Re-simulating the actual local Universe

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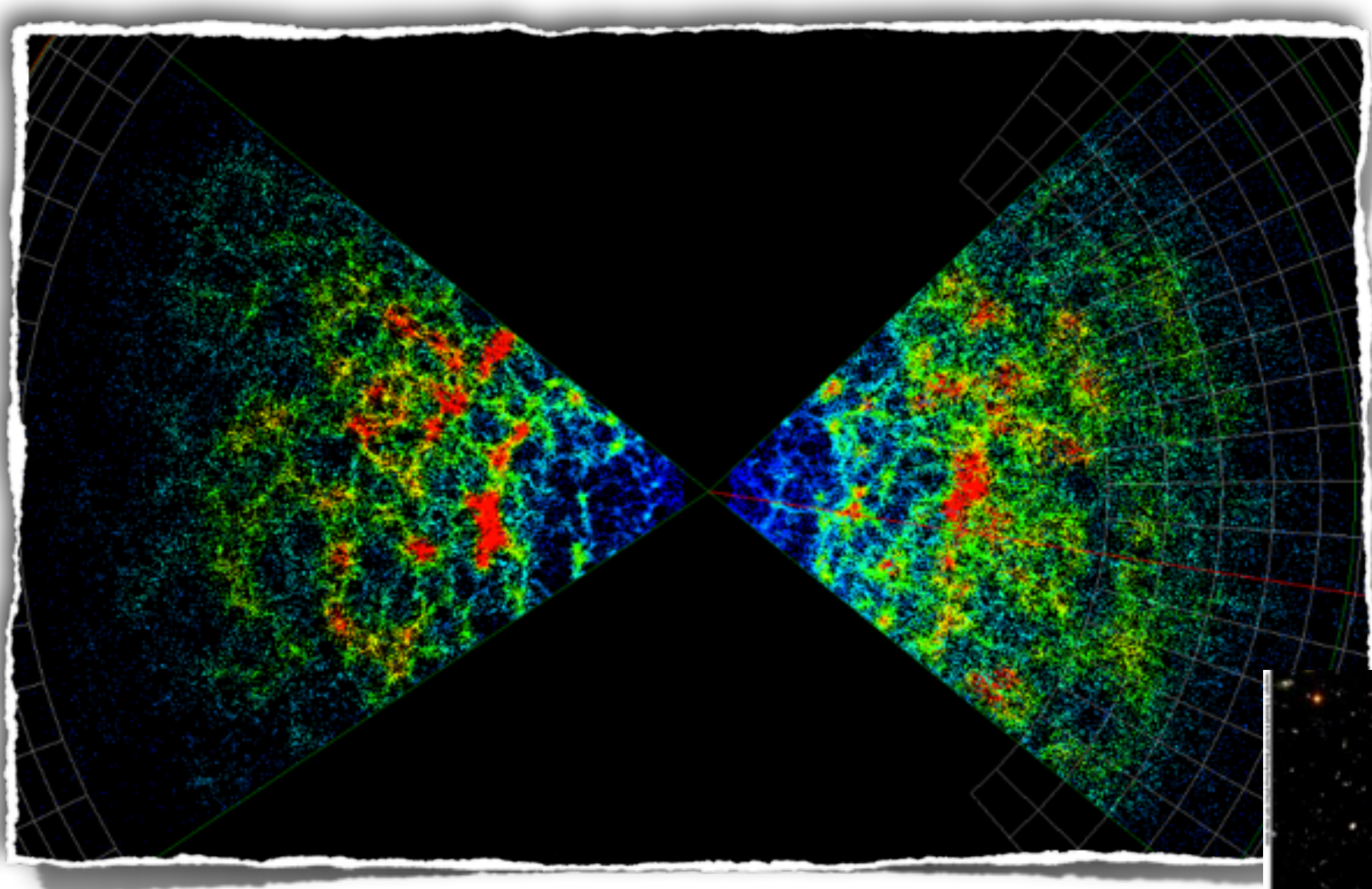
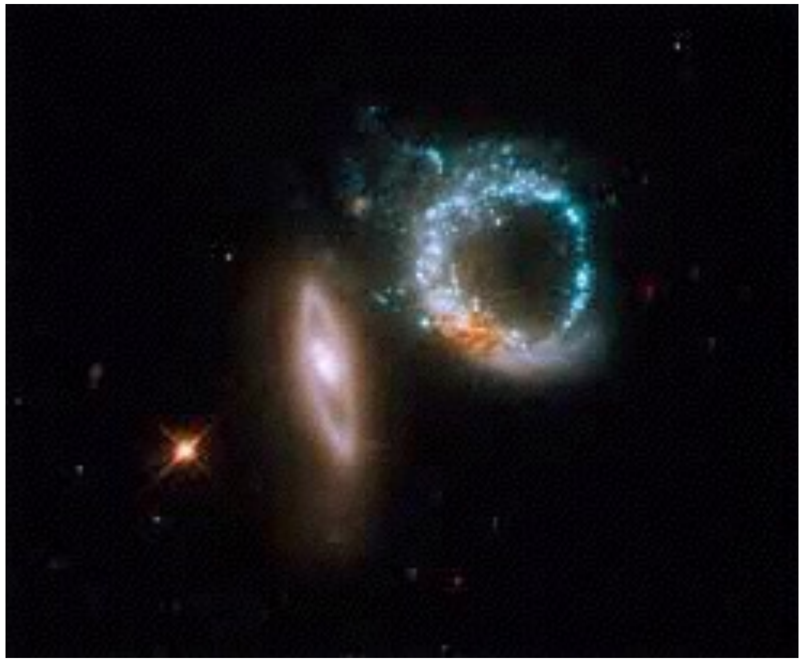
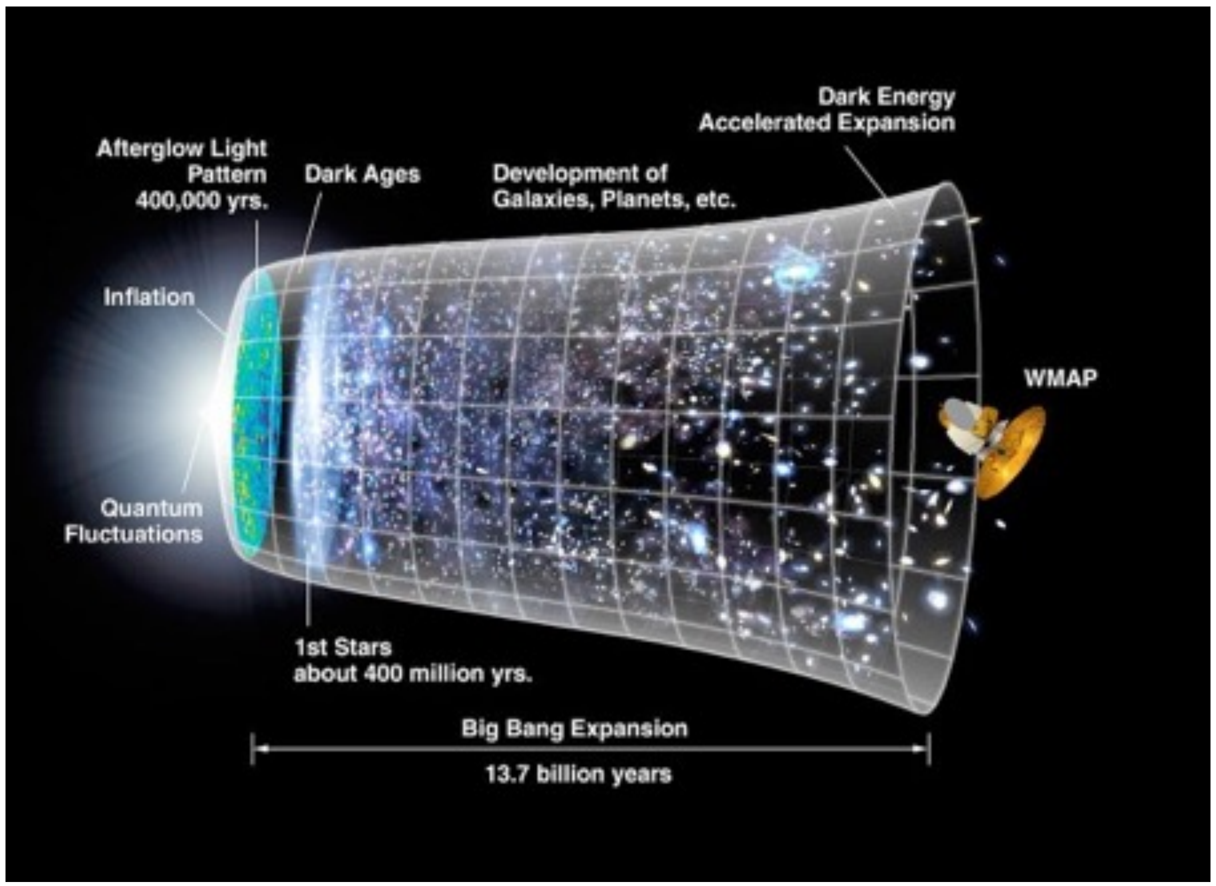
KIAA, 2016



Galaxies come in a variety of sizes, masses, and shapes...



