The Cosmic Large-Scale Structure in X-rays (CLASSIX) Cluster Survey

IV. Superclusters in the local Universe at $z \leq 0.03^*$

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ABSTRACT

It is important to map the large-scale matter distribution in the local Universe for cosmological studies, such as the tracing of the large-scale peculiar velocity flow, the characterisation of the environment for different astronomical objects, and for precision measurements of cosmological parameters. We used X-ray luminous clusters to map this matter distribution and find that about 51% of the groups and clusters are members of superclusters which occupy only a few percent of the volume. In this paper we provide a detailed description of these large-scale structures. With a friends-to-friends algorithm, we find eight superclusters with a cluster overdensity ratio of at least two with five or more galaxy group and cluster members in the cosmic volume out to $z = 0.03$. The four most prominent ones are the Perseus-Pisces, the Centaurus, the Coma, and the Hercules supercluster, with lengths from about 40 to over 100 Mpc and estimated masses of $0.6-2.2 \times 10^{16} M_{\odot}$. The largest of these structures is the Perseus-Pisces supercluster. The four smaller superclusters include the Local and the Abell 400 supercluster and two superclusters in the constellations Sagittarius and Lacerta. We provide detailed maps, member catalogues, and physical descriptions of the eight superclusters. By constructing superclusters with a range of cluster sub-samples with different lower X-ray luminosity limits, we show that the main structures are always reliably recovered.

Key words. galaxies: clusters: general – cosmology: observations – large-scale structure of Universe – X-rays: galaxies: clusters

1. Introduction

Galaxy clusters are good tracers of the large-scale matter distribution in the Universe (e.g., Bardeen et al. 1986; Kaiser 1986; Böhringer et al. 2020). The most frequent way to characterise the large-scale structure traced by galaxy clusters is the two point correlation function or its Fourier counterpart, the power spectrum (e.g., Hauser & Peebles 1973; Bahcall & Soneira 1983). This does not capture, however, larger non-linear structures in the cluster distribution called superclusters. Such structures have become interesting astrophysical study objects and they can also be used to test cosmological and structure formation models (e.g., Basilakos et al. 2001; Einasto et al. 2021).

Superclusters were detected and characterised as soon as large galaxy and photographic surveys such as the Shapley-Ames survey of bright galaxies and the National Geographic-Palomar Observatory Sky Survey became available (e.g., Shapley 1932; Abell 1961). Oort (1983) provided a comprehensive review of the status of supercluster research at the time. He already described the Local, the Perseus, the Coma, and the Hydra-Centaurus superclusters as the major nearby large-scale structures, together with a few smaller superclusters (at distances <50 Mpc) and the more distant Corona-Borealis Supercluster. He noted sizes of about 40 to 90 Mpc and possibly larger and points out the interesting finding by Giovanelli et al. (1983) (see also Giovanelli et al. 1986) that the filamentary structure of the Perseus supercluster is traced much sharper by early-type compared to late-type galaxies. The latter discovery shows that superclusters as a whole have their own distinct astrophysical properties. The astrophysical interest in superclusters as laboratories for the study of galaxy evolution is now well established by more detailed investigations of the galaxy population in supercluster environments (e.g., Park et al. 2007; Lietzen et al. 2012; Alpaslan et al. 2015; Einasto et al. 2020).

With the availability of redshifts for galaxy clusters more detailed supercluster studies were conducted (Bahcall & Soneira 1984; Zucca et al. 1993; Einasto et al. 1997, 2003a,b; Livio & Madsen 2012), mostly on Abell’s catalogue and its southern extension (Abell 1958; Abell et al. 1989). The superclusters were found in these studies mostly by a friends-of-friends technique. Einasto et al. (2001) also included two small samples of X-ray detected clusters. When large galaxy redshift surveys were published, superclusters were also constructed from the galaxy distribution, mainly by detecting overdense regions above a certain threshold in galaxy or luminosity density maps from the 2dFGRS (Einasto et al. 2007a,b) and the Sloan Digital Sky Survey (SDSS) (e.g., Einasto et al. 2006; Costa-Duarte et al. 2011; Luparello et al. 2011). The similarity of the structures found with clusters and with galaxies was, for example, discussed by Luparello et al. (2011). Radio observations of HI in galaxies were used to extend the optical studies of large-scale structures also into the regions of high extinction (e.g., Hauschildt 1987; Chamaraux et al. 1990; Ramatsoku et al. 2016; Kraan-Korteweg et al. 2018).

Except for Einasto et al. (2001) and the HI observations, these studies have been based on optical data. For galaxy clusters as tracer objects, X-ray detections have the advantage that the X-ray emission ensures that the systems are gravitationally bound, the X-ray luminosity is closely related to the cluster masses of $0.6-2.2 \times 10^{16} M_{\odot}$.

* Based on observations at the European Southern Observatory La Silla, Chile and the German-Spanish Observatory at Calar Alto.
mass, for example, (Pratt et al., 2009), and projection effects are minimised. In addition the heavily used galaxy cluster catalogue of Abell has no clear selection function. Therefore it is worth to make a fresh approach based on our large and highly complete sample of X-ray luminous galaxy clusters from the CLASSIX (Cosmic Large-Scale Structure in X-rays) galaxy cluster survey, which has a well defined selection function. With its flux-limit, the survey provides an X-ray luminosity-limited (and closely mass-limited) cluster sample in each redshift shell. We have shown not only with various tests applied to observations, but also with cosmological simulations, that the X-ray luminous clusters provide true probes of the large-scale matter distribution, as further described in Sect. 2.

In a series of papers we used the sample of CLASSIX galaxy clusters to explore the cosmography of the local Universe at $z \geq 0.03$. In Böhringer et al. (2020) we have shown that our cosmic neighbourhood has a lower matter density by about 15–30% out to 0.1 $\rho_{DM}$ the number of SC members and $wN_{CL}$ the weighted number of members. The SC volume is in units of 10$^{4}$ Mpc$^{-3}$, $M_{CL_{tot}}$ is the sum of the $m_{200}$ cluster masses in units of 10$^{15}$ $M_{\odot}$, $M_{est}$ is the estimated SC mass in units of 10$^{15}$ $M_{\odot}$, and the length is in units of Mpc. The cluster density, $n_{CL}$, is in units of 10$^{-6}$ Mpc$^{-3}$ and the overdensity ratios $R_{CL}$ and $R_{DM}$ are defined in the text.

Table 1. Properties of the superclusters in the local Universe at $z \geq 0.03$ constructed with a minimal linking length, $l_{0} = 19$ Mpc.

<table>
<thead>
<tr>
<th>Name</th>
<th>$N_{CL}$</th>
<th>$wN_{CL}$</th>
<th>Volume</th>
<th>$M_{CL_{tot}}$</th>
<th>$M_{est}$</th>
<th>Length</th>
<th>$\langle z \rangle$</th>
<th>$z_{min}$</th>
<th>$z_{max}$</th>
<th>$n_{CL}$</th>
<th>$R_{CL}$</th>
<th>$R_{DM}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PP</td>
<td>22</td>
<td>58.3</td>
<td>2.9</td>
<td>35.8</td>
<td>24.9</td>
<td>115.7</td>
<td>0.0205</td>
<td>0.0147</td>
<td>0.0314</td>
<td>2.0</td>
<td>2.8</td>
<td>2.1</td>
</tr>
<tr>
<td>PP$_{in}$</td>
<td>20</td>
<td>49.0</td>
<td>2.8</td>
<td>31.6</td>
<td>21.5</td>
<td>115.7</td>
<td>0.0195</td>
<td>0.0147</td>
<td>0.0300</td>
<td>1.8</td>
<td>2.4</td>
<td>1.9</td>
</tr>
<tr>
<td>A400</td>
<td>7</td>
<td>14.6</td>
<td>1.1</td>
<td>5.0</td>
<td>6.8</td>
<td>45.8</td>
<td>0.0202</td>
<td>0.0171</td>
<td>0.0243</td>
<td>1.4</td>
<td>1.9</td>
<td>1.6</td>
</tr>
<tr>
<td>Vir</td>
<td>5</td>
<td>5.0</td>
<td>0.5</td>
<td>2.4</td>
<td>2.5</td>
<td>18.4</td>
<td>0.0044</td>
<td>0.0031</td>
<td>0.0062</td>
<td>1.0</td>
<td>1.4</td>
<td>1.2</td>
</tr>
<tr>
<td>Cen</td>
<td>10</td>
<td>11.7</td>
<td>1.0</td>
<td>7.1</td>
<td>5.6</td>
<td>37.1</td>
<td>0.0131</td>
<td>0.0087</td>
<td>0.0160</td>
<td>1.2</td>
<td>1.6</td>
<td>1.4</td>
</tr>
<tr>
<td>Coma</td>
<td>13</td>
<td>37.8</td>
<td>2.3</td>
<td>18.9</td>
<td>16.8</td>
<td>78.0</td>
<td>0.0254</td>
<td>0.0202</td>
<td>0.0322</td>
<td>1.7</td>
<td>2.3</td>
<td>1.8</td>
</tr>
<tr>
<td>Coma$_{in}$</td>
<td>11</td>
<td>28.8</td>
<td>1.9</td>
<td>16.8</td>
<td>13.0</td>
<td>64.8</td>
<td>0.0242</td>
<td>0.0202</td>
<td>0.0280</td>
<td>1.5</td>
<td>2.1</td>
<td>1.7</td>
</tr>
<tr>
<td>Her</td>
<td>24</td>
<td>94.0</td>
<td>3.7</td>
<td>26.0</td>
<td>38.7</td>
<td>141.1</td>
<td>0.0297</td>
<td>0.0236</td>
<td>0.0349</td>
<td>2.6</td>
<td>3.6</td>
<td>2.6</td>
</tr>
<tr>
<td>Her$_{in}$</td>
<td>10</td>
<td>30.6</td>
<td>1.7</td>
<td>6.7</td>
<td>13.4</td>
<td>71.1</td>
<td>0.0270</td>
<td>0.0206</td>
<td>0.0297</td>
<td>1.8</td>
<td>2.5</td>
<td>1.9</td>
</tr>
<tr>
<td>Sag</td>
<td>6</td>
<td>11.4</td>
<td>0.9</td>
<td>2.7</td>
<td>5.5</td>
<td>33.8</td>
<td>0.0204</td>
<td>0.0191</td>
<td>0.0246</td>
<td>1.2</td>
<td>1.7</td>
<td>1.4</td>
</tr>
<tr>
<td>Lac</td>
<td>6</td>
<td>9.7</td>
<td>0.6</td>
<td>4.4</td>
<td>4.3</td>
<td>19.9</td>
<td>0.0178</td>
<td>0.0169</td>
<td>0.0192</td>
<td>1.7</td>
<td>2.3</td>
<td>1.8</td>
</tr>
</tbody>
</table>

