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THE UNIVERSITY OF WESTERN AUSTRALIA

Charlotte Welker

Mergers and Gas accretion onto galaxies: the imprint of the cosmic web

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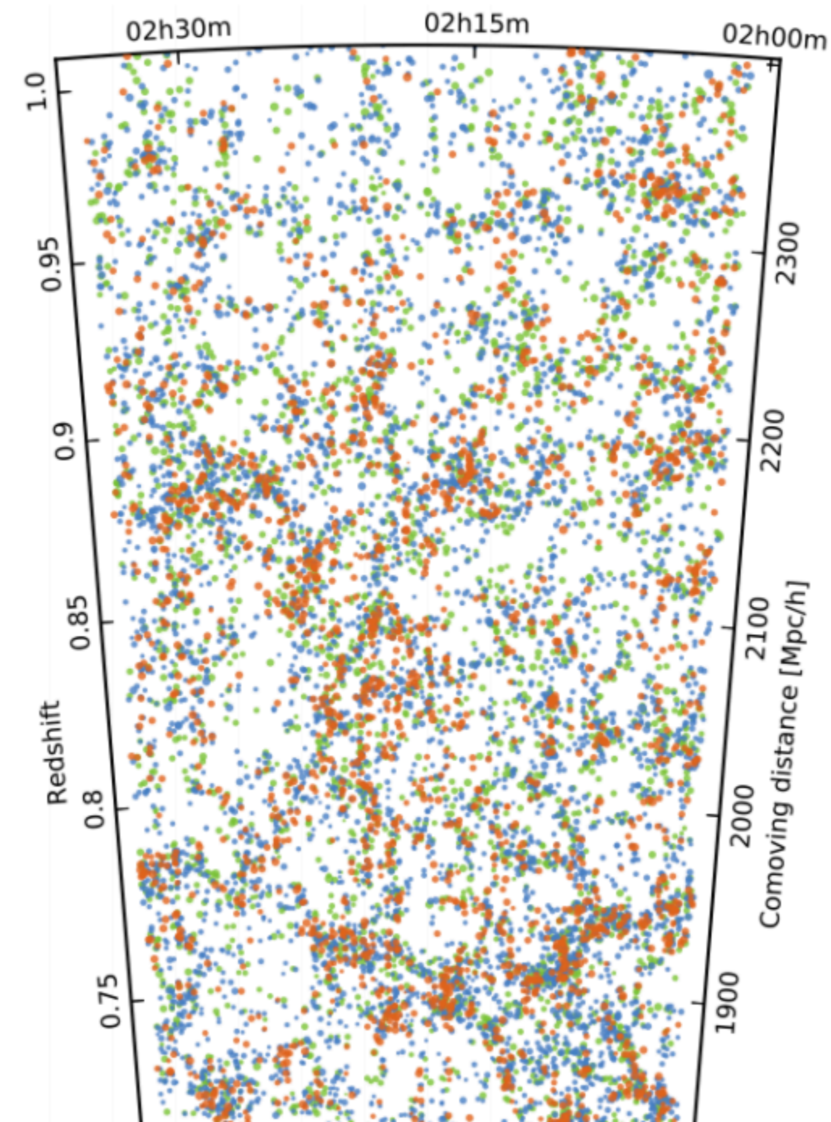
Galaxy formation in the cosmic web

Credit: Guzzo & VIPERS team (2013)

☛ Galactic properties correlated to anisotropically distributed density:

Implications?

Red galaxies
Green valley
Blue galaxies



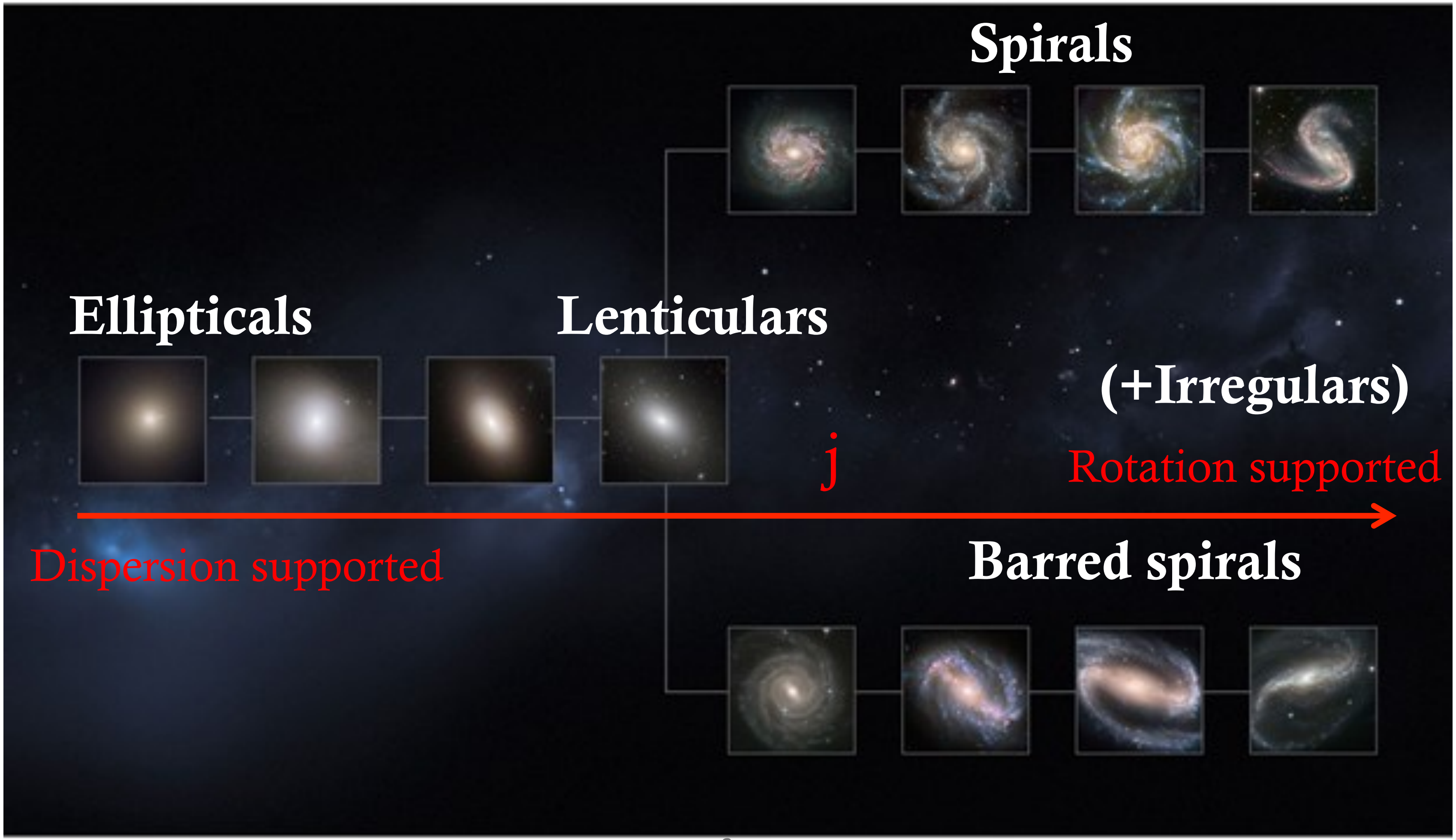
☛ Angular momentum

hidden variable?

The Hubble sequence

Hubble (1936)

Credit: NASA, ESA, M. Kornmesser



Simulations in this talk:

- ☛ Cosmological Hydrodynamical runs with Gadget and Ramses.
- ☛ Hydrodynamical zooms on haloes with Gadget, Ramses, Arepo.
- ☛ Large scale cosmological "full physics" run with Ramses: **Horizon-AGN**

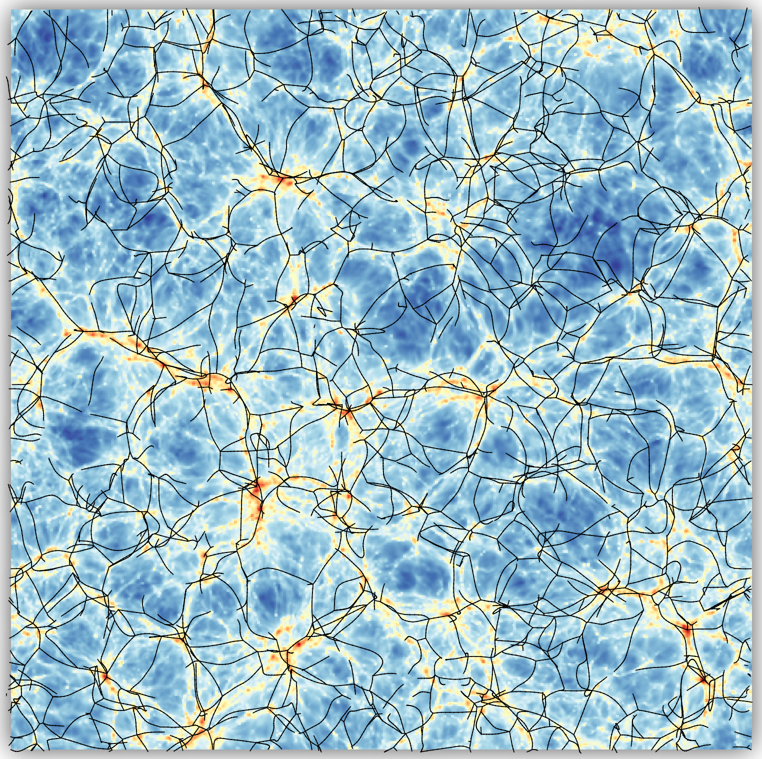
  100 Mpc.h-1 cubic box
  UV reheating, cooling, star formation, metal release
  feedback from SNI, SNII, AGN: quasar and jets

  1 kpc maximal resolution

Tracing spin swings in the Cosmic web

Pick your favourite cosmic web extractor….

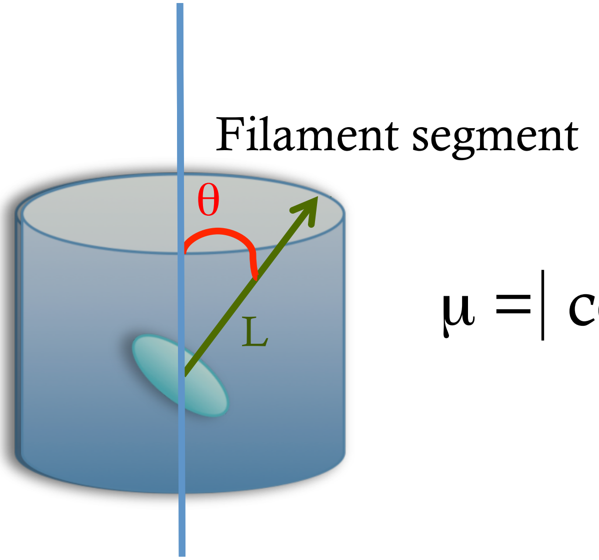
Gas, 10 Mpc projected map



- Horizon-AGN: Skeleton (Sousbie 2009 +DisPerse, Sousbie 2011)

- Detecting the ridge lines of the density field
- Fully connected network
- Topolological extractor, naturally multiscale

- **DisPerse:** can be applied on real data (particles or grids)
- No smoothing: persistence level, "S/N ratio threshold"

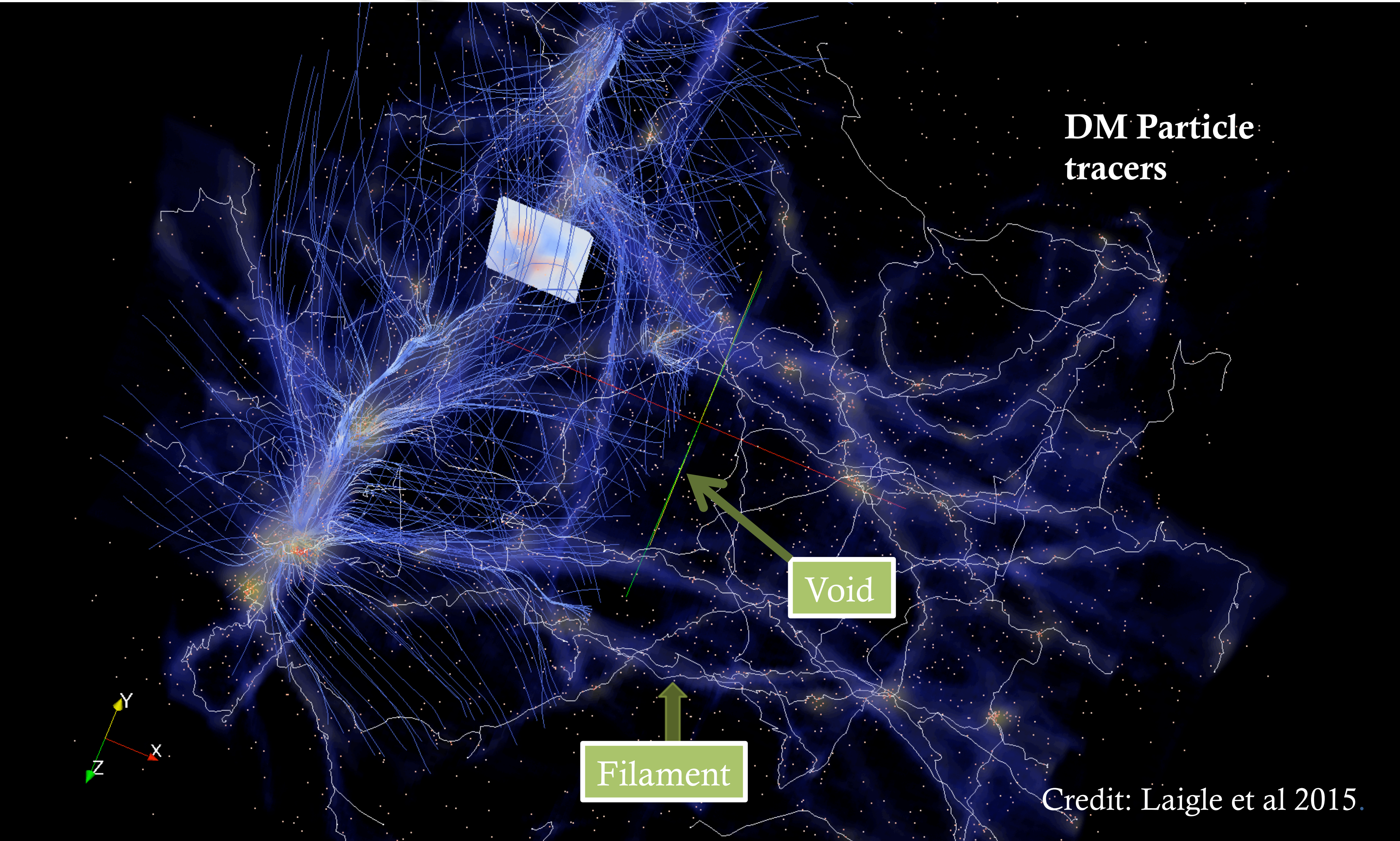


$$\mu = |\cos(\theta)|$$

[1] Kinematics of the cosmic web: a brief recap

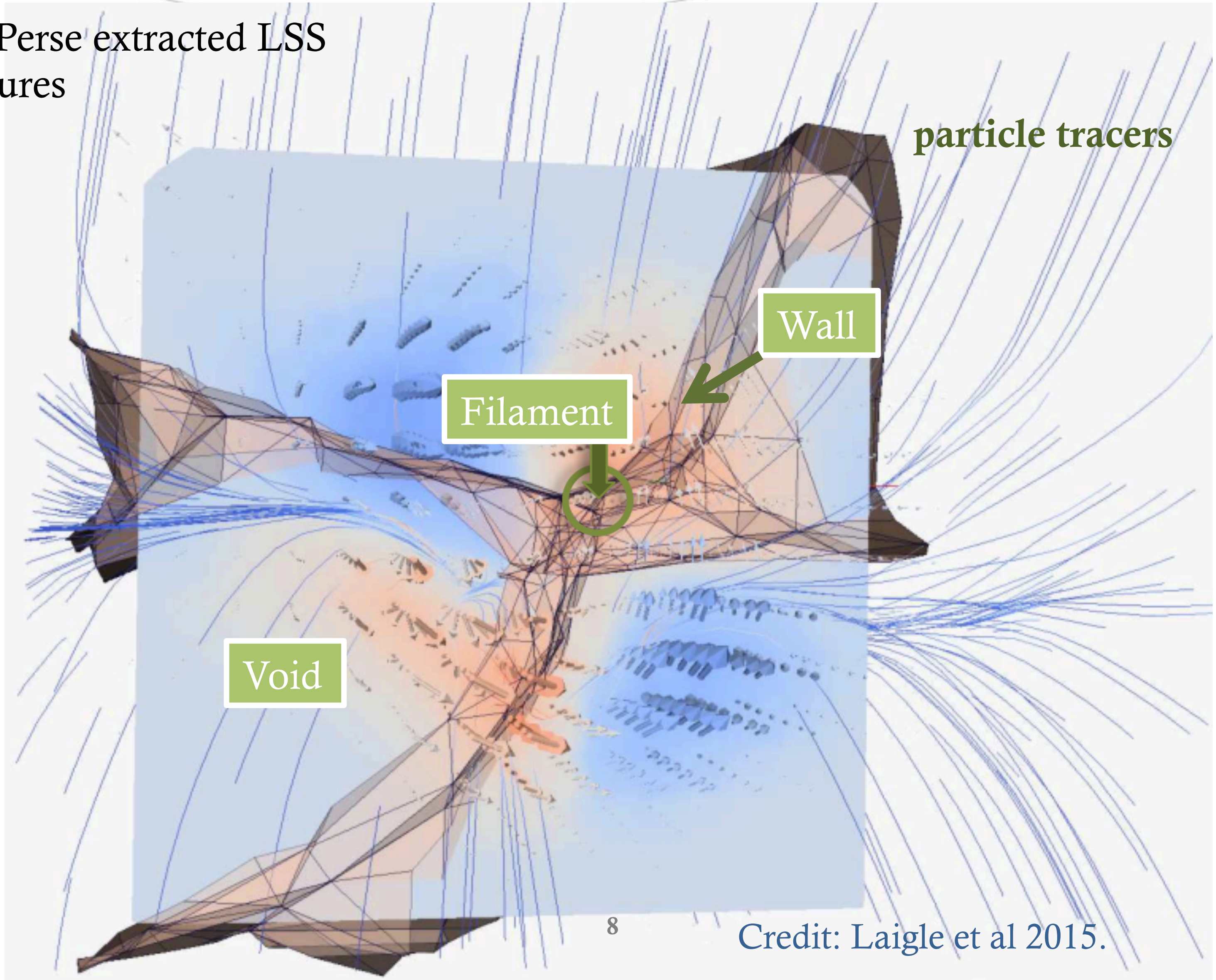
Cosmic Flows in the vicinity of filaments.