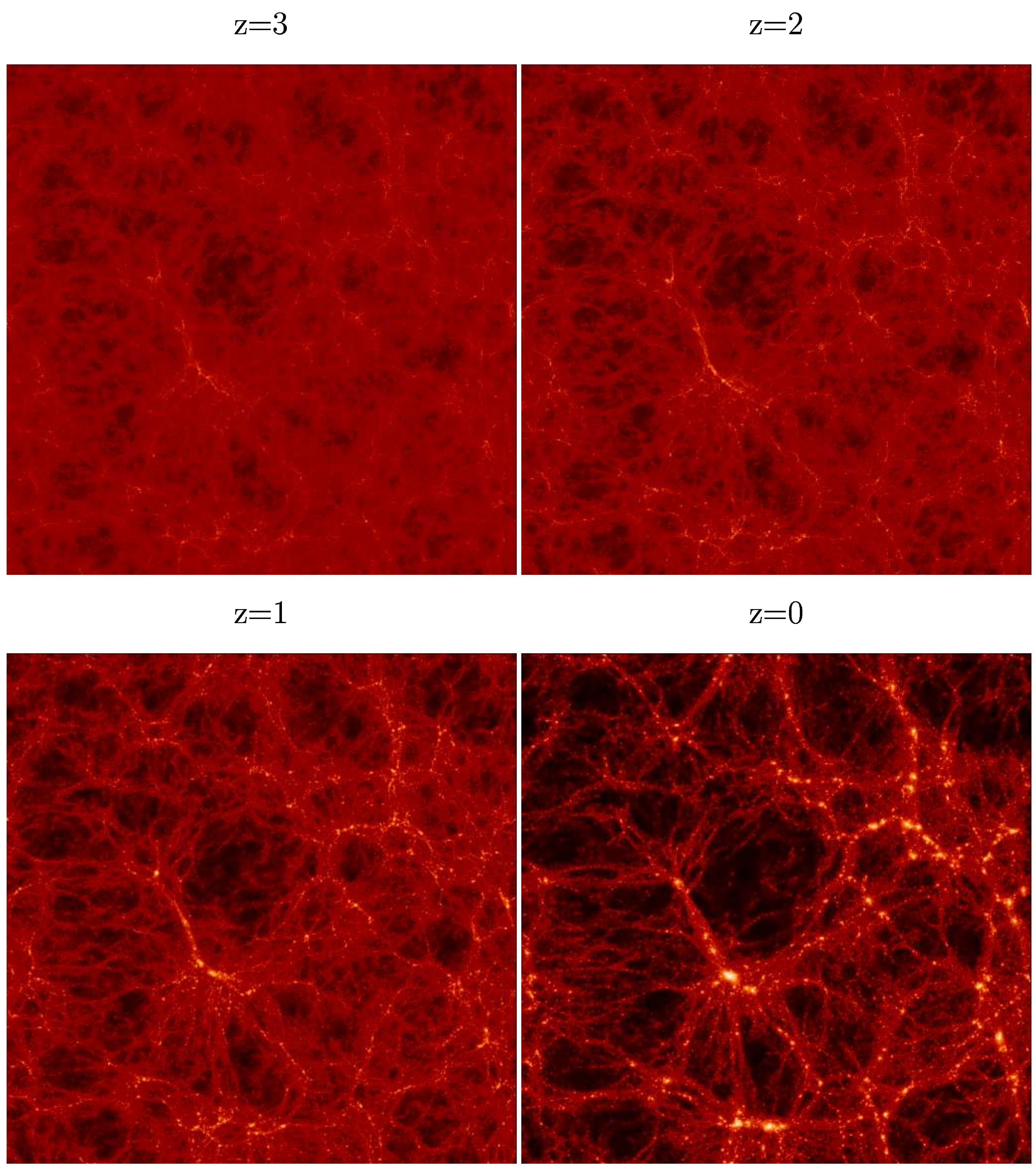
The standard paradigm

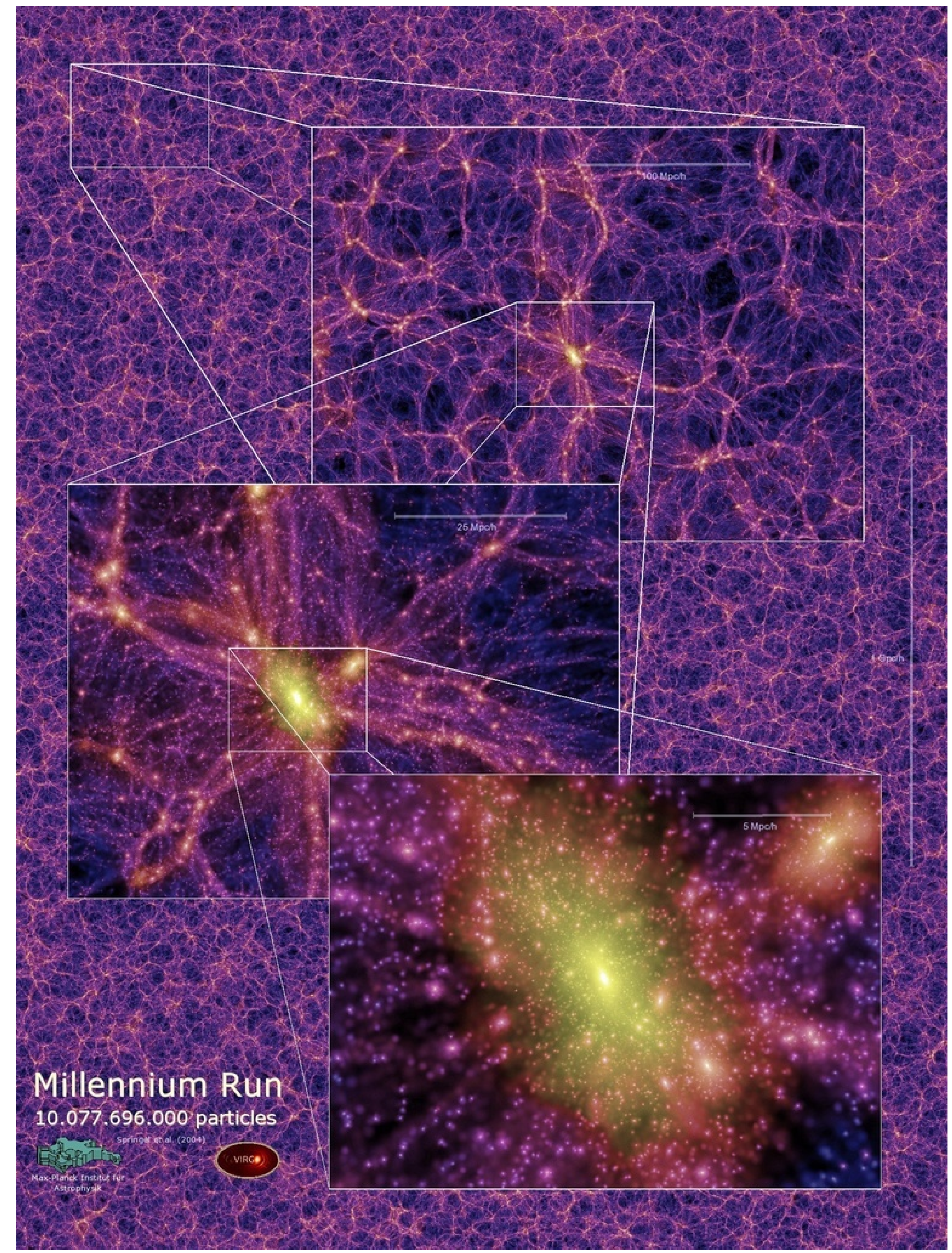


- Big Bang cosmology
- The Universe is dominated by cold dark matter and dark energy
- Primordial perturbations, probably generated by inflation, well constrained by observation (CMB; LSS etc)
- Cosmological models

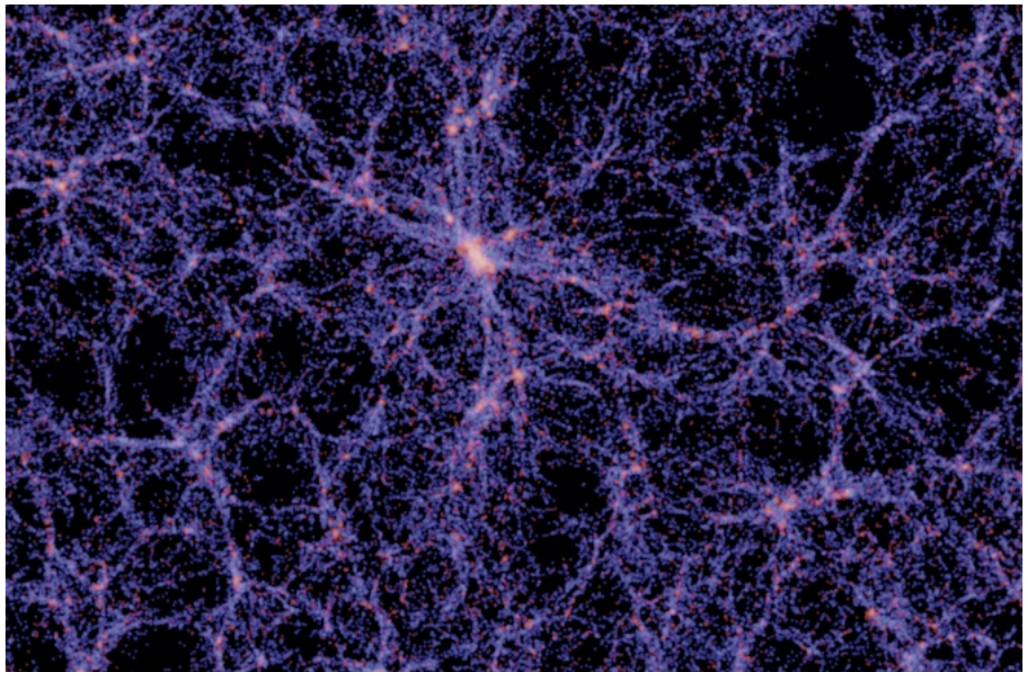
$$k = 0;\ \Omega_m = 0.25;\ \Lambda = 0.75;\ h = 0.7;\ \Omega_b = 0.04;\ n = 1$$

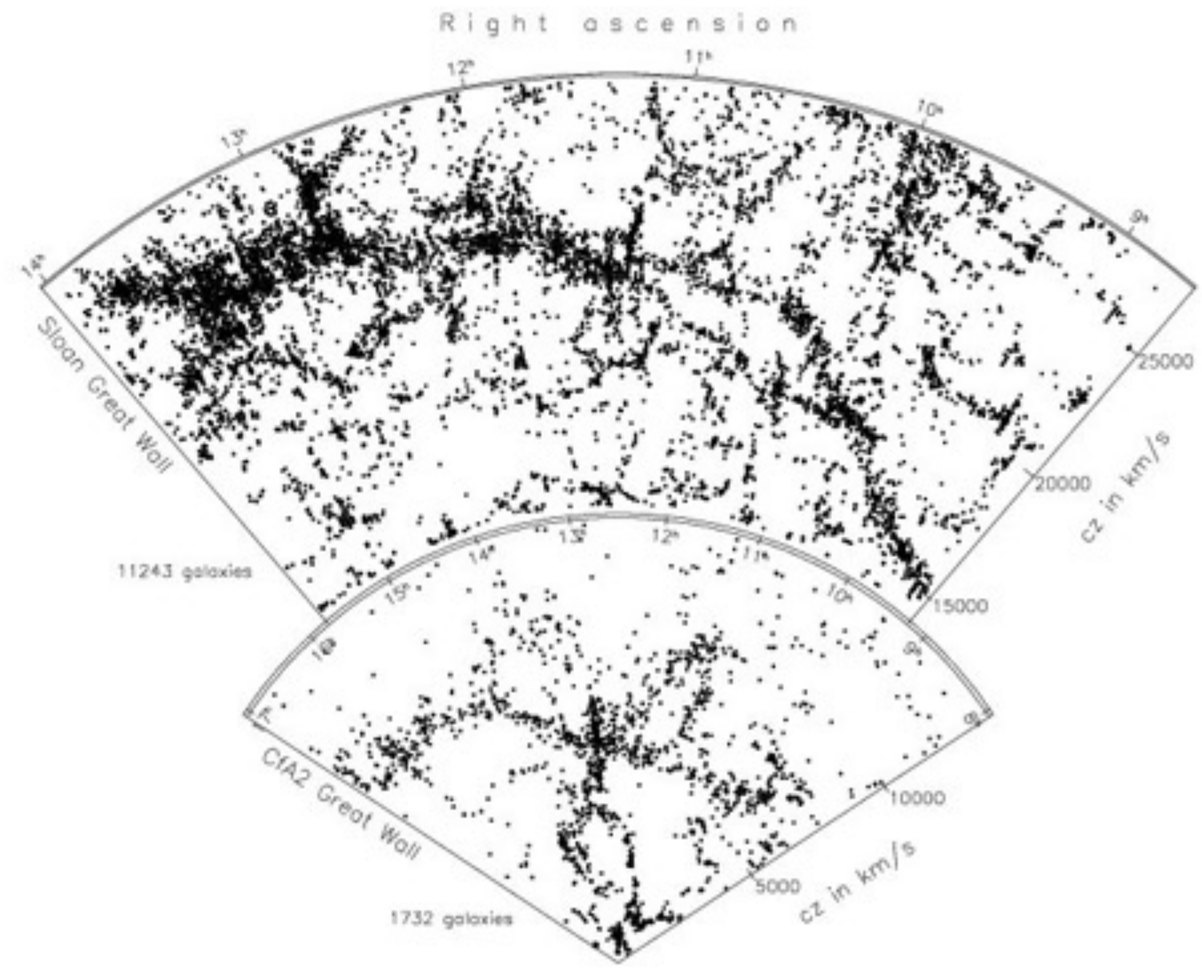
Numerical simulation results





How do we test theory with observation





Needs constrained reconstruction

If we can accurately reconstruct the initial condition of the local Universe, then we can

(1) study the histories of the structures we observe;
(2) compare data and theory 'directly' (without cosmic variance).

Reconstructing the initial density field
From $\rho_{\mathrm{f}}(\mathbf{x})$ to $\delta_j(\mathrm{k})$

$$Q(\delta_j(\mathbf{k})|\rho_{\mathrm{f}}(\mathbf{x})) = \mathrm{e}^{-\sum_{\mathbf{x}}[\rho_{\mathrm{mod}}(\mathbf{x})-\rho_{\mathrm{f}}(\mathbf{x})]^2\omega(\mathbf{x})/2\sigma_{\mathrm{f}}^2(\mathbf{x})} \prod_{\mathbf{k}}^{\mathrm{half}} \prod_{j=0}^{1} \frac{1}{[\pi P_{\mathrm{lin}}(k)]^{1/2}} \mathrm{e}^{-[\delta_j(\mathbf{k})]^2/P_{\mathrm{lin}}(k)}$$

(likelihood) (prior)

From $\delta_j(\mathrm{k})$ to $\rho_{\mathrm{mod}}(\mathbf{x})$ 2LP T; MZA; etc

We adopted PM (Wang et al. 2014)

From current density field to initial density field: Hamiltonian Markov Chain Monte Carlo method

In this subsection, we briefly outline the HMC method (see Hanson 2001; Taylor et al. 2008; JW12 for some more detailed descriptions). The method is itself based on an analogy to solving a physical system in Hamiltonian dynamics. As a first step, we define the potential of the system to be the negative of the logarithm of the target probability distribution,

$$\begin{aligned} \psi[\delta_j(\mathbf{k})] &\equiv -\ln[Q(\delta_j(\mathbf{k})|\rho_{\rm f}(\mathbf{x}))] \\ &= \sum_{\mathbf{k}}^{\rm half} \ln[\pi P_{\rm lin}(k)] + \sum_{\mathbf{k}}^{\rm half}\sum_{j=0}^{1} \frac{[\delta_j(\mathbf{k})]^2}{P_{\rm lin}(k)} + \sum_{\mathbf{x}} \frac{[\rho_{\rm mod}(\mathbf{x}) - \rho_{\rm f}(\mathbf{x})]^2 \omega(\mathbf{x})}{2\sigma_{\rm f}^2(\mathbf{x})} \,. \end{aligned} \tag{4}$$

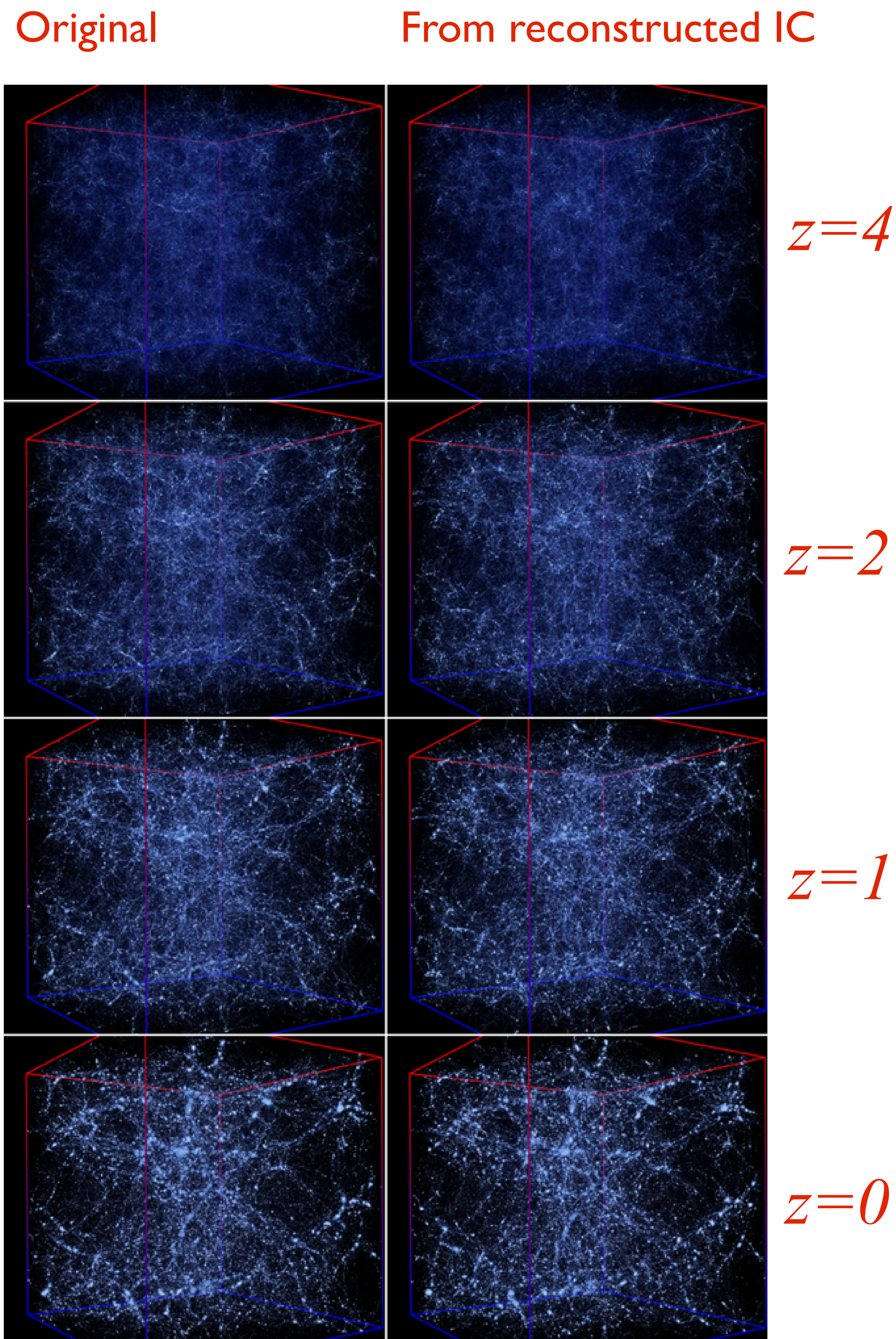
For each $\delta_j(\mathbf{k})$, a momentum variable, $p_j(\mathbf{k})$, and a mass variable, $m_j(\mathbf{k})$, are introduced. The Hamiltonian of the fictitious system can then be written as

