Galaxy alignment and the physical origin

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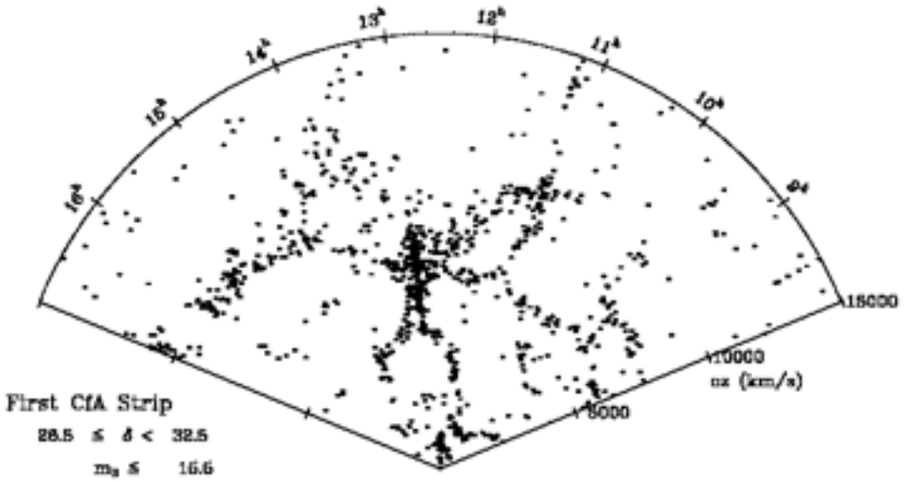
How to describe galaxy distribution in space?



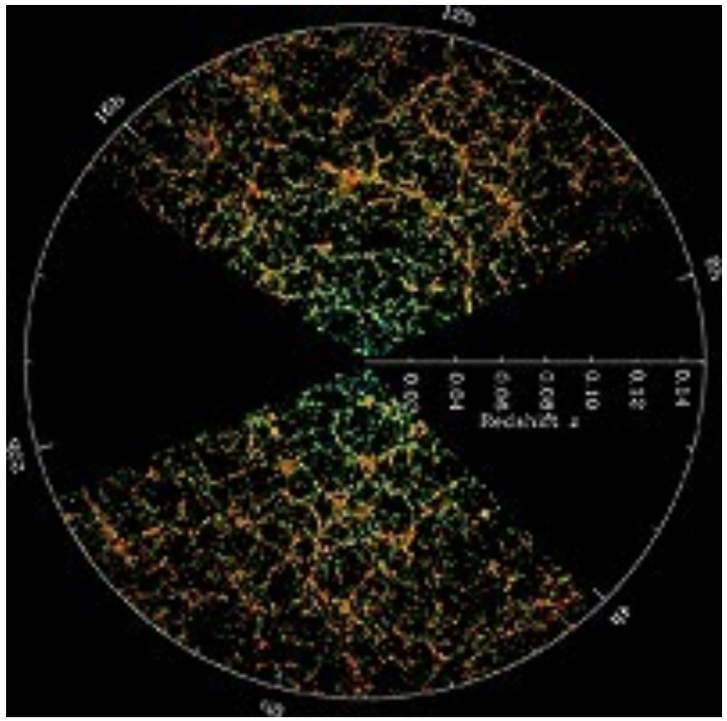
in 1980,great wall

- Correlation function: 2-points, 3-points etc (1980, Peebles)
- 2PCF describes how galaxies are biased with dark matter distribution
- 2PCF etc can well constrain the cosmological parameters

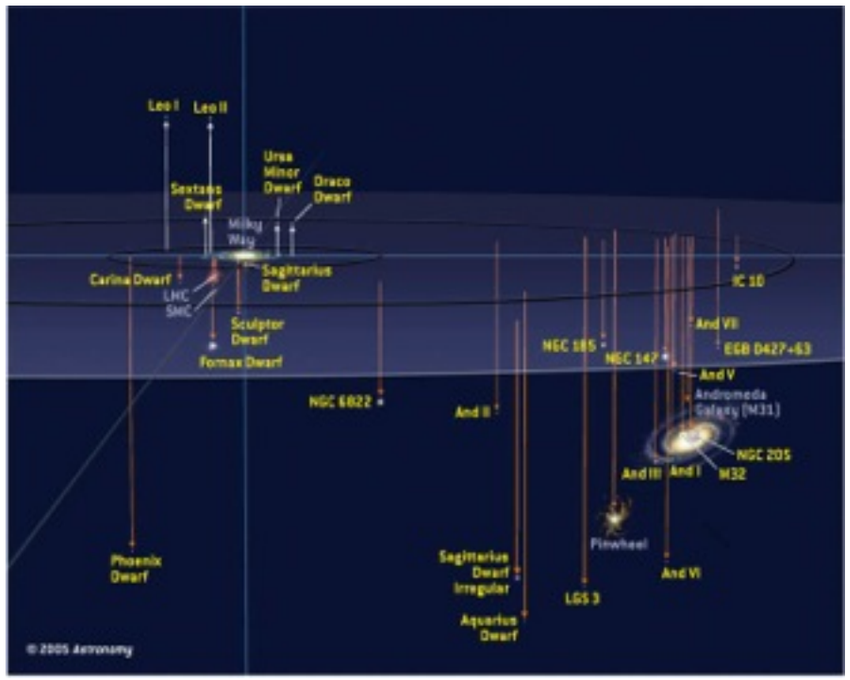
Two-point correlation

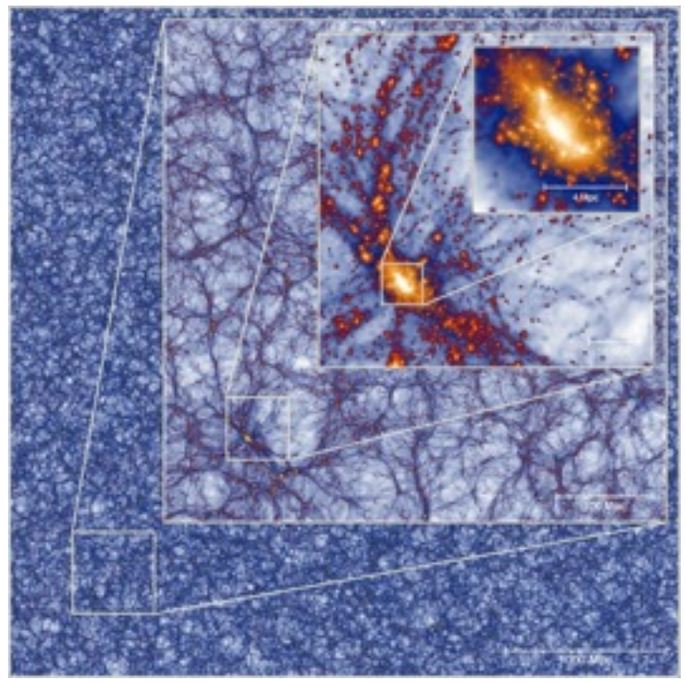
?

2PCF widely used for 2dFGRS/SDSS



Galaxy alignment is seen on different scales

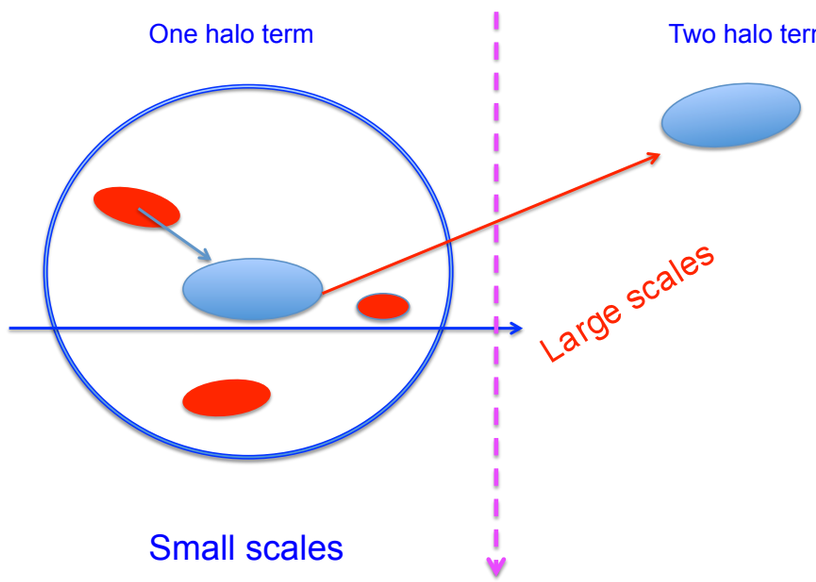




Galaxy alignment

- satellite-satellite
- satellite-central
- central-central
- central-LSS

Several types of galaxy alignment



In addition to galaxy clustering, Why do we care galaxy alignment?

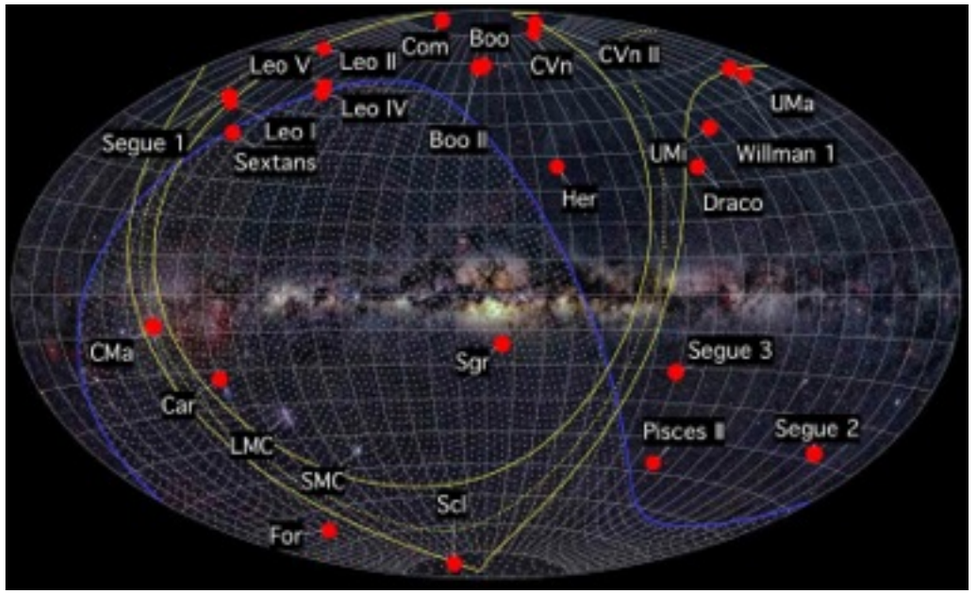
On small scale (one-halo term)

- Infer dark matter halo shape from galaxy alignment
- alignment to infer galaxy formation?
- primordial anisotropic accretion or evolution (Nature vs Nurture?)

