# The cosmic web and halo alignment

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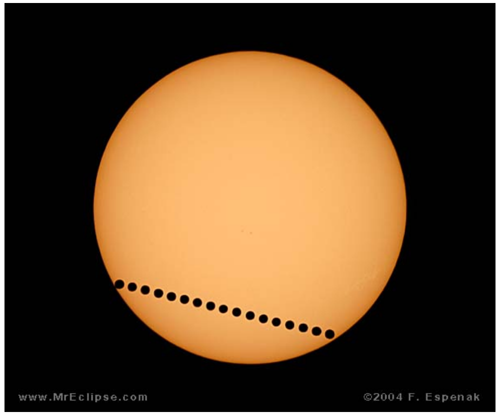
**Alexander Knebe** (Madrid)
**Matthias Steinmetz** (Potsdam),

Libeskind et al 2012, to be submitted (... soon ...)




The Transit of Venus, 2012

*The Adoration of the Magi with St Anthony Abbot,* Unknown, Netherlands, 1390

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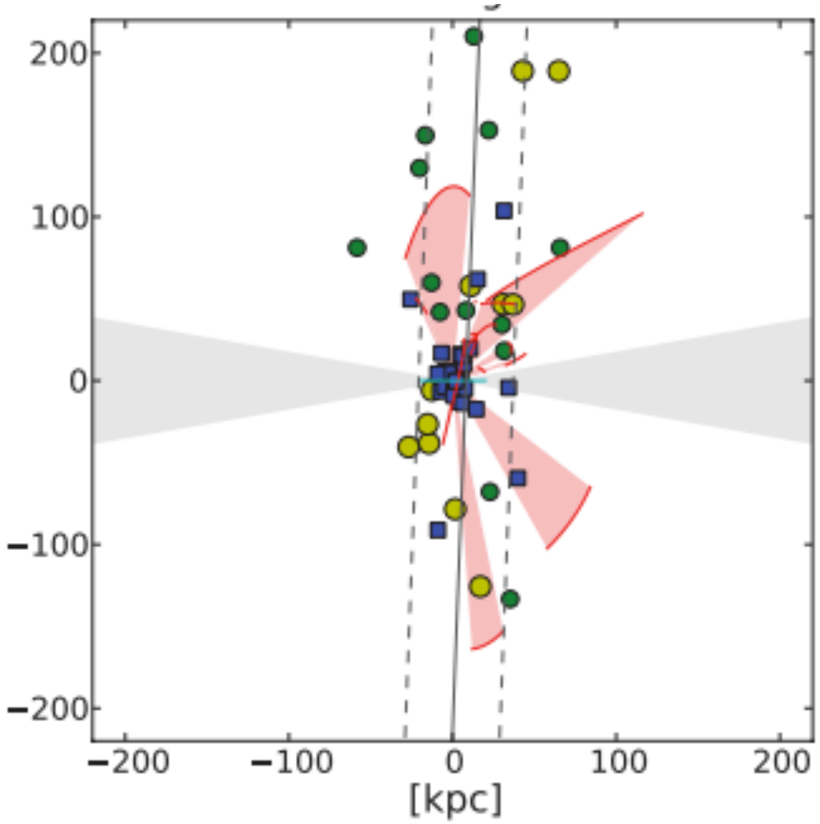
# Galaxy and satellite galaxy alignments




Pawlowski et al 2012

The alignment of satellite galaxies (the "disc of Satellites") is a thorn in the side of CDM

May be due to preferential infall, but… from where?

Aqarius halo, Springel et al 2008

*Therefore, in order to keep me from becoming conceited, I was given a* ***thorn in my flesh*** *… to torment me.*
2 Corinthians 12:7

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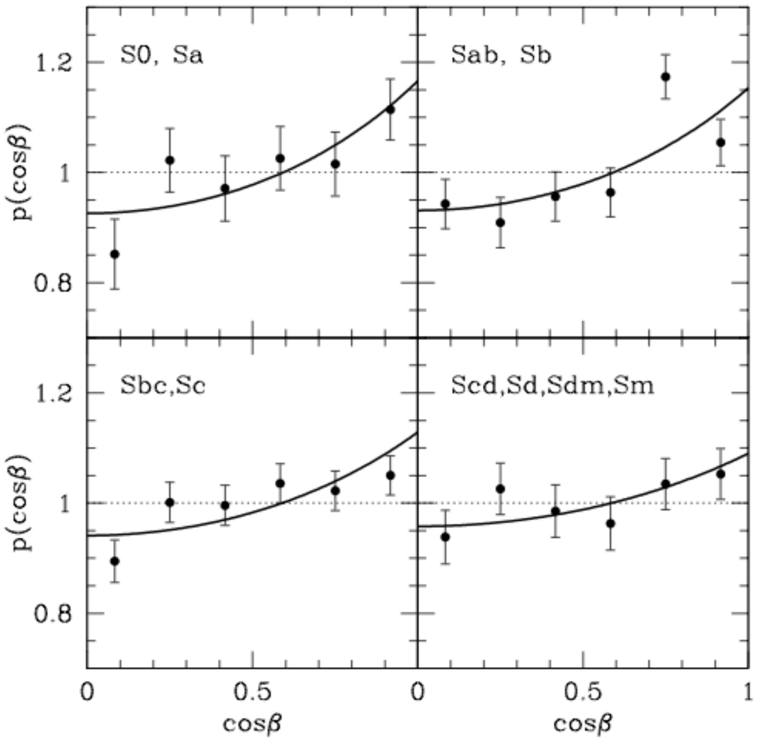
What causes the aniostropic infall of satellite galaxies? What determines their trajectory and orbit? Is it related to the large scale structure ?

Galaxy spins are related to LSS – why not satellite trajectories?




Lee & Erdogdu 2007:

Alignment of a galaxy's spin axis with the intermediate axes of the local shear tensor from the reconstructed tidal field of 2MASS

Tidal Torque theory predicts an alignment between J and the intermediate axis of the shear

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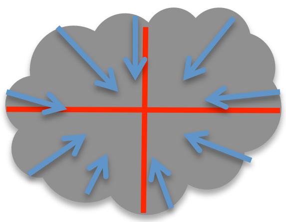

Collapsing proto-halo at high redshift with Inertia Tensor of 2nd moments $I_{\alpha\beta}$

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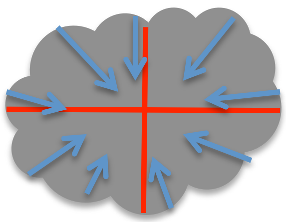

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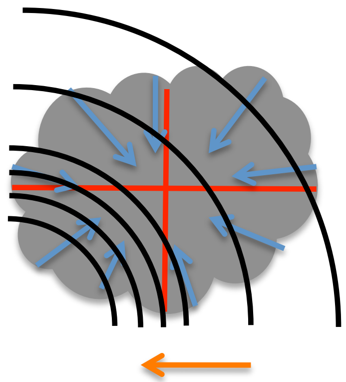

$\nabla\Phi$

Gravitational field $\Phi(r)$ with gradient $\nabla\Phi$

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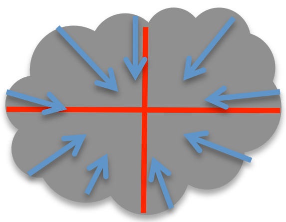

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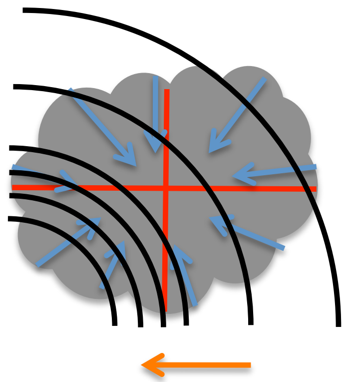

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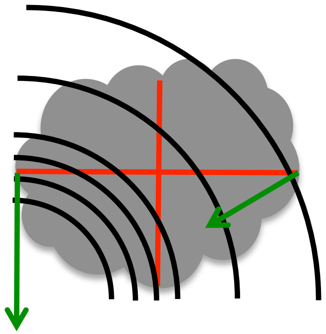

tidal shear $\Sigma_{\alpha\beta}$

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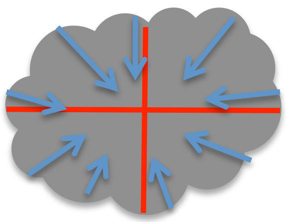

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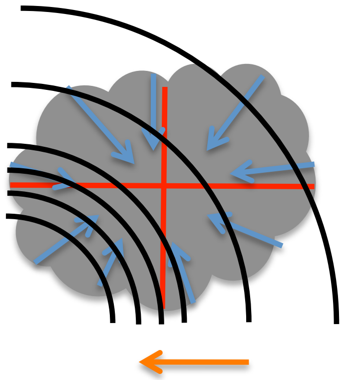

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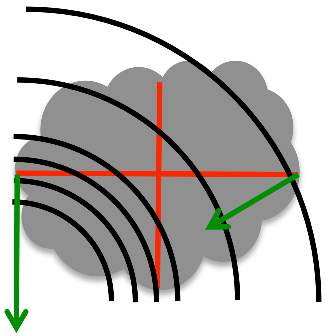

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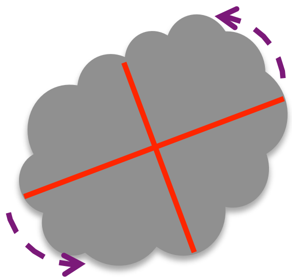
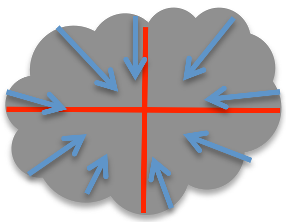


Angular momentum acquired through tidal torques

Tidal Torque theory predicts an alignment between J and the intermediate axis of the shear



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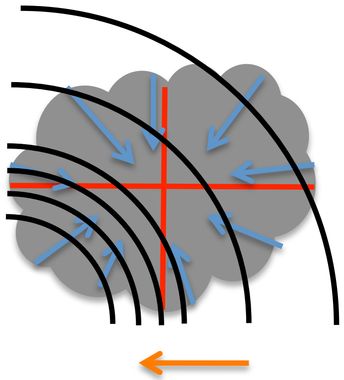

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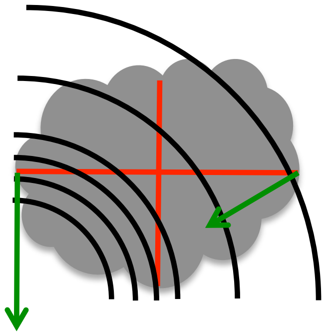

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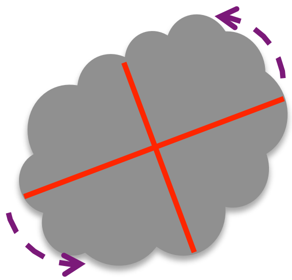


Angular momentum acquired through tidal torques

As the proto-halo collapses it decouples from the Shear flow; at some point the "lever arms" of the inertia tensor are too small for any more torques to be imparted. Tidal torques stop.

Tidal Torque theory predicts an alignment between J and the intermediate axis of the shear

$$L_i = \epsilon_{ijk} T_{jl} I_{lk},$$

Angular momentum

Inertia tensor

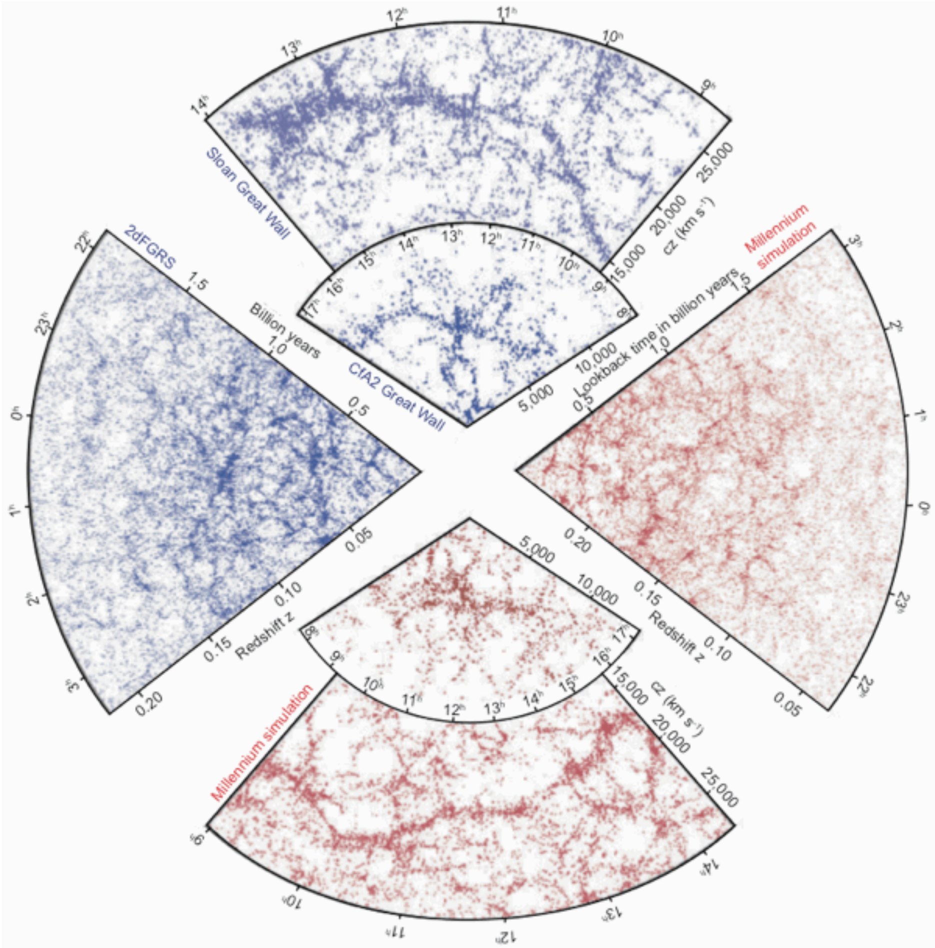
Tidal shear

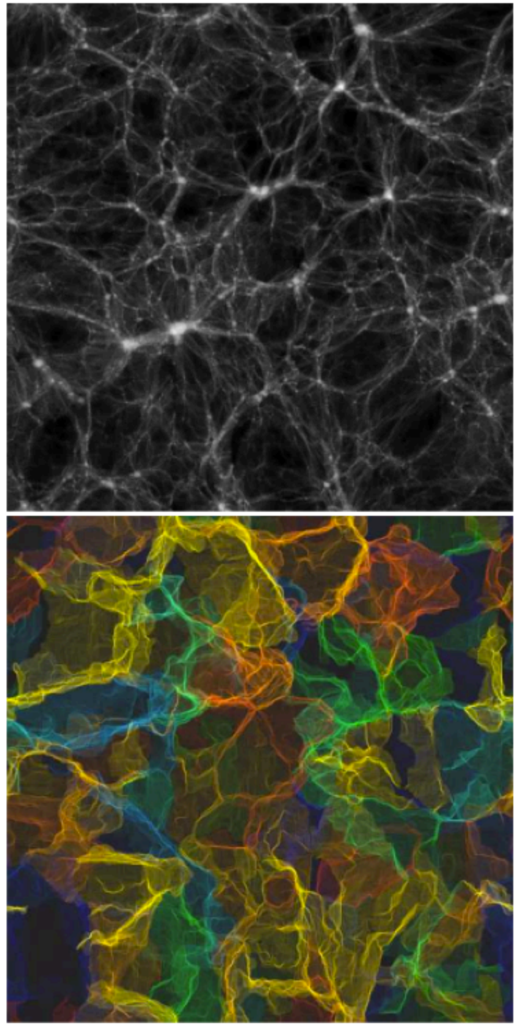
In the principle axis of the shear $(T_{ij})$, this can be written as

$$L_1 \propto (\lambda_2 - \lambda_3) I_{23}, \quad \underbrace{L_2 \propto (\lambda_3 - \lambda_1) I_{31},}_{\text{Greatest, hence halo spin should align with the intermediate axis of the Shear}} \quad L_3 \propto (\lambda_1 - \lambda_2) I_{12}$$

Lee & Lee 2006
Lee & Erdogdu 2008
+ others

Shear can be used to quantify the Cosmic web (Bond et al 1996)



Springel et al 2005

How does the web effect galaxy formation?