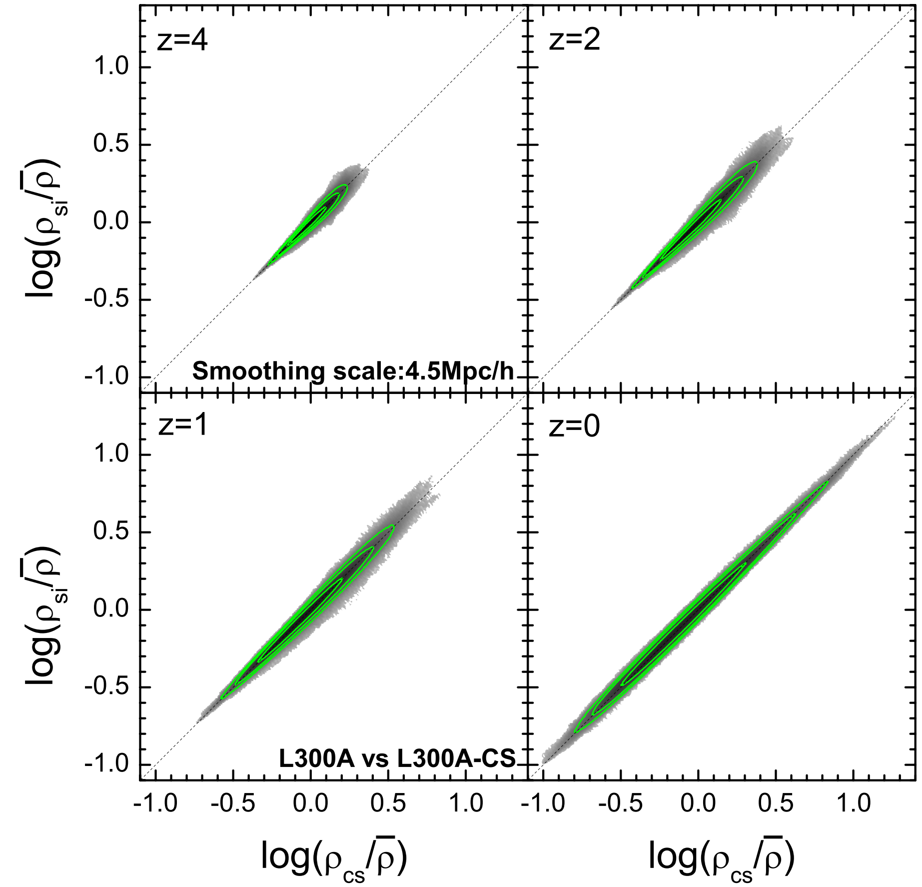
$$H = \sum_{\mathbf{k}}^{\rm half}\sum_{j=0}^{1} \frac{p_j^2(\mathbf{k})}{2m_j(\mathbf{k})} + \psi[\delta_j(\mathbf{k})] \,. \tag{5}$$

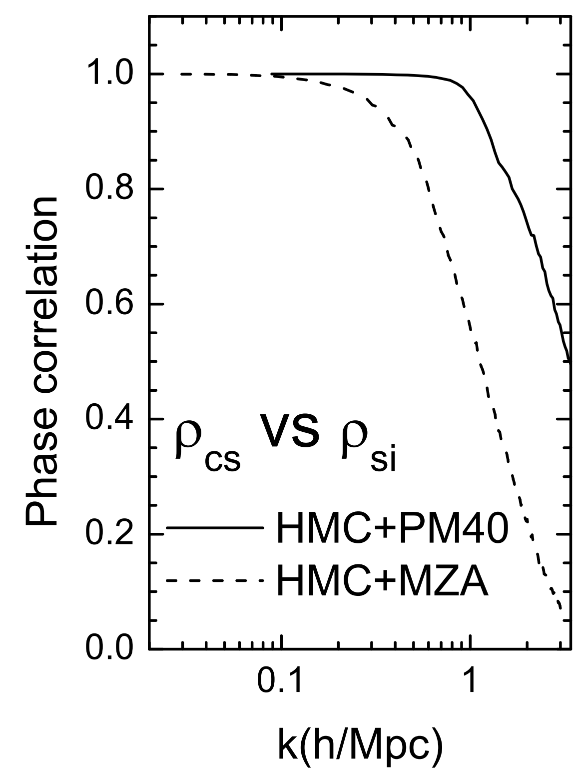
The statistical properties of the system is given by the partition function, $\exp(-H)$, which can be separated into a Gaussian distribution in momenta $p_j(\mathbf{k})$ multiplied by the target distribution,

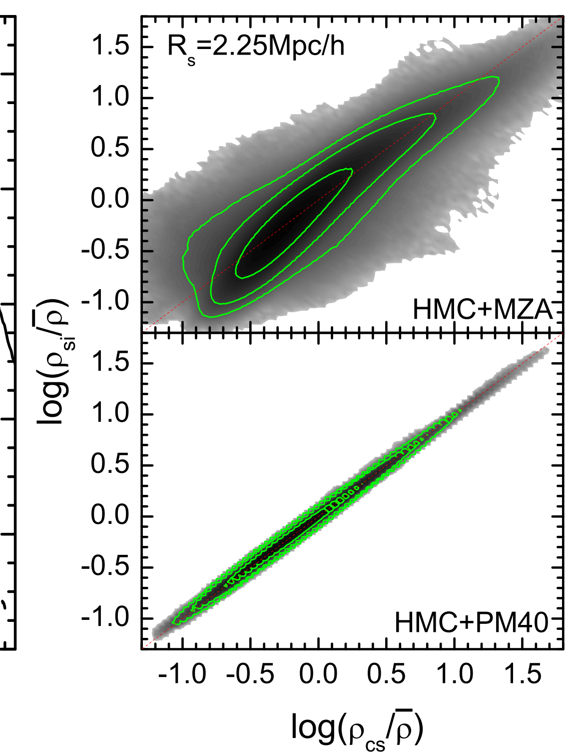
$$\exp(-H) = Q[\delta_j(\mathbf{k})|\rho_{\rm f}(\mathbf{x})] \prod_{\mathbf{k}}^{\rm half}\prod_{j=0}^{1} {\rm e}^{-\frac{p_j^2(\mathbf{k})}{2m_j(\mathbf{k})}} \,. \tag{6}$$

Thus, the target probability distribution can be obtained by first sampling this partition function and then marginalizing over momenta (i.e setting all the momenta to be zero).

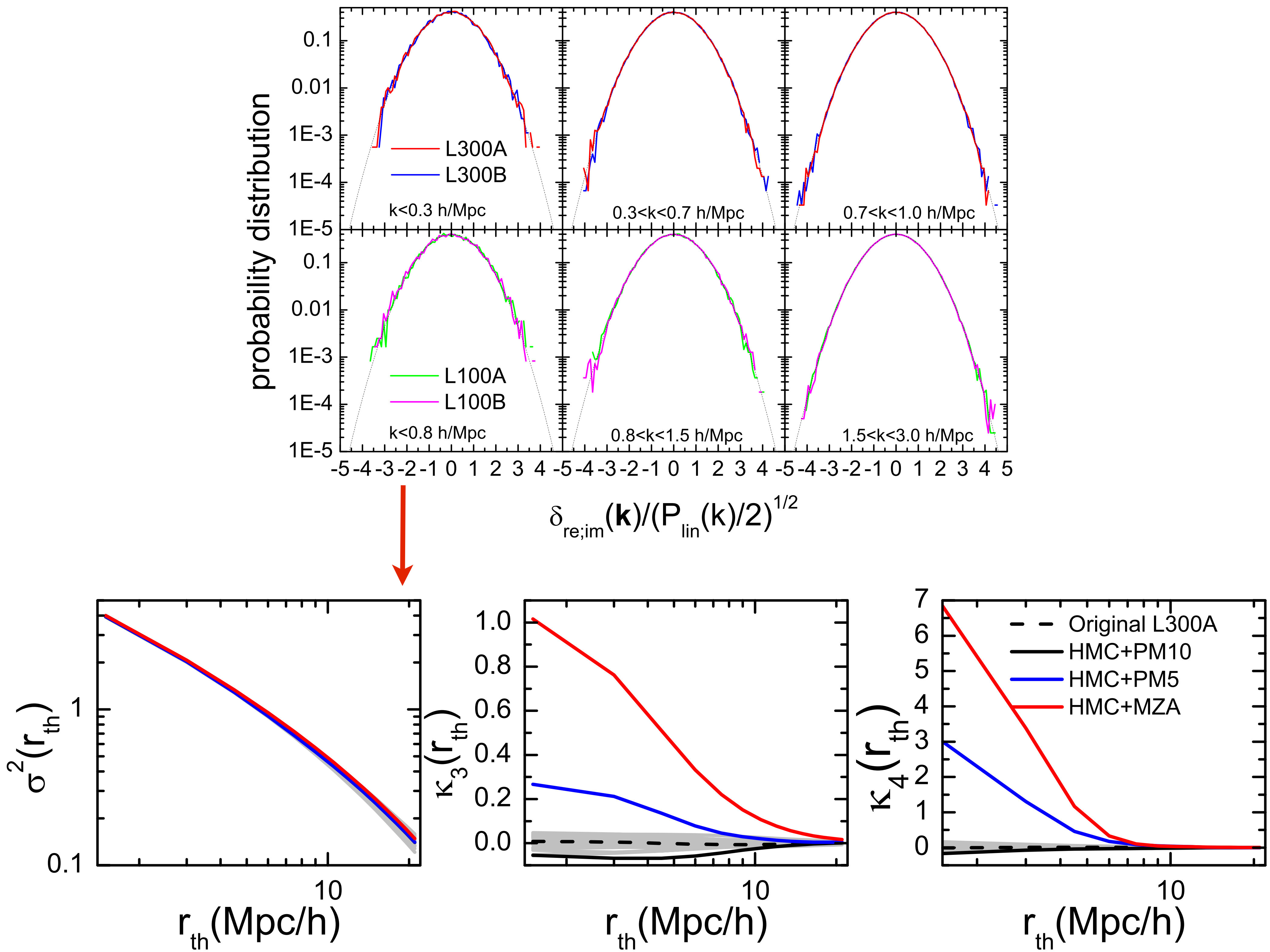

Original
From reconstructed IC
z=4
z=2
z=1
z=0


z=4
z=2
z=1
z=0
Smoothing scale:4.5Mpc/h
L300A vs L300A-CS
$\log(\rho_{si}/\bar{\rho})$
$\log(\rho_{cs}/\bar{\rho})$


Phase correlation
ρ_{cs} vs ρ_{si}
HMC+PM40
HMC+MZA
k(h/Mpc)


R_s=2.25Mpc/h
HMC+MZA
HMC+PM40
$\log(\rho_{si}/\bar{\rho})$
$\log(\rho_{cs}/\bar{\rho})$