Kinematics of the cosmic web



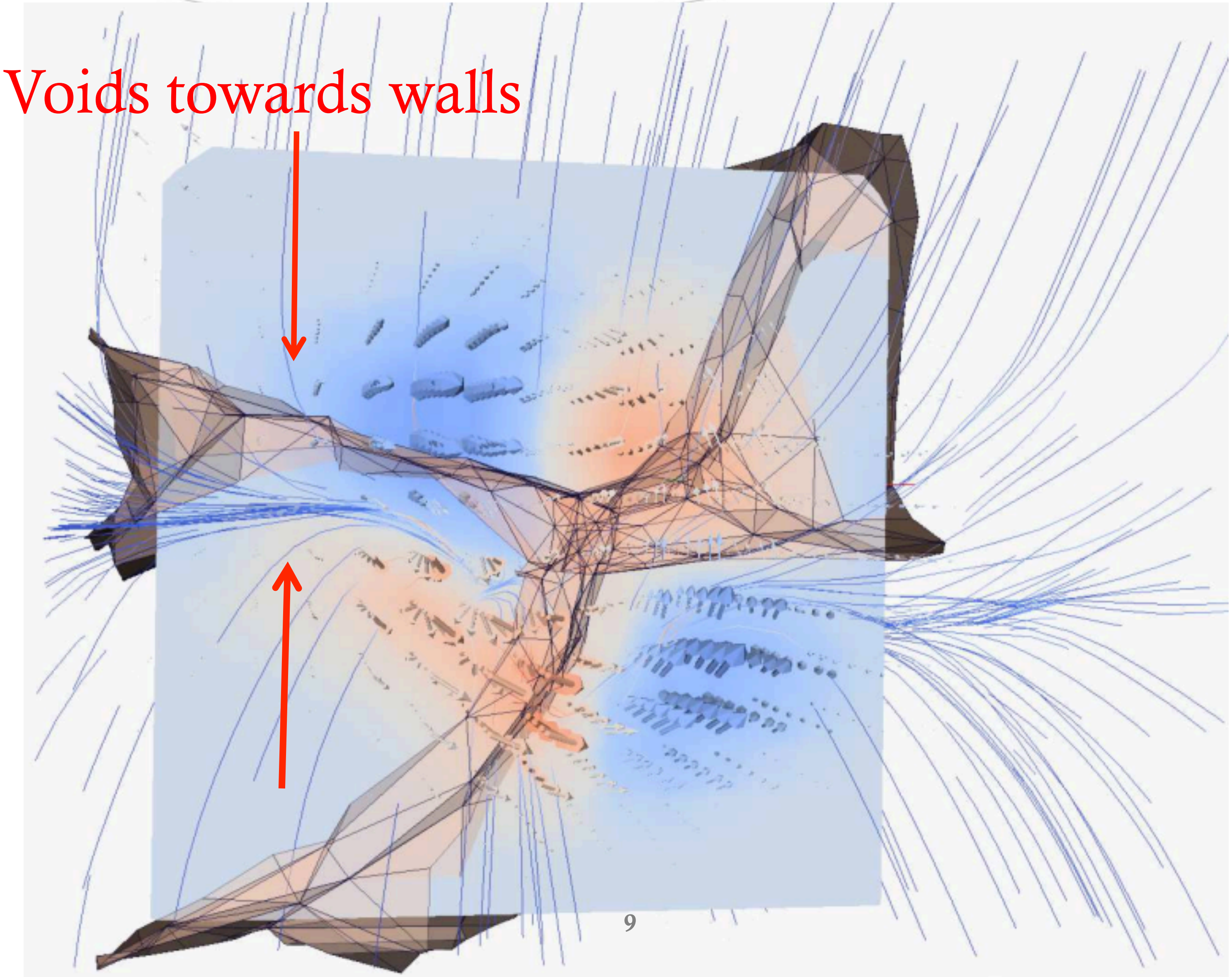
Kinematics of the cosmic web

DisPerse extracted LSS features

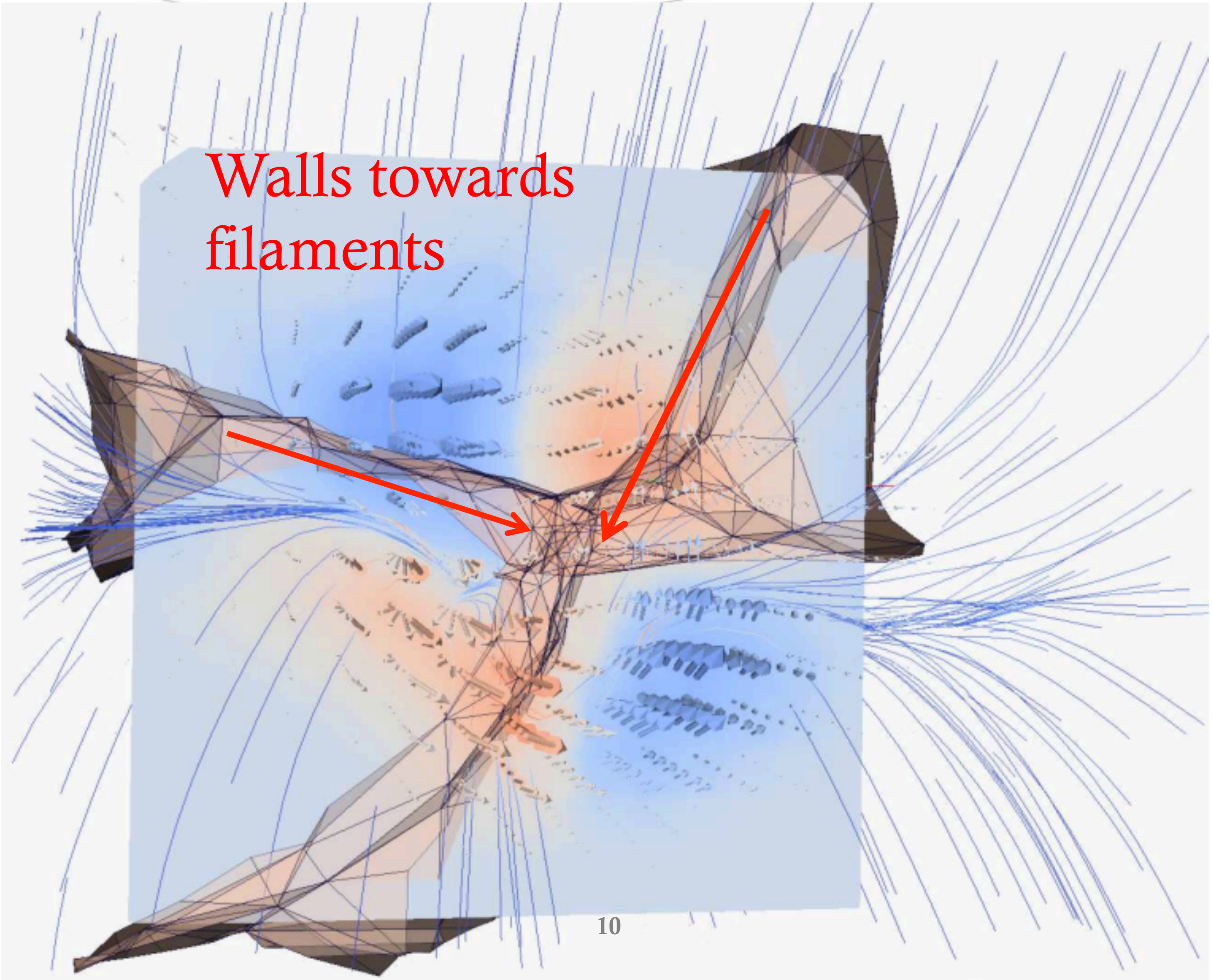


Credit: Laigle et al 2015.

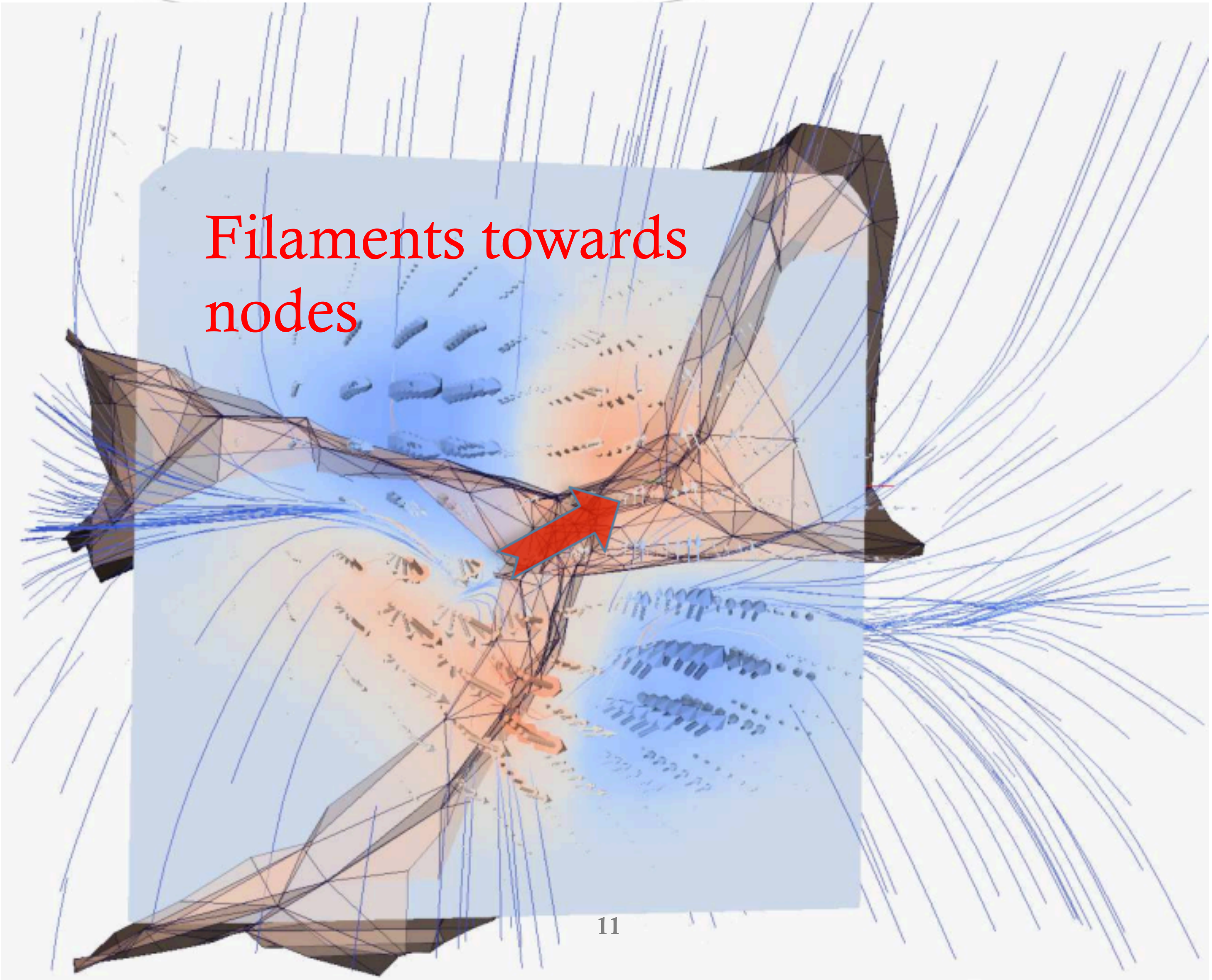
Kinematics of the cosmic web



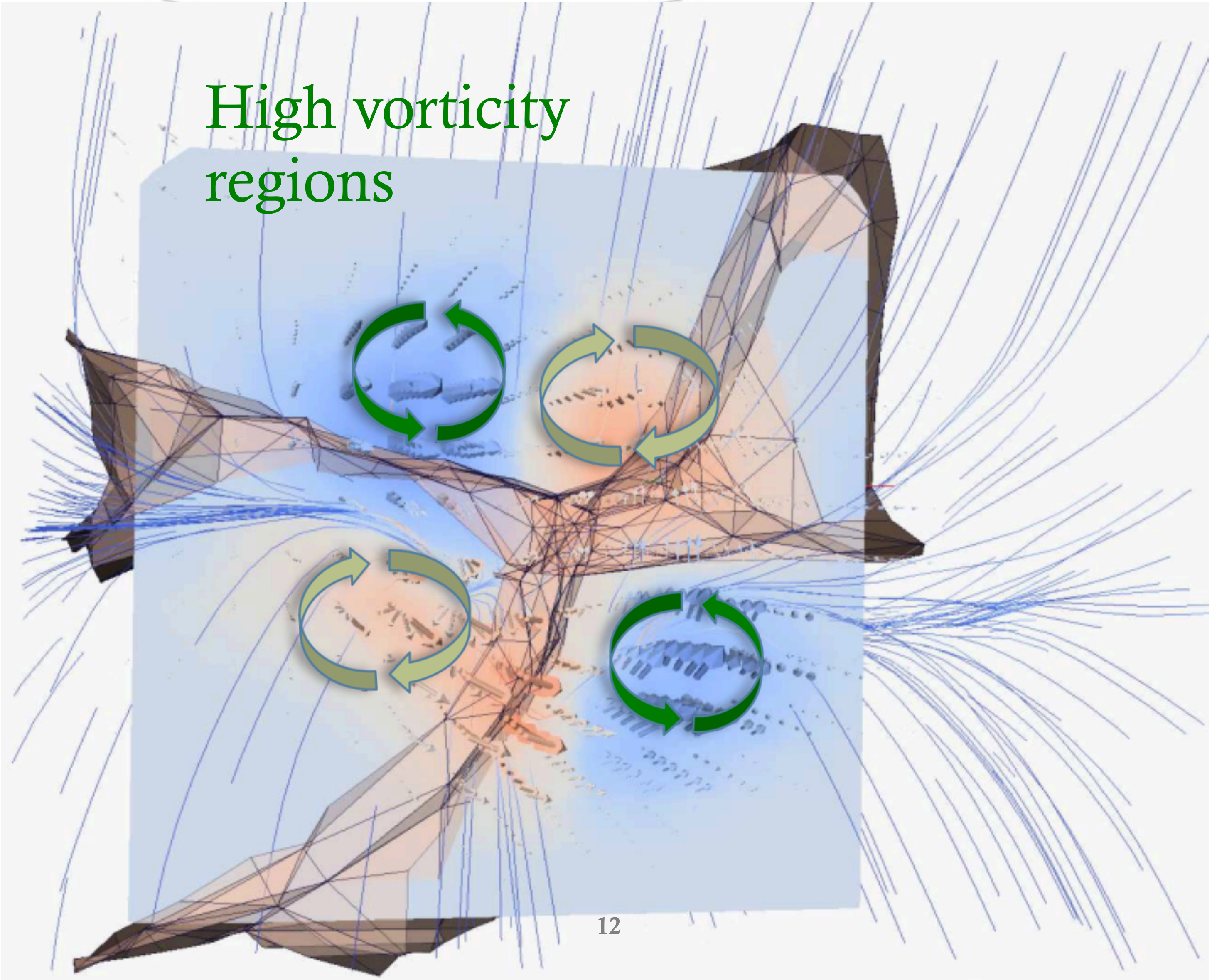
Kinematics of the cosmic web



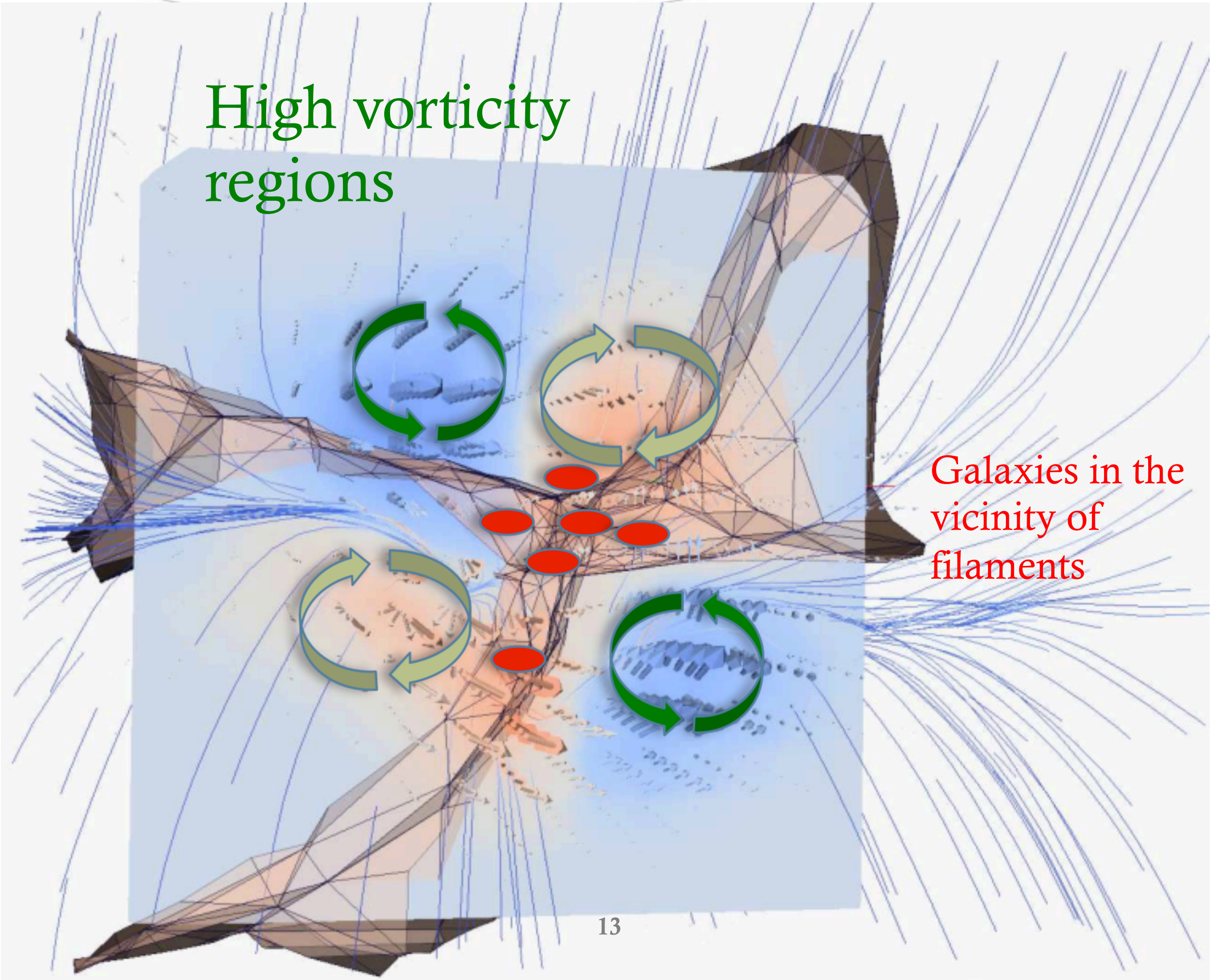
Kinematics of the cosmic web



Kinematics of the cosmic web



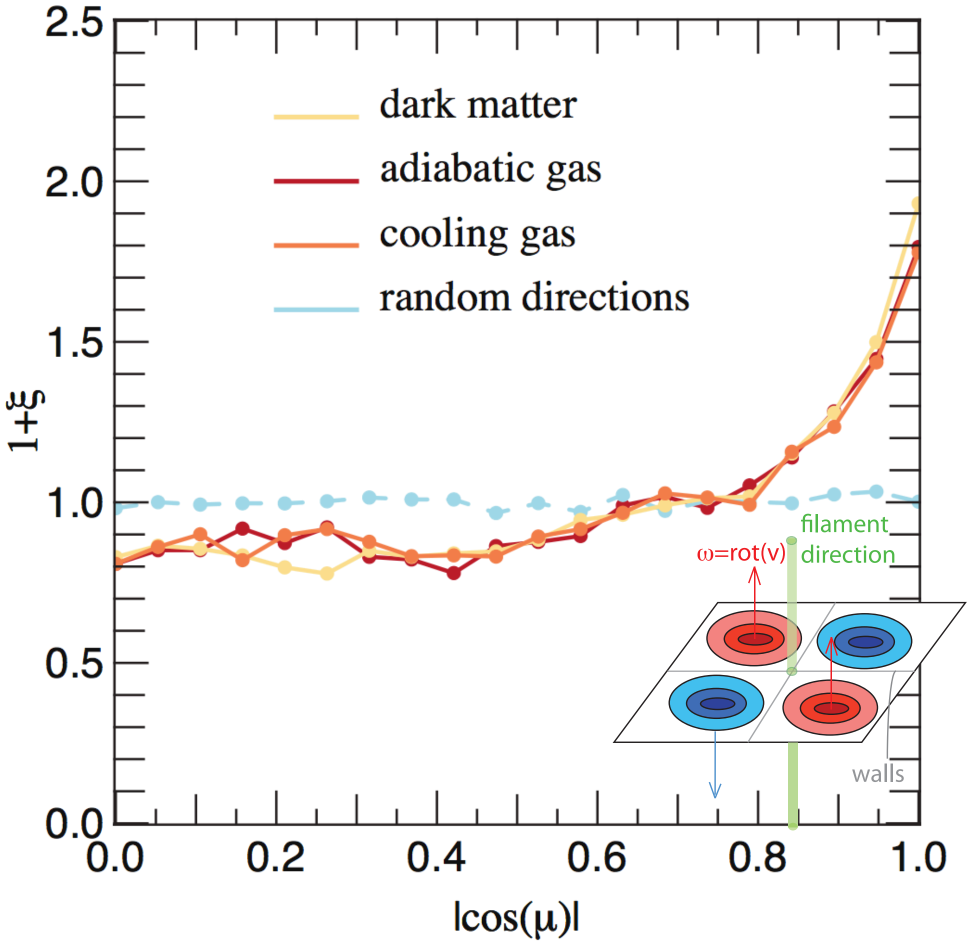
Kinematics of the cosmic web



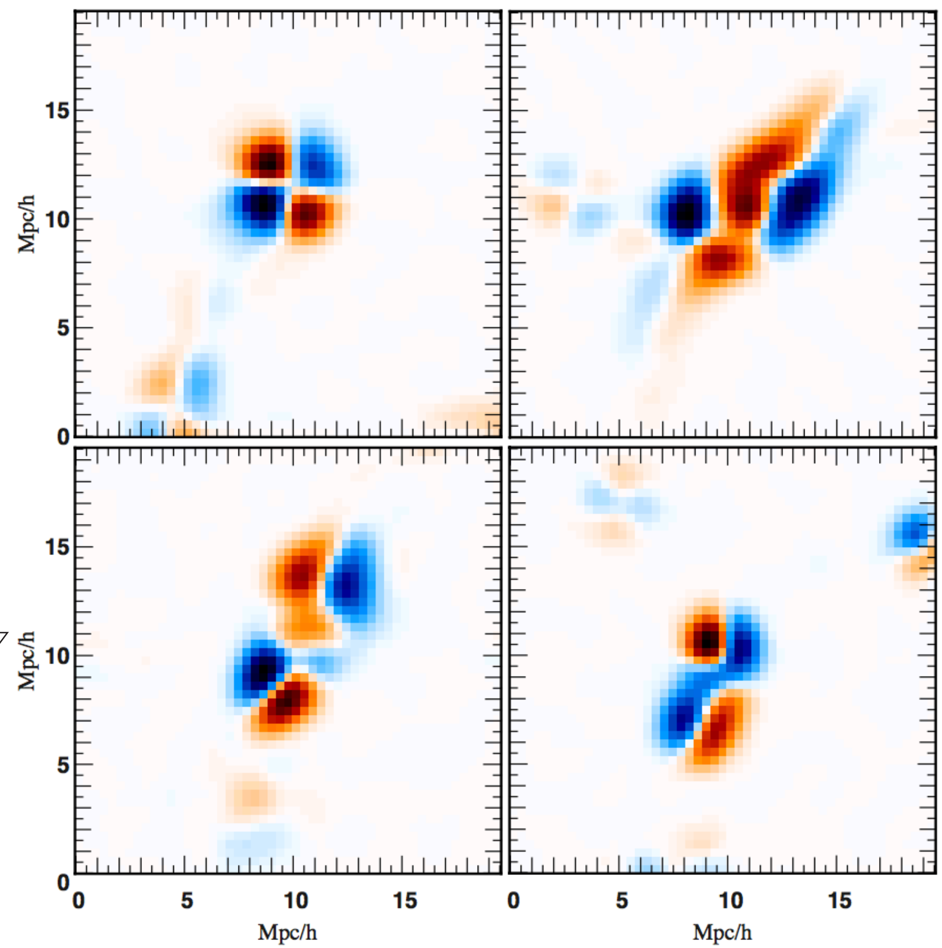
Vorticity-filament alignment

Laigle et al 2015

PDF of the vorticity-filament angle



Vorticity Sz maps (filament cross-sections)



Credit: Laigle et al 2015.

