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## **3D Identification and Reconstruction of $z \sim 1$ Clusters: Prospects for the DEEP2 Redshift Survey**

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### **Abstract.**

We have developed a geometrical method based on 3D Voronoi polyhedra and Delaunay tessellation for identifying and reconstructing clusters of galaxies in the next generation of deep, flux-limited redshift surveys. We here describe this algorithm and tests of it using mock catalogs that simulate the DEEP2/DEIMOS redshift survey, which will begin observations in the Spring of 2002 and will provide a detailed three dimensional map of the large scale structure up to redshift 1.5.

### **1. Introduction**

Over the past few years there has been considerable work on the detection of two-dimensional galaxy overdensities in wide field imaging surveys for subsequent spectroscopic follow up. However, these systematic searches for clusters, fuelled by the availability of large CCD camera mosaics, are in many cases biased towards high density peaks of the galaxy distribution.

With the next generation of large multi-object spectrographs in their final construction phase, deep redshift surveys (Keck/DEEP2 and VLT/VIRMOS) are well within the horizon. It is now worthwhile to address the more ambitious task of constructing a three dimensional, statistically complete sample of high redshift galaxy clusters. Here we describe a fully automated and objective algorithm for identifying and reconstructing galaxy systems, based upon 3D Voronoi polyhedra and Delaunay triangulation.

### **2. Method**

A Voronoi partition of the space into minimally sized convex polytopes is a natural way to measure packing. A Voronoi polyhedron is the uniquely defined region of space around a galaxy (seed), within which each point is closer to the seed than to any other galaxy. The faces of the Voronoi cell are formed by planes perpendicular to the vectors between a galaxy and its neighbors. The volume inside the polyhedron is inversely proportional to the packing efficiency of its central galaxy; a large cell volume is indicative of an isolated galaxy. The Delaunay triangulation is the geometrical dual of the Voronoi partition and is defined by the tetrahedron whose vertices are the 4 galaxies with the property that the uniquely determined circumscribing sphere does not contain any other galaxy.

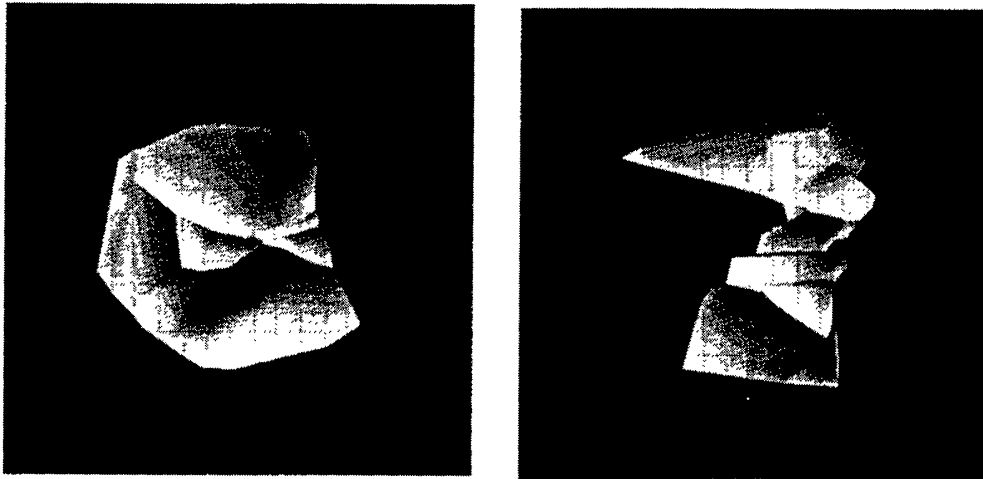


Figure 1. Voronoi reconstruction of a cluster with 10 galaxies in the DEEP2 mock catalog. The Voronoi cells encompassing the cluster are shown in real space (*left*) and in redshift space (*right*).

We thus may identify high-density peaks by selecting as “cluster seeds” the centers of all the Voronoi cells with volume smaller than some threshold, and then use the scale length of the Delaunay mesh to infer the strength of the physical aggregation. We then can define an adaptive cylindrical window in redshift space (elongated in the  $z$  direction) with dimensions determined by the local scale factor and process all the Delaunay connected galaxies with a rapidly converging “inclusion-exclusion” logic to identify cluster members.

