The Zeldovich Universe:
Genesis and Growth of the Cosmic Web
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Tracing high redshift cosmic web with quasar systems

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Abstract. We study the cosmic web at redshifts $1.0 \leqslant z \leqslant 1.8$ using quasar systems based on quasar data from the SDSS DR7 QSO catalogue. Quasar systems were determined with a friend-of-friend (FoF) algorithm at a series of linking lengths. At the linking lengths $l \leqslant 30\ h^{-1}$ Mpc the diameters of quasar systems are smaller than the diameters of random systems, and are comparable to the sizes of galaxy superclusters in the local Universe. The mean space density of quasar systems is close to the mean space density of local rich superclusters. At larger linking lengths the diameters of quasar systems are comparable with the sizes of supercluster complexes in our cosmic neighbourhood. The richest quasar systems have diameters exceeding 500 h^{-1} Mpc. Very rich systems can be found also in random distribution but the percolating system which penetrate the whole sample volume appears in quasar sample at smaller linking length than in random samples showing that the large-scale distribution of quasar systems differs from random distribution. Quasar system catalogues at our web pages (`http://www.aai.ee/ maret/QSOsystems.html`) serve as a database to search for superclusters of galaxies and to trace the cosmic web at high redshifts.

Keywords. Cosmology: large-scale structure of the Universe; quasars: general

1. Introduction

According to the contemporary cosmological paradigm the cosmic web formed and evolved from tiny density perturbations in the very early Universe by hierarchical growth driven by gravity (van de Weygaert & Schaap (2009) and references therein). To understand how the cosmic web formed and evolved we need to describe and quantify it at low and high redshifts. Large galaxy redshift surveys like SDSS enable us to describe the cosmic web in our neighbourhood in detail. One source of information about the cosmic structures at high redshifts is the distribution of quasars — energetic nuclei of massive galaxies. Already decades ago several studies described large systems in quasar distribution (Webster(1982), Clowes & Campusano (1991), Clowes *et al.* (2012), Clowes *et al.* (2013)) which are known as Large Quasar Groups (LQGs). LQGs may trace distant galaxy superclusters (Komberg *et al.* 1996). The large-scale distribution of quasar systems gives us information about the cosmic web at high redshifts which are not yet covered by large and wide galaxy surveys.

The aim of our study is to study the high redshift cosmic web using data about quasar systems. We find quasar systems and analyse their properties and large-scale distribution at redshifts $1.0 \leqslant z \leqslant 1.8$ using quasar data from Schneider *et al.* (2010) catalogue of quasars, based on the Sloan Digital Sky Survey Data Release 7.

We select from this catalogue a subsample of quasars in the redshift interval $1.0 \leqslant z \leqslant 1.8$, and apply i-magnitude limit $i = 19.1$. In order to reduce the edge effects of our analysis, we limit the data in the area of SDSS sky coordinate limits $-55 \leqslant \lambda \leqslant 55$ degrees and $-33 \leqslant \eta \leqslant 35$ degrees. Our final sample contains data of 22381 quasars.

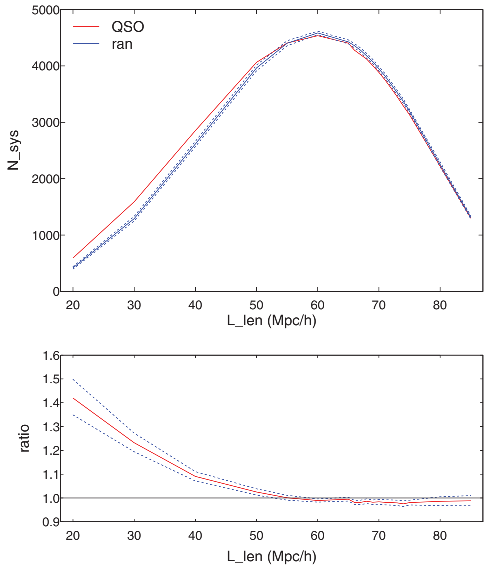

Figure 1. The number of quasar and random systems (upper panel) and the ratio of the numbers of quasar and random systems (lower panel) vs. the linking length. Red solid line denote quasar systems, and blue lines denote random systems, black line shows ratio 1.

