The large-scale orientations of disc galaxies

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with
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Overview

Galaxy formation happens in cosmic context

Main question: are disc galaxies oriented w.r.t. the large-scale structure?

How to define large-scale structure?

Are halo/galaxy orientations correlated with it?

Why bother?

Correlated galaxy orientations = bias for weak lensing (DE surveys)

Orientations are a proxy for formation processes

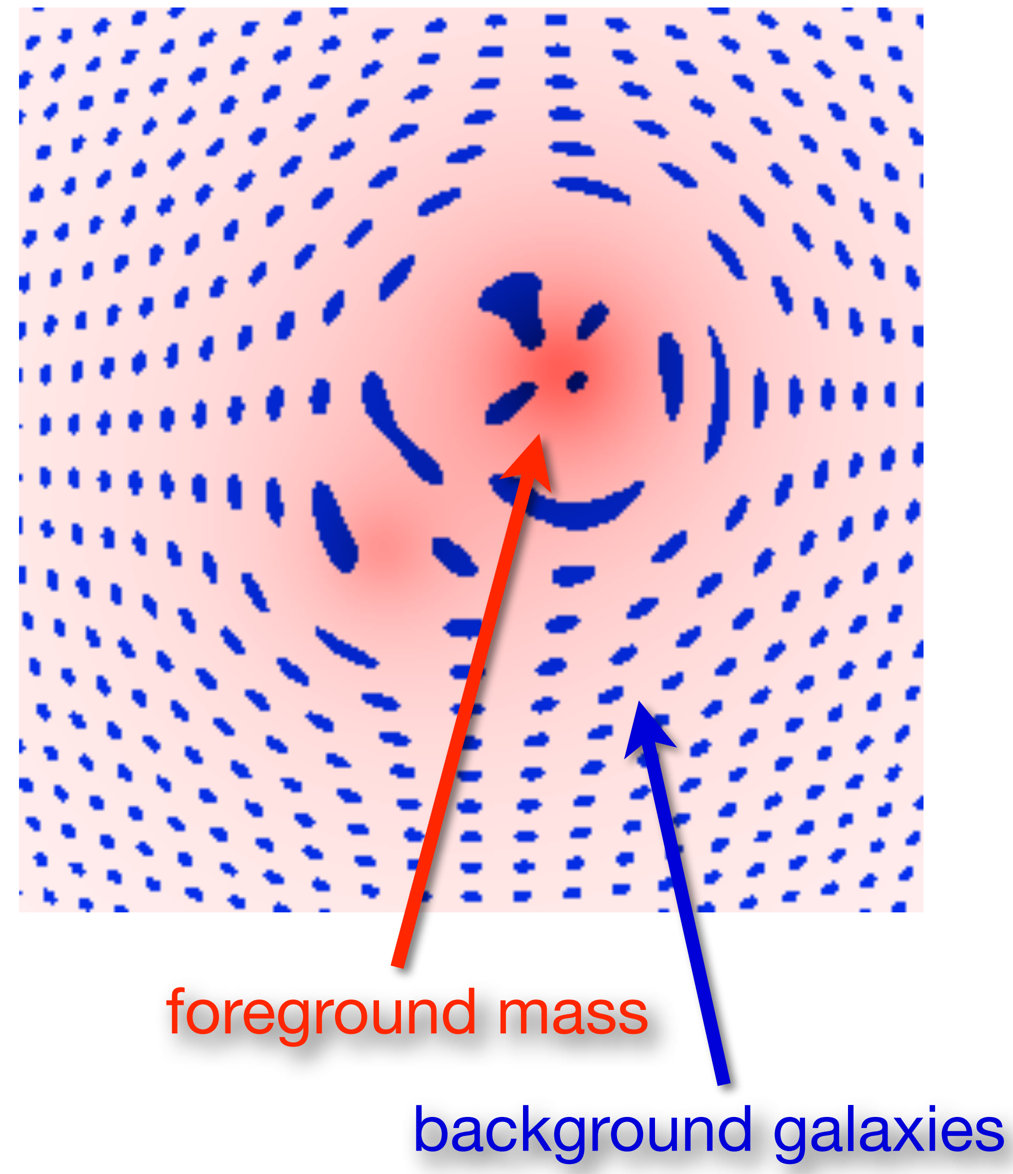
Importance of Alignments for Weak Lensing

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**:

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



Observable is total ellipticity

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

Correlation function thus becomes

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

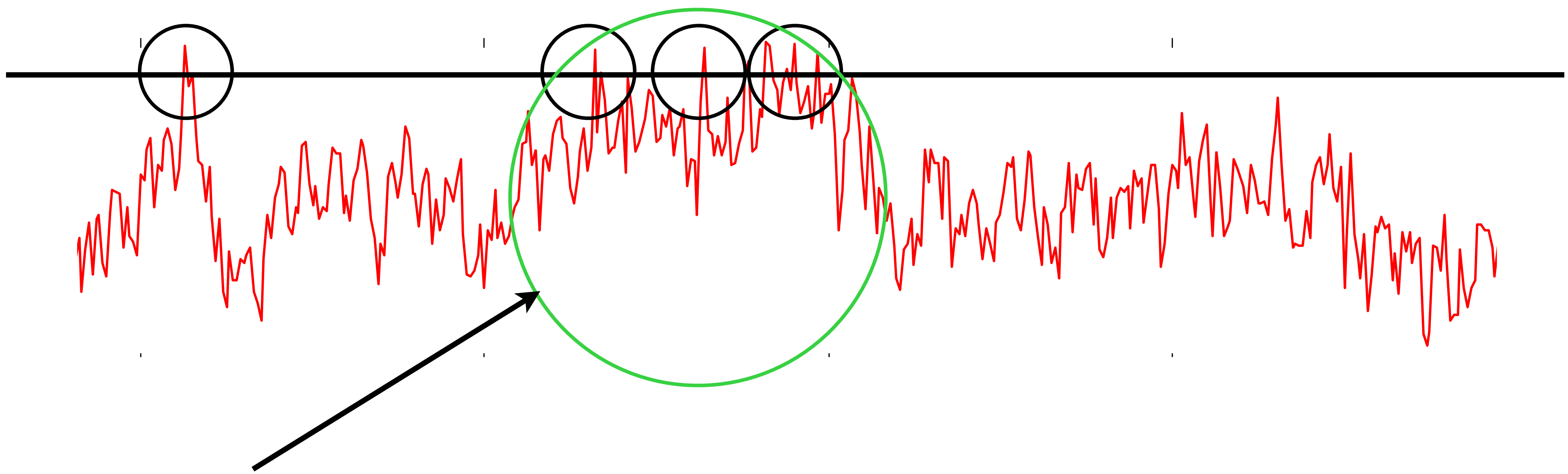
structure — GI — II

→ Contaminant for dark energy obs.

