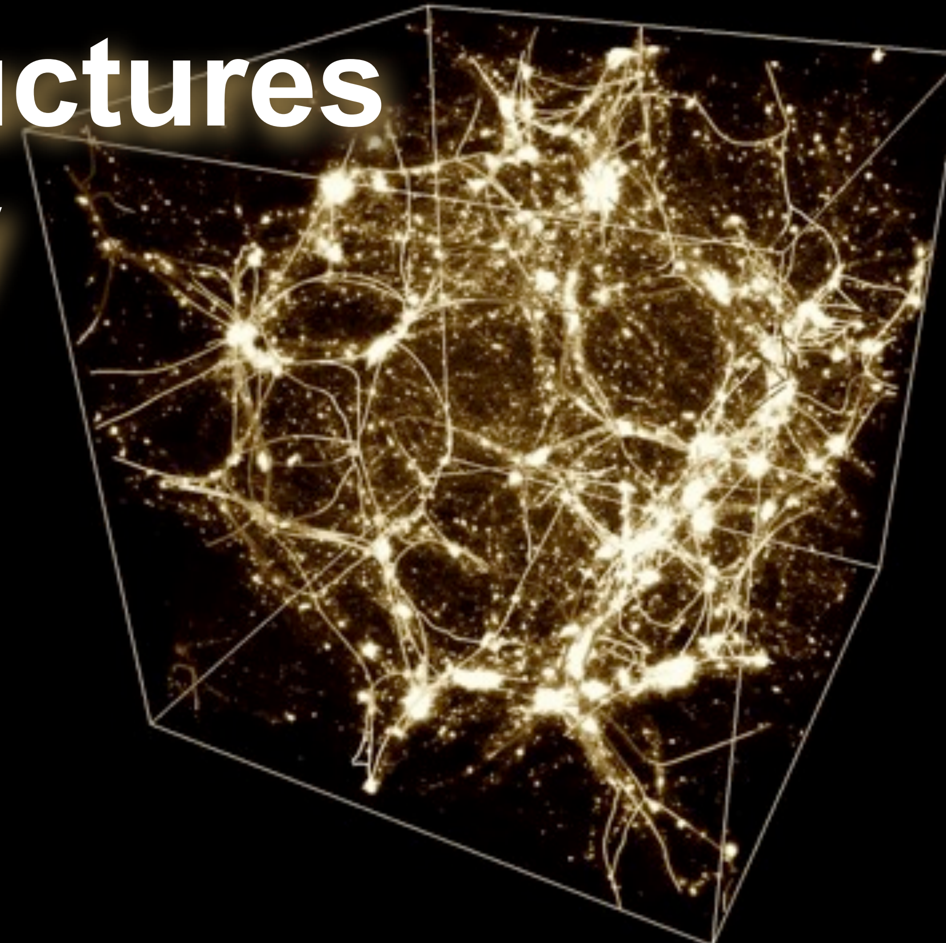
# Connecting Large Scale Structures to Galaxy morphology

Can we predict the morphology of galaxies **on** the cosmic web **from first principles**?

Is the cosmic web **driving** the Hubble sequence?



MareNostrum z=1.55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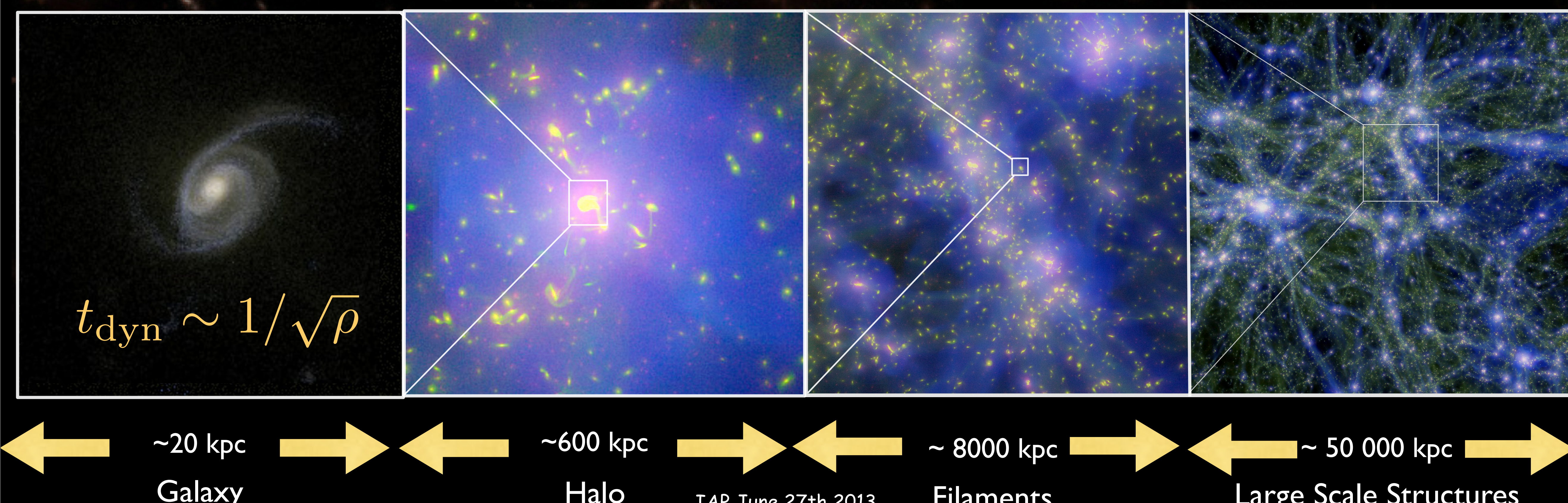
**Institut d'astrophysique de paris**

**S. Codis, C. Laigle, C. Welker T. Kimm D. Pogosyan, J. Devriendt, Y Dubois+ Horizon Collaboration**


IAP June 27th 2013

(c)Taysun Kimm +E. Pharabod

# Outline

- **How discs build up from persistent cosmic web?**
- **How dark halo's spin flip relative to filament?**
- **Why are they initially aligned with filaments? Why the transition mass? *Eulerian* view**
- **What is the corresponding Lagrangian theory?**

# Outline

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***Galactic morphology is driven by AM acquisition through anisotropic secondary infall, coming from larger scales, which are less dense, hence more steady; cold flows provide the link.***

(c)Taysun Kimm +E. Pharabod

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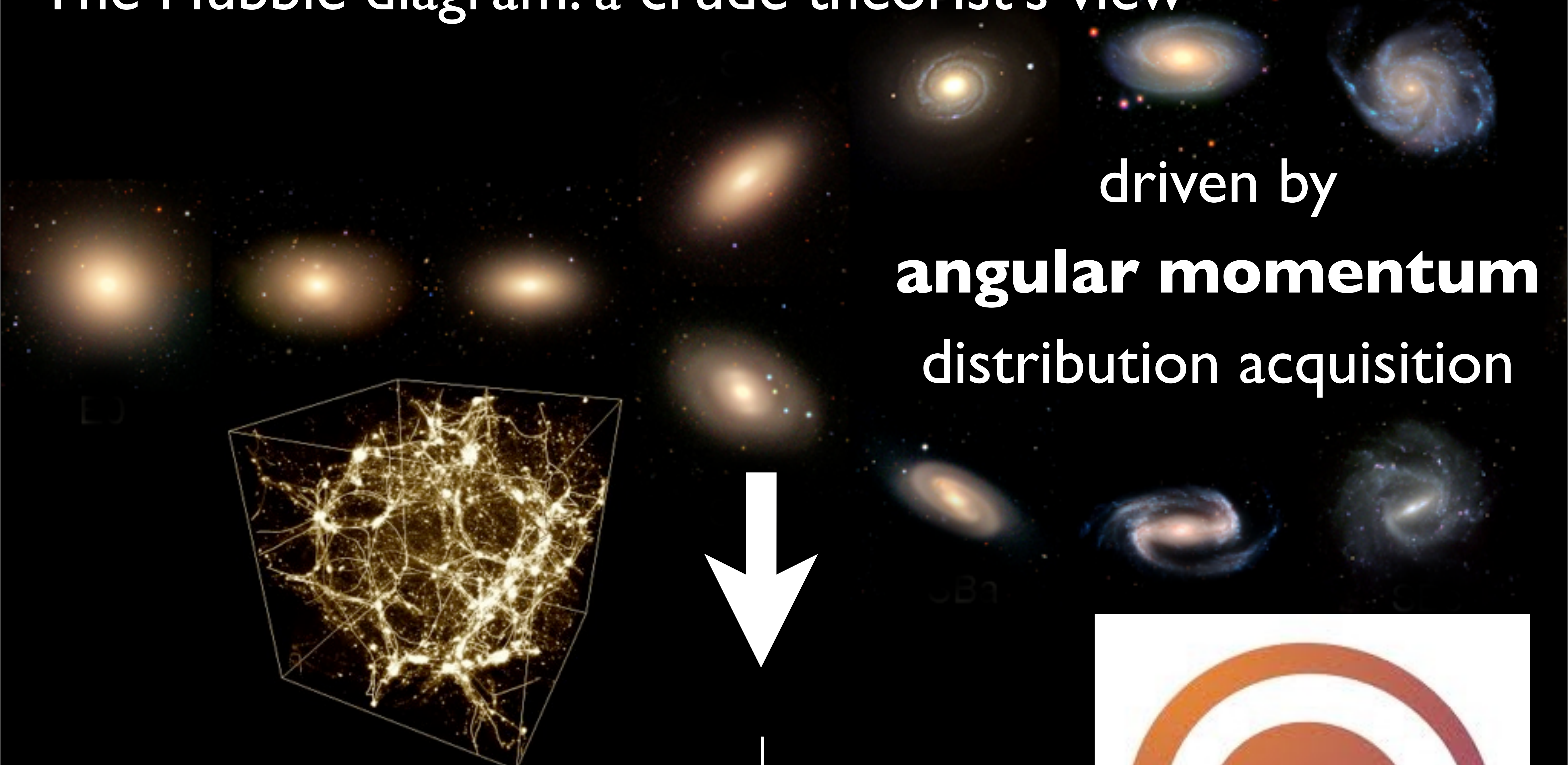
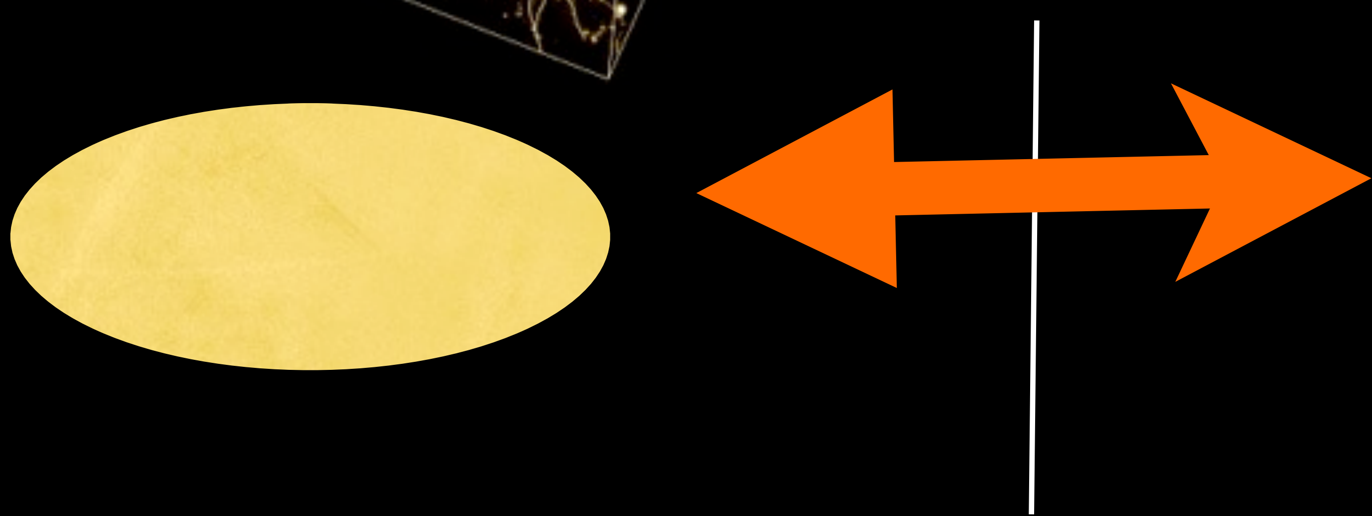
***Galactic morphology is driven by AM acquisition through anisotropic secondary infall, coming from larger scales, which are less dense, hence more steady; cold flows provide the link.***

***Where galaxies form does matter, and can be traced back to ICs***
***Flattened filaments generate point-reflection-symmetric AM/vorticity distributior***
***they induce the observed spin transition mass & the helicity of cold flows***

# The Hubble diagram: a crude theorist's view



driven by
**angular momentum**
distribution acquisition



What drives coherent secondary infall?

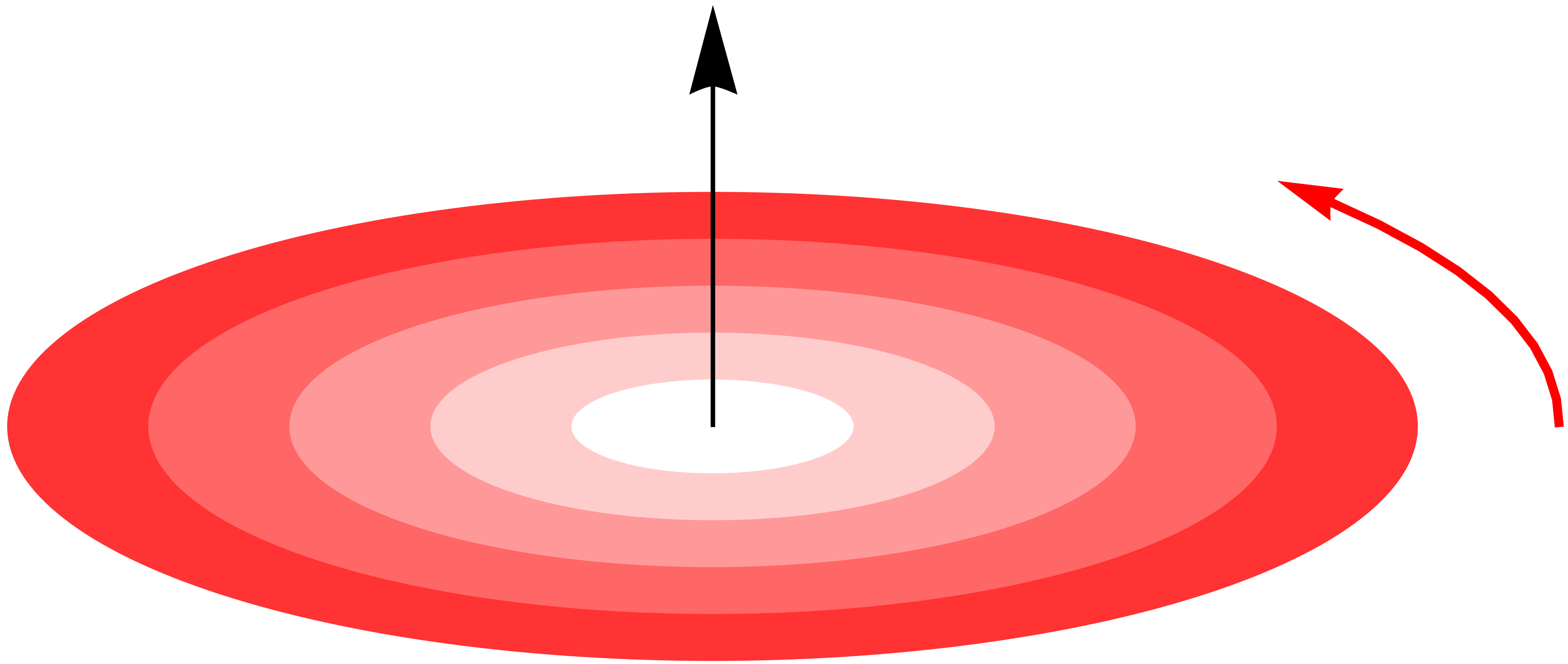
• **How discs build up from persistent cosmic web?**

# Part I Outline

- **4 trivial facts about galaxies in their web**
  - **what's a disc?**
  - **what's a void?**
  - **what's a shock?**
  - **what do numerical hydro suggest?**
- The proposition
- Various proofs of various value?

# Fact number **one**

"theoretically", a galactic disc:

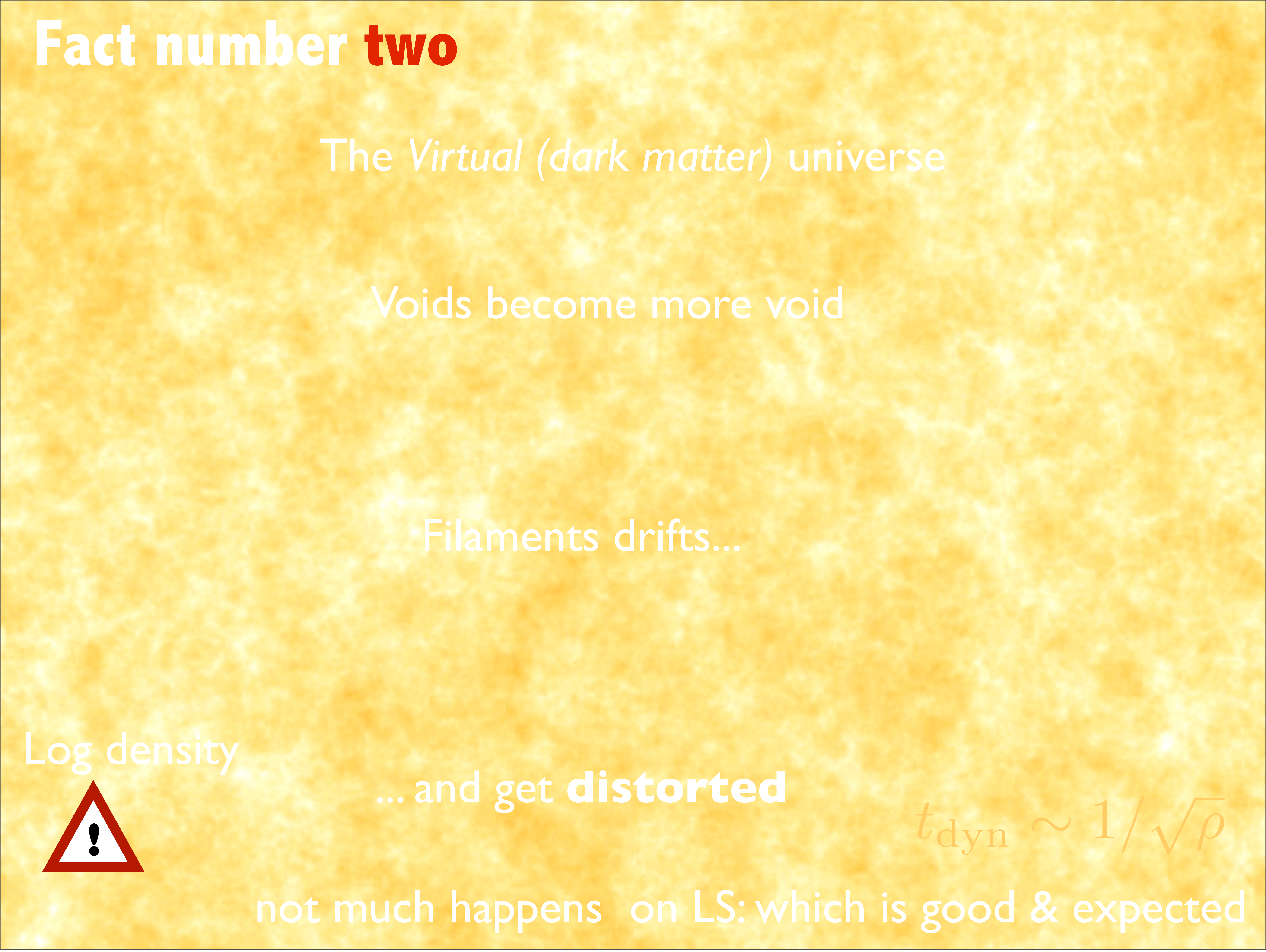


An ensemble of ring made of gas,

- turning around the same axis
- whose outer parts rotate with
  **more** angular momentum  (flat rotation curve)

# Fact number **two**

The *Virtual (dark matter)* universe




Voids become more void

Filaments drifts...

... and get **distorted**

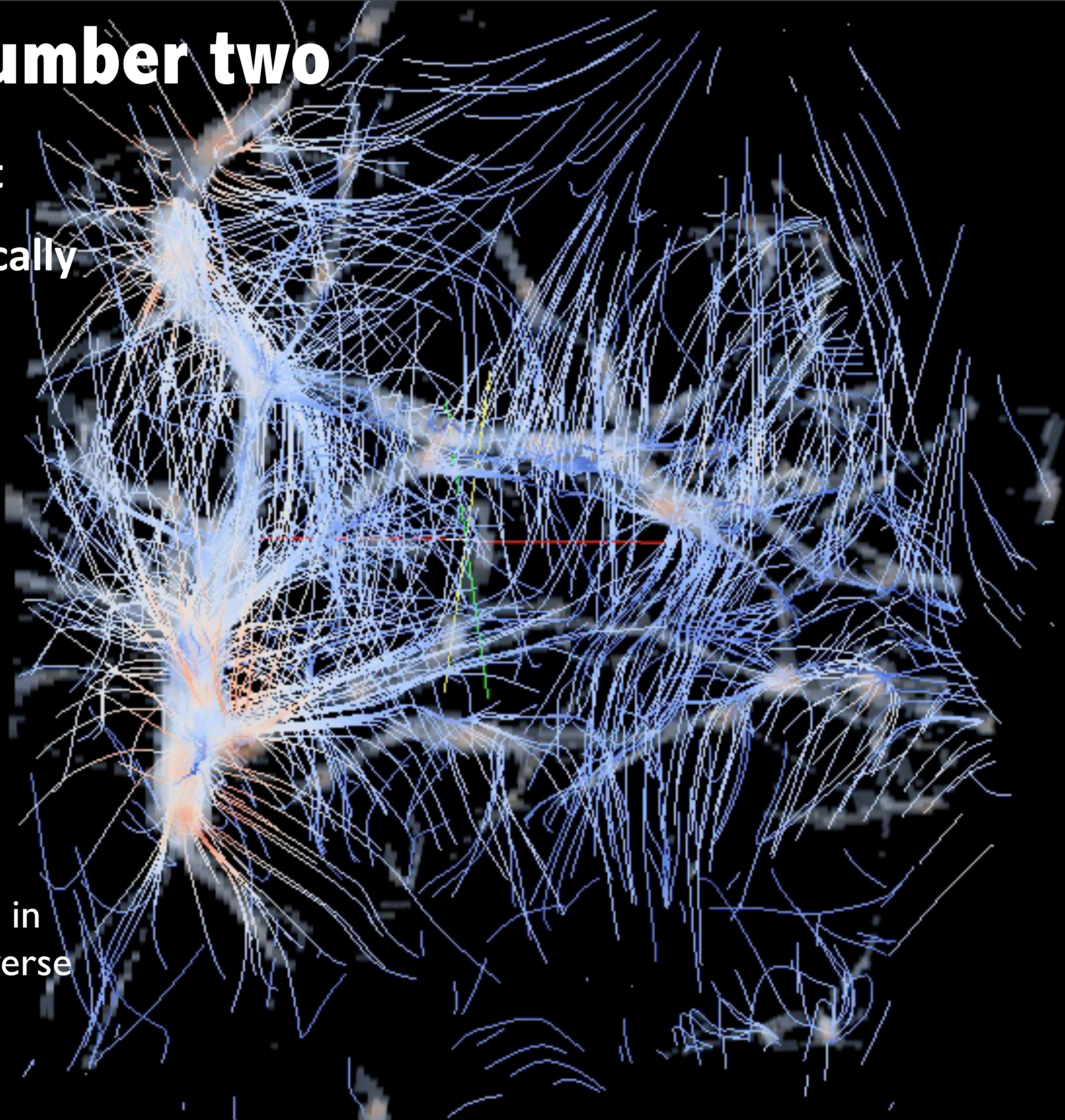
$t_{\rm dyn} \sim 1/\sqrt{\rho}$

not much happens  on LS: which is good & expected

# Fact number two

**Peak attract**

**catastrophically**

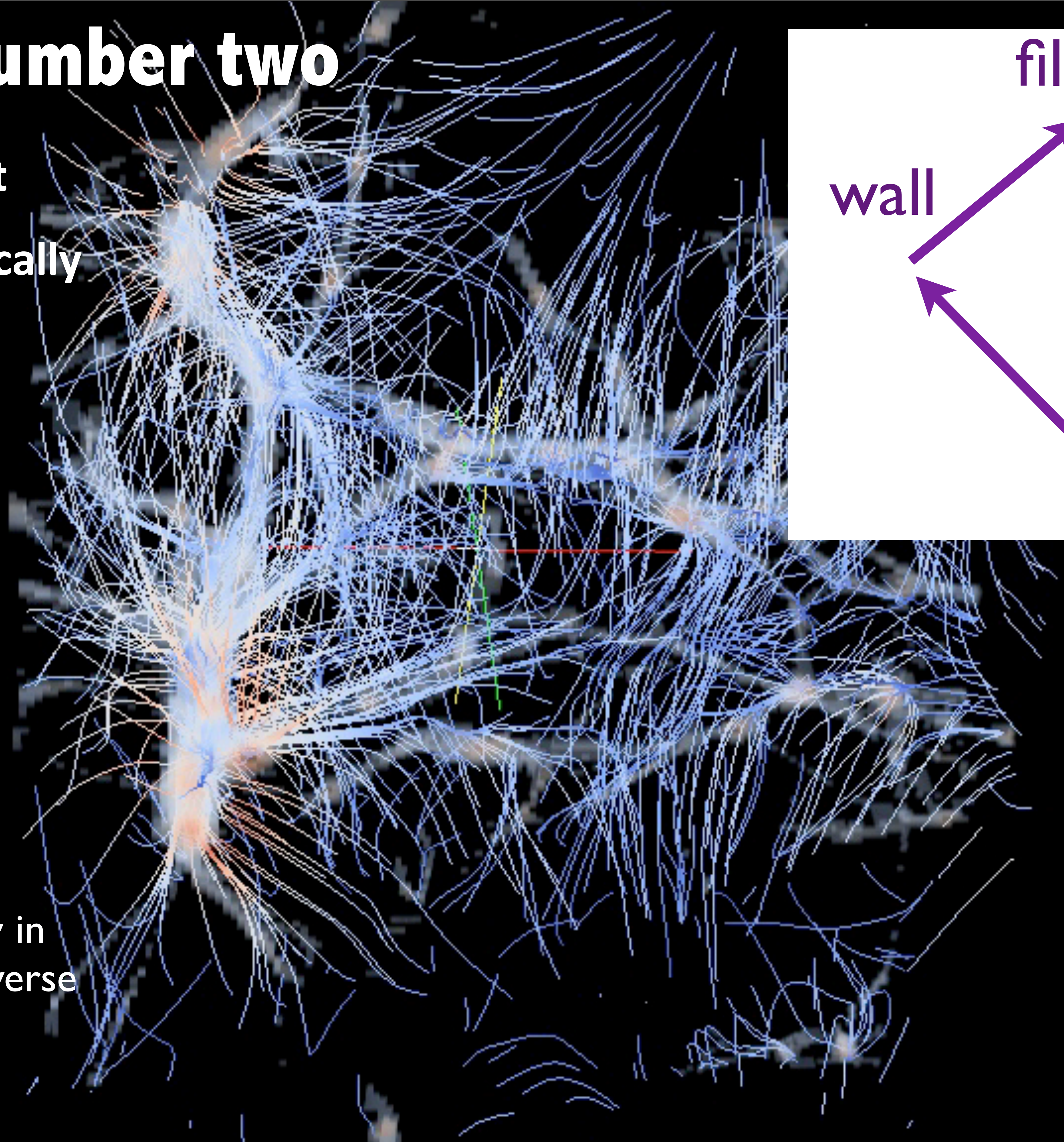


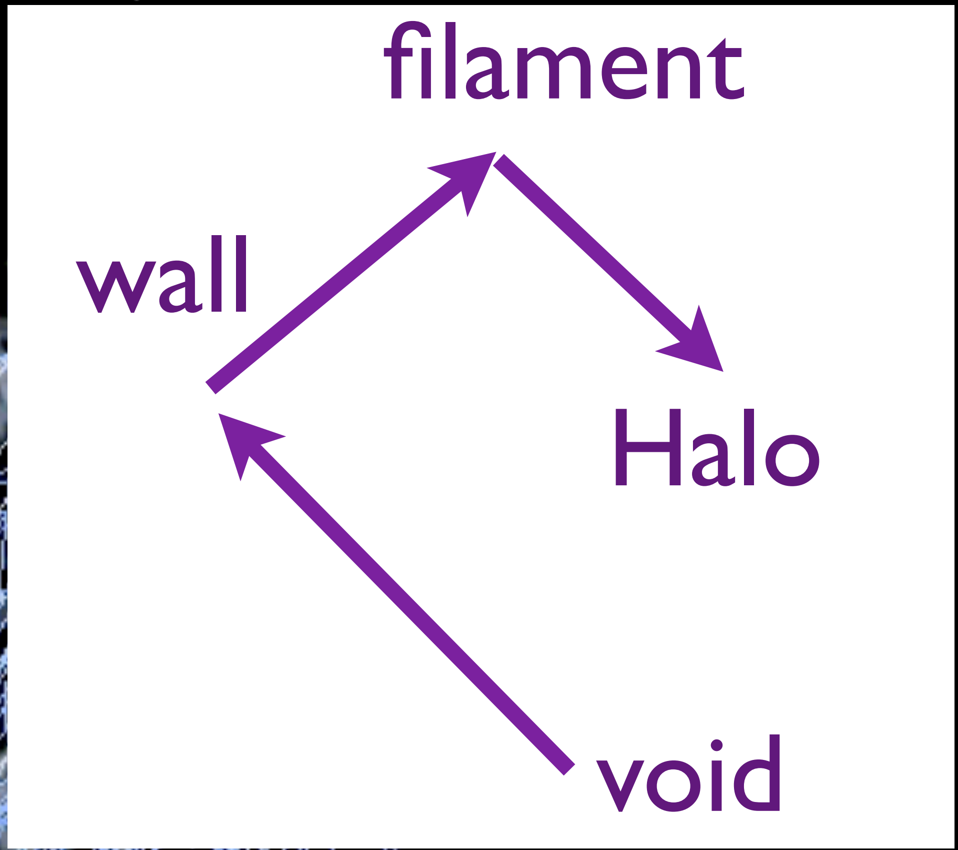
Velocity flow in
expanding universe

**BUT surrounding void repel (contrast<0)  & contribute to secondary infall.**

# Fact number two

Peak attract catastrophically






Velocity flow in expanding universe

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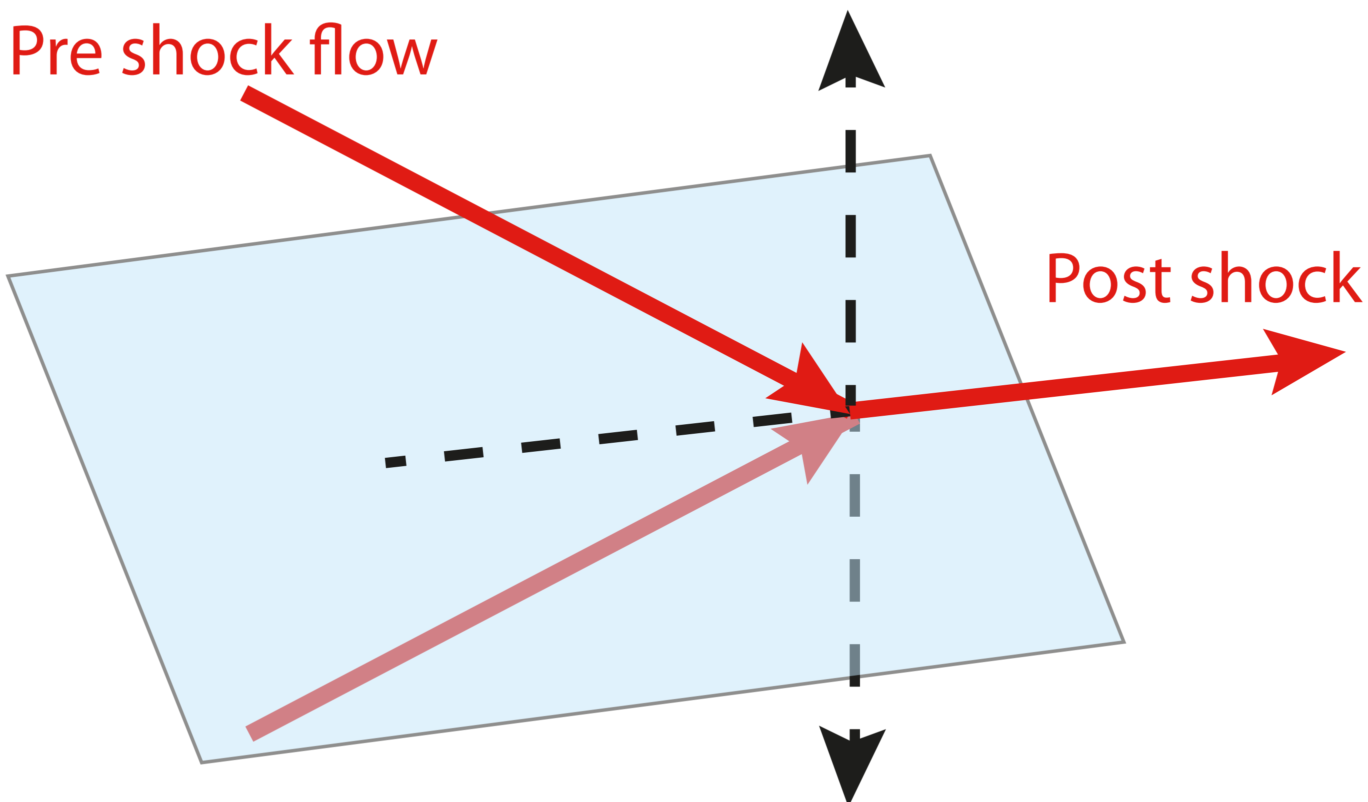
# Fact number three

## "theoretically", a shock:




Gas, unlike dark matters, shocks (iso-T) and

**follows closely the cosmic web**

→ **cosmic web is** important **for galaxy morphology**

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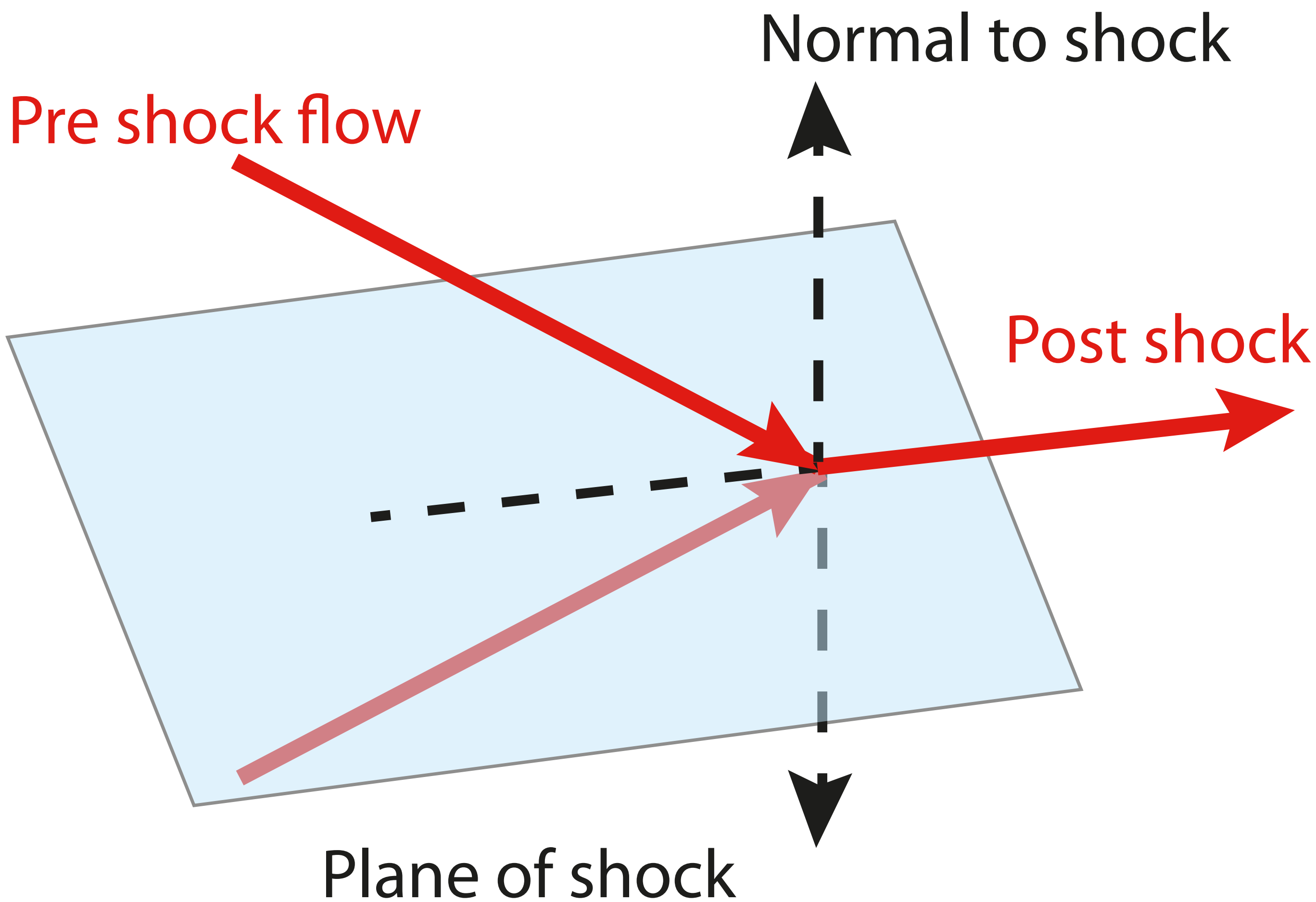


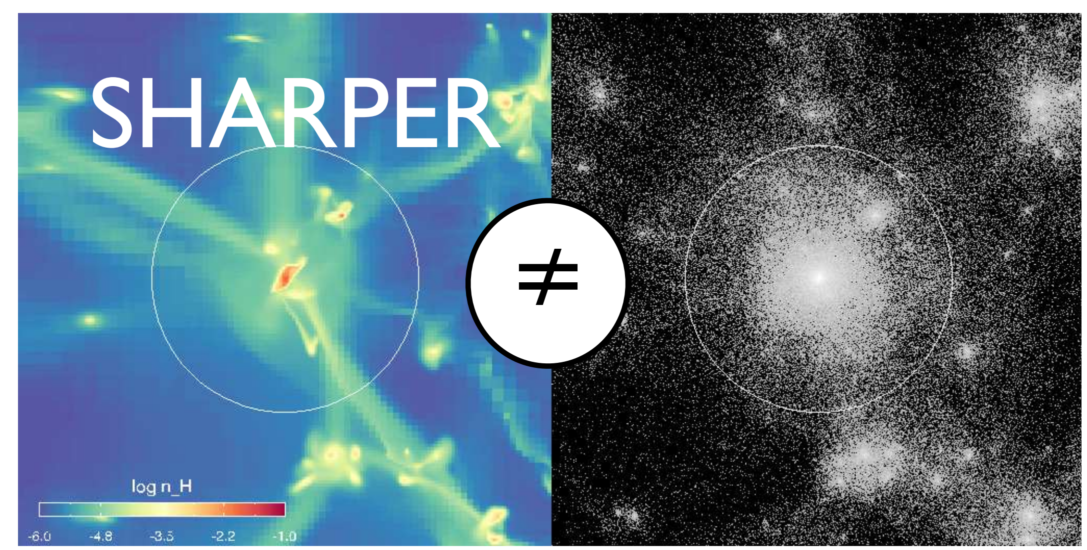


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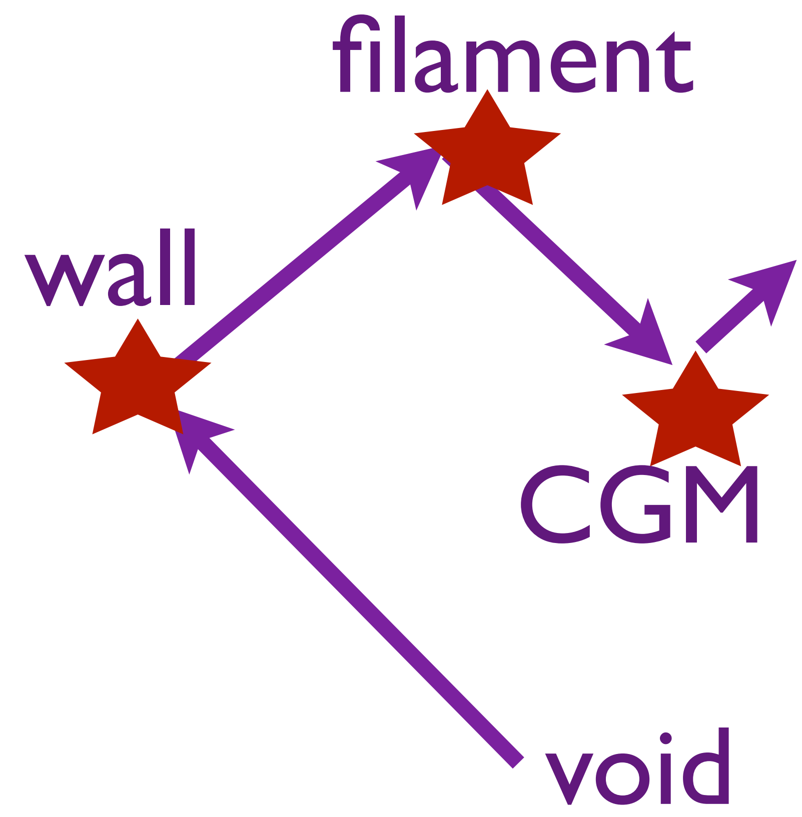


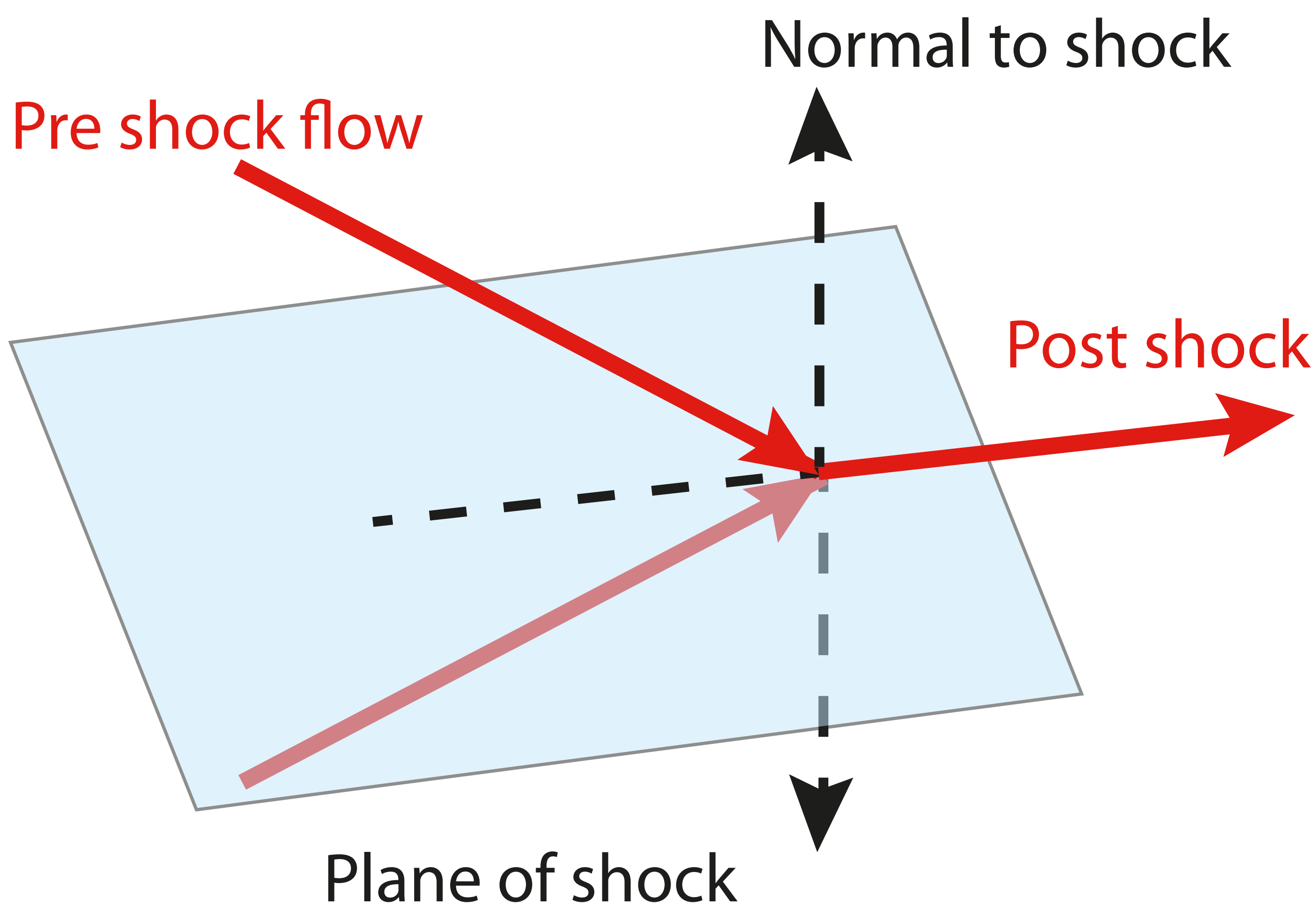


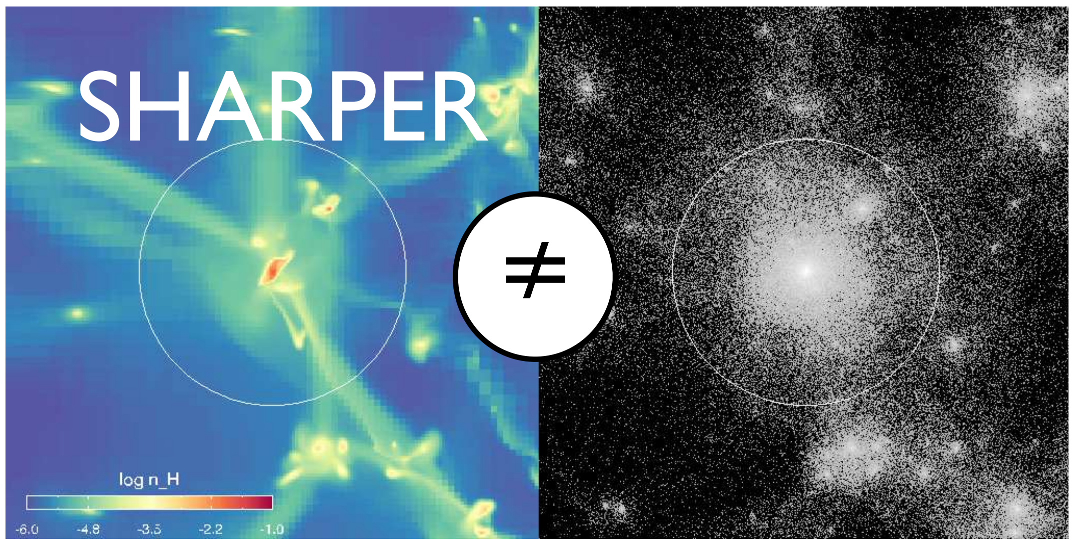


Gas, unlike dark matters, shocks (iso-T) and

**follows closely the cosmic web**

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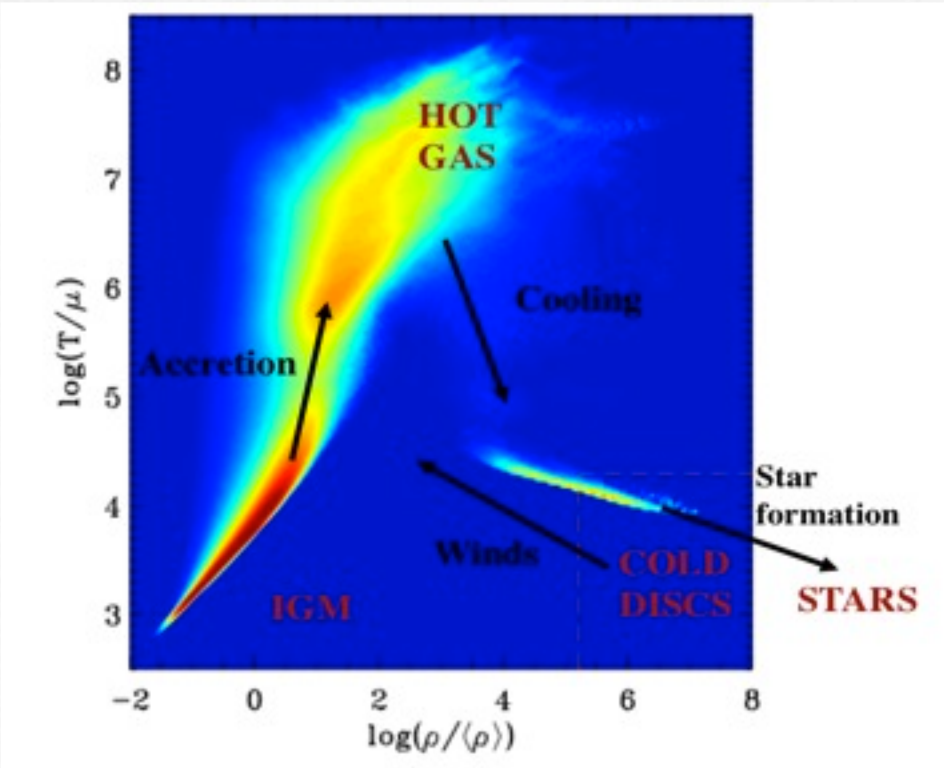
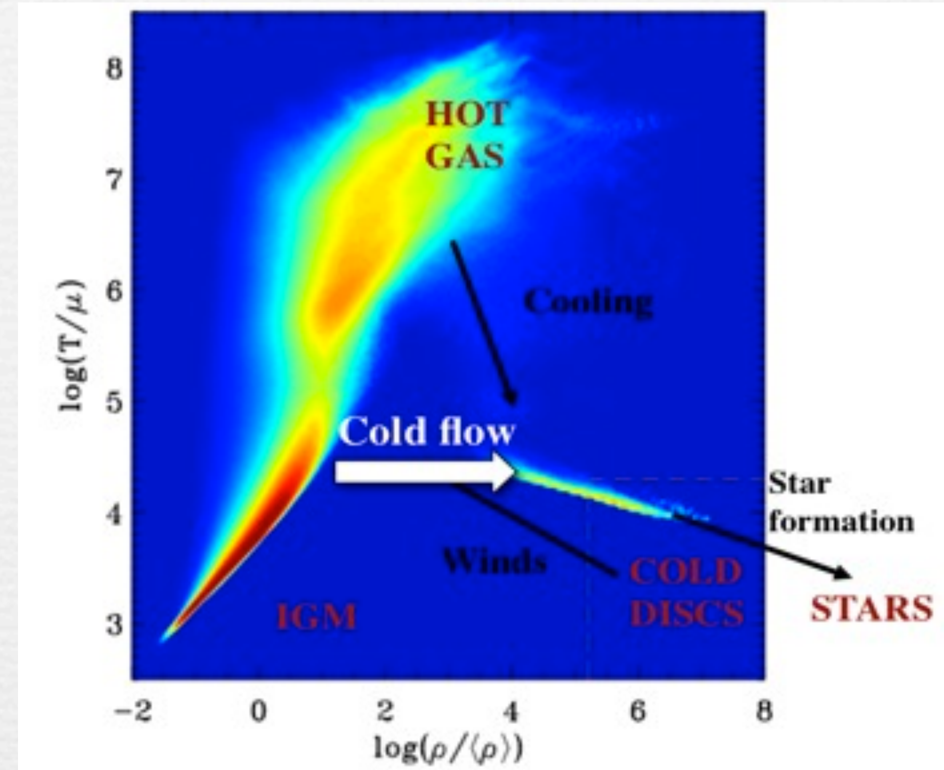
# @ high z / low mass



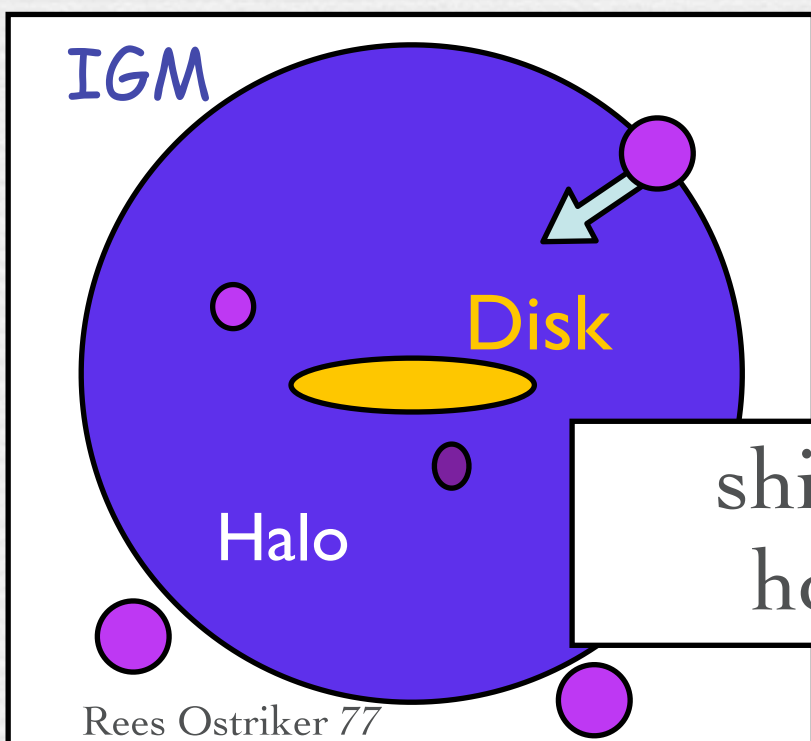

Paradigm
shift

cf Binney 77 !!



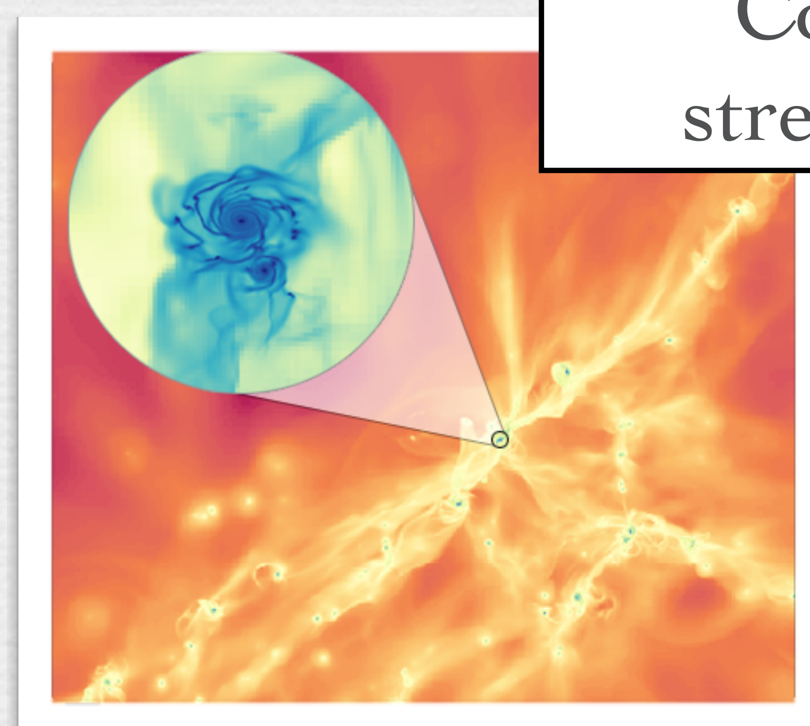

Gas shocks
isothermally
in LSS

« Interface » @ Virial Radius




shielding (?)
hot corona

Cold
streams



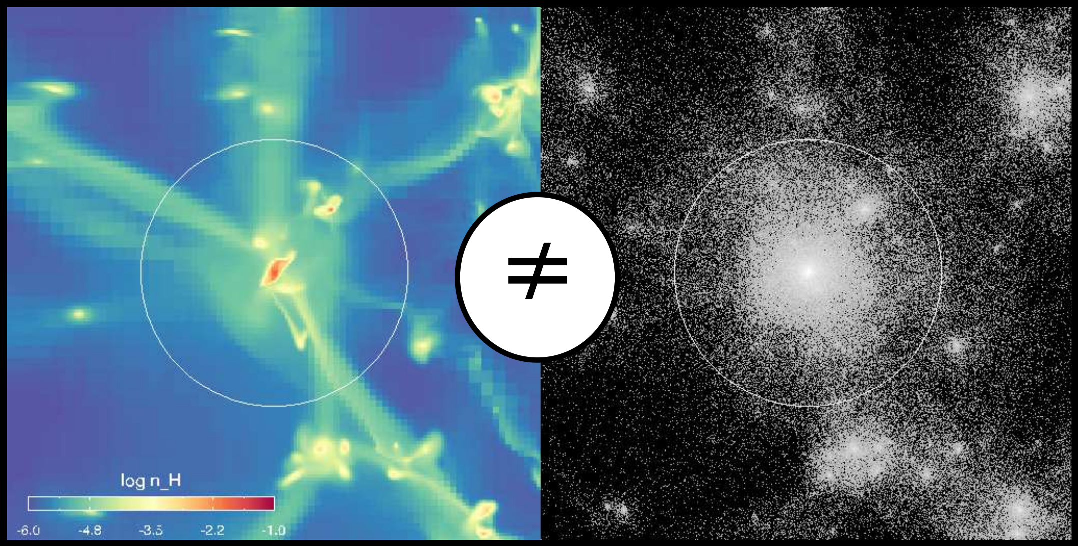
Katz 2002

@ high redshift

# Fact number four

The *Virtual (hydrodynamical)* universe

z=99.00




Cosmic web SHARPER

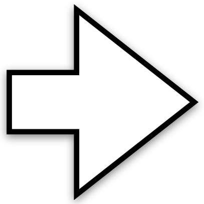
2 kpc

Agertz et al. (2009)

we see cold flows + recurrent disk reformation
LSS drives secondary infall & SPIN ALIGNMENT

# Context & clues

standard hierarchical clustering picture



halo rigging

aka completely useless (nautical) analogy that probably only the author understands

- ☑ disc must have a coherent stratified angular momentum
- ☑ surrounding void/wall repel (contrast<0) contribute to secondary infall
- ☑ gas shocks isothermally during shell crossing,  follows filaments closely
- ☑ there are discs on the sky and in numerical simulations
- ☑ galaxies form and evolve ***on*** the cosmic web (anisotropic PBS)

# Part I Outline

- 4 trivial facts about galaxies in their web
- **the proposition**
- various proofs of various value?

# The proposition in one sentence

Disks form because LSS are large *(dynamically young)* and *(partially)* an-isotropic :
they induce persistent angular momentum
advection of cold gas along filaments
which stratifies
accordingly so as to (re)build discs
continuously.

# Part I Outline

- 4 trivial facts about galaxies in their web
- The proposition
- **Various proofs of various value?**
  - smoking gun?
  - lots of hand waving ??
  - robust statistics?

# Clues from LSS

"Proof by halo centric environment"

a.k.a

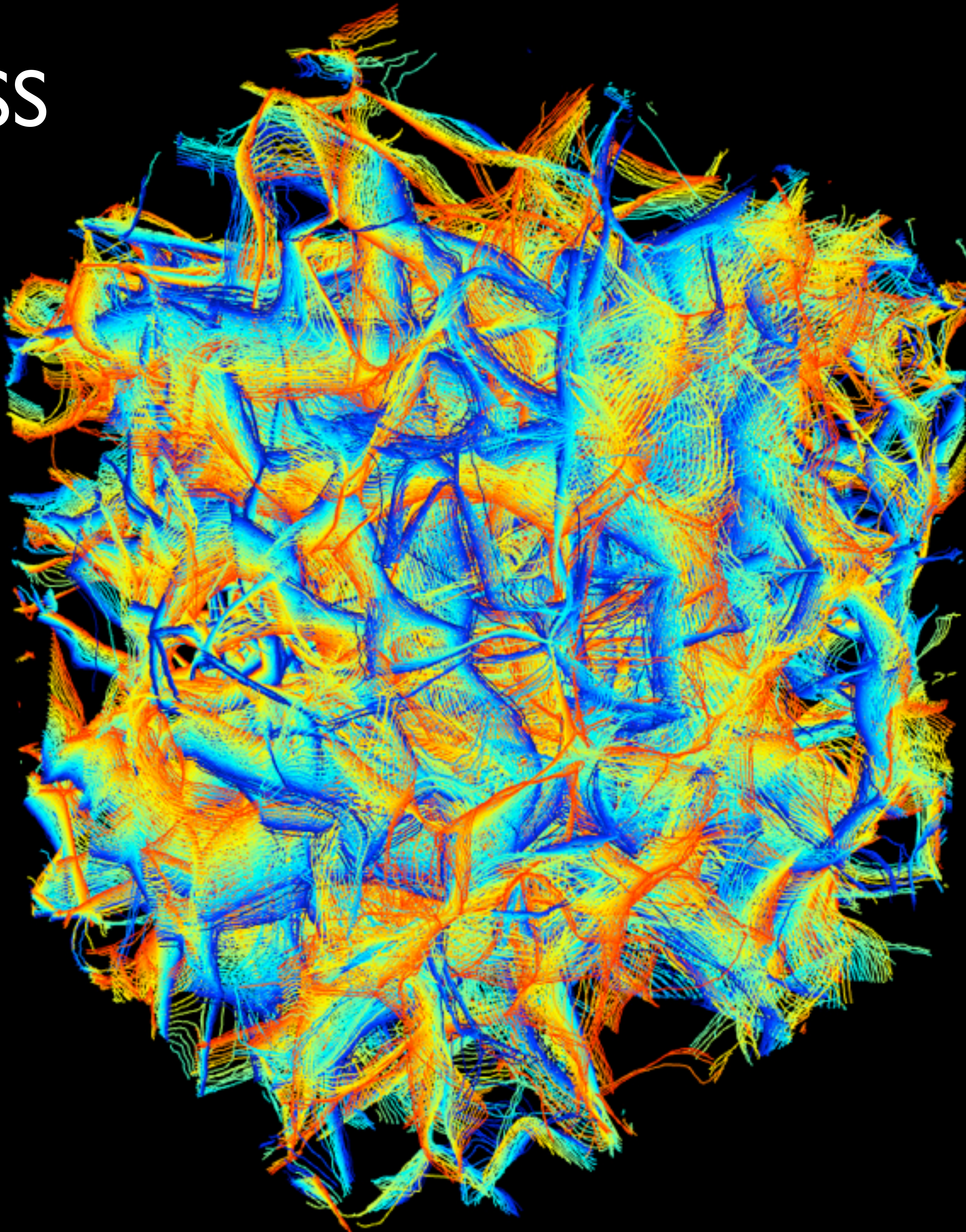
proof by hypnosis,

fishy analogy &

mathematical jargon

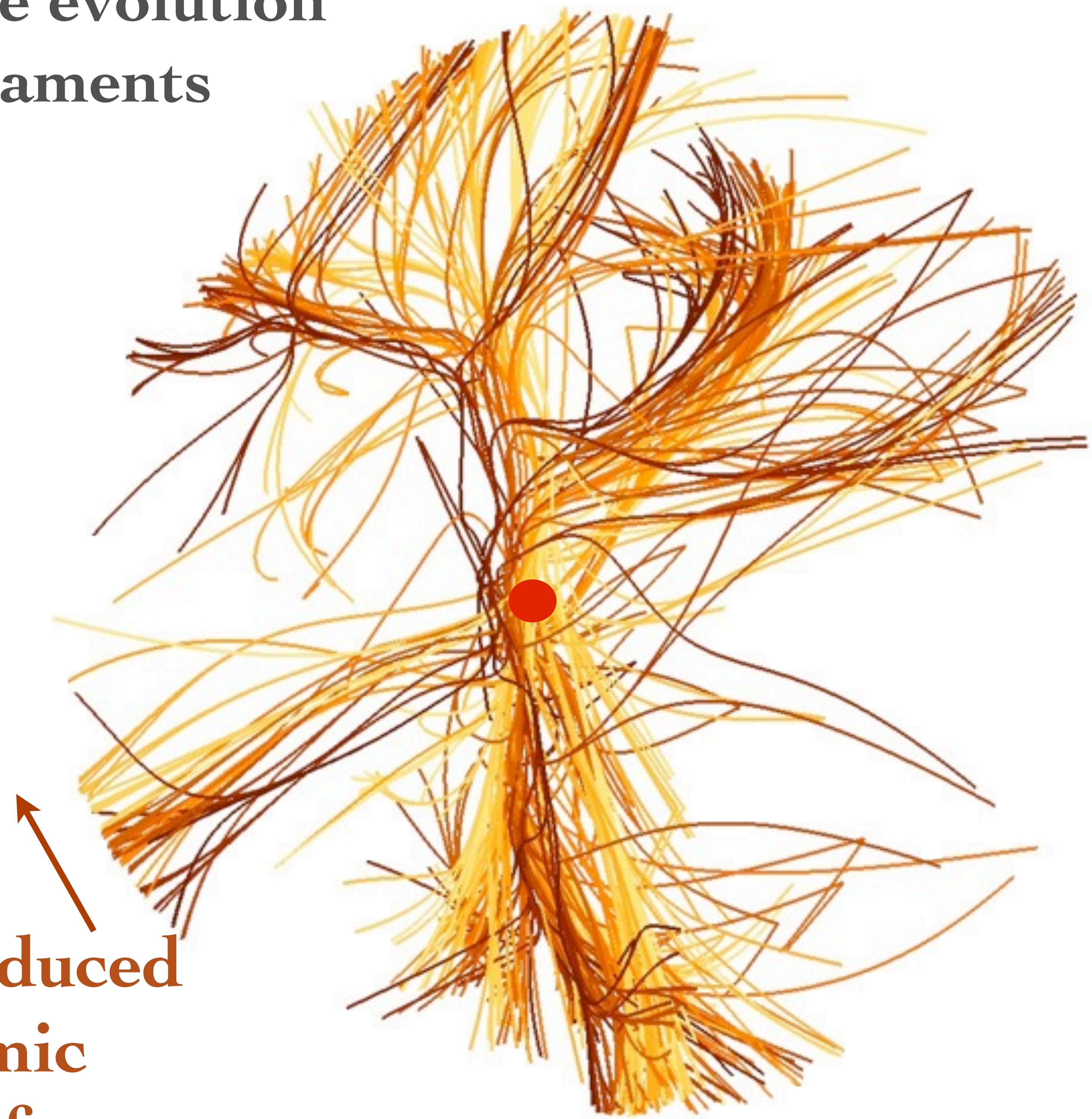
# Time line of LSS

full history of universe
at once !