The gaseous cosmic web

☛ DM particles shell-cross but gas shocks and radiatively cools:

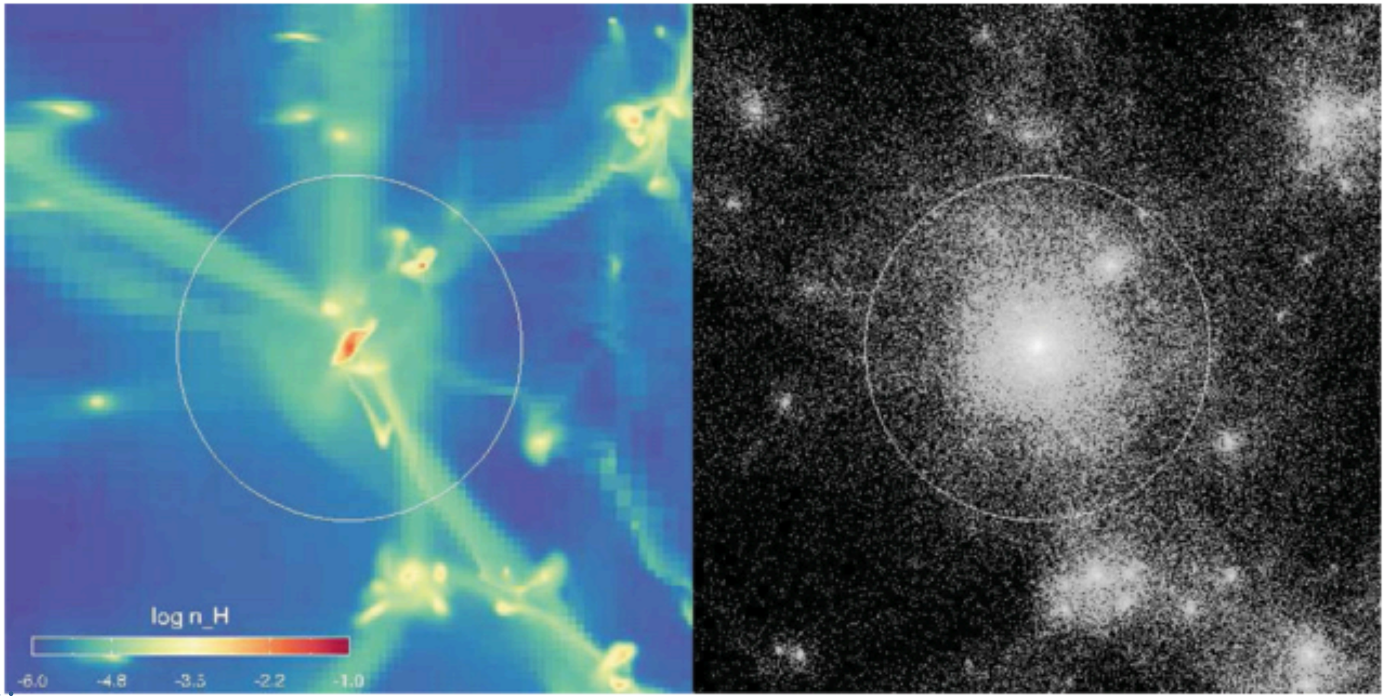
gas filaments significantly thinner than DM counterpart!

Gas (AMR) **Dark matter particles**

Z=3.8

Mh=2 10^12 Msun

Rvir=79 kpc



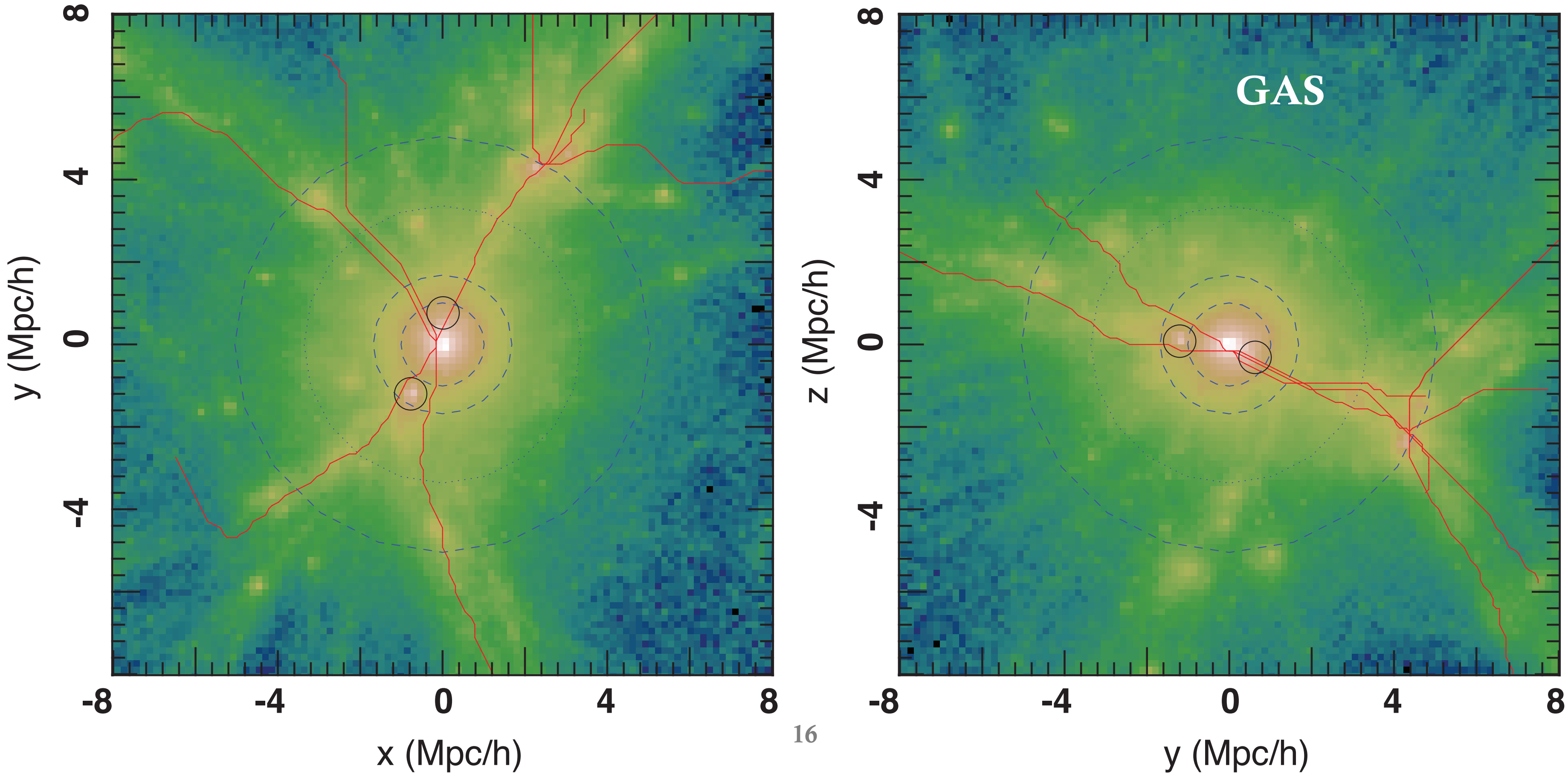
Credit: Pichon et al 2011.

2.1) Structure of gas inflows

Nifty comparison, in prep

Large scales:

- 10^14 -10^15 Msun clusters: connectivity remains around 3-5



2.1) Structure of gas inflows

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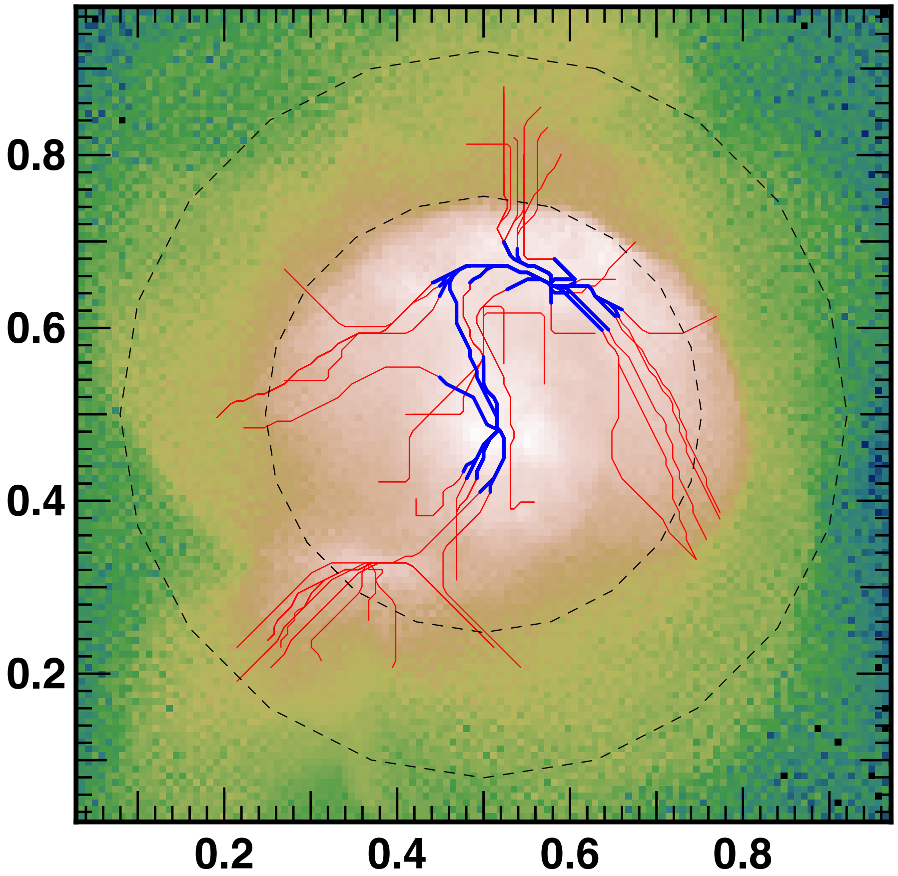


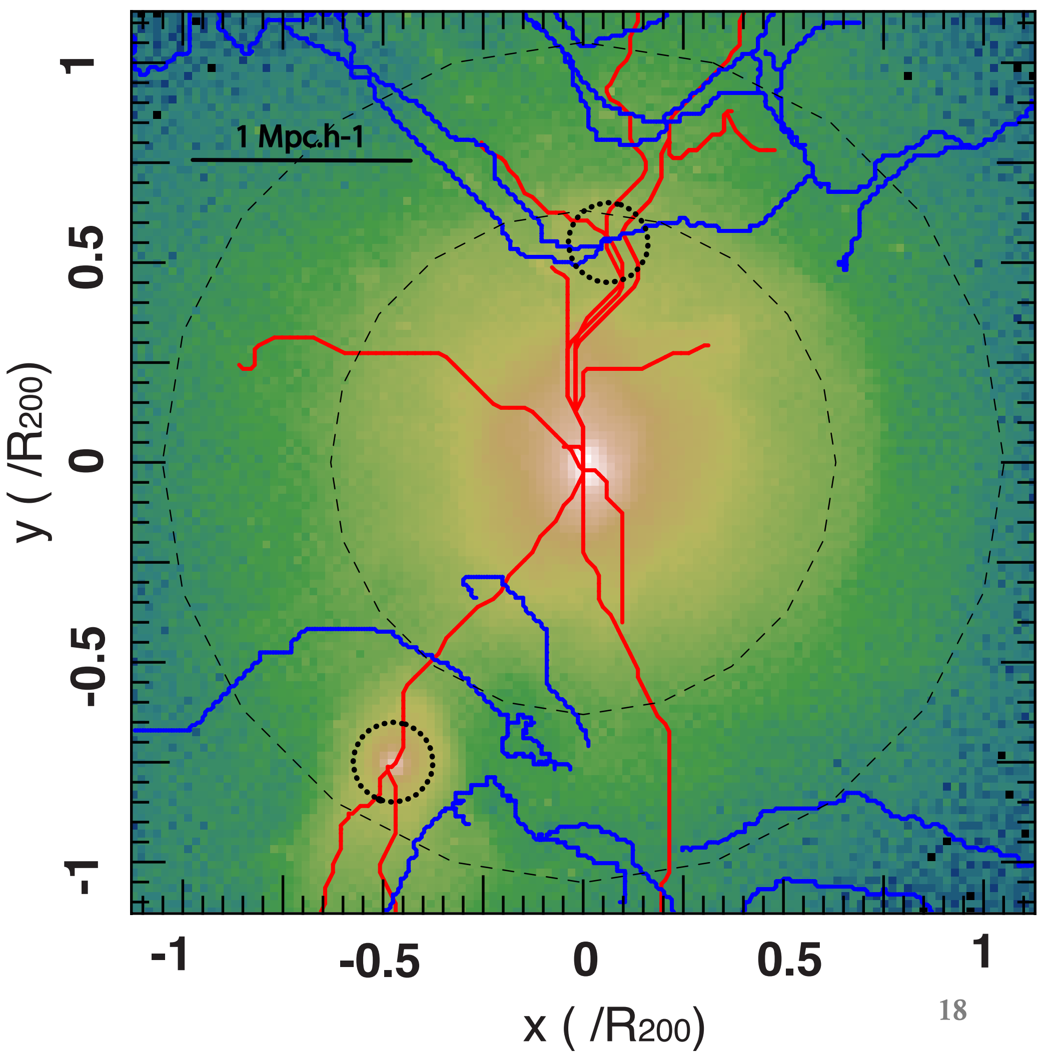
Skeleton (filaments)

Highest robustness

- filamentary structure survives shocks at ~1-2 Rvir
- Tested with RAMSES, GADGET, AREPO (Nifty comparison)

2.1) Structure of gas inflows

Nifty comparison, in prep



Skeleton (filaments)

Anti-skeleton (depletion contours)

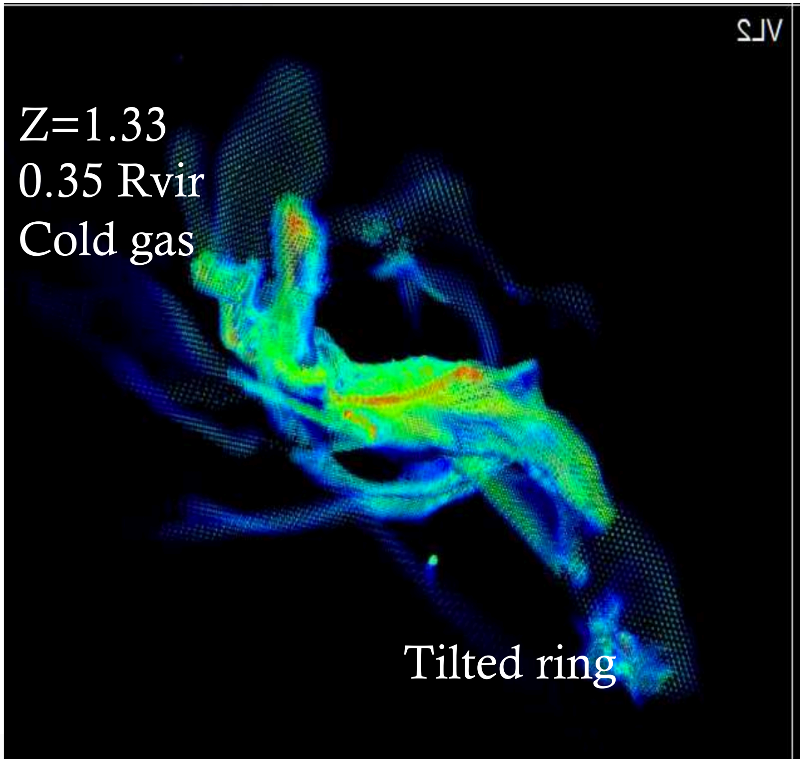
- filamentary structure survives shocks at ~1-2 Rvir
- Tested with RAMSES, GADGET, AREPO (Nifty comparison)

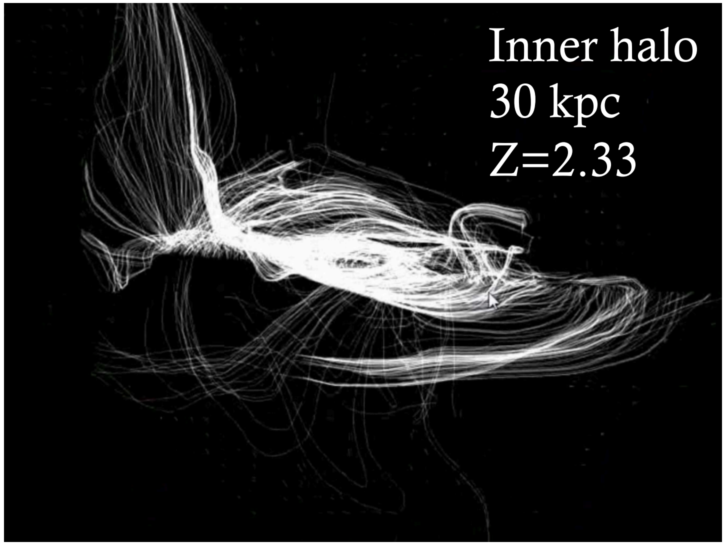
Structure of gas inflows

Cold flows at z>1

- torques from misaligned halo/galaxy
- Net angular momentum transfer from neighbouring "pushing" voids (cause braided vorticity tubes).

