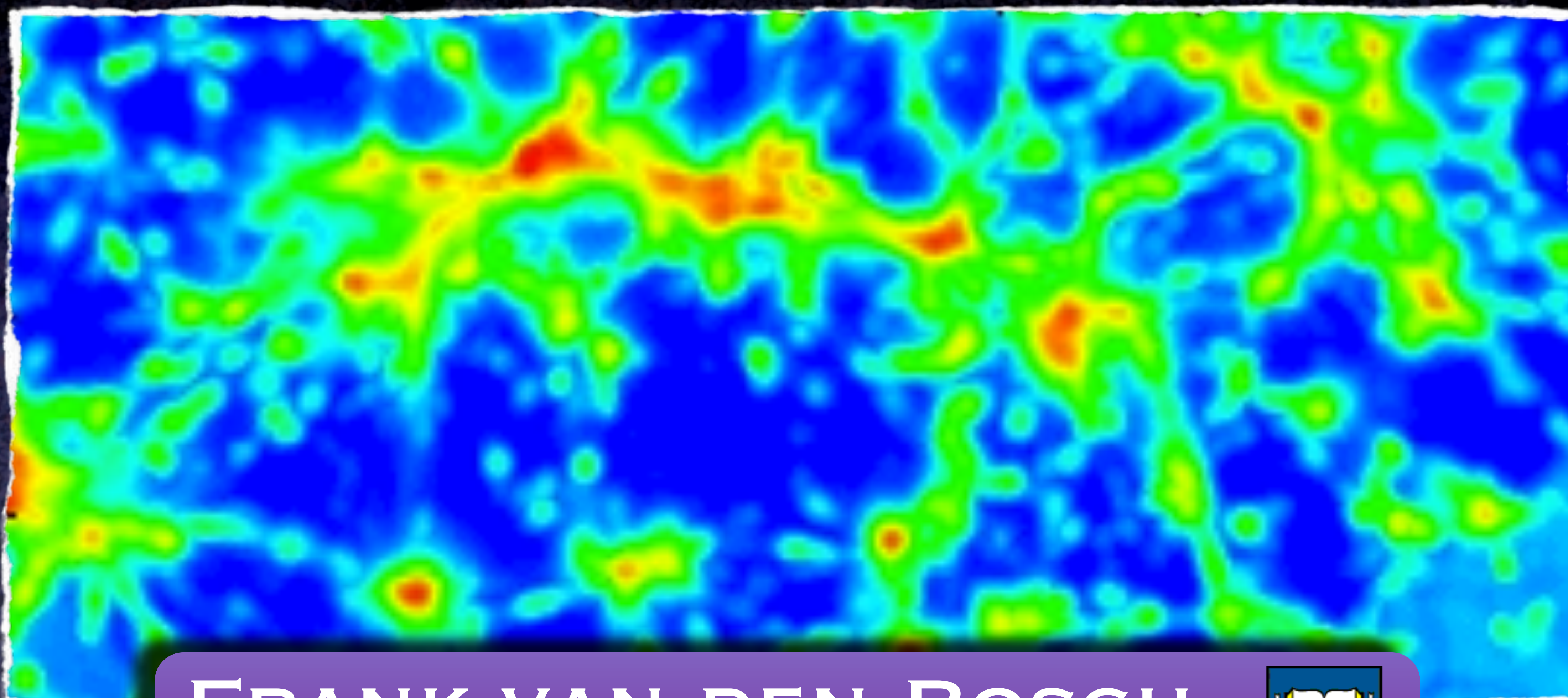
Reconstructing Density, Velocity & Tidal Fields from Galaxy Groups in the SDSS



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In collaboration with:
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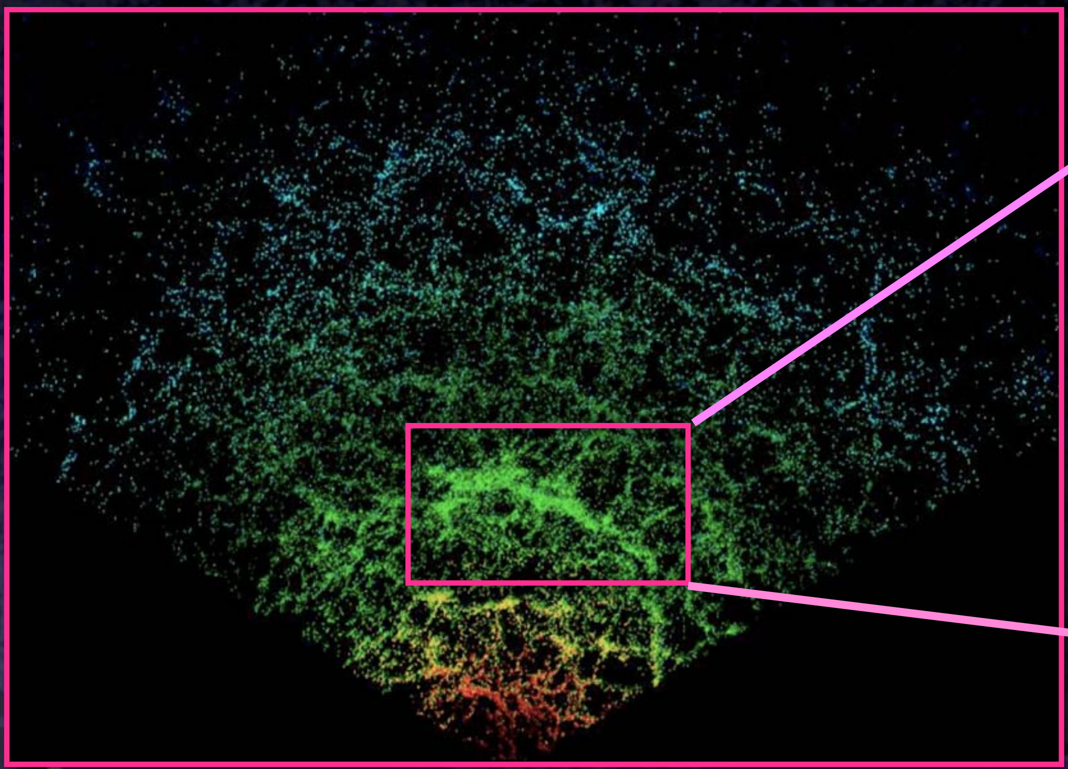
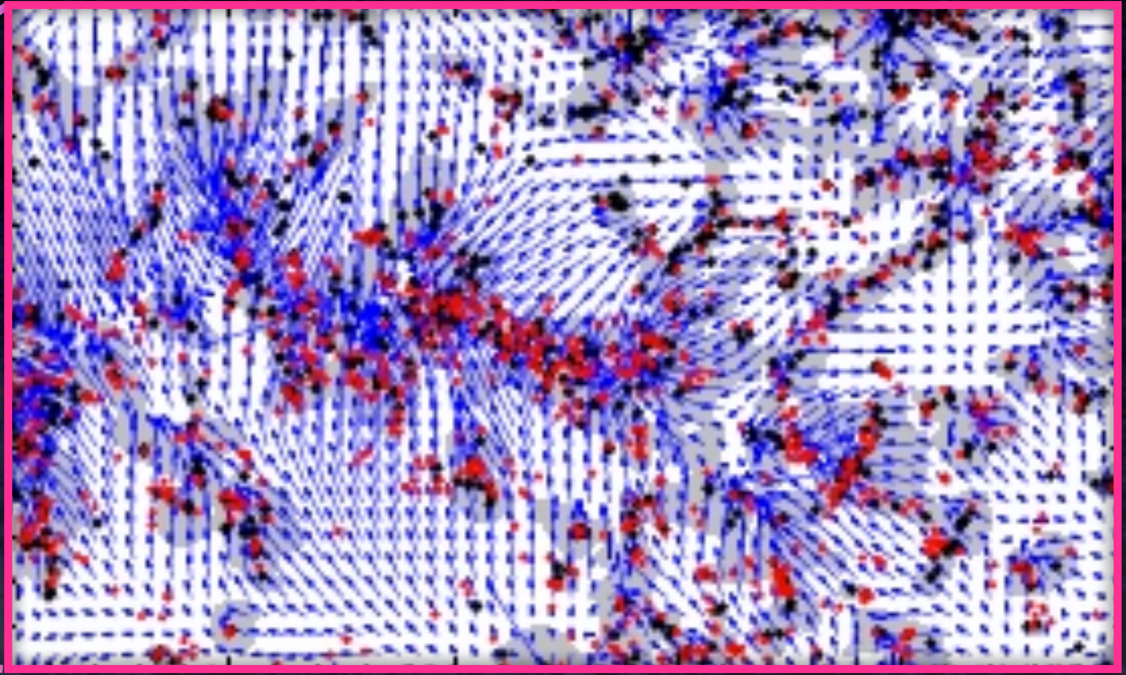
Introduction: Motivation & Goal

GOAL: reconstruct the density, velocity and tidal fields from the SDSS Main Galaxy Sample





IDEOLOGY:

- Develop a reconstruction method which accounts for the fact that galaxy bias depends on galaxy properties.
- Use galaxy group (=halo) catalogue as starting point, rather than galaxy distribution (i.e., halo bias is well understood)

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Our reconstruction, presented in Wang et al. (2009) is motivated by success of halo model, which models $\rho(\vec{x})$ in terms of its halo building blocks

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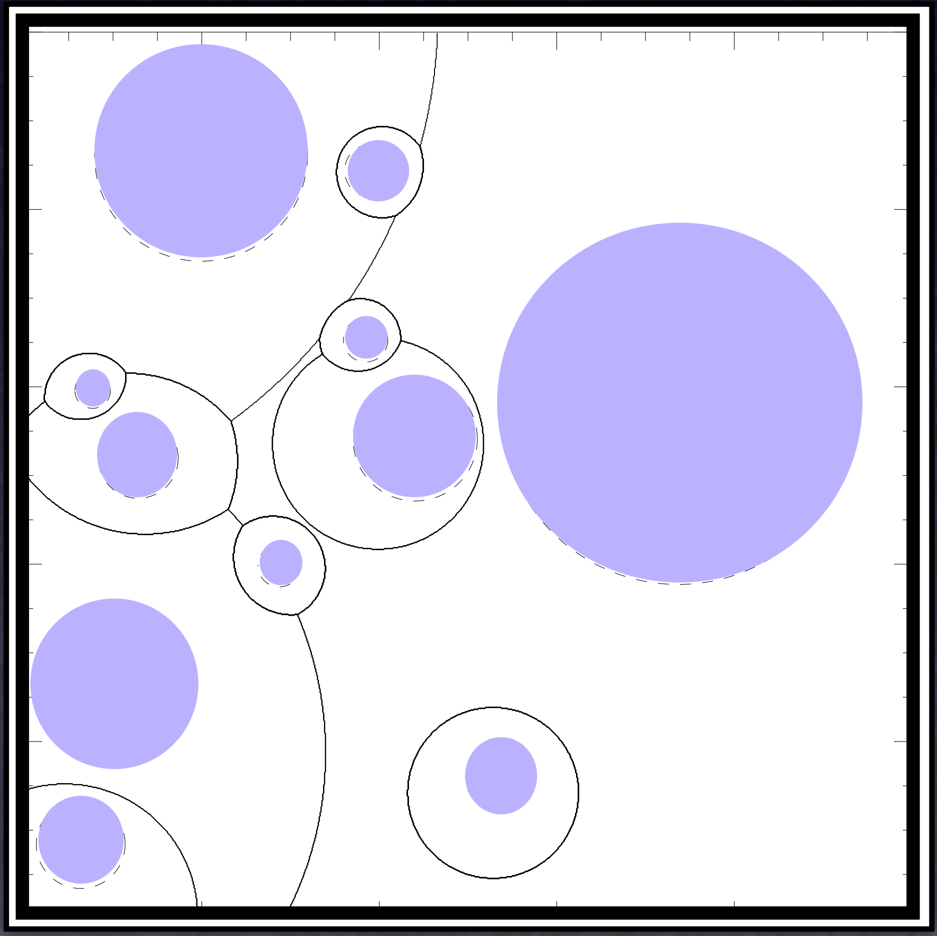
Step 3: Associate each of the groups with a domain; sum of all these (in real space) domains has to be volume filling