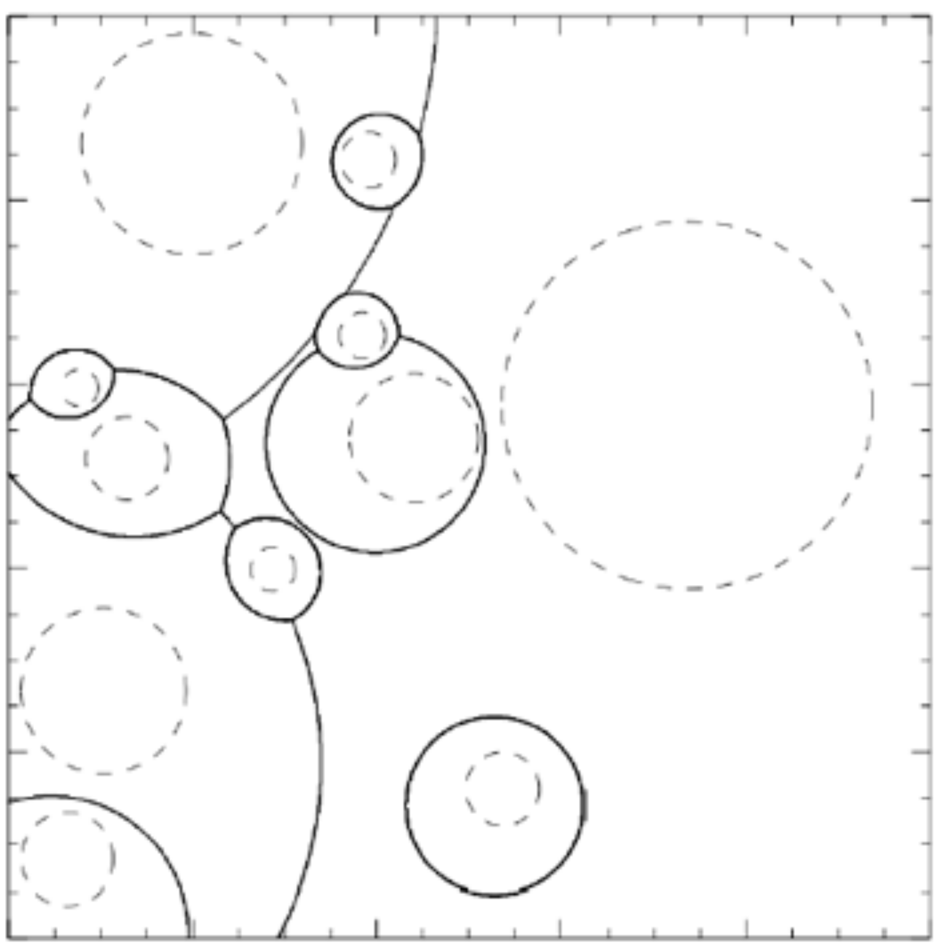
Gaussianity



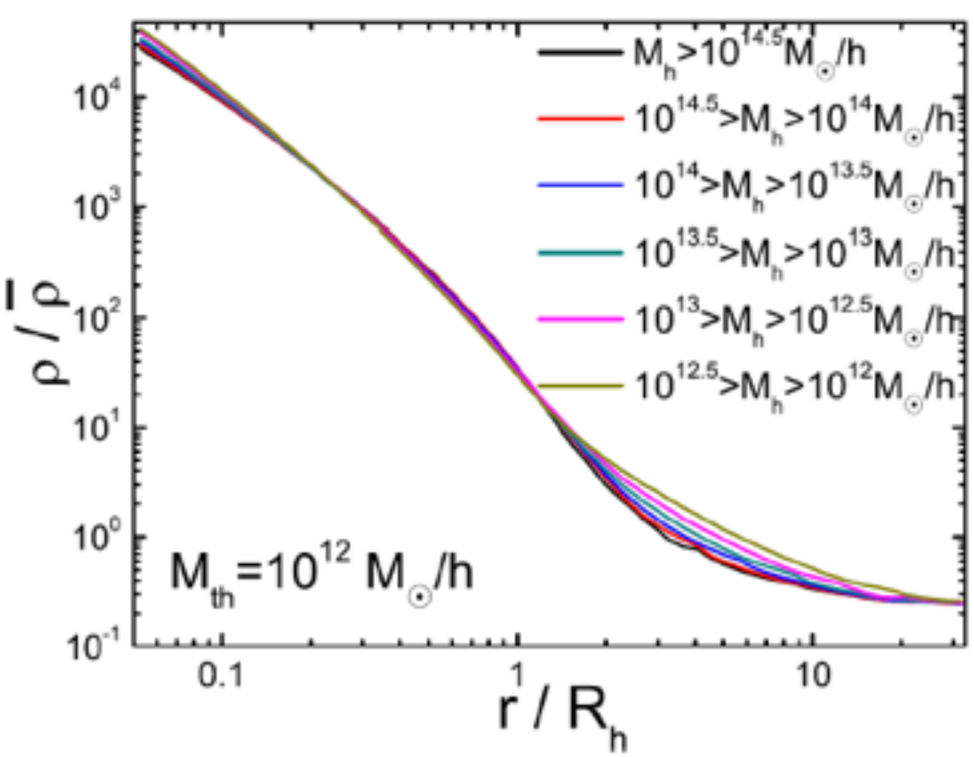
Reconstruction of the current density field from dark matter halos (Wang et al. 2009)

(1) Each point in space is assigned to its nearest halo according to distance scaled by halo virial radius;

(2) The density at the point is given by the cross-correlation between halos and mass in their domains given by a chosen cosmological model.

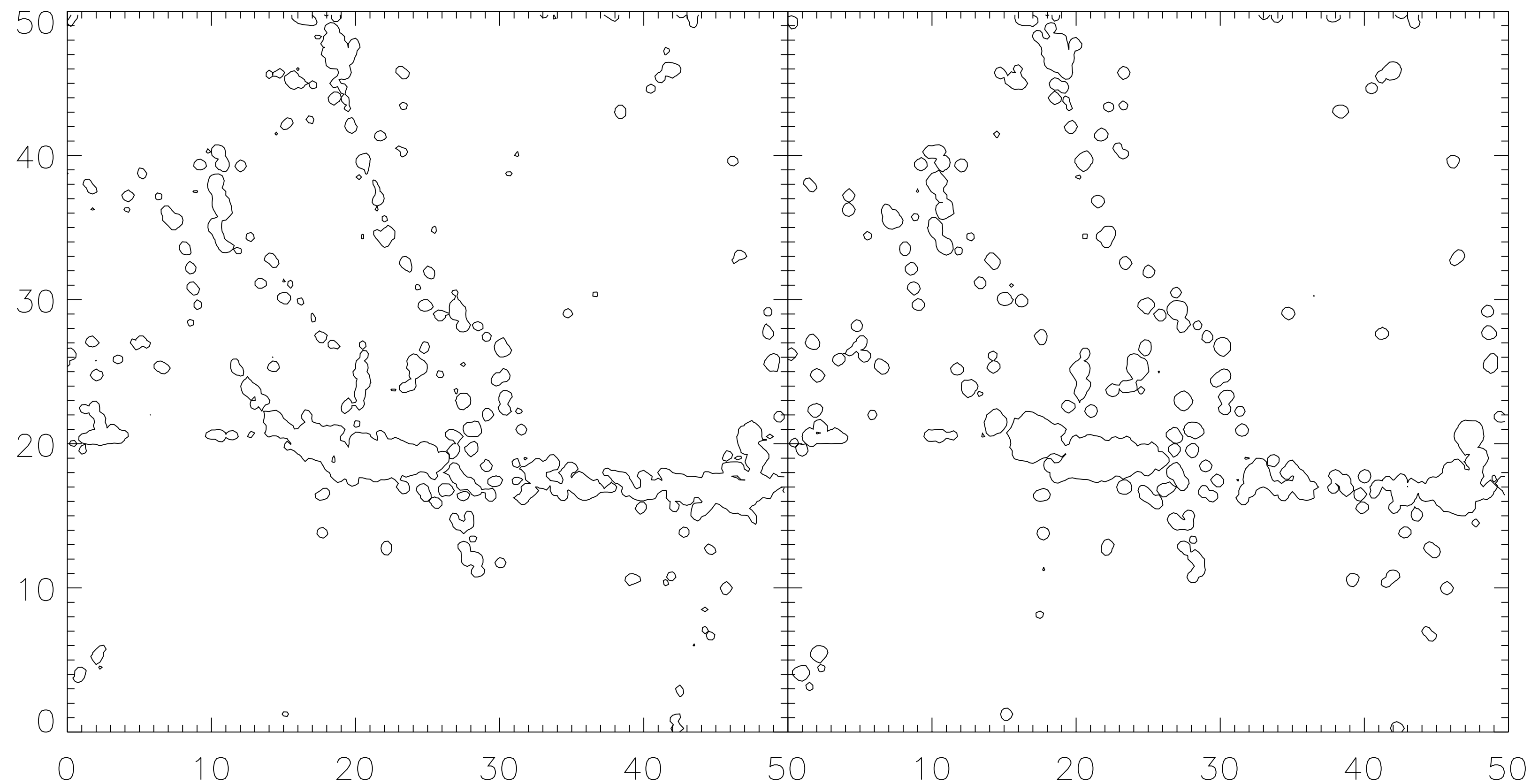


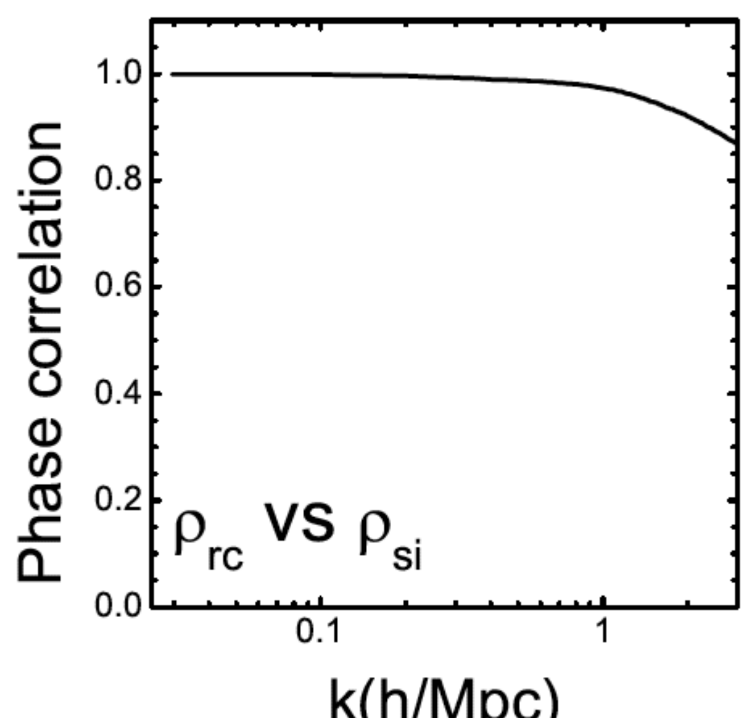
- Halo Domain $r_p = \frac{r_h}{R_h}$
- Domain Cross Correlation