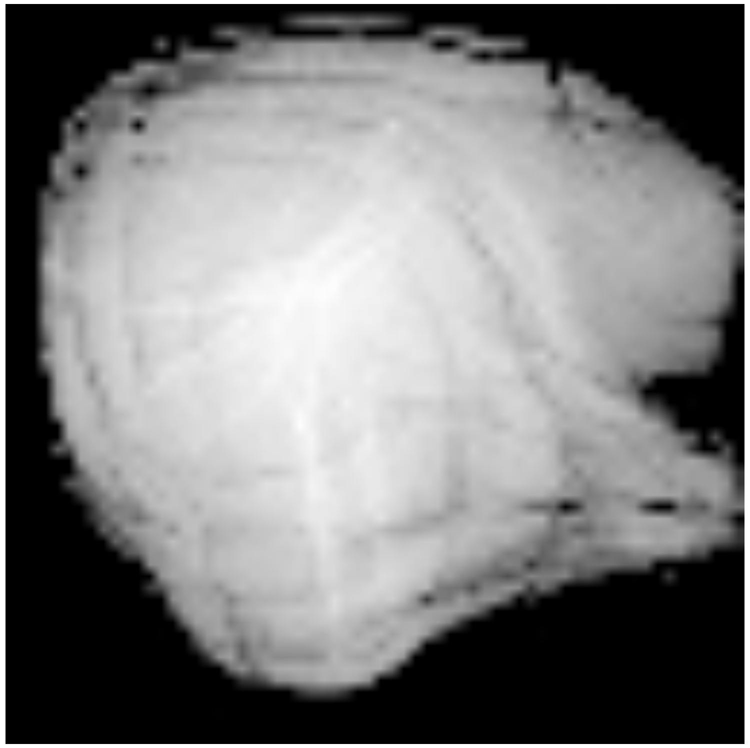
# Drift of filaments

**Time-line evolution of filaments**



**void induced cosmic drift**

# Drift of filaments

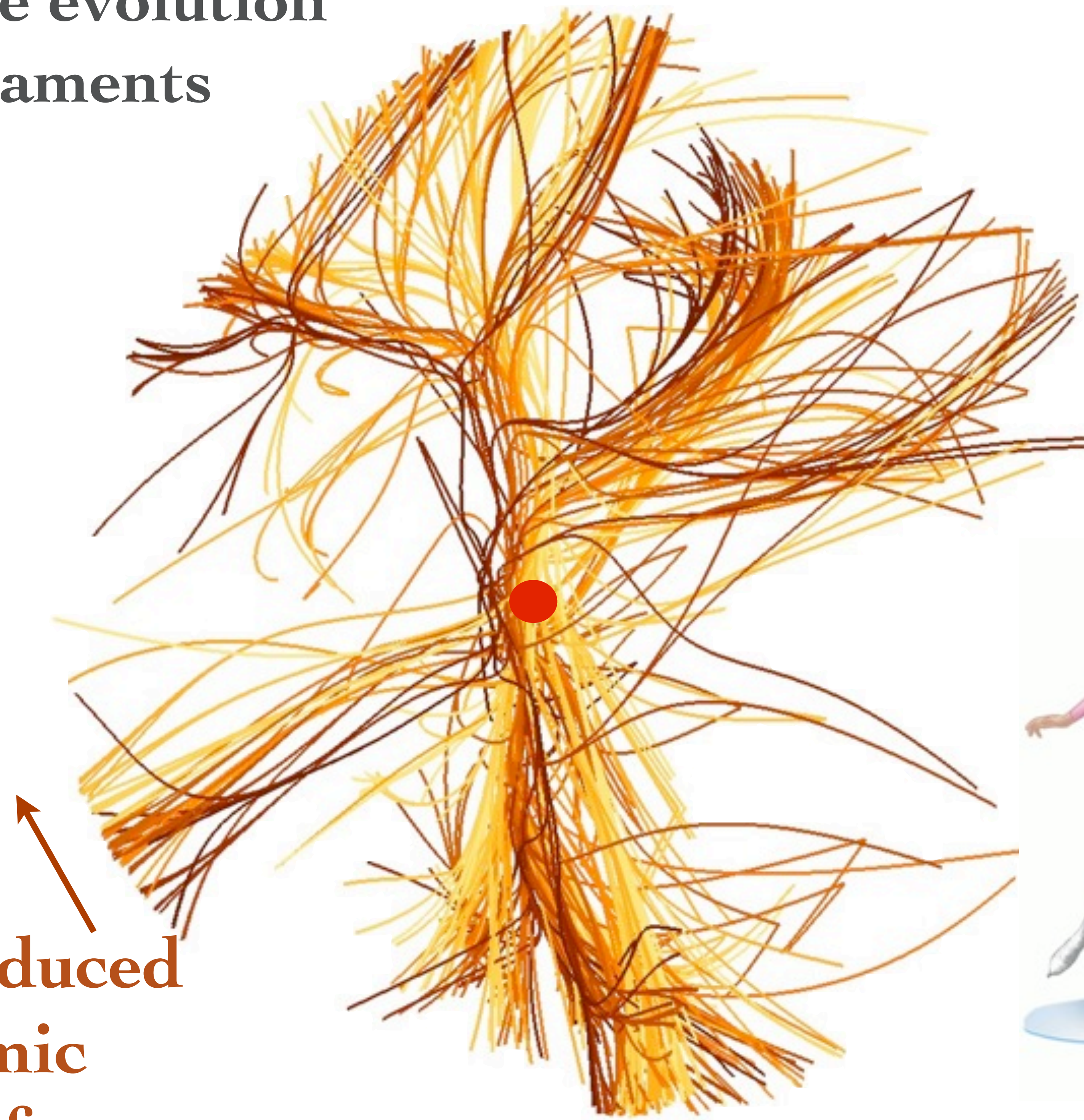


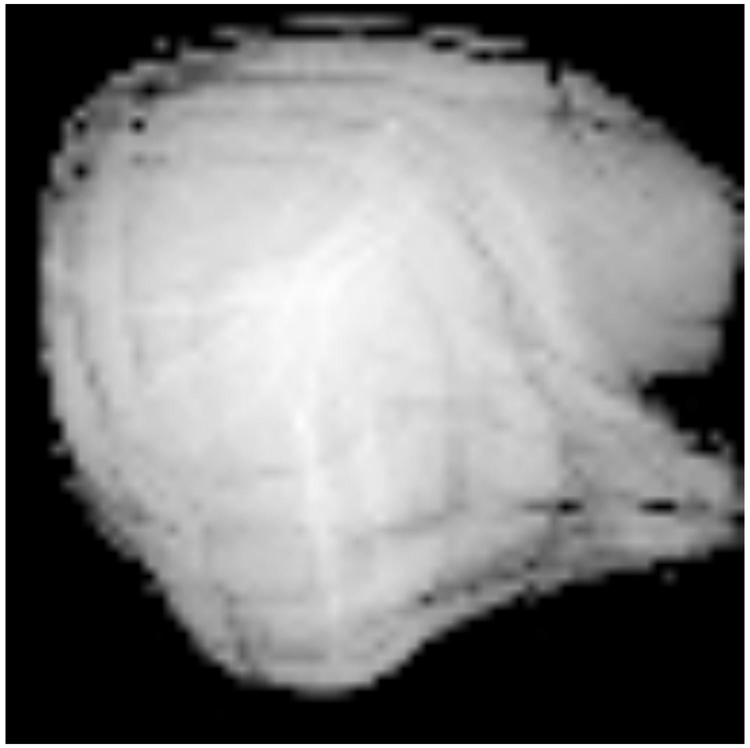
**Time-line evolution of filaments**

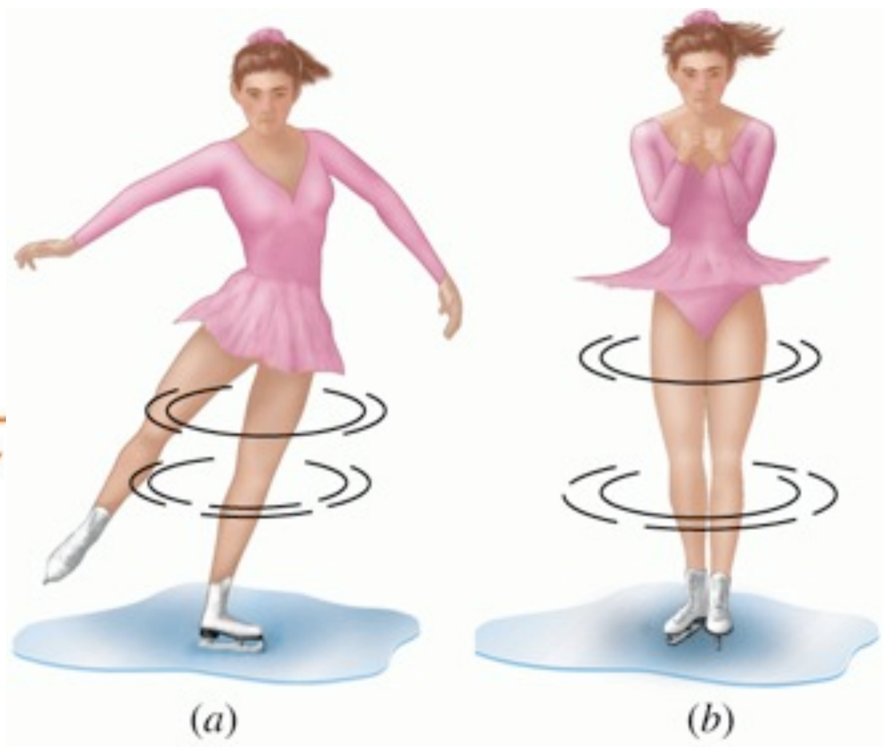
**void induced cosmic drift**

# Drift of filaments

**Time-line evolution of filaments**

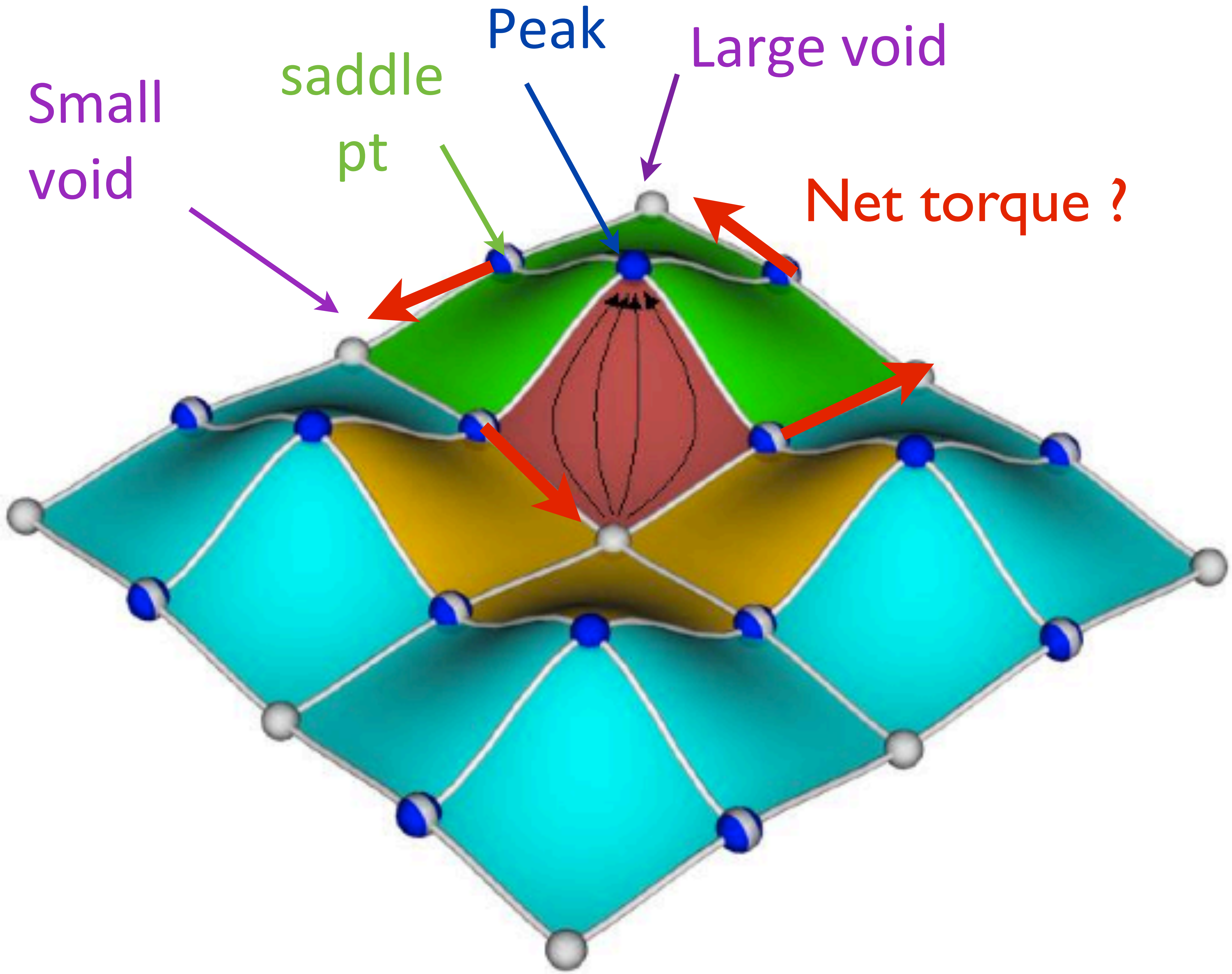







**void induced cosmic drift**

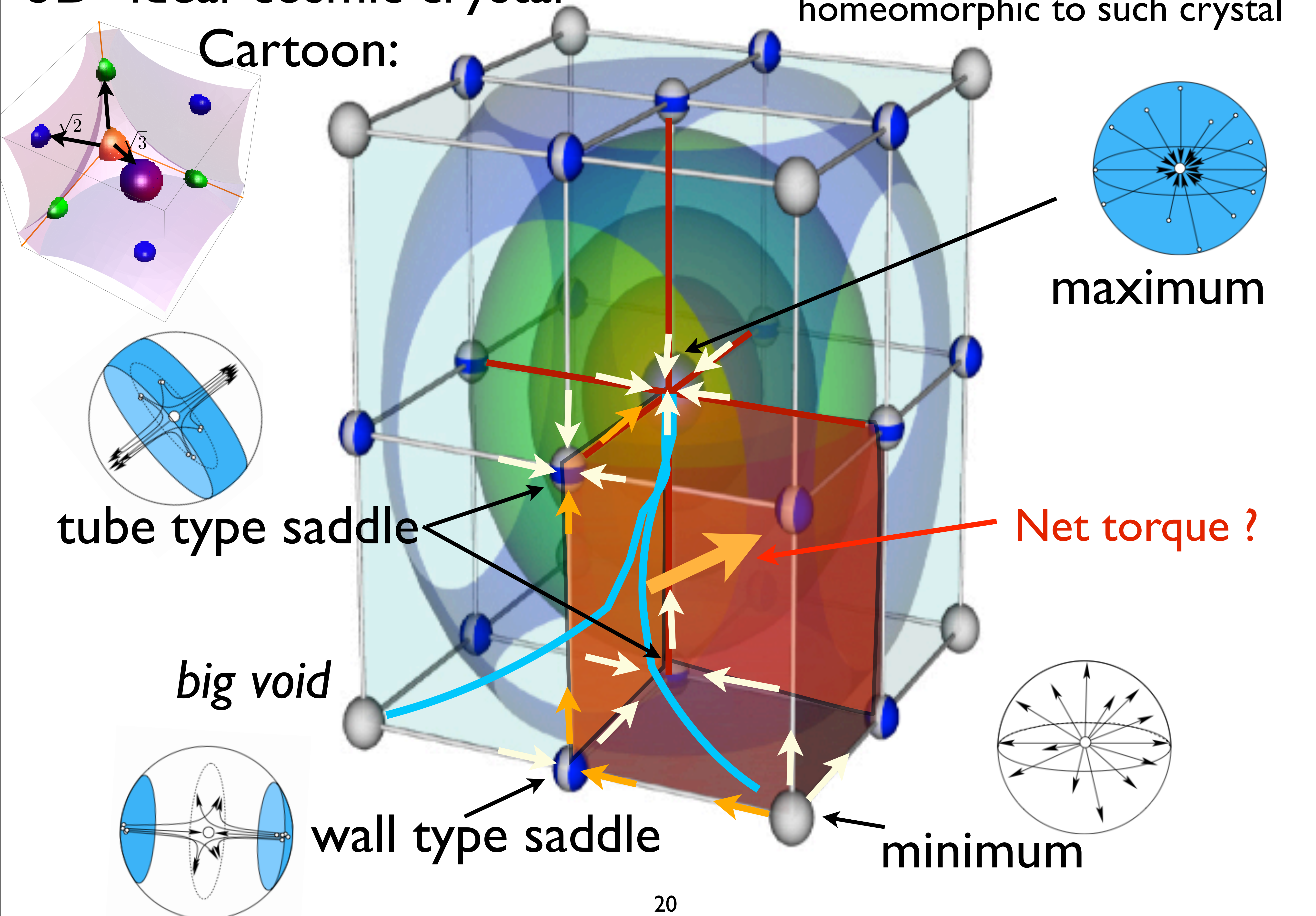
# 2D Cartoon of "ideal" cosmic environment :




Mean local cosmic initial condition homeomorphic to such crystal

# 3D "ideal"cosmic crystal Cartoon:

Mean local cosmic initial condition homeomorphic to such crystal



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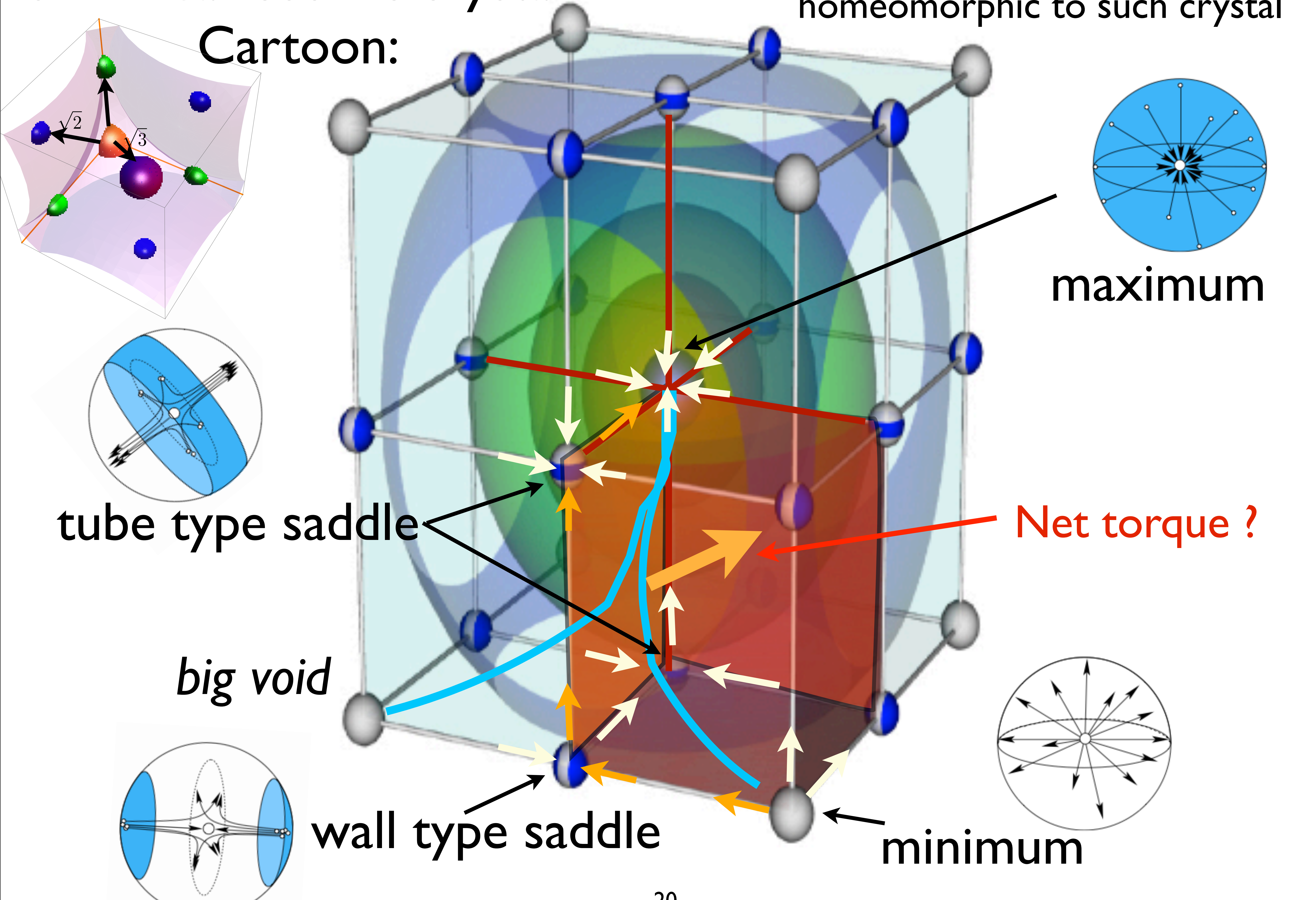



*biased by assumed isotropy: generically one fil+wall*

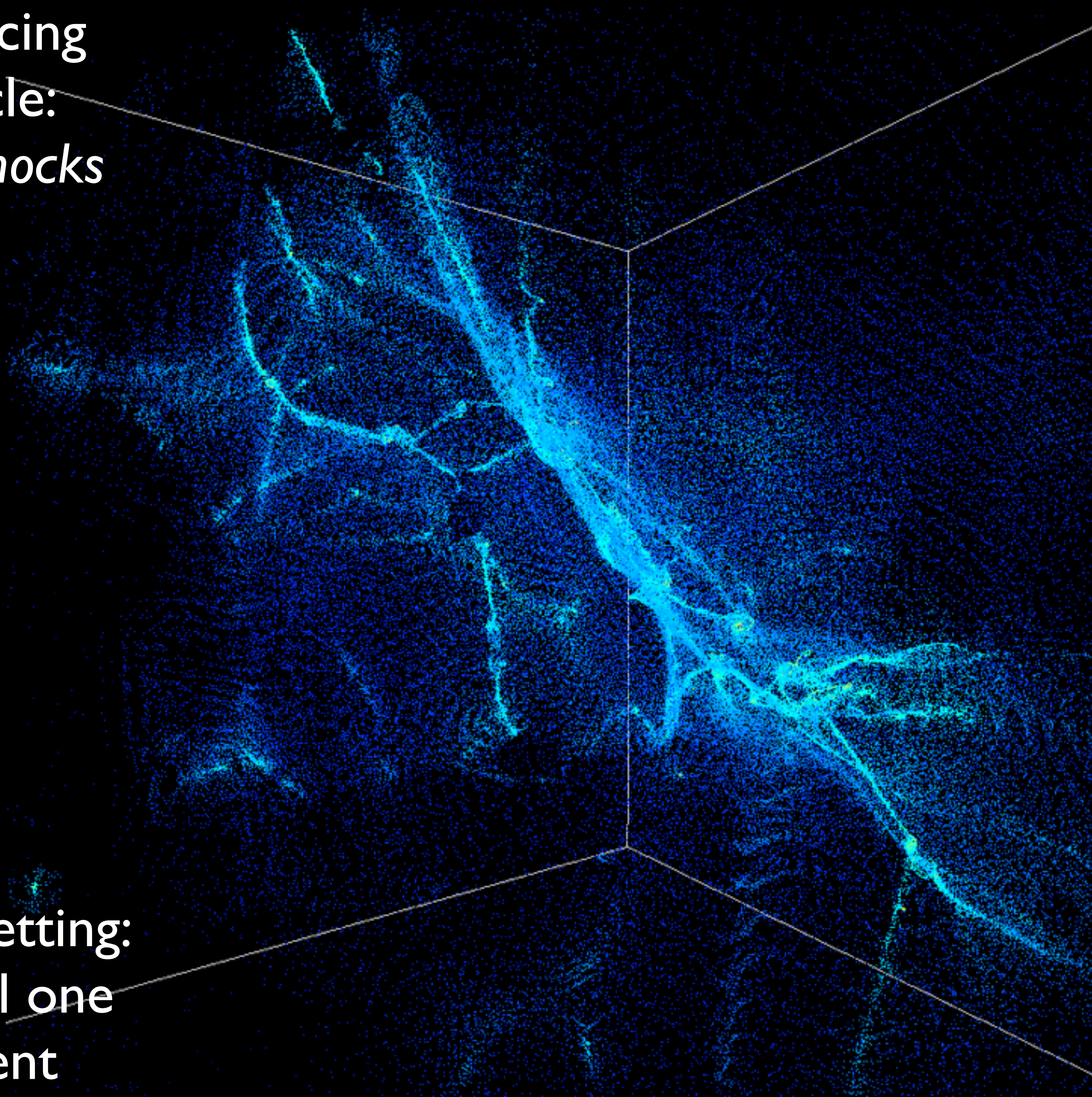
**Do we see this?**

"Proof" by visualisation of hydrodynamical simulation

a.k.a

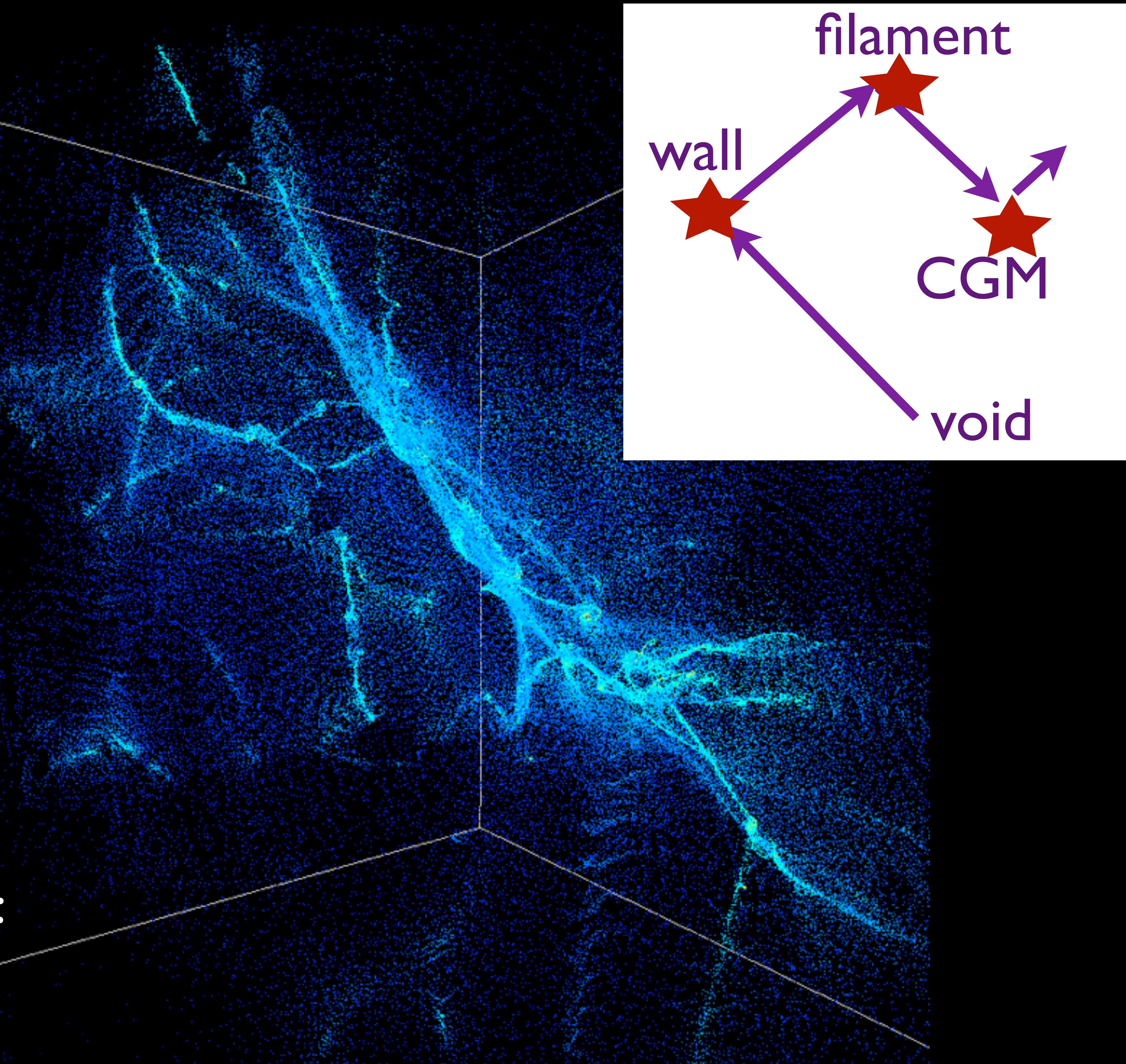
proof by pretty pictures

gas tracing particle: *follow shocks*



typical setting: one wall one filament

gas tracing particle:
*follow shocks*

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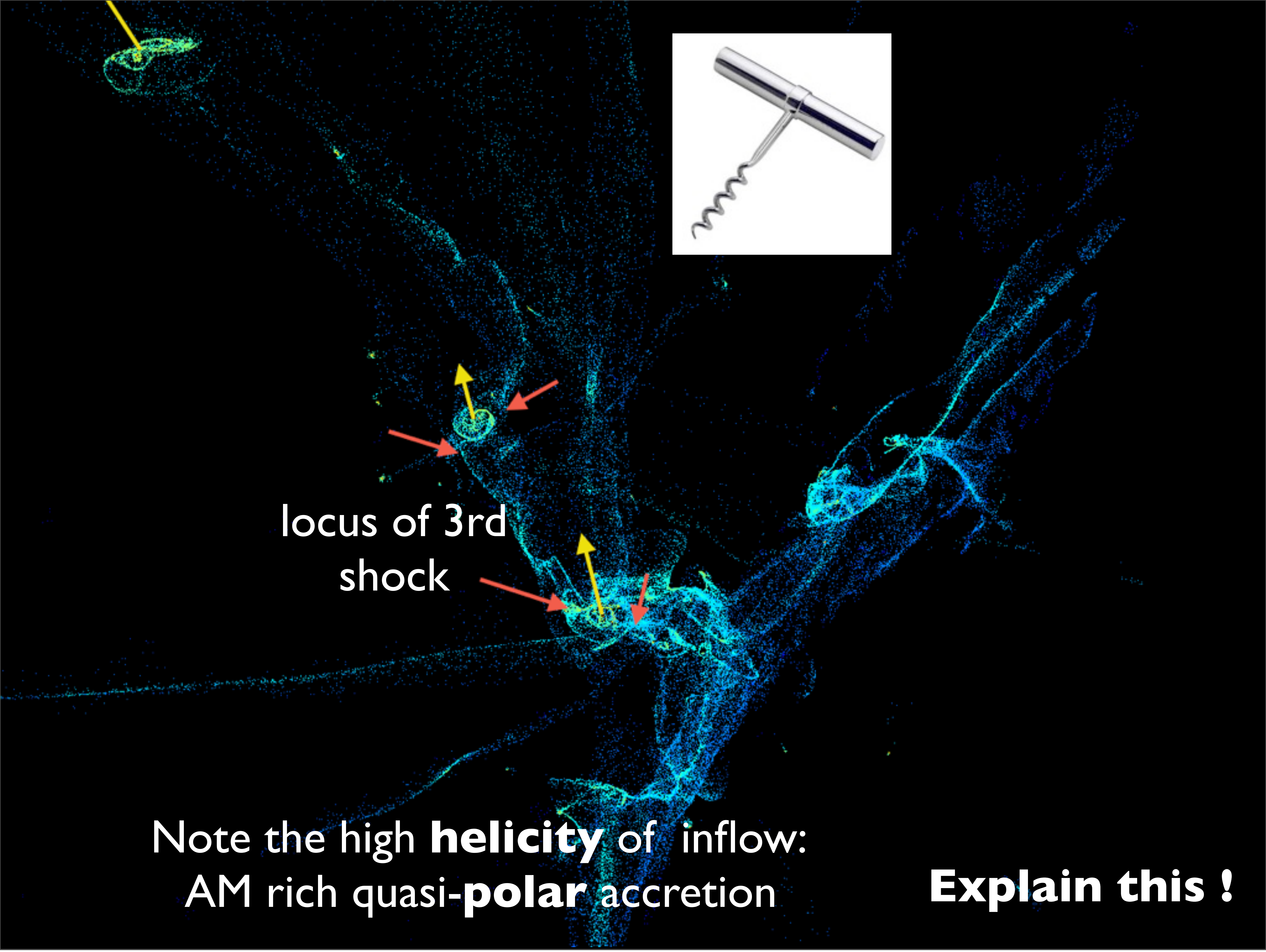
one wall one filament

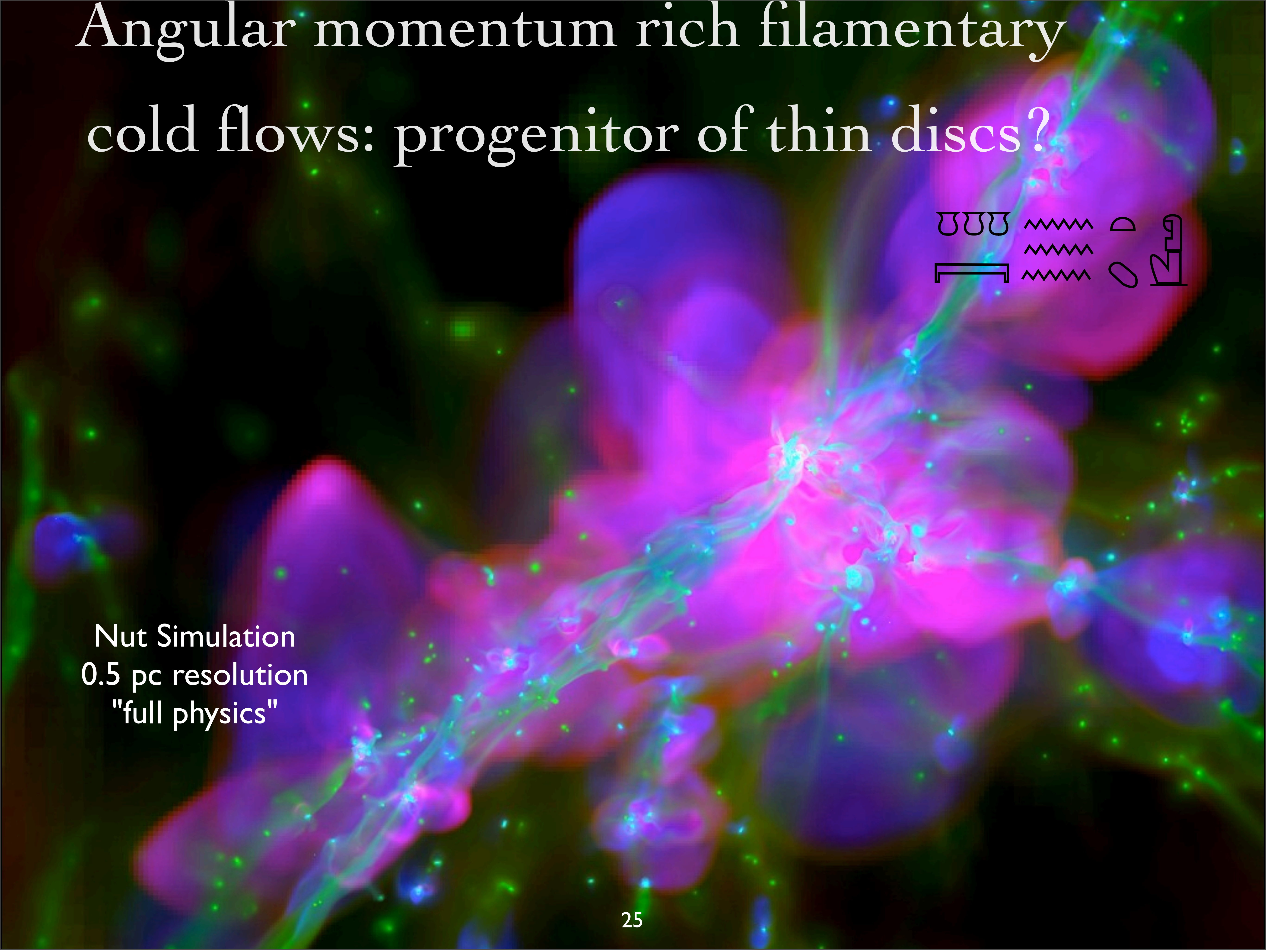

locus of 3rd
shock
Note the high **helicity** of inflow:
AM rich quasi-**polar** accretion
**Explain this !**

Can we trace this back in time?

"Proof" by tagging

a.k.a "Proof" by looking at **ONE** object !

# Angular momentum rich filamentary cold flows: progenitor of thin discs?



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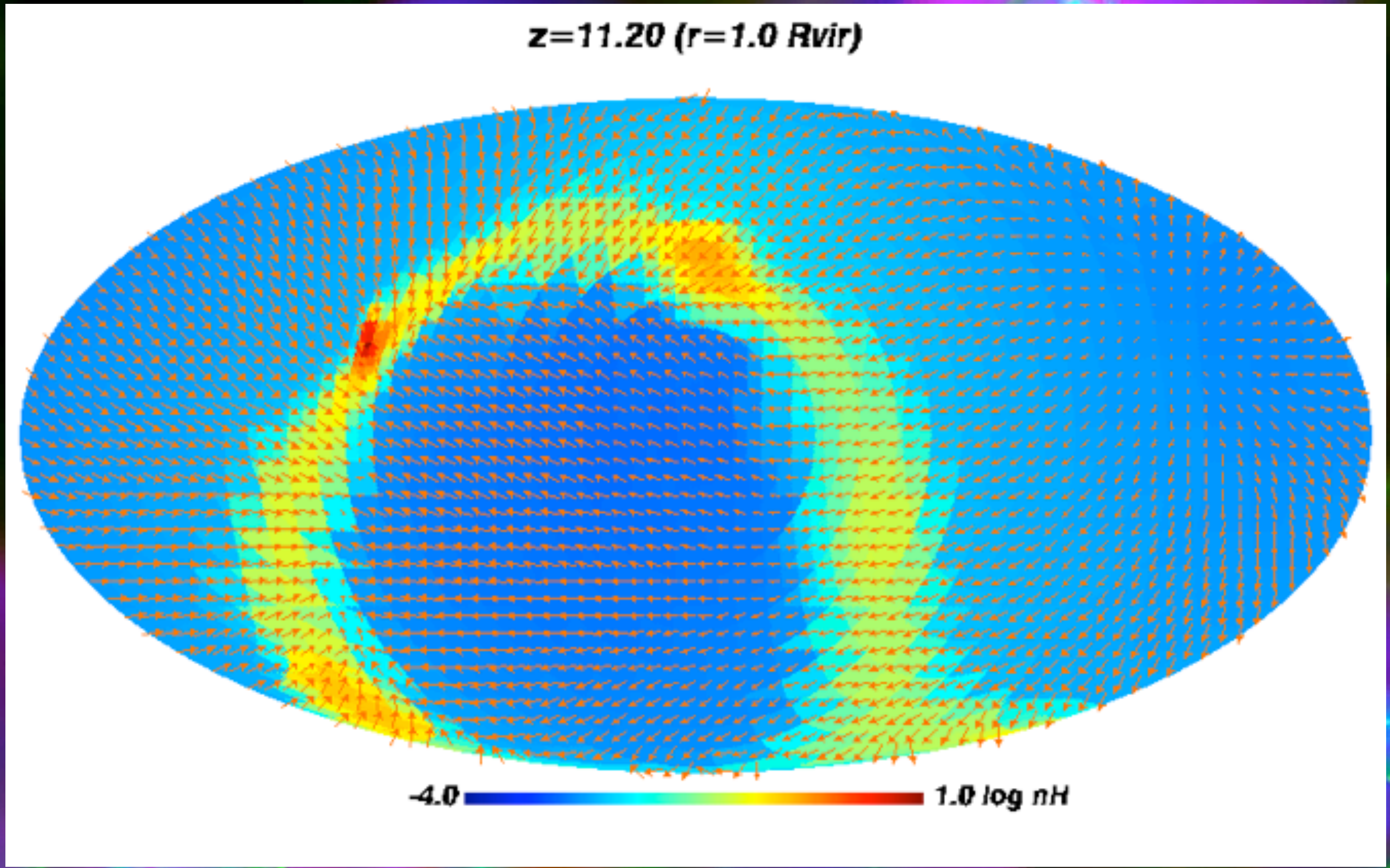
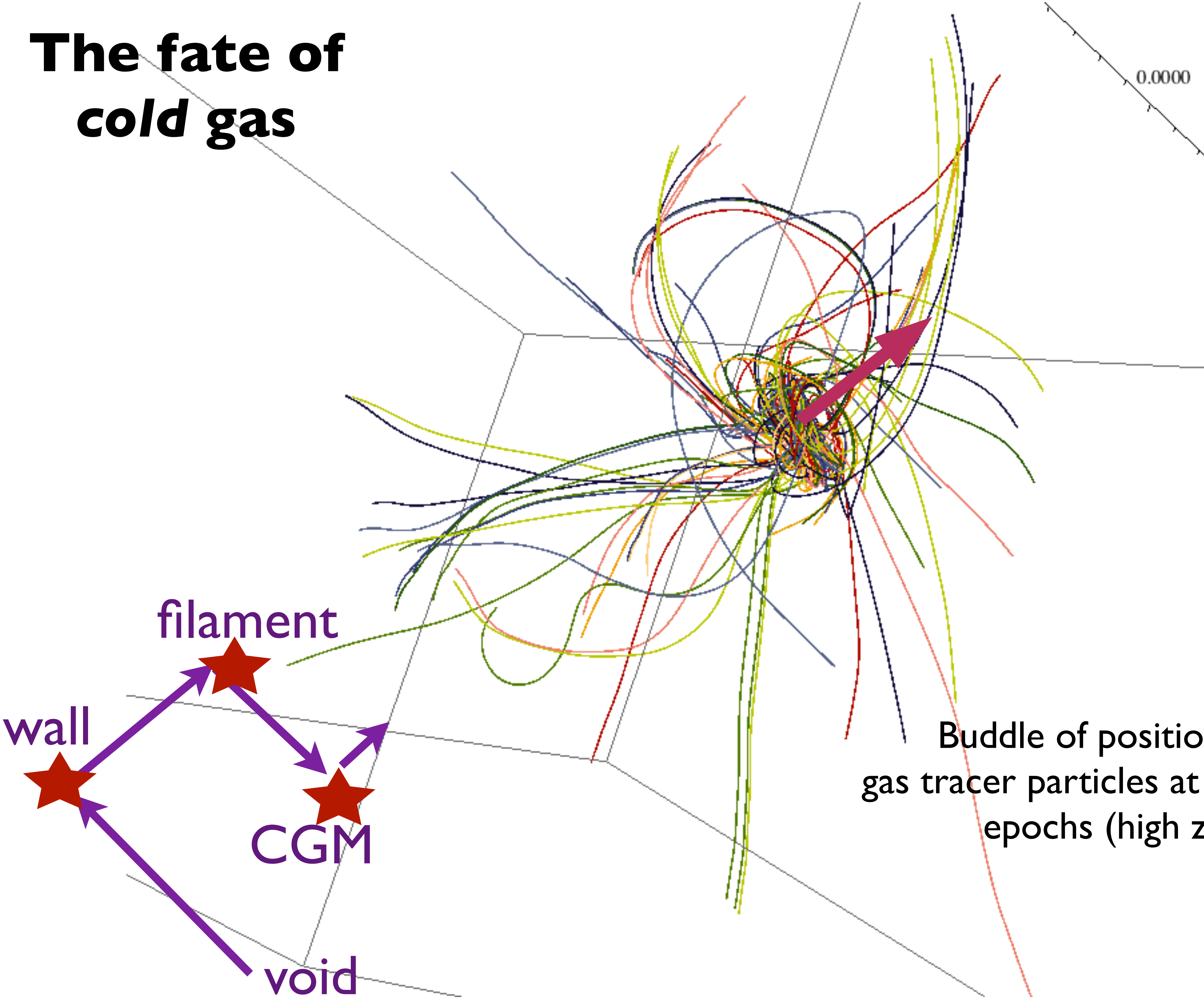
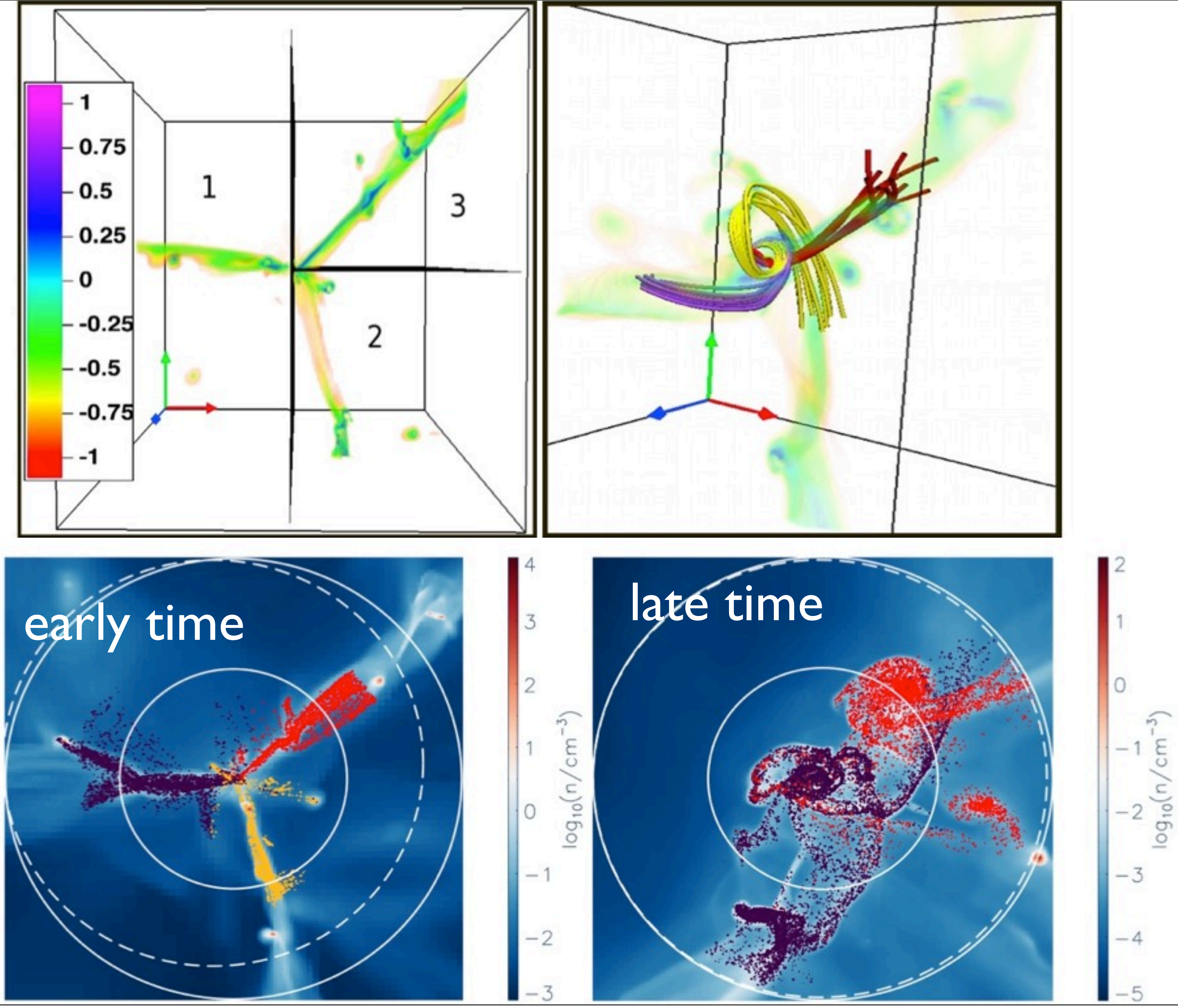



Nut Simulation
0.5 pc resolution
"full physics"

# The fate of *cold* gas

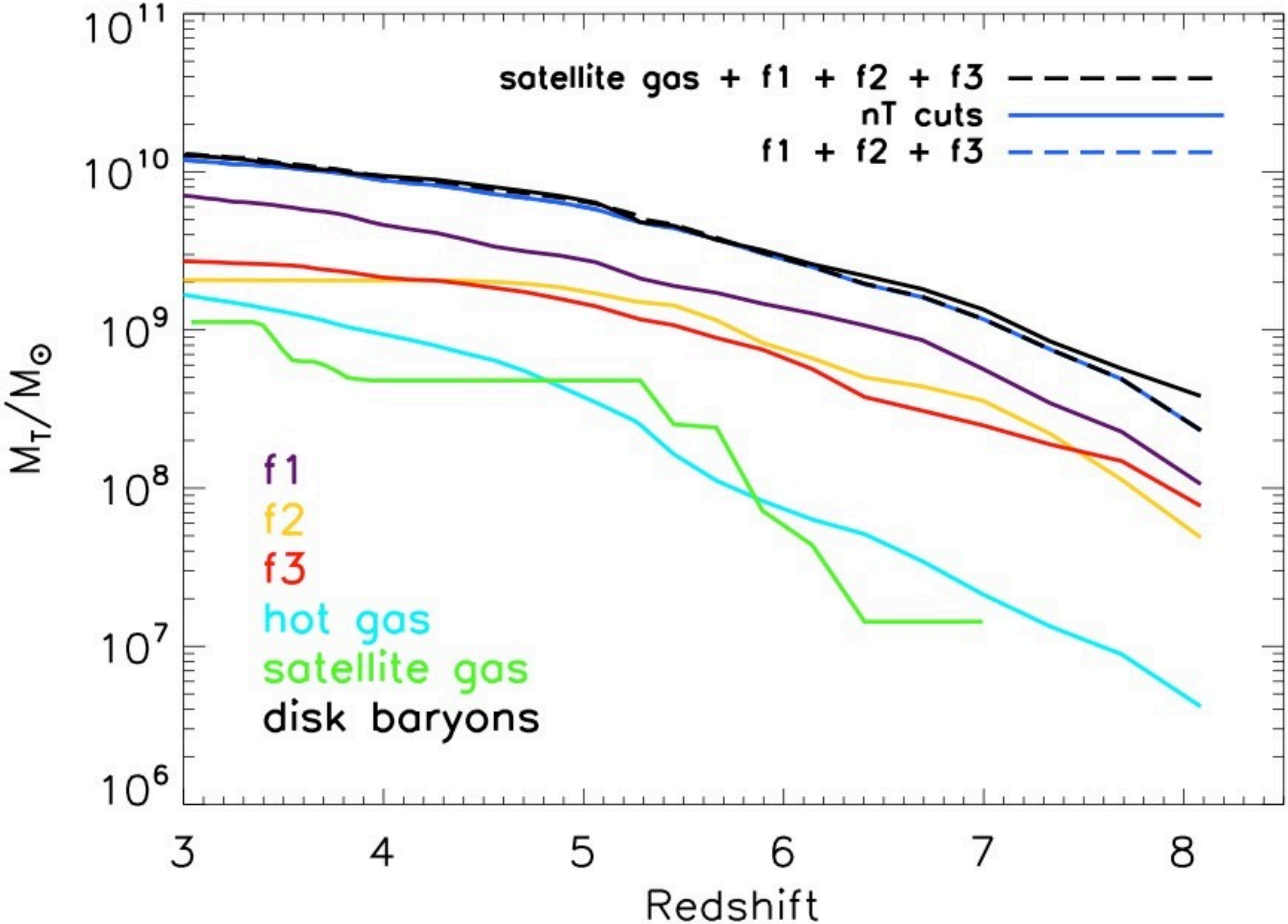



Buddle of position of
gas tracer particles at different
epochs (high z)

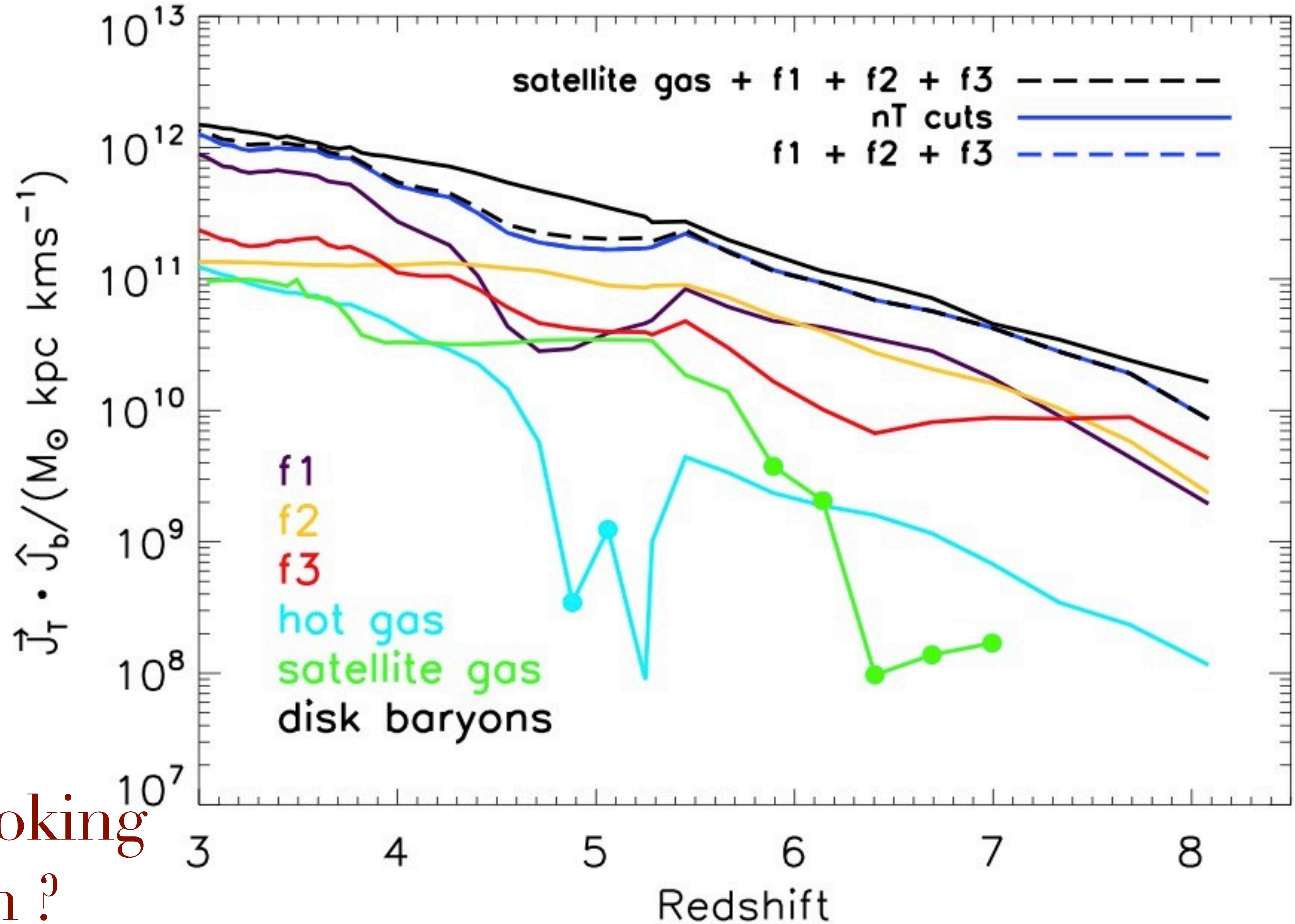


1
2
3
1
0.75
0.5
0.25
0
-0.25
-0.5
-0.75
-1
early time
late time
log10(n/cm-3)
log10(n/cm-3)

# Mass in disc originate from filaments



# Angular momentum in disc originate from filaments




Smoking gun ?

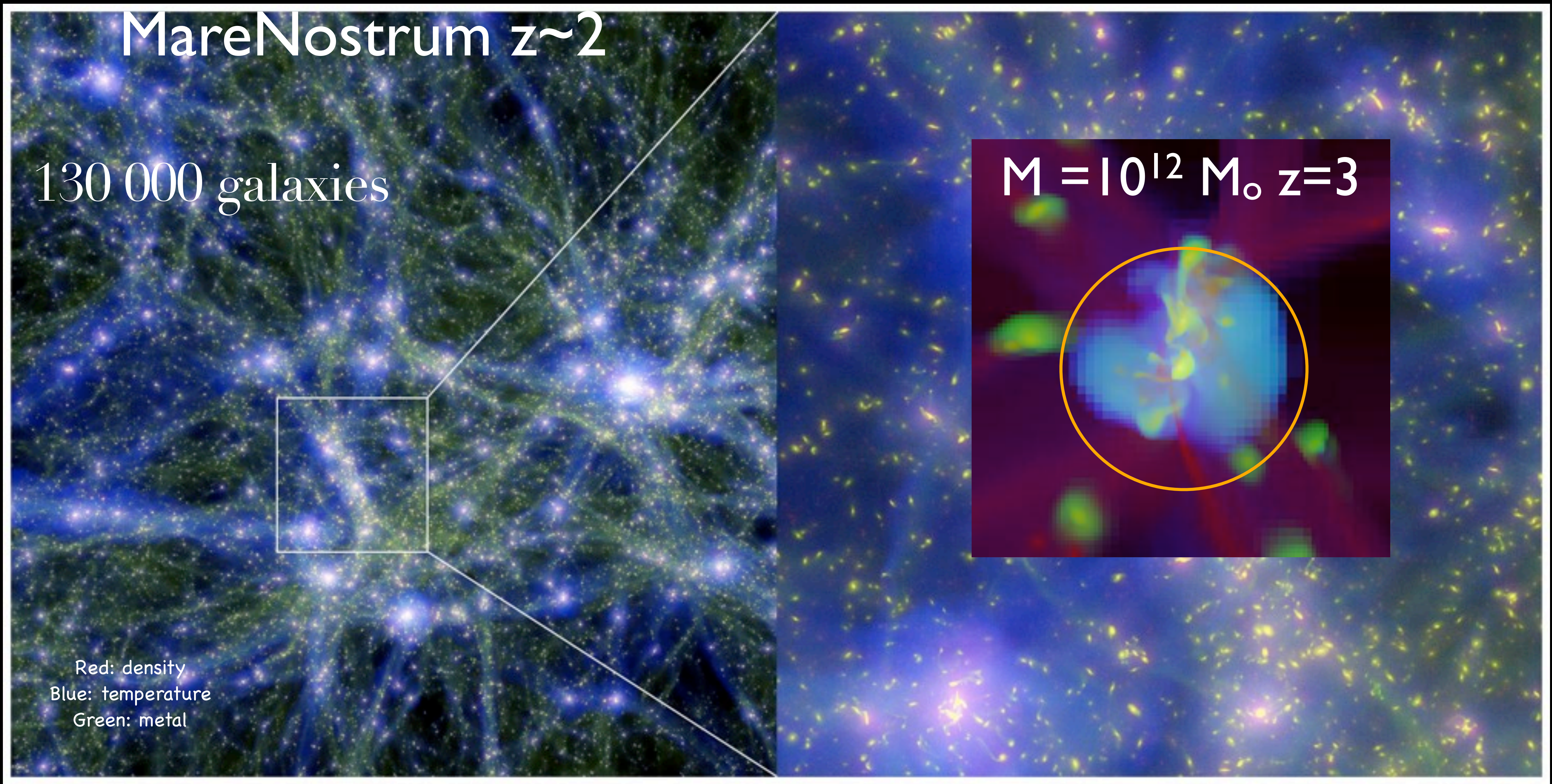
# Can it be made quantitative?