Notes. The superclusters are: PP = Perseus-Pisces SC, A400 = A400 SC, Coma = Coma SC, Vir = Local SC, Cen = Centaurus SC, Her = Hercules SC, Sag = Sagittarius SC, Lac = Lacerta SC. The suffix $_{in}$ designates that part of the supercluster which lies inside $l_{0} = 0.03$, otherwise the redshift constraint was relaxed in the SC construction. $N_{CL}$ is the number of SC members and $wN_{CL}$ the weighted number of members. The SC volume is in units of 10$^{4}$ Mpc$^{-3}$, $M_{CL_{tot}}$ is the sum of the $m_{200}$ cluster masses in units of 10$^{15}$ $M_{\odot}$, $M_{est}$ is the estimated SC mass in units of 10$^{15}$ $M_{\odot}$, and the length is in units of Mpc. The cluster density, $n_{CL}$, is in units of 10$^{-6}$ Mpc$^{-3}$ and the overdensity ratios $R_{CL}$ and $R_{DM}$ are defined in the text.

Table 2. Properties of the same superclusters as shown in Table 1, but here the volume and mass estimates are based on volumes determined with a radius of 10 Mpc around each cluster.

<table>
<thead>
<tr>
<th>Name</th>
<th>Volume</th>
<th>$M_{cl}$</th>
<th>$n_{CL}$</th>
<th>$R_{CL}$</th>
<th>$R_{DM}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PP</td>
<td>0.7</td>
<td>21.5</td>
<td>8.9</td>
<td>12.4</td>
<td>8.1</td>
</tr>
<tr>
<td>PP$_{in}$</td>
<td>0.6</td>
<td>18.2</td>
<td>7.8</td>
<td>10.9</td>
<td>7.2</td>
</tr>
<tr>
<td>A400</td>
<td>0.2</td>
<td>5.5</td>
<td>6.3</td>
<td>8.8</td>
<td>5.8</td>
</tr>
<tr>
<td>Vir</td>
<td>0.1</td>
<td>1.9</td>
<td>5.3</td>
<td>7.4</td>
<td>5.0</td>
</tr>
<tr>
<td>Cen</td>
<td>0.2</td>
<td>4.5</td>
<td>4.8</td>
<td>6.7</td>
<td>4.5</td>
</tr>
<tr>
<td>Coma</td>
<td>0.5</td>
<td>14.1</td>
<td>7.2</td>
<td>12.8</td>
<td>7.1</td>
</tr>
<tr>
<td>Coma$_{in}$</td>
<td>0.4</td>
<td>10.8</td>
<td>7.1</td>
<td>9.9</td>
<td>6.6</td>
</tr>
<tr>
<td>Her</td>
<td>0.8</td>
<td>34.3</td>
<td>12.3</td>
<td>17.1</td>
<td>11.0</td>
</tr>
<tr>
<td>Her$_{in}$</td>
<td>0.4</td>
<td>11.3</td>
<td>8.4</td>
<td>11.7</td>
<td>7.7</td>
</tr>
<tr>
<td>Sag</td>
<td>0.2</td>
<td>4.3</td>
<td>5.8</td>
<td>8.1</td>
<td>5.4</td>
</tr>
<tr>
<td>Lac</td>
<td>0.1</td>
<td>3.6</td>
<td>8.0</td>
<td>11.0</td>
<td>7.3</td>
</tr>
</tbody>
</table>

Notes. For an explanation of the labels of rows and columns see Table 1.

In Sect. 3 we describe the CLASSIX galaxy cluster survey and its applications to large-scale structure studies and Sect. 3 deals with methodological aspects. The results of our analysis is presented in Sect. 4 with a detailed description of the SC. Section 5 provides a discussion and Sect. 6 the summary and conclusion. In the Appendix we provide X-ray/optical images of the members of six of the eight superclusters (the Perseus-Pisces and the A400 superclusters have already been described in detail in Böhringer et al. (2021b)). For physical properties which depend on distance we adopt the following cosmological parameters: a Hubble constant of $H_{0} = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_{m} = 0.3$, and a spatially flat metric. For the cosmographical analysis we use Supergalactic coordinates, defined by the location of the Supergalactic North Pole at $l_{0} = 47.3700^{\circ}$ and $b_{0} = 6.3200^{\circ}$, as established by De Vaucouleurs et al. in the 3rd Catalog of Bright Galaxies (1991, see also Lahav et al. 2000). X-ray luminosities are determined in the ROSAT band, 0.1–2.4 keV.

2. The CLASSIX galaxy cluster survey

The CLASSIX galaxy cluster survey, which comprises the REFLEX II survey in the southern sky (Böhringer et al., 2013) and the NORAS II survey in the northern hemisphere
The statistical properties of the cluster distribution in the ZoA is therefore somewhat qualitative. We also added three known X-ray luminous clusters in the ZoA at higher \( n_H \), also detected in the RASS.

The CLASSIX galaxy cluster survey is compiled from the X-ray detection of galaxy clusters in the ROSAT All-Sky Survey (RASS, Trümper 1993; Voges et al. 1999). The survey construction, selection function, and tests of the completeness are described in Böhringer et al. (2013, 2017). In brief, the nominal unabsorbed flux limit for the galaxy cluster detection in the RASS is \( 1.8 \times 10^{-12} \text{erg s}^{-1} \text{cm}^{-2} \) at 0.1–2.4 keV. For the present study we use a minimum source photon count limit of 20. Under these conditions the nominal flux limit quoted above is reached in about 80\% of the survey. In regions with lower exposure and higher interstellar absorption the flux limit is accordingly higher (see Fig. 11 in Böhringer et al. 2013 and Fig. 5 in Böhringer et al. 2017). This effect is well modelled and taken into account in the survey selection function. The survey selection function as a function of sky position and redshift is described in Böhringer et al. (2013) for REFLEX II and Böhringer et al. (2017) for NORAS II, where numerical data are provided in the on-line material.

In total we found 146 groups and clusters of galaxies with these selection criteria and with \( L_X \geq 10^{42} \text{erg s}^{-1} \) in the study region at \( z \leq 0.03 \), which provides us with a sufficiently high cluster density for the mapping of the large-scale structure. The average distance between clusters in this region is about 36.8 Mpc. We have shown in Böhringer et al. (2020) that the cluster density is a robust biased measure of the matter density with an accuracy corresponding roughly to the Poisson uncertainty of the cluster counting statistics. This is based on an analysis of the correlation of cluster and matter density in the Millennium Simulations (Springel et al. 2005). The bias found in this study is consistent with the theoretical predictions (e.g., Tinker et al. 2010; Balaguera-Antolínez et al. 2011).

We have used the REFLEX I (Böhringer et al. 2004) and REFLEX II surveys to study the cosmic large-scale matter distribution through, for example, the correlation function (Collins et al. 2000), the power spectrum (Schuecker et al. 2001, 2002, 2003a,b; Balaguera-Antolínez et al. 2011, 2012), Minkowski functionals, (Kerscher et al. 2001), and for the
study of superclusters (Chon & Böhringer 2013; Chon et al. 2014). We found the results consistent with theoretical expectations, which helped to establish the use of clusters for cosmographical investigations.

The X-ray luminosity and mass of clusters are important parameters in this study. The X-ray luminosity in the 0.1 to 2.4 keV energy band was derived within a cluster radius of \( r_{500} \). To estimate the cluster mass from the observed X-ray luminosity, we use the scaling relation from Pratt et al. (2009) as described in Böhringer et al. (2014, 2021b).

