# CHAPTER 4C.

# Cosmic Web
# Clustering

*Impressions of the IAU308 audience during a session,*
*at the Conference Hall of Tallinn University.*

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*The Zeldovich Universe:*
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# Evolution of the galaxy correlation function at redshifts $0.2 < z < 3$

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**Abstract.** We determine the auto-correlation function (ACF) of galaxies using massive deep galaxy surveys for which distances to individual objects are assessed using photometric redshifts. The method is applied to the 2deg COSMOS survey of $\sim 300000$ galaxies with $i+ < 25$ and $z_{\rm ph} \lesssim 3$. The distance estimates based on photometric redshifts are not sufficiently accurate to be directly used to determine the ACF. Nevertheless, the photometric redshifts carry statistical information on the data distribution on (very) large scales. The investigation of the surface distribution of galaxies in several redshift (=distance) bins allows us to determine the spatial (3D) ACF over the redshift range of $0.2 - 3.2$ or look back time of $2.4 - 11.5$ Gy.

**Keywords.** galaxies: distances and redshifts, galaxies: statistics, large-scale structure of universe

## 1. Observational material

Efficient means to quantify the galaxy clustering at small and medium scales are the auto-correlation functions (ACF). The two-point ACF $\xi(r) = \langle n(\mathbf{x})\, n(\mathbf{x}+\mathbf{r})\rangle / \langle n\rangle^2 - 1$, where $n(\mathbf{x})$ is the position dependent spatial density of galaxies and $\langle ...\rangle$ denotes averaging over the survey volume. Over a wide range of separations $r$ the ACF is adequately approximated by a power law $\xi(r) = (r/r_{\rm o})^{\gamma}$.

If no information on the galaxy radial distance is available, the amplitude of spatial correlations is derived from the 2D correlation function. Here, we use the photometric redshifts as a tool to assess the number of the galaxy-galaxy pairs resulting from the clustering and due to random coincidences in the celestial sphere. The photometric redshifts ($z_{\rm ph}$), as compared to spectroscopic ones, are substantially less accurate distance indicators. Nevertheless, they provide a raw estimate of the galaxy position. Thus, photometric redshifts could be used to statistically identify and extract random pairs, and to increase in this way the S/N ratio of the correlation amplitude measurement. The multi-band photometry allows for massive estimates of redshifts down to magnitudes of $\sim 25$ reaching $z \approx 3$ (e.g. Ilbert *et al.* 2009) In the calculations below we carefully take into account an imprecise nature of photometric redshifts.

The COSMOS galaxies are distributed within a square of 84 arcmin a side centered at $\alpha_c = 150.1°$ and $\delta_c = 2.2°$ (Taniguchi *et al.* 2007). The catalog contains 385065 objects in the deep Subaru Area, of which almost 252000 have been classified as galaxies brighter than $i^+_{\rm AB} = 25$. For all these galaxies $z_{\rm ph}$ are listed in the COSMOS photometric redshift catalog by Ilbert *et al.* (2009) available through the Web site of IPAC/IRSA. A comparison of $z_{\rm ph}$ data with the available $z_{\rm sp}$ measurements shows that a large majority of $z_{\rm ph}$ is subject to minimal errors. However, below $i^+_{\rm AB} = 23$ sharply increases number of 'catastrophic' errors, where the $z_{\rm ph} - z_{\rm sp}$ differences are scattered without any characteristic scale. We precisely model the $z_{\rm ph} - z_{\rm sp}$ deviations in the consecutive magnitude bands.

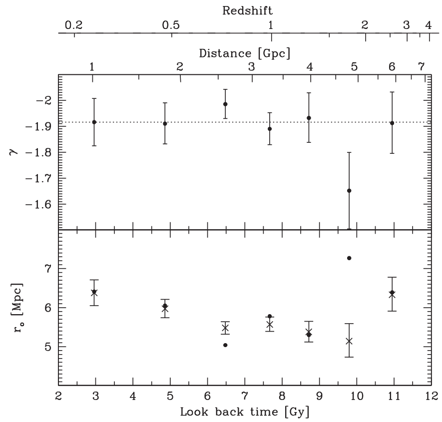


**Figure 1.** Variations of slope and the normalization of the ACF of the most luminous galaxies in the data as a function of look back time. The simultaneous fitting of $\gamma$ and $r_o$ (full dots) induces a correlation of both parameters. Crosses show the $r_o$ distribution for the slope fixed at the average value of $\gamma = -1.92$.

## 2. Results

We take the photometric redshifts, $z_{ph}$, as a working estimate of the comoving distances for all the galaxies. The whole galaxy sample is divided into 7 distance bins between $\sim 650$ and $\sim 6550$ Mpc. The radial depth of each bin is larger than 600 Mpc. Thus, it is also much larger than the maximum distance at which the ACF differs from 0.

First, we determine the 2D ACF for the each distance bin. Around randomly chosen galaxy from the given bin cluster predominantly galaxies belonging to the same bin. Because of the $z_{ph}$ errors, one can expect also some residual enhancement of galaxies assigned to other bins. Nevertheless, both distributions are distinctly different. A comparison of the surface density profiles formed by galaxies from the same bin and from all the other bins, accompanied by the $z_{ph} - z_{sp}$ statistics, allows us to determine the ACF assuming the power law: $w(p) = w_o\, p^{\zeta}$, where $p$ is the distance in the plane of the sky.

Exponent $\zeta$ in the power law approximation of the 2D ACF is directly related to the slope of the spatial ACF: $\gamma = \zeta - 1$. To retrieve the normalization of the spatial correlations, $r_o$, from the 2D function one needs the information on the radial distribution of the average galaxy density in the sample. In the present analysis the galaxy concentration varies systematically with the distance. A radial scale of this trend is substantially larger than the clustering scale and it can be appropriately modeled using the photometric redshifts. Our estimates of $\gamma$ and $r_o$, shown in Fig. 1, cover a very wide range of redshifts, presently unavailable to the spectroscopic redshift surveys in massive scale. The present measurements of the ACF parameters at moderate and high redshifts essentially do not deviate from those determined at low redshifts. It indicates that both the ACF slope and the correlation length remained stable for at least 11 billion years.

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