"Proof" by robust statistical analysis

a.k.a

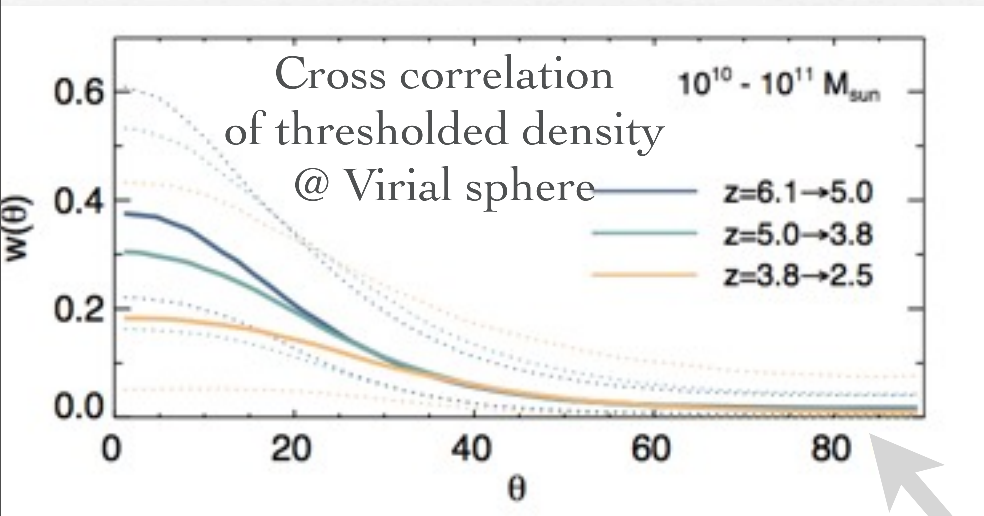
lies, damn lies and statistics

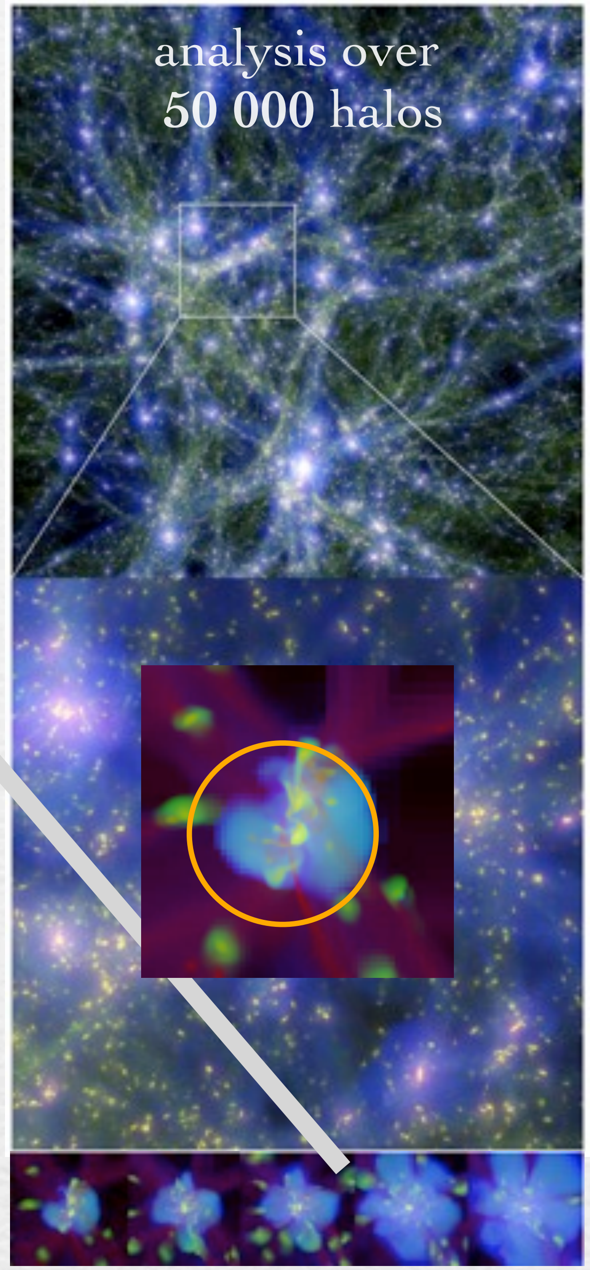
# Anisotropic accretion: cold flows driven by LSS

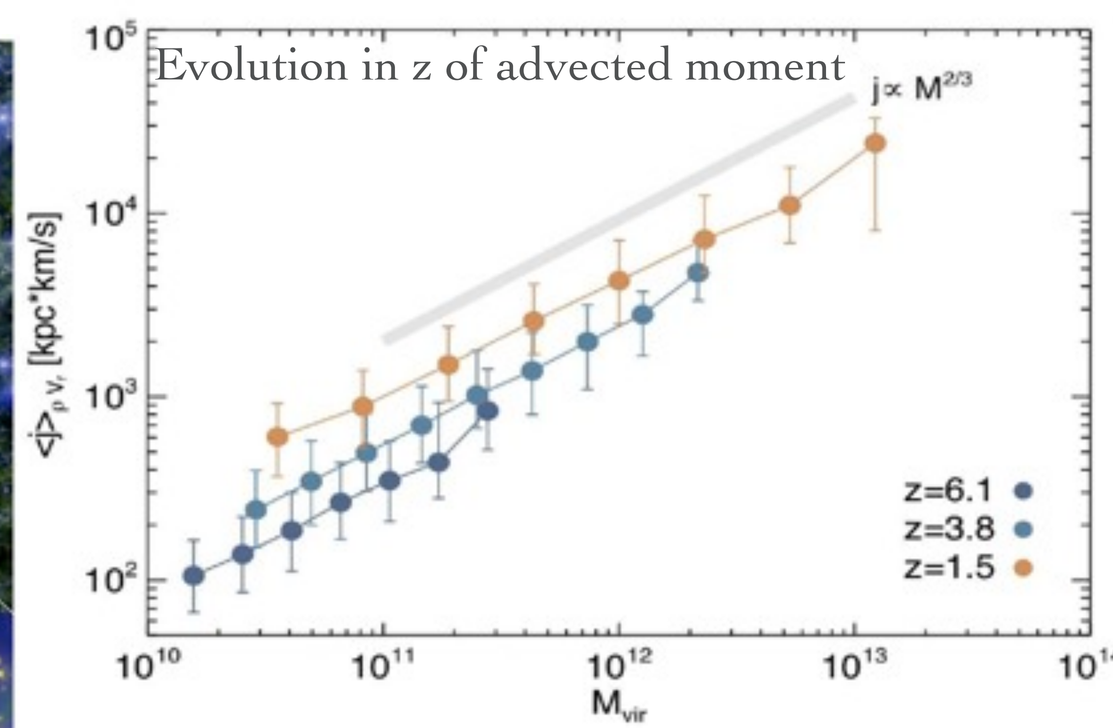



- Use LSS dynamics to statistically analyse AM infall @ Rvir

$$w(\theta) = \sum_{l,m} \langle a_{lm} b^*_{lm} \rangle P_l(\cos(\theta)) / \sqrt{(} \sum_{l,m} \langle |a_{lm}|^2 \rangle \sum_{l,m} \langle |b_{lm}|^2 \rangle ) \, ,$$



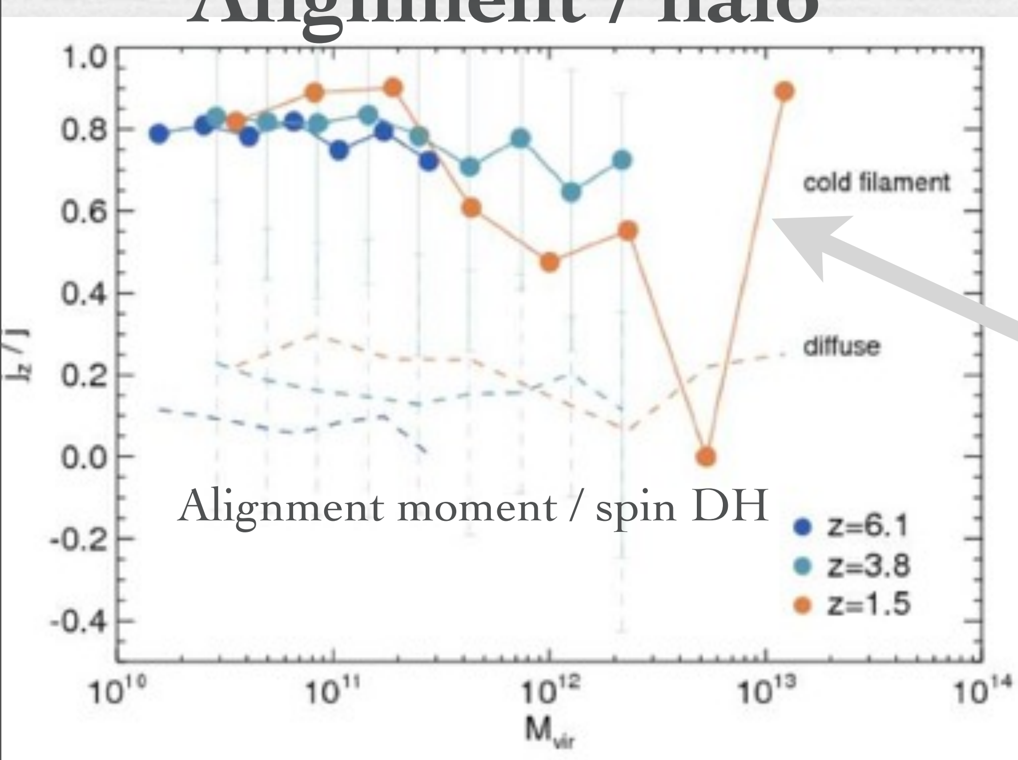



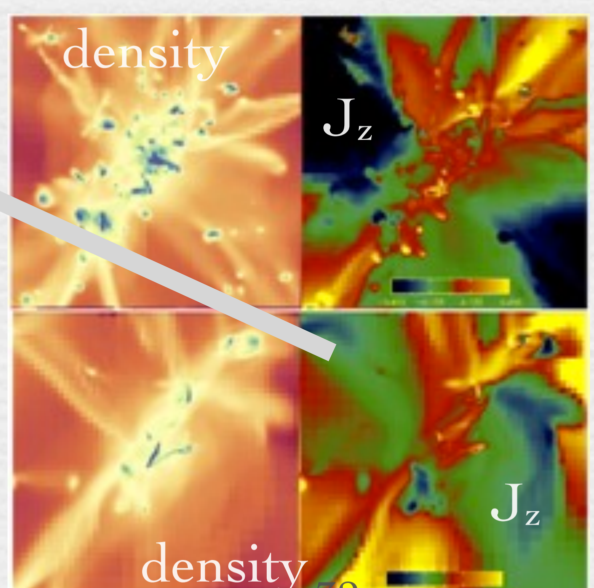

# Filamentary Accretion: coherent orientation

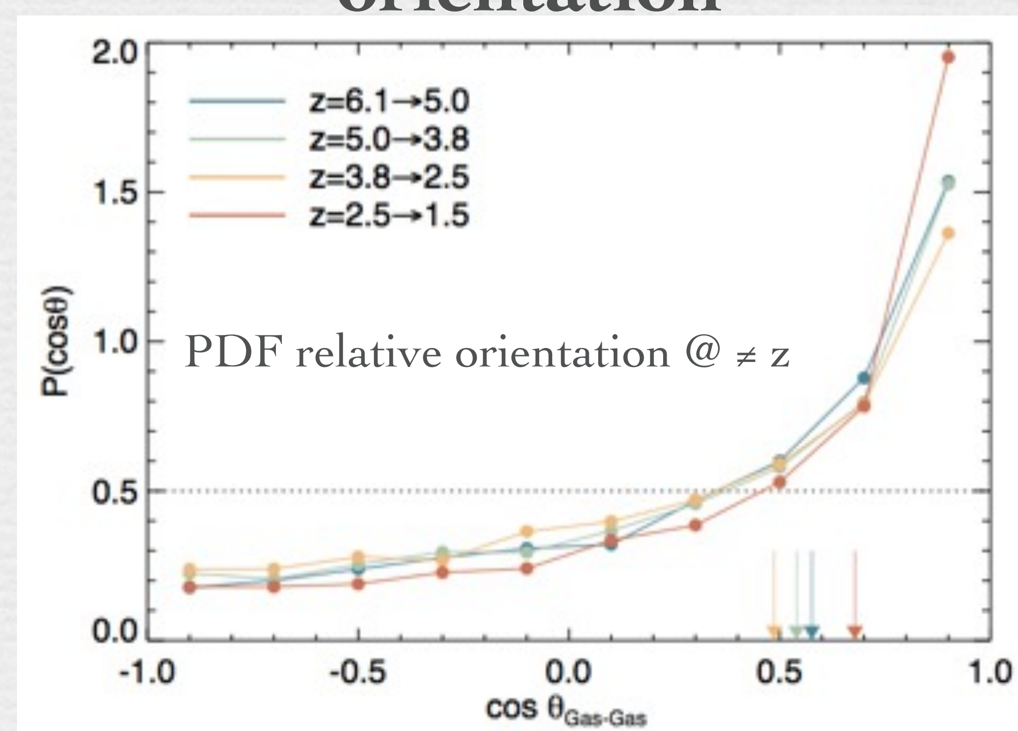
# growth of |ang moment|

# Advected Ang Moment Alignment / halo

# Coherent ang. moment orientation



Disks form because LSS are large *(dynamically young)* and *(partially)* an-isotropic : they induce persistent angular momentum advection of cold gas along filaments which stratifies accordingly so as to (re)build discs continuously.

*typically one wall one filament: dynamical implication?*

initial galactic infall is AM rich
but quasi polar in the CGM
-> spin // to embedding filament

This is the raison d'être of cosmic web :-)

# PART II

# What's happening on larger scales?

How is the cosmic web woven?

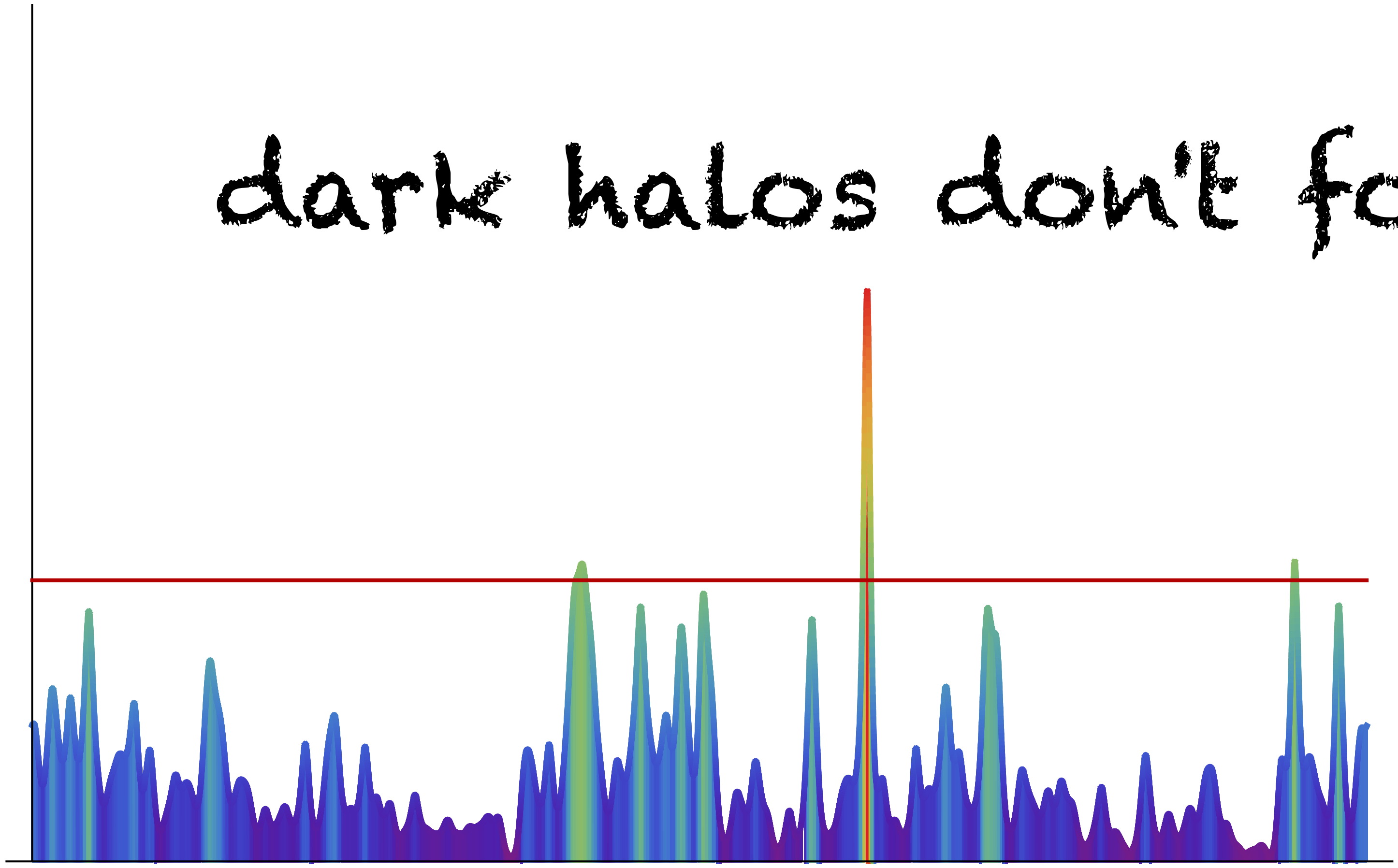
i.e Where do galaxies form in our Universe?

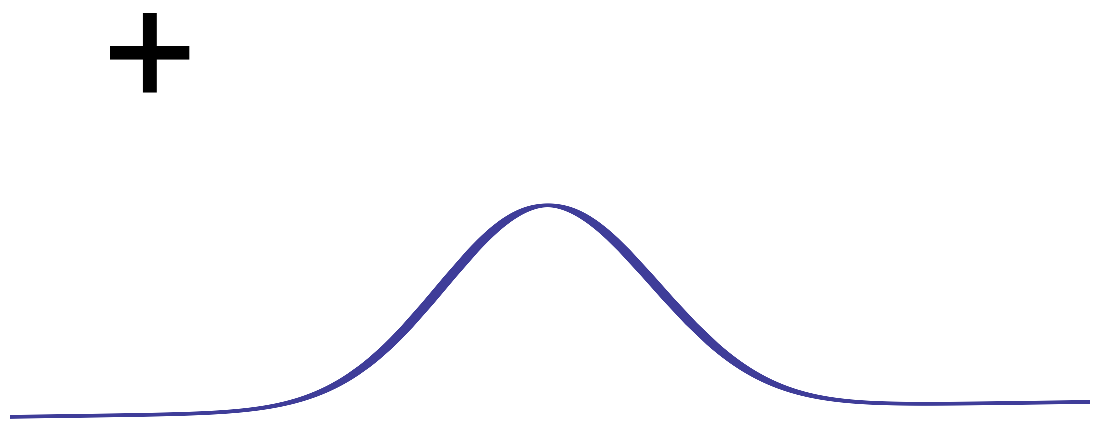
What are the dynamical implications?

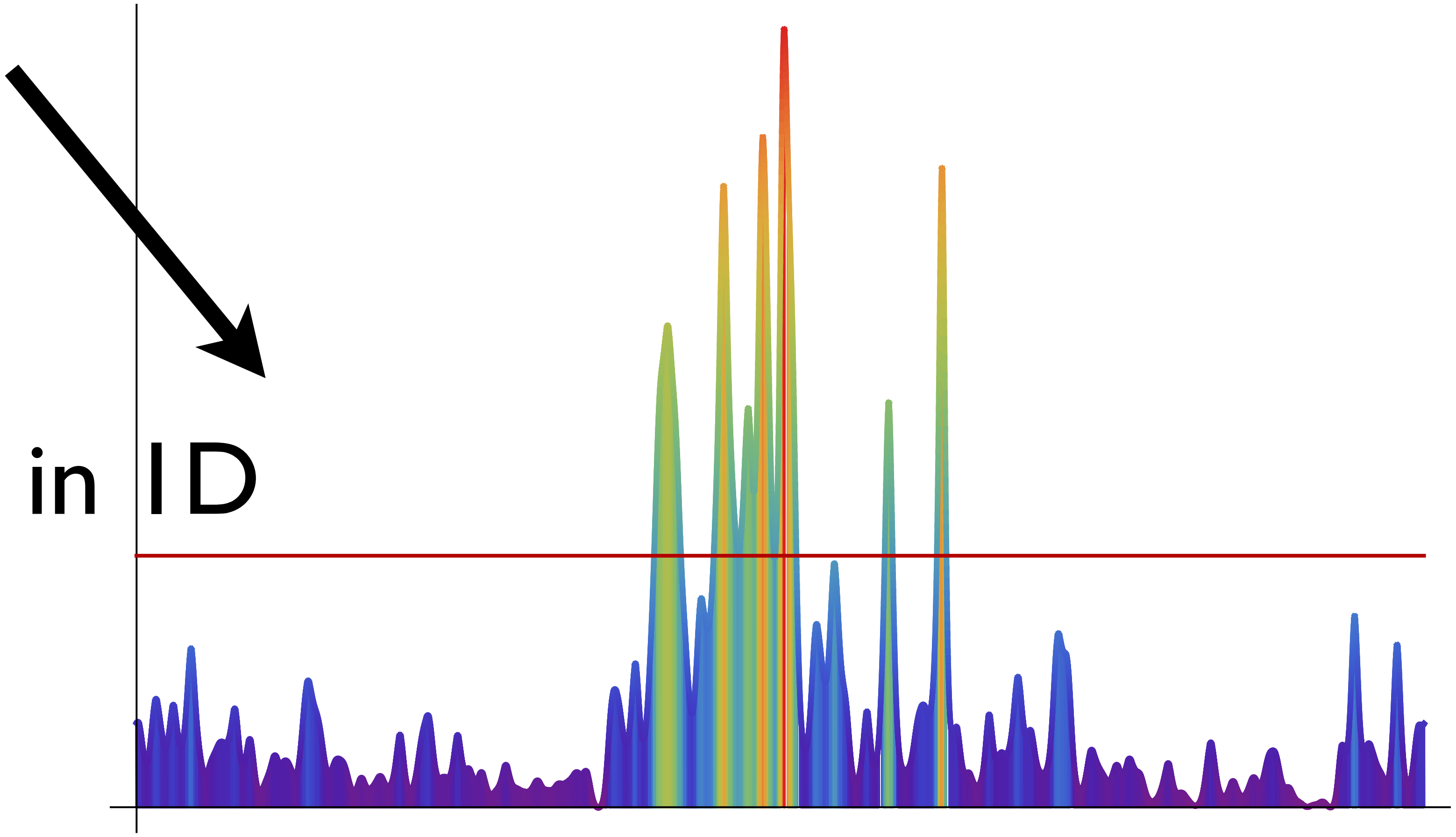
Why?

- How discs build up from persistent cosmic web?
- **How dark halo's spin flip relative to filament? Why are they initially aligned with filaments? Why the transition mass? Eulerian view**
- What is the corresponding Lagrangian theory?

# dark halos don't form anywhere

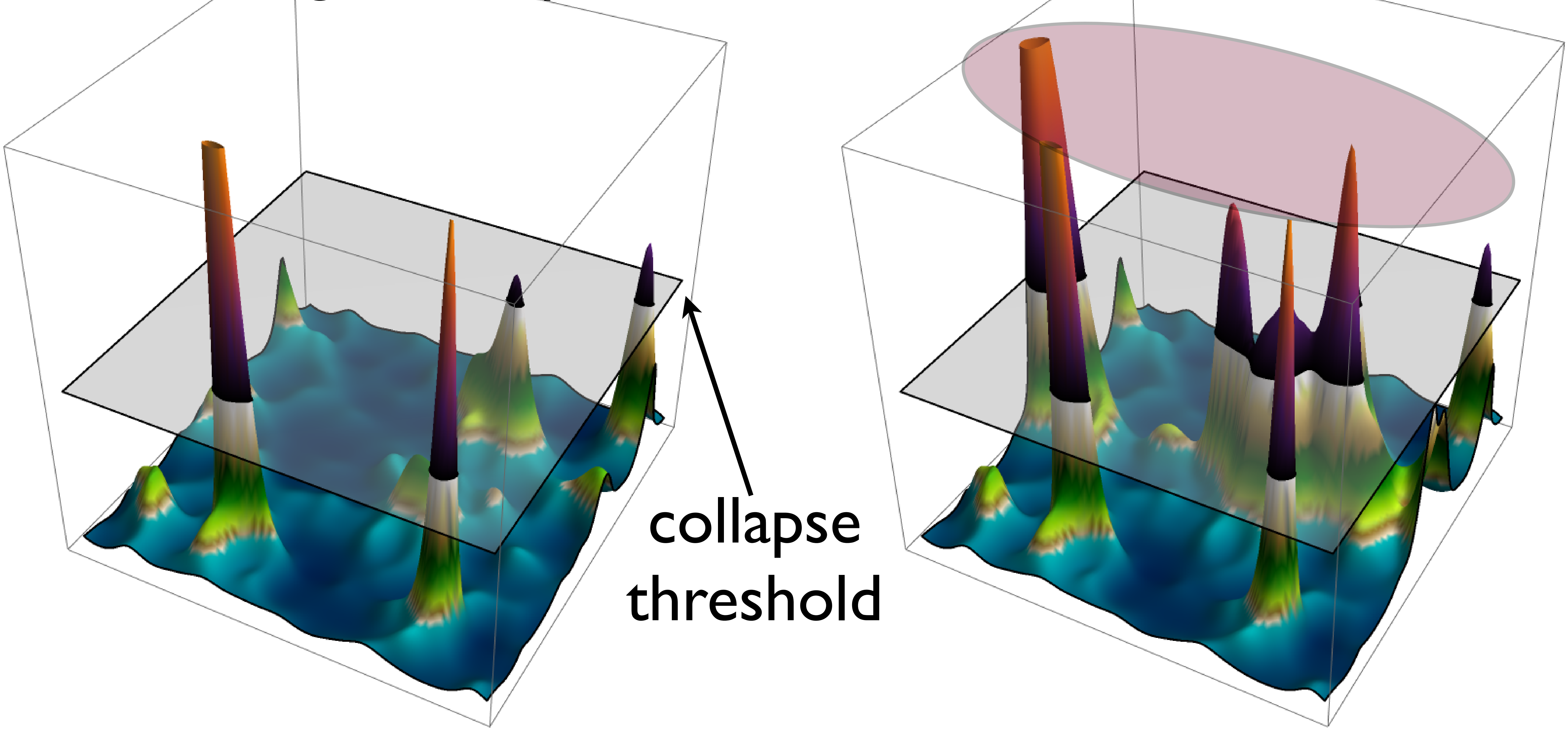






Peak background split in 1D

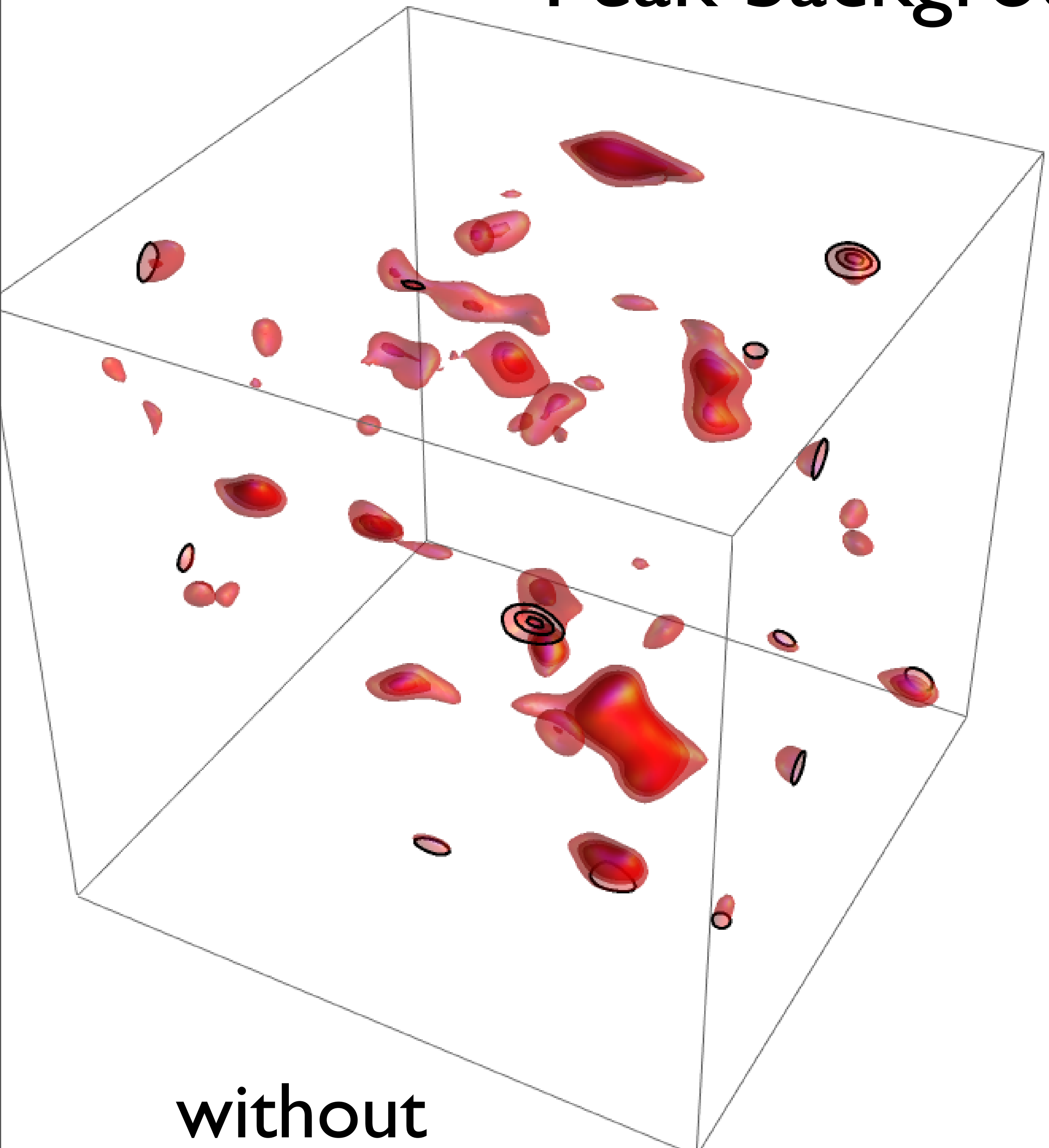
# Peak background split in 2D

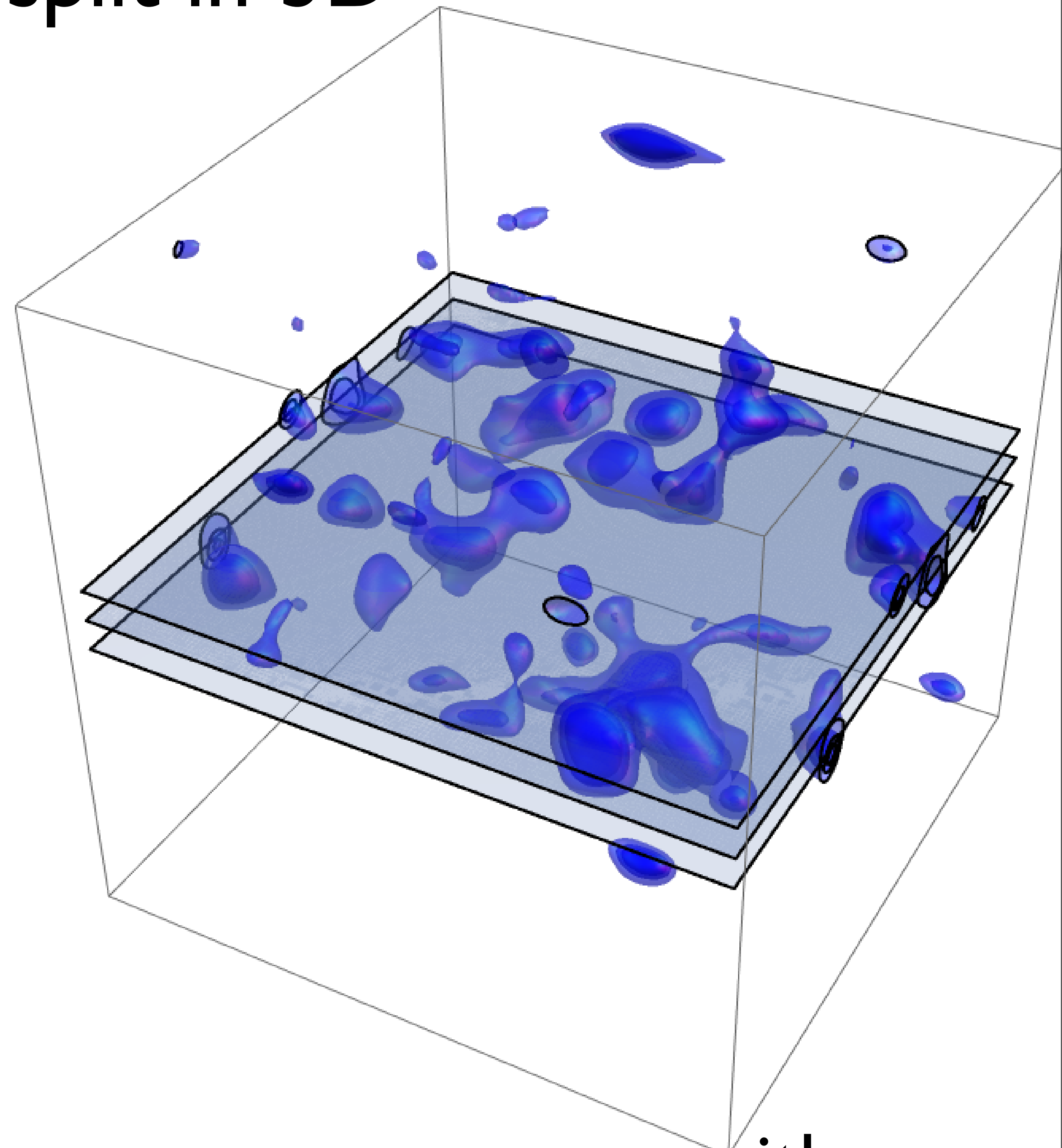



without
boost

with filamentary
boost

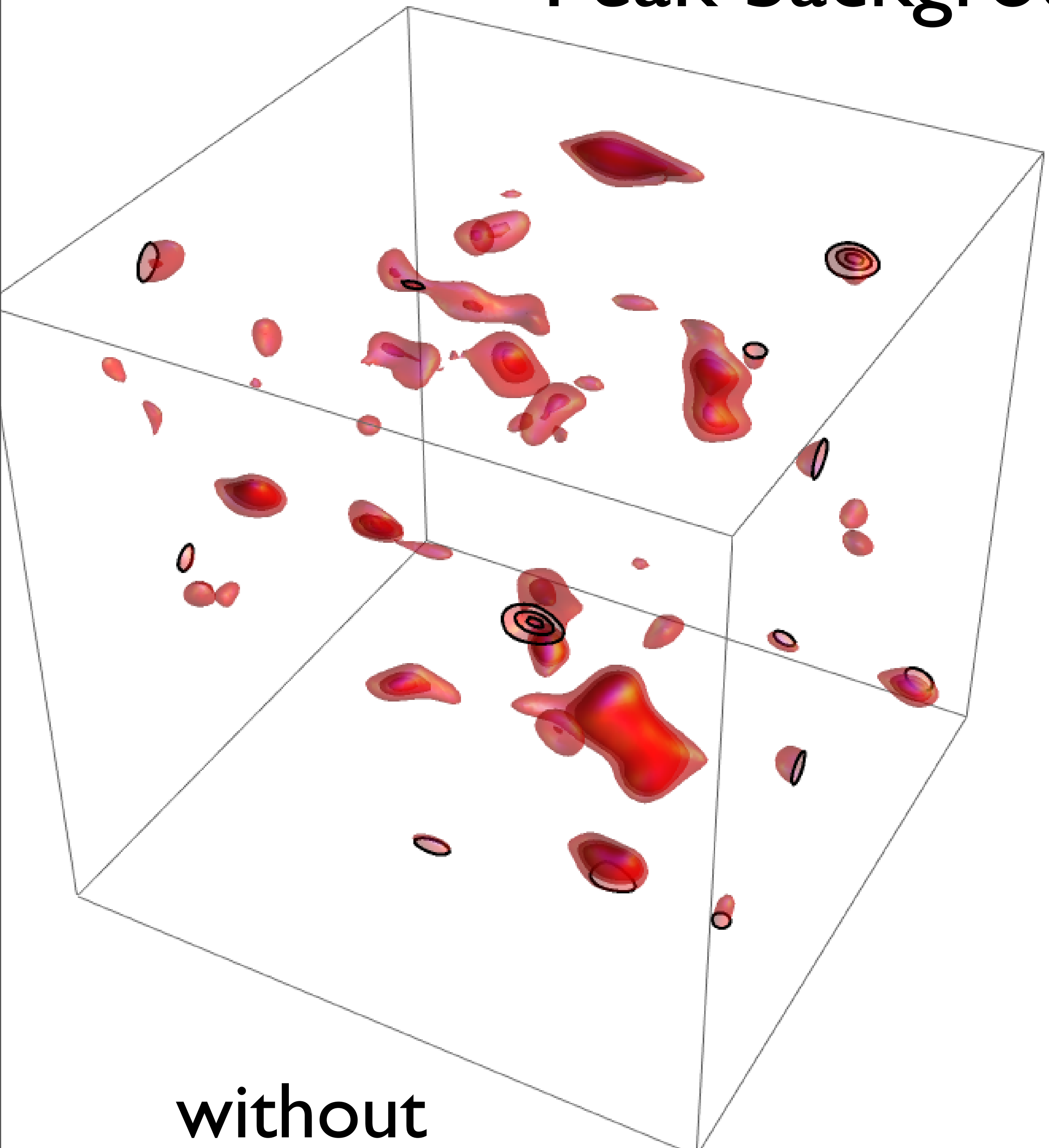
# Peak background split in 3D

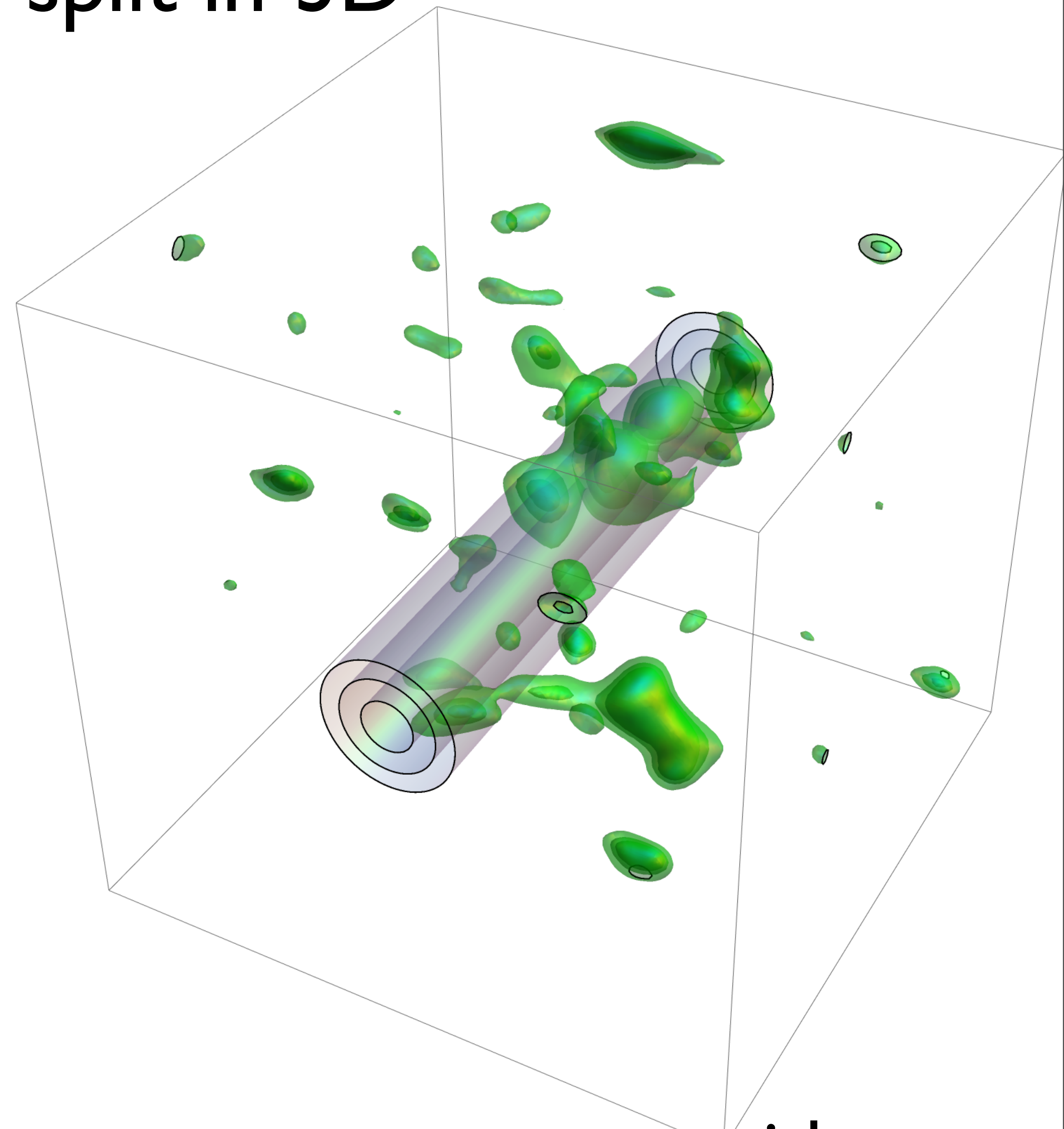



**Does this anisotropic biassing have a dynamical signature? yes!**

# Peak background split in 3D



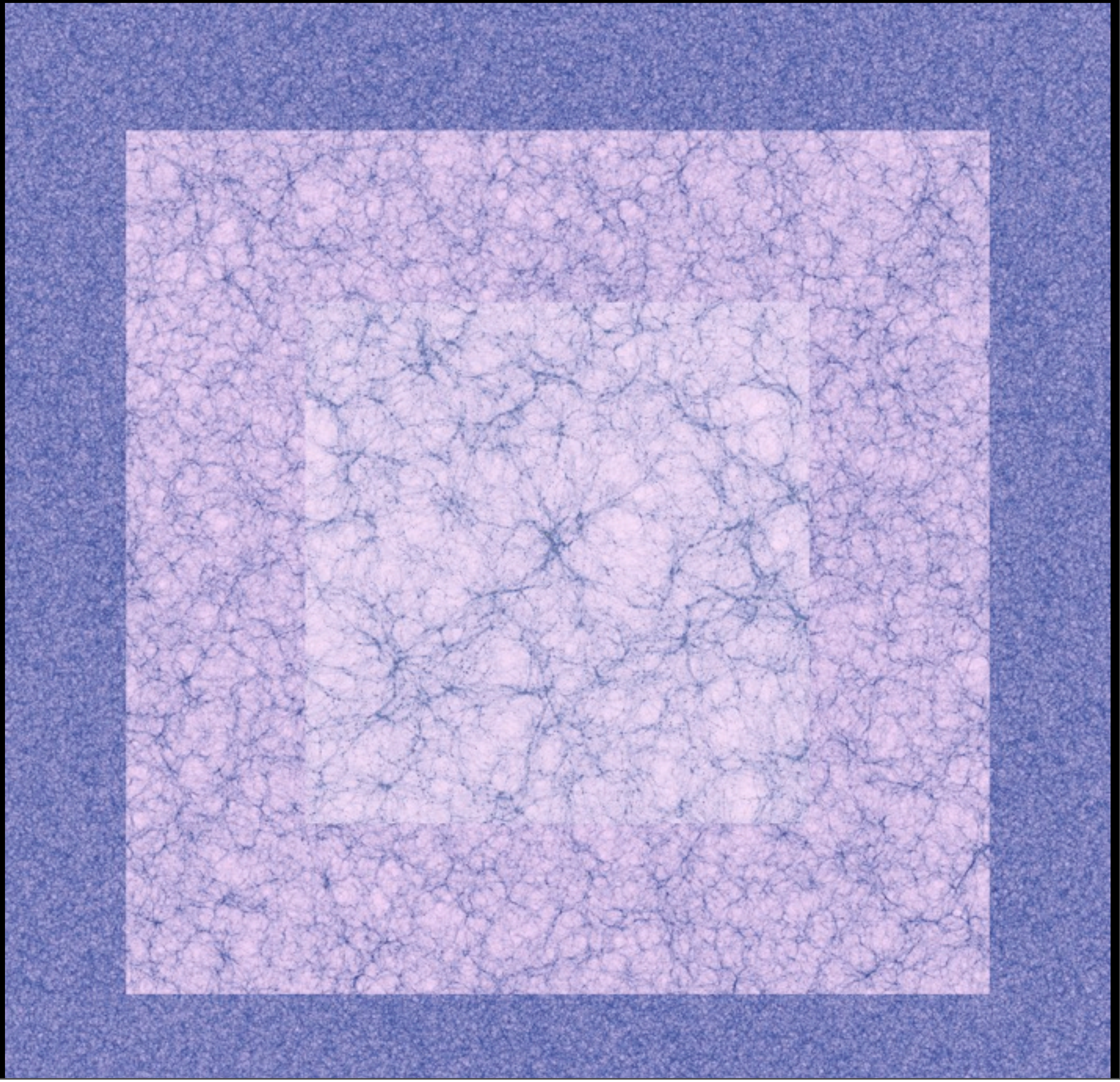

**Does this anisotropic biassing have a dynamical signature? yes!**

# Orientation of the spins w.r.t the filaments

**Horizon 4Pi:**

DM only
2 Gpc/h periodic box
$4096^3$ DM part.
43 million dark halos at z=0

(Teyssier et al, 2009)

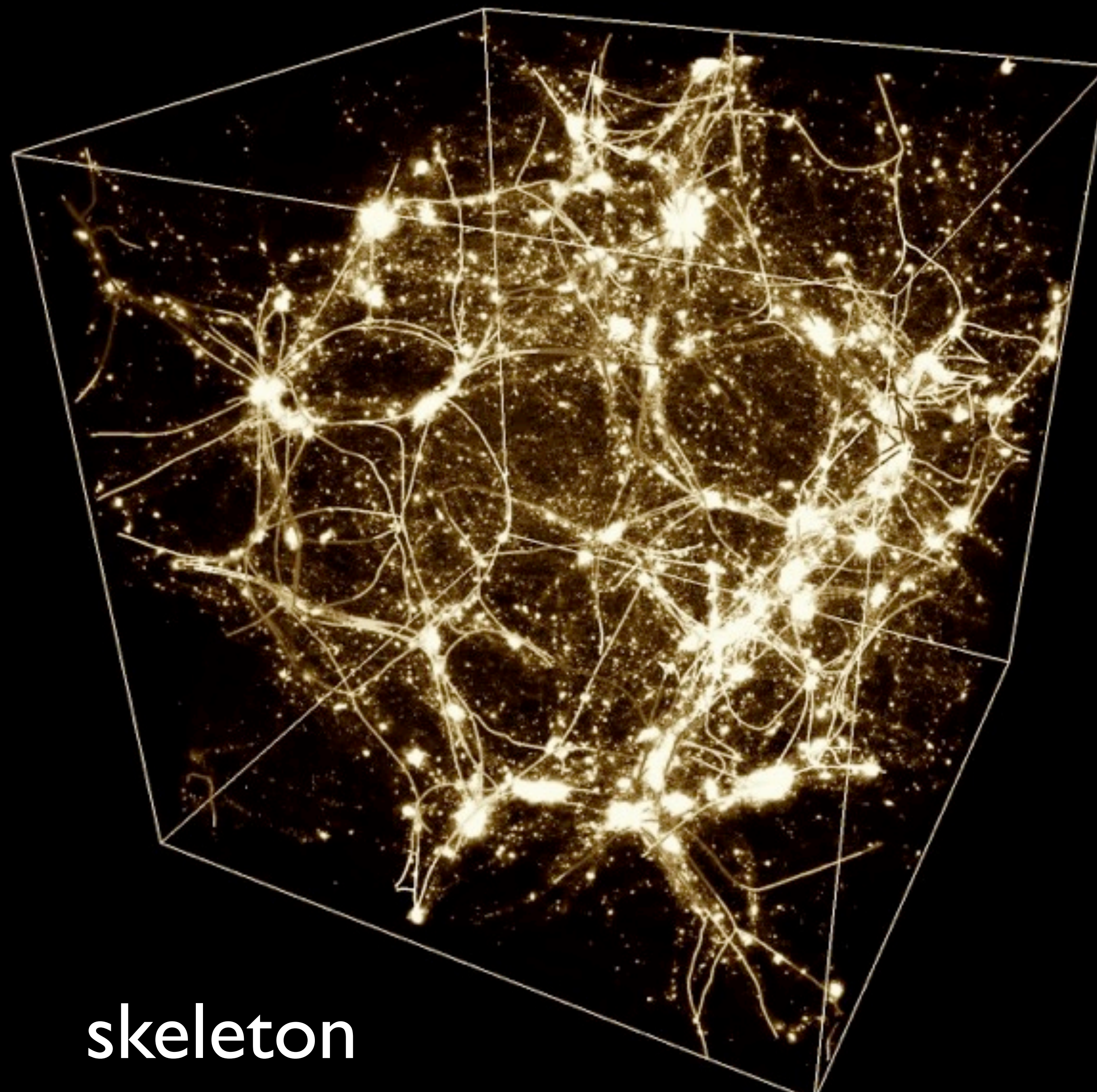


# Orientation of the spins w.r.t the filaments

## Horizon 4Pi:

DM only
2 Gpc/h periodic box
$4096^3$ DM part.
43 million dark halos at z=0

(Teyssier et al, 2009)



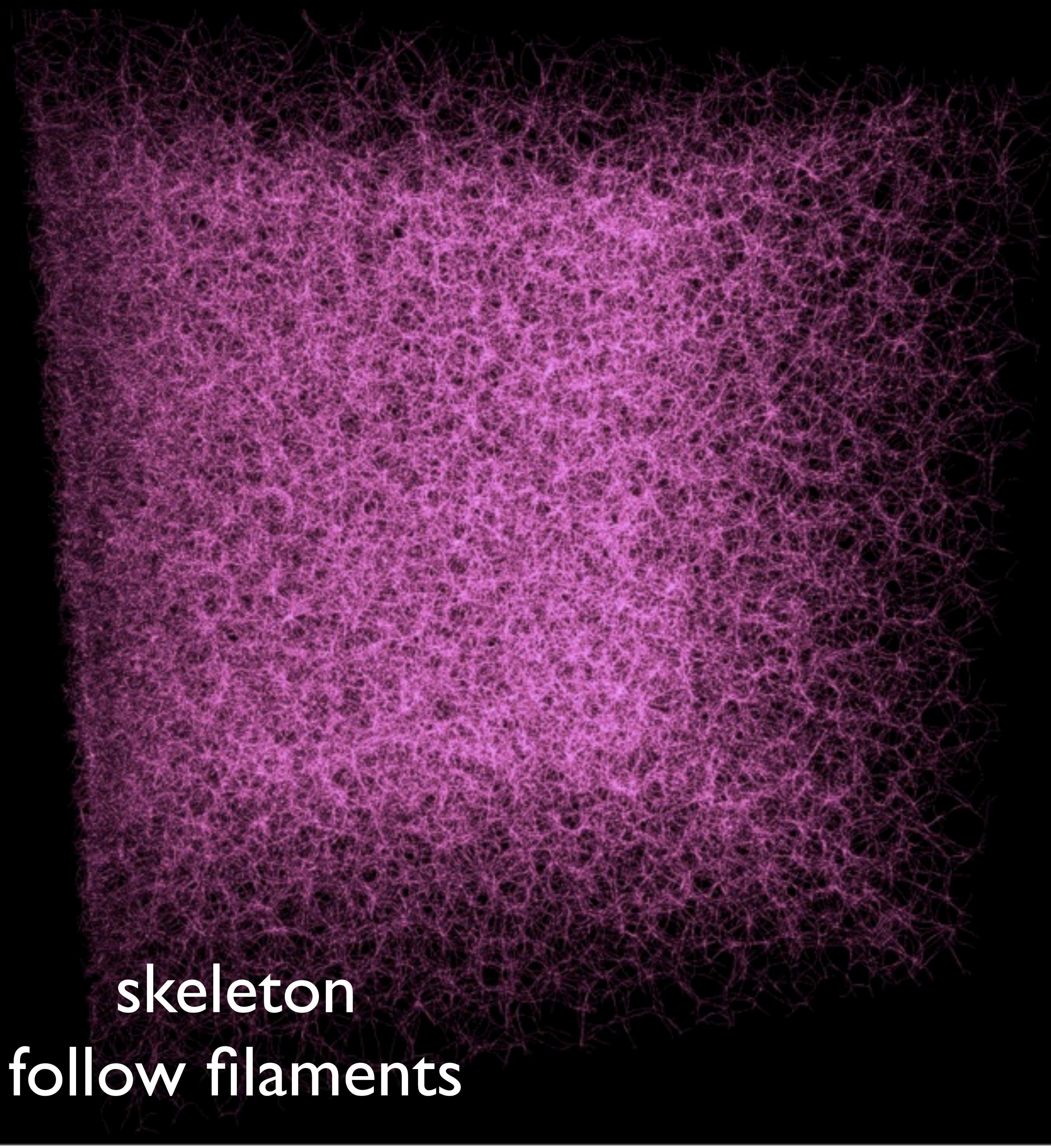
skeleton
follow filaments

# Orientation of the spins w.r.t the filaments

## Horizon 4Pi:

DM only
2 Gpc/h periodic box
$4096^3$ DM part.
43 million dark halos at z=0

(Teyssier et al, 2009)



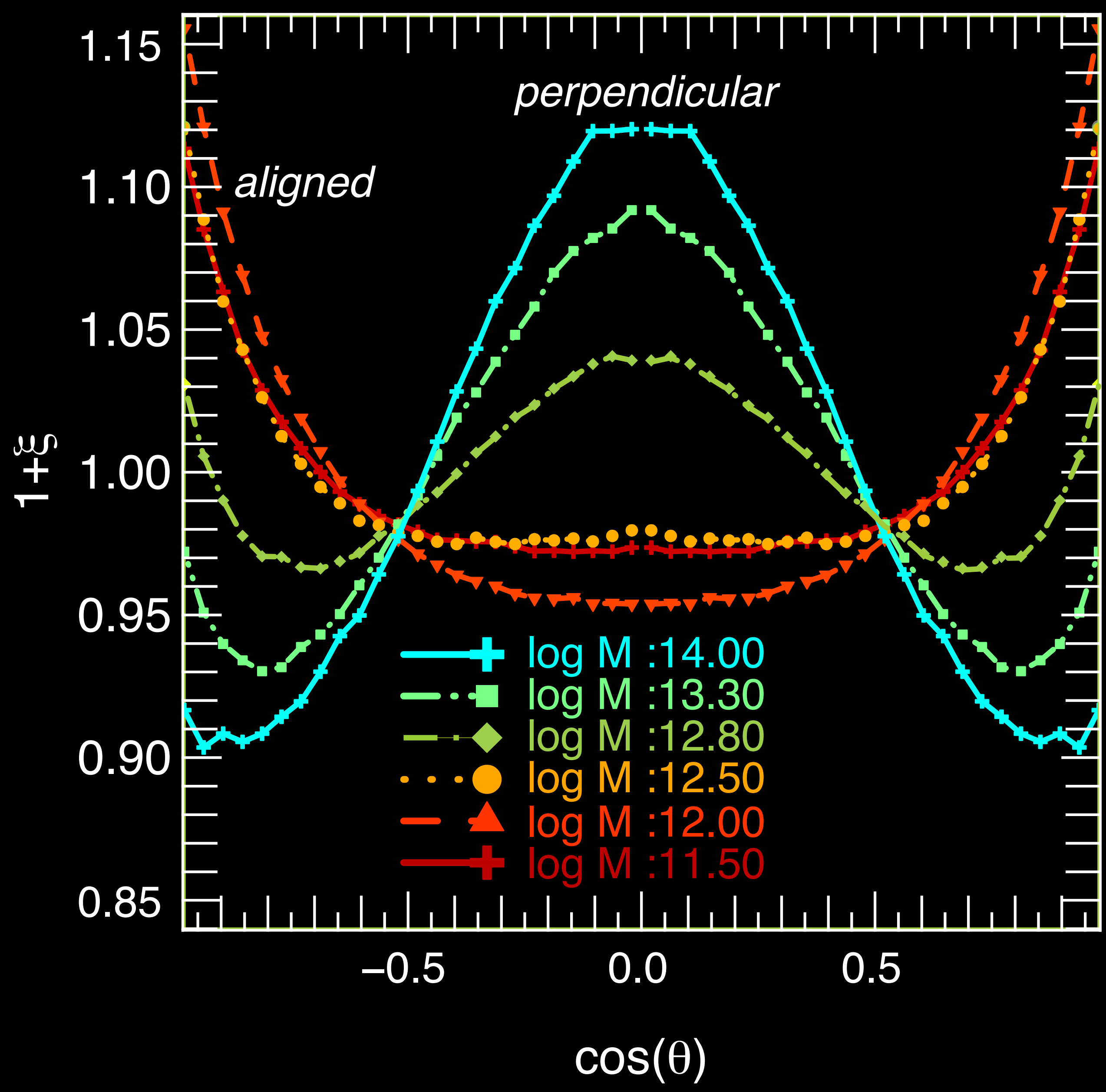
# Excess probability of alignment between the spins and their host filament

mass transition:

$M < M_{\rm crit}$ : aligned

$M > M_{\rm crit}$ : perpendicular

# Excess probability of alignment between the spins and their host filament




mass transition:

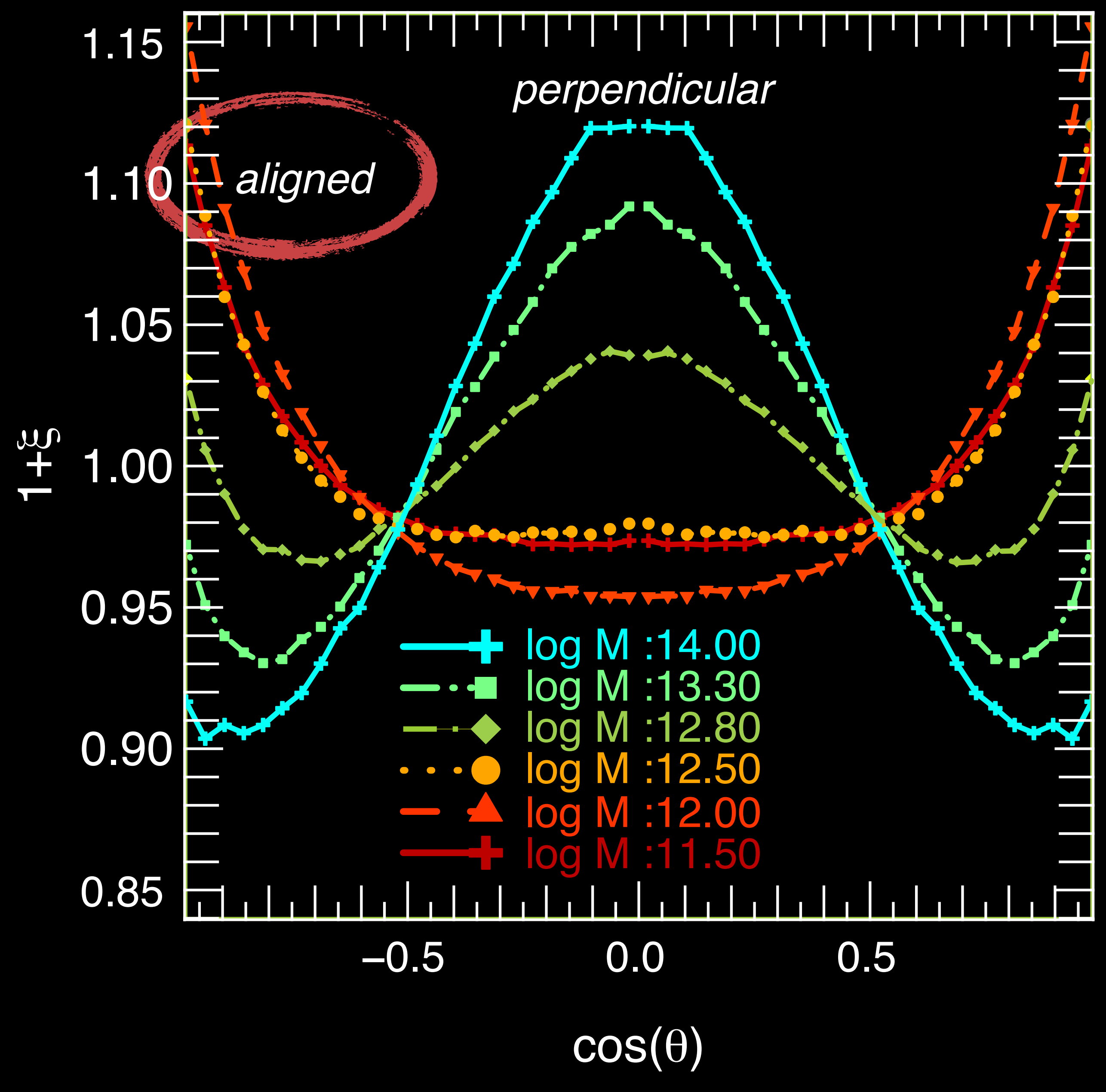
$$M_{\rm crit} = 4 \cdot 10^{12} M_\odot$$

$M < M_{\rm crit}$ : aligned

$M > M_{\rm crit}$ : perpendicular

- In agreement with other numerical studies e.g Bailin & Steinmetz (2005); Aragon-Calvo et al. (2007,2013); Hahn et al. (2007); Paz et al. (2008)
- Confirmed by observations e.g Tempel et al 2013 using the SDSS data

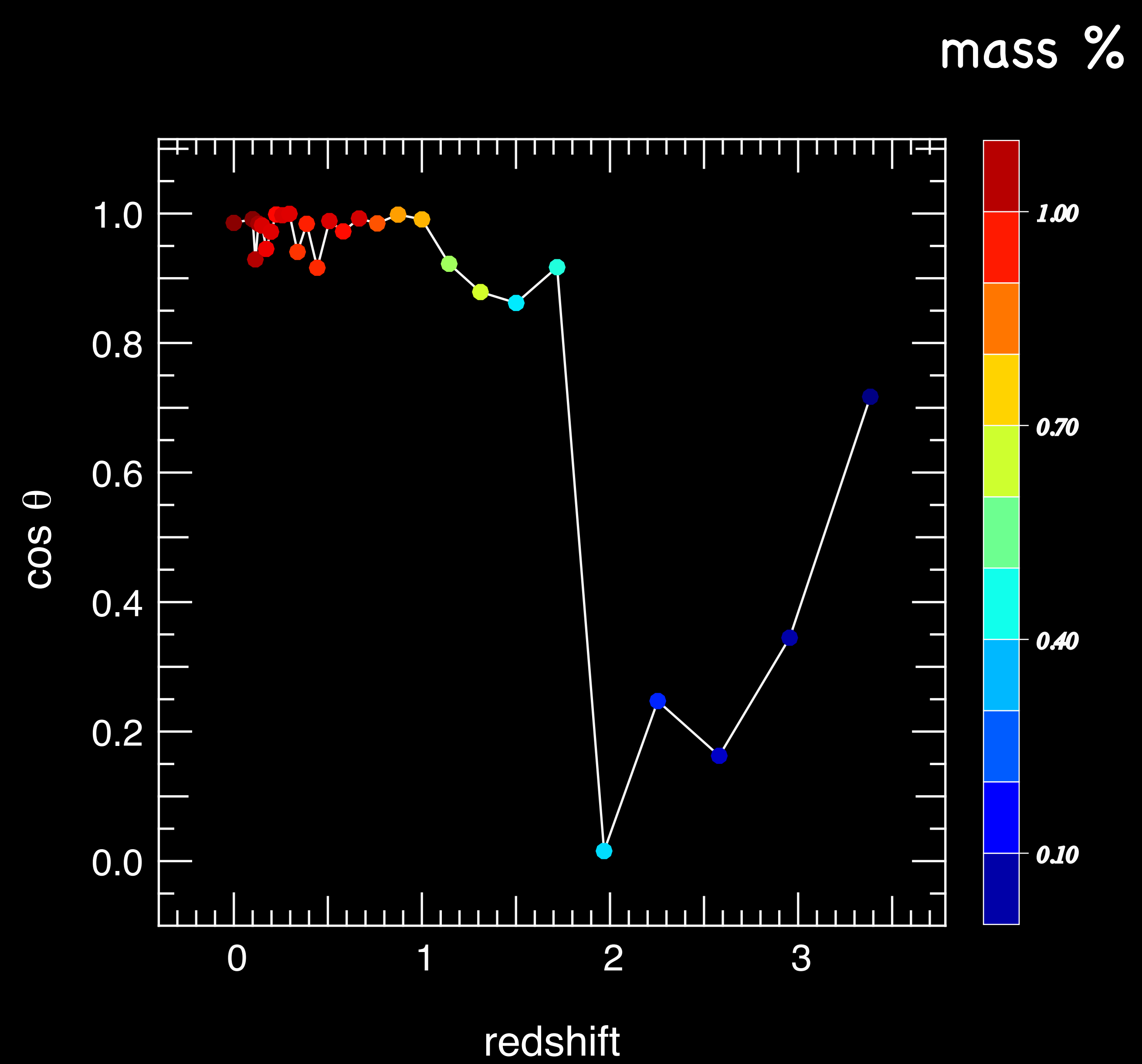
# Low-mass haloes: $M < M_{\rm crit}$




$M_{\rm crit} = 4 \cdot 10^{12} M_\odot$

## mass transition:

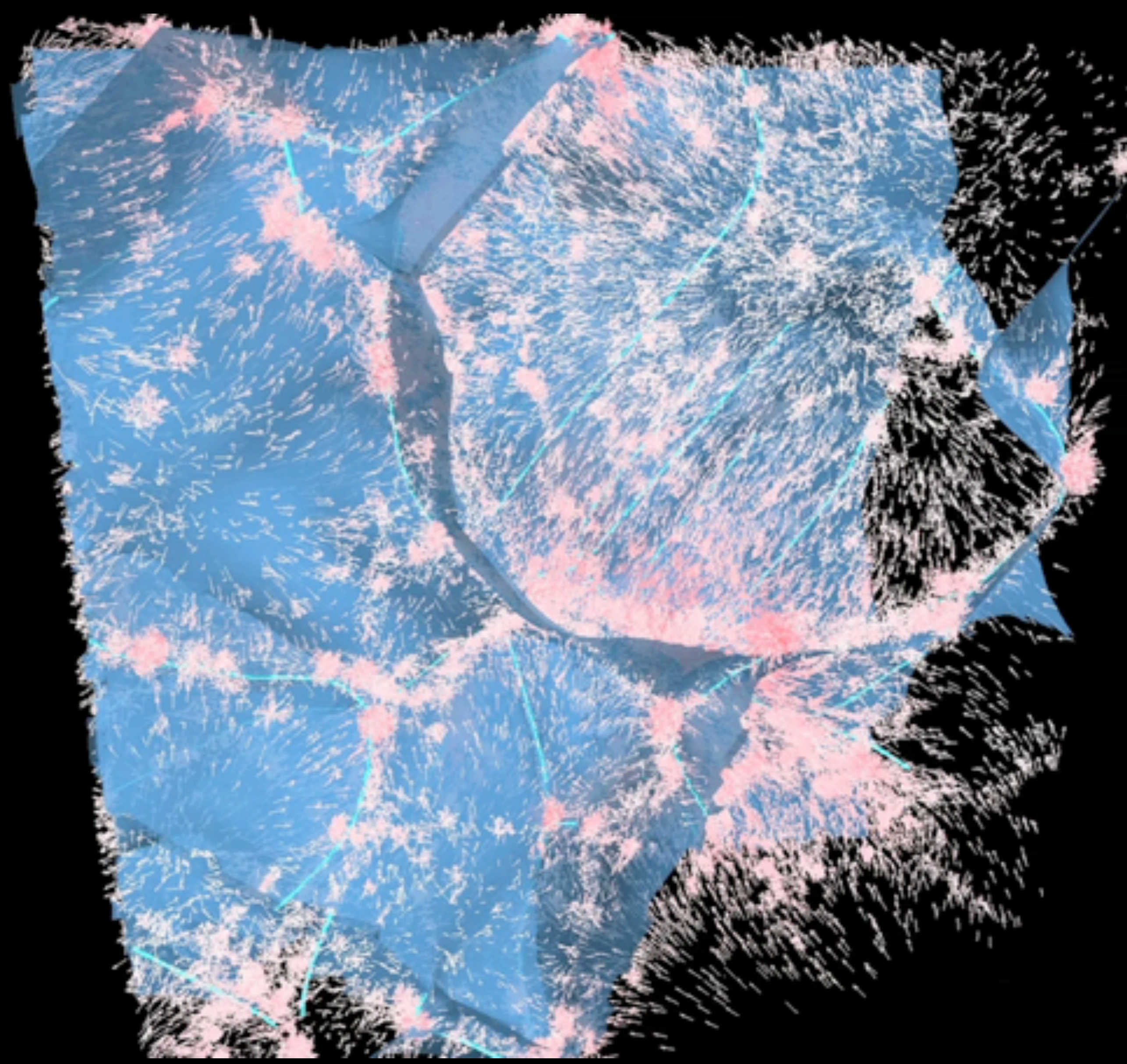
$M < M_{\rm crit}$ : aligned



# How does the formation of the filaments generate spin parallel to them?

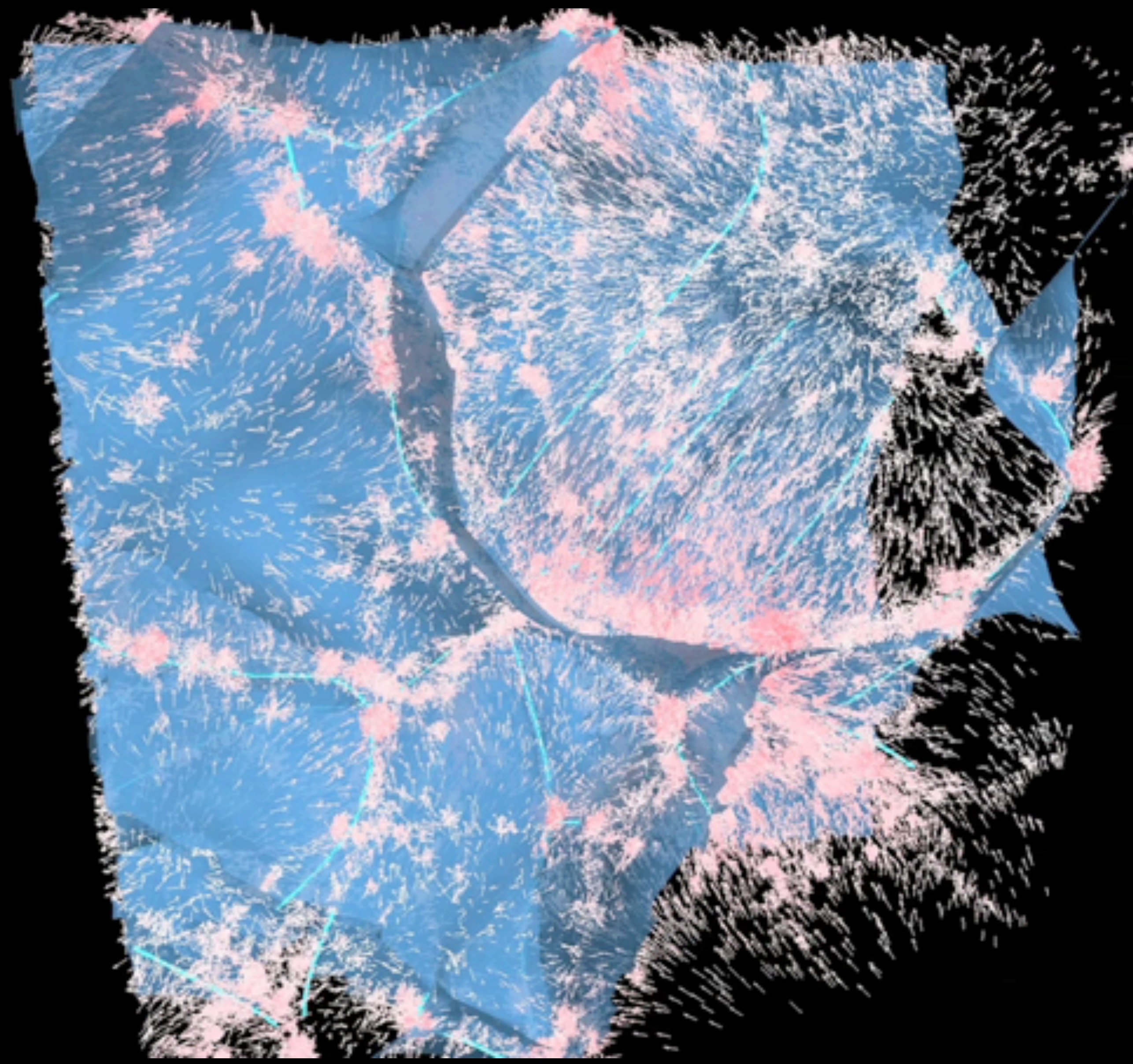
Voids/wall saddle repel...