### 3. Methods

A FoF method was used to construct the superclusters. Because the flux limited survey features an increasing luminosity limit with redshift (as shown in Fig. A.1), the mean distance between clusters is also a function of redshift. As a consequence the linking length of the FoF algorithm has to be adjusted to this luminosity limit which we achieve by means of a weighting scheme. The weights were calculated from an integration of the luminosity function, \( \phi(L_X) \), as follows:

\[
\begin{align*}
  w_i &= \frac{\int_{L_{X0}}^{L_i} \phi(L_X) dL}{\int_{L_{X0}}^{\infty} \phi(L_X) dL},
\end{align*}
\]

where \( L_{X0} \) is the nominal lower X-ray luminosity limit of the sample and \( L_i \) is the lower luminosity limit that can be reached at the sky location and redshift of the cluster to be weighed. In the FoF algorithm we adopt a minimal linking length, \( l_0 \), and we adjust the linking length \( l_i = l_0 \times (w_i)^{1/3} \) if \( L_i \) is higher than \( L_{X0} \). Since the linking length is calculated for each cluster at its location, we take the average \( l_i \) of both clusters in the percolation process by means of the formula \( l = l_0 \times (2/(1/w_1 + 1/w_2))^{1/3} \).

For this study we adopted a lower X-ray luminosity limit of \( 10^{42} \, \text{erg s}^{-1} \). With this value for \( l_0 \), the volume is limited in most of the sky out to a redshift of \( z \approx 0.016 \). For the linking length we used a minimal value of \( l_0 = 19 \, \text{Mpc} \). This corresponds approximately to an overdensity ratio, \( R_{500} = n_{500}/n_{cr} \), of about a factor of 2 compared to the mean density of clusters in the nearby Universe. This factor is obtained as follows. From the X-ray luminosity function obtained by Böhringer et al. (2014) we determined the mean density of CLASSIX clusters with \( L_X \geq 10^{42} \, \text{erg s}^{-1} \) to be \( 7.2 \times 10^{-3} \, \text{Mpc}^{-3} \). The linking length for an overdensity ratio, \( R \), of a factor of 2 is then given by:

\[
  l = R^{-1/3} \times n^{-1/3} \sim 19 \, \text{Mpc}.
\]

The adopted luminosity limit corresponds to a cluster mass limit of about \( m_{200} \sim 2.1 \times 10^{15} \, \text{M}_\odot \). We are therefore including less massive galaxy groups in our study. They are definitely gravitationally bound entities, as shown by their extended X-ray emission, but are optically often characterised by a giant elliptical galaxy surrounded by a few smaller galaxies, which in its extreme is called a ‘fossil group’.

### 4. Results

#### 4.1. The superclusters

The goal to study structures at low matter overdensities, but larger in size than smaller superclusters, led us select the requirement that the SC contain at least five members. A study of the multiplicity function, that is the number distribution of SC as a function of the number of members, discussed in the next subsection, provides a justification for this choice. Figure 2 shows the multiplicity function derived for a minimal linking length of 19 Mpc. We note that the number of SC with four members or less increases fast towards low richness, very similar to the distribution we find for a simulated random cluster distribution with same volume and spatial density. However, SC with more than five members are much more frequent in the data than in the random simulations. Thus, these larger SC are special, while the smaller ones can also be produced by shot noise. Being generous
in the lower number cut, we included the bin of SC with five members in the transition region in our study.

With this requirement and the adopted linking length we found eight SC. They are listed together with some of their main properties in Tables 1 and 2 and shown in an Aitho.

We adopted this as the most obvious choice, because it yields an overdensity ratio of about 2, consistent with the above considerations concerning the linking length. One could in principle also argue that one should only take half the radius to the next nearest neighbour. We provide the results from such calculations with an alternative sphere radius of 10 Mpc in Table 2. We note that this results in a decrease of the estimated SC mass by only 13–23% (27% in the case of the Local SC).

### 4.2. Supercluster multiplicity function

The multiplicity function of SC, that is their richness distribution, is an interesting statistical tool to gain some understanding of the nature of the structures. We show in Fig. 2 the multiplicity function resulting from the SC construction with a minimal linking length of 19 Mpc, relaxing the requirement of a minimum number of members. We note that the distribution shows a steep increase in the number of SC for less than five members towards low richness, while we see a long tail in the distribution with more than five members. To better understand these results, we performed simulations of spatially random distributions of clusters with the same study volume and total number and subjected them to the same SC construction process. We repeated these simulations 1000 times and compare the mean results of these to the observations in Fig. 2. At the low richness end ($N_{\text{CL}} < 5$) the random distribution reproduces the observations quite well. This implies that the steep increase towards low richness can be produced by shot noise. However, in the high richness tail the simulated SC are much less frequent than the observed ones, underlining the conclusion that these structures are especially interesting.

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**Table 4. Groups and clusters which are members of the Centaurus SC.**

<table>
<thead>
<tr>
<th>Name</th>
<th>RA</th>
<th>Dec</th>
<th>Redshift</th>
<th>$F_X$</th>
<th>Error</th>
<th>$L_X$</th>
<th>$m_{200}$</th>
<th>$r_{out}$</th>
<th>$n_H$</th>
<th>Alt. name</th>
</tr>
</thead>
<tbody>
<tr>
<td>RXCJ1248.7-4118</td>
<td>192.1997</td>
<td>−41.3078</td>
<td>0.0114</td>
<td>251.0173</td>
<td>2.40</td>
<td>0.7665</td>
<td>3.165</td>
<td>80.0</td>
<td>8.3</td>
<td>A 3526 (Centaurus)</td>
</tr>
<tr>
<td>RXCJ1304.2-3030</td>
<td>196.0696</td>
<td>−30.5154</td>
<td>0.0117</td>
<td>8.8235</td>
<td>13.60</td>
<td>0.0299</td>
<td>0.424</td>
<td>20.0</td>
<td>6.2</td>
<td>NGC 4936</td>
</tr>
<tr>
<td>RXCJ1307.2-4023</td>
<td>196.8136</td>
<td>−40.3950</td>
<td>0.0159</td>
<td>2.3100</td>
<td>18.70</td>
<td>0.0154</td>
<td>0.280</td>
<td>11.0</td>
<td>6.7</td>
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<td>0.0087</td>
<td>72.5643</td>
<td>4.00</td>
<td>1.0357</td>
<td>1.083</td>
<td>36.0</td>
<td>4.9</td>
<td>NGC 5044</td>
</tr>
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<td>3.1000</td>
<td>21.80</td>
<td>0.0136</td>
<td>0.260</td>
<td>9.0</td>
<td>8.5</td>
<td>NGC5090/5091</td>
</tr>
<tr>
<td>RXCJ1336.6-3357</td>
<td>204.1616</td>
<td>−33.9584</td>
<td>0.0123</td>
<td>2.4243</td>
<td>18.00</td>
<td>0.0107</td>
<td>0.224</td>
<td>9.5</td>
<td>4.1</td>
<td>A 3565</td>
</tr>
<tr>
<td>RXCJ1347.2-3025</td>
<td>206.8014</td>
<td>−30.4194</td>
<td>0.0145</td>
<td>2.5884</td>
<td>50.60</td>
<td>0.0152</td>
<td>0.278</td>
<td>10.0</td>
<td>4.4</td>
<td>A 3574W</td>
</tr>
<tr>
<td>RXCJ1349.3-3018</td>
<td>207.3304</td>
<td>−30.3094</td>
<td>0.0160</td>
<td>8.2988</td>
<td>25.00</td>
<td>0.0504</td>
<td>0.584</td>
<td>20.0</td>
<td>4.4</td>
<td>A 3574E</td>
</tr>
<tr>
<td>RXCJ1352.8-2829</td>
<td>208.2140</td>
<td>−28.4977</td>
<td>0.0159</td>
<td>2.0869</td>
<td>30.80</td>
<td>0.0149</td>
<td>0.274</td>
<td>9.0</td>
<td>4.4</td>
<td>NGC 5328</td>
</tr>
<tr>
<td>RXCJ1403.5-3359</td>
<td>210.8995</td>
<td>−33.9879</td>
<td>0.0132</td>
<td>9.0368</td>
<td>14.40</td>
<td>0.0402</td>
<td>0.508</td>
<td>17.0</td>
<td>5.6</td>
<td>AS 0753</td>
</tr>
</tbody>
</table>

**Notes.** The meaning of the columns is the same as in Table 3.
4.3. The Local Supercluster with the Virgo cluster

The structure found including the Virgo cluster, listed in Table 3, is the Local SC (de Vaucouleurs 1953, 1956, 1958). It contains only one galaxy cluster, Virgo, and several smaller galaxy groups. If we would have applied the same strict criteria, that we applied to the other superclusters, the Local SC would not have been included. We considered the Virgo cluster as three separate dynamical units, the X-ray halos around the giant elliptical galaxies M87, M86 and M49, which can be distinguished in the RASS. Among these X-ray halos, M49 falls (with its luminosity of \( L_X \sim 3 \times 10^{43} \text{erg s}^{-1} \)) below the sample luminosity limit and is thus excluded. The halos of M87 and M86 overlap on the sky, but one can model the X-ray surface brightness distribution with two distinct halos (Böhringer et al. 1994). Also in redshift space the two halos can be distinguished (e.g., Binggeli et al. 1987). For other systems we considered different components only if they do not overlap on the sky in the RASS. Allowing for this exception for the nearby Virgo cluster provided us with five X-ray halo members for the Local SC, making it part of the SC sample.

