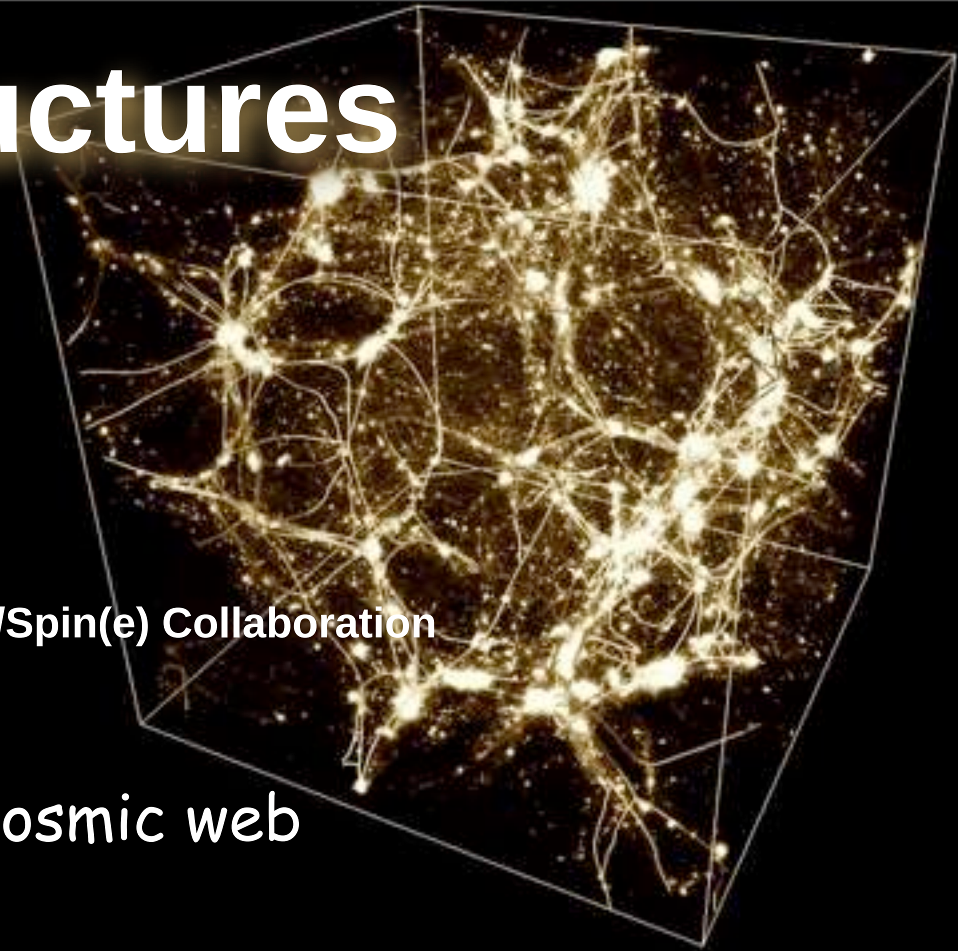
Connecting Large Scale Structures to galactic spin



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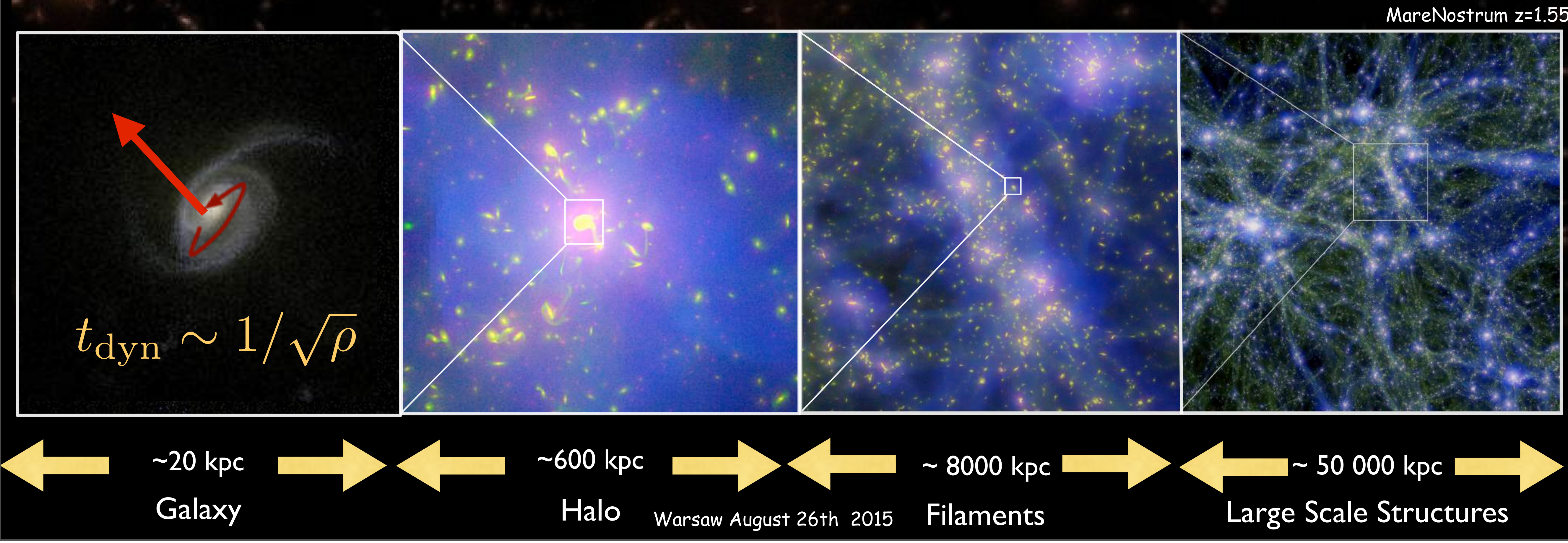
S. Codis, C. Laigle, C. Welker T. Kimm D. Pogosyan, J. Devriendt, Y Dubois+ Horizon/Spin(e) Collaboration

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



Outline

- **What is the geometry of spin near saddle?**
- **How do dark halo's spin flip relative to filament**
- **Why does it induce a transition mass:** ***Euliean*** **&** **Lagrangian** **theory?**

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Why do we care?

- *Weak lensing*
- AM stratification drives **morphology**
- Galaxy formation is *not* a 1D manifold
- *Because we can understand something !*

(c)Taysun Kimm +E. Pharabod

Outline

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Why do we care?

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- Galaxy formation is *not* a 1D manifold
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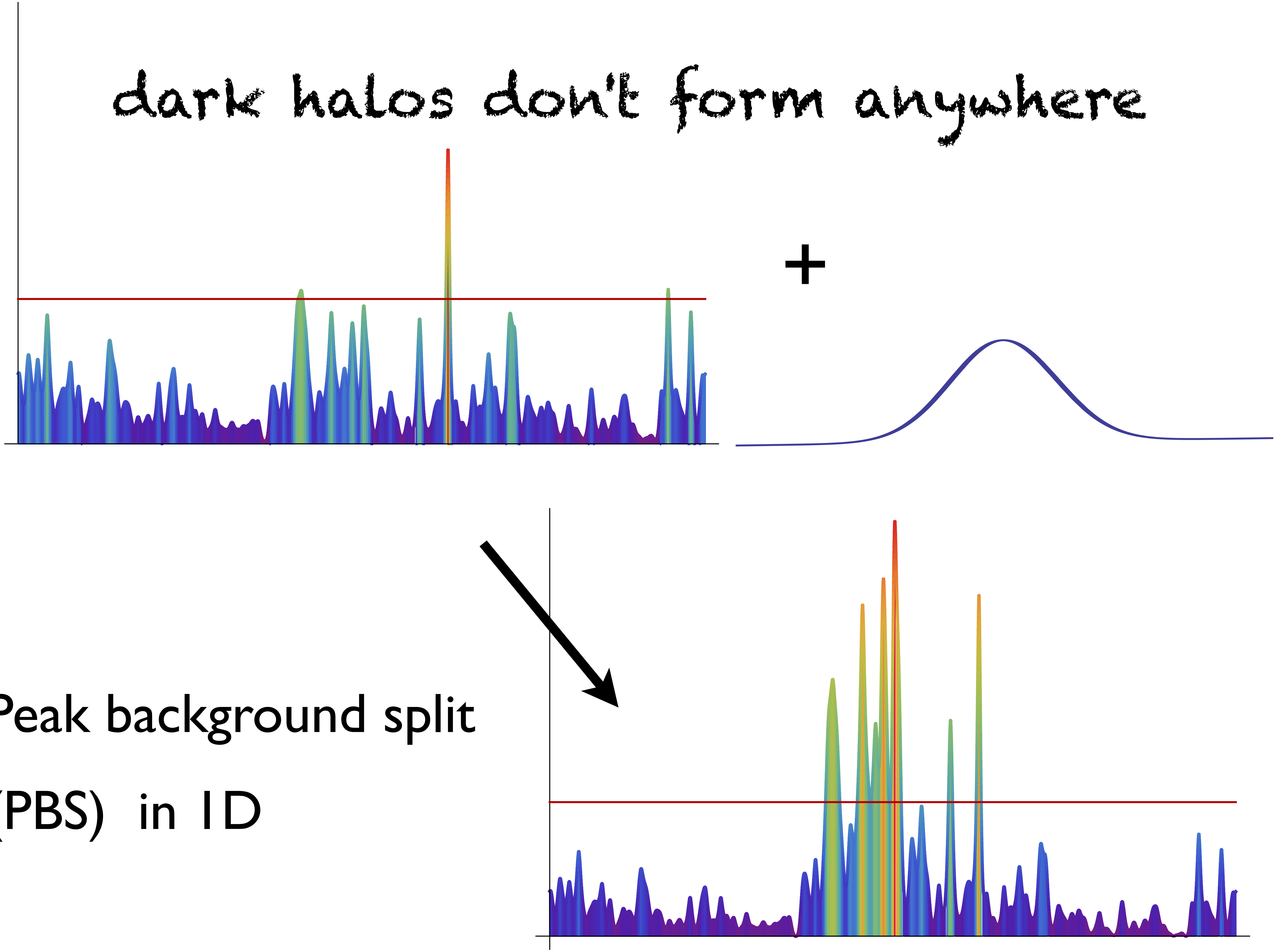
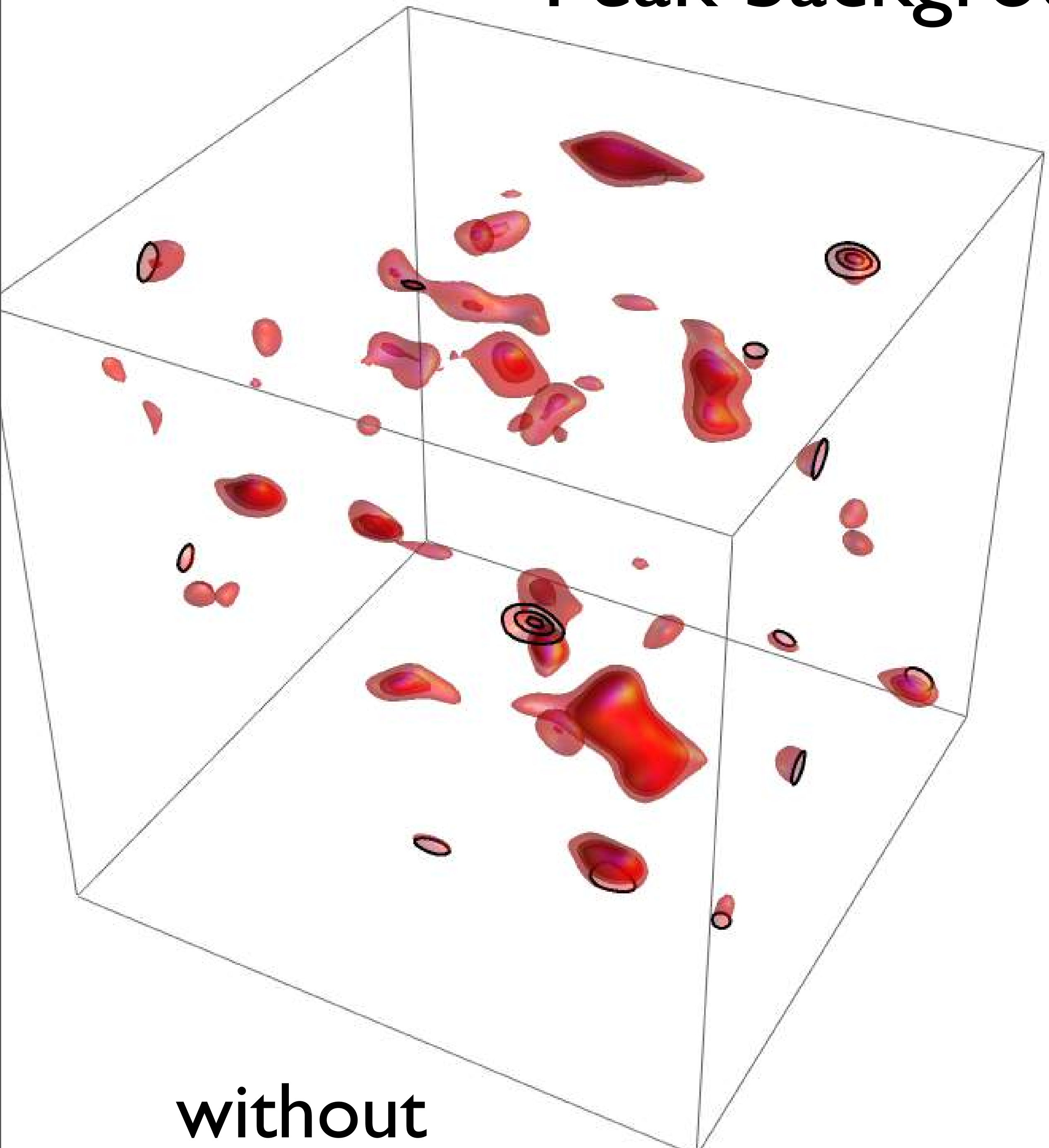
Where galaxies form does matter, and can be traced back to ICs.
Flattened filaments generate point-reflection-symmetric AM/vorticity distribution:
they induce the observed spin transition mass



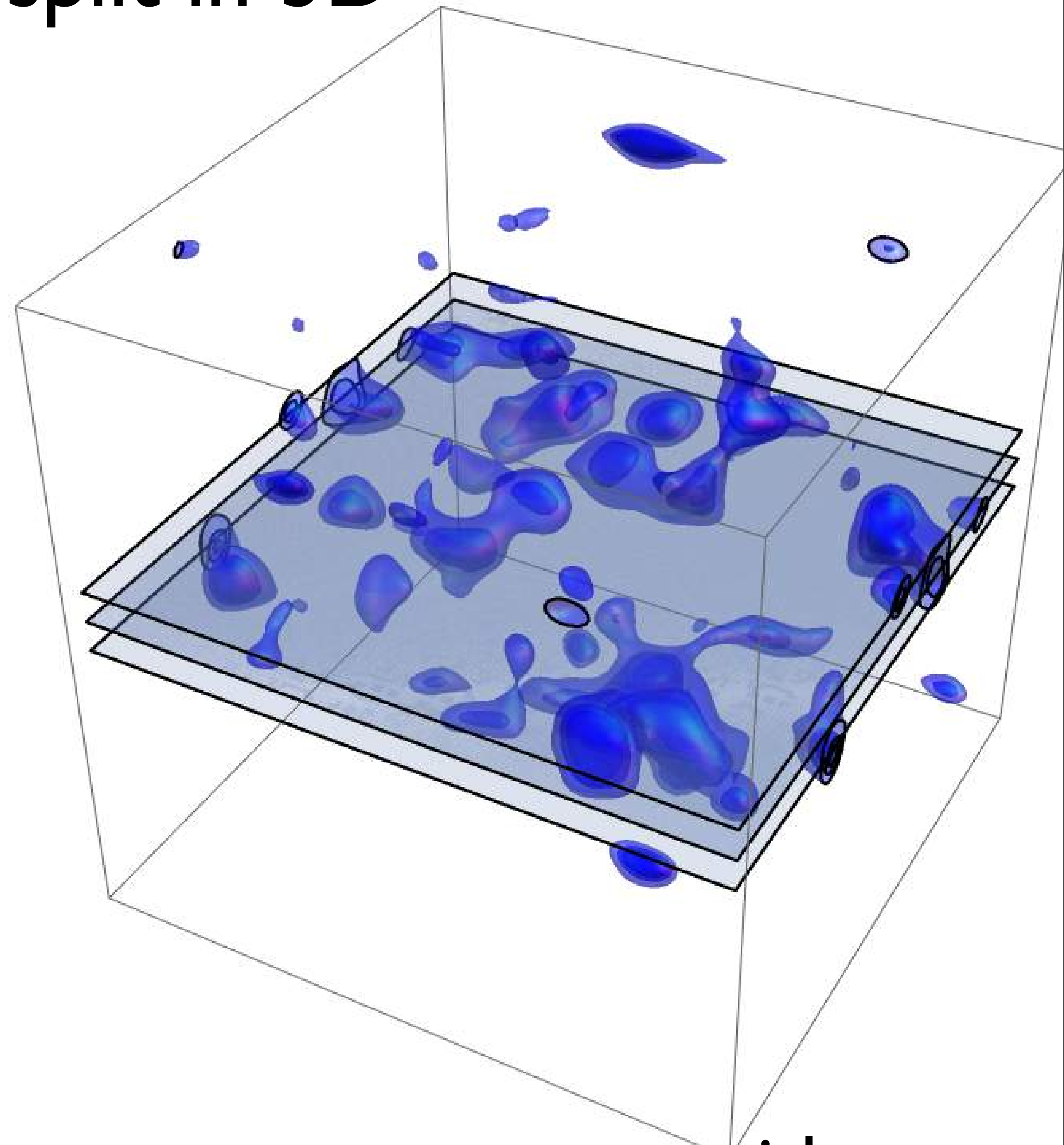
Peak background split

(PBS) in 1D

Peak background split in 3D



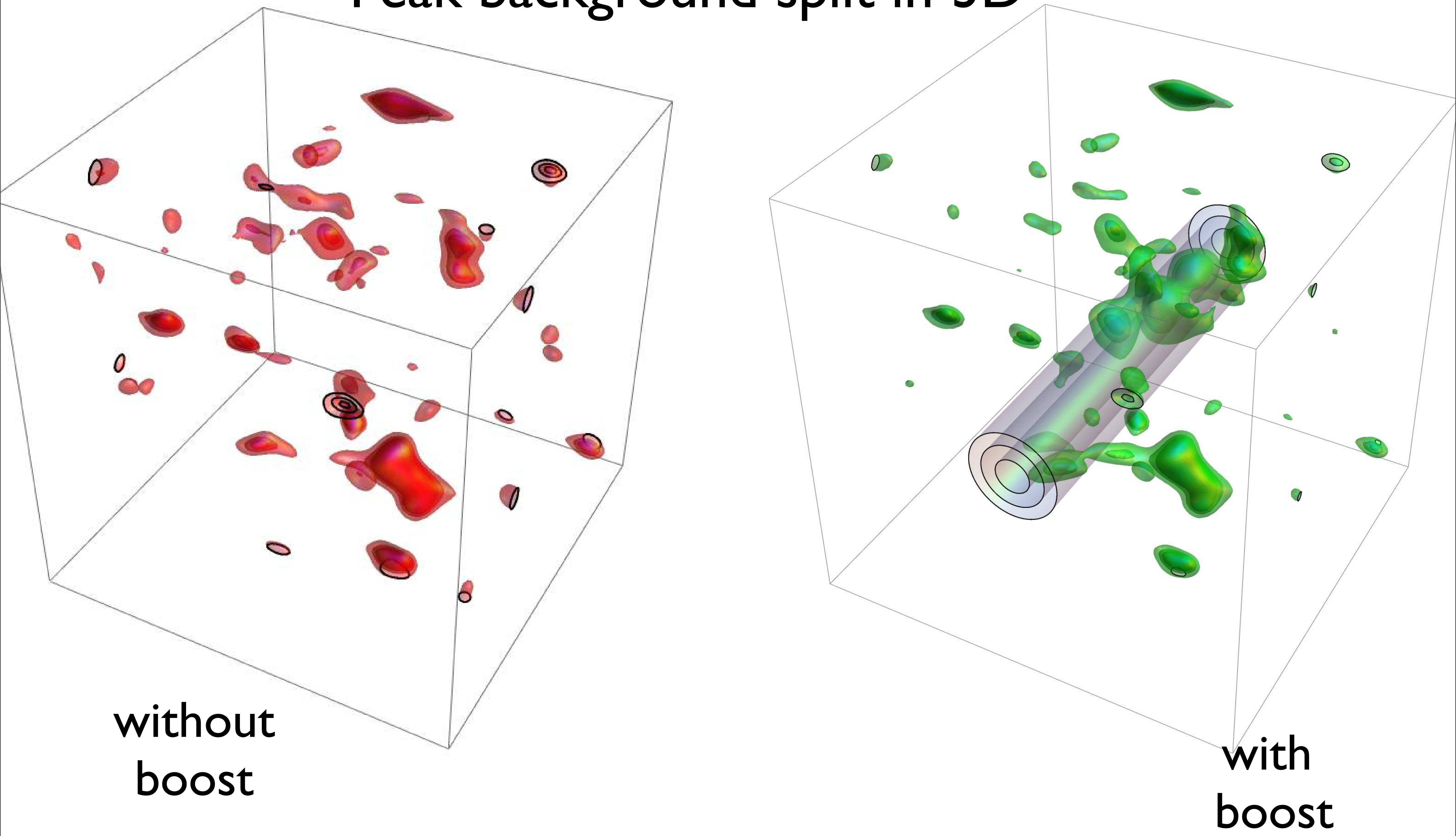
without
boost



with
boost

Does this anisotropic biassing have a dynamical signature? *yes! in term of spin!*

Peak background split in 3D



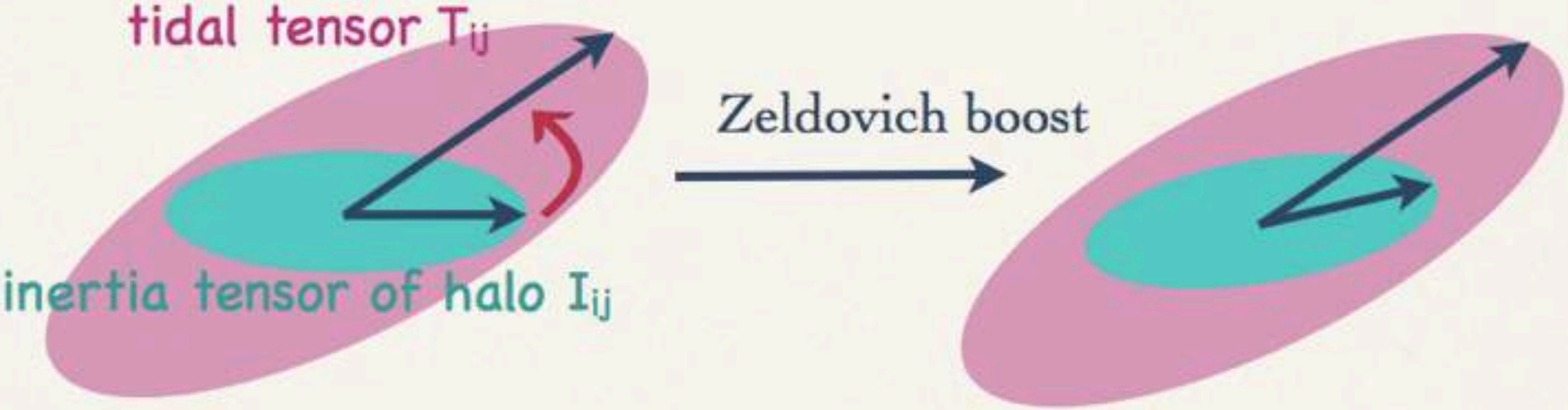
Does this anisotropic biassing have a dynamical signature? *yes! in term of spin!*

Tidal Torque Theory in one cartoon

Can we understand where spin and vorticity alignments come from?