Helix like structure (Pichon 2011, Danovich 2015)





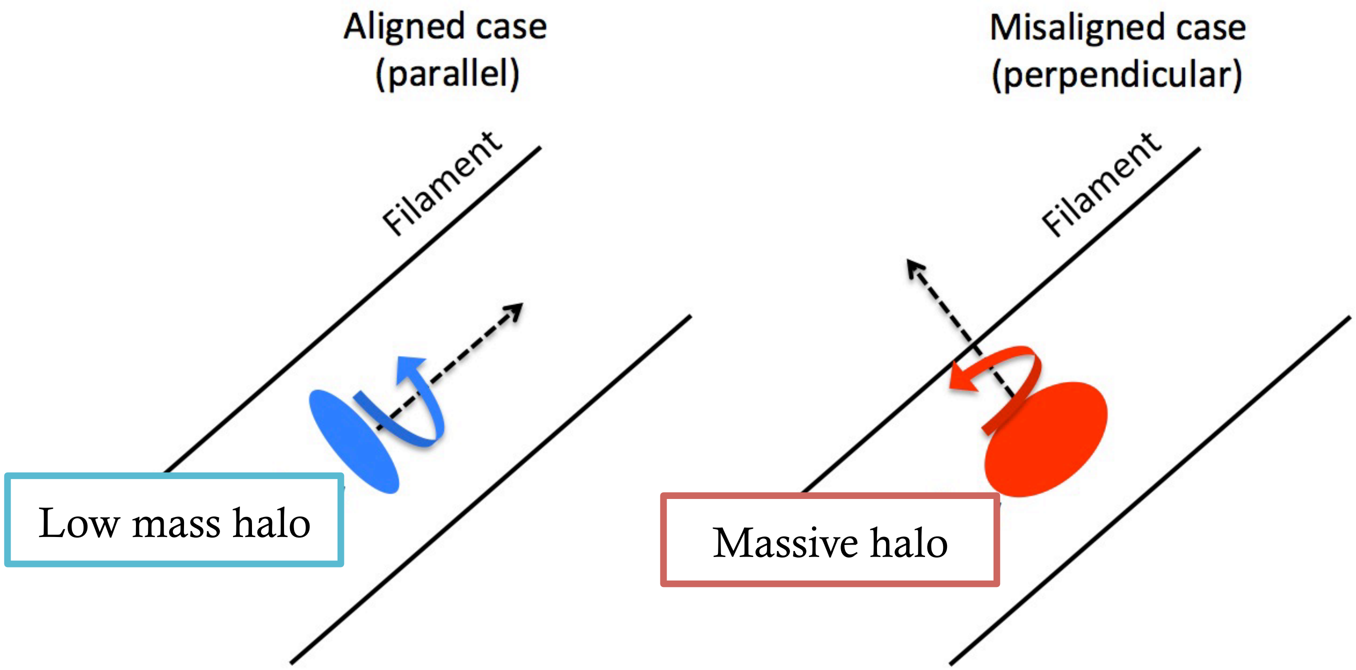
streamlines

Credit: Danovich 2015.

[2a] Impact on the spin of haloes and galaxies

1) Simulated haloes
2) Simulated galaxies
3) Real galaxies

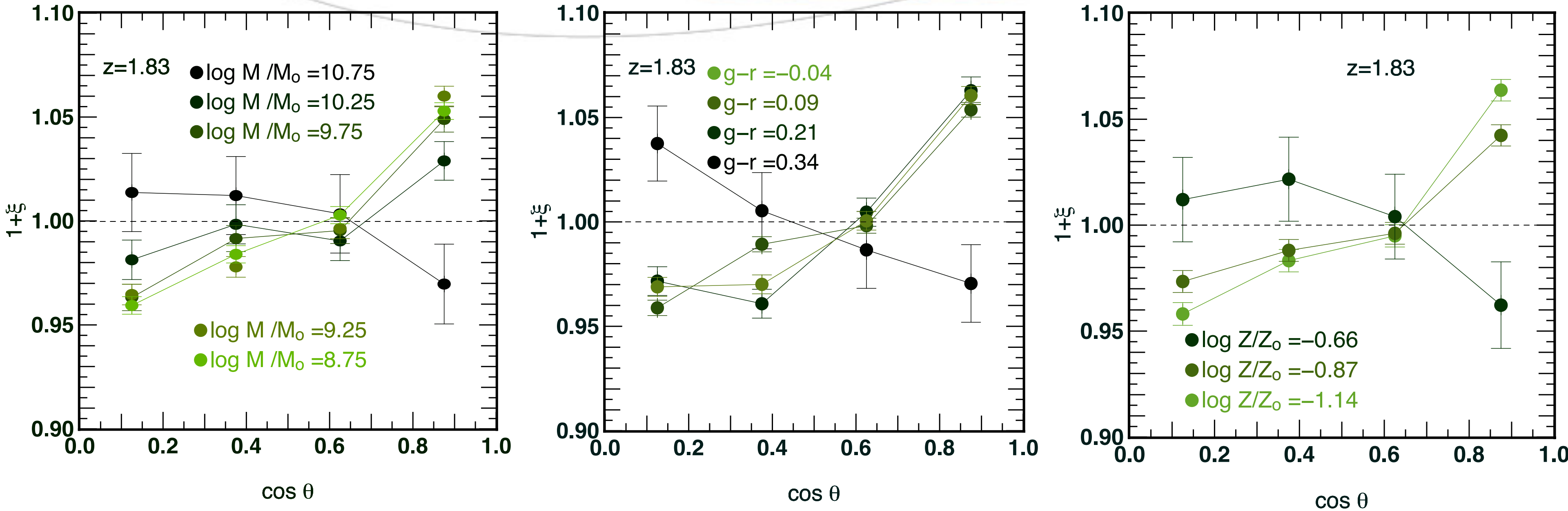
Swings for dark haloes in simulations…



Aragon-Calvo 2007, Hahn 2007, Paz 2008, Codis 2012

It holds true for synthetic galaxies (multiple tracers)

Spin orientation distribution for galaxies



☛ **We recover the alignement/ perpendicular signal.**
Consistent with dark haloes

Log(M$_{trans}$/M$_{sun}$)= 10.25-10.75

- Low-mass, young, centrifugally supported, metal-poor, bluer galaxies : aligned
- Massive, high velocity dispersion, red, metal-rich old galaxies: perpendicular

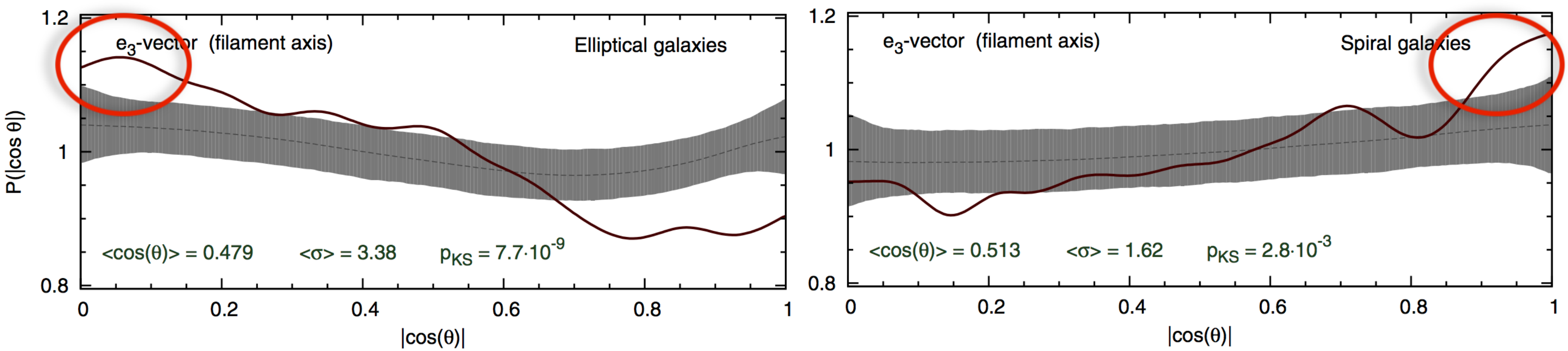
Dubois, Pichon, Welker et al 2015

… and real galaxies likewise!

☛ recent observations in SDSS

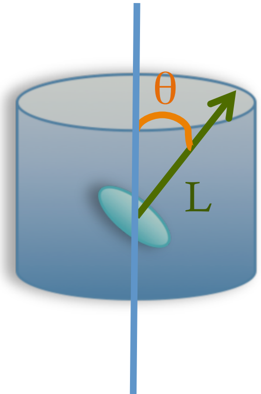
Tempel & Libeskind 2013

! z<0.5



SDSS DR8

- **Elliptical galaxies**: perpendicular to filaments
- **Spiral galaxies**: aligned with filaments



$\mu = |\cos(\theta)|$

[2b] Mechanisms of spin acquisition

1) Eulerian view: smooth accretion vs mergers
2) Lagrangian theory

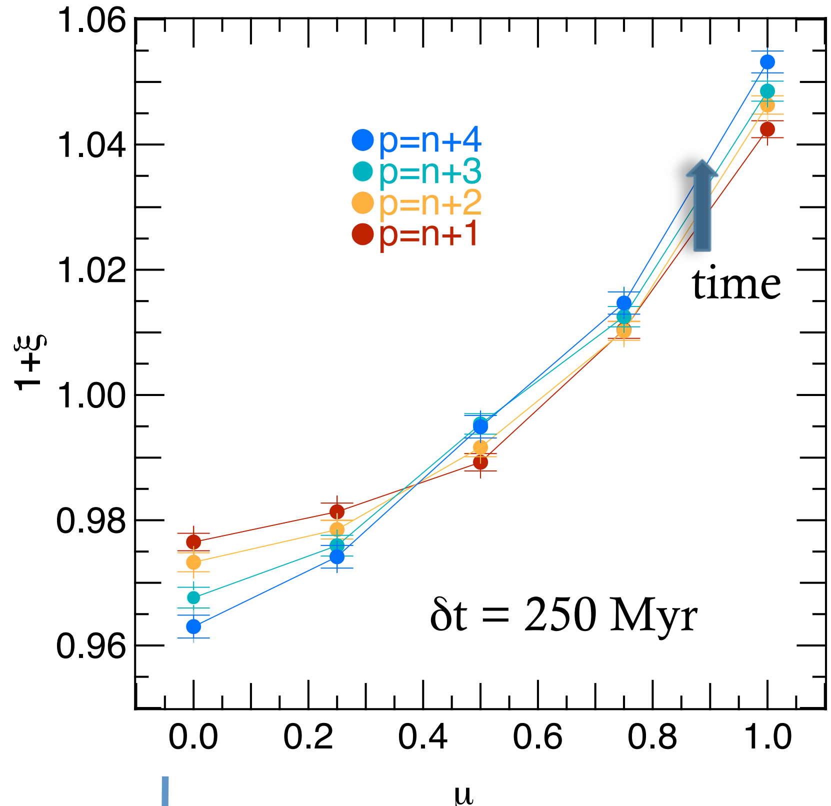
Spin swing dynamics

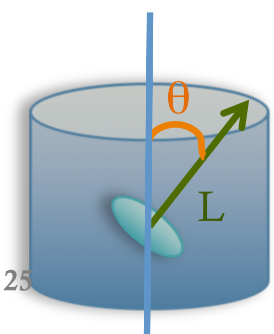
Smooth accretion

SMOOTH ACCRETION

- ☛ Gas inflows (re)-align galaxies with their filament

PDF of μ over 4 timesteps δt





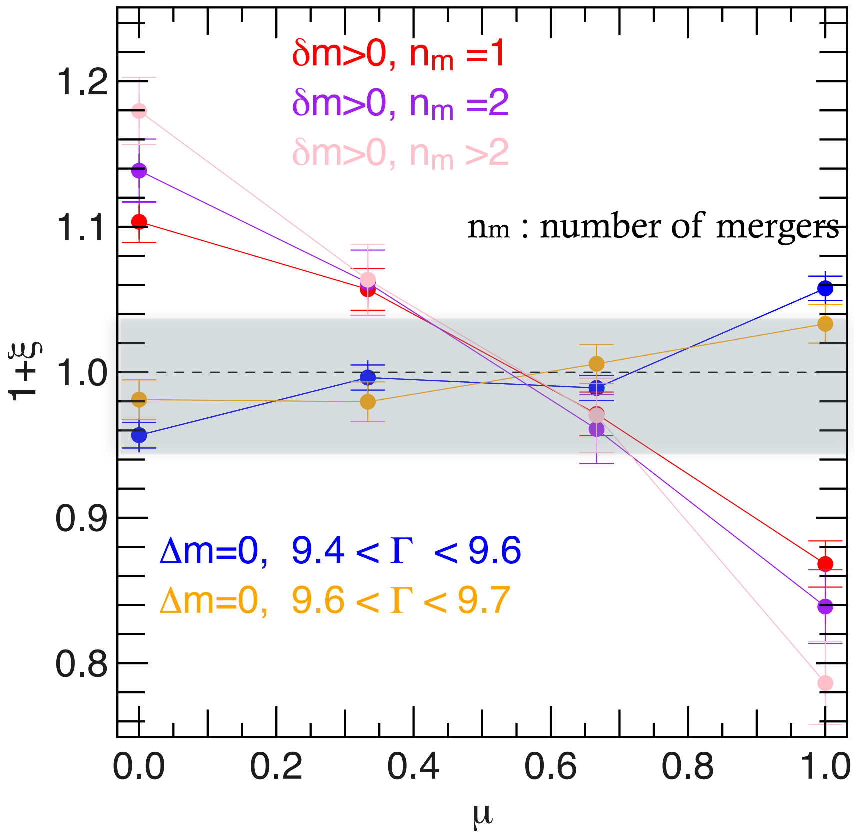
$\mu = |\cos(\theta)|$ Spin-filament angle

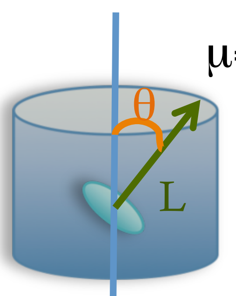
- ξ : excess probability

Spin swing dynamics

Mergers

PDF of μ for different merging histories



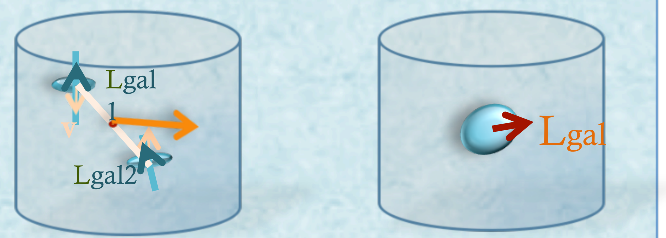


$\mu = |\cos(\theta)|$

Red to pink:
merged between z=5.2 and z=1.8

Blue to yellow:
never merged, $\Gamma = \log(M/M_{sun})$

MERGERS



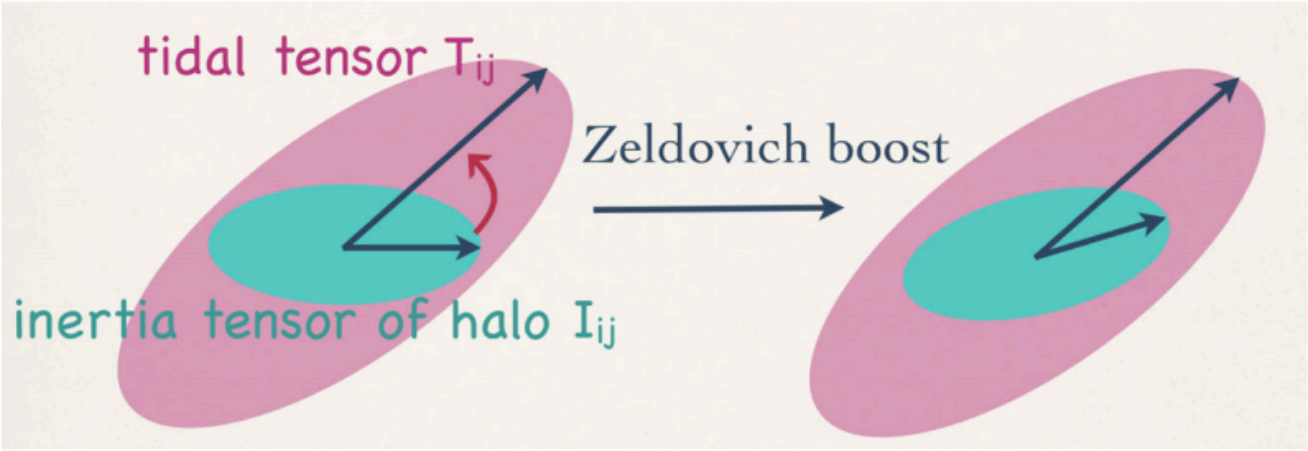
- Mergers drive galactic spin flips.
- ☛ Mergers flip the spin perpendicular to the filament

Stronger signal than for galactic properties!

A lagrangian theory exits!

See Codis et al 2015.

Tidal Torque Theory: $$L_i = \sum_{j,k,l} a^2(t)\dot{D}_+(t)\epsilon_{ijk} I_{jl} T_{lk}$$



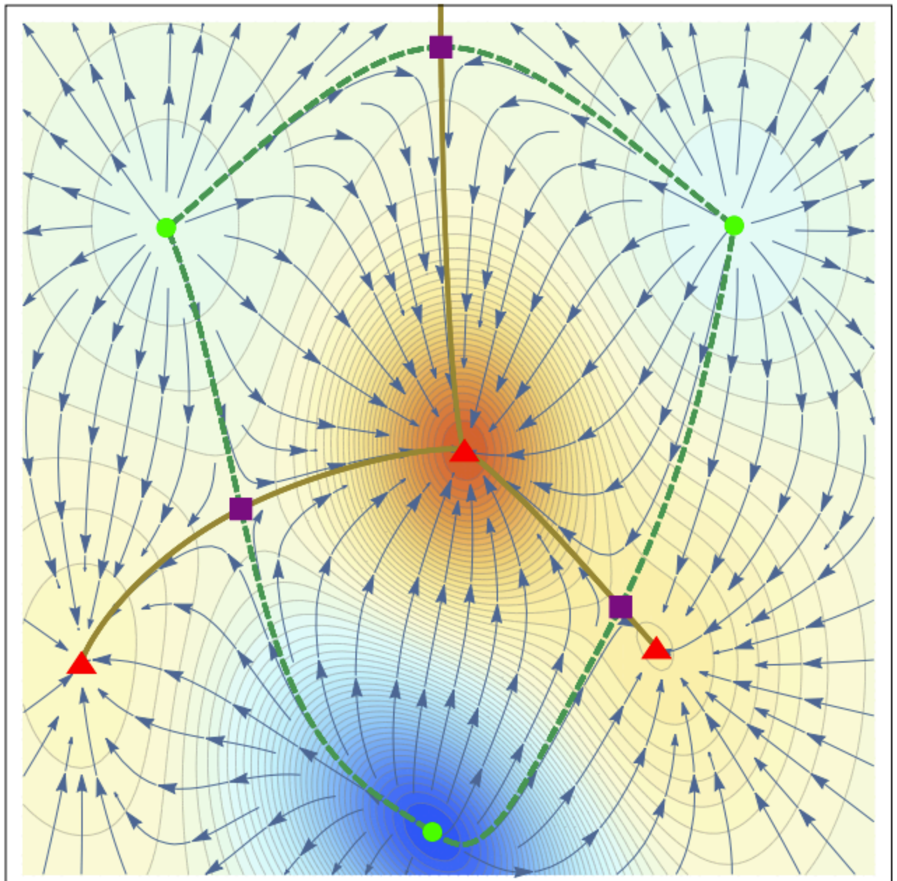
☛ **In the vicinity of a filament: anisotropic environment !**

See Codis et al 2015.

Insights from lagrangian theory

See Codis et al 2015.

