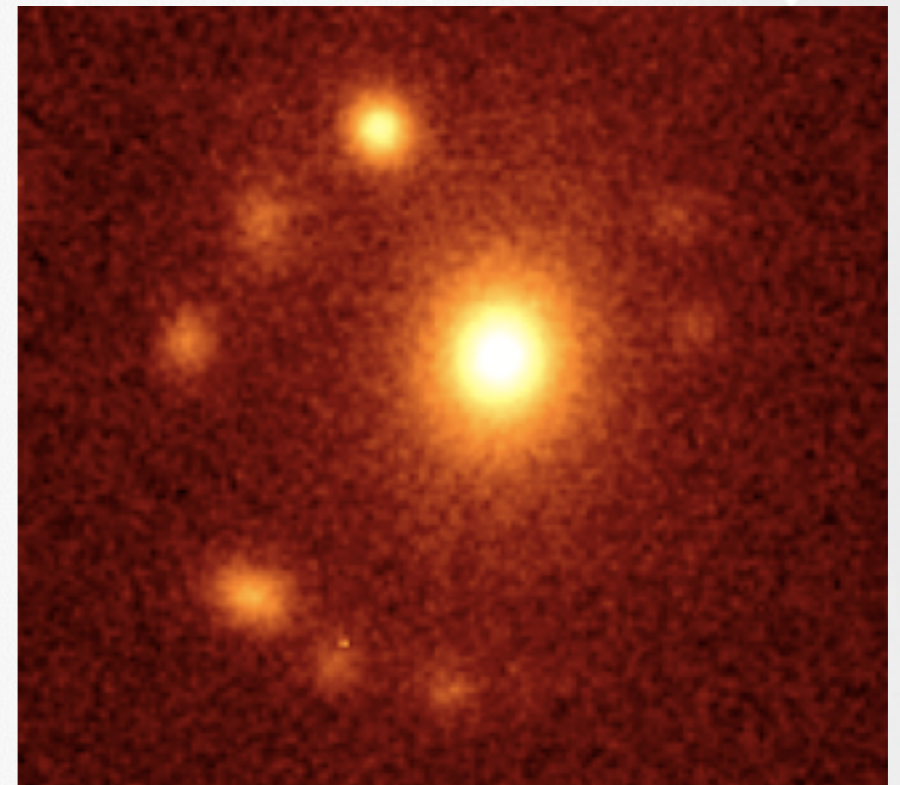
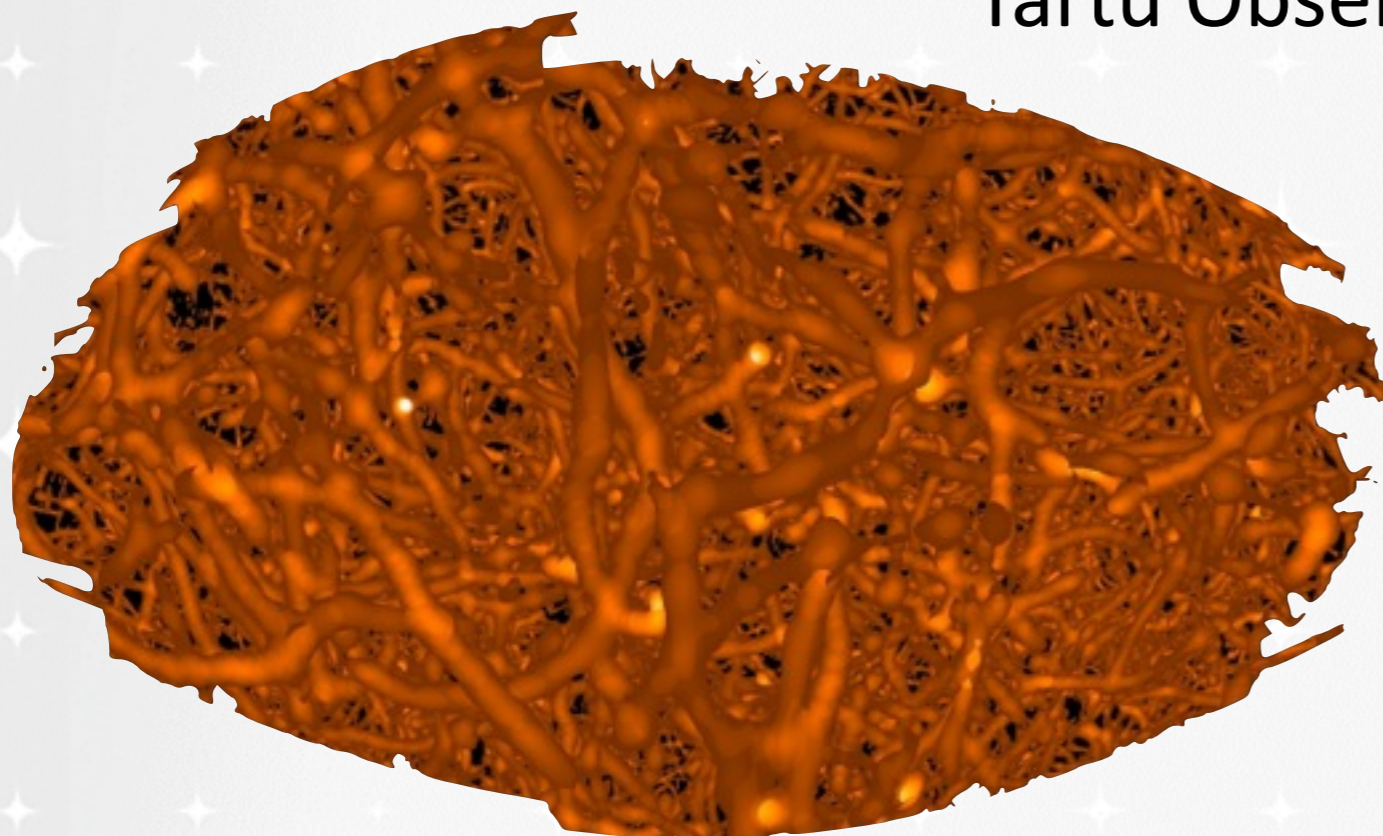




Detecting filamentary pattern in the cosmic web: galaxy filaments as pearl necklaces

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IAU308, Tallinn



Outline

- ✦ Detecting filamentary pattern spine in the galaxy distribution.
Probabilistic approach: marked point process (Bisous model) to detect the filamentary network.

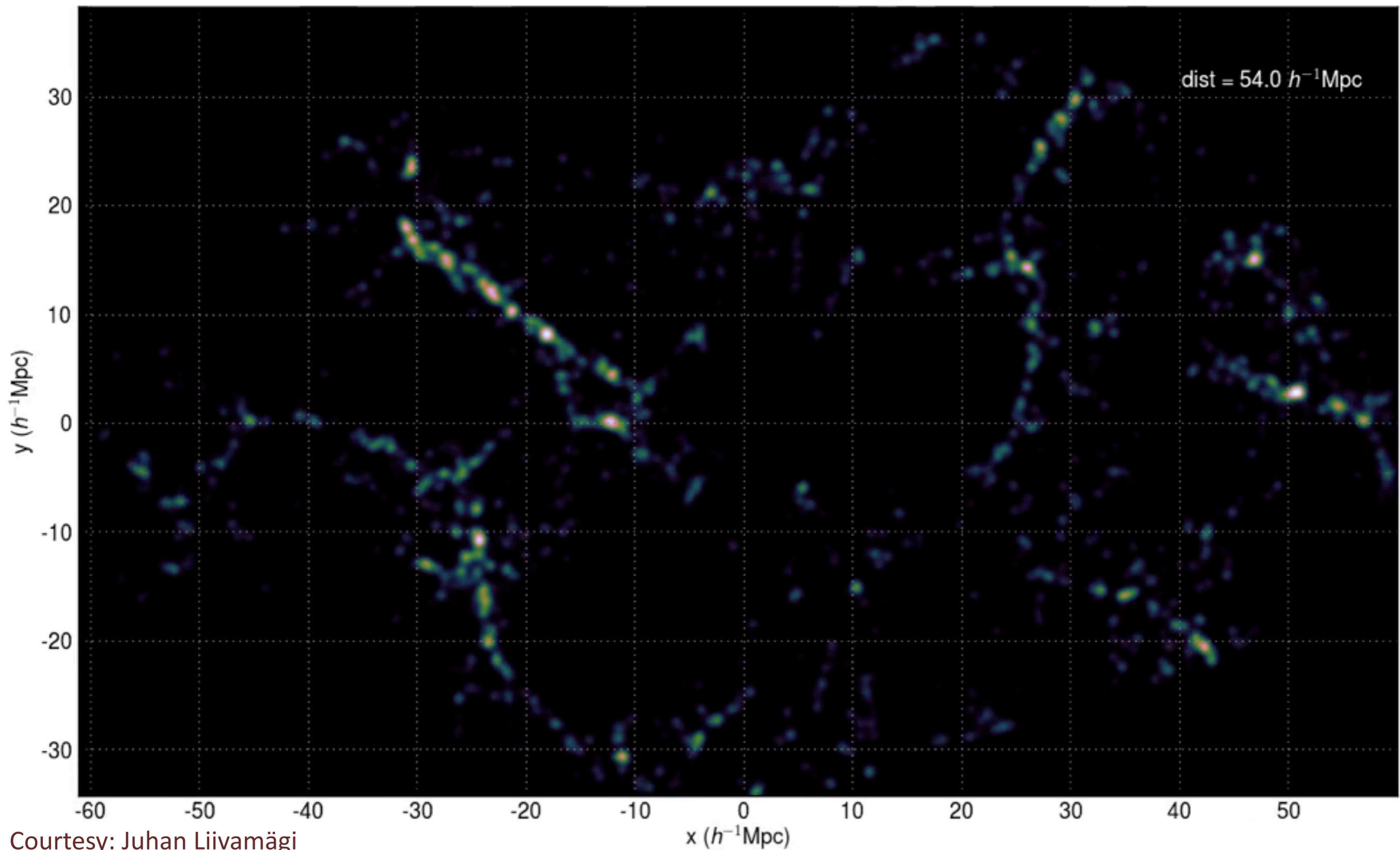
arXiv:1308.2533 “Detecting filamentary pattern in the cosmic web: a catalogue of filaments for the SDSS”

- ✦ The distribution of galaxies along galaxy filaments to search for regularities in galaxy and group distributions.