In our algorithm, the parameters defining the adaptive search window are only weakly dependent on the galaxy density gradient which inevitably occurs in a flux limited survey, since our smoothing procedure immediately identifies regions of enhanced clustering where galaxies are generally more luminous. Moreover the number of cluster interlopers aggregated into a system in a redshift space analysis is minimized and we simultaneously obtain a non-parametric local estimate of the surrounding density environment for each galaxy and a quantitative measure of the distribution of cosmological voids in the survey volume.

### 3. Results

We have tested our reconstruction scheme using mock catalogs modelling the DEEP2 Redshift Survey (Davis et al. 2000) derived from GIF simulations (Coil et al. 2001). This survey will obtain high quality spectra for  $\sim 60000$  galaxies between  $z=0.7-1.5$  using the Keck 2 Telescope and DEIMOS spectrograph, with the twin goals of studying the evolution of the properties and the large-scale clustering of high redshift galaxies. We used a LCDM model with  $\Omega_m = 0.3$ ,  $\Omega_\Lambda = 0.7$ ,  $h = 0.7$  and  $\sigma_8 = 0.9$ . In order to mimic the selection function of the magnitude limited survey we make a rest-frame B-band cut of 23.4, which at  $z \sim 1$  corresponds to an apparent I-band magnitude with the appropriate K-correction matching the DEEP2 photometric selection criteria ( $I_{AB} < 23.5$ ). In Fig. 2a we present a mock catalog for one DEEP2-like field collapsed along

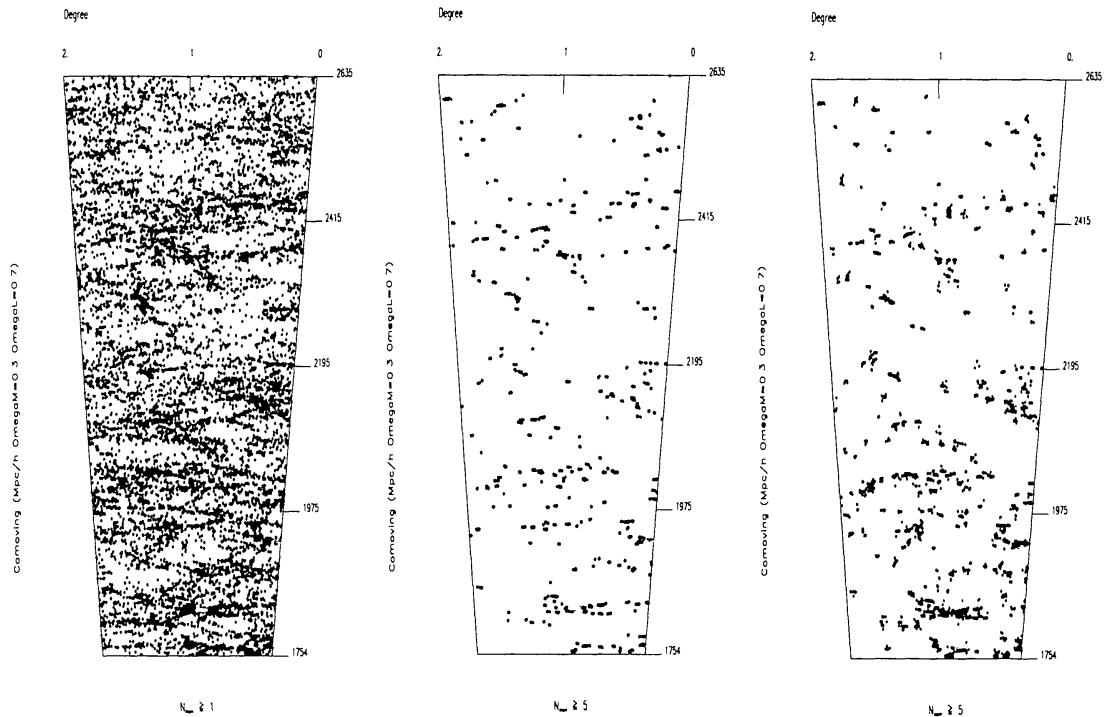


Figure 2. *Left:* One DEEP2 mock catalog in the redshift range  $z=(0.7,1.2)$ . *Center:* large-scale spatial distribution of clusters with more than 5 members identified in real space using a “Friends of Friends” algorithm. *Right:* Voronoi-Delaunay reconstruction in redshift space.

the smallest axis, covering the redshift range  $z=0.7-1.2$  (a depth which corresponds to selecting the 1200 l/mm grating in the DEIMOS spectrograph) and containing a volume of roughly  $10^6 \text{ Mpc h}^{-3}$  ( $\sim 15000$  galaxies). We have used six independent mock catalogs to determine how well the algorithm performs in identifying clusters of galaxies.