The mean space density of quasars is very low, approximately $1.1 \cdot 10^{-6}(\mathrm{h}^{-1}\mathrm{Mpc})^{-3}$, therefore it is important to understand whether their distribution differs from random distribution. To compare quasar and random distributions we generated random samples with the same number of points, and sky coordinate and redshift limits as quasar samples.

We assume the standard cosmological parameters: the Hubble parameter $H_0 = 100\ h$ km s^{-1} Mpc^{-1}, the matter density $\Omega_{\mathrm{m}} = 0.27$, and the dark energy density $\Omega_\Lambda = 0.73$.

2. Results

We determined quasar and random systems with the friend-of-friend (FoF) algorithm at a series of linking lengths and present catalogues of quasar systems. FoF method collects objects into systems if they have at least one common neighbour closer than a linking length. At each linking length we found the number of systems in quasar and random samples with at least two members, calculated multiplicity functions of systems, and analysed the richness and size of systems. For details we refer to Einasto *et al.* (2014).

Up to the linking lengths approximately 50 h^{-1} Mpc the number of quasar systems is larger than the number of systems in random catalogues (Fig. 1), at larger linking lengths the number of systems becomes similar to that in random catalogue. The number of systems in both quasar and random catalogues reaches maximum at 60 h^{-1} Mpc. At higher values of the linking lengths systems begin to join into larger systems and the number of systems decreases. Multiplicity functions in Fig. 2 show that at the linking length $l = 85\ h^{-1}$ Mpc about half of quasars join the richest quasar system — a percolation occurs. In random catalogues the richest system is much smaller than the richest quasar system. Therefore FoF analysis shows that the distribution of quasars and the properties of quasar systems differ from random at small and large linking lengths.

In Fig. 3 we compare the distribution of diameters (maximum distance between quasar pairs in a system) of quasar and random systems at the linking lengths 30 and 70 h^{-1} Mpc. At the linking length 30 h^{-1} Mpc in the whole diameter interval the number of quasar

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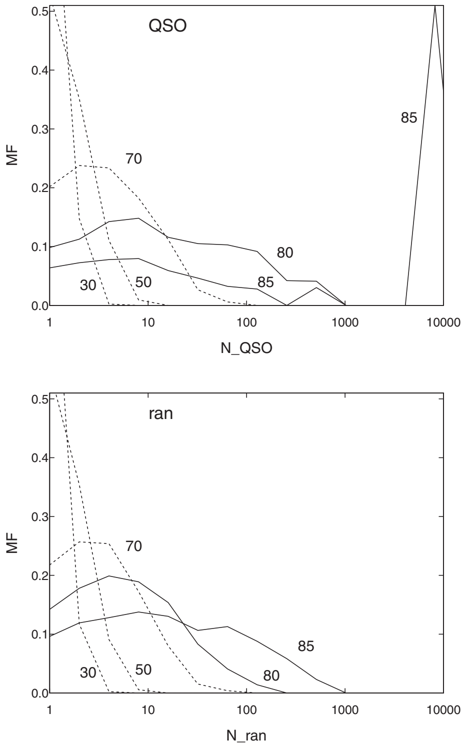

Figure 2. Multiplicity functions MF (the fraction of systems of different richness) of quasar (upper panel) and random (lower panel) data at the linking lengths 30, 50, 70, 80, and 85 h^{-1} Mpc.

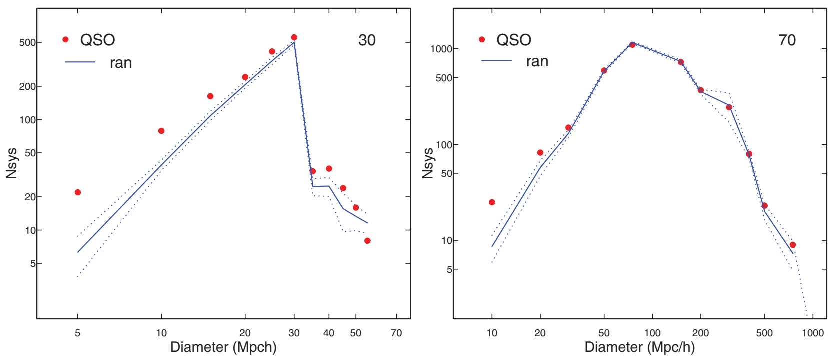

Figure 3. Number of quasar (red dots) and random (blue lines) systems of different diameter for linking lengths 30 and 70 h^{-1} Mpc (upper and lower panel, correspondingly).