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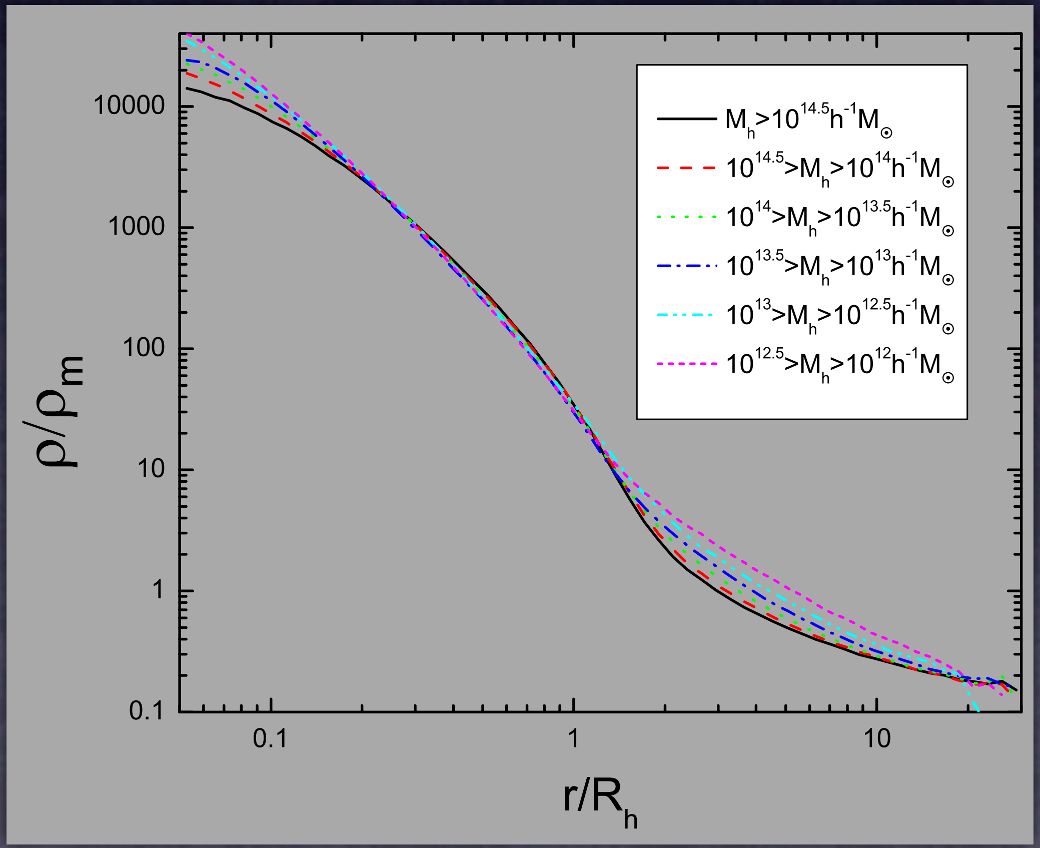

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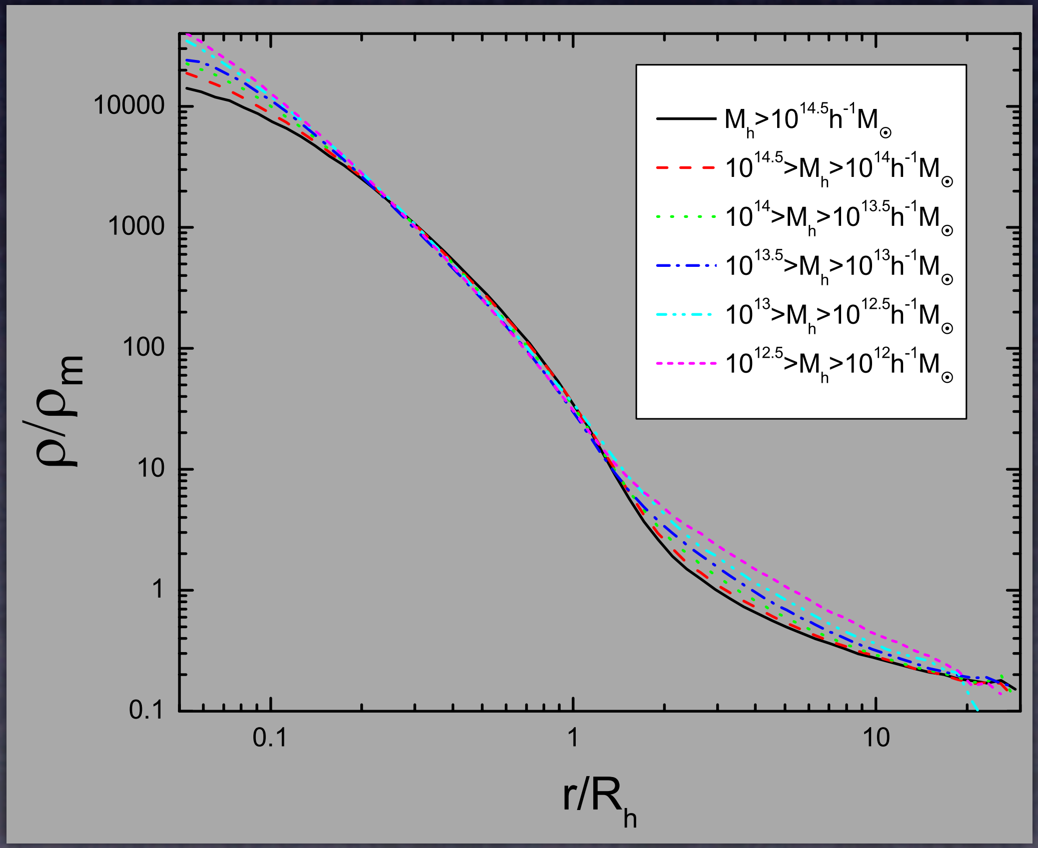
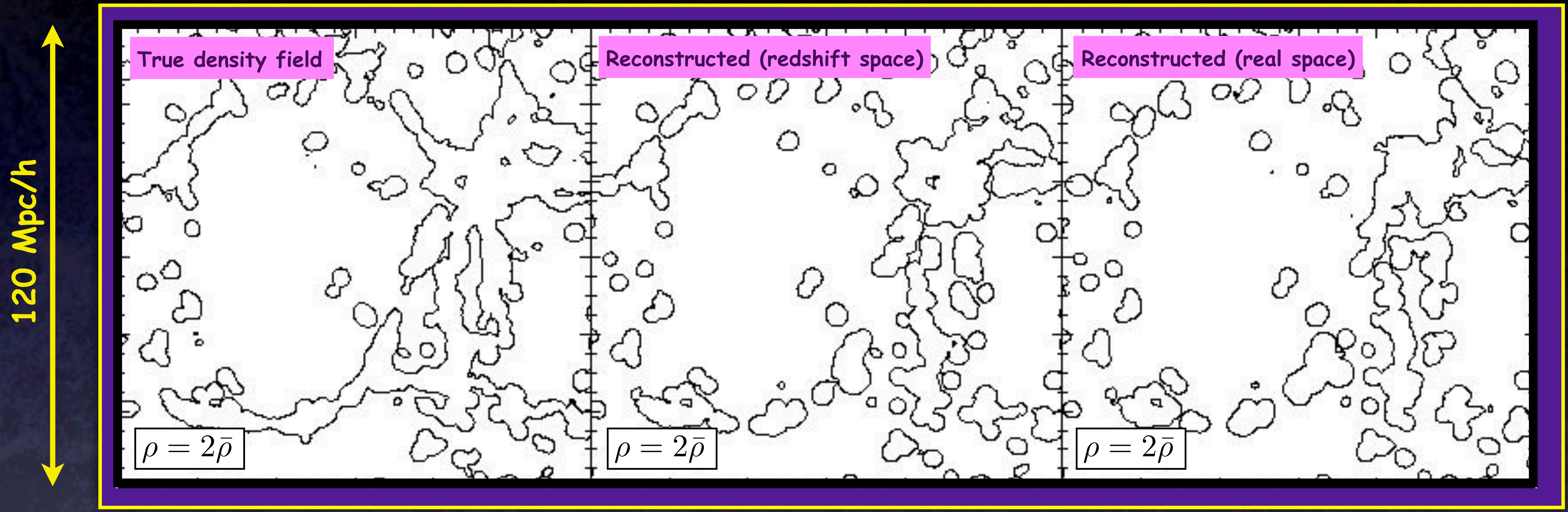


Step 5: Using group locations in real space, their domains, and their halo-matter cross correlations, Monte Carlo sample reconstructed density field using large number of particles

The Reconstructed Density Field

By construction, the reconstructed density field cannot resolve structures on a mass scale $M < M_{\rm th}$. However, on larger scales our reconstruction method works extremely well, especially after redshift space corrections.