In addition, inspecting the X-ray luminosities of the five objects of the Local SC, we find that three of them have a low luminosity within a factor of two of the luminosity limit and the fourth one is only slightly more luminous. Therefore the only massive object in this structure is the main body of the Virgo cluster formed by the halo of M87. If we would have set the lower luminosity limit to \( \geq 2 \times 10^{42} \text{erg s}^{-1} \), the only two members left would have been M87 and NGC4636. We show in Fig. A.1 the mean luminosity limit as a function of redshift. One notes that a luminosity limit \( L_X > 2 \times 10^{42} \text{erg s}^{-1} \) effectively applies for all systems with redshifts \( z \geq 0.0203 \). Thus again the Local SC would not have been included if it would not be so close. But we had a strong interest to include this well known SC in the description of the local cosmography of our Universe.

Figure 3 shows the three-dimensional configuration of the group of clusters. The two components of the Virgo cluster and NGC4636 form a tight group as well as the pair consisting of NGC5813 and NGC5846, while the two associations have a separation of about 17 Mpc, close to the linking length. Further properties of this SC are given in Tables 1 and 2, with an estimated mass of about \( 1.9 \times 2.5 \times 10^{15} M_\odot \).

4.4. The Centaurus Supercluster

The Centaurus SC is found with ten members whose properties are listed in Table 4. The Centaurus cluster, A3526, is by far the most massive object. One galaxy group, NGC 5090/5091 is located in the ZoA at \( b_1 \sim 18.1^\circ \). Figure 4 shows a three-dimensional representation of the SC and its location with respect to the Local SC. The Centaurus SC is mostly oriented along the Supergalactic plane. Its has a length of about 37.1 Mpc with an extension in the SGZ direction of only about 15.2 Mpc. The estimated mass is about \( 4.5-5.6 \times 10^{15} M_\odot \). It is located close to the Local SC. A linking length of 20.3 instead of 19 Mpc would merge the two superclusters through the systems RXCJ1315.3-1623 and RXCJ1501.1+0141.

In Fig. 5 we show three projections of the Centaurus SC in Supergalactic coordinates. In this and similarly for the following figures we indicate the estimated cluster masses by the size of the symbols, with a diameter scaling with the cube root of the mass of the SC. In Fig. 4 it appears on the left (low values of SGY) together with the group NGC5090/5091 (which has the lowest SGY coordinate). The second most massive system in the SC is the group NGC 5044, with an estimated mass, \( m_{200} \), of about \( 1.08 \times 10^{14} M_\odot \). The other SC members have estimated masses below \( 6 \times 10^{13} M_\odot \). RXCJ1349.3-3018, A3574E, includes an X-ray bright AGN, the X-ray emission of which was subtracted in this analysis, as further explained in the Appendix.

In the literature this structure is often described as part of the Hydra-Centaurus SC. With our recipe to construct the nearby
SC, the Hydra cluster, A1060, fails to be merged with the Centaurus SC by a large margin. Similarly, the other two prominent clusters in this region, Antlia and Norma (A3627), are too distant to be linked. For the Hydra, Norma and Antlia clusters we find a distance to the nearest Centaurus SC member of 27.2, 35.1 and 22.9 Mpc, respectively, while the linking length with the weighting for the specific location turns out to be, 19, 20.3 and 19 Mpc. We discuss this further below, when we compare different linking schemes.

4.5. The Coma Supercluster

The Coma Supercluster, often also referred to as the Great Wall, is found with 11 group and cluster members in the volume out to \(z = 0.03\). If we relax the boundary constraint, two more clusters are associated to this SC at redshifts \(z = 0.03-0.0322\) as shown in Table 5. The two most prominent members of the Coma SC are the Coma cluster and A1367. All other groups and clusters have estimated masses below \(1.5 \times 10^{14} M_\odot\).

Figure 6 displays a three-dimensional representation of the Coma SC. This structure has a slightly larger extent in the SGZ direction of 55.4 (65.3) Mpc compared to the SGX and SYG directions with an extent of 50.2 (61.8) and 38.0 (52.4) Mpc, respectively, where the number in brackets refer to the structure including the two clusters at \(z > 0.03\). Compared to the Perseus-Pisces and Centaurus SC it is oriented much more in a perpendicular direction to the Supergalactic plane. The total length of the Coma SC is 64.8 (78) Mpc. It is thus the third largest supercluster, also in mass, next to the Perseus-Pisces and Hercules SC.

A display of the Coma SC in three projections in Supergalactic coordinates is given by Fig. 7. The five most prominent members of the Coma SC are identified: we note that the Coma cluster and NGC 522 (RXCJ1334.3+3441) are located at positive SGZ coordinates and are separated from most other groups and clusters in the SC. NGC 522 (RXCJ1334.3+3441) is also the object furthest to the east in the sky. The two clusters with \(z > 0.03\) have the most negative SGZ coordinates.

4.6. The Hercules Supercluster

The SC with the members shown in Table 6 consists of ten groups and poor clusters. The SC is located more than 60 Mpc above the Supergalactic plane (Figs. 8, and 9). It is part of a larger structure with its major parts outside the radius of \(z = 0.03\). The core of this larger structure is the classical Hercules SC, with the members A2147, A2151, A2152 (e.g., Shapley 1932; Abell 1961; Tarenghi et al. 1979, 1980; Giovanelli et al. 1997). Abell (1961) considered the former three clusters together with A2162, A2197 and A2199 as one supergalactic system (‘second order cluster’). Barmby & Huchra (1998) included further clusters, A2107, A2063 and A2052 as possible members of the SC. Apart from A2197 which lies at the boundary of our study region all these clusters are located at \(z > 0.03\). What we observe in our study-volume is just the extension of this much more massive structure, that is linked together if we extend the friends-of-friends analysis with our recipe beyond \(z = 0.03\). We describe the entire structure in more detail in a subsequent publication and concentrate here on our study volume.

The part of the Hercules SC inside the study region contains mostly less massive systems with masses below 10^{13} M_\odot, except for RXCJ11715.3+5724 (NGC 6338) with an estimated mass of about \(m_{200} = 1.7 \times 10^{13} M_\odot\). The next massive object is RXCJ1629.6+4049 (A2197E) through which this structure connects to the classical Hercules SC. Figure 8 shows the locations of the Hercules SC members at \(z \leq 0.03\) and a few clusters at higher redshift including the concentration A2197E, 2197W and A2199.

NGC 6338 has been observed with Chandra and XMM-Newton and studied in detail by Pandage et al. (2012) and O’Sullivan et al. (2019). It is found to be an interesting merger of a smaller group with the main system. NGC 6338 also hosts interesting radio lobe cavities. The temperature outside the core is about 2–3 keV (O’Sullivan et al. 2019).

4.7. The Sagittarius Supercluster

Six objects in the southern sky, as listed in Table 7, are linked together to a supercluster in the constellation of Sagittarius. We have not found a previous description of this structure and thus refer to it as the Sagittarius SC. All members have estimated masses below \(m_{200} = 7 \times 10^{12} M_\odot\). The most massive one is the group around the galaxy ESO 460-004 (\(m_{200} = 6.5 \times 10^{13} M_\odot\)). Figure 10 provides a three-dimensional representation of the structure. The SC has a length of 33.8 Mpc and an estimated mass of \(4.3-5.5 \times 10^{15} M_\odot\).
4.8. The Lacerta Supercluster

In Supergalactic coordinates the Lacerta SC is located about 40 to 50 Mpc above the Perseus-Pisces SC. It contains six members all of which have estimated masses below $m_{200} = 1.1 \times 10^{14} M_{\odot}$, as listed in Table 8. The SC is entirely located in the ZoA. Figure 11 provides a three-dimensional view on the SC. One notes the close pair of the two groups, UGC 12491 (CIZA2318.6+4257) and NGC 7618, which have almost the same redshift. They both have been found in Chandra observations to be interesting interacting systems with sloshing cold fronts (Kraft et al. 2006).

The SC has a length of 19.9 Mpc and an estimated mass of $3.6 - 4.3 \times 10^{15} M_{\odot}$. Apart from the Local SC it is the smallest of the SC in the study volume. We show below that it merges with the Perseus-Pisces SC with linking schemes at a higher X-ray luminosity limit.

4.9. Overview

Figure 12 provides an overview of all the structures in the study volume in a three-dimensional representation. Among the two panels, the lower one provides a slightly better separation of the SC. While in total we found 146 groups and clusters with $L_x \geq 10^{42}$ erg s$^{-1}$ at $z \leq 0.03$; 75 of these are part of superclusters (a fraction of 51%). This result is similar to that found for superclusters in the entire REFLEX survey by Chon & Böhringer (2013). If we compare the volumes based on the values in Table 1, however, we find that the SC occupy only ~14% of the study volume at $z \leq 0.03$. Using the alternative volume calculation with 10 Mpc radius of Table 2, the volume fraction is only about 1.8%.