The cosmic web can be classified either by looking at the velocity shear tensor

$$\Sigma_{\alpha\beta} = -\frac{1}{2}\left(\frac{\partial v_\alpha}{\partial r_\beta} + \frac{\partial v_\beta}{\partial r_\alpha}\right)/H_0,$$

We can diagonalize the shear tensor to obtain the eigenvectors $\hat{e}_i$ and eigenvalues $\lambda_i$.
(Order them such that $\lambda_1 > \lambda_2 > \lambda_3$)

By counting the number of eigenvalues above a given threshold $\lambda_{th}$ we can classify each point (cell) in space according to the web

See Ofer Metuki's talk

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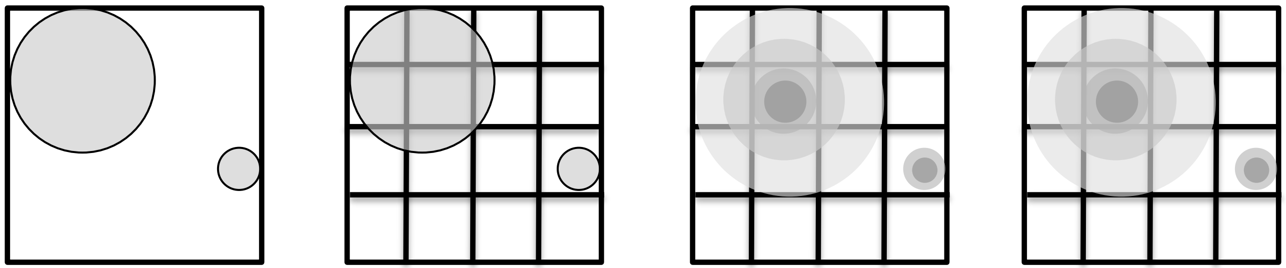

Simulation Grid smoothing shear

See Ofer Metuki's talk

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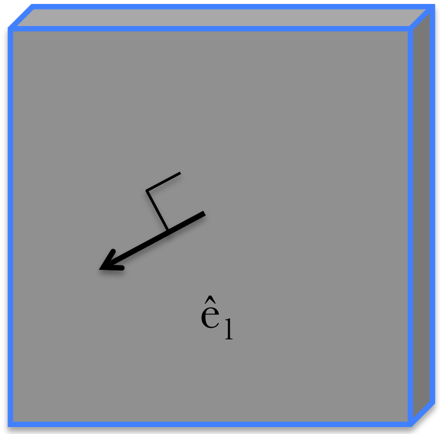
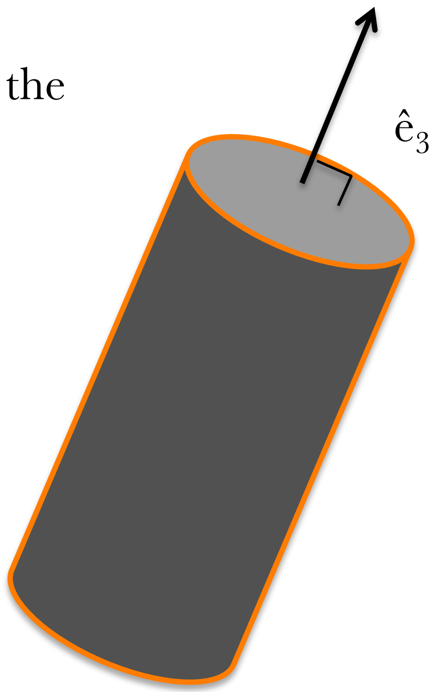
**VOID** $\lambda_{th} > \lambda_1 > \lambda_2 > \lambda_3$ All three eigenvectors of the shear tensor are expanding

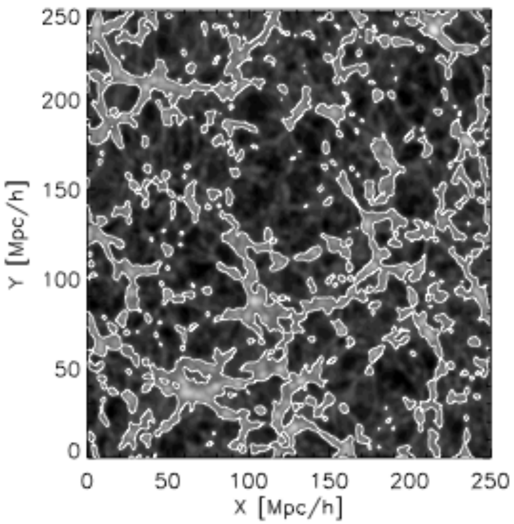
**SHEET** $\lambda_1 > \lambda_{th}$ ; $\lambda_2, \lambda_3 < \lambda_{th}$ Collapse along one axis ($\hat{e}_1$), expansion along the two ($\hat{e}_2$, $\hat{e}_3$)

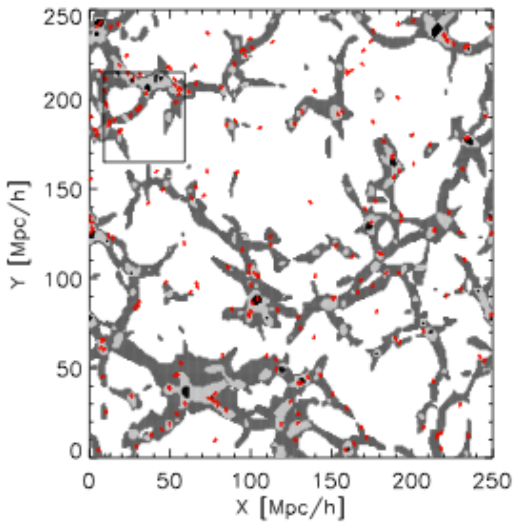
**FILAMENT** $\lambda_1, \lambda_2 > \lambda_{th}$ ; $\lambda_3 < \lambda_{th}$ Collapse along two axes ($\hat{e}_1$, $\hat{e}_2$), expansion along the other ($\hat{e}_3$)

**KNOT** $\lambda_1 > \lambda_2 > \lambda_3 > \lambda_{th}$ All three eigenvectors of the shear tensor are collapsing






*Bolshoi* (Klypin et al 2011)

$L_{box}$=250 $h^{-1}$ Mpc with
$2048^3 \approx$ 8 billion particles
$m_{DM}$~ 1.3 × 108 $h^{-1}M_\odot$
$r_{soft}$~ 1 kpc.

$256^3$ grid cells = ~1 Mpc

This is a **kinematical** classification, not a geometric one – hence it is interesting to compare with kinematic halo properties such as halo **spin** and subhalo **orbital angular momentum**

h=0.7,
$\Omega_\Lambda$ =0.73,
$\Omega_m$ =0.27,
$\Omega_b$ =0.046,
n= 0.95
$\sigma_8$ = 0.82.

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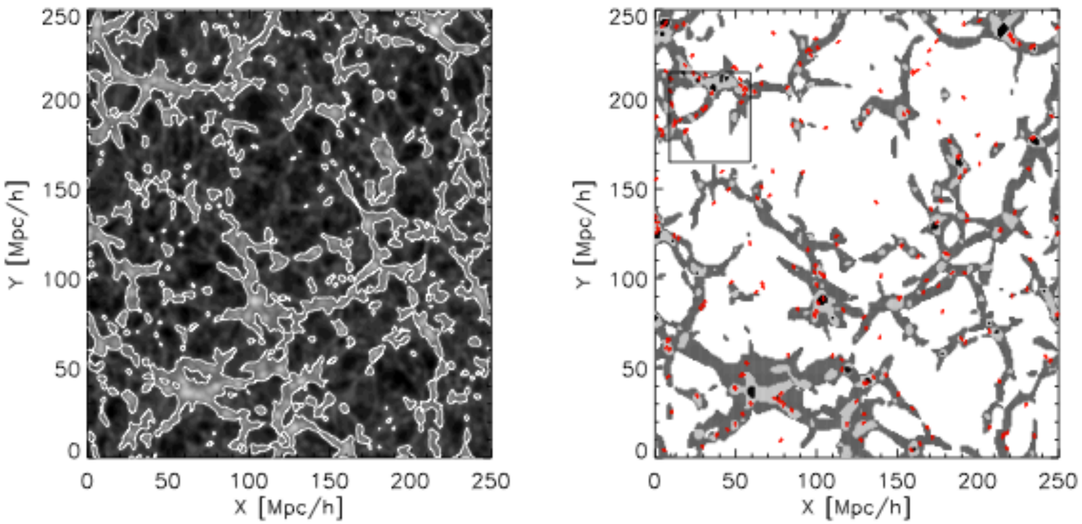
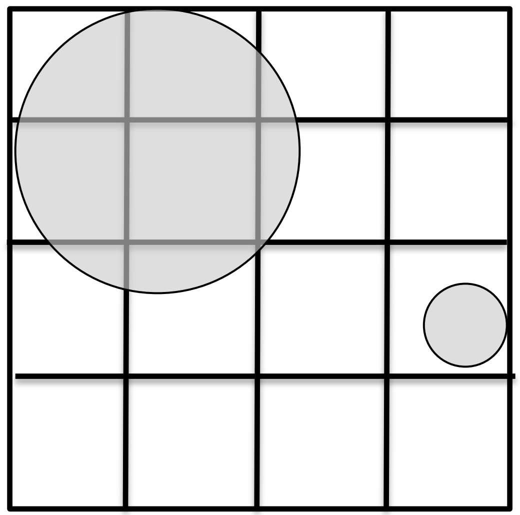



Grid size selection is important:

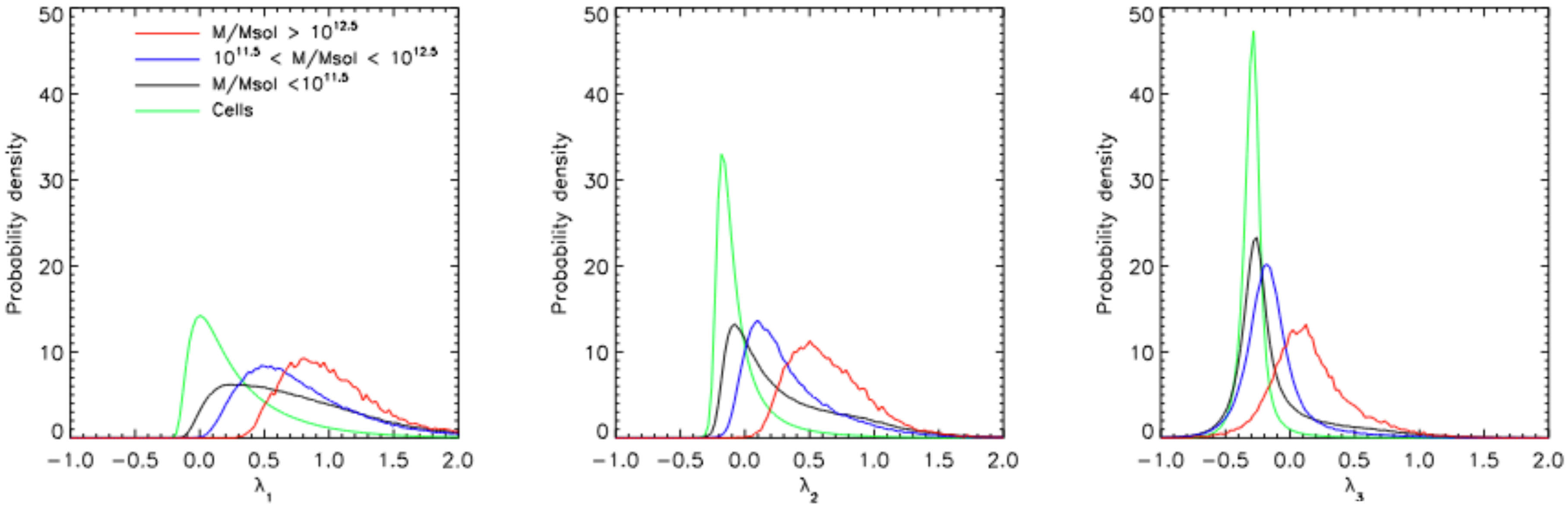
We want to probe the Large Scale (> rvir) alignment not the internal alignment.

BAD!



GOOD!

## The distribution of measured eigenvalues




$$\begin{aligned} \lambda_1 &\in [\lambda_2, \infty) \\ \lambda_2 &\in [\lambda_3, \lambda_1] \\ \lambda_3 &\in (-\infty, \lambda_2] \end{aligned}$$

Mass dependent bias – More massive haloes, the greater the eigenvalues

Just as the distribution of haloes is biased towards high density peaks so to is the value of the cosmic shear.

How can we quantifying the uniformity of the eigenvalues

1. *Triaxiality:*

$(\lambda_1^2-\lambda_3^2)/(\lambda_1^2-\lambda_2^2)$ **FAILS** since the ordering of $\lambda$'s is by value not magnitude

2. *Eigenvalue ratio*

$\lambda_1/\lambda_3$ **FAILS** for the same reason – also sign makes it a problem

3. Bardeen et al 1986, *eccentricty*

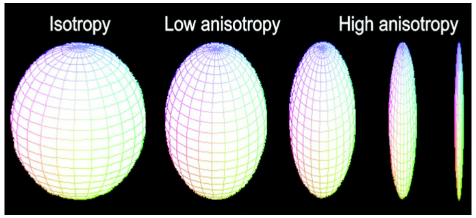
$e = (\lambda_1-\lambda_3)/ 2 \mid \lambda_1+\lambda_2+\lambda_3 \mid$

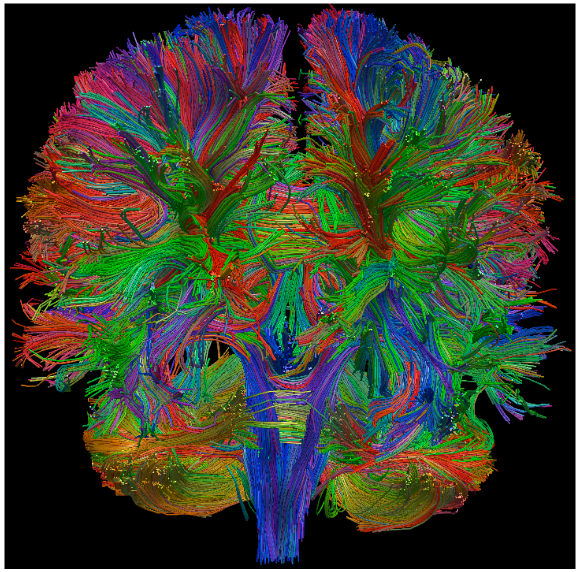
**FAILS** when e.g. $\lambda_1 \sim -\lambda_3$ and $\lambda_2 \sim 0$, $e \rightarrow$ infty. Also, unbound