winding of walls



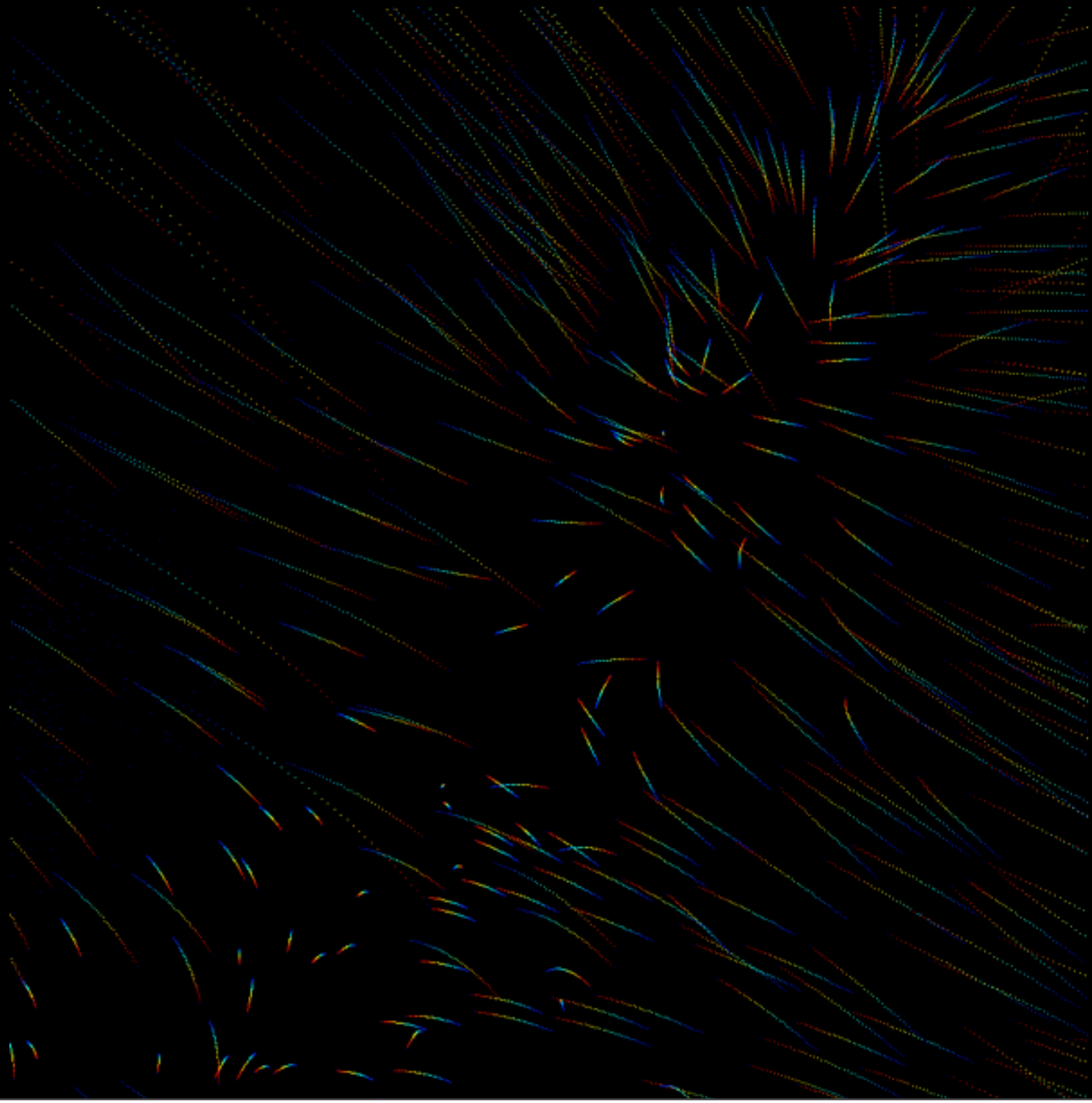
# How does the formation of the filaments generate spin parallel to them?

winding of walls



# How does the formation of the filaments generate spin parallel to them?

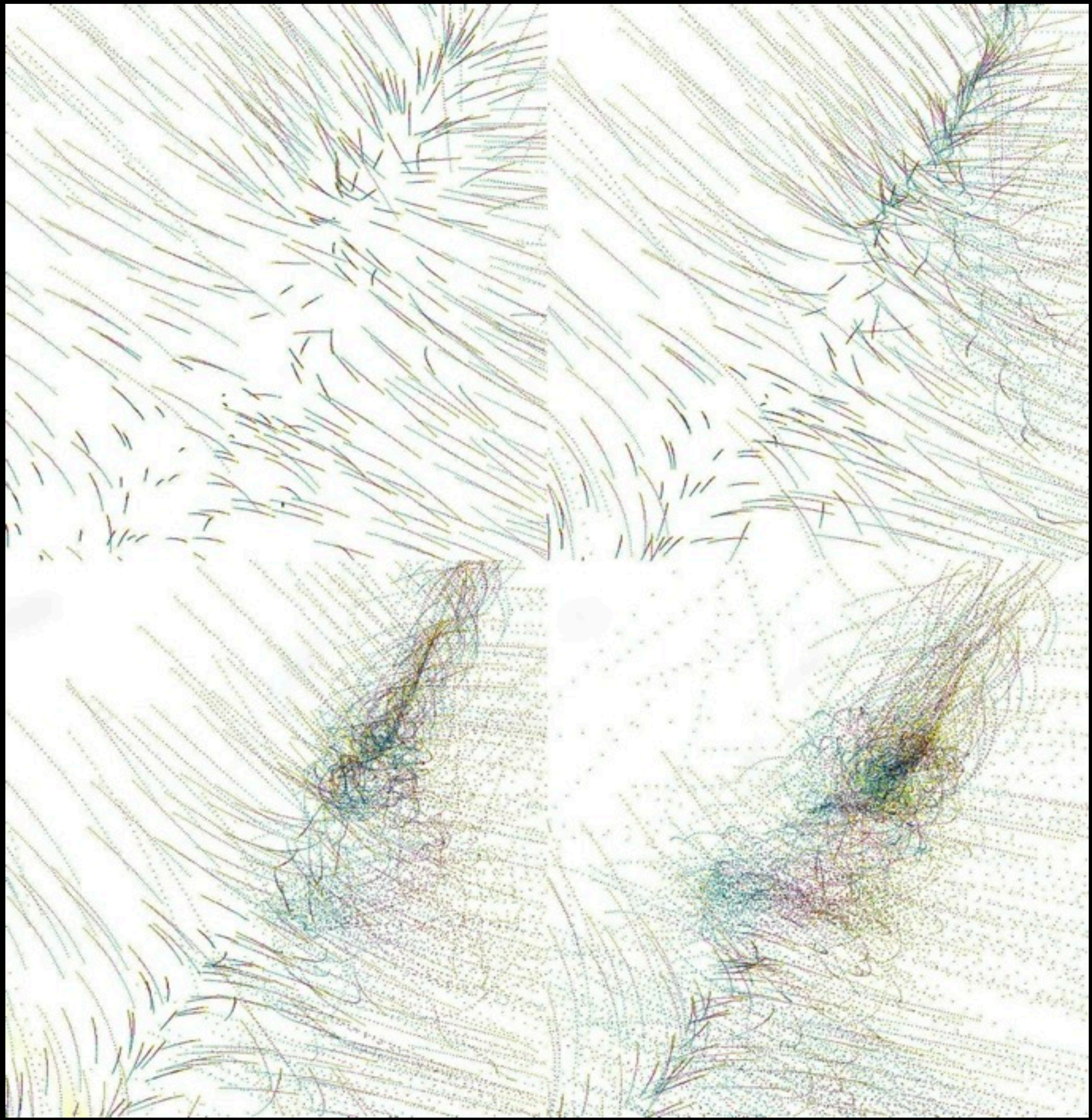
winding of walls



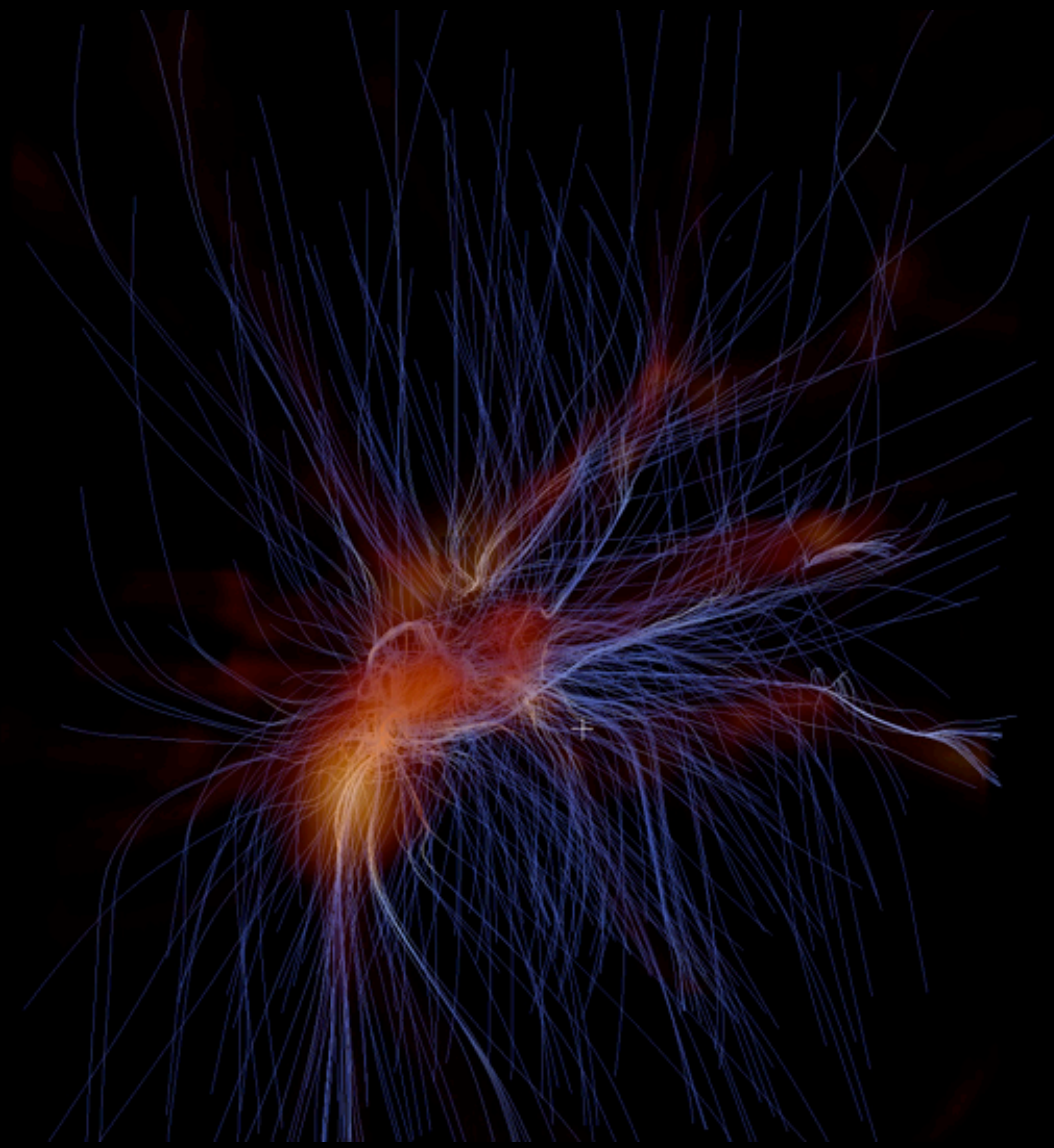
Winding of walls
onto filaments
generate spin
//
to filament

->

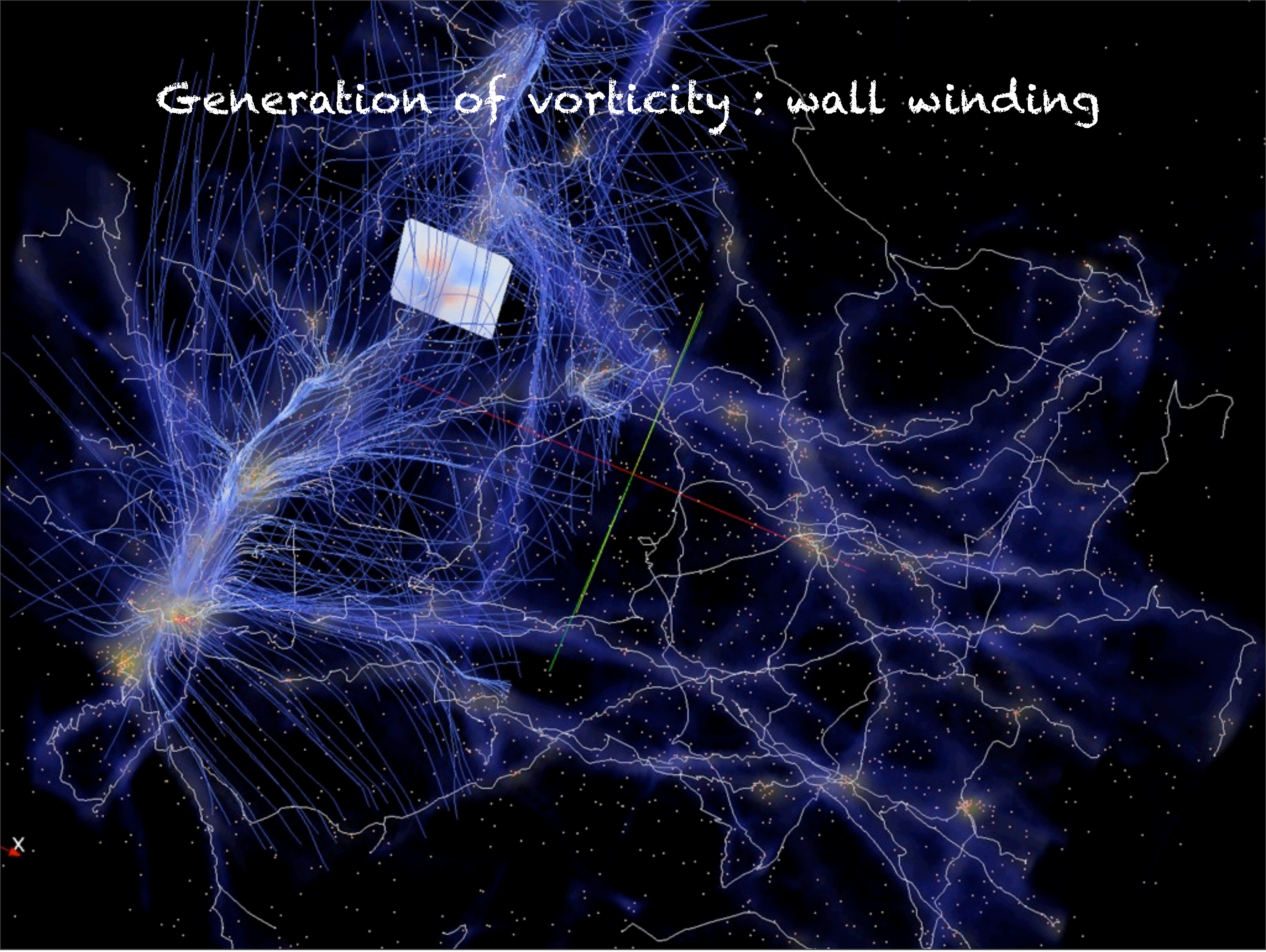
Vorticity?



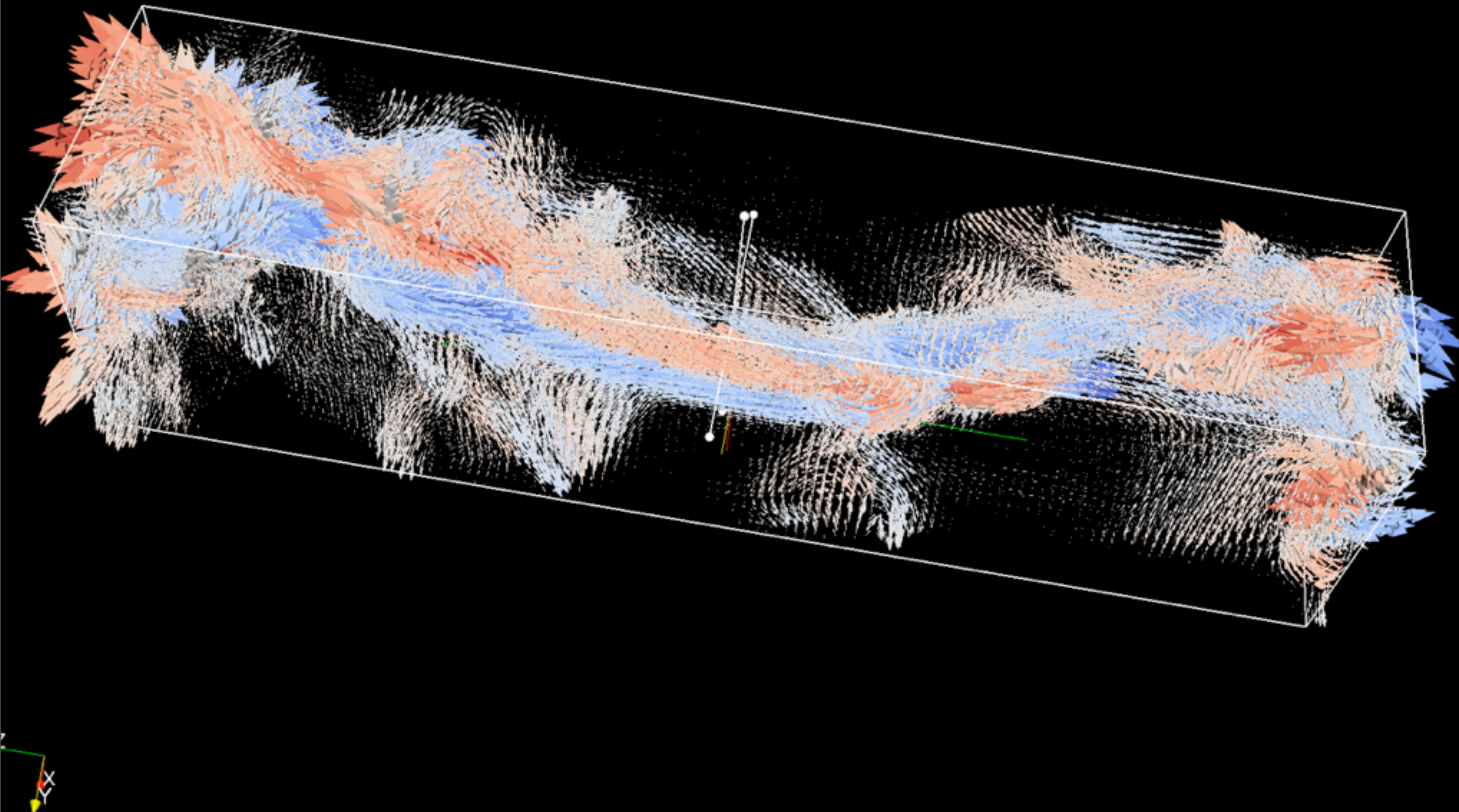
# Focussing on main filament



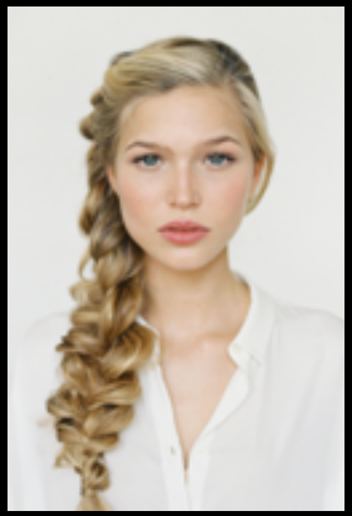
# Generation of vorticity : wall winding

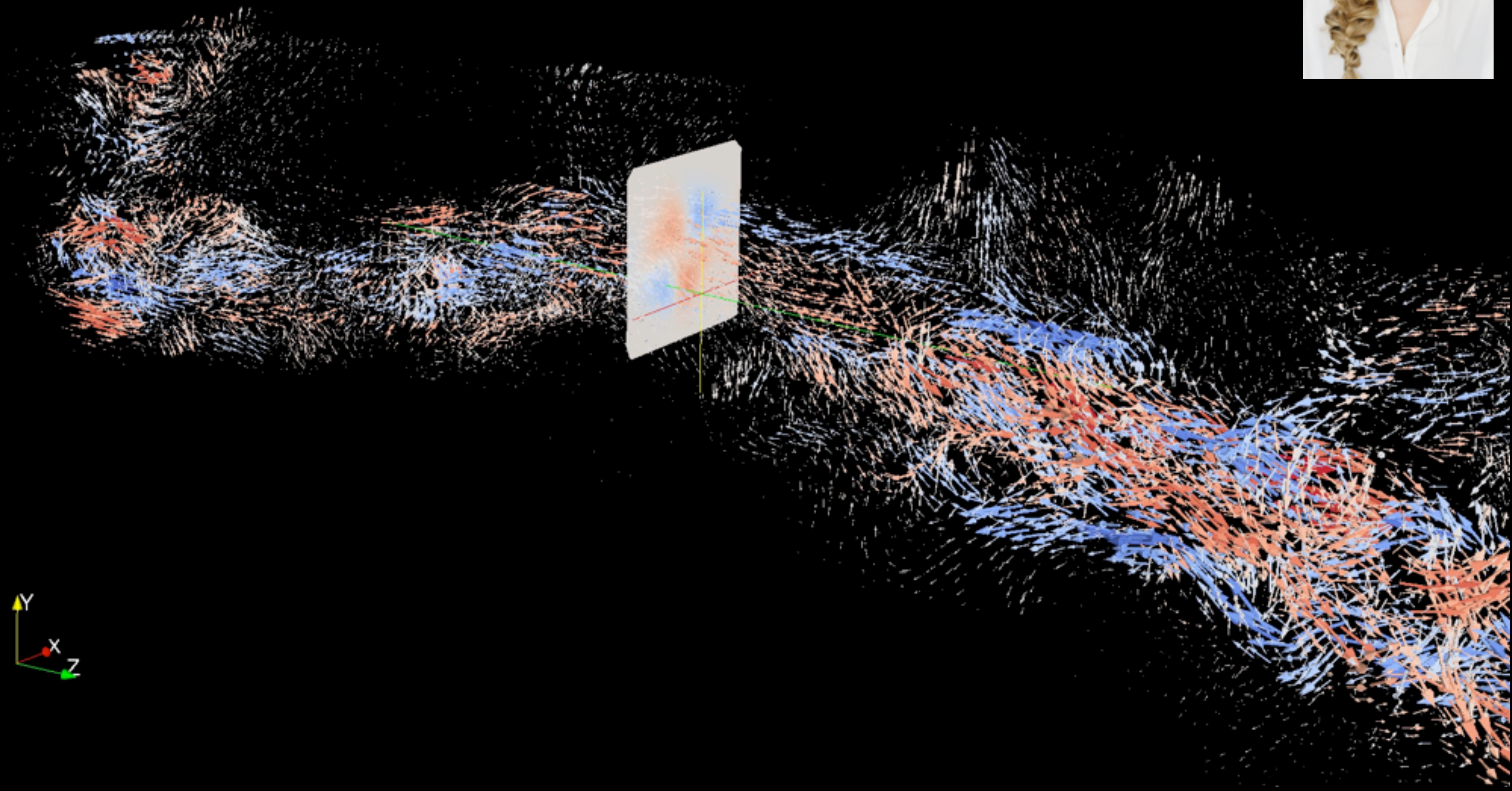


# Alignement of vorticity with cosmic web

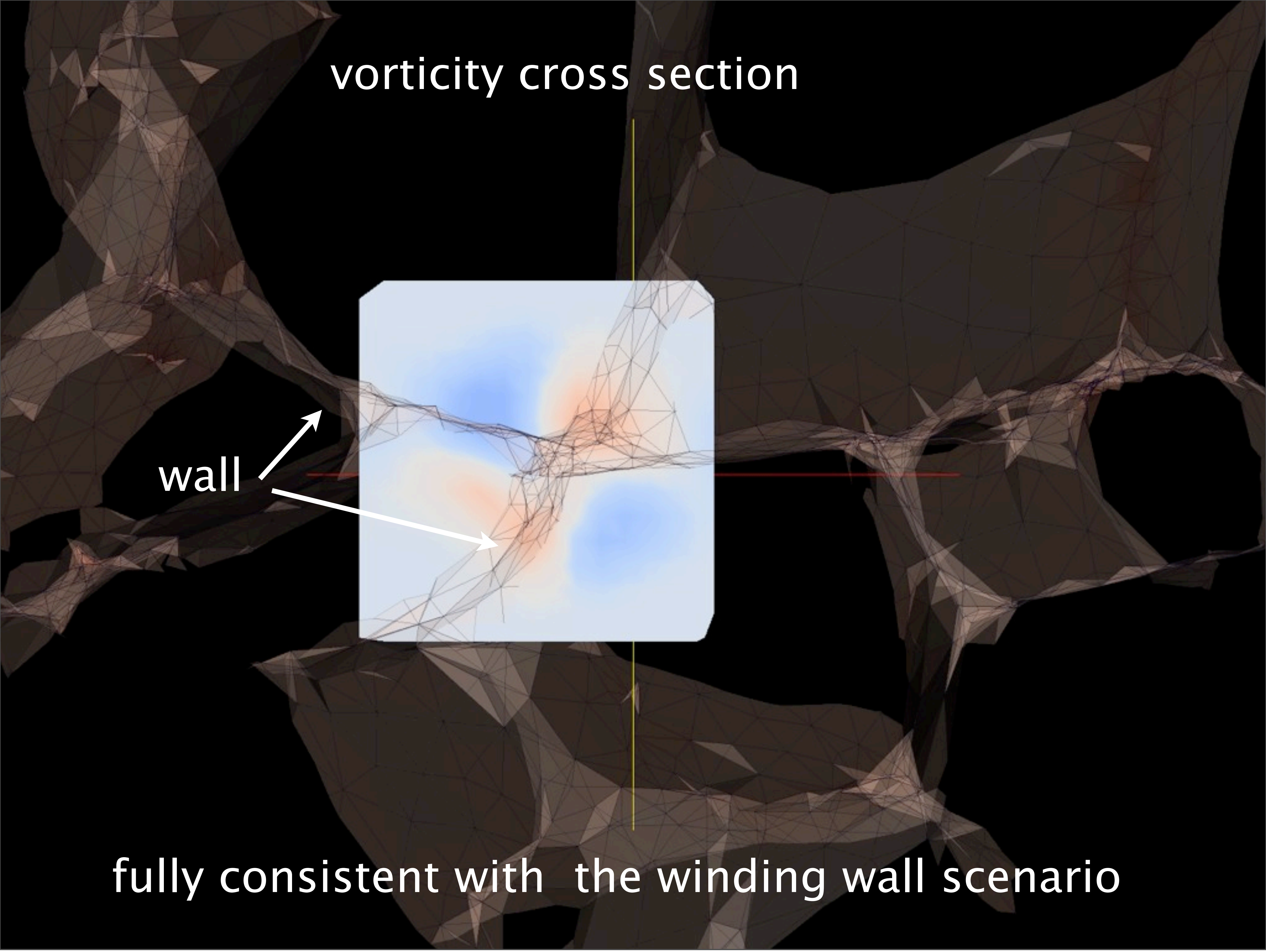


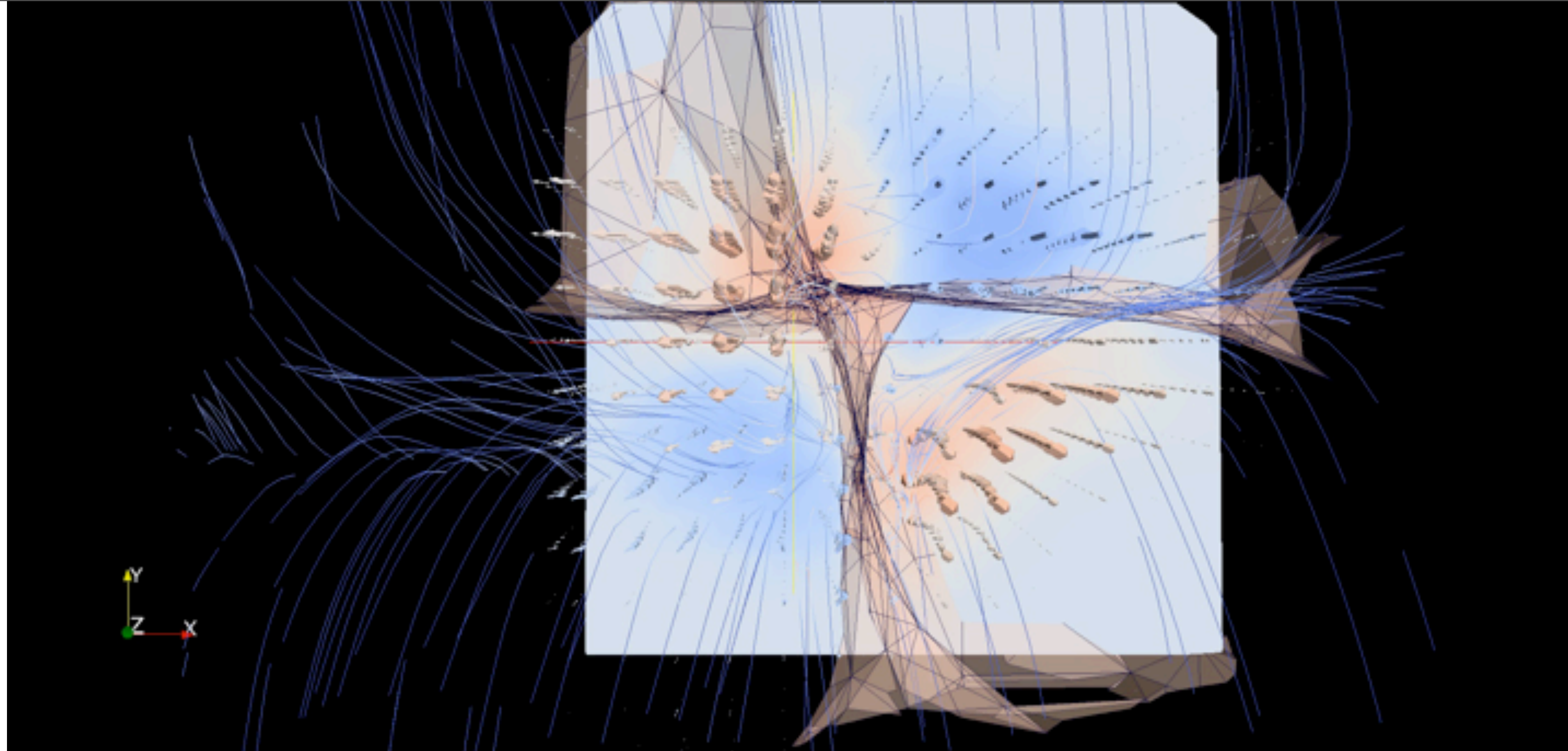
# Alignement of vorticity with cosmic web

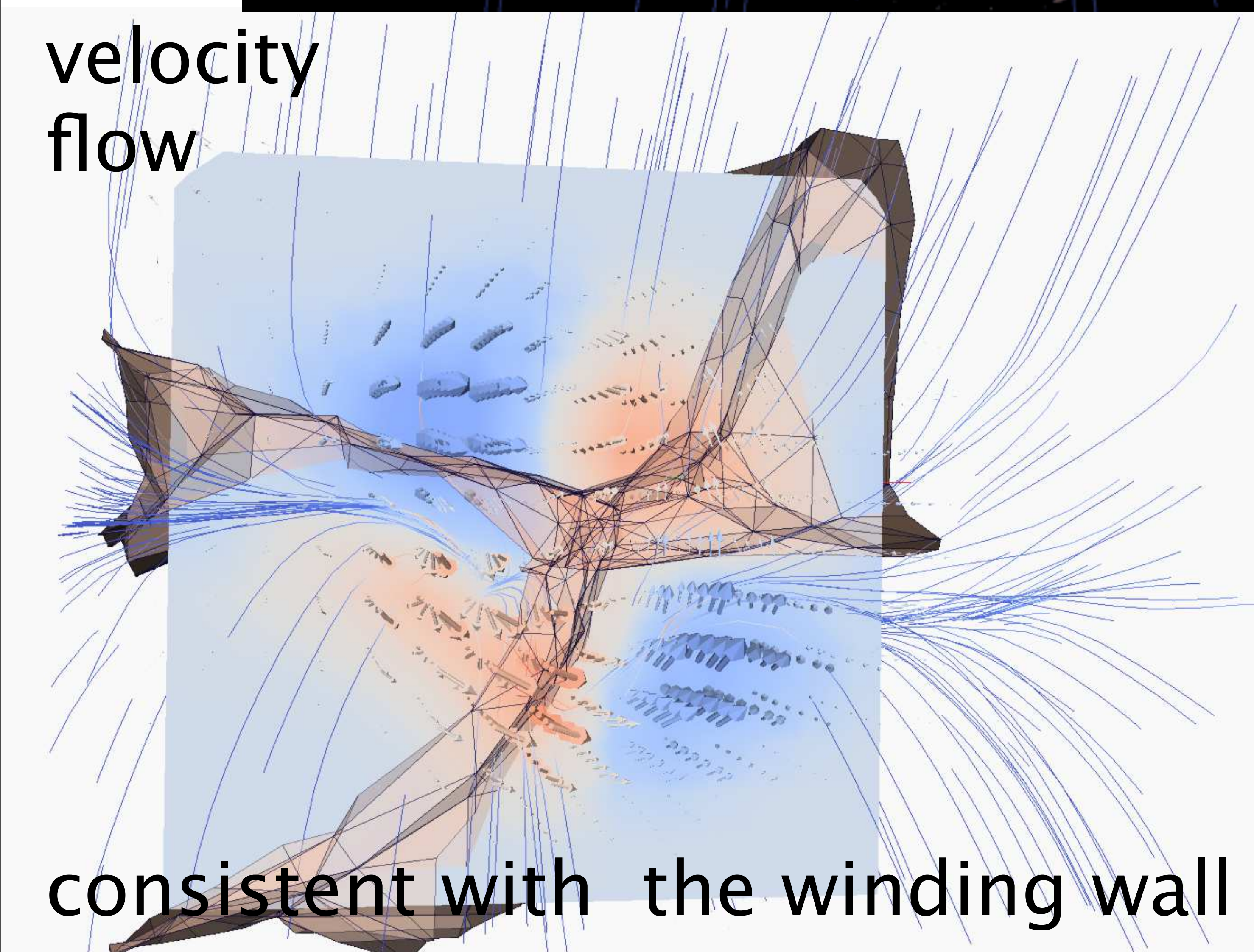


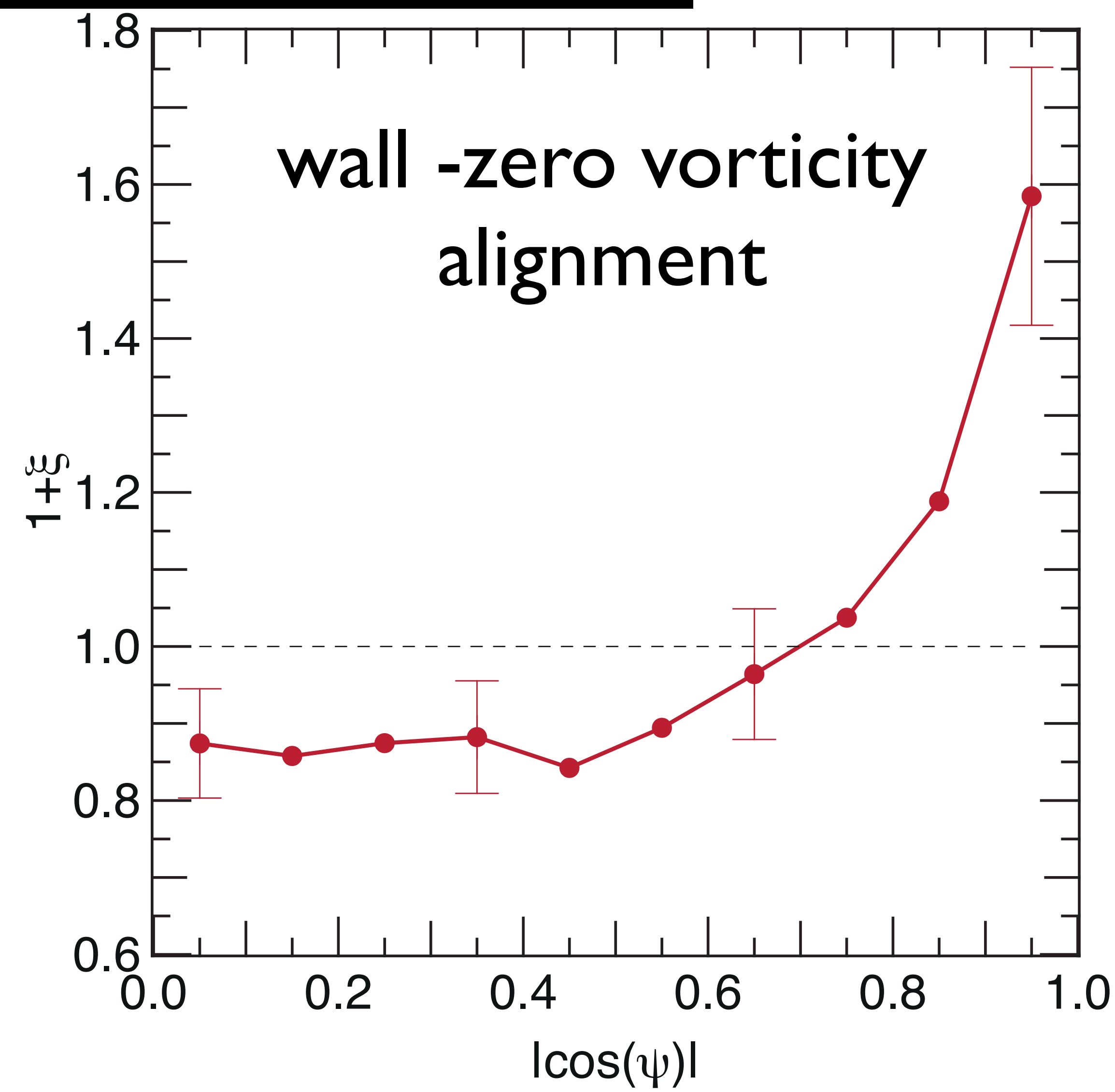



braids structure of vorticity.

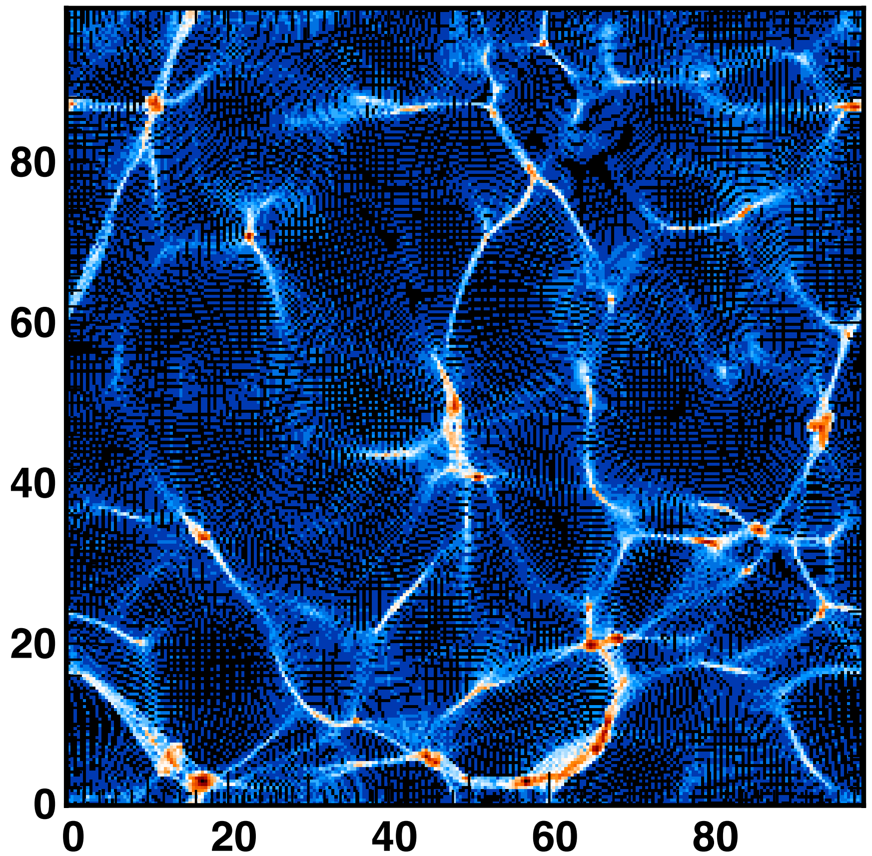

vorticity cross section
wall
fully consistent with the winding wall scenario


Y
Z
X

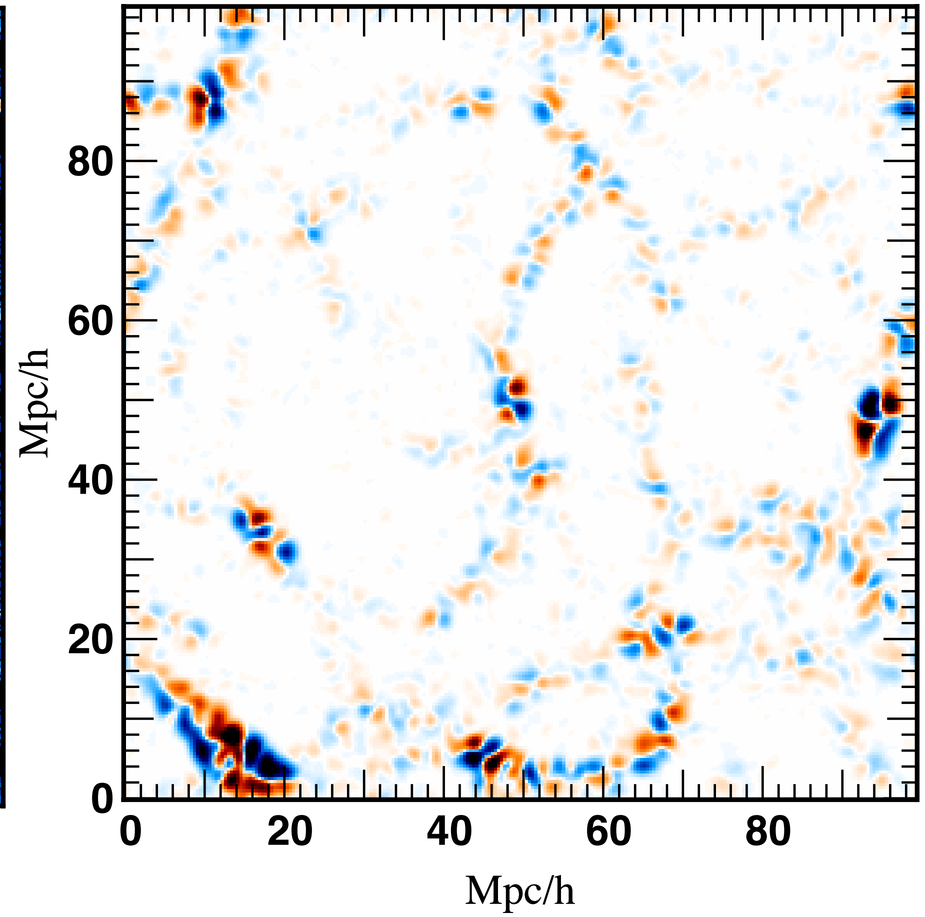

velocity
flow
consistent with the winding wall


wall -zero vorticity
alignment
1+ξ
|cos(ψ)|
0.6
0.8
1.0
1.2
1.4
1.6
1.8
0.0
0.2
0.4
0.6
0.8
1.0

# Locus of vorticity



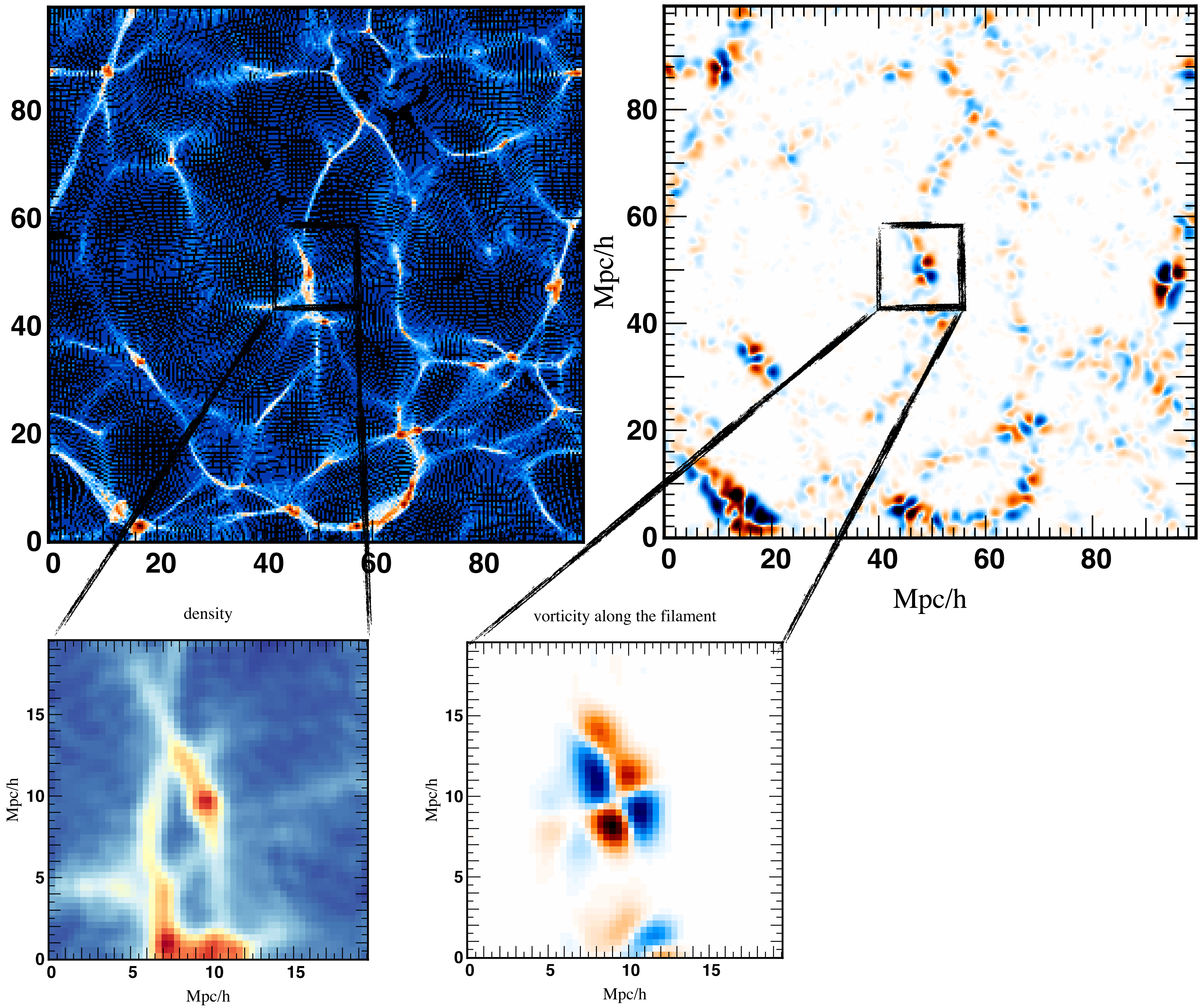

Density




Vorticity

Density & vorticity slice  in a DM simulation.

# Locus of vorticity



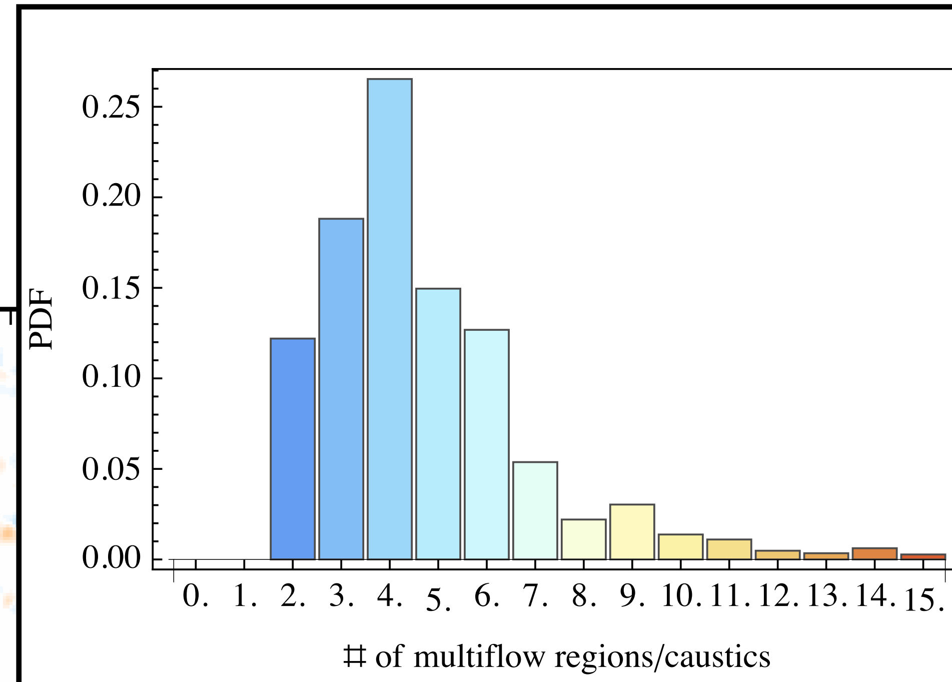

density

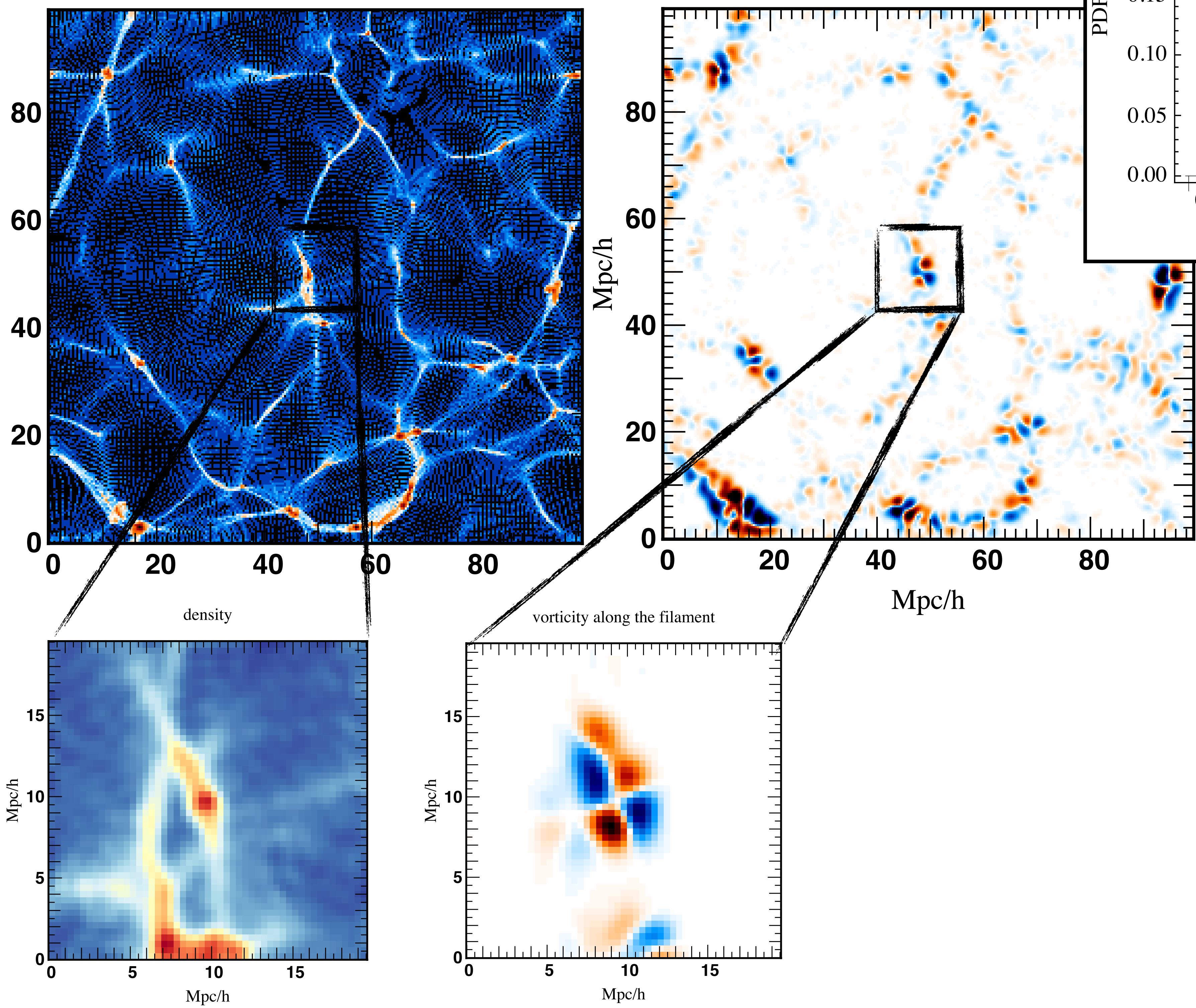
vorticity

* vorticity is confined to filaments.
* Vorticity is aligned with filament

**region of constant polarity are smaller !**

# Locus of vorticity



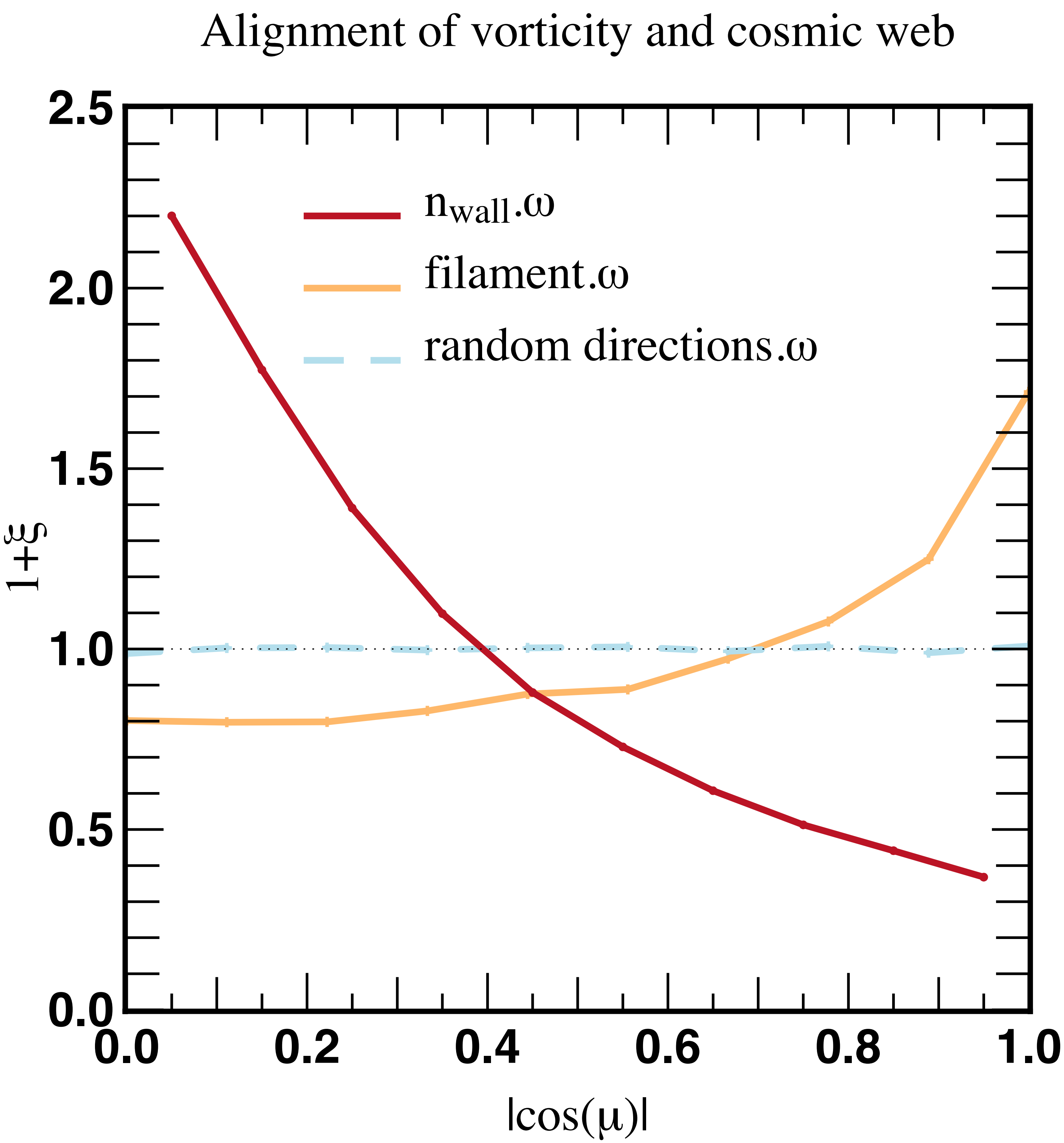

density

vorticity

- ✳ vorticity is confined to filaments.
- ✳ Vorticity is aligned with filament
- ✳caustics are ~ quadripolar