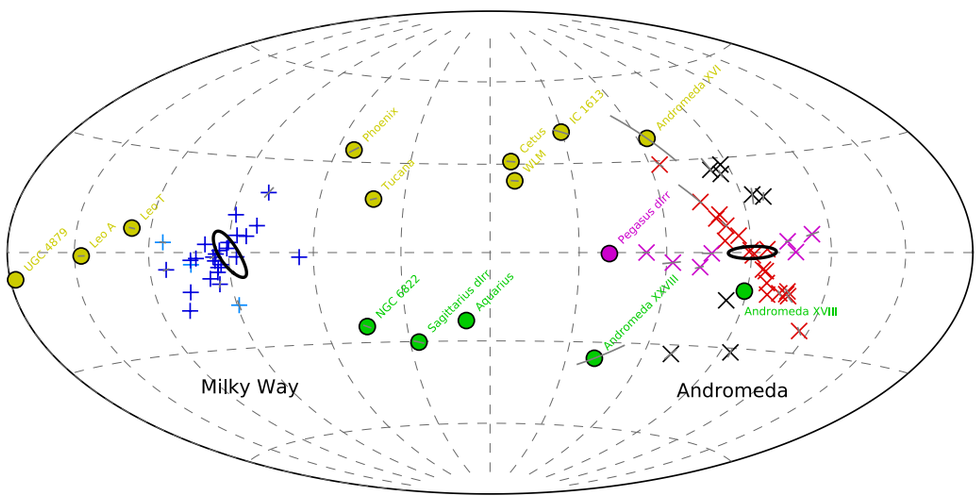
On large scales (two-halo term)

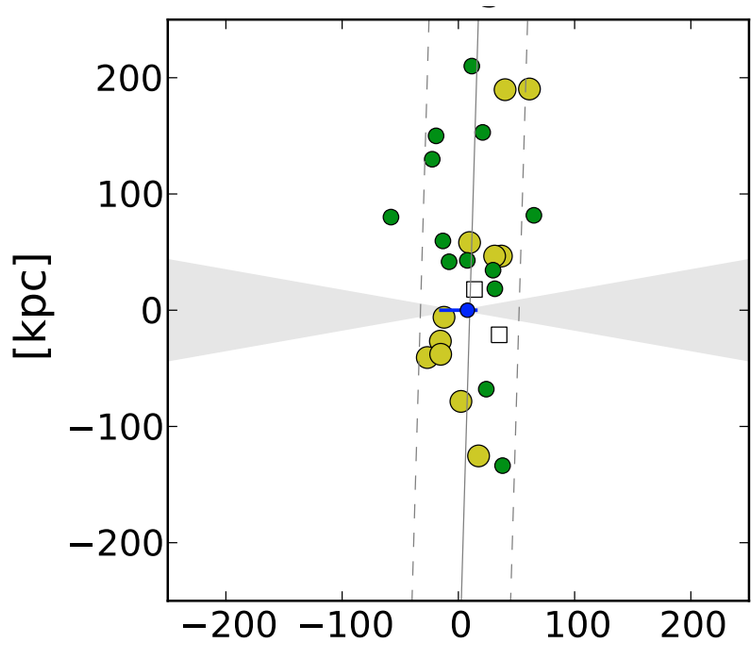
- Interaction of halo shape to cosmic tidal field
- intrinsic alignment of galaxies (crucial to weak lensing)
- formation of cosmic web?
- dependence on DM/DE properties?

1,satellite-satellite: The great circle (co-rotated plane)



Satellite galaxy in the Milky Way



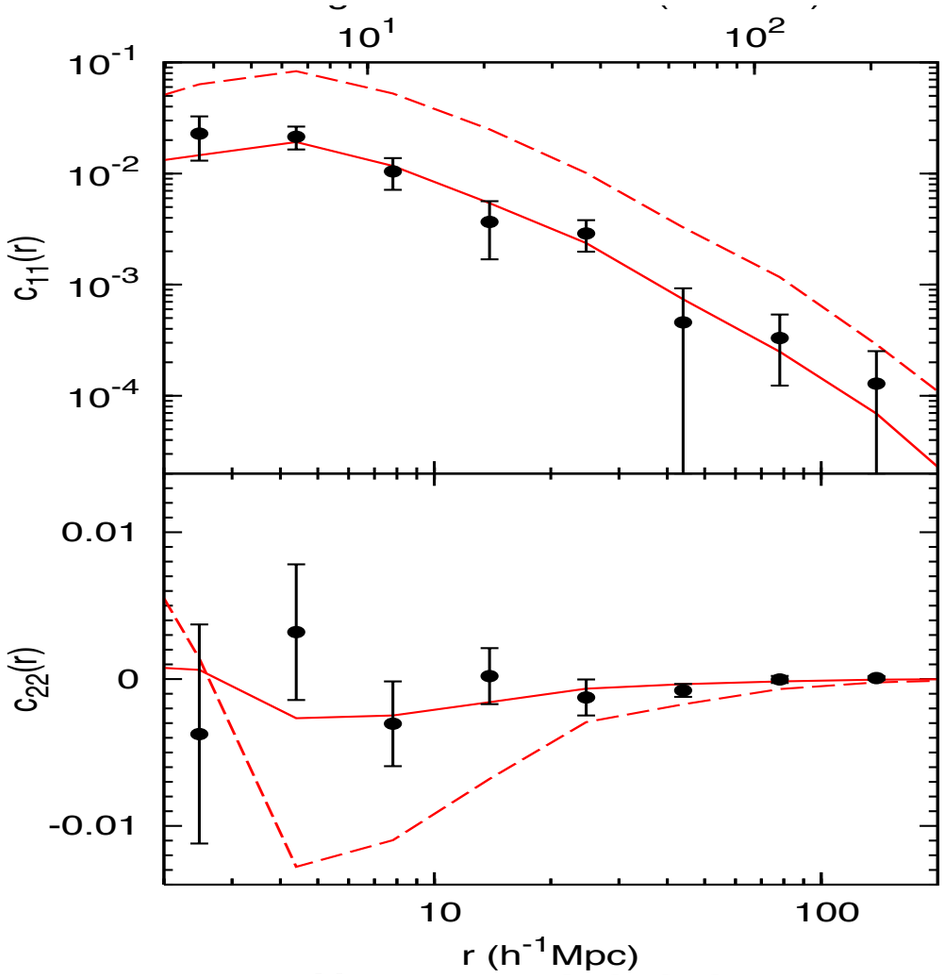


Kroupa 2005

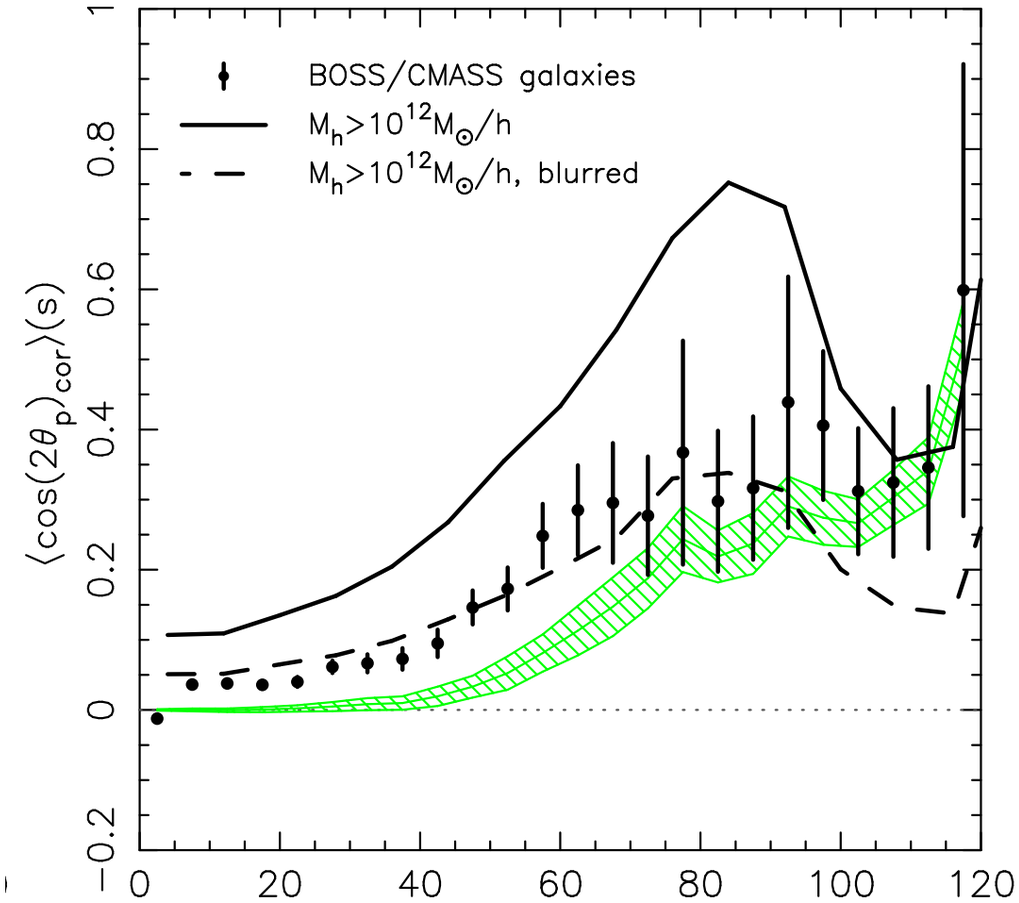
- 2005:Milky Way satellites are in a thin disc
- 2007:The same is true in M31, but weaker
- 2013: Satellites in the disc are co-rotated !