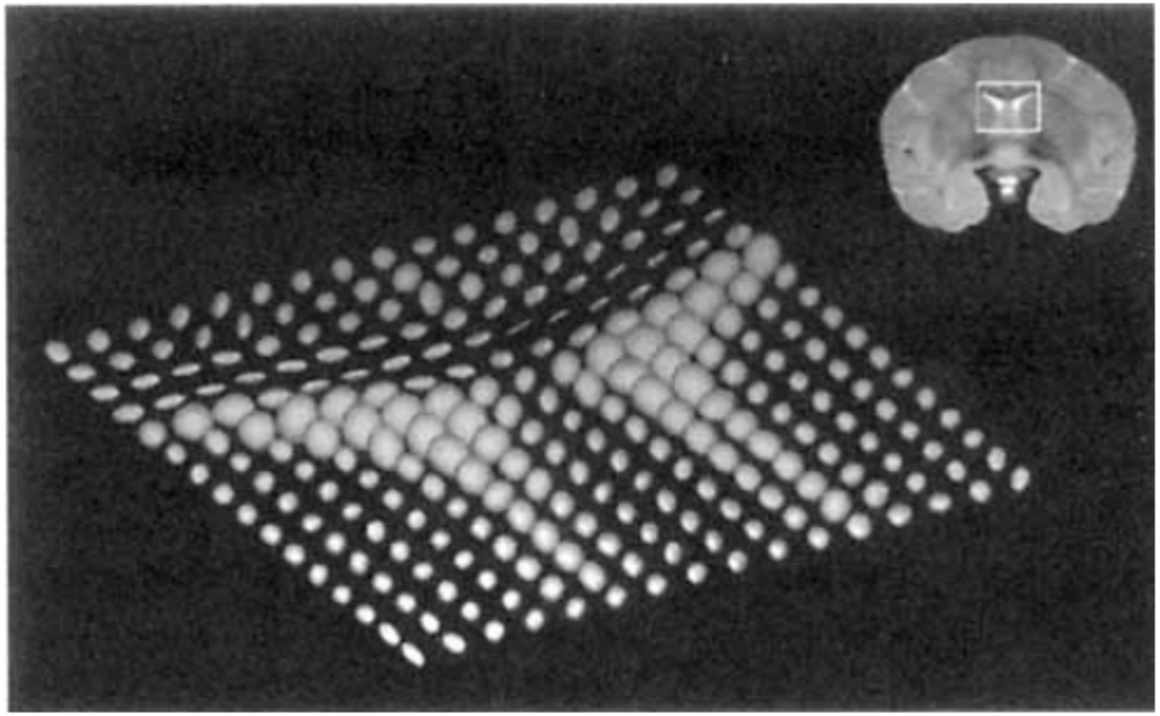
All these measures are **WEB TYPE DEPENDENT**

Quantifying the uniformity of the shear with the Fractional Anisotropy *FA:*

$$\mathrm{FA} = \frac{1}{\sqrt{3}}\sqrt{\frac{(\lambda_1-\lambda_3)^2+(\lambda_2-\lambda_3)^2+(\lambda_1-\lambda_2)^2}{\lambda_1^2+\lambda_2^2+\lambda_3^2}}$$





P. J. Basser *Inferring microstructural features and the physiological state of tissues from diffusion-weighted images*. NMR in Biomedical Imaging, 8, 333 (1995)

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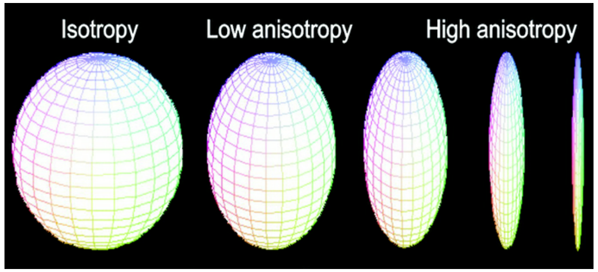


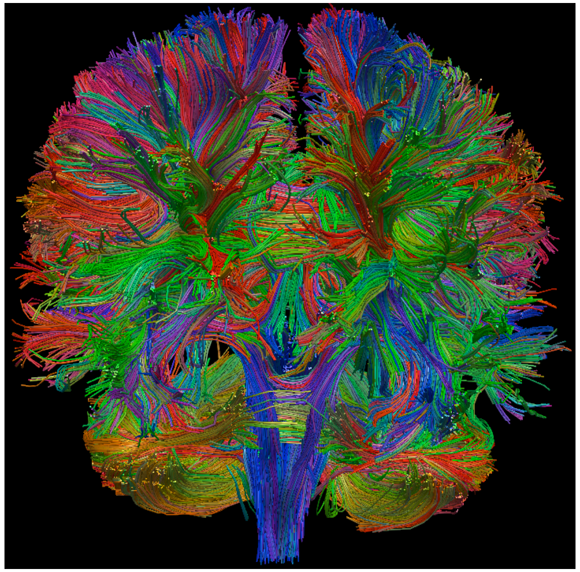

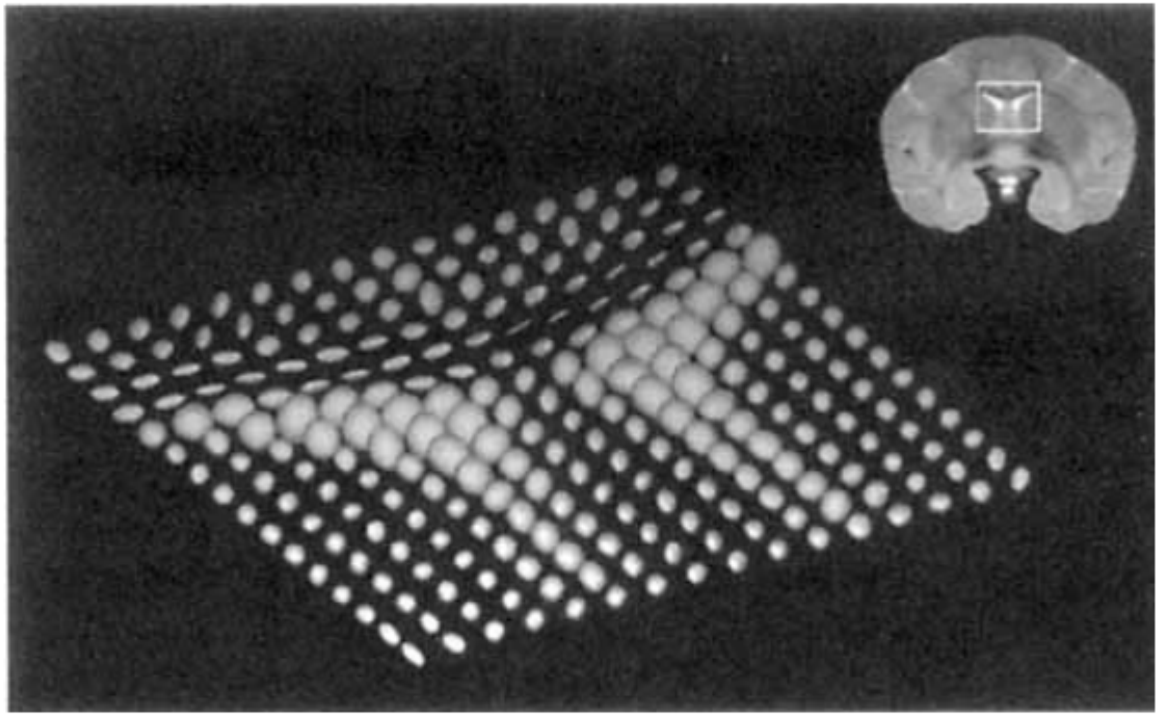

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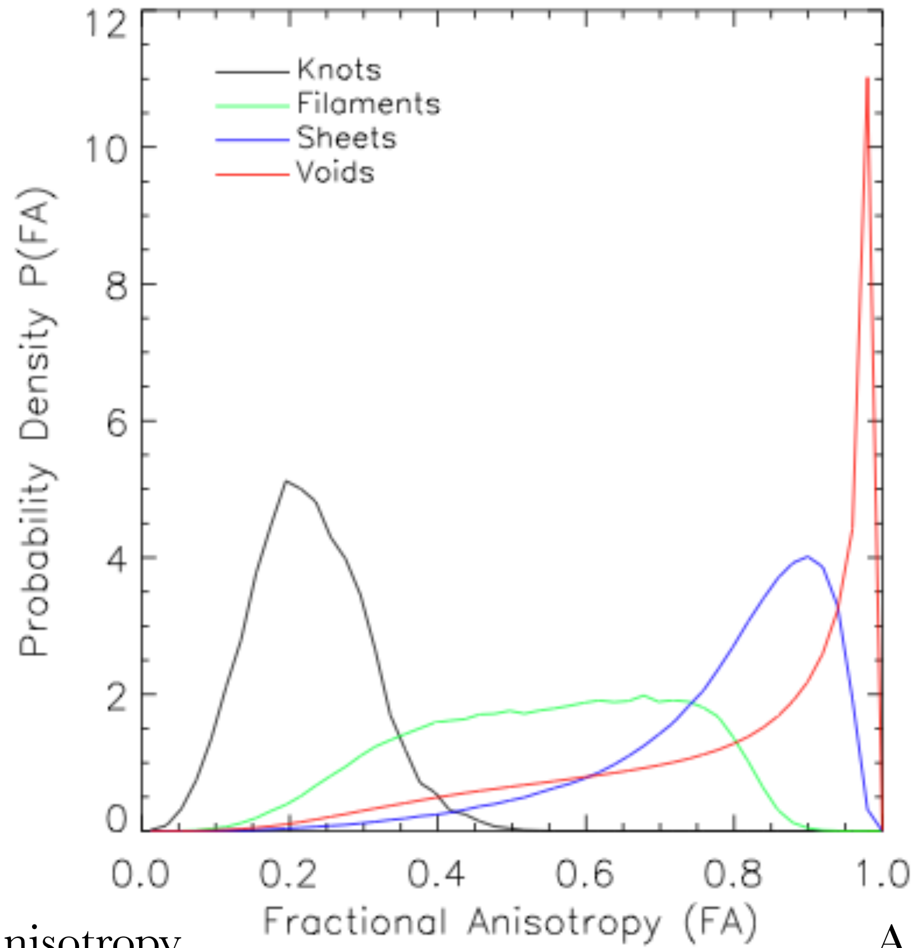


No anisotropy

A lot of anisotropy

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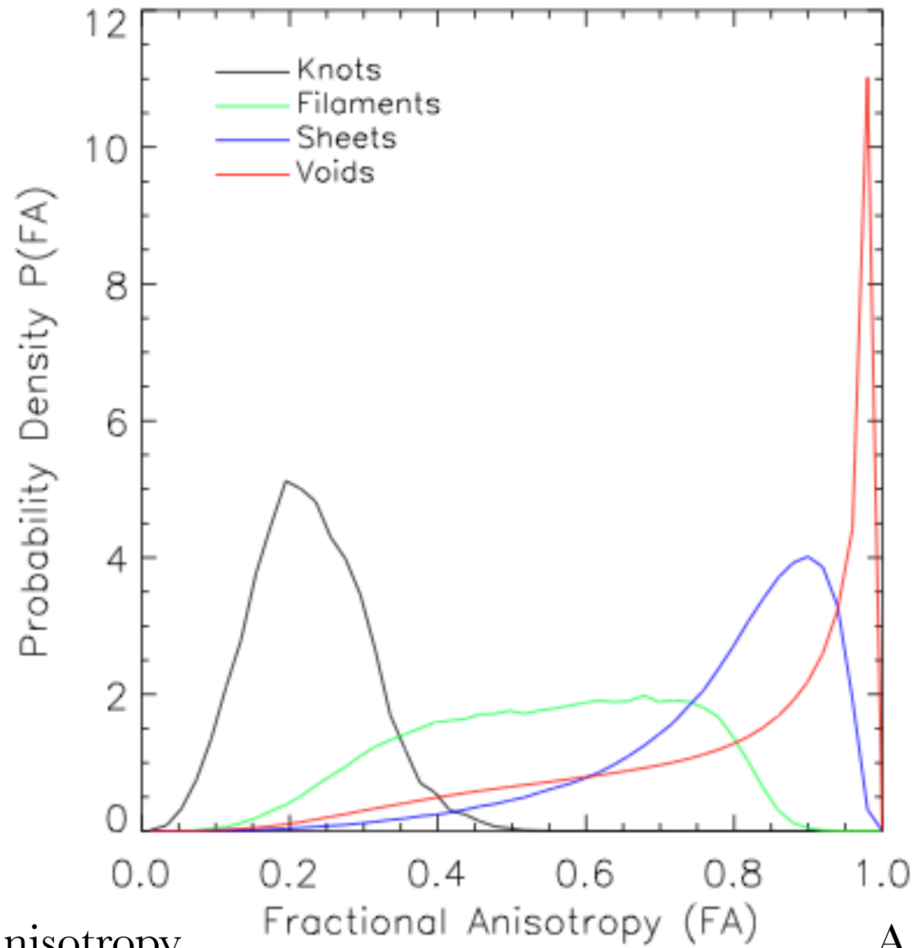


No anisotropy

A lot of anisotropy

1. Knots are the most isotropic
2. Voids are highly anisotropic
3. Sheets and filaments span many anisotropy types

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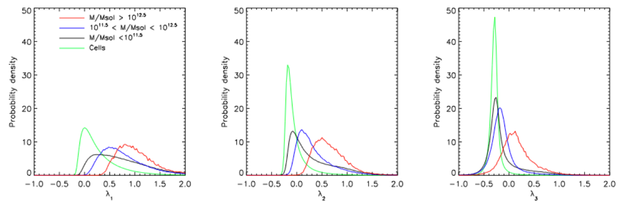
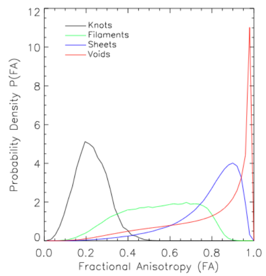
(1) Calculate Shear eigenvalues

$$\Sigma_{\alpha\beta} = -\frac{1}{2}\left(\frac{\partial v_\alpha}{\partial r_\beta} + \frac{\partial v_\beta}{\partial r_\alpha}\right)/H_0,$$

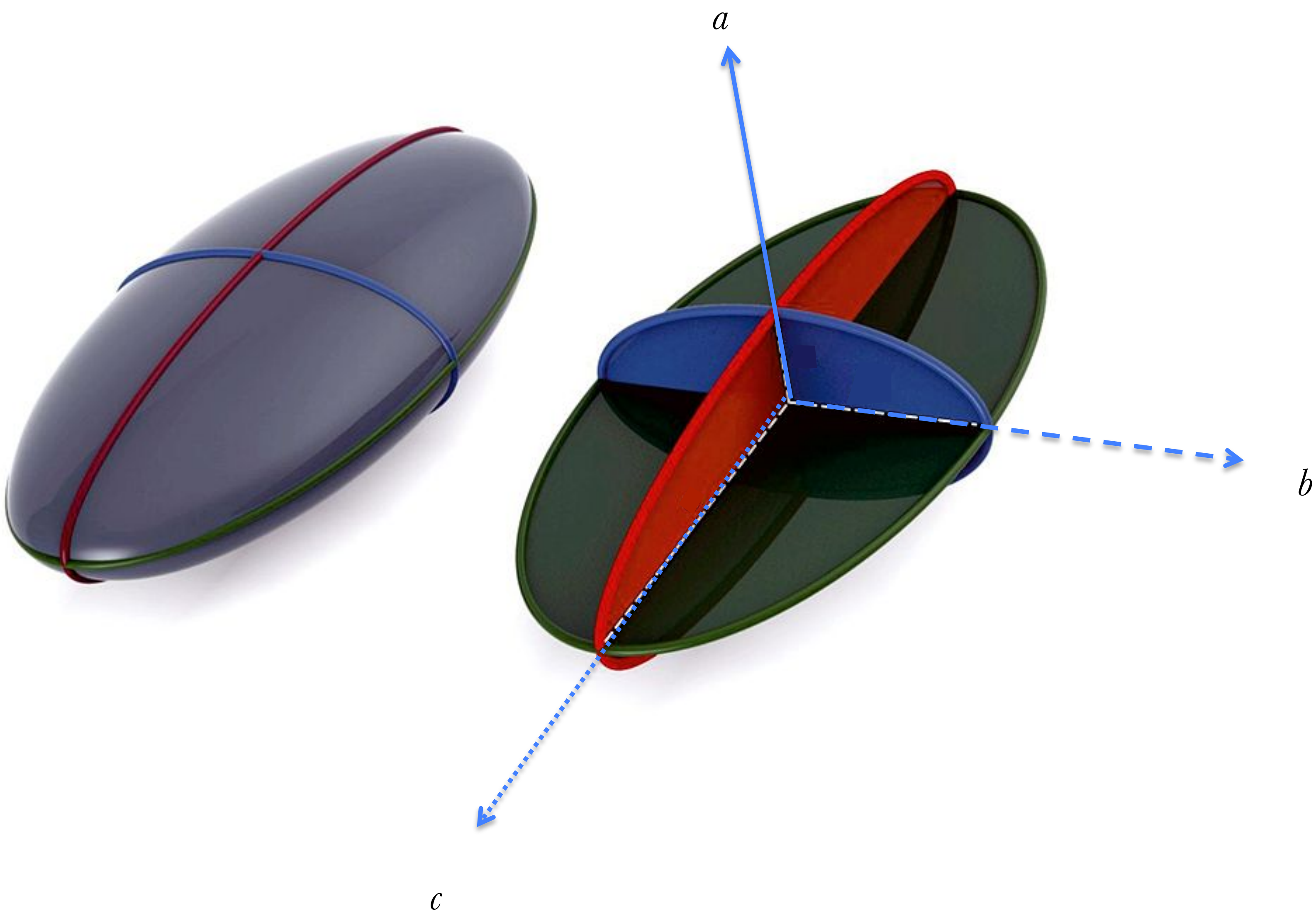
(2) Looked at their distribution and quantified their isotropy




(3) How are haloes aligned with the web (eigenvalues) and how does this depend on isotropy?