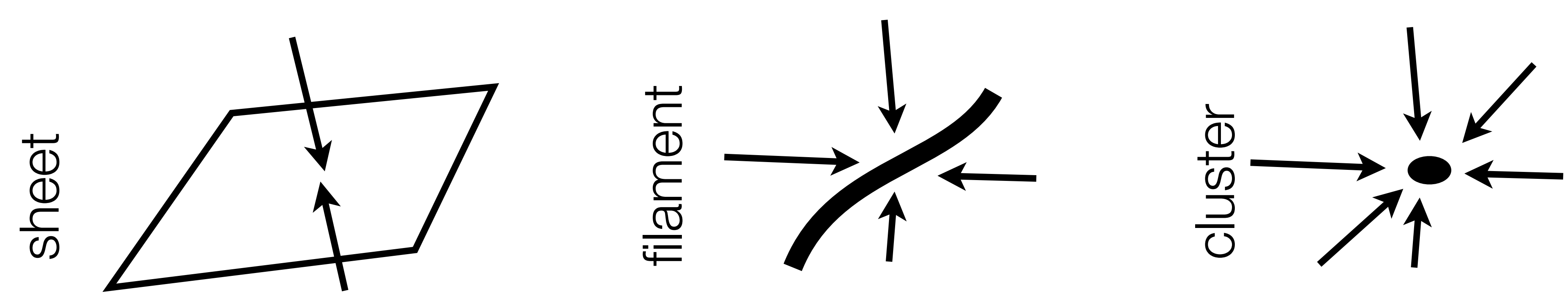
→ **Signal for galaxy formation**

Galaxy/Halo Formation & Large-Scale Structure

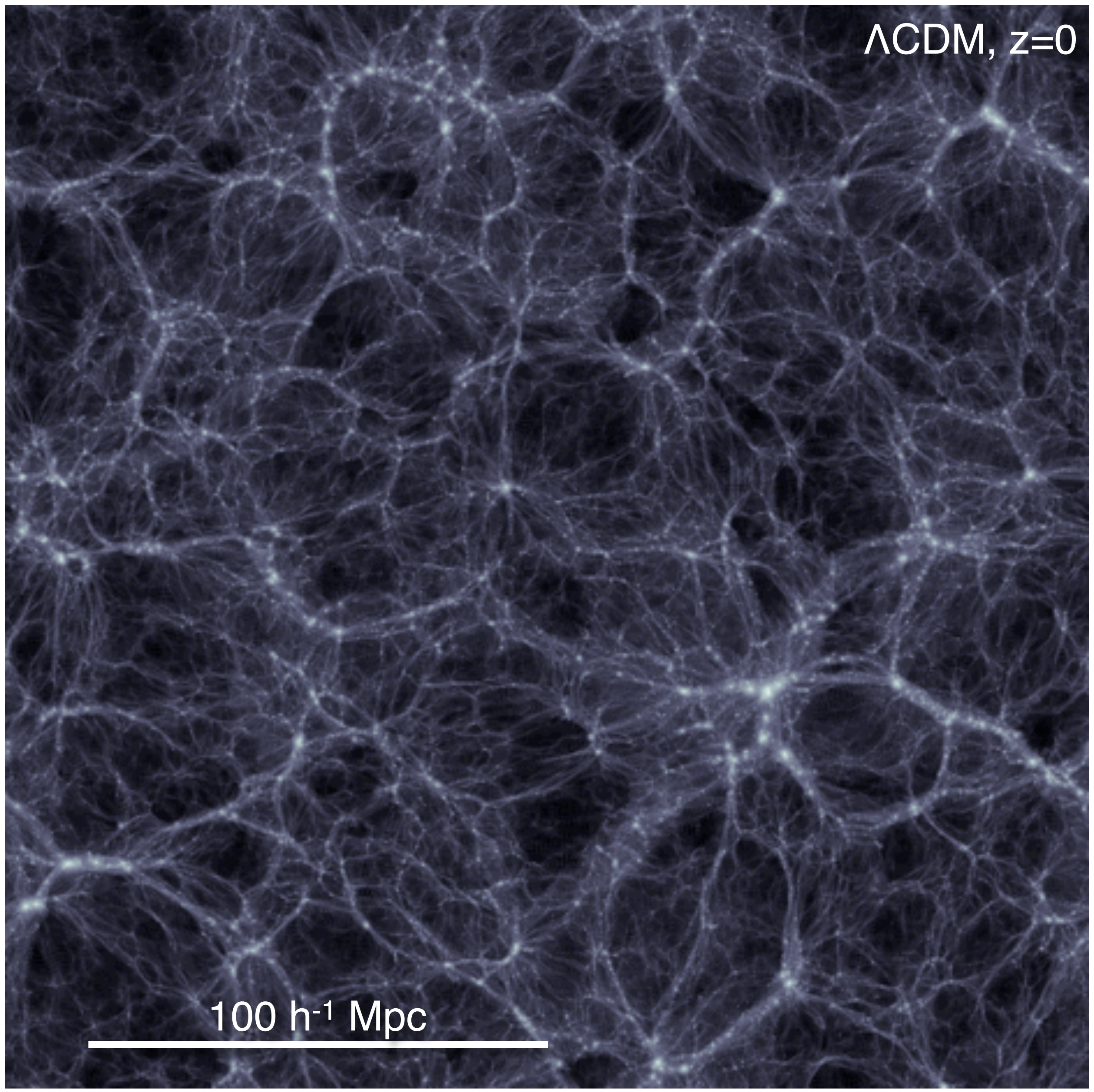
Peaks exceeding threshold collapse to form virialised galaxies/haloes



Larger scale fluctuations collapse ‘incompletely’ and subseq. along 3 axes



The Formation of the Web



(snapshot from simulation with 1024^3 particles, 240 Mpc/h periodic box)

Zel'dovich Approximation:

- 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)

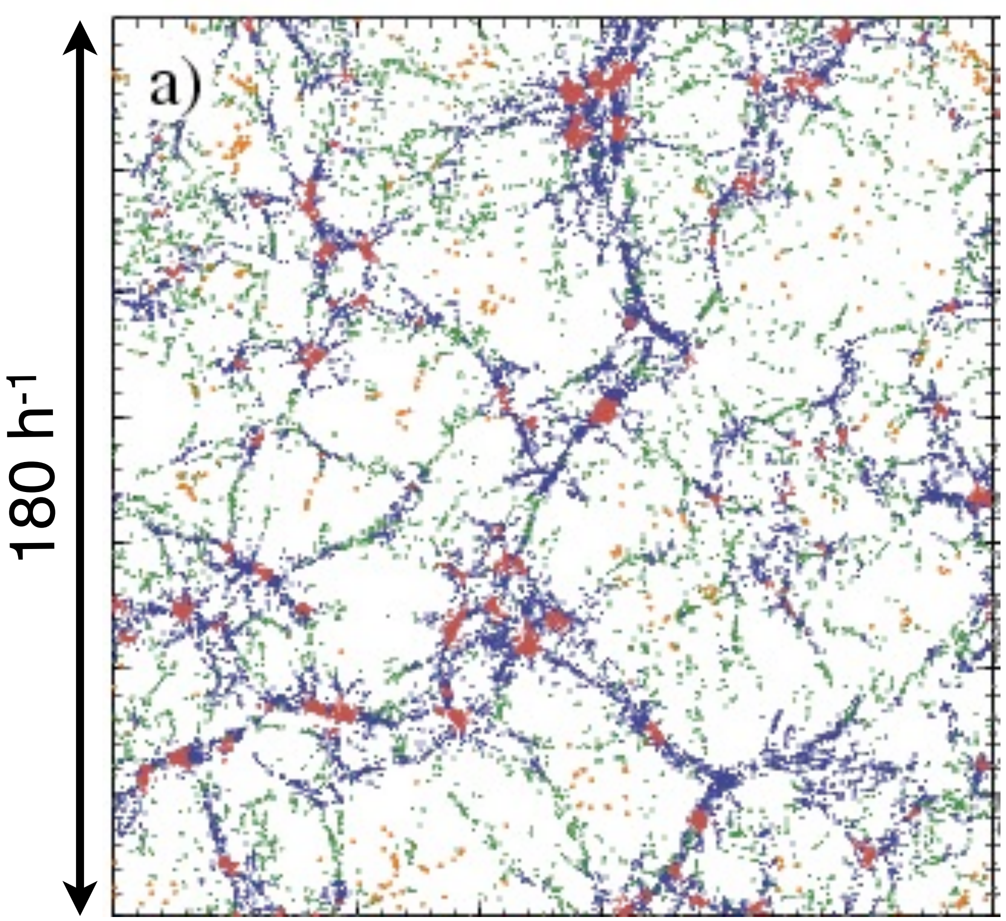
- "pancake" formation, $\lambda_1, \lambda_2, \lambda_3$ predict asymptotic morphology.
- In reality this is a multi-scale phenomenon.

Does the large-scale structure influence galaxy formation?

How to quantify LSS?

