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Detecting cosmic filamentary network with stochastic Bisous model

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Abstract. The Bisous model is a tool that uses stochastic methods to detect the network of galactic filaments. This model is explicitly developed to detect the structure from observational data, using only galaxy positions as input. This paper shows that the Bisous model gives reliable results and including photometric data improves the resulting filamentary network. We used MultiDark-Galaxies catalogue to create a mock with photometric redshifts and samples with different galaxy number densities. We found that the filaments detected with the Bisous model are reliable; 85% of the detected filaments are unchanged compared to results with more complete input data. Adding photometric data improves the fraction of galaxies in filaments. Using the confusion matrix technique, we found the false discovery rate to always be below 5% when using photometric data.

Keywords. methods: data analysis, methods: statistical, galaxies: statistics, large-scale structure of the Universe

1. The Bisous filament finder

The Bisous model is a stochastic tool used to identify the spines of the filaments using the spatial distribution of galaxies or haloes (Tempel *et al.* 2014, Tempel *et al.* 2016).

First, the Bisous randomly populates the volume with cylinders. Each configuration of cylinders in the volume has a defined energy value, which depends on the position of the cylinders in relation to the underlying data of haloes and the interconnectedness of the cylinders (see Tempel *et al.* 2016 for mathematical definitions). Using the Metropolis-Hastings algorithm and the simulated annealing procedure, the Bisous model minimises the system's energy by randomly adding, removing, or changing the cylinders†. The results are averaged over a hundred Bisous runs to suppress Poisson noise from the random process.

2. Data

We used the MultiDark-Galaxies galaxy catalogue, which uses a dark matter-only simulation with a semi-analytical model for galaxies (Knebe *et al.* 2018, Klypin *et al.* 2016).

For mock photometric data, we added a random shift to galaxies' distances. We created three types of samples. Photometric-only samples with gaussian uncertainties with standard deviations of $\sigma = 1$ to 10 Mpc and mixed samples with both photometric data ($\sigma = 5$ Mpc and 10 Mpc), the standard deviation is constant within a single sample. Spectroscopic data with $s = 10$ to 50 % of the brightest galaxies that have exact distances. All of these samples have the same amount of galaxies but different amounts of spectroscopic galaxies. For example, $\sigma 5 s 40$ means 40% of the brightest galaxies have

† For an animation, see: https://www.aai.ee/~elmo/sdss-filaments/sdss_filaments.mp4

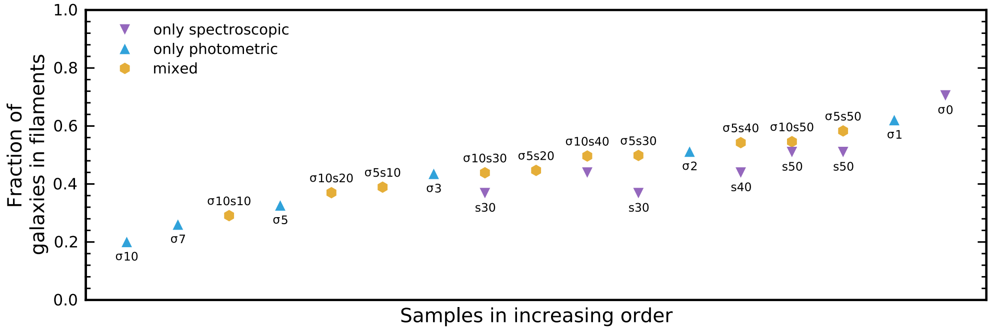

Figure 1. Fraction of galaxies in filaments with different samples. The sample $\sigma0$ indicates the ideal case where all the galaxies have spectroscopic redshifts, we use it as our ground truth. Other spectroscopic-only samples are for reference to show how adding photometric data (in mixed samples) improves the fraction of galaxies in filaments.

exact positions, other 60% have distances with random shifts with a gaussian ($\sigma = 5$ Mpc) profile. For reference, we also included the spectroscopic-only samples; for example, $s30$ has only 30% of the brightest galaxies. These spectroscopic-only samples have fewer galaxies than photometric-only and mixed samples.

3. Results

Bisous model with different galaxy number densities. The results are presented in Muru & Tempel (2021). In summary, the higher the galaxy input density, the more complete the detected filamentary network compared to the results from highest density data, which we use as a ground truth. We also showed that the filaments detected by the Bisous model are reliable. That means 85% of the filaments do not change even if higher density input data is used.

Usefulness of photometric data. In SDSS DR12, there are about 100 times more photometric galaxies than spectroscopic ones and using those would help to increase input data density. The distance for photometric galaxies has high uncertainty but Kruuse *et al.* (2019) show that photometric galaxies are correlated with the filamentary pattern. The fraction of galaxies in filaments with photometric and mixed samples in Figure 1 show that adding photometric galaxies improves the number of galaxies in filaments. This result indicates that improving the input data galaxy number density with galaxies that only have photometric redshifts improves the overall detected filamentary network in contrast to only using galaxies with spectroscopic redshifts. We analysed the results with the confusion matrix technique using $\sigma0$ (all the galaxies have spectroscopic redshifts) as ground truth. We found that the false discovery rate is below 5% for every sample, both mixed and photometric-only.

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