☛ Proto-filament in the initial density field:



➢ Line connecting two maxima (proto-nodes) through a saddle point

maximum

saddle point

minimum

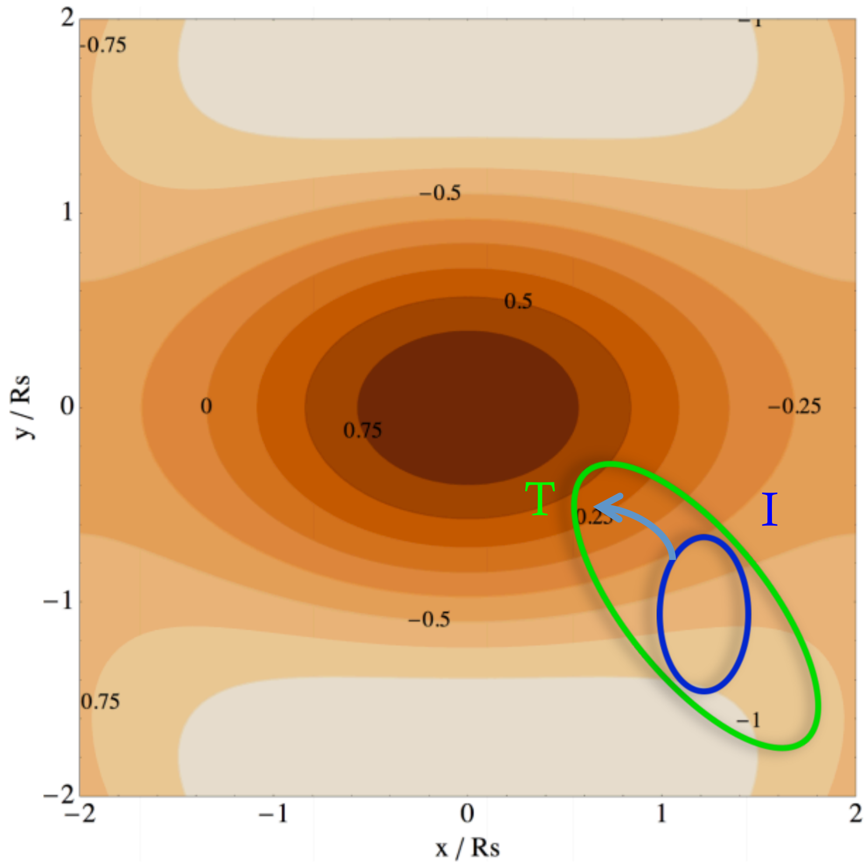
2D gaussian random field

Insights from lagrangian theory

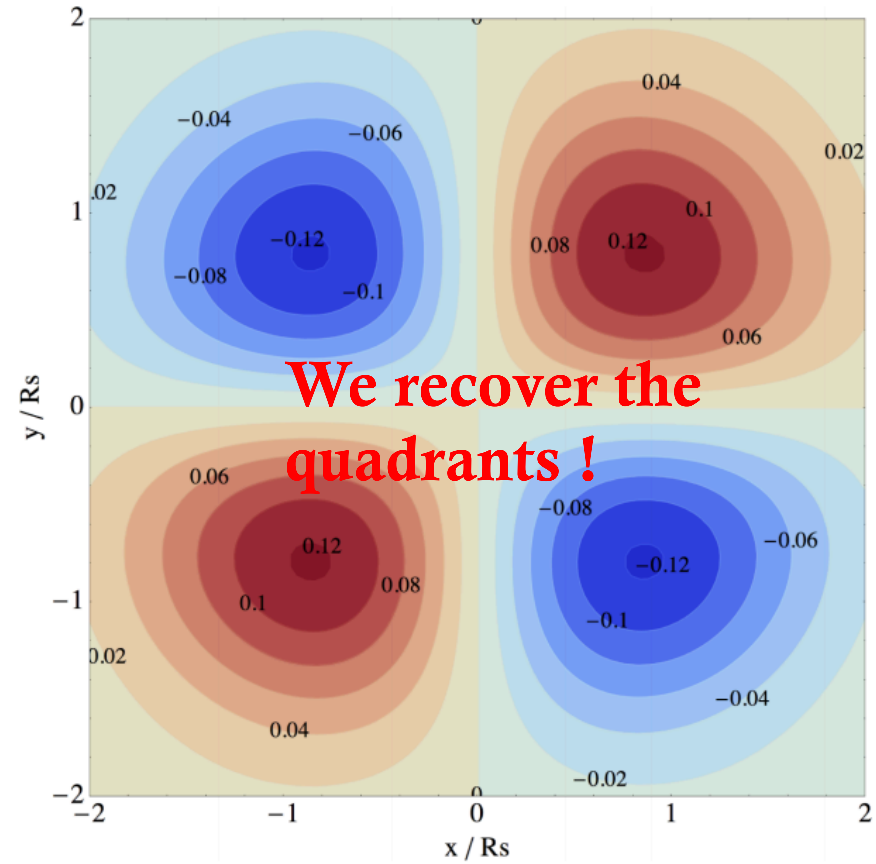
See Codis et al 2015.

In the plane of the saddle point orthogonal to filament:

2D density map



2D spin map

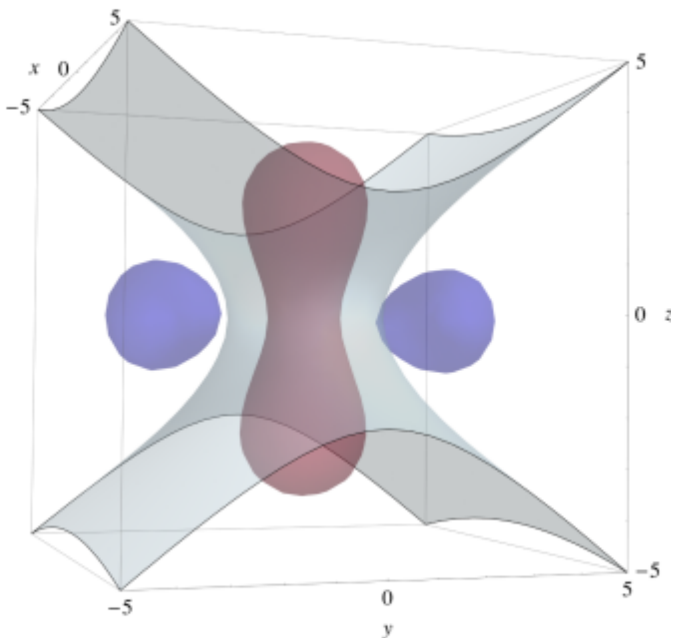


Insights from lagrangian theory

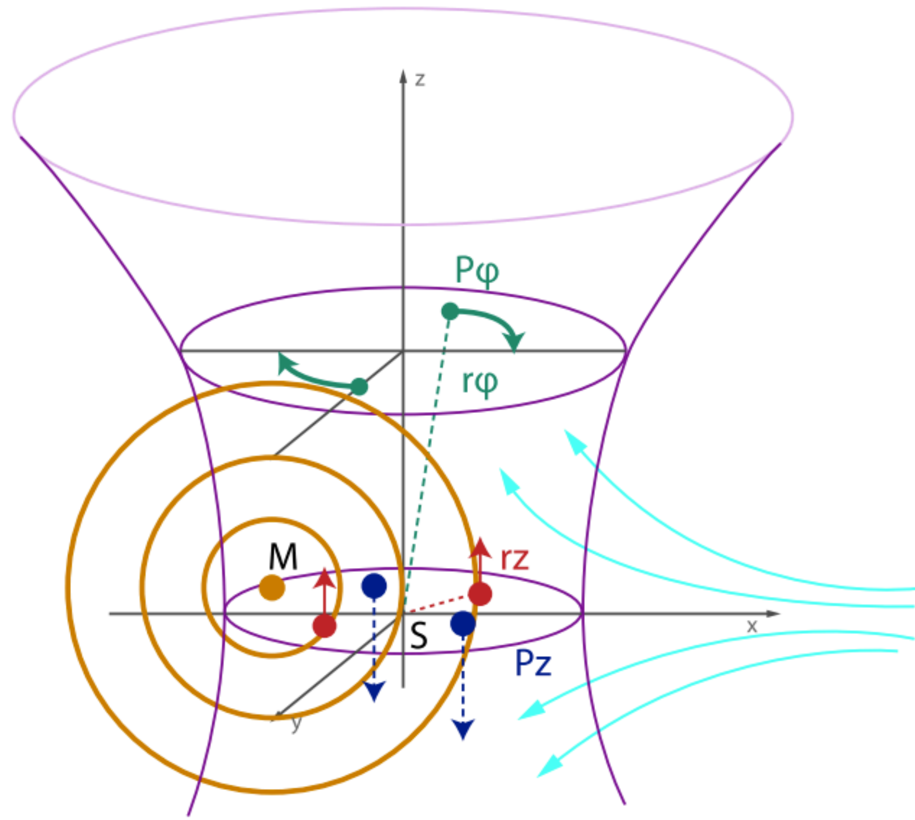
See Codis et al 2015.

- ☛ Same GRF analysis around a filament-type saddle point constraint in 3D:
- ☛ Compute expectations for δ and ***s***

Density map



Sketch of the spin distribution

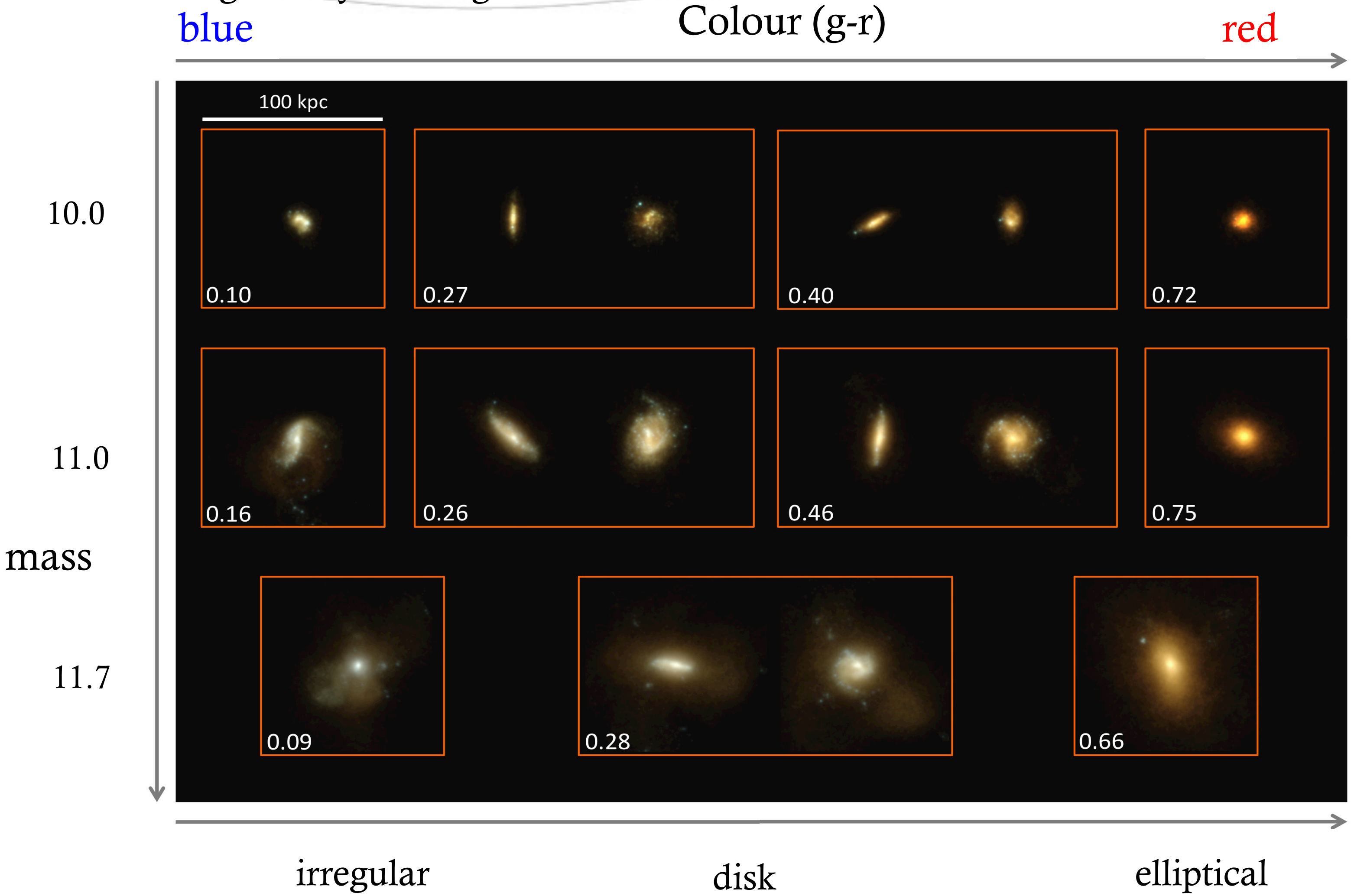


[2c] Impact on the mopholgy of galaxies

Statistical study in Horizon-AGN

Morphological variety in Horizon-AGN

Rest-frame colour images of synthetic galaxies



Galactic Morphologies

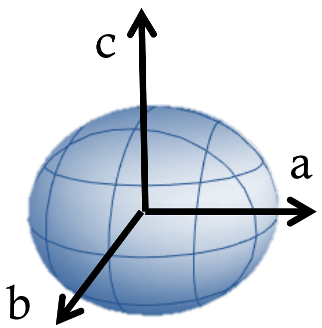
Inertia tensor:

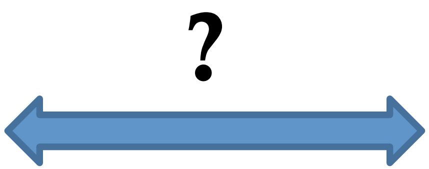
$$I_{ij} = \Sigma_l m^l (\delta_{ij}.(x^l_k.x^l_k) - x^l_i.x^l_j)$$

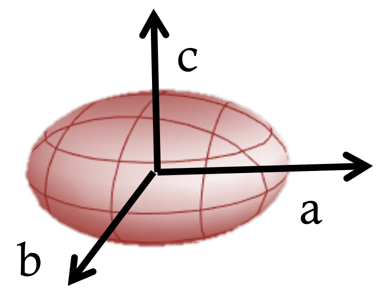
Moments and ellipsoid axis:

$$\lambda_1 > \lambda_2 > \lambda_3$$

$$c < b < a$$







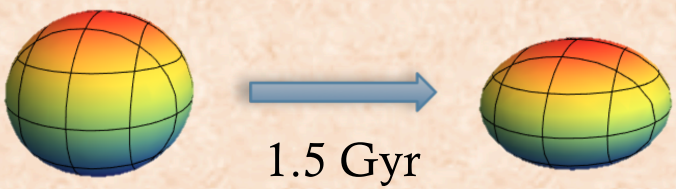
- Spheroids: $c/a > 0.7$
  $b/a > 0.8$

- Disks : $c/a < 0.45$
  $b/a < 0.55$

Galactic morphologies: Smooth accretion

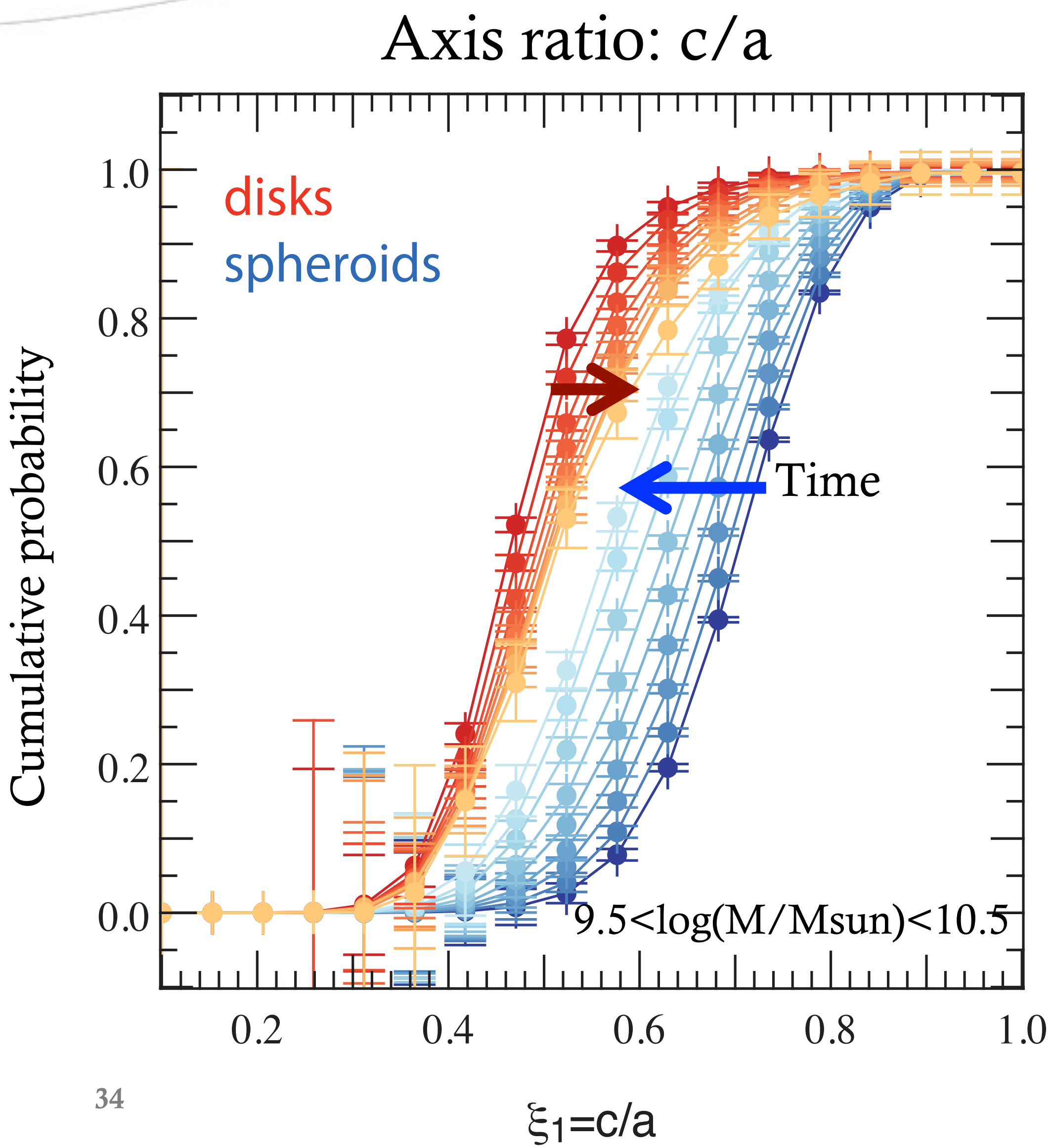
SMOOTH ACCRETION

- Gas inflows flatten spheroids over time along the filament direction



Dark to light: 1.5 Gyr

Cumulative probability of axis ratios ξ over a time step (250 Myr)

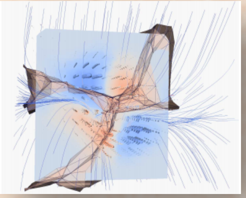


Galactic morphologies: Smooth accretion

SMOOTH ACCRETION

- Gas inflows flatten spheroids over time along the filament direction

Up to the transition mass!