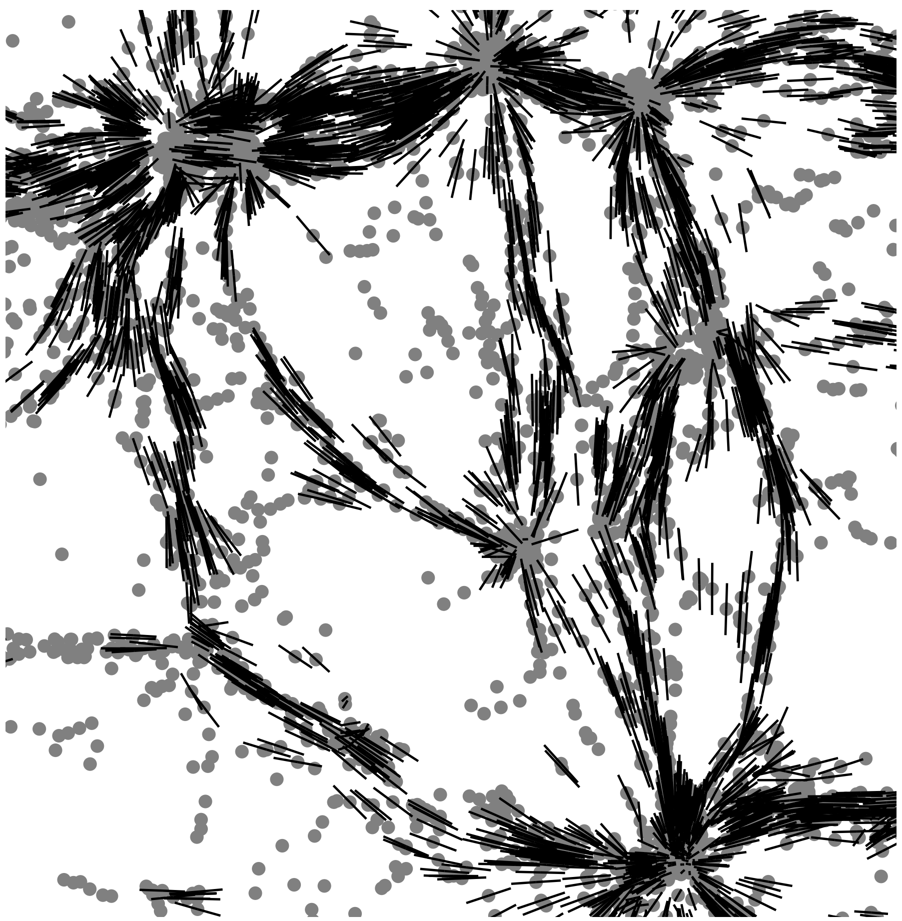
Use the smoothed tidal field to classify LSS:

Eigenvalue signature describes expansion/contraction:



OH, Porciani, Carollo, Dekel, 2007a/b

Eigenvectors describe direction thereof:



Galactic AM: Tidal Torque Theory

Definition of Angular Momentum

$$\mathbf{J} = \int_V \mathrm{d}^3 r \, \rho(\mathbf{r}, t) \, (\mathbf{r}(t) - \langle \mathbf{r}(t) \rangle) \times (\mathbf{v}(t) - \langle \mathbf{v}(t) \rangle)$$

Use Quasi-Linear Evolution from Zel'dovich Approximation

$$\mathbf{x}(\mathbf{q}, t) \equiv \mathbf{q} + \mathbf{L}(\mathbf{q}, t) \qquad \mathbf{L} = -D_+(t) \boldsymbol{\nabla} \Phi(\mathbf{q})$$

~gravitational potential

Perform series expansion of the gravitational potential, then at first order

$$\mathbf{J} = a^2 \dot{D}_+(t) \epsilon_{ijk} I_{jl} T_{lk}$$

where

$$T_{ij} \equiv -\partial^2 \Phi / \partial q_i \partial q_j$$

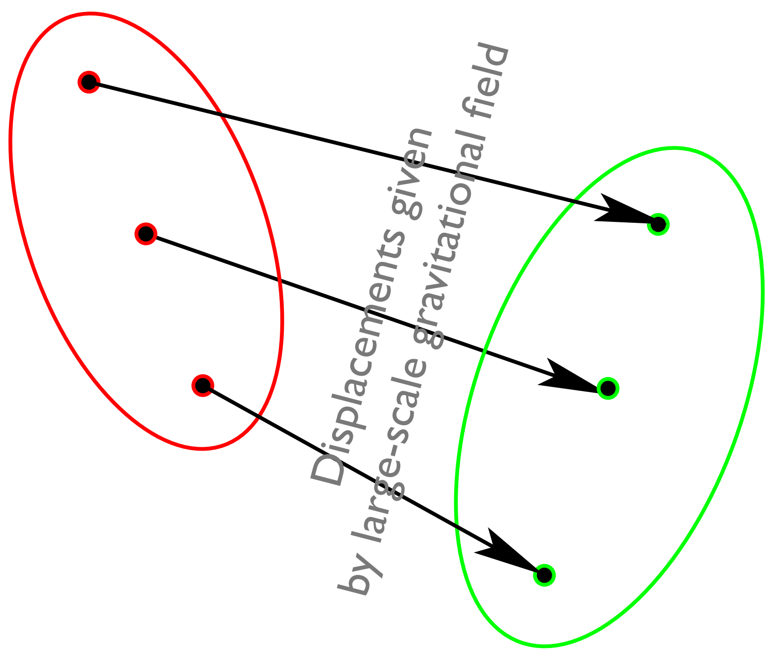
tidal tensor (second order term)

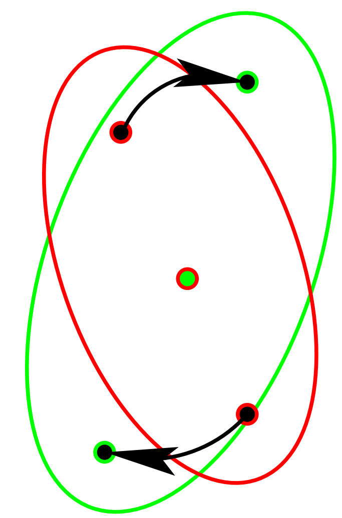
$$I_{ij} \equiv \rho_0 a_0^3 \int_{V_L} \mathrm{d}^3 q \, (q_i - \langle q_i \rangle) \, (q_j - \langle q_j \rangle)$$

moment of inertia tensor

Tidal Torques

Euler frame *Lagrange frame*





From Schaefer (2009), IJMP D

Linear variation
of displacements
in real space...

...generates
angular momentum
in comoving space

Nonzero angular momentum will result
if moment of inertia is misaligned with tidal field

True for haloes: AM from misalignment...

Alignment angle:

$$\beta \equiv 1 - \left(\frac{\mathcal{I}_{12}^2 + \mathcal{I}_{23}^2 + \mathcal{I}_{31}^2}{\mathcal{I}_{11}^2 + \mathcal{I}_{22}^2 + \mathcal{I}_{33}^2} \right)^{1/2}$$