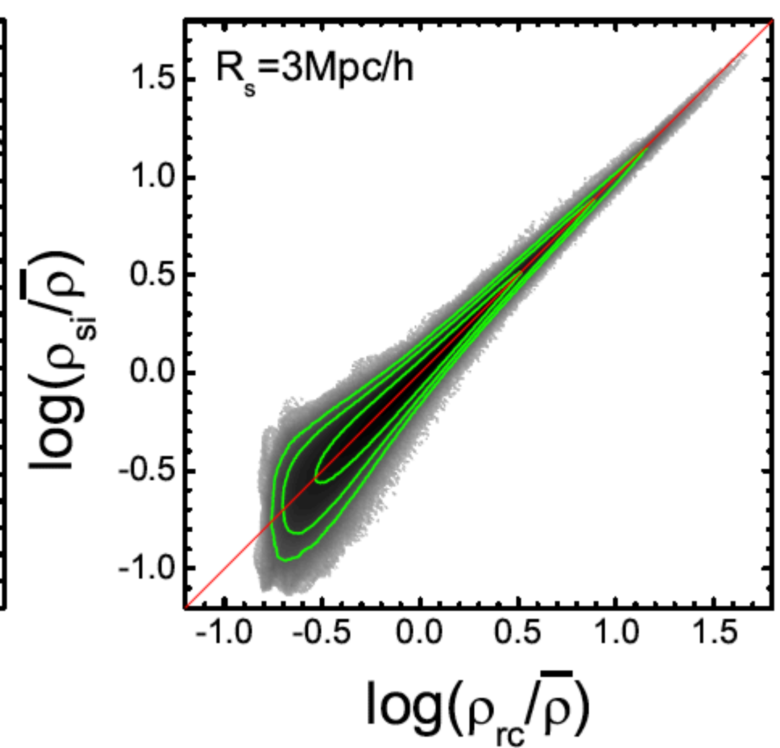


Using halos with masses > 10^12 M_sun

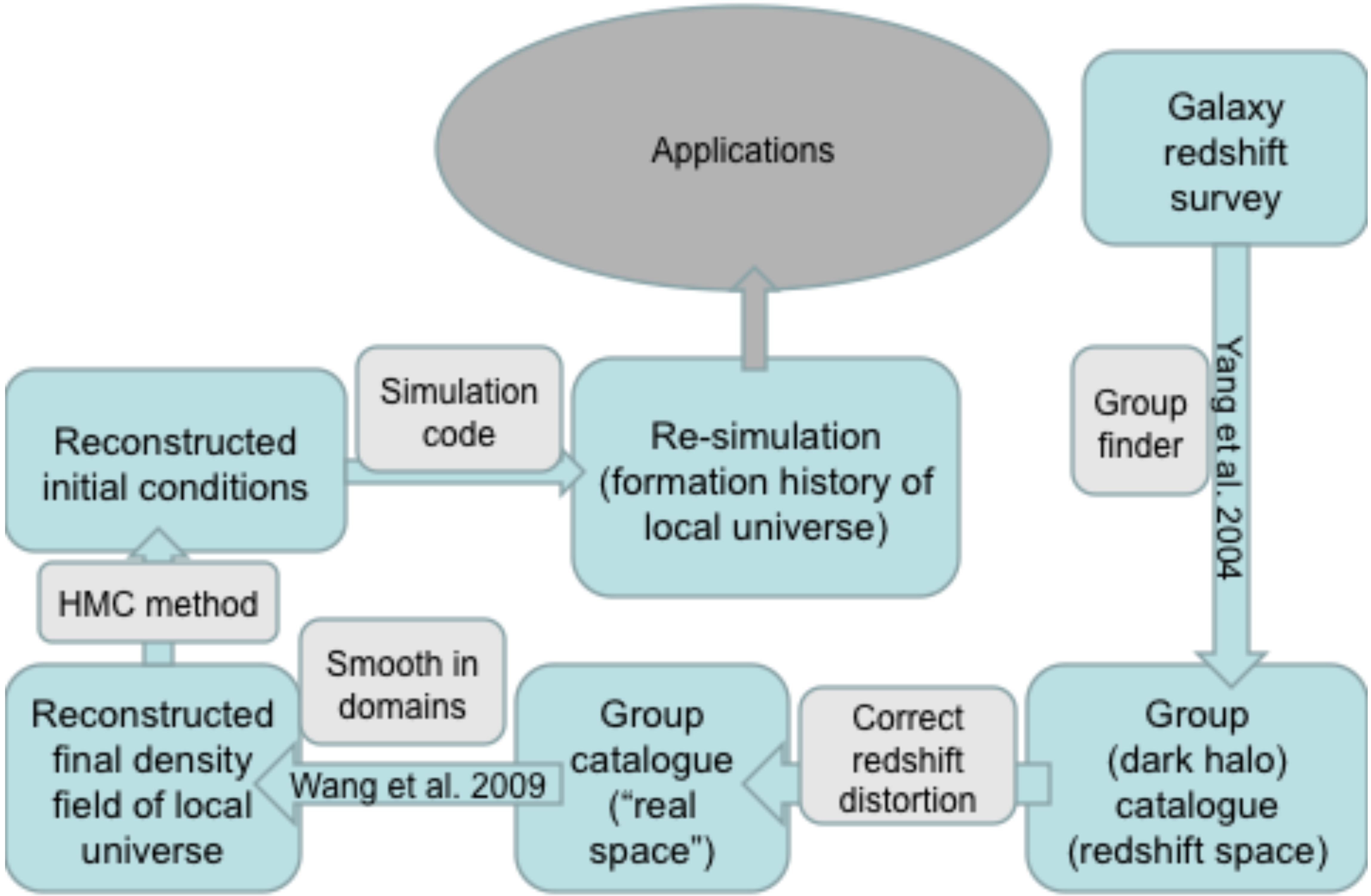
Original Reconstructed





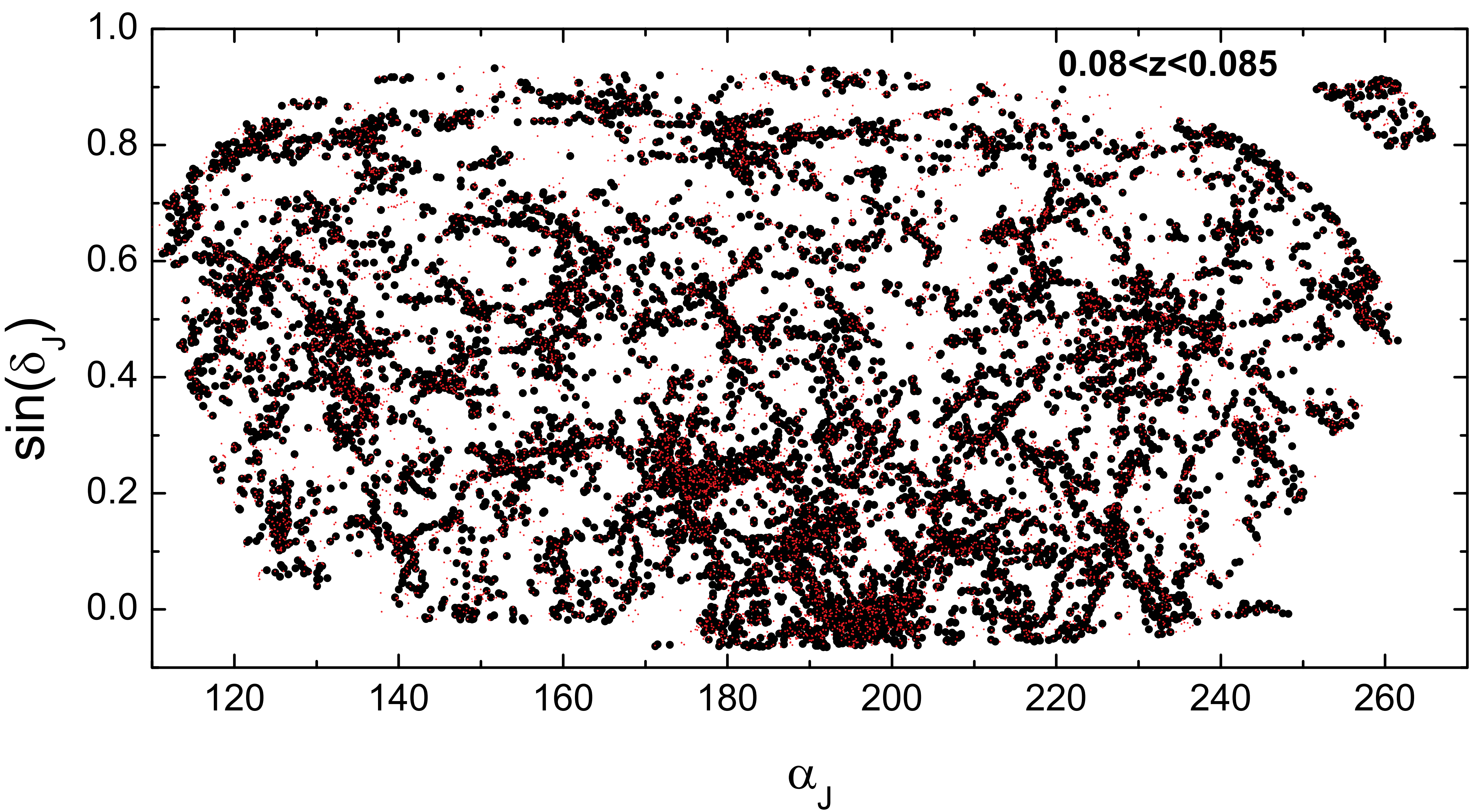


The ELUCID Project



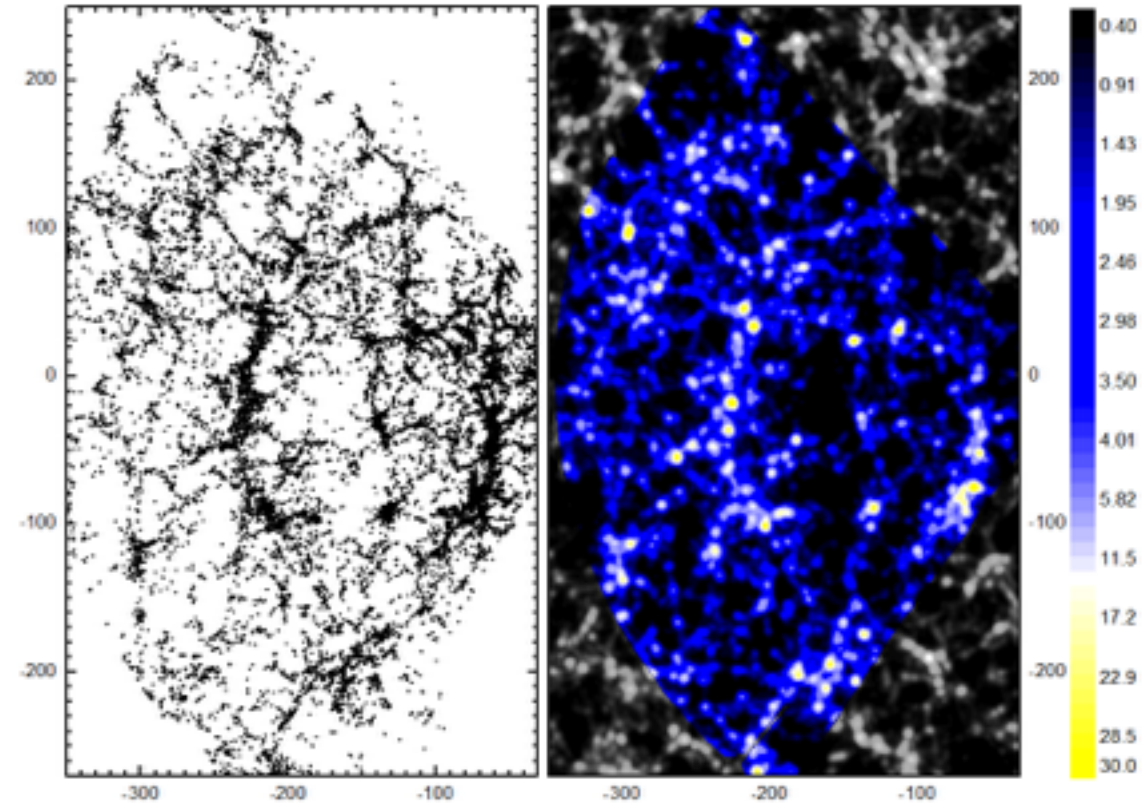
Reconstructing the current density field using groups/halos above a certain mass

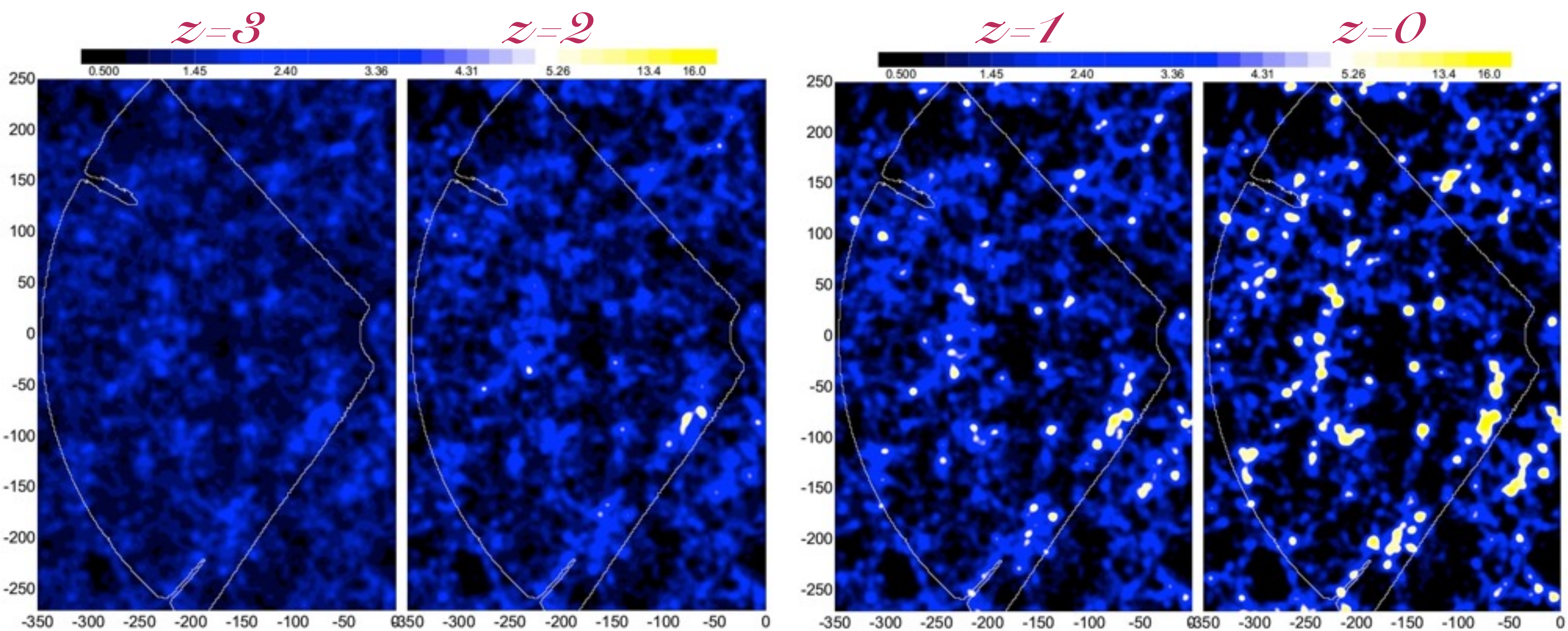
$M_{\rm th} = 10^{12}h^{-1}{\rm M}_\odot$ limited by SDSS redshift survey