Inspecting the cluster and SC distribution in the plot, we note two clear asymmetries. In equatorial coordinates we find 86 clusters in the northern compared to 60 in the southern sky, which is an overabundance by about 1.5σ in the north. But looking at the number of cluster which are members of SC we find a more than 6σ difference, 57 compared to 18, respectively. Thus there are clearly more SC in the northern sky, including the Perseus-Pisces SC, most of the A400, the Local, the Coma, the Hercules, and the Lacerta SC, compared to Centaurus and Sagittarius SC in the southern sky (see also Fig. 1). The other inhomogeneity concerns the SC distribution with respect to the Supergalactic SGZ coordinate. There is no significant difference in the number above and below $SGZ = 0$: 67/79 for all clusters, 39/36 for clusters in SC. But there is a striking difference if we compare the number of clusters at $SGZ \geq 50$ Mpc with those at $SGZ \leq -50$ Mpc, which
Table 6. Groups and clusters which are members of the Hercules SC at $z \leq 0.03$.

<table>
<thead>
<tr>
<th>Name</th>
<th>RA</th>
<th>Dec</th>
<th>Redshift</th>
<th>$F_X$</th>
<th>Error</th>
<th>$L_X$</th>
<th>$m_{200}$</th>
<th>$r_{out}$</th>
<th>$n_H$</th>
<th>Alt. name</th>
</tr>
</thead>
<tbody>
<tr>
<td>RXCJ1629.6+4049</td>
<td>247.4245</td>
<td>40.8231</td>
<td>0.0297</td>
<td>4.2600</td>
<td>18.00</td>
<td>0.0876</td>
<td>0.818</td>
<td>15.0</td>
<td>1.0</td>
<td>A 2197E</td>
</tr>
<tr>
<td>RXCJ1649.3+5325</td>
<td>252.3283</td>
<td>53.4230</td>
<td>0.0298</td>
<td>2.8180</td>
<td>13.00</td>
<td>0.0579</td>
<td>0.632</td>
<td>13.5</td>
<td>2.8</td>
<td>Arp 330</td>
</tr>
<tr>
<td>RXCJ1714.3+4341</td>
<td>258.5802</td>
<td>43.6882</td>
<td>0.0276</td>
<td>3.0830</td>
<td>9.90</td>
<td>0.0570</td>
<td>0.627</td>
<td>12.0</td>
<td>2.2</td>
<td>NGC 6329</td>
</tr>
<tr>
<td>RXCJ1715.3+5724</td>
<td>258.8401</td>
<td>57.4082</td>
<td>0.0293</td>
<td>13.9714</td>
<td>3.50</td>
<td>0.2858</td>
<td>1.704</td>
<td>17.0</td>
<td>2.8</td>
<td>NGC 6338</td>
</tr>
<tr>
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<td>0.0271</td>
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<td>10.60</td>
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<td>3.2</td>
<td>NGC 6370</td>
</tr>
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<td>RXCJ1736.3+6803</td>
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<td>68.0569</td>
<td>0.0256</td>
<td>2.0965</td>
<td>10.00</td>
<td>0.0316</td>
<td>0.435</td>
<td>15.0</td>
<td>4.4</td>
<td>NGC 6420(a)</td>
</tr>
<tr>
<td>RXCJ1755.8+6236</td>
<td>268.9557</td>
<td>62.6124</td>
<td>0.0259</td>
<td>3.9252</td>
<td>5.00</td>
<td>0.0610</td>
<td>0.655</td>
<td>16.0</td>
<td>3.4</td>
<td>VII Zw 767</td>
</tr>
<tr>
<td>RXCJ1806.5+6135</td>
<td>271.6432</td>
<td>61.5974</td>
<td>0.0236</td>
<td>1.5521</td>
<td>20.00</td>
<td>0.0239</td>
<td>0.368</td>
<td>7.5</td>
<td>3.5</td>
<td>UGC 11202</td>
</tr>
<tr>
<td>RXCJ1818.7+5017</td>
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<td>50.2837</td>
<td>0.0262</td>
<td>1.4078</td>
<td>12.00</td>
<td>0.0233</td>
<td>0.260</td>
<td>11.0</td>
<td>4.1</td>
<td>UGC 11465</td>
</tr>
</tbody>
</table>

Notes. The meaning of the columns is the same as in Table 3. (a) These two clusters were previously identified in the RASS North Ecliptic Pole survey by Henry et al. (1995) and are listed there by their RASS source names: RX J1736.4+6804 and RX J1755.8+6236.

is 29/18 for all clusters and 16/0 for clusters in SC. Thus we find no SC in the volume of $z \leq 0.03$ and $S G Z \leq -50 \text{ Mpc}$. We also note the strong segregation towards the Supergalactic plane, that we studied in detail in Böhringer et al. (2021a). Among the eight supercluster, the four major ones, Perseus-Pisces, Centaurus, Coma, and Hercules SC, are clearly recognised as the largest structures.

5. Discussion

5.1. Effect of the lower luminosity limit for member clusters

We have constructed the SC described above with groups and clusters of galaxies with a low X-ray luminosity limit, much lower than what was typically used in the past. The advantage of this procedure is that we can base the cluster density mapping on a sufficiently high cluster density, which is less subject to shot noise. But it also raises the interesting question, in how much the SC found depend on this lower luminosity limit. To test this, we conducted the following study. We repeated the SC construction with a series of schemes involving an increasing X-ray luminosity limit. By increasing this limit, we are thinning out the cluster density. To compensate for this, we increased the linking length accordingly. This was done using the following equation,

$$
\tilde{L}_0 = \left( \frac{n_{CL}(L_{X0})}{n_{CL}(L_{X})} \right)^{1/3} L_0,
$$

where $L_0$ is the nominal (minimal) linking length defined in Sect. 3, $\tilde{L}_0$ is the new nominal linking length, $n_{CL}(L_{X})$ is the cluster density as a function of lower luminosity limit, where $L_{X0}$ and $L_{X}$ are the nominal and new lower X-ray luminosity limits. For this study we varied $L_{X0}$ over an order of magnitude in eight steps including the linking schemes listed in Table 9, which gives the values of the lower luminosity limit, $L_{X0}$, and the nominal linking length, $\tilde{L}_0$, for each step. With each step the density mapping gets noisier. To provide a feeling for this effect, we give in the forth row, labelled $N_{CL}$, the number of clusters at $z \leq 0.03$ above $L_{X0}$. Up to step four we only consider SC with at least five members, as done above. From step 5 on we also consider structures with four members, since the statistics gets considerably poorer. In this exercise we are including only groups and clusters at redshifts $z \leq 0.03$.

The smaller structures do not survive all the steps. The Local SC gets merged with the Centaurus SC already in step 2, similar to the behaviour we saw in Sect. 4.3. The A400 SC, which does not contain many massive clusters, is not recovered in step 3. The Sagittarius SC is lost in step 4 and the Lacerta SC survives with four members up to step 4 and merges in step 5 with the Perseus-Pisces SC. Only the larger SC survive till the highest luminosity limit, except for the Hercules supercluster (lost in step 4). The latter has its core outside the considered redshift range and it would only survive if we had included also this part. The fact that the smaller structures are not traced well if we lower the statistics is not surprising, since the density mapping is just not fine enough to recognise them.

In Figs. 13–15 we give an impression how the larger structures survive the increase of the X-ray luminosity limit. In these figures the solid circles and squares show the structure recovered at the lowest and the large open circles the structure found at the highest X-ray luminosity limit. For the Perseus-Pisces SC we note in Fig. 13 that the main chain of clusters of this SC is found over the complete luminosity limit range. However, while a small ensemble of galaxy groups found at the lowest $L_{X0}$ in the west of the SC is lost at higher $L_{X0}$, the Lacerta SC with four clusters is linked to the Perseus-Pisces SC on the western side in step 5.

For the Centaurus cluster (Fig. 14) the first step brings a significant increase, where the Local SC is linked with two members and also Hydra, Antlia and another cluster are added. At
the highest luminosity limit also the Norma cluster and another luminous cluster in the ZoA gets linked. For the Coma SC, shown in Fig. 15, we note less changes. In step 3 two groups around the galaxies NGC 5129 and NGC 5171 get linked and then the overall structure remains with fewer members until the highest luminosity limit.

Thus we find that the construction of SC with the FoF scheme applied here is robust and not much sensitive to the details of the linking parameters for the given overdensity selection. There is some change in the linking of different small extensions and an overall trend that the structures become slightly larger with increasing luminosity limit. But the main structures stay the same. Another very important fact is that no new structure appeared in this process that would have been missed in the first analysis.

It is interesting to note that the linking of the clusters at higher $\tilde{L}_X$ finds the Hydra-Centaurus SC as one unit, which is similar to most descriptions in the literature. Similarly interesting is the merging of the Perseus-Pisces and Lacerta SC at higher $\tilde{L}_X$. In this case the inclusion of the Lacerta members indicates an upturn of the Perseus-Pisces SC on the western side. Such an upturn is prominently seen in the galaxy distribution if radio observations in HI are included in the redshift surveys. Kraan-Korteweg et al. (2018) show in their Fig. 10 the galaxy distribution around the Perseus-Pisces SC and one can clearly note the pronounced filament of the SC. Around $l_{II} \sim 115^\circ$ and $b_{II} \sim -30^\circ$ this galaxy filament turns northward in Galactic coordinates and crosses the equatorial plane around $l_{II} = 90^\circ$. The ensemble of galaxy groups of the Lacerta SC falls roughly into the middle of this upturning filament and thus also traces this SC extension.