Alignment of halo shape – halo is defined by the inertia tensor *a, b, c*

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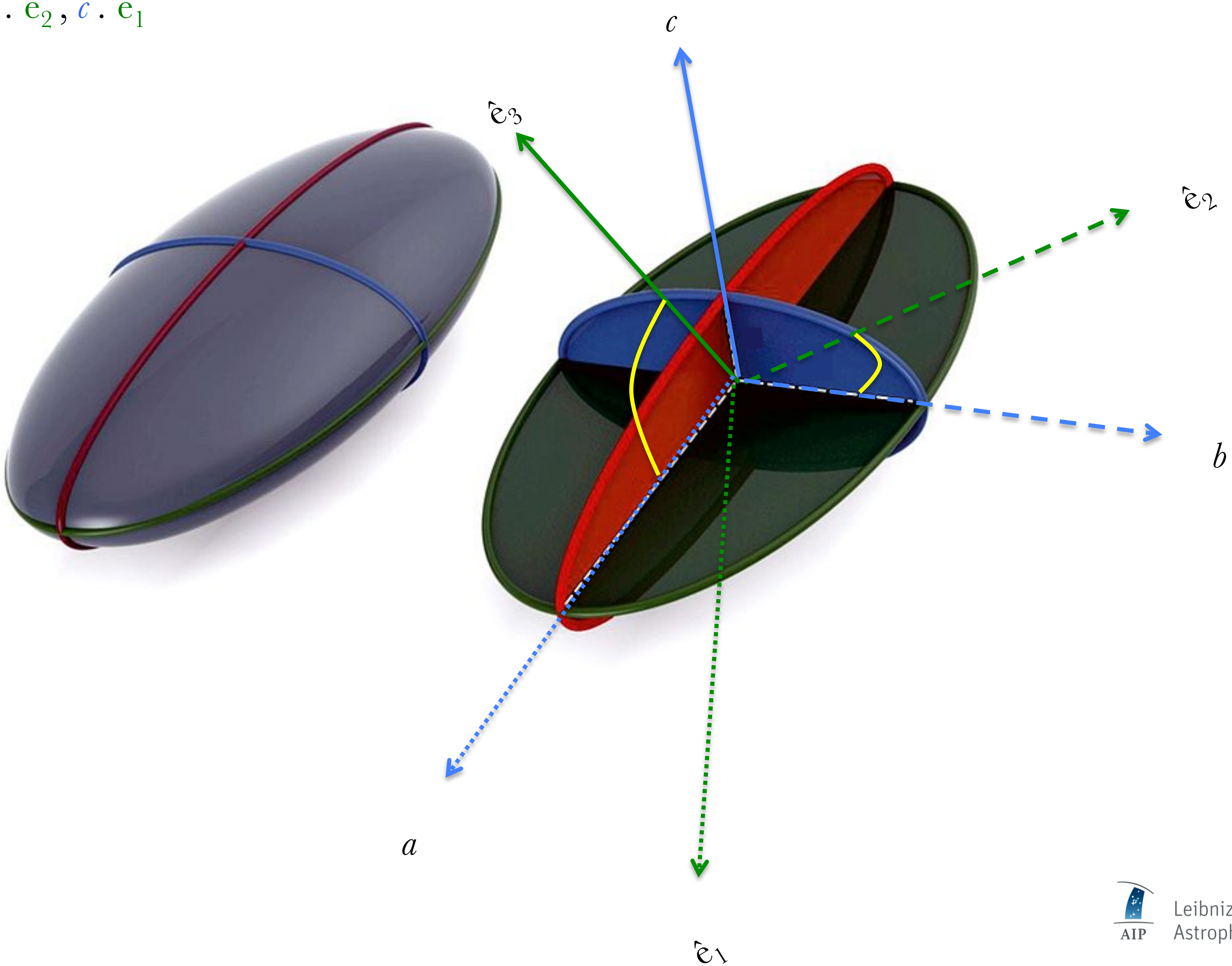
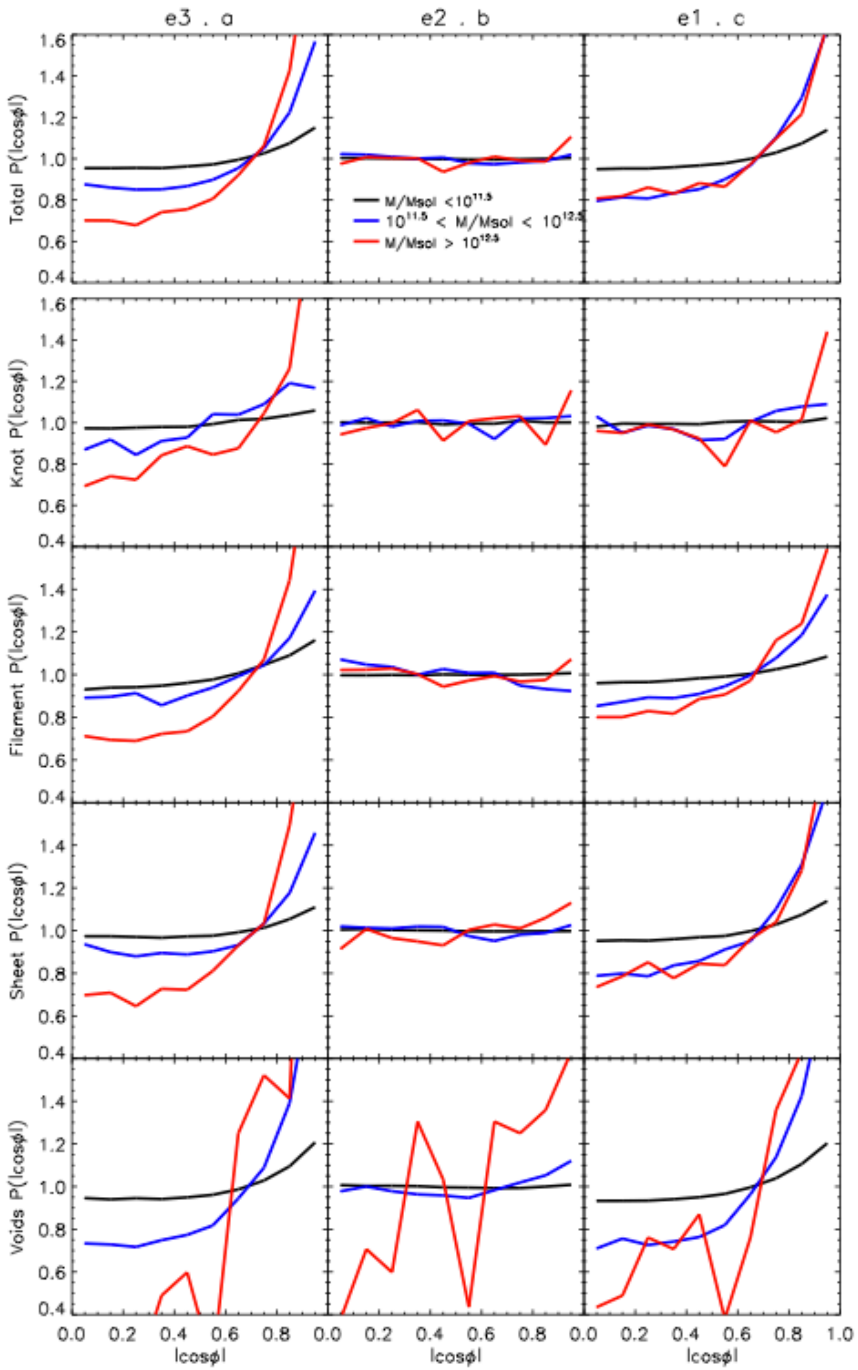
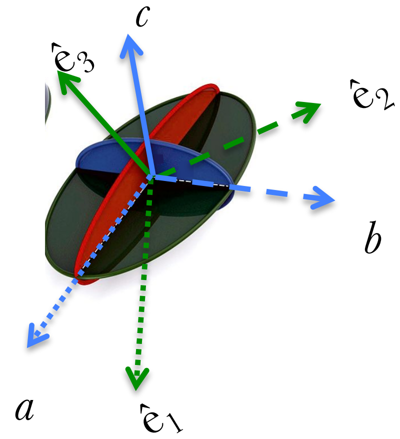
Alignment of halo shape – halo is defined by the inertia tensor *a, b, c*

Use the principle axes of the web $\hat{e}_1, \hat{e}_2, \hat{e}_3$ and construct angular distribution of

$a \cdot \hat{e}_3, b \cdot \hat{e}_2, c \cdot \hat{e}_1$






Web INDEPENDENT

Strength is mass DEPENDENT

Statistically significant alignment of *a* with $\hat{e}_3$ at all masses

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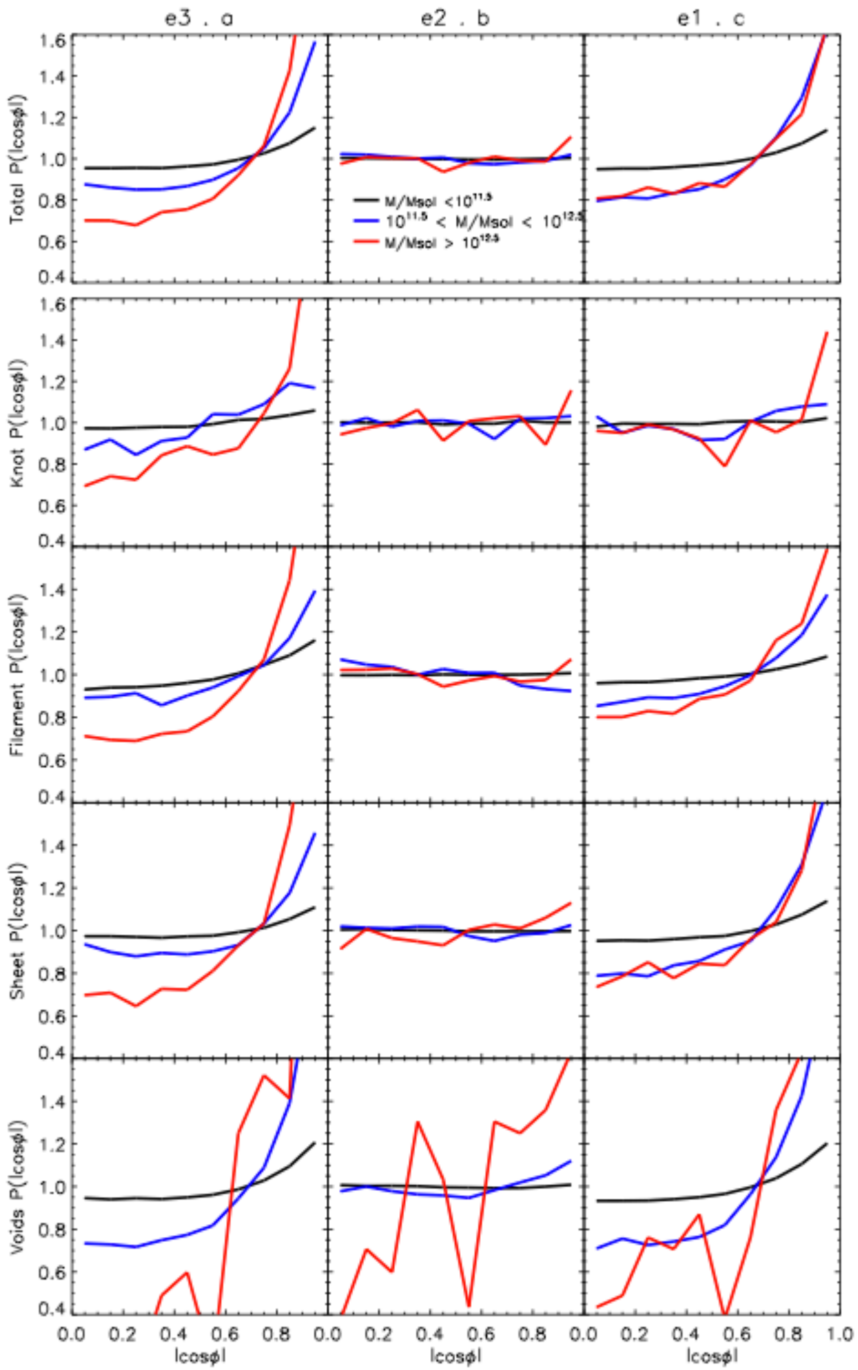
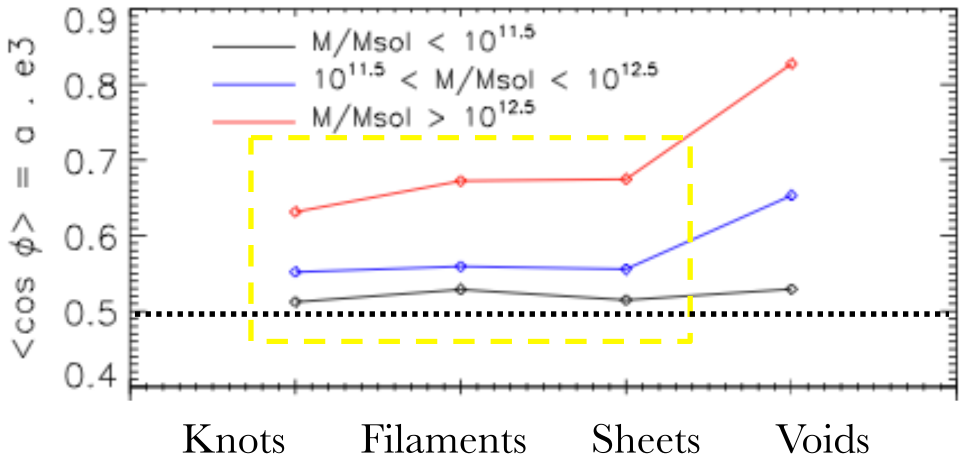
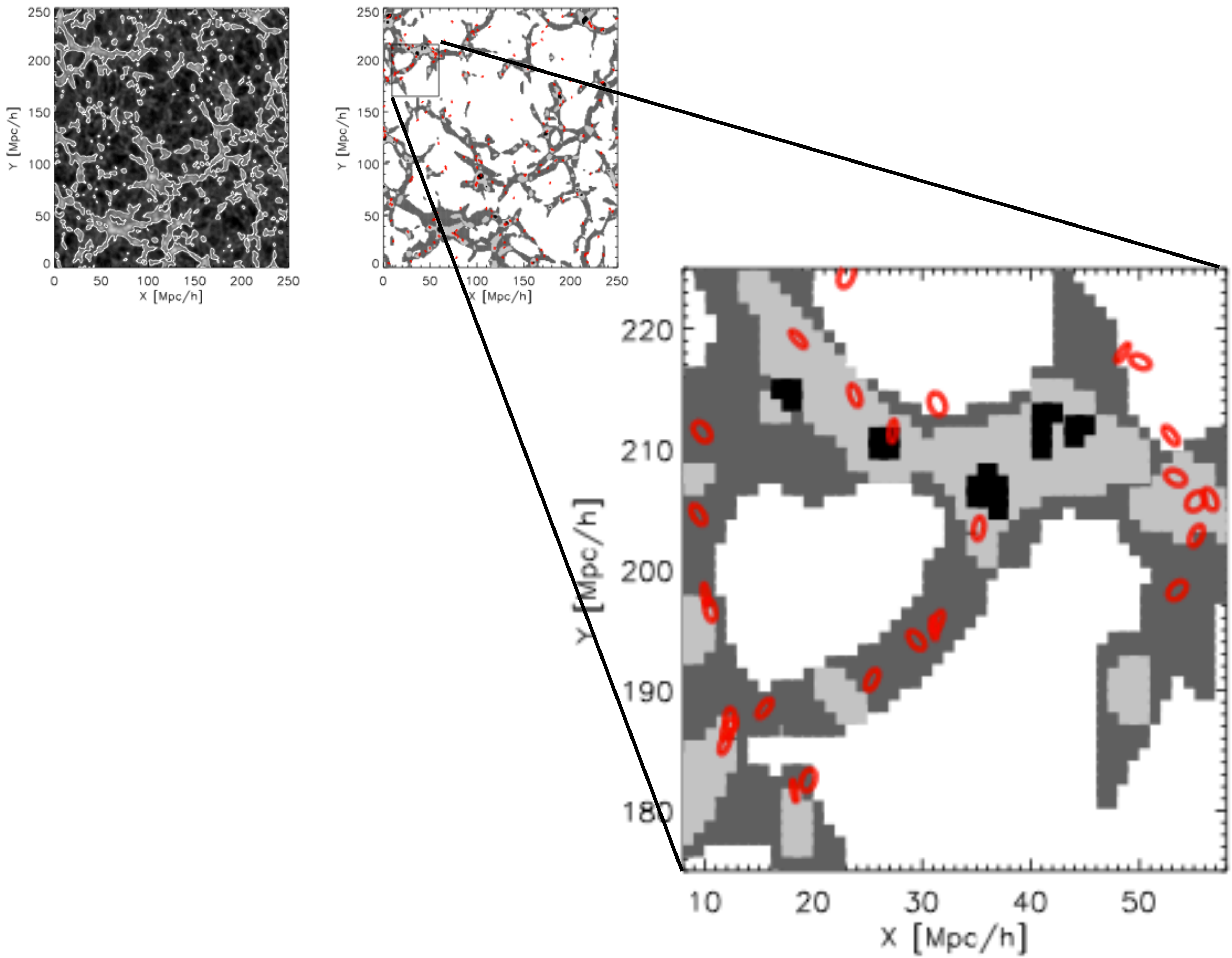