To determine the “true” distribution of clusters, we have applied in real space (volume-limited simulation) a standard percolation algorithm optimised for selecting virialized objects (mean overdensity  $\sim 180$ ). The resulting distribution of those clusters with more than 5 members is shown in Fig 2b. Cluster candidates selected by the Voronoi–Delauney algorithm applied in redshift space (flux-limited simulation) are shown in Fig 2c. Note how the large-scale pattern defined by galaxy systems and the associations of clusters in higher order structures reproduce in an unbiased way the underlying real space landscape.

#### 4. Statistical tests

The evolution of the comoving abundance of clusters as a function of their velocity dispersion  $\sigma$  and redshift  $z$  is a sensitive function of cosmological parameters (see Newman et al. 2001). The statistical significance and robustness of the clus-

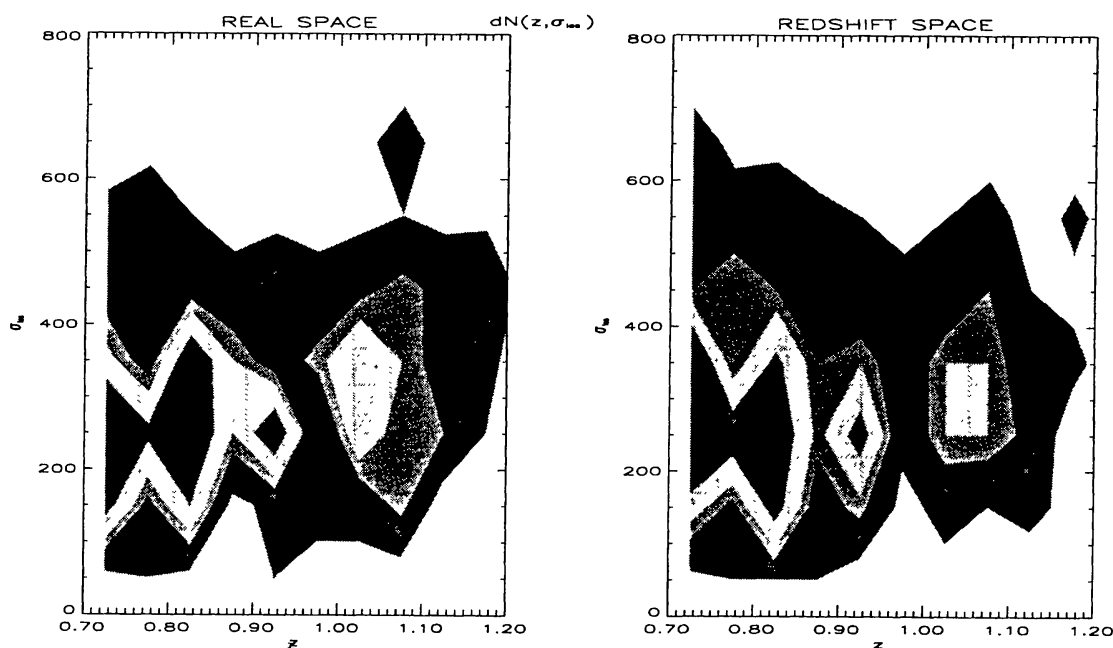


Figure 3. Differential number count of cluster as a function of the redshift  $z$  and the projected velocity dispersion  $\sigma$ . The parent distribution of cluster counts identified in real space is shown on the left, while the observed distribution recovered in redshift space with our method is plotted on the right. Density levels, smoothed by 0.05 in  $z$  and 50 km/s in  $\sigma$ , are spaced with  $\Delta=2$  intervals.

ter abundance test depends critically on an unbiased mapping of the distribution properties of the cluster observables between real to redshift space.

We have investigated the differential and integral distribution functions of the number of reconstructed clusters as a function of their richness, velocity dispersion and redshift. The Kolmogorov-Smirnov statistical test confirms the similarity between the real and reconstructed distributions, and thus the reliability of our algorithm. This can be seen visually in Fig. 4 where we show the two-dimensional distributions of the real and reconstructed clusters in redshift  $z$  and projected velocity dispersion  $\sigma$ .

The DEEP2 survey is a collaborative project among astronomers at UC, Caltech and the Univ. of Hawaii. Details of the project can be found at the URL <http://astro/berkeley.edu/deep>.

## References

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