off-diagonal elements to be small compared to the diagonal elements (Heymans et al. 2006):

\[
(\mathcal{P}_{\text{psm}})^{-1} \mathcal{P}_{\text{sh}} \equiv \frac{\text{tr}(\mathcal{P}_{\text{sh}})}{\text{tr}(\mathcal{P}_{\text{psm}})} \delta_{ea} =: T^* \delta_{ea} ,
\] (5.9)

where \( \delta_{ea} \) denotes the Kronecker symbol. Thus, our pipeline evaluates for each galaxy:

\[
e_a = \frac{2\delta_{ab}}{\text{tr}(\mathcal{P}_{\text{sh}} - T^* \mathcal{P}_{\text{sh}} \delta_{ea})} \left[ e_\beta - \mathcal{P}_{\text{psm}} q_T^{*} \right] .
\] (5.10)

which contains no more matrix inversions. The quantity \( T^* \) and the anisotropy kernel \( q_T^{*} \) are determined as functions of the image coordinates \( x \) and \( y \) by fitting polynomial functions to the values measured from stars. For \( T^*(x, y) \), we generally use a quadratic function; the highest degree \( d_{\text{ani}} \) for fitting \( q_T^*(x, y) \) is adjusted to the amount of anisotropy in the respective image (Sect. 5.4.4). Based on an observation by Hoekstra et al. (1998) that these quantities depend on the angular extent \( \theta_g \) of the source, the “TS” implementation performs these fits for several Gaussian smoothing scales \( \sigma_g \) and chooses \( q_T^*(x, y) \) and \( T^*(x, y) \) from the appropriate bin in \( \sigma_g \). Before we now proceed to outline the practical implementation of the pipeline, along the lines of Erben et al. (2001), we discuss the performance of our method in the context of the state-of-the-art of shape measurement.

### 5.4.2 Measuring Shear from Cluster Lenses

Shear measurement remains the pivotal problem in weak lensing and an active field of research. The “TS” shear measurement pipeline we use, based on the original KSB (Kaiser et al. 1995) algorithm and improvements by Erben et al. (2001) was subject to extensive tests based on mock images realistically simulating ground-based cosmic shear surveys as part of the Shear Testing Programme (STEP, Heymans et al. 2006; Massey et al. 2007). A shear calibration factor, discussed in greater detail in Sect. 6.1.4), was introduced based on the results of Heymans et al. (2006).
There are different families of shape measurement algorithms which are presented by Massey et al. (2007) and Bridle et al. (2010). Following the Massey et al. (2007) classification, methods are sorted based on whether they correct for the PSF by subtraction or deconvolution and whether they reconstruct the sheared image “passively” from basic components or by “actively” shearing a basic image. The “TS” pipeline, amongst other KSB implementations, is listed as a passive method and as a subtraction method by Massey et al. (2007).

Shear measurement techniques based on fitting a set of suited basis function to the sheared galaxy image, e.g. shapelets based on Hermite polynomials (e.g., Bernstein & Jarvis 2002; Refregier 2003; Refregier & Bacon 2003) address the problem from a different perspective. Recent results (Melchior et al. 2010; Voigt & Bridle 2010), however, show the fundamental limitations of the shapelet approach in WL. Finding the best-fit representation for the brightness distribution of each galaxy from a set of basic brightness distributions by Bayesian inference, the Lensfit method (Miller et al. 2007; Kitching et al. 2008) deserves particular mentioning. In the context of cluster WL, it has successfully been applied in a regime of high stellar anisotropy (Dietrich et al. 2009).

Evolving out of the STEP project, in the GREAT08 challenge (Bridle et al. 2010), shear measurement techniques were tested and compared on improved simulations, aiming at the higher accuracy needed for future space-based cosmic shear surveys. In the publicly announced project, a wider community participated, introducing successful new algorithms, e.g. those stacking galaxy images before the actual shear measurement. Rowe (2010) revisits the problem of PSF modelling for weak lensing and deals with spatial variation of the PSF.

Up to now, no dedicated comparison of shear measurement techniques has been performed that specially addresses their relative performance in a cluster WL situation where, on average and especially in the cluster centres, the shear is higher than the largest input shear \( \gamma = 0.1 \) used in STEP or GREAT08. Methods involving stacking of galaxies before shear measurement are likely less useful in cluster lensing. We point out that performing detailed simulations of cluster lenses and improving shear measurement methods using these remain worthwhile tasks for the study of galaxy clusters. In the meantime, KSB offers a relatively well-known WL technique for clusters.