**region of constant polarity are smaller !**

# Alignement of vorticity with cosmic web



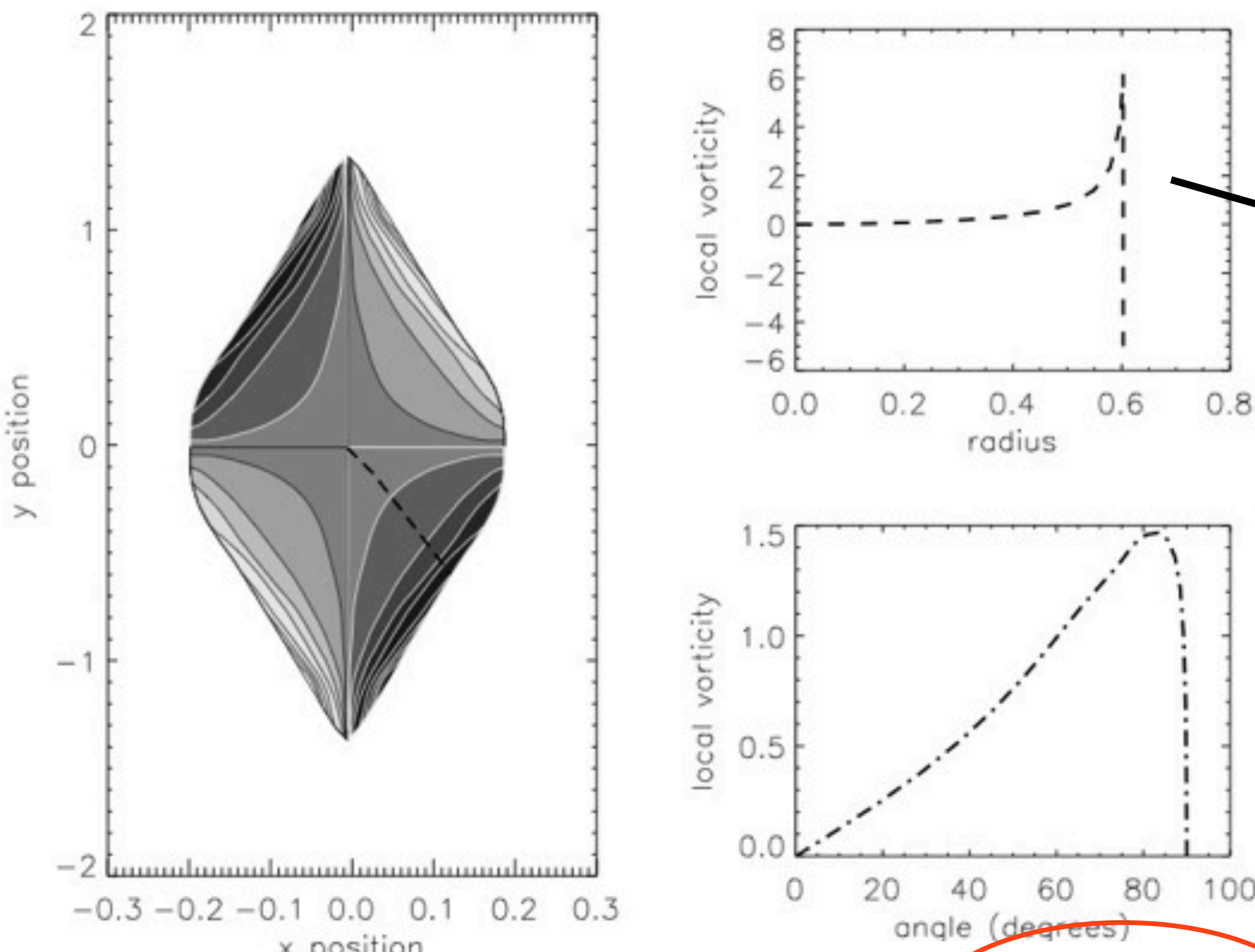

Vorticity is aligned with filaments

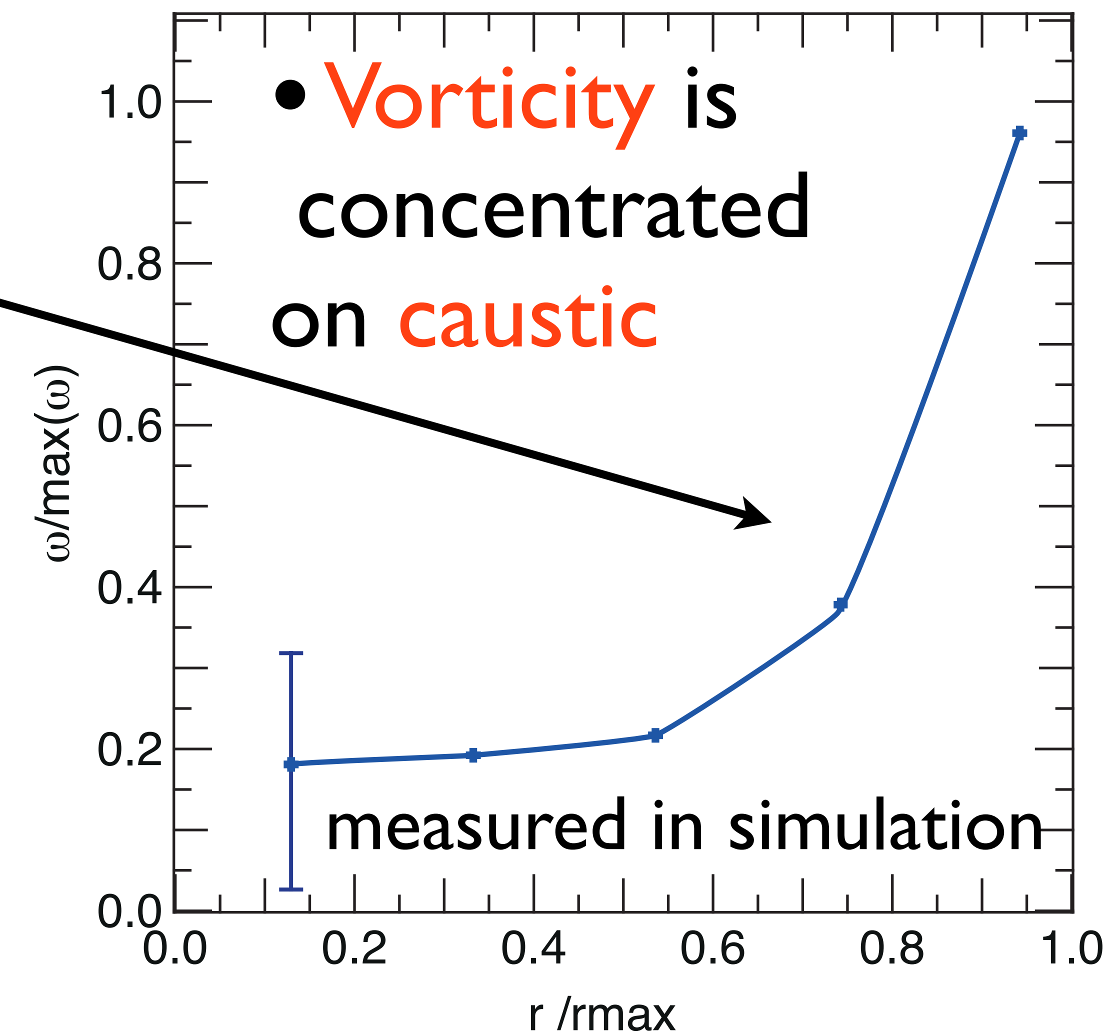
In walls, vorticity is perpendicular to the normal of walls

# Cross section of vorticity in caustic

$$\omega_k(\mathbf{x}) = \sum_{i,j} \epsilon^{k,j,i} \frac{\partial \mathbf{u}_i(\mathbf{x})}{\partial \mathbf{x}_j} = \sum_{i,j} \epsilon^{k,j,i} \left( \left[ \sum_{\text{flow } s} \frac{\partial \rho(\mathbf{q}_s)}{\partial \mathbf{q}_{sl}} (D^{-1})_{j,l}\, \mathbf{u}_i(\mathbf{q}_s) \right] \left[ \sum_{\text{flow } s} \rho(\mathbf{q}_s) \right] - \left[ \sum_{\text{flow } s} \rho(\mathbf{q}_s) \mathbf{u}_i(\mathbf{q}_s) \right] \times \left[ \sum_{\text{flow } s} \frac{\partial \rho(\mathbf{q}_s)}{\partial \mathbf{q}_{sl}} (D^{-1})_{j,l} \right] \right) \Big/ \left[ \sum_{\text{flow } s} \rho(\mathbf{q}_s) \mathbf{u}_i(\mathbf{q}_s) \right]^2 ,$$

Pichon Bernardeau, 1999



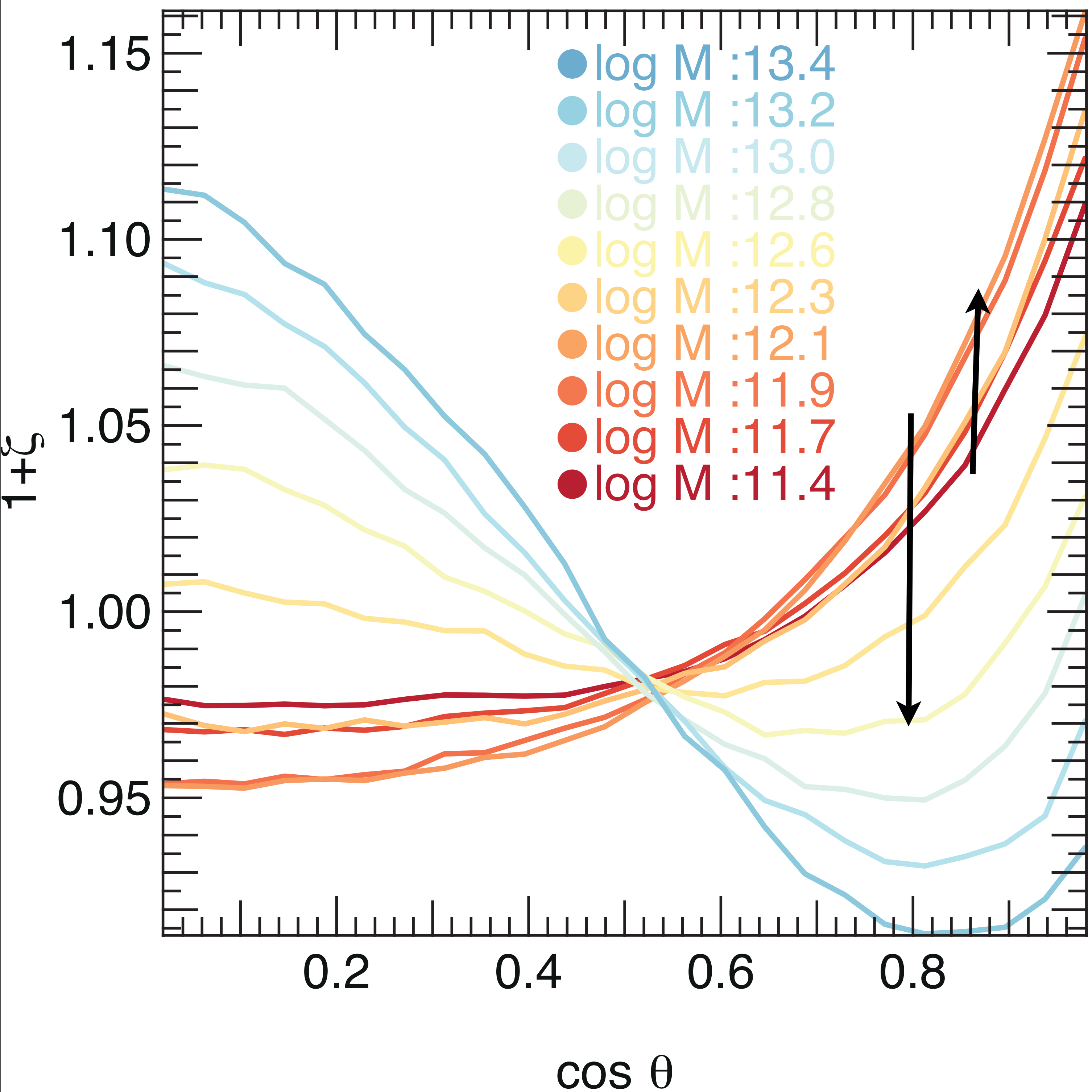

$$\omega(\mathbf{x}) \approx -\rho(\mathbf{q}_3)\, \sqrt{\eta}\, (\mathbf{x}_0 - \mathbf{x})_\perp^{-1/2} (\mathbf{u}(\mathbf{q}_3) - \mathbf{u}(\mathbf{q}_0))_\parallel / 2.$$

Revisit

# Alignement of spin with cosmic web

vorticity
max on edge

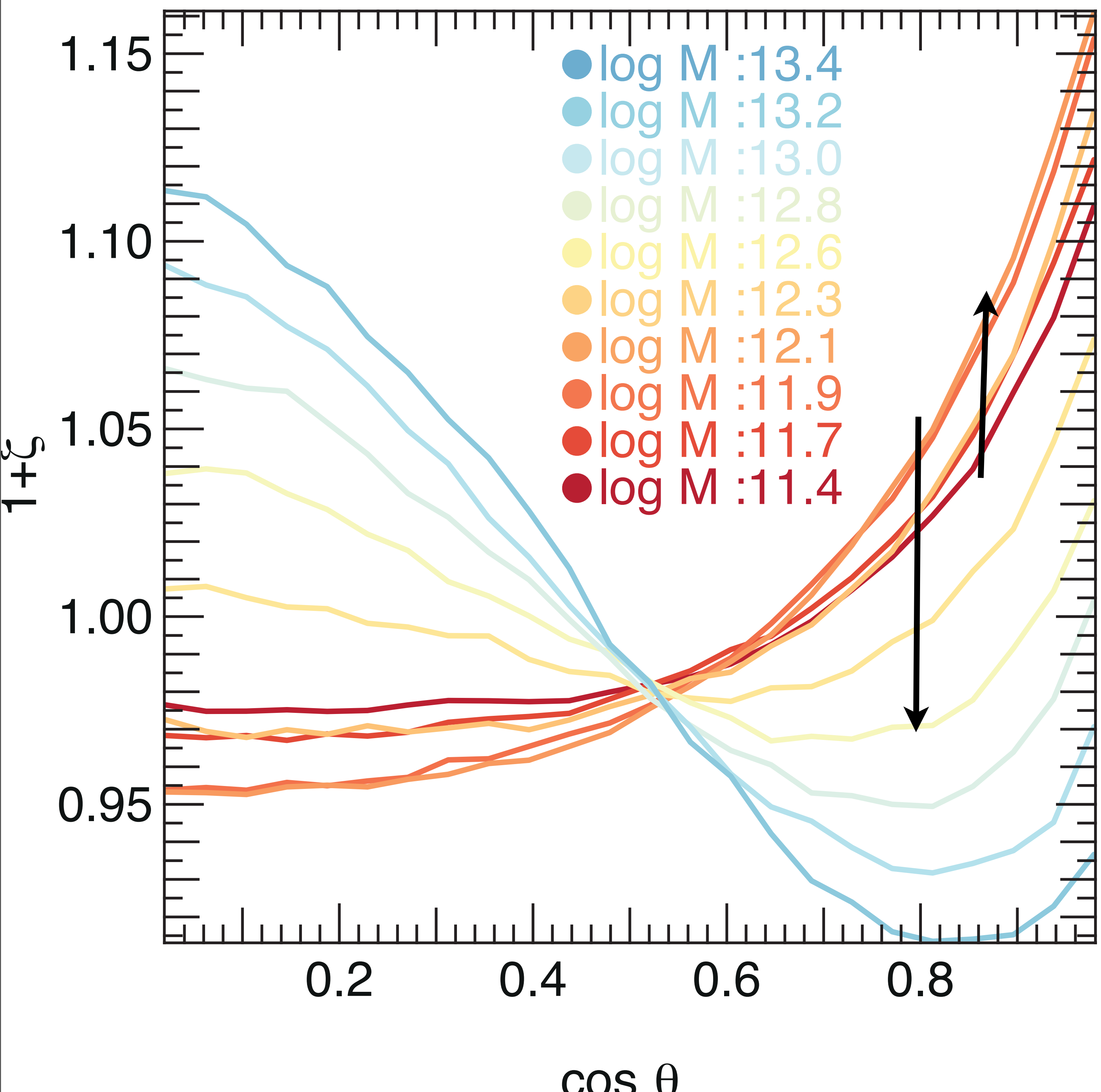
Spin alignment first INCREASES with mass !!!

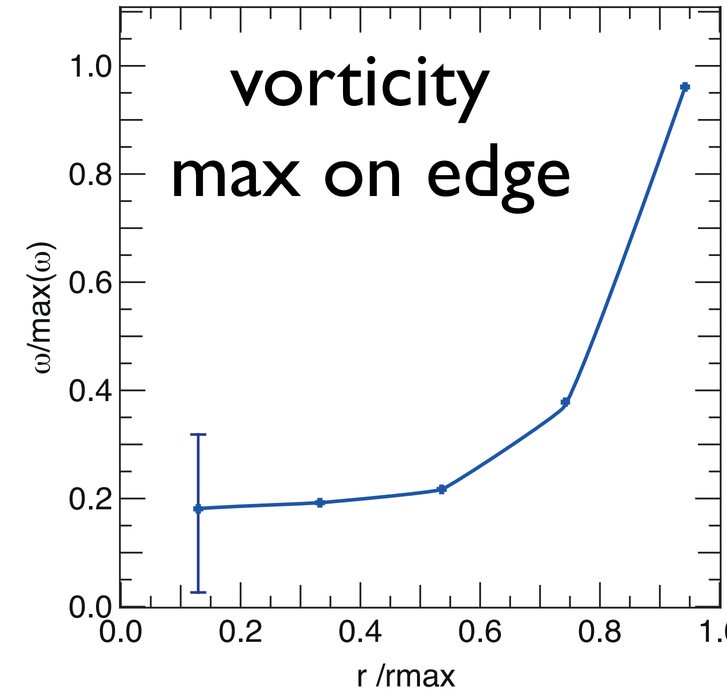


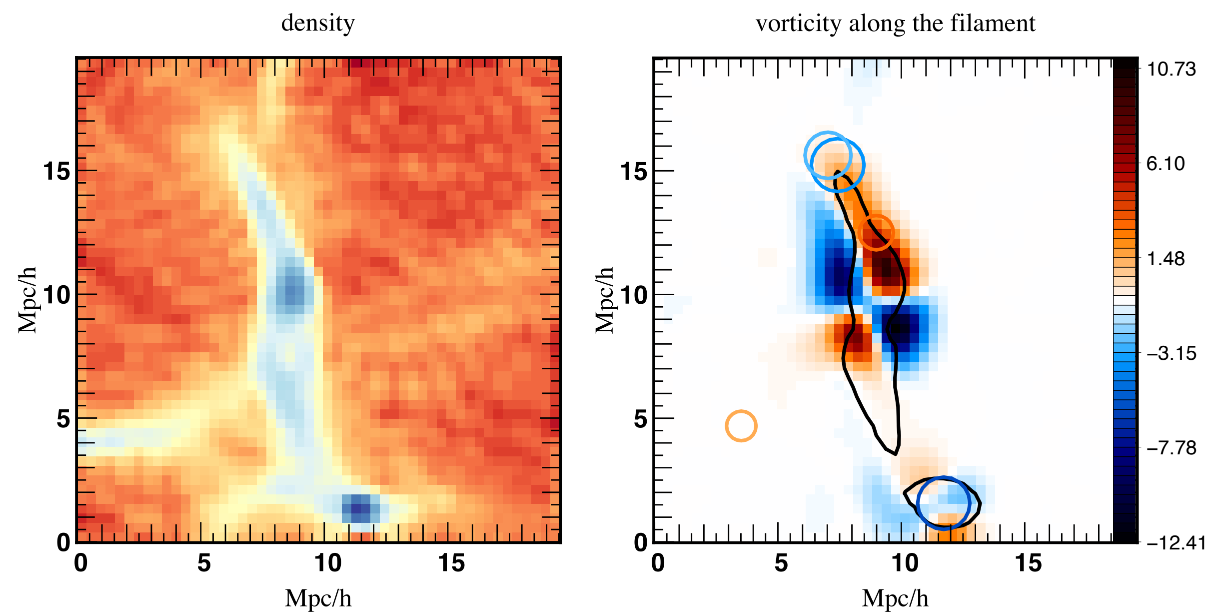
Revisit

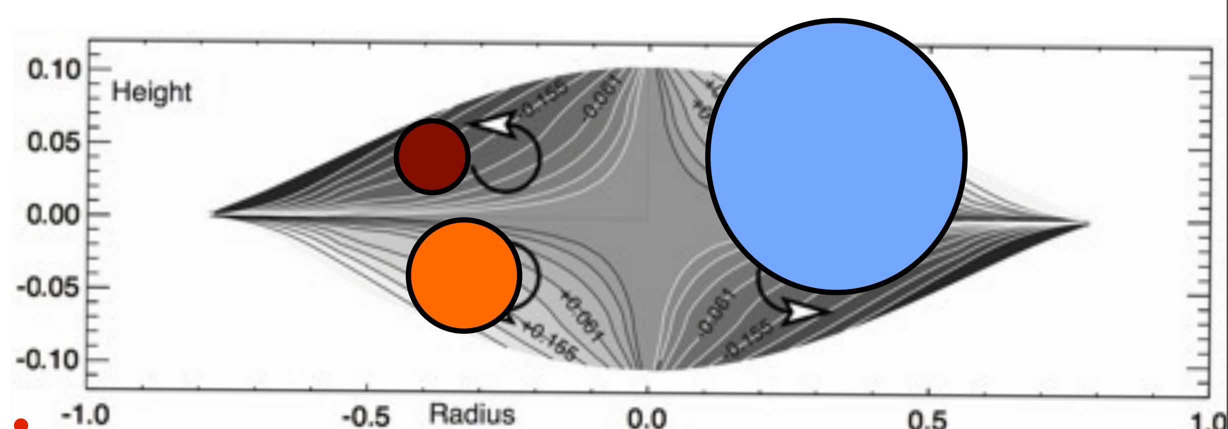
# Alignement of spin with cosmic web

Spin alignment first INCREASES with mass !!!



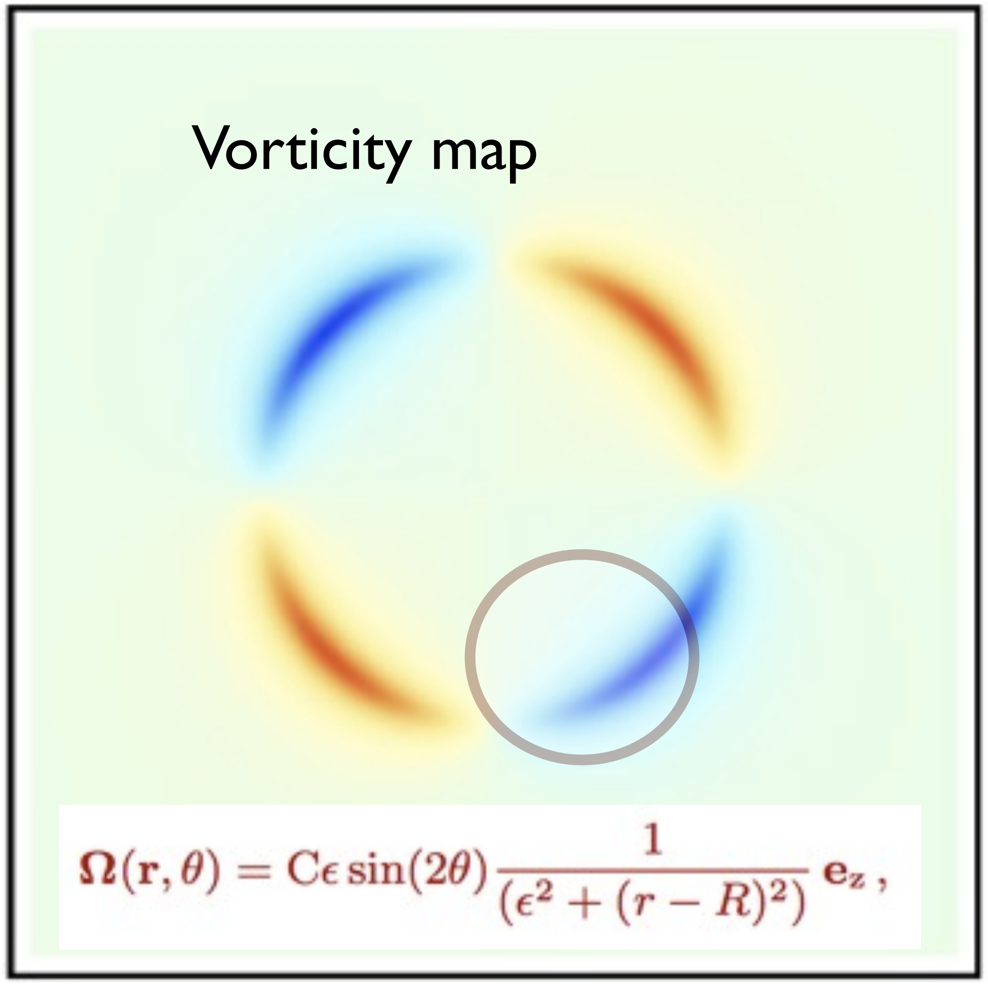



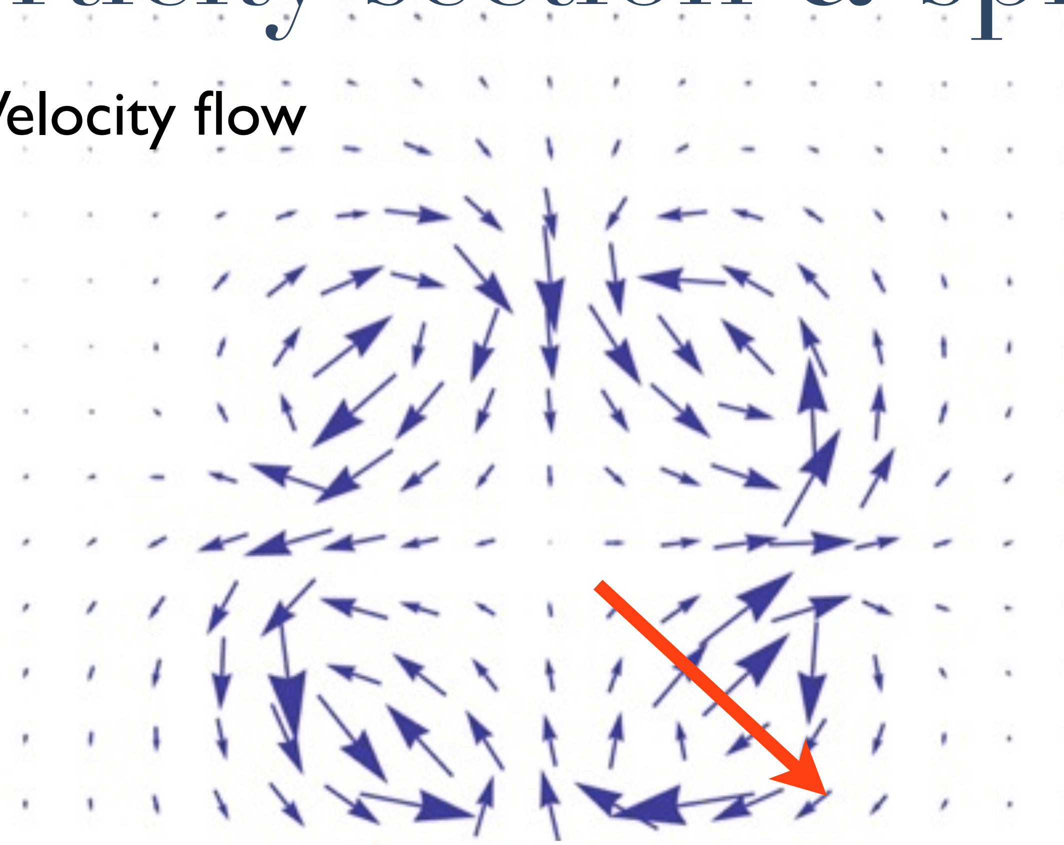




**Spin flip imposed by caustic size**

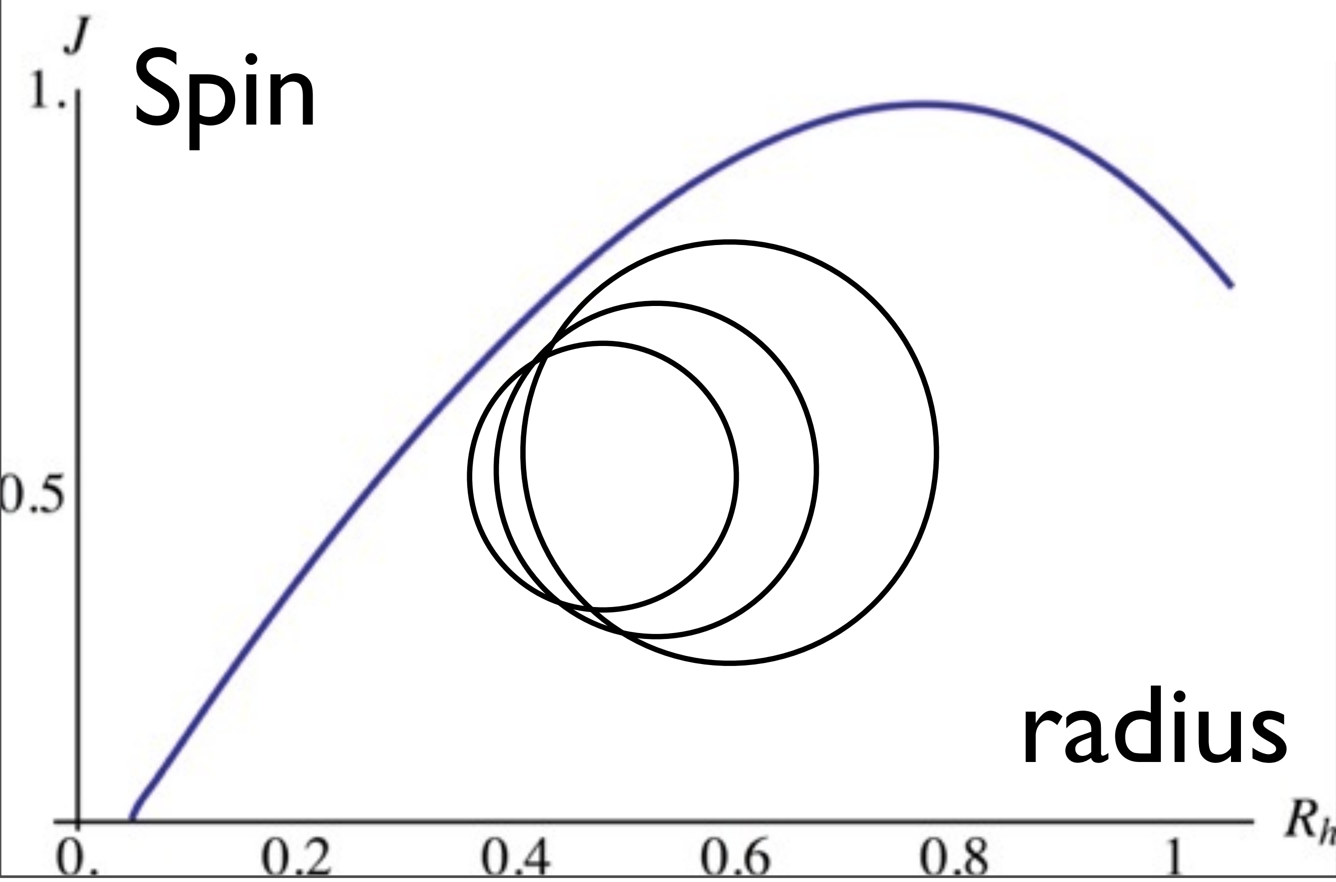
# A toy model for vorticity section & spin flip

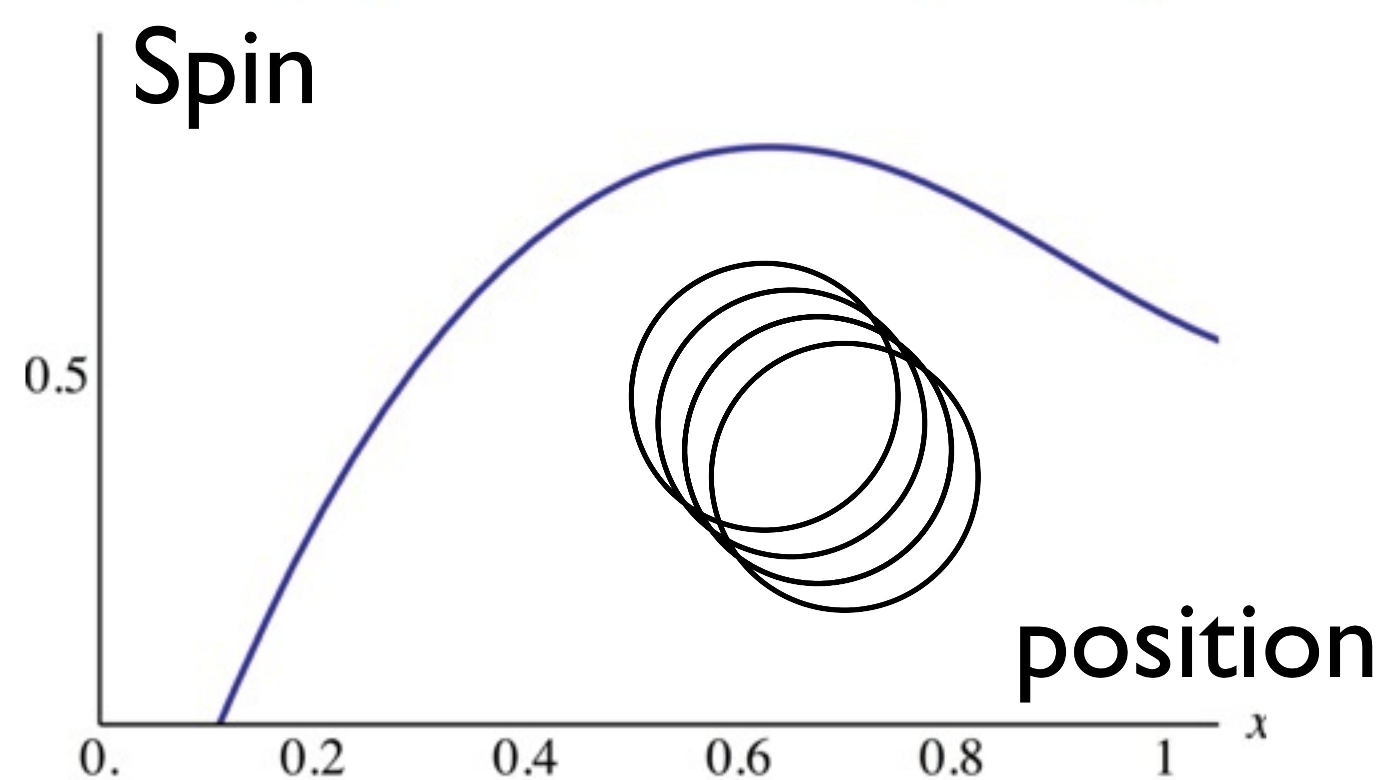



$$\mathbf{\Omega}(\mathbf{r},\theta) = C\epsilon\sin(2\theta)\frac{1}{(\epsilon^2+(r-R)^2)}\mathbf{e}_z\,,$$




$$\mathbf{v}(\mathbf{r},\theta) = \frac{1}{4\pi}\int_{\mathcal{V}}\nabla\times\mathbf{\Omega}(\mathbf{r}',\theta')\frac{1}{|\mathbf{r}-\mathbf{r}'|}\mathrm{d}\mathcal{V}\,.$$



# Horizon-AGN simulation

II — (1)

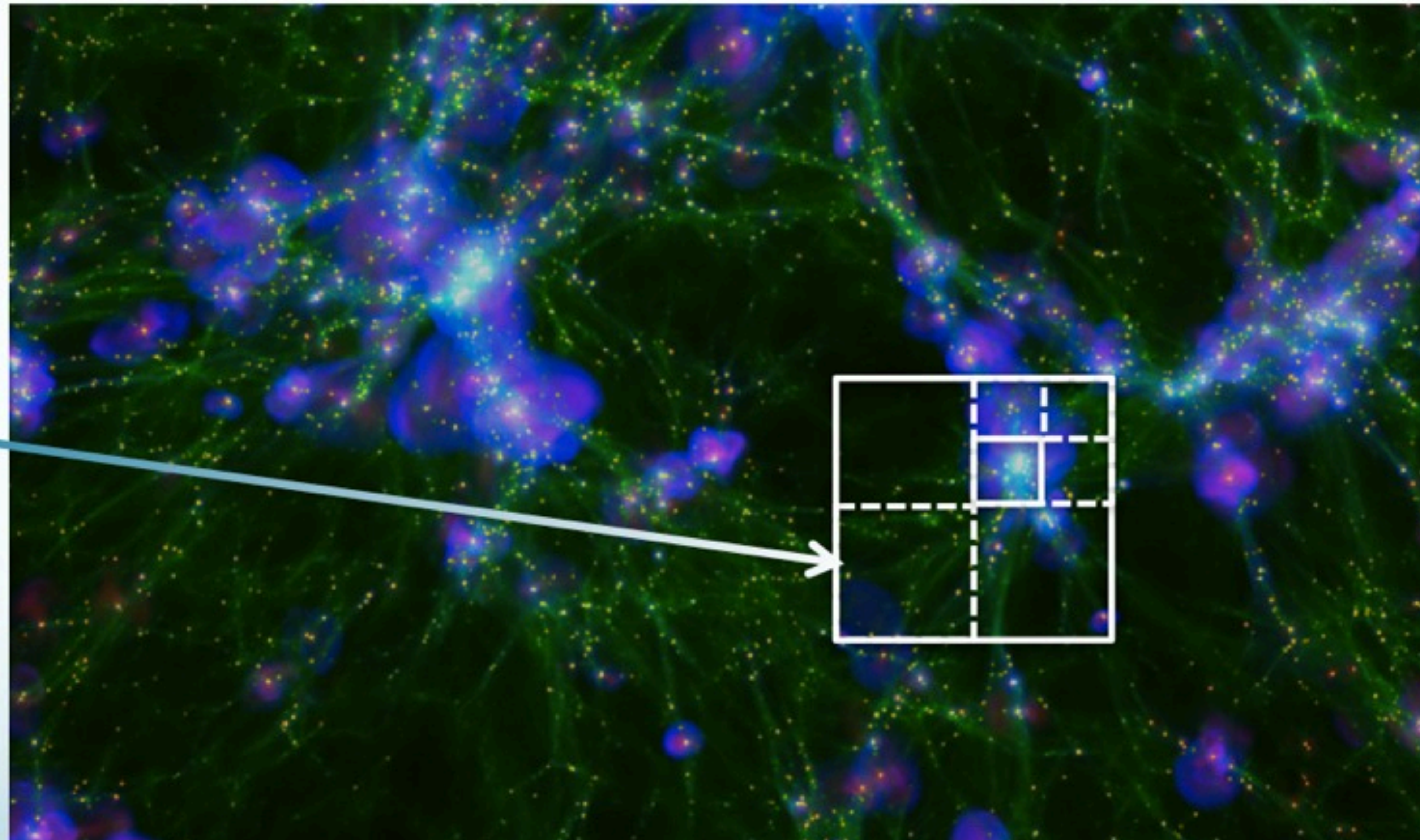
Full physics large-scale hydrodynamical cosmological AMR simulation with AGN

Run with RAMSES code

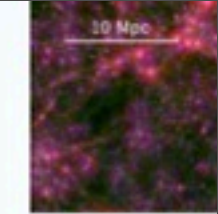
(R.Teyssier)

DM particles: $1024^3$

Max. refinement: $2^{17}$



*Dubois et al. 2014*

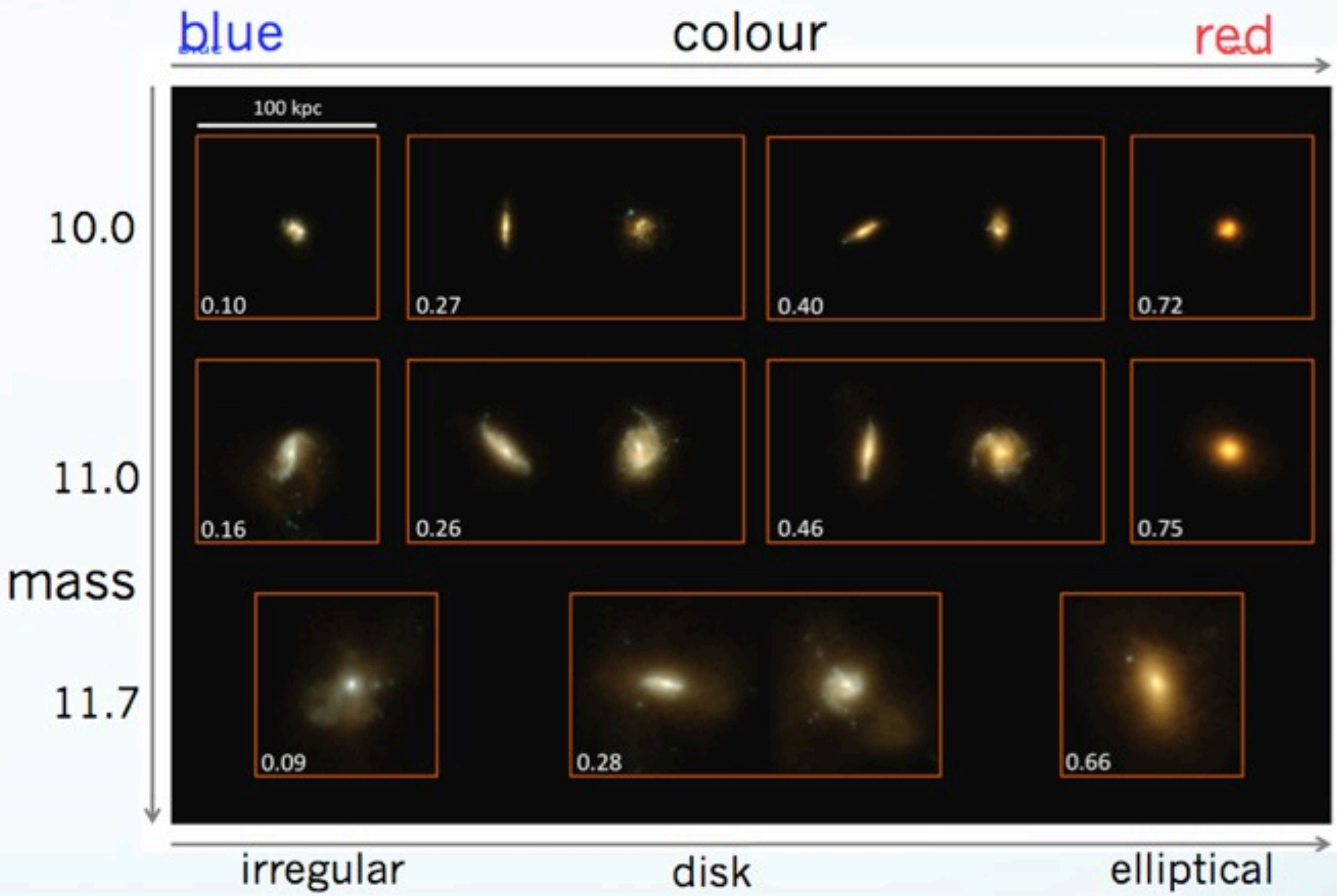


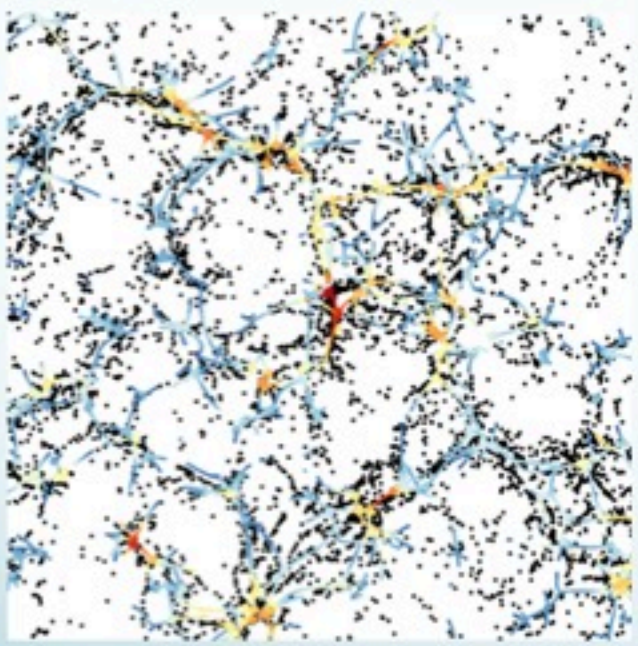
II (2) **Horizon-AGN**

- **100 Mpc.h-1 square box. run down to z=1.2 with LCDM cosmology:**

  - 150 000 galaxies and
  - 300 000 dark haloes

  in a snapshot.



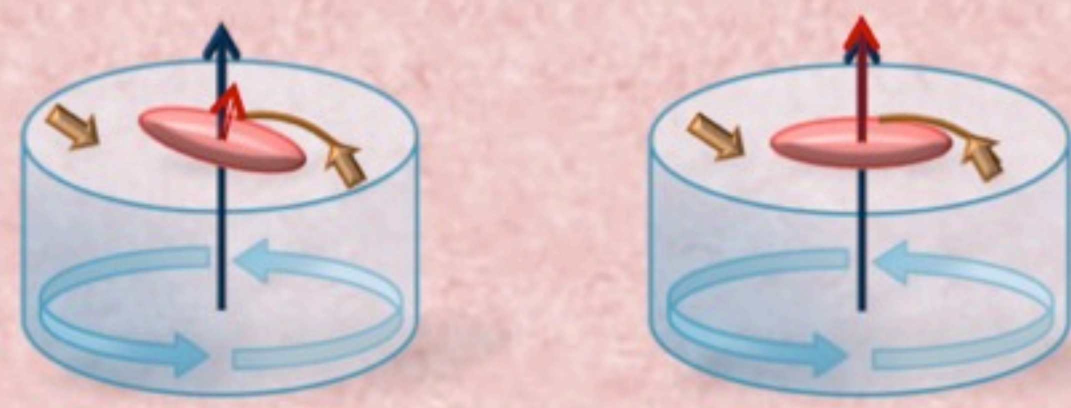



- Horizon-AGN: skeleton

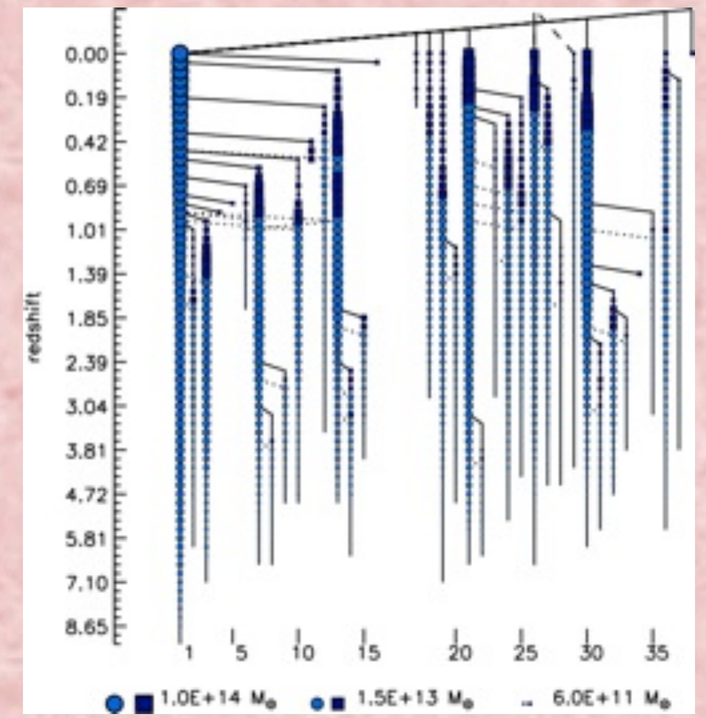
- **Various physical features:**
  . Star formation
  . Feedback: supernovae, AGN, ...
  . Cooling: H,He+metal contribution
  . Metals

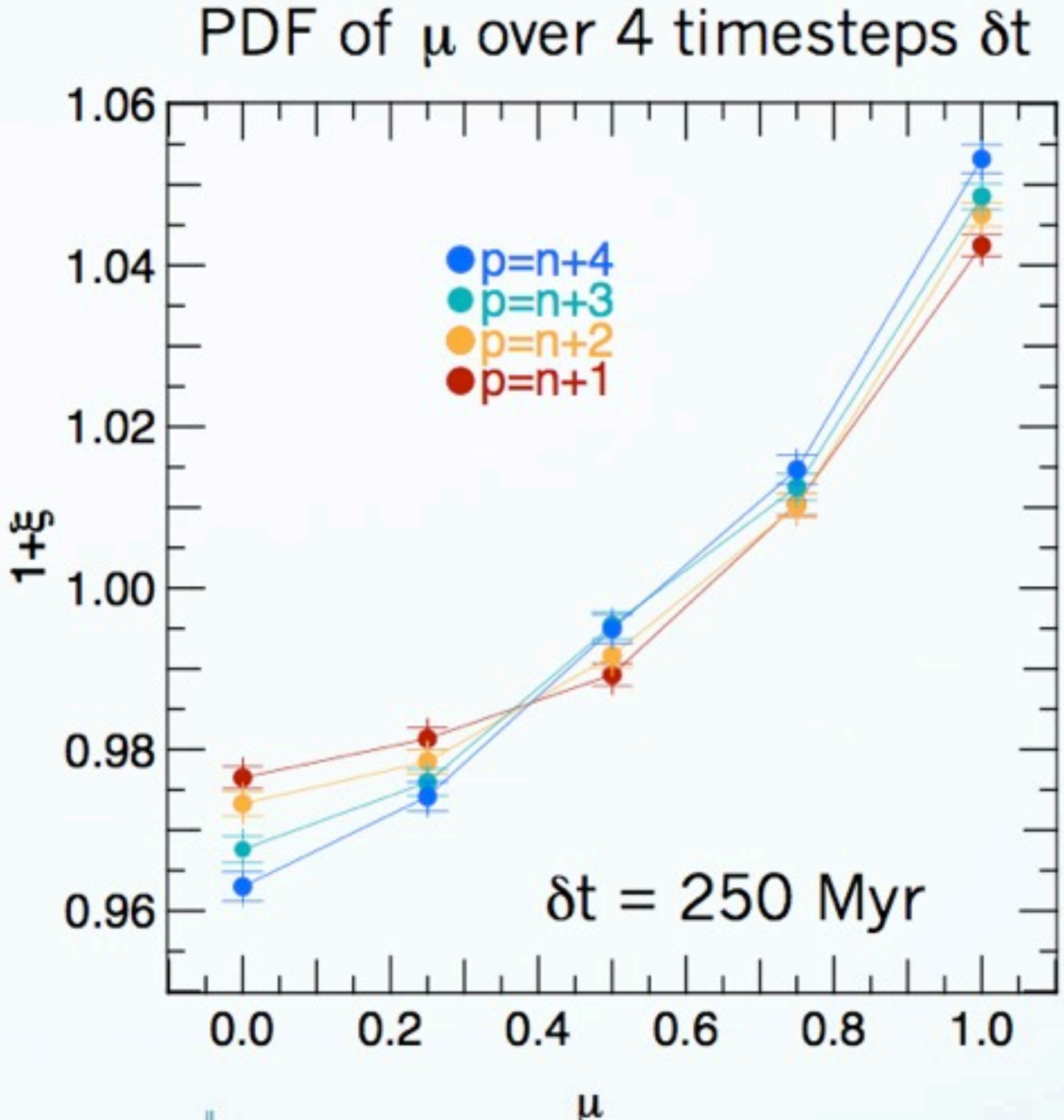
*Dubois, Pichon, Welker et al., 2014*

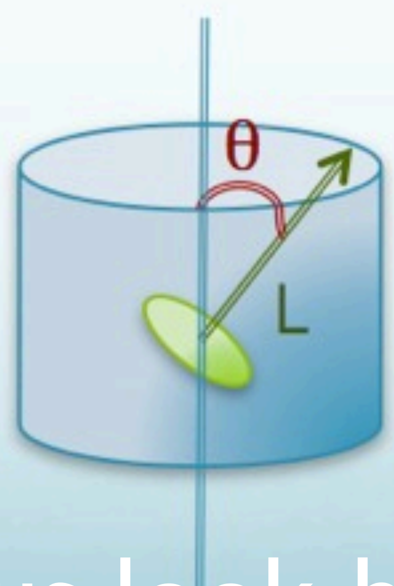
# SMOOTH ACCRETION



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



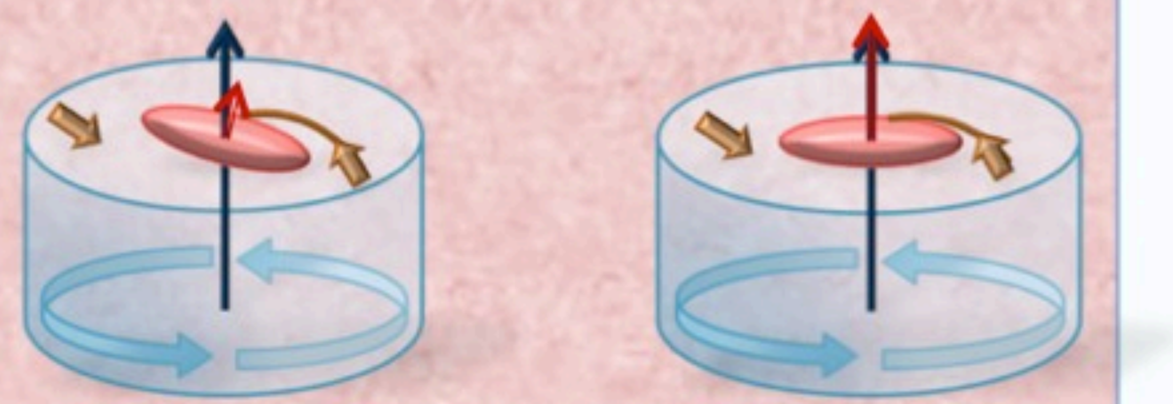




$\mu = |\cos(\theta)|$

- Spin-filament angle
- ξ : excess probability

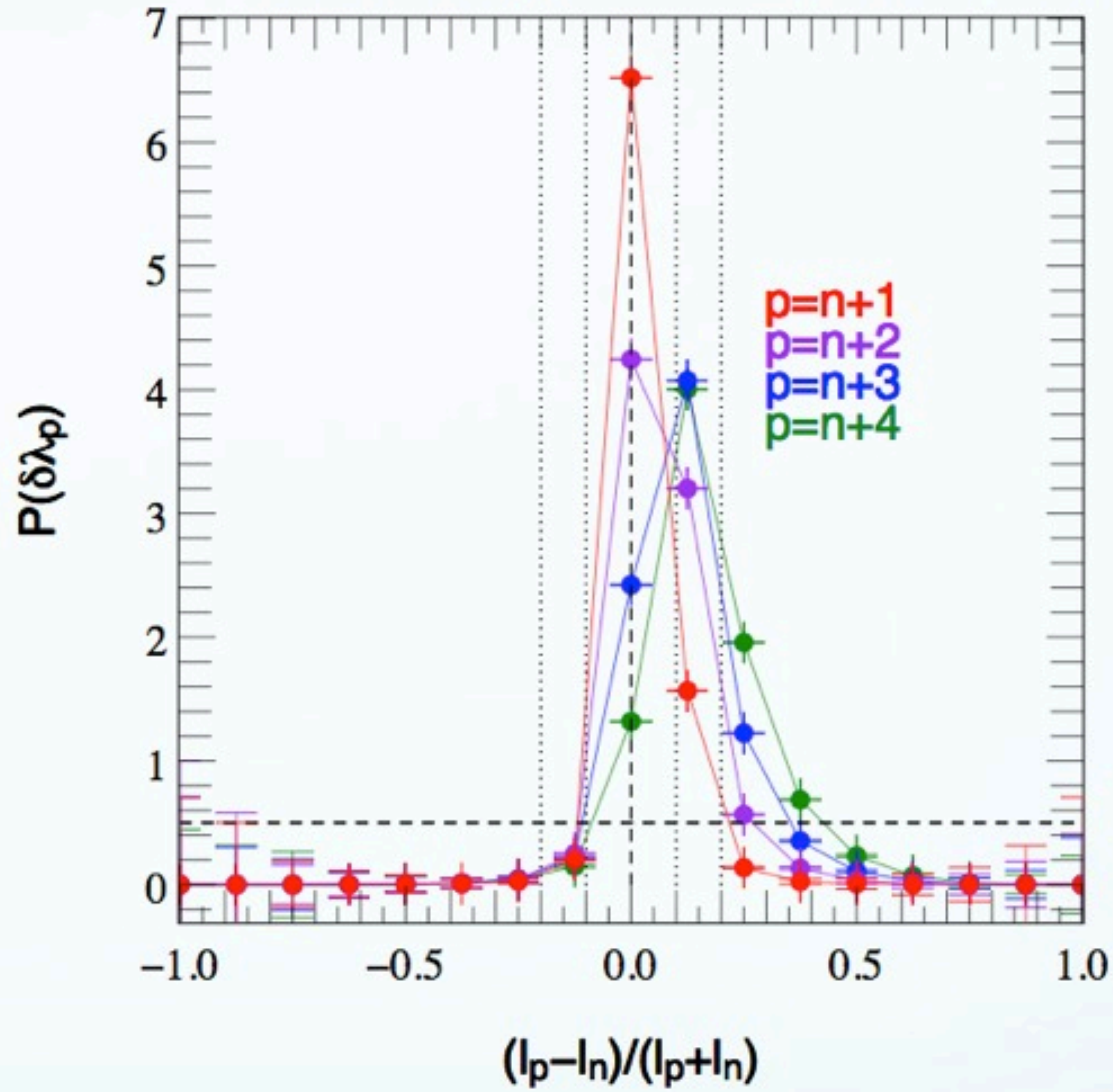
## no merger : orientation versus look-back time

## SMOOTH ACCRETION



- Gas inflows (re)-align galaxies with their filament
- Gas inflows build up the galactic spin

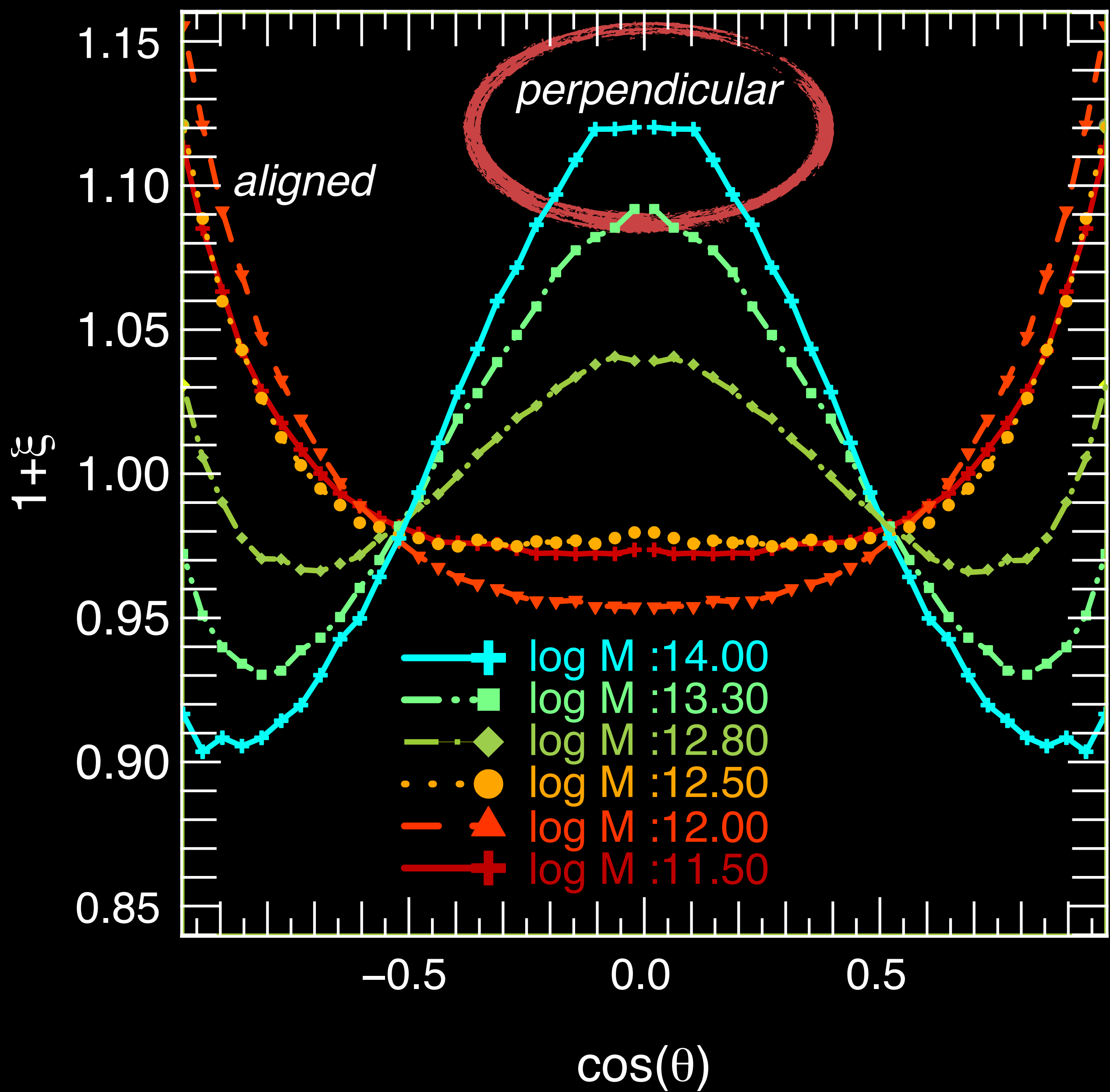
PDF of $\delta\lambda(p)$ for 4 different $\delta t_p$




- $\delta\lambda(p)$ : angular momentum contrast over timestep $\delta t_p=(p-n)*\delta t$

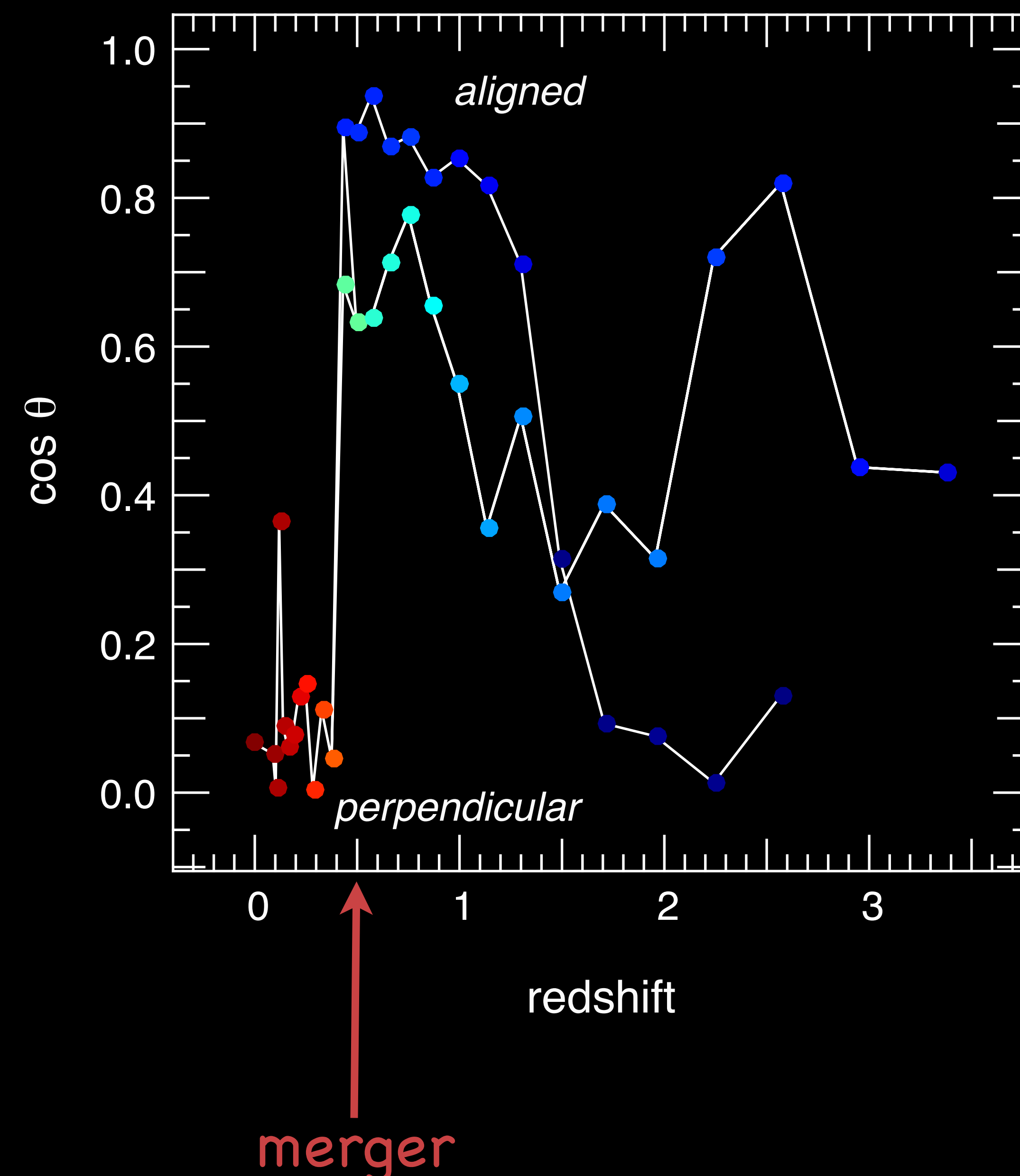
# no merger : spin amplitude versus look-back time