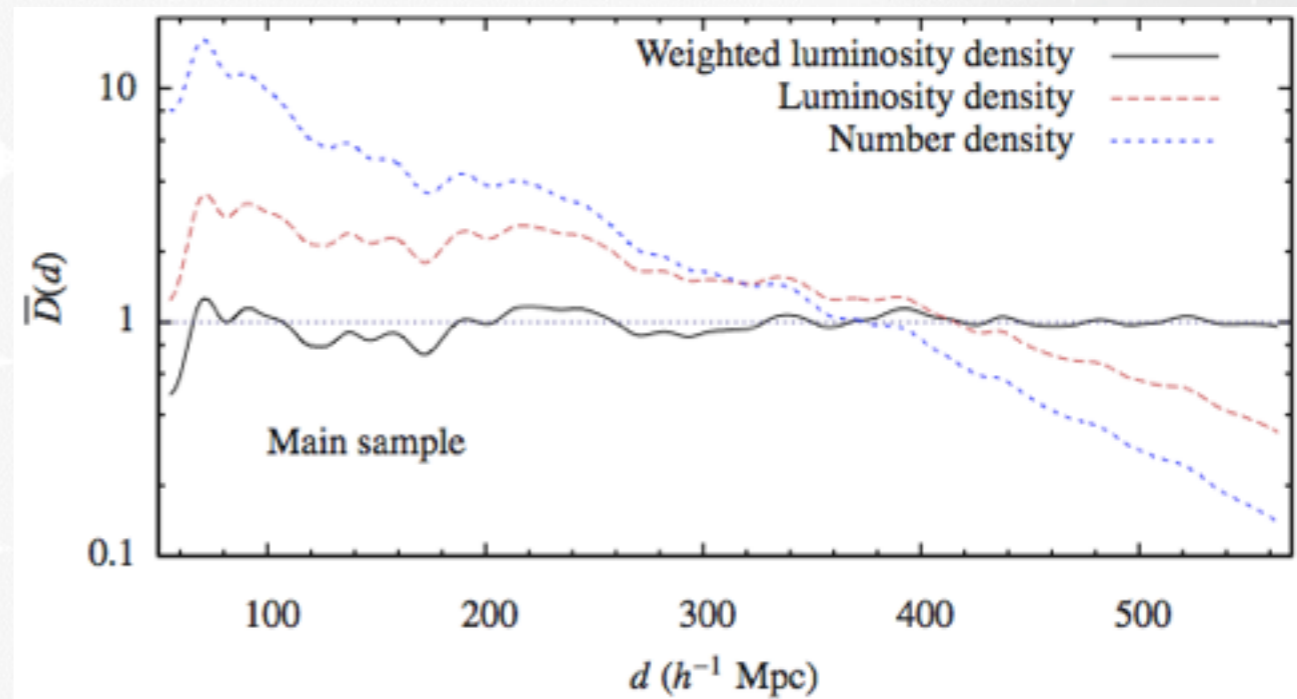
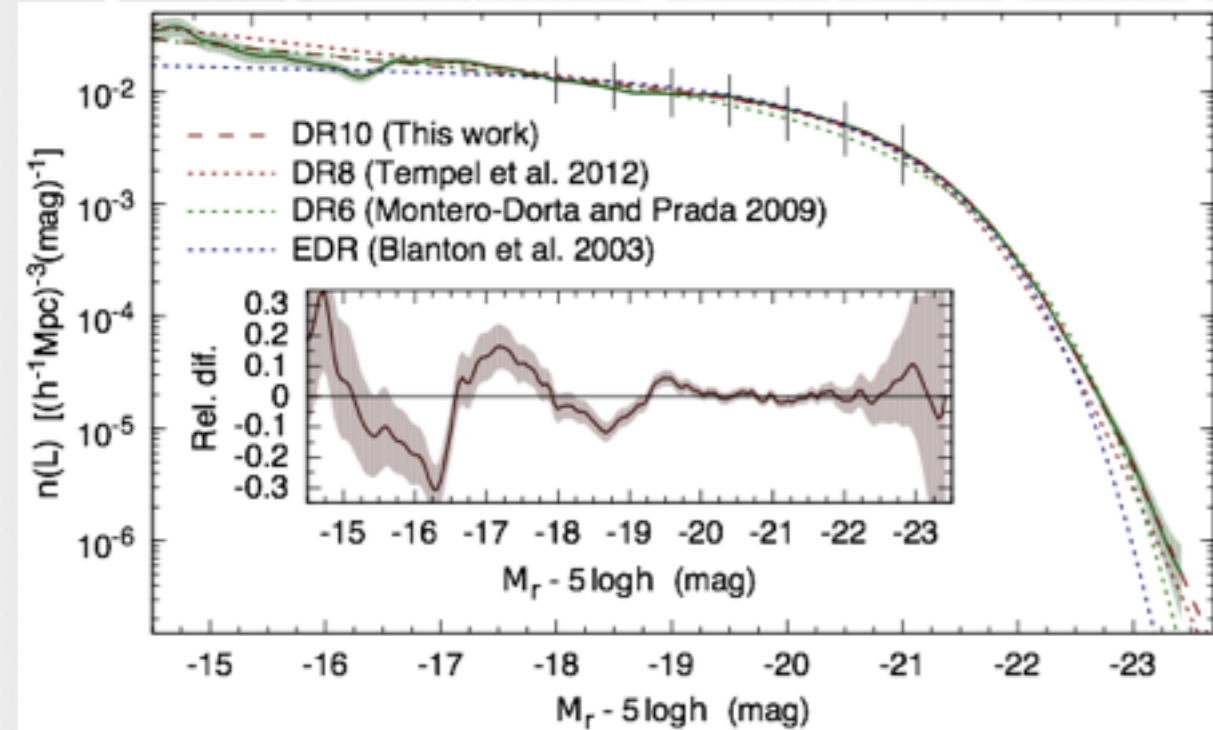
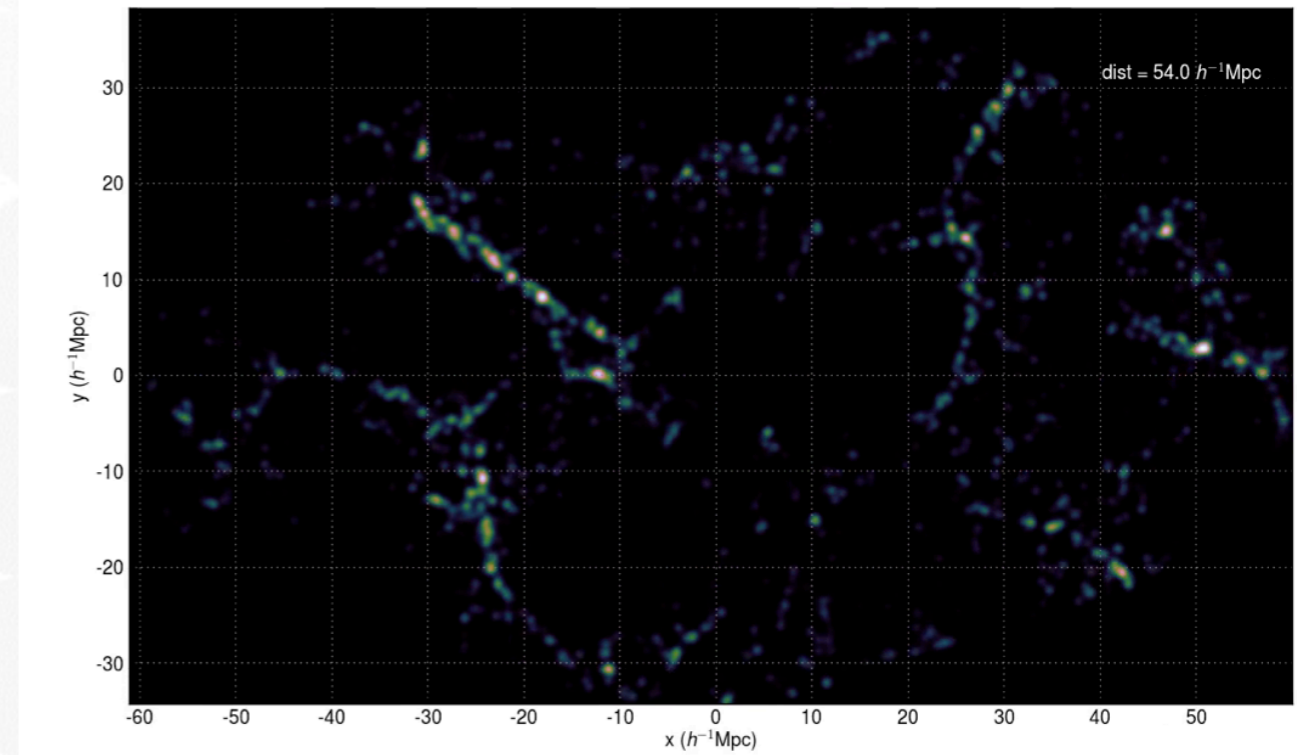
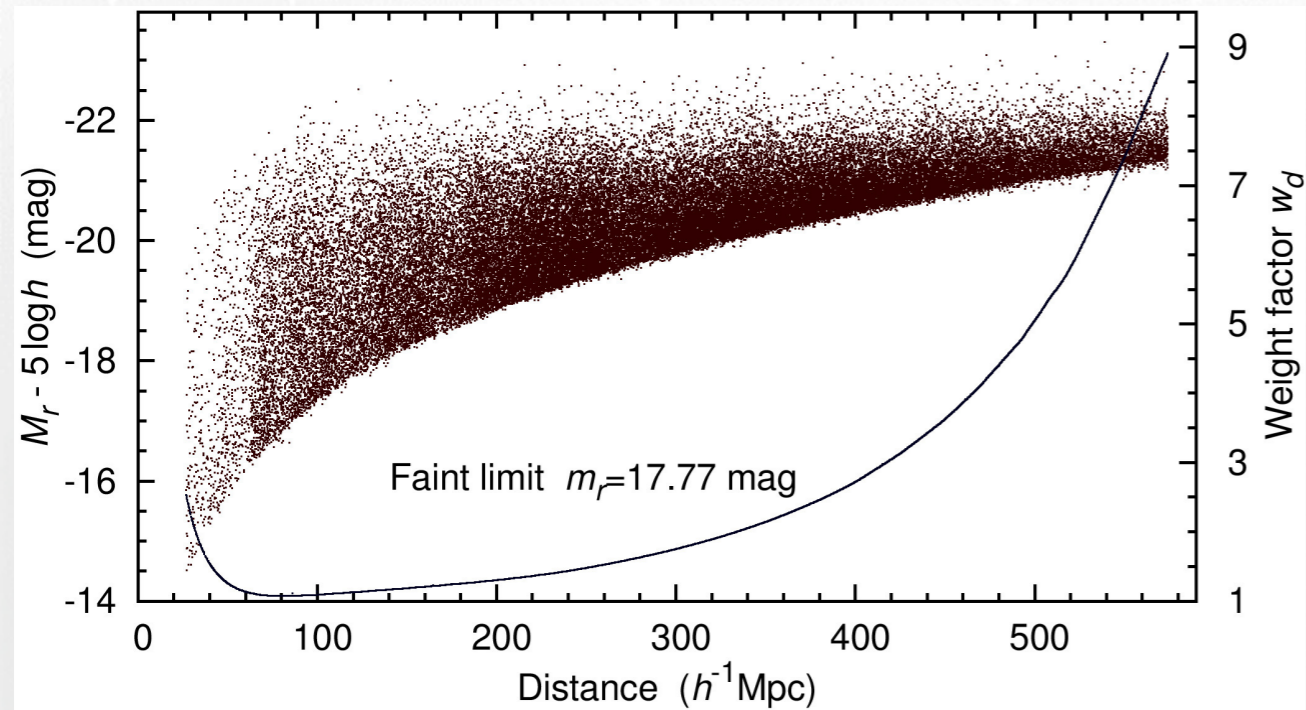
arXiv:1406.4357 “Galaxy filaments as pearl necklaces”



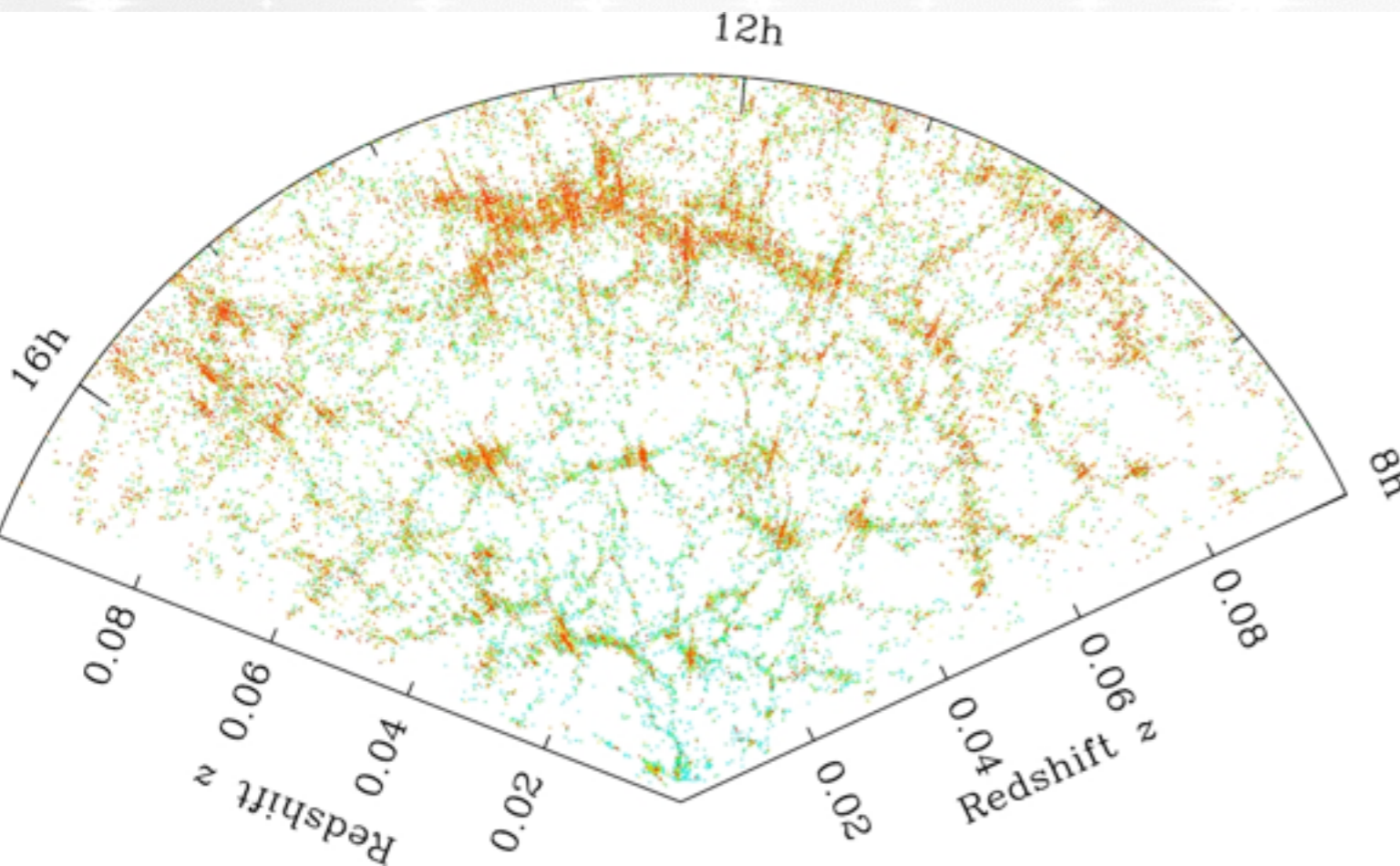
Observations: SDSS



Observations: selection effects (1)

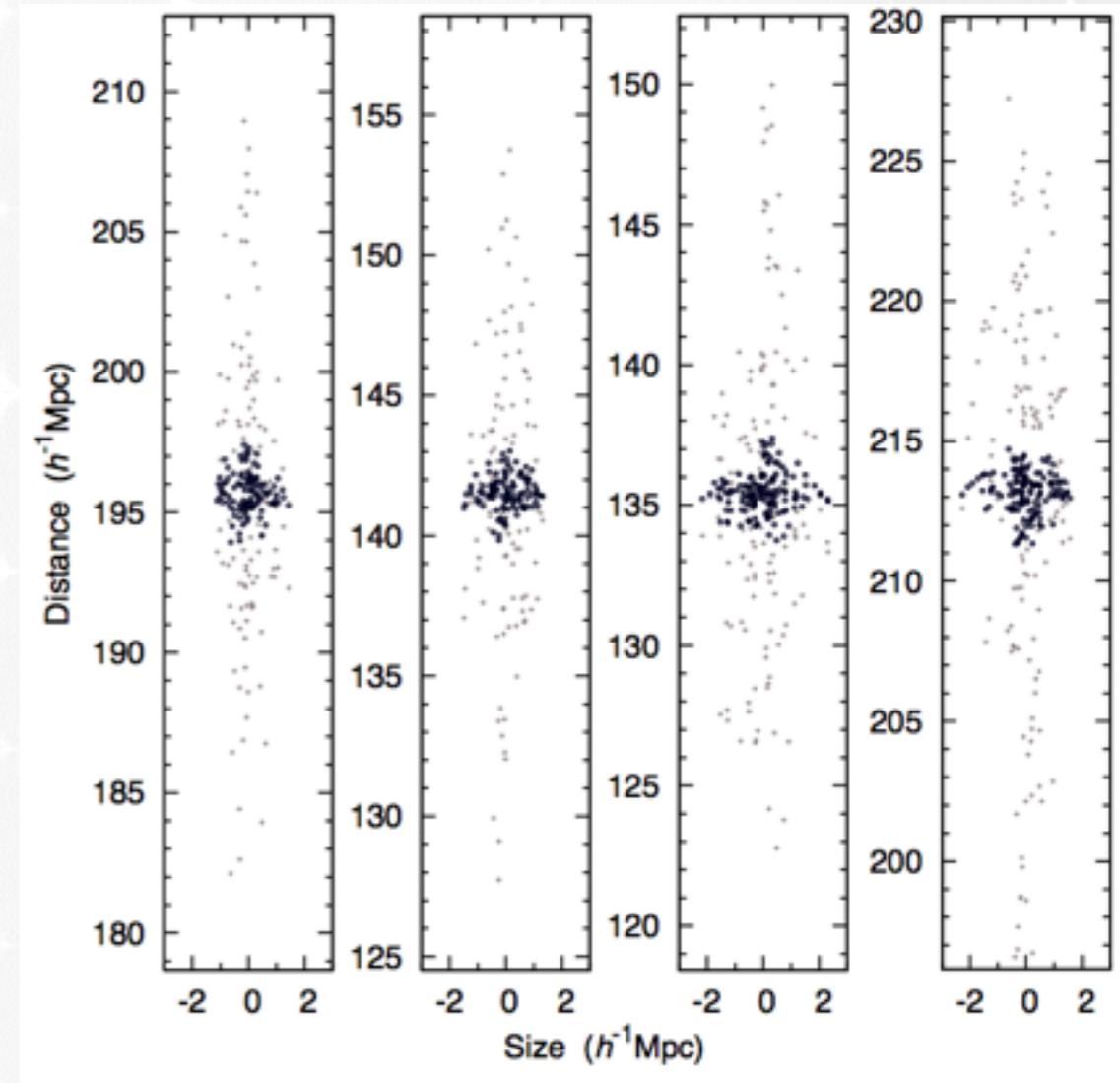


Observations: selection effects (2)



Finger-of-god effect:

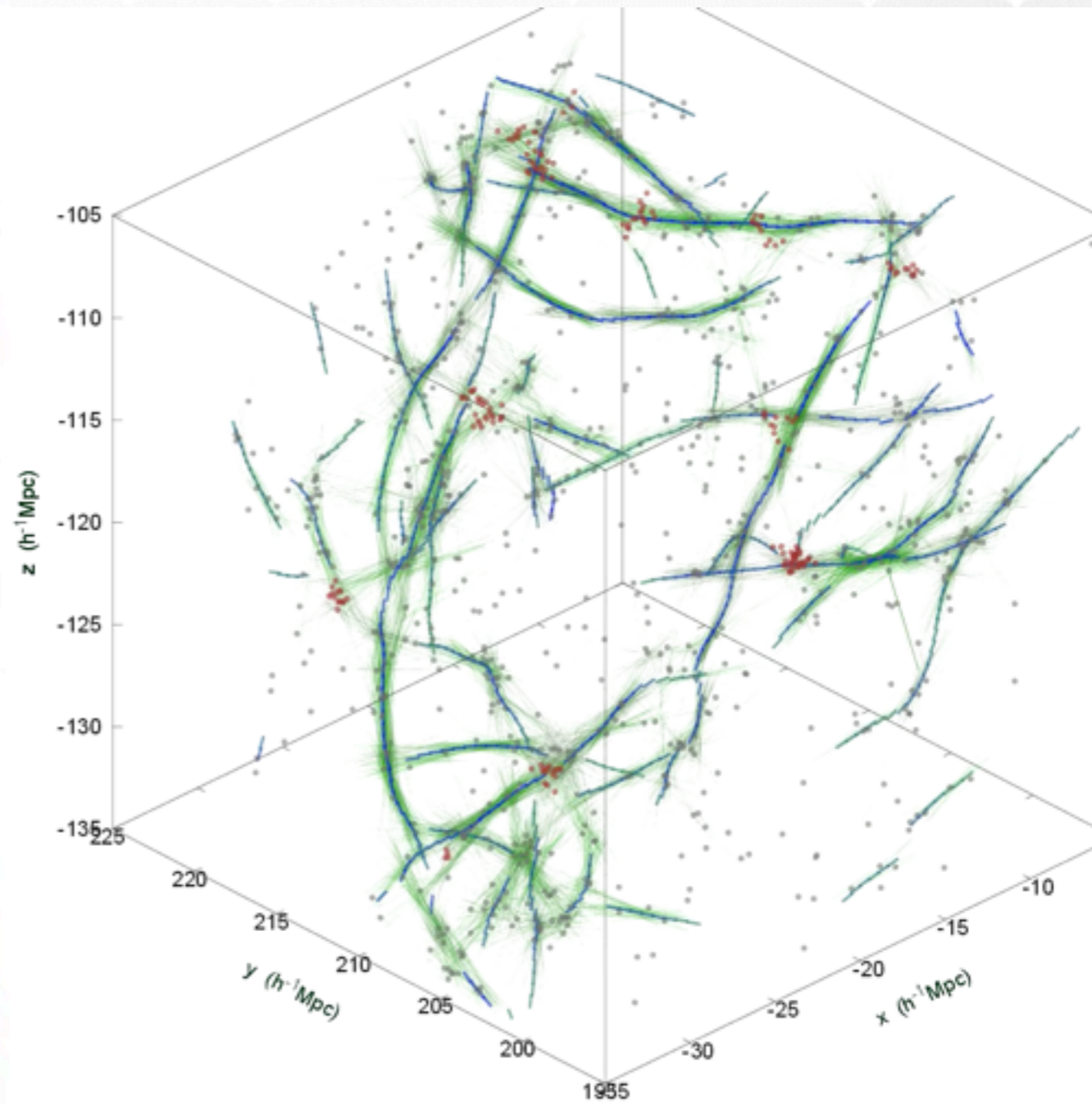
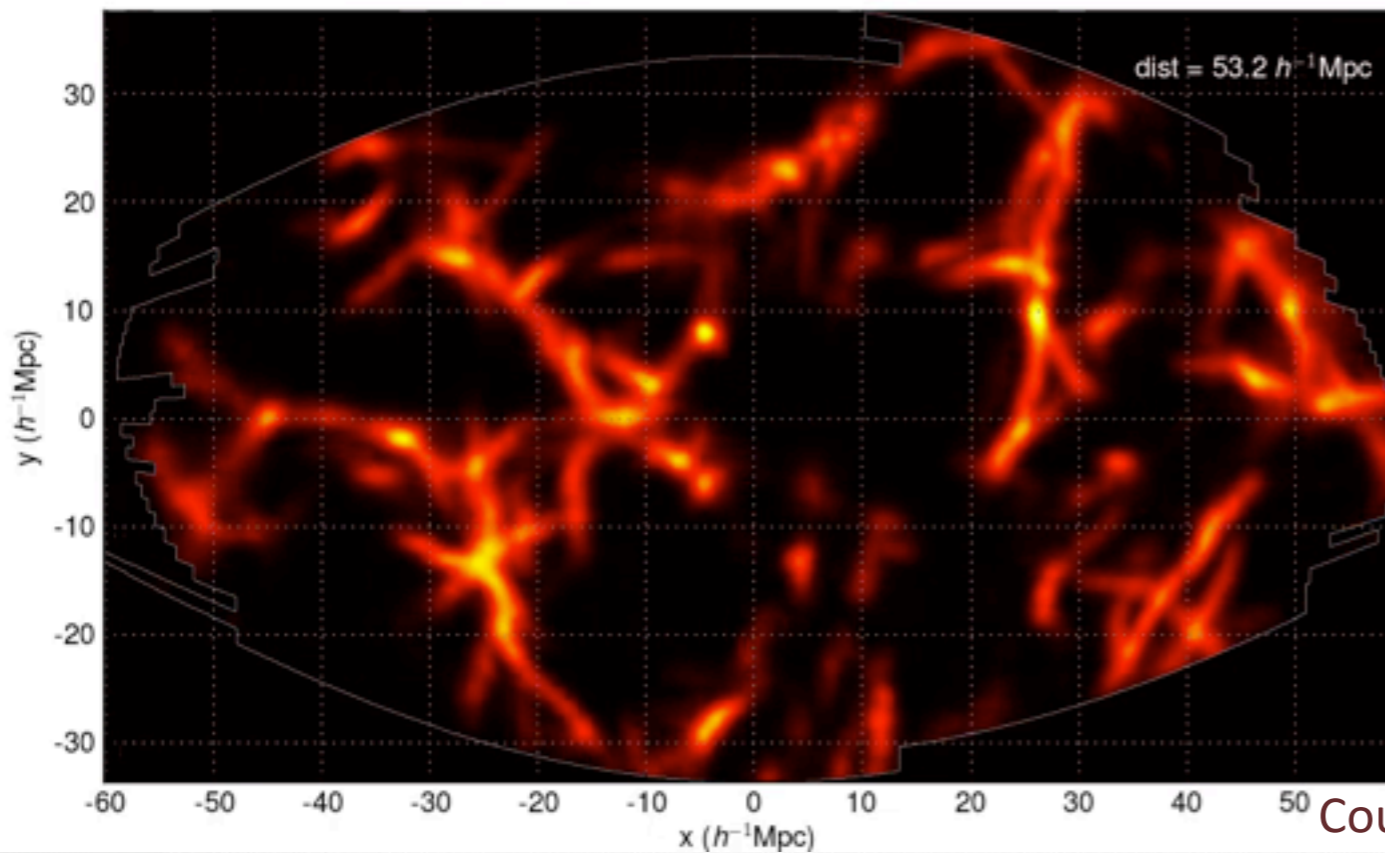
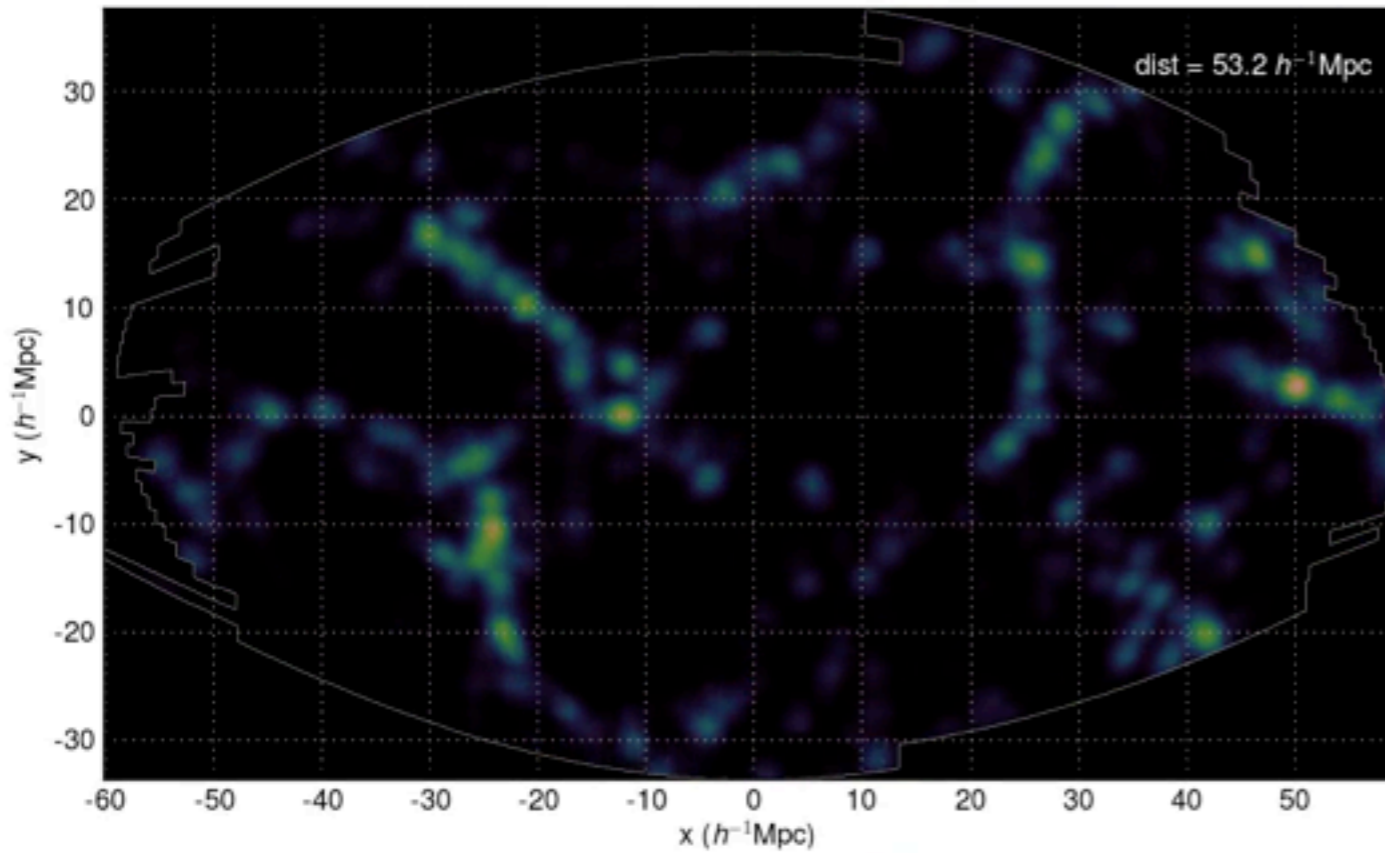
Tully & Fisher (1978), IAU Symposium 79,
Large Scale Structures in the Universe,
Tallinn, September 12-16, 1977



Tempel et al. (2012)

Using friends-of-friends galaxy groups,
we suppress the finger-of-god distortions.

Detected filamentary pattern



Tempel et al. (2014)

Courtesy: Juhan Liivamägi

Marked point process (Bisous model)

- ✦ The key idea is to see the filamentary network as an object point process.
- ✦ Cylinders are simplest objects to define a piece of filament.
- ✦ Interactions help to form a network.
- ✦ Metropolis-Hastings algorithm (together with simulated annealing) to sample probability distribution.

Stoica et al. (2003, 2005)

Stoica, Martinez, Saar (2007, 2010)

Tempel et al. (2014), arxiv:1308.2533

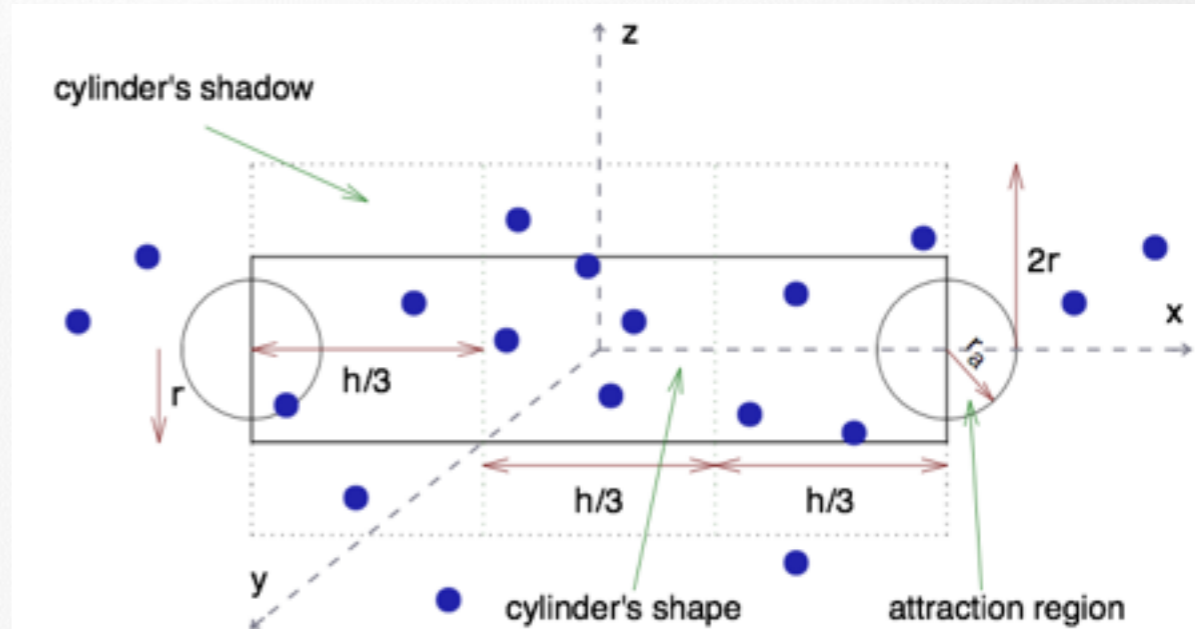


Figure 1. Two-dimensional projection of a cylinder with its shadow within a pattern of galaxies. The attraction regions are shown as spheres. The exact shape of the cylinder, its shadow and attraction regions depend on the model.