An important difference in WL pipelines is whether and how they apply weighting of shear estimates (see Table 4 of Massey et al. 2007). In the “TS” implementation we use, each galaxy is weighted equally.\(^\text{10}\) Weighting of galaxies takes into account the different quality of shear estimates based on the signal-to-noise ratio of the galaxy from which the shear is measured, the error in the shear estimator itself, or variations in the intrinsic ellipticities for galaxies of different magnitude and size \( \vartheta \) in the image. Hoekstra et al. (2000) devised a widely used weighting technique based on an estimate of the error in the KSB algorithm. Clowe et al. (2006b), in their study of clusters from the ESO Distant Cluster Survey use a weighting scheme built on the detection significances of the source galaxies. Erben et al. (2001) introduced the weighting factor

\[
    w_i = \left( \sigma_{e,NN}^2 + \sigma^2 \right)^{-1},
\]

where \( \sigma_{e,NN}^2 \) denotes the variance of the shear estimated for the \( N = 12 \) nearest neighbours in half-light radius–magnitude space and \( \sigma^2 \) the variance of ellipticities in the whole sample. The underlying idea is that Eq. 5.11 provides a weight to the \( i \)-th galaxy by comparing its intrinsic ellipticity to that of the total (unlensed) galaxy population. Hetterscheidt et al. (2007) found the weighting (Eq. 5.11) to provide an effectively similar weighting as the Hoekstra et al. (2000) scheme. We plan to introduce the Erben et al. (2001) weighting into our lensing analysis as a future improvement.\(^\text{11}\)

\(^\text{10}\)We note that Table A1 of Heymans et al. (2006) lists a weighting scheme based on Erben et al. (2001) for the “TS” pipeline. The version used for our analyses, however, derives from the Massey et al. (2007) variant which doesn’t include weighting.

\(^\text{11}\)A test of the weighting (Eq. 5.11) gave inconclusive results in a very early version of our CL.0030+2618 analysis.
5.4.3 The KSB Catalogue and Galaxy Shape Catalogue

In the following, we describe how shear estimates are distilled from input images. An outline of the initial KSB pipeline routines was already given in Sect. 5.3.1, such that we now focus on the features that are different in the main pipeline. For the clusters that were observed in three bands, catalogues are created from the images using the SExtractor double detection mode in which sources are identified in the lensing band image at its original seeing. Photometric quantities (fluxes, magnitudes) are determined at these coordinates from the measurement images in the three bands $g'r'i'$ convolved to the poorest seeing (cf. Table 4.2). This common procedure ensures that the aperture has the same size compared to the PSF in all filters and thus meaningful colour.
Table 5.3: Parameters defining the galaxy shape catalogues. It is $N_{\text{KSB}}$ the number of sources in the KSB catalogue, while the galaxy shape catalogue counts $N_{\text{gal}}$ sources and a number density of $n_{\text{gal}}$. The parameters $\theta^*_\text{min}$, $\theta^*_\text{max}$, $r^*_\text{min}$, and $r^*_\text{max}$ delineate the stellar locus (Fig. 5.7). The galaxy shape catalogue considers sources $\theta > \theta^*_\text{max}$ for $r^*_\text{min} < r'_{\text{AUTO}} < r^*_\text{max}$ and $\theta > \theta^\text{ana}_\text{min}$ for $r'_{\text{AUTO}} \geq r^*_\text{max}$. Also given is the degree $d_{\text{ani}}$ of the polynomial for PSF anisotropy correction and the stellar integration limit $\ell_{\text{SIL}}$ in units of stellar flux radii.