MW and M31 are special?
need large galaxy sample

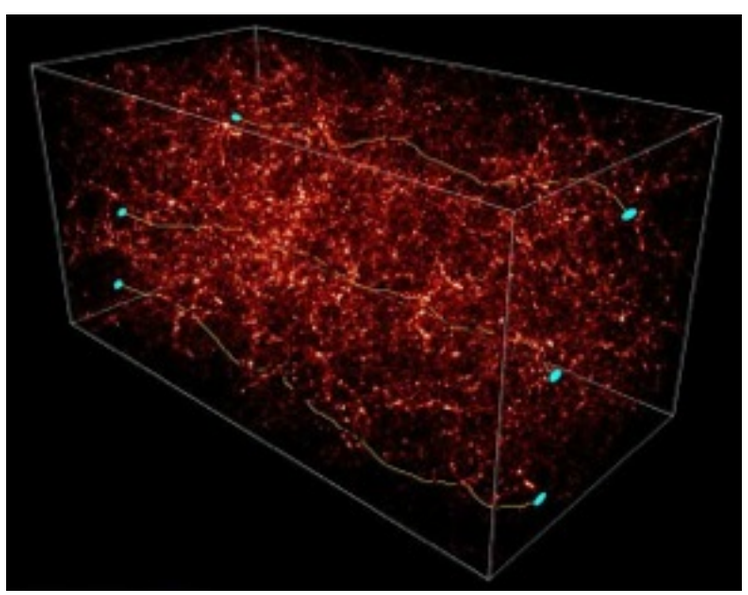
3, Central-Central alignment



Jing+ 2009

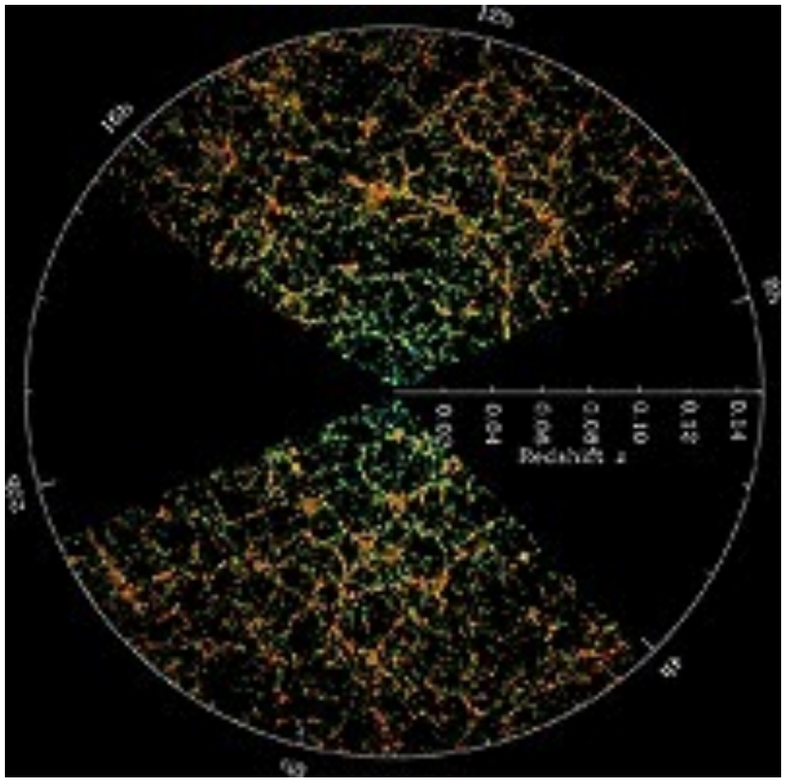


Li+ 2015

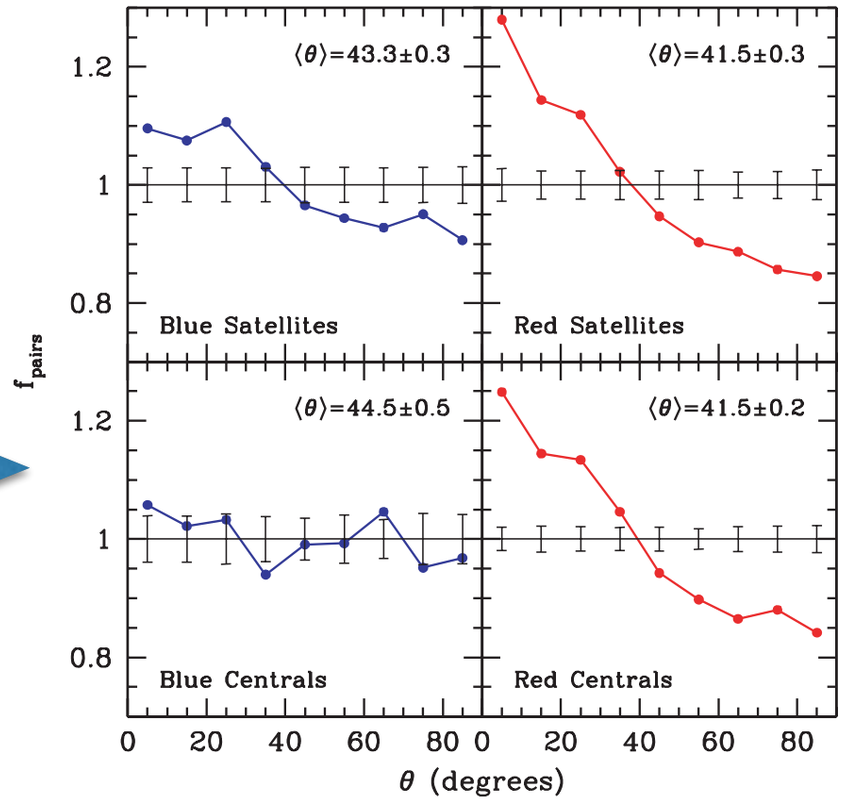


Galaxy(Halo) intrinsic alignment is crucial for Weak Lensing cosmology

2,satellite-central alignment



group galaxy



Brainerd 05, Yang+06

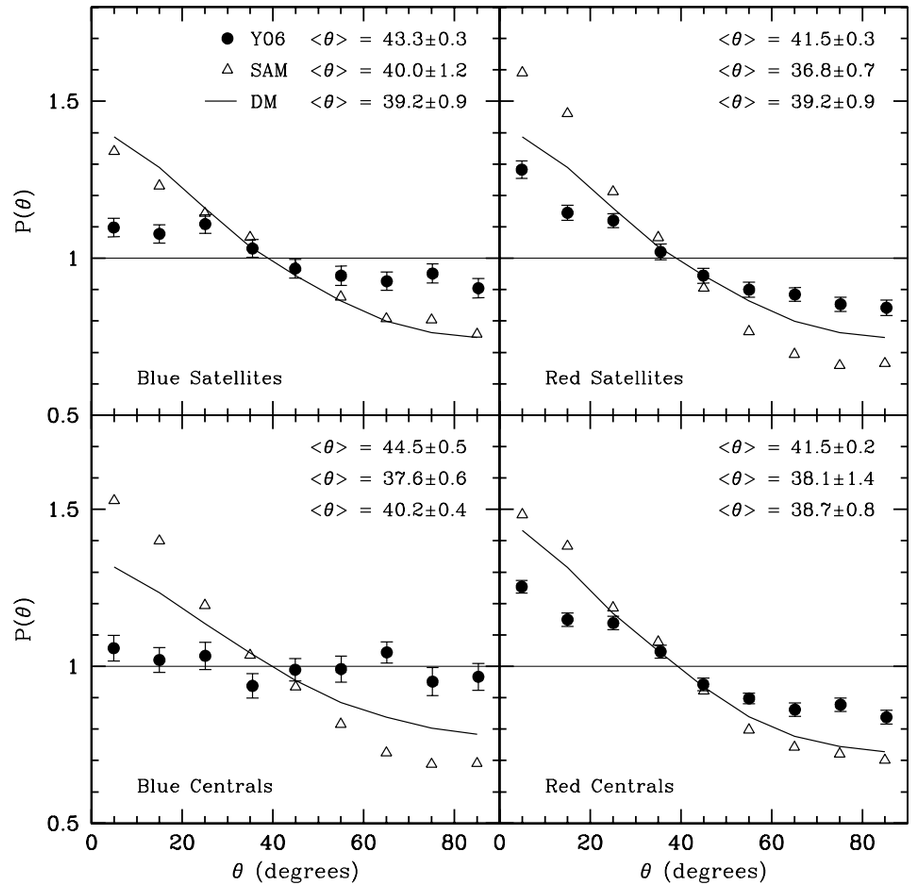
From 2dFGRS and SDSS

- satellite galaxies are aligned with the major axis of central galaxy
- stronger alignment for red centrals
- strong alignment for red satellites

Modeling the satellite-central alignment

Halo is triaxial

Kang et al. 07 using SAM



results

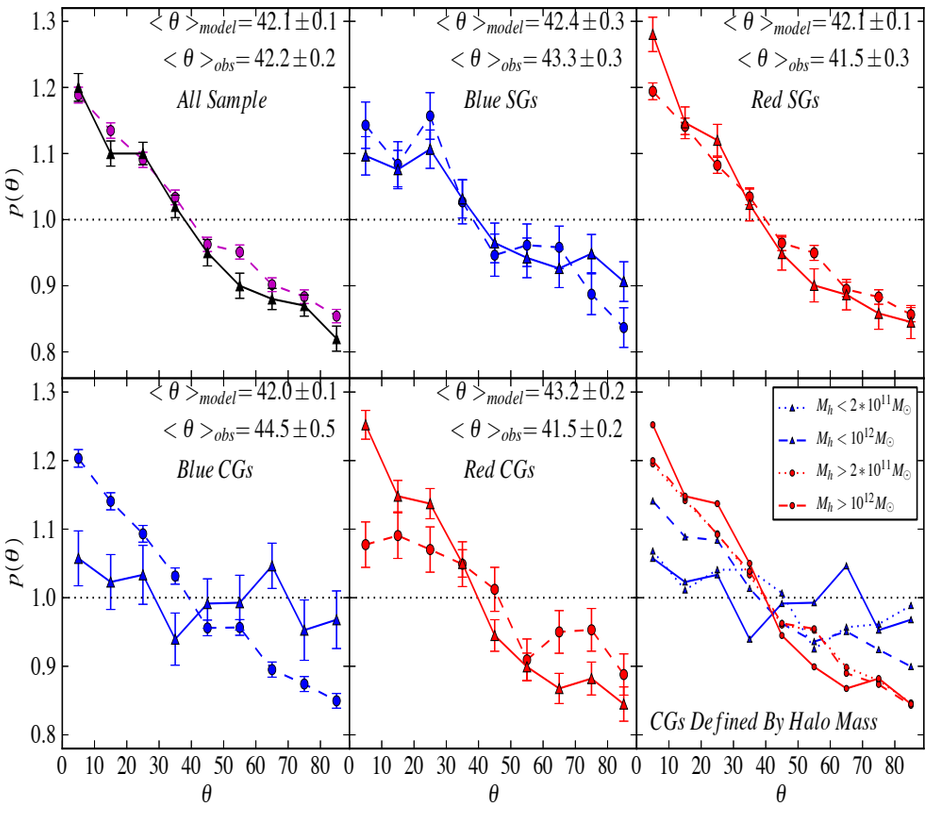
- if central galaxy follow major axis of DM halo (inside virial radius): signal too strong
- need some mis-alignment (inner DM halo, or spin) signal is OK, but no color dependence

N-body study is limited as its difficult to properly determine the shape of central galaxy

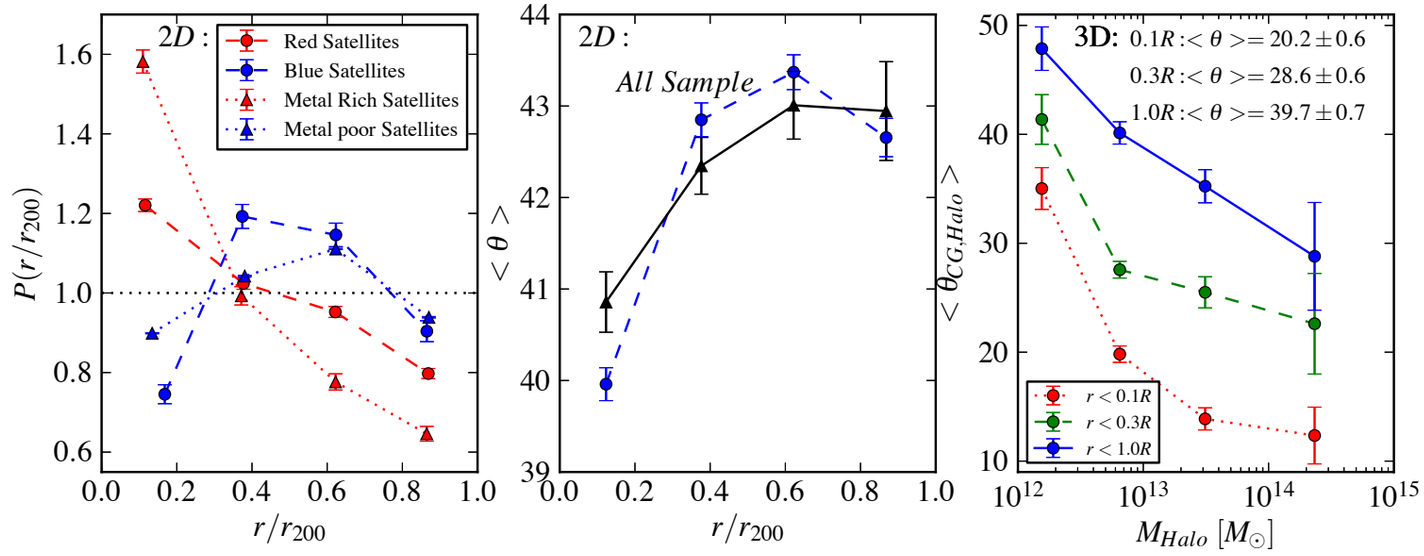
Modeling the satellite-central alignment

Using hydro-dynamical simulation: star formation, SN feedback (no AGN feedback)

alignment: dependence on color



alignment with radius



Dong X, Kang X et al. 2014

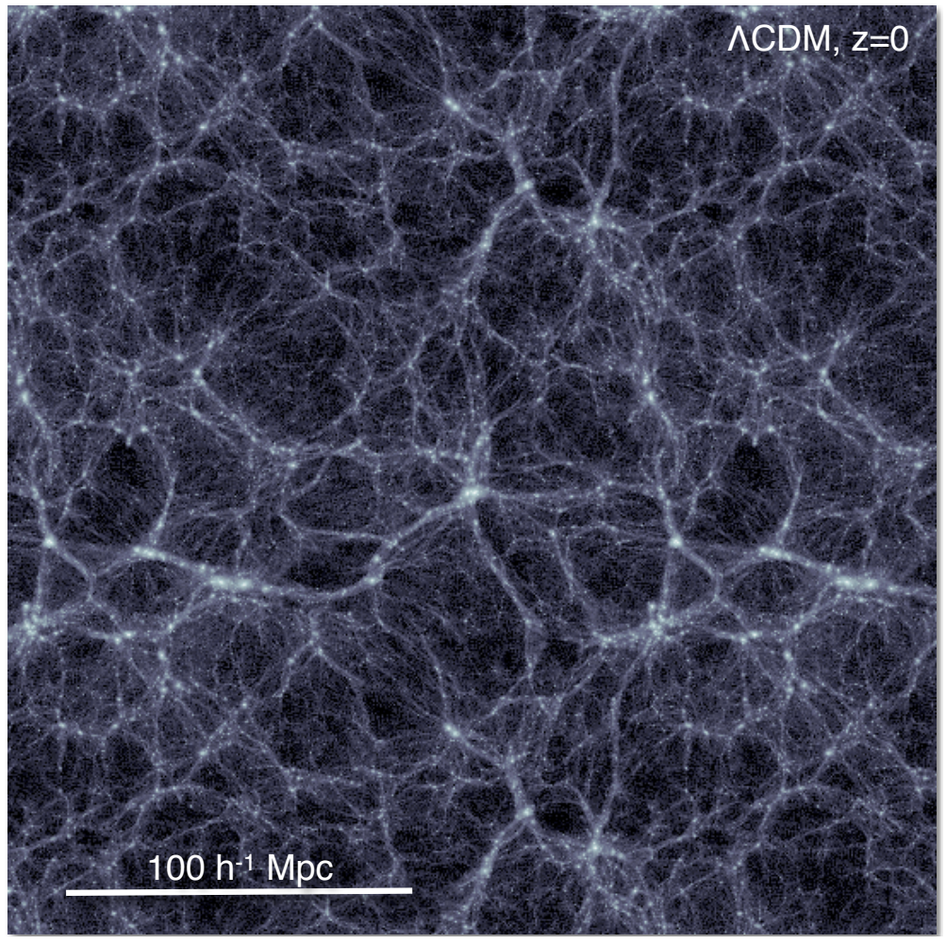
Result

★There is mis-alignment between shape of central galaxy and DM halo

★Their misalignment is a function of halo mass (color dependence of central)