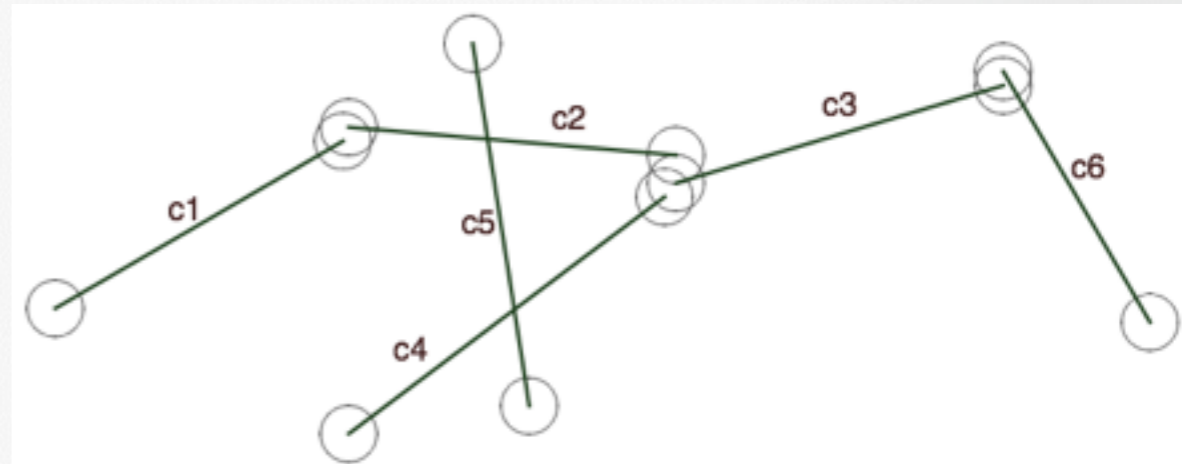
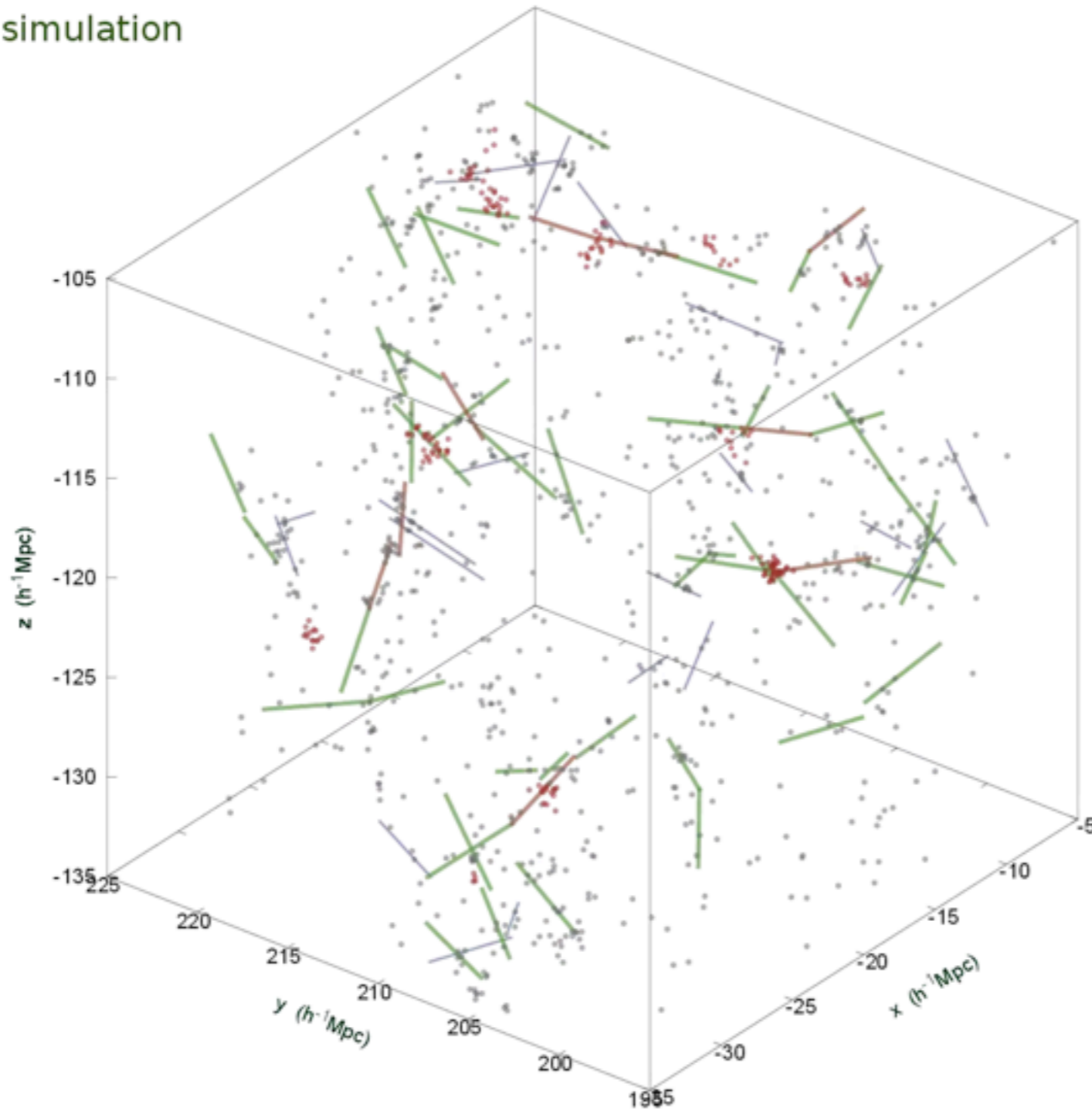


Figure 2. Two dimensional representation of cylinder configuration: attraction regions are shown with spheres. In this configuration...

Bisous model in action

Single MCMC simulation

- 0-connected cylinders
- 1-connected cylinders
- 2-connected cylinders
- Galaxies
- Galaxies in groups



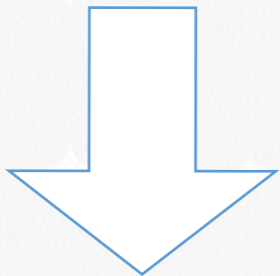


Bisous model: key questions

- ✦ What is the local definition for a filament?
- ✦ How connected is the filamentary network?
- ✦ What is the scale of galactic filaments?
- ✦ How to describe the multi-scale nature of filaments?

Extracting filament spines

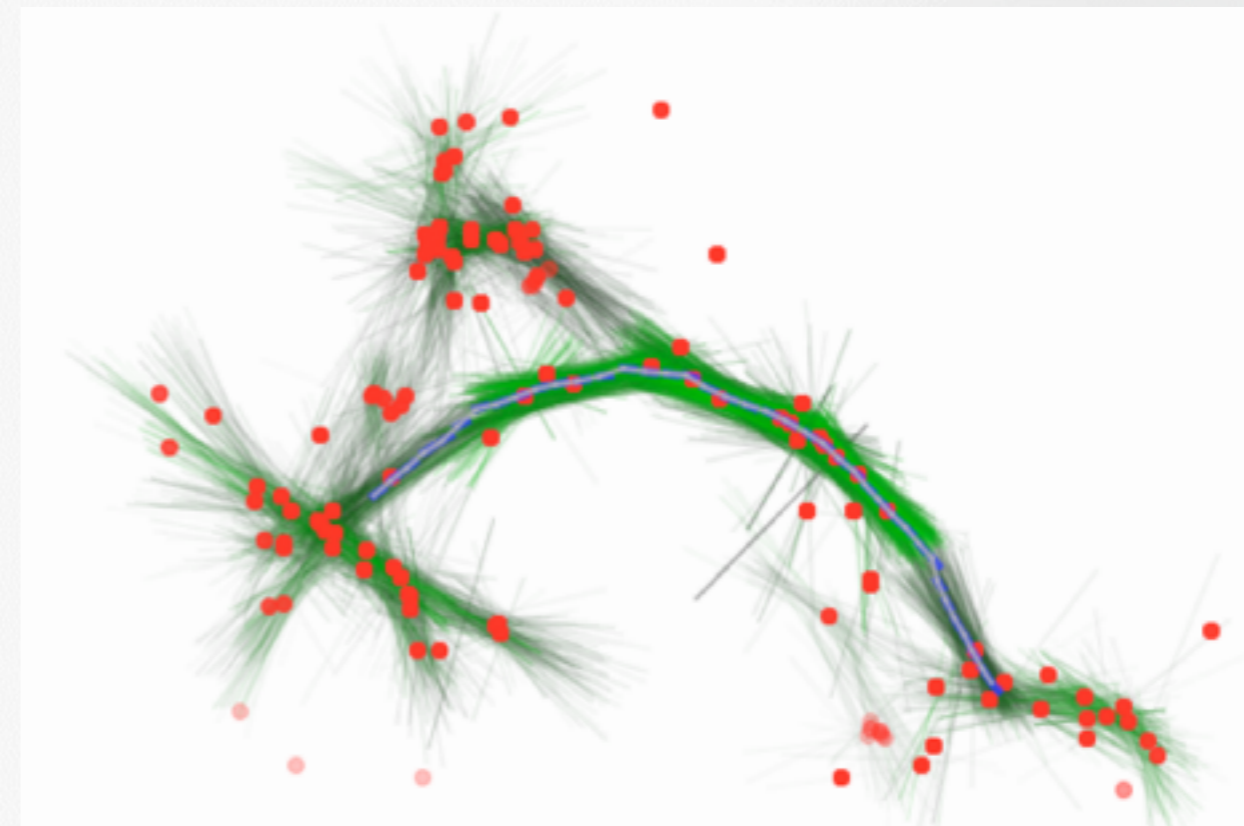
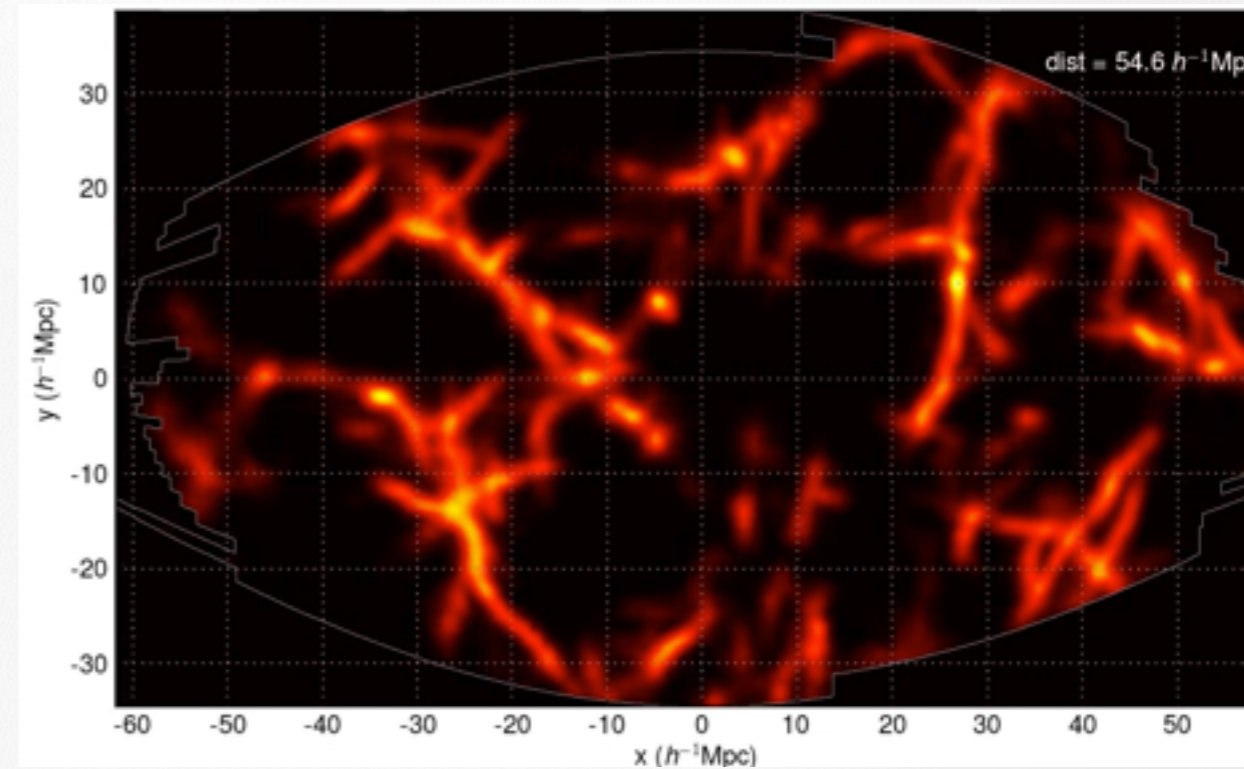
- ✦ Bisous model: set of simulations (50 simulations)
- ✦ Many independent realisations in every simulation