-usual tidal torque theory

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



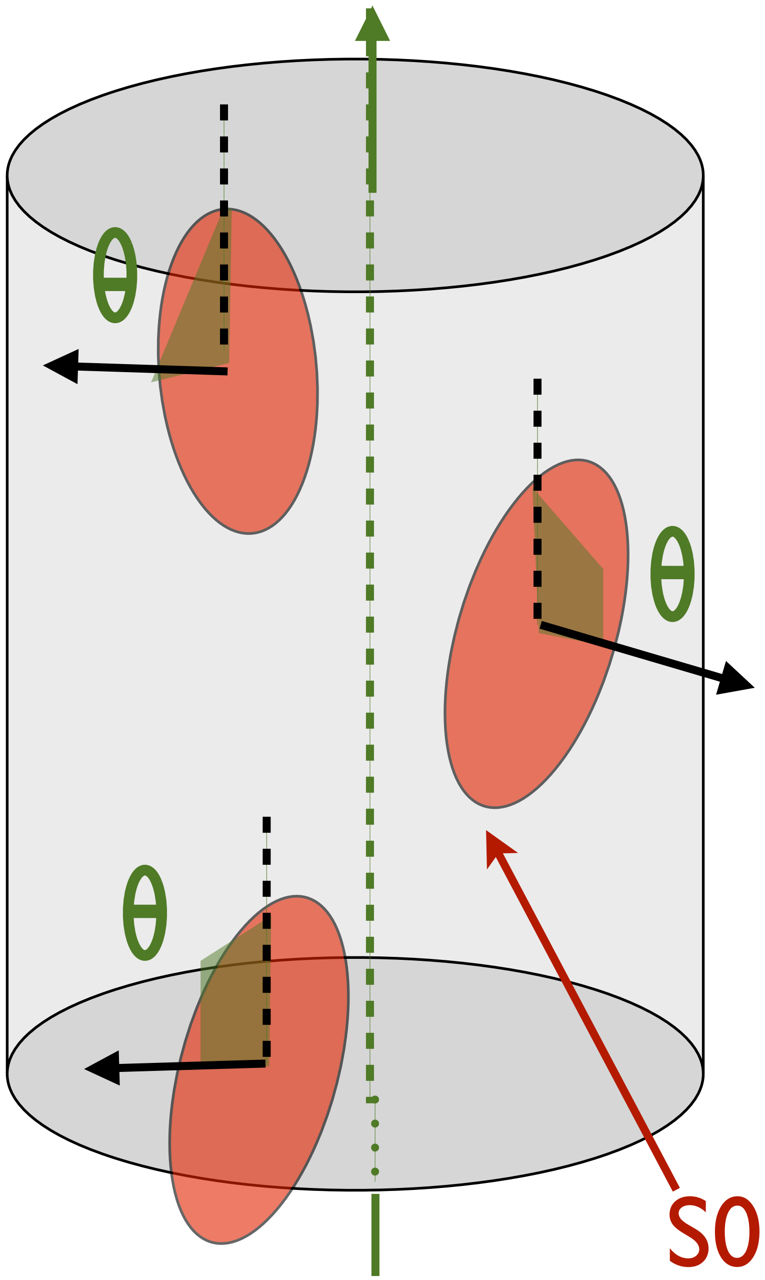
YES! via conditional TTT subject to PBS

"Cond' prob, good stuff!"

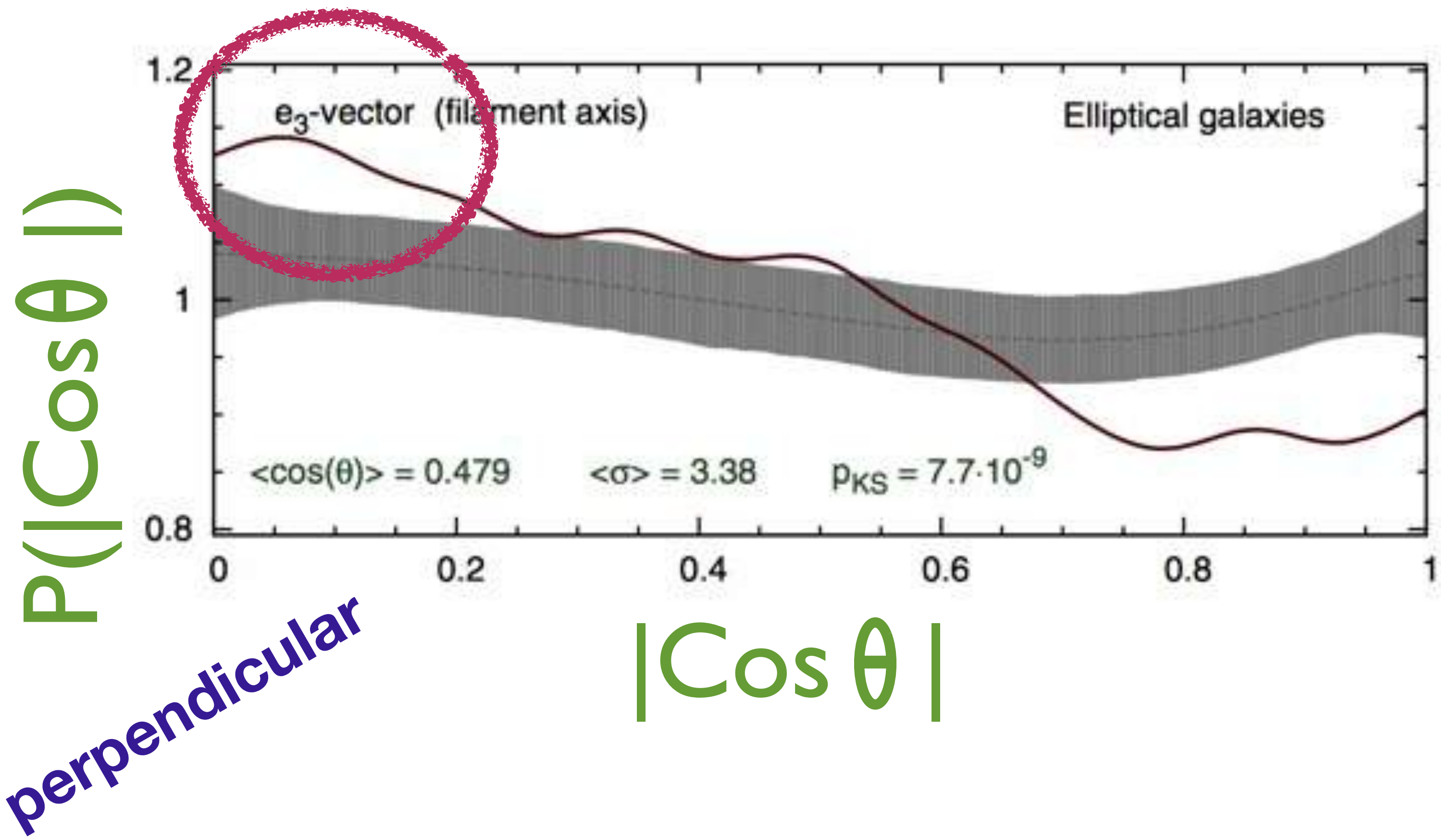
Et Voilà !

Evidences of galaxy spin - filament alignment

Cosmic Filament



Tempel+ (2013) in the SDSS



See also:
Aragon-Calvo+ 2007, Hahn+ 2007, Paz+ 2008, Zhang+ 2009, Codis+ 2012, Libeskind+ 2013, Aragon-Calvo 2013, Dubois+ 2014

Evidences of galaxy spin - filament alignment

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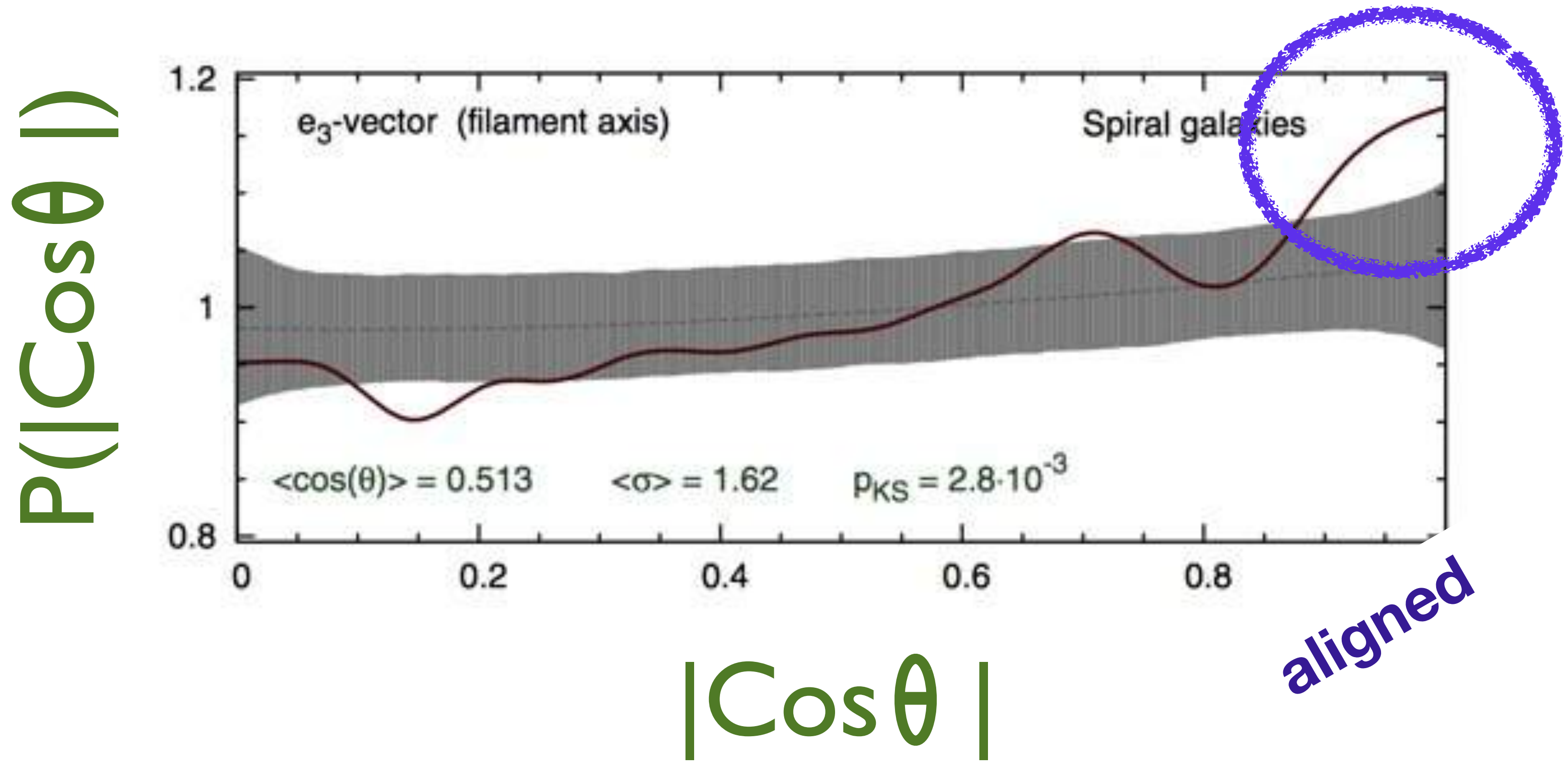

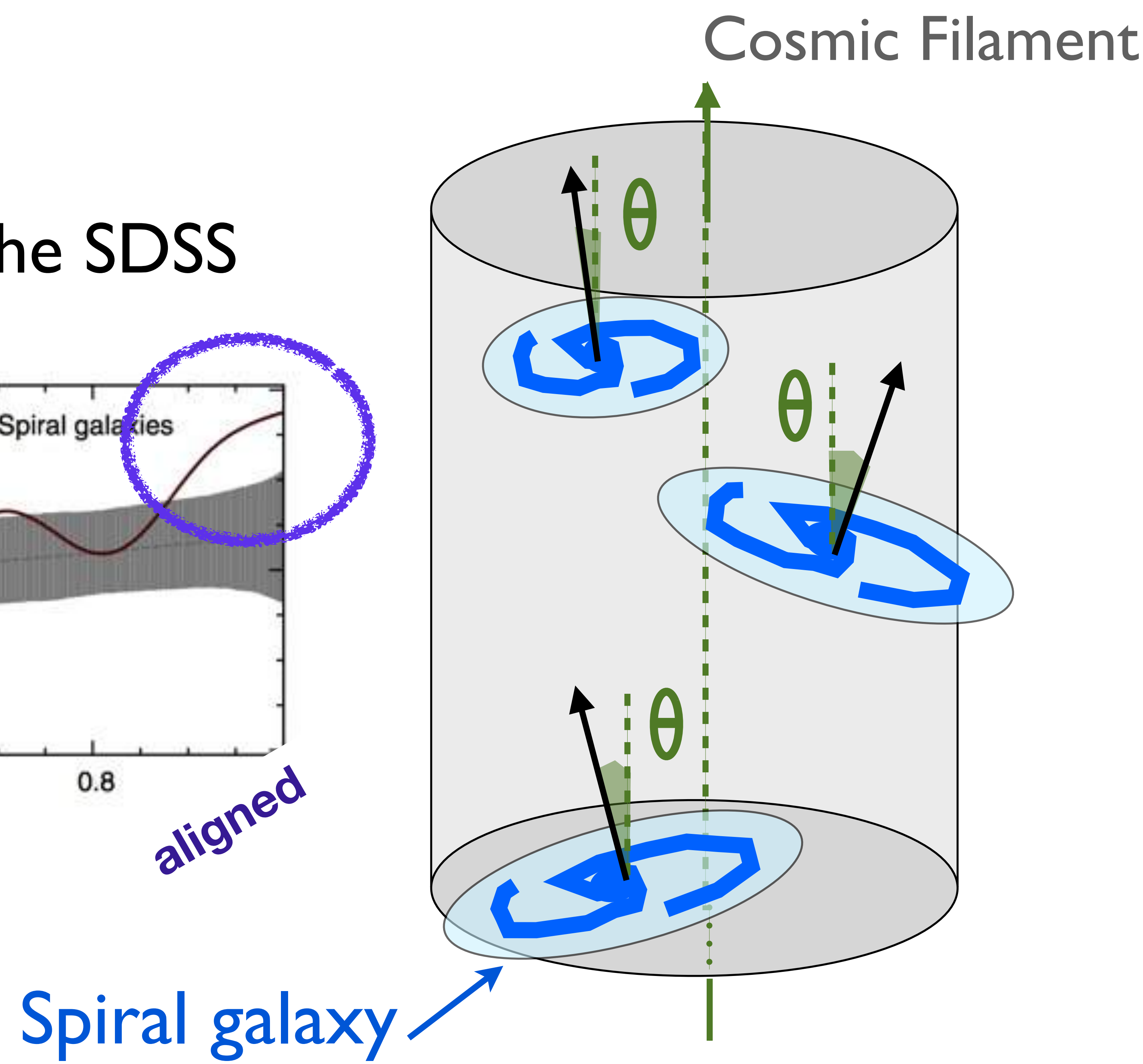

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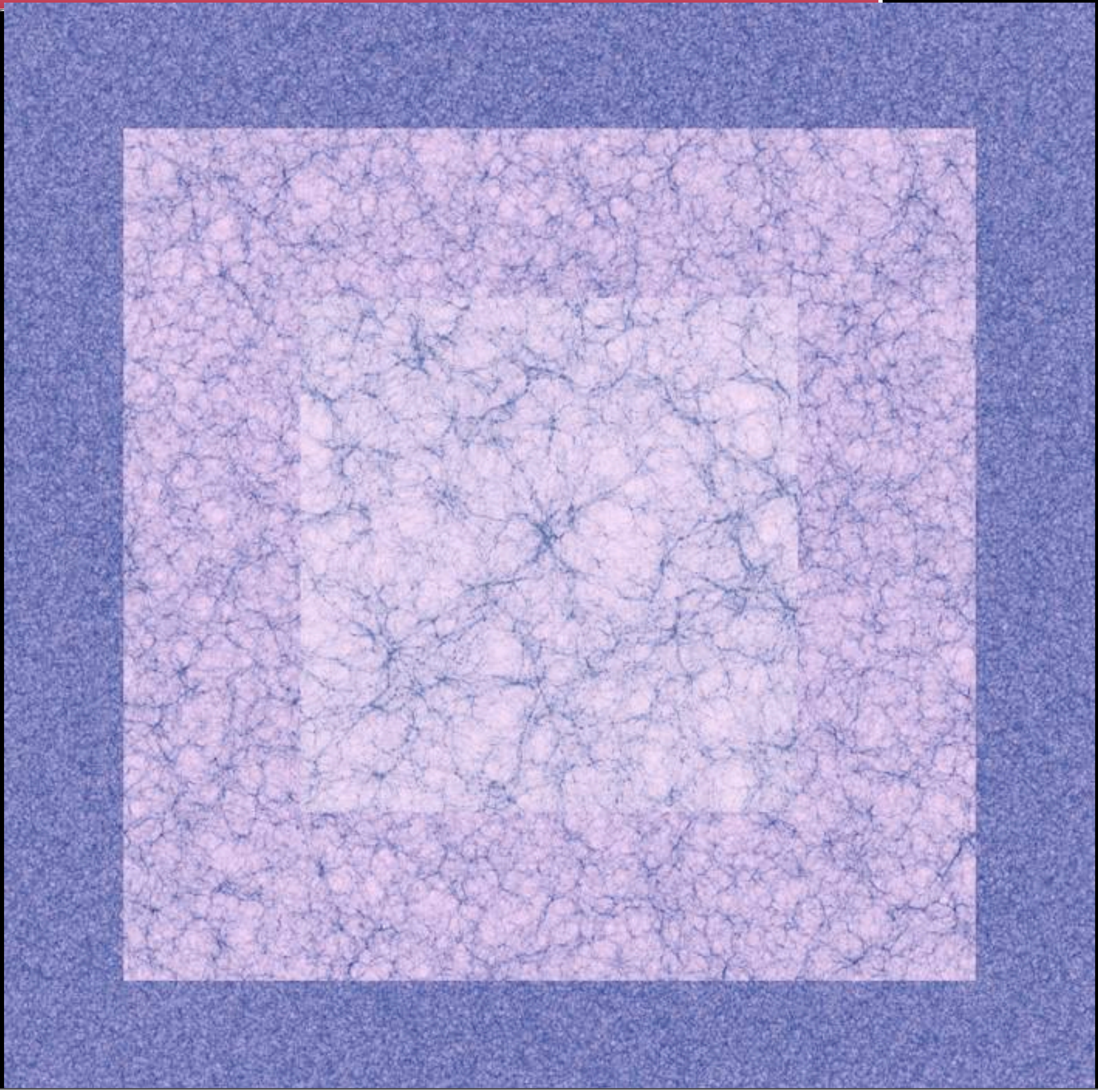
Orientation of the spins w.r.t the filaments

Horizon 4Pi:

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

(Teyssier et al, 2009)