★misalignment is a function of radial distance (red satellites in inner halo,blues at outer region)

4: Alignment with LSS:
I. define the LSS environment



Zel'dovich approximation for formation of cosmic web

$$\mathbf{x}(t) = \mathbf{q} + D(t)\,\nabla\psi(\mathbf{q})\ ,$$

$$\rho(\mathbf{x}) = \frac{\bar{\rho}}{[1 - D\,\lambda_1(\mathbf{q})]\,[1 - D\,\lambda_2(\mathbf{q})]\,[1 - D\,\lambda_3(\mathbf{q})]}$$

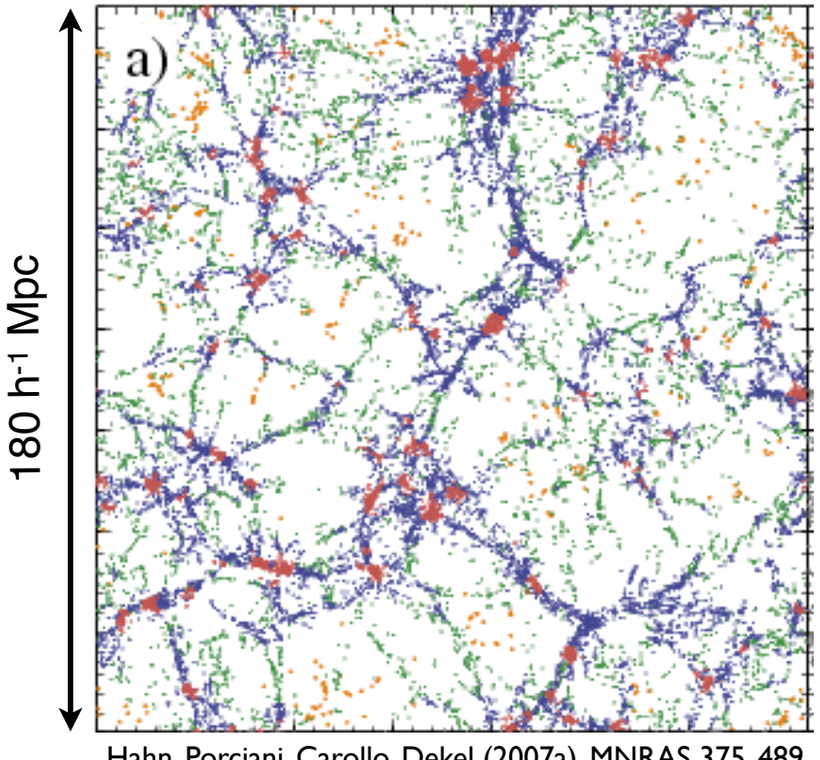
λ ~ eig of $(\partial_i \partial_j\, \phi)$

Sheet—>Filament—>Node

Following Zeldovich, Hahn+2007. define the LSS environment:

- smooth the density field
- compute the potential
- compute eigenvector of tidal field

$$T_{ij}(\boldsymbol{x}) = \frac{\partial^2 \phi}{\partial x_i \partial x_j},$$

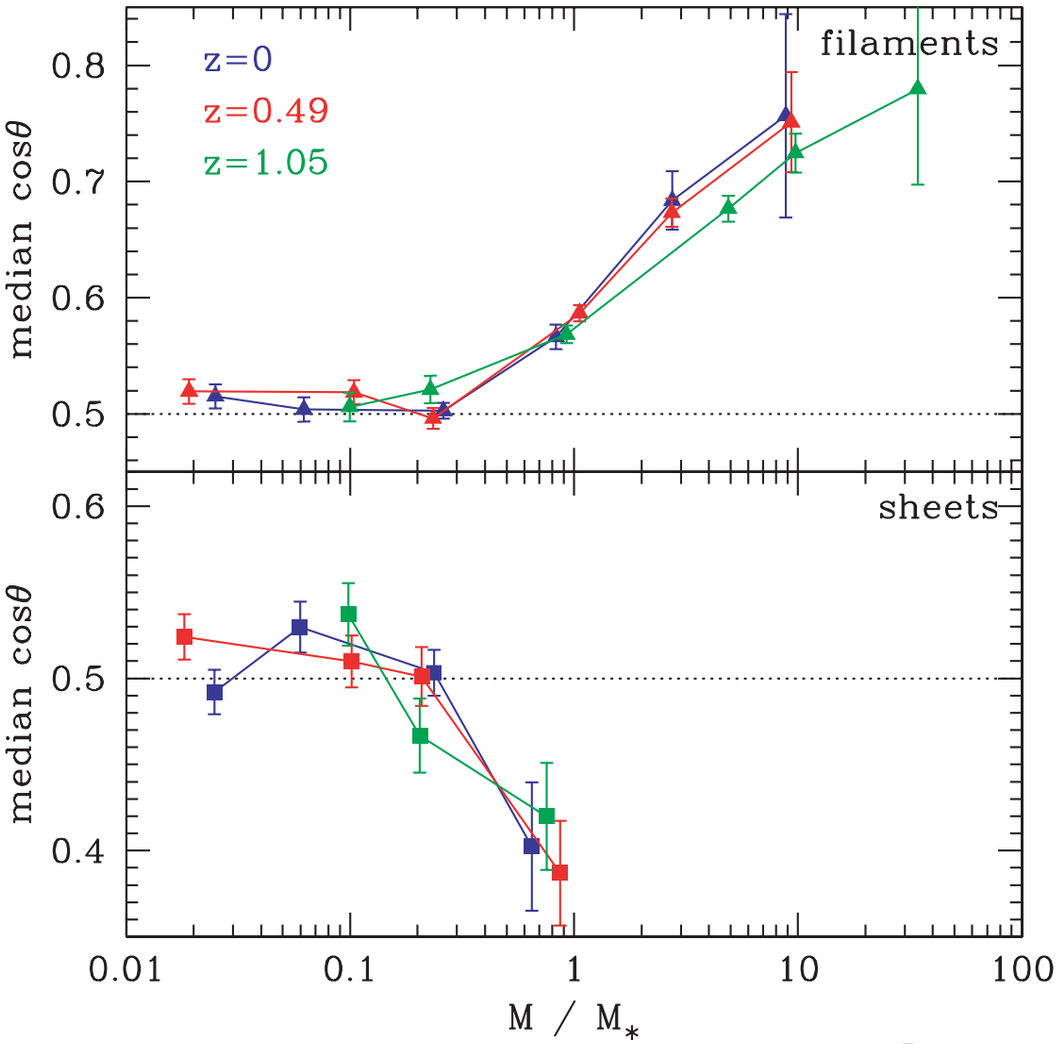


Hahn, Porciani, Carollo, Dekel (2007a), MNRAS 375, 489

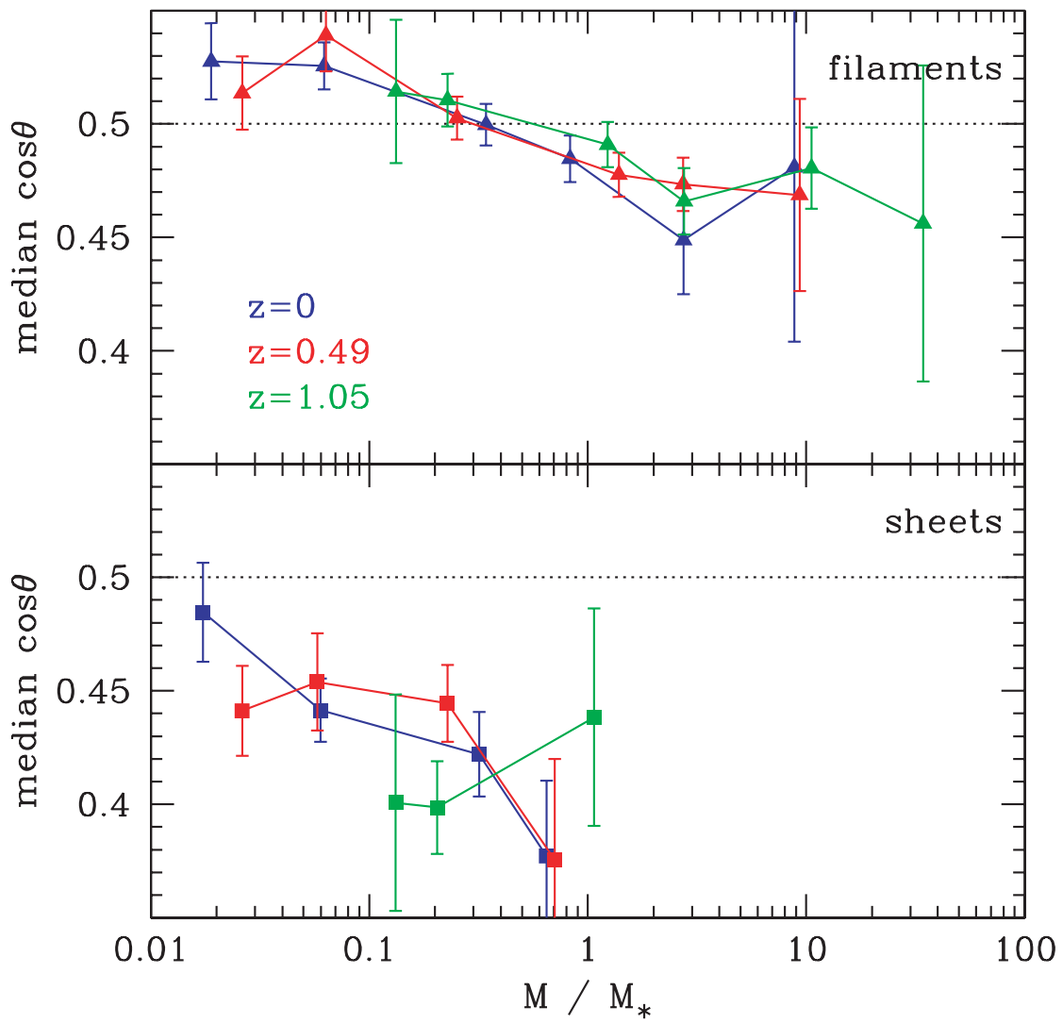
- number of +- eigenvalue determine: voids, sheet, filament, nodes