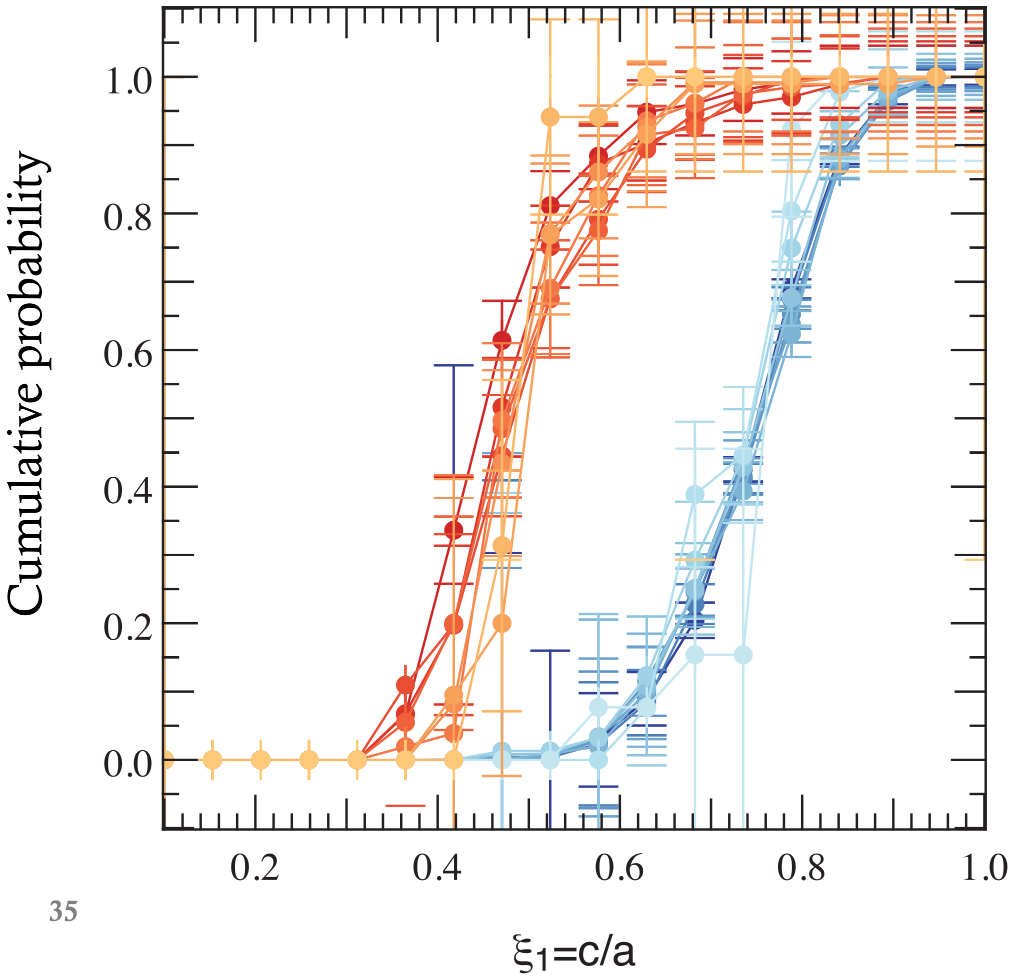


Dark to light: 1.5 Gyr

Cumulative probability of axis ratios ξ over a time step (250 Myr)

log(M/Msun)>10.5

Axis ratio: c/a

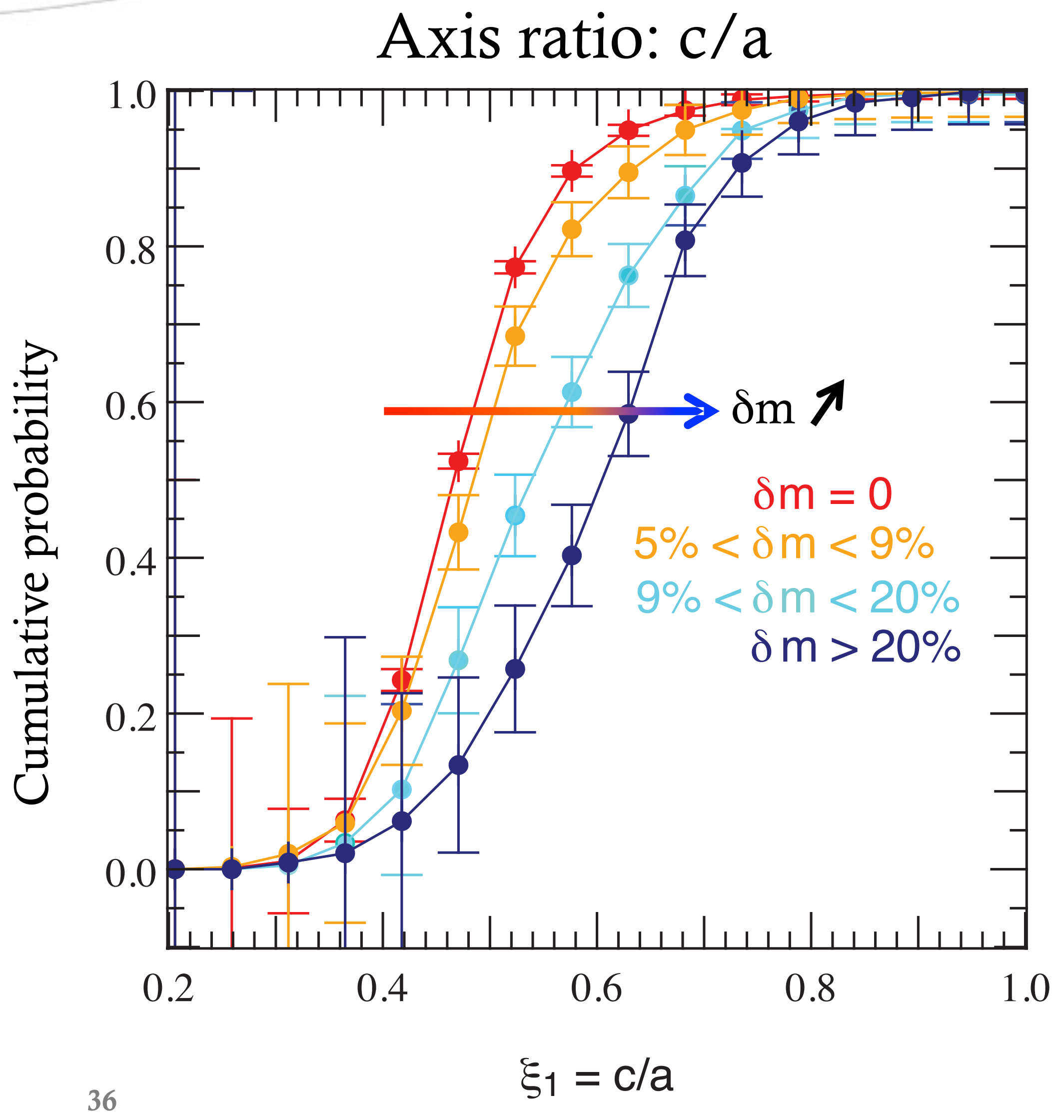


Galactic morphologies: Mergers

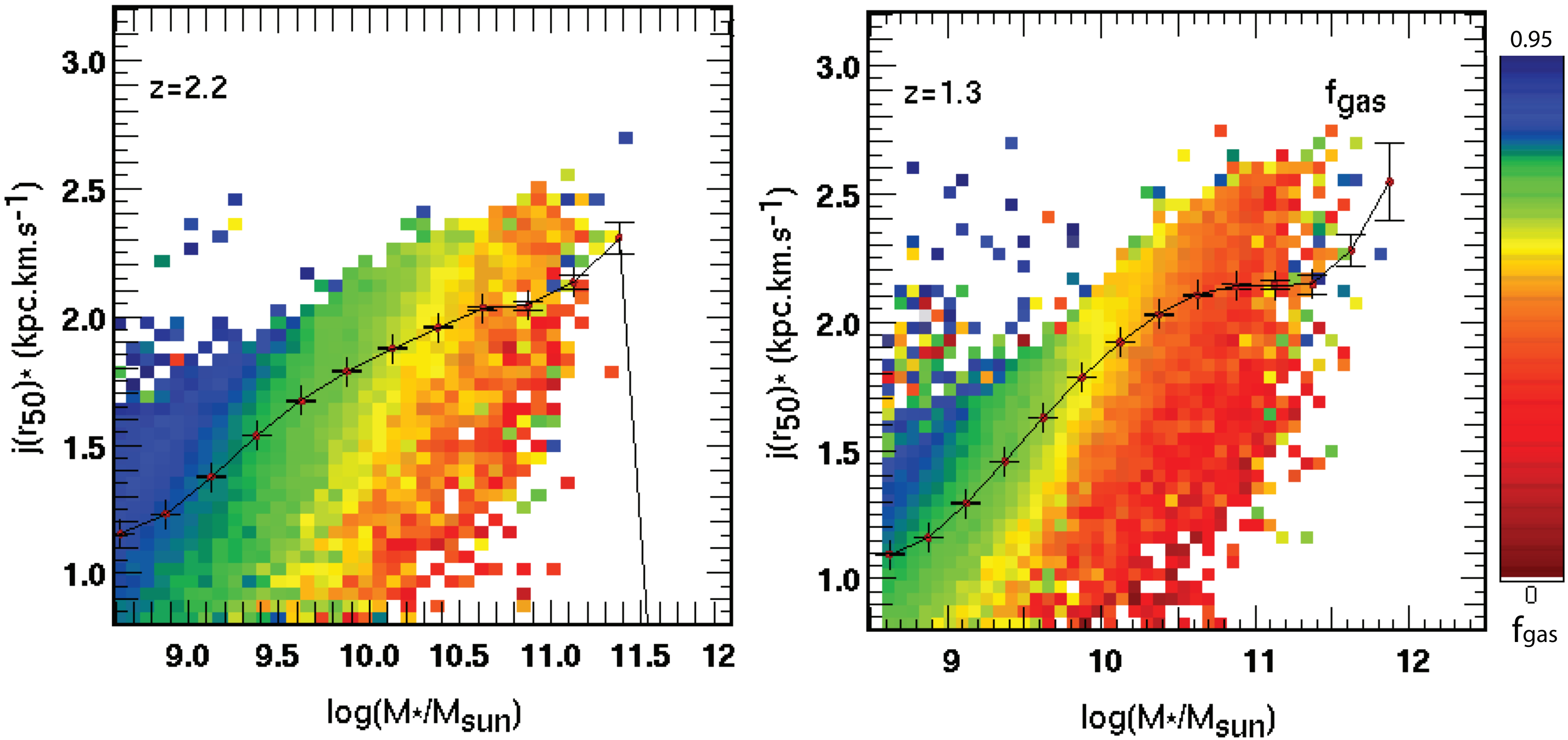
MERGERS

- Mergers turn disks into spheroids
- Even minor mergers can create spheroid remnants

Cumulative probability of axis ratios ξ for mergers with different mass ratios over a time step (250 Myr)

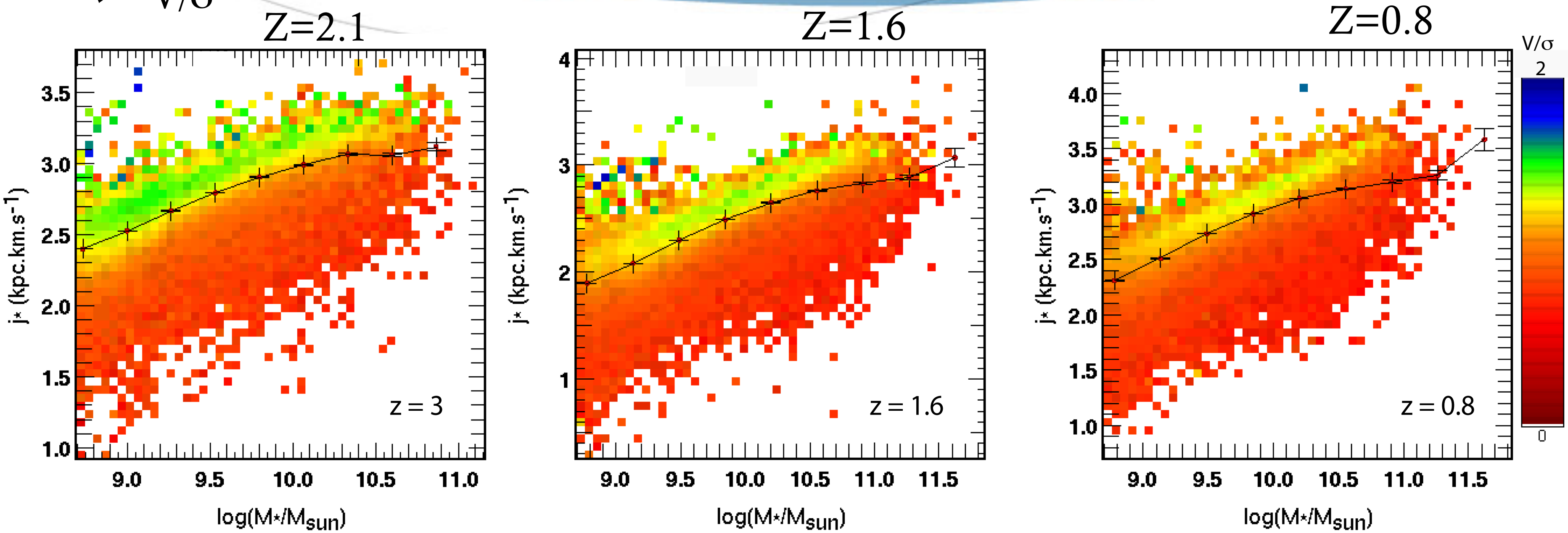


j-M scaling relations : variations with gas fraction

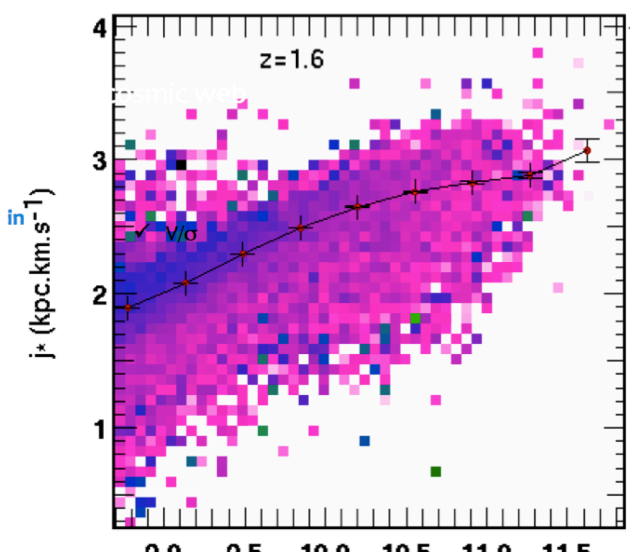


j-M-morphology scaling relations

- ✓ V/σ



- ✓ Main filament inflow contribution



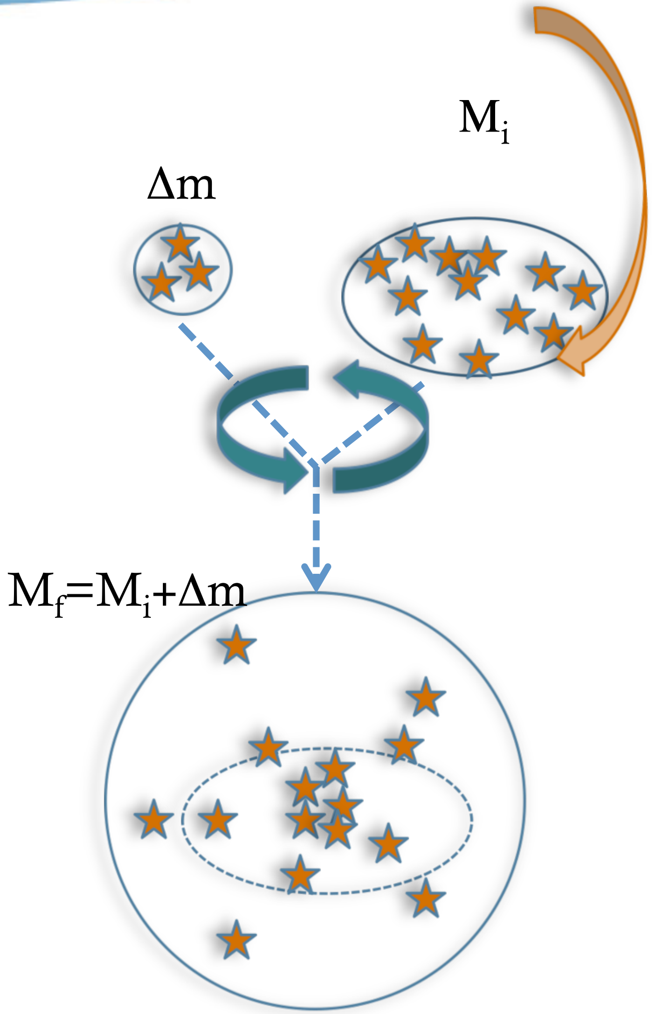
Summary I

- ☛ Spin swings recovered for galaxies.

- ☛ Smooth accretion builds up the spin parallel to filaments and reform disks.

- ☛ Minor and major mergers destroy disks and flip the spin orthogonal to the filament.

Implications for satellites in the Local Universe and detectability?



[3] Impact on the morphology of clusters at z<1

Is satellite distribution imprinted by the collimated nature of the filamentary infall ?

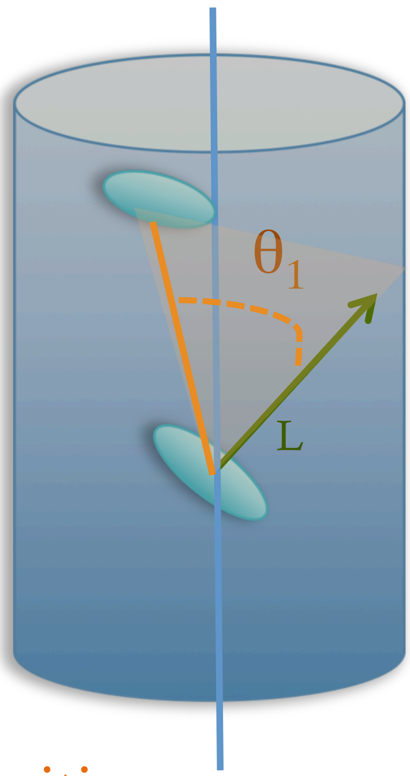
(recall cold gas flows at z>1)

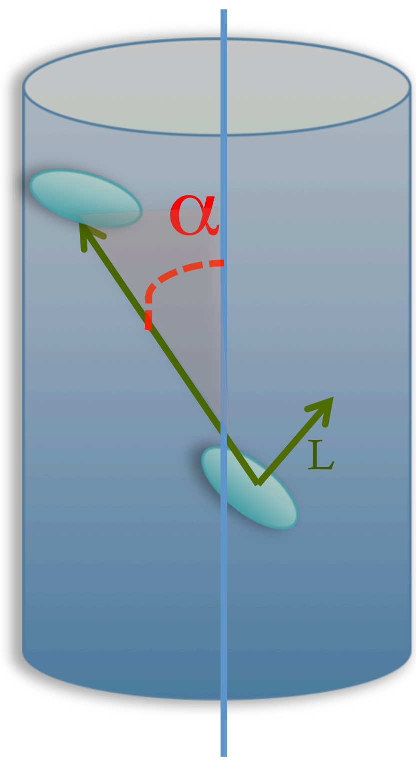
[3]

Tracing galactic alignments

See also: Yang 2006, Ibata 2014, Libeskind 2015

See also: Tempel 2015, Libeskind 2015





$\mu_1 = |\cos(\theta_1)|$

Minor axis-position
(or spin-position)

$\nu = |\cos(\alpha)|$

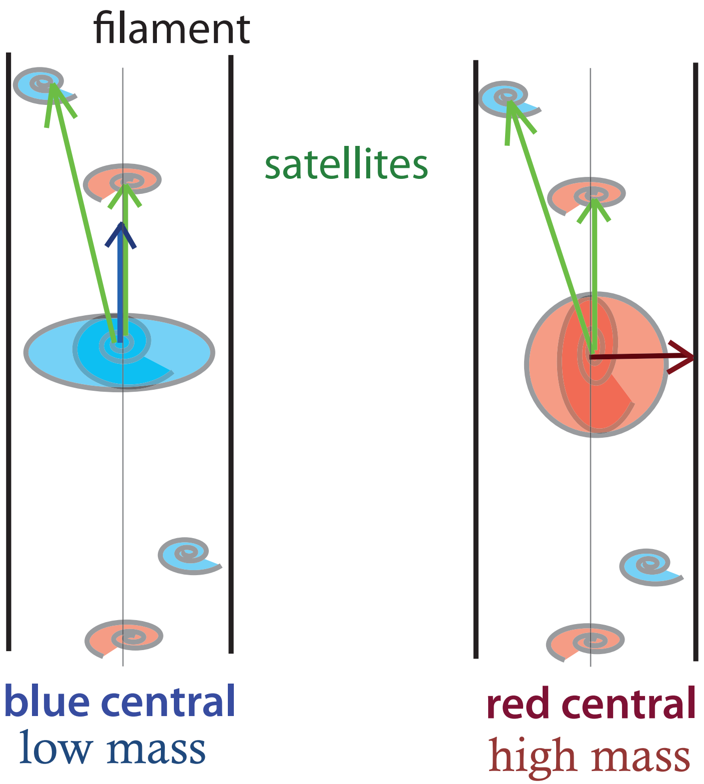
Position-filament

[3]

