Galaxy Formation in the Filamentary Cosmic Web

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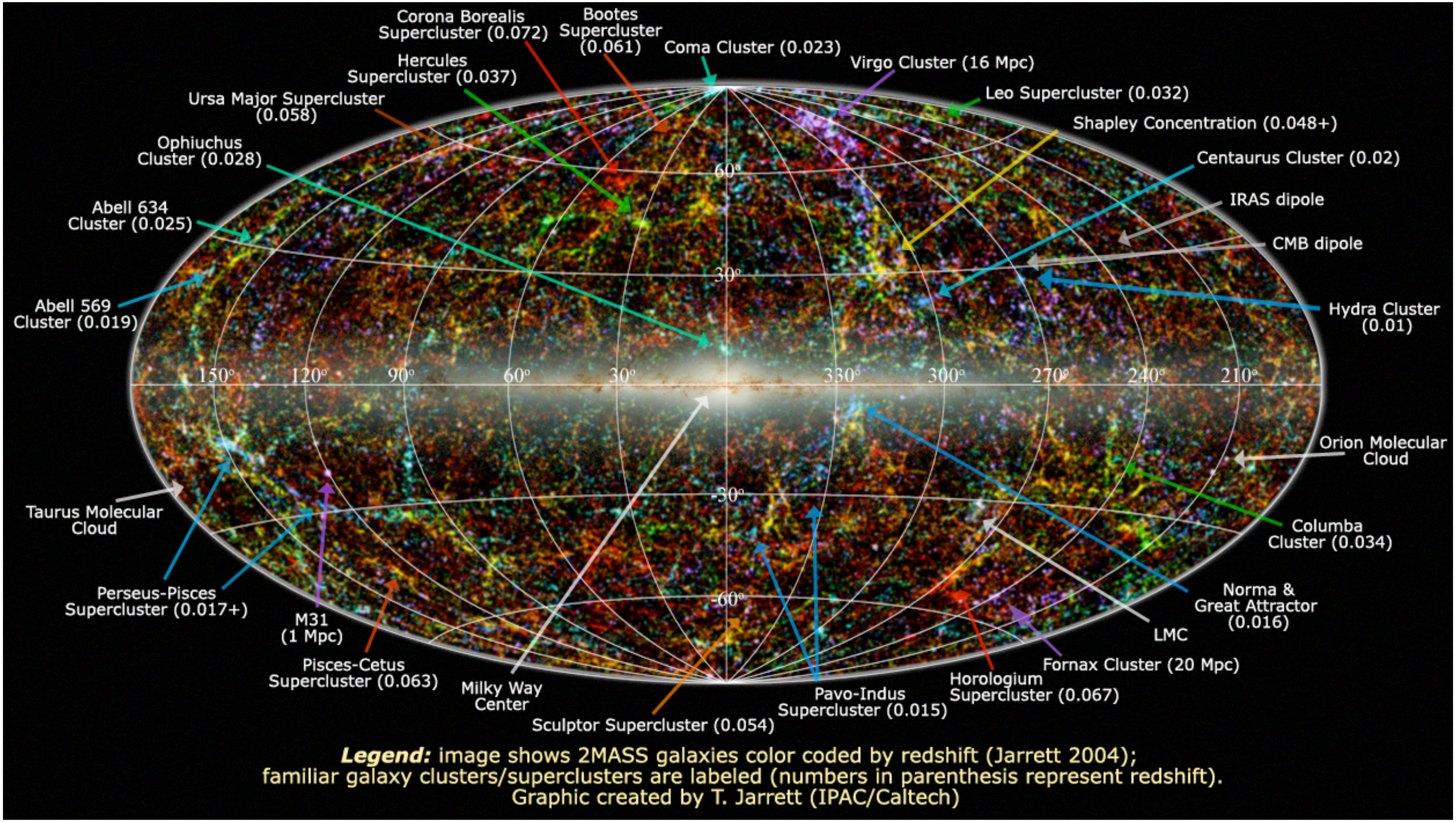
Outline:

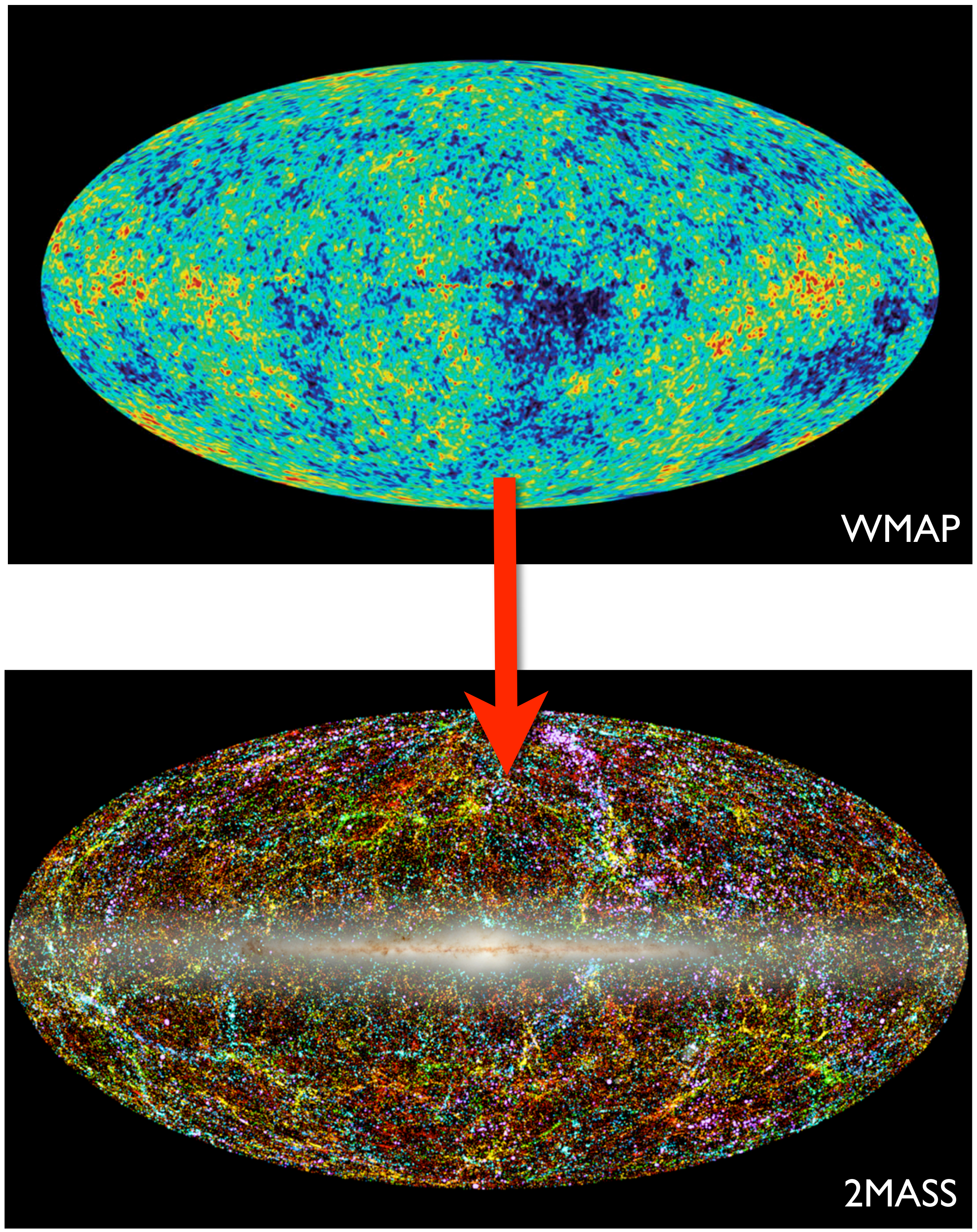
- How to define the cosmic environment in simulations?
- How does it affect the formation/evolution of haloes?
- Are halo orientations correlated with LSS - if so, how?
- What are the implications of these correlations for
  (1) cosmic shear, (2) galaxy formation?

The Cosmic Web

Our place in the cosmic web



The web from first principles



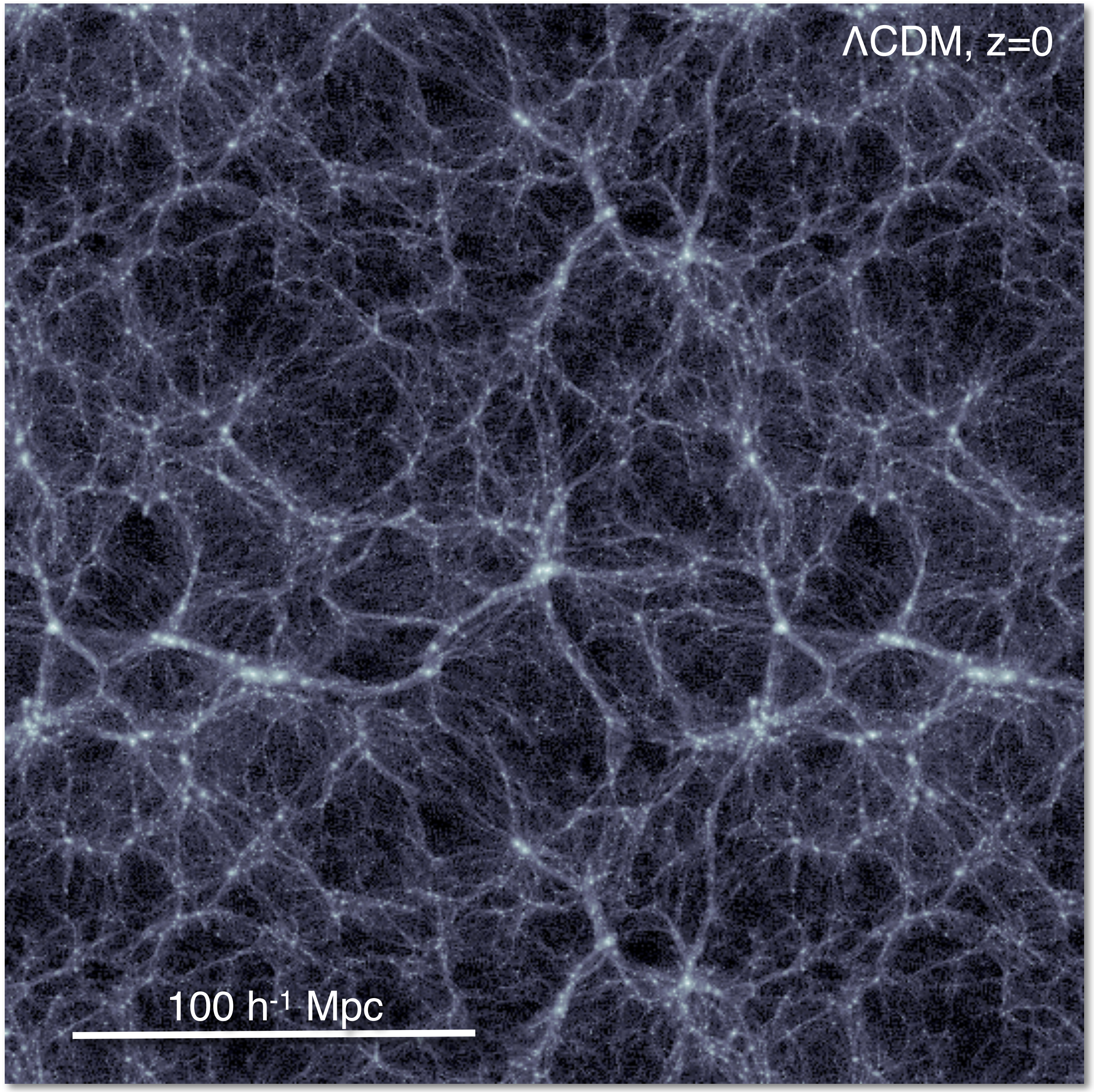
Early Universe Physics predicts the spectrum of density fluctuations.