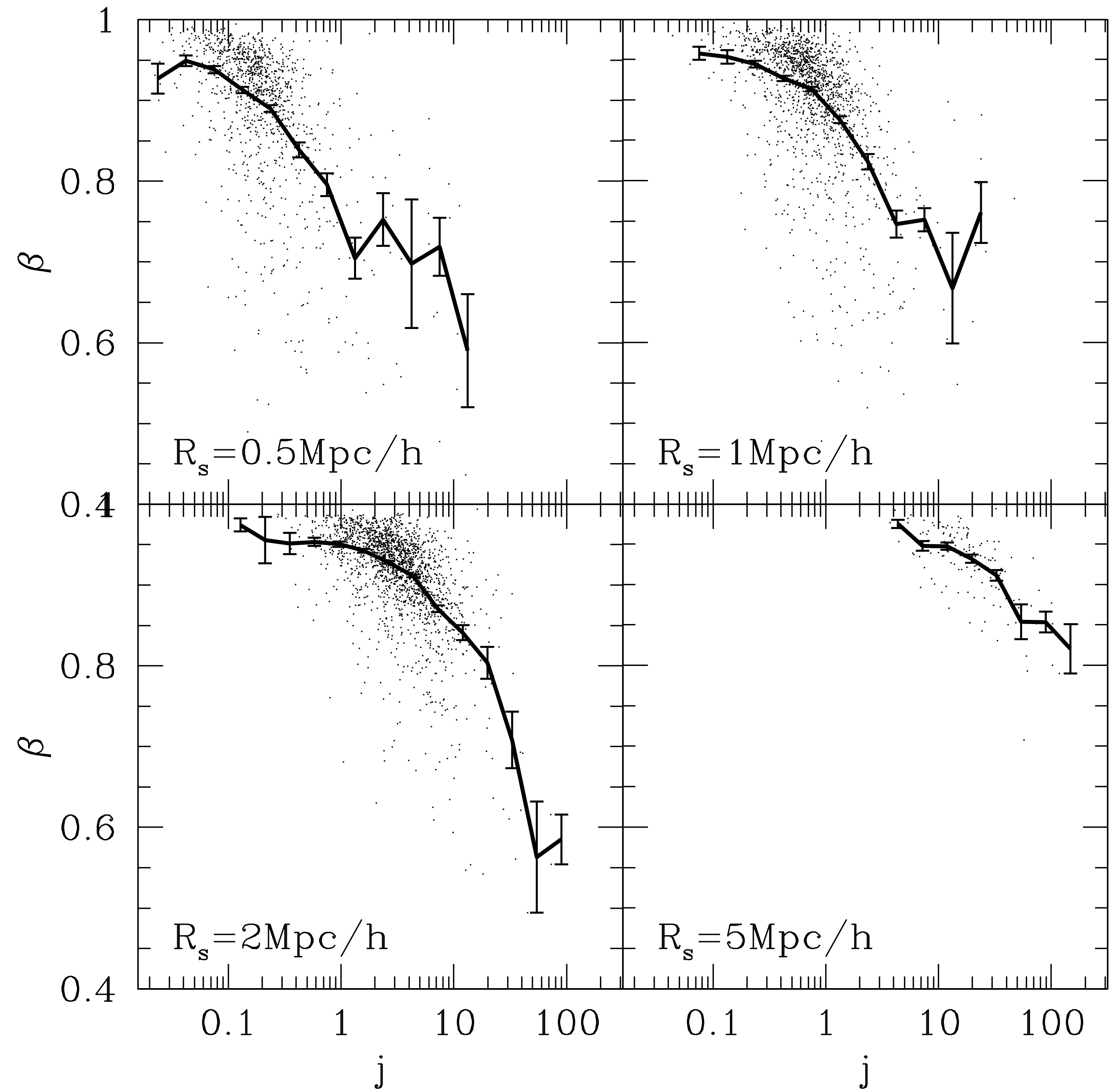
I_{ij} in T_{ij} principal axis frame.

At all halo masses:

haloes with largest initial misalignment

acquire highest specific AM

see also Porciani, Dekel & Hoffman (2001)



Lee, OH, Porciani, 2009

And what about orientations?

Tidal torque theory result:

$$\mathbf{J} = a^2 \dot{D}_+(t) \epsilon_{ijk} I_{jl} T_{lk}$$

In principal axis frame of the Tidal Tensor:

$$\begin{aligned} J_1 &\propto (\lambda_2 - \lambda_3) I_{23}, \\ J_2 &\propto (\lambda_3 - \lambda_1) I_{31}, \\ J_3 &\propto (\lambda_1 - \lambda_2) I_{12}. \end{aligned}$$

Define (w.l.o.g.) axes v_1, v_2, v_3 of T_{ij} so that $\lambda_1 < \lambda_2 < \lambda_3$ then:

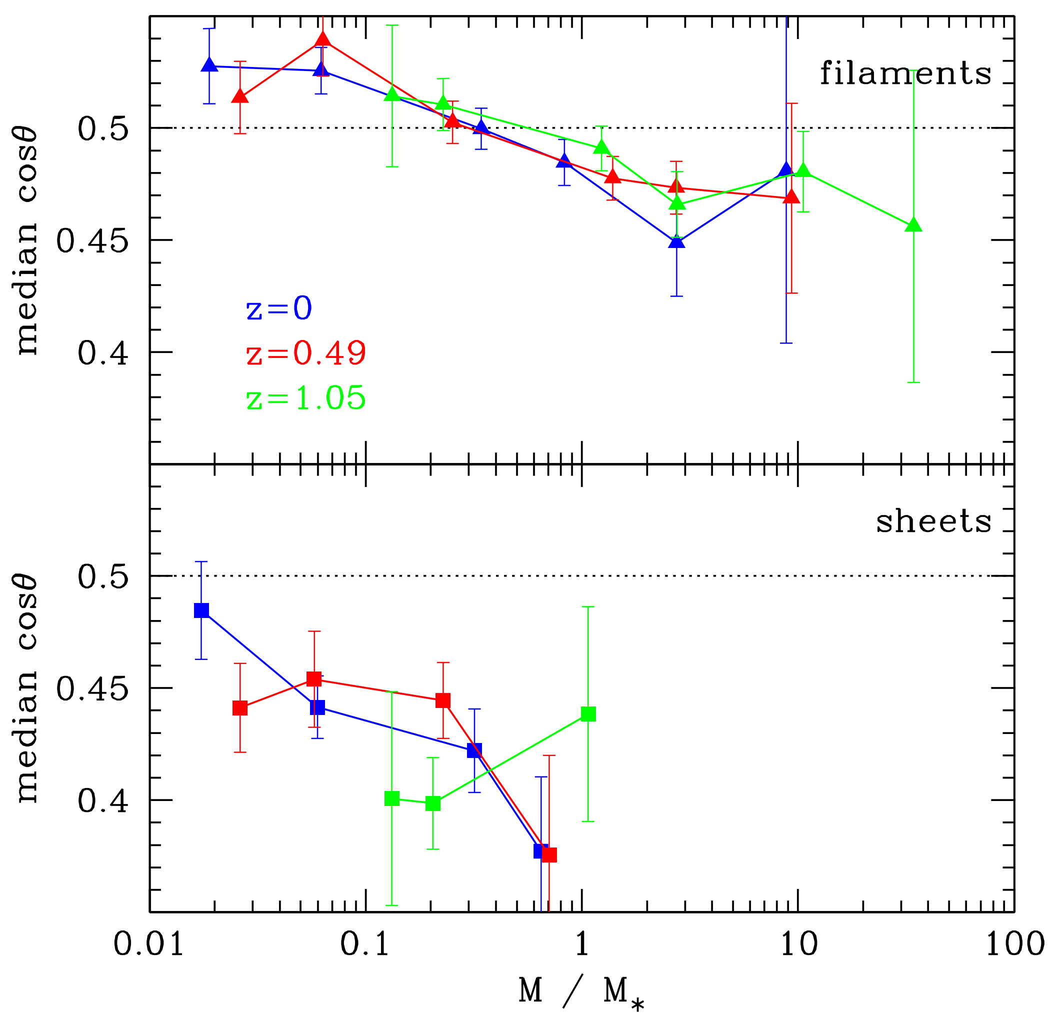
J_2 should be largest, i.e. alignment between v_2 and J strongest

(in statistical sample, assuming T and I uncorrelated)