10 000 000 hrs CPU



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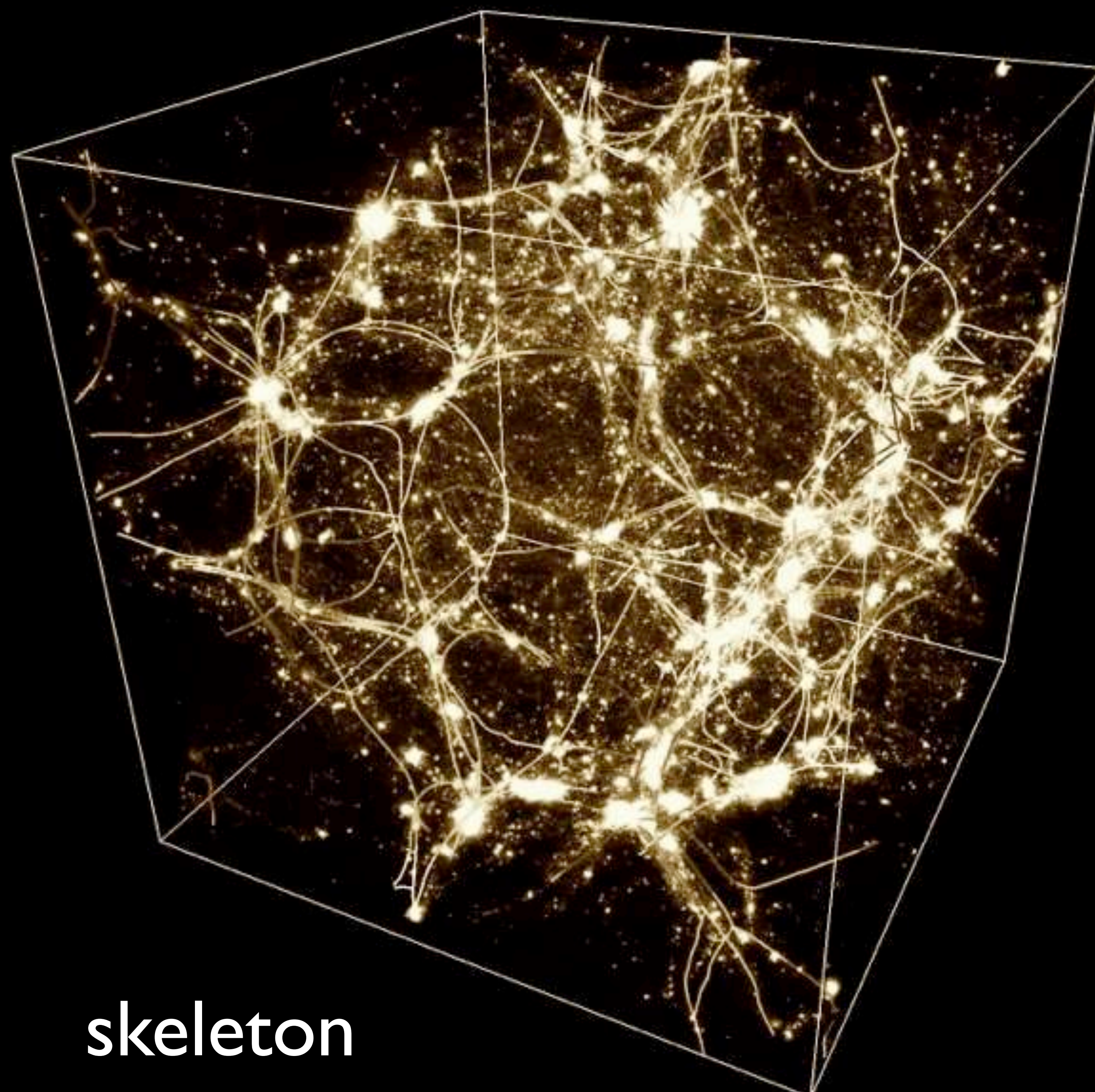

skeleton
follow filaments

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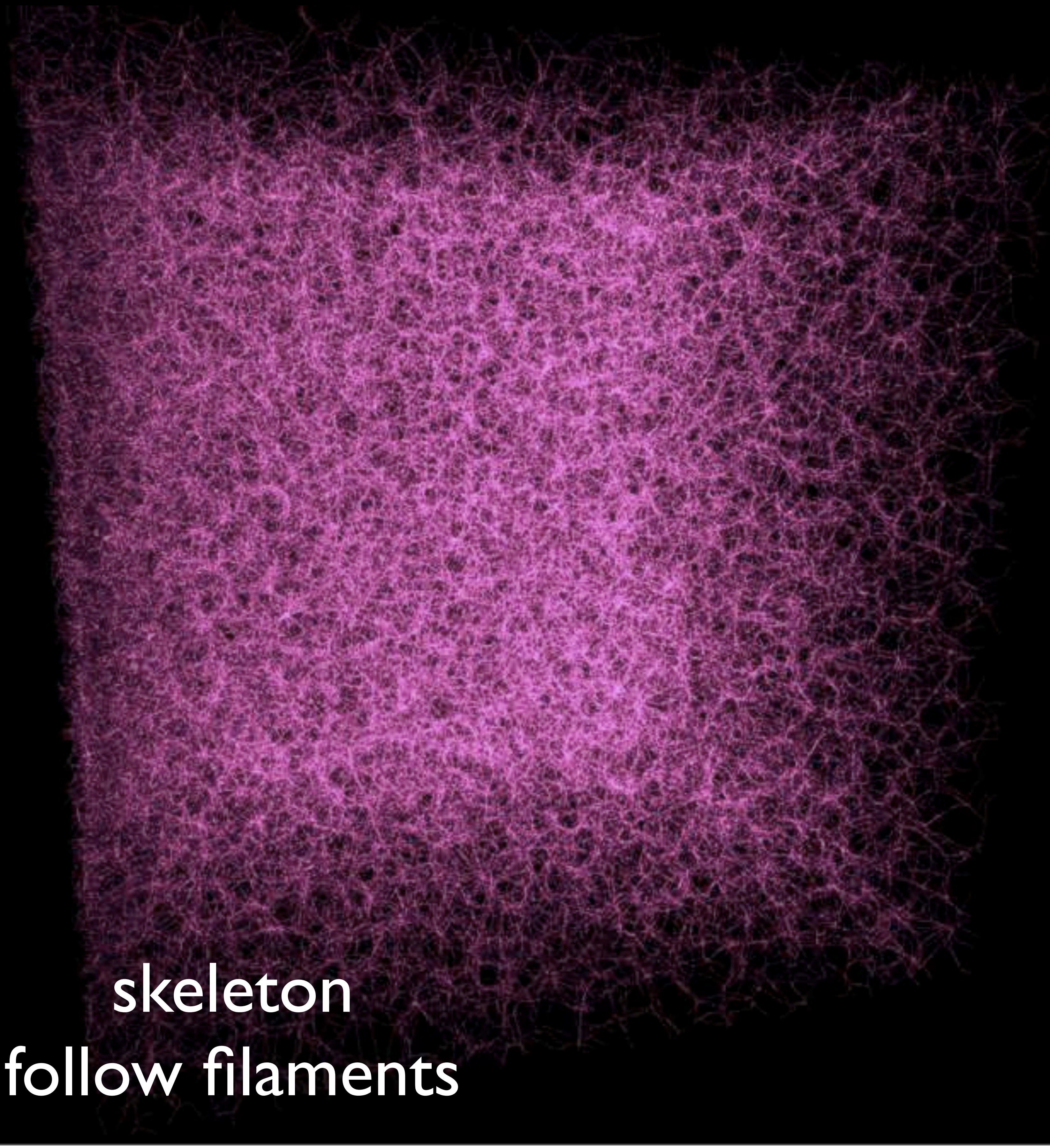


skeleton
follow filaments

Excess probability of alignment between the spins and their host filament

mass transition:

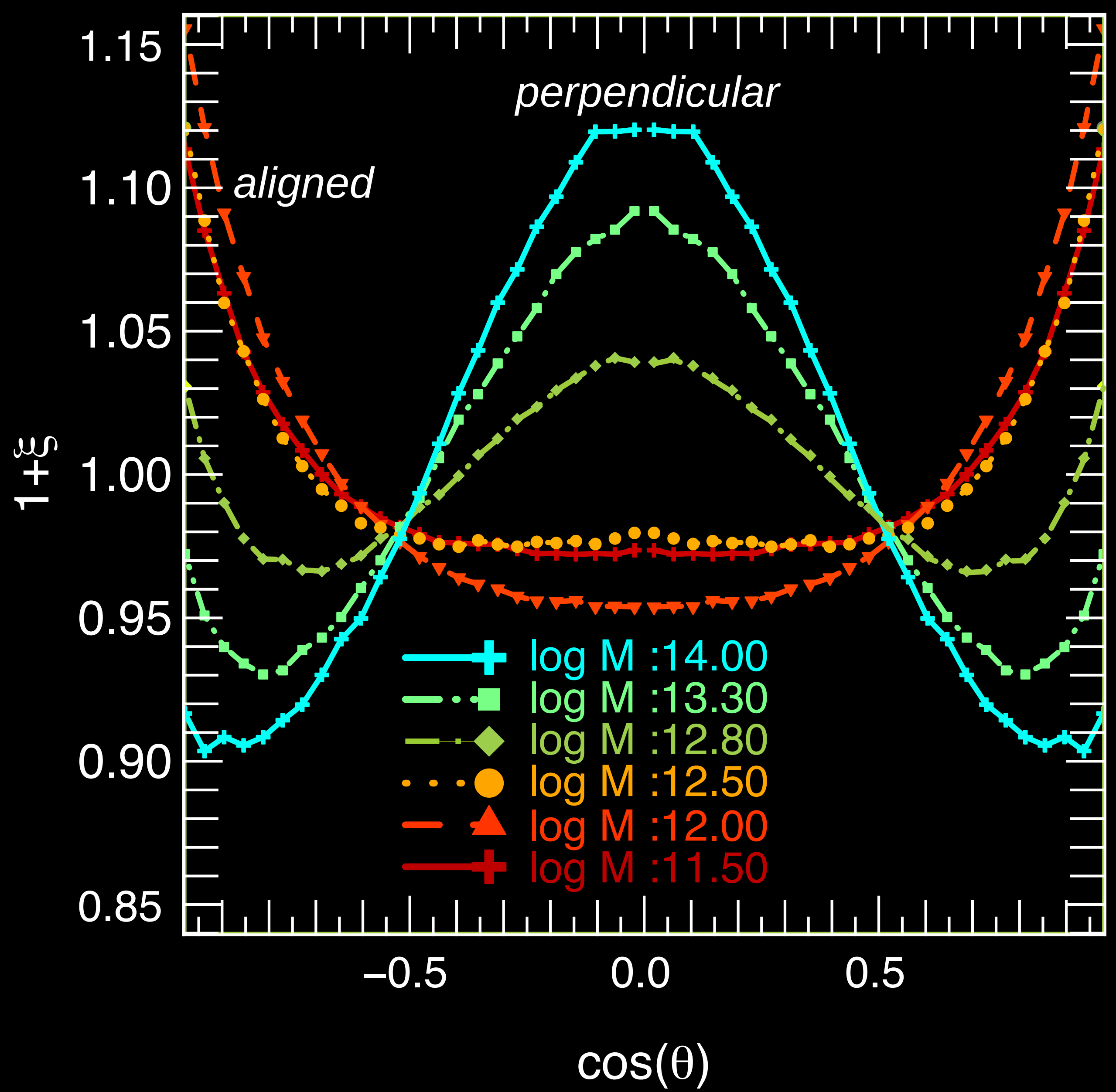
$$M_{\rm crit} = 4 \cdot 10^{12} M_{\odot}$$

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

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

(Codis et al, 2012)

Excess probability of alignment between the spins and their host filament



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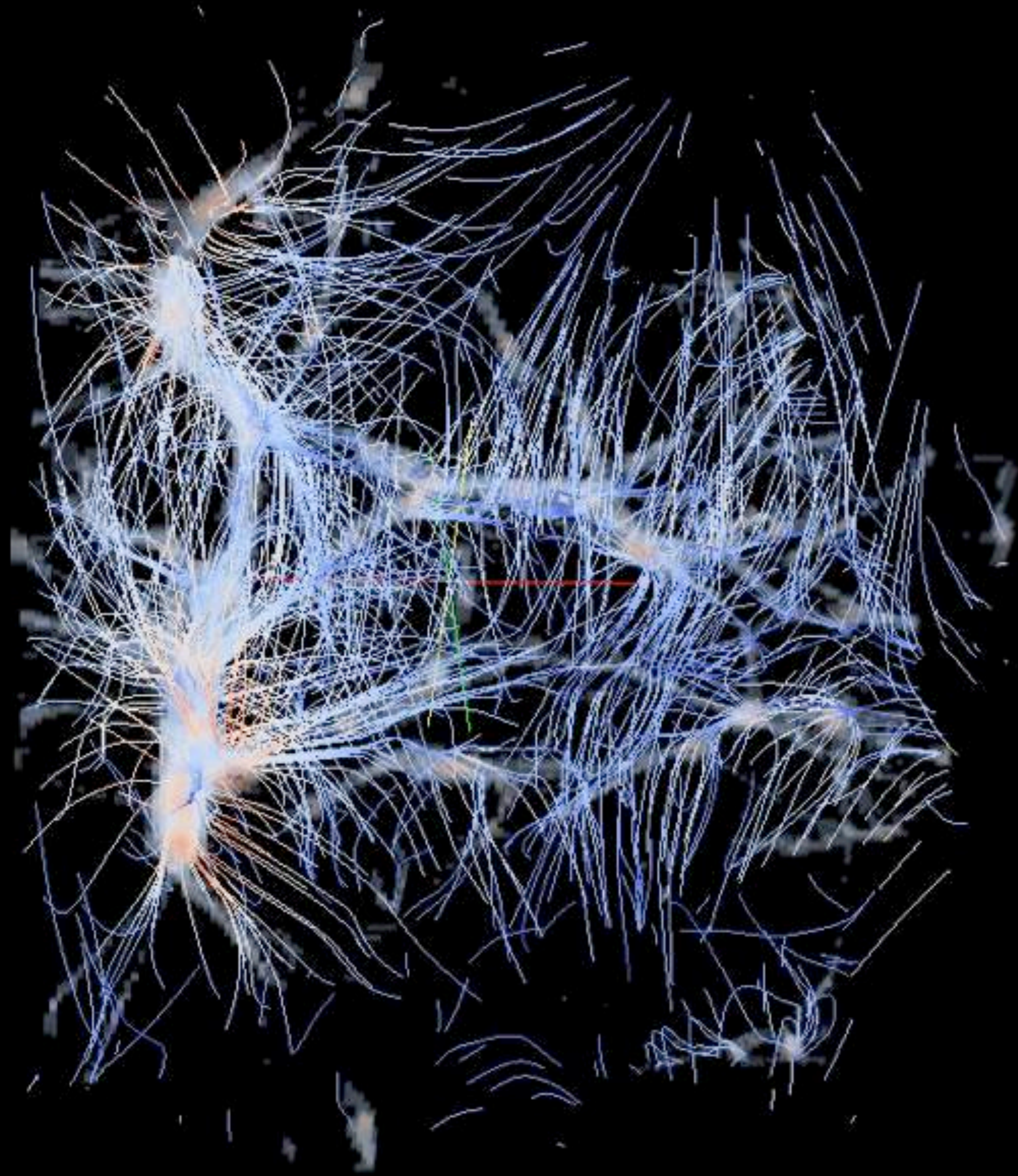
How does the formation of the filaments generate spin parallel to them?

Voids/wall saddle repel...



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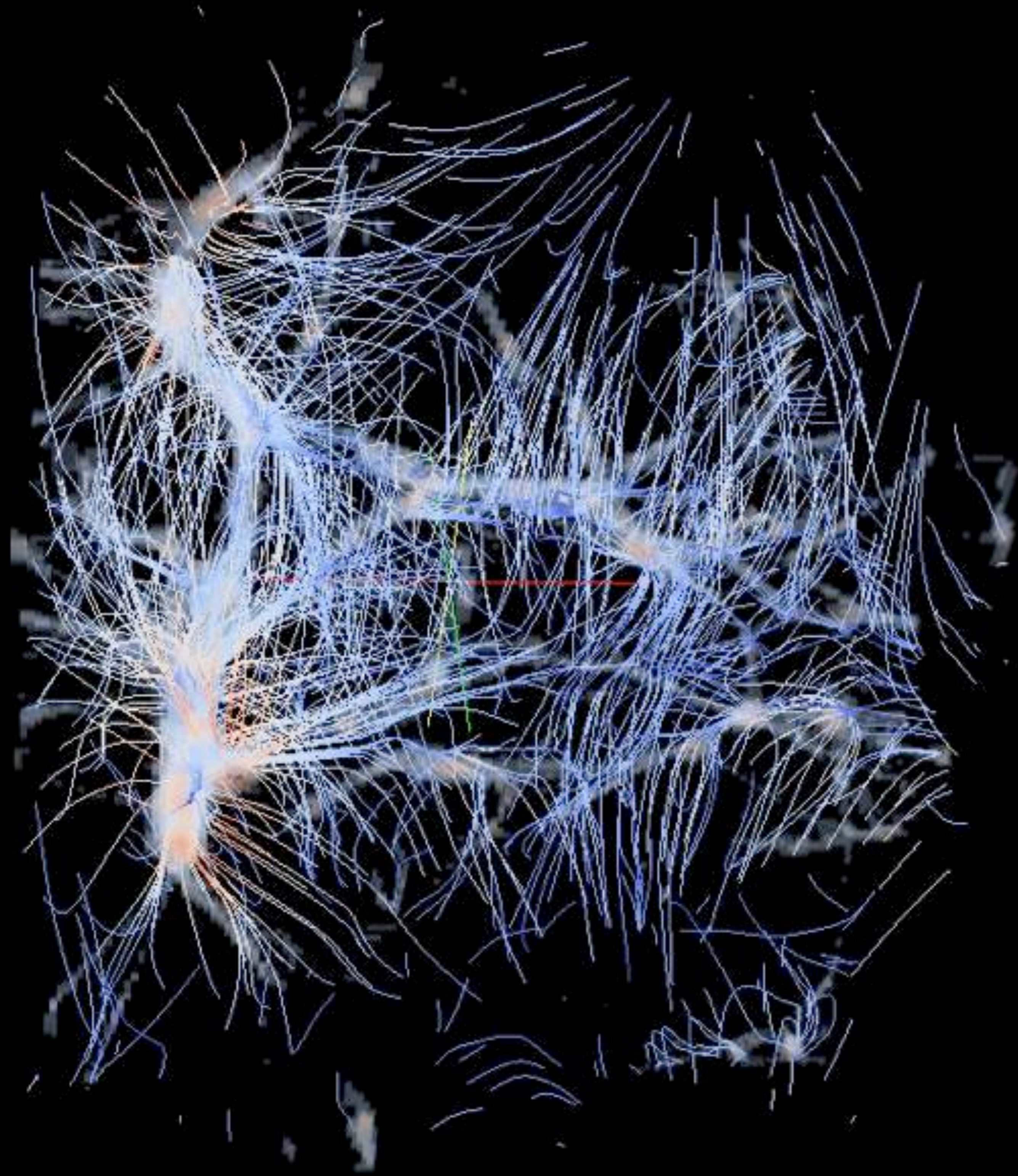
Voids/wall saddle repel...

winding of walls into filaments



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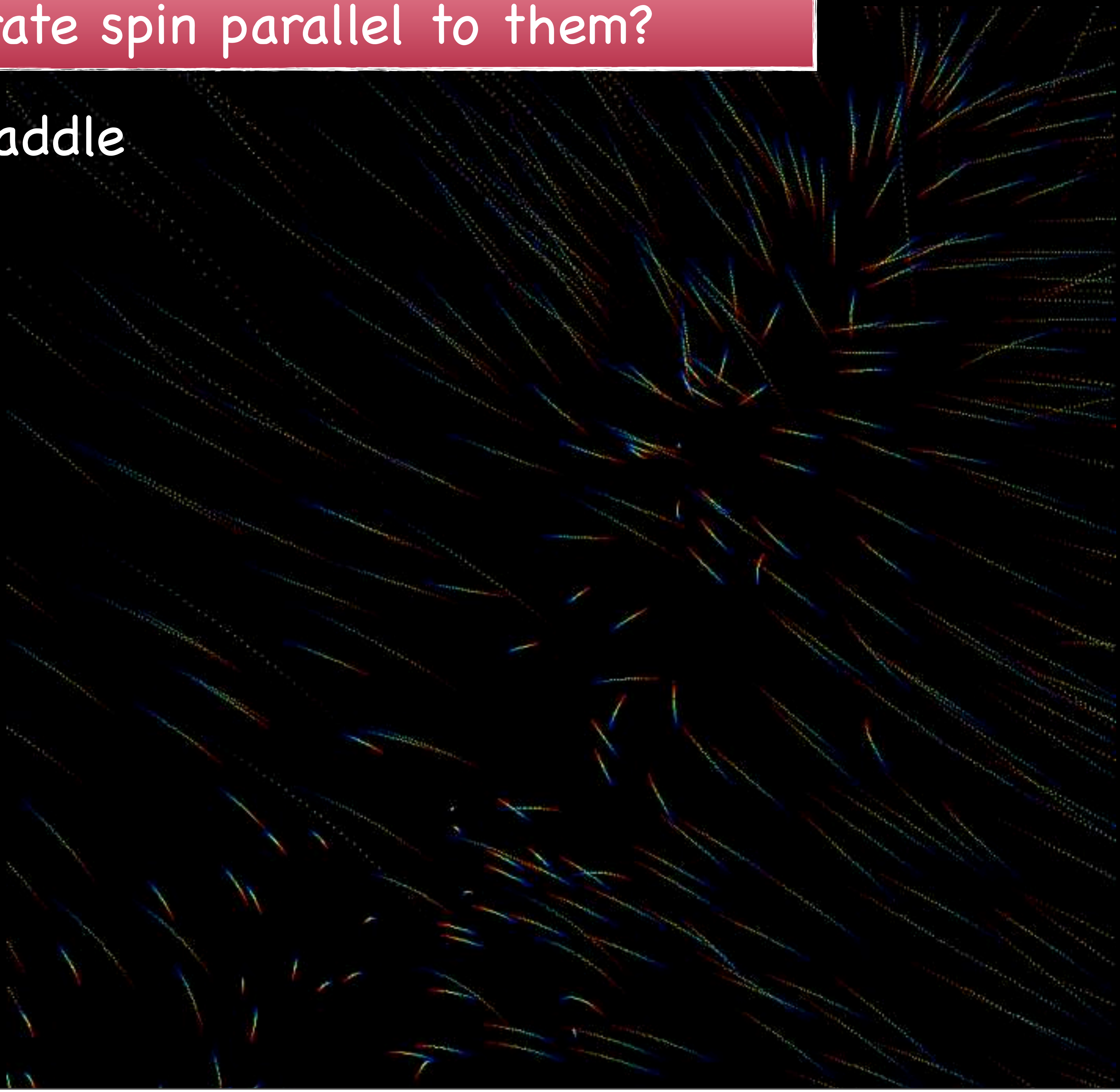
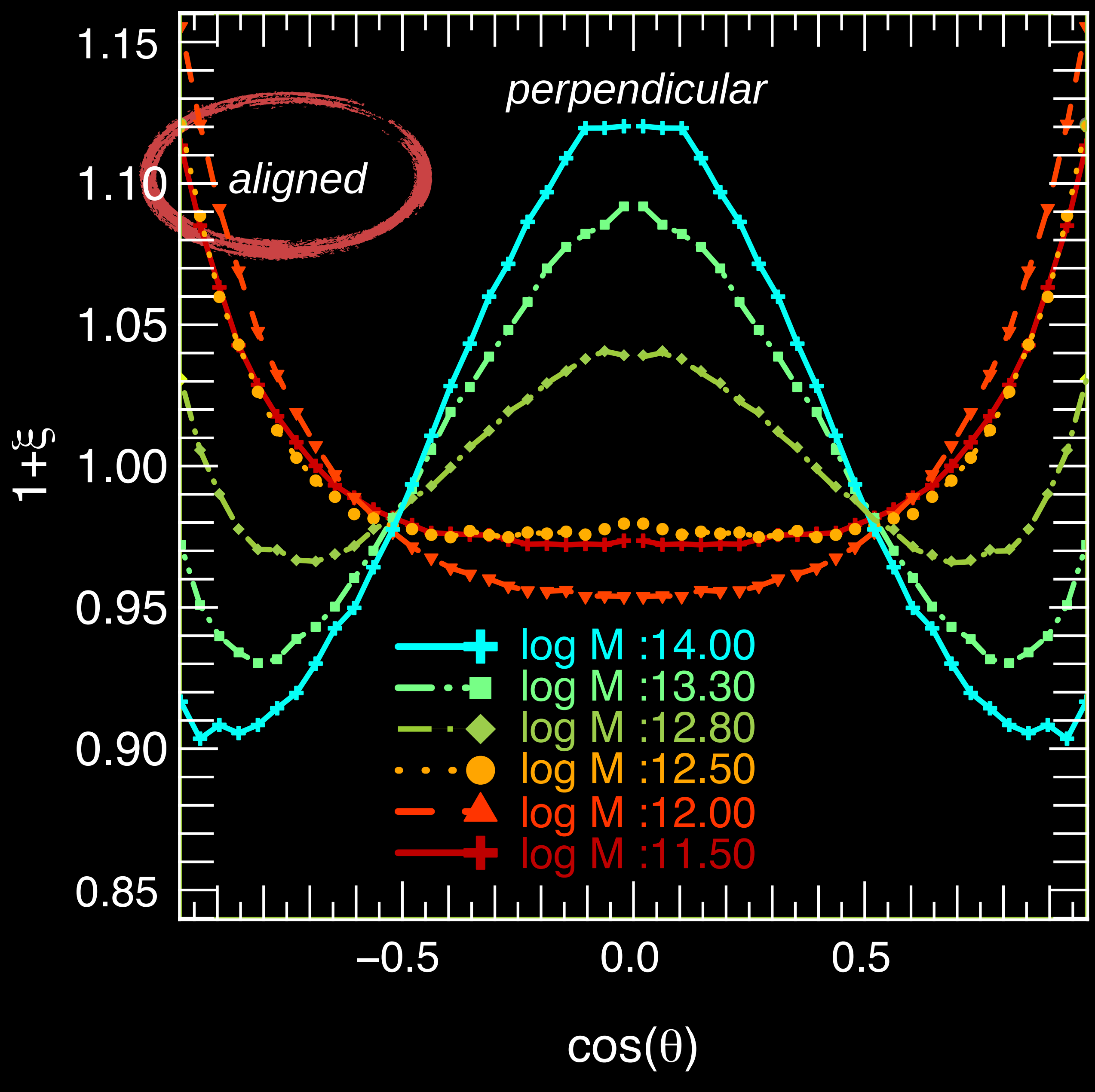