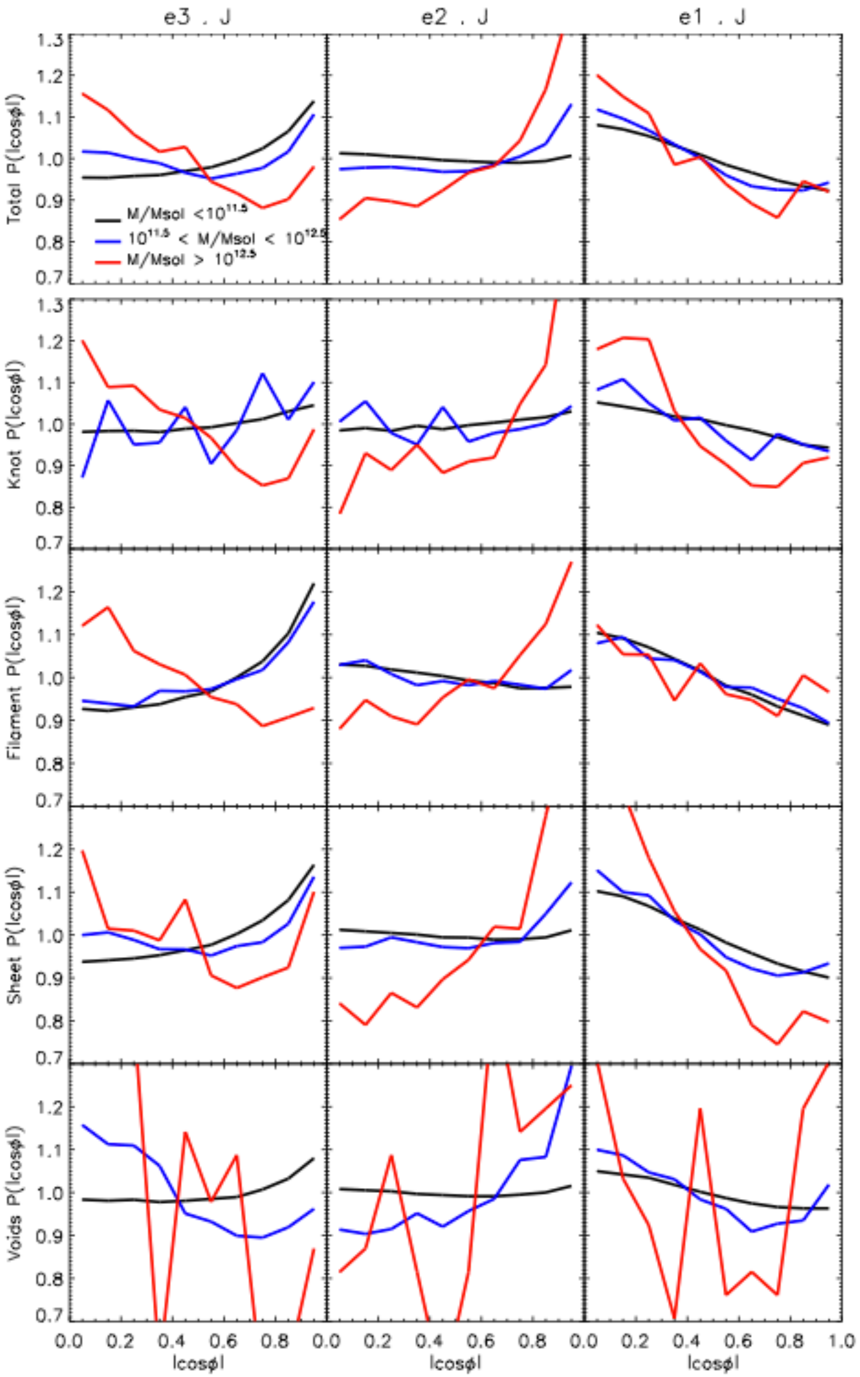

Web INDEPENDENT (a bit stronger in voids: could be statistical )

Strength is mass DEPENDENT

Statistically significant alignment of *a* with $\hat{e}_3$ at all masses



Y [Mpc/h]
X [Mpc/h]
Y [Mpc/h]
X [Mpc/h]
Y [Mpc/h]
X [Mpc/h]




spin alignment

Look at the angle formed between a halo's spin and the principle axes of the cosmic web

- Alignment with $e_2$ is confirmed

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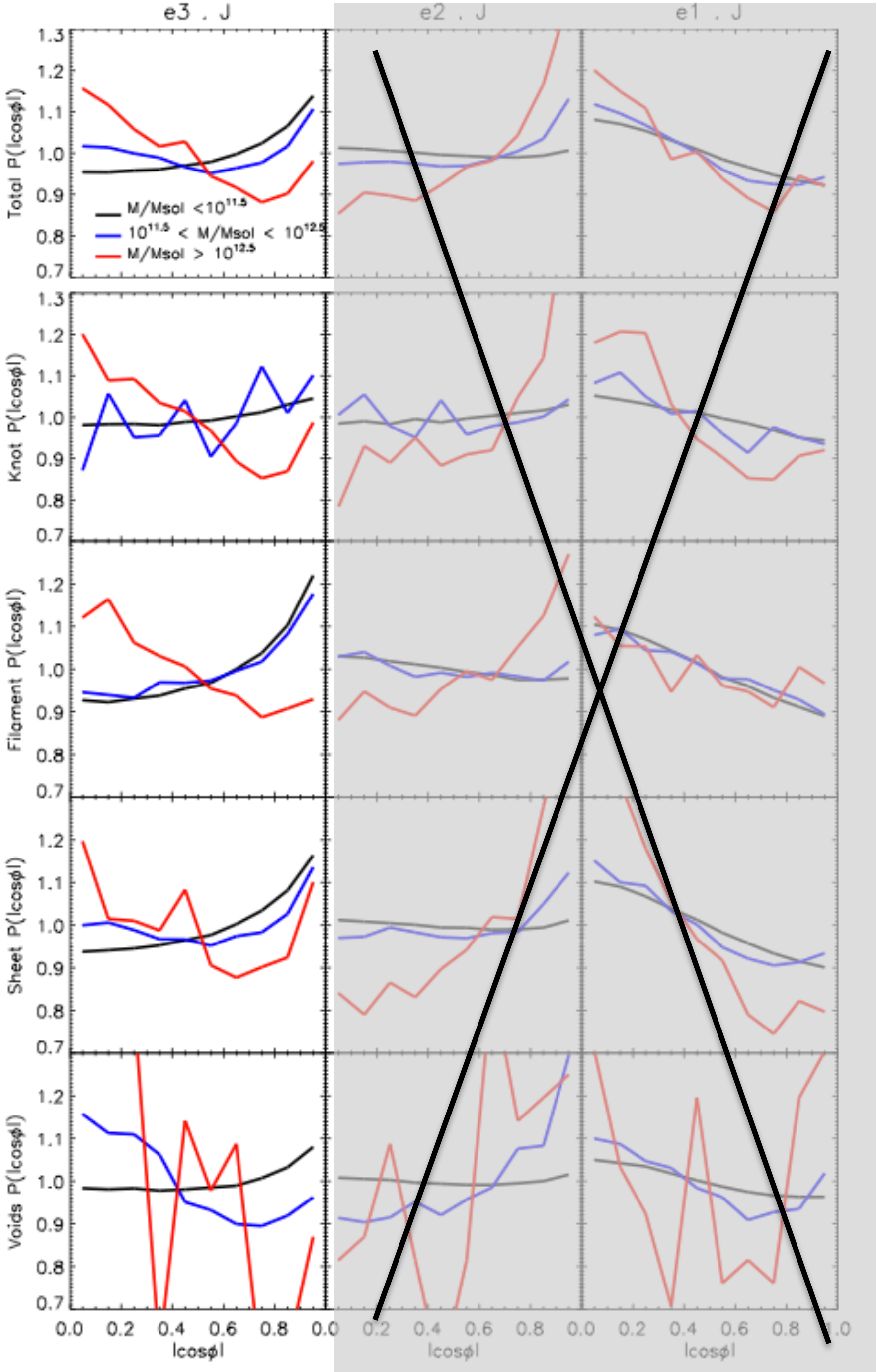


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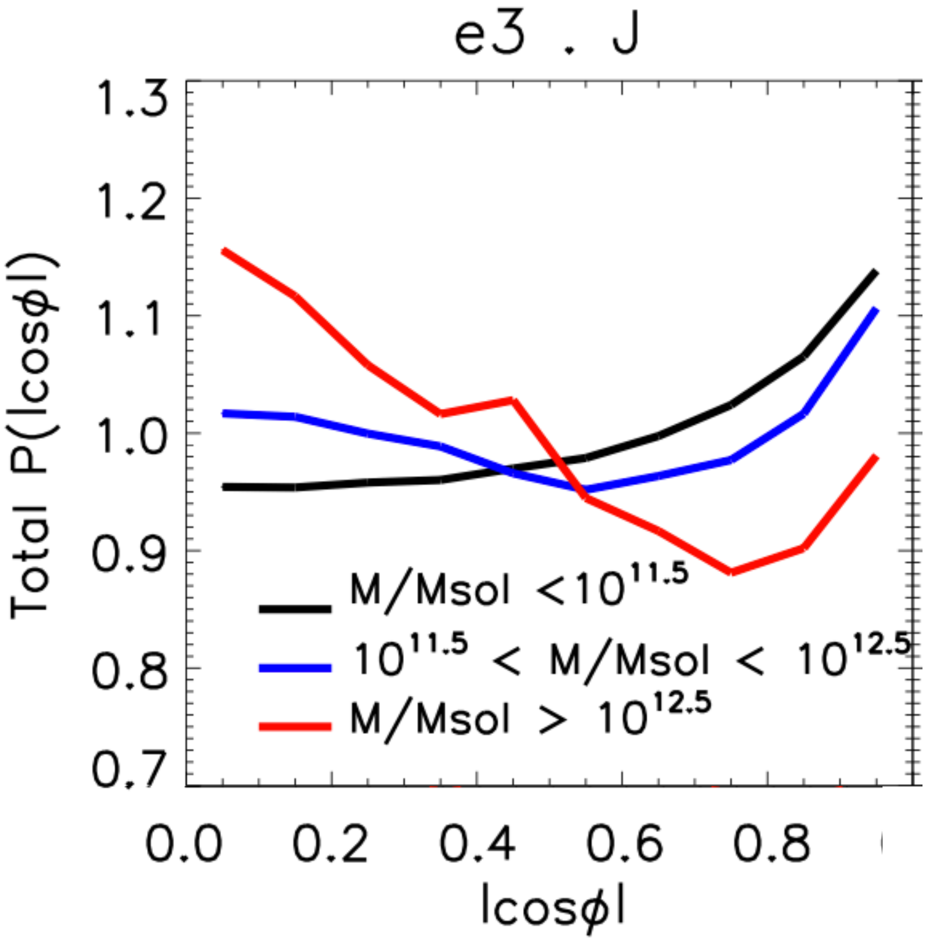
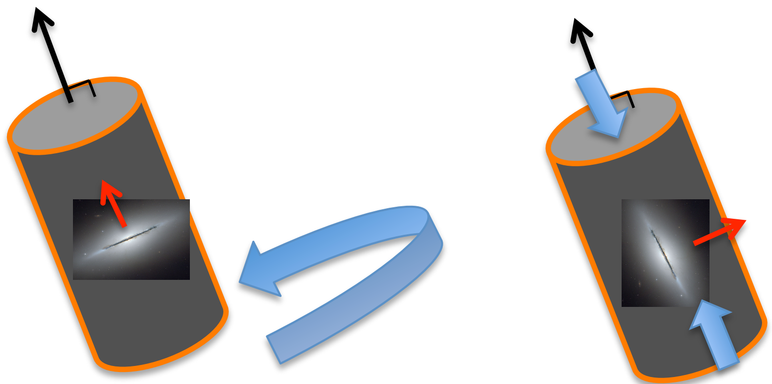



Low mass haloes aligned with $\hat{e}_3$

High mass haloes aligned perpendicular to $\hat{e}_3$

Spin flip occurs at 1e12 (Codis et al, Aragon-Calvo et al) as a halo's merger history goes from being accretion dominated to merger dominated