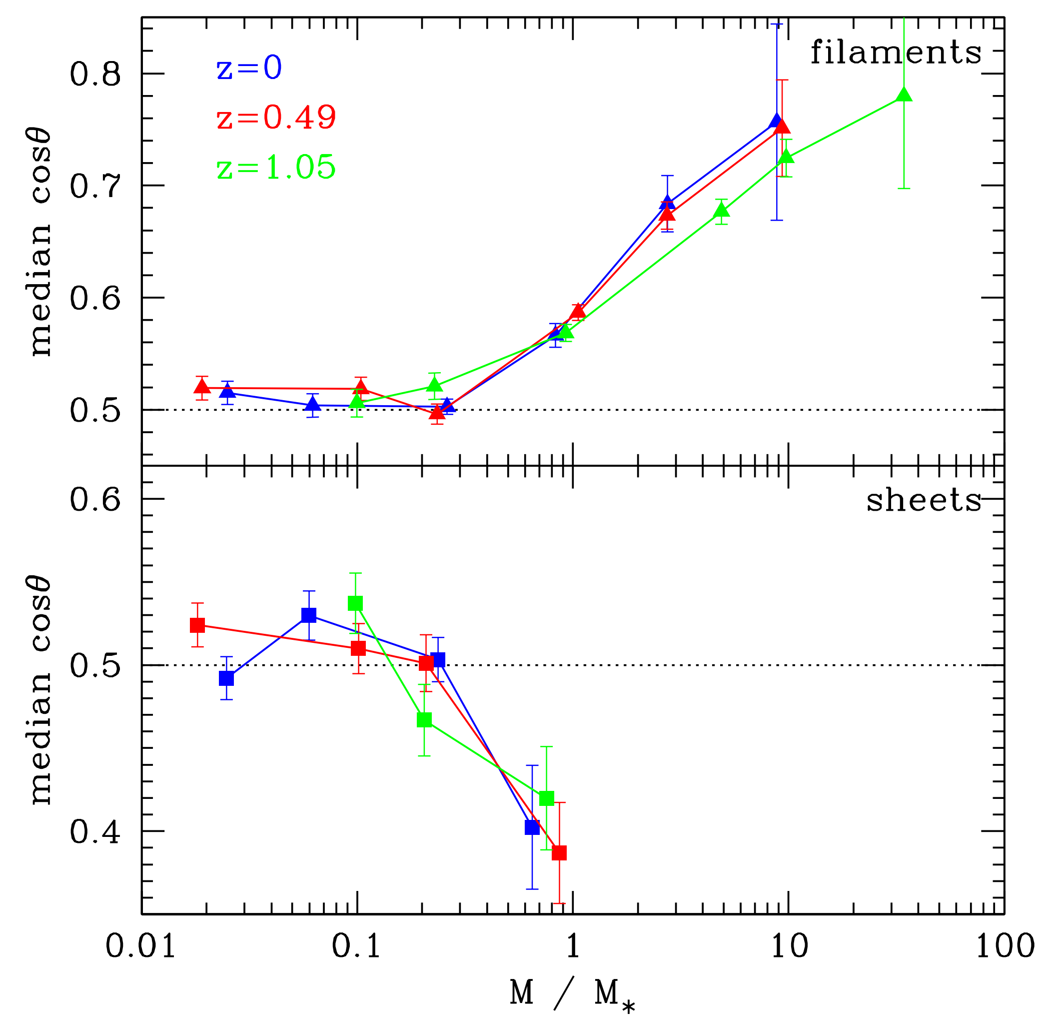
Navarro et al. (2004) find TTT confirmed for isolated galaxies

Are halos preferentially oriented?

Spin orientation:



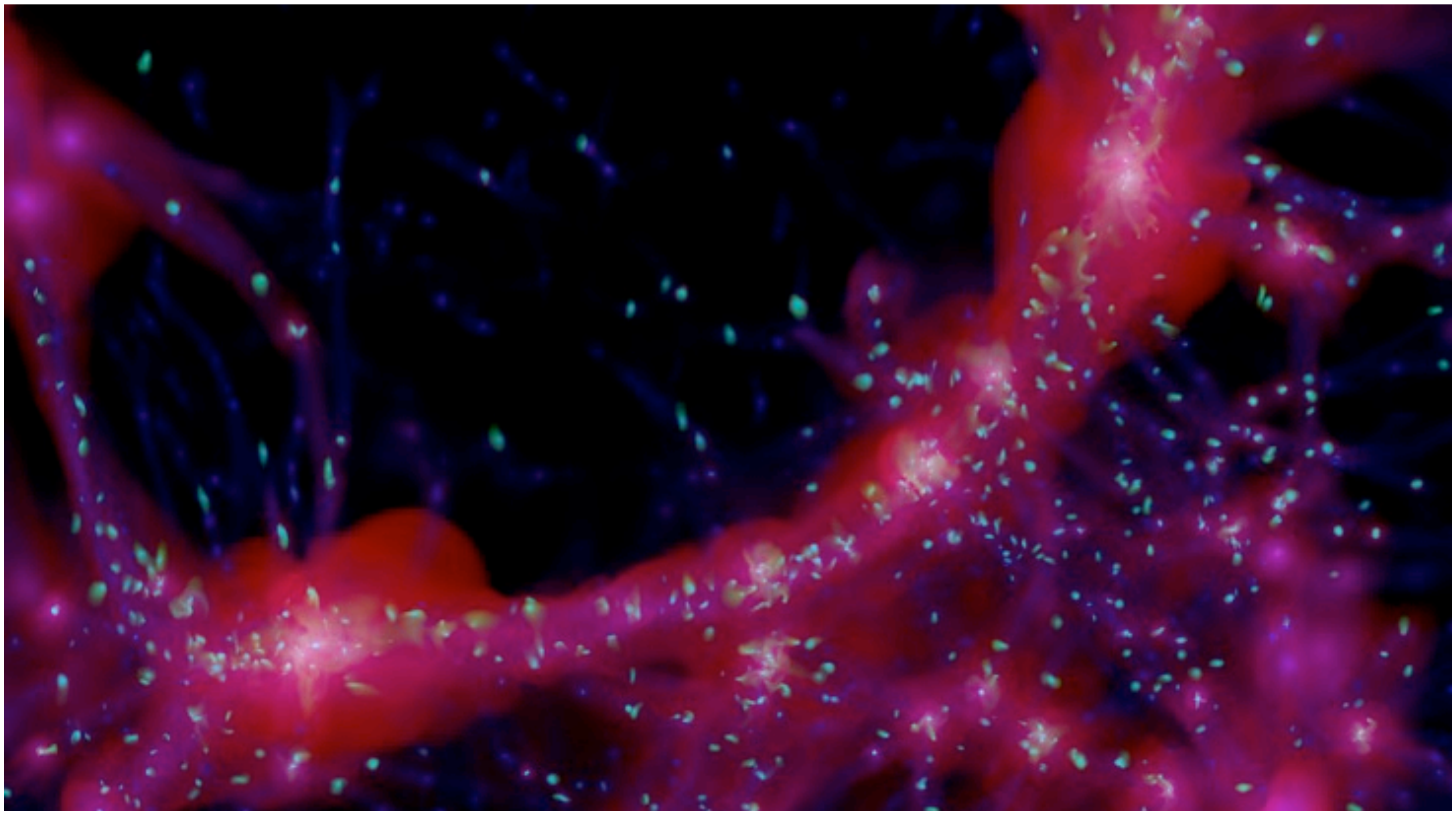
Shape orientation:



OH, Carollo, Porciani, Dekel (2007)