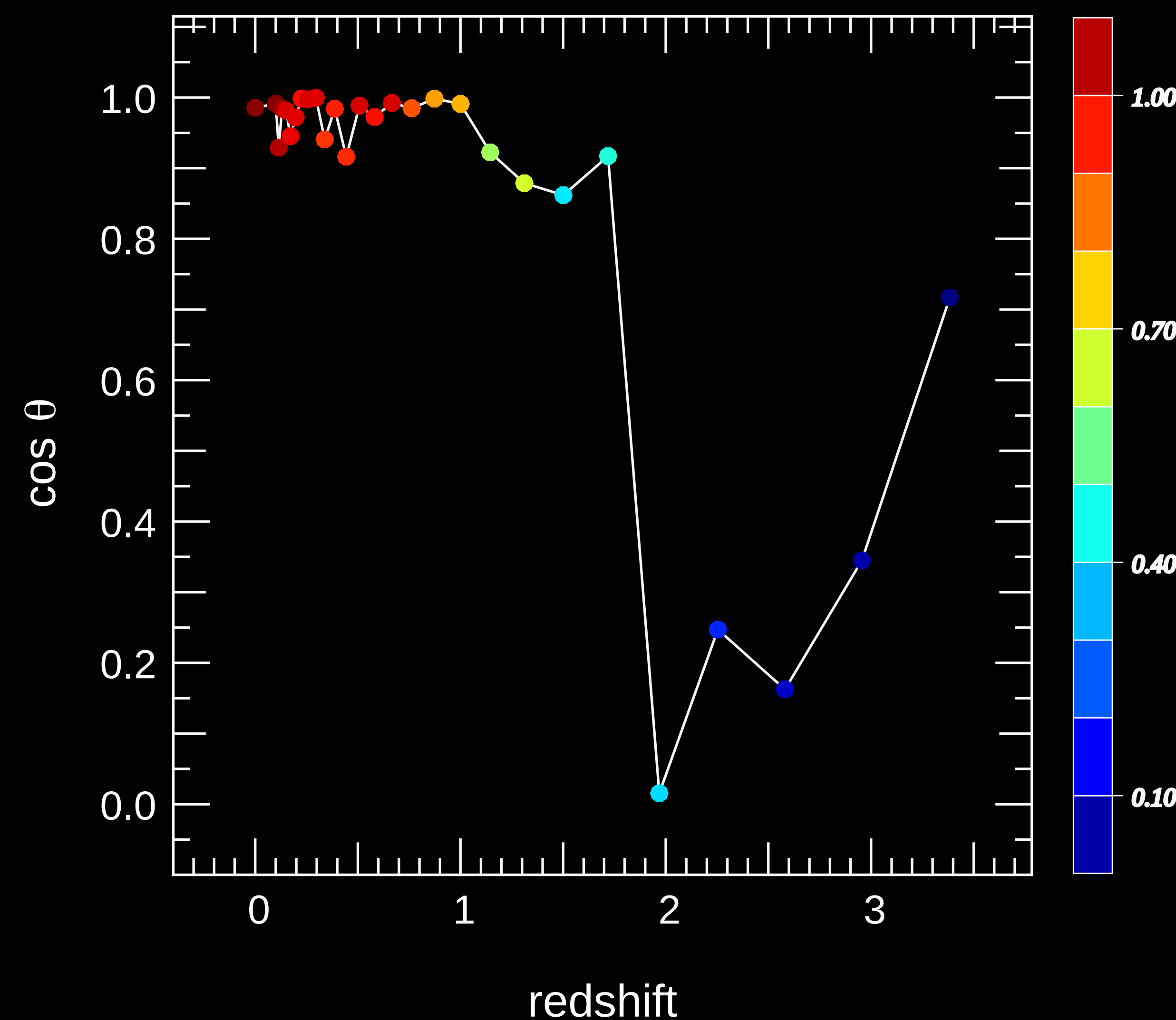
Low-mass haloes: $M < M_{crit}$



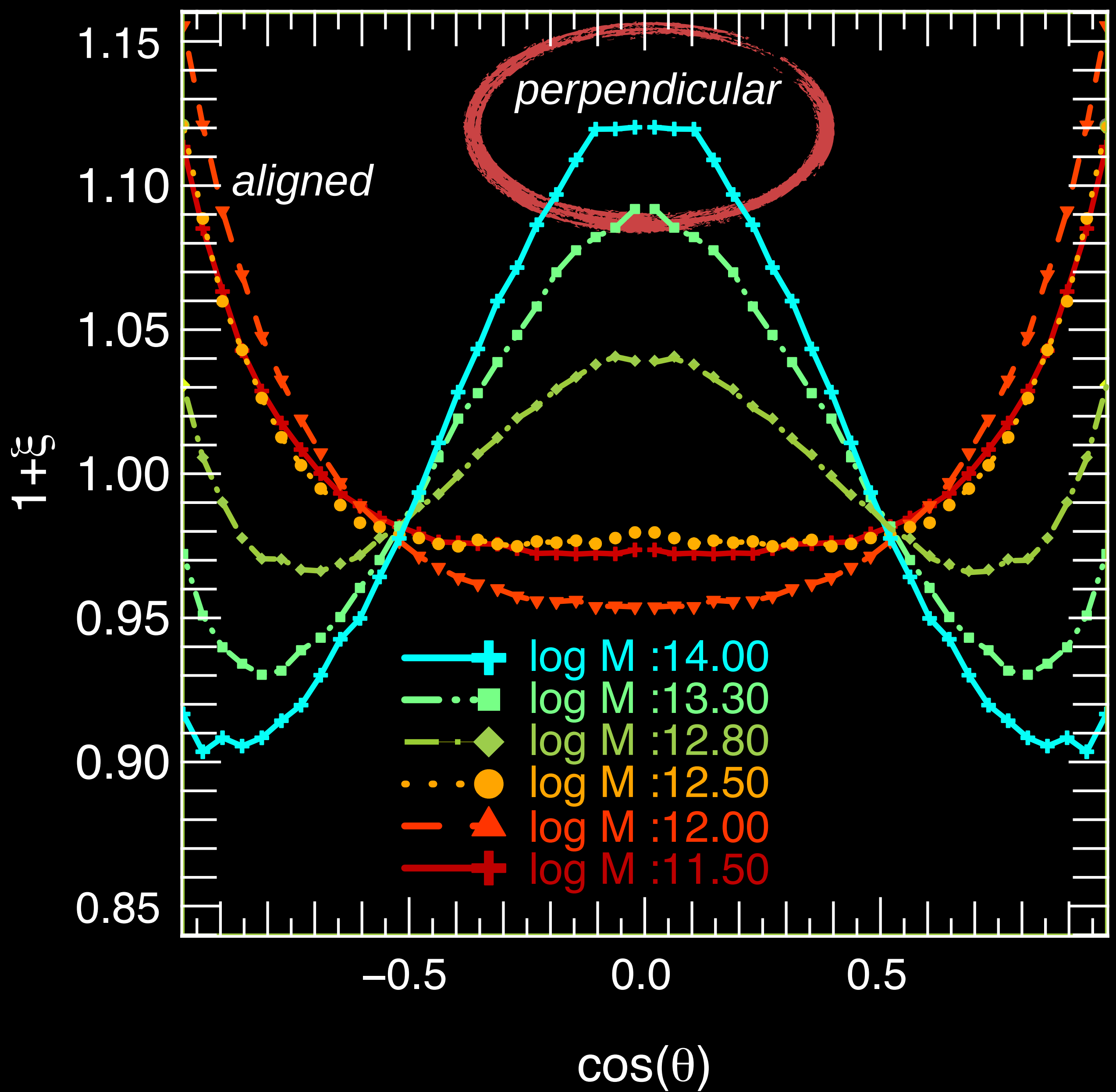
$$M_{crit} = 4 \cdot 10^{12} M_{\odot}$$

-formed at high z during the formation within filaments

-no major merger but smooth accretion until z=0

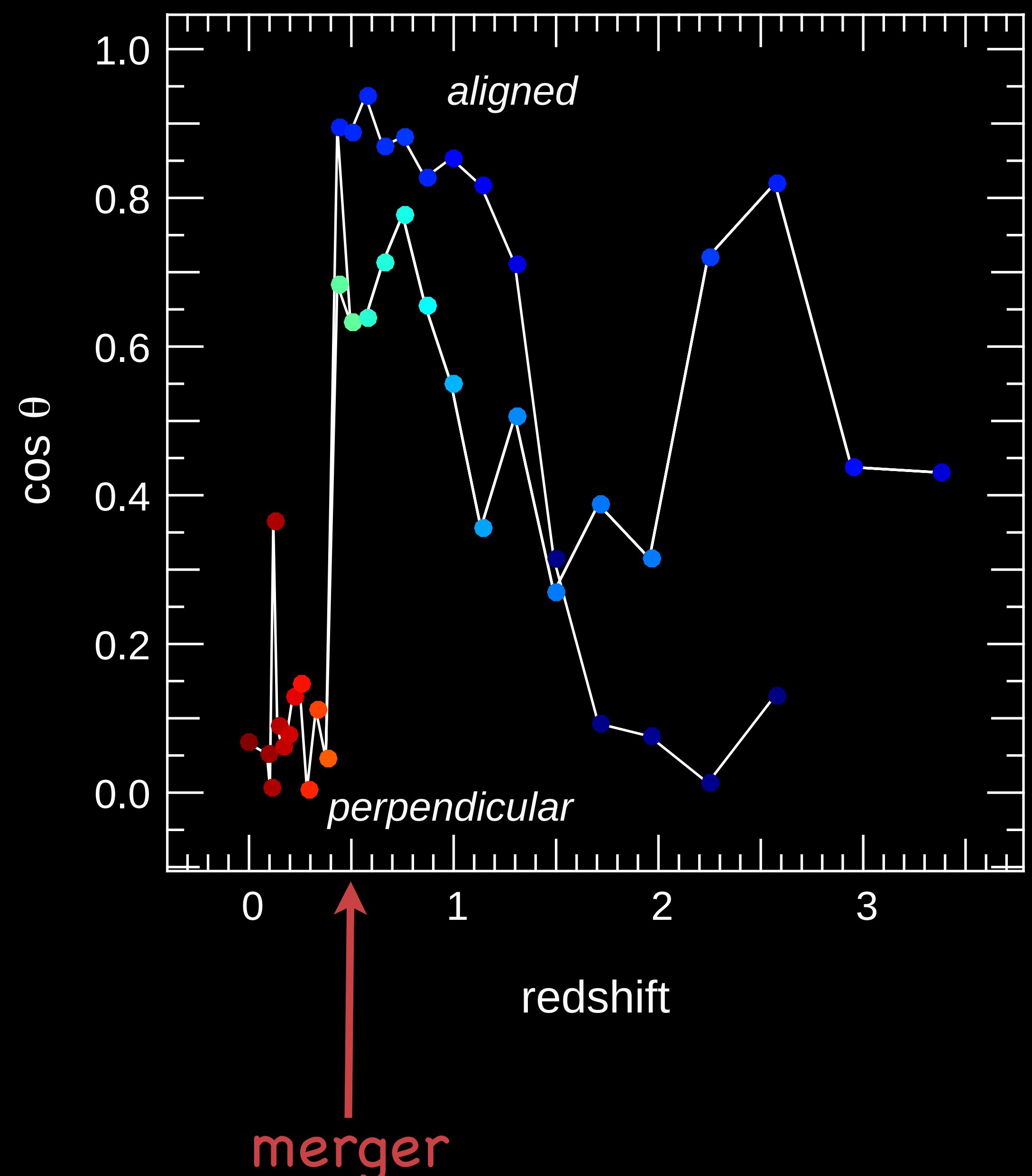


High-mass haloes: $M > M_{\rm crit}$



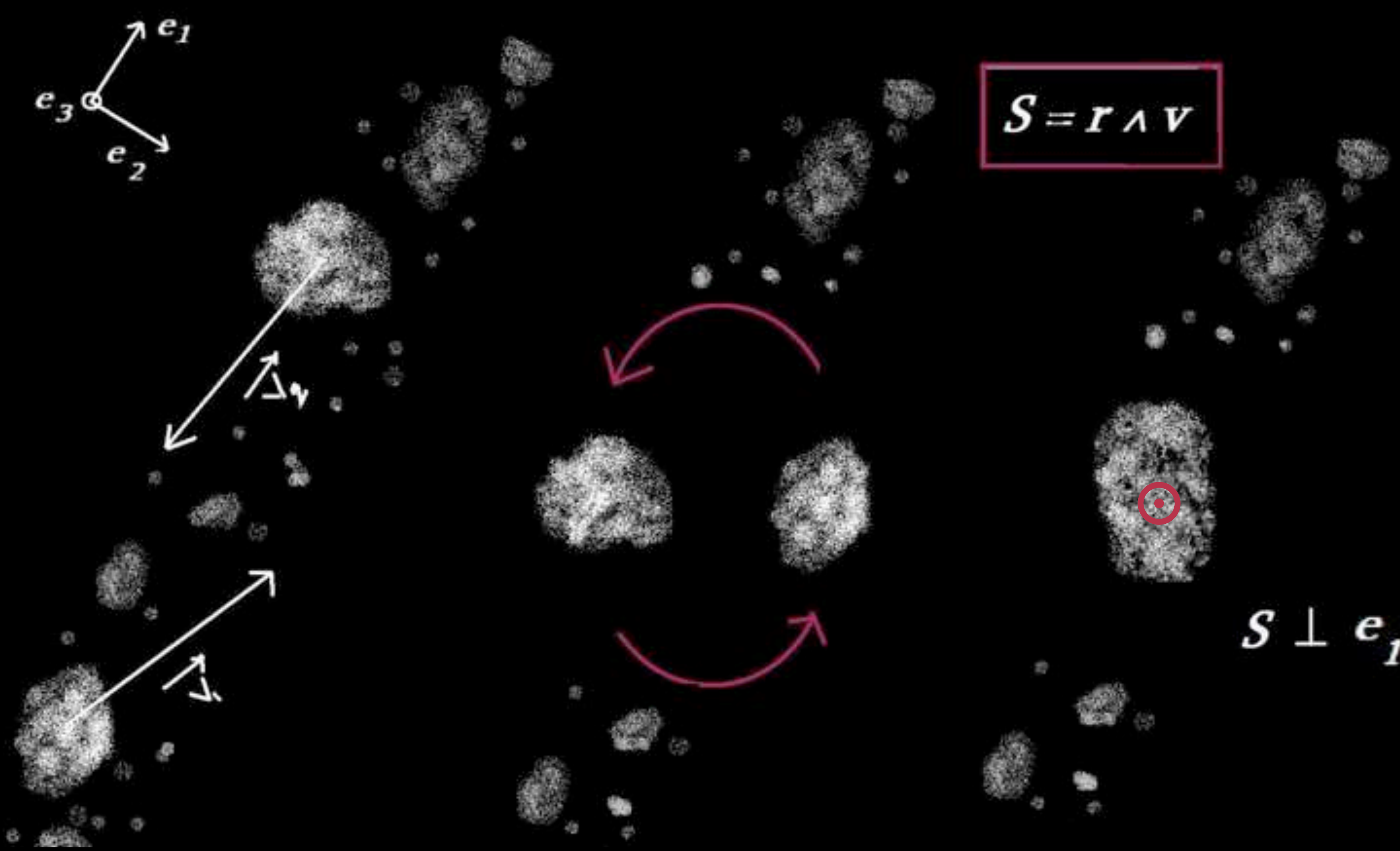
$$M_{\rm crit} = 4 \cdot 10^{12} M_{\odot}$$

formed at low z by mergers inside the filaments

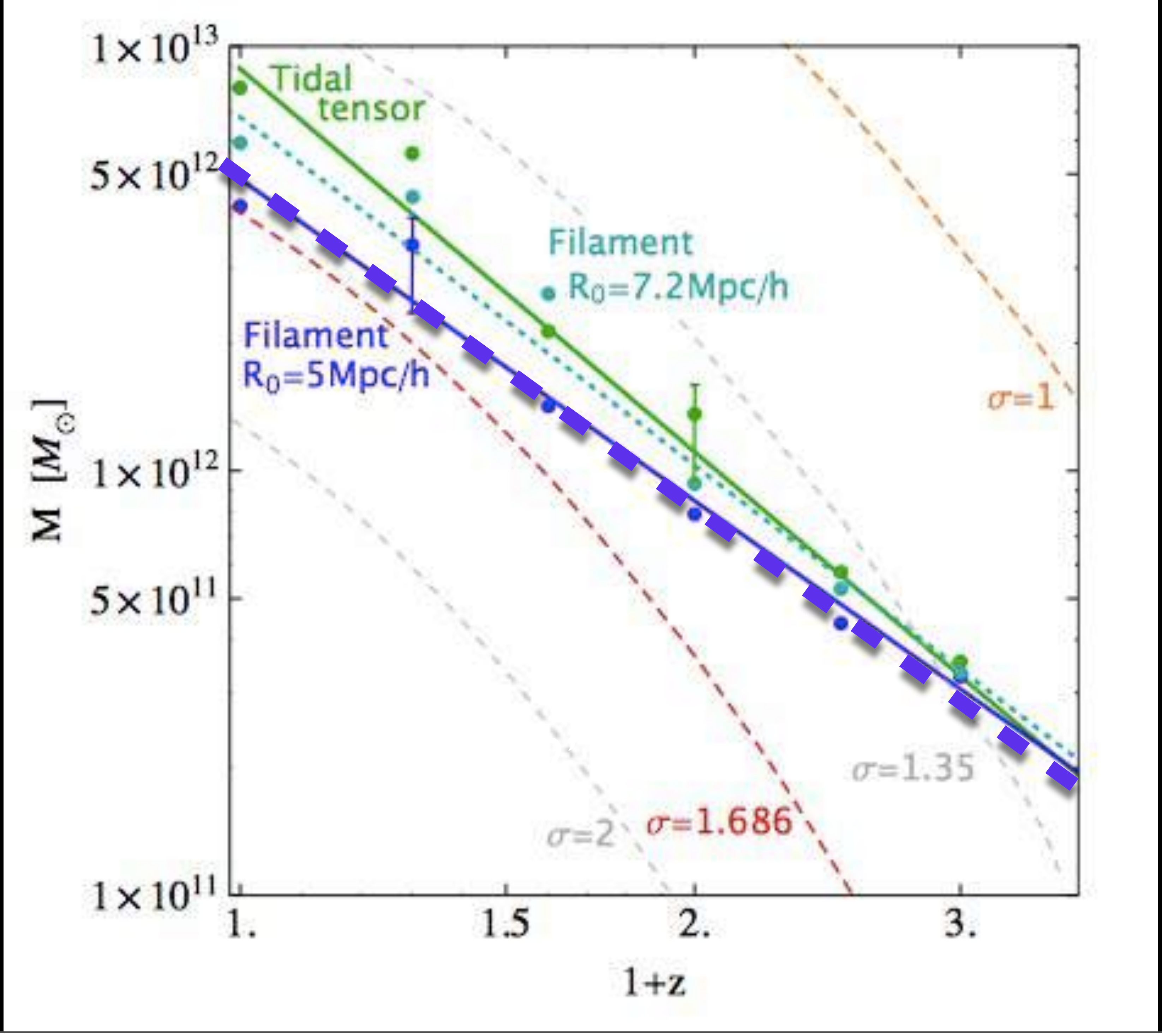


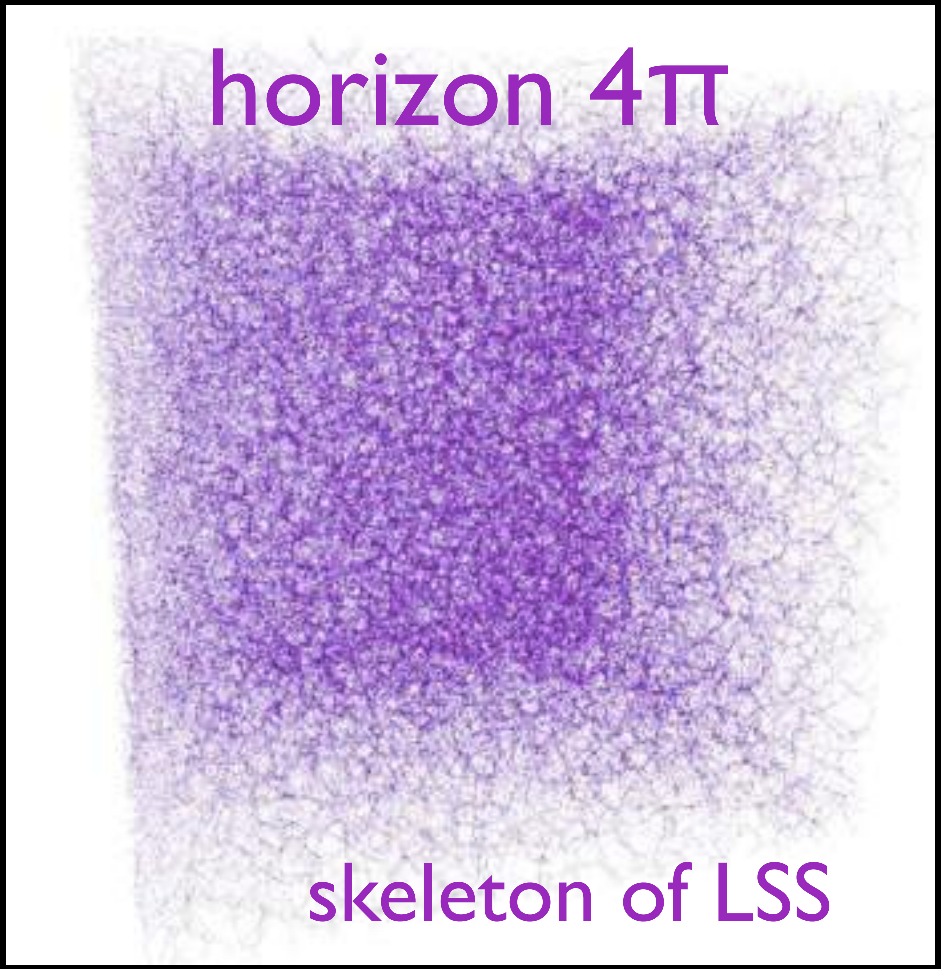
How do mergers along the filaments create spin perpendicular to them?