5.2. Comparison to previous studies of superclusters of clusters

Of the eight systems in our sample of SC, the five most prominent structures have been previously known and are, for example, described in the review by Oort (1983). For these SC we can compare the size of the systems quoted in the review with our findings. The size of the Local SC was given as $\sim 28.6$ Mpc (18.5 Mpc), for the Perseus SC $54$ Mpc (116 Mpc), for the Coma SC $65$–$114$ Mpc (78 Mpc), for Hydra-Centaurus SC $64$ Mpc (37 Mpc), and for the Hercules SC $100$ Mpc (140 Mpc), where the numbers in brackets are our results from Table 1. The sizes from Oort (1983) were converted from a scaling with $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$ to the value of $70$ km s$^{-1}$ Mpc$^{-1}$ used here. The largest differences are for the Perseus SC, where we now include an extension through the ZoA, and for the Centaurus SC where we have not included the complex around the Hydra cluster as discussed in the previous section. Already Joeveer & Einasto (1978) found that the Perseus-Pisces SC is the most prominent superstructure in the nearby Universe. They assigned a mass of about $2 \times 10^{16} h_{70}^{-2} M_\odot$ to this SC which is similar to our result. This earlier mass is a little smaller as the extension across the ZoA was not included. Overall these major structures have been recognised in a similar way in many different studies, some of which were already mentioned above in the corresponding sections of the SC, which shows that their recognition in the galaxy cluster distribution as distinct superstructures is robust.

5.3. Comparison to other studies of the large-scale structure

Our results can also be compared to methods of characterising the cosmic large-scale structure other than those using galaxy clusters, such as the cosmic flow analysis based on galaxy peculiar velocities, the study of the galaxy density distribution, and various ways of geometrical characterisations of the cosmic web.
The use of galaxy peculiar velocities to trace the matter distribution in the Universe is a sensitive method, but restricted to the local Universe in the volume in which peculiar velocities can be determined with sufficient precision. That our results are also confined to the nearby Universe in only a slightly larger volume, makes a comparison with the results from a cosmic flow analysis, like those of the group of Tully, interesting. In Fig. 1 of Tully et al. (2019) the four major nearby mass concentration labelled as Virgo and Great Attractor, Coma, Perseus-Pisces, and Hercules, are the same five major structures we found here. Starting from our local position we find that the Local SC is closely linked to the Centaurus or Hydra-Centaurus complex. This is what Tully et al. (2014) found in their streaming analysis which links the Local SC, to the Great Attractor in the Hydra-Centaurus region. All of this together with the Norma cluster is combined into the Laniakea SC. In a stricter mathematical approach to segment the major structure in the local cosmic flows by Dupuy et al. (2019, 2020) the authors isolate the structures into basins of attraction by following individual streamlines to common destinations. They used the Constrained Local UniversE Simulations (CLUES; Yepes et al. 2009; Gottlöber et al. 2010) for their study and identified as major attractors the Laniakea SC (volume = \(5 \times 10^5\) (Mpc \(h^{-1}\)) \(^3\)), Coma SC (volume = \(1 \times 10^6\) (Mpc \(h^{-1}\)) \(^3\)), and Perseus-Pisces SC (volume = \(7 \times 10^5\) (Mpc \(h^{-1}\)) \(^3\)). The typical mass of their basins of attraction is about \(5 \times 10^{16}\) \(M_\odot\) \(h^{-1}\). The volumes are about three to five times larger than the values we find and the typical mass is about two to three times higher than that for the larger structures in our sample. This difference is due to the different definitions of the structures. While we only consider the overdense regions of the SC, the basins of attraction include the complete surroundings of the SC. Accounting for this fact by considering the filling factors of our SC, the results become quite similar.

Most of the more recent studies of SC in the galaxy distribution are based on the SDSS or the 2degree Field Galaxy Redshift Survey (2dFGRS) at redshifts outside our study volume. Therefore we can only make a statistical comparison. Einasto et al. (2007a,b) have identified SC in the 2dFGRS with a density field method, finding large structures in the galaxy density distribution smoothed with an Epanechnikov kernel of radius 8 \(h^{-1}\) Mpc as overdensities. The richest of these SC have typical radii of about 50 to slightly over 100 \(h^{-1}\) Mpc. They also analyse cosmological simulations, the Millennium run galaxy catalogue by Croton et al. (2006), for comparison and find SC with similar sizes. These structures can well be identified with the type of SC we find. Liivamaegi et al. (2012) identified and studied superclusters in a similar way in the SDSS with the density field method. For a plausible density threshold \(D \sim 5\) for the selection of SC they find the largest SC to have diameters of 100–200 \(h^{-1}\) Mpc. With the extended percolation analysis Einasto et al. (2018, 2019, 2021) detected SC in the galaxy distribution of the SDSS with a similar density threshold of \(D = 5\) as used by Liivamaegi et al. (2012) and find that the size function is cut off at diameters slightly larger than 100 \(h^{-1}\) Mpc. Einasto et al. (2016) have analysed the region of the Sloan Great Wall with a similar recipe as Liivamaegi et al. (2012). This is one of the largest structures found with an estimated length of about 328 \(h^{-1}\) Mpc. In their analysis the Sloan Great Wall breaks up into two larger and three smaller SC. The two larger SC have masses in the range 1–2 \(10^{16}\) \(M_\odot\). We therefore note that these studies of SC in the galaxy distribution, which cover a much larger cosmic volume, do not unveil much larger SC than what we found in the nearby Universe.

An overview on different geometrical ways to characterise the cosmic web is for example given by Cautun et al. (2014) (see also Liebeskind et al. 2018). They identify structures with different morphologies in the cosmic web: clusters, filaments, sheets, and voids. They find that filaments dominate the cosmic web at least since \(z \sim 2\), carrying about 50% of the total mass at present. The filaments have a fractal distributions over a range of scales and most of the mass is carried by the most massive filaments. The largest filaments have an extent over 100 \(h^{-1}\) Mpc and connect several clusters in a linear configuration. Therefore we can identify the superclusters we find with the massive filaments of the geometrical analysis. We thus find good agreement, with the minor exception, that we would not stress that these structures are generally linear chains of clusters, which we find in such a pronounced way particularly for the Perseus-Pisces SC.

### Table 7. Groups and clusters which are members of the Sagittarius SC.

<table>
<thead>
<tr>
<th>Name</th>
<th>RA</th>
<th>Dec</th>
<th>redshift</th>
<th>(F_X)</th>
<th>Error</th>
<th>(L_X)</th>
<th>(m_{200})</th>
<th>(r_{out})</th>
<th>(n_H)</th>
<th>Alt. name</th>
</tr>
</thead>
<tbody>
<tr>
<td>RXCJ1928.2-2930</td>
<td>292.0661</td>
<td>−29.5002</td>
<td>0.0246</td>
<td>2.9196</td>
<td>19.30</td>
<td>0.0602</td>
<td>0.649</td>
<td>5.5</td>
<td>8.5</td>
<td>ESO 460-G004</td>
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<tr>
<td>RXCJ1944.0-2824</td>
<td>296.0096</td>
<td>−28.4007</td>
<td>0.0200</td>
<td>3.1075</td>
<td>22.60</td>
<td>0.0325</td>
<td>0.445</td>
<td>10.0</td>
<td>10.6</td>
<td>NGC 6816</td>
</tr>
<tr>
<td>RXCJ2000.6-3837</td>
<td>300.1505</td>
<td>−38.6231</td>
<td>0.0191</td>
<td>3.4630</td>
<td>20.00</td>
<td>0.0283</td>
<td>0.425</td>
<td>14.5</td>
<td>6.6</td>
<td>−</td>
</tr>
<tr>
<td>RXCJ2018.4-4102</td>
<td>304.6065</td>
<td>−41.0466</td>
<td>0.0192</td>
<td>4.4508</td>
<td>16.60</td>
<td>0.0461</td>
<td>0.552</td>
<td>9.5</td>
<td>4.7</td>
<td>IC 4991 (b)</td>
</tr>
<tr>
<td>RXCJ2029.2-2240</td>
<td>307.3020</td>
<td>−22.6717</td>
<td>0.0196</td>
<td>1.6227</td>
<td>22.00</td>
<td>0.0203</td>
<td>0.331</td>
<td>6.0</td>
<td>5.2</td>
<td>ESO 528-G008</td>
</tr>
<tr>
<td>RXCJ2035.7-2513</td>
<td>308.9348</td>
<td>−25.2178</td>
<td>0.0200</td>
<td>2.5383</td>
<td>28.10</td>
<td>0.0250</td>
<td>0.378</td>
<td>12.5</td>
<td>4.5</td>
<td>A 3698</td>
</tr>
</tbody>
</table>

**Notes.** The meaning of the columns is the same as in Table 3. The central galaxy of the group is WISEA J00035.61-383736.4 with \(z = 0.01946\) and a brightness of around 15th magnitude. Another member of this group somewhat offset from the centre is IC4931 at \(z = 0.02004\). This group was also identified in the search for galaxy groups in the 2MASS redshift survey as object no. 12252 by Crook et al. (2007).
example, a lower luminosity limit of what clearer picture of the differ-
ence is caused by the two most luminous clusters. We get a some-
thing in the study of all the superstes-clusters in the REFLEX sample
and in simulations by Chon & Böhringer (2013) and Chon et al.
(2014). Figure 16 shows the luminosity distribution for the clus-
ters at (2014). The hint to a difference becomes clearer for the four largest
SC compared to those in the field (in the left panel) and for members of
members lost and gained by the next linking step. If less than five members are found in steps 1 to 4 and less than four members in
steps 5 to 8, the structure is no longer considered and marked as lost.