I. Halo-LSS alignment from simulation

Halo major axis-LSS



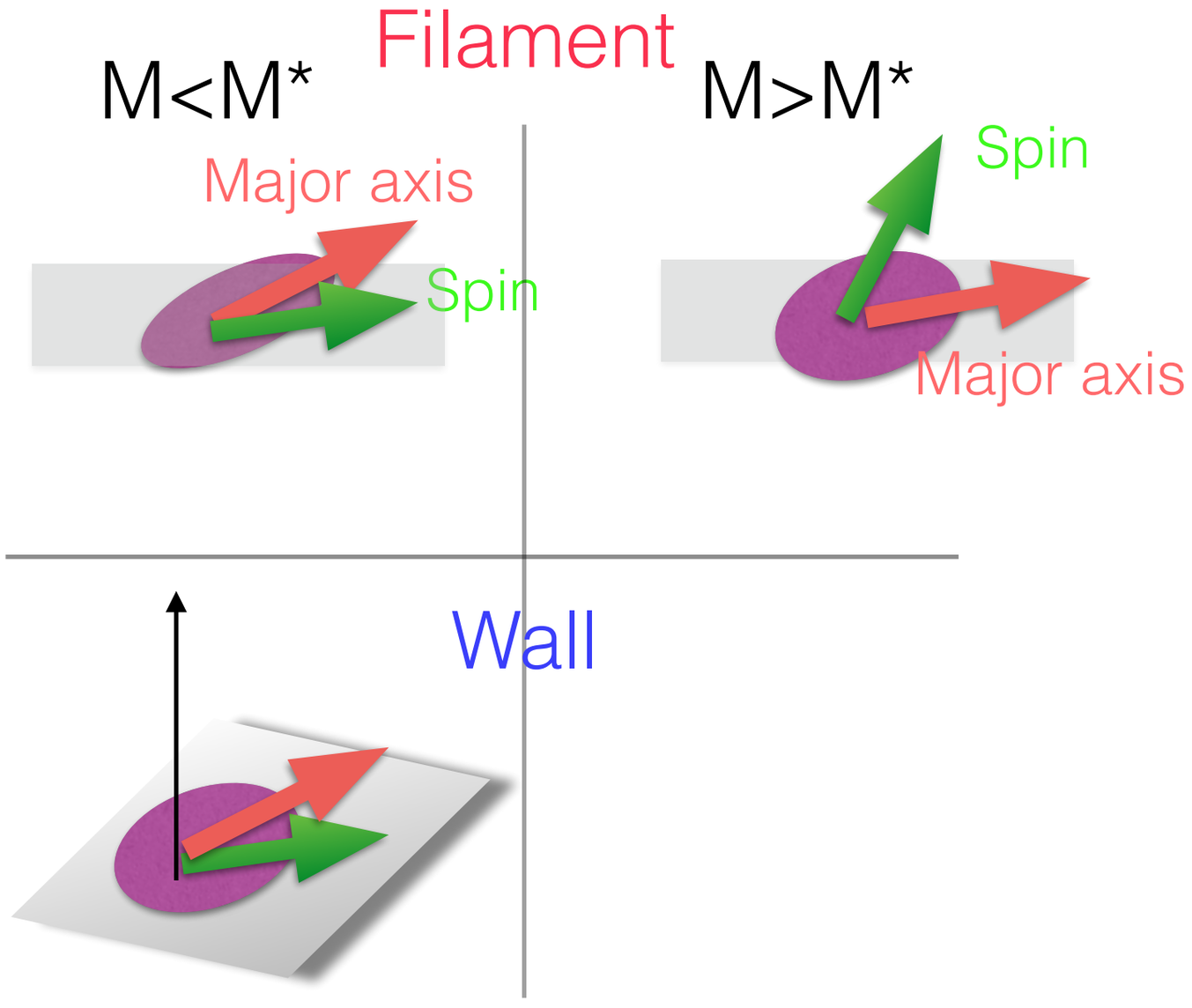
Halo spin -LSS



Hahn+ 2007,Codis+12 $M_{flip} \sim 10^{12} M_{sun} * (1+z)^{-2.5}$

These correlation are widely confirmed by many others using simulations (Aragon-Calvo+08, Codis+12, Libeskind+14, Kang & Wang 15 …..)

Space configuration of Halo shape & Spin



Major axis of halo: align with the least collapsed direction

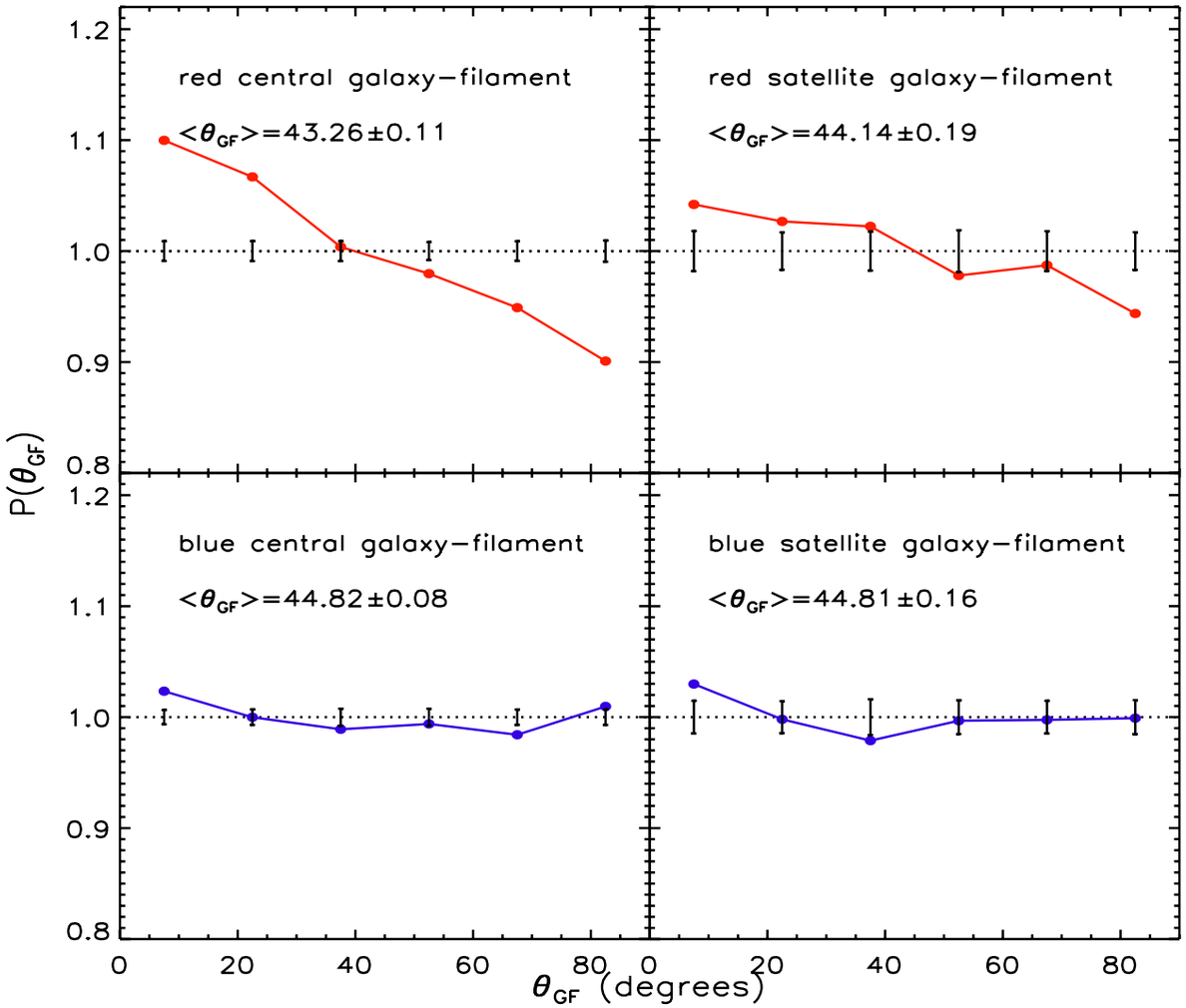
Minor axis of halo: align with the most collapsed direction

Spin of halo : normal to the mass accretion direction

Why there is a mass dependence?

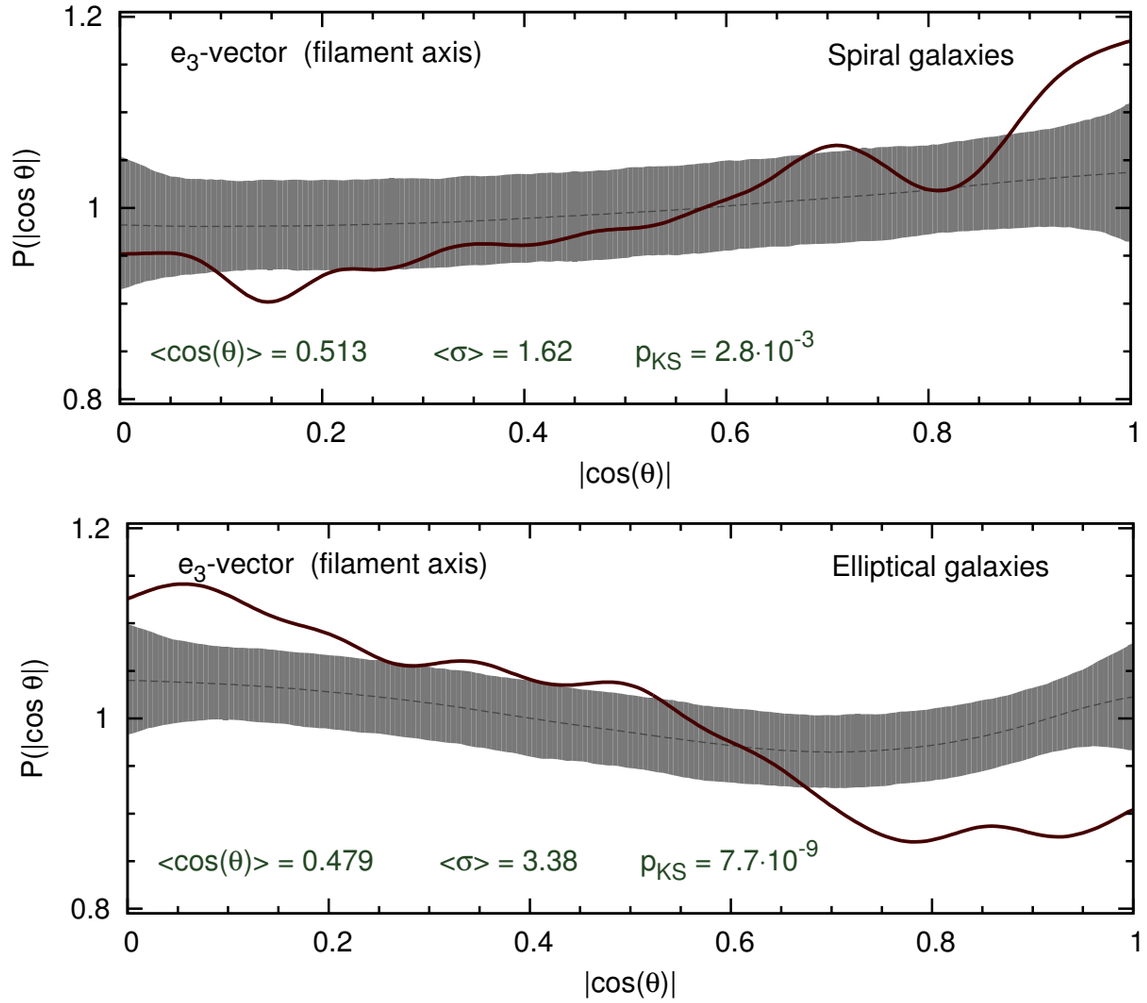
II. Galaxy-LSS alignment from observation