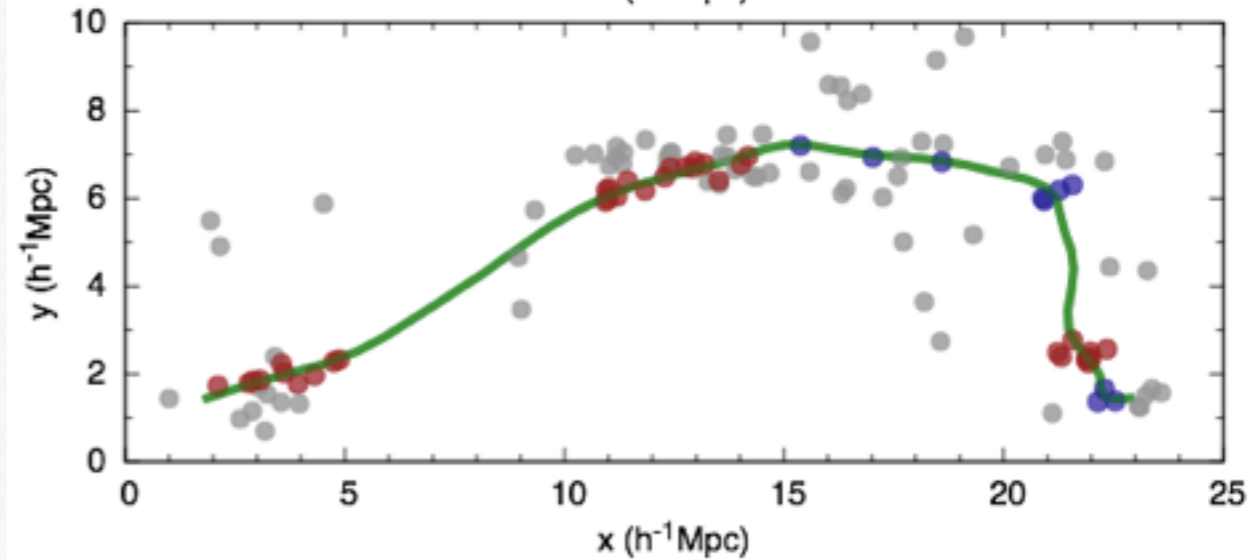
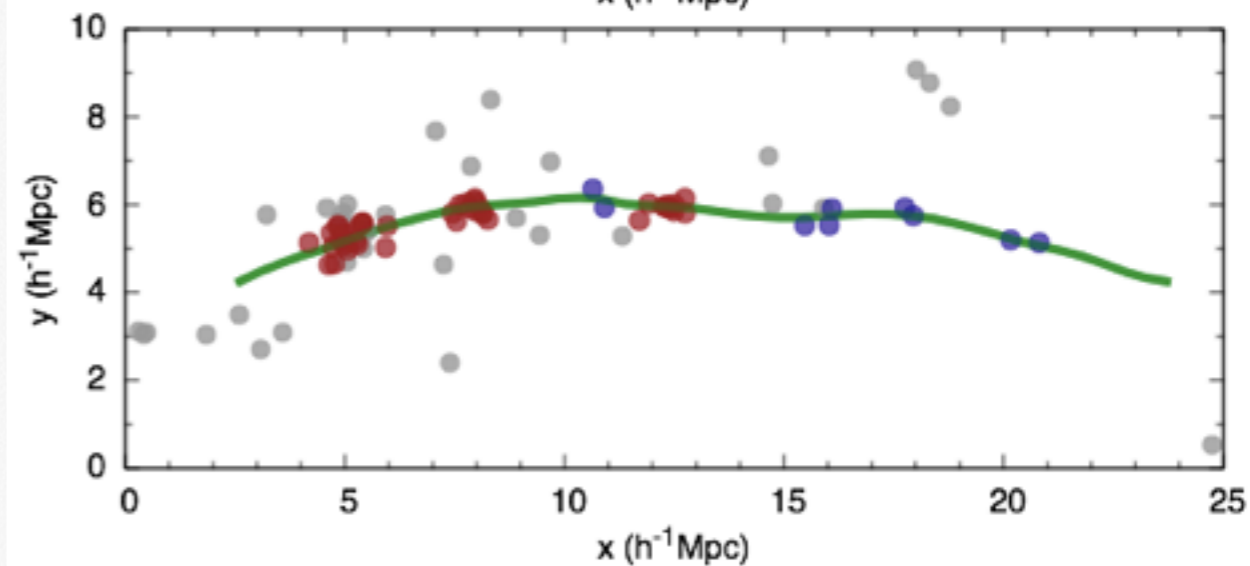
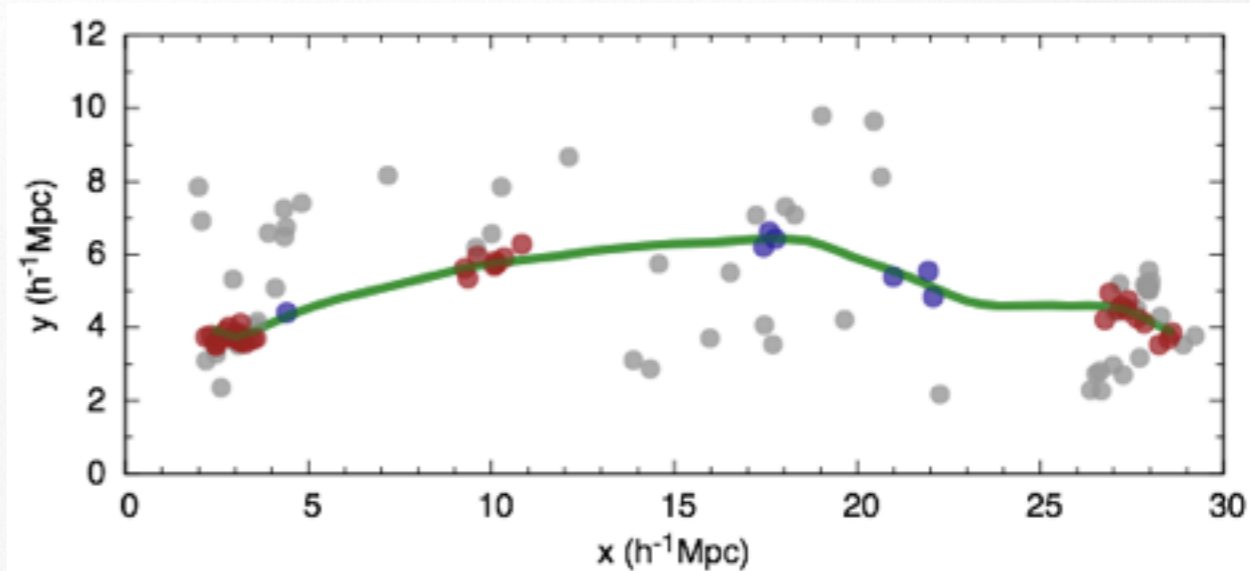
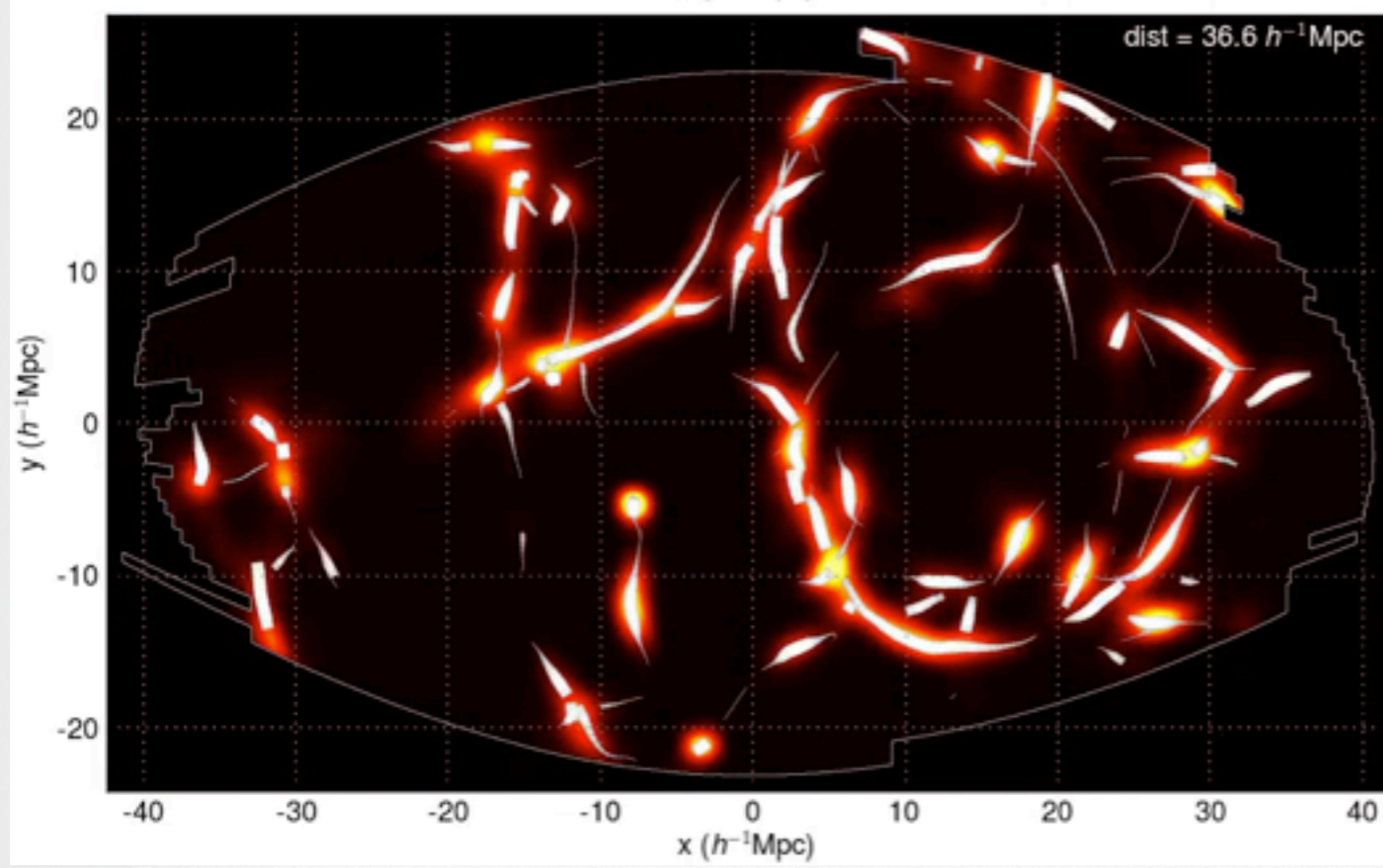
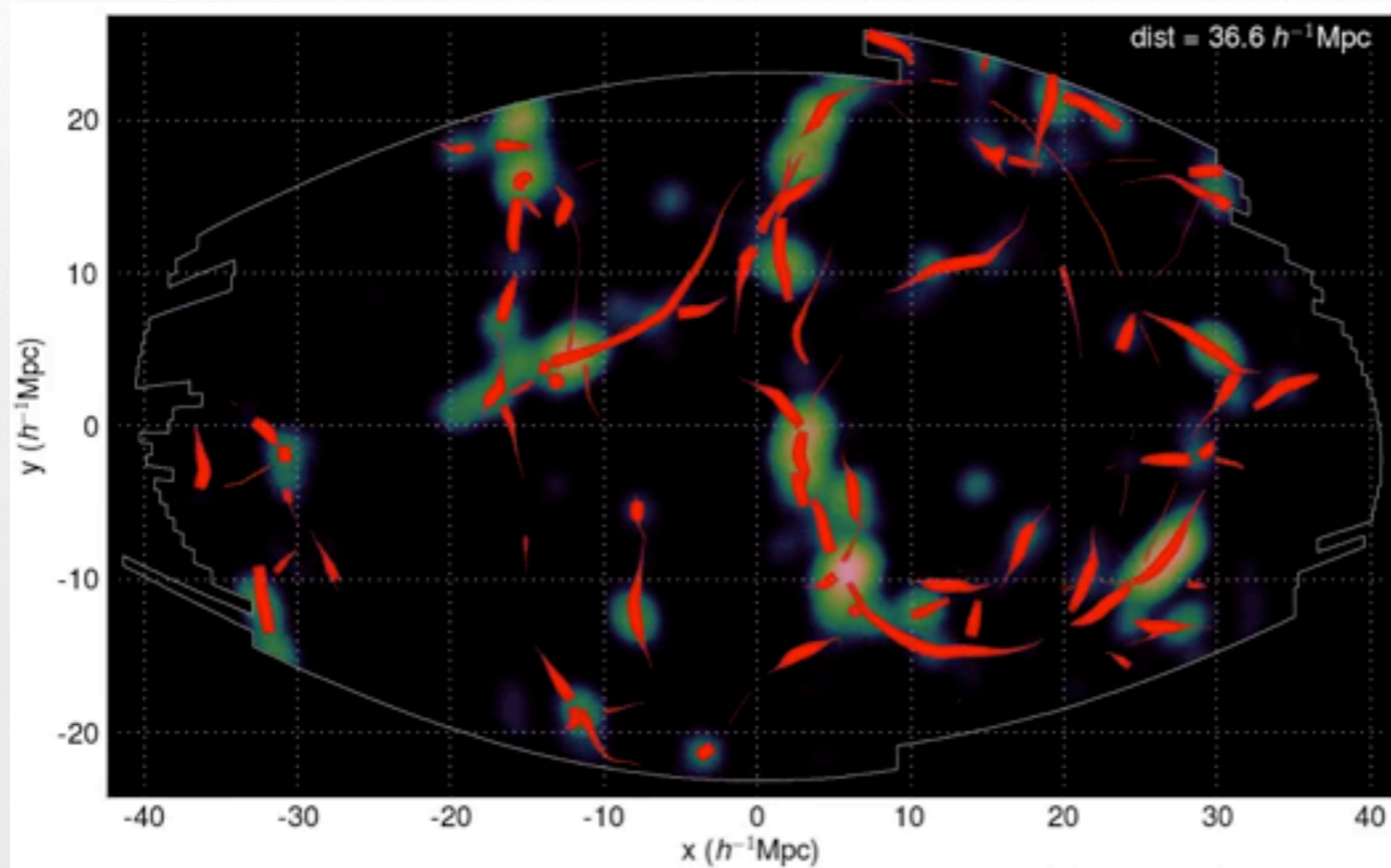
- ✦ Density field of filaments
- ✦ Orientation field of filaments