<table>
<thead>
<tr>
<th>Cluster field</th>
<th>$N_{\text{KSB}}$</th>
<th>$\theta^*_\text{min}$ [px]</th>
<th>$\theta^\text{ana}_\text{min}$ [px]</th>
<th>$\theta^*_\text{max}$ [px]</th>
<th>$r^*_\text{min}$ [mag]</th>
<th>$r^*_\text{max}$ [mag]</th>
<th>$N_{\text{gal}}$</th>
<th>$n_{\text{gal}}$ [arcmin$^{-2}$]</th>
<th>$d_{\text{ani}}$</th>
<th>$\ell_{\text{SIL}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CL0030+2618</td>
<td>31173</td>
<td>2.55</td>
<td>2.80</td>
<td>2.95</td>
<td>16.75</td>
<td>22.5</td>
<td>15760</td>
<td>22.6</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>CL0159+0030</td>
<td>21541</td>
<td>2.65</td>
<td>2.95</td>
<td>3.10</td>
<td>17.5</td>
<td>22.5</td>
<td>10927</td>
<td>18.9</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>CL0230+1836</td>
<td>18714</td>
<td>2.05</td>
<td>2.33</td>
<td>2.45</td>
<td>16.75</td>
<td>22.5</td>
<td>8449</td>
<td>13.2</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>CL0809+2811</td>
<td>20889</td>
<td>2.35</td>
<td>2.66</td>
<td>2.80</td>
<td>17.0</td>
<td>22.5</td>
<td>10358</td>
<td>16.6</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>CL1357+6232</td>
<td>19186</td>
<td>2.85</td>
<td>3.18</td>
<td>3.35</td>
<td>17.5</td>
<td>22.25</td>
<td>9253</td>
<td>14.2</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>CL1416+4446</td>
<td>29375</td>
<td>2.55</td>
<td>2.80</td>
<td>2.95</td>
<td>16.75</td>
<td>22.5</td>
<td>14865</td>
<td>21.0</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>CL1641+4001</td>
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<td>3.135</td>
<td>3.30</td>
<td>16.75</td>
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<td>12569</td>
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<td>3</td>
<td>3</td>
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<td>2.95</td>
<td>3.10</td>
<td>16.75</td>
<td>22.5</td>
<td>14102</td>
<td>20.7</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

indices can be measured. Here, we also apply the flag images created for the coadded images (Sect. 5.1.3) to SExtractor. Sources centred within a flagged region are treated similar to those with missing data and cut from the catalogue together with the blended sources (Sect. 5.3.1).

The photometric properties determined from the three bands are merged into one catalogue that is primarily based on the detection image. For consistency, the double detection mode is also used for the clusters where only $r'$-band images exist. The detection image is then identical to the measurement image.

From the resulting “SExtractor” catalogues, problematic sources are removed. Figure 5.11 illustrates how the cuts (cf. Sect. 5.3.1) work that result in the “pre-KSB” catalogue of sources for which shape measurement is attempted. Objects marked with only one ring in Fig. 5.11 are affected by the cuts on $\theta^*_\text{d} < 10$ px and flagged objects. We note that prominent cluster galaxies, e.g. the BCG of CL 1416+4446 to the right and below the centre of Fig. 5.11, typically consist of several blended SExtractor peaks and also are extended objects (i.e. larger than 10 px).

We note that the KSB catalogue presented in Fig. 5.7 and all catalogues discussed here-after only contain objects for which a half-light radius $\theta$ could be successfully determined by analyselflac. Objects for which the measurements in the (noisy) data yield negative fluxes, semi-major axes, or second-order brightness moments, or which lie close to the image border are removed from the catalogue, reducing its size by a few percent. This can also be seen from Fig. 5.11 where the vast majority of sources that pass the first filter are present in the KSB catalogue (marked by three rings).

Figure 5.7 shows the distribution of these sources in the apparent radius – magnitude space. The prominent stellar locus enables us to define a sample of stars by applying the thresholds $\theta^*_\text{min} < \theta < \theta^*_\text{max}$ and $r^*_\text{min} < r'_{\text{AUTO}} < r^*_\text{max}$ (the shaded areas in Fig. 5.7) from which the PSF anisotropy $e^\prime_\delta$ in Eq. (5.7) is determined.

In creating the galaxy shape catalogue, we regard as unsaturated galaxies all objects $r'_{\text{AUTO}} > r^*_\text{max}$ (i.e., fainter than the brightest unsaturated point sources) and more extended than $\theta > \theta^*_\text{max}$ for $r'_{\text{AUTO}} < r^*_\text{max}$ and $\theta > \theta^\text{ana}_\text{min}$ for $r'_{\text{AUTO}} \geq r^*_\text{max}$, respectively. The latter is justifiable because although for bright sources it is easy to distinguish galaxies from point sources, there is a significant population
of faint galaxies for which a very small radius is measured by the SExtractor algorithm. Thus, we relax the radius criterion by 5% for sources fainter than \( r^{*\text{max}} \).