Binggeli effect, seen in many observations

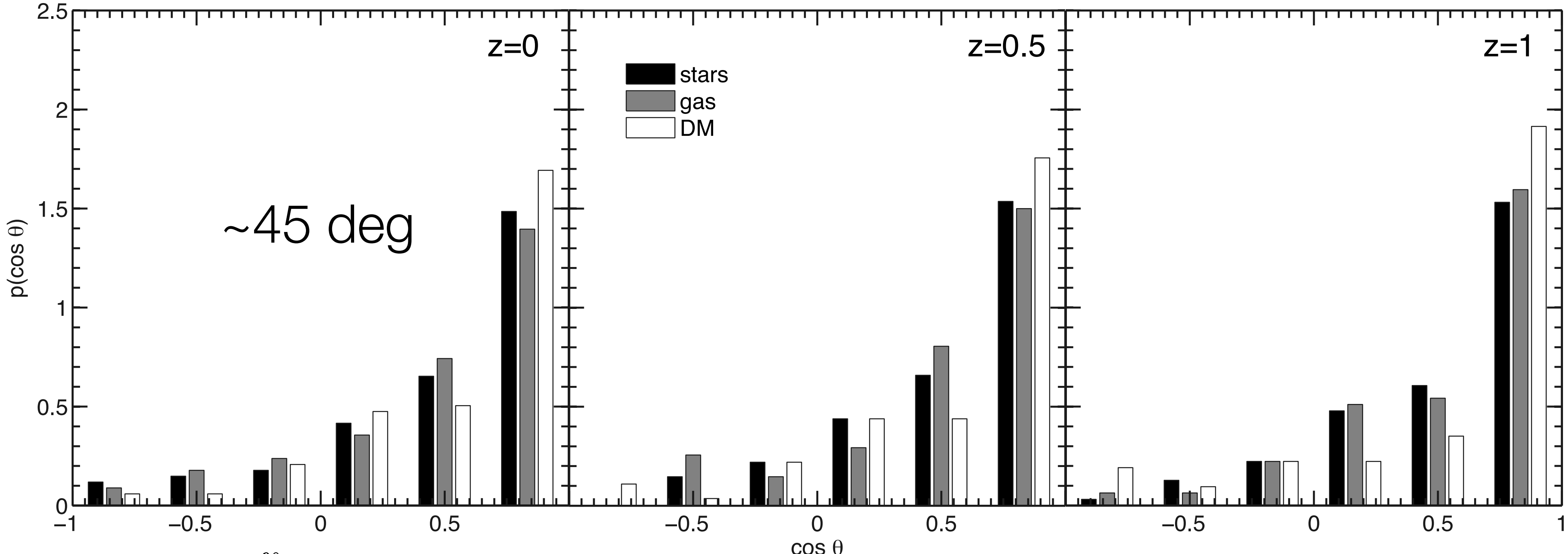
Adding Baryons: Simulation Set-up



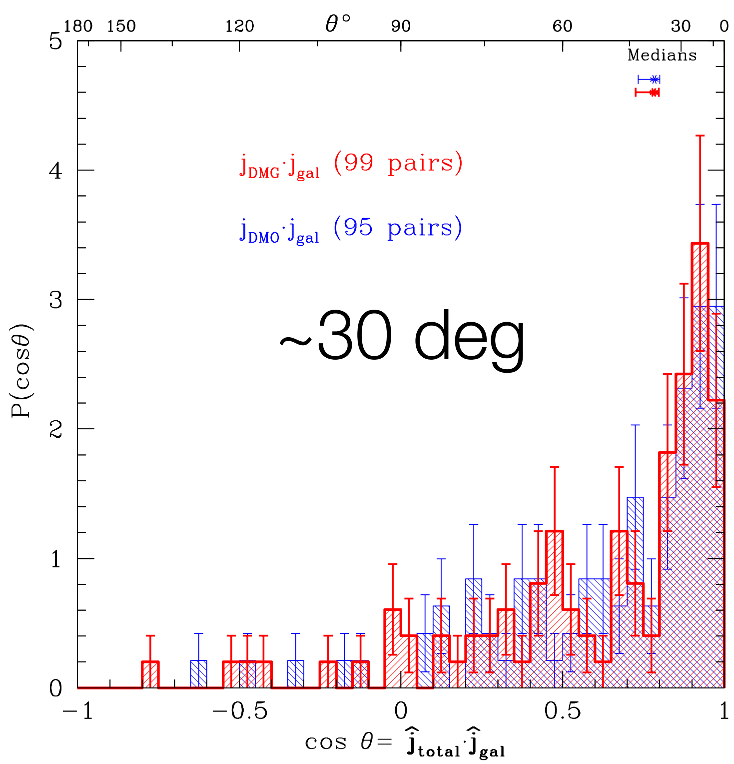
RAMSES AMR zoom simulation
high-res of a single filament ~25Mpc/h in 100Mpc/h box
0.38 h^{-1}kpc physical resolution down to z=0
cooling to 10^4K, metal enrichment, star formation & supernova feedback

Going from halos to galaxies?

angle galaxy - host halo



OH, Teyssier, Carollo (2010)



Bett et al. 2010

rel. broad distribution.
some counter-rotating.

see also van den Bosch et al. (2002), Bailin & Steinmetz (2005)

baryon physics influence?

environmental influence?

Galaxy-LSS alignments

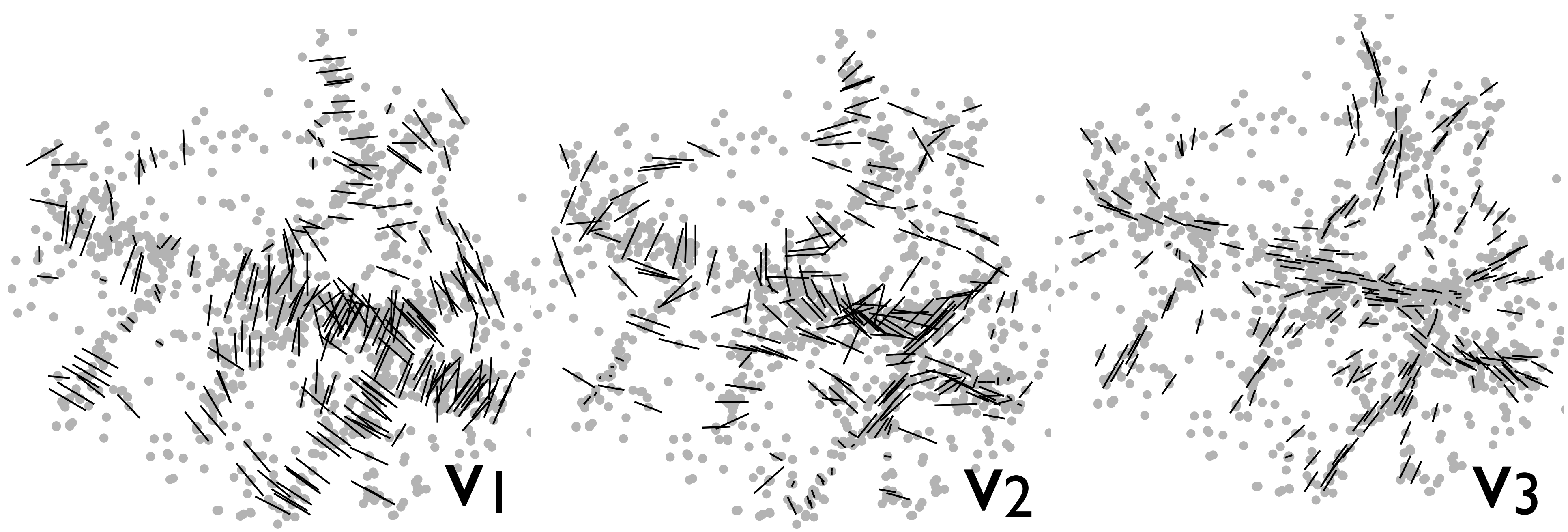
~100 well-resolved galaxies.

shown are synthetic stellar light images, i',r',g' bands with dust

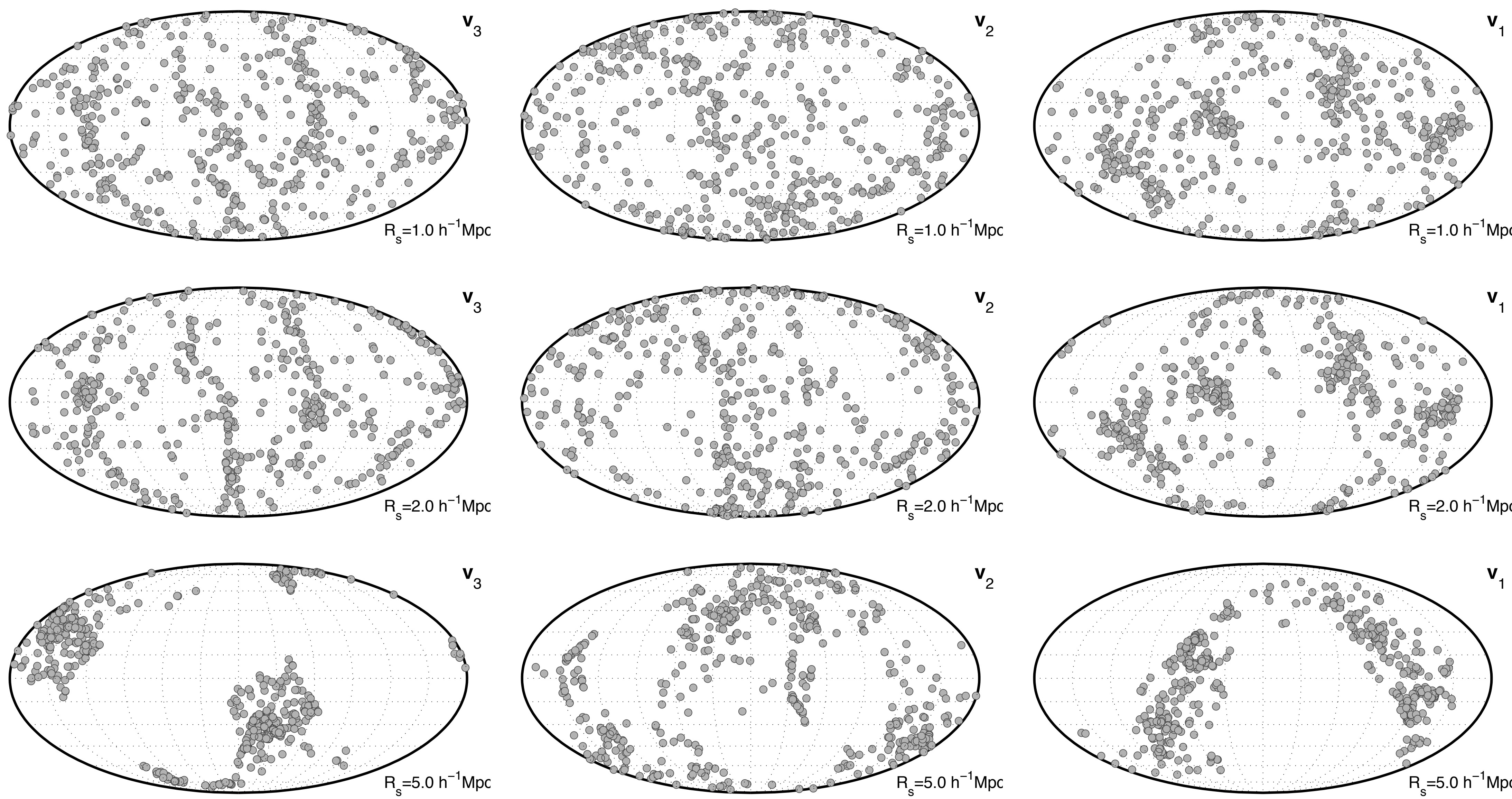
measure their stellar, gas, DM angular momentum