Create a random realisation and evolve it under self-gravity in an expanding background space-time.

$$\nabla^2\phi = \frac{3H_0^2}{2}\Omega_{m,0}\,\frac{\delta}{a}$$

$$\frac{d\mathbf{p}}{da} = -\frac{\boldsymbol{\nabla}\phi}{\dot{a}}, \qquad \frac{d\mathbf{x}}{da} = \frac{\mathbf{p}}{\dot{a}a^2}$$

The Formation of the Web



(snapshot from simulation in Hahn et al. 2007a/b)

- In 1st order Lagrangian perturbation theory, general perturbations collapse subsequently along 3 axes:

$$\rho(\vec{q},t) = \frac{\rho(\vec{q},0)}{[1-D_+(t)\lambda_1]\,[1-D_+(t)\lambda_2]\,[1-D_+(t)\lambda_3]}$$

$$\lambda_k \propto \mathrm{eig}\left(\,\partial_i\partial_j\Phi\,\right)$$

(Zel'dovich 1970)

- "pancake" formation, $\lambda_1, \lambda_2, \lambda_3$ predict asymptotic morphology.
- In reality this is a multi-scale phenomenon (remember Press-Schechter theory).

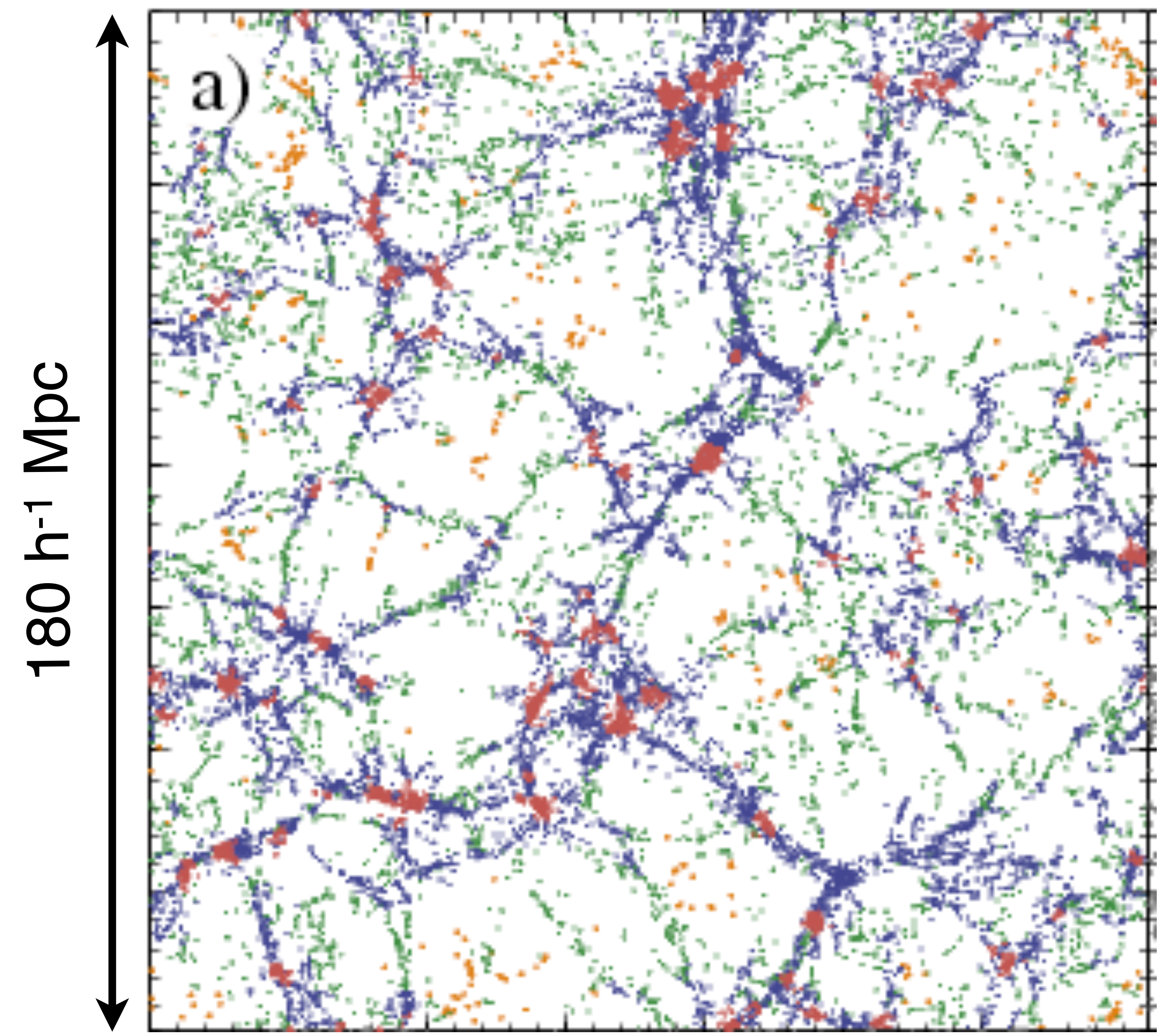
Can we use this to quantify the web in simulations?

A Natural Definition of Halo Environment

i. smooth density field
ii. compute potential
iii. compute eigenstructure of tidal tensor

$$T_{ij} \propto \partial_i \partial_j \Phi$$

- cluster $(+++)$
- filament $(++-)$
- sheet $(+--)$
- void $(---)$



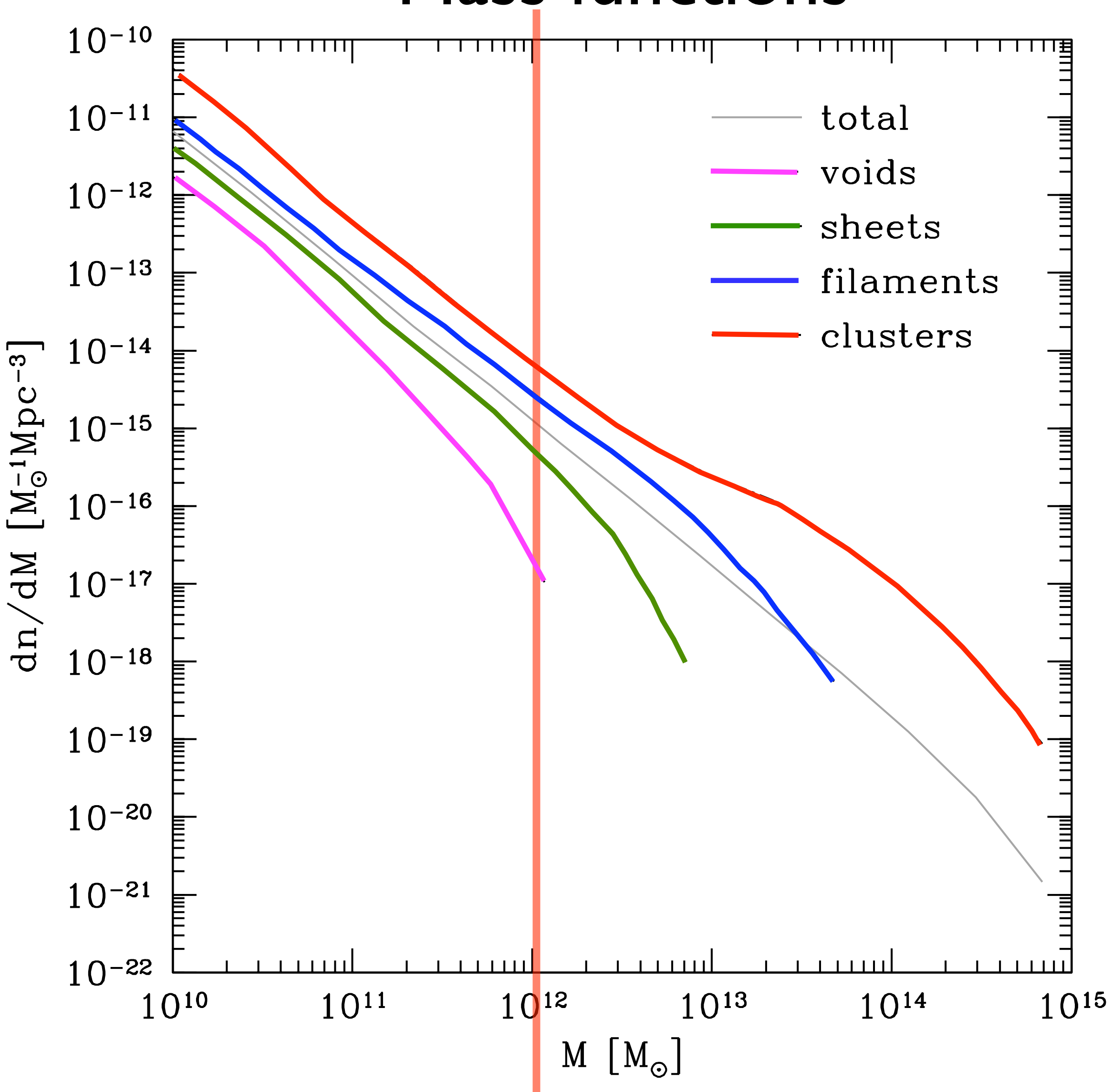
Hahn, Porciani, Carollo, Dekel (2007a), MNRAS 375, 489

(as Zel'dovich approx. BUT on evolved non-linear field)