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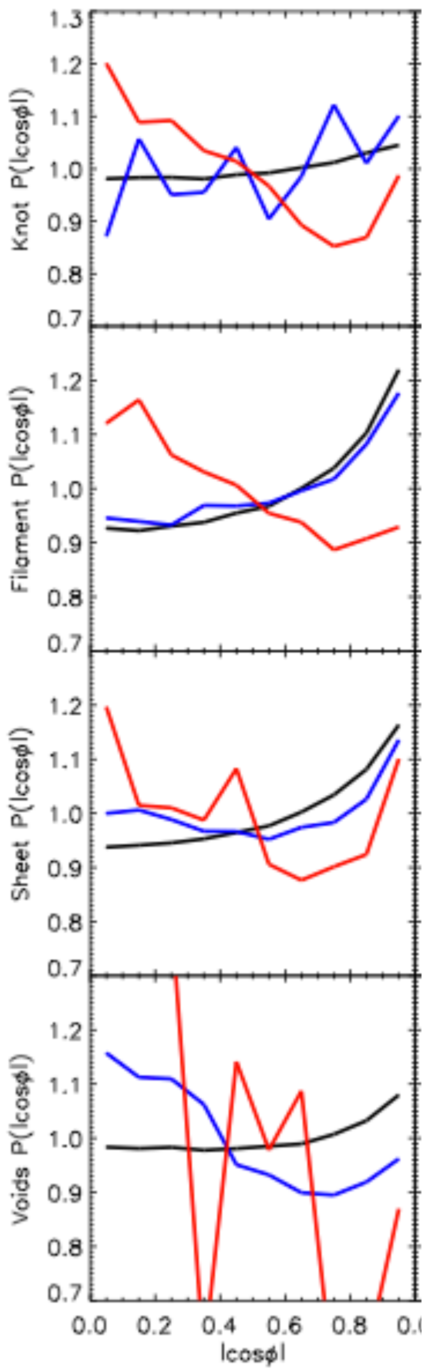
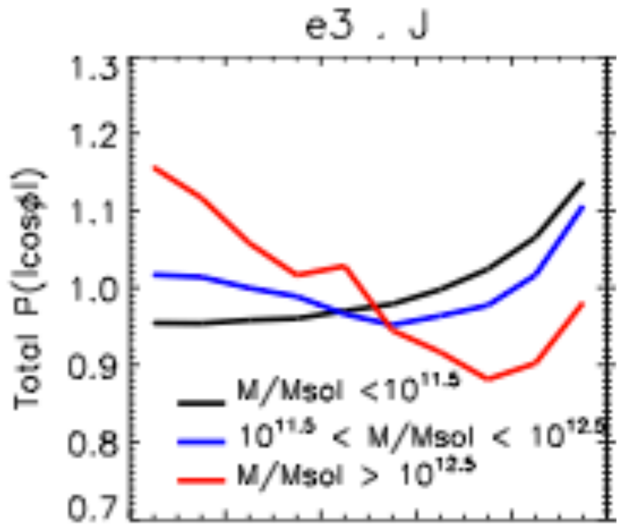
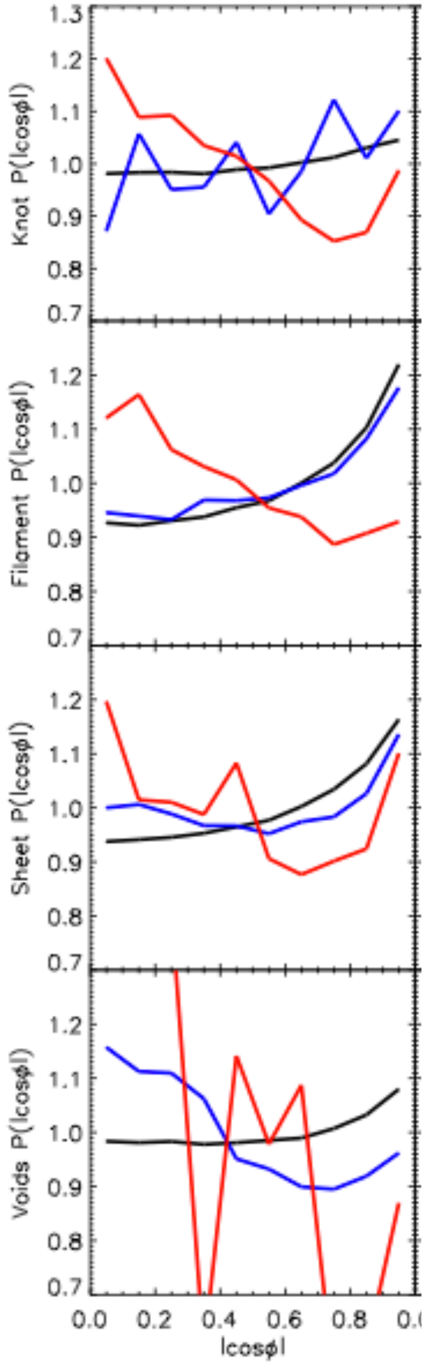



Spin alignment is web independent, but the mass transition is web dependent.



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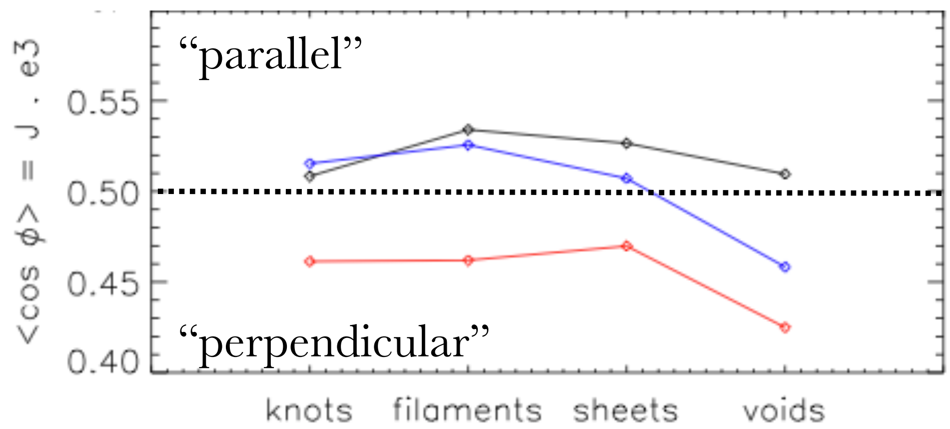
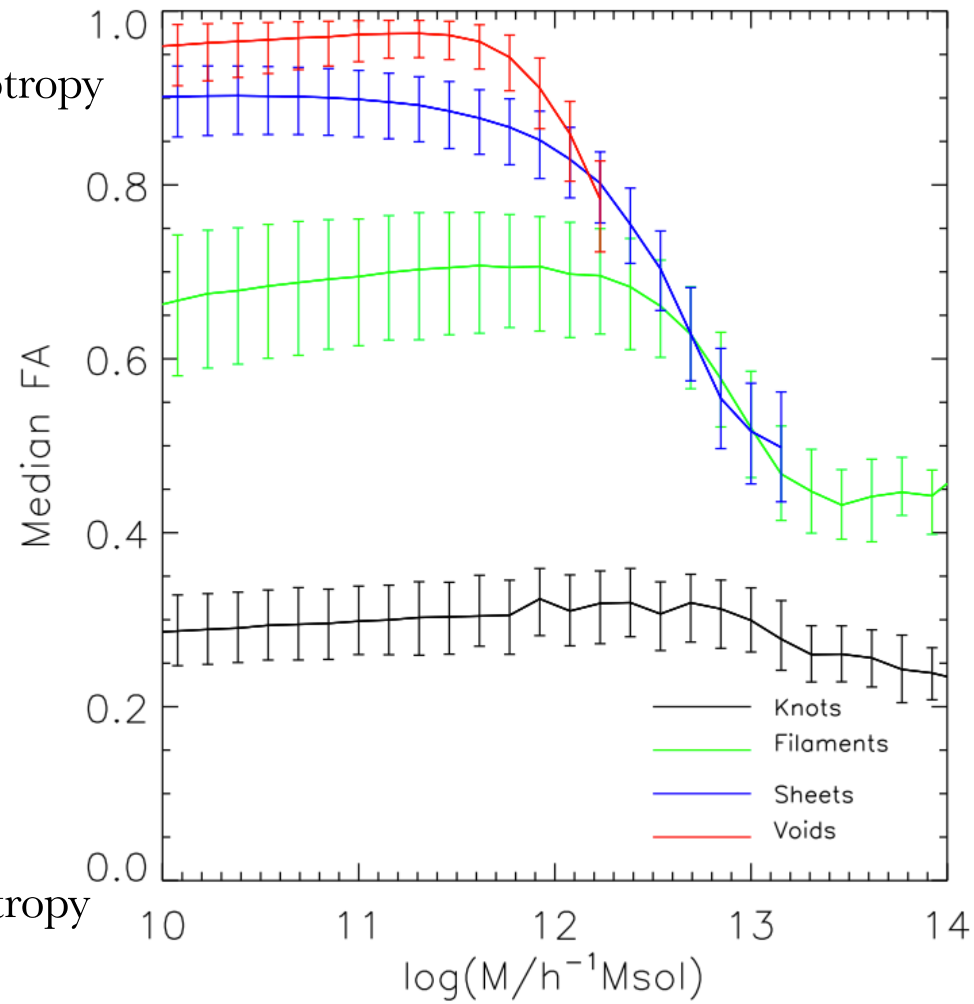


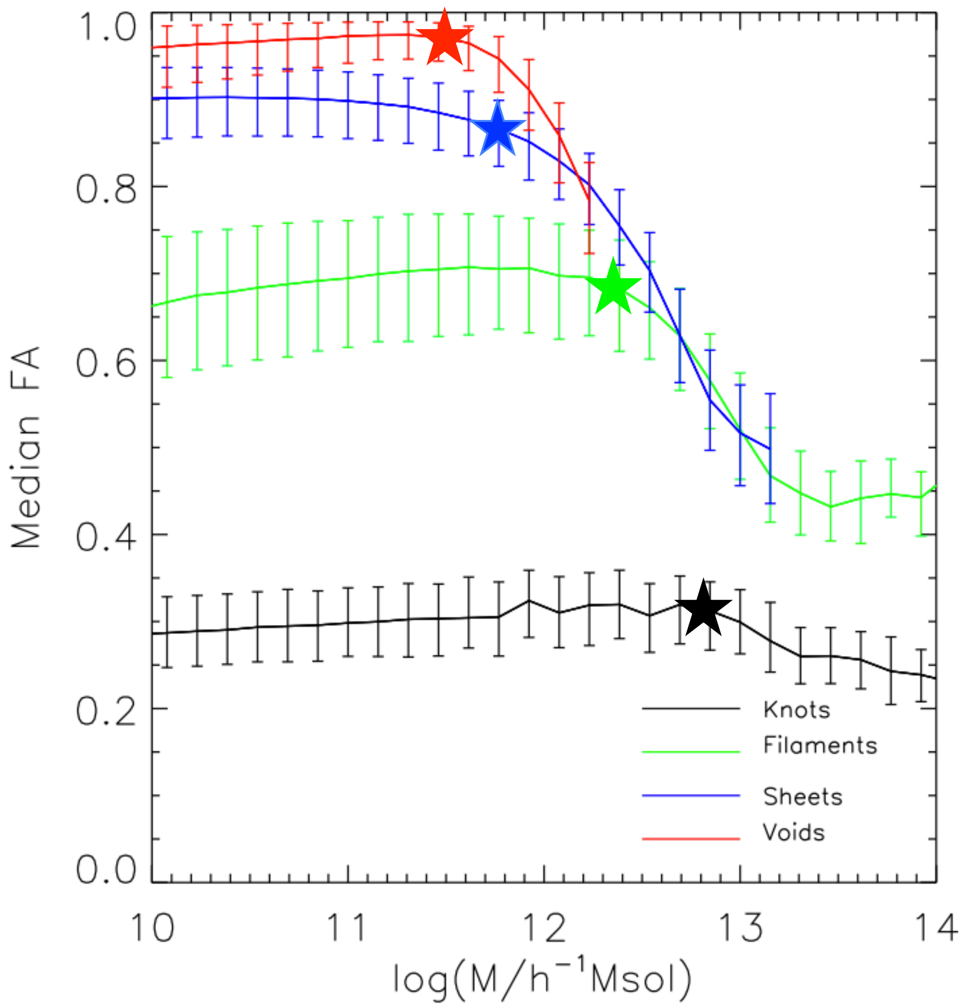

Does the uniformity of the shear play a role?

High anisotropy




Low anisotropy

Mass of halo is correlated with the *FA*




Mass is constant with respect to *FA* until a critical mass after which mass becomes correlated with *FA*.

Knots ~ $10^{12.8}$ $M_{sol}$
Filaments ~ $10^{12.4}$ $M_{sol}$
Sheets ~ $10^{11.8}$ $M_{sol}$
Voids ~ $10^{11.4}$ $M_{sol}$

"Low" mass haloes exist in regions of any *FA*, while high mass haloes tend to prefer low *FA*

Mass of halo is correlated with the *FA*

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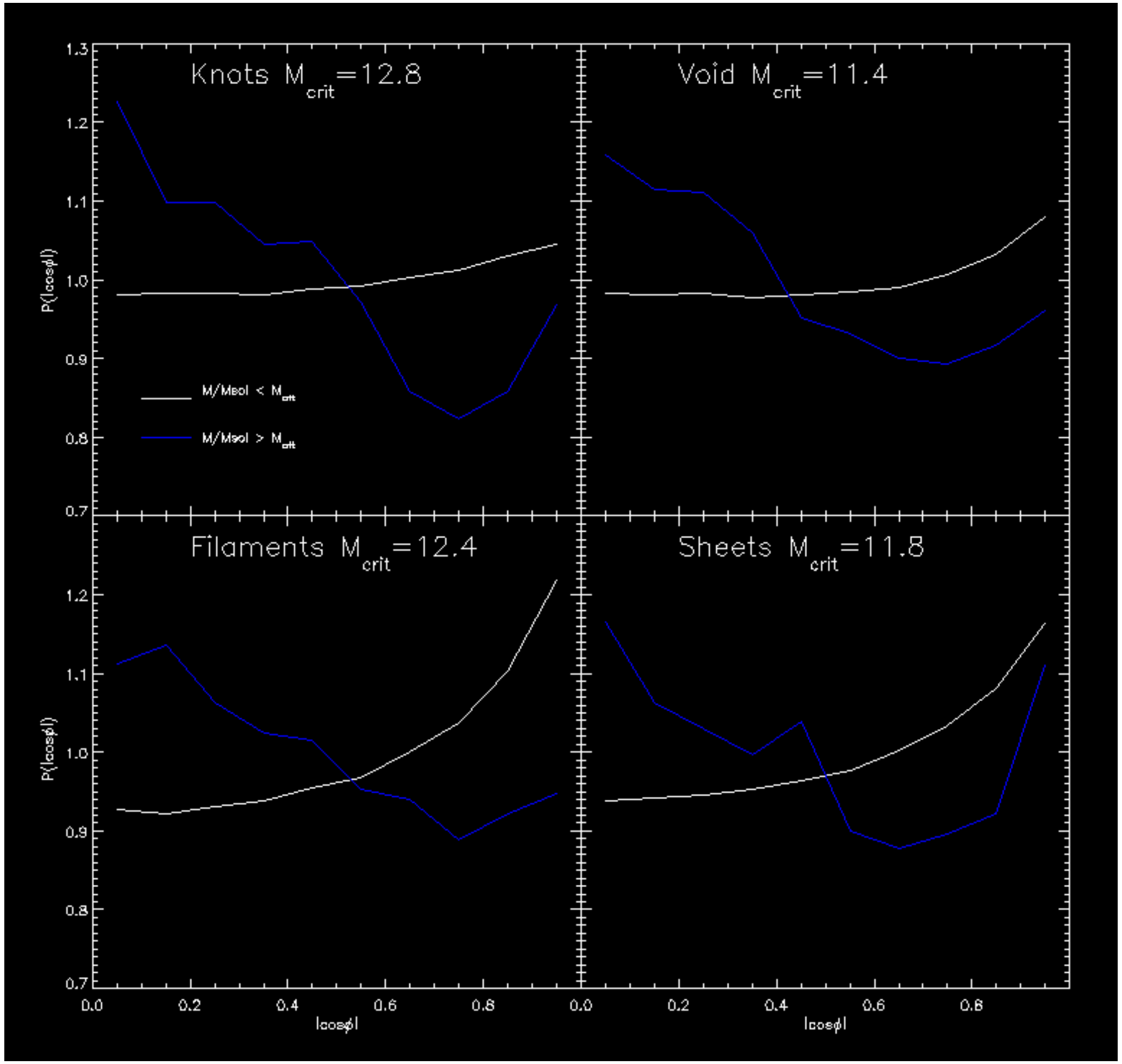


Alignment of J with $e_3$ following these cuts gives the proper mass of the transition