Galaxy Major axis-Filament



Zhang Y+2013

Spin - Filament

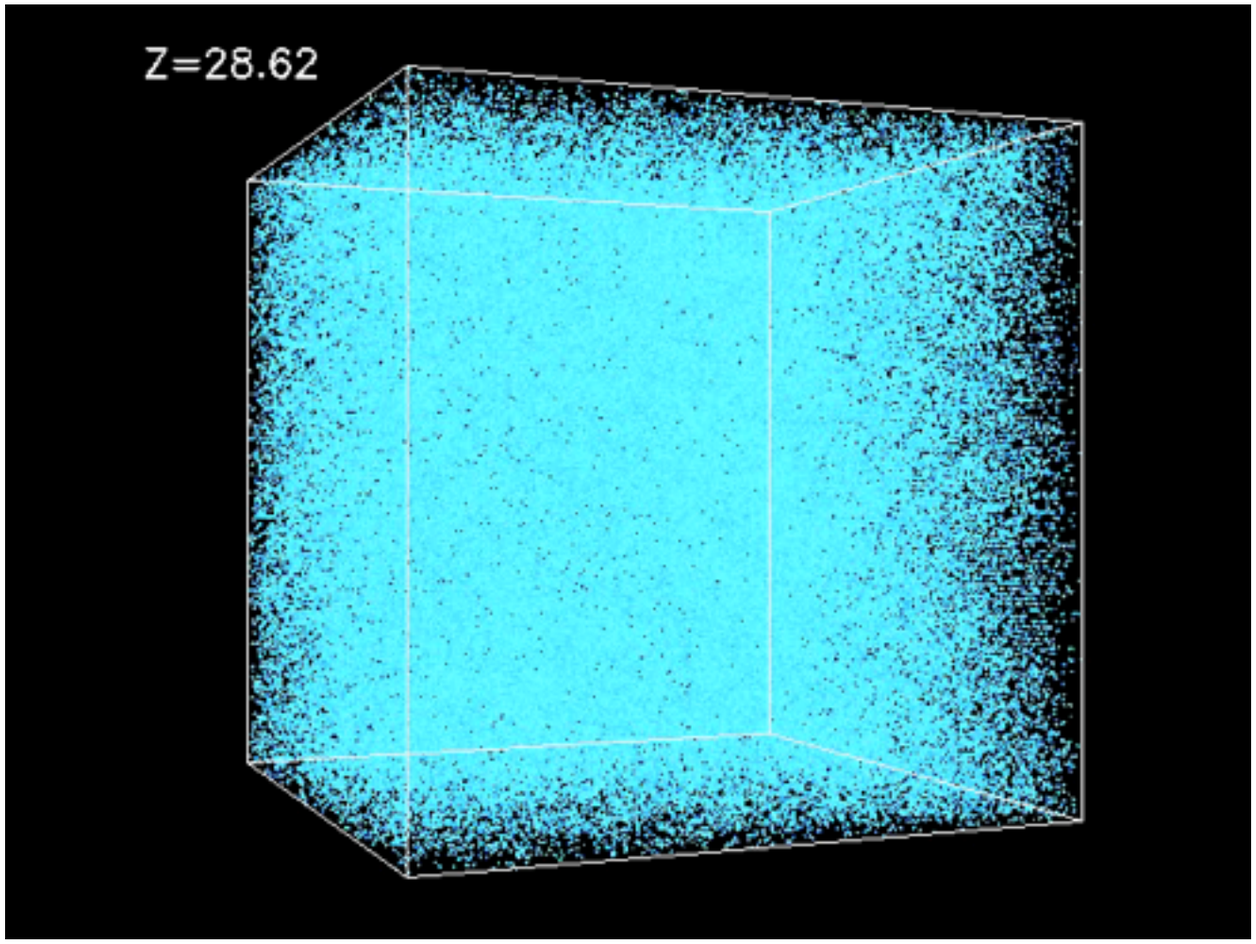


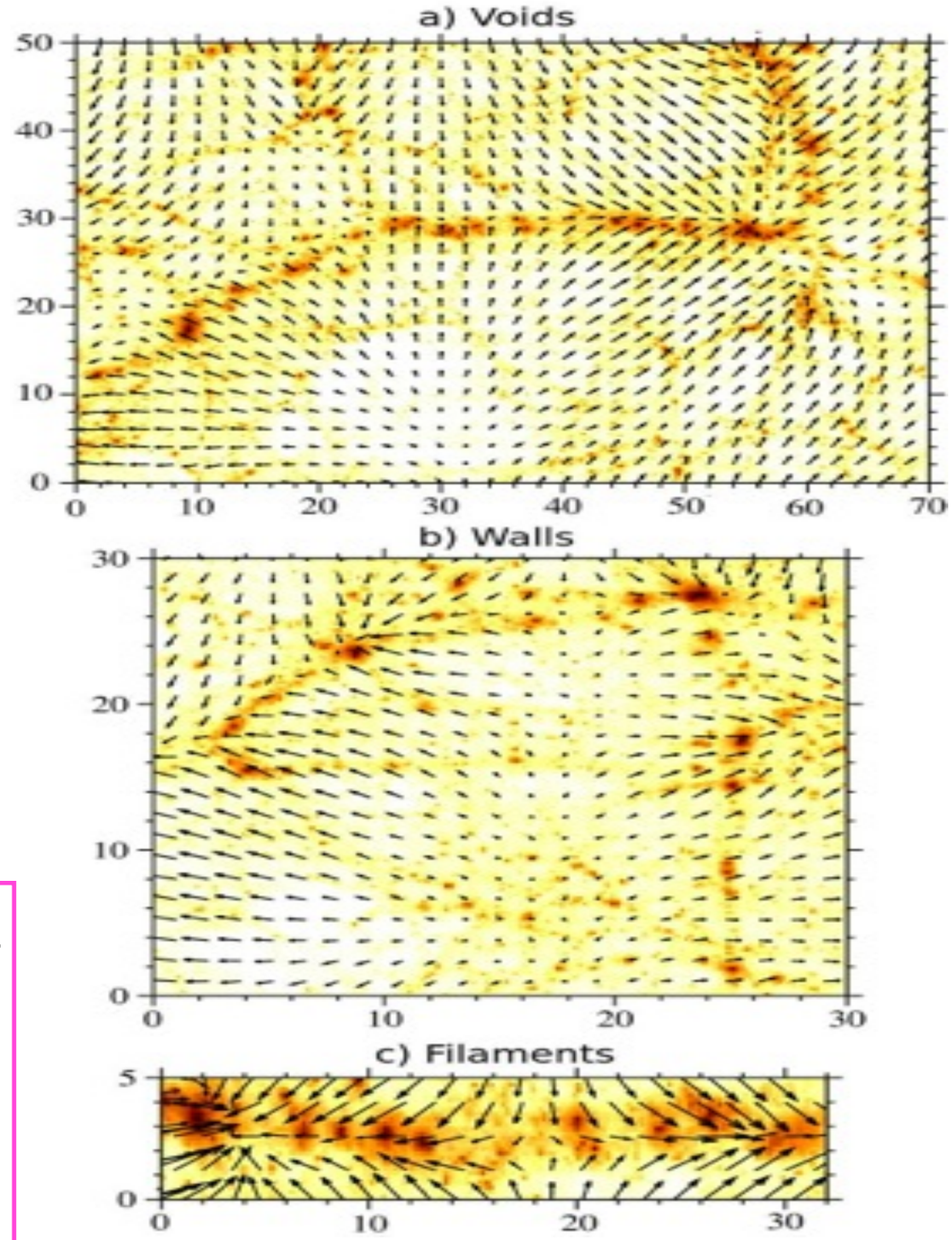
Tempel & Libeskind 2014

Observations agree well with Theory !

Signal is weaker (galaxy-halo misalignment)

A common scenario for mass flow in cosmic web





- mass flow from Voids —> Wall —>Filament —>Nodes
- environment of halo changes as Wall—>Filament-Nodes
- the velocity field around cosmic web determines the spin-LSS correlation!

Codis+12, Cautun+14

original idea from Bond+96, van de Weygaert 96

This scenario is basically right
but details to be declared

From this cosmic mass flow, we expect

- in Wall, spin is parallel to wall.
- In Filament, spin is perpendicular to filament

But, simulations have found

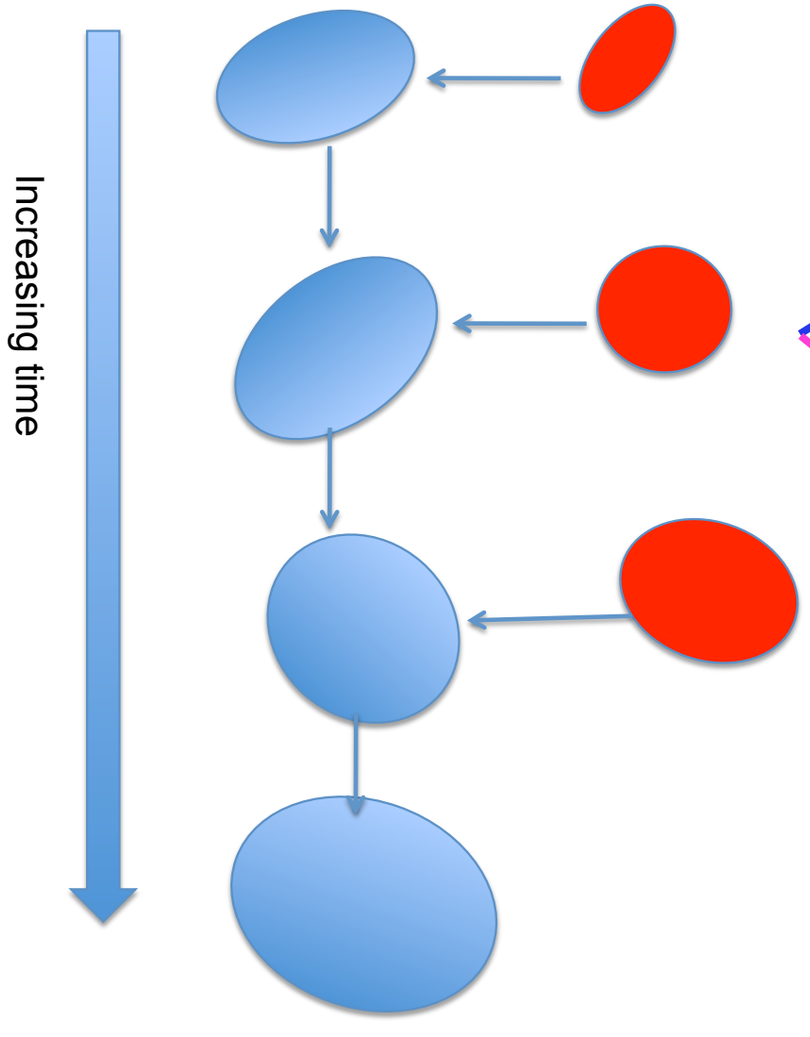
In Filament, there is still a mass dependence (spin flip)

Any dependence on halo migrating time ?
(from wall to filament)
can we see the spin flip during the history of
a massive halo?

tracing the evolution of halo mass accretion and spin

N-body simulation

- WMAP7 cosmology, LCDM
- box: 200Mpc/h, 1024^3 particles
- Full merger trees are constructed for every halo from z=10 to z=0



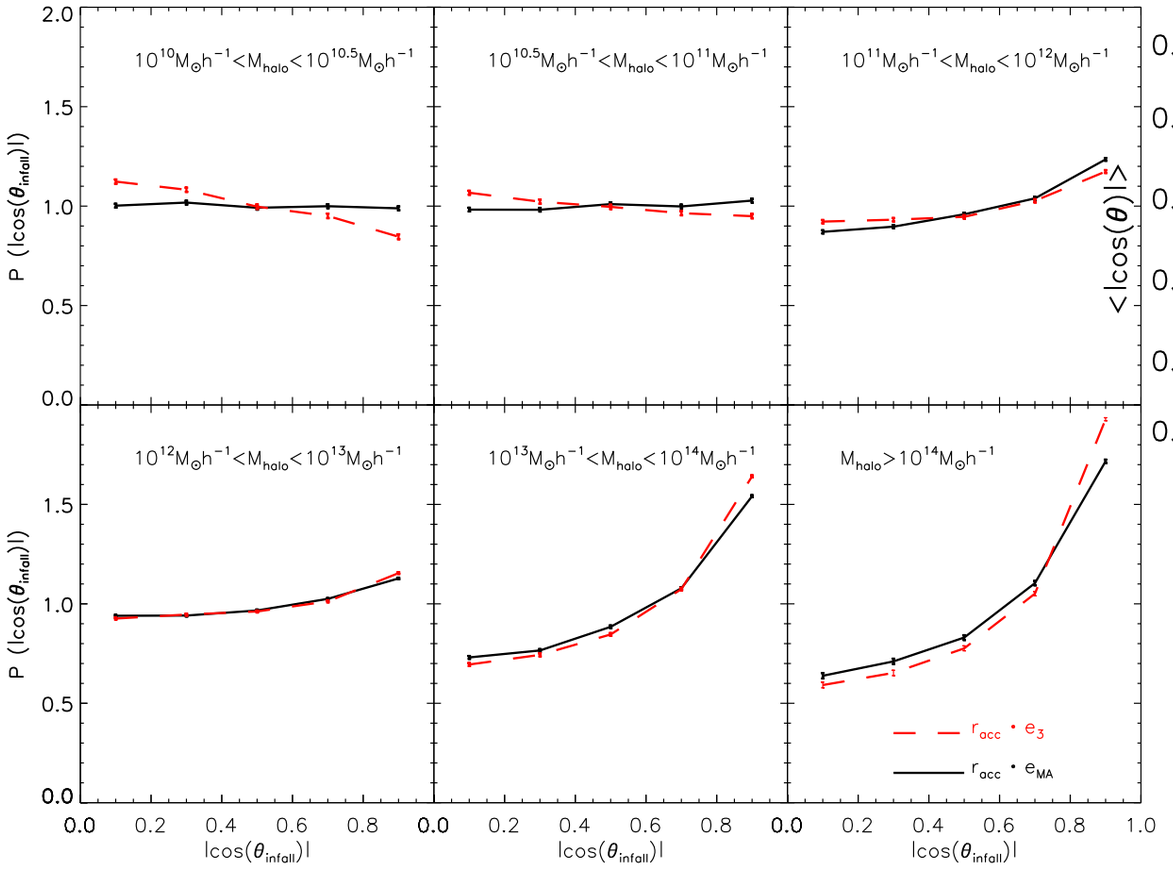
1) accretion along Halo major axis (λ_1):