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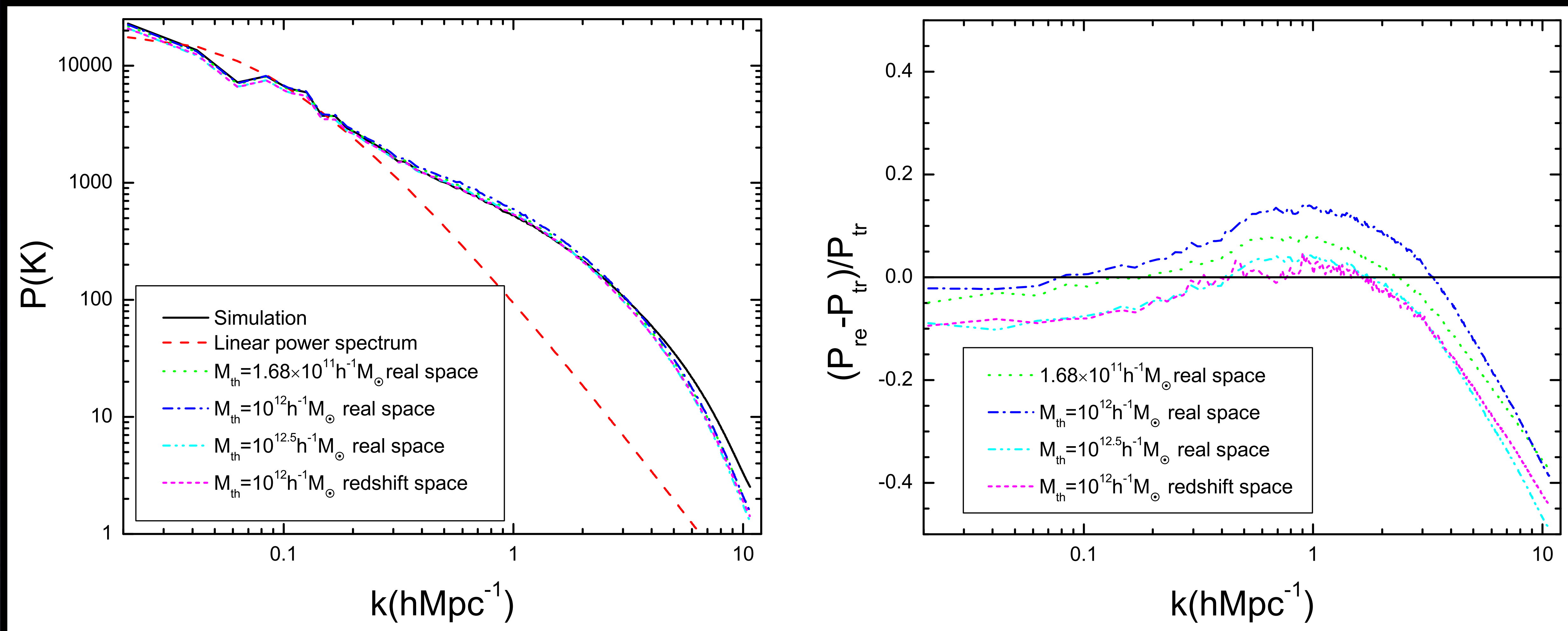

Matter power spectrum is recovered to better than ~15% for $k < 3\,h{\rm Mpc}^{-1}$

The Cosmic Velocity Field in Linear Theory

In linear regime, the peculiar velocity is given by peculiar potential according to

$$\boxed{\mathbf{v} = -\frac{1}{4\pi G\bar{\rho}a}\,\frac{\dot{D}}{D}\,\nabla\phi}$$

The peculiar potential is related to the overdensity field via the Poisson eq.

$$\boxed{\nabla^2\phi = 4\pi G\bar{\rho}\delta}$$

Combining these two equations and working in Fourier space:

$$\boxed{v(\mathbf{k}) = H\,a\,f(\Omega)\,\frac{i\mathbf{k}}{k^2}\,\delta(\mathbf{k})}$$ where $$\boxed{f(\Omega) \equiv \frac{\mathrm{d}\ln D}{\mathrm{d}\ln a} \simeq \Omega_{\mathrm{m}}^{0.6}}$$

This equation basically just states that, for a given cosmology, the linear velocity field is simple given by the gradient of the density field

Reconstructing the Cosmic Velocity Field

Since we wish to reconstruct the **linear** velocity field, we only need to know the large-scale (linear) density field, which is well sampled by the most massive haloes.

Step 1: Using the Yang et al. (2007) group catalogue, pick all groups (=haloes) above a given mass threshold $(M_{\rm th} \sim 10^{12} h^{-1} M_\odot)$

Step 2: Construct Cartesian grid, and assign halo mass M to each grid cell that hosts a halo with mass $M > M_{\rm th}$. Convolve this density field with Gaussian filter of mass scale $M_{\rm s} \sim 10^{14.75} h^{-1} M_\odot$, and compute the corresponding overdensity field $\delta_{\rm h}(\mathbf{x})$. FFT to obtain $\delta_{\rm h}(\mathbf{k})$.

Step 3: Compute

$$\boxed{\mathbf{v}(\mathbf{k}) = H\, a\, f(\Omega) \frac{i\mathbf{k}}{k^2} \delta(\mathbf{k}) = \frac{1}{\bar{b}_{\rm h}} H\, a\, f(\Omega) \frac{i\mathbf{k}}{k^2} \delta_{\rm h}(\mathbf{k})}$$

where

$$\boxed{\bar{b}_{\rm h} = \frac{\int_{M_{\rm th}}^{\infty} M\, b_{\rm h}(M)\, n(M)\, {\rm d}M}{\int_{M_{\rm th}}^{\infty} M\, n(M)\, {\rm d}M}}$$

Step 4: Correct positions of these groups for redshift space distortions.

Step 5: Go back to step 2 and iterate until convergence.

Reconstructing the Cosmic Tidal Field

At each location in space, we compute the tidal tensor $\mathcal{T}_{ij} = \partial_i \, \partial_j \phi$, where the peculiar potential is easily obtained from the density field $\delta_{\rm h}(\mathbf{x})$ by solving the Poisson equation (in Fourier space).

$$\boxed{\nabla^2 \phi = 4\pi G \bar{\rho} \delta = 4\pi G \bar{\rho} \frac{\delta_{\rm h}}{\bar{b}_{\rm h}}} \xrightarrow{\text{in Fourier space}} \boxed{\phi(\mathbf{k}) = -\frac{4\pi G \bar{\rho}}{\bar{b}_{\rm h}} \, a^2 \, \frac{\delta_{\rm h}(\mathbf{k})}{k^2}}$$

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Finally we obtain the eigenvalues $T_1 > T_2 > T_3$ at each grid point by diagonalizing the corresponding tidal tensor. Following Hahn et al. (2007), we use these to characterize the morphologies of the cosmic web:

CLUSTER:	$(T_1, T_2, T_3) > 0$
FILAMENT:	$(T_1, T_2) > 0, T_3 < 0$
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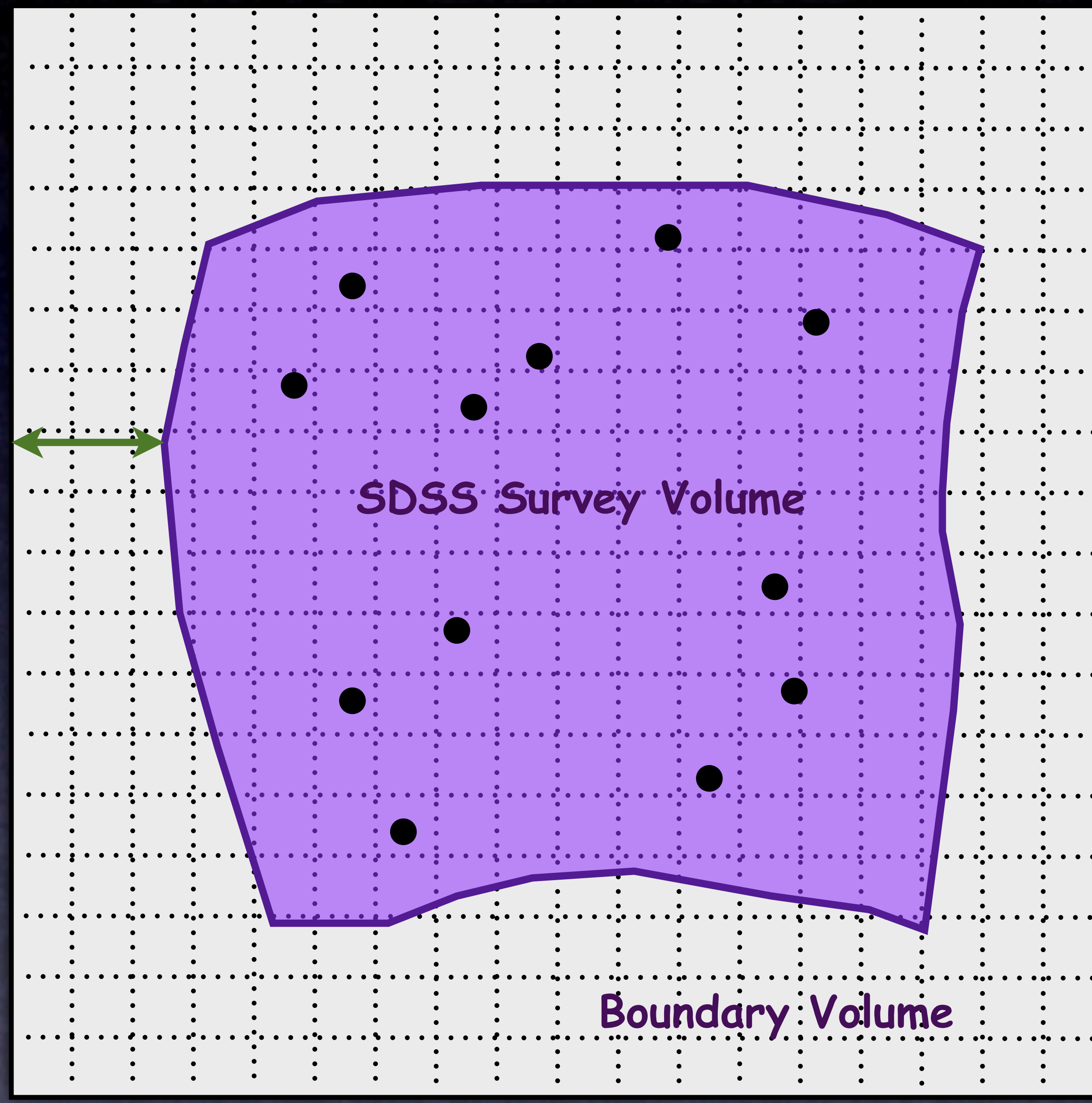
The density field represented by the most massive groups in the SDSS allows us to quantify the cosmic web in a meaningful way

Survey Boundary Effects

Embed SDSS Survey Volume in cubic volume that is ~100 Mpc/h larger on each side than Survey Volume. Inside Boundary Volume set $\delta_{\rm h} = 0$