Halo Formation and Evolution in the Cosmic Web

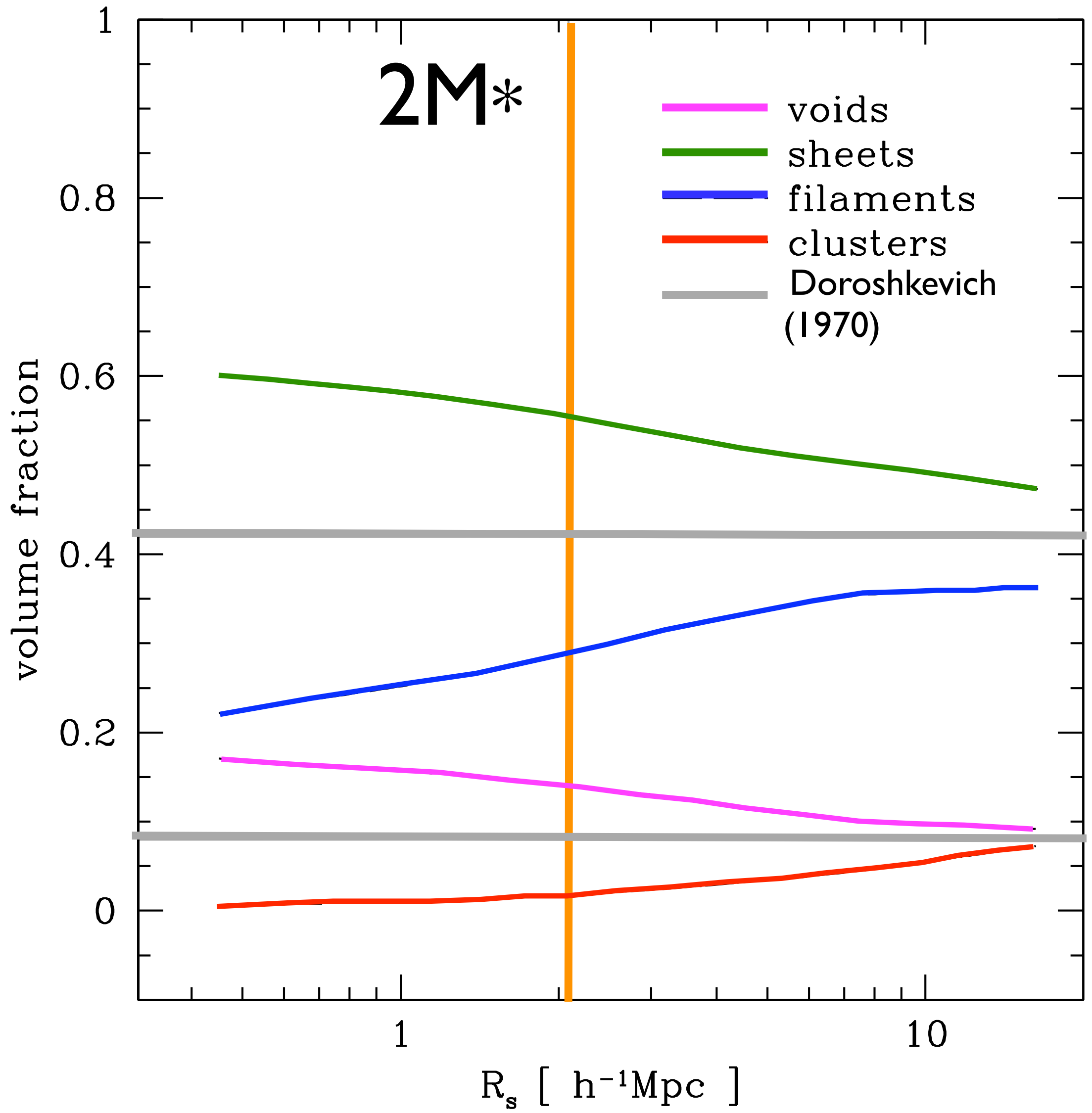
Clusters, Filaments, Sheets and Voids

Mass functions



At given mass increasingly more likely to be a subhalo in richer environments

Volume fractions

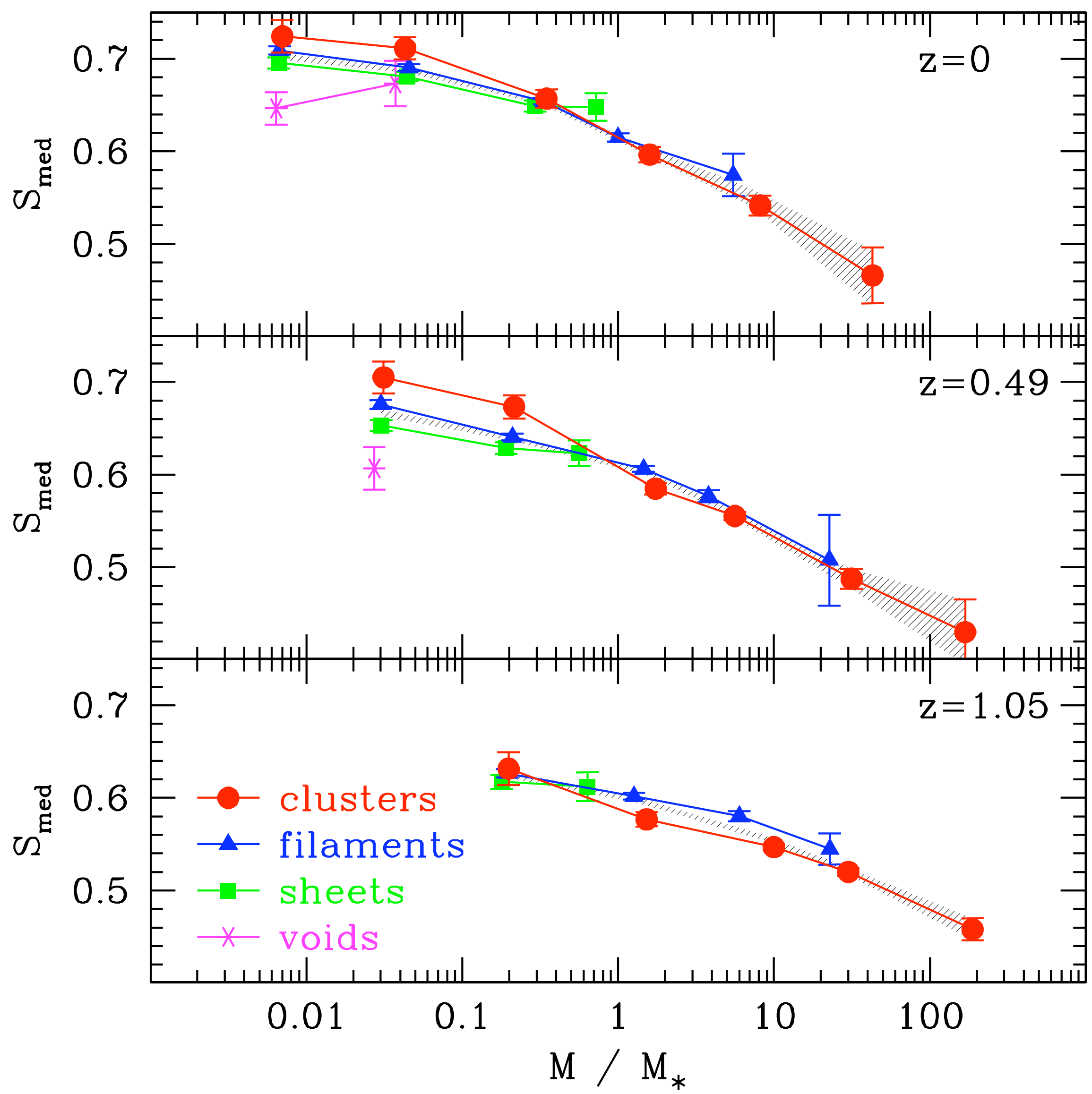


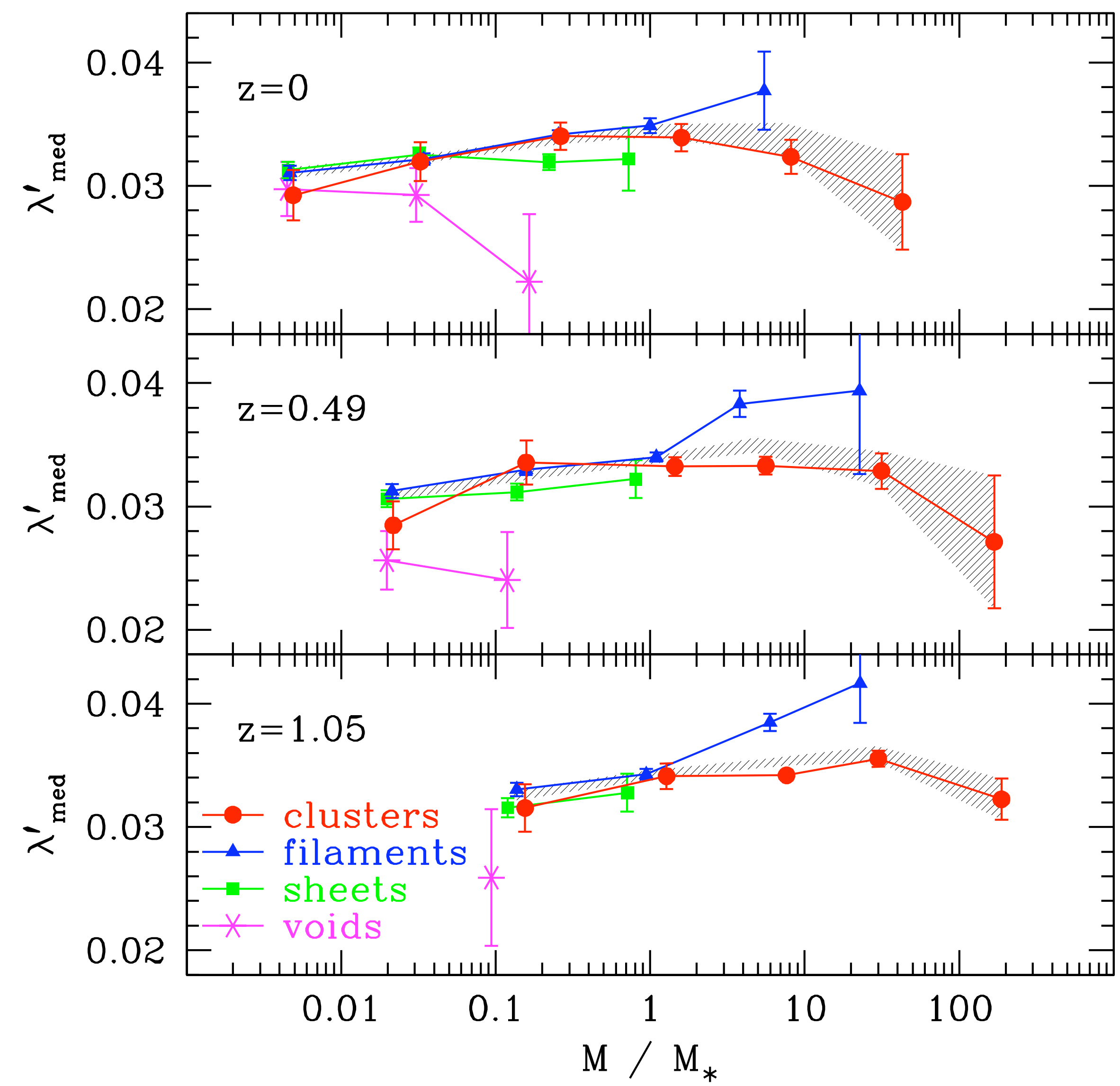
Hahn, Porciani, Carollo, Dekel, (2007a), MNRAS 375, 489

Environment Dependence 1: Shapes and Spin

Halo Sphericity $S = \frac{l_3}{l_1}$

Halo Spin Parameter $\lambda' = \frac{|\mathbf{J}_{\rm vir}|}{\sqrt{2GR_{\rm vir}}M_{\rm vir}^{3/2}}$