Halos catch up with each other along the filaments



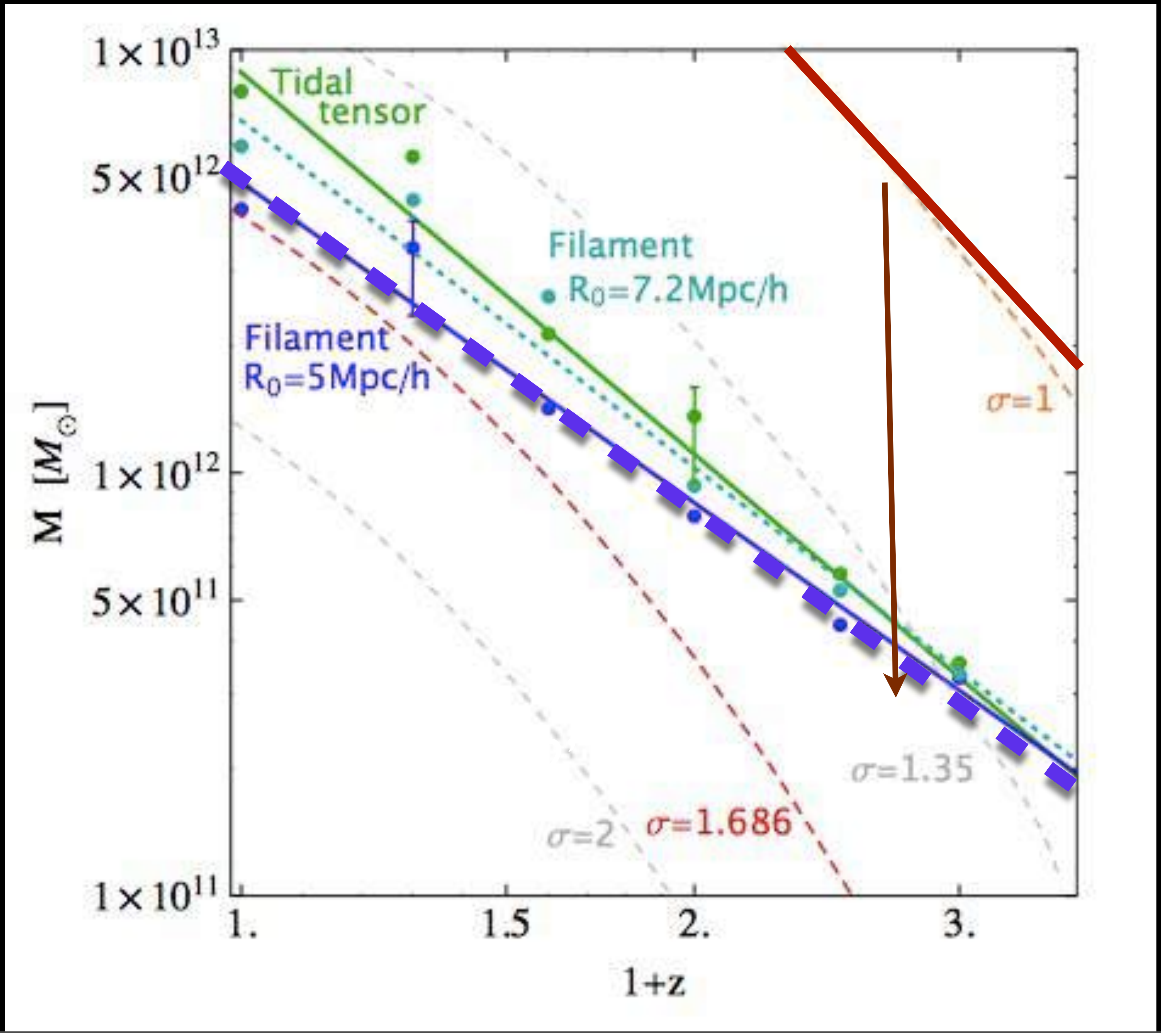
Explain transition mass?

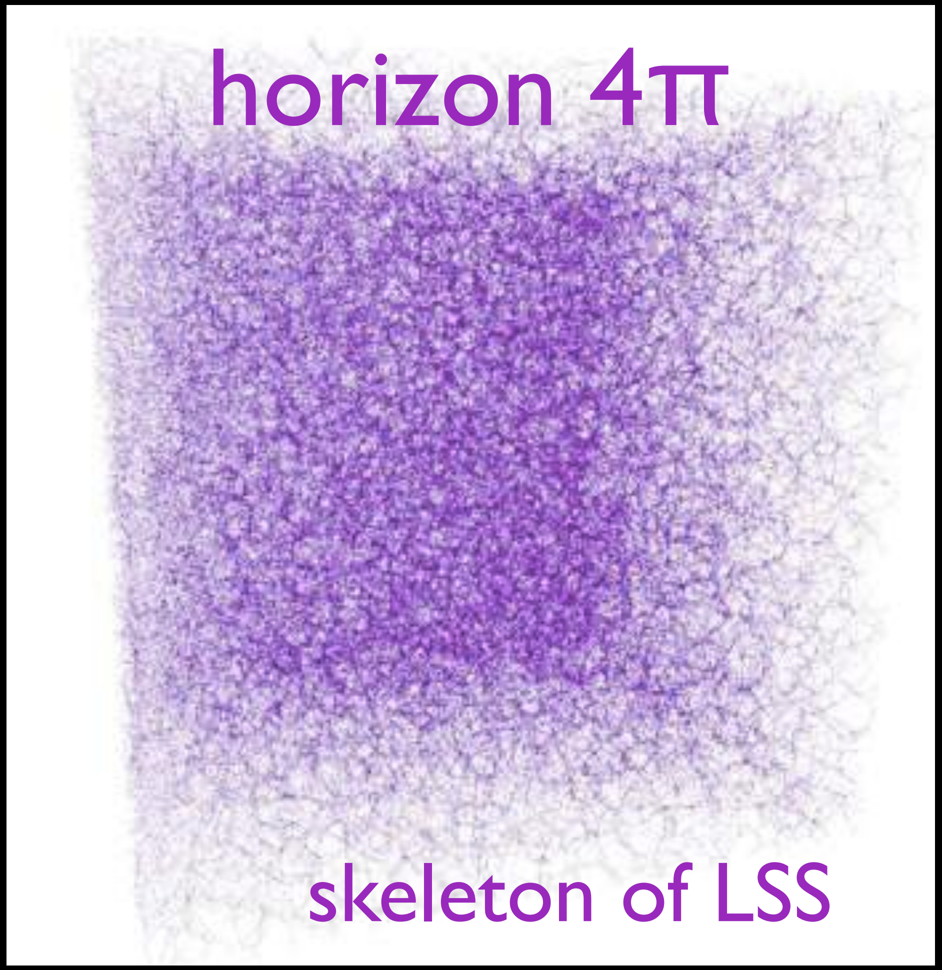




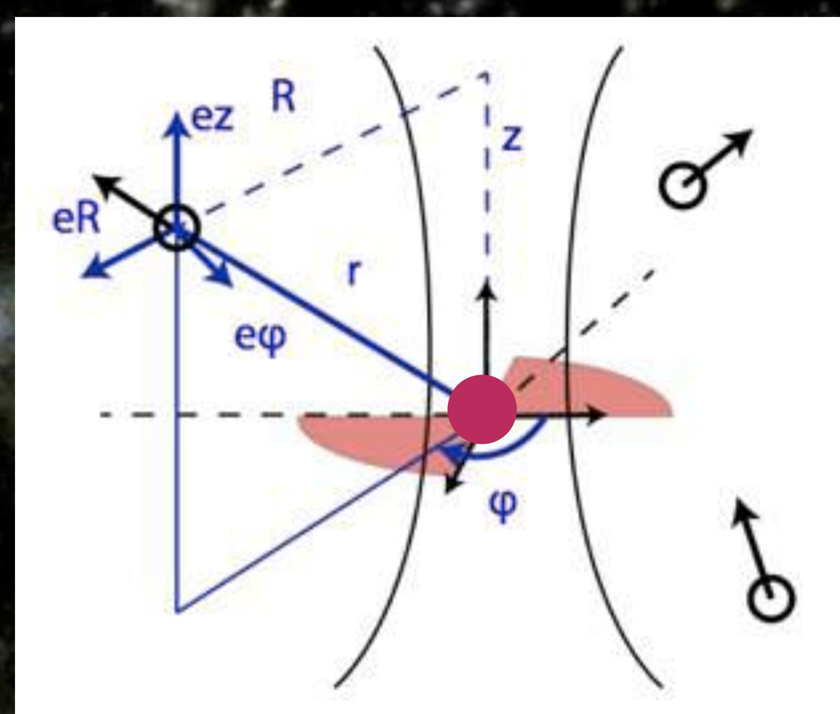
Explain transition mass?

Transition mass versus redshift: **what's wrong???**





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



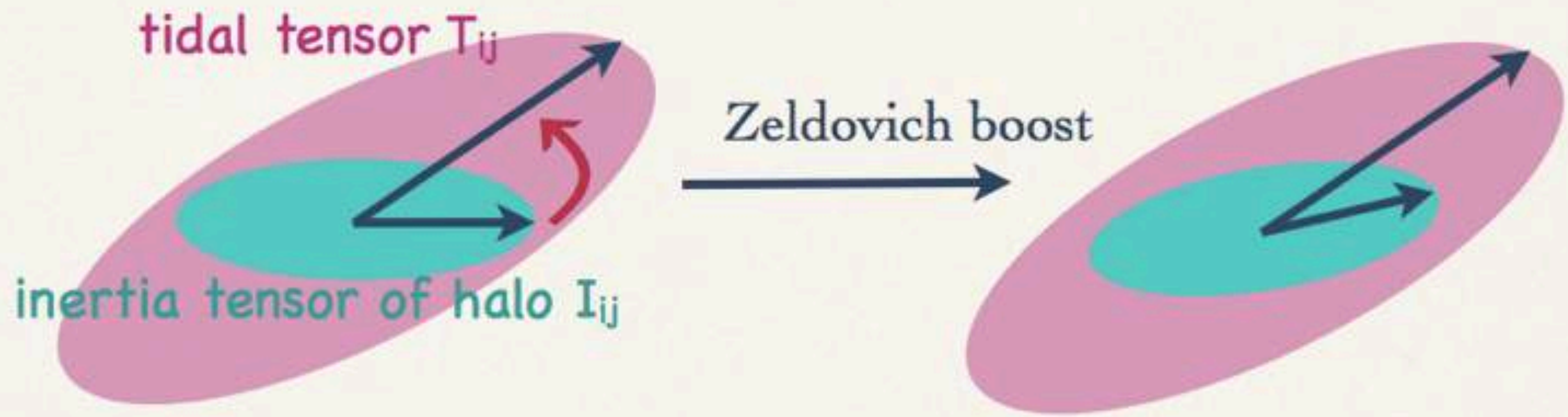
- The Idea
  - walls/filament/peak locally bias differentially tidal and inertia tensor: spin alignment reflect this in TTT
- The picture
  - Geometry of spin near saddle: point reflection symmetric distribution, 1/10 of 'naive size'
- The Maths
  - Very simple **ab initio** prediction for **mass transition**

The Lagrangian view of spin/LSS connection

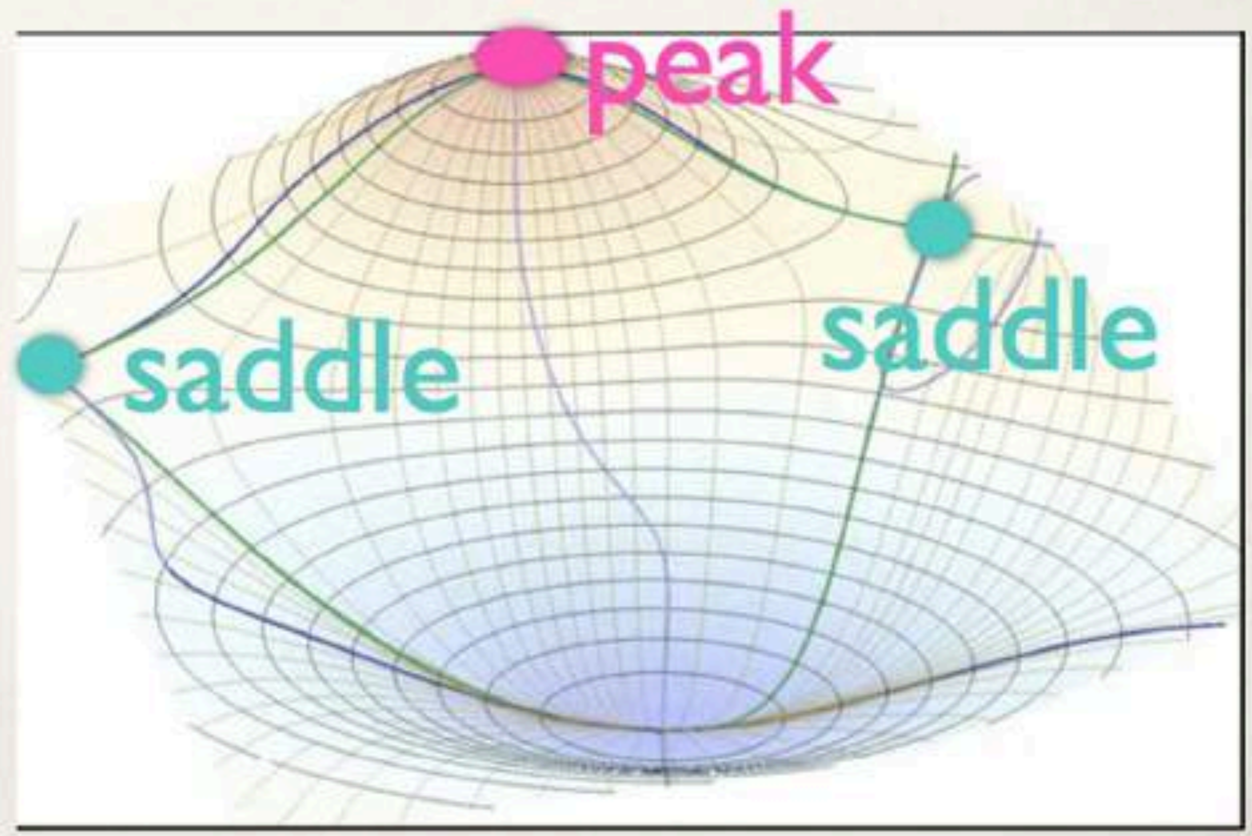
Can we understand where spin and vorticity alignments come from?

-usual tidal torque theory

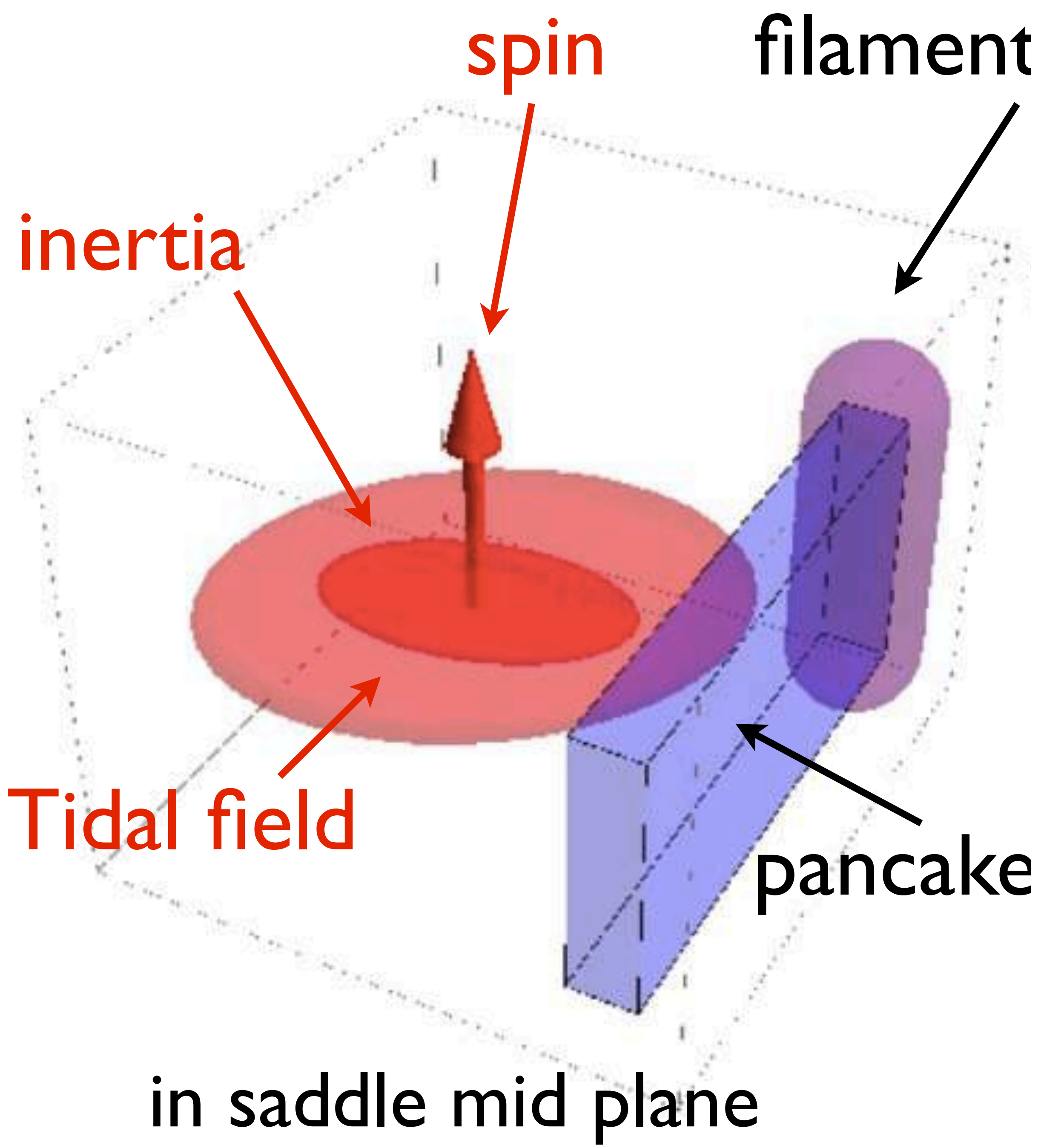
$$L_k = \varepsilon_{ijk} I_{li} T_{lj}$$