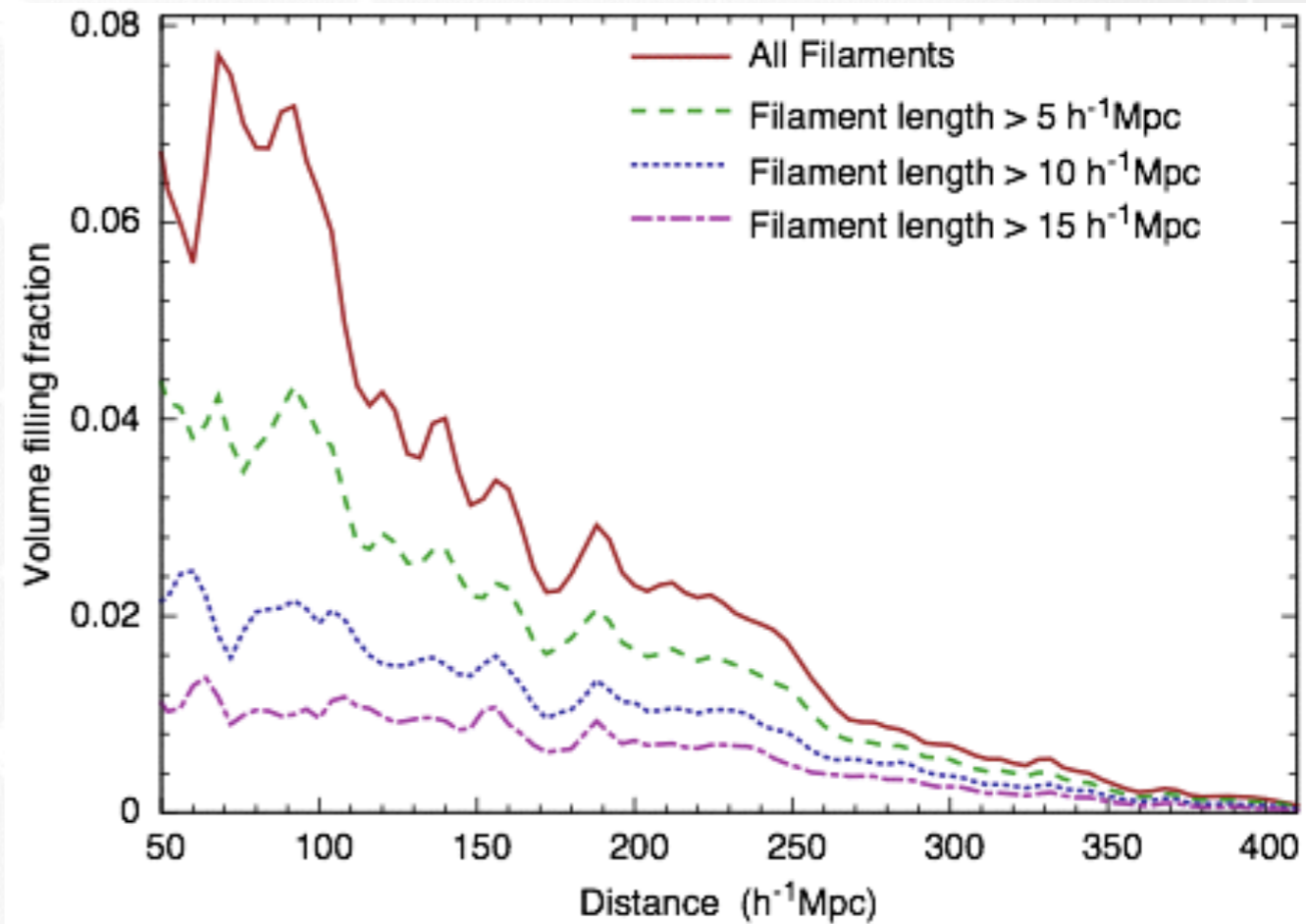
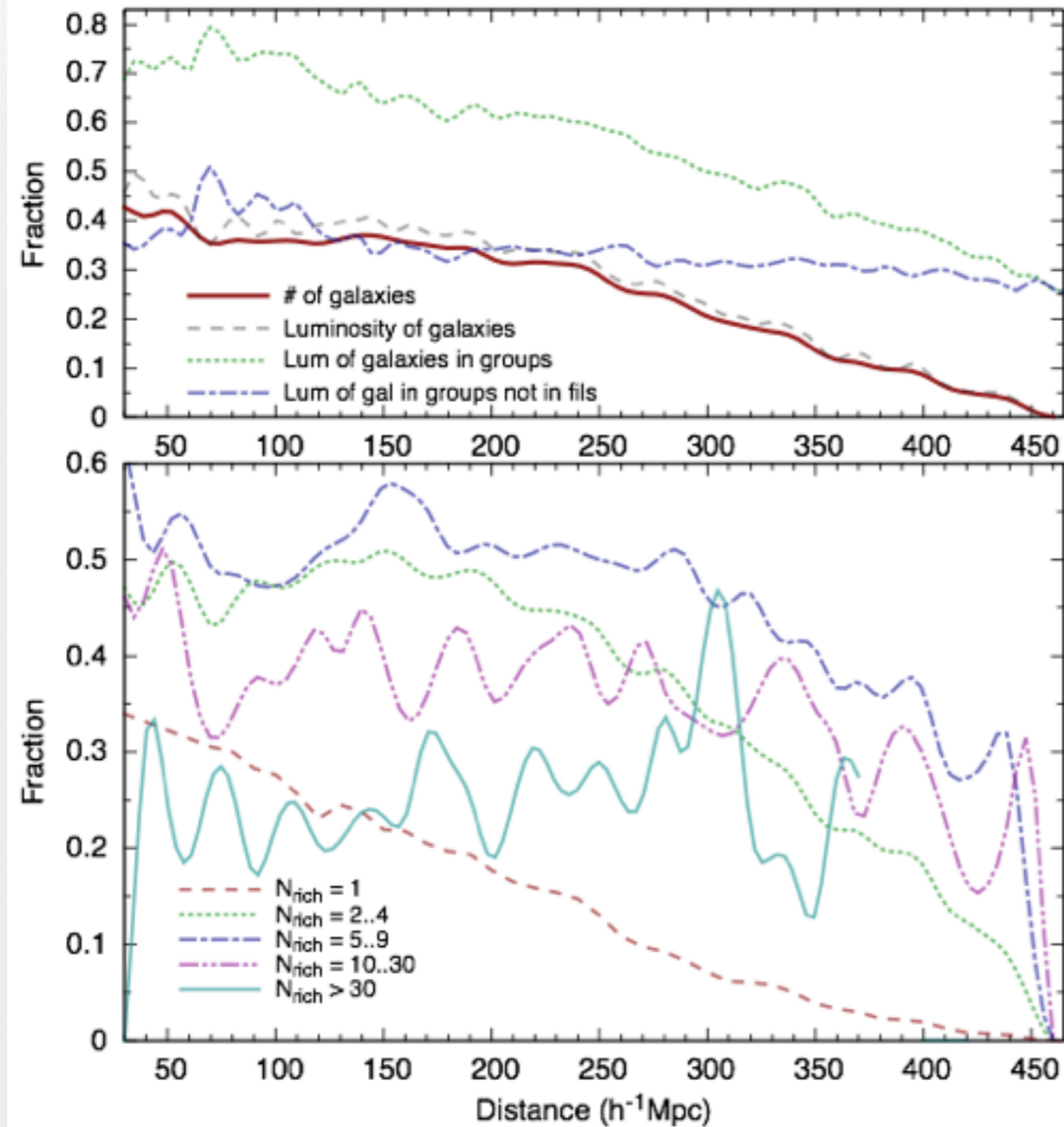
- ✦ Single filament spines



Detected filament spines



A catalogue of filaments for the SDSS



Tempel et al. (2014), arxiv:1308.2533

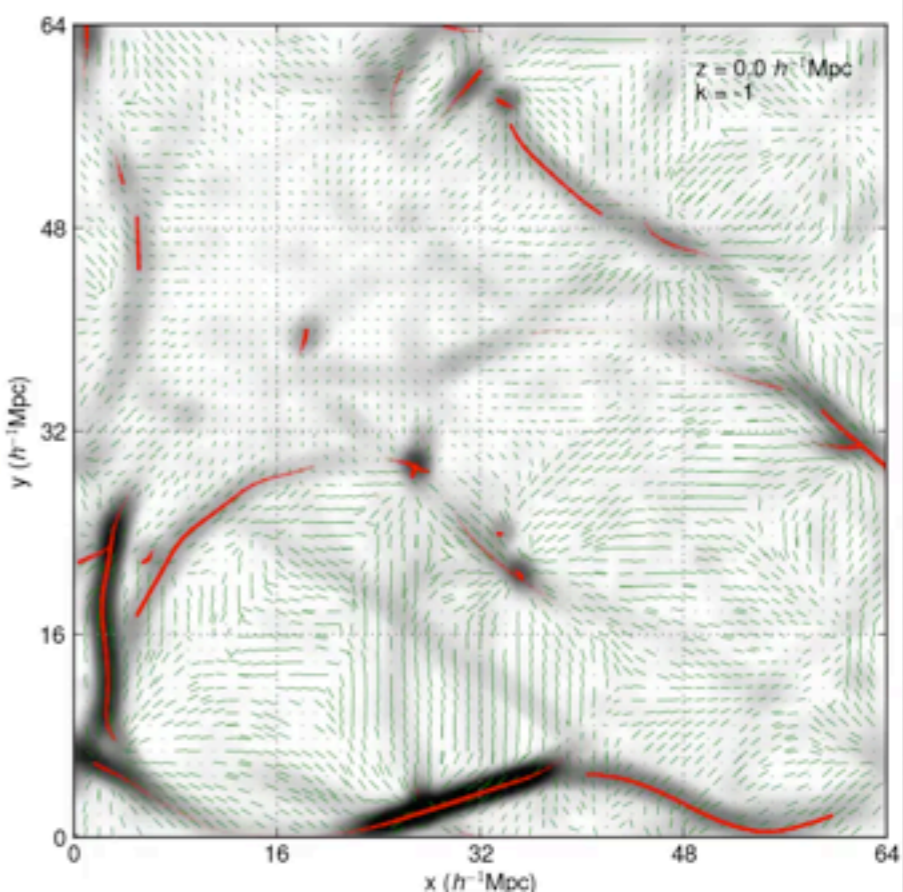
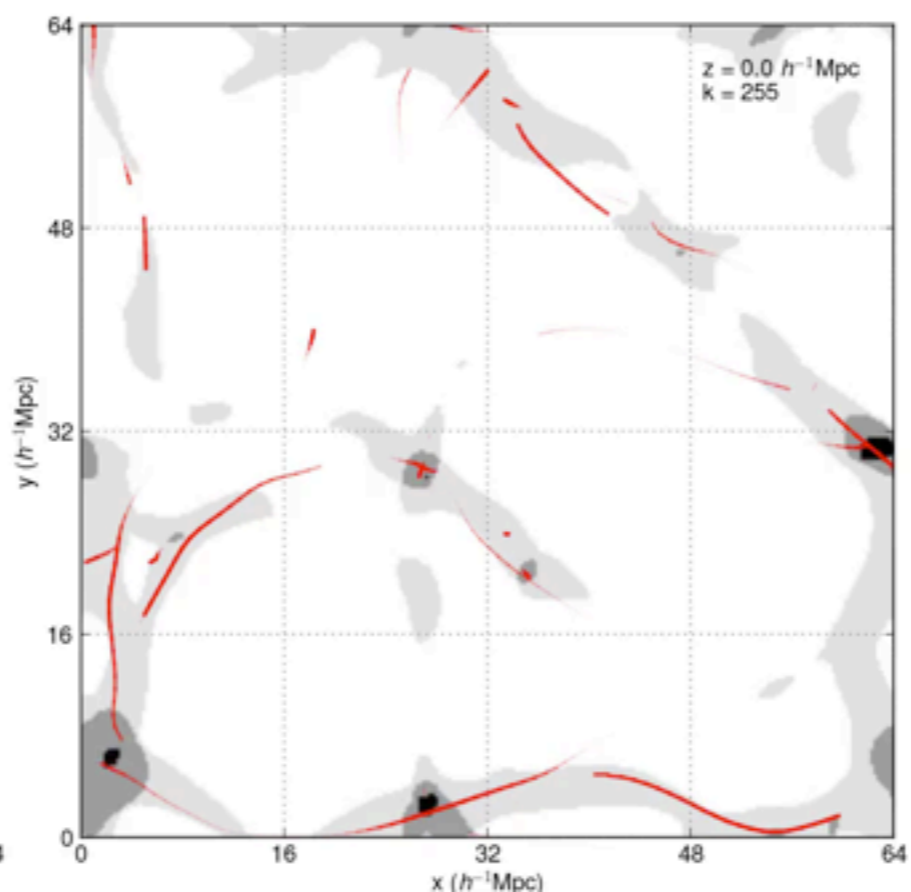
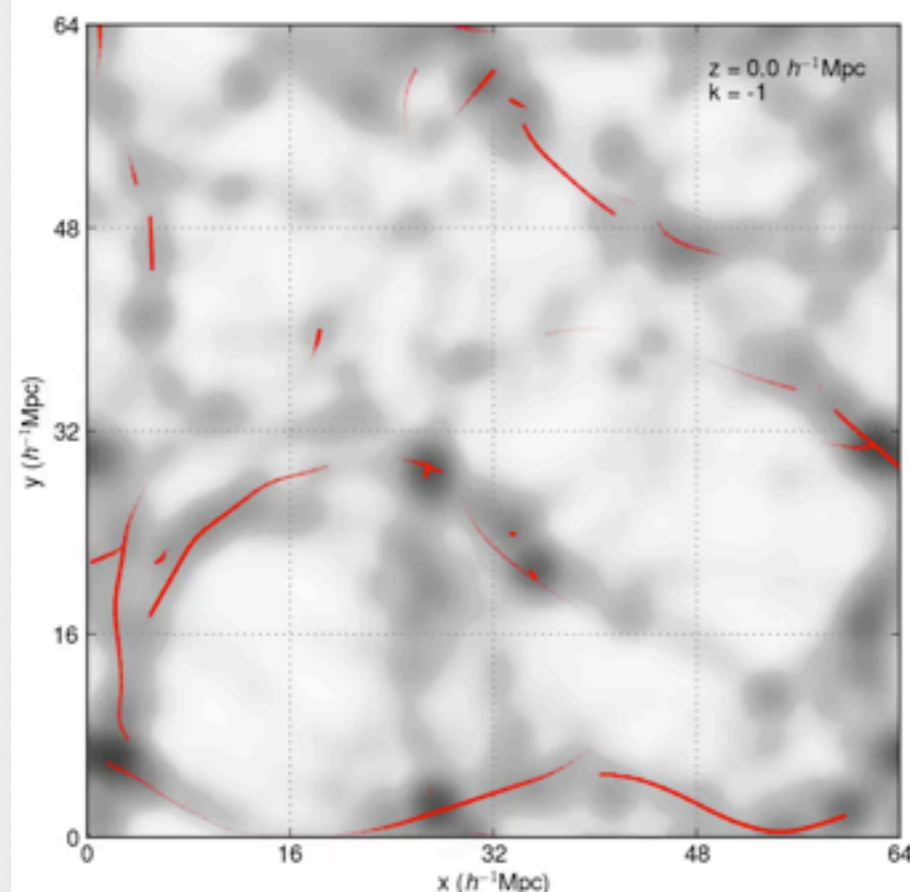
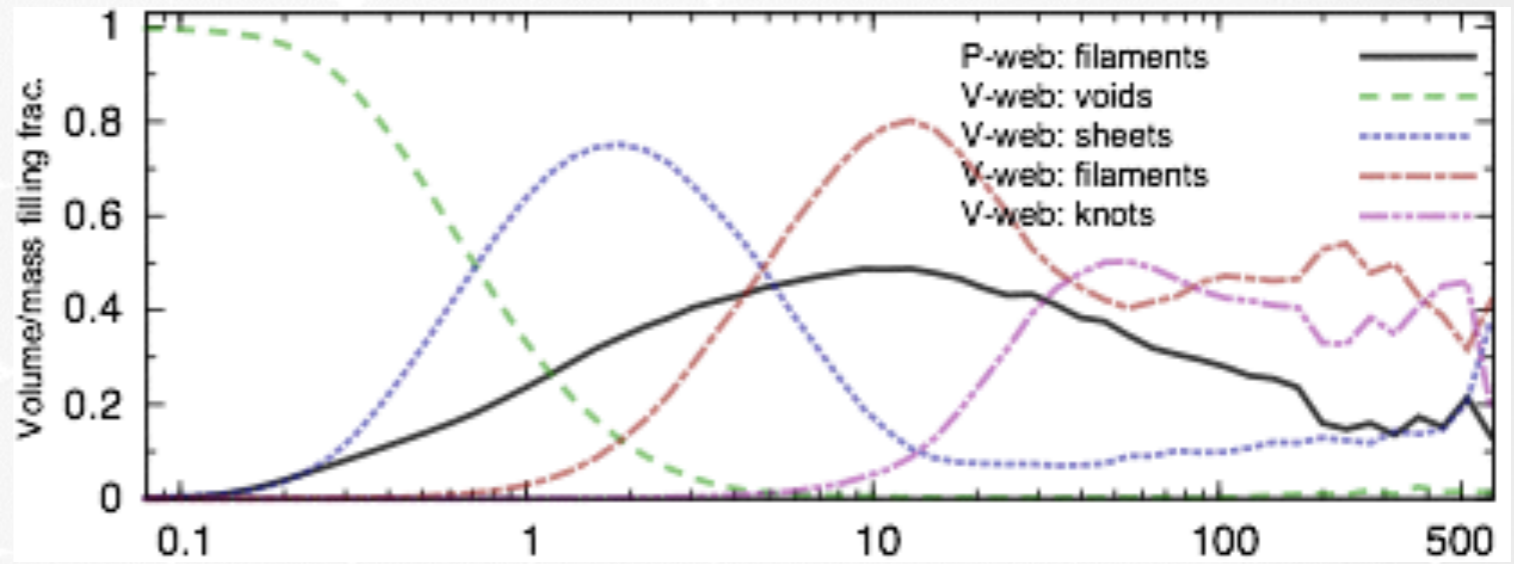
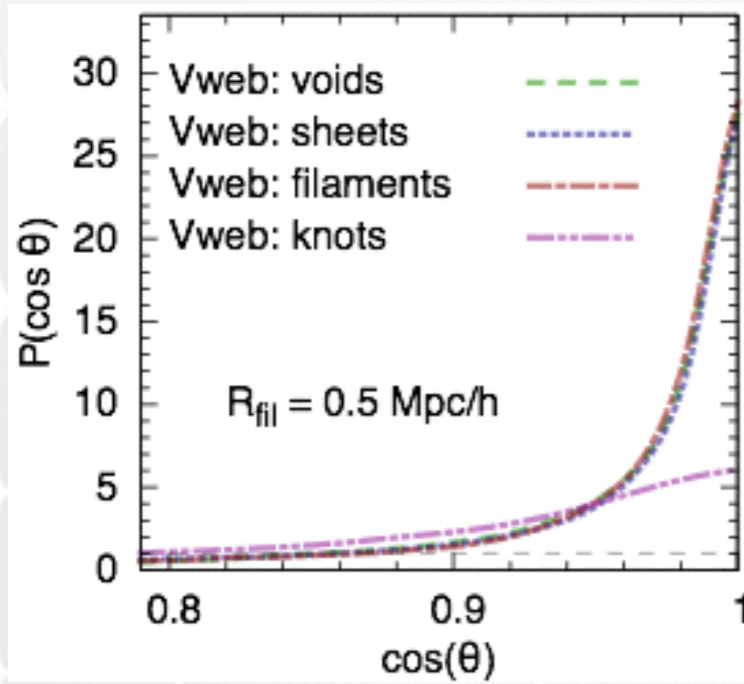
<http://cosmodb.to.ee>