Filamentary and coplanar trends: expected correlation

All satellites within 5 R_{vir}

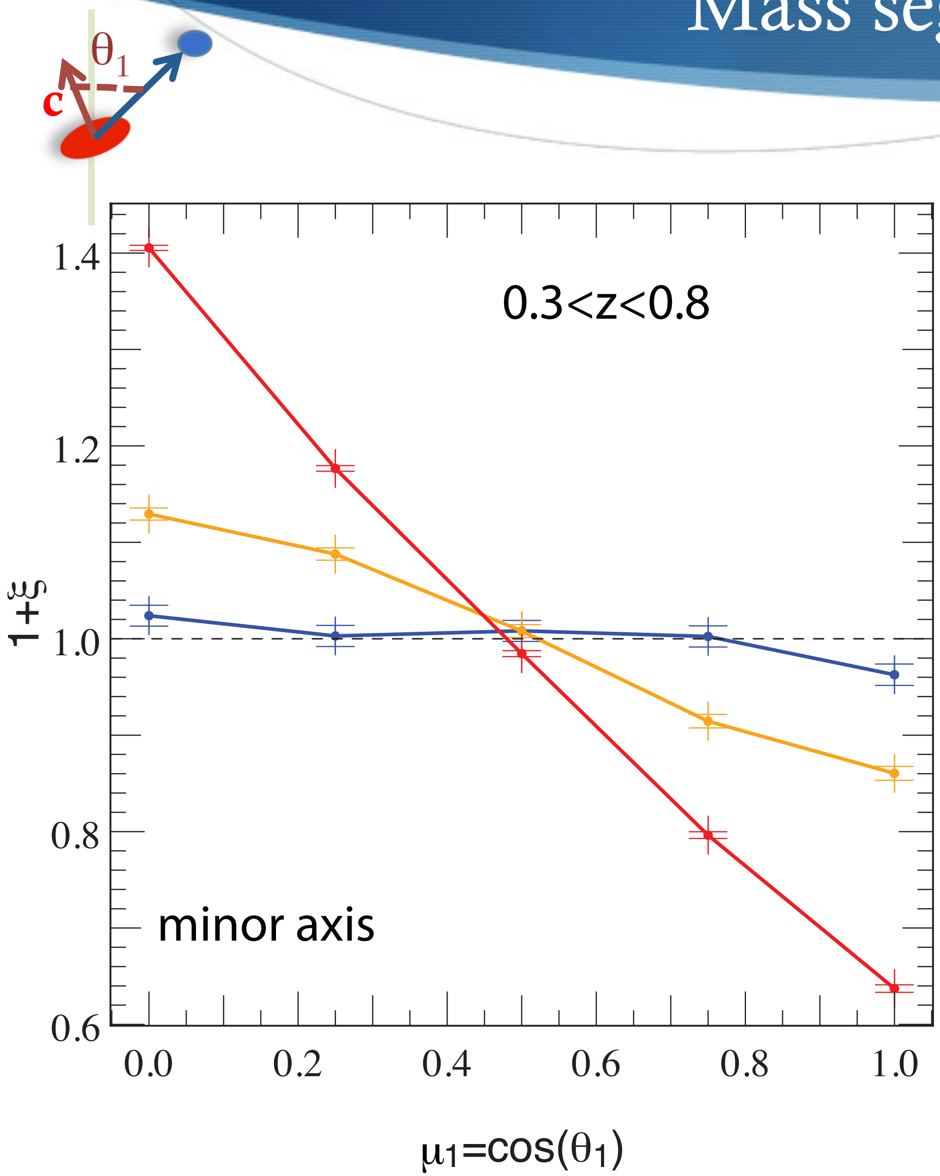
Galactic plane
Orthogonal to filament

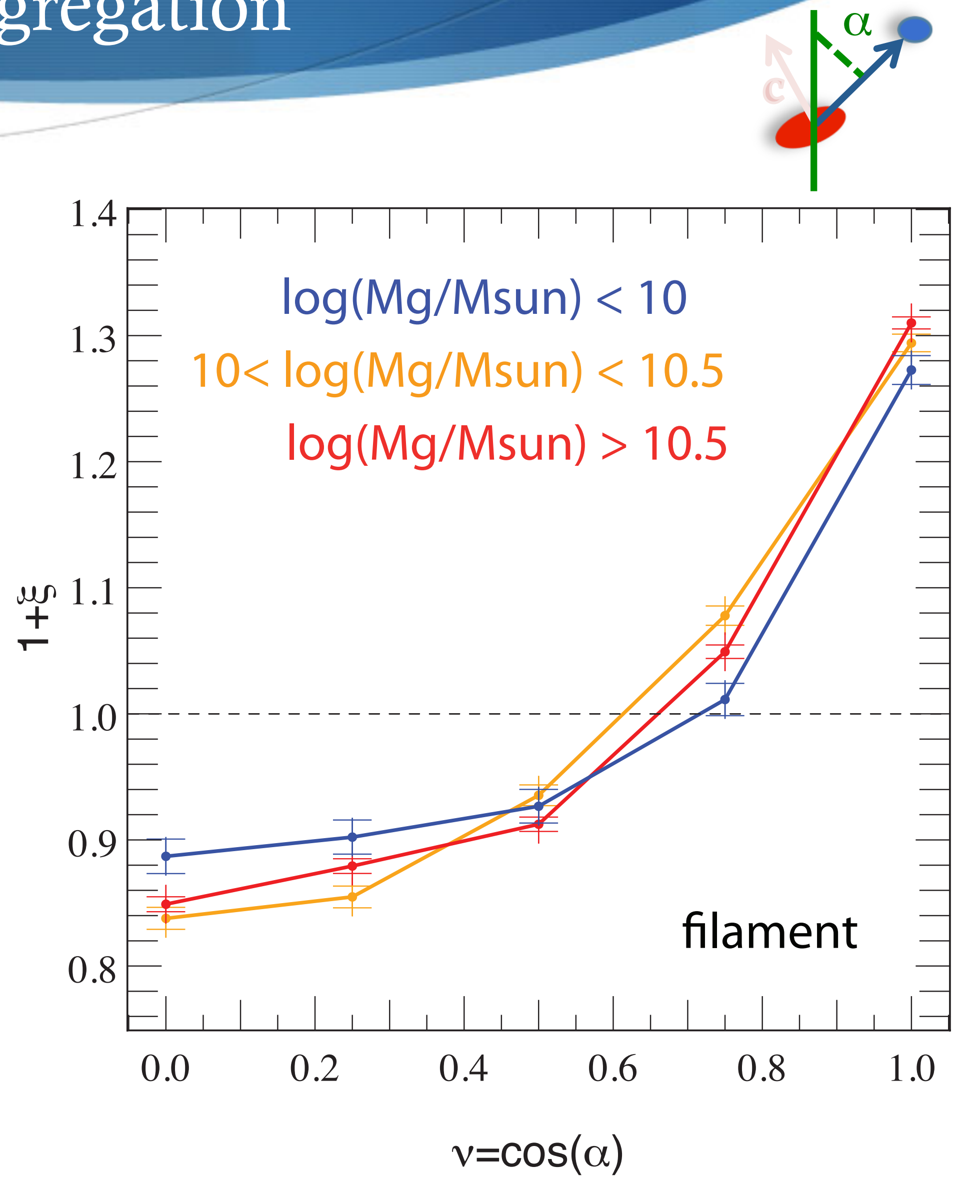


Galactic plane
Parallel to filament

☛ Satellites aligned with filament
⇒ mass segregation for the coplanar trend.

Filamentary and coplanar trends: Mass segregation

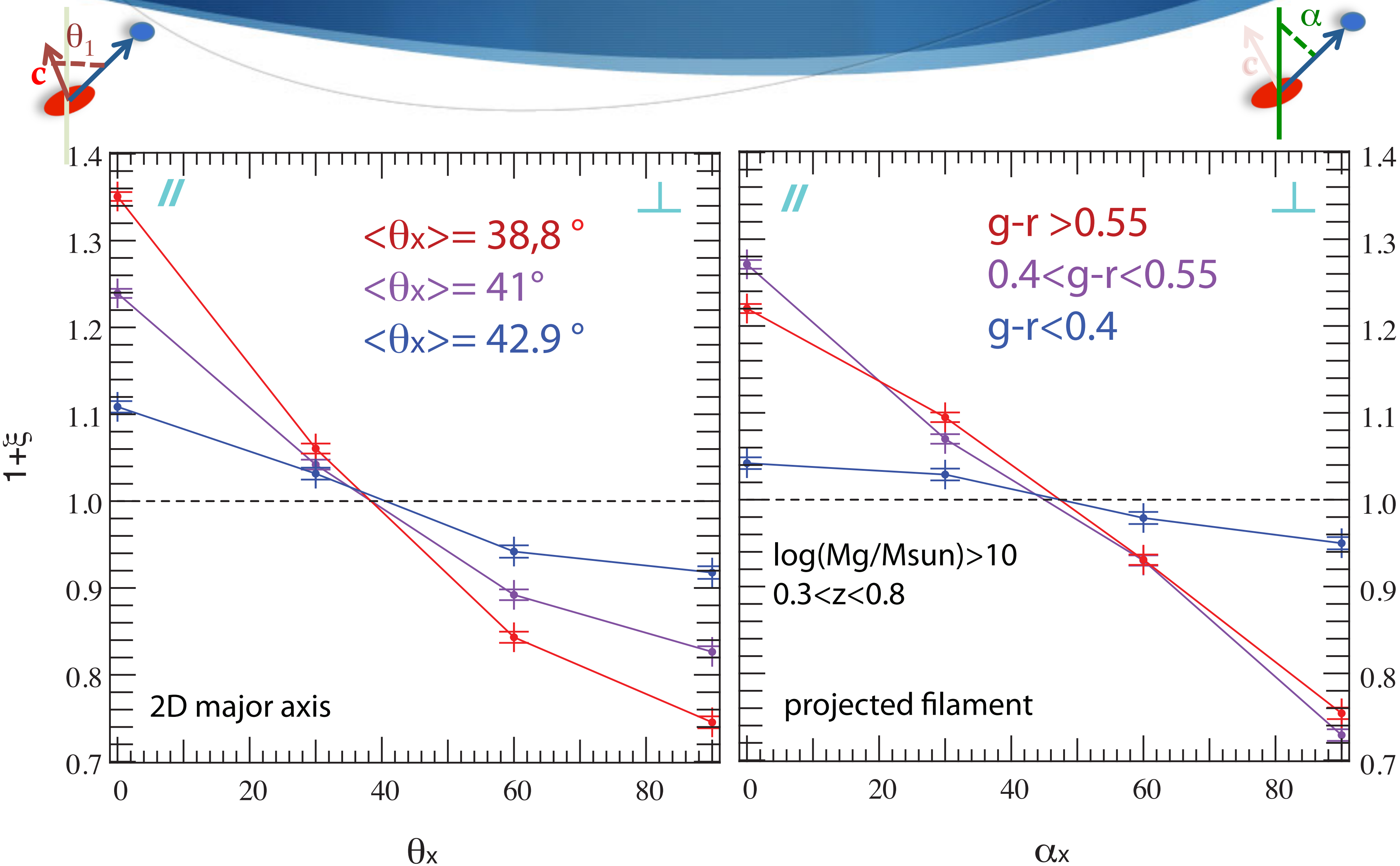




Consistent with Observations: Sales 2004, Brainerd 2005, Yang 2006

[3]

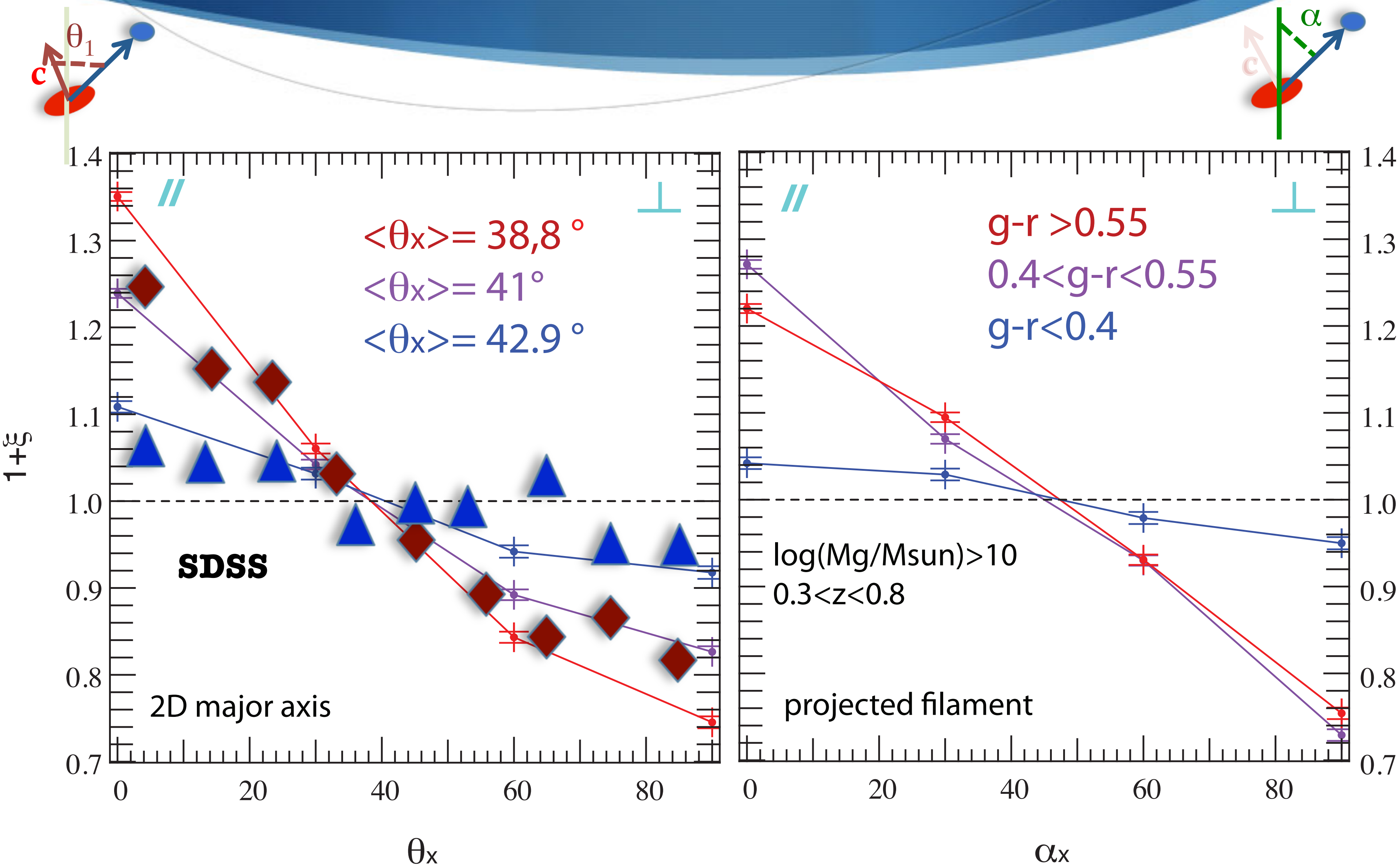
Projected Alignment Trends



Consistent with Observations: Sales 2004, Brainerd 2005, Yang 2006

[3]

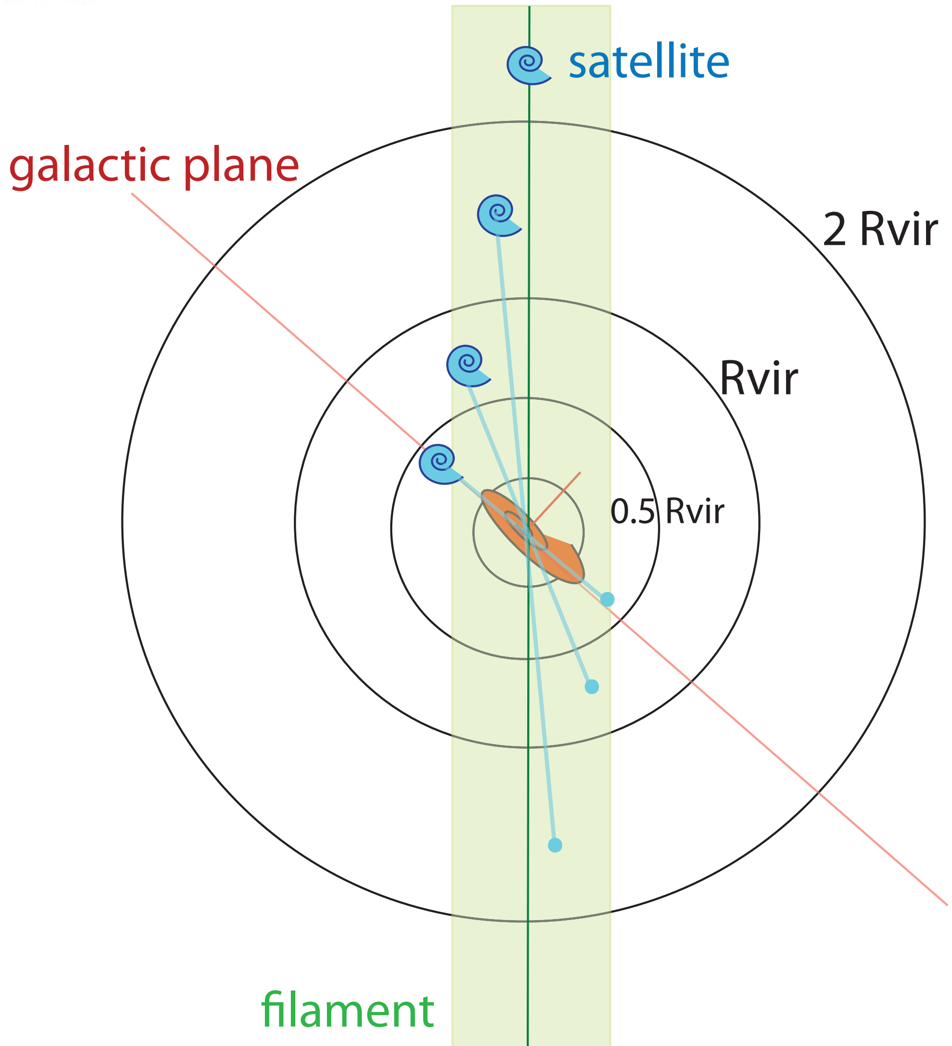
Projected Alignment Trends



Consistent with Observations: Sales 2004, Brainerd 2005, **Yang 2006**

[3] Filamentary and coplanar trends: Transition

☛ Transition between: the **filamentary trend** (outskirt of the halo) and the **coplanar trend** (vicinity of the central).