&

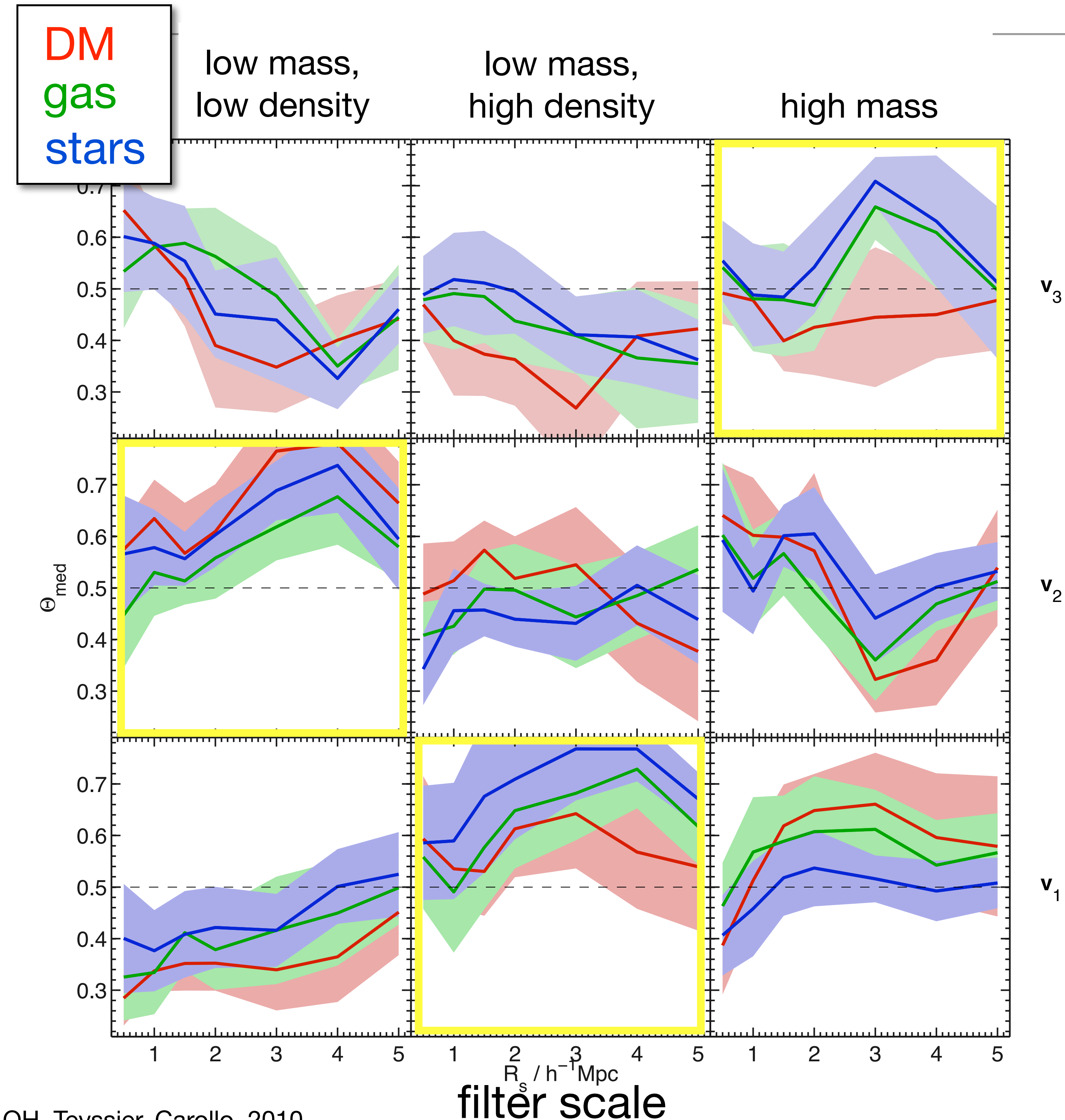
correlate with tidal field



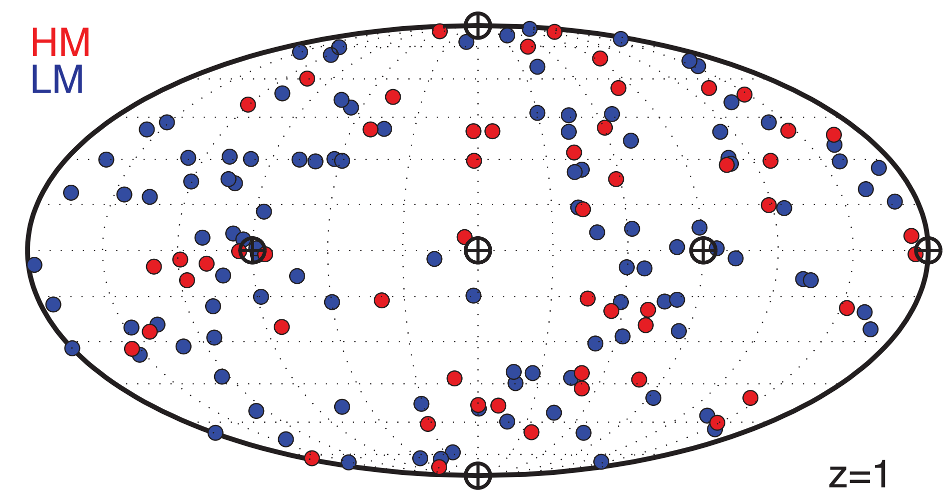
The tidal field seen by the galaxies...