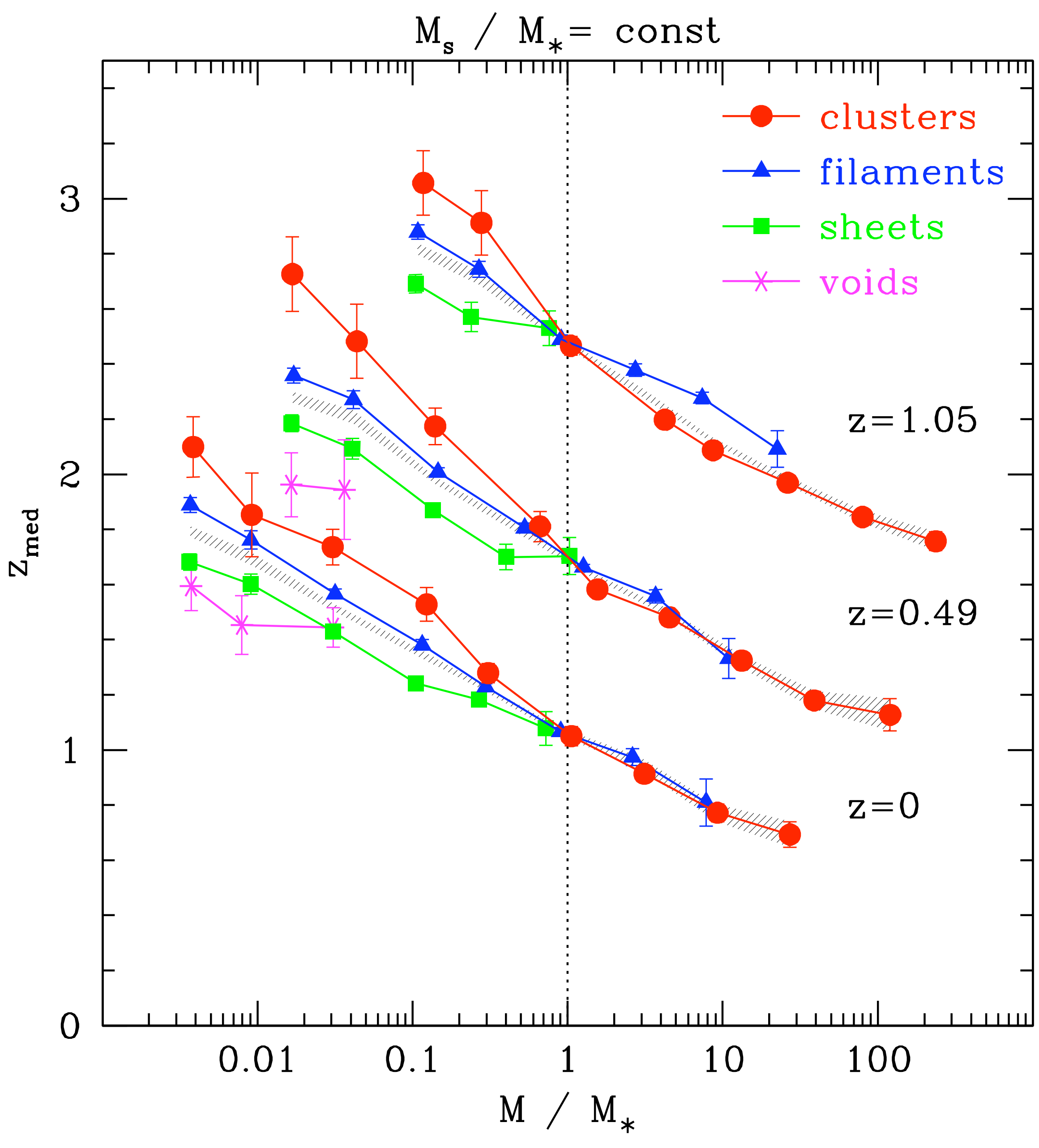




shapes depend sensitively on halo definition

Hahn, Carollo, Porciani, Dekel, (2007b), MNRAS 381, 41

Environment Dependence 2: The Assembly Bias (i)



Hahn, Carollo, Porciani, Dekel, (2007b), MNRAS 381, 41

Haloes <M* in dense regions are older

or equivalently:

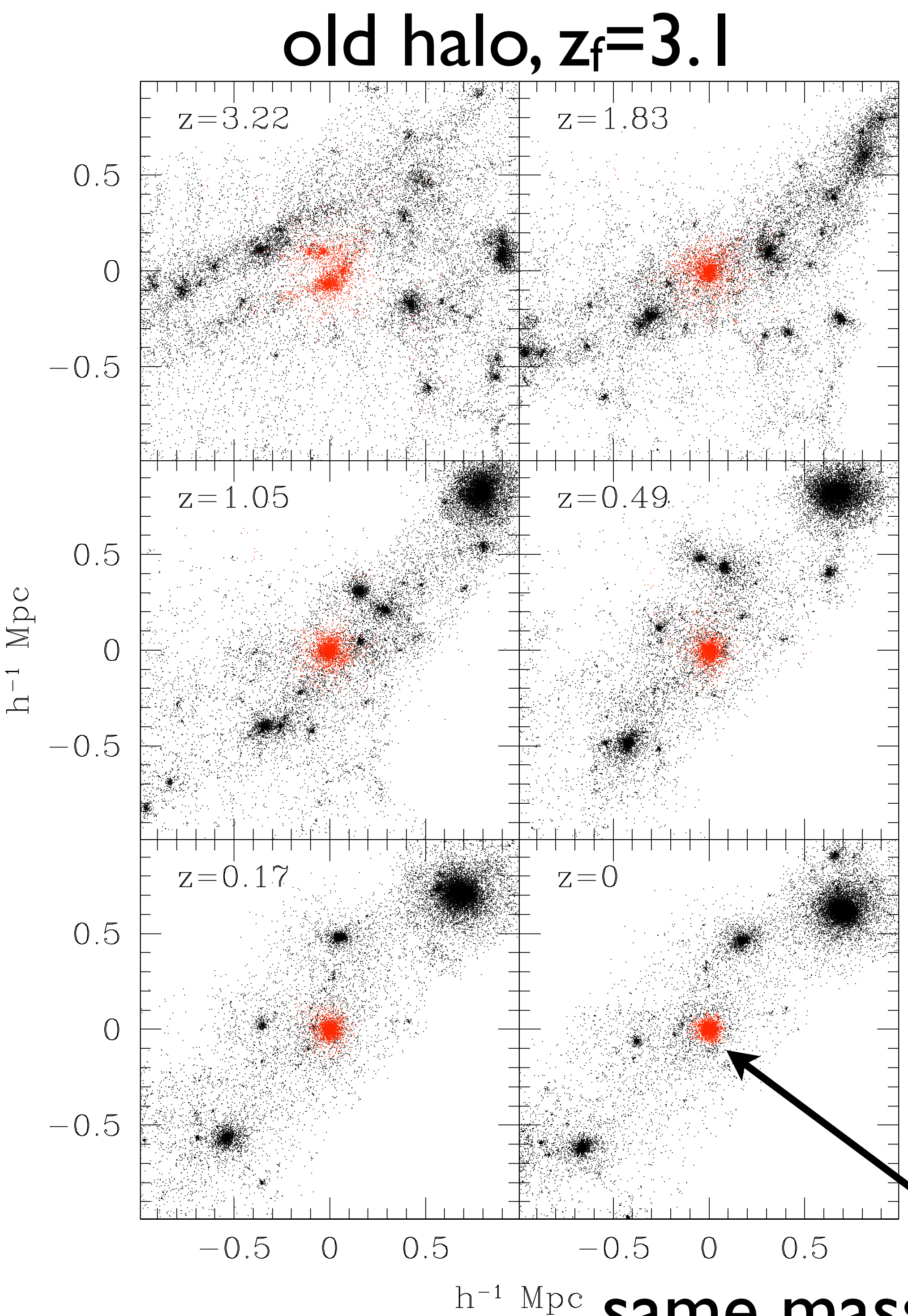
Old haloes are more clustered

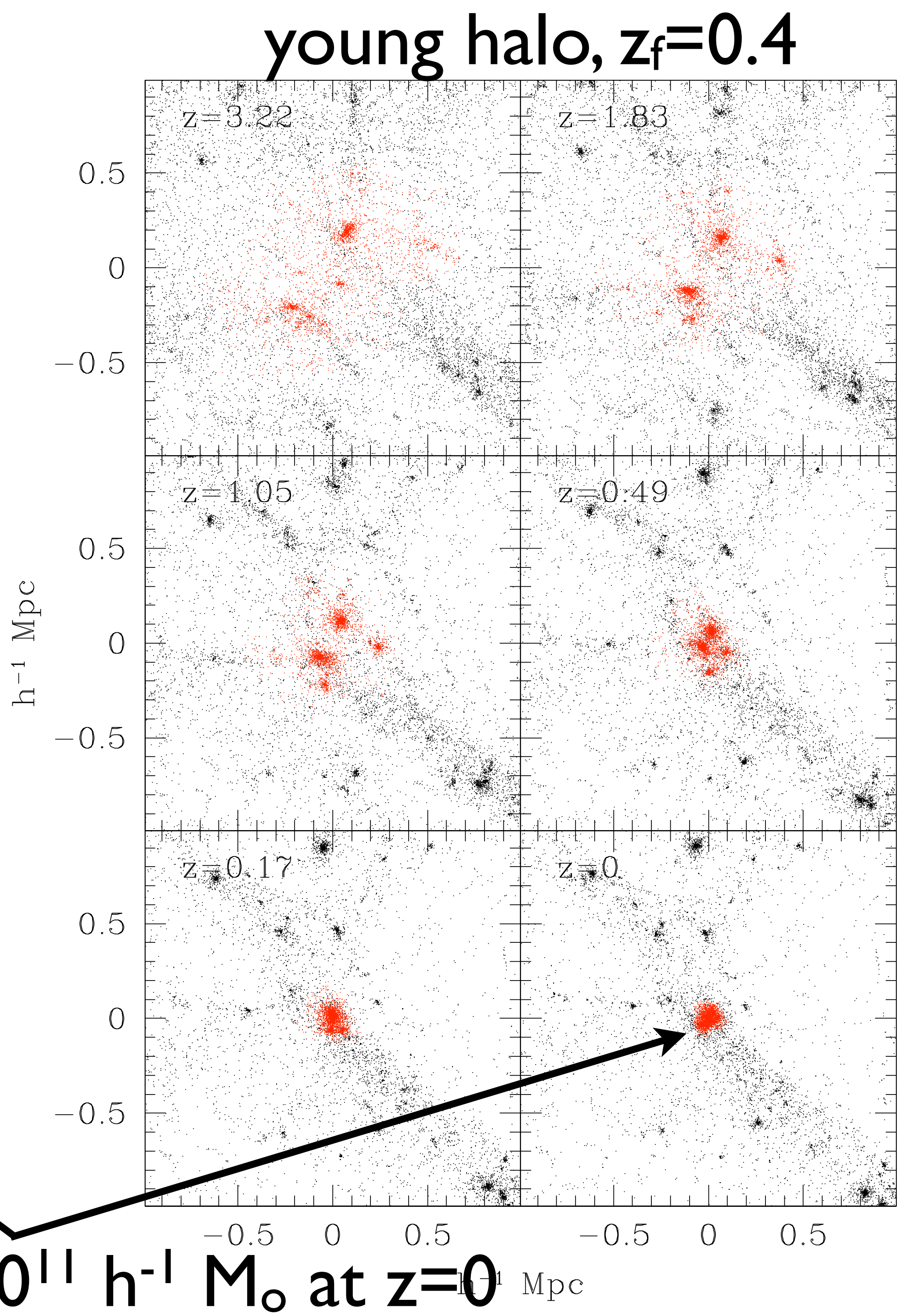
(e.g. Sheth & Tormen 2004, Gao et al. 2005, Wechsler et al. 2006)

- hot flow? (Wang et al. 2007)
- stripped haloes? (e.g. Diemand et al. 2007)

See Wetzel et al. (2007), Dalal, White et al. (2008) for M>M*

The Origin of the Assembly Bias (i)