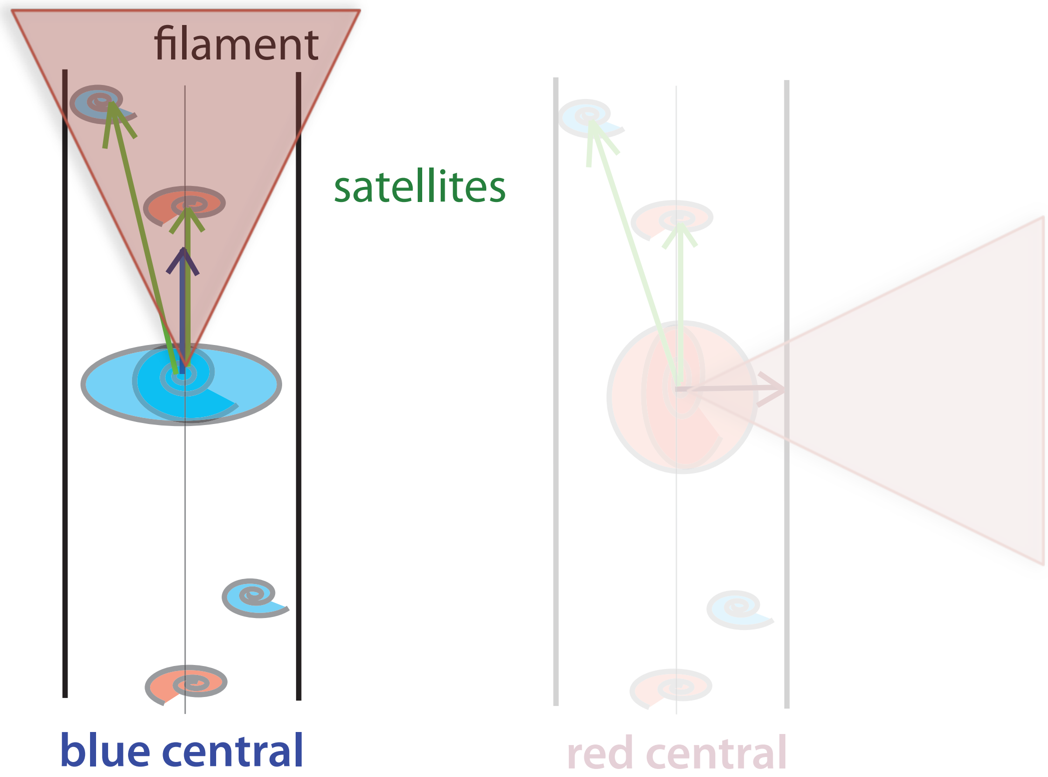


In observations: Zaritsky 1997

[3]

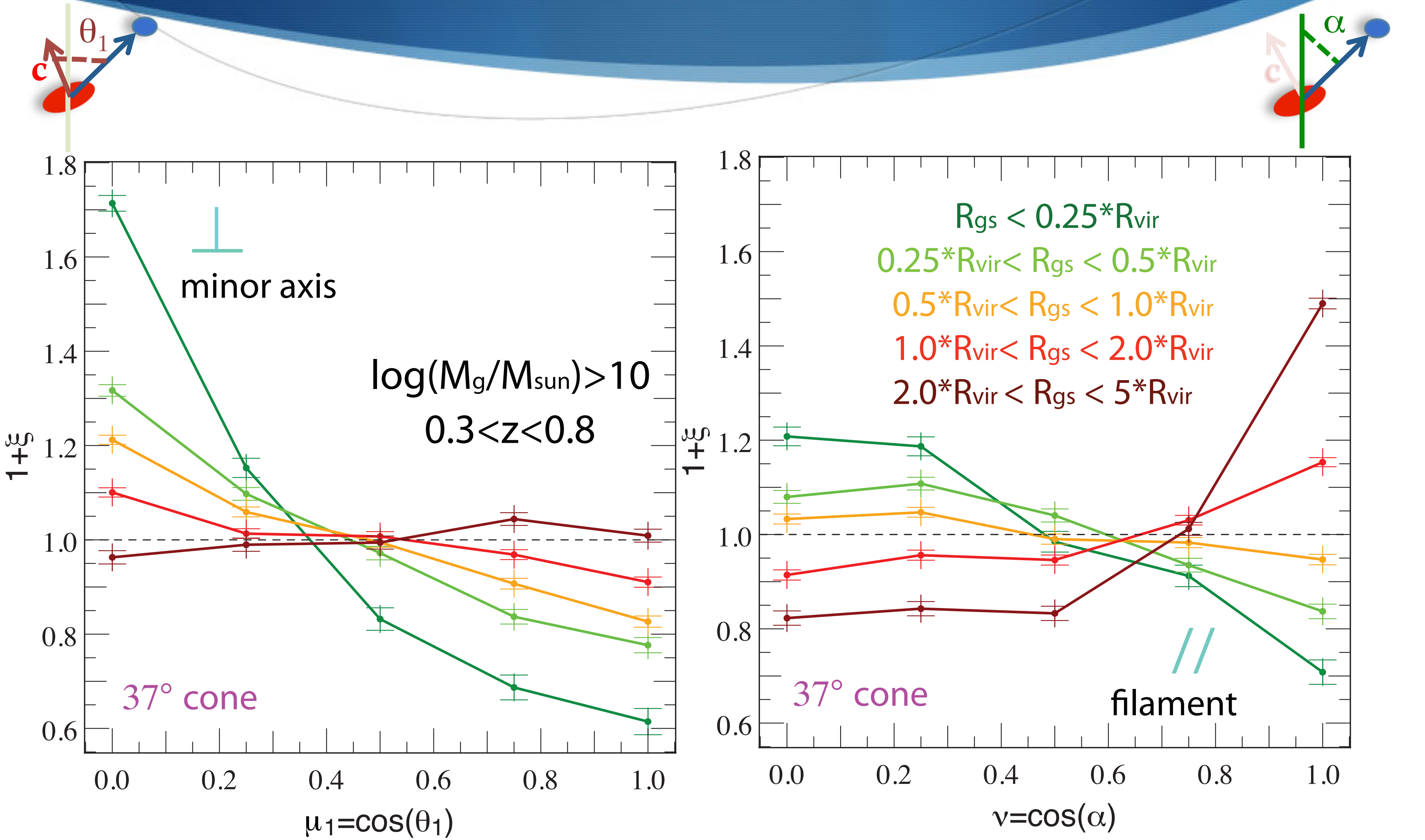
Central spin orientation selection

37 degree
angle cuts



[3]

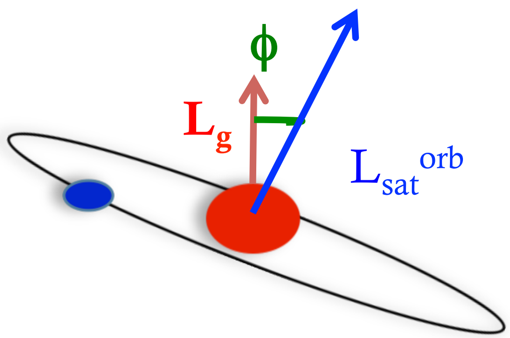
Evolution with distance to host



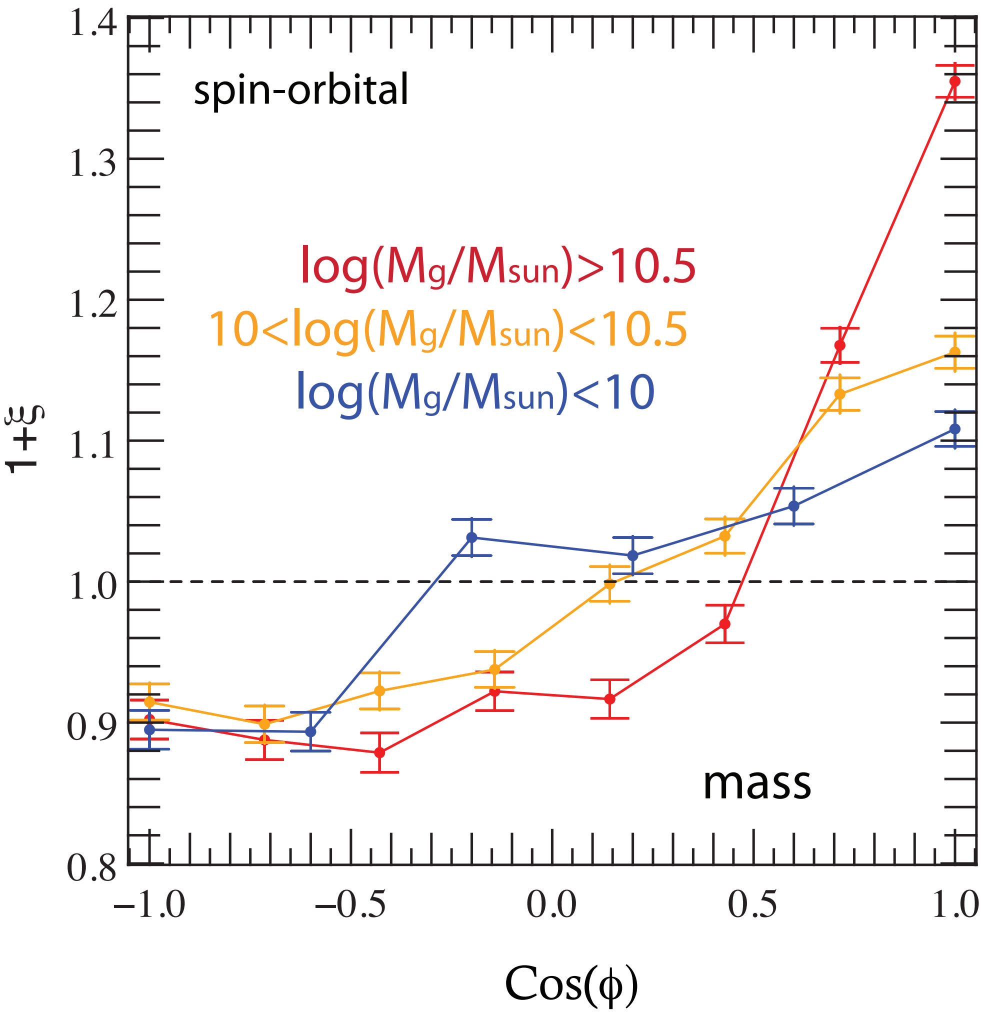
Kinematic signature

☛ Satellites align their orbital momentum with the spin of massive centrals

☛ Consistent trends w.r.t distance to host



central
satellite

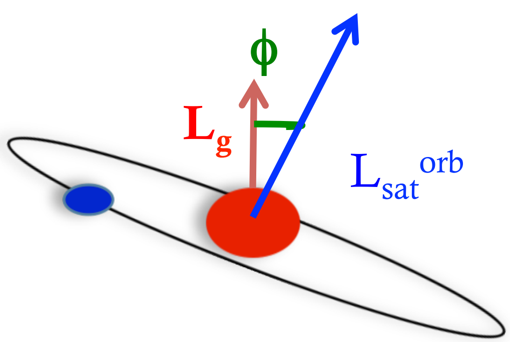


See also: Ibata 2014

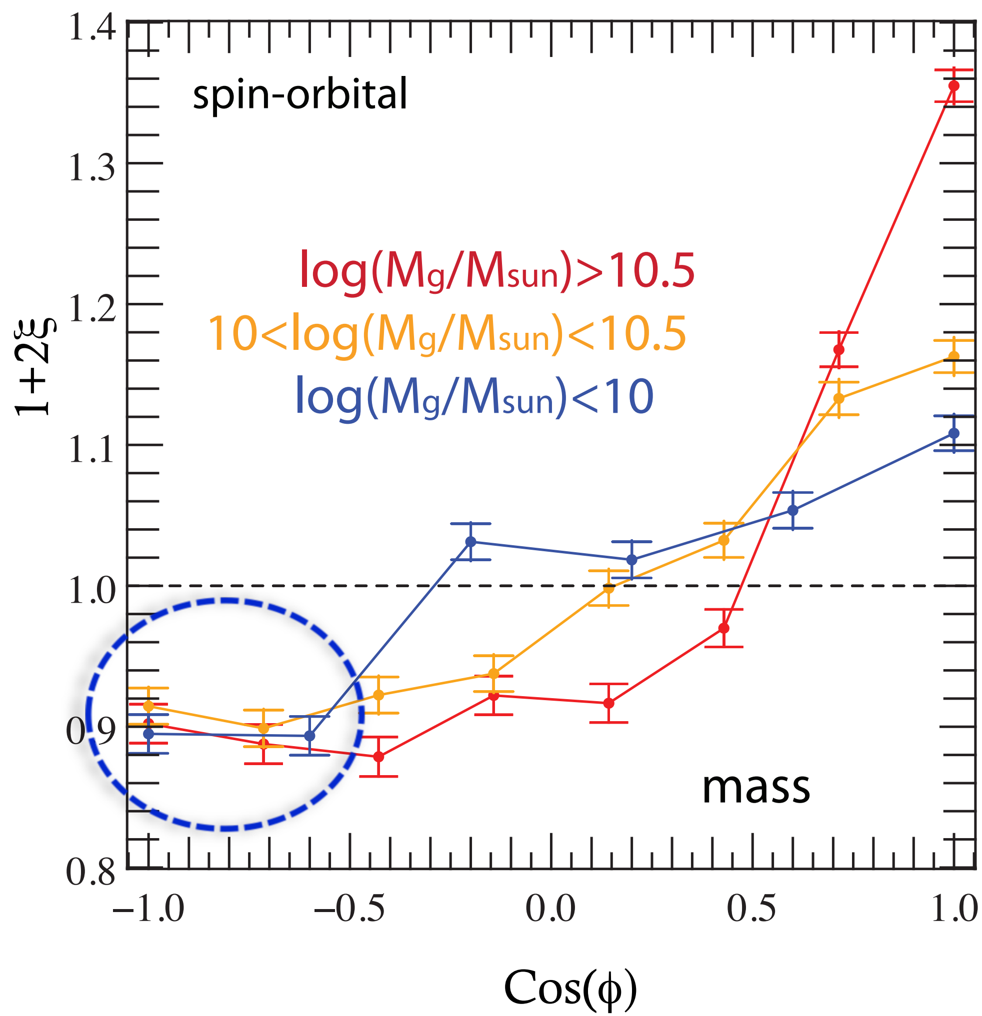
Kinematic signature

☛ Satellites align their orbital momentum with the spin of massive centrals

✔ Corotation!



central
satellite



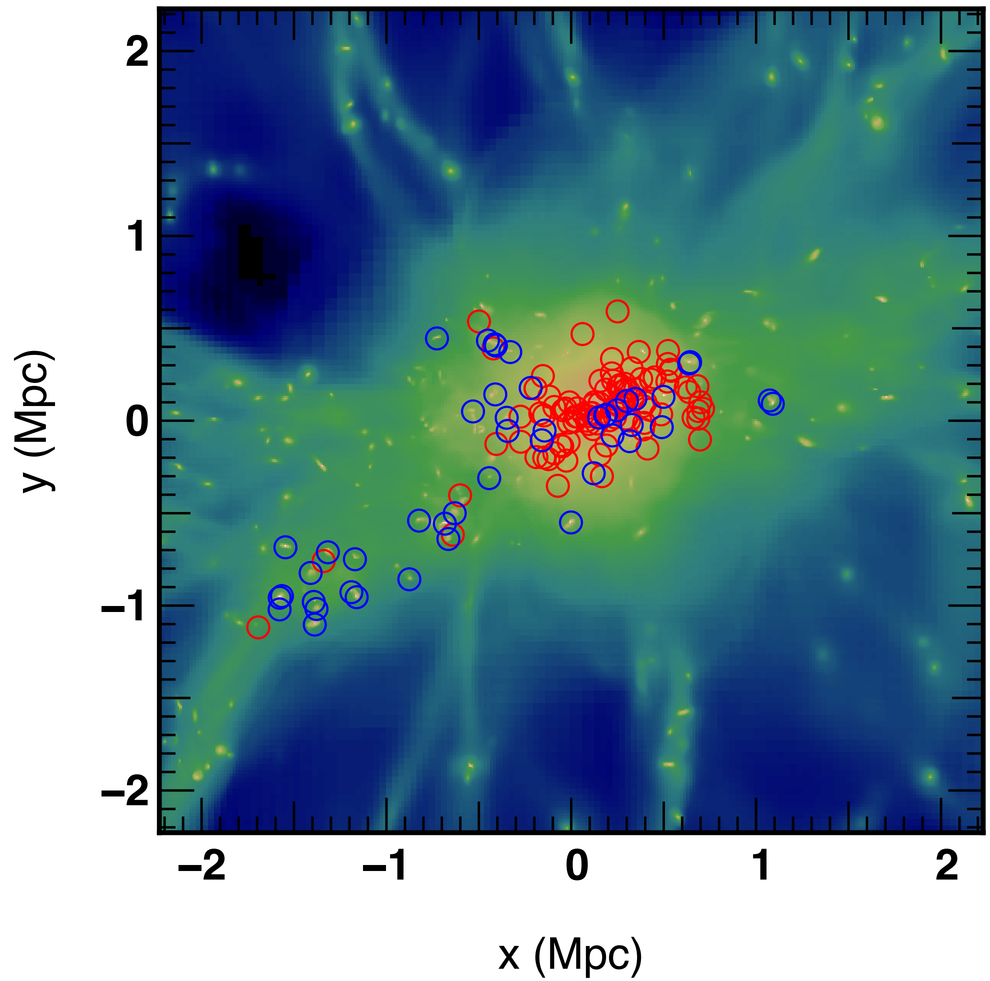
See also: Ibata 2014

Summary

☛ Satellites aligned with filament
⇒ mass segregation for the coplanar trend.

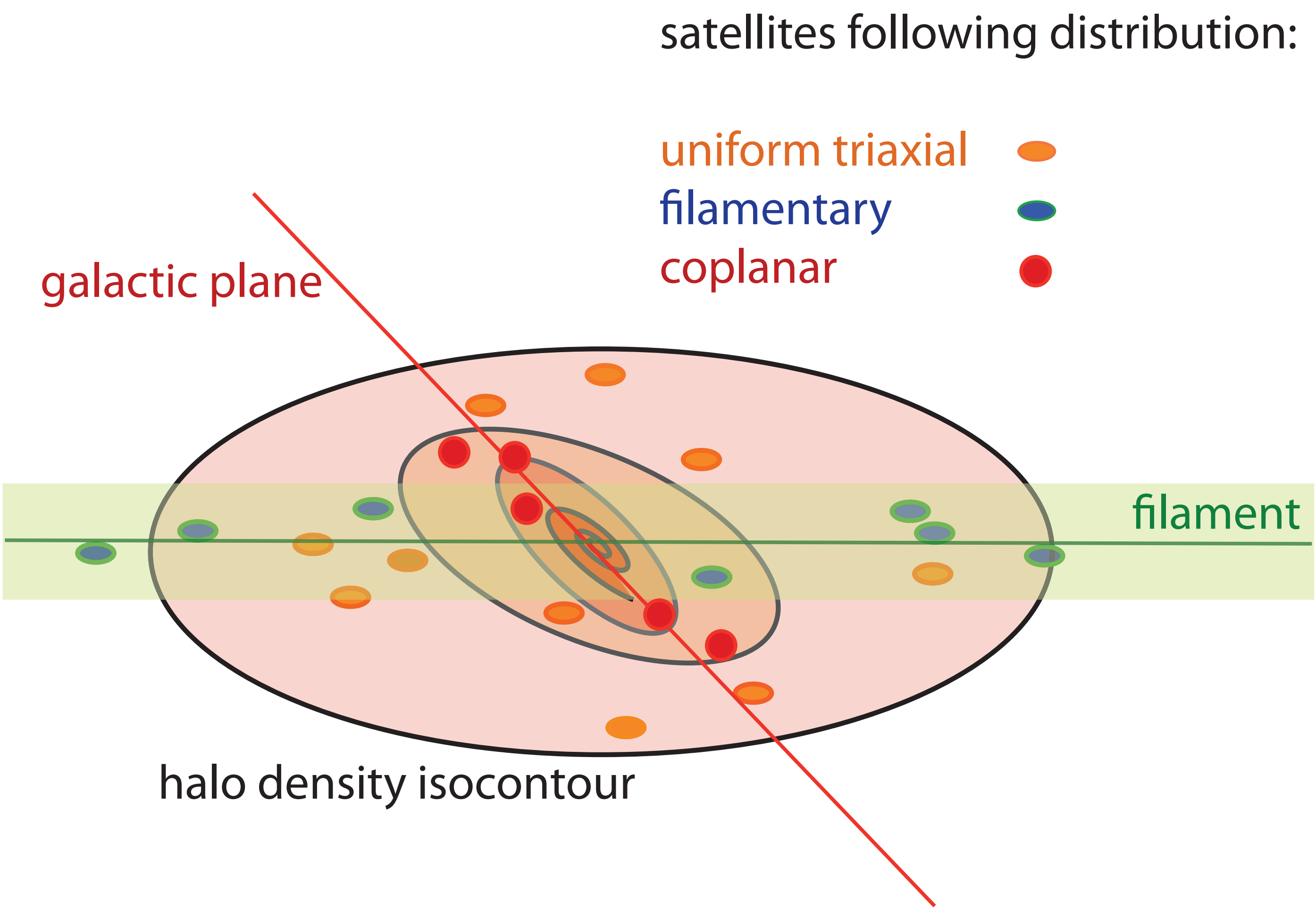
☛ Transition between the **filamentary trend** and the **coplanar trend**

☛ Satellites align their orbital momentum with the spin of massive centrals

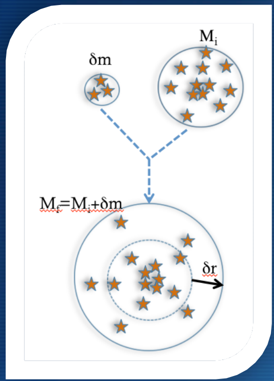


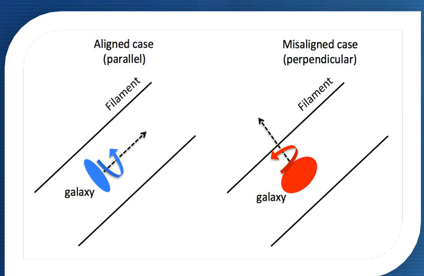
[3]

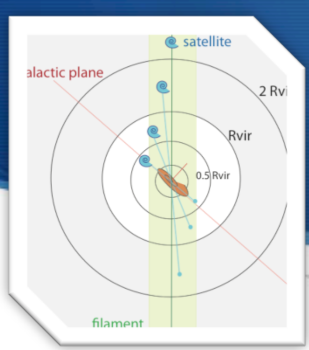
Summary


satellites following distribution:
uniform triaxial
filamentary
coplanar
galactic plane
filament
halo density isocontour

Conclusion







✓ Tight connection between the **LSS geometry and galactic properties**:

- ➢ **Gas inflow** explains angular momentum spin-up and consecutive (re)-building of disks at z>1.
- ➢ **Mergers** account for spin swings observed for massive galaxies in the cosmic web.
- ➢ **Satellites infall** generates the separation dependent angular distribution of satellites around their central host.