Knots ~ $10^{12.8}$ $M_{sol}$
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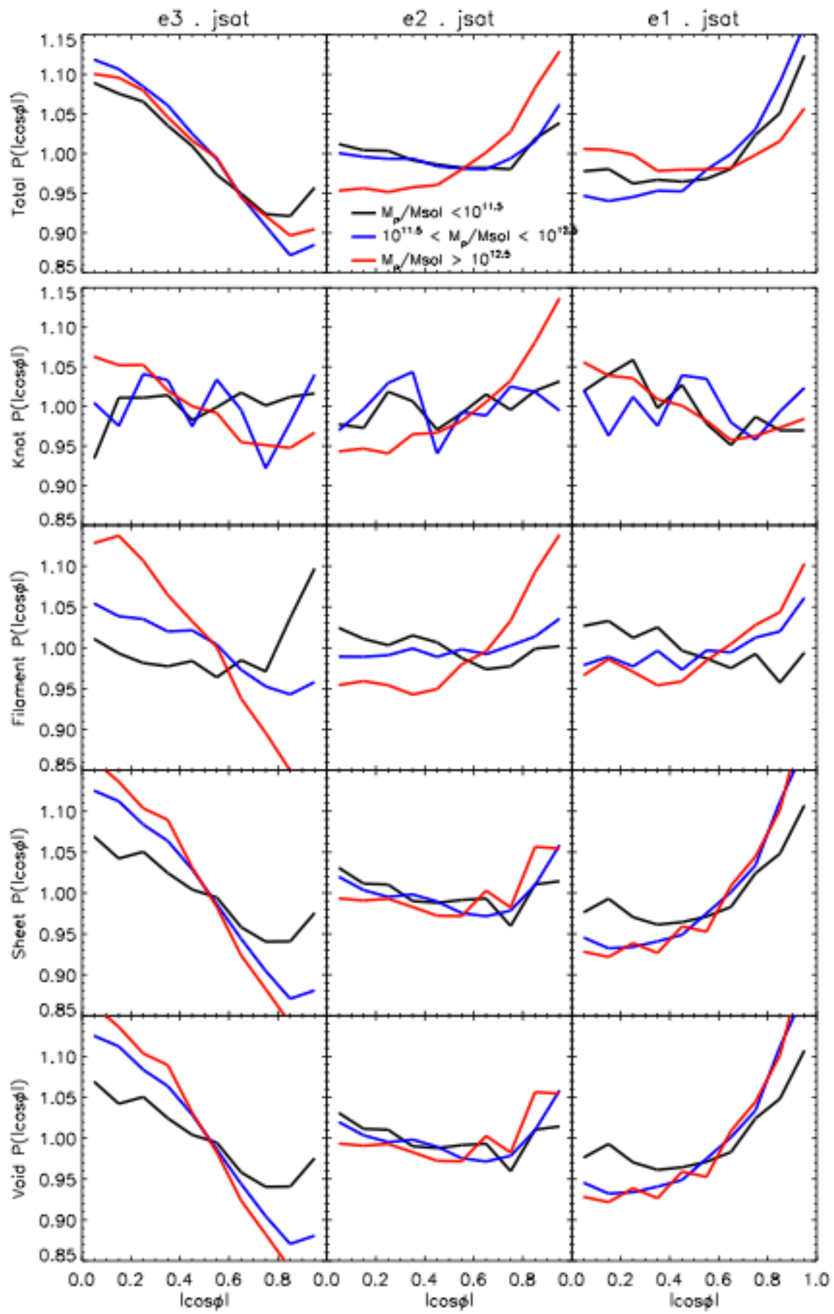
Sheets ~ $10^{11.8}$ $M_{sol}$
Voids ~ $10^{11.4}$ $M_{sol}$




Alignment of subhalo orbital J with shear divided by parent halo mass

Random except for the largest parent haloes

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# Conclusions

1. Strong alignment found between a halo's shape and the cosmic web
2. An alignment is also found between the Spin and the cosmic web – the sense of which is mass dependent – high mass haloes spin perpendicular to $e_3$.
3. The mass transition at which haloes go from spinning parallel to perpendicular is web dependent
4. The cosmic shear eigenvalue relationship can be characterized with the fractional anisotropy
5. There exist a mass above which halo mass correlates with *FA*
6. That mass is roughly the same at which halo spin flips
7. Subhalo orbits also reflect the large scale structure

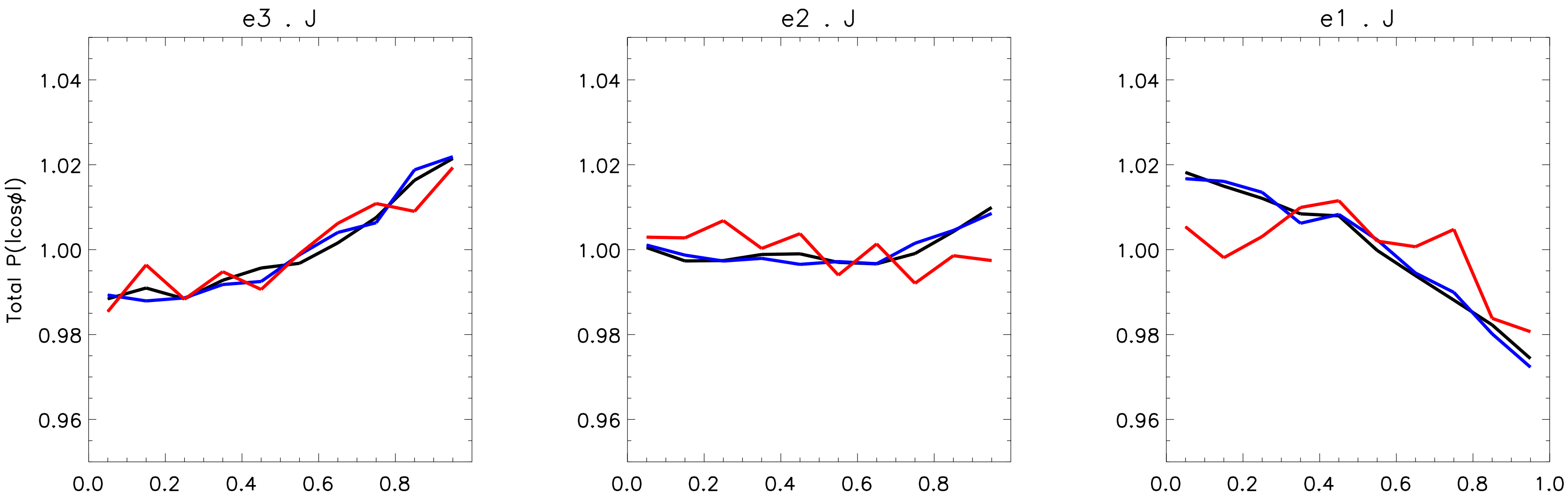
We can test for the effects of grid resolution by refining it to span $1000^3$ cells = 250 kpc

Upper Mass limit is thus $\sim 10^{11.5}$Msol

$M < 10^{10}$

$10^{10} < M < 10^{11}$

$M > 10^{11}$




All spins are parallel to $e_3$

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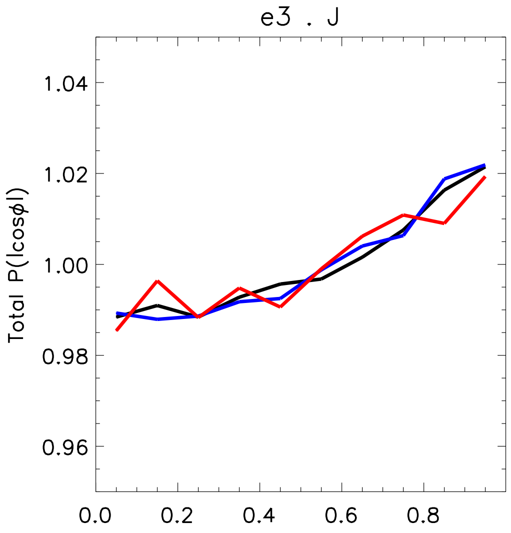


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## Conclusions

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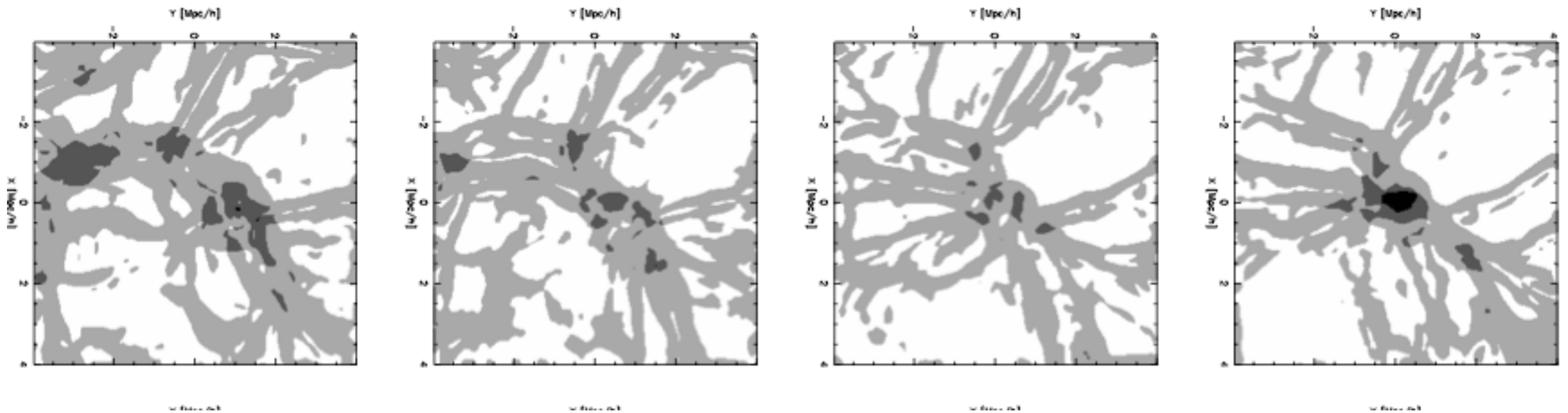
THANK YOU!


Y [Mpc/h]
X [Mpc/h]
Y [Mpc/h]
X [Mpc/h]
Y [Mpc/h]
X [Mpc/h]
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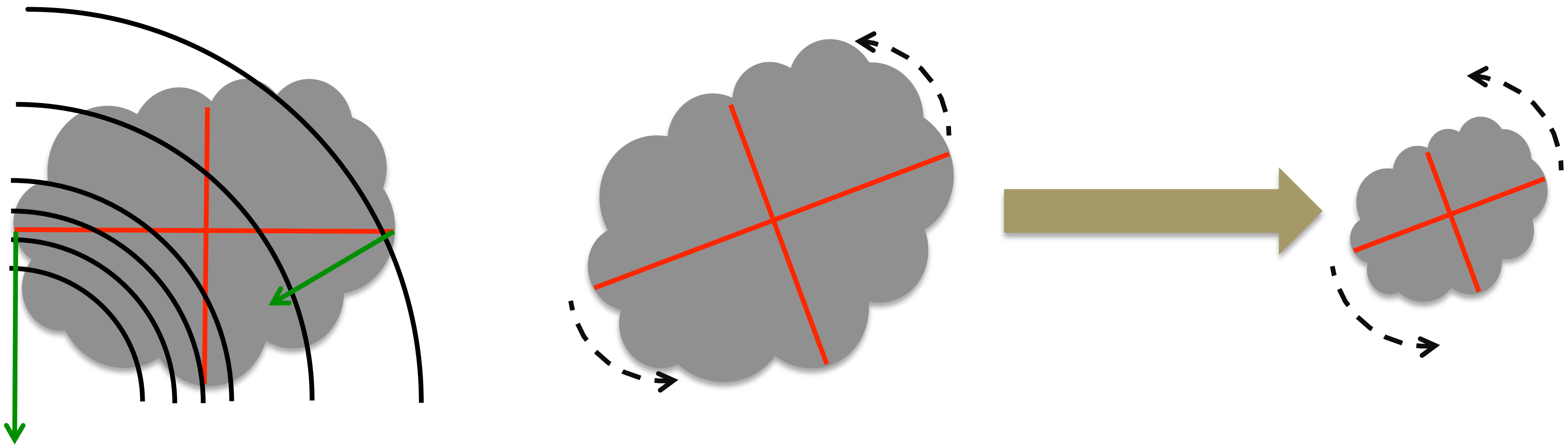
After the tidal torques have been applied, what happens to the spins of haloes?

What about their substructure orbital spin?

What do numerical simulations indicate?



Gravitational field $\Phi(r)$
with gradient $\nabla\Phi$
causes a tidal shear $\Sigma_{\alpha\beta}$

As the proto-halo collapses it decouples from the Shear flow; at some point the "lever arms" of the inertia tensor are too small for any more torques to be imparted.
Tidal torques stop.

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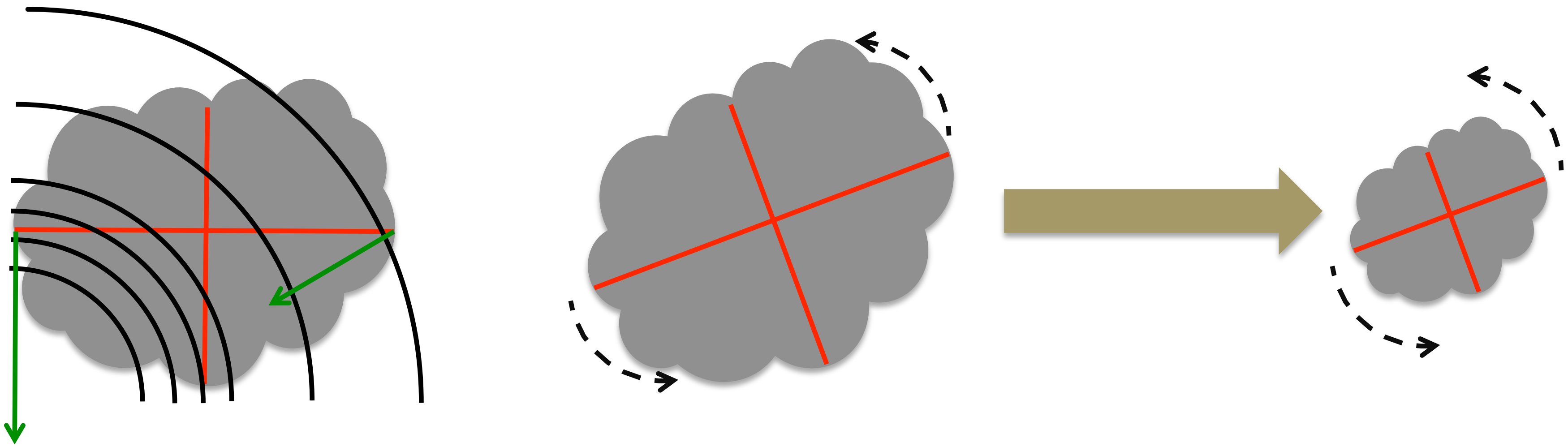
How do galaxies/haloes get their spin?