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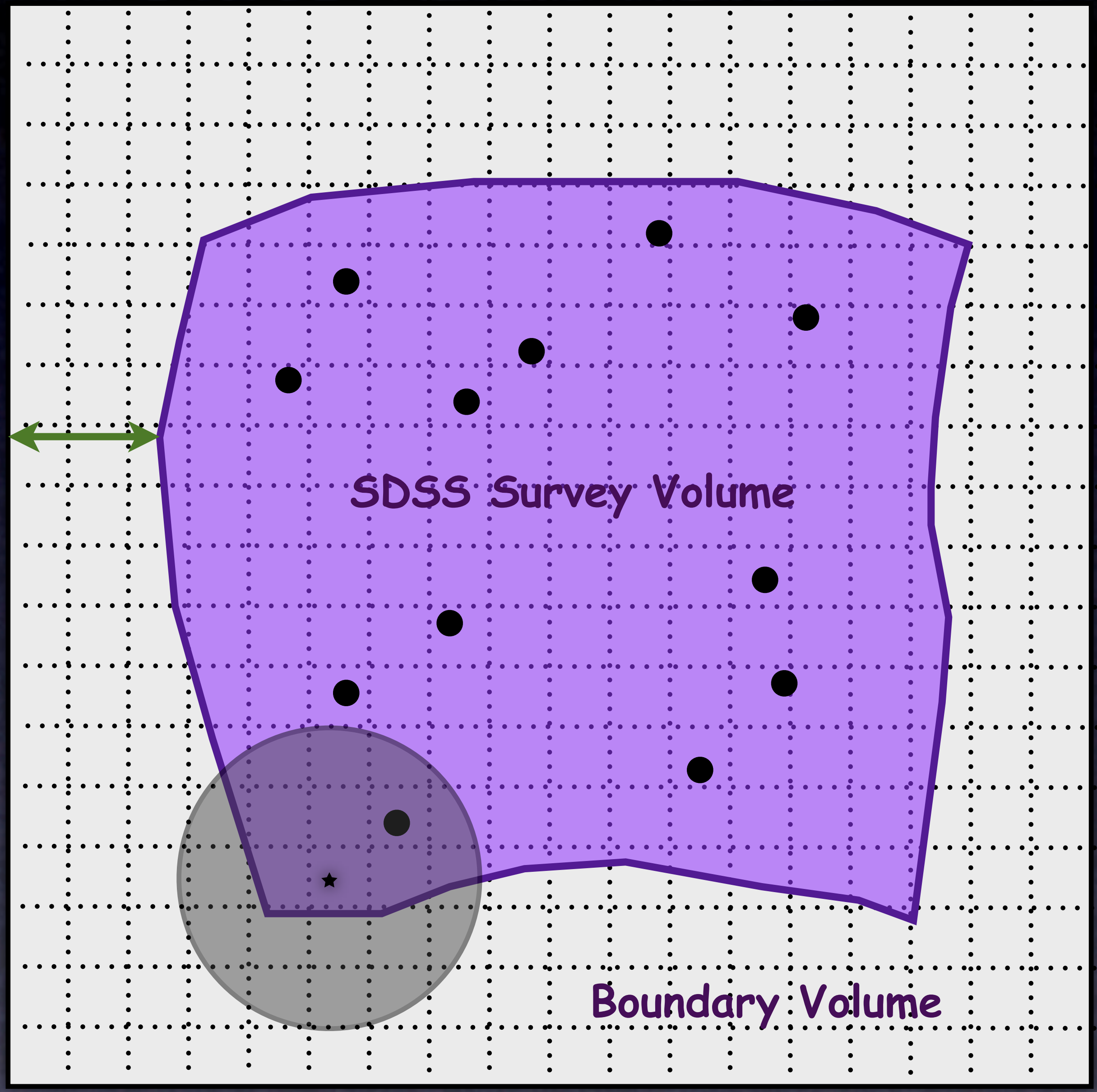

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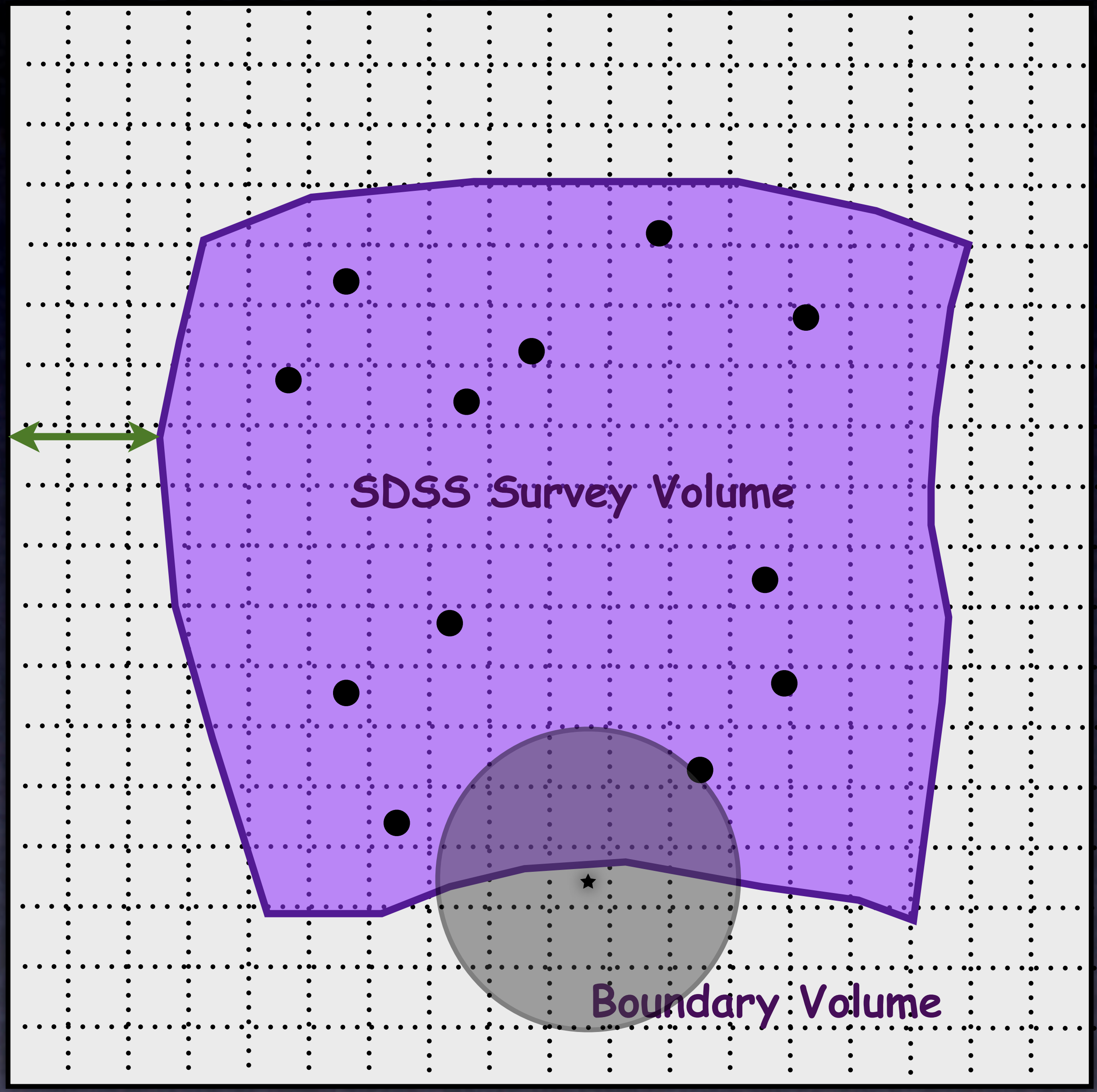

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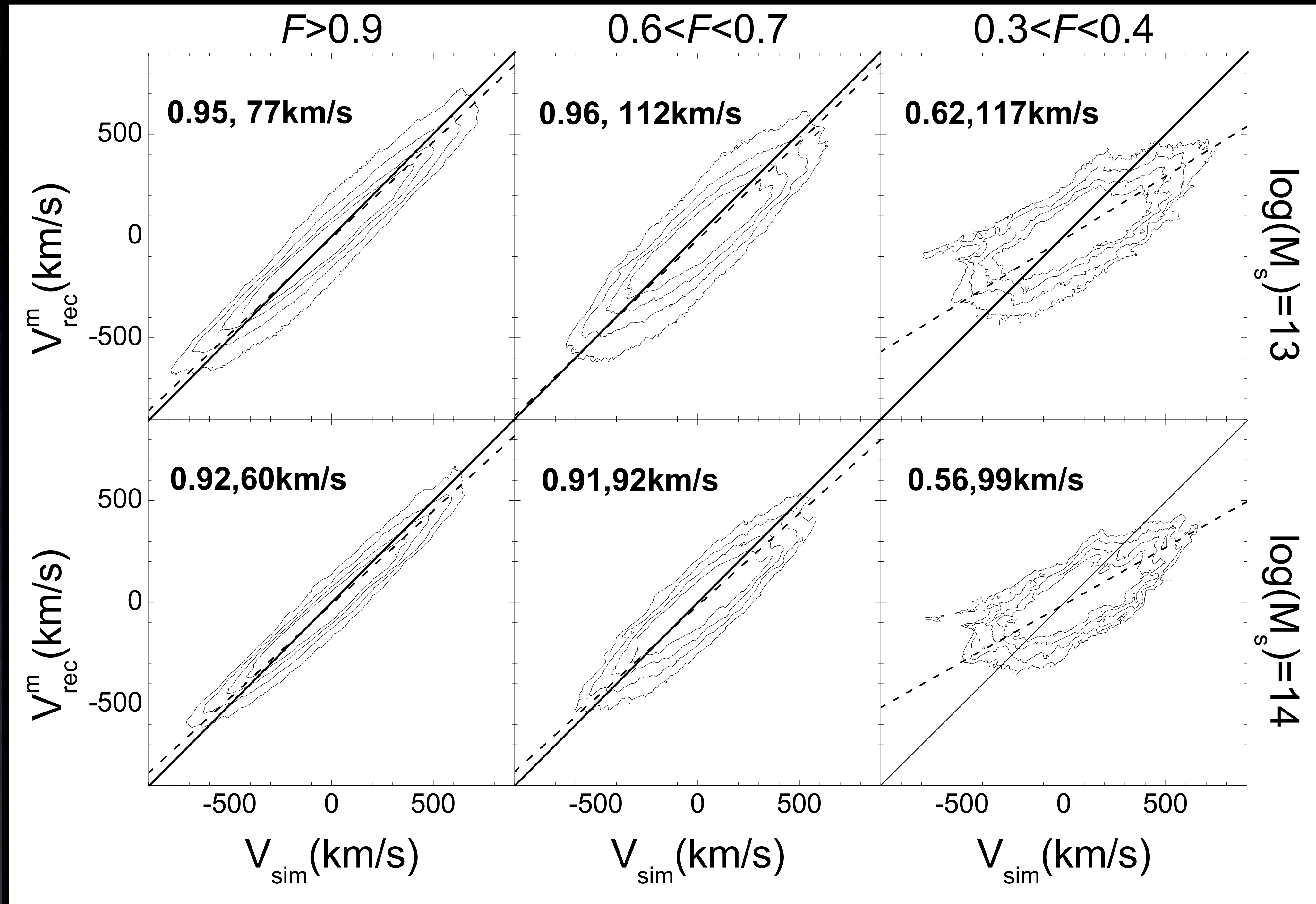
Tests with Realistic Mock SDSS Catalogue