However, among those small objects there is a population of faint stars that can not be distinguished from poorly resolved galaxies using an apparent size – magnitude diagram alone that cause a dilution of the lensing signal relative to a perfect star – galaxy distinction. Our decision to nevertheless include these small sources in our catalogue is based on the resulting higher cluster weak lensing signal compared to that produced by a more conservative criterion (e.g., \( \theta / \theta^{\text{max}} \geq 1.10 \) for the galaxies fainter than \( r^{*\text{max}} \)). We call “galaxy shape catalogue” the list of objects that pass both this galaxy selection and the cuts for signal quality discussed in Sect. 6.1.4. This important catalogue yields the final “lensing catalogue” by means of the background selection discussed in Sect. 6.1.1. Applying these cuts, the source numbers in the galaxy shape catalogues for our eight cluster fields correspond to galaxy densities of 13–23 galaxies/arcmin\(^2\) (Table 5.3). The drastic reduction in source counts compared to the KSB catalogue (usually by \( \sim 50\% \)) can be attributed mainly to the small and faint objects whose nature cannot be determined from the \( \theta - r^{*\text{AUTO}} \)-plots.

### 5.4.4 The PSF Properties of MMT/Megacam

As mentioned in Sect. 5.4.1, the PSF anisotropy kernel \( q_\gamma = (F^{\text{ani}})^{-1} e_\gamma^* \) in Eq. (5.10) is determined by a polynomial fit. This is practically equivalent to fitting a model \( e^{\text{cor}} = \sum_k \sum_\ell p_{k\ell} x^k y^\ell \) with \( 0 \leq k \leq d_{\text{ani}} \) and \( 0 \leq \ell \leq d_{\text{ani}} - k \), defined globally over the entire field-of-view. The best-fit solution in the case \( d_{\text{ani}} = 5 \) we adopt here is shown in the middle panels of Fig. 5.12, while the residual ellipticities of the stars \( e^{\text{ani}} \) are displayed in the panels to the right. We chose the aperture stellar integration radius \( \ell_{\text{SIL}} \) (measured in units of \( \theta_g \)) such that the PSF is sufficiently covered out to its wings, i.e. increasing \( \ell_{\text{SIL}} \) does not result in a larger measured \( e_\gamma^* \).

We aim to reduce both the mean \( \langle e^{\text{ani}}_\gamma \rangle \) of the residual ellipticities and their dispersions. \( \sigma(e^{\text{ani}}_\gamma) \). We find that a polynomial order as high as \( d_{\text{ani}} = 5 \) is necessary to effectively correct for the distinctive quadrupolar pattern in the spatial distribution of the “raw” stellar ellipticities (see lower left and middle panels of Fig. 5.12). There is no obvious relation between the zones of preferred orientation of the PSF ellipticity in Fig. 5.12 and the \( 4 \times 9 \) chip detector layout of Megacam. Some of the PSF ellipticity patterns are qualitatively similar to the one found for CL 0030+2618, whereas others show the same preferred orientation of the PSF ellipticity over the whole area. Two of these cases are presented in Fig. 5.13, for a field with large PSF anisotropy (CL 1357+6232) and with low PSF anisotropy (CL 1641+4001), respectively. The corresponding plots for the remaining clusters are shown in Figs. B.1 to B.5 in Appendix B.1. Table 5.3 lists the values of \( d_{\text{ani}} \) and \( \ell_{\text{SIL}} \) adopted in these cases. Comparing the anisotropy patterns in all eight cluster fields, we conclude that these patterns are variable and not congruent with the chip boundaries. Although Fig. 5.13 demonstrates that the residuals of anisotropy correction increase with higher initial anisotropy, this anisotropy is still removed effectively in the most extreme case of CL 1416+4446. In the following discussion, we will focus on CL 0030+2618, a more typical case in terms of initial PSF anisotropy.

By stacking images in which the PSF anisotropy is different in magnitude and orientation (cf. Figs. 5.8 to 5.10), we already reduce the ellipticity caused by the imaging system before any correction is applied. The total amount of PSF anisotropy present in our Megacam coadded images is small. Before correction, we measure \( \langle e_1 \rangle = 1.77 \times 10^{-5}, \langle e_2 \rangle = -4.03 \times 10^{-3}, \sigma(e_1) = \).
5.4. KSB ANALYSIS

CHAPTER 5. DATA REDUCTION

Figure 5.12: Correction of PSF anisotropy of the CL0030+2618 $r'$ band used in the analysis. The upper panel shows the distribution of the ellipticity components $e_{1,2}$ of the stars identified in the field, and the numerical values of their dispersions $\sigma_{1,2} := \sigma(e_{1,2})$. The “whisker plots” in the lower panel show how the size and orientation of PSF anisotropy vary as a function of the spatial coordinates $x$ and $y$. On the left, the situation before correction, i.e., the ellipticities as measured in the stars are depicted. The middle two plots give the fit by a global fifth order polynomial in $x$ and $y$. Residuals after this correction is applied are presented in the plots on the right.