Mis-alignment between the inertia tensor and gravitational tidal tensor imparts torques

**Tidal Torque Theory** (Hoyle 1949; Peebles 1969; Doroshkevich 1970; White 1984, Catelan & Theuns 1996; Crittenden et al. 2001; **Schäfer 2009**)



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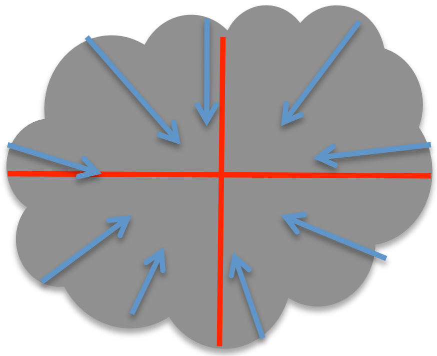

Collapsing proto-halo at high redshift
with Inertia Tensor of 2nd moments $I_{\alpha\beta}$

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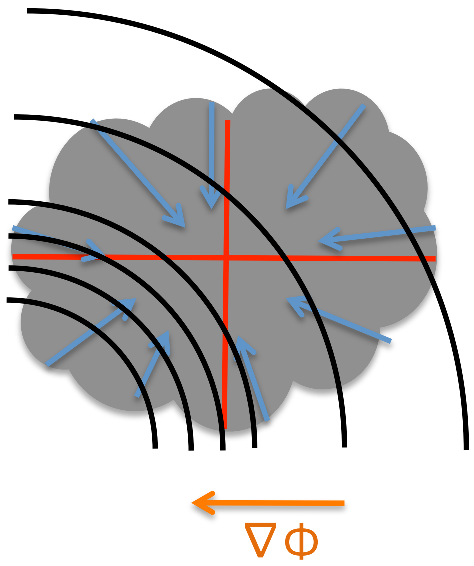


Gravitational field $\Phi$(r) with gradient $\nabla\Phi$

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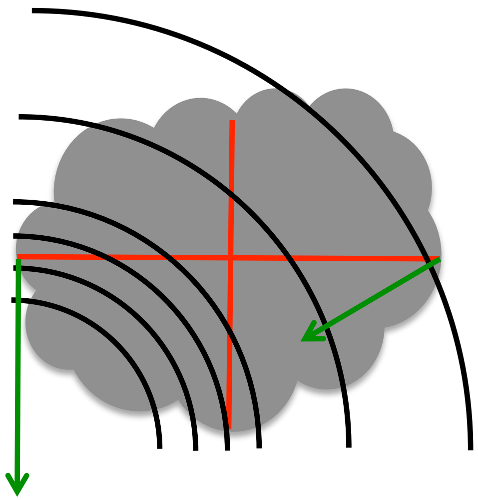

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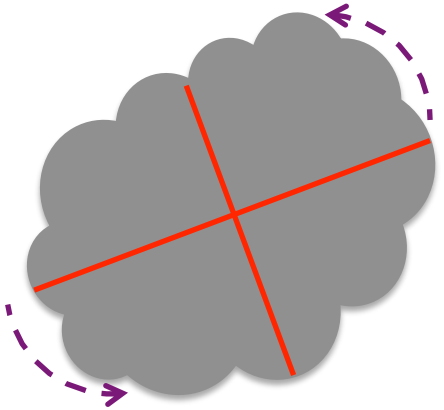

Angular momentum acquired through tidal torques

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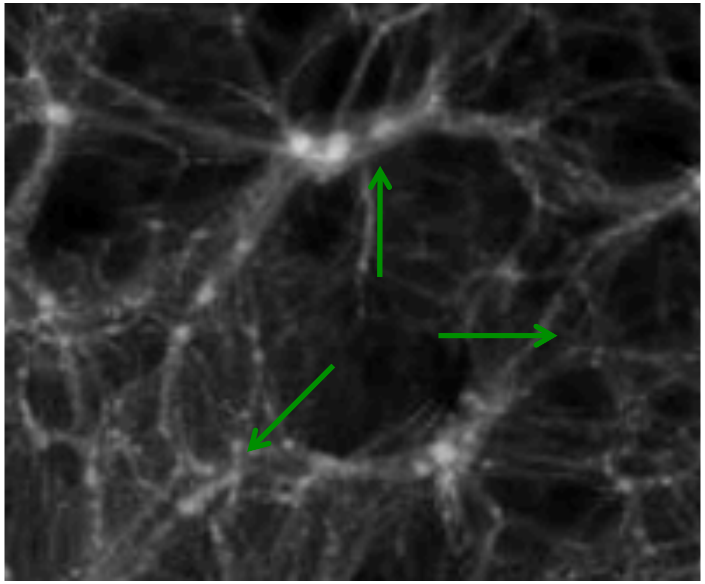
**VOID** $\lambda_{th} > \lambda_1 > \lambda_2 > \lambda_3$ All three eigenvectors of the shear tensor are expanding



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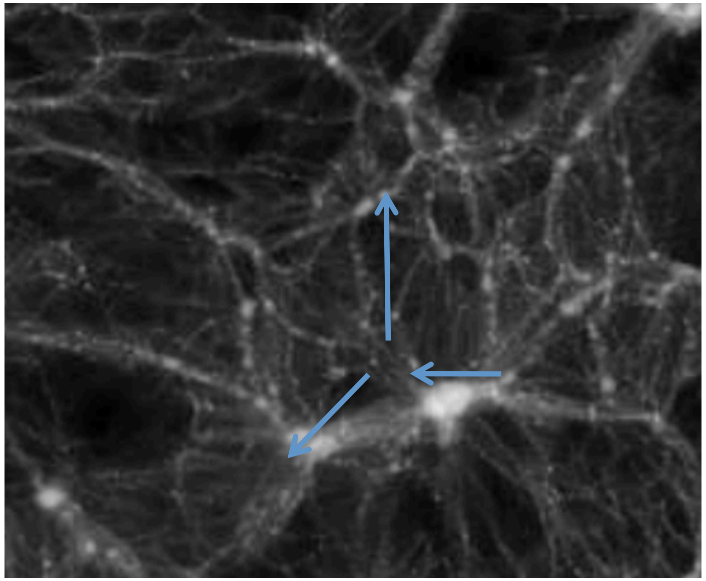
**SHEET** $\lambda_1 > \lambda_{th}$ ; $\lambda_2, \lambda_3 < \lambda_{th}$ Collapse along one axis ($\hat{e}_1$), expansion along the two ($\hat{e}_2$, $\hat{e}_3$)



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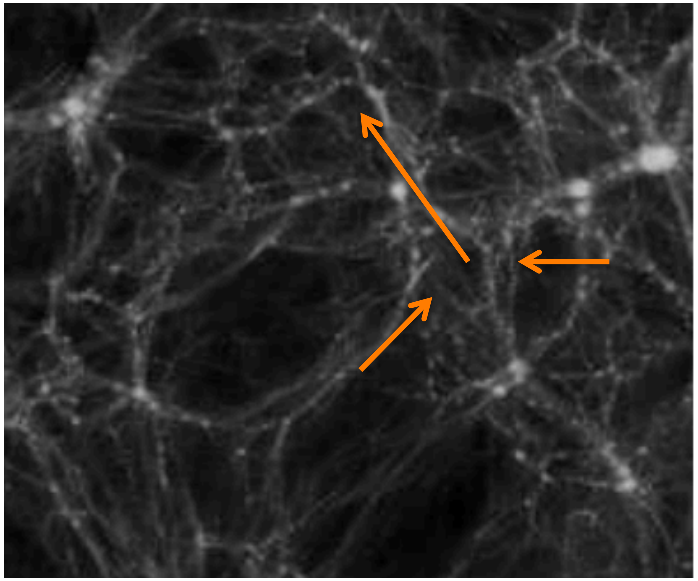
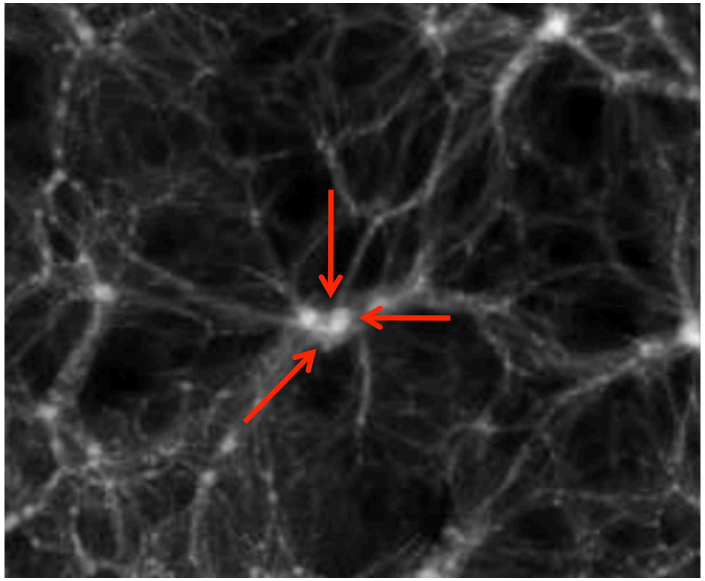
**FILAMENT** $\lambda_{1}, \lambda_{2} > \lambda_{th}$ ; $\lambda_{3} < \lambda_{th}$ Collapse along two axes ($\hat{e}_1$, $\hat{e}_2$), expansion along the other ($\hat{e}_3$)





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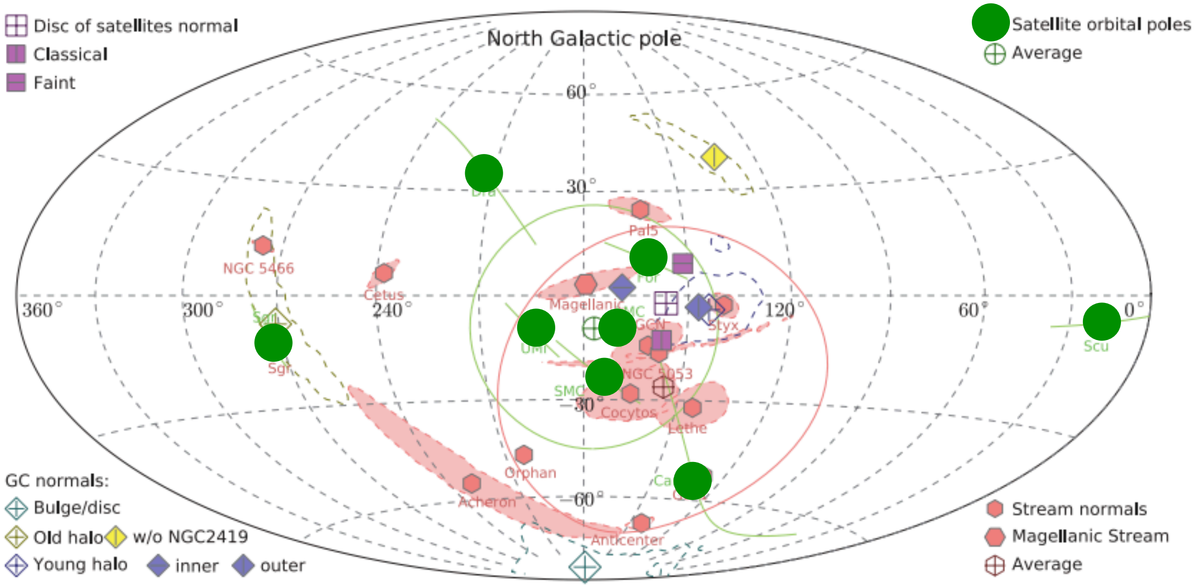
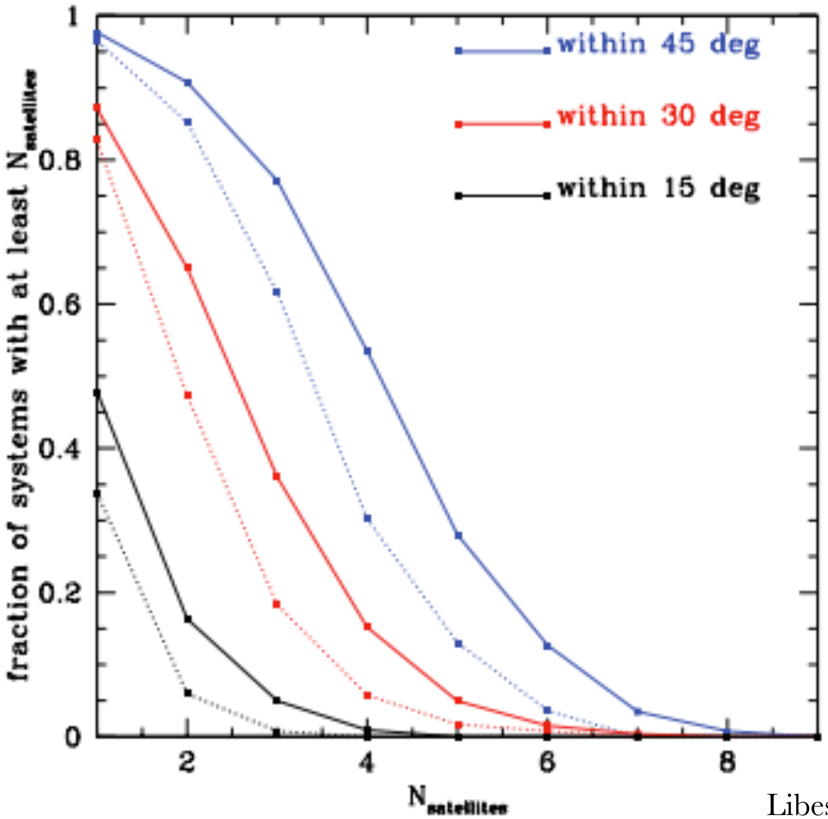
**KNOT** $\lambda_1 > \lambda_2 > \lambda_3 > \lambda_{th}$ All three eigenvectors of the shear tensor are collapsing

Velocities exacerbate the situation and threaten the CDM model




Pawlowski et al 2012




Libeskind et al 2009

A minimum of 3 (and up to a maximum of 8) *classical* satellites appear to be moving within 30 deg of the normal to the plane they define.

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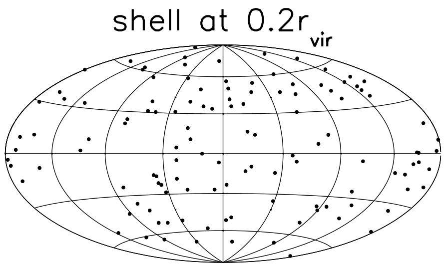
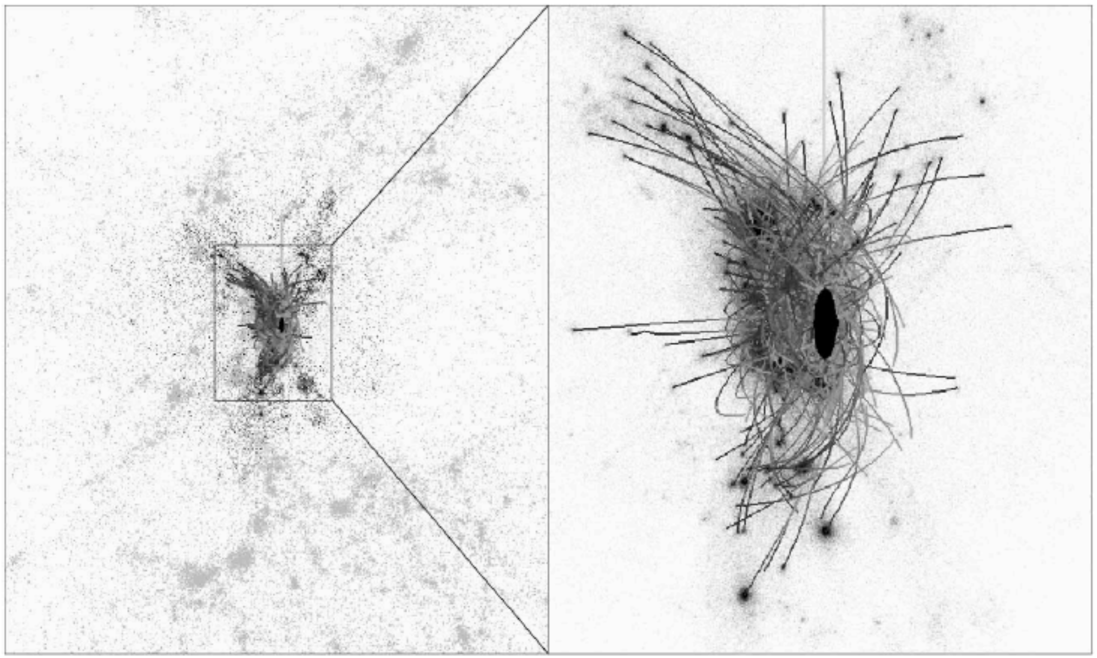
Anisotropy of orbits at accretion leads to anisotropic z=0 distributions – preferential infall




Libeskind et al 2011
Knebe et al 2004



+ Li & Helmi 2008, Lovell et al 2011, Vera-ciro et al 2011 *et cetera*