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



Tidal/Inertia mis-alignment



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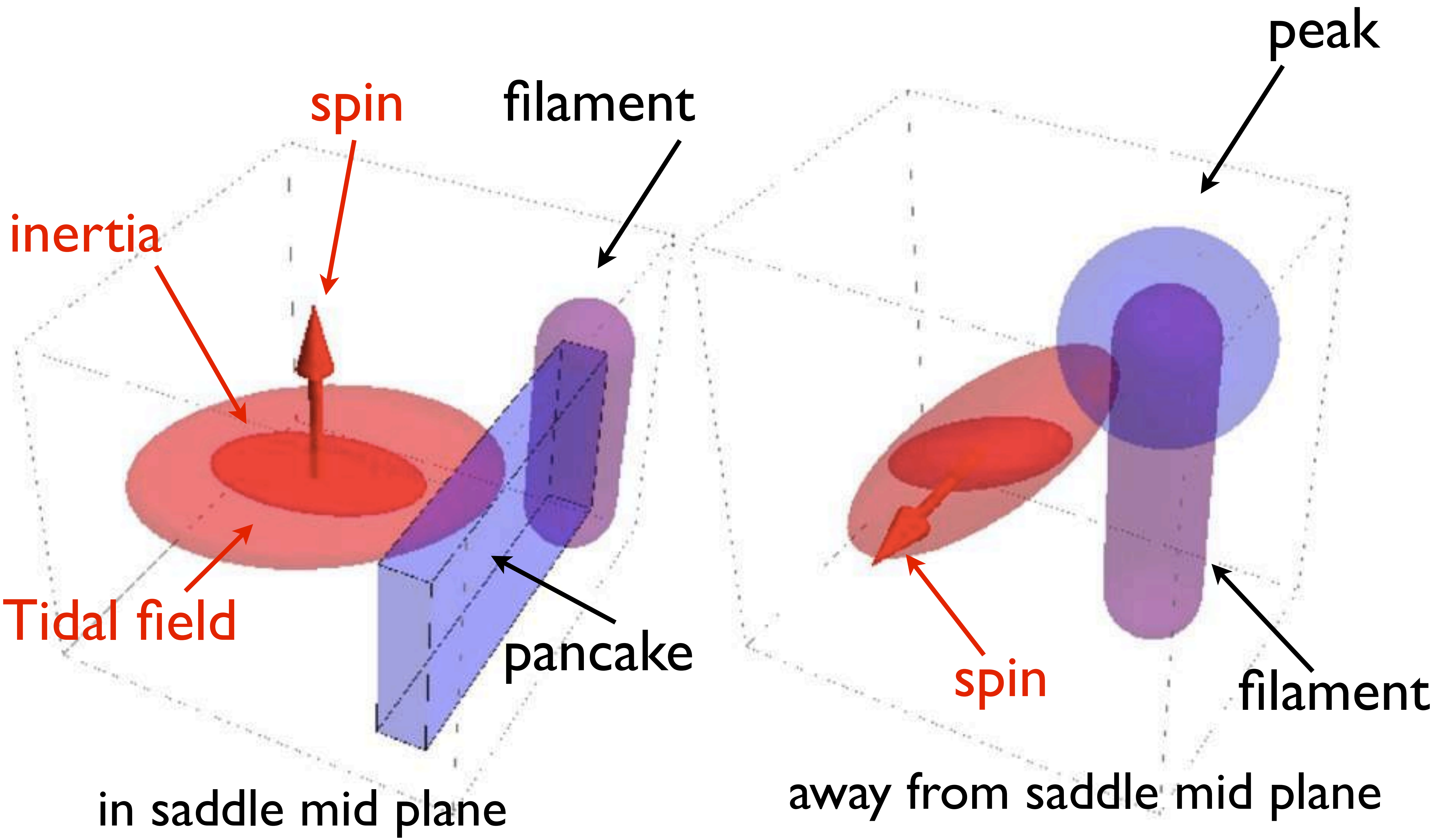
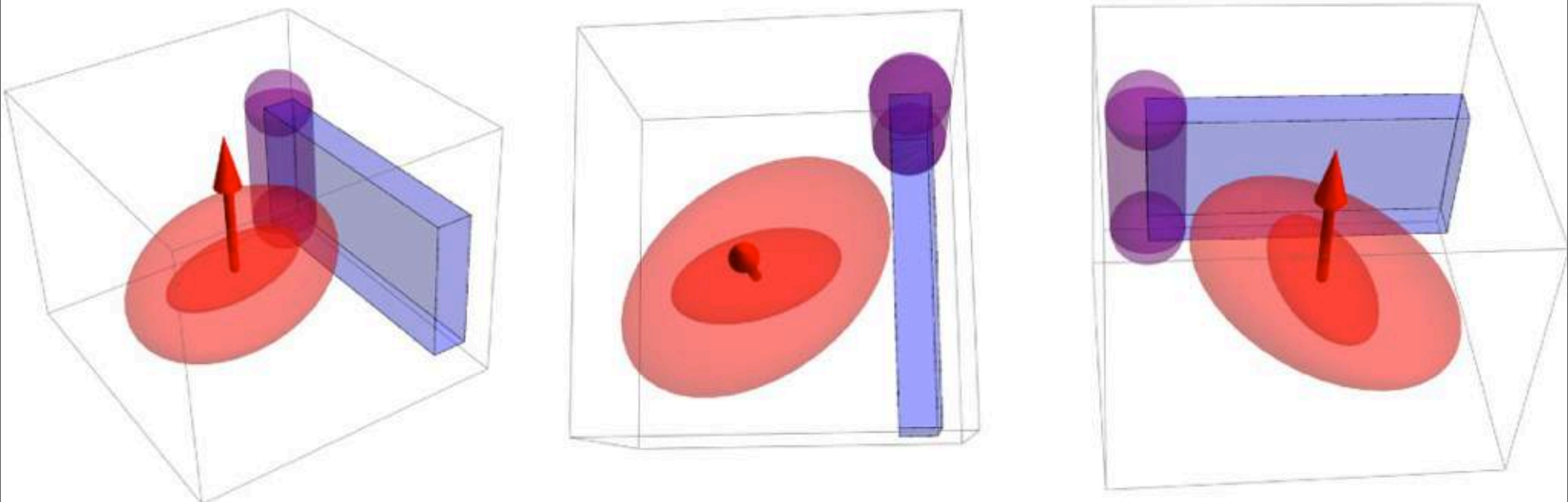
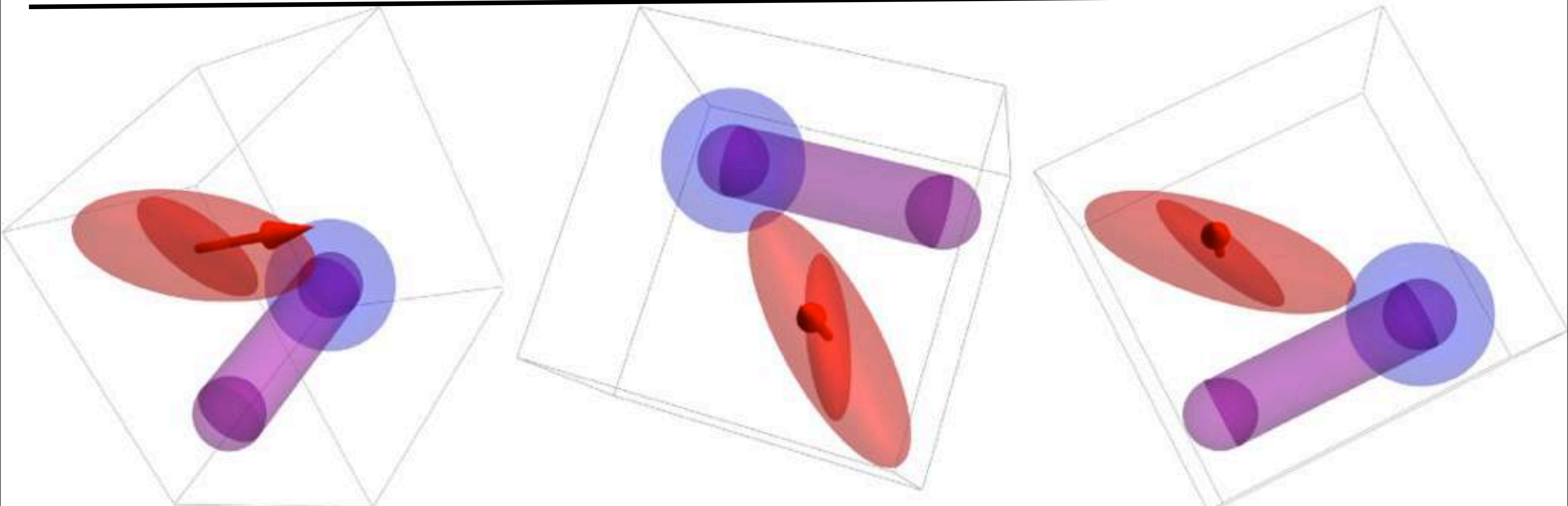


spin wall -filament





spin filament-cluster

animation?

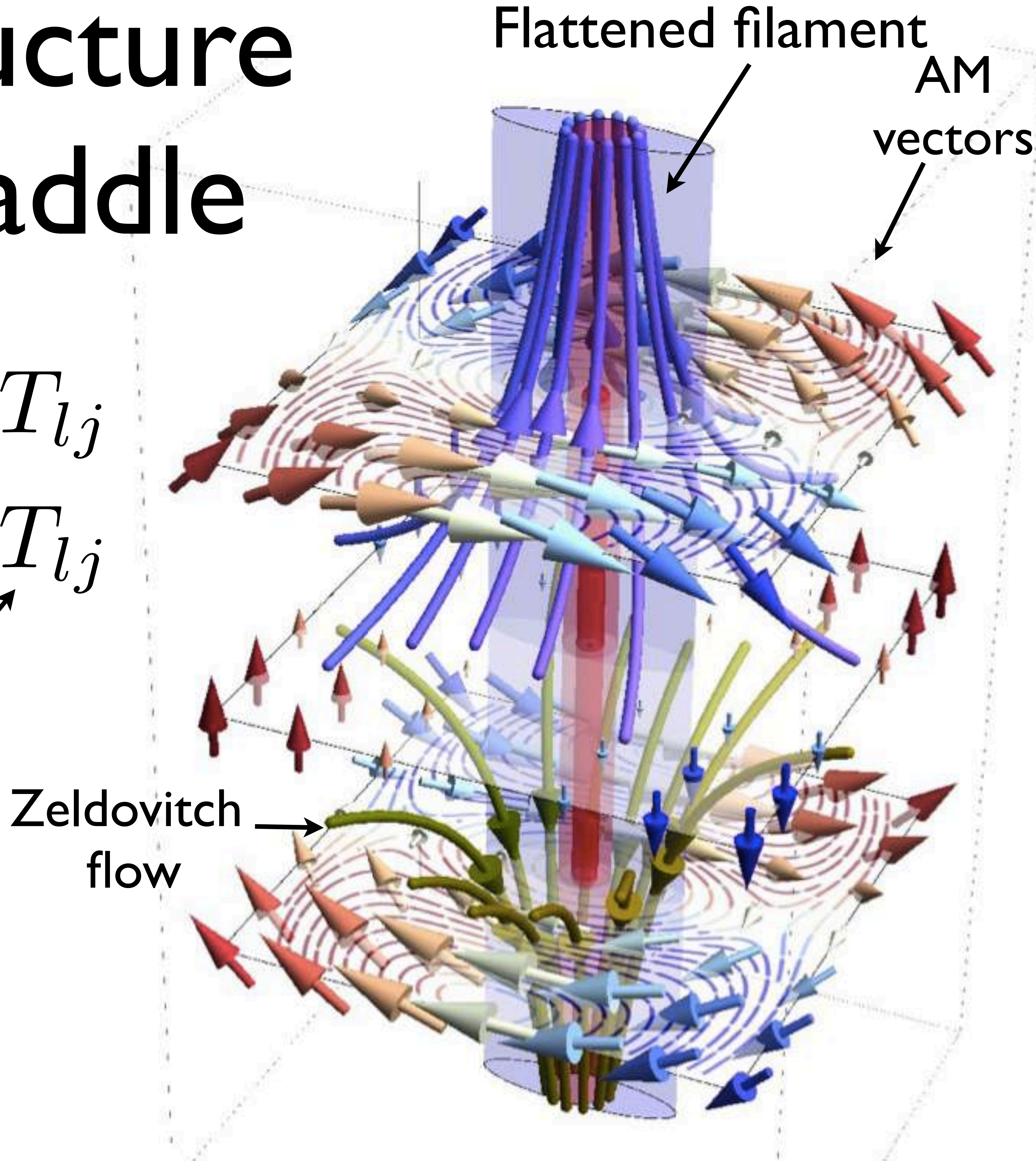
Spin structure near Saddle

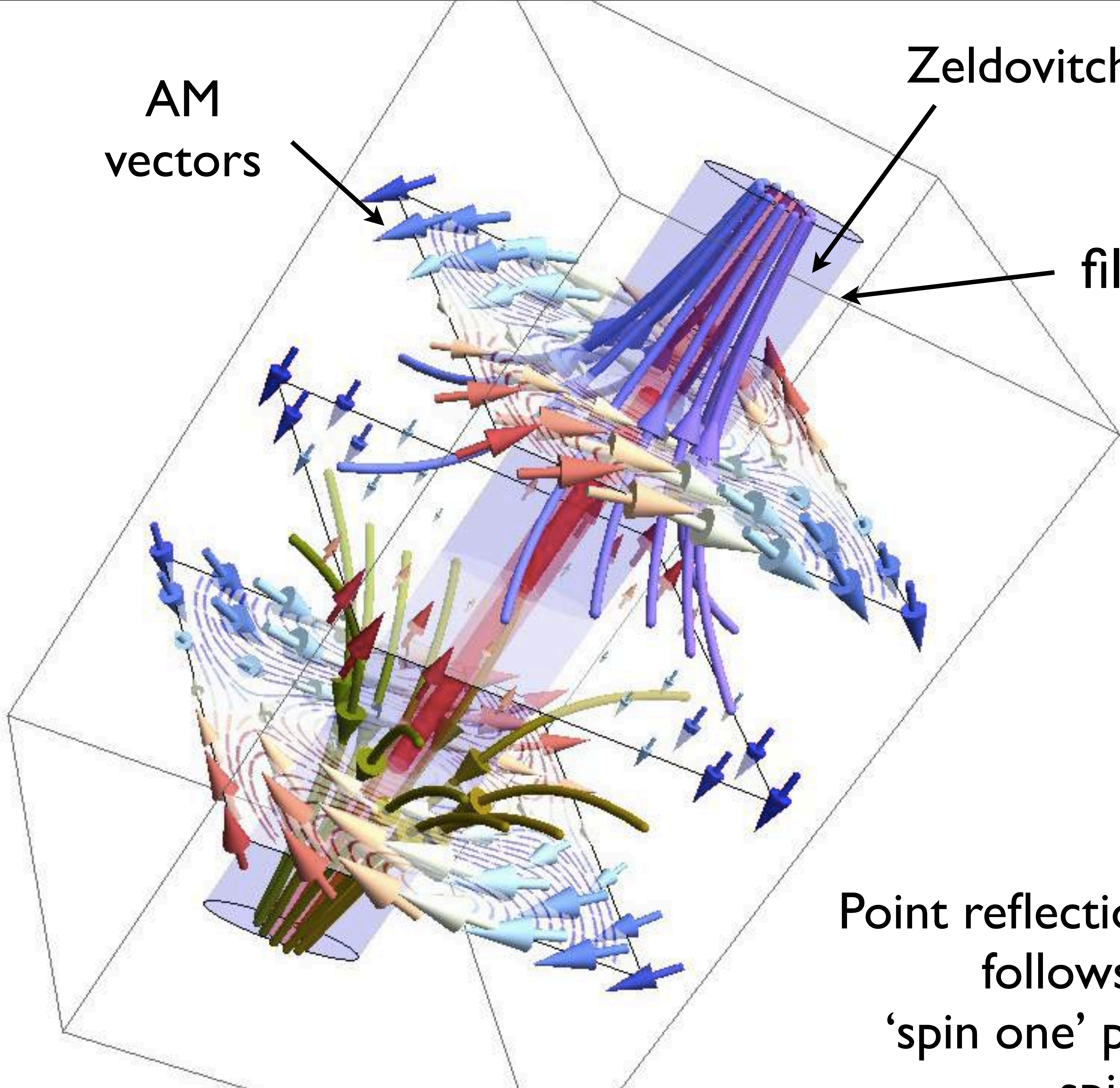
$$L_k = \varepsilon_{ijk} I_{li} T_{lj}$$

$$\approx \varepsilon_{ijk} H_{li} T_{lj}$$

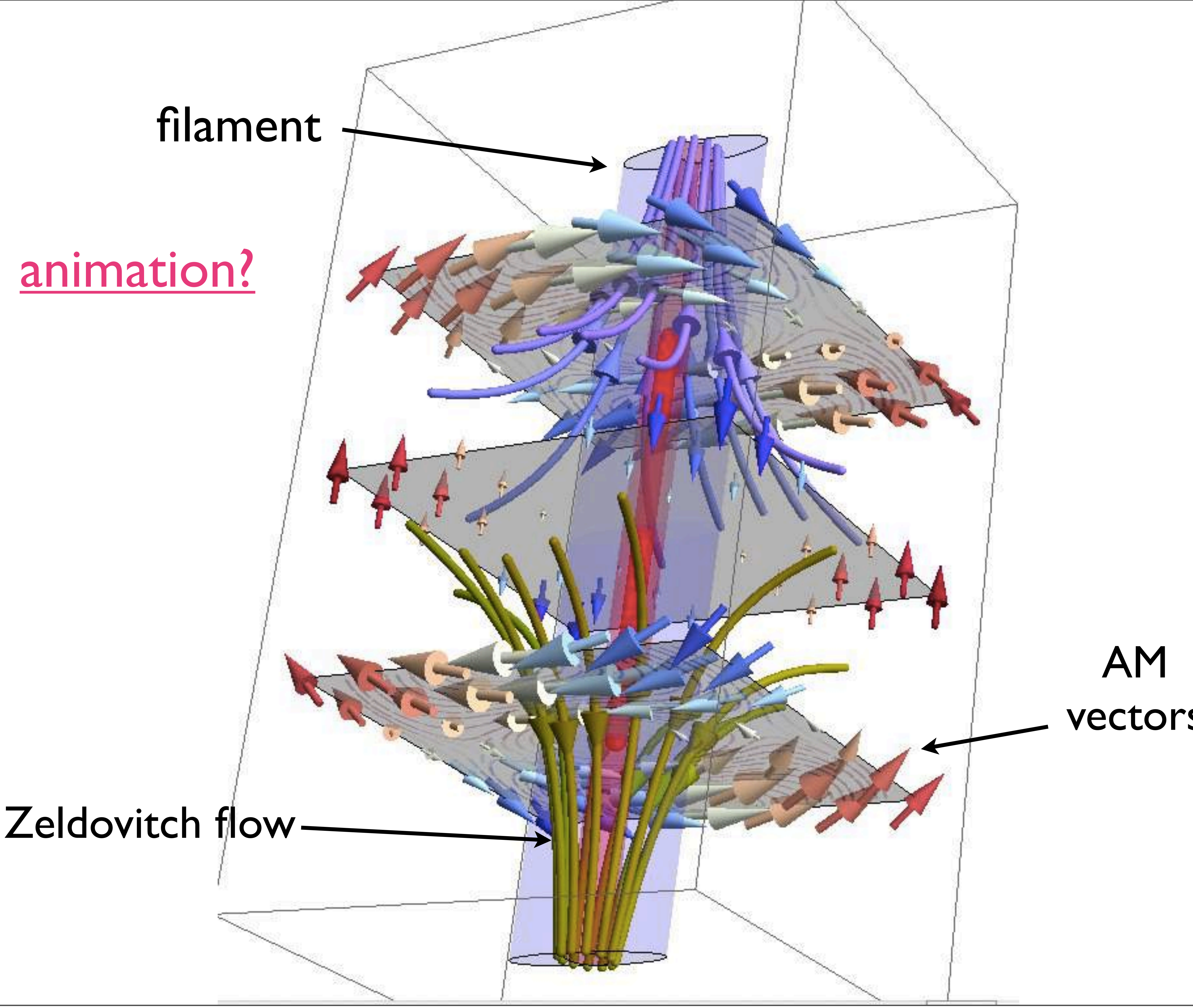
Hessian

Tidal





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


filament
animation?
AM
vectors
Zeldovitch flow

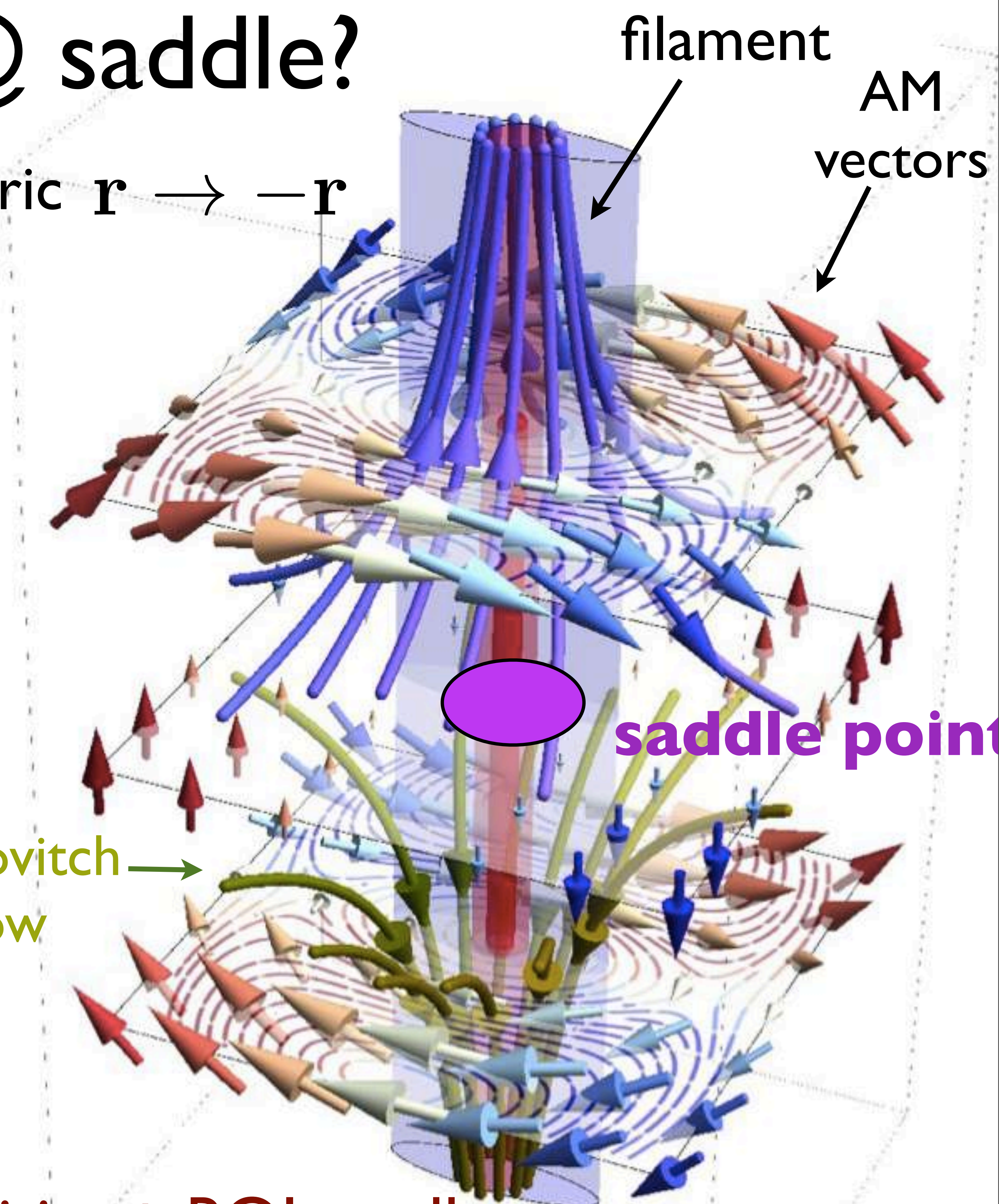
3D TTT@ saddle?