systems with a given diameter is higher than that of random systems, the difference is statistically highly significant. At larger linking lengths ($l \geqslant 40$ h^{-1} Mpc; we show this for 70 h^{-1} Mpc) the number of quasar systems with diameters up to 20 h^{-1} Mpc is always larger than the number of random systems at these diameters. From diameters ≈ 30 h^{-1} Mpc the number of systems of different diameter in quasar and random catalogues becomes similar. Among both quasar and random systems there are several very large systems with diameters larger than 500 h^{-1} Mpc.

In Fig. 4 we show the median, and minimum and maximum values of quasar system diameters vs. their richness at the linking lengths 50 and 70 h^{-1} Mpc. At the linking

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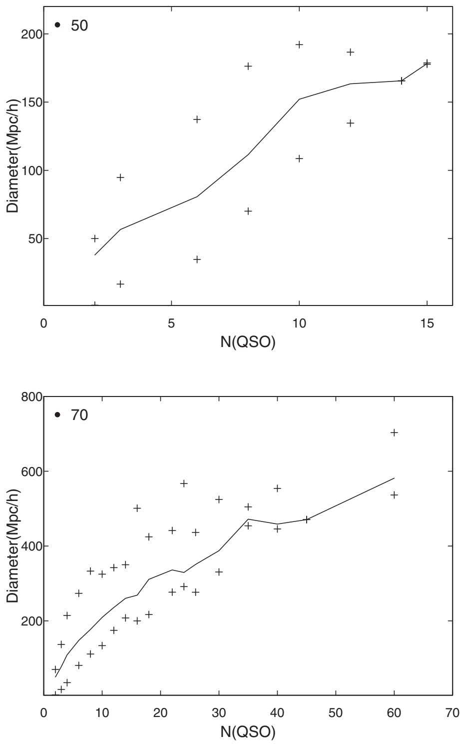

Figure 4. System richness N_{QSO} vs. their diameter D_{max} for quasars for linking lengths 50 and 70 h^{-1} Mpc. Lines show median values of diameters, crosses denote the smallest and the largest diameters.

length 50 h^{-1} Mpc the sizes of the richest quasar systems, $\approx 200\ h^{-1}$ Mpc, are comparable to the sizes of the richest superclusters in the local Universe (Einasto *et al.* 1994). The mean space density of quasar systems of order of $10^{-7}(\mathrm{h}^{-1}\mathrm{Mpc})^{-3}$, this is close to the mean space density of local rich superclusters (Einasto *et al.* 1997).

The sizes of the largest quasar systems at $l = 70\ h^{-1}$ Mpc, $500 - 700\ h^{-1}$ Mpc, are comparable with the sizes of supercluster complexes in the local Universe (Einasto *et al.* (2011c), Liivamägi *et al.* (2012)). At this linking length we obtain systems of the same size also from the random catalogues.

We show in Fig. 5 the distribution of quasars in systems of various richness at linking length 70 h^{-1} Mpc in cartesian coordinates x, y, and z (see Einasto *et al.* (2014)):

$$
\begin{aligned}
x &= -d \sin \lambda, \\
y &= d \cos \lambda \cos \eta, \\
z &= d \cos \lambda \sin \eta,
\end{aligned}
\tag{2.1}
$$

where d is the comoving distance, and λ and η are the SDSS survey coordinates. We plot in the figure also quasars from the richest systems at $l = 20\ h^{-1}$ Mpc (quasar triplets).