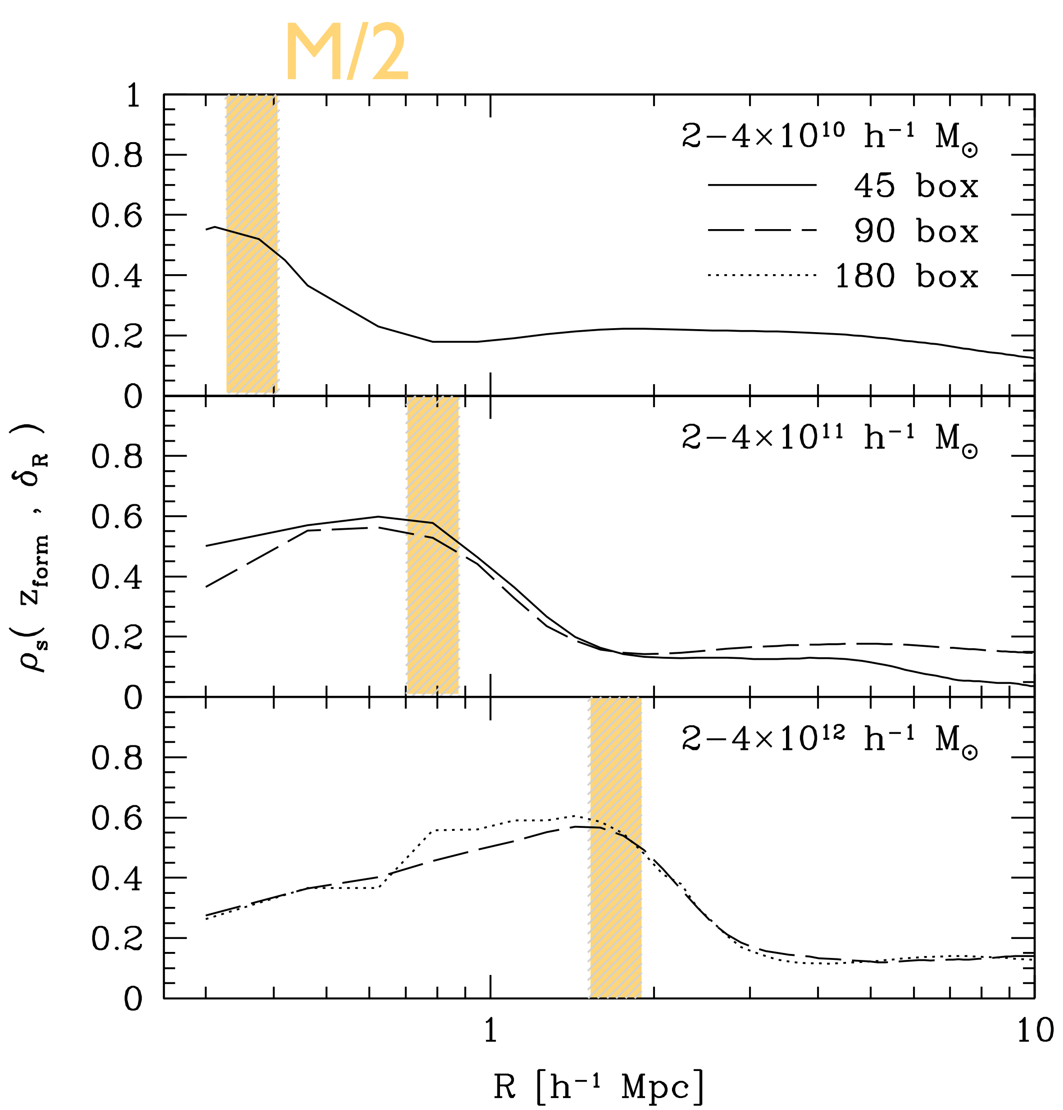


same mass $10^{11}\ h^{-1}\ M_\odot$ at z=0

Hahn, Porciani, Dekel, Carollo (2008), MNRAS subm., arXiv:0803:4211

The Assembly Bias (ii)

Initial conditions: halo age depends on density on large scales



Hahn, Porciani, Dekel, Carollo (2008), MNRAS subm., arXiv:0803:4211

Tidal effects due to another halo

A short calculation shows:

tidal radius $r_{\rm Hill} \simeq d \left(\frac{m}{3M}\right)^{1/3}$

Expect mass loss when $r_{\rm Hill} < r_{\rm vir}$

This is equivalent to

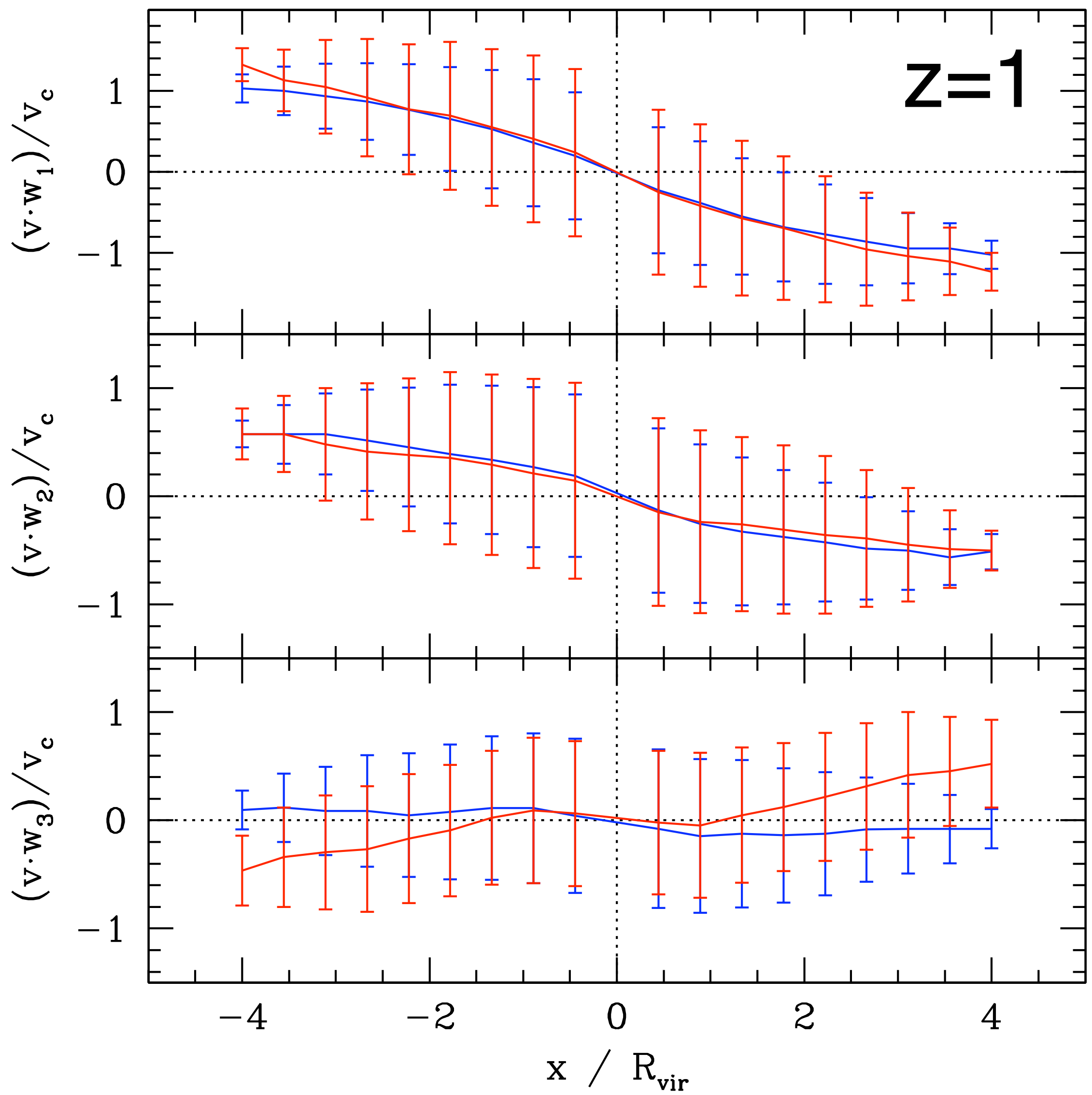
$$d < 3^{1/3} R_{\rm vir} \simeq 1.5 R_{\rm vir}$$

Tides affect assembly of haloes before they enter another halo.

expect suppressed growth if tidal radius inside turnaround radius

The Origin of the Assembly Bias (iii)

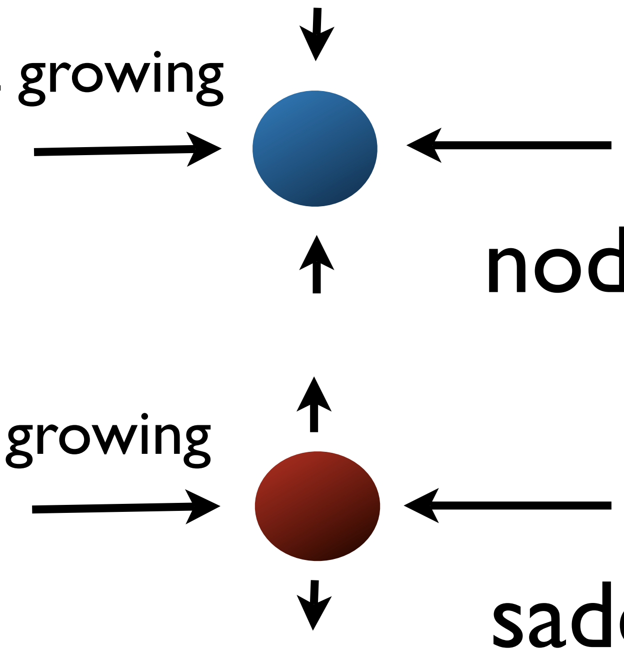
Velocity field along main axes of velocity deformation tensor



stripped haloes excluded, M(0) ~ 2-4x10^{10} h^{-1} $M_\odot$

Definition:

$$\mathbf{w}_i = \mathrm{eigenvec}\left(\frac{1}{2}\left[\frac{\partial v_k}{\partial r_l} + \frac{\partial v_l}{\partial r_k}\right]\right)$$



$\Rightarrow$ suppression of growth (see also Dalal et al. 2008)

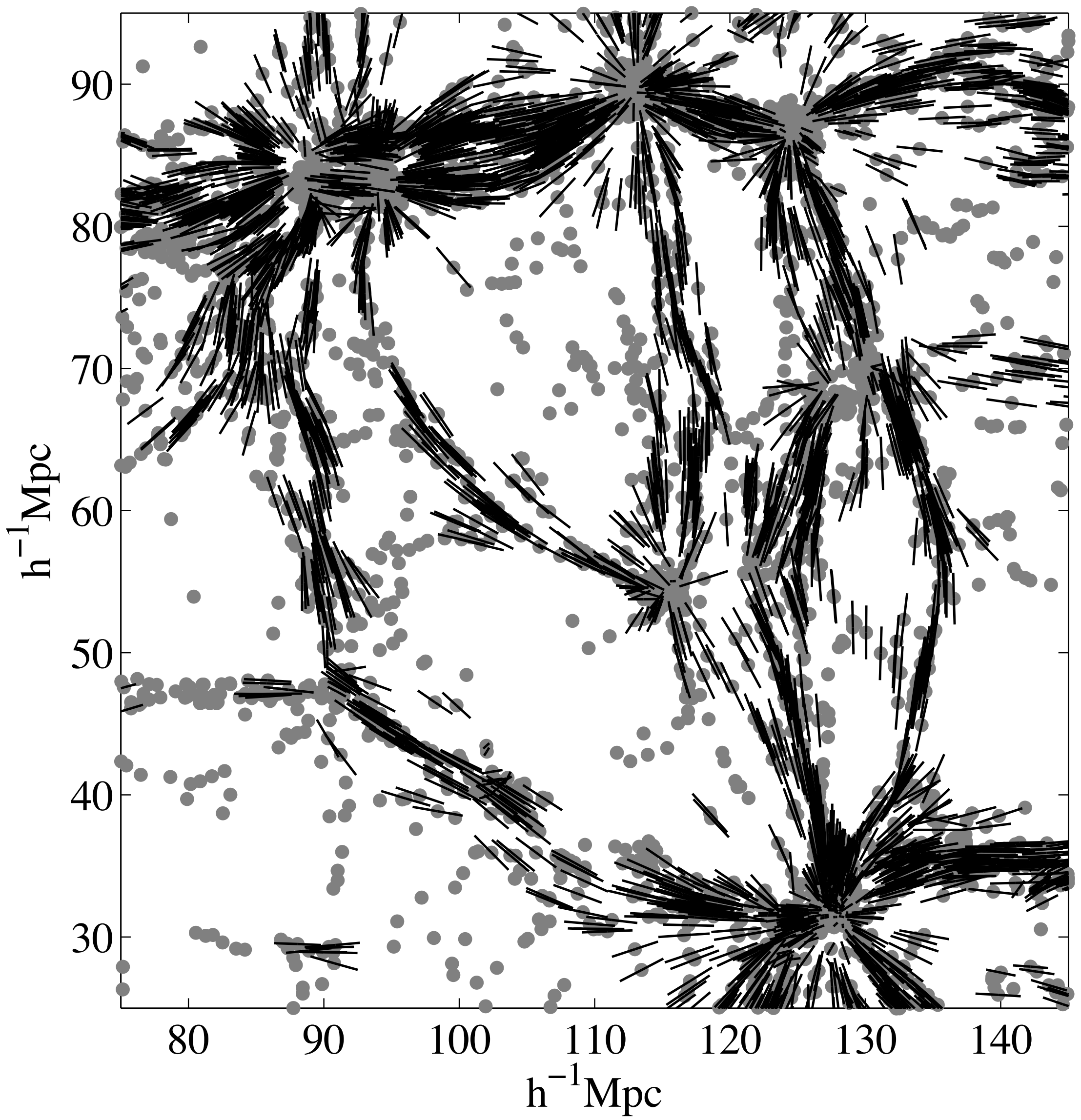
also would make shape of Lagrangian patches dependent on late time tidal field (cf. Sandvik et al. 2007)