Table 8. Groups and clusters which are members of the Lacerta SC.

<table>
<thead>
<tr>
<th>Name</th>
<th>RA</th>
<th>Dec</th>
<th>redshift</th>
<th>$F_X$</th>
<th>Error</th>
<th>$L_X$</th>
<th>$m_{200}$</th>
<th>$r_{out}$</th>
<th>$n_H$</th>
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<tbody>
<tr>
<td>RXCJ2215.6+3717</td>
<td>333.9159</td>
<td>37.2908</td>
<td>0.0192</td>
<td>13.2201</td>
<td>7.20</td>
<td>0.1196</td>
<td>0.997</td>
<td>17.5</td>
<td>14.6</td>
<td>NGC 7242</td>
</tr>
<tr>
<td>RXCJ2222.4+3612</td>
<td>335.6112</td>
<td>36.2141</td>
<td>0.0169</td>
<td>1.4443</td>
<td>18.10</td>
<td>0.0146</td>
<td>0.271</td>
<td>5.5</td>
<td>12.3</td>
<td>NGC 7265</td>
</tr>
<tr>
<td>RXCJ2224.2+3608</td>
<td>336.0558</td>
<td>36.1336</td>
<td>0.0186</td>
<td>6.4139</td>
<td>10.30</td>
<td>0.0549</td>
<td>0.616</td>
<td>15.0</td>
<td>12.3</td>
<td>NGC 7274</td>
</tr>
<tr>
<td>RXCJ2231.0+3920</td>
<td>337.7690</td>
<td>39.3336</td>
<td>0.0171</td>
<td>4.2679</td>
<td>11.50</td>
<td>0.0337</td>
<td>0.455</td>
<td>11.0</td>
<td>12.0</td>
<td>NGC 7276</td>
</tr>
<tr>
<td>RXCJ2318.6+4257</td>
<td>349.6694</td>
<td>42.9616</td>
<td>0.0174</td>
<td>16.8028</td>
<td>6.80</td>
<td>0.1271</td>
<td>1.036</td>
<td>18.0</td>
<td>11.8</td>
<td>CIZAJ2318.6+4257</td>
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<td>RXCJ2319.7+4251</td>
<td>349.9398</td>
<td>42.8611</td>
<td>0.0173</td>
<td>16.3837</td>
<td>6.70</td>
<td>0.1236</td>
<td>1.018</td>
<td>18.0</td>
<td>11.8</td>
<td>NGC 7618</td>
</tr>
</tbody>
</table>

Notes. The meaning of the columns is the same as in Table 3. (a) Also identified as WBL group 679 (White et al. 1999). (b) Also identified as WBL group 681, the redshift above is that of the group. (c) The group features two bright elliptical galaxies, UC 12064 with a distance of about 3.4 arcmin to the reference coordinate and MCG+06-49-027 with a distance of about 5.2 arcmin, both at the redshift of the group. (d) Central dominant galaxy is UGC 12491.

Table 9. Supercluster membership as a function of the lower X-ray luminosity limit, $L_{X_0}$.

<table>
<thead>
<tr>
<th>Scheme</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
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<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{X_0}$</td>
<td>0.01</td>
<td>0.02</td>
<td>0.03</td>
<td>0.04</td>
<td>0.05</td>
<td>0.06</td>
<td>0.07</td>
<td>0.1</td>
<td>1.0</td>
<td>10.0</td>
</tr>
<tr>
<td>$l_0$</td>
<td>19.0</td>
<td>23.59</td>
<td>26.84</td>
<td>29.40</td>
<td>31.59</td>
<td>33.52</td>
<td>35.26</td>
<td>39.72</td>
<td>39.72</td>
<td></td>
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<tr>
<td>$N_{CL}$</td>
<td>146</td>
<td>121</td>
<td>105</td>
<td>87</td>
<td>69</td>
<td>55</td>
<td>49</td>
<td>41</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes. The table provides also the minimum linking length, $l_0$, and the number of clusters in the study volume, $N_{CL}$, as a function of the lower luminosity limit. For each SC we show in the second column the number of clusters linked in the first linking step and in subsequent columns the number of members lost and gained by the next linking step. If less than five members are found in steps 1 to 4 and less than four members in steps 5 to 8, the structure is no longer considered and marked as lost.

5.4. Luminosity distribution of Supercluster members

In our previous study on the Perseus-Pisces and A400 SC, we found a hint that the clusters in SC are on average more X-ray luminous than in the field. This was found at high significance in the study of all the superstes-clusters in the REFLEX sample and in simulations by Chon & Böhringer (2013) and Chon et al. (2014). Figure 16 shows the luminosity distribution for the clusters at $z \leq 0.03$ inside and outside the superclusters. There are more very luminous clusters in SC, but at the low luminosity end we see also more small systems in the SC. The mean X-ray luminosity of all clusters is $L_X = 2.0 \times 10^{43}$ erg s$^{-1}$ for the field and $L_X = 2.5 \times 10^{43}$ erg s$^{-1}$ for the SC members. The difference is caused by the two most luminous clusters. We get a somewhat clearer picture of the difference of the luminosity distribution, if we concentrate on clusters at higher luminosity, with, for example, a lower luminosity limit of $L_X = 0.5 \times 10^{43}$ erg s$^{-1}$. This is shown in Fig. 17 for the comparison of members in all SC to those in the field (in the left panel) and for members of the four largest SC compared to the field (in the right panel). The hint to a difference becomes clearer for the four largest SC, while the four smaller SC rather dilute this difference. It is also interesting that the SC contain also a large number of small systems, which weaken the overall trend. Kolmogorov-Smirnov statistical tests show, however, that these results are not highly significant and better statistics is needed to firmly establish these findings.

Fig. 11. Three-dimensional representation the Lacerta SC in Super-
galactic coordinates. The galaxy groups are designated by the names of their central galaxies, except for one unmarked object, which contains the giant elliptical UC 12064 slightly off-centre.

6. Summary and conclusion

We searched for large-scale structures in the matter distribution in the nearby Universe at $z \leq 0.03$ with overdensity ratios of about two by means of the distribution of X-ray luminous galaxy groups and clusters with an estimated mass larger than about $m_{200} = 2.1 \times 10^{13} M_\odot$. In total we found eight superclusters with
Fig. 12. Three-dimensional representation of all supercluster found within \( z \leq 0.03 \) with at least five members and a minimum linking length of \( l_0 = 19 \) Mpc. The structures marked in colour are: red = Perseus-Pisces SC, red-brown = A400 SC, violet = Local SC, orange = Centaurus SC, siena = Coma SC, dark blue = Hercules SC, turquoise = Sagittarius SC, light green = Lacerta SC. Non-supercluster members are shown as black open circles.

at least five group or cluster members. Four of these are smaller with estimated masses in the range of \( 2 - 7 \times 10^{15} M_\odot \). They are the Local, the A400, the Sagittarius and the Lacerta SC. The latter two are structures which have not been described as such. These smaller structures are only found by including less massive groups of galaxies with low X-ray luminosities of a few \( 10^{42} \) erg s\(^{-1}\).

The other four SC are well known, prominent mass concentrations, the Perseus-Pisces SC, the Centaurus SC (sometimes identified as Great Attractor), the Coma SC with the
massive Coma cluster, and the low redshift part of the Hercules SC. These have estimated masses in the range $0.5 - 2.2 \times 10^{16} M_{\odot}$. The largest structure is clearly the Perseus-Pisces SC. We showed that variations of the structure construction schemes robustly recover approximately the same prominent structures and no other structures appeared for a wide range of construction parameters. These major structures are consistent with the results from the analysis of cosmic flows from galaxy peculiar velocities (e.g., Tully et al. 2019) and also with other large-scale structure studies.

We provided catalogues and maps of all the member groups and clusters in the Appendix and verified that all of them show significantly extended X-ray emission in the ROSAT All-Sky
Survey. In total 51% of all the X-ray luminous groups and clusters at $z \leq 0.03$ are members of these SC. This characterisation of the large-scale environment of superclusters in the local Universe should be interesting for studies of the environmental dependence of the properties of different astronomical objects. It is also important for a better understanding of our local reference system from which we perform precision cosmology observations.

Acknowledgements. We thank the referee, Jaan Einasto, for very helpful comments and suggestions. We acknowledge support of the Deutsche Forschungsgemeinschaft through the Munich Excellence Cluster ‘Universe’. G.C. acknowledges support by the DLR under grant no. 50 OR 1905.

References
Appendix A: Additional material

A.1. Survey luminosity limit as function of redshift

For our analysis we used a nominal X-ray luminosity limit of $10^{42} \text{ erg s}^{-1}$. This luminosity limit is reached in the RASS only at redshifts below about $z \sim 0.0146$. Fig. A.1 shows how the average lower X-ray luminosity limit in the RASS varies with redshift. This is taken into account when adjusting the linking length as described in section 3. While here we show the average value in the survey, the linking length adjustment also takes the local variations into account, which are due to varying exposure time and interstellar absorption.