Application to SDSS

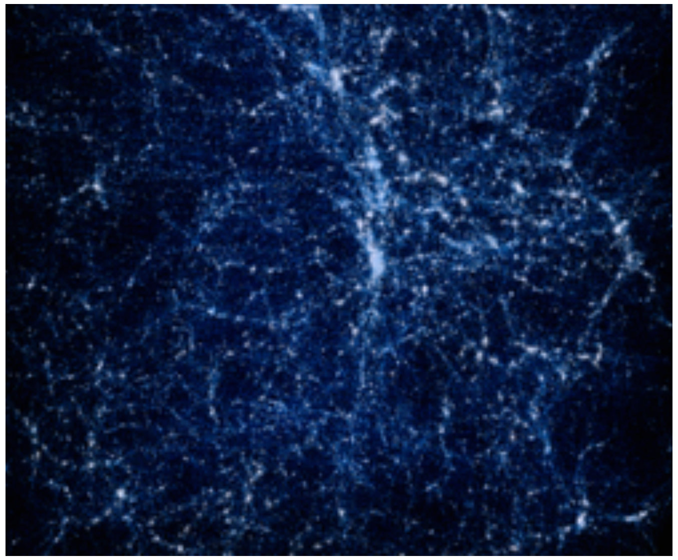
The Great Wall Region



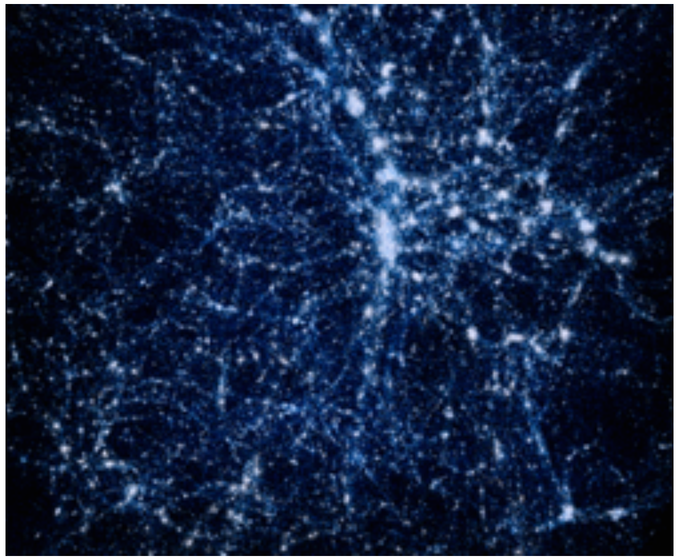


Formation of Coma Cluster

z=3

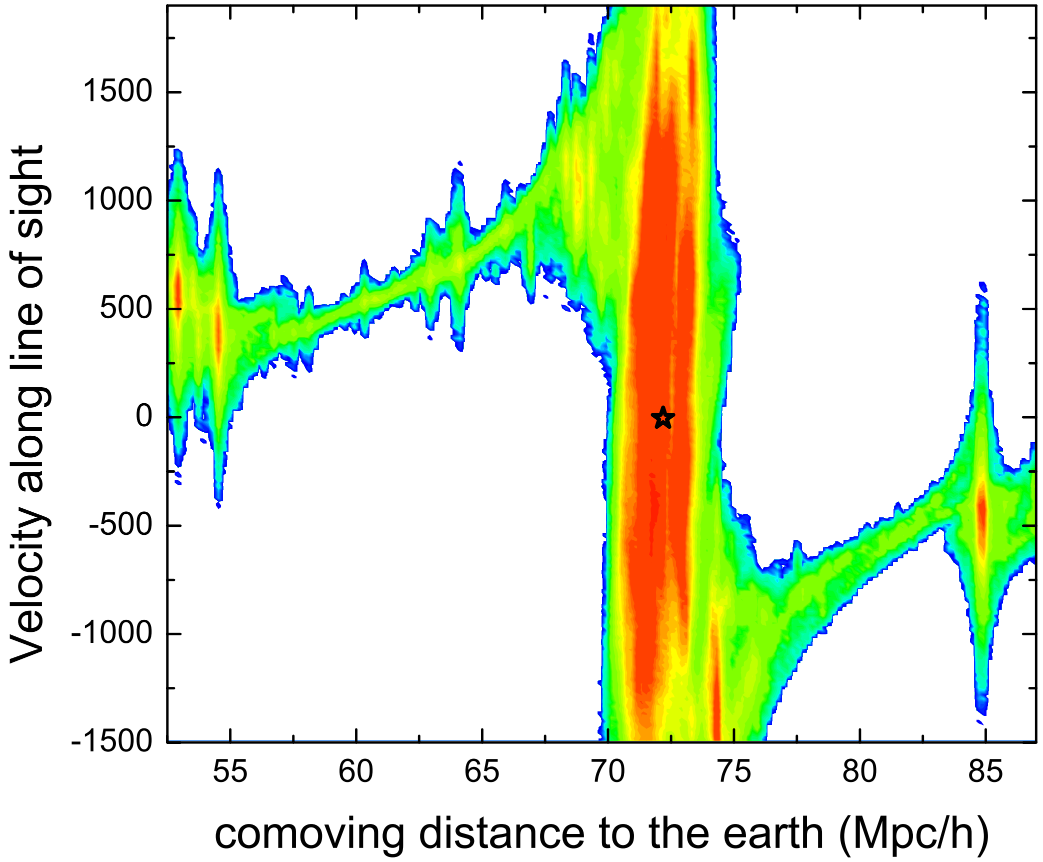


z=2

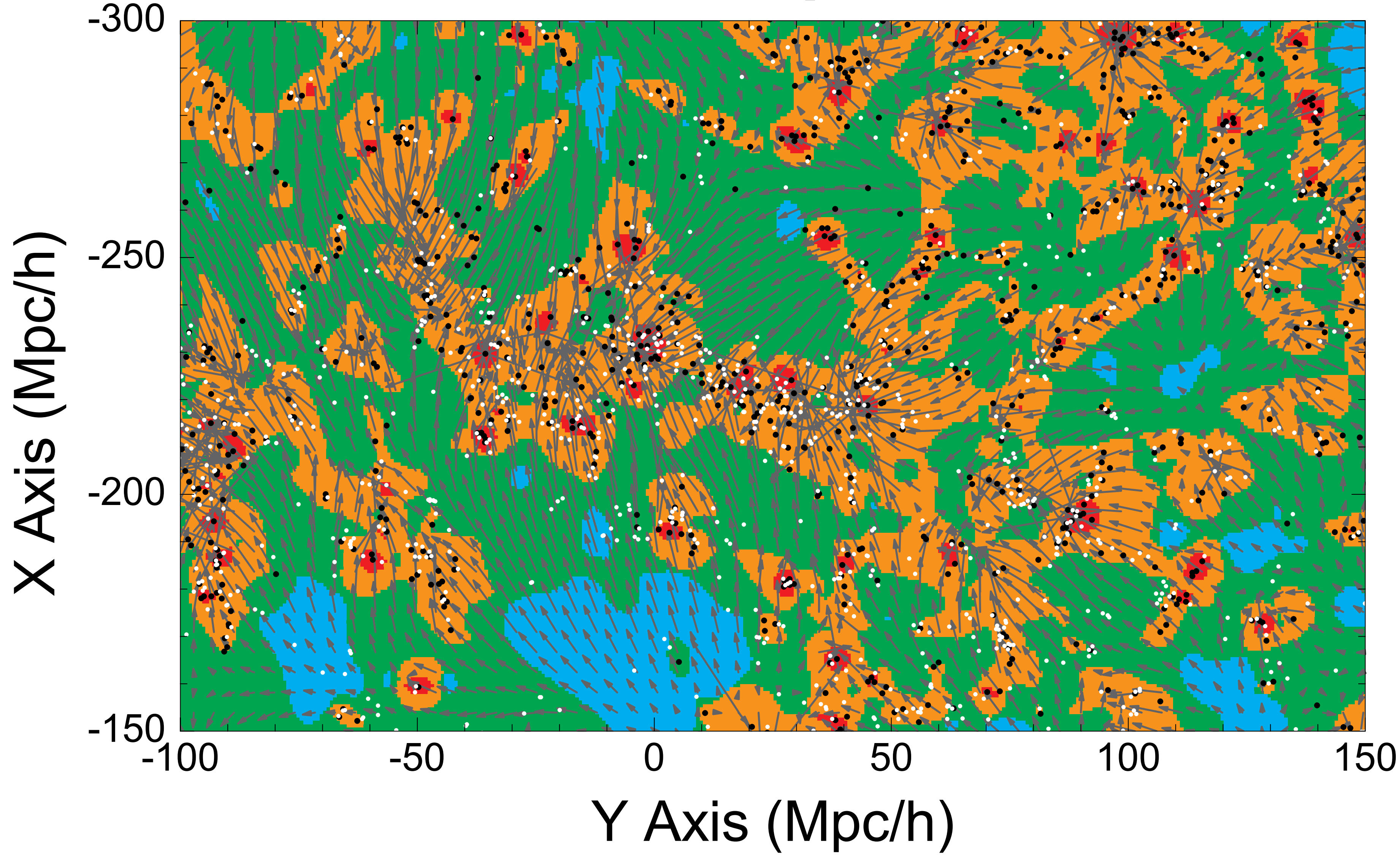


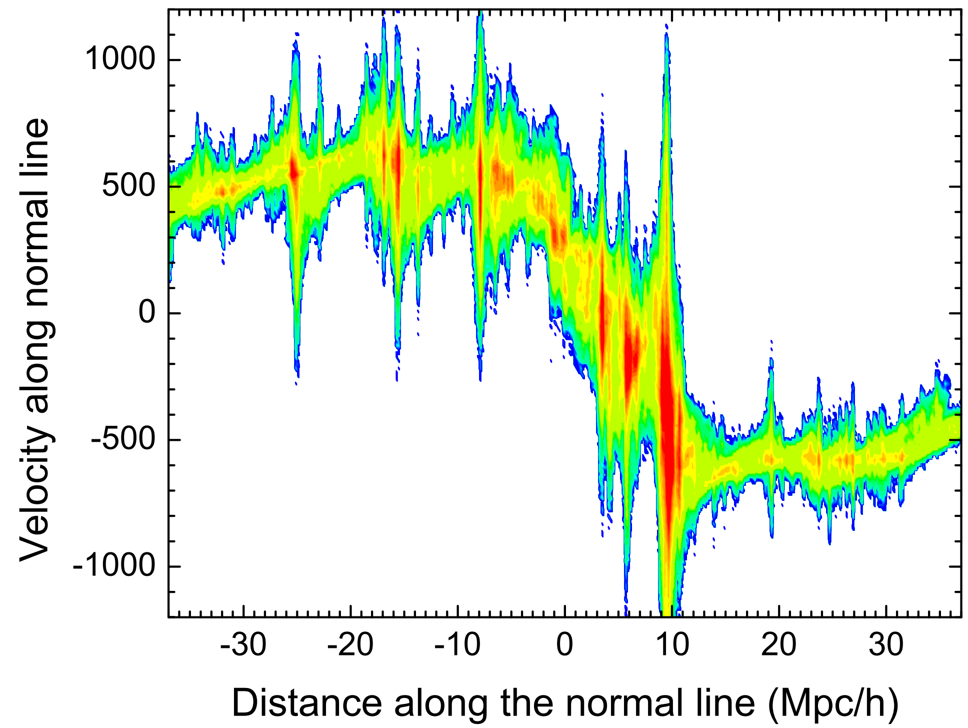
z=1

z=0

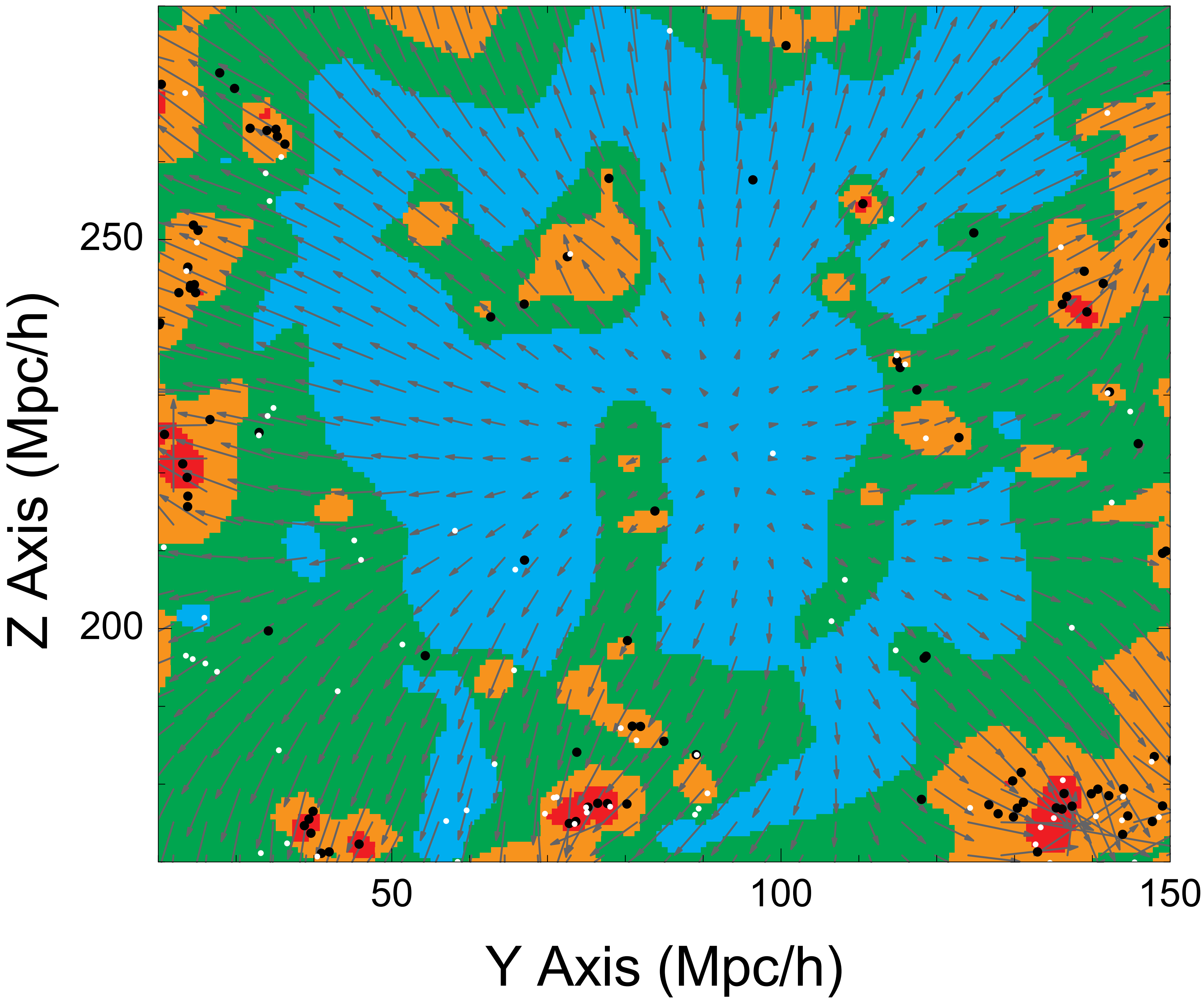