Different mass filtering scales

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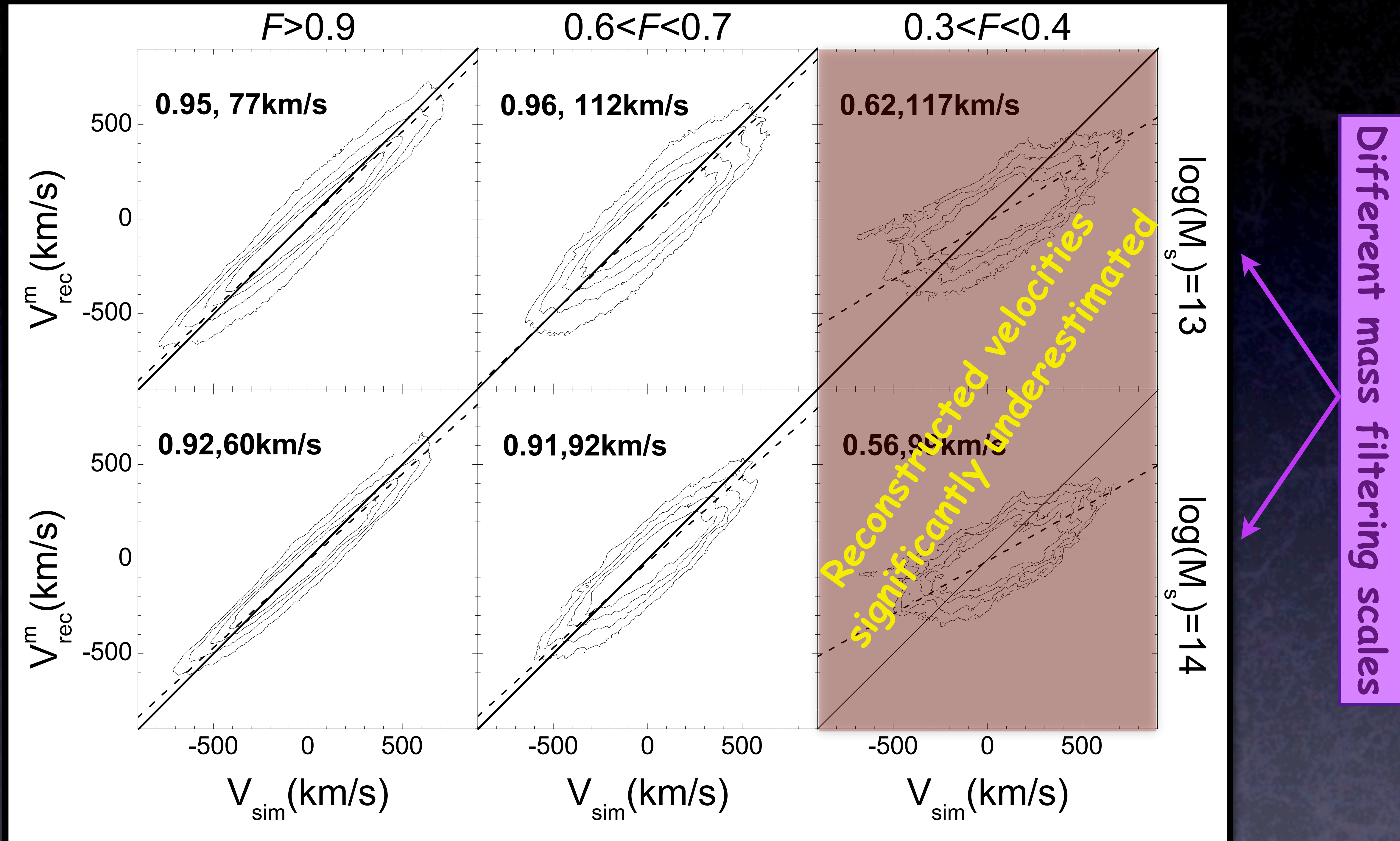

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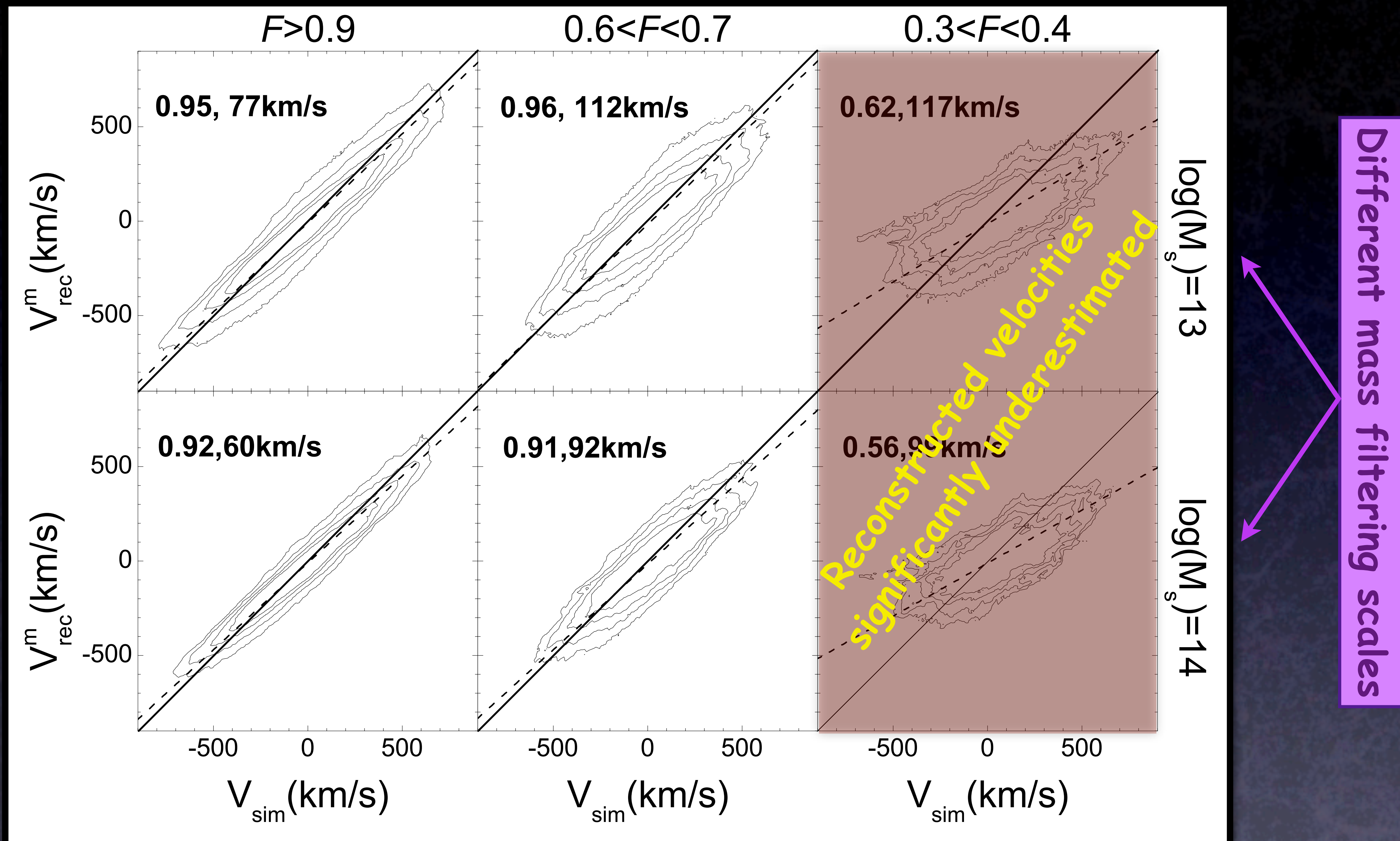
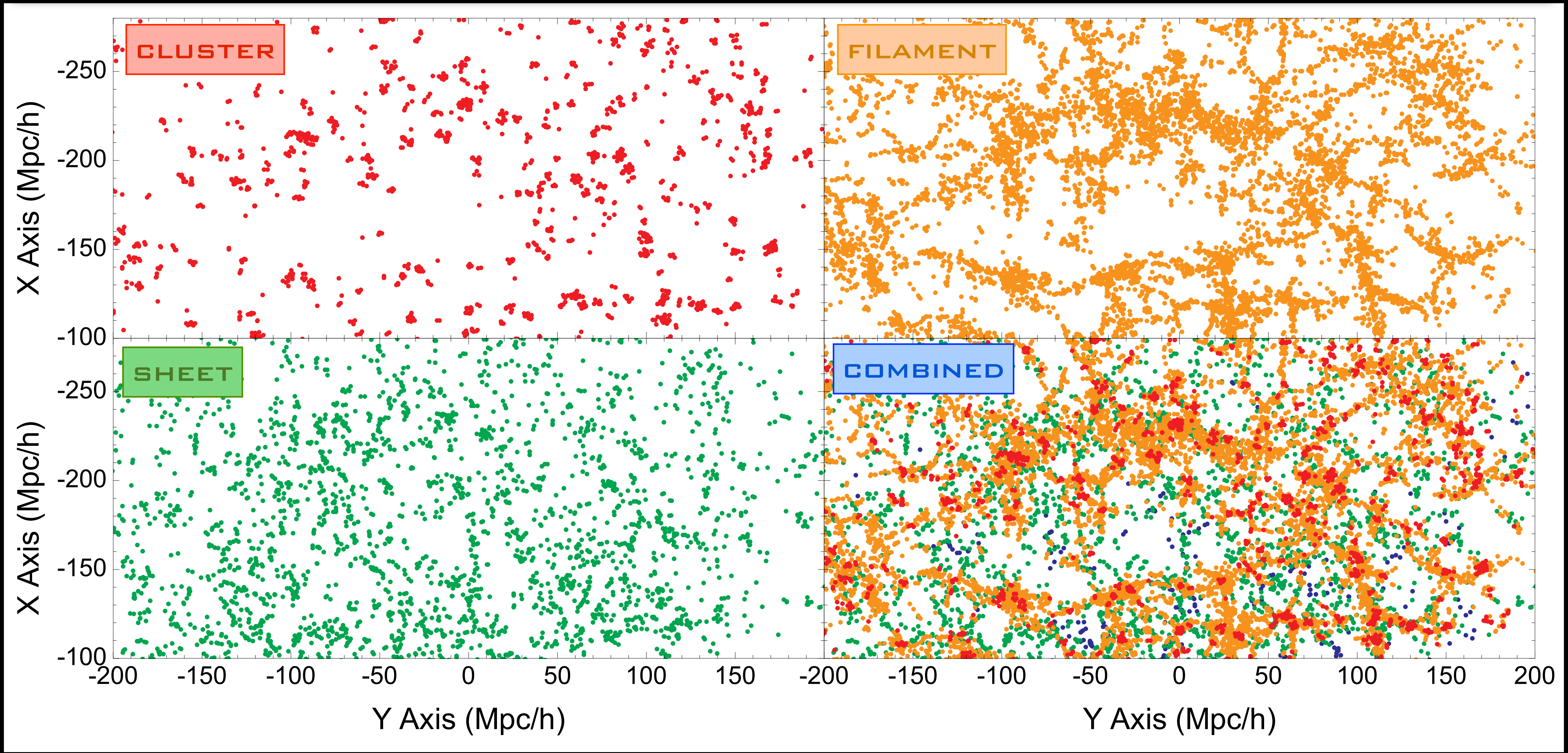


Velocity field can be accurately reconstructed for grid cells with F>0.6.
Roughly 66% of SDSS Survey Volume meets this criterion

