The relative orientation of clusters’ major elongation axes and clusters’ angular momenta is studied using a large N-body simulation in a box of 500 base length for a standard ΛCDM model. Employing the technique of mark correlation functions, we successfully separated the correlations in the orientation from the well known clustering signal traced by the two-point correlation function. The correlations in the orientation are highly significant for our sample of 3000 clusters. We found an alignment of neighboring clusters, i.e. an enhanced probability of the major elongation axes of neighboring cluster pairs to be in parallel with each other. At 10 separation the amplitude of this signal is ~ 10% above the value expected from random orientations, and it vanishes on scales larger than 15. The “filamentary” alignment between cluster’s major elongation axes and the lines pointing towards neighboring clusters shows even stronger deviations from random orientation, which can be detected out to scales of 100, both in 2D and 3D analyses. Similarly, strong correlations of the angular momentum were seen. Also a clear signal in the scalar correlation of the absolute value of the angular momentum, the spin parameter and the mass was found. They extend up to 50 and have an amplitude of 40%, 15%, and 10% above a random distribution at 10 separation, respectively.

The study of orientation effects between galaxy clusters has a long and controversial history in cosmology. In a seminal study, Binggeli:shape claimed that galaxy clusters are highly eccentric and oriented relative to neighboring clusters if lying at separations smaller than 15. Further, he found anisotropies in the cluster distribution on scales up to 50. Following studies found no or weak statistical significance for orientation effects between neighboring clusters or between cluster orientation and the orientation of the central dominant galaxy, cp. Struble:new, Flin:alignment, and Rhee:mirror. Remarkable was the apparent absence Ulmer:alignment of orientation effects in projected X-ray contours of clusters, but it should be noted that the cluster samples at this time were small. Analyzing a large set of 637 Abell clusters, Plionis:up150 found highly significant alignment effects on scales below 10 that become weaker but extend up to 150. More objectively selected, but smaller cluster samples seemed to put into question the reality of this signal, cp. Fong:2d and Martin:miR. However, Chambers:x-contours found significant nearest neighbor alignment of cluster X-ray isophotes using data from Einstein and ROSAT. With the advent of rich cluster catalogues as the optical Enacs survey Katgert:enacs-i and the X-ray based Reflex survey Boehringer:reflex, the question of orientation effects in clusters should attract renewed attention. Sufficiently large and well defined cluster samples showing only weak contamination by projection effects seem to be necessary to clarify this uncertain situation.

Strong stimulus to study orientation effects in clusters came from early ideas that a possible relative orientation between neighboring clusters or of clusters in the same supercluster should reflect the underlying structure formation mechanism. Binney:prolat proposed that tidal interactions of evolving protocluster systems may lead to the growth of anisotropies of clusters and to relative orientation effects. Later, van-Haarlem:merging used numerical simulations of CDM models to demonstrate that clusters are elongated along the incoming direction of the last major merger. In the same spirit, West:merging found that clusters grow by accretion and merging of surrounding matter that falls into the deep cluster potential wells along sheet-like and filamentary high density regions. Therefore, the cluster formation is tightly connected with the supercluster network that characterizes the large-scale matter distribution in the universe. High-resolution simulations showing this effect are described by the Virgo collaboration, cp. Colberg:virgo. Onuora:alignment found a significant alignment signal up to scales of 30 for a ΛCDM model, whereas in a τCDM model the signal extended only up to scales of 15.

To quantify the alignment of the galaxy clusters, we use a large ΛCDM simulation in a box of 500 side length. We identify a set of 3000 clusters. As statistical tools we employ mark correlation functions (MCF), as introduced to cosmology by Beisbart:luminosity. In this article we will extend this formalism to allow for vector valued marks. The direction of the major axis of the mass ellipsoid serves as the vector mark. Tightly connected with the elongation of clusters is its internal rotation. According to Doroshkevich:origin and White:angular, the primary angular momentum of bound objects is due to tidal interaction between...
the elongated protostructures after decoupling from cosmic expansion and before turn-around. More recent studies find that the angular momentum of dark matter halos is later modified by the merging history of their building blocks, cp. vitvitska:origin and porciani:testingI, porciani:testingII. Therefore, we utilise the angular momentum as an additional mark for the study of the correlation of inner properties of simulated clusters, and we compare it with the orientation effects.

The plan of the paper is as follows. In the next section, we describe our numerical simulation, the selection of a cluster sample and the precision with which we can determine structure parameters from it. Next we discuss the MCFs that are relevant for our studies. In particular, we use special MCFs for vector marks to quantify correlations of orientation. In Sect. sect:shape we investigate correlations in the spatial orientation of clusters both in 3D and in the projected mass distribution. In Sect. sect:angular we present a MCF analysis using the angular momentum, mass and spin taken as vector and scalar marks, respectively. We conclude with a summary of the results.

Cluster sample in numerical simulations sect:simulation We utilize the AP3M code of couchman:mesh to follow the dynamics of $256^3$ particles in a box of 500 with periodic boundary conditions. We employ a cold dark matter model with a cosmological constant $\Omega_\Lambda = 0.7$, a matter density $\Omega_m = 1 - \Omega_\Lambda$, and a Hubble constant $H_0 = 100h$ km/s/Mpc with $h = 0.7$. The age of the universe in this model is $\approx 13.5$ Gyrs. The normalization, given by the linear mass variance of dark matter on 8 scale, $\sigma_8 = 0.87$, is in accordance with the four year COBE DMR observations as well as the observed abundance of galaxy clusters. The code uses glass-like initial conditions, cp. knebe:formation. The initial power spectrum was calculated with the CMBFAST code seljak:cmbfast. We start the simulations at an initial redshift $z = 25$. Up to this time the Zeldovich approximation provides accurate results on the scales considered here. We employ a comoving softening length of $100 h^{-1}$ kpc, and 1000 integration steps that are enough to avoid strong gravitational scattering effects on small scales, cp. knebe:resolution. With this softening length, the inner cores or break radii of the cluster sized halos are resolved. For our statistical analysis the big simulation volume provides us with a sufficient number of clusters embedded into the large scale structure network. In particular an accurate representation of the large scale tidal field is important for getting stable orientation results. The particle mass in the simulation is $6.2 \times 10^{11}$, comparable to the mass of one single galaxy. For reliable cluster orientations and angular momenta, the number of particles per cluster should not drop below a minimum of a few hundred of particles.

We search for bound systems using a friends-of-friends algorithm. In our $\Lambda$CDM model the virialization overdensity $\rho/\rho_{\text{mean}}$ at $z = 0$ is $\approx 330$ kitayama:semianalytic which corresponds (for spherical isothermal systems) to a linking length of 0.17 times the mean inter particle distance. These bound systems are our clusters of galaxies, i.e. our cluster sized halos. The 3000 most massive ones are the constituents of our mock cluster sample. The mean distance between clusters in this sample is 34.7, which is in agreement with the mean distance of clusters in the Reflex cluster survey boehringer:reflex. The most massive cluster has a mass of $2.3 \times 10^{15}$, resolved with 3700 particles, the lightest still has $1.4 \times 10^{14}$ which corresponds to 224 particles.

The two-point correlation function $\xi(r)$ of the cluster sized halos in redshift space shows the expected behavior (Fig. fig:corr) compatible with the correlation function of the Reflex clusters determined in collins:spatial. The correlation length is 16, quantifying the amplitude of the correlation function. At scales of about 70 $\xi(r)$ becomes negative. figure center 0.95!figure1.ps

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