Hahn, Porciani, Dekel, Carollo (2008), MNRAS subm., arXiv:0803:4211

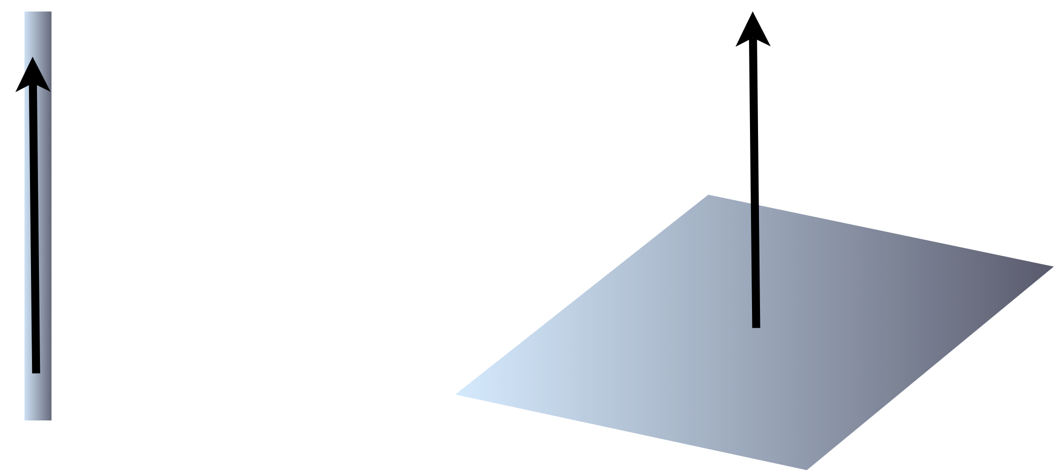
LSS-galaxy alignments

Alignments with LSS (i)

filament EVs



probe alignment with structure
using tidal field eigenvectors



filament

sheet

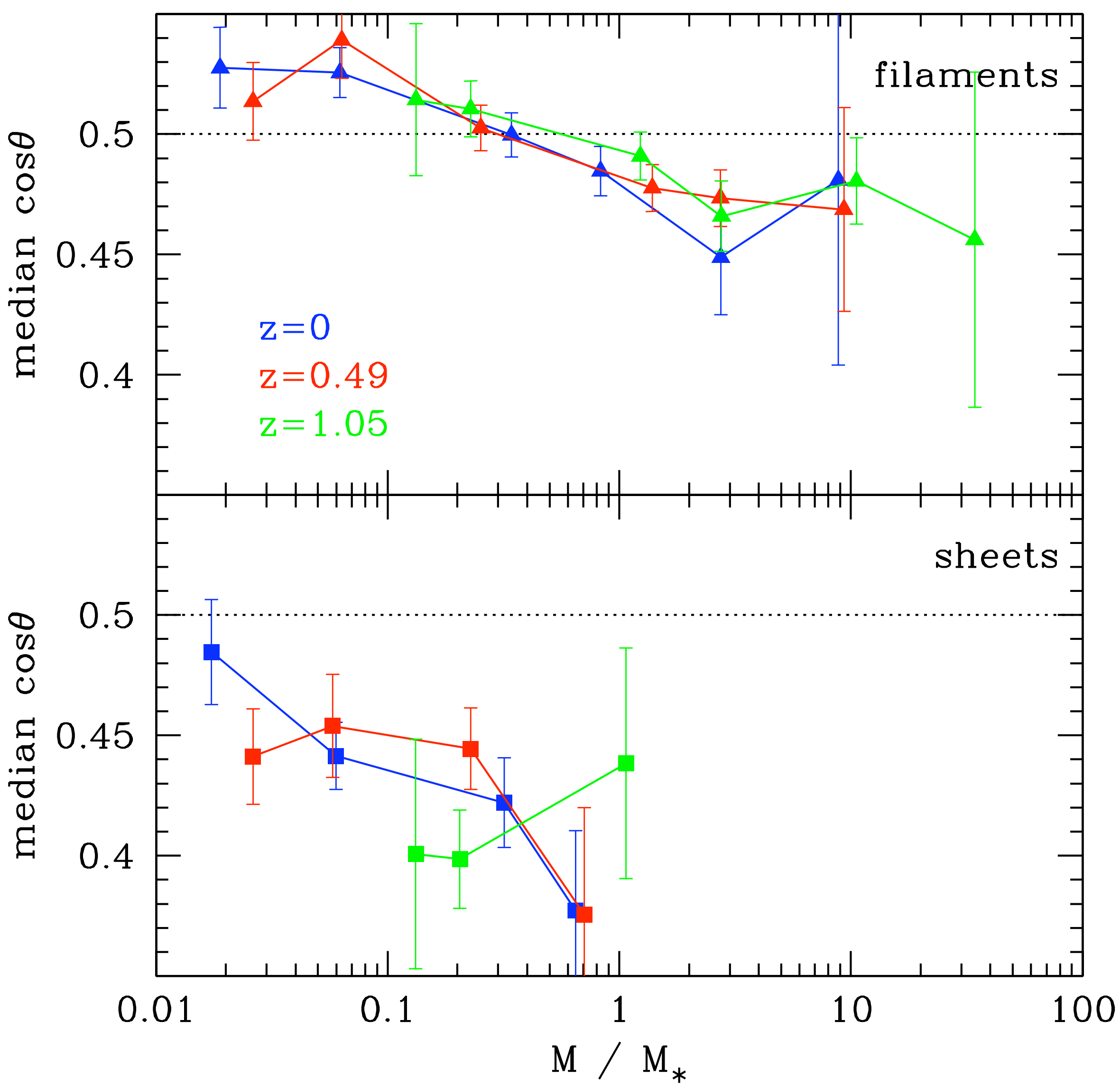
This will teach us about
how halos are oriented in the web:

take their spin as indicative for how disks would be oriented and shapes for ellipticals.

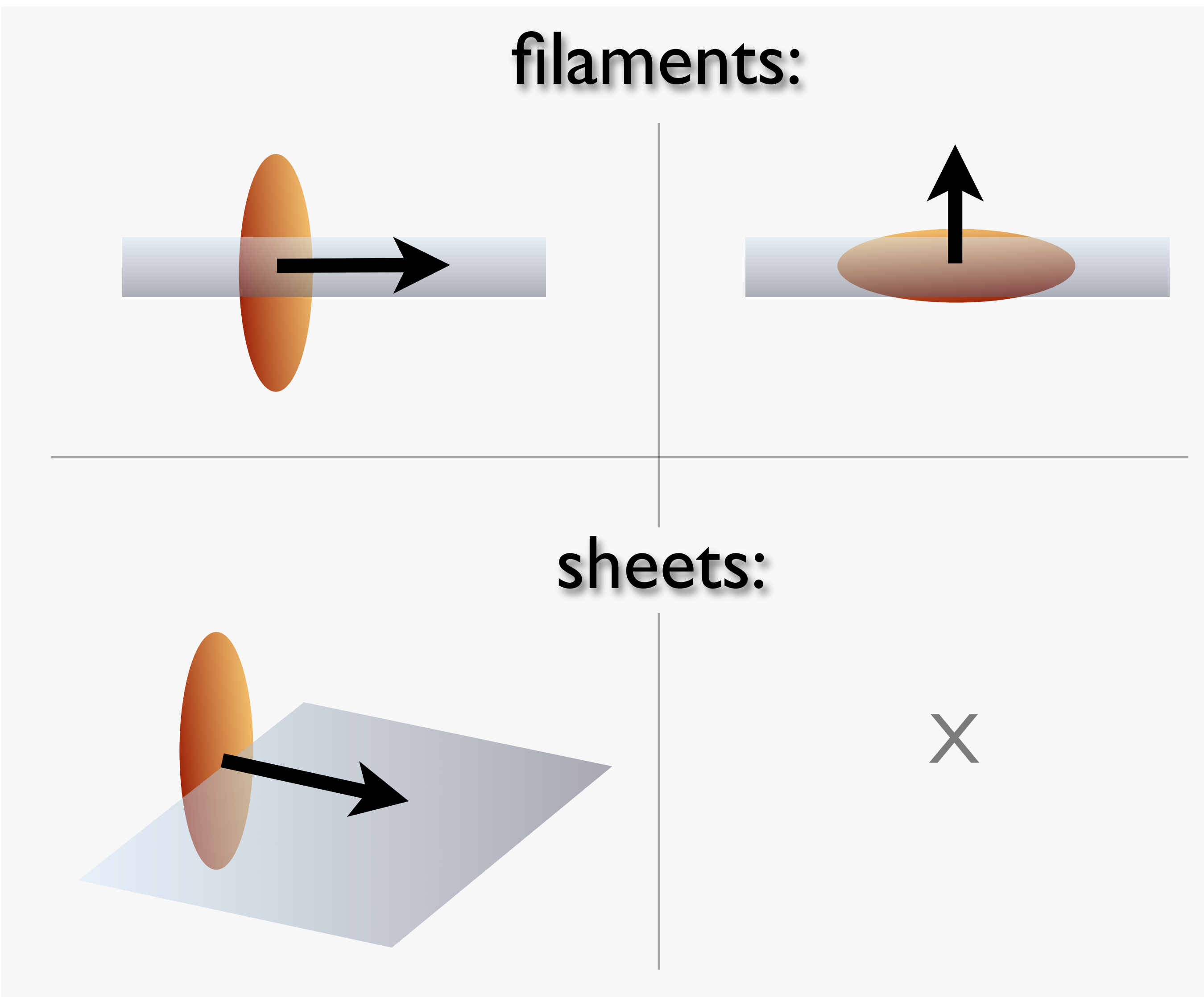
Hahn, Carollo, Porciani, Dekel, (2007b), MNRAS 381, 41