- point reflection symmetric $\mathbf{r} \to -\mathbf{r}$
- vanish if no a-symmetry

perp. along e_φ

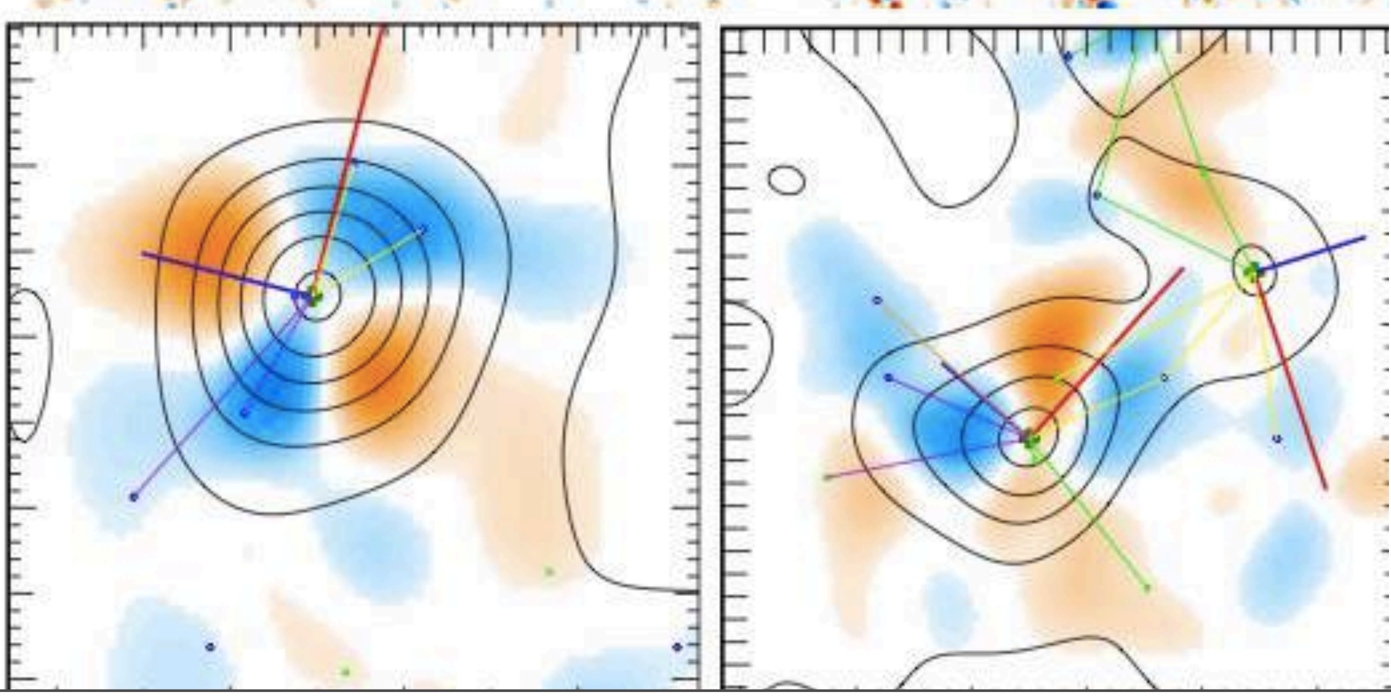
spin //
to filament

perp =
along e_φ



spatial transition+ ROI smaller

Does it work with log-Gaussian Random Fields?



point reflection symmetry for realistic sets of saddles from log GRF

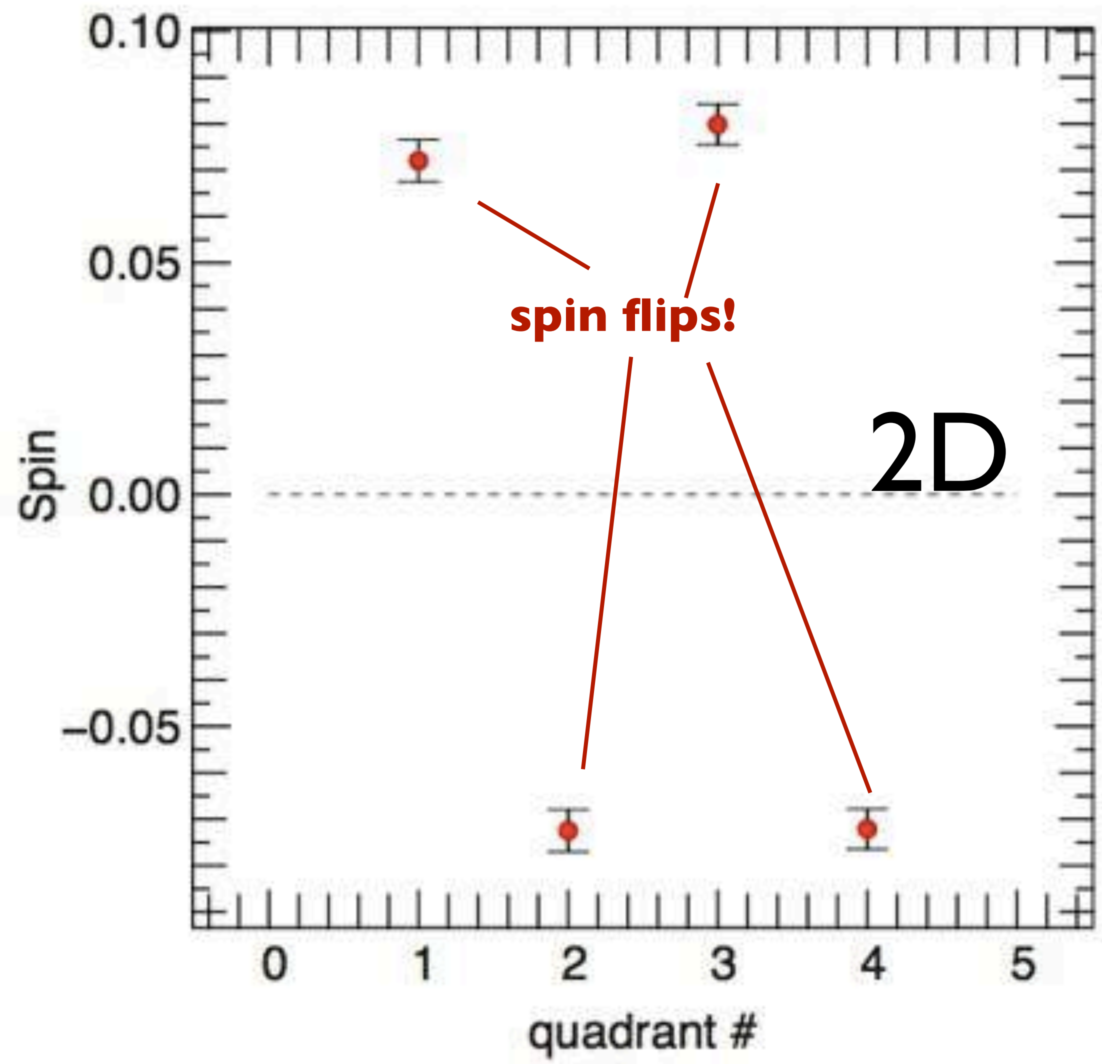
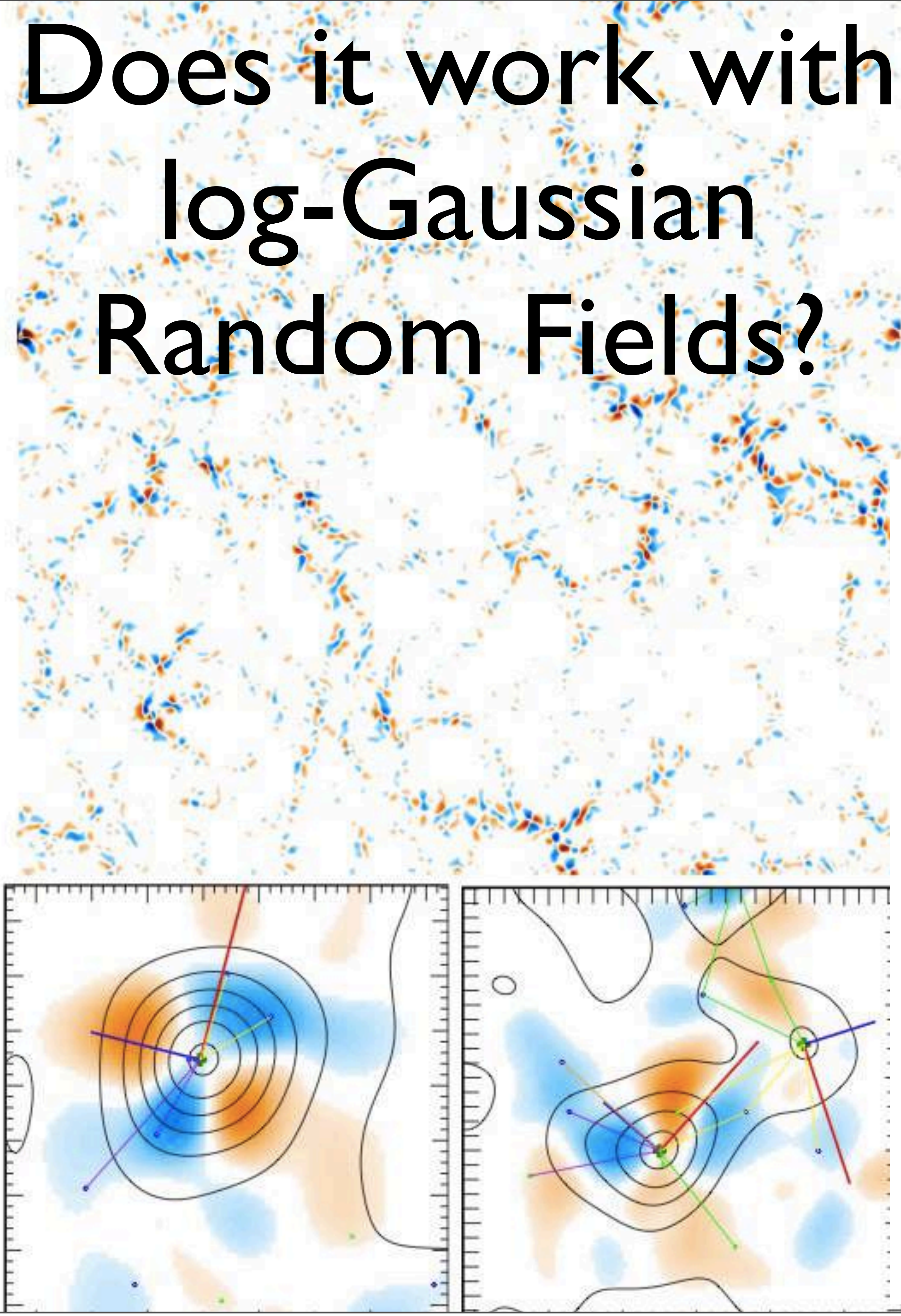


Figure 11. Alignment of 'spin' along $\mathbf{e}_z$ in 2D as a function of quadrant rank, clockwise. As expected, from one quadrant to the next, the spin is flipping sign.

Does it work with log-Gaussian Random Fields?



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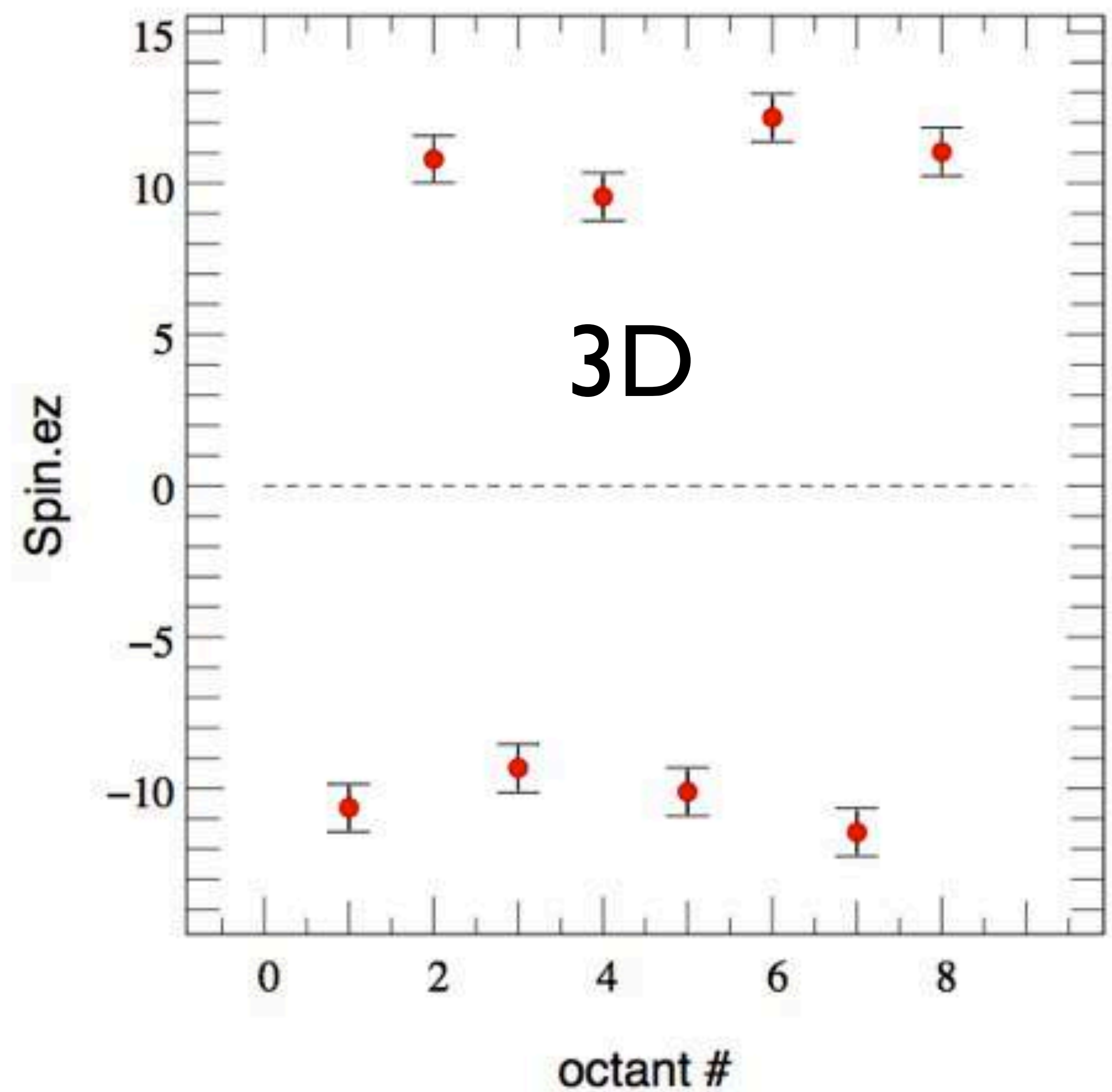
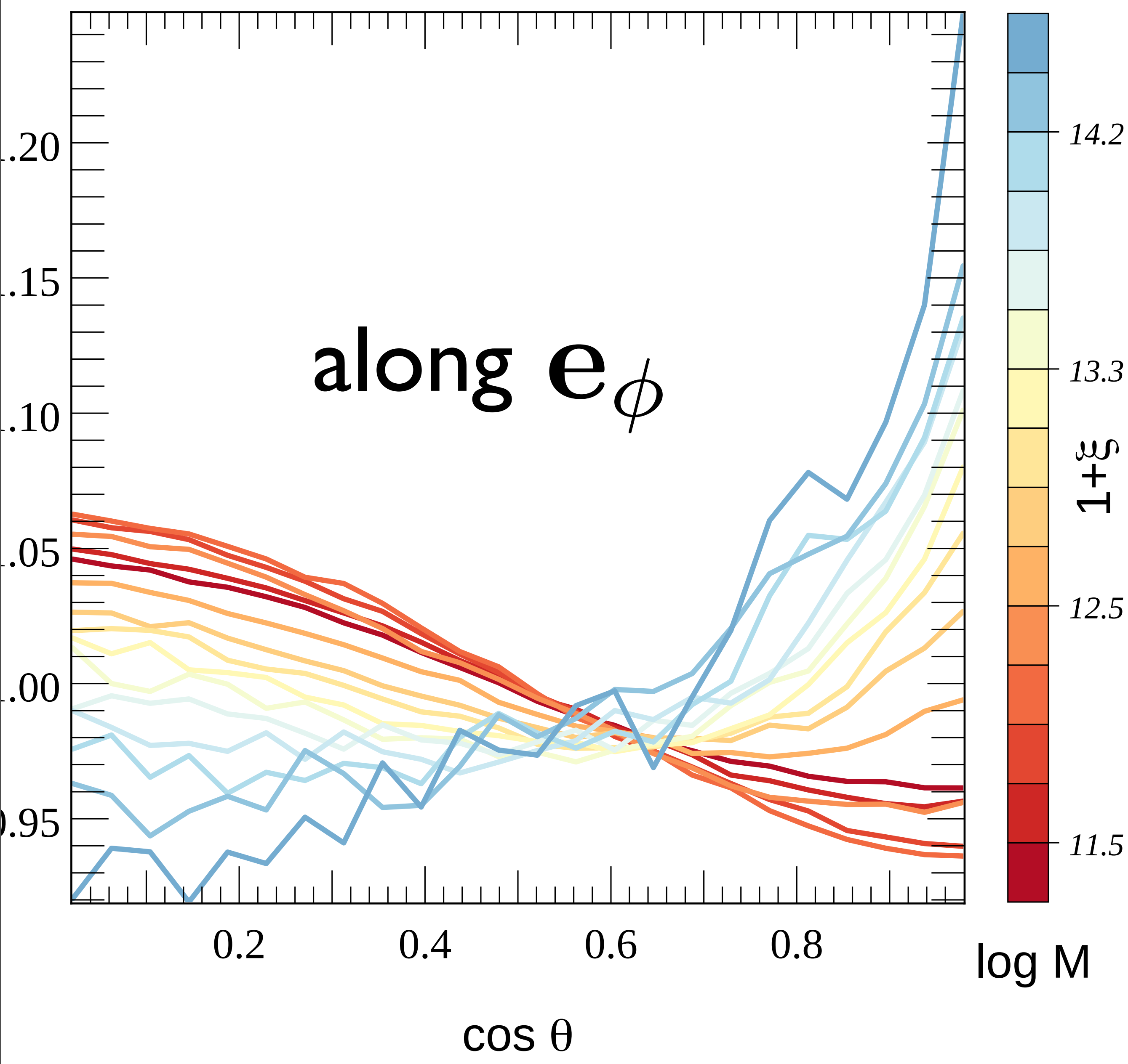
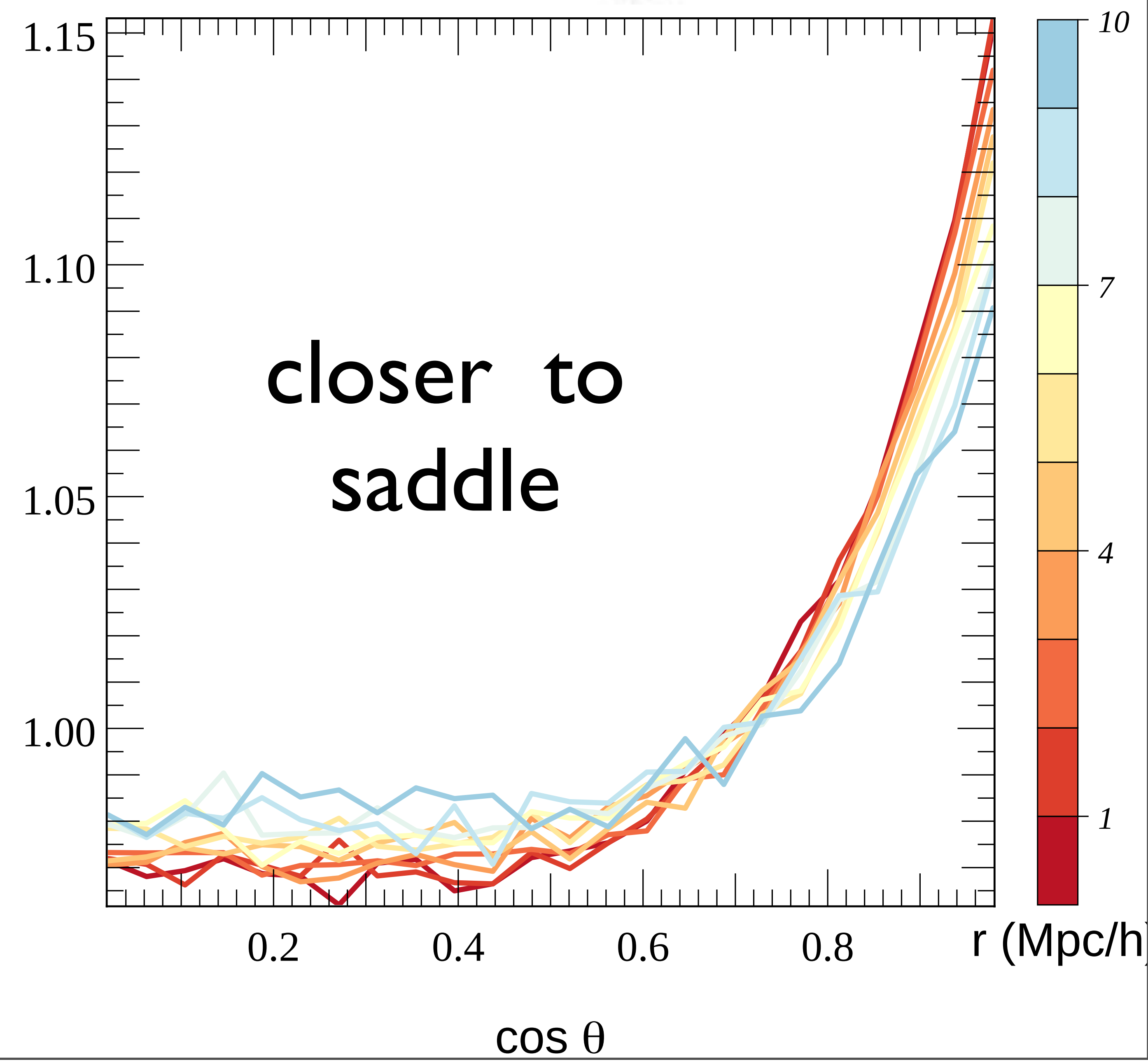


Does it work with Dark matter @ z=0?