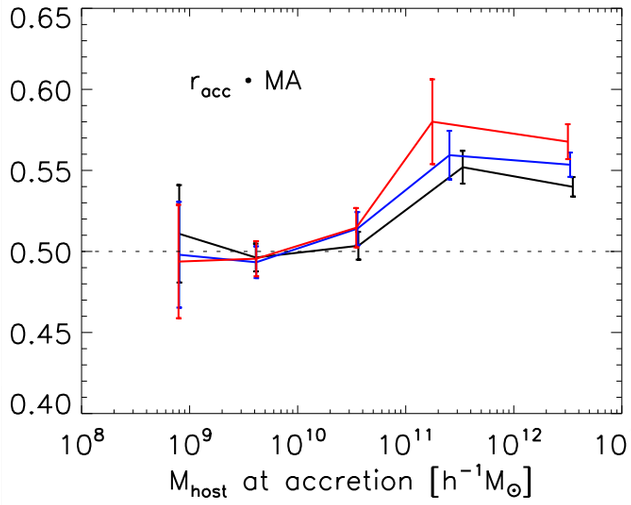
2) accretion along e3 of LSS (λ_3): The least compressed direction

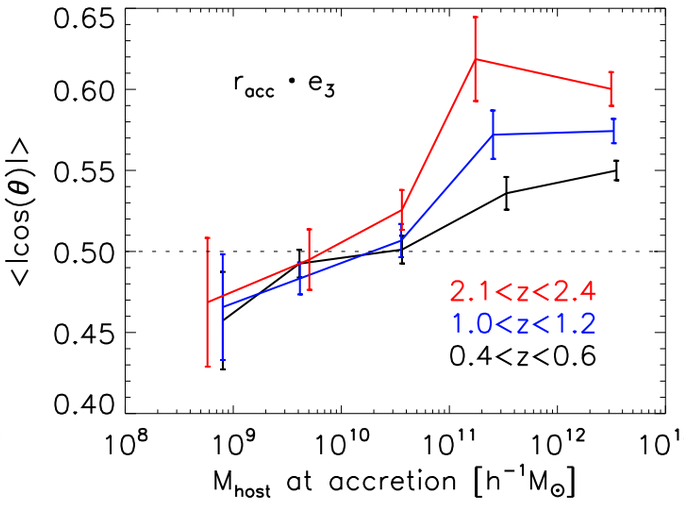
subhalos accretion along halo major axis and e3 of LSS dependence on host halo mass (selected at z=0)

black: along halo major axis
red: along e3 of LSS

halo mass dependence







Kang & Wang, 2015 ApJ

we find:
Accretion along halo major axis: universal
Accretion along e3 of LSS: not universal

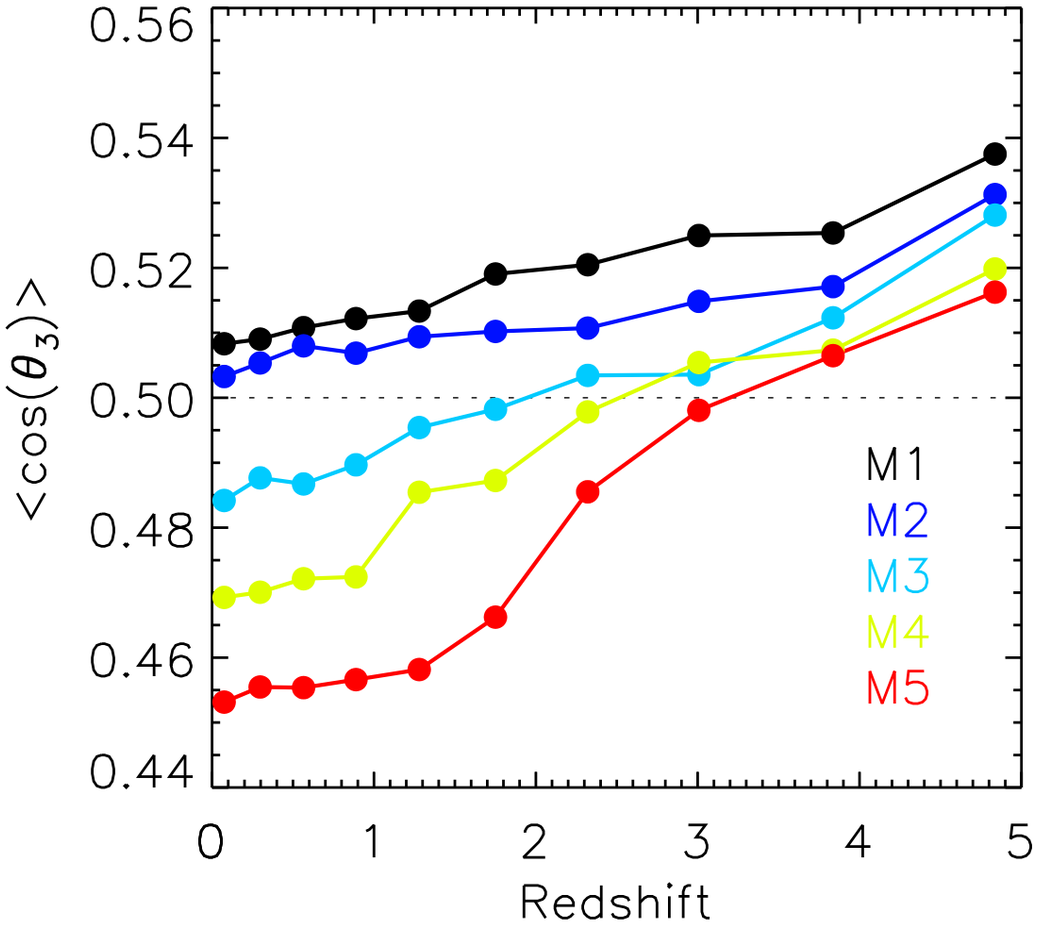
Libeskind+14, Universal along e3 of LSS
(their mass bin is too wide)

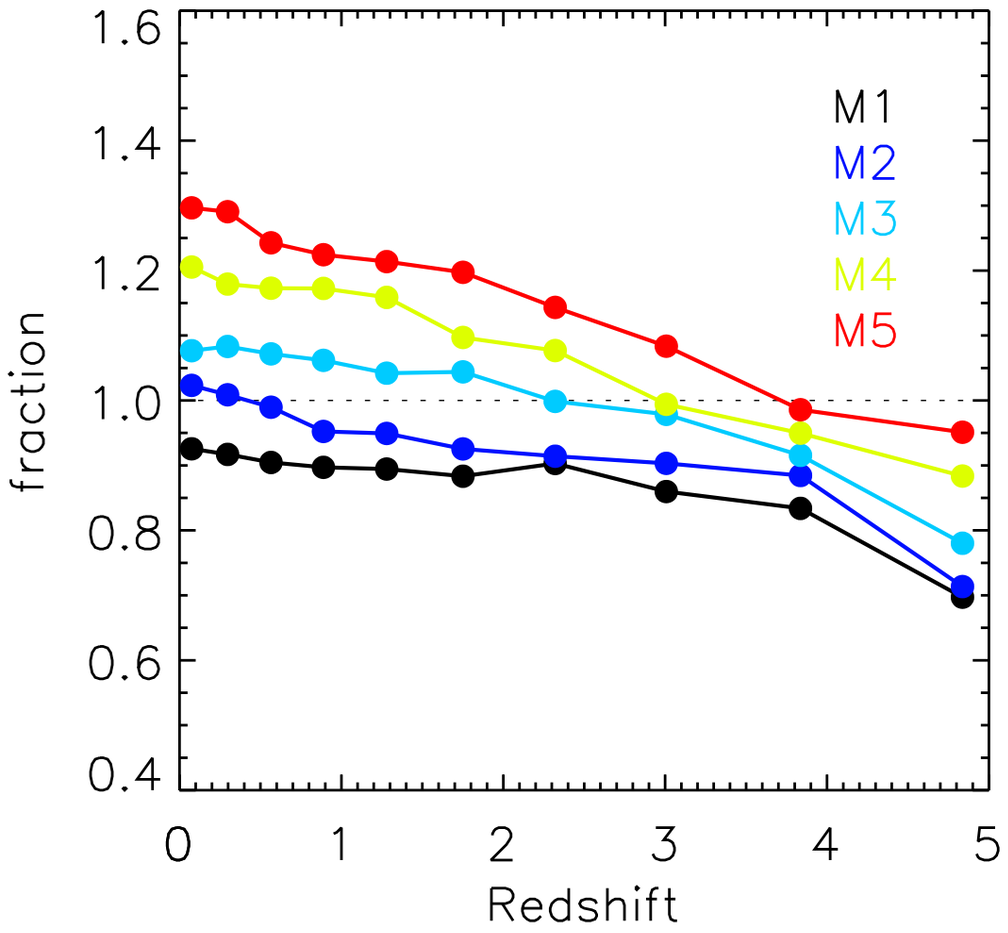
The evolution of spin-LSS and mass accretion