# High-mass haloes: $M > M_{\rm crit}$



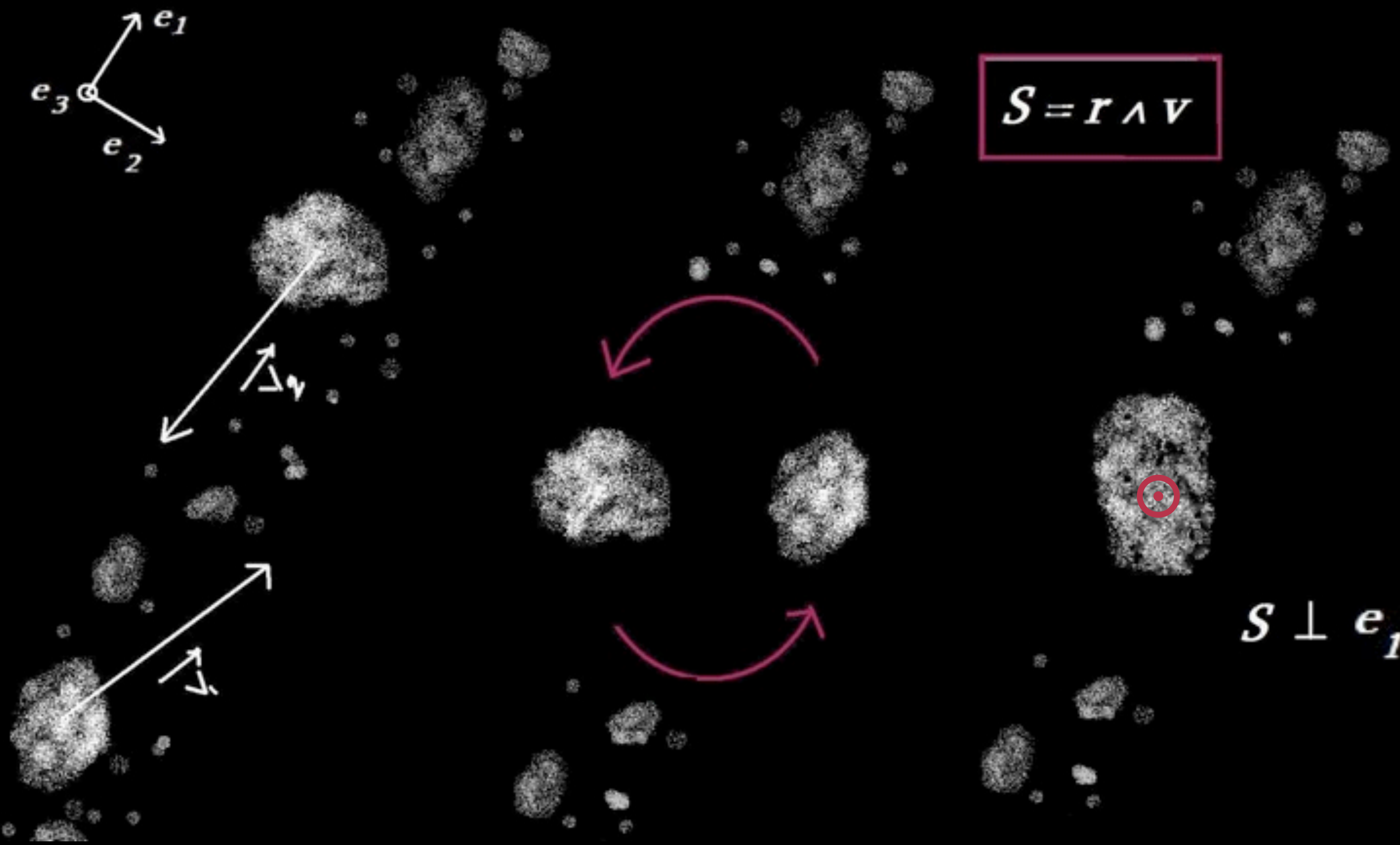

$$M_{\rm crit} = 4 \cdot 10^{12} M_\odot$$

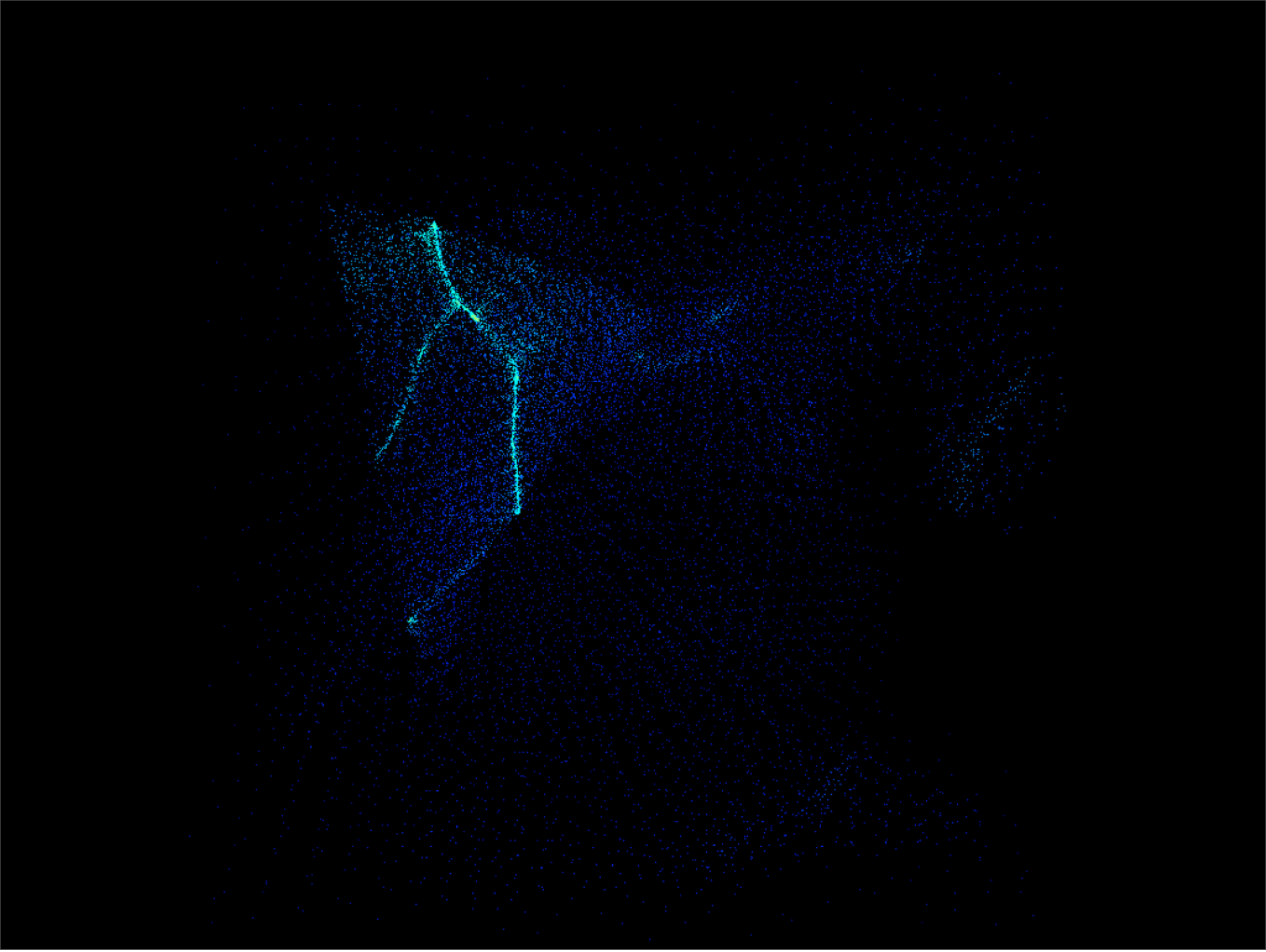
formed at low z by mergers inside the filaments

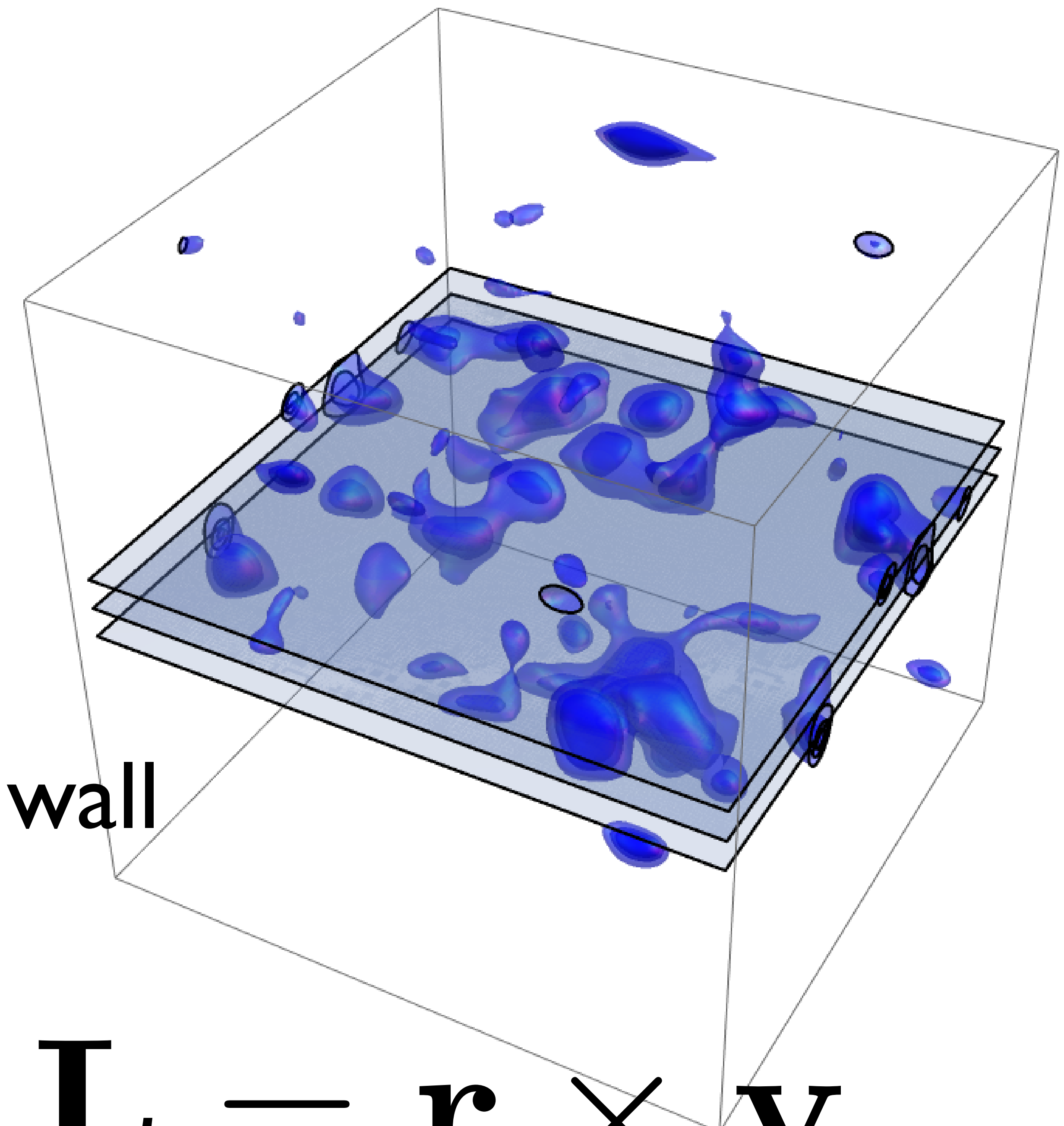


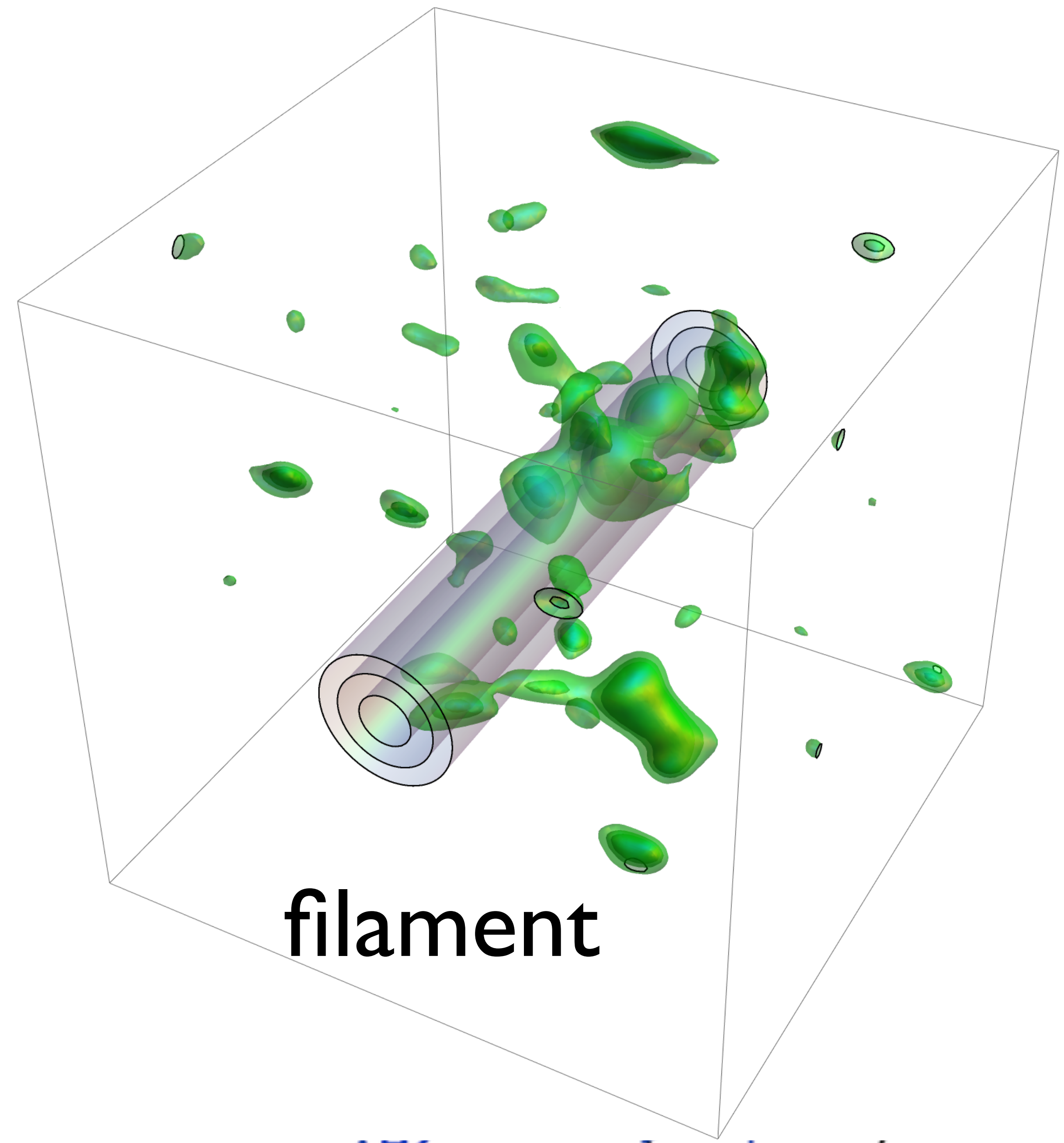
# How do mergers along the filaments create spin perpendicular to them?

halos catch up with each other along the filaments





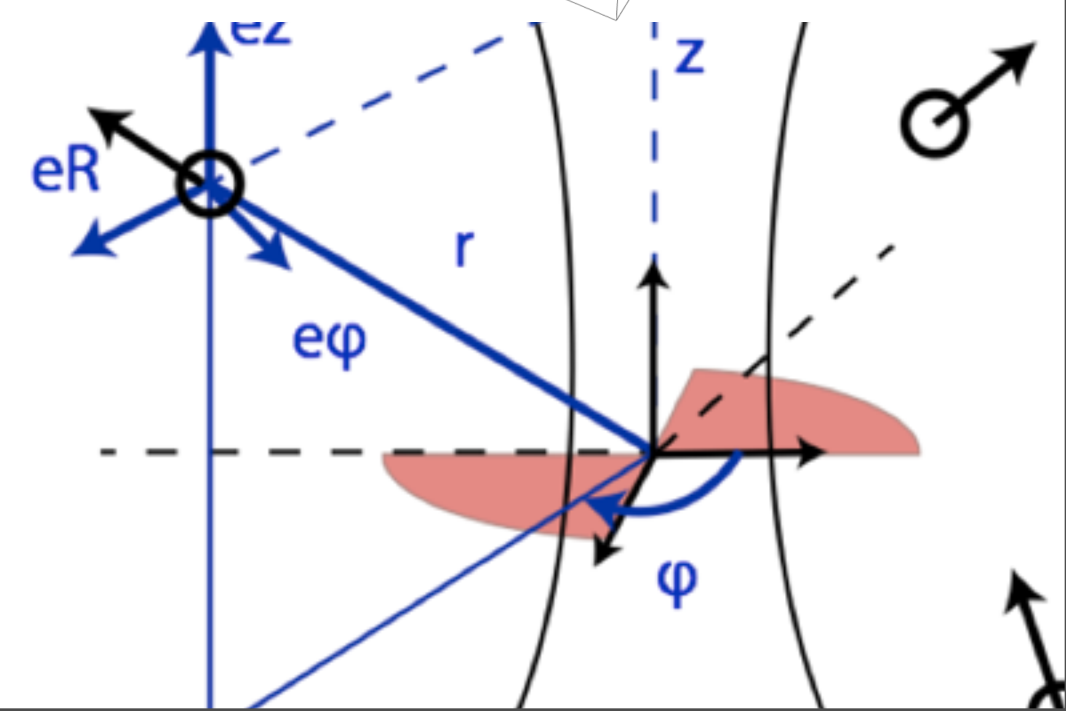


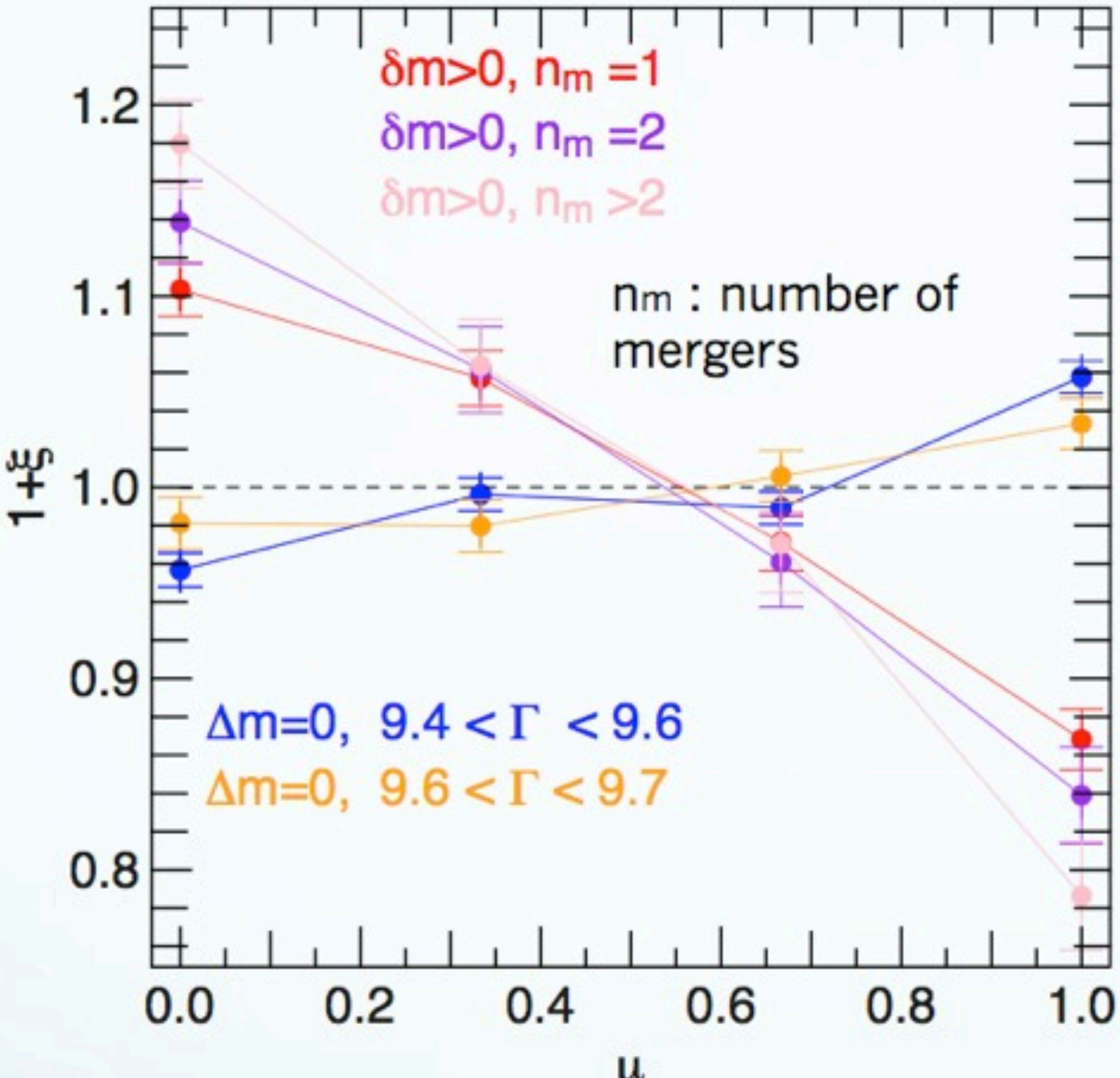

$$\mathbf{L} = \mathbf{r} \times \mathbf{v}$$

If pancake $\ni$ filament

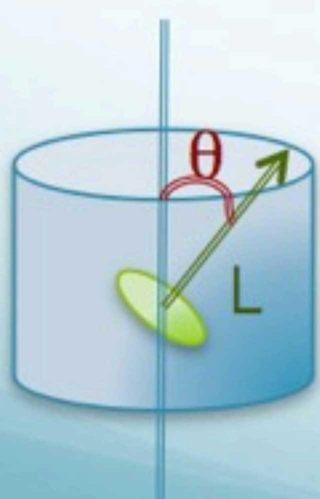
$\longrightarrow$ mergers along $e_\phi$



## PDF of μ for different merging histories

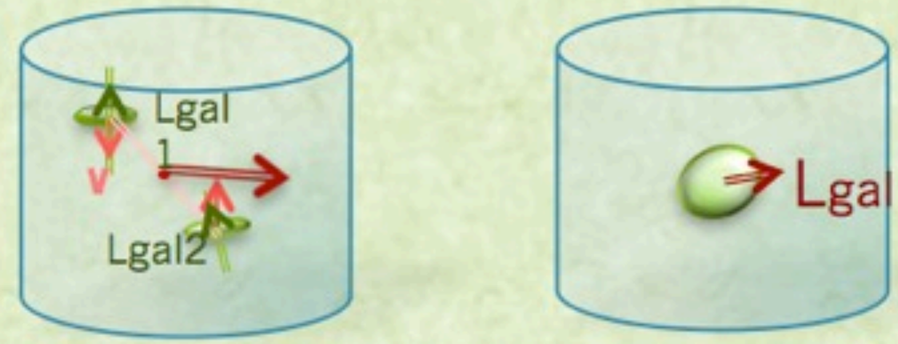



Merger rate
better tracer of flip




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

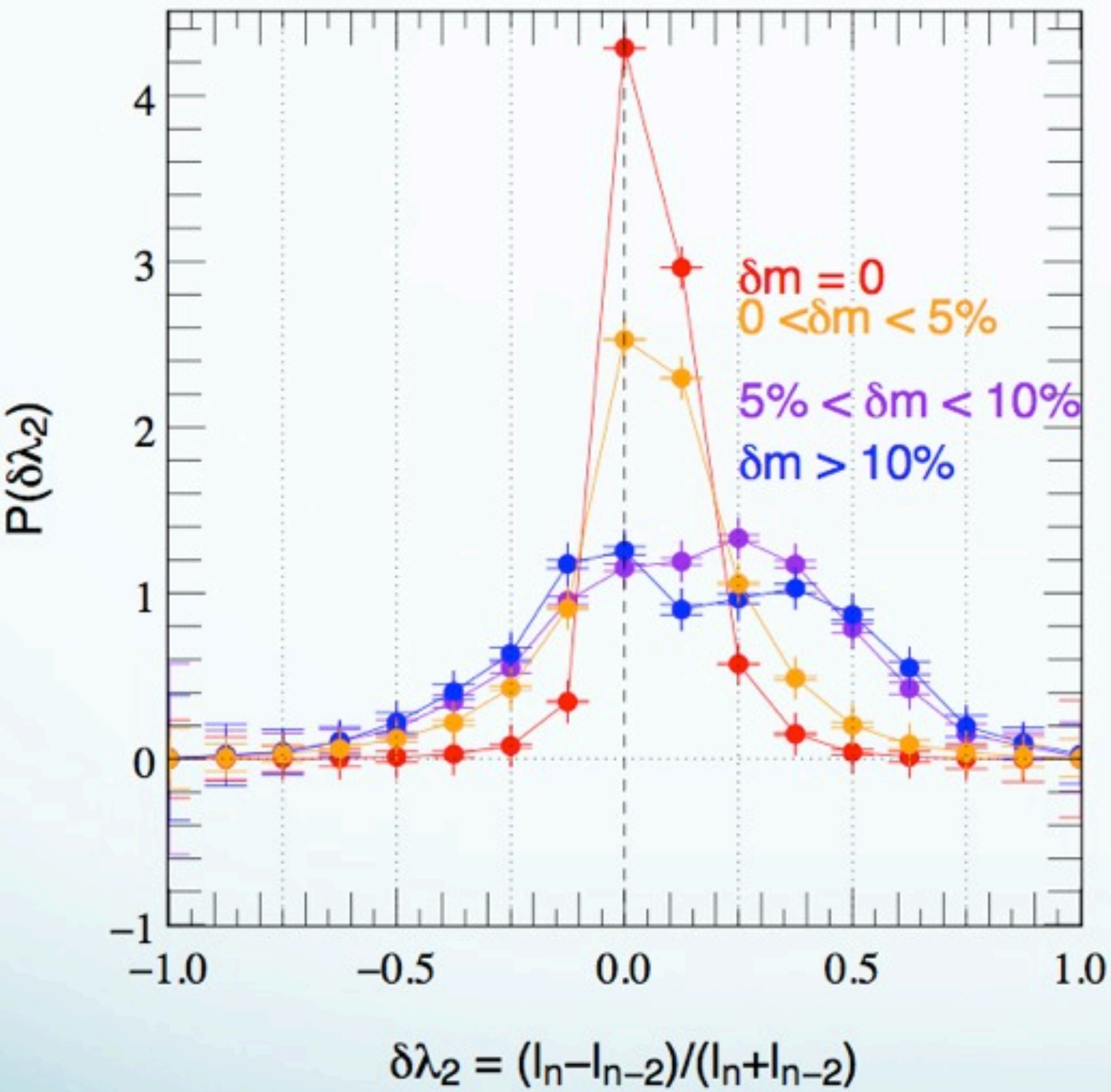
## MERGERS



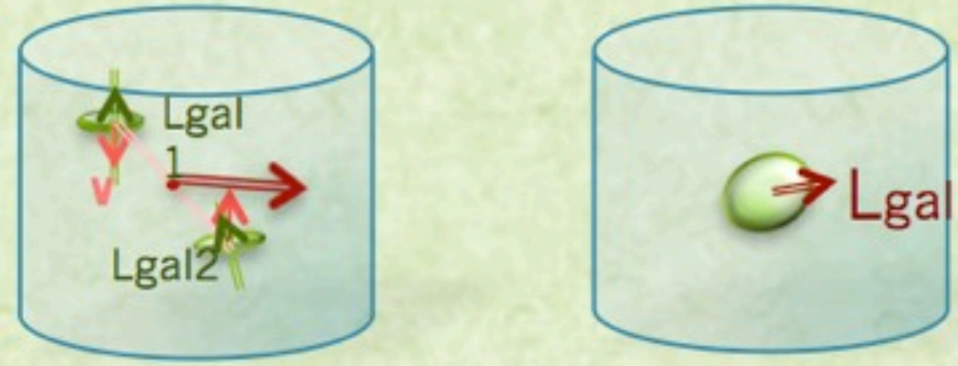

- Mergers drive galactic spin flips.
- Mergers flip the spin perpendicular to the filament

- Red to pink : merged between z=5.2 and z=1.8
- Blue to yellow : nerver merged, $\Gamma = \log(M/M_{sun})$

PDF of the angular momentum contrast for different merging histories




## MERGERS

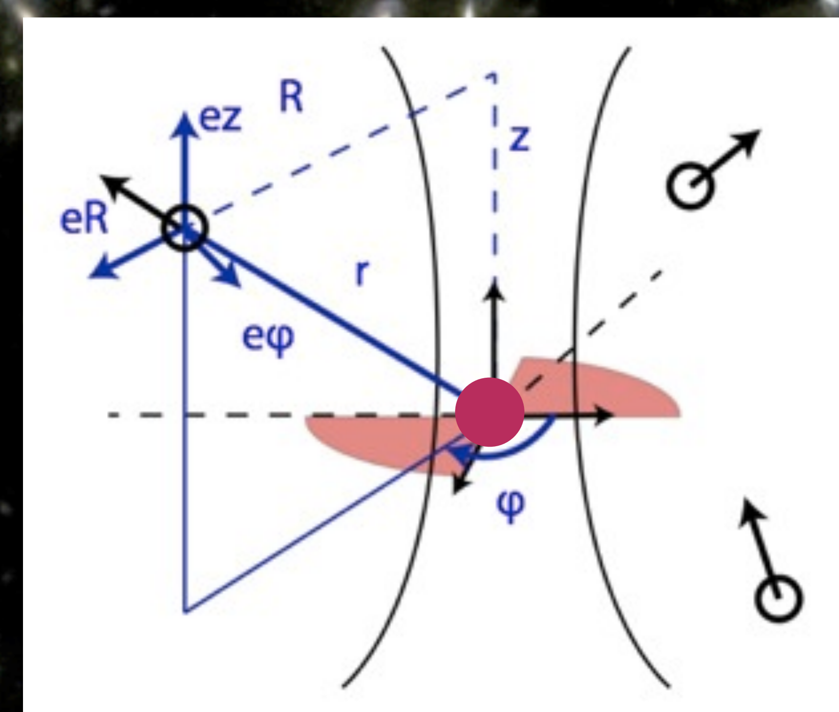



- Mergers drive galactic spin flips.
- Mergers flip the spin perpendicular to the filament
- Mergers build up the spin on average

- How discs build up from persistent cosmic web?
- **How dark halo's spin flip relative to filament? Why are they initially aligned with filaments? Why the transition mass? Eulerian view**
- **What is the corresponding Lagrangian theory?**

# Part III

Tidal torque theory with a peak background split near a **saddle**



# Part III Outline

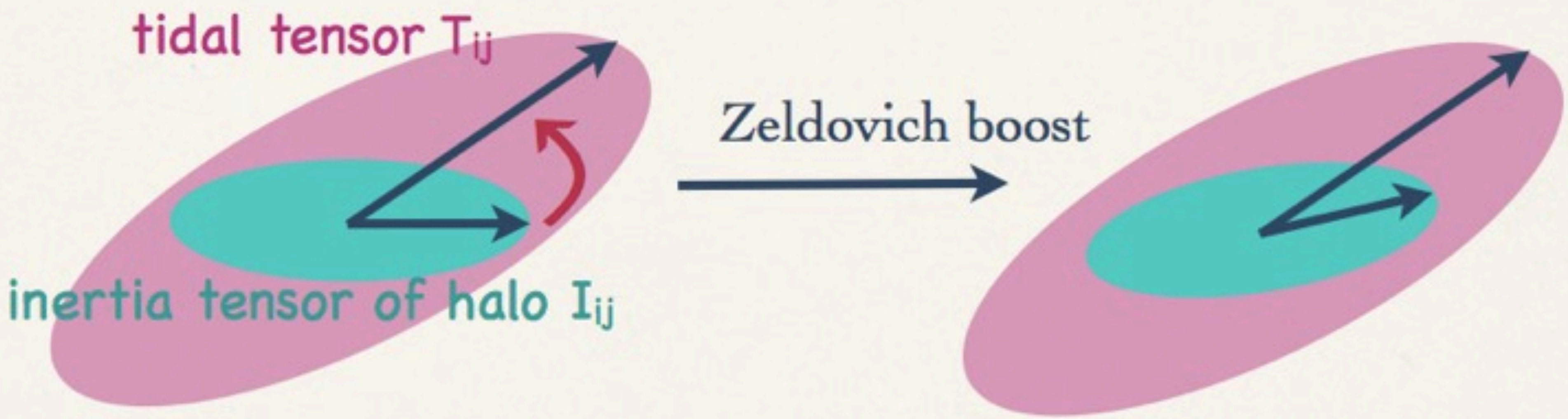
- The Idea
  - walls/filament/peak locally bias differentially tidal and inertia tensor: spin alignment reflect this in TTT
- The picture
  - Geometry of spin near saddle: point reflection symmetric distribution
- The Maths
  - Very simple **ab initio** prediction for mass transition

The Lagrangian view of spin/LSS connection

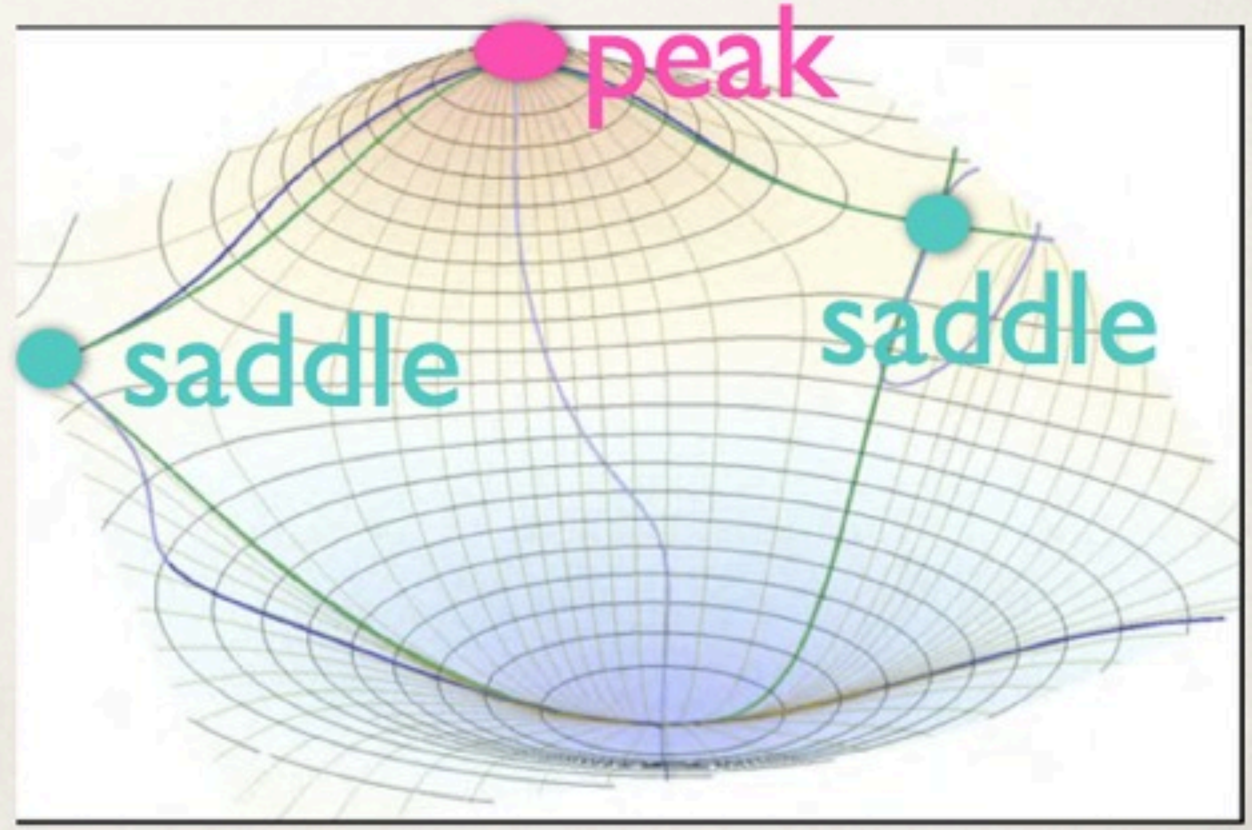
# Can we understand where spin and vorticity alignments come from?

-usual tidal torque theory

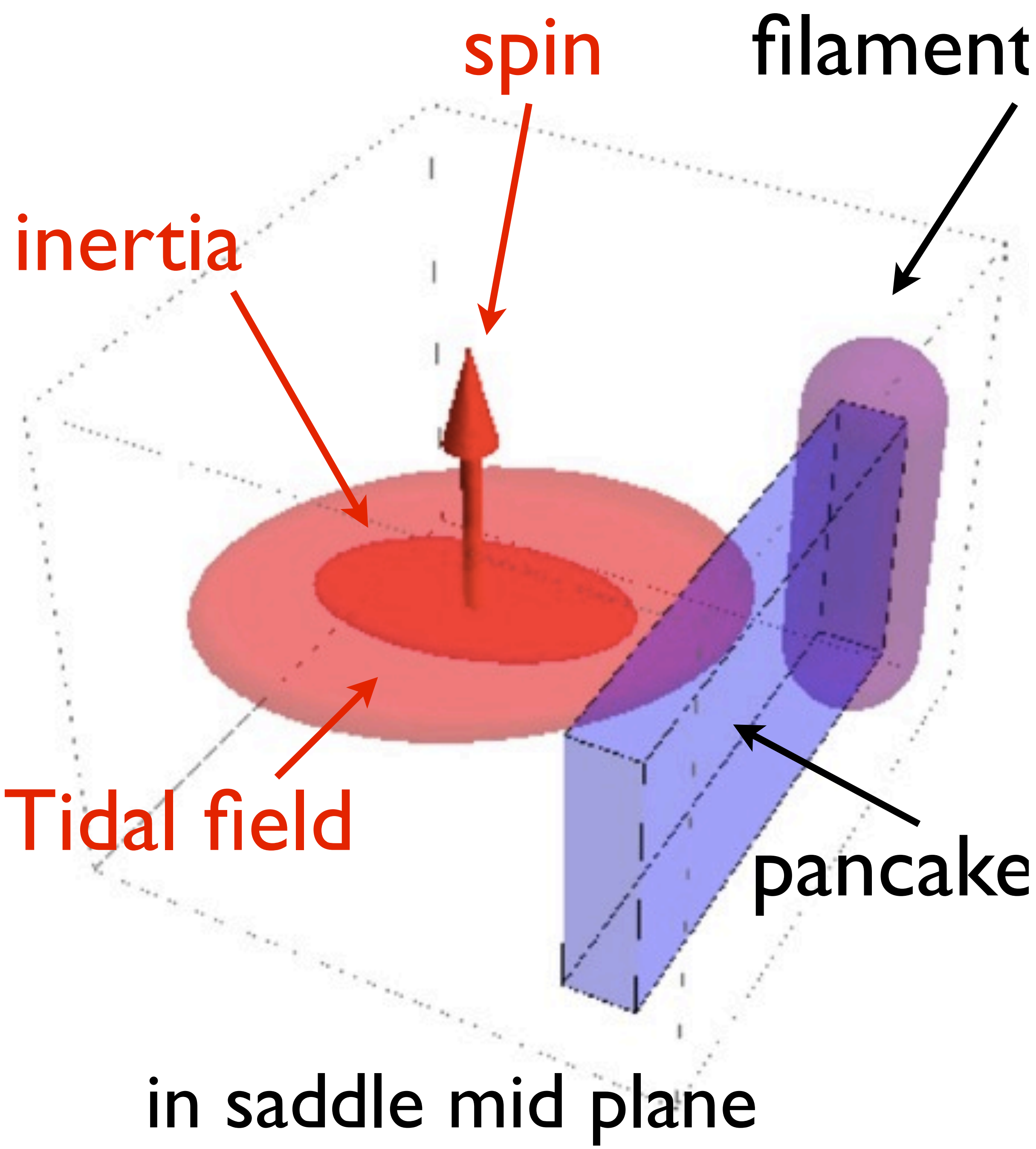
$$L_k = \varepsilon_{ijk} I_{li} T_{lj}$$



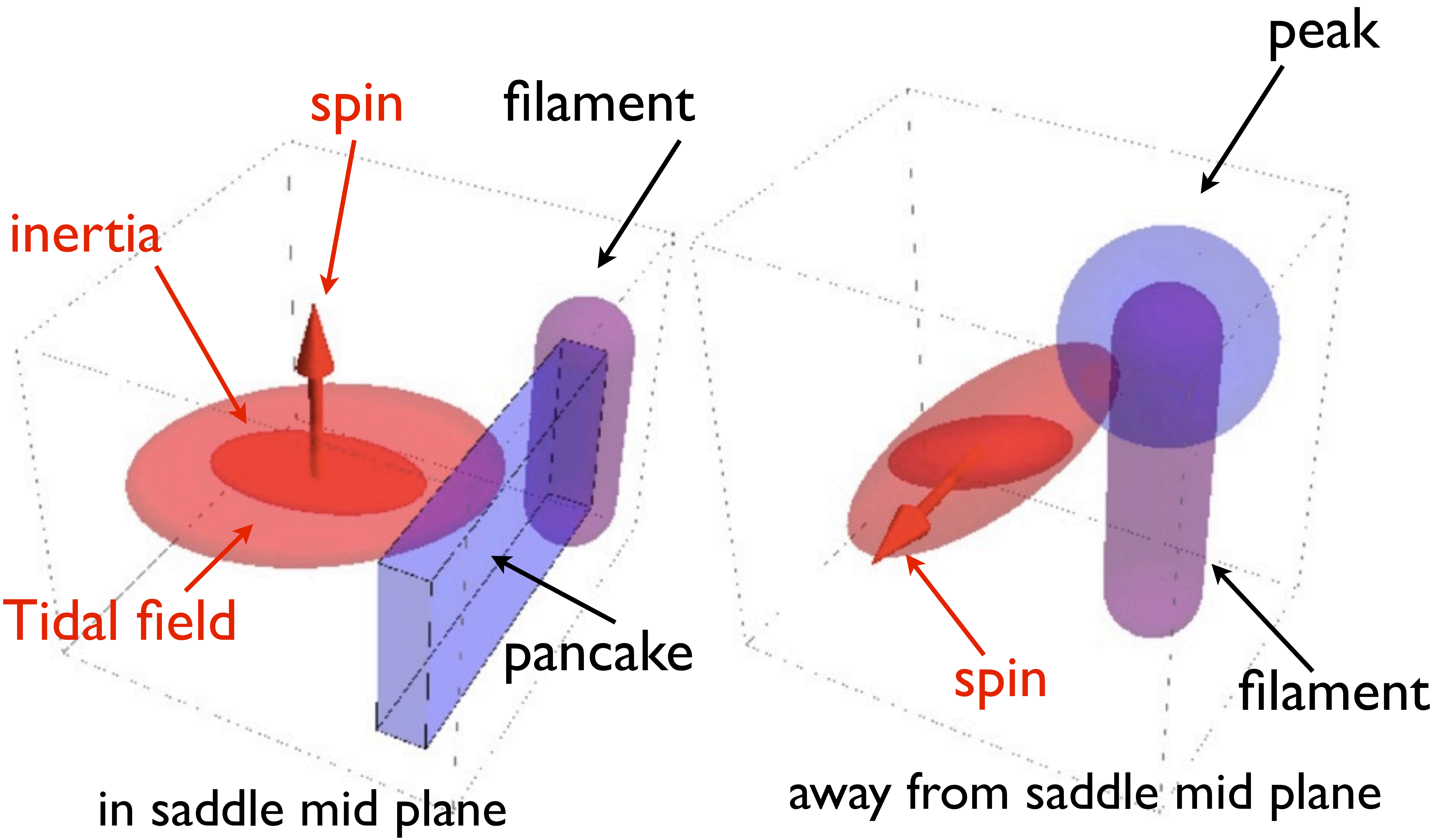

-anisotropy of the cosmic web:
surrounding of a saddle point with typical geometry



# Tidal/Inertia mis-alignment



# Tidal/Inertia mis-alignment



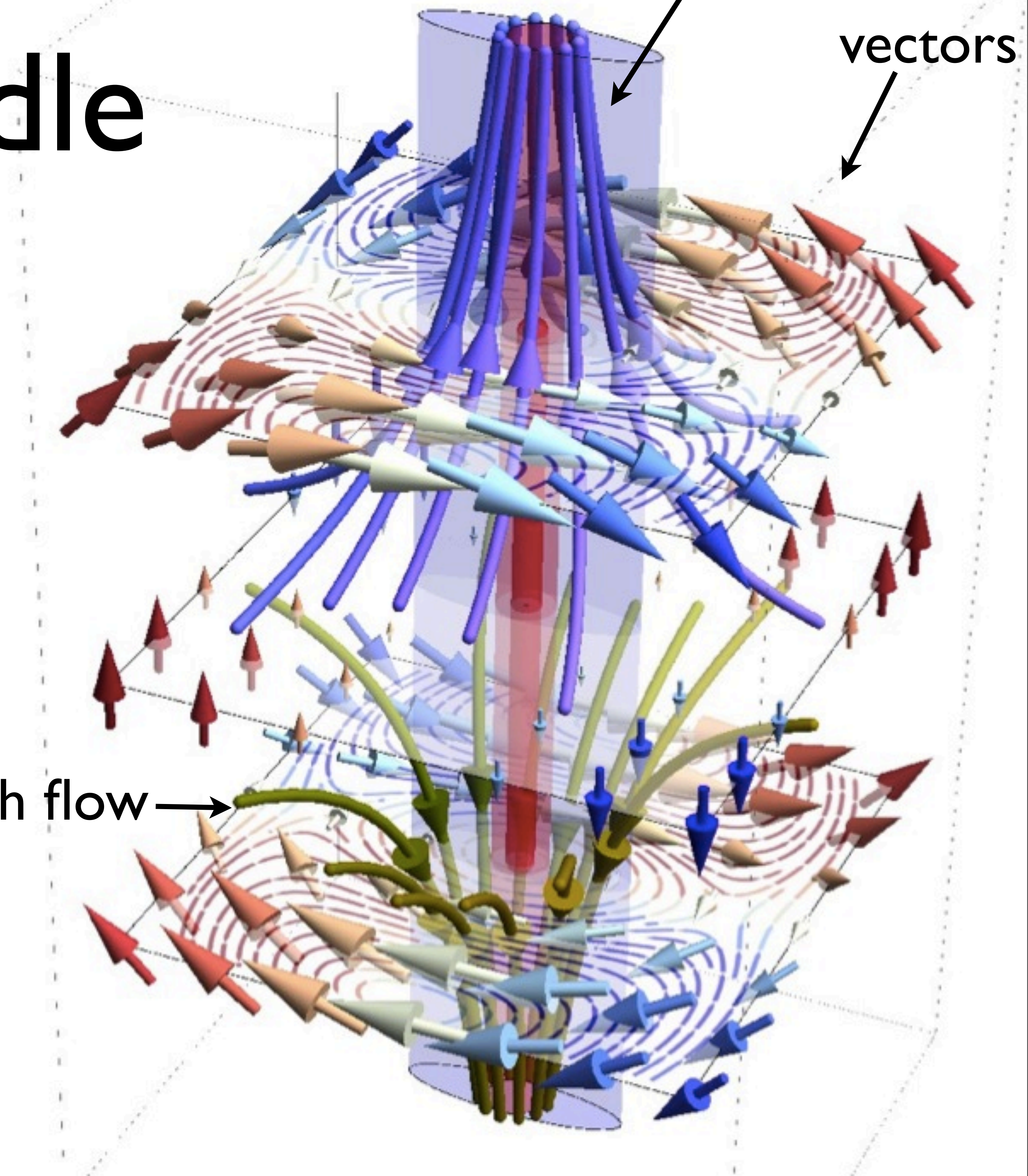
# Spin structure near Saddle

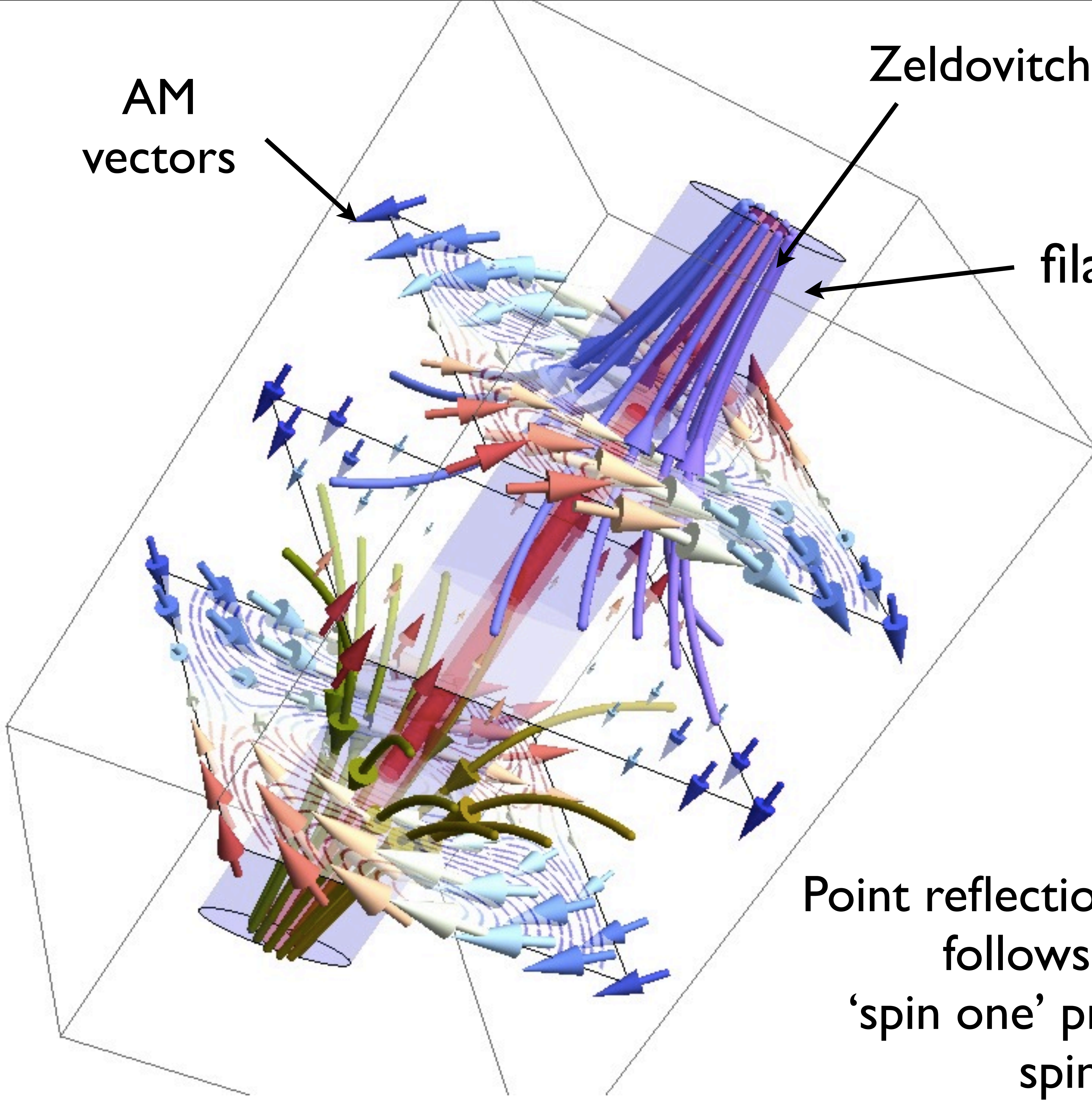
$$L_k = \varepsilon_{ijk} I_{li} T_{lj}$$
$$\approx \varepsilon_{ijk} H_{li} T_{lj}$$

Hessian

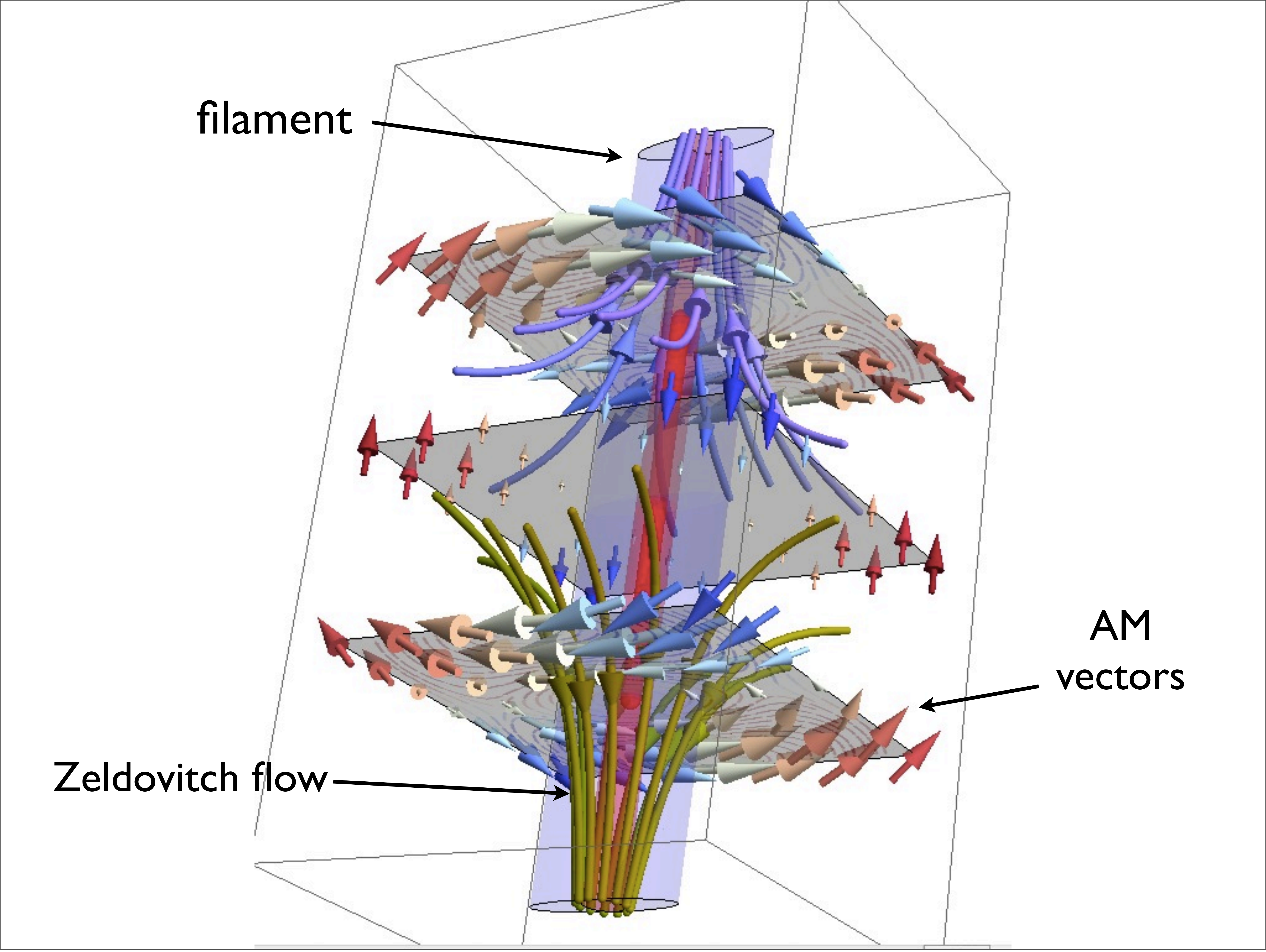
Tidal

Zeldovitch flow






Point reflection symmetry
follows from
'spin one' property of
spin !



filament
AM
vectors
Zeldovitch flow

# TTT@ saddle?

the Gaussain joint PDF of the derivatives of the field, $\mathbf{X} = \{x_{ij}, x_{ijk}, x_{ijkl}\}$ and $\mathbf{Y} = \{y_{ij}, y_{ijk}, y_{ijkl}\}$ in two given locations ($\mathbf{r}_x$ and $\mathbf{r}_y$ separated by a distance $r = |\mathbf{r}_x - \mathbf{r}_y|$) obeys

$$\mathrm{PDF}(\mathbf{X}, \mathbf{Y}) = \frac{1}{\det|2\pi\mathbf{C}|^{1/2}} \times$$

$$\exp\left(-\frac{1}{2}\begin{bmatrix}\mathbf{X}\\ \mathbf{Y}\end{bmatrix}^{\mathrm{T}} \cdot \begin{bmatrix}\mathbf{C}_0 & \mathbf{C}_\gamma \\ \mathbf{C}_\gamma^{\mathrm{T}} & \mathbf{C}_0\end{bmatrix}^{-1} \cdot \begin{bmatrix}\mathbf{X}\\ \mathbf{Y}\end{bmatrix}\right), \quad \text{(A2)}$$

subject to the "saddle" constraints (2D)

*height*

$$x_{0,2} + x_{2,0} = \nu,\ x_{1,2} + x_{3,0} = 0,\ x_{0,3} + x_{2,1} = 0,$$

*zero gradient*

$$\kappa \cos(2\theta) = \frac{1}{2}(x_{4,0} - x_{0,4}),\ \kappa \sin(2\theta) = -x_{1,3} - x_{3,1}.$$

*parametrized curvature*

# TTT@ saddle?

the Gaussain joint PDF of the derivatives of the field, $\mathbf{X} = \{x_{ij}, x_{ijk}, x_{ijkl}\}$ and $\mathbf{Y} = \{y_{ij}, y_{ijk}, y_{ijkl}\}$ in two given locations ($\mathbf{r}_x$ and $\mathbf{r}_y$ separated by a distance $r = |\mathbf{r}_x - \mathbf{r}_y|$) obeys

$$\mathrm{PDF}(\mathbf{X},$$

$$\exp\left(-\frac{1}{2}\begin{bmatrix}\mathbf{X}\\ \mathbf{Y}\end{bmatrix}^{\mathrm{T}} \cdot$$

3D

$$x_{0,0,2} + x_{0,2,0} + x_{2,0,0} = \nu\,,\;\; x_{1,0,2} + x_{1,2,0} + x_{3,0,0} = 0,$$
$$x_{0,1,2} + x_{0,3,0} + x_{2,1,0} = 0,\;\; x_{0,0,3} + x_{0,2,1} + x_{2,0,1} = 0,$$
$$\kappa_{1,1} = \frac{1}{3}\left(x_{2,0,2} - x_{0,0,4} - 2x_{0,2,2} - x_{0,4,0} + x_{2,2,0} + 2x_{4,0,0}\right),$$
$$\kappa_{1,2} = x_{1,1,2} + x_{1,3,0} + x_{3,1,0},\;\; \kappa_{1,3} = x_{1,0,3} + x_{1,2,1} + x_{3,0,1},$$
$$\kappa_{2,2} = \frac{1}{3}\left(x_{0,2,2} - x_{0,0,4} + 2x_{0,4,0} - 2x_{2,0,2} + x_{2,2,0} - x_{4,0,0}\right),$$
$$\kappa_{2,3} = x_{0,1,3} + x_{0,3,1} + x_{2,1,1}\,. \tag{B4}$$

subject to the "saddle" constraints (2D)

*height*

$$x_{0,2} + x_{2,0} = \nu,\;\; x_{1,2} + x_{3,0} = 0,\;\; x_{0,3} + x_{2,1} = 0,$$

*zero gradient*

$$\kappa\cos(2\theta) = \frac{1}{2}\left(x_{4,0} - x_{0,4}\right),\;\; \kappa\sin(2\theta) = -x_{1,3} - x_{3,1}\,.$$

*parametrized curvature*

Define the spin at point $\mathbf{r}_y$ along the $z$ direction as the anti-symmetric contraction of the de-traced tidal field and hessian:

(2D)

$$L(\mathbf{r}_y) = \varepsilon_{ij}\overline{y}_{il}\overline{y}_{jmml} = (y_{2,0} - y_{0,2})(y_{1,3} + y_{3,1}) + \frac{y_{1,1}}{2}(y_{0,4} - y_{4,0}) - \frac{y_{1,1}}{2}(y_{4,0} - y_{0,4}) . \qquad (A3)$$

It is then fairly straightforward to compute the corresponding constrained expectation, $\langle L|\text{pk}\rangle$, for $L$ as

$$L_z(r,\theta,\kappa,\nu) = \int L(\mathbf{Y})\text{PDF}(\mathbf{X},\mathbf{Y}|\text{pk})\text{d}\mathbf{X}\text{d}\mathbf{Y} . \qquad (A4)$$

e.g. for n=-2 Incredibly simple prediction !

$$L_z = \kappa\frac{r^4\sin(2\theta)}{144}e^{-\frac{r^2}{2}}\left(\sqrt{6}\kappa\left(r^2-4\right)\cos(2\theta)+6\nu\right) .$$

asymmetry

# 2D Theory of Tidal Torque @ saddle?

$L_z \propto r^4 \sin 2\theta$ at small radius

$L_z \propto \sin 2\theta \exp(-r^2)$ at large radius

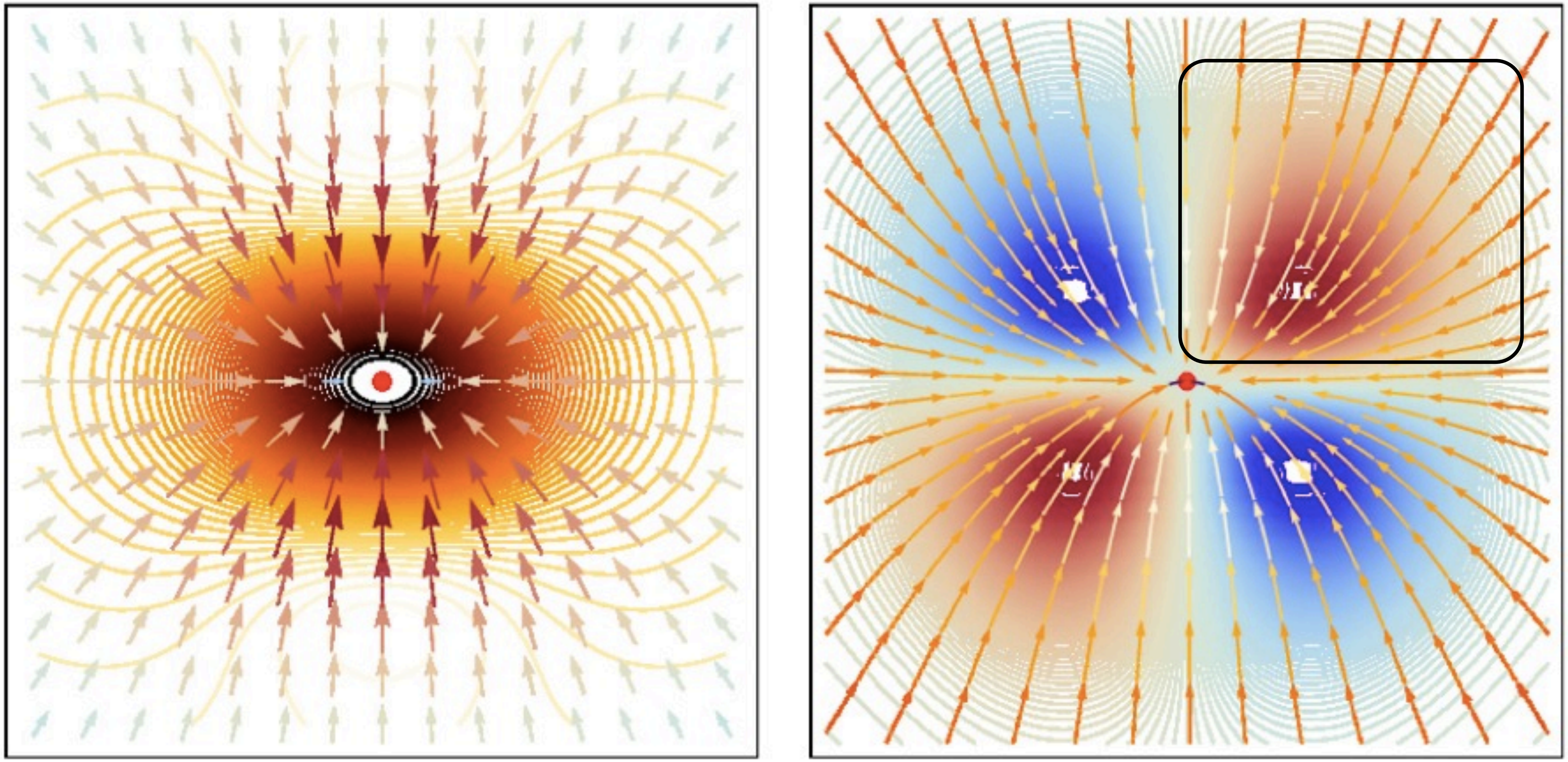


**Figure 4.** left: cross section of 2D Lagrangian patch near a saddle point; right: corresponding momentum (colour coded) and transverse velocity flow.