Alignment with the LSS (ii) - disks

spin-alignment



$M < M_*$ $M > M_*$

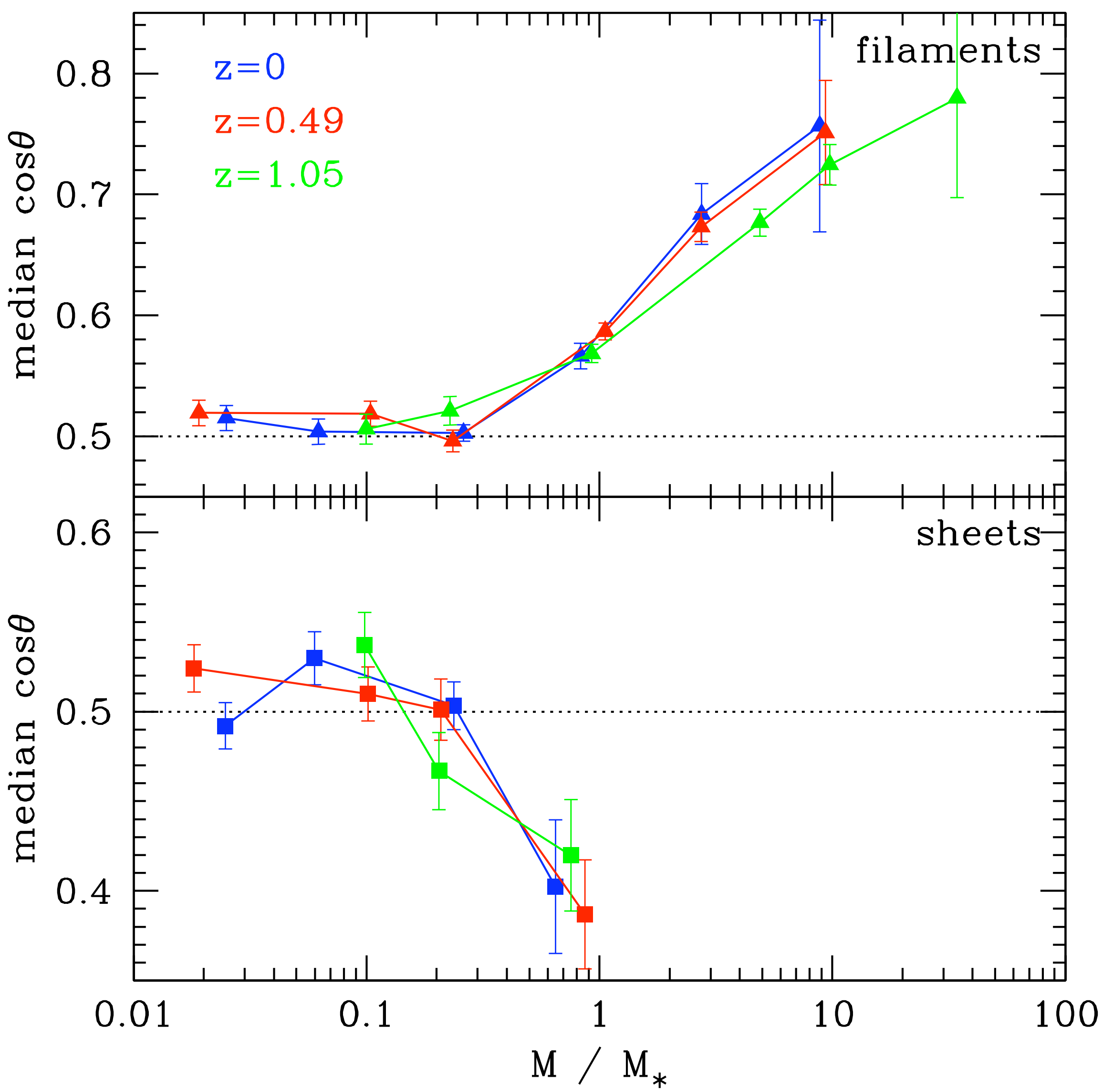


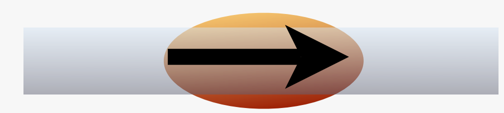
mass dependent (see also Aragon-Calvo et al. 2007, Paz et al. 2008)

Hahn, Carollo, Porciani, Dekel, (2007b), MNRAS 381, 41

Alignment with the LSS (iii) - ellipticals

major axis-alignment



	$M < M_*$	$M > M_*$
filaments:	random?	
sheets:	random?	X

Hahn, Carollo, Porciani, Dekel, (2007b), MNRAS 381, 41

In Progress...

Importance of Alignments for Weak Lensing

Lensing potential

$$\phi(\boldsymbol{\theta}, \chi_s) = \frac{2}{c^2} \int_0^{\chi_s} \mathrm{d}\chi \frac{d_A(\chi_s - \chi)}{d_A(\chi_s) d_A(\chi)} \Phi(\chi, d_A(\chi)\boldsymbol{\theta})$$

weak shear is a weighted integral of the **tidal field**:

$$\gamma_1 = \frac{1}{2}(\phi_{,11} - \phi_{,22})$$
$$\gamma_2 = \phi_{,12}$$

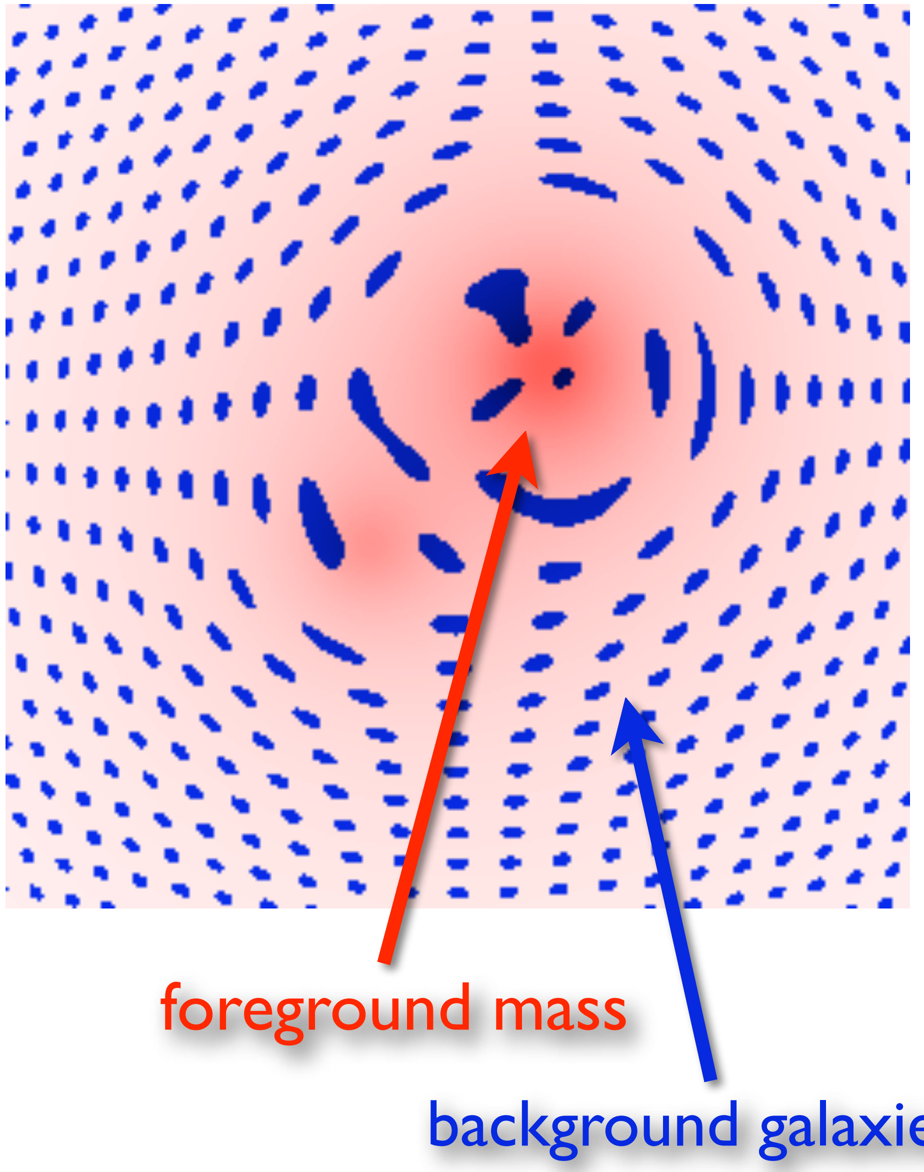
Observable is total ellipticity

$$\epsilon_{\rm obs} = \gamma + \epsilon_I$$

Correlation function thus becomes

$$\langle \epsilon_{\rm obs} \epsilon'_{\rm obs} \rangle = \langle \gamma\, \gamma' \rangle + \langle \gamma\, \epsilon'_I \rangle + \langle \epsilon_I\, \gamma' \rangle + \langle \epsilon_I\, \epsilon'_I \rangle$$

structure GI II



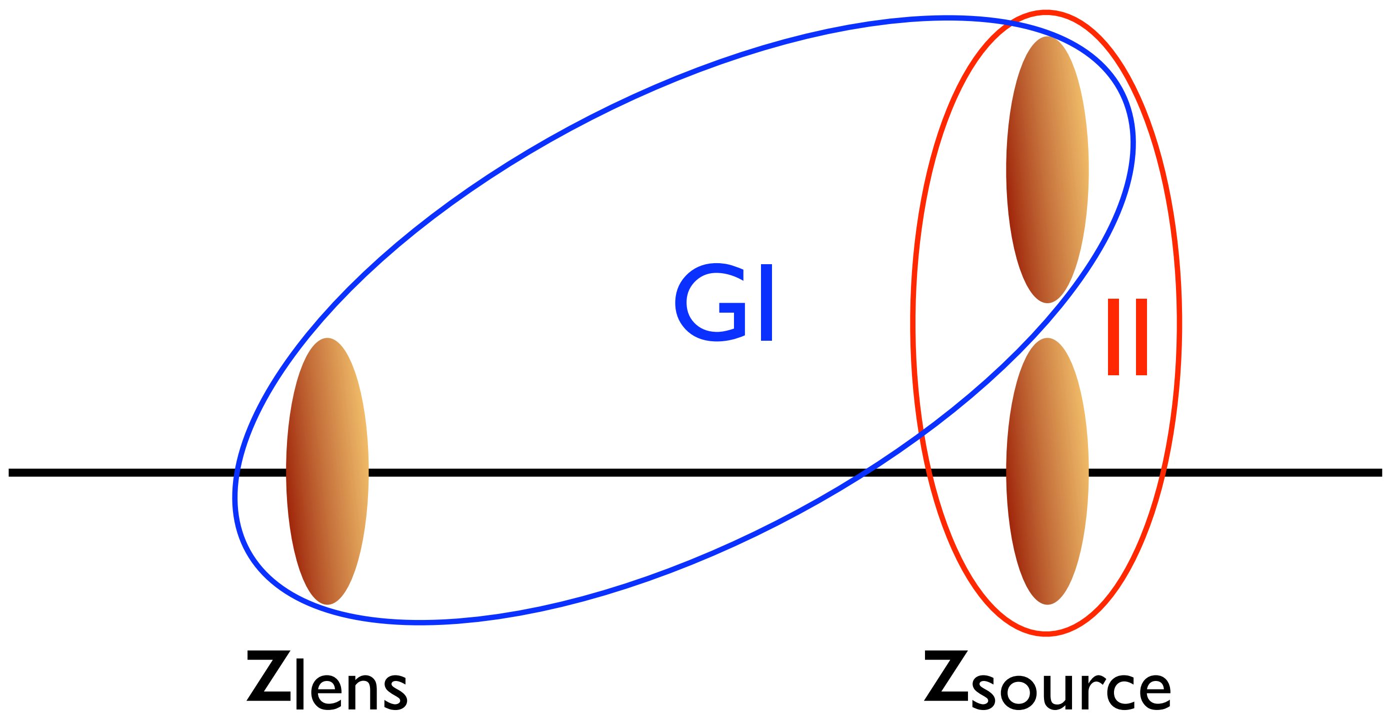
Alignments - Contaminant and Signal

$$II = \langle \epsilon_I \, \epsilon'_I \rangle$$

Arises, when close galaxies are intrinsically aligned to one another
Can be removed by downweighting close pairs
(e.g. King & Schneider 2002, Heymans & Heavens 2003).