Results: Application to SDSS DR7

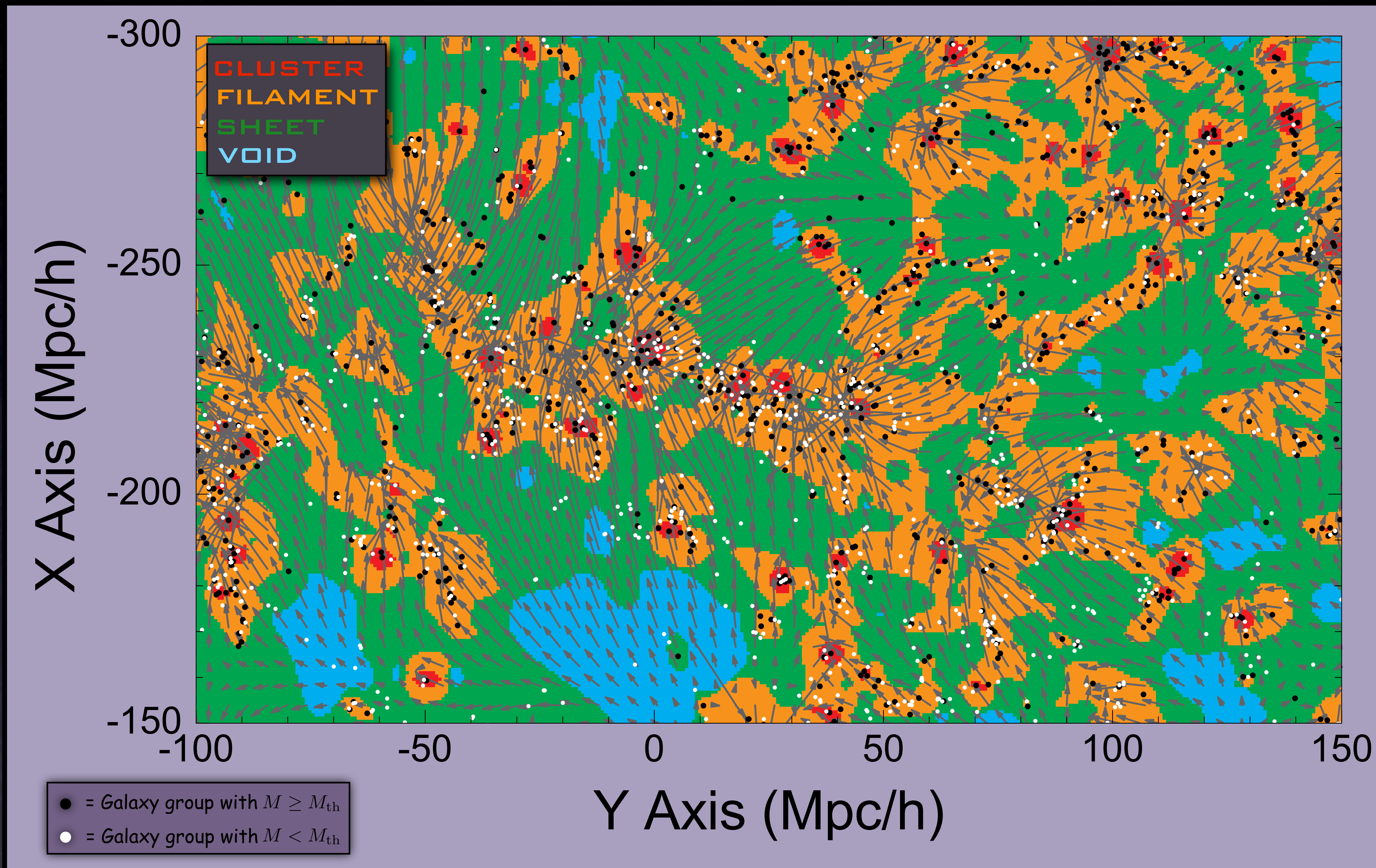
Volume Filling Fractions: cluster [1.9%], filament [31.8%], sheet [53.2%], void [13.1%]



Classification of cosmic web in slice of 16 $h^{-1}\mathrm{Mpc}$ thickness enclosing SDSS Great Wall. Each dot represents a galaxy group in SDSS DR7 Group Catalogue of Yang et al.

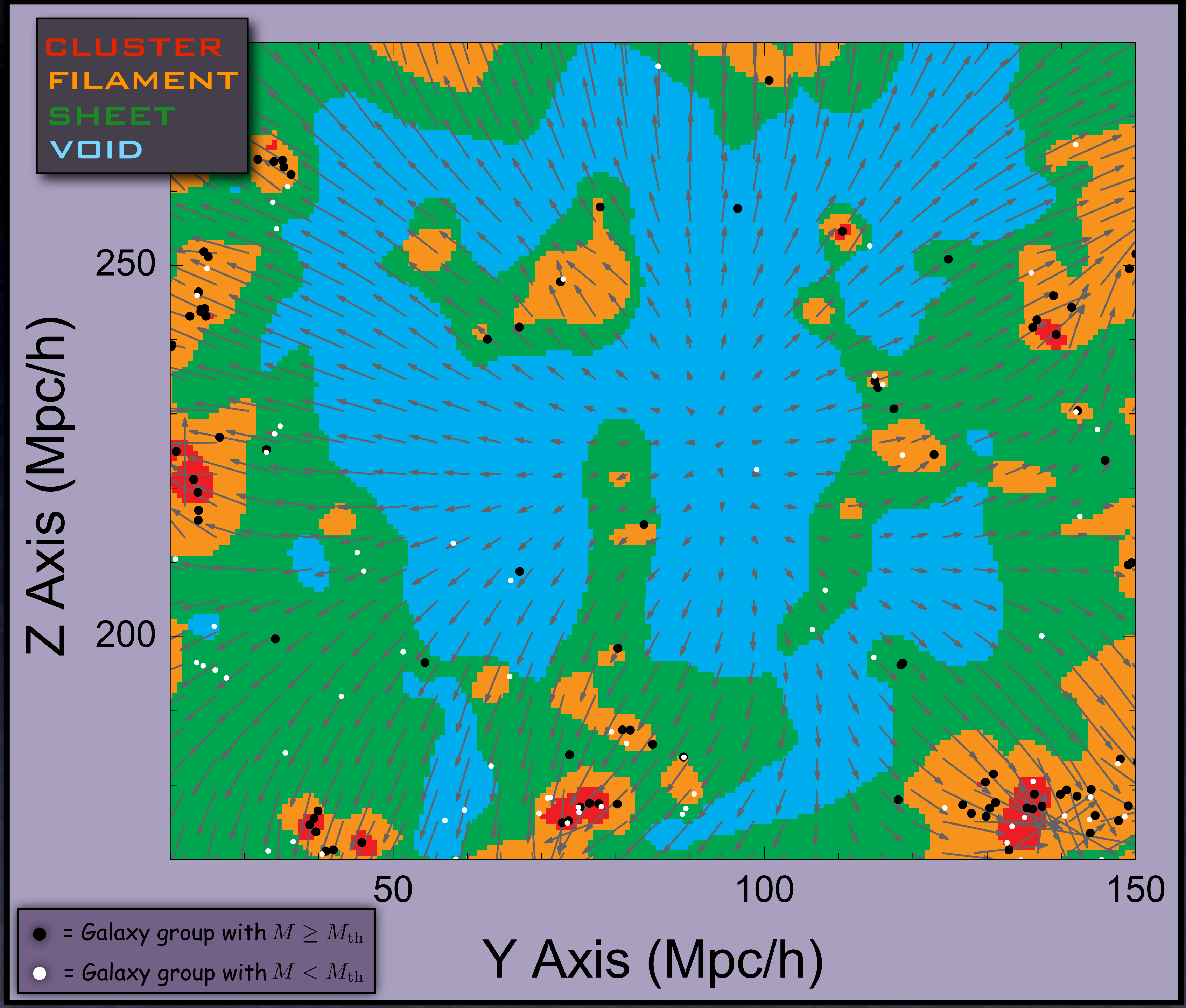
NOTE: voids (blue dots) are poorly sampled by galaxy groups...

The SDSS Great Wall up close



Notice how velocity field diverges from VOIDS and converges on CLUSTERS

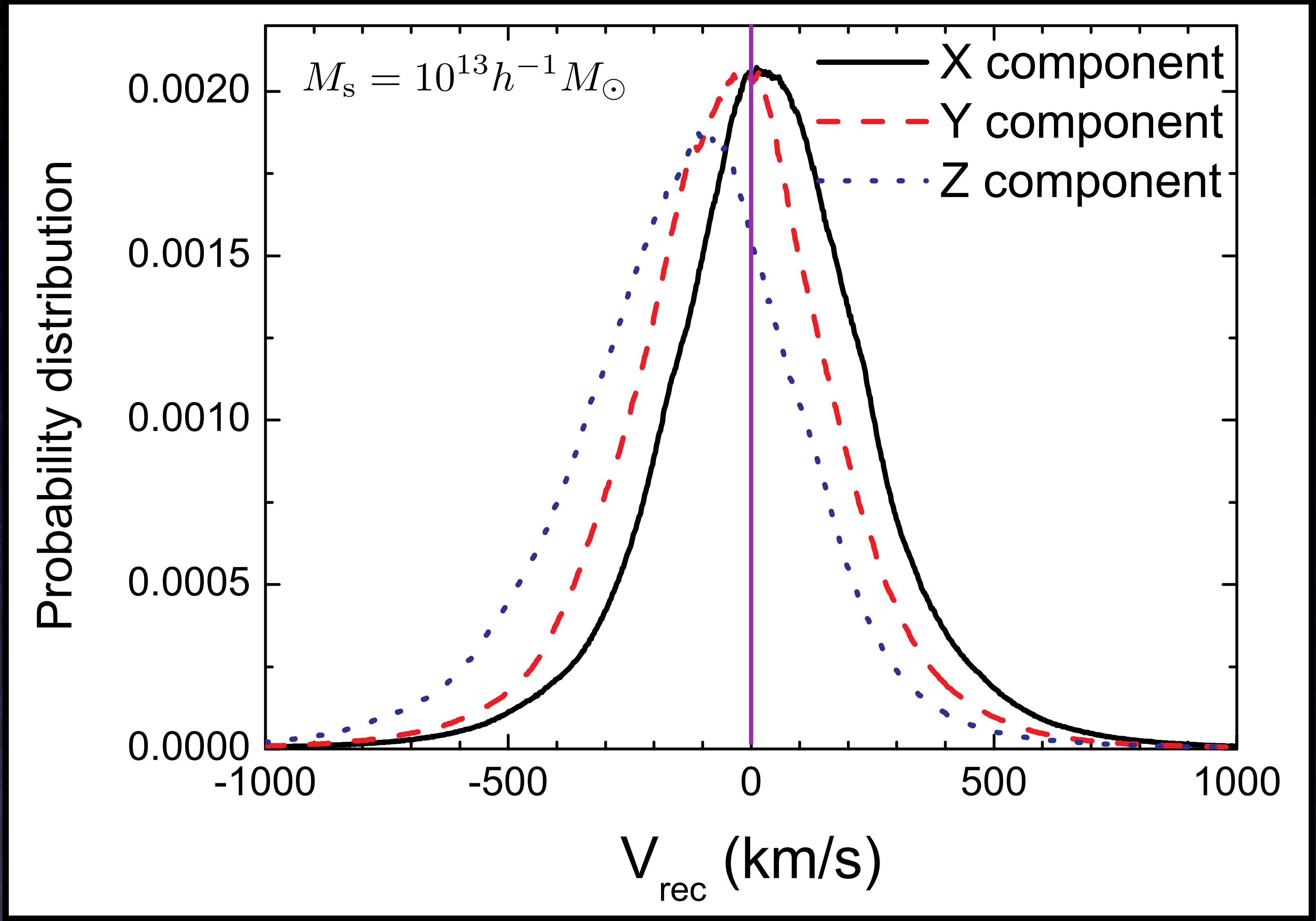
Voiding a void



The diverging velocity flow from a large (~100 Mpc/h diameter) void

Evidence for Large-Scale Bulk Flow

The velocity distribution of all grid cells in SDSS Survey Volume with F>0.6



$$X = r(z)\cos\delta\ \cos\alpha$$
$$Y = r(z)\cos\delta\ \sin\alpha$$
$$Z = r(z)\sin\delta$$

The mean velocity in Z-direction is -120 km/s. Since most of SDSS Survey Volume has Z>0, while "Great Wall" is located near Z=0, this suggests that a huge volume (R~170 Mpc/h) is undergoing a bulk flow towards the SDSS Great Wall...