# Link with Eulerian vorticity?

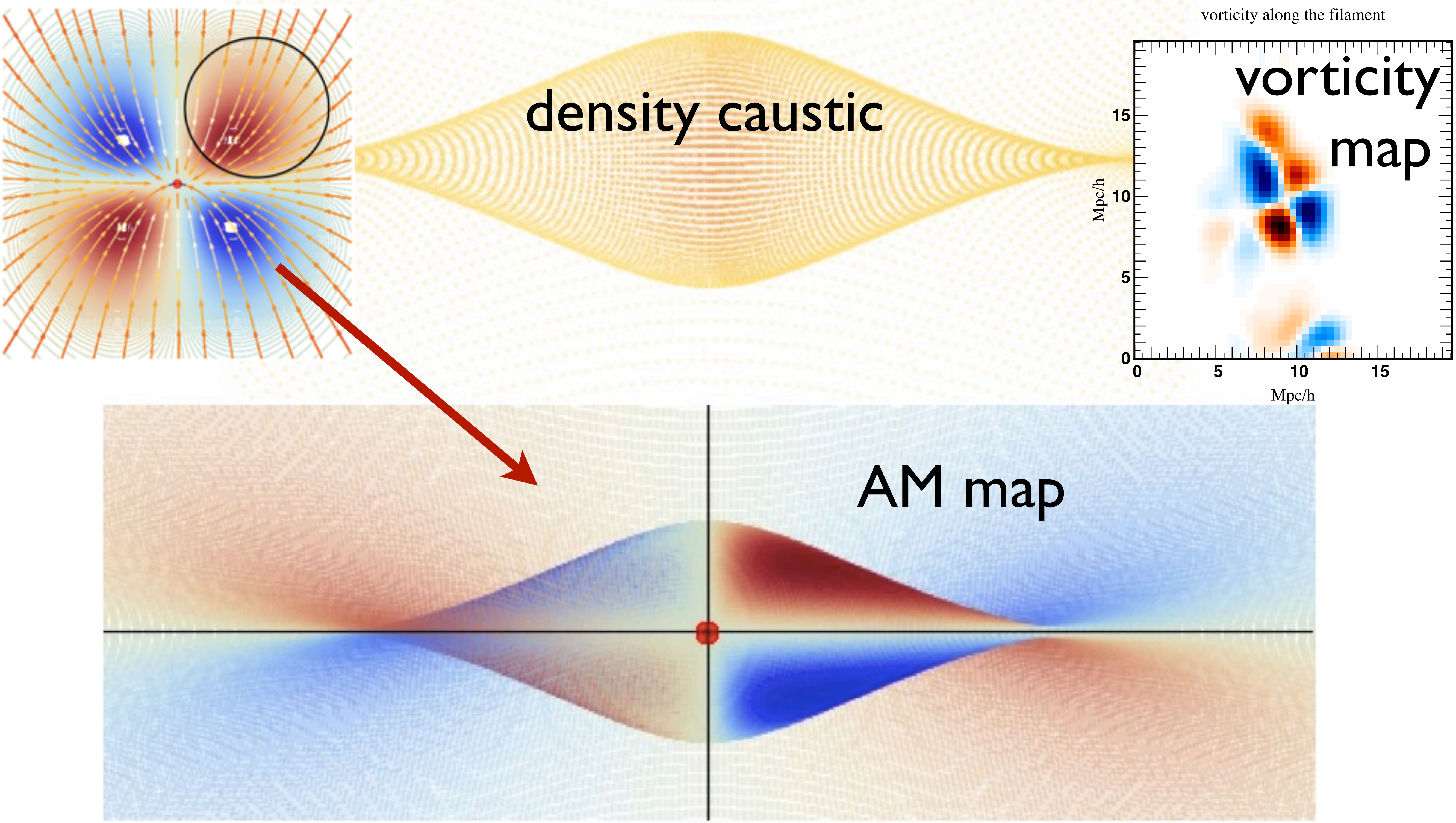
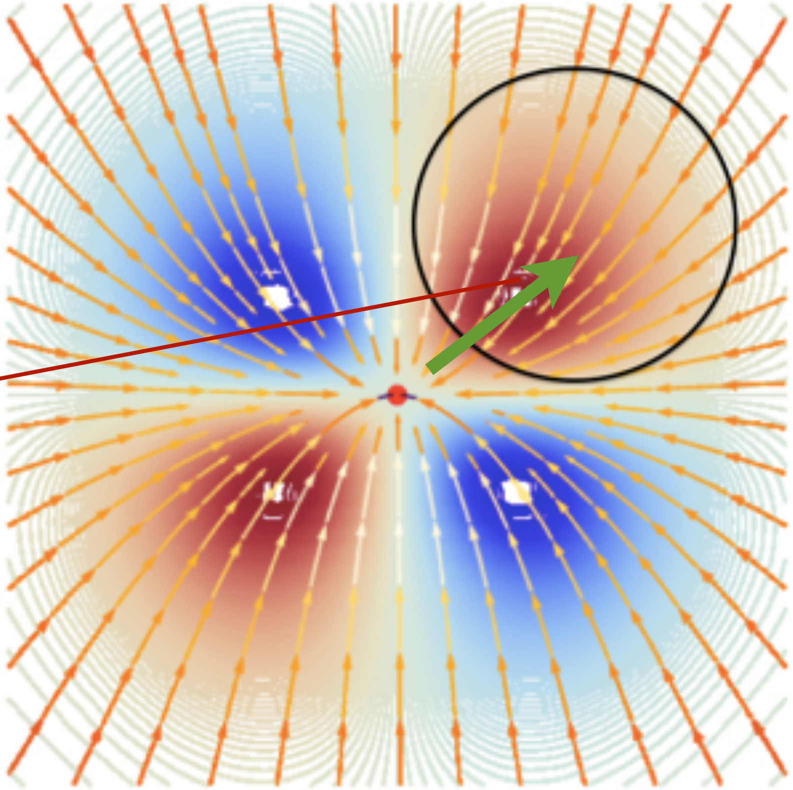



**Figure 5.** top: Density caustic; Bottom: Zeldovitch mapping of the spin distribution

# Explain transition mass?

$$\mathcal{M}_{\rm tr}(L_s) = \Sigma_0 \int d\nu\, d\kappa \mathcal{A}(\nu,\kappa)\mathcal{P}(\nu,\kappa|{\rm pk})\,,$$



radius @ maxima

where the area of a quadrant is

$$\mathcal{A} = \frac{1}{4}\pi\frac{\lambda_2}{\lambda_1}(2r_\star)^2\,,$$

aspect ratio

2D

The pdf of the shape is

$$P(\nu,\kappa) = \frac{\kappa}{\sqrt{2\pi}} e^{-4\kappa^2-\frac{1}{2}\nu^2}\mathrm{erfc}\left(\frac{2\kappa-\gamma\nu}{\sqrt{2-2\gamma^2}}\right)\,.$$

height asymmetry shape parameter

so the scaling of the transition mass

$$\mathcal{M}_{\rm tr}(z) = \Delta N\frac{\lambda_{2,\star}}{\lambda_{1,\star}}\left(\frac{r_\star}{L_s}\right)^2 M_s(z) \equiv \alpha M_s\,,$$

where $\Delta N = \mathcal{P}(\nu_\star,\kappa_\star|{\rm pk})\Delta\nu\Delta\kappa$, and $M_s(z) \equiv \pi L_s^2(z)\Sigma_0$.

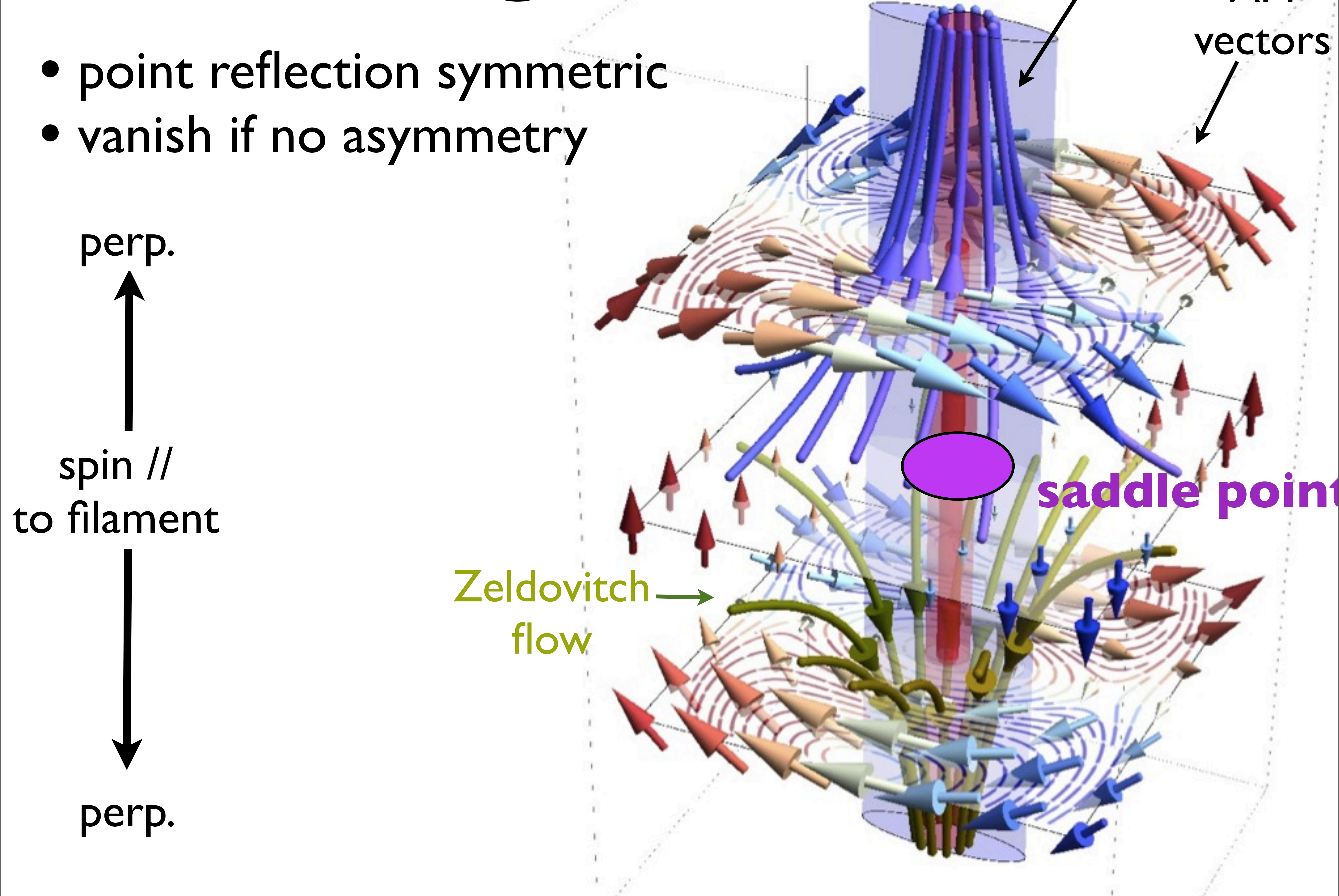
power index

$$\alpha(n) = \frac{n+5}{27} + \frac{1}{11}\,.$$

$$\boxed{\alpha(-5) \sim 1/11.}$$

# 3D TTT@ saddle?

- point reflection symmetric
- vanish if no asymmetry



# 3D TTT@ saddle?

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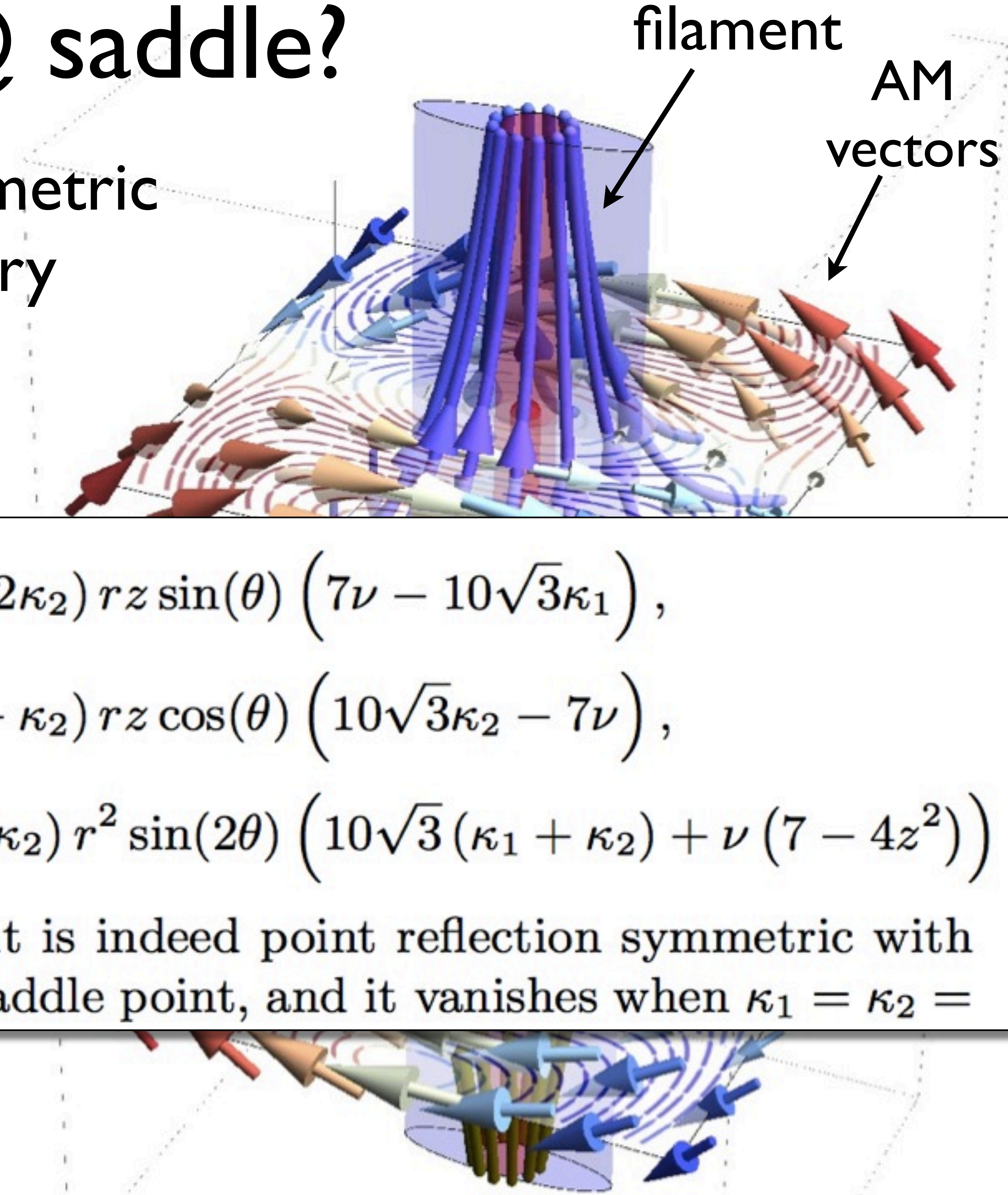



perp.

↑

spin //
to filament

↓

perp.

$$L_x = \frac{1}{210}(\kappa_1 + 2\kappa_2)\, r z \sin(\theta)\left(7\nu - 10\sqrt{3}\kappa_1\right),$$

$$L_y = \frac{1}{210}(2\kappa_1 + \kappa_2)\, r z \cos(\theta)\left(10\sqrt{3}\kappa_2 - 7\nu\right),$$

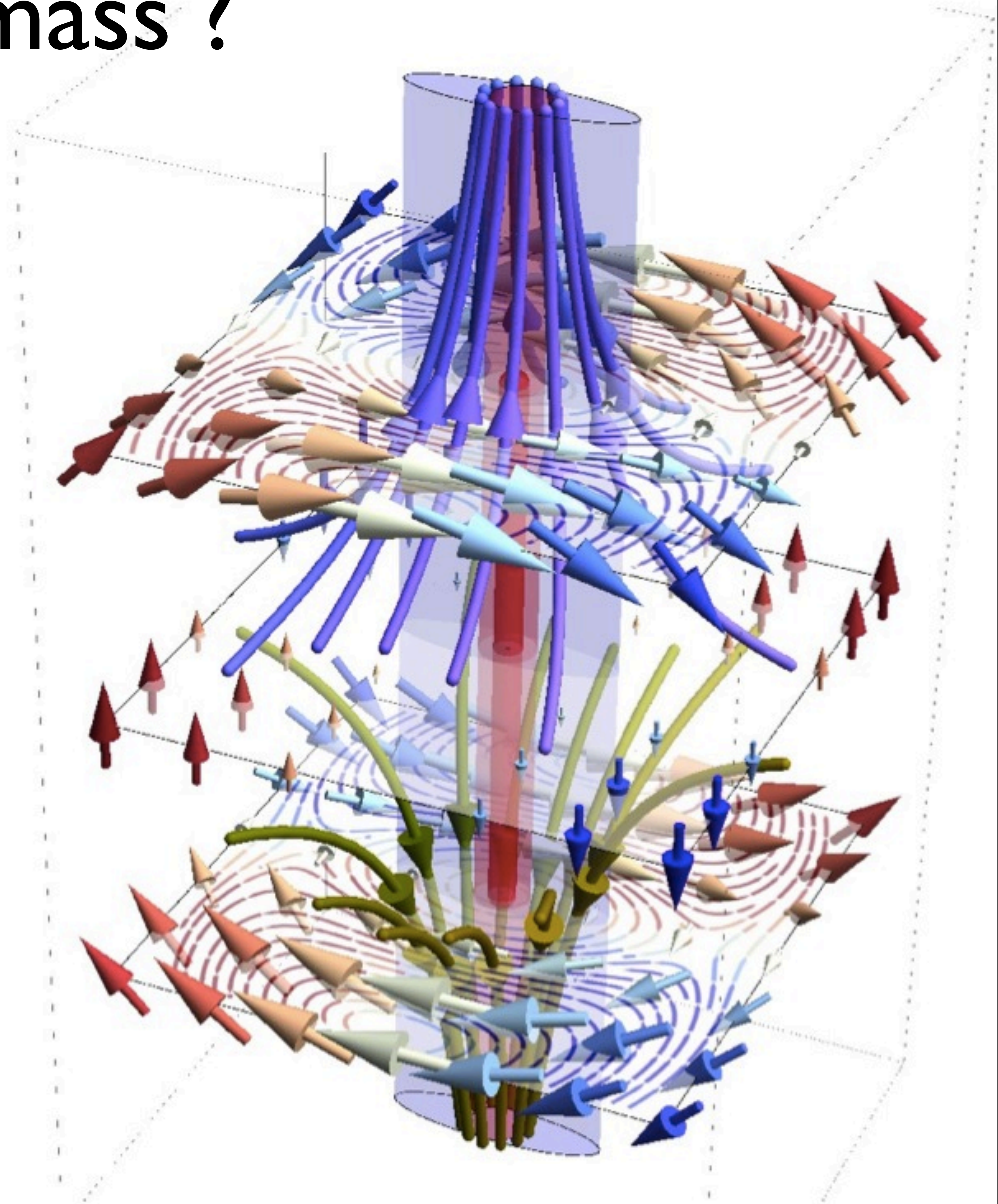
$$L_z = \frac{1}{420}(\kappa_1 - \kappa_2)\, r^2 \sin(2\theta)\left(10\sqrt{3}(\kappa_1 + \kappa_2) + \nu\left(7 - 4z^2\right)\right)$$

We check that it is indeed point reflection symmetric with respect to the saddle point, and it vanishes when $\kappa_1 = \kappa_2 =$

# 3D Transition mass ?

Lagrangian theory
capture spin flip !

Transition mass
associated
with **size**
of quadrant



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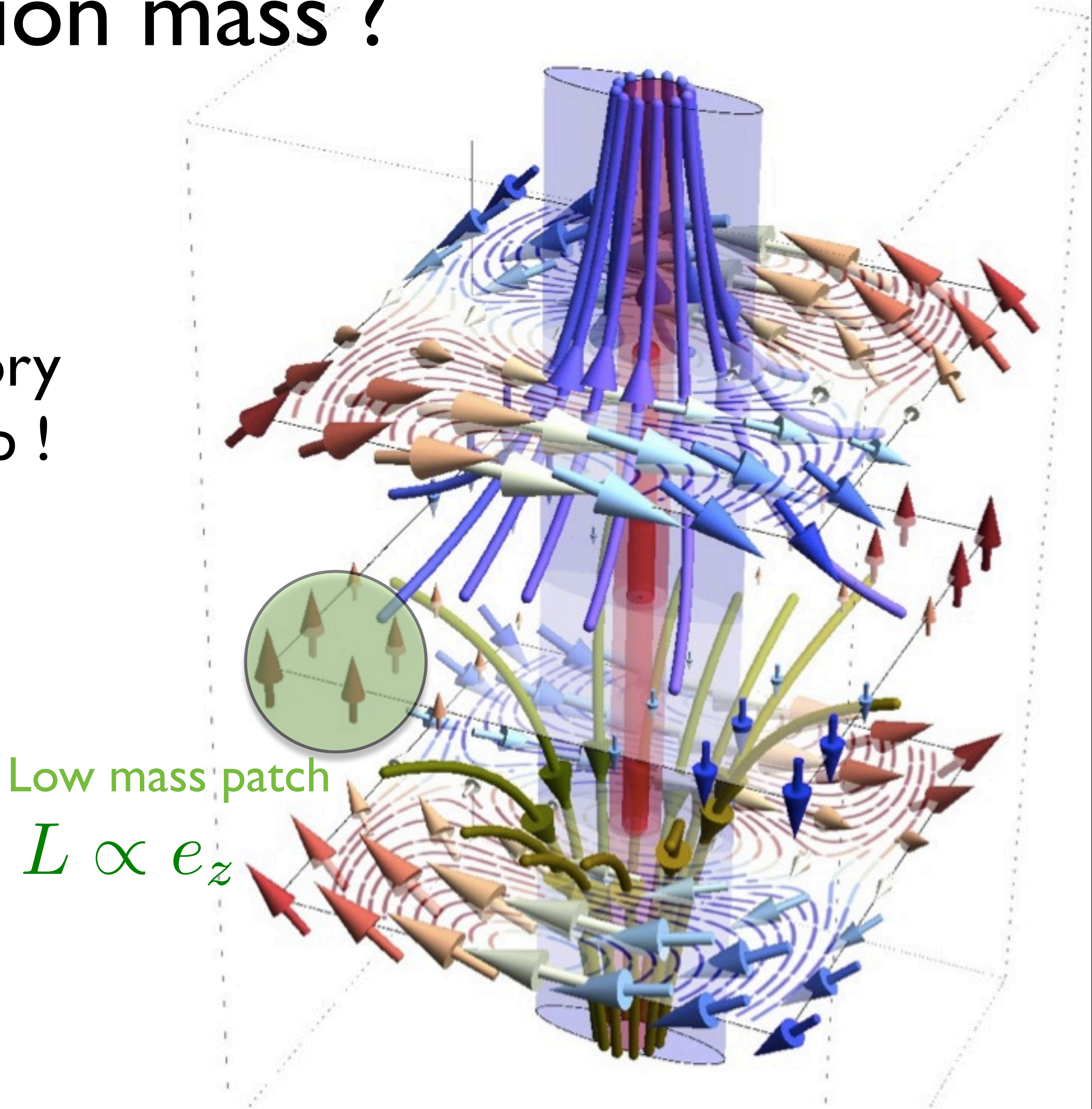

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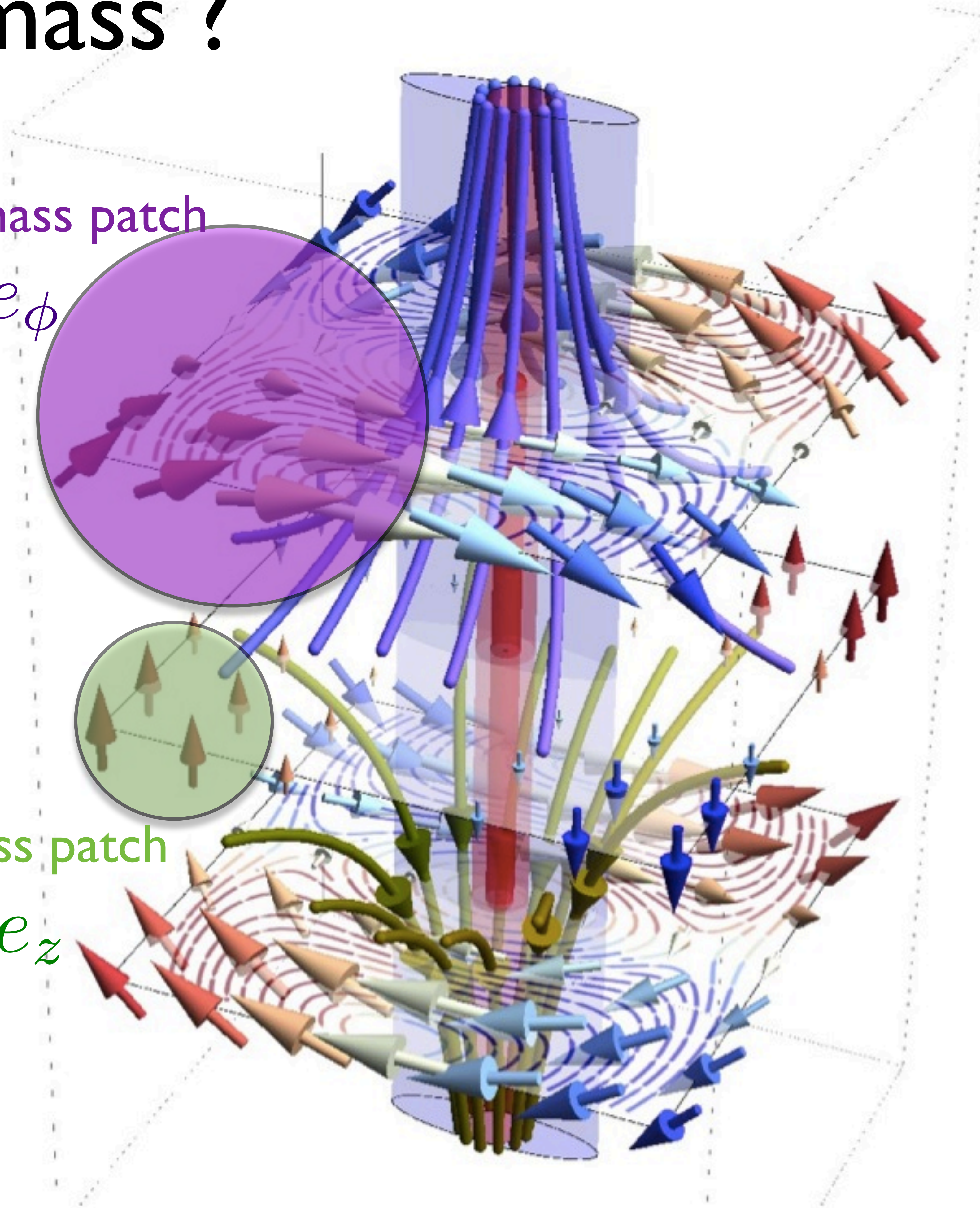


Geometry of the saddle provides **a natural 'metric'** (local frame as defined by Hessian @ saddle) relative to which **dynamical evolution** of DH is predicted.

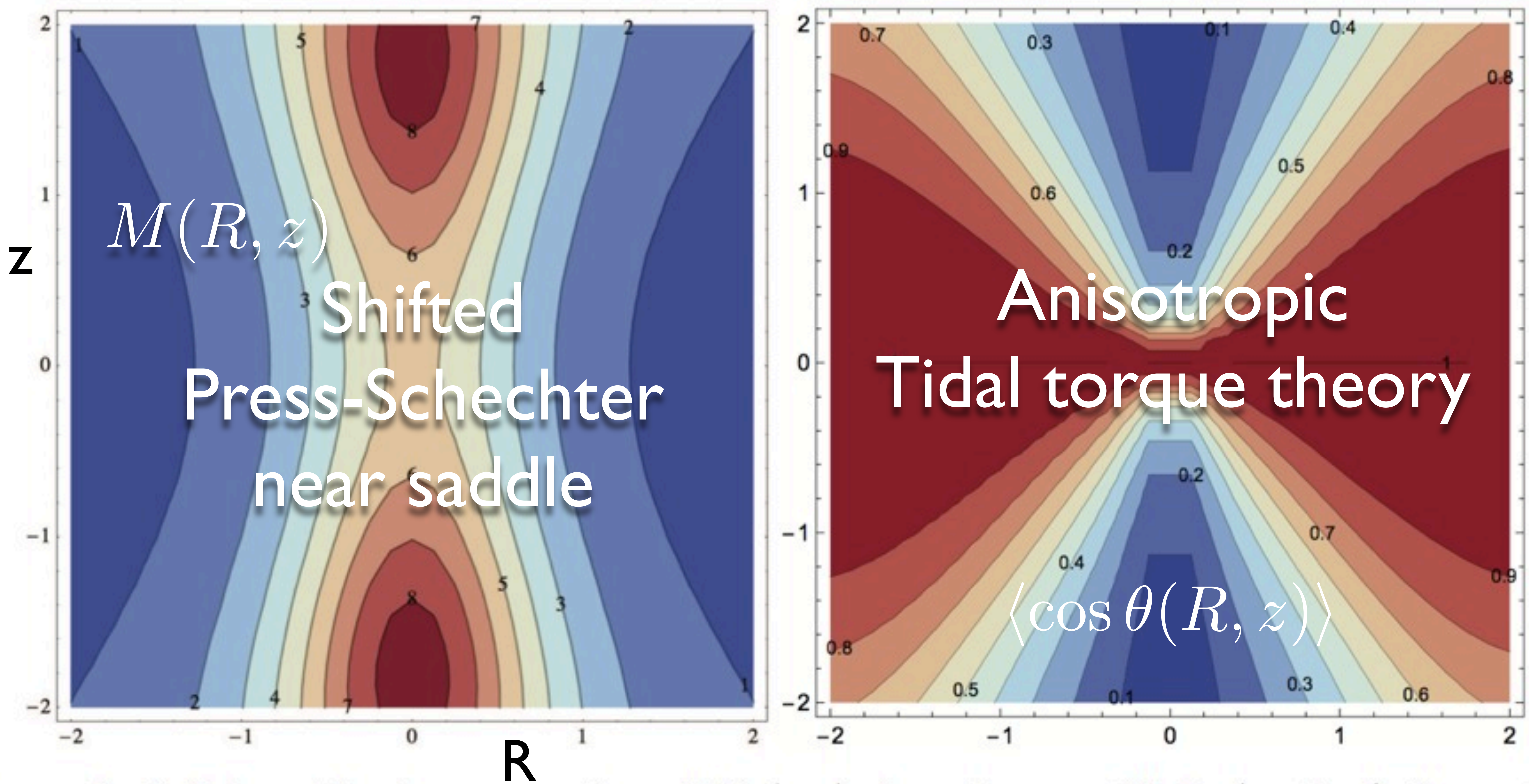



**Figure 5.** *Left:* logarithmic cross section of $M_p(r, z)$ along the most likely (vertical) filament (in units of $10^{12} M_\odot$). *Right:* corresponding cross section of $\langle \cos\hat{\theta} \rangle(r, z)$. The mass of halos increases towards the nodes, while the spin flips.

Geometry of the saddle provides **a natural 'metric'** (local frame as defined by Hessian @ saddle) relative to which **dynamical evolution** of DH is predicted.

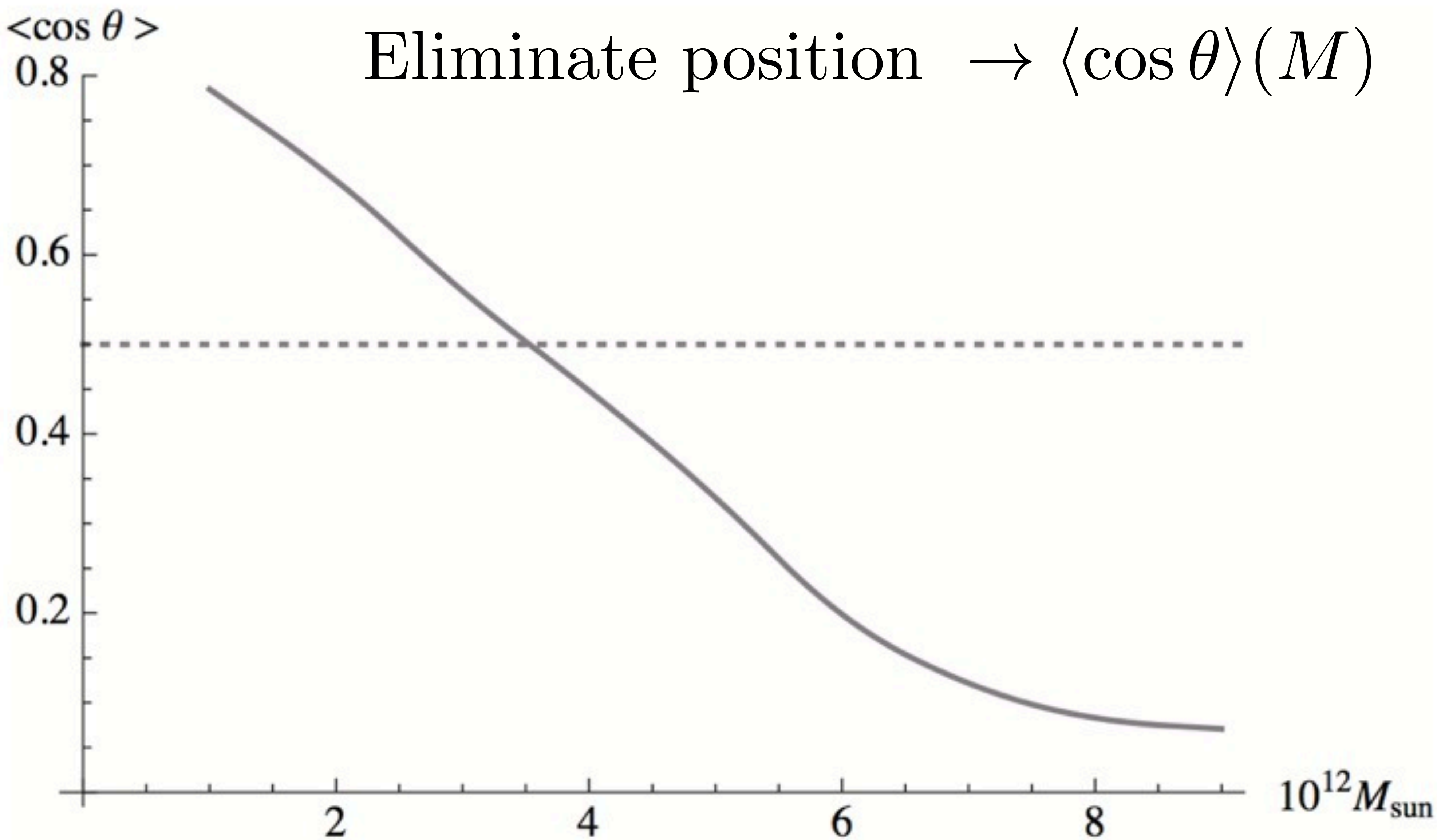
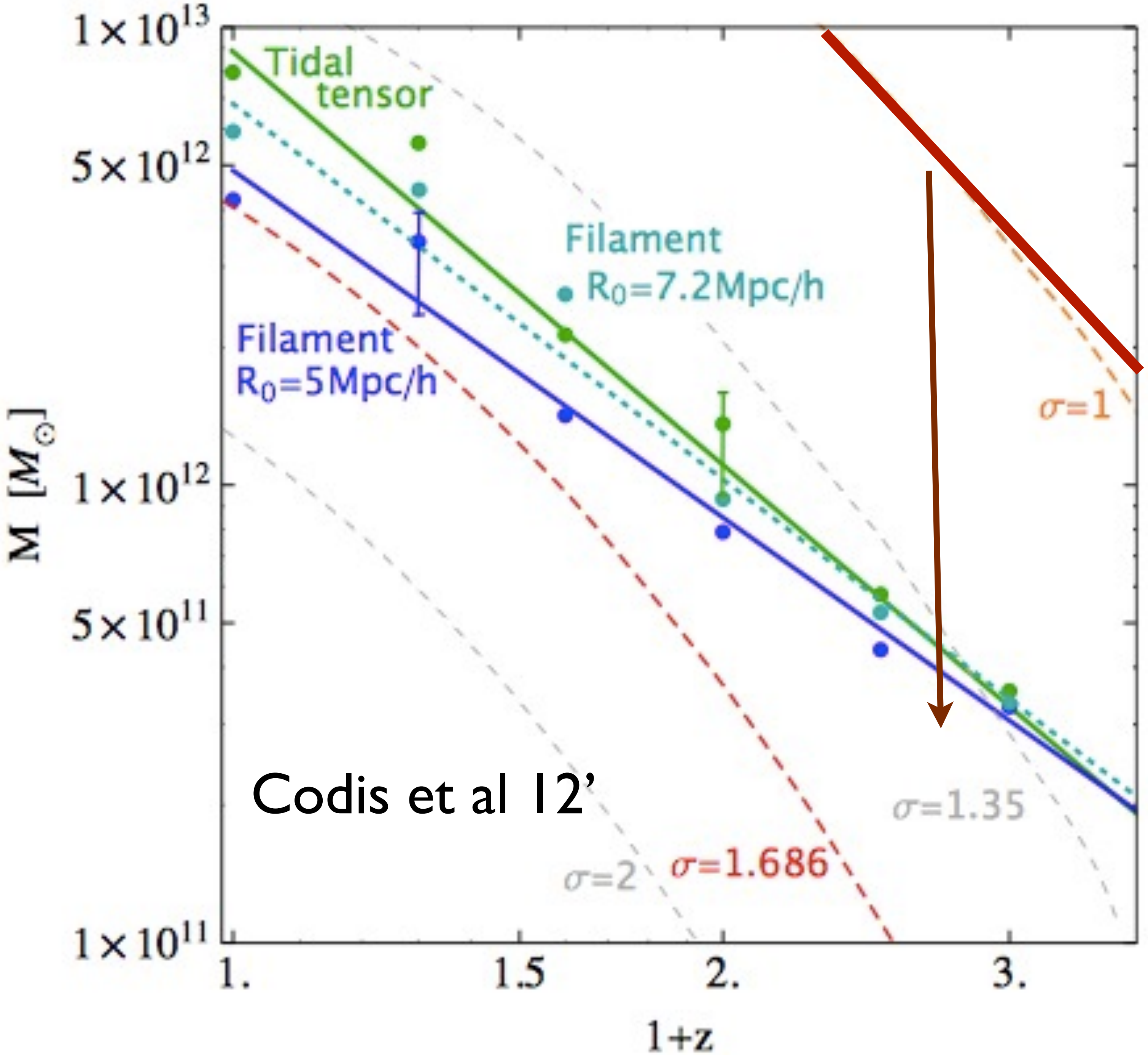



**Figure 6.** Mean alignment between spin and filament as a function of mass for a filament smoothing scale of 5 Mpc/$h$. The spin flip transition mass is around $4\,10^{12}\,M_{\odot}$.

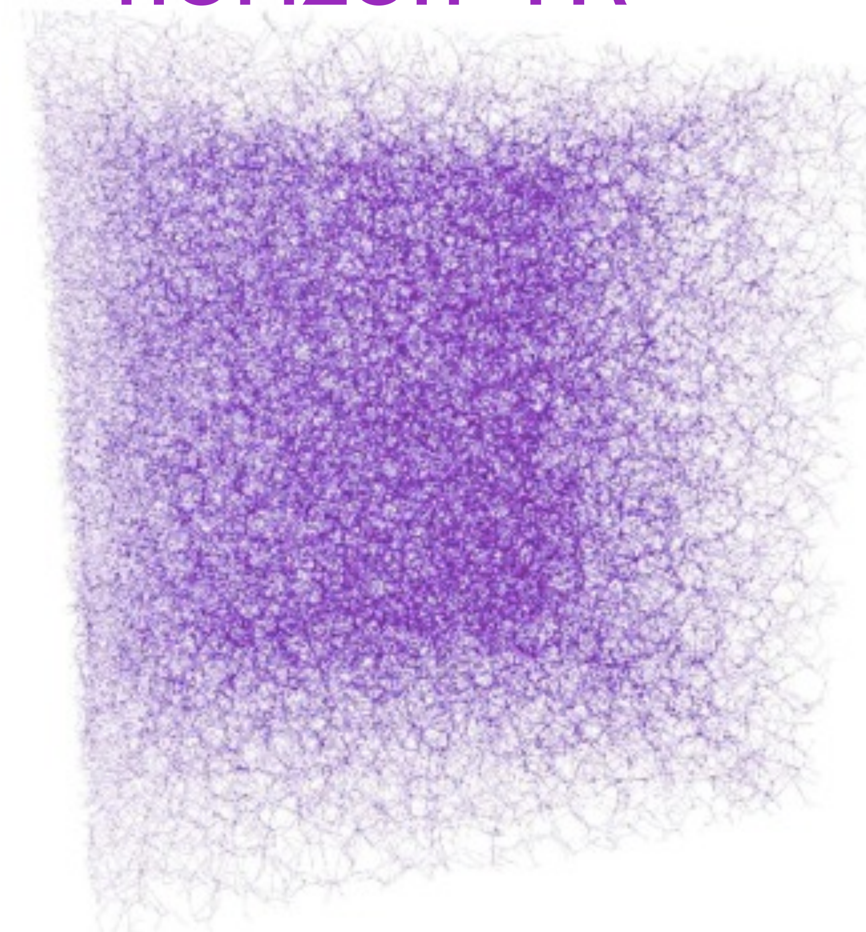
towards the nodes, while the spin flips.

# Explain transition mass?

Transition mass versus redshift




horizon 4π

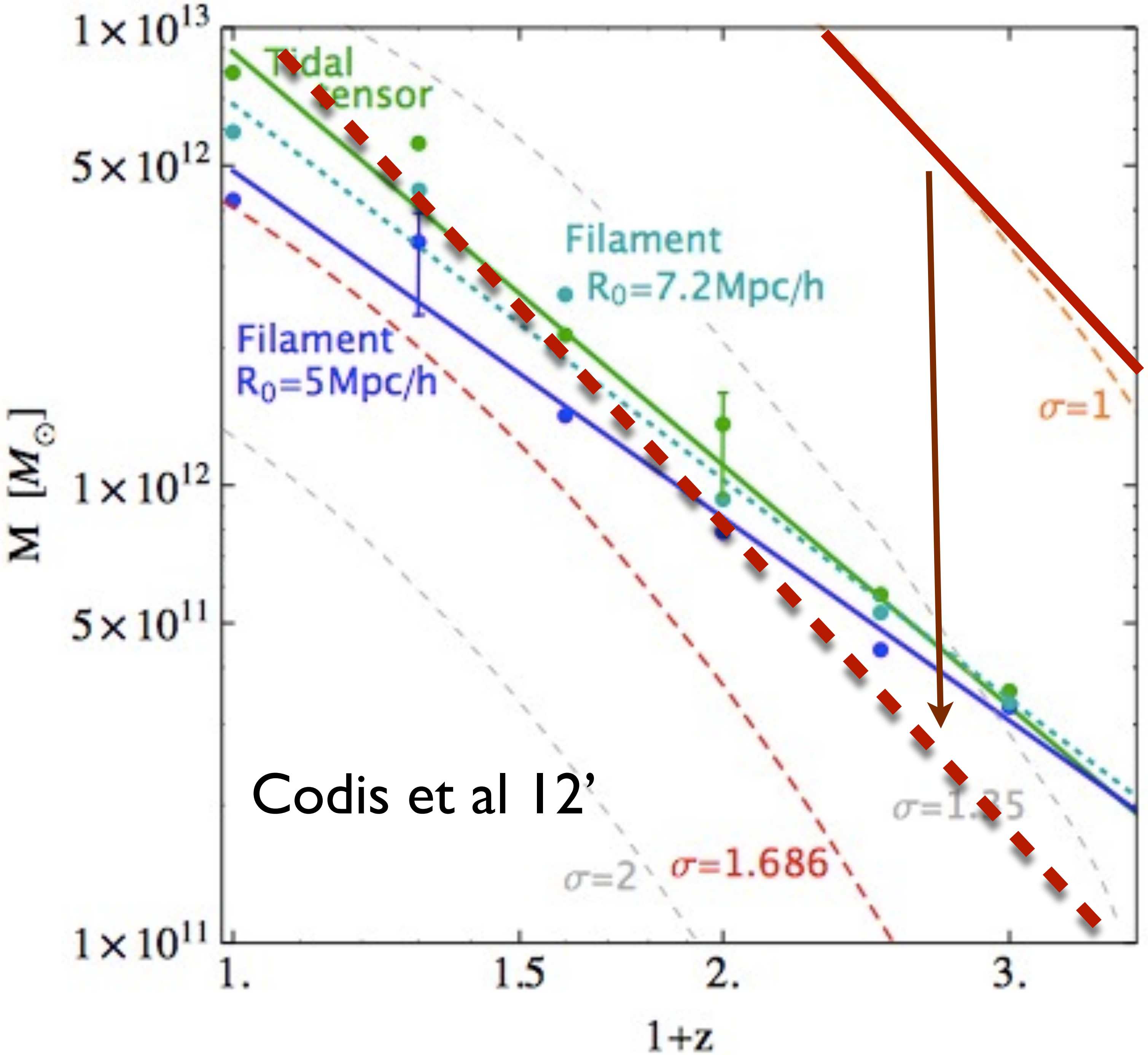


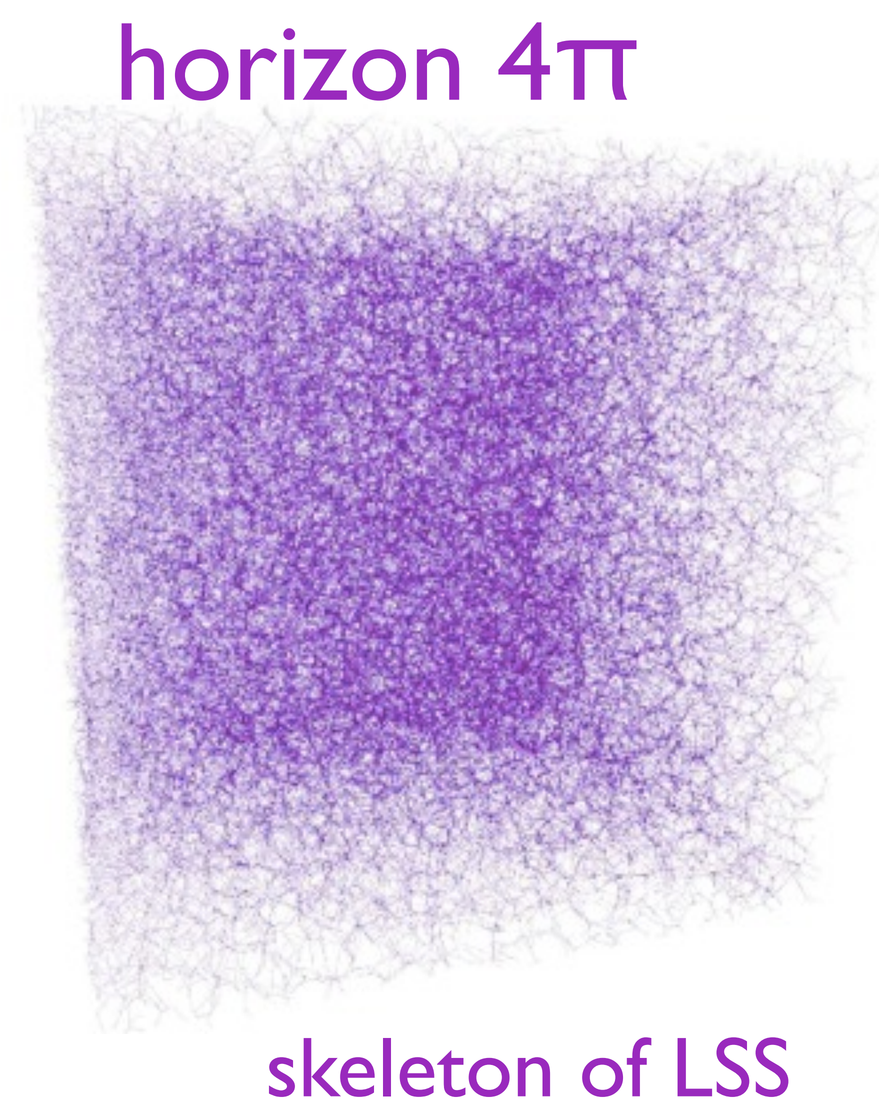
skeleton of LSS

*Only 2 ingredients*: a) spin is spin one b) filaments flattened

# Explain transition mass?

Transition mass versus redshift

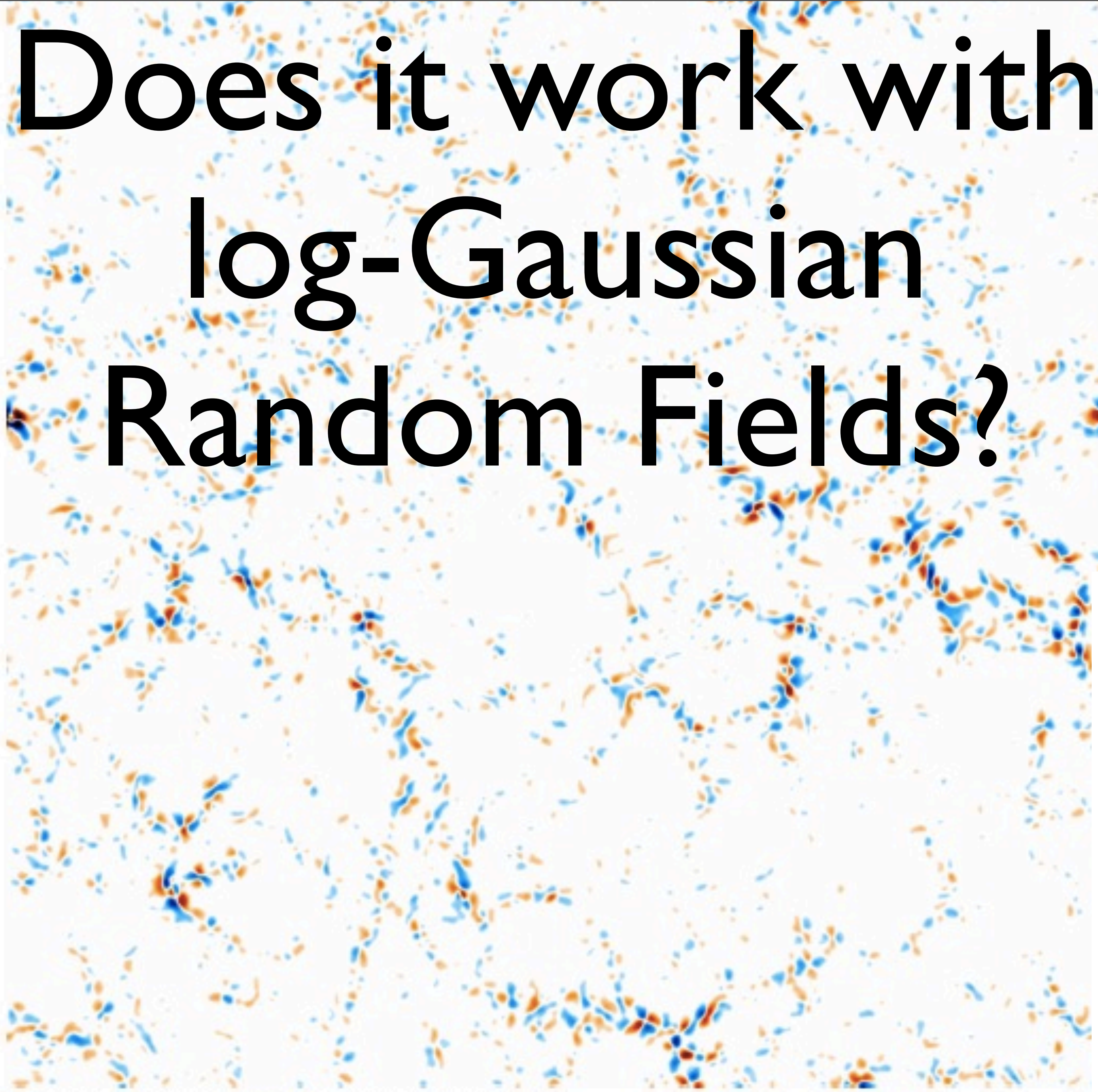


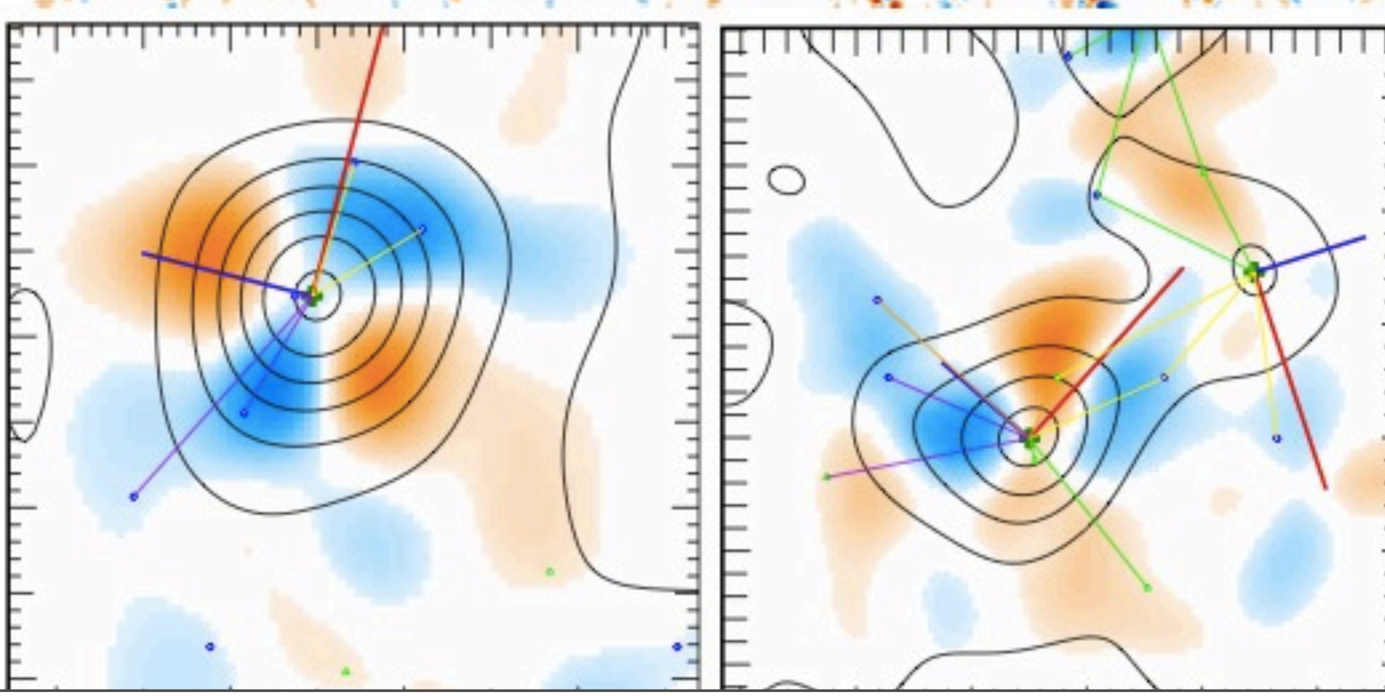




*Only 2 ingredients*: a) spin is spin one b) filaments flattened

# Does it work with log-Gaussian Random Fields?

# 2D





## point reflection symmetry for realistic sets of saddles from log GRF

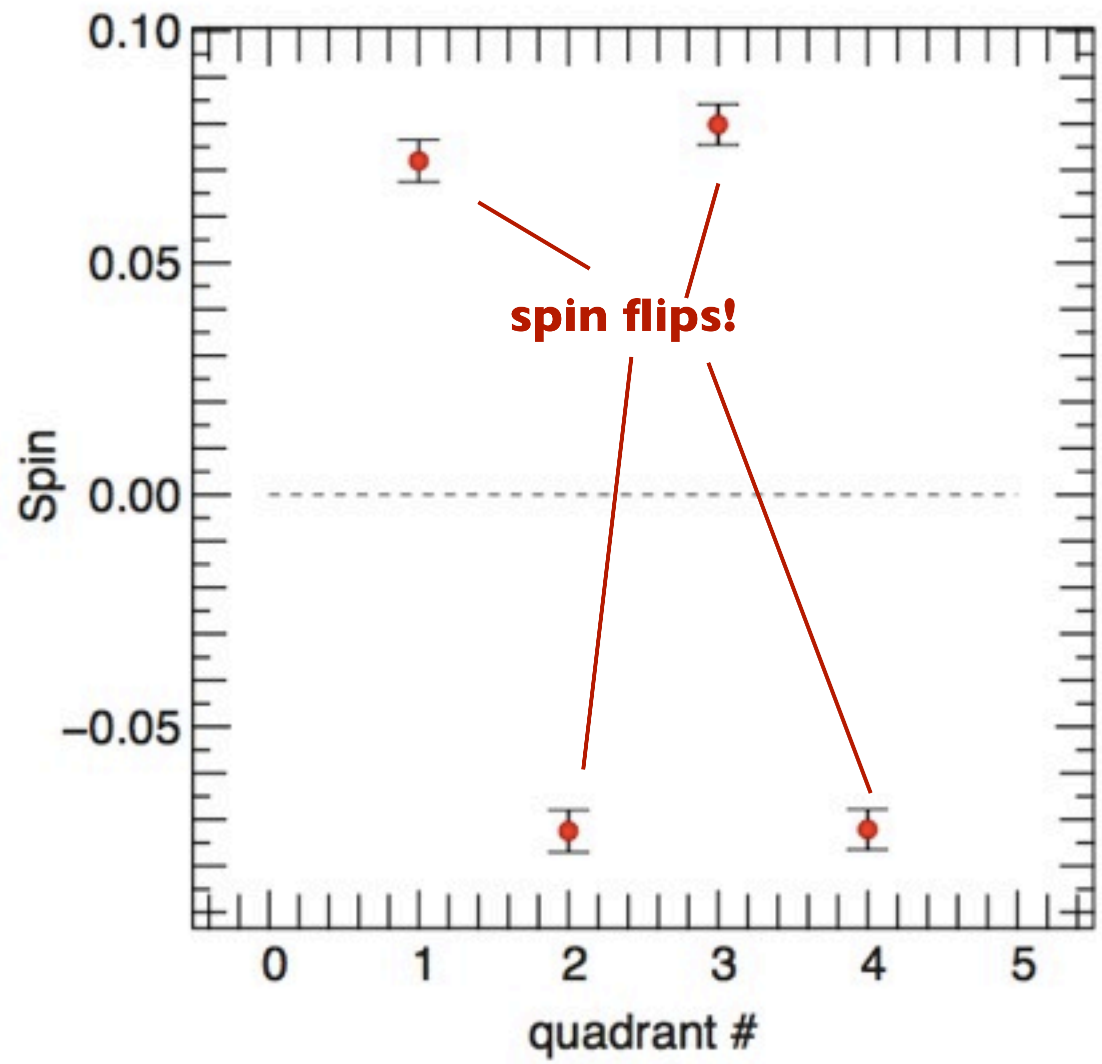


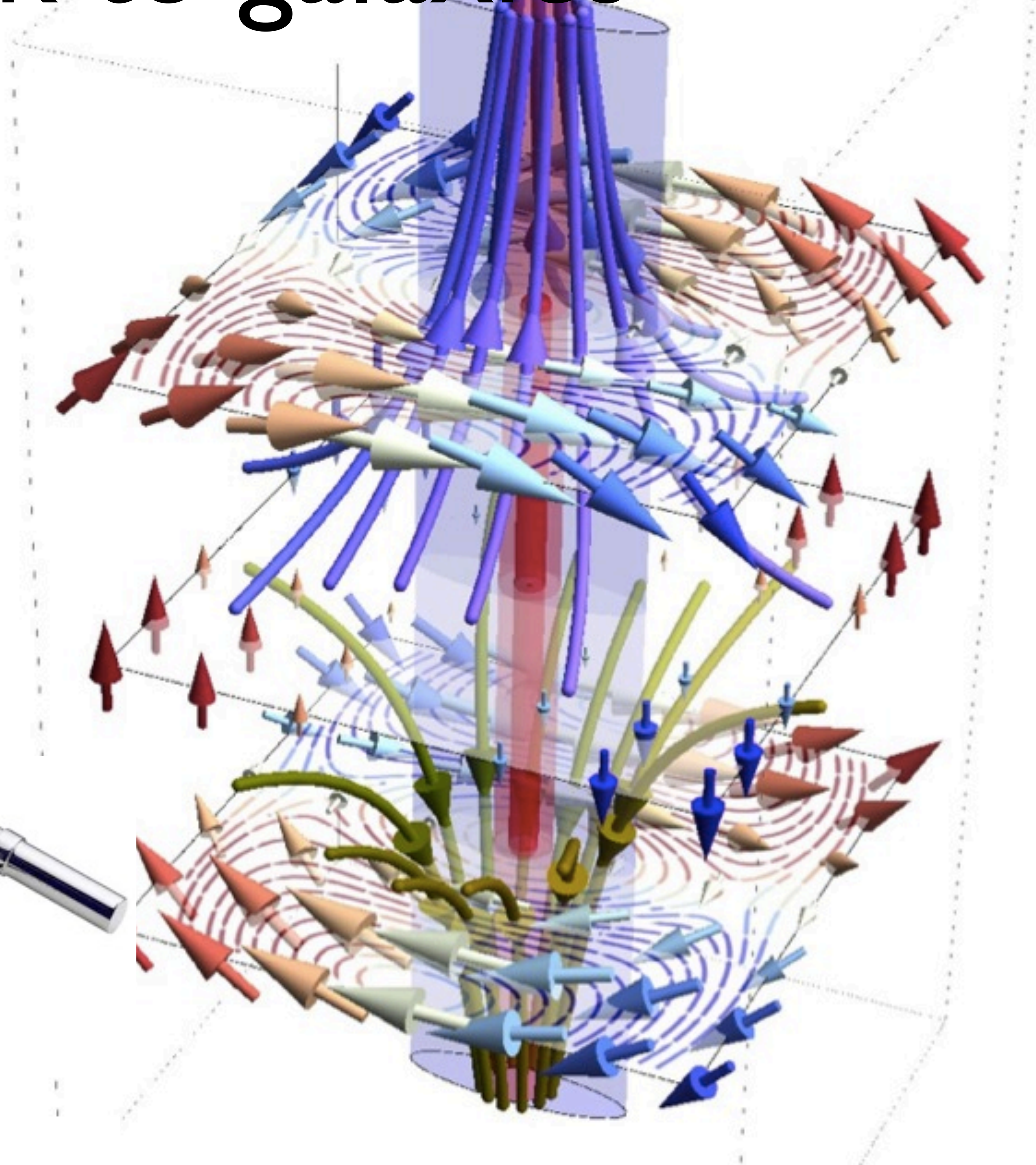

**Figure 11.** Alignment of 'spin' along $\mathbf{e}_z$ in 2D as a function of quadrant rank, clockwise. As expected, from one quadrant to the next, the spin is flipping sign.