Visual inspection of Fig. 5 shows that very rich quasar systems form a certain pattern. In some areas of the figure there are underdense regions between rich quasar systems with diameters of about 400 h^{-1} Mpc (e.q. in the upper panel between $-1000 < x < 1000\ h^{-1}$ Mpc). The size of underdense regions in this figure is much larger than the sizes of typical large voids in the local Universe (see Einasto *et al.* (2011a)) but is close to the sizes of the largest voids covered by SDSS survey (Einasto *et al.* (2011b), Park

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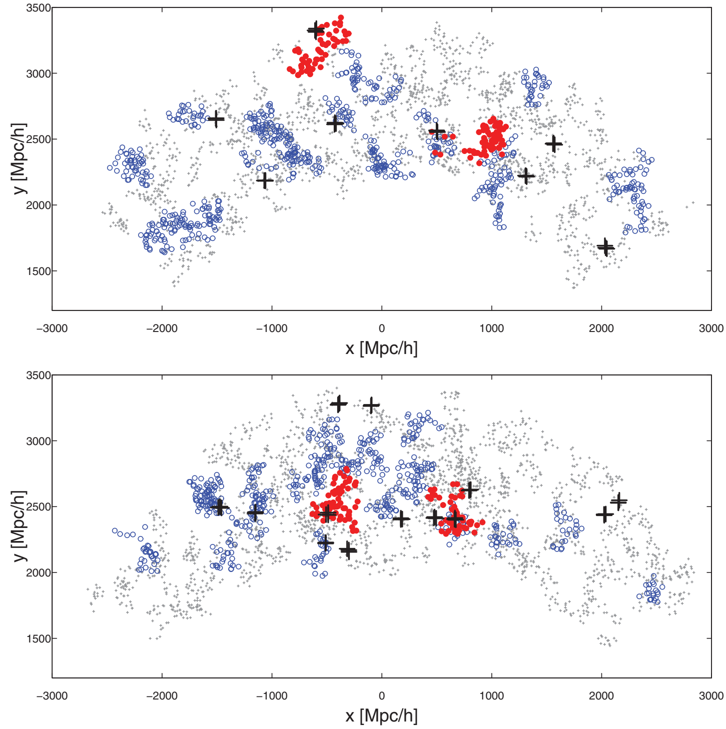

Figure 5. Distribution of QSO systems at the linking length 70 h^{-1} Mpc in x and y coordinates in two slices by z coordinate (upper panel: $z \leqslant 0$ h^{-1} Mpc, lower panel: $z > 0$ h^{-1} Mpc). Grey dots denote quasars in systems with $10 \leqslant N_{QSO} \leqslant 24$, blue circles denote quasars in systems with $25 \leqslant N_{QSO} \leqslant 49$, and red filled circles denote quasars in systems with $N_{QSO} \geqslant 50$. Black crosses denote quasar triplets at a linking length 20 h^{-1} Mpc.

et al.(2012)). Very rich systems were found also from random catalogues but the percolation analysis shows that the large-scale distribution of quasar systems differs from random distribution. We shall analyse the large scale distribution of quasar systems in detail in another study.

The richest system at the linking length $l = 70$ h^{-1} Mpc at $x \approx 1000$ h^{-1} Mpc and $y \approx 2500$ h^{-1} Mpc is the Huge-LQG described in Clowes *et al.* (2013). The presence of very rich systems as supercluster complexes is an essential property of the cosmic web, and do not violate homogeneity of the universe at very large scales, as claimed by Clowes *et al.* (2013).

3. Summary

We determined quasar systems at a series of linking lengths, and found that at small linking lengths their diameters and space density are similar to those of rich galaxy superclusters in the local Universe. At the linking lengths $l \geqslant 50$ h^{-1} Mpc the diameters of the richest quasar systems are comparable with the sizes of supercluster complexes in our cosmic neighbourhood, exceeding 500 h^{-1} Mpc. Systems of similar richness were determined also in random catalogues but the large-scale distribution of quasar systems differs from random distribution. We may conclude that quasar systems as markers of galaxy superclusters and supercluster complexes give us a snapshot of the high-redshift cosmic web. Quasar system catalogues serve as a database to search for high-redshift superclusters of galaxies and to trace the cosmic web at high redshifts.

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