Reconstructing the Density Field; Method II

Finally, we explore a new method to reconstruct the cosmic density field, which is different from (complementary to) method of Wang et al. (2009).

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Step 1: Uniformly distribute N particles over the SDSS Survey Volume.

Step 2: Displace each particle using our reconstructed velocity field (at z=0) and the Zel'dovich approximation:

$$\boxed{\mathbf{r} = \mathbf{r}_i - \frac{D(a)}{4\pi G \bar{\rho}_{\rm m} a^3} \nabla \Phi_i = \mathbf{r}_i + \frac{\mathbf{v}_0(\mathbf{r}_i)}{H_0\, a_0\, f(\Omega_0)} \frac{D(a)}{D(a_0)}}$$

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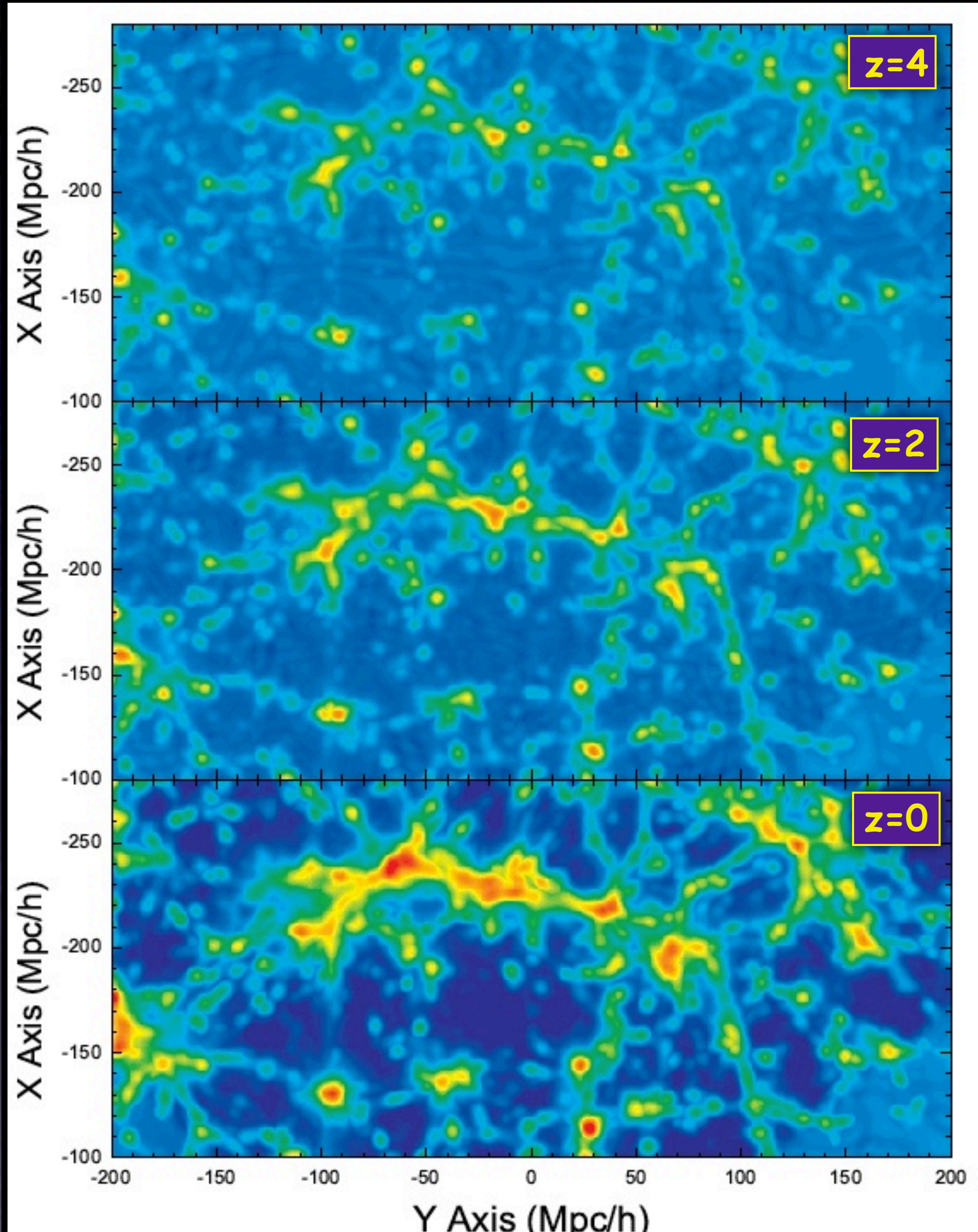
Currently we are comparing our two methods, and testing their performance using detailed mock galaxy catalogs based on N-body simulations.

Formation of the SDSS Great Wall



The reconstructed cosmic density field in region centered on SDSS Great Wall. Results are shown at z=4,2 & 0

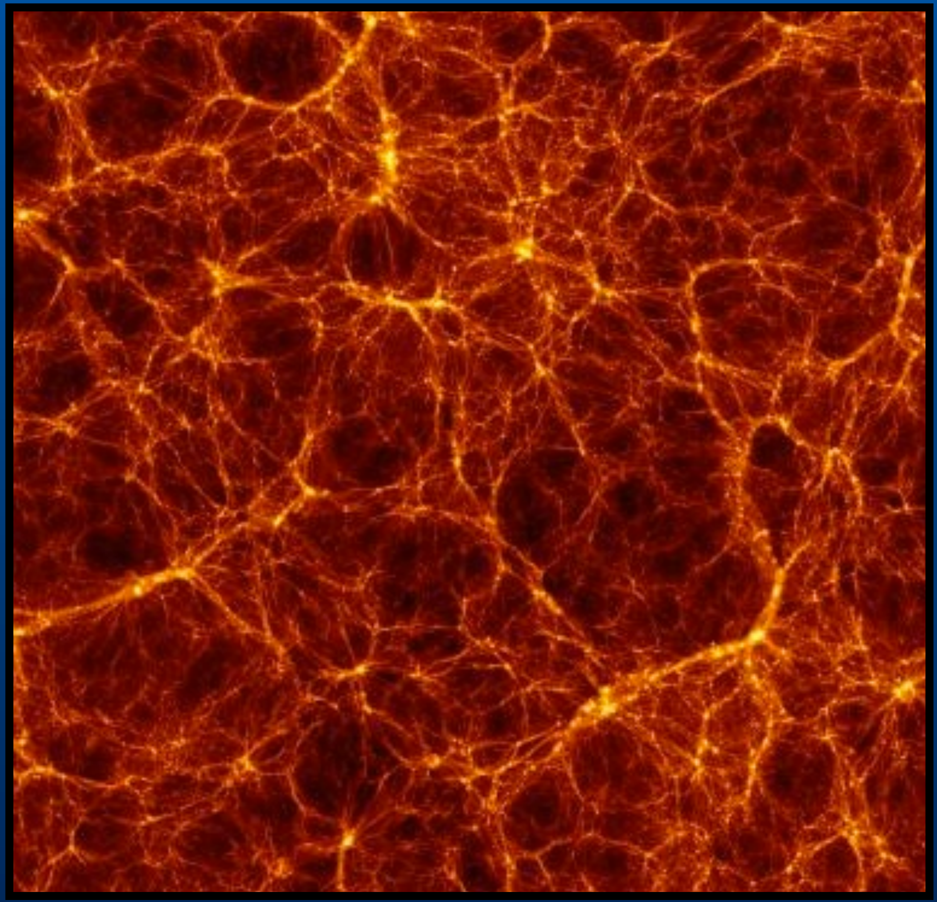
At each location in the SDSS Survey Volume our method can provide the (large scale) "merger history" as function of time.
Put differently, we can provide the cosmic web characterization [CLUSTER,FILAMENT,SHEET,VOID] at each point in space and time.

Applications

Galaxy Formation

Characterization of cosmic web allows studies of environment dependence (halo mass++) & galaxy alignment. We can also correlate galaxy properties with formation history of LSS.