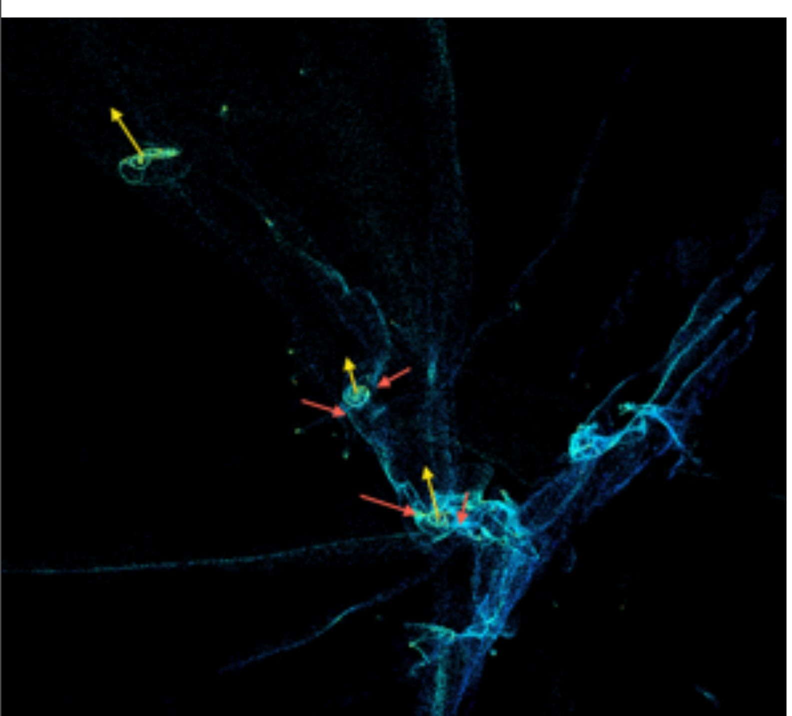
# Back to galaxies

Filaments
=
**metric** for spin build up of galaxies

AM built up via cold flows occurs near extrema of helicity (v.L) either side of saddles!

$$\varepsilon_{ijk}\,\delta_{li}\,\psi_{lj}\,\psi_k$$





define epoch of maximal AM accretion

# Back to galaxies

Filaments
=
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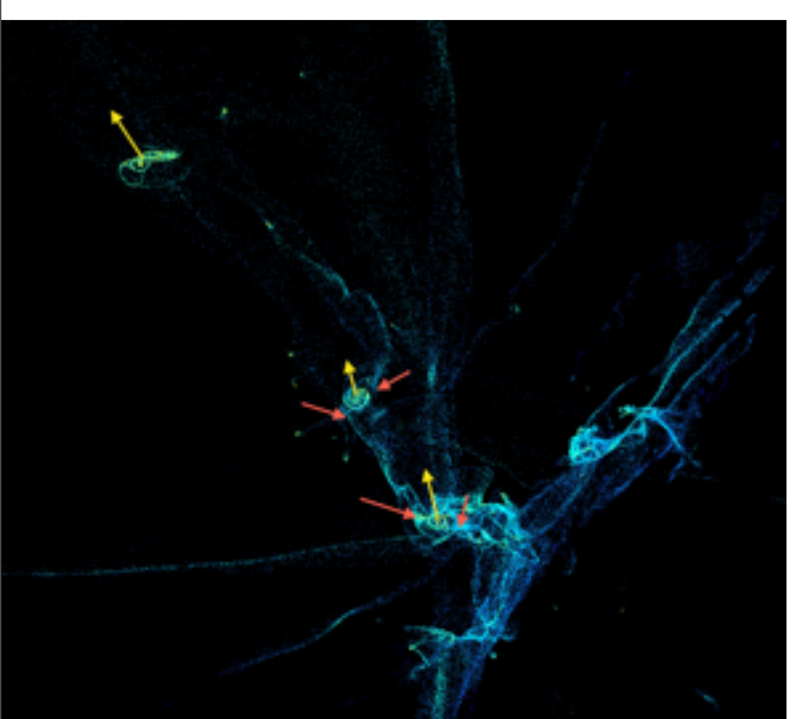
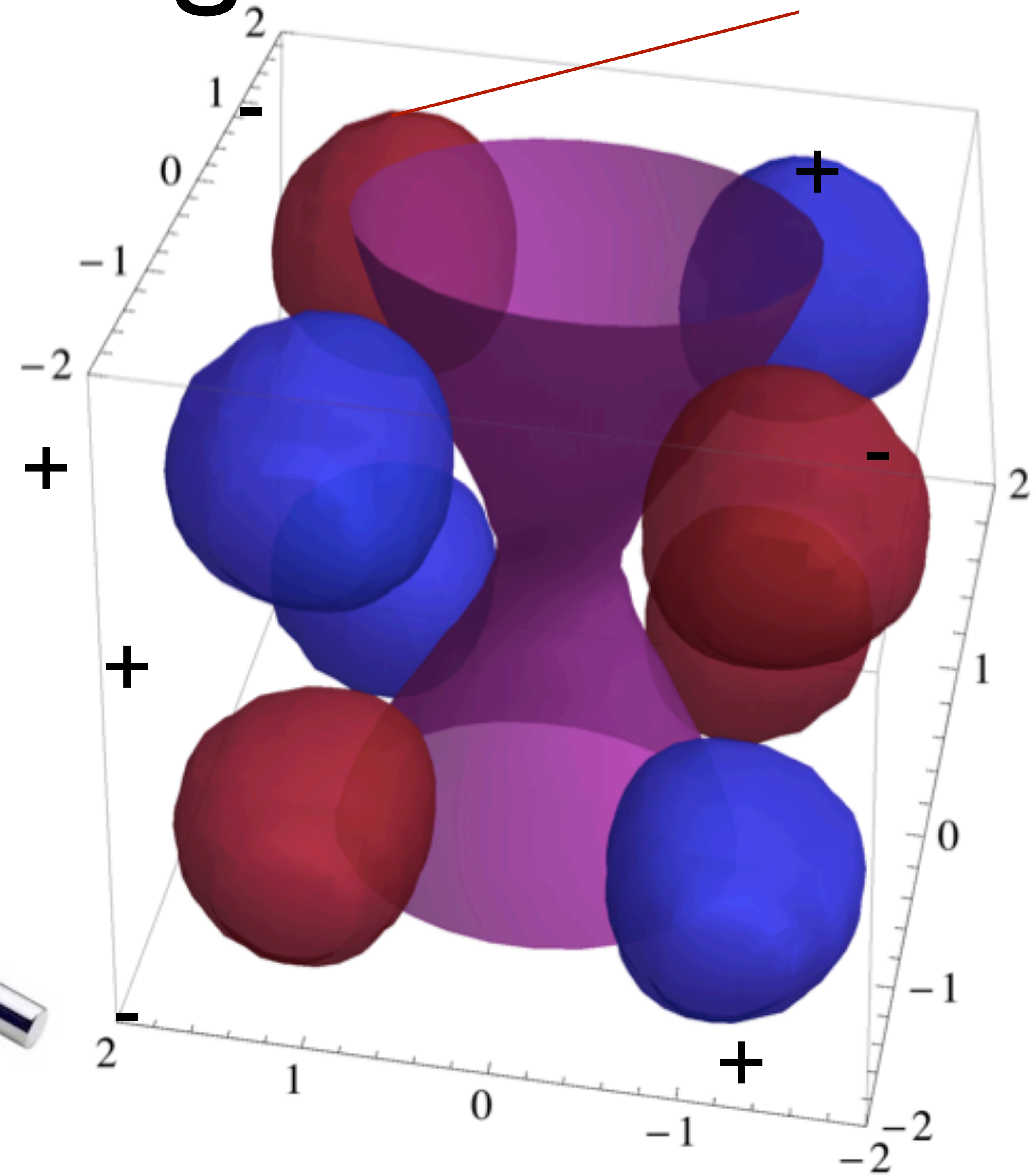
AM built up via cold flows occurs near extrema of helicity (v.L) either side of saddles!

$$\varepsilon_{ijk}\,\delta_{li}\,\psi_{lj}\,\psi_k$$



predicted Lagrangian extrema of 'helicity'




define epoch of maximal AM accretion

# Take home message...

- Morphology (= AM stratification) driven by LSS via *cold flows* in cosmic web: it explains Es & Sps where, how & why from **IC**s
- Signature in correlation between *morphology* and *internal* kinematic structure of cosmic web.
- Process driven by simple dynamics: $t_{\rm dyn} \sim 1/\sqrt{\rho}\,, \quad \text{shock}$

  - requires updating TTT to **saddles**: simple theory :-)

***Where galaxies form does matter, and can be traced back to ICs***
***Flattened filaments generate point-reflection-symmetric AM/vorticity distribution: they induce the observed spin transition mass & helicity of cold flows***

For more details: Pichon et al. 2011 Codis et al 2012, Tillson et al 2012, Laigle et al 2014 Dubois et al 2014 Welker et al 2014, Pichon et al. 2014

# What about galaxies ??

- Horizon-AGN simulation Jade (CINES)
  (PI Y. Dubois, Co-I J. Devriendt & C. Pichon)
  – $L_{box}$=100 Mpc/h
  – $1024^3$ DM particles $M_{DM,res}=8x10^7$ $M_{sun}$
  – Finest cell resolution dx=1 kpc
  – Gas cooling & UV background heating
  – Low efficiency star formation
  – Stellar winds + SNII + SNIa
  – O, Fe, C, N, Si, Mg, H
  – AGN feedback radio/quasar
- Outputs
  (backed up and analyzed on BEYOND)
  – Simulation outputs
  – Lightcones (1°x1°) performed on-the-fly
    - Dark Matter (position, velocity)
    - Gas (position, density, velocity, pressure, chemistry)
    - Stars (position, mass, velocity, age, chemistry)
    - Black holes (position, mass, velocity, accretion rate)
- z=1.5 using 3 Mhours on 4096 cores

PART IV

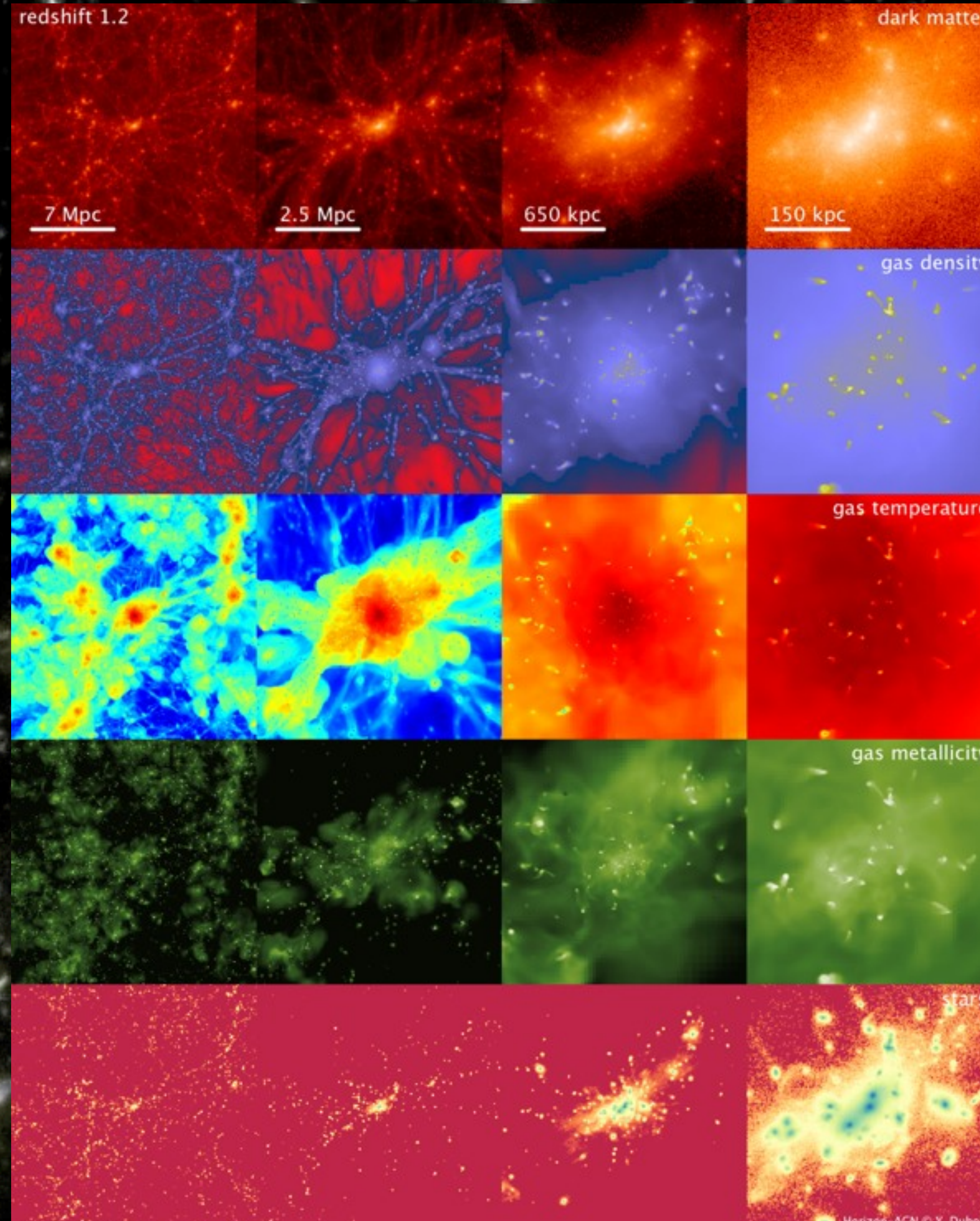
horizon-AGN.projet-horizon.fr

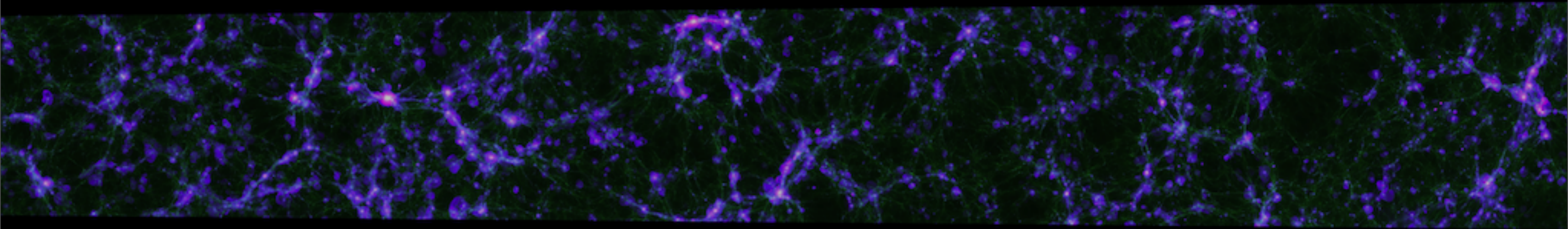
z=1.2

# Part V Outline

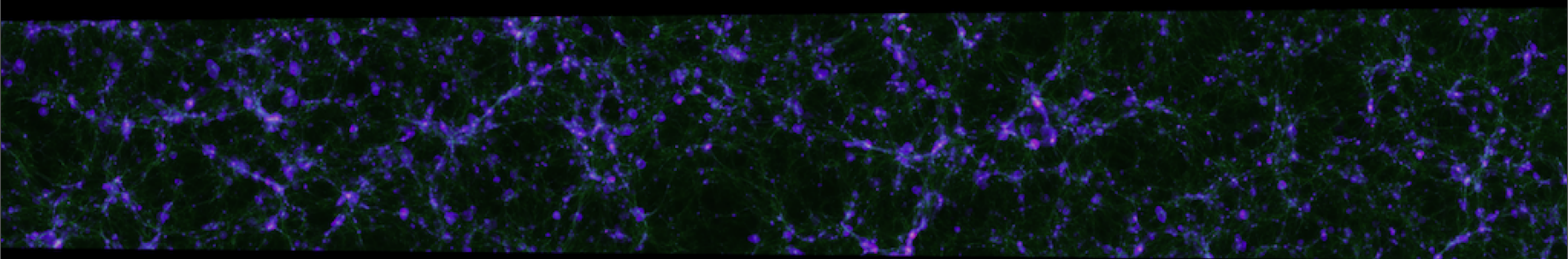
- Can morphology/physics trace spin flip?
- Are transition masses consistent?
- The fate of forming galaxies
- The fate of merging galaxies

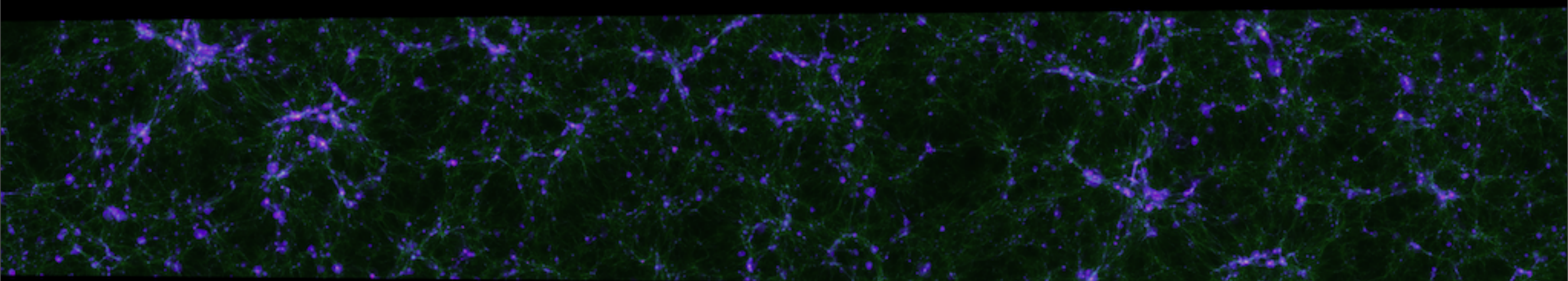
# physical fields



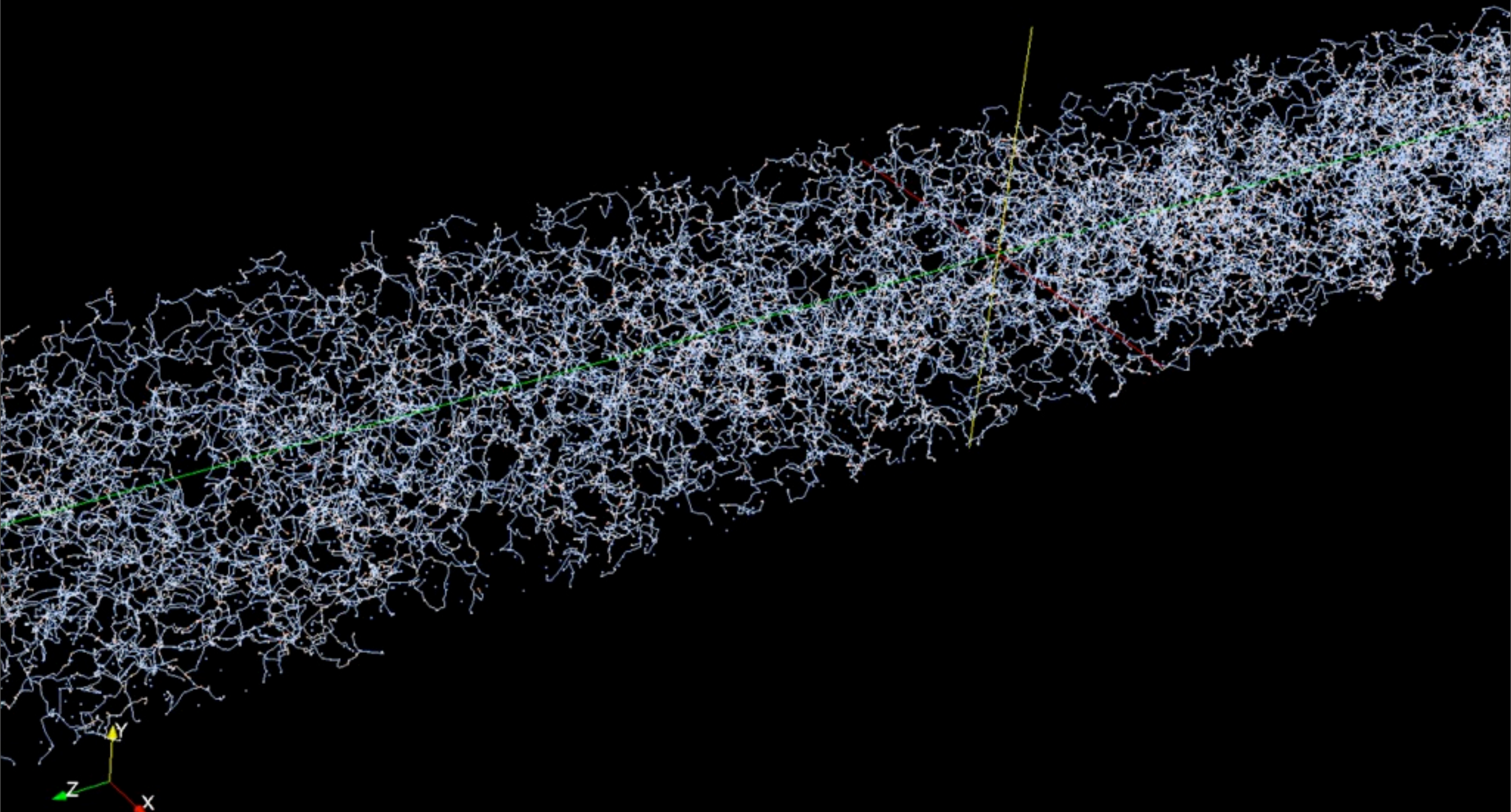


# Baryonic light cone

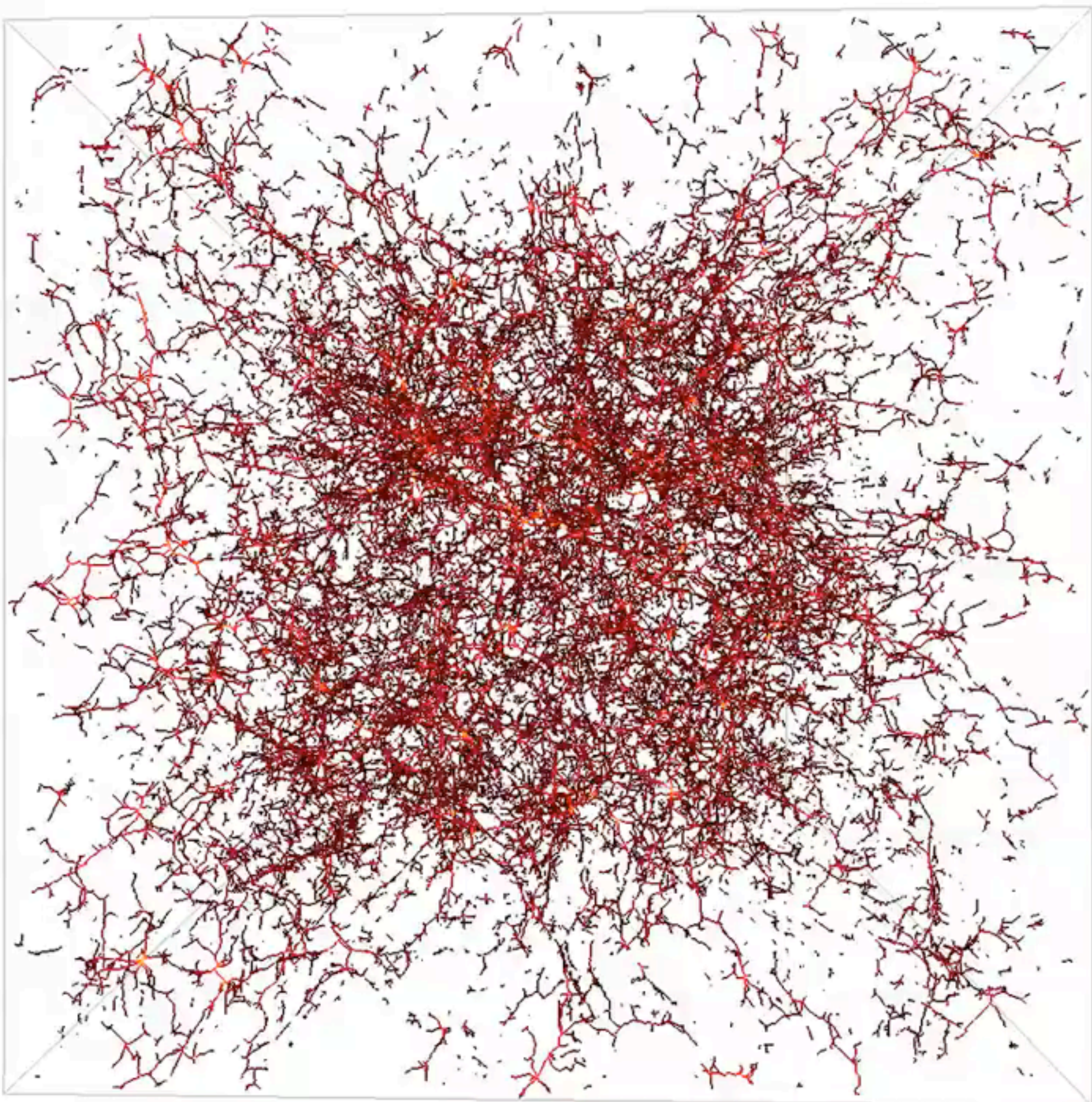




# Skeleton from BH catalogue

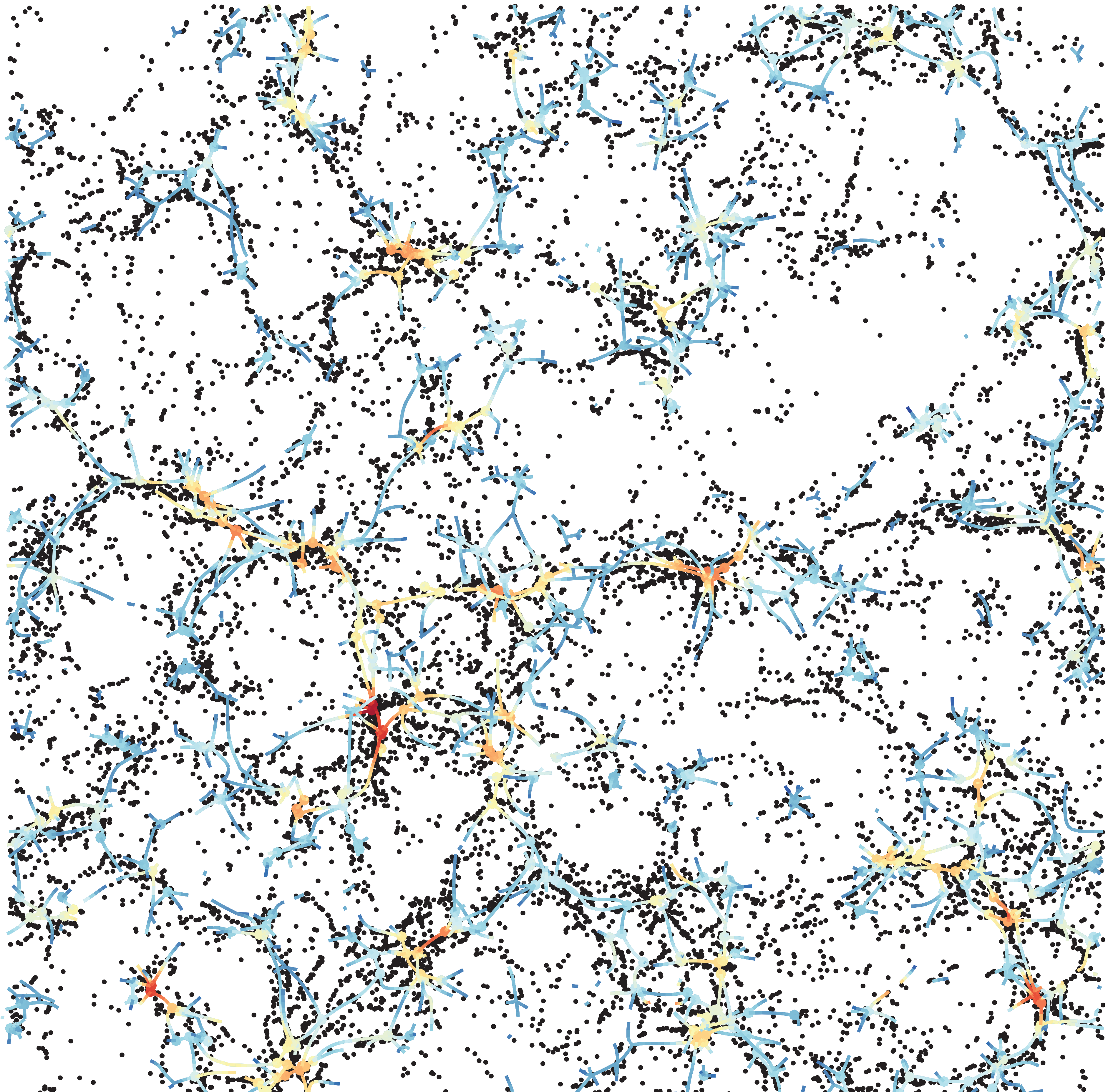


# Skeleton of box



results on spin alignment independent of code used (persistence/watershed)

# Galaxies versus dense filaments



Galaxies are strongly

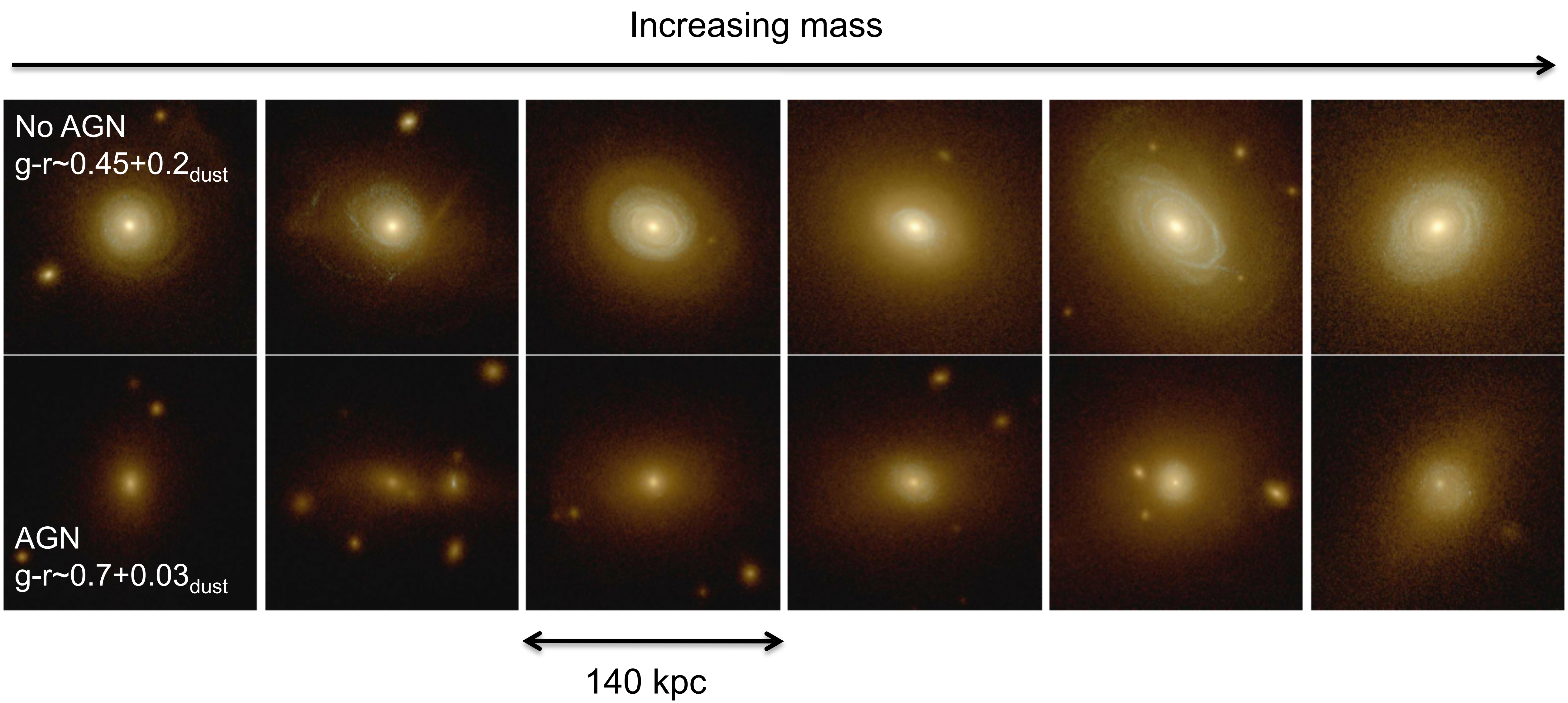
clustered

near filaments

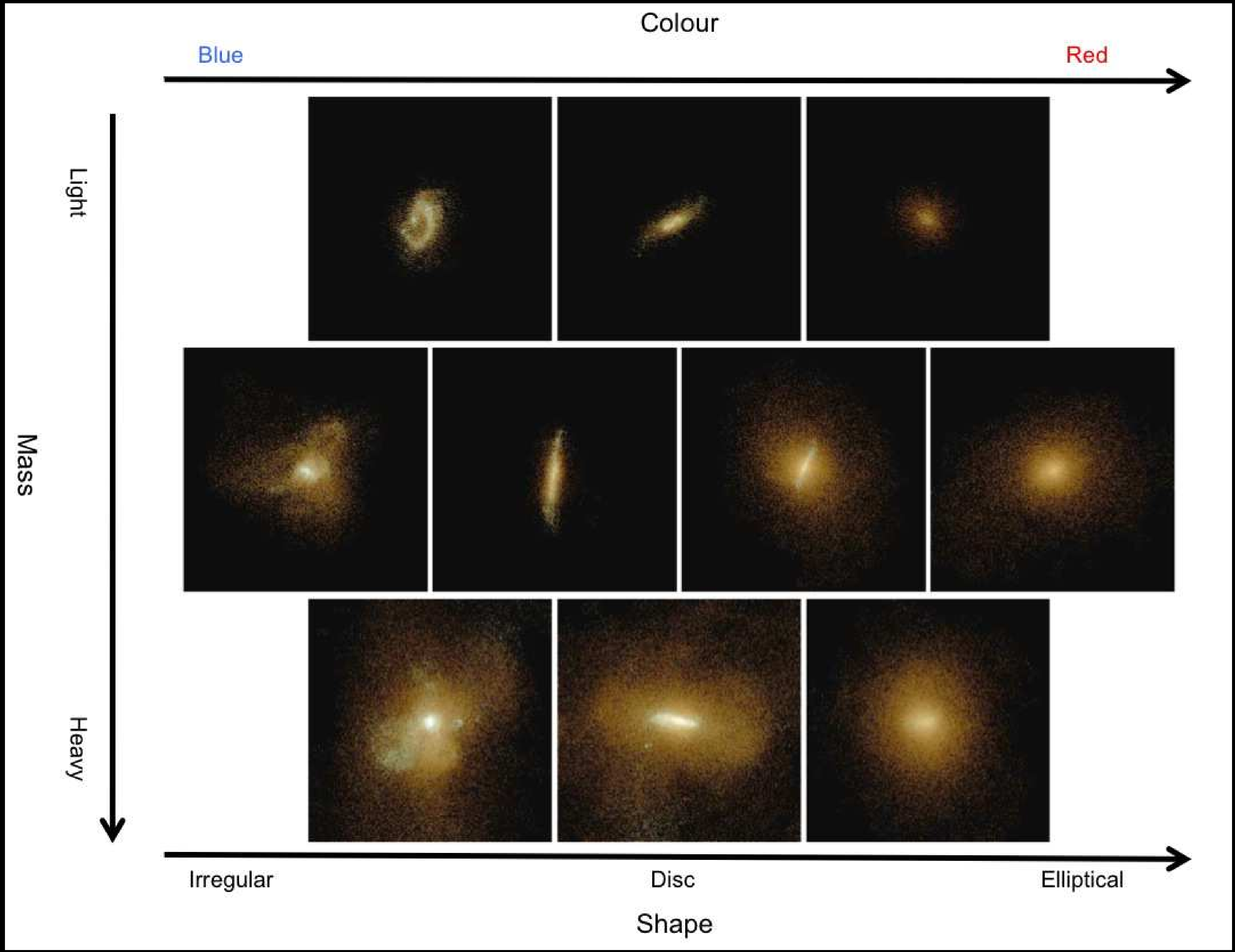
# can morphology trace spin flip ?

- thanks to AGN feedback we have morphological diversity

## Can we get massive galaxies that look like ellipticals ?

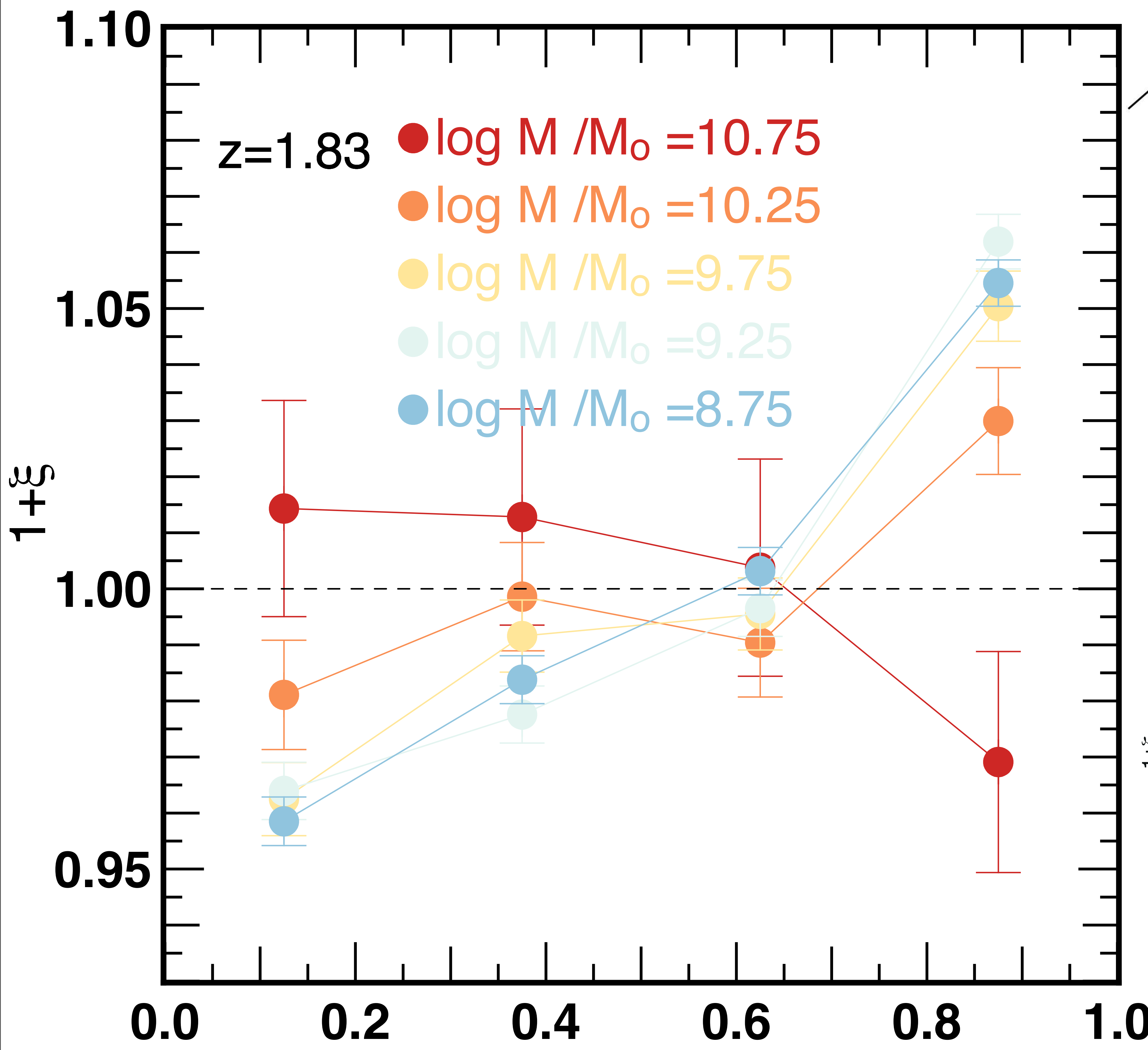


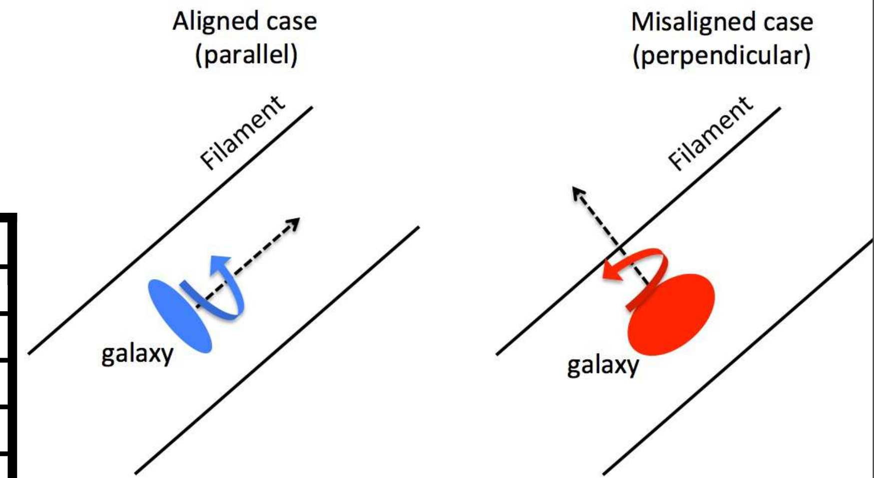

*Dubois, Gavazzi, Peirani, Silk, 2013*



Colour
Blue
Red
Light
Mass
Heavy
Irregular
Disc
Elliptical
Shape

# Filament-galactic spin & mass



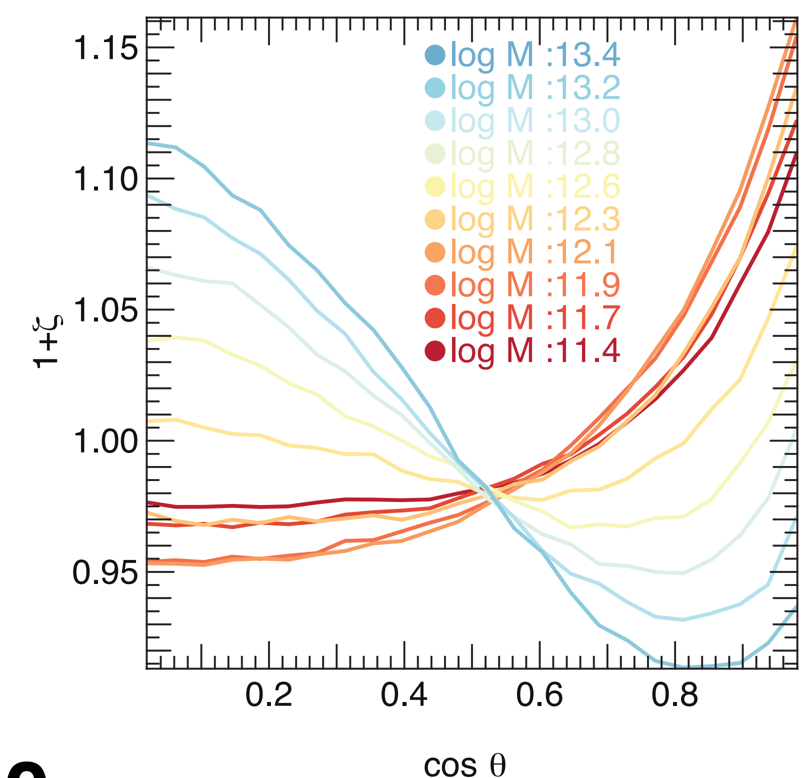
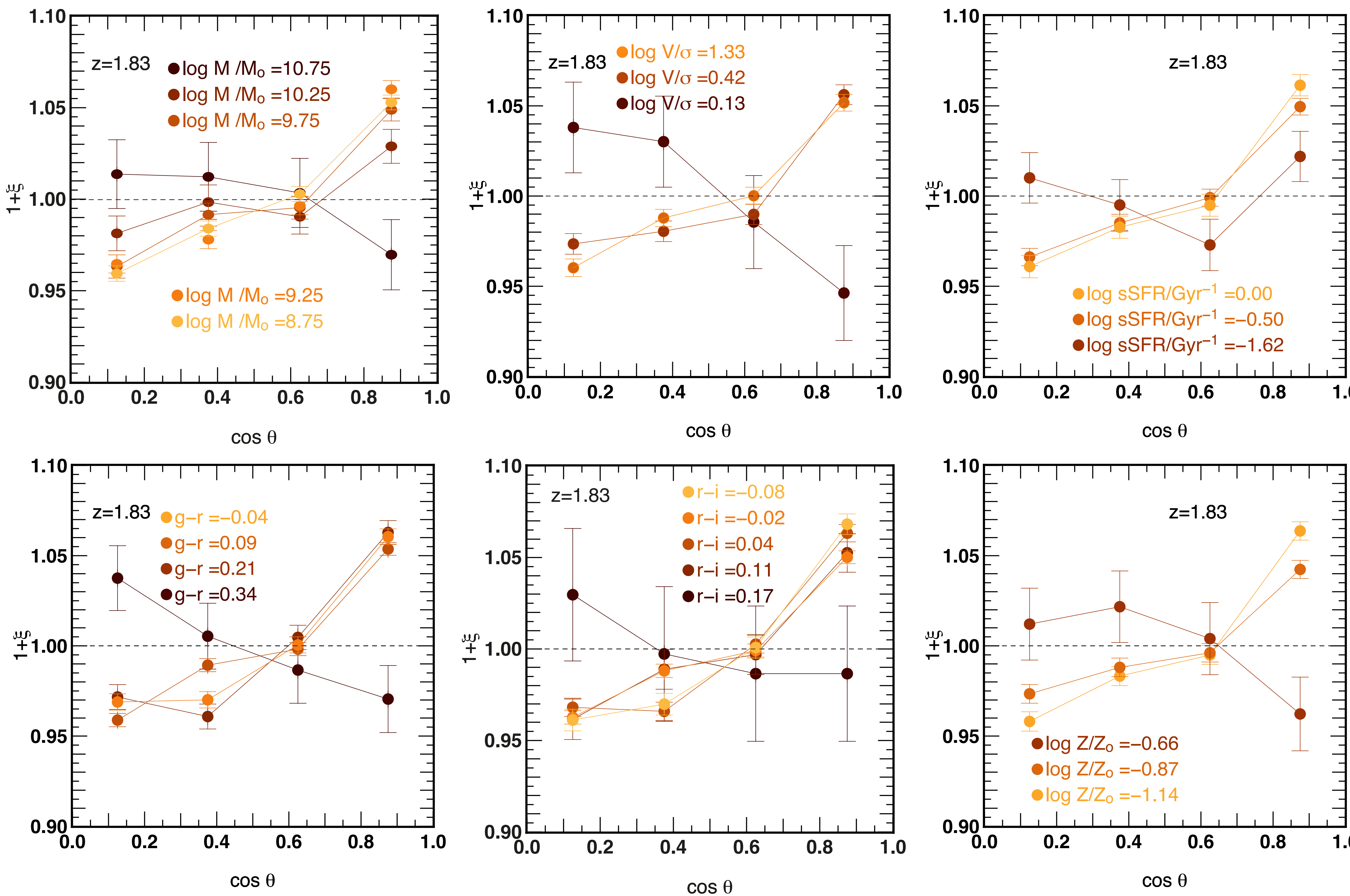



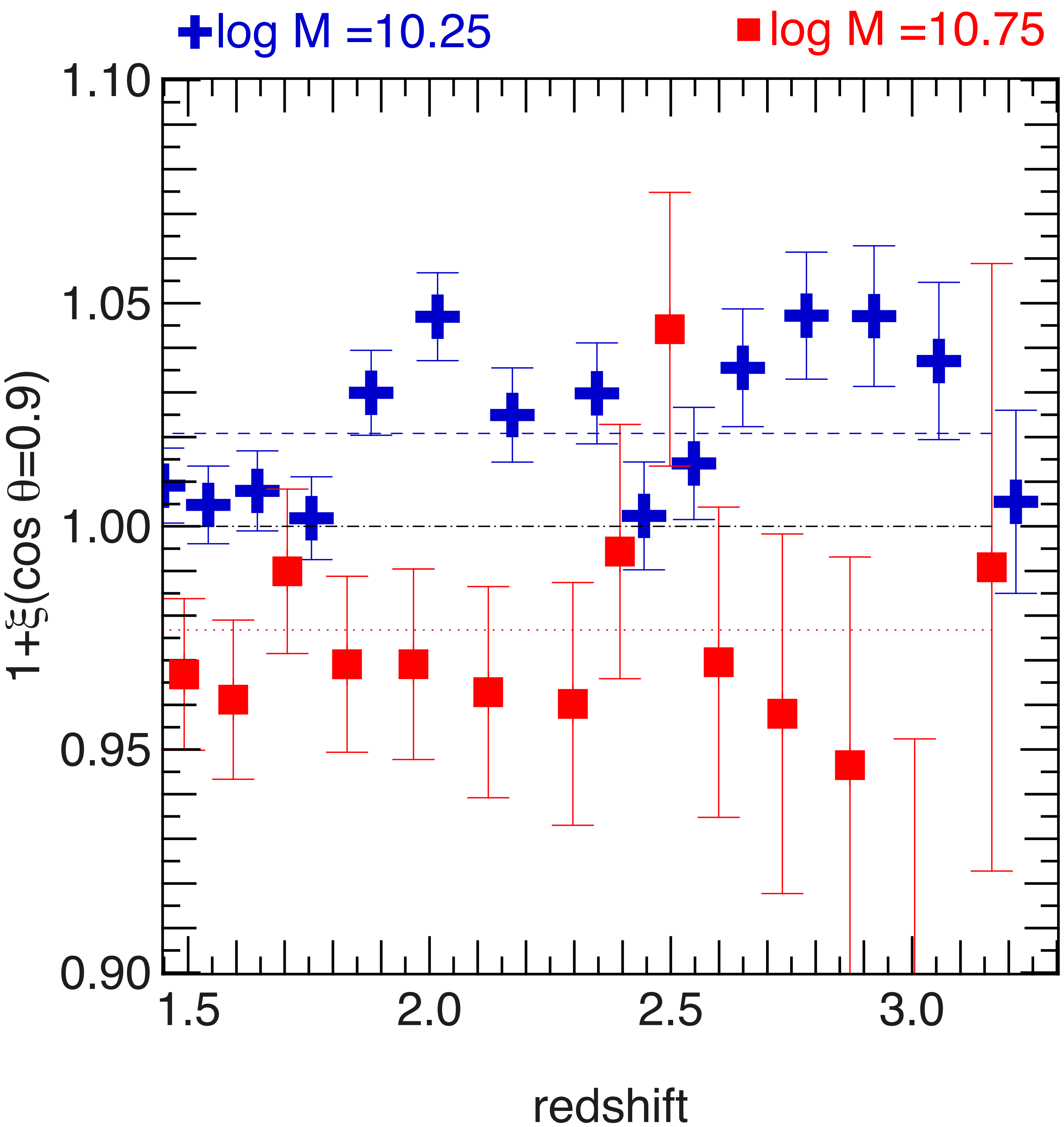

**Figure 10.** The probability distribution of the cosine of the angle between the spin of dark halos and the direction of the clos-

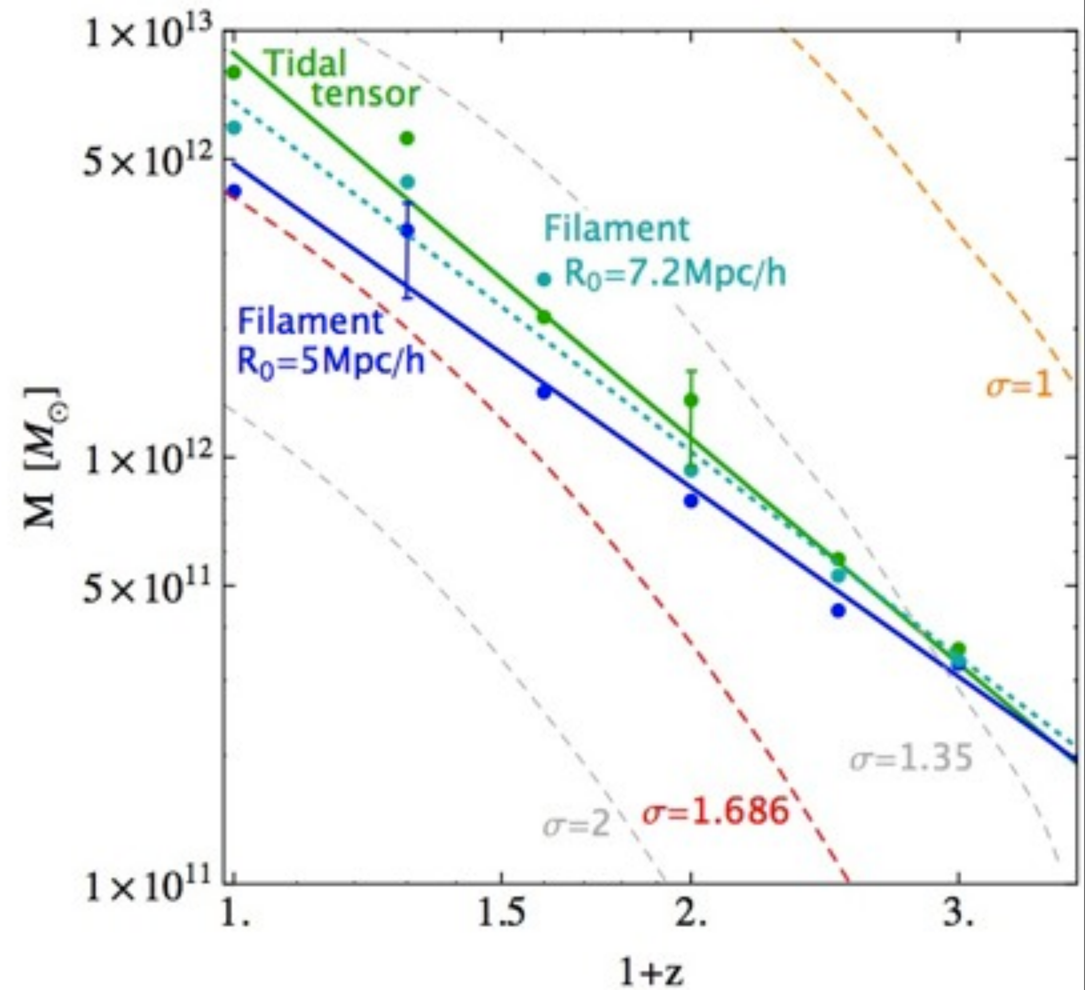
# Can morphological/physical properties of galaxies trace spin flip?

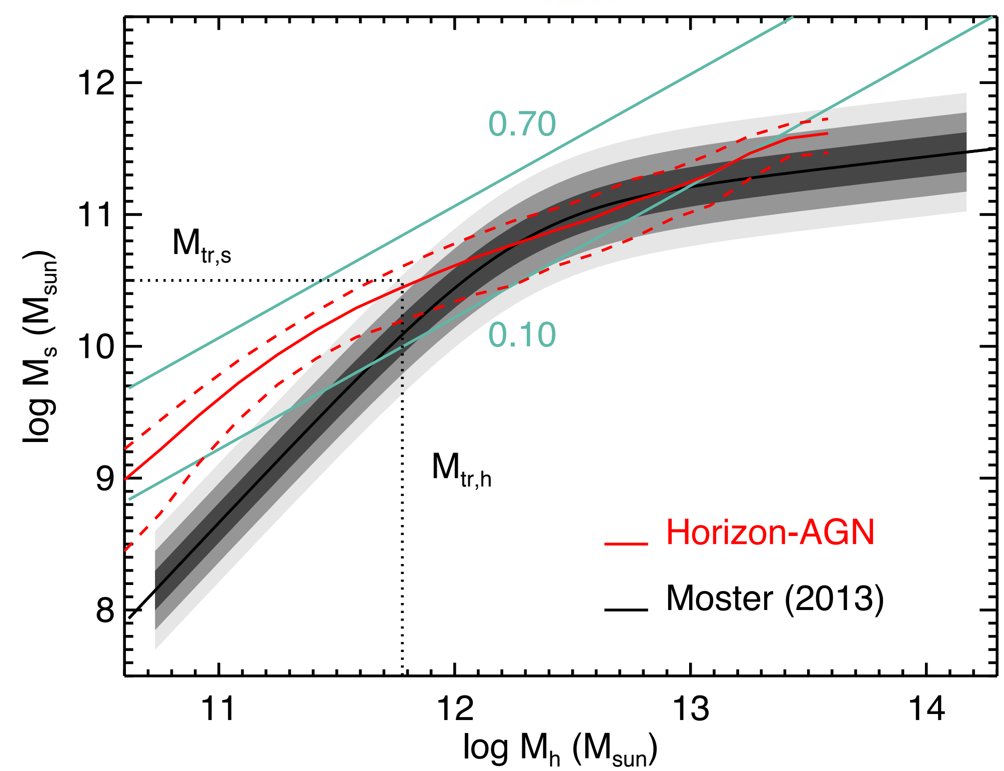


is morphometric
transition mass
consistent
with DM ?

# Mass transition as a function of redshift



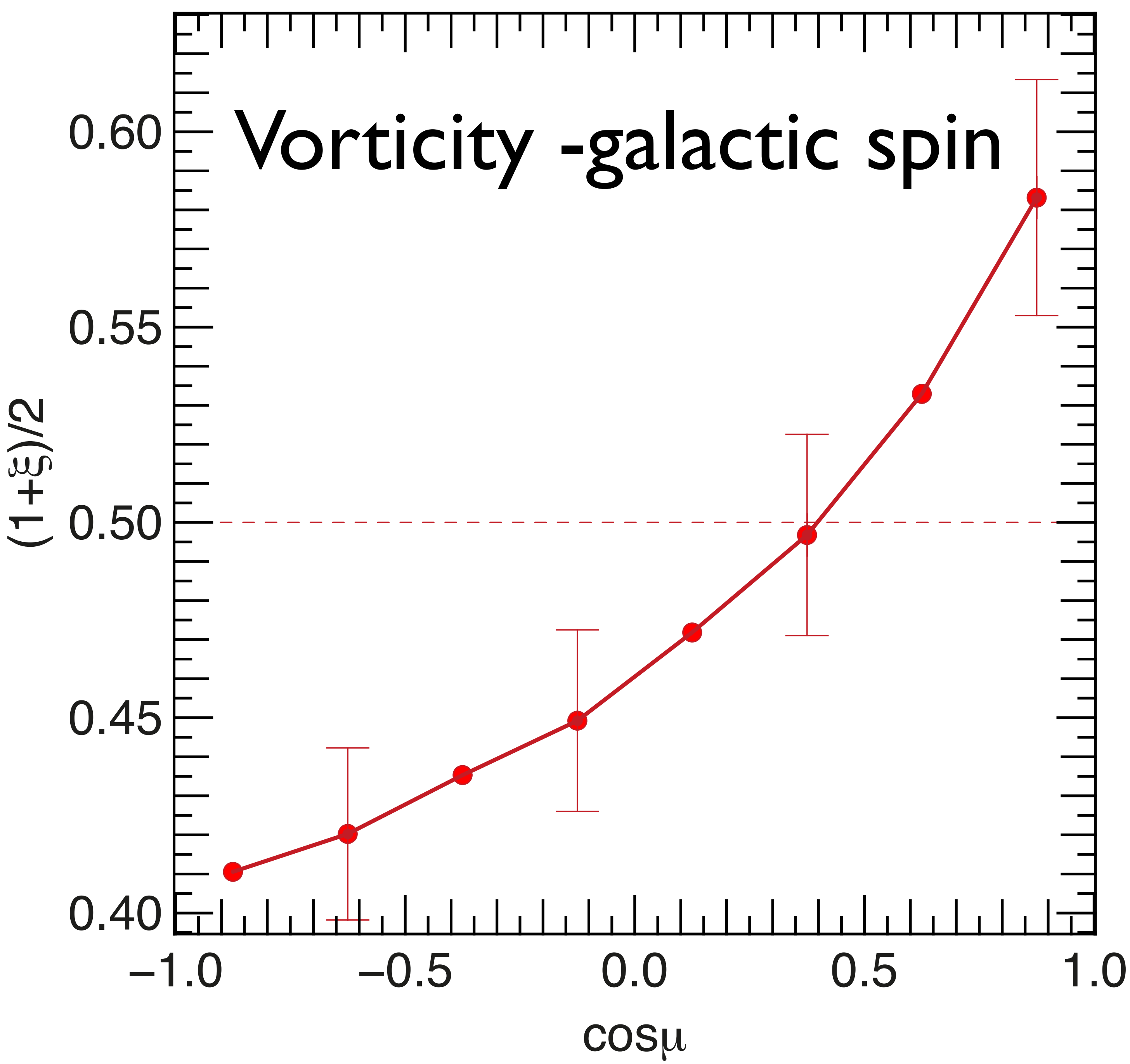



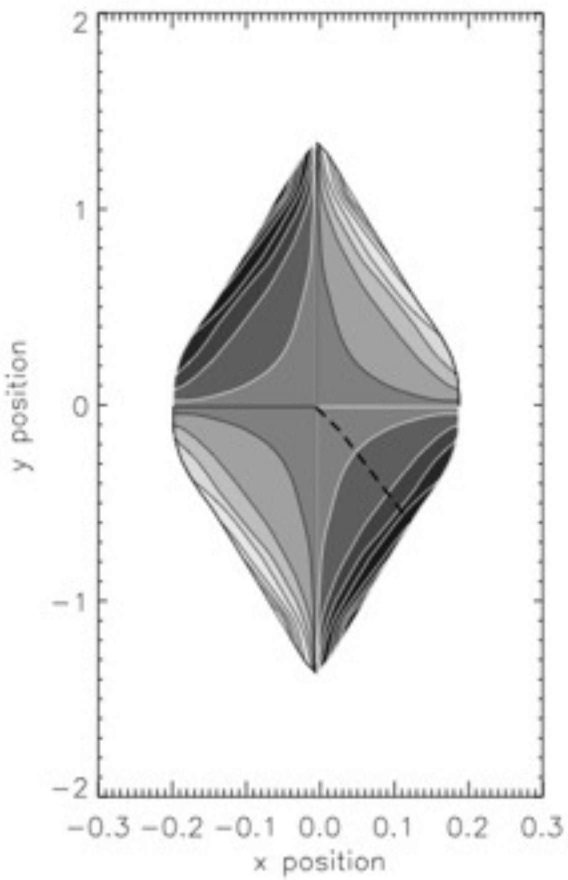




Stellar mass transition ~ $2 \cdot 10^{10} M_\odot$ is consistent with earlier findings of a dark matter mass transition for the orientation of the spin of dark halos of $6 \cdot 10^{11} M_\odot$ at that redshift.

# Final point 1/2:
# low mass galaxies

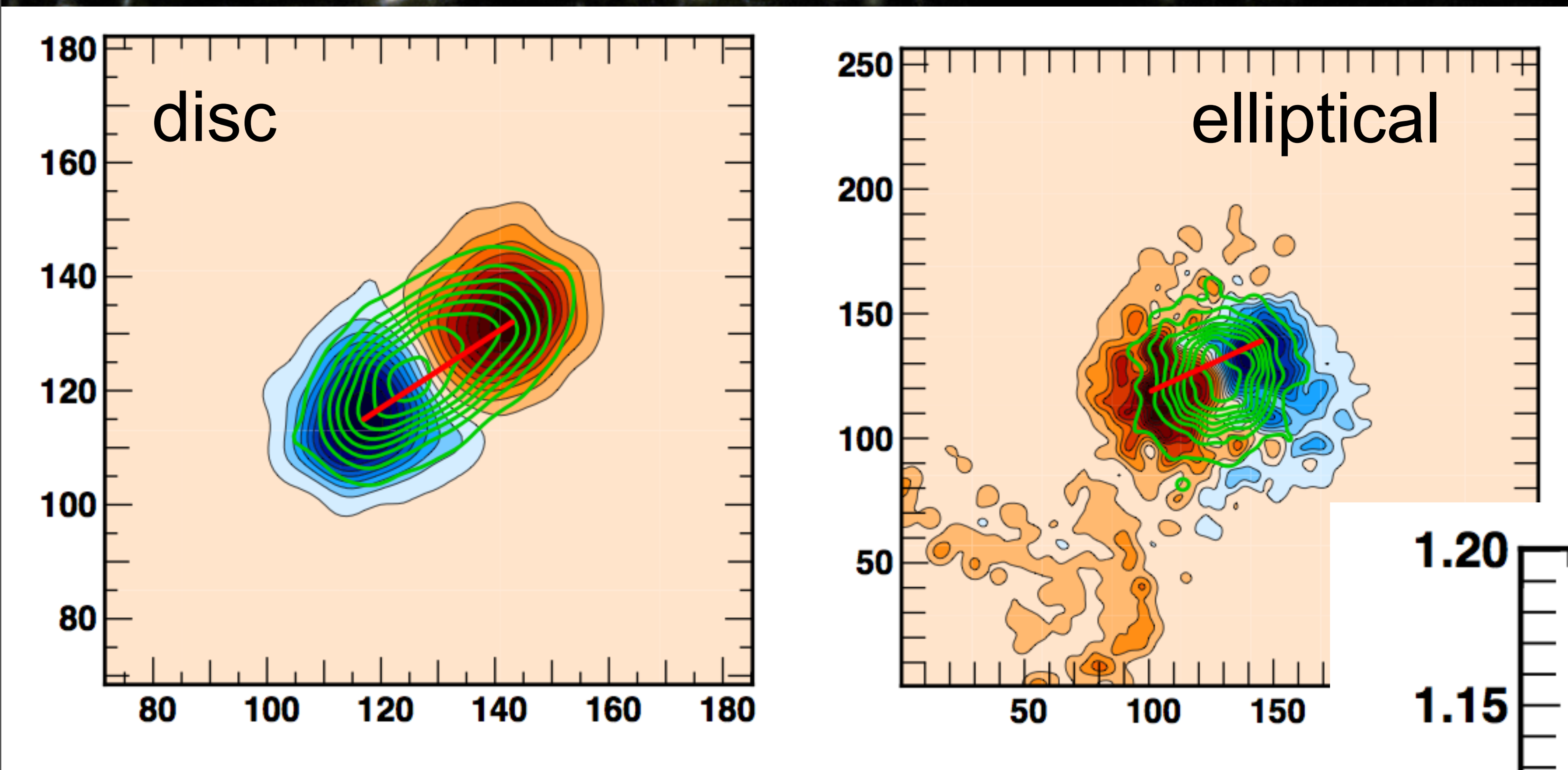
# What is the *physical* origin of low mass **galaxies** spin-filament alignment ?
# Vorticity arising from kin. structure of filament!



# Final point 2/2:
# high mass galaxies

## Are the imprints of LSS noticeable on galaxy properties ?




Horizon-AGN
>150 000 galaxies