Velocity field

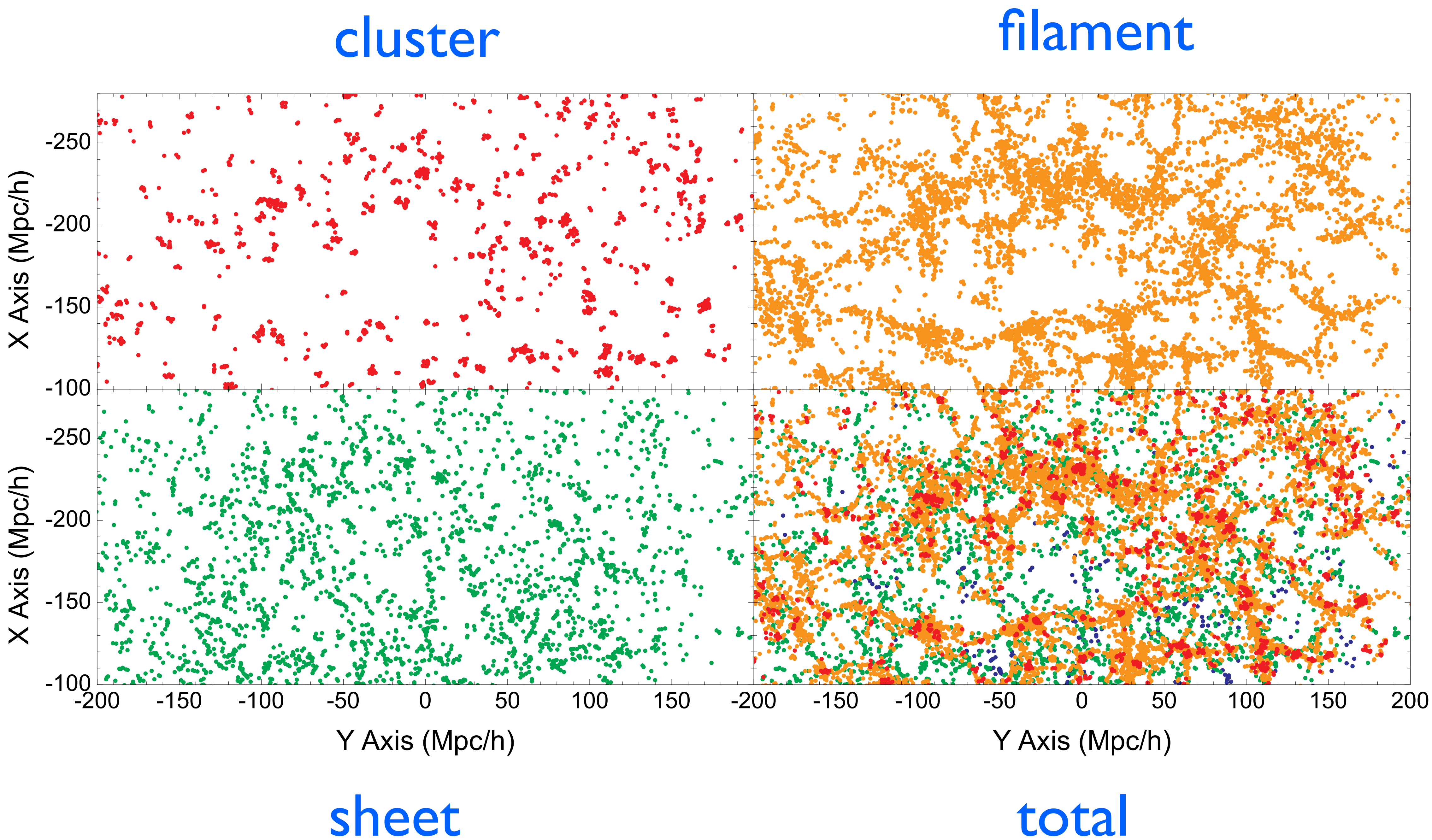




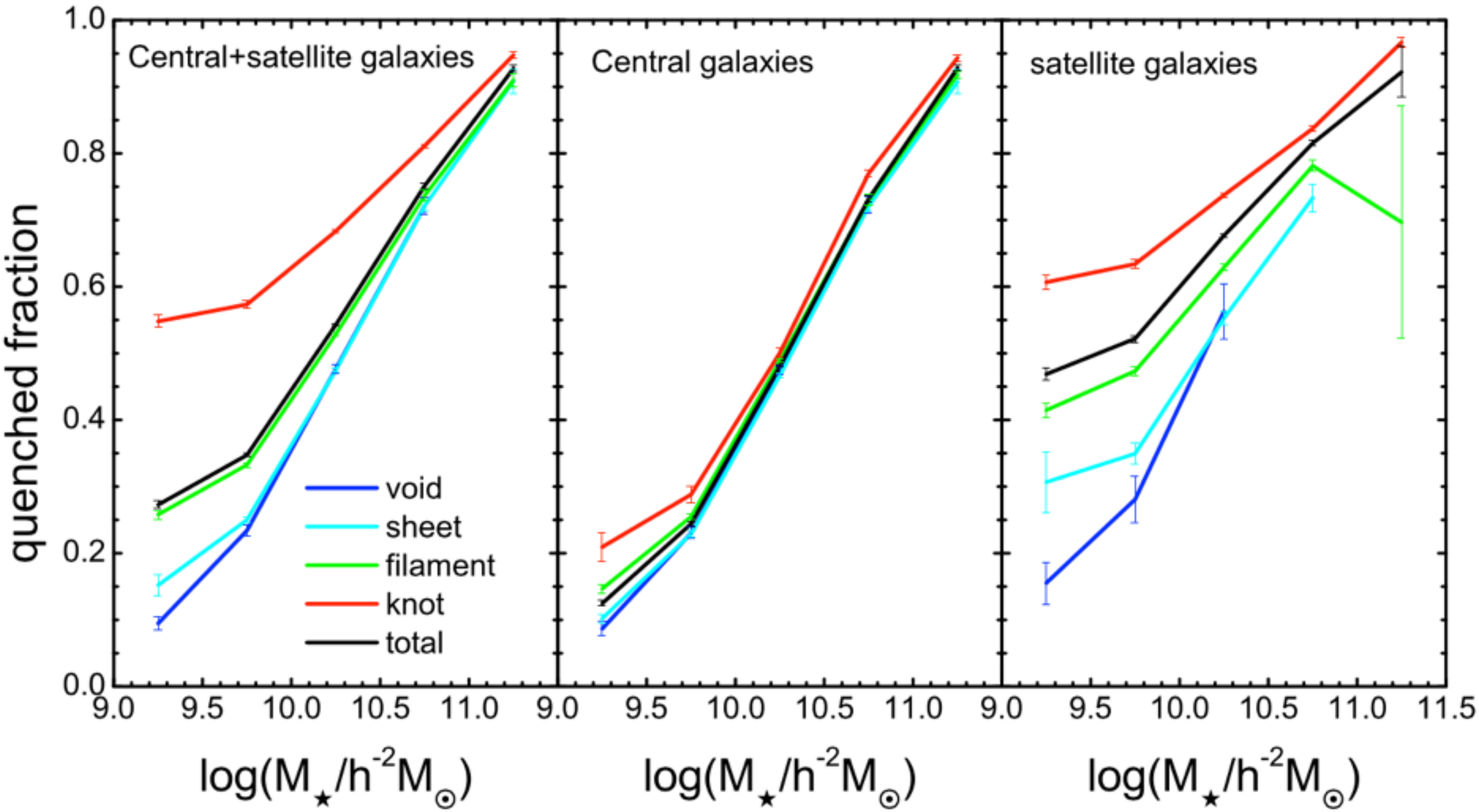
In a void region



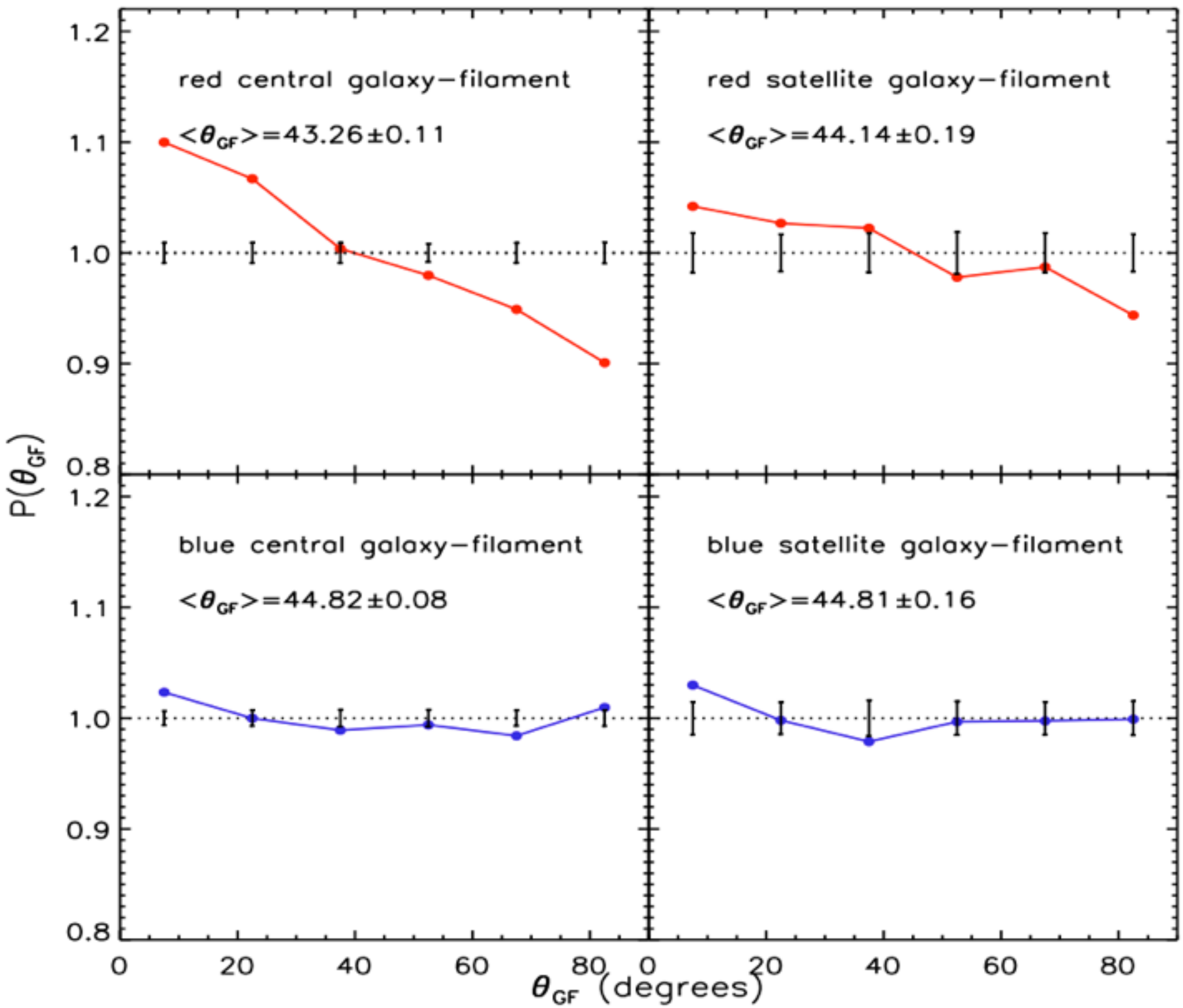
Classification based on eigenvalues of tidal tensor



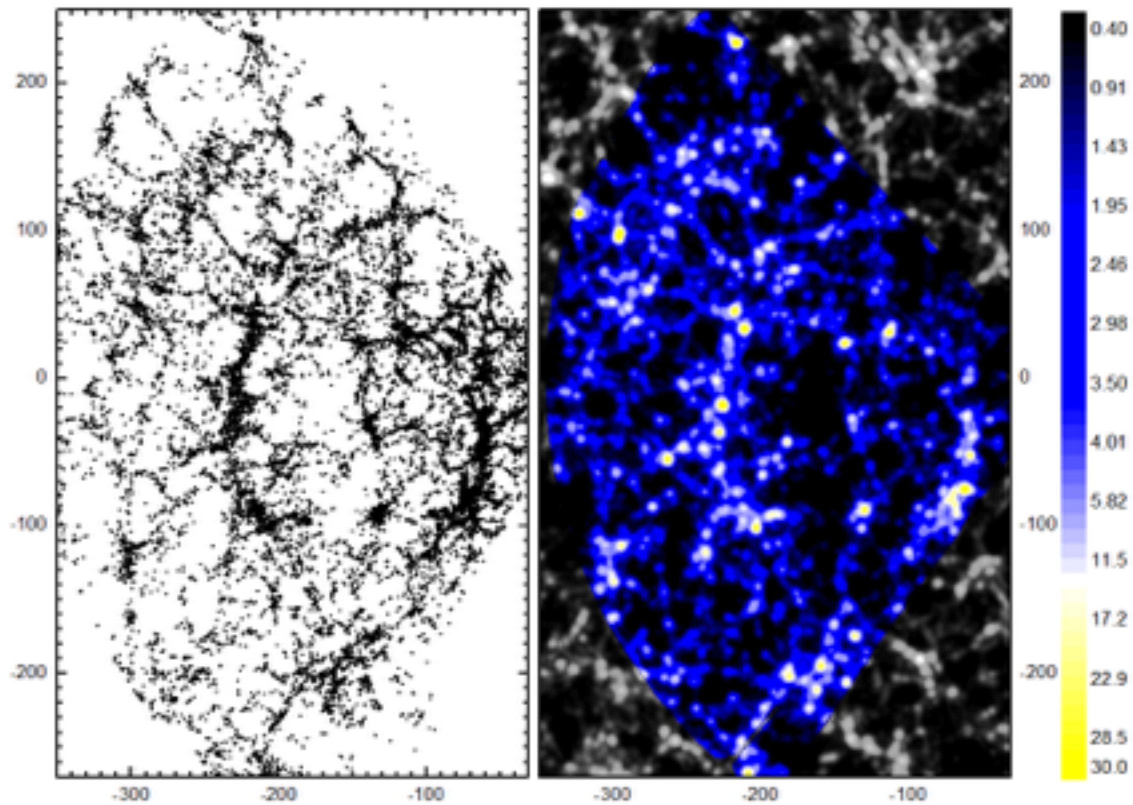
Applications: galaxy population in different environments