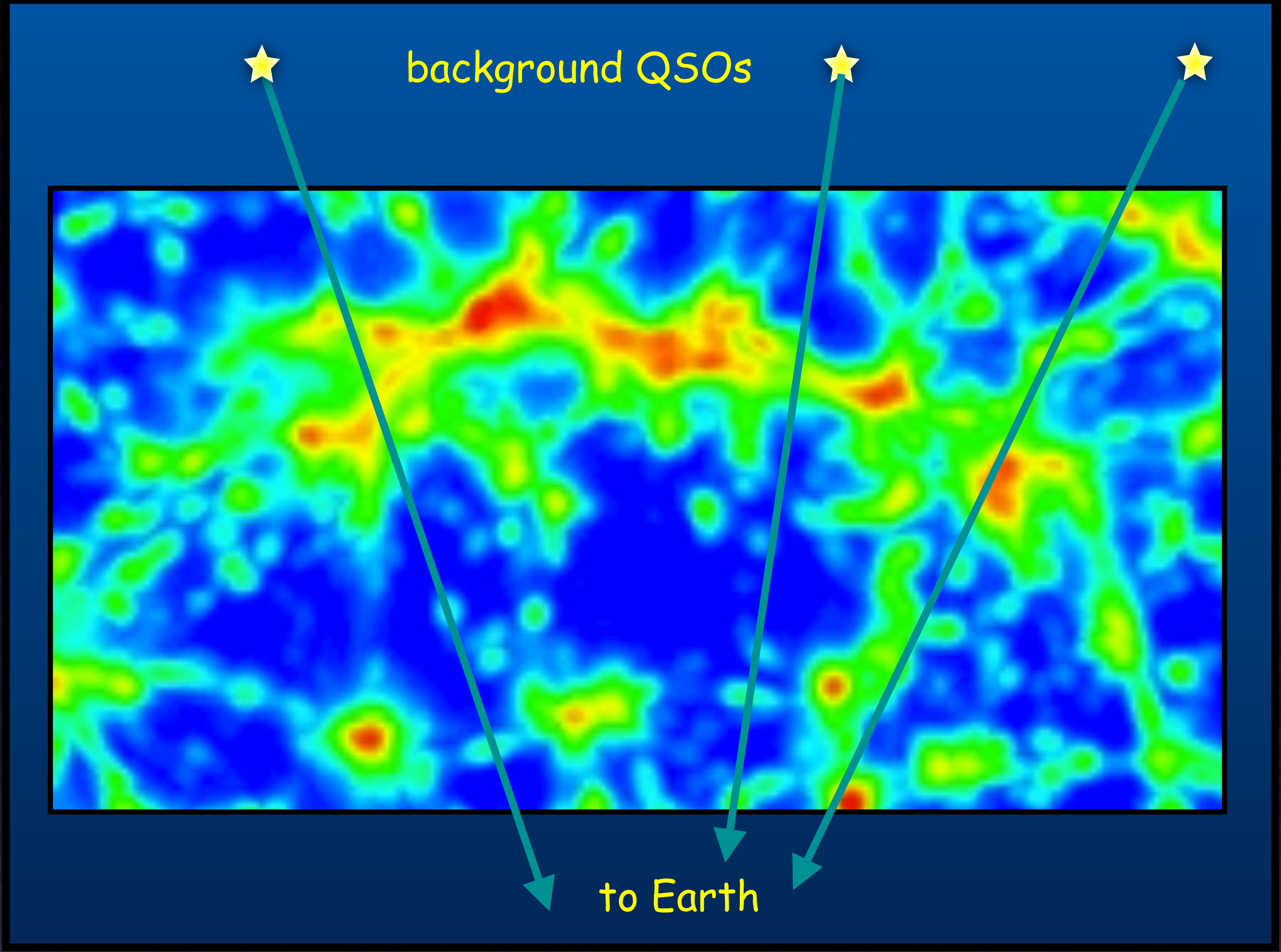
Constrained Simulations



The reconstructed velocity field can be used as ICs for a constrained simulations of the SDSS Survey Volume.

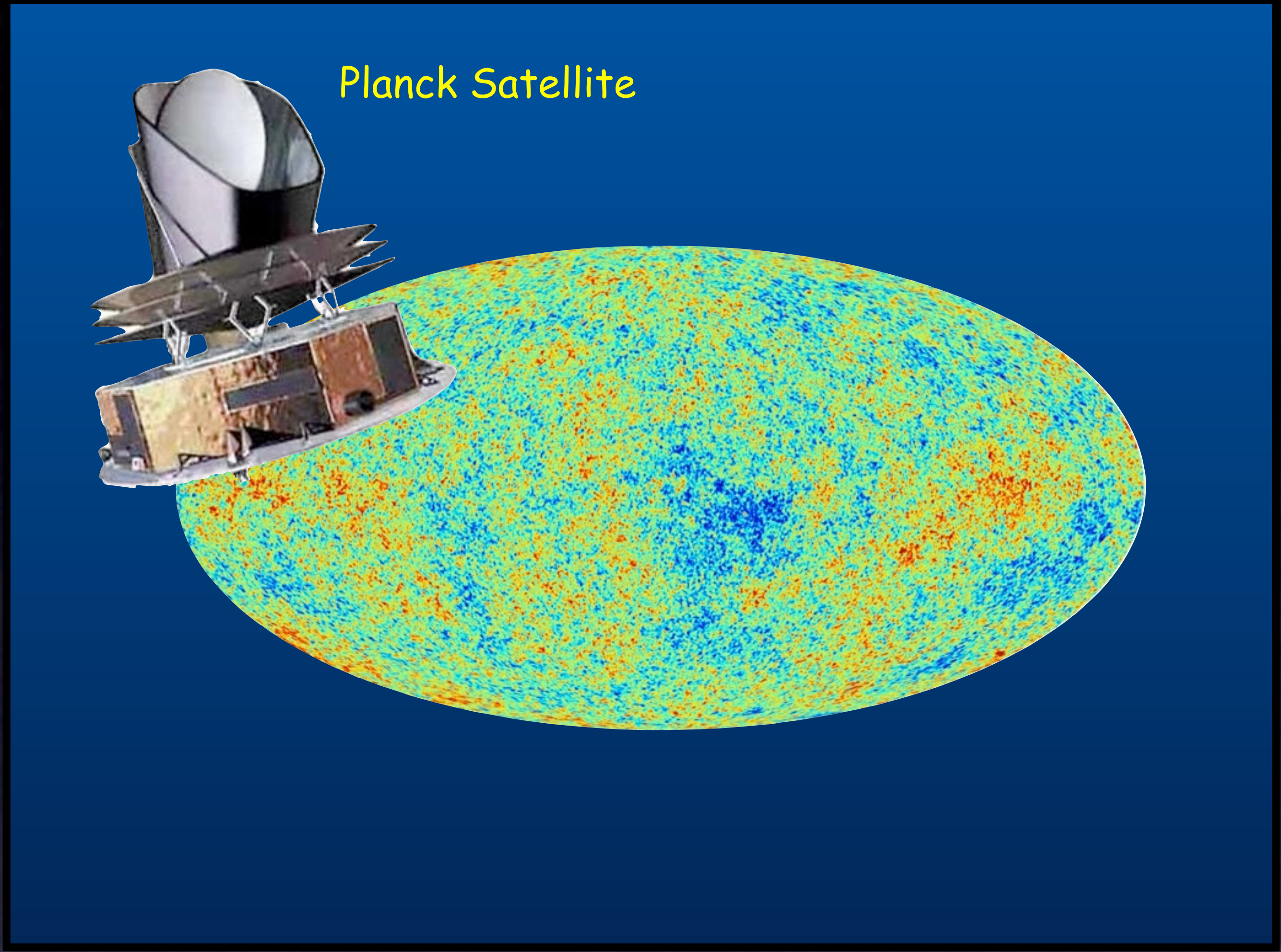
More Applications...

Probing the IGM



Cross-correlating low-z QSO absorption lines (from FUSE & COS) with SDSS density distribution constrains temperatures & metallicities of filaments and sheets.

Predicting kSZ effect



Detailed knowledge of the peculiar velocities of groups & clusters allows us to predict the kSZ effect, which can be tested with ongoing missions such as ACT and Planck.

Conclusions

For each location in the SDSS DR7 Survey Volume, we have estimates of

- Reconstructed density field as function of time
- Reconstructed (linear) velocity field
- Reconstructed (large-scale) tidal field
- Classification of cosmic web in CLUSTER, FILAMENT, SHEET & VOID

These data have many applications for studies of galaxy formation, large scale structure, the IGM & cosmology, and will be made publicly available!

We have detected a large-scale bulk flow of ~120 km/s in a very large volume (equivalent to sphere of radius ~170 Mpc/h), which seems to be produced by the massive structures associated with SDSS Great Wall.

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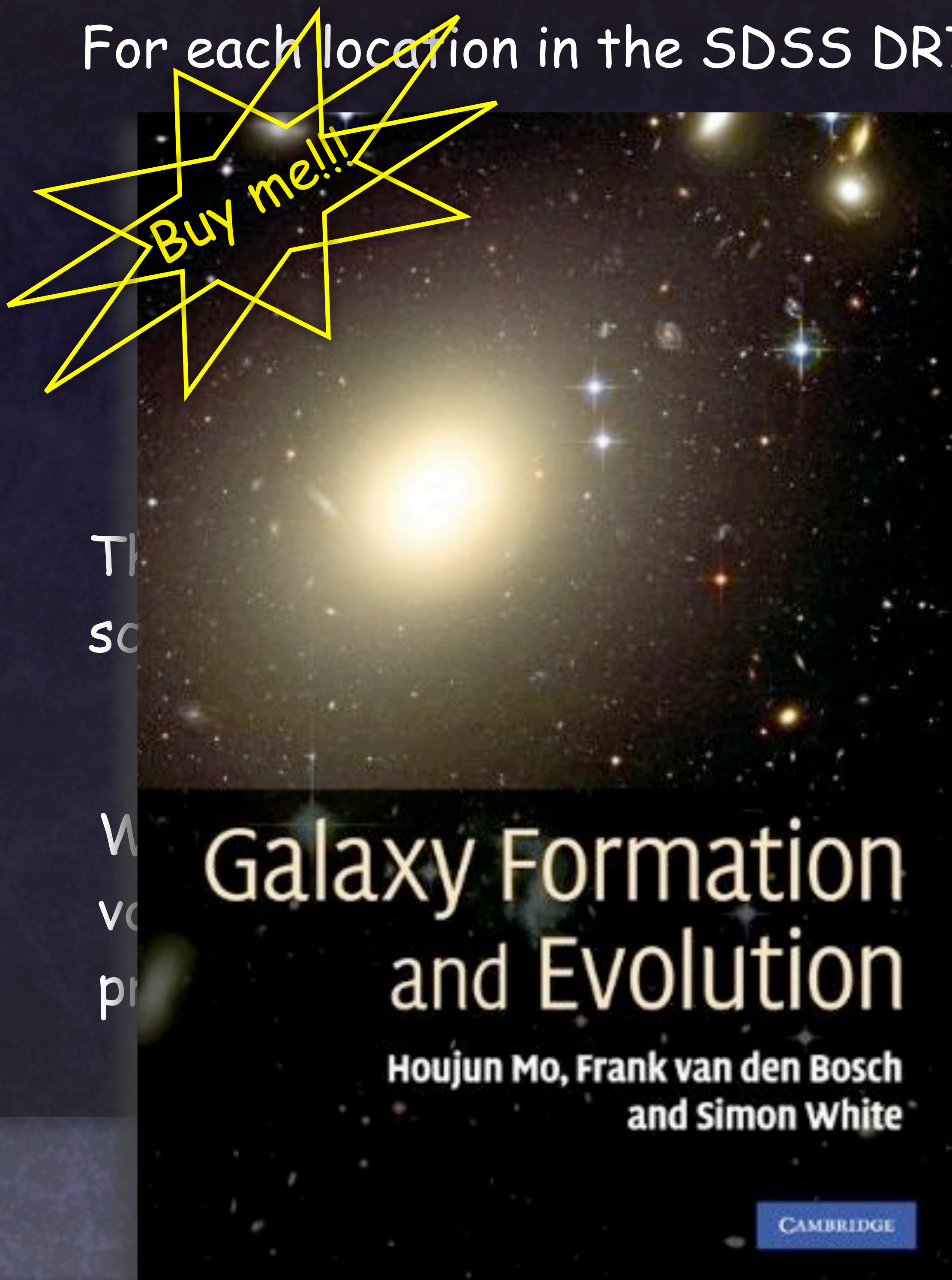

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