![Survey luminosity limit as function of redshift](image)

Fig. A.1. Mean survey luminosity limit of the CLASSIX Survey at $|b| > 20^\circ$ as a function of redshift. The dashed lines show the different X-ray luminosity limits used in the study in the discussion section and the redshift limit.

A.2. Images of the Local Supercluster members

Fig. A.1 provides images of the member groups and clusters of the Local Supercluster. The optical images are obtained from the Digital Sky Survey (DSS) scans of photographic plates and the contours show the X-ray surface brightness observed in the RASS.

All groups and clusters of this structure have significantly extended X-ray emission in the RASS and no peculiar X-ray spectral properties. The two groups, NGC 5813 and NGC 5846, have been observed in deep Chandra observations, NGC 5813 by Randall et al. (2015) and NGC 5846 by Machacek et al. (2011), and interesting cavities and interaction effects of the central AGN with the intragroup medium were found.

A.3. Images of the Centaurus Supercluster members

Figs. A.3 and A.4 provide images of the Centaurus SC with X-ray surface brightness contours from the RASS overlayed on optical Digital Sky Survey images. For two clusters, RXCJ1349.3-3018 (A3574E) and RXCJ1403.5-3359 (NGC5328) we also show optical images with X-ray surface brightness contours from XMM-Newton observations. For the XMM-Newton data the exposures of the three detectors were combined with a scaling of the pn-images by a factor of 3.3 with respect to the MOS images.

All members of the Centaurus SC shown here have significantly extended X-ray emission in the RASS and no peculiar X-ray spectral properties. An exception is the cluster RXCJ1349.3-3018 (A3574E) which harbours an X-ray bright Sy 1.2 galaxy, IC4329A, which outshines the cluster. In the RASS image, which is shown in Fig. A.4 upper right, we see mostly a point source and the additional cluster emission is difficult to distinguish. Using, however, a pointed ROSAT observation and even better an observation with XMM-Newton (shown in Fig. A.4 middle left) we could separate the point source emission from the AGN to get approximate values for the cluster emission. This deblended X-ray luminosity is listed in Table 4.

The two components of A3574, RXCJ1347.2-3025 and RXCJ1349.3-3018, appear as two distinct X-ray emission regions in the RASS. One of the Centaurus SC members, RXCJ1321.2-4342, NGC 5090/5091 is located in the ZoA, at $b_{HI} \sim 18.8^\circ$.

A.4. Images of the Coma Supercluster members

In this section we provide images of the member groups and clusters of the Coma SC (Figs. A.5, A.6 and A.7). The images show overlays of X-ray contours from RASS on DSS images produced in the same way as in the previous sections. For two clusters with interesting internal structures, A1185 (RXCJ1110.5+2843) and A1367 (RXCJ1145.0+1936), we also show images with X-ray contours from XMM-Newton observations. We do not show an image of Coma because the cluster is so large and there are plenty of detailed images available in the literature, for example the new image obtained with eROSITA by Churazov et al. (2021). All groups and clusters of the Coma SC shown here have significantly extended X-ray emission in the RASS and no peculiar X-ray spectral properties.

A.5. Images of the Hercules Supercluster members

This section provides images of the members of the Hercules supercluster at $z \leq 0.03$ (Figs. A.8, A.9). The images show overlays of X-ray contours from RASS on DSS images produced in the same way as in the previous sections.

Since this extension of the Hercules SC is less well known we remark on some of the cluster identifications. All groups and clusters have clearly extended X-ray emission in the RASS and no peculiar spectral properties. RXCJ1629.6+4049 is one of two parts of the cluster Abell 2197, which was found to have two clearly distinct X-ray emitting components, A2197 W and A2197 E, in the RASS (Muriel et al. 1996). The clusters RXCJ1736.3+6803 and RXCJ1755.8+6236 have already been identified in the RASS North Ecliptic Pole survey (Henry et al. 1995) and they are described in detail in this publication. RXCJ1714.3+4341 has also been found as a WBL group by White et al. (1999). RXCJ1723.4+5658 has been identified as a group of galaxies by van der Linden et al. (2007), and RXCJ1736.3+6803 by Lee et al. (2017). One of the clusters, RXCJ1941.7+5037 lies in the ZoA at $b_{HI} \sim 13.3^\circ$.

A.6. Images of the Sagittarius Supercluster members

This section provides images of the groups and clusters of the Sagittarius SC (Fig. A.10). The images show overlays of X-ray contours from RASS on DSS images produced in the same way as in the previous sections. All objects have significantly extended X-ray emission in the RASS and no unexpected spectral properties.
Fig. A.2. Images of the Local Supercluster. Shown are contours of the X-ray surface brightness superposed on optical Digital Sky Survey images. All images in this and the following sections are oriented such that north is up and east to the left. **Upper left**: RXCJ1226.2+1257, M86. **Upper right**: RXCJ1230.7+1223, M87. **Middle left**: RXCJ1242.8+0241, NGC 4636. **Middle right**: RXCJ1501.1+0141, NGC 5813. **Lower left**: RXCJ1506.4+0136, NGC 5846. **Lower right**: RXCJ1507.5+0141, NGC 5850.
Fig. A.3. Members of the Centaurus Supercluster. Contours of the X-ray surface brightness superposed on optical images from the DSS database. The X-ray data are taken from the RASS or XMM-Newton observations. **Upper left:** RXCJ1248.7-4118, A3526, Centaurus cluster, **Upper right:** RXCJ1304.2-3030, NGC 4936, **Middle left:** RXCJ1307.2-4023, ESO-3230.0159, **Middle right:** RXCJ1315.3-1623, NGC 5044, **Lower left:** RXCJ1321.2-4342, NGC 5090/5091, **Lower right:** RXCJ1336.6-3357, A 3565.
Fig. A.4. Members of the Centaurus Supercluster continued. **Upper left:** RXCJ1347.2-3025, A 3574 W **Upper right:** RXCJ1349.3-3018, A 3574 E **Middle left:** XMM-Newton image of RXCJ1349.3-3018, A3574 E **Middle right:** RXCJ1352.8-2829, NGC 5328, **Lower left:** RXCJ1403.5-3359, AS 753 **Lower right:** XMM-Newton image of RXCJ1403.5-3359, AS 753.
Fig. A.5. Members of the Coma Supercluster. **Upper left:** RXCJ1109.7+2146, A 1177. **Upper right:** RXCJ1110.5+2843, A 1185. **Middle left:** XMM-Newton image of RXCJ1110.5+2843, A1885. **Middle right:** RXCJ1122.3+2419, HCG 51. **Lower left:** RXCJ1145.0+1936, A1367. **Lower right:** XMM-Newton image of RXCJ1145.0+1936, A1367.
A.7. Images of the Lacerta Supercluster members

This section provides images of the groups and clusters of the Lacerta SC (Fig. A.11). The images show overlays of X-ray contours from RASS on DSS images produced in the same way as in the previous sections. All objects have significantly extended X-ray emission in the RASS and no unexpected spectral properties.

A.8. Properties of supplementary clusters

Table A.1 provides data on those additional clusters, which were linked to Centaurus SC and the Coma SC with the alternative linking schemes discussed in section 5.
Fig. A.8. Members of the Hercules supercluster. Upper left: RXCJ1629.6+4049, A2197 E. Upper right: RXCJ1649.3+5325, Arp 330. Middle left: RXCJ1714.3+4341, NGC 6329, Middle right: RXCJ1715.3+5724, NGC 6338, Lower left: RXCJ1723.4+5658, NGC 6370, Lower right: RXCJ1736.3+6803, NGC 6420.
Fig. A.9. Members of the Hercules supercluster continued. **Upper left:** RXCJ1755.8+6236 in the North Ecliptic Pole region, **Upper right:** RXCJ1806.5+6135, VII Zw 767, **Middle left:** RXCJ1818.7+5017, UGC 11202 **Middle right:** RXCJ1941.7+5037, UGC 11465.

Table A.1. Groups and clusters which were found with the alternative linking schemes to be SC members.

<table>
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<tr>
<th>name</th>
<th>RA</th>
<th>Dec</th>
<th>redshift</th>
<th>flux</th>
<th>err.</th>
<th>$L_X$</th>
<th>$m_{200}$</th>
<th>$n_{H}$</th>
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<th>alt. name</th>
</tr>
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<tbody>
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<td>RXCJ1030.0-3521</td>
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<td>21.1936</td>
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**Notes:** The meaning of the columns is the same as in Table 3, except for the column labelled 'memb.', which provides the name of the SC of which the cluster is a member: C = Centaurus, G = Coma Supercluster.
Fig. A.10. Members of the Sagittarius Supercluster. **Upper left:** RXCJ1928.2-2930, ESO 460-G004, **Upper right:** RXCJ1944.0-2824, NGC6816, **Middle left:** RXCJ2000.6-3837, **Middle right:** RXCJ2018.4-4102, IC 4991, **Lower left:** RXCJ2029.2-2240, ESO 528 - G008, **Lower right:** RXCJ2035.7-2513, A3698.
Fig. A11. Members of the Lacerta Supercluster. Upper left: RXCJ2215.6+3717, NGC 7242. Upper right: RXCJ2222.4+3612, NGC 7265. Middle left: RXCJ2224.2+3608, NGC 7274. Middle right: RXCJ2231.0+3920. Lower left: RXCJ2318.6+4257, UGC 12491. Lower right: RXCJ2319.7+4251, NGC 7618.