spin-e3 correlation

mass accretion-e3 correlation

black line: low-mass halo, red lines: massive halo





There are evolution effects, at earlier times

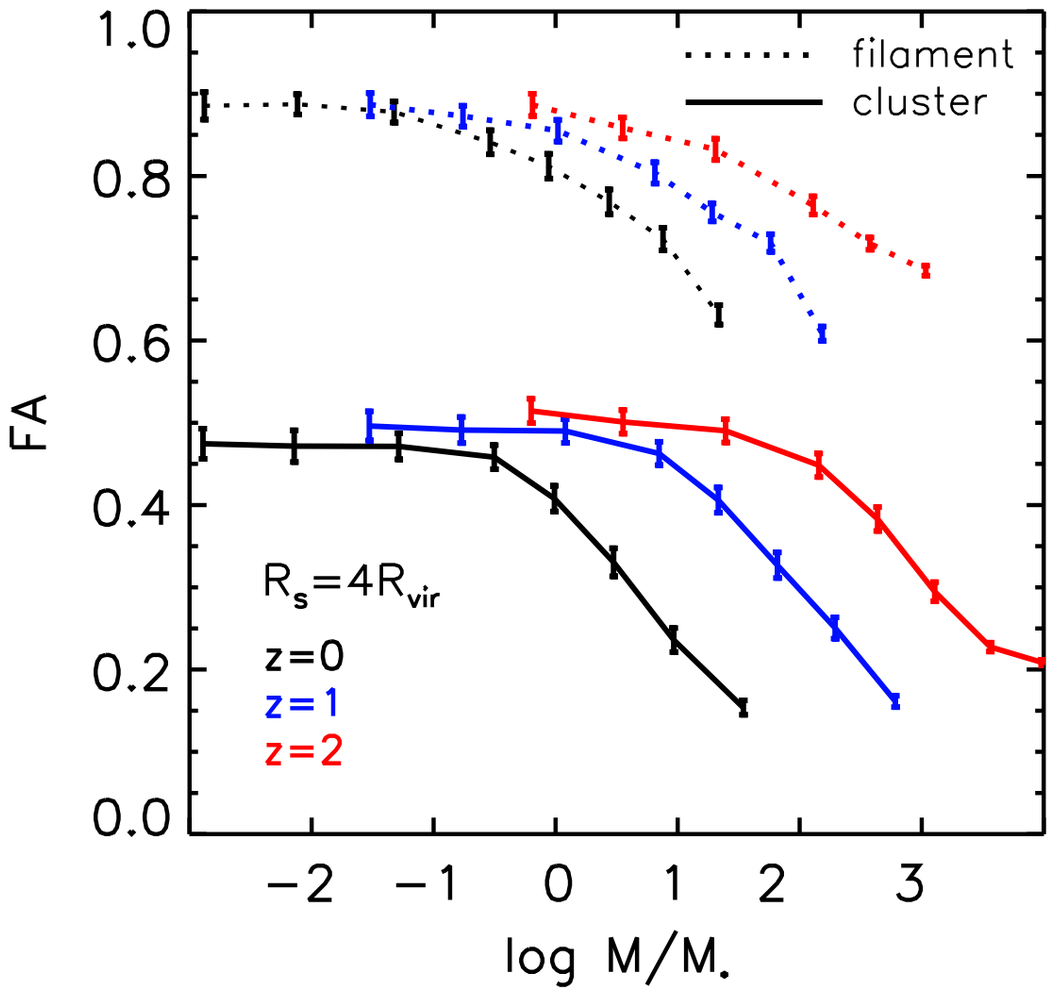
- mass accretion is perpendicular to Filament
- Spin is parallel to Filament

Wang & Kang, 2016 in prep

An useful parameter for anisotropic collapse

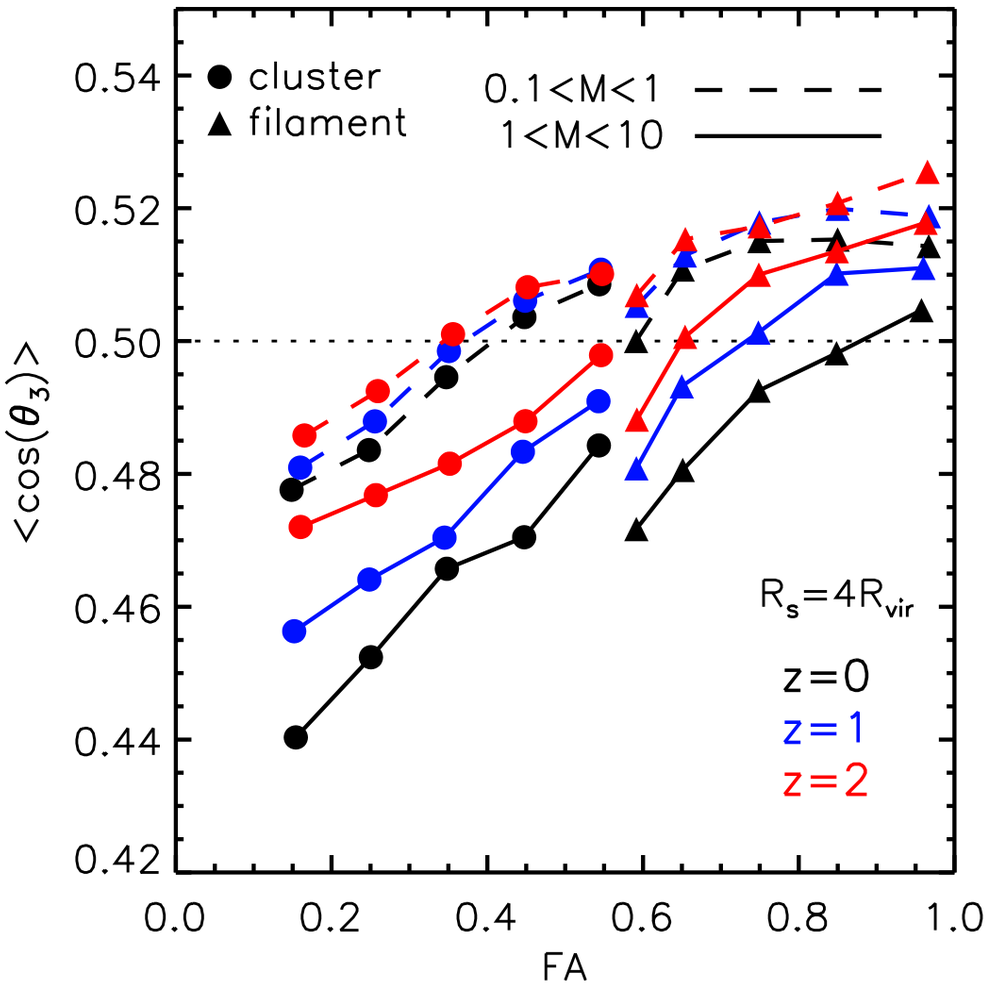
$$\mathrm{FA} = \frac{1}{\sqrt{3}}\sqrt{\frac{(\lambda_1-\lambda_3)^2+(\lambda_2-\lambda_3)^2+(\lambda_1-\lambda_2)^2}{\lambda_1^2+\lambda_2^2+\lambda_3^2}},$$

λ ~ eig of $(\partial_i\partial_j \Phi)$



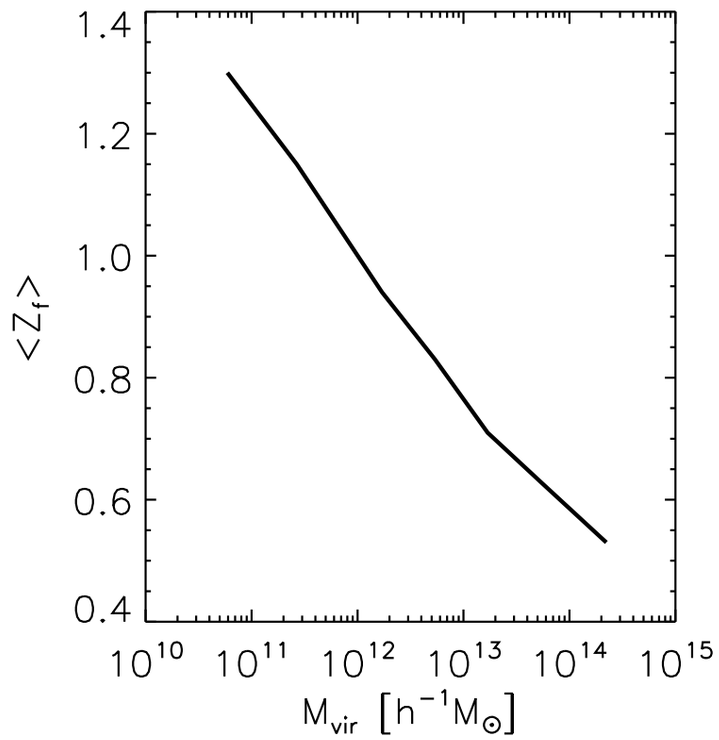
Wang & Kang, 2016 in prep

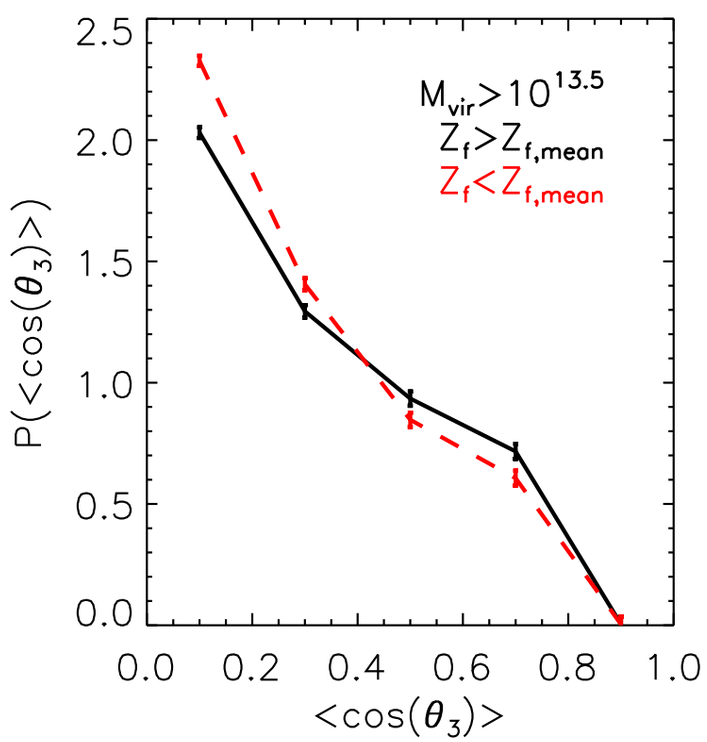
Large FA: highly anisotropy
Lower FA: collapse happen on all directions

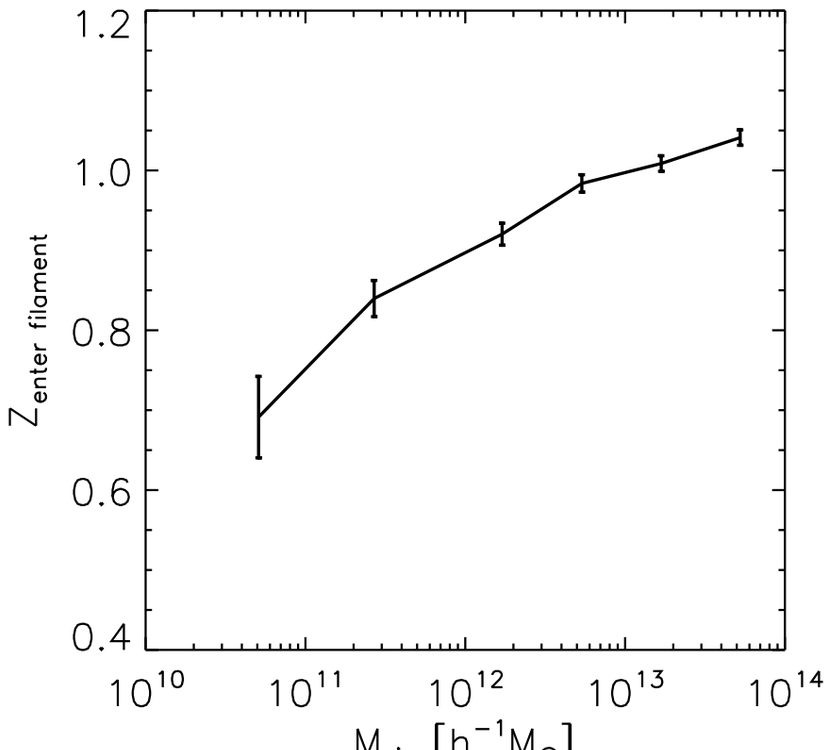


Nodes: spin is normal to e3
Filament: mass dependence

Dependence on time of formation and entering in Filament







Spin-LSS: dependence on Z_formation and Z_filament

- Later formed halo is more perpendicular to filament
- Massive haloes: entering filament first, and then formed later (spin is build by mass accretion along filament)
- Low-mass halo: forms early, but entering filament later (spin is build when they were in wall)

Wang & Kang, 2016 in prep

Summary

- Galaxies are distributed anisotropically on different scales

On small scales

- satellite-central alignment can be ascribed to primordial anisotropy at accretion or the triaxial nature of DM halo
- central galaxy is better aligned with inner halo shape, and alignment increases with halo mass
- subhalo accretion along halo major axis is universal, being strong in massive haloes

On large scales

- Halo spin-LSS is not universal (subhalo accretion along LSS is not universal)
- Low-mass halo forms early, but enter filament later (spin is formed in wall, so parallel to filament)
- High-mass halo enter filament early, but form later (spin is formed in filament by mass accretion along it)

Thank you !