Alignment of Discs with LSS at z=1



OH, Teyssier, Carollo, 2010

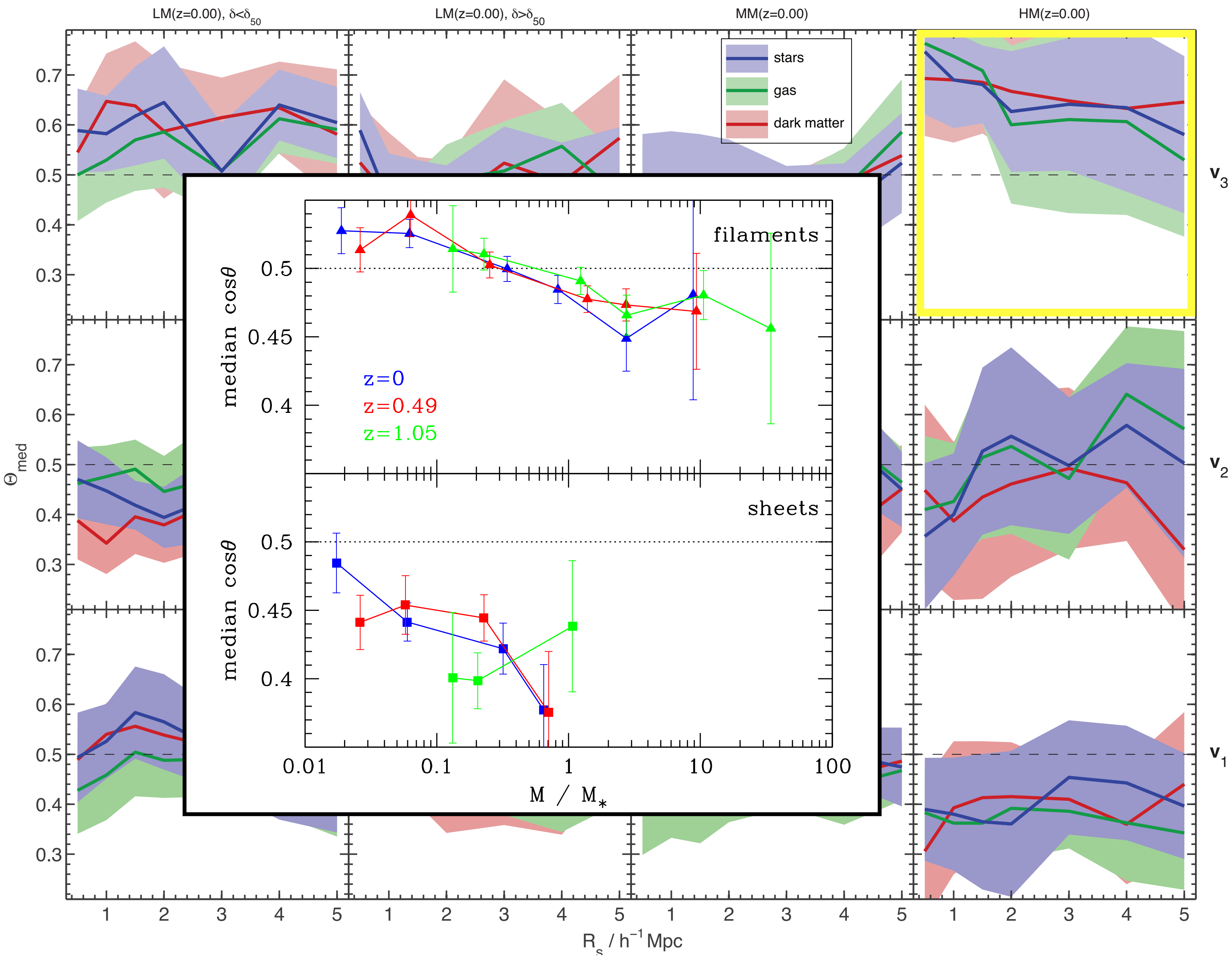


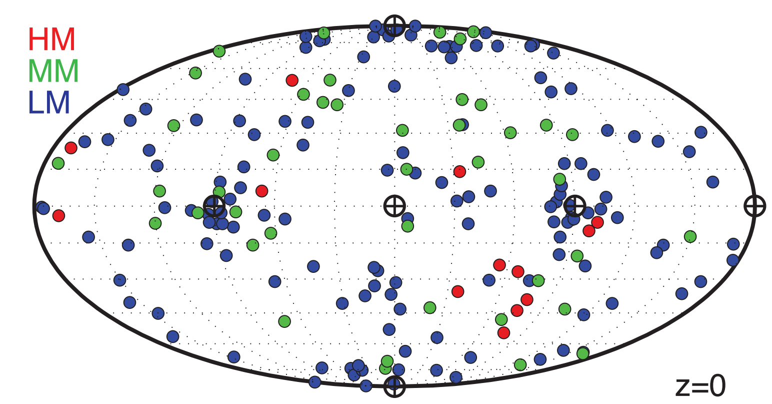
Orientations of disks depend on:

- mass
- scale
- environment density

- **TTT fossil alignment with v_2 for low-mass galaxies in low-density environments!**
- **Alignment with v_3 at high masses.**
- **Mis-alignment of DM and baryons at high masses**

Alignment of Discs with LSS: z=0





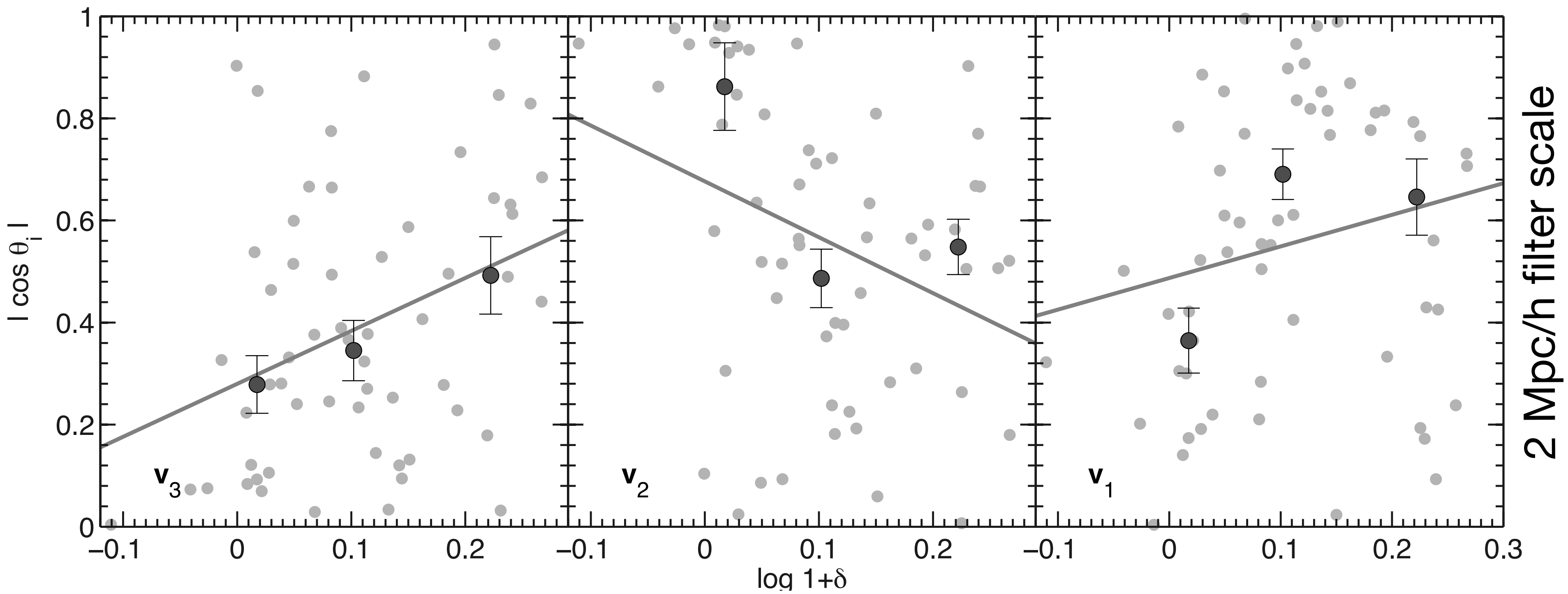
Only alignment at high masses survives

Opposite to DM only result

OH, Teyssier, Carollo, 2010

Density Dependence of Alignment at z=1

Low mass galaxies:



OH, Teyssier, Carollo 2010

Change of alignment with environmental overdensity.

Investigation of its origin currently in progress:

- Reorientation through mergers? (mergers are more frequent in high density regions) - no evidence so far
- Non-linear tides? (tides experienced by galaxies change strongly in non-linear density field)
- Baryon physics? (Ram pressure, accretion difference)

Summary & Conclusion

- Tidal field eigenstructure allows a robust characterization of cosmic large-scale structure
- Using the eigenvectors of the smoothed tidal fields we find a mass-dependent alignment-signal of halo spins and shapes
- We find a mass-, scale- and density dependent alignment of disc galaxies.
- In particular: (1) fossile TTT predicted alignment at low masses in low-density environments. (2) alignment of the most massive galaxies with their surrounding filaments.
- The origin of this scale, mass and density dependence is under investigation. Stay tuned...