$GI = \langle \epsilon_I \, \gamma' \rangle$ (Hirata & Seljak 2004)

Arises, when galaxies intrinsically aligned with tidal field
Can possibly be dealt with by modelling the signal, or by nulling contribution if redshifts are precise (Joachimi&Schneider 2008).



→ Contaminant for dark energy

→ Signal for galaxy formation

Modelling Intrinsic Alignments from Simulations

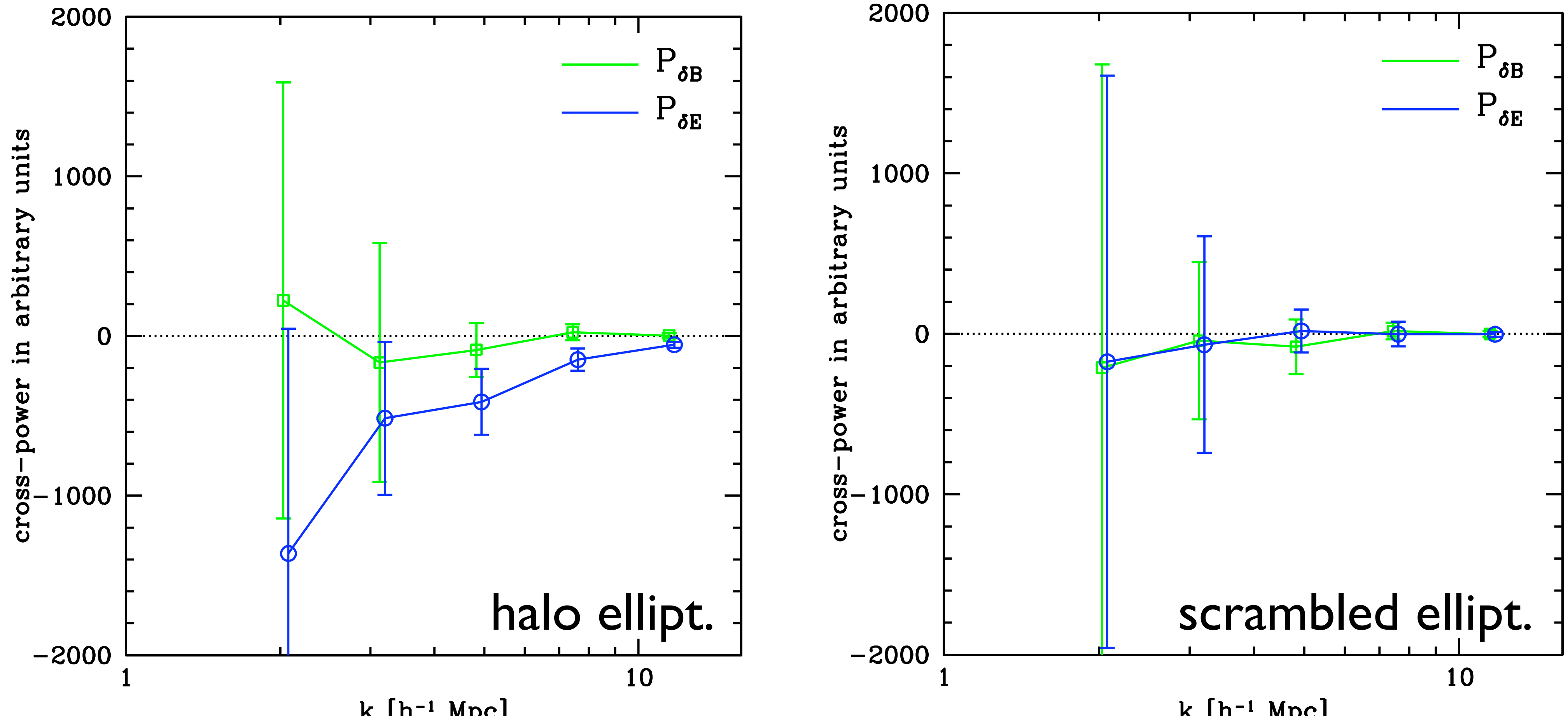
Linear alignment model:

$$P_{\delta\gamma}(k,z) = -\frac{C\bar{\rho}_m(z)}{(1+z)D_+(z)}P_{\delta\delta}(k) =: b_\gamma(z)P_{\delta\delta}(k)$$

Bridle & King 2007, but see also Heymans, White et al. 2006

What is the mass/scale/redshift/satellite-vs-central dependence of this ‘bias’?

Use DM only + recipe to measure in sims. Include subhaloes.



Hahn & Amara, in preparation

The next step: full hydro simulations

include baryons, cooling, star formation and feedback

↓

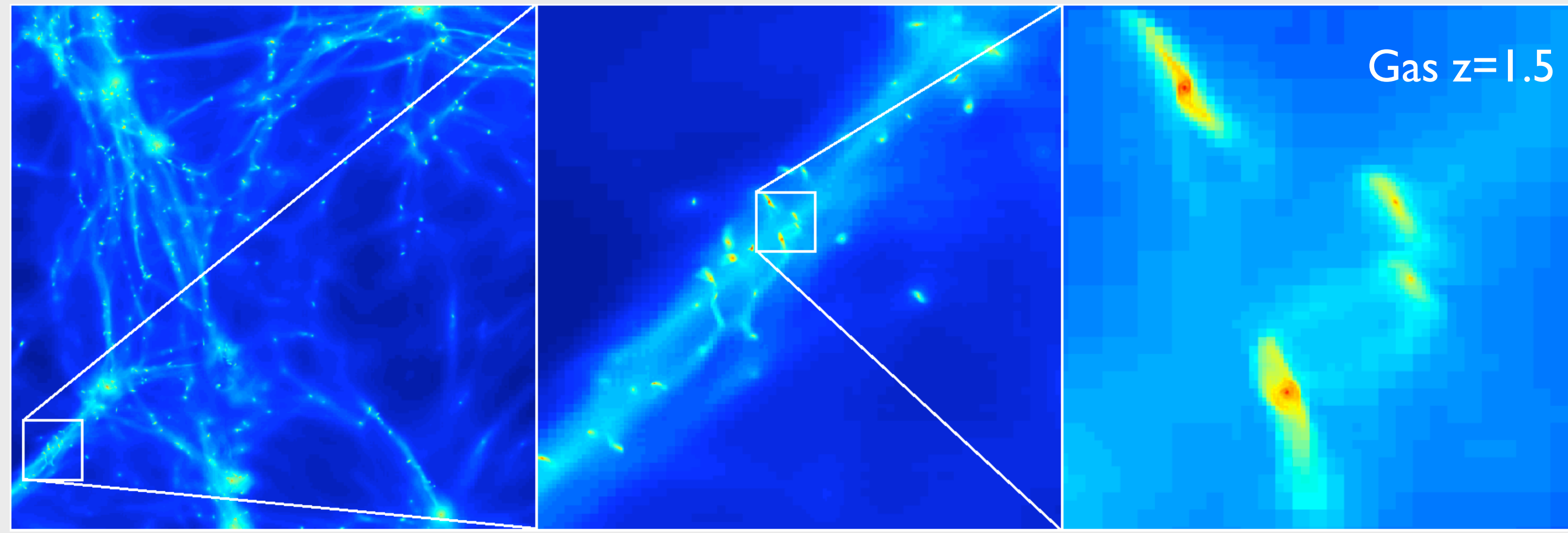
computational cost explodes

↓

take small refinement volume and measure correlations with tidal field

↓

working hypothesis:
if we understand how galaxies form in the web, we'll hopefully understand intrinsic alignments



RAMSES (Teyssier 2002)
AMR simulation
currently running:

Stars z=0.5

- 0.38 kpc/h physical resolution
- Lagrangian refinement region placed on single filament
- total box 100 Mpc/h
- roughly ~300 well resolved galaxies by z=0
- roughly 10^8 star particles by z=0

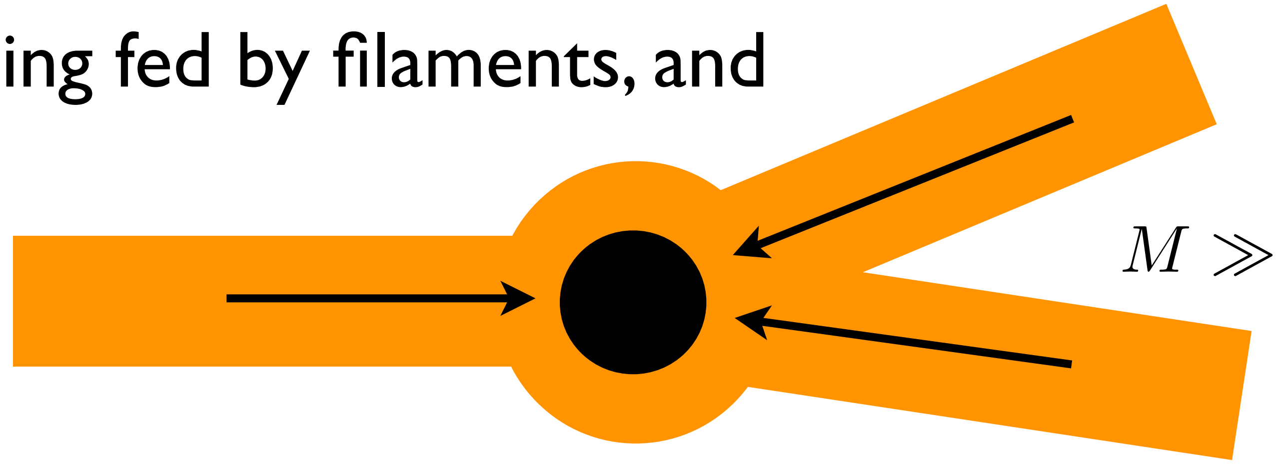
Summary & Conclusions

- Signature of smoothed tidal field eigenvalues allows a robust classification of large-scale structure
- Tides influencing the collapse of matter onto haloes seems to explain assembly bias at low masses
- Using the eigenvectors of the smoothed tidal fields we find a mass-dependent alignment-signal of halo spins and shapes
- We can use weak lensing to study these alignments
- Use simulations to understand them, model them and remove them from cosmic shear measurements
- Hydro results are coming...

Connection between assembly and alignment?

A speculation - to be studied in simulations:

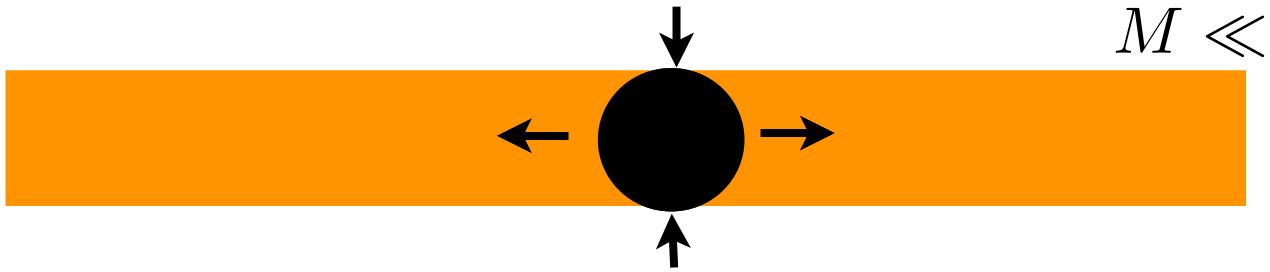
difference between
(1) being fed by filaments, and



$M \gg M_*$

(2) flowing along filaments

$M \ll M_*$



cf. cold accretion?

If the large-scale structure leaves its signature in galactic orientations, we can learn about galaxy formation from weak lensing efforts.