Applications of filamentary network

Orientation of cosmic web filaments with respect to the underlying velocity field

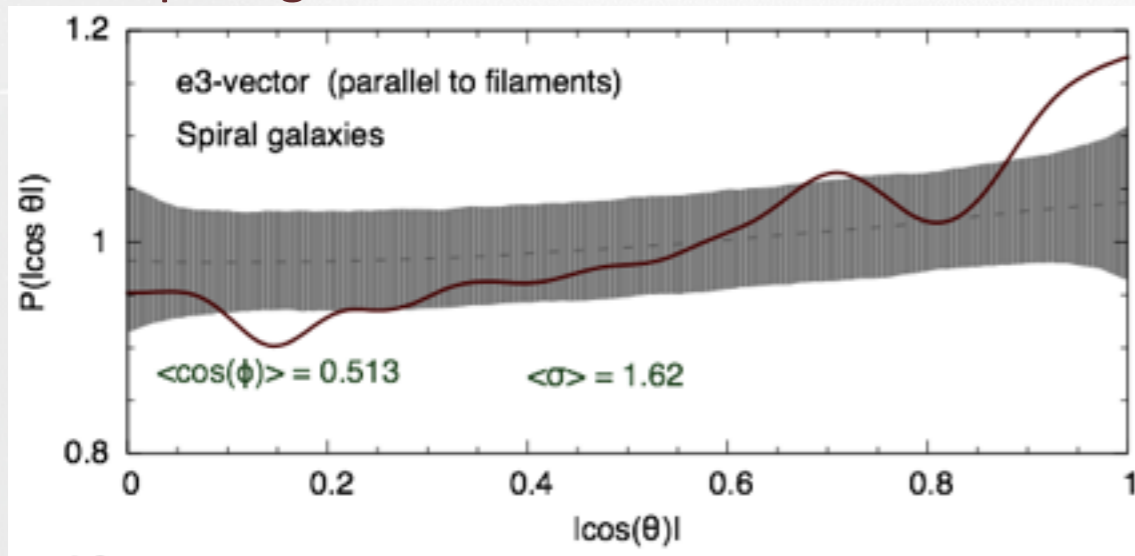
Tempel, Libeskind, Hoffmann et al. (2014)



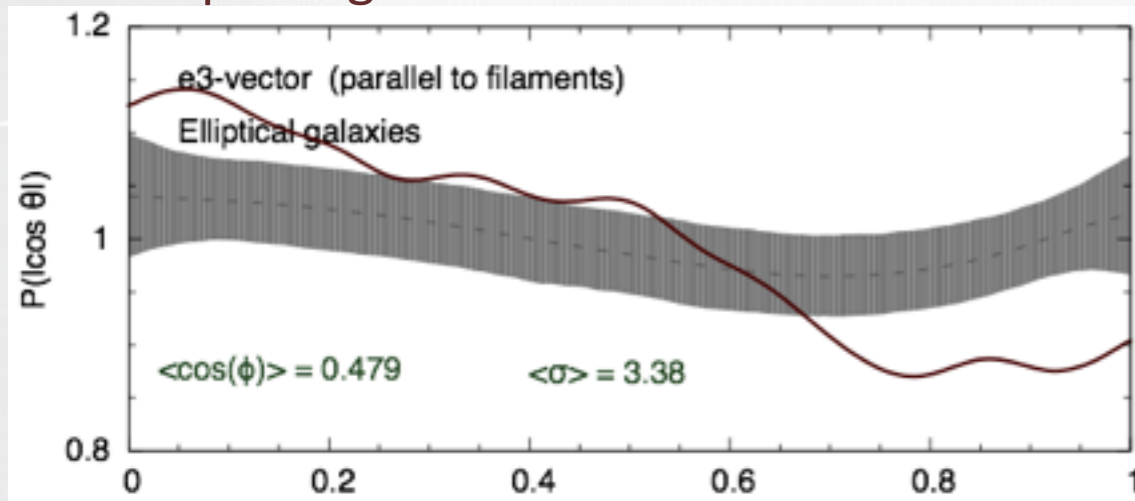
Galaxy Spin Alignment in Filaments: Observational Evidence

Tempel & Libeskind (2013); Tempel, Stoica & Saar (2013)

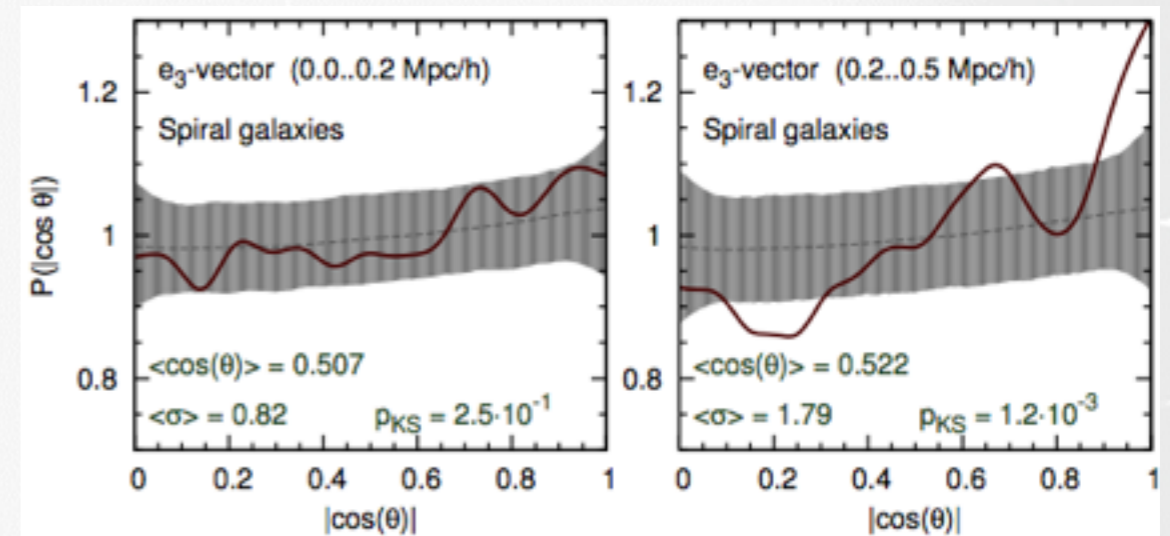
Spiral galaxies



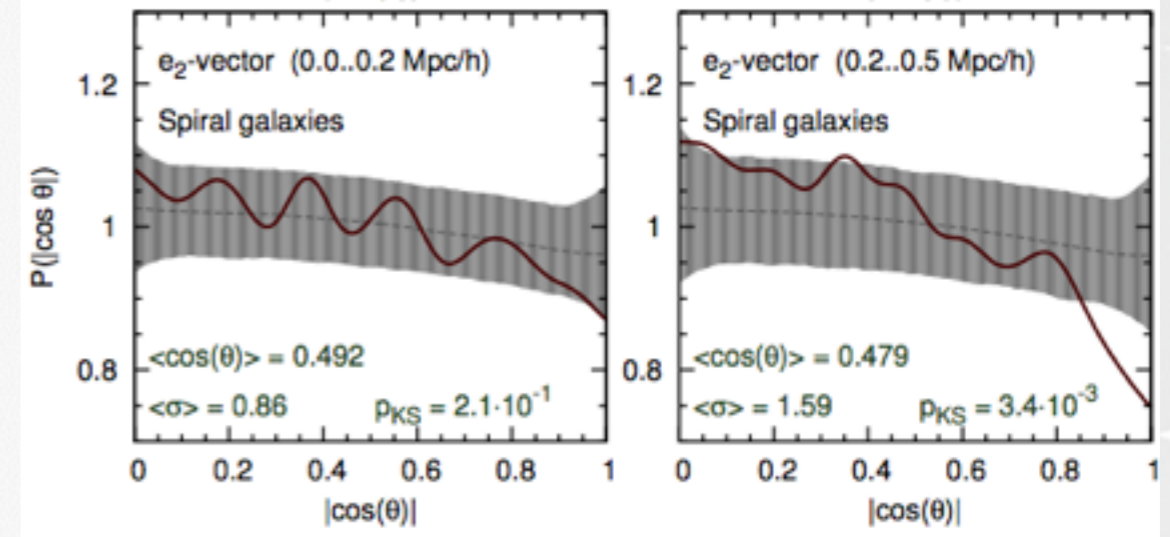
Elliptical galaxies



Inner part



Outer part

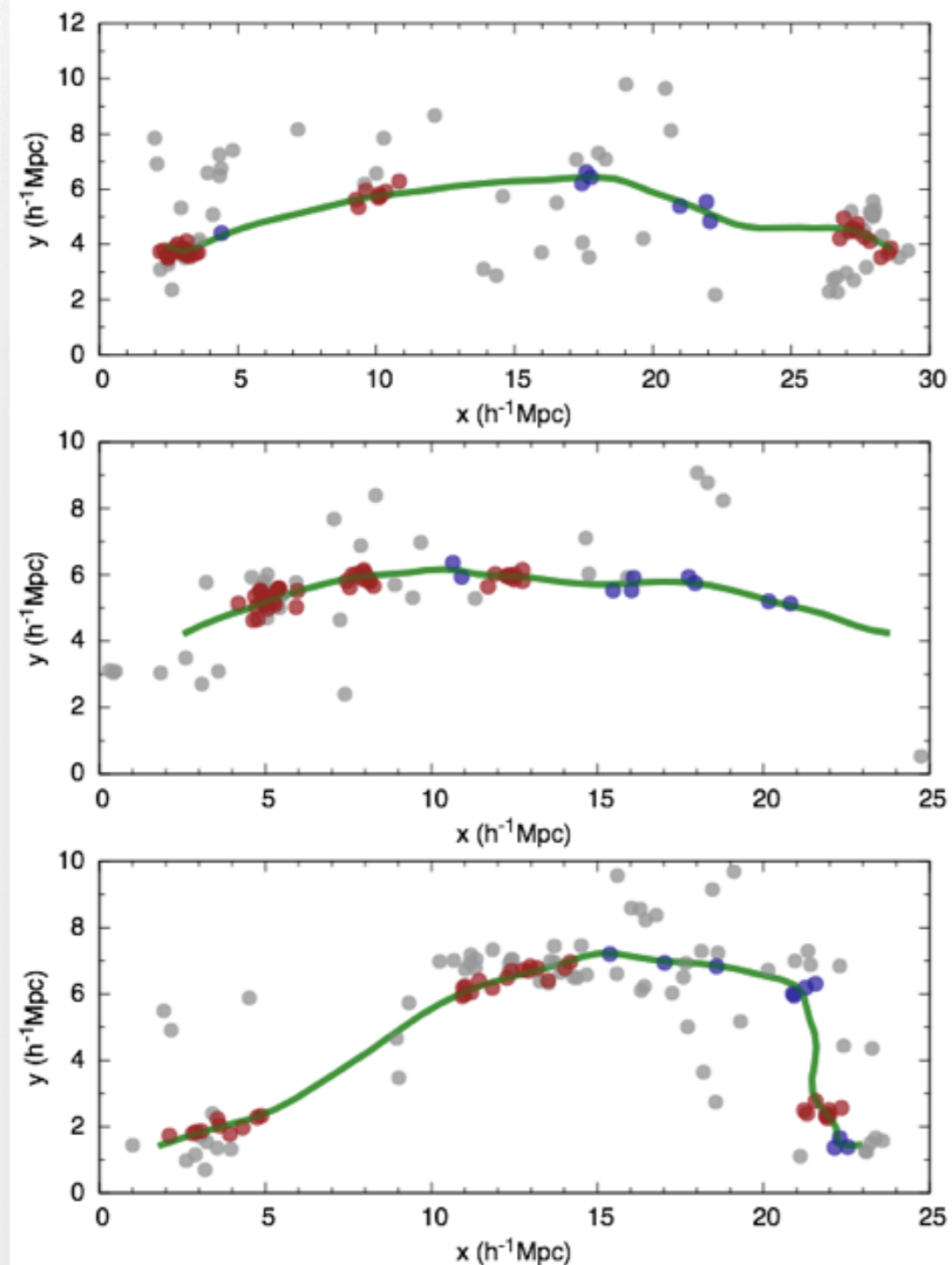




Galaxy filaments as pearl necklaces

Tempel et al. (2014), arXiv:1406.4357

Data and methods



Pair correlation function:

$$\widehat{\xi}(r) = 1 + \frac{DD(r)}{RR(r)} - 2\frac{DR(r)}{RR(r)},$$

Rayleigh Z-squared statistics:

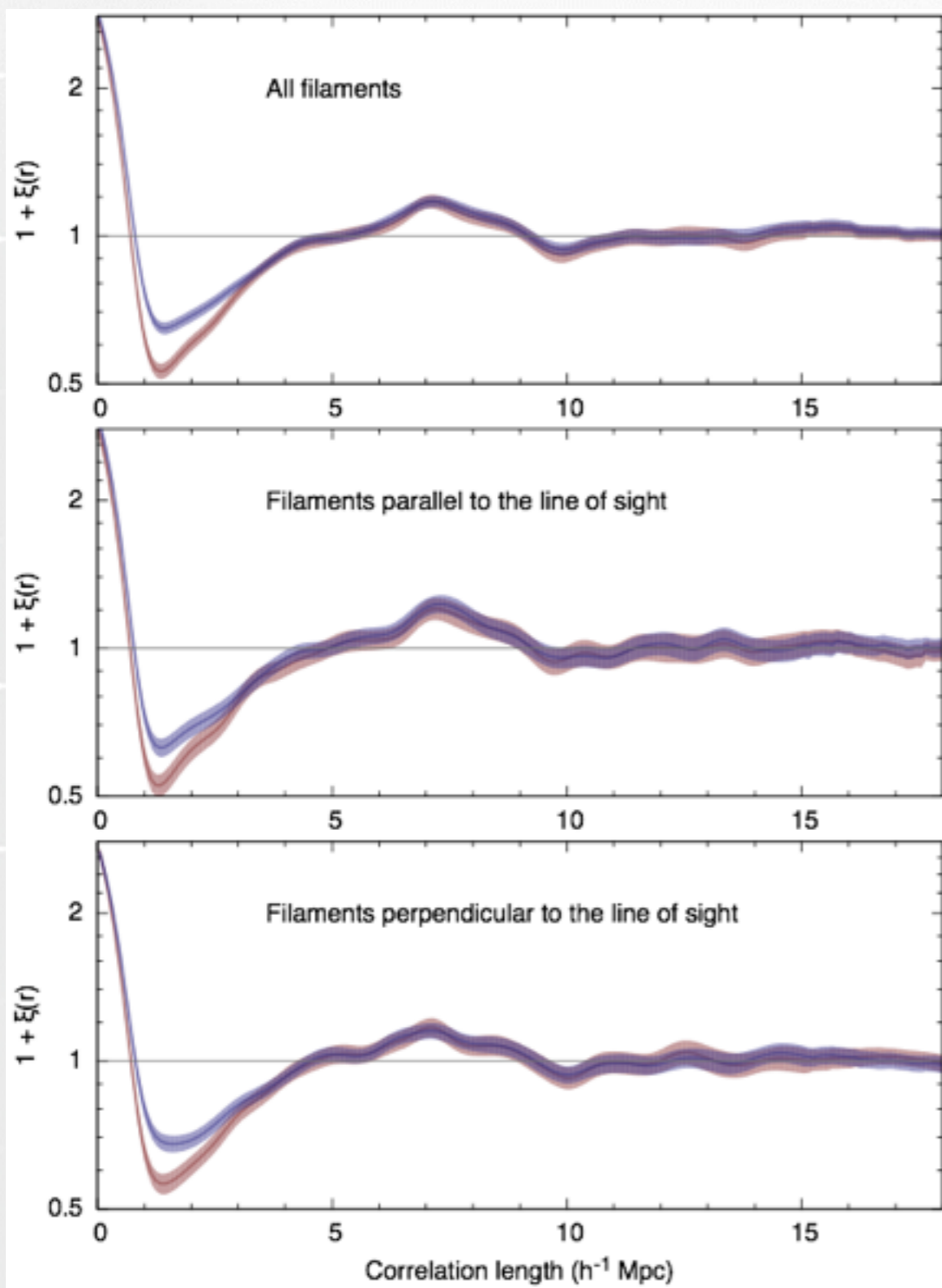
The algorithm works as following. For each filament, we produce a periodogram using the Z_1^2 (Rayleigh statistics),

$$Z_1^2 = \frac{2}{N} \left[\left(\sum_{j=1}^N \cos \phi_j \right)^2 + \left(\sum_{j=1}^N \sin \phi_j \right)^2 \right], \quad (4)$$

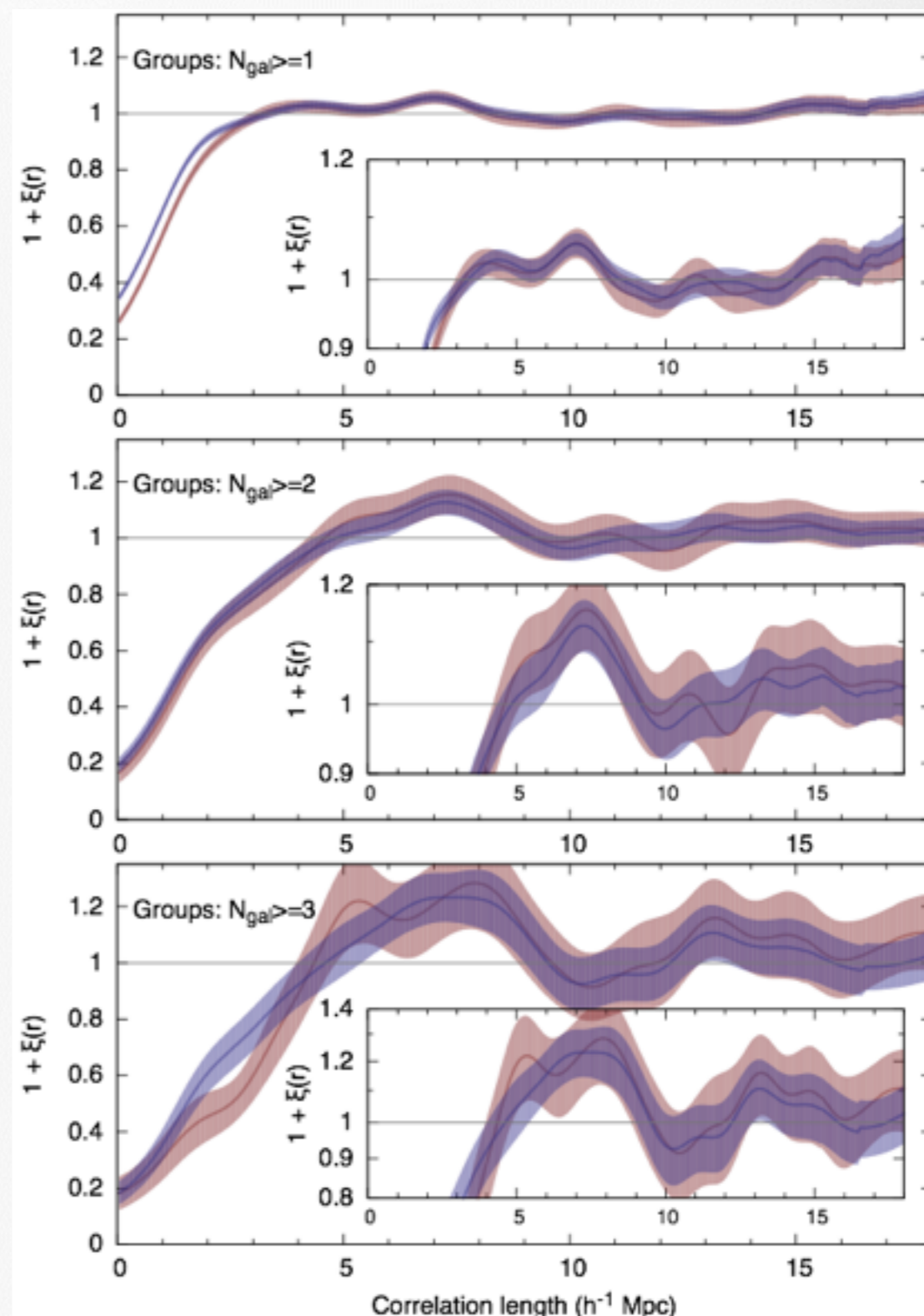
where N is the number of galaxies in a filament and $\phi_j = 2\pi l_j/d$ is the phase value for a galaxy j for a fixed period d ; l_j is a galaxy j distance along the filament spine from the beginning of the filament.

Pair correlation function along filaments

Galaxies



Groups



Regularity of galaxies along filaments

Galaxies

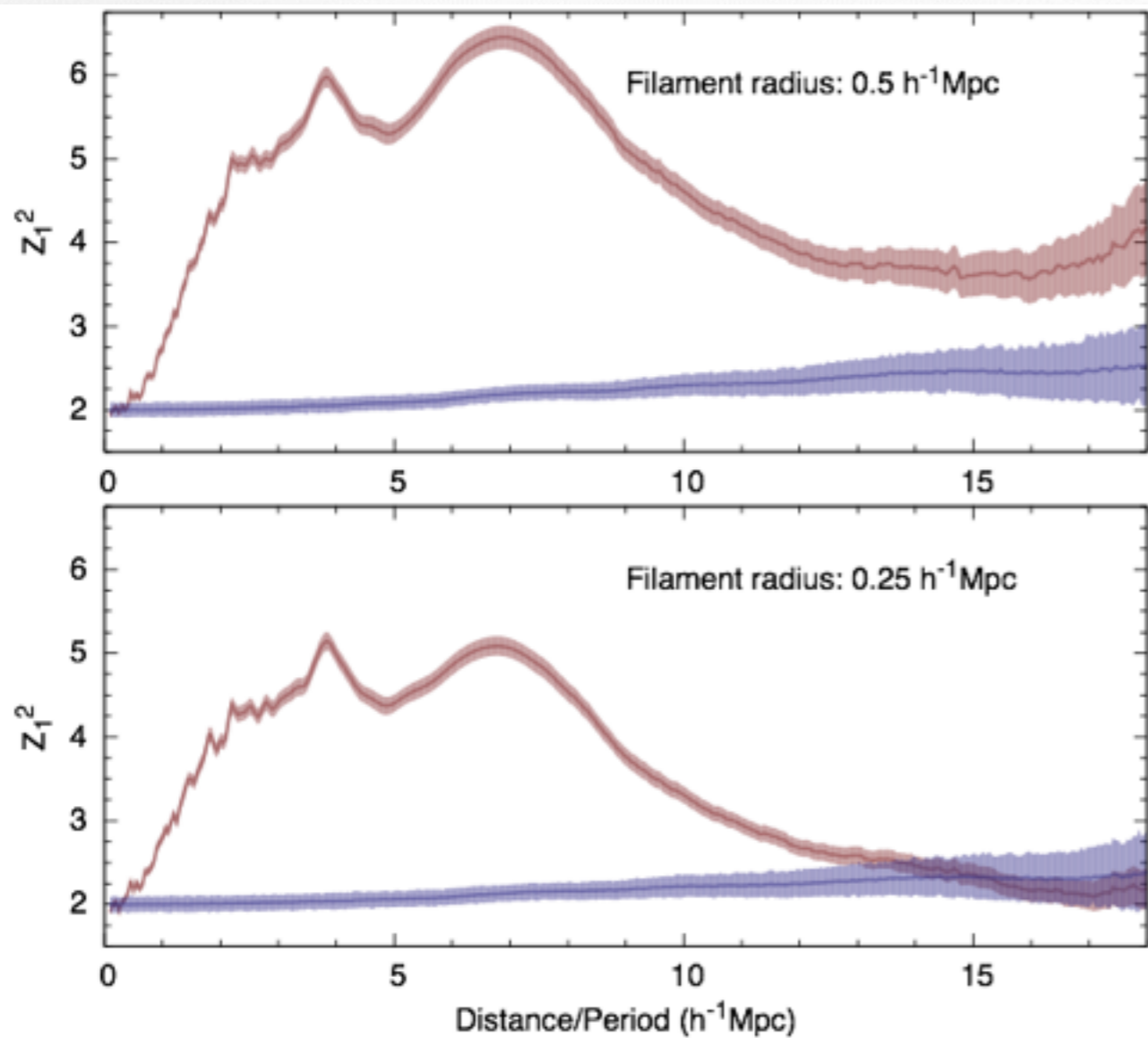
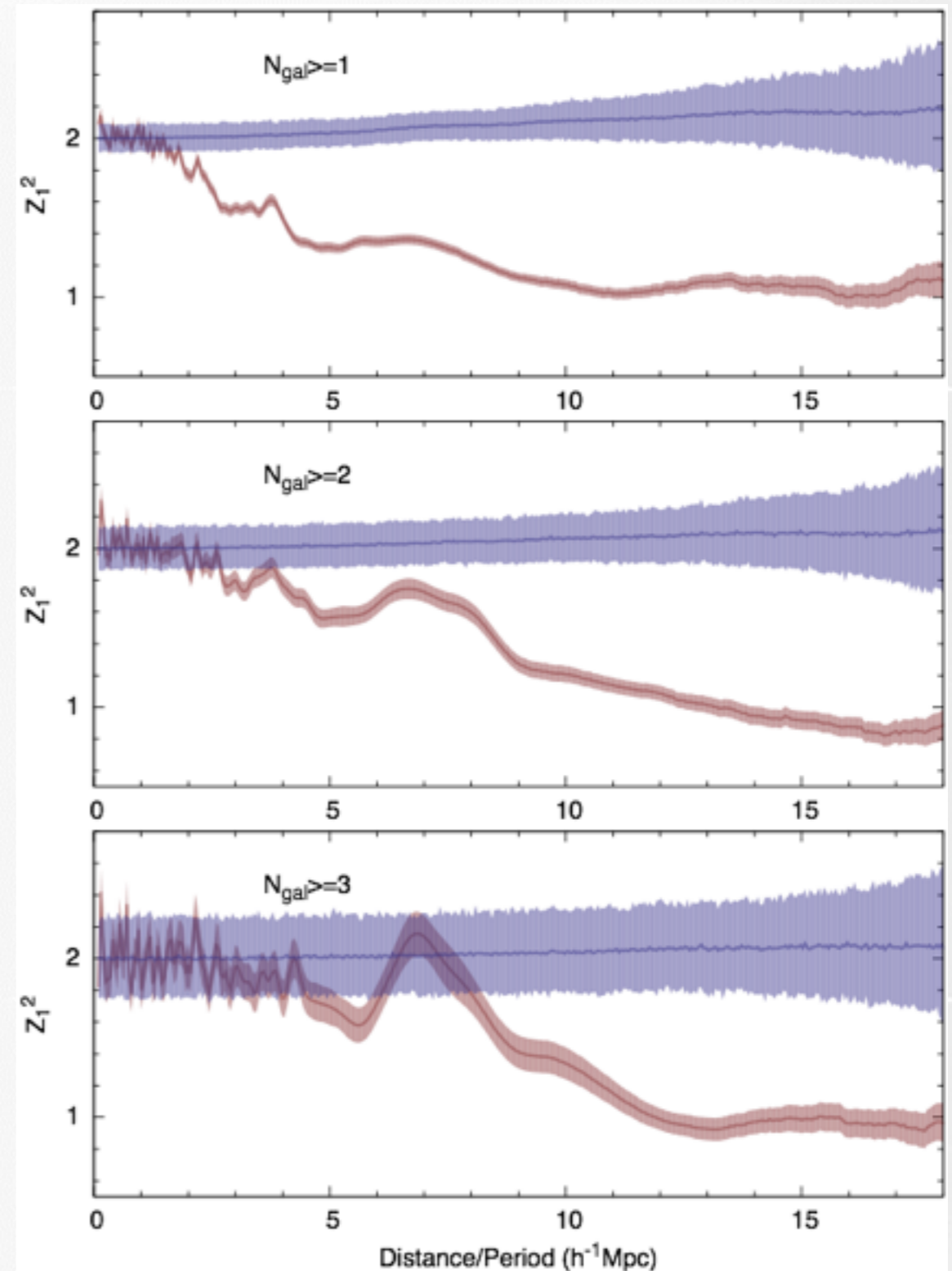


Fig. 7. The Rayleigh (Z-squared) statistic Z_1^2 for a given distance (period). The upper panel shows the results for galaxies closer than $0.5 h^{-1}\text{Mpc}$ to the filament axis and the lower panel shows the results for galaxies closer than $0.25 h^{-1}\text{Mpc}$. The red line shows the Z_1^2 statistics together with the jackknife 95% confidence estimate. The blue line shows the results from Monte Carlo simulations for the null hypothesis together with the 95% confidence limits.

Groups



Summary

- ✦ We developed a probabilistic model for filamentary network detection, based on marked point processes (the Bisous model).
- ✦ We applied the Bisous model to the SDSS dataset and generated a catalogue of filaments (<http://cosmodb.to.ee>).
- ✦ We studied the distribution of galaxies/groups along filaments and showed that they tend to form a regular pattern. The characteristic length of the pattern is about 7 Mpc/h.
- ✦ We propose that this well-defined characteristic scale could be used as a cosmological test.