$6.15 \times 10^{-3}$, $\sigma(e_2) = 1.03 \times 10^{-2}$, and $\sigma(|e|) = 6.19 \times 10^{-3}$, which decrease after the correction to $\langle e_{\text{ani}}^1 \rangle = -5.60 \times 10^{-7}$, $\langle e_{\text{ani}}^2 \rangle = -2.60 \times 10^{-5}$, $\sigma(e_{\text{ani}}^1) = 3.87 \times 10^{-3}$, $\sigma(e_{\text{ani}}^2) = 3.49 \times 10^{-3}$, and $\sigma(|e_{\text{ani}}|) = 2.90 \times 10^{-3}$, respectively. We note that the very small average for the individual components before correction is caused by the partial cancellation of anisotropies from different parts of the field-of-view. Thus, MMT/MEGACAM shows a similar degree of PSF anisotropy as other instruments from which lensing signals were measured successfully, e.g., MEGAPRIME/MEGACAM on CFHT (Sembolini et al. 2006) or Subaru’s SUPREME-CAM (Okabe & Umetsu 2008). The latter authors measured larger values for the anisotropy components before correction: $\langle e_1 \rangle = 1.41 \times 10^{-2}$, $\langle e_2 \rangle = 1.63 \times 10^{-2}$, and $\sigma(|e|) = 2.32 \times 10^{-2}$, as an RMS average of seven galaxy cluster fields. However, Okabe & Umetsu (2008) find a simple spatial pattern for SUPREME-CAM.

We further assess the performance of the correction polynomial by analysing the anisotropy-corrected ellipticities $e_{\text{gal},d}^\text{ani,cor}$ of galaxies as a function of the amount of correction $e_{\text{cor}}$ applied to them by the polynomial fit. Theoretically, the expected positive correlation between the uncorrected ellipticities and the correcting polynomial should be removed and $e_{\text{gal}}(e_{\text{cor}})$ thus have a scatter
Figure 5.13: Same as Fig. 5.12, but for the $r'$-bands of CL 1416+4446 (upper plot) and CL 1641+4001 (lower plots). These fields show the correction for a high (CL 1416+4446) and low (CL 1641+4001) level of initial PSF anisotropy.
5.4. KSB ANALYSIS

Figure 5.14: The effect of the polynomial correction for the PSF anisotropy on the ellipticities of galaxies averaged in equally populated bins. As a function of the amount of correction $e^{\text{cor}}$ applied to the components $\delta = 1$ (left panels) and $\delta = 2$ (right panels), we show the raw ellipticities before correction in the upper panels and the PSF-corrected ellipticities $\varepsilon$ in the lower panels. The bars in the abscissa and ordinate denote the range of the bin and the standard deviation in the ellipticity in this bin, respectively. The plot shows the CL0030+2618 field.

around zero. We note that most of the anisotropy is present in the $\delta = 2$ component from the beginning (Fig. 5.14). This is removed in the corrected ellipticities, with $\langle e^{\text{ani}}_{\text{gal},2} \rangle = -0.0010 \pm 0.0010$ being marginally consistent with zero in the standard deviation. In the $\delta = 1$ component, we measure a residual anisotropy of $\langle e^{\text{ani}}_{\text{gal},1} \rangle = -0.0026 \pm 0.0010$, which is one order of magnitude smaller than the lensing signal we are about to measure.

As an alternative to the $n=5$ polynomial correction to the entire image, we consider a piecewise solution based on the pattern of preferred orientation in Fig. 5.12. Dividing the field into four regions at $y = 6100$ px and at $x = 4300$ px for $y < 6100$ px and $x = 5800$ px for $y > 6100$ px with a polynomial degree up to $n = 5$ we do not find a significant improvement in $\langle e^{\text{ani},\ast} \rangle$, $\sigma(e^{\text{ani},\ast})$, or $e^{\text{ani}}_{\text{gal}}(e^{\text{cor}})$ over the simpler model defined over the whole field.

We conclude that, although we find small-scale changes in the PSF ellipticity that have to be modelled by a polynomial of relatively high order, the more important point is that the PSF anisotropy varies smoothly as a function of the position on the detector surface in every individual exposure, showing a simpler pattern than Fig. 5.12. Consequently, it can be modelled by a smooth function, which is a necessary prerequisite for using the instrument with the current weak lensing analysis pipelines. Thus, we have shown that weak lensing work is feasible using MMT MEGACAM.

68