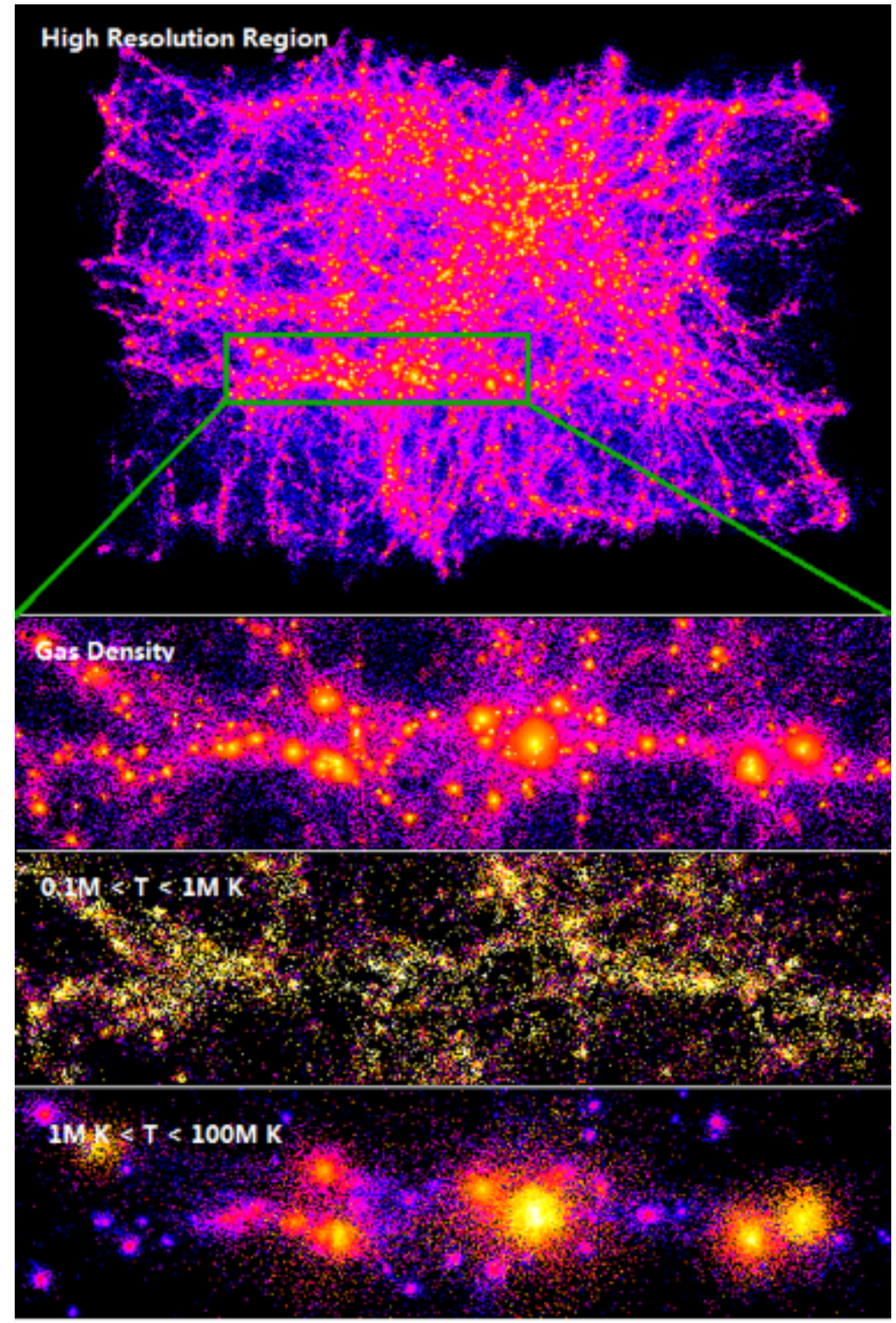


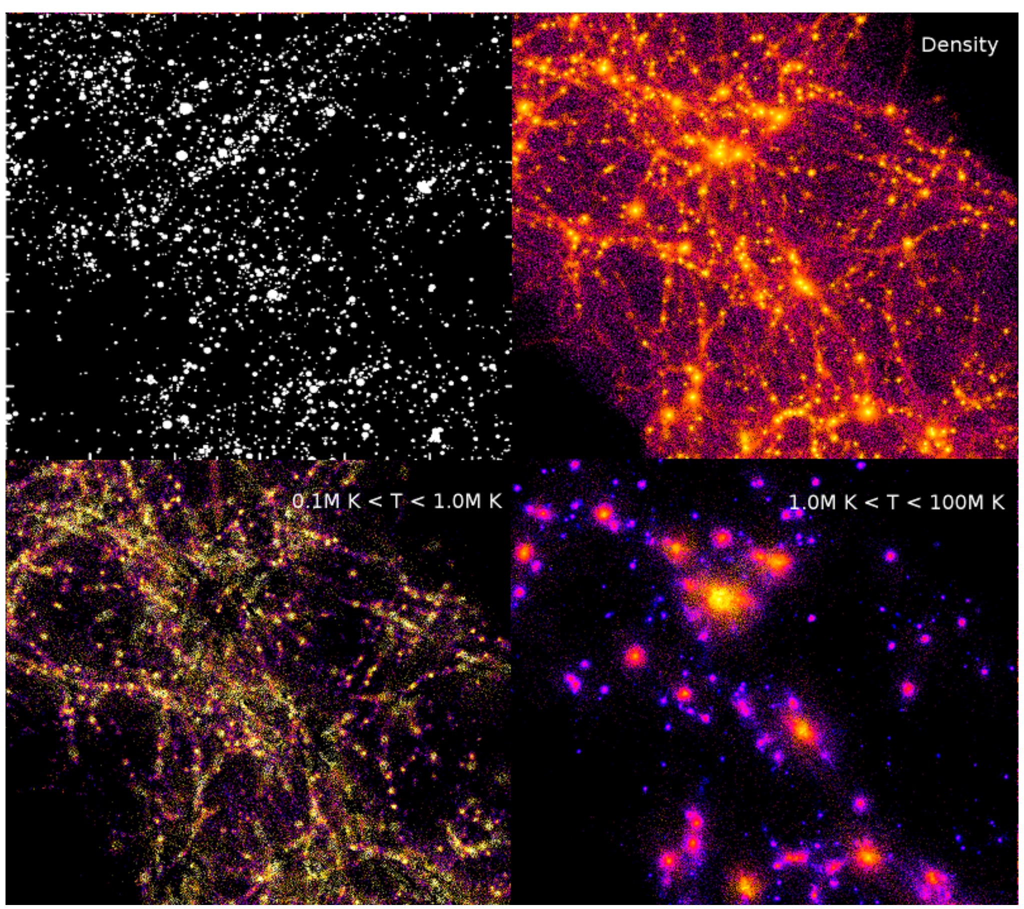
Alignments of galaxies with LSS

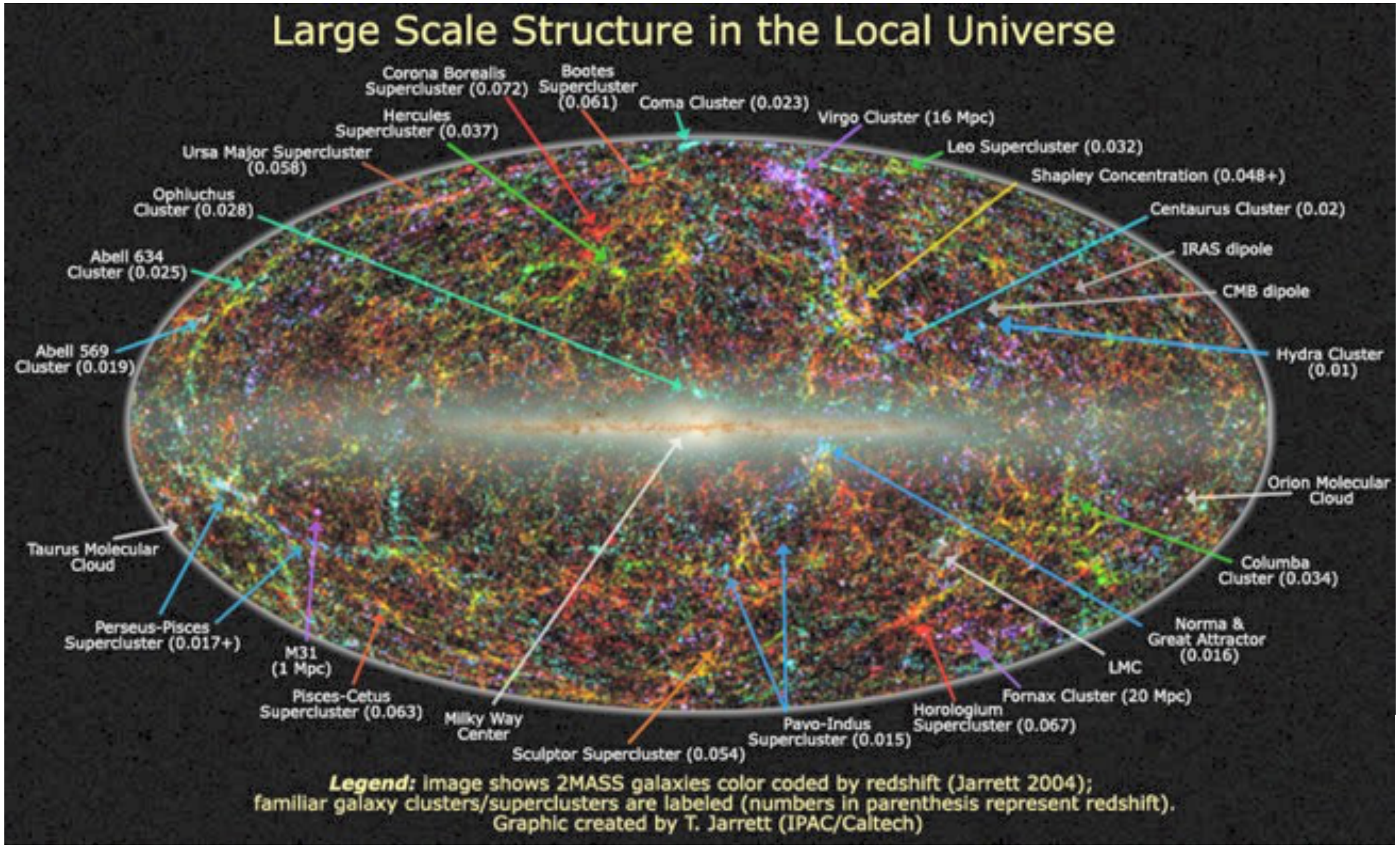


Constrained hydrodynamic simulations

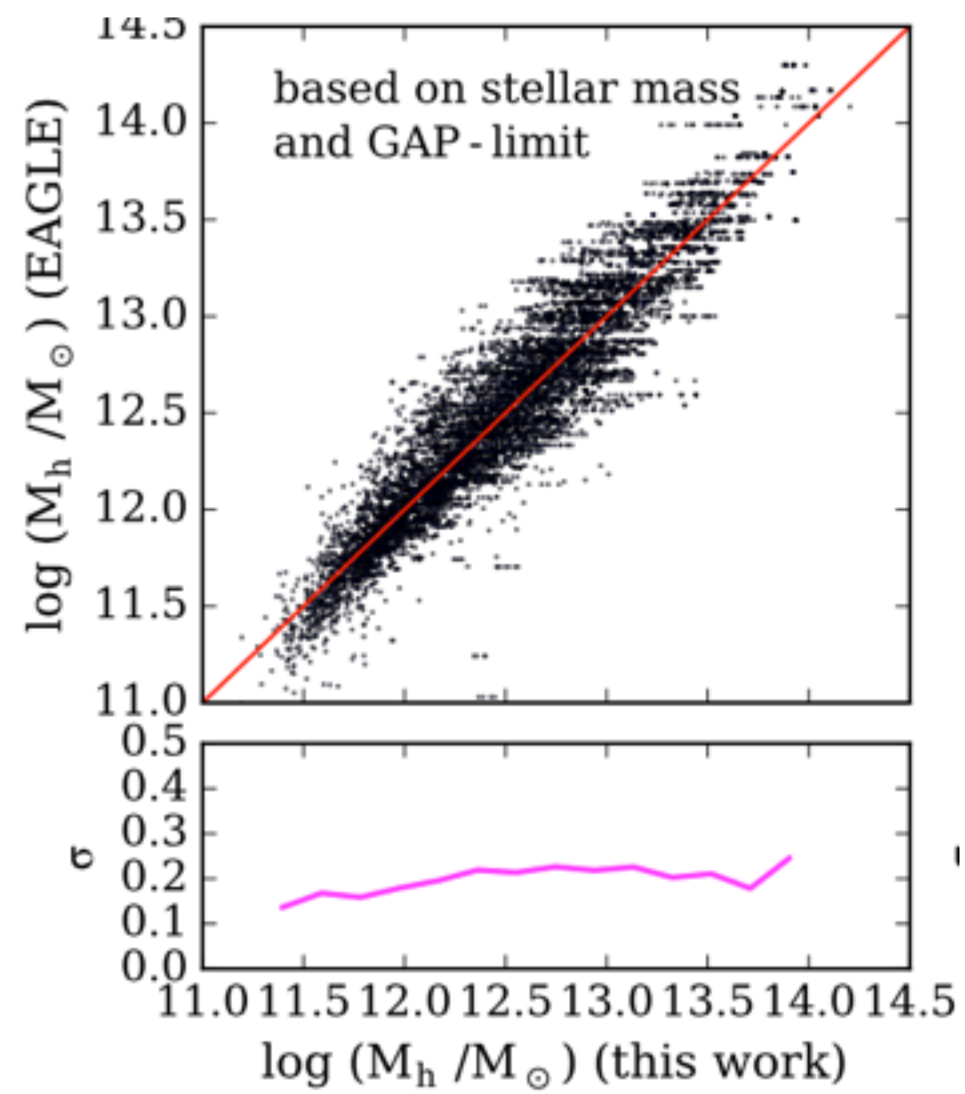








Applications to all sky surveys: 2MASS



Summary

- For a given cosmology, galaxy groups identified from local large redshift surveys can be used to reconstruct the initial density field.
- Simulations with such initial conditions allow us to trace the evolution of the local Universe.

Available: constrained N-body simulation, 500Mpc/h box; 3072^3 particles

Applications

- large-scale environments of galaxies;
- cosmic variance in constrained simulations;
- halo merger trees for galaxy formation modeling;
- gas simulations of large-scale structures;
- fossils of earlier Universe (e.g. re-ionization sources);
- Local Group (near field cosmology);
- resources for constructing mock catalogs for big surveys.