Clear predictions of aTTT





2D Spin acquisition near peaks

Codis, Pichon, Pogosyan, in prep.

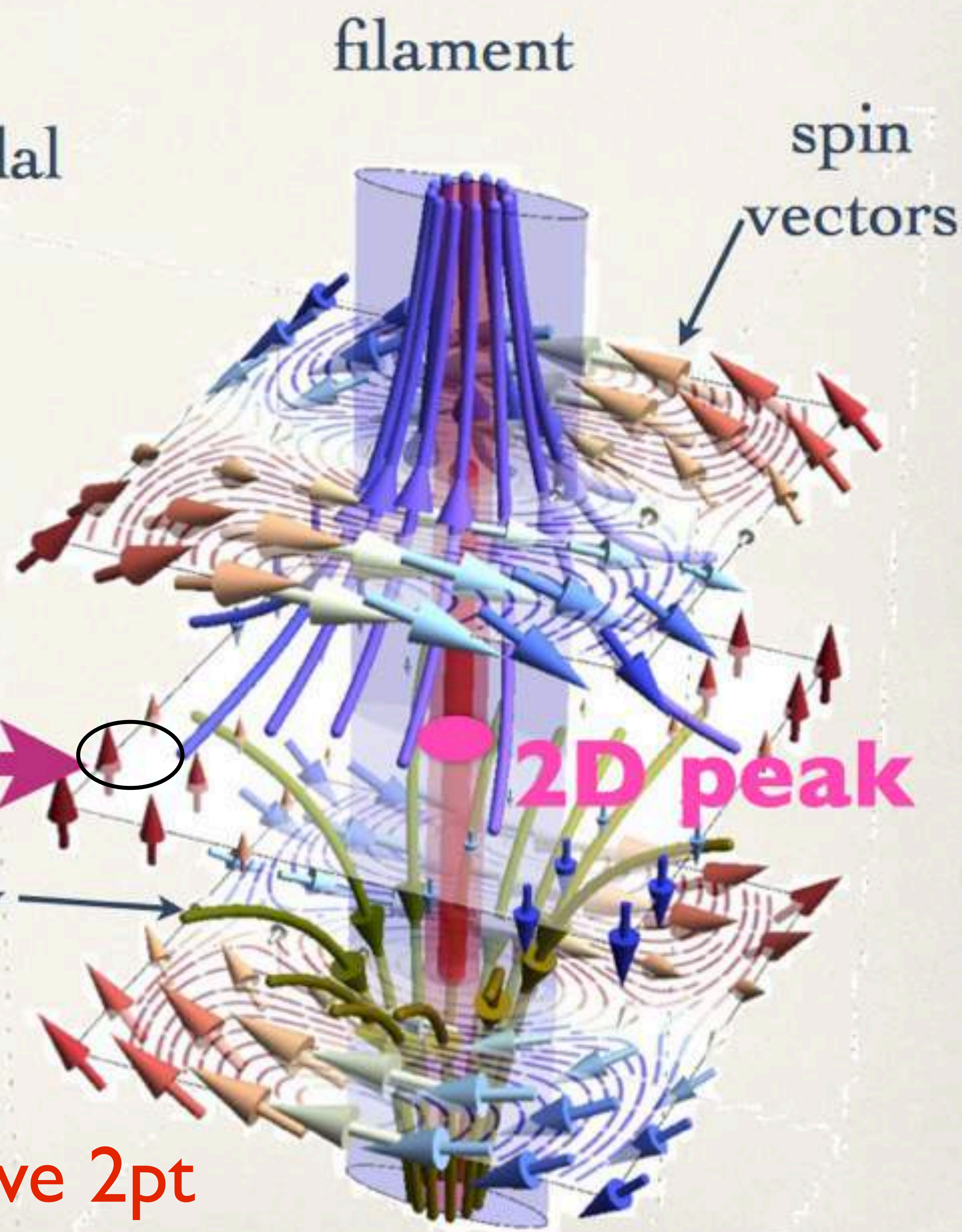
$$L_k = \varepsilon_{ijk} I_{li} T_{lj}$$
$$\approx \varepsilon_{ijk} H_{li} T_{lj}$$

Tidal

Hessian

<L|peak>$_{2D}$?

Zeldovich flow



Theory will involve 2pt correlation of field AND 2nd derivatives

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

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

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

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

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

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

3D

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)

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

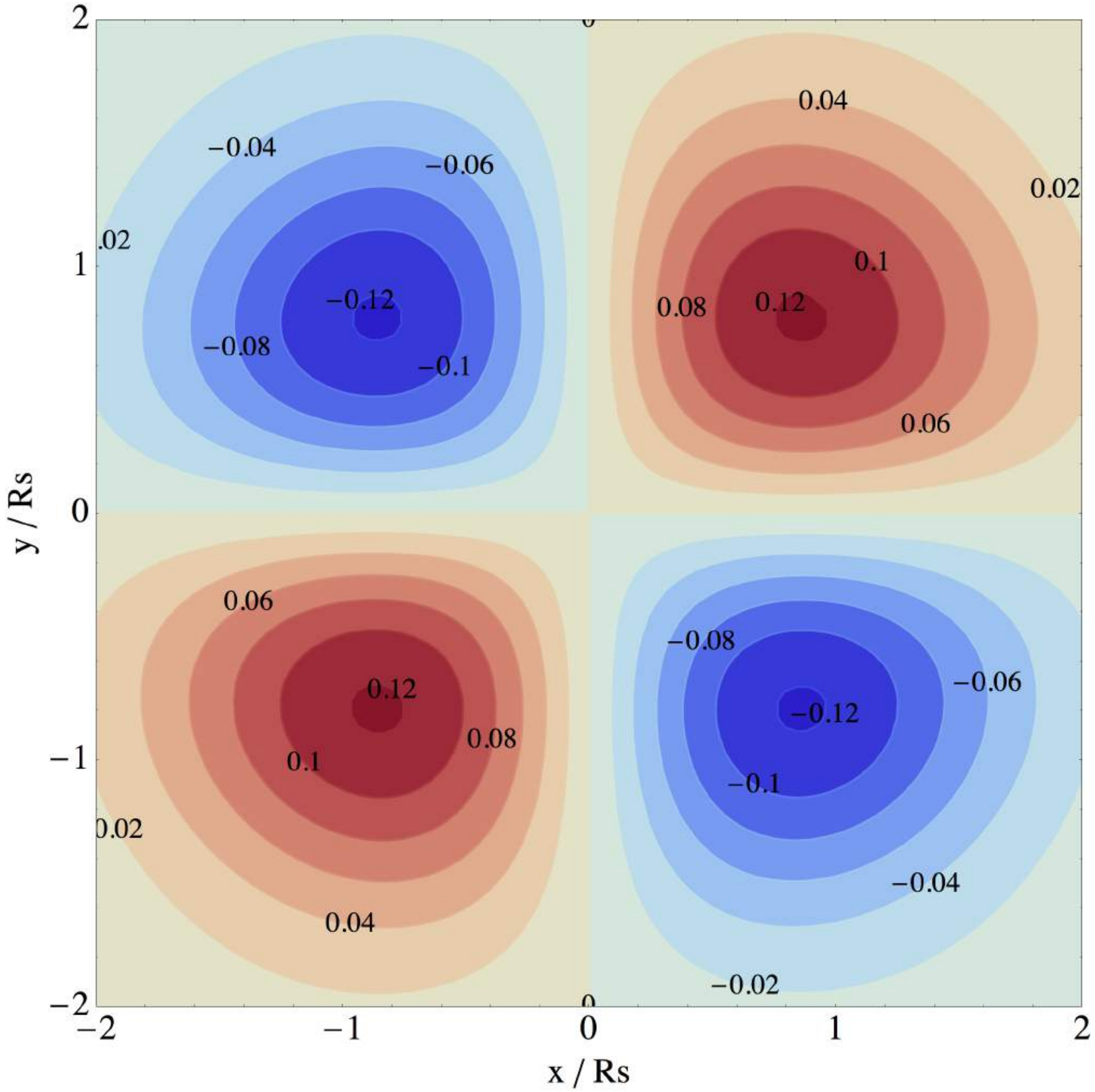
It is then fairly straightforward to compute the corresponding constrained expectation, $\langle L|\mathrm{pk}\rangle$, for L as

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

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
finite extent
anti-ymmetry



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

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

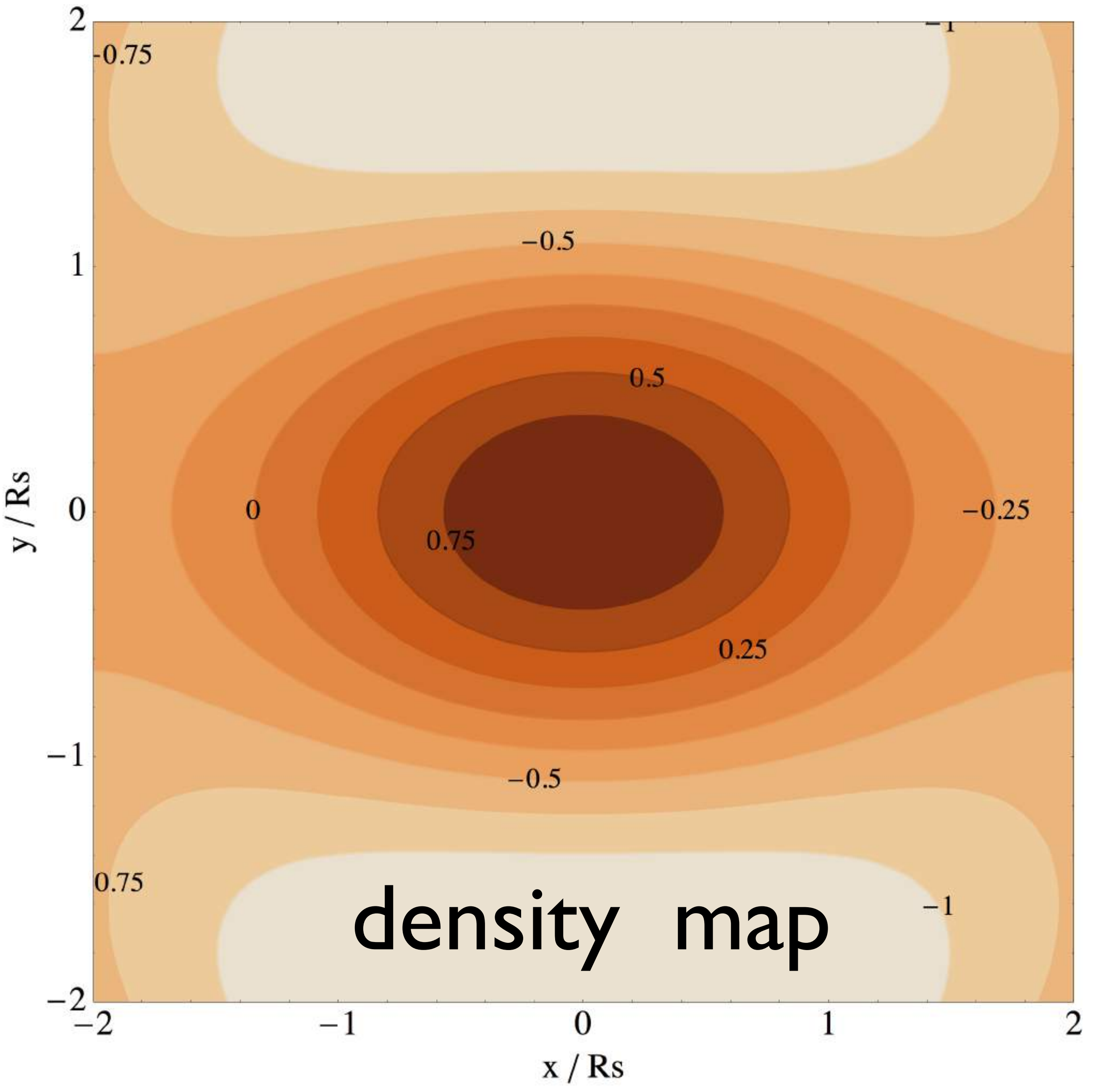
asymmetry **finite extent** **anti-ymmetry**

2D Theory of Tidal Torque @ saddle?

$$\delta(\mathbf{r},\kappa,I_1,\nu|\mathrm{ext}) = \frac{I_1(\xi^{\Delta\Delta}_{\phi\delta}+\gamma\xi^{\Delta\Delta}_{\phi\phi})+\nu(\xi^{\Delta\Delta}_{\phi\phi}+\gamma\xi^{\Delta\Delta}_{\phi\delta})}{1-\gamma^2} + 4\left(\hat{\mathbf{r}}^{\mathrm{T}}\cdot\overline{\mathbf{H}}\cdot\hat{\mathbf{r}}\right)\xi^{\Delta+}_{\phi\delta}\,,$$

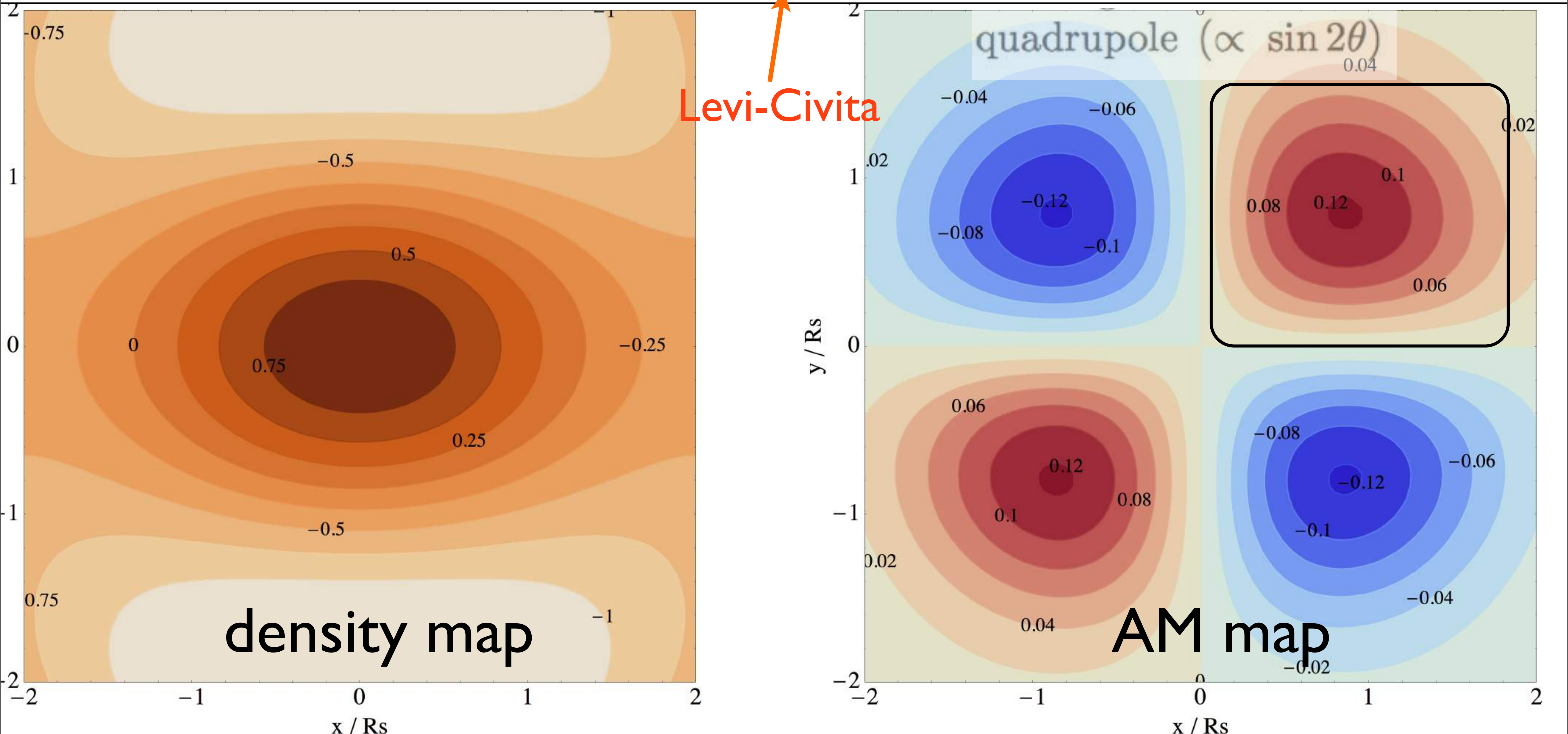
Hessian

$$f^+ = (f_{11}-f_{22})/2 \text{ and } f^\times = f_{12}.$$



2D Theory of Tidal Torque @ saddle?

$$\langle L_z|\mathrm{ext}\rangle = L_z(\mathbf{r},\kappa,I_1,\nu|\mathrm{ext}) = -16(\hat{\mathbf{r}}^{\mathrm{T}}\cdot\epsilon\cdot\overline{\mathbf{H}}\cdot\hat{\mathbf{r}})\left(L_z^{(1)}(r)+2(\hat{\mathbf{r}}^{\mathrm{T}}\cdot\overline{\mathbf{H}}\cdot\hat{\mathbf{r}})L_z^{(2)}(r)\right)$$



$$L_z^{(1)}(r) = \frac{\nu}{1-\gamma^2}\left[(\xi^{\Delta+}_{\phi\phi}+\gamma\xi^{\Delta+}_{\phi\delta})\xi^{\times\times}_{\delta\delta} - (\xi^{\Delta+}_{\phi\delta}+\gamma\xi^{\Delta+}_{\delta\delta})\xi^{\times\times}_{\phi\delta}\right]$$

$$L_z^{(2)}(r) = (\xi^{\Delta\Delta}_{\phi x}\xi^{\times\times}_{\delta\delta} - \xi^{\times\times}_{\phi\delta}\xi^{\Delta\Delta}_{\delta\delta}) + \frac{I_1}{1-\gamma^2}\left[(\xi^{\Delta+}_{\phi\delta}+\gamma\xi^{\Delta+}_{\phi\phi})\xi^{\times\times}_{\delta\delta} - (\xi^{\Delta+}_{\delta\delta}+\gamma\xi^{\Delta+}_{\phi\delta})\xi^{\times\times}_{\phi\delta}\right]$$

In order to compute the spin distribution, the formalism developed in Section 2 is easily extended to 3D. A critical (including saddle condition) point constraint is imposed. The resulting mean density field subject to that constraint becomes (in units of σ_2):

$$\delta(\mathbf{r},\kappa,I_1,\nu|\mathrm{ext}) = \frac{I_1(\xi_{\phi\delta}^{\Delta\Delta}+\gamma\xi_{\phi\phi}^{\Delta\Delta})}{1-\gamma^2} + \frac{\nu(\xi_{\phi\phi}^{\Delta\Delta}+\gamma\xi_{\phi\delta}^{\Delta\Delta})}{1-\gamma^2} + \frac{15}{2}\left(\hat{\mathbf{r}}^{\mathrm{T}}\cdot\overline{\mathbf{H}}\cdot\hat{\mathbf{r}}\right)\xi_{\phi\delta}^{\Delta+}, \quad (3.1)$$

where again $\overline{\mathbf{H}}$ is the *detraced* Hessian of the density and $\hat{\mathbf{r}}=\mathbf{r}/r$ and we define in 3D $\xi_{\phi x}^{\Delta+}$ as $\xi_{\phi\delta}^{\Delta+}=\langle\Delta\delta,\phi^+\rangle$, with $\phi^+=\phi_{11}-(\phi_{22}+\phi_{33})/2$. Note that $\hat{\mathbf{r}}^{\mathrm{T}}\cdot\overline{\mathbf{H}}\cdot\hat{\mathbf{r}}$ is a scalar quantity defined explicitly as $\hat{r}_i\overline{H}_{ij}\hat{r}_j$. As in 2D, the expected spin can also be computed. In 3D, the spin is a vector, which components are given by $L_i=\varepsilon_{ijk}\delta_{kl}\phi_{lj}$, with $\boldsymbol{\epsilon}$ the rank 3 Levi Civita tensor. It is found to be orthogonal to the separation and can be written as the sum of two terms

$$\mathbf{L}(\mathbf{r},\kappa,I_1,\nu|\mathrm{ext}) = -15\left(\mathbf{L}^{(1)}(r)+\mathbf{L}^{(2)}(\mathbf{r})\right)\cdot(\hat{\mathbf{r}}^{\mathrm{T}}\cdot\boldsymbol{\epsilon}\cdot\overline{\mathbf{H}}\cdot\hat{\mathbf{r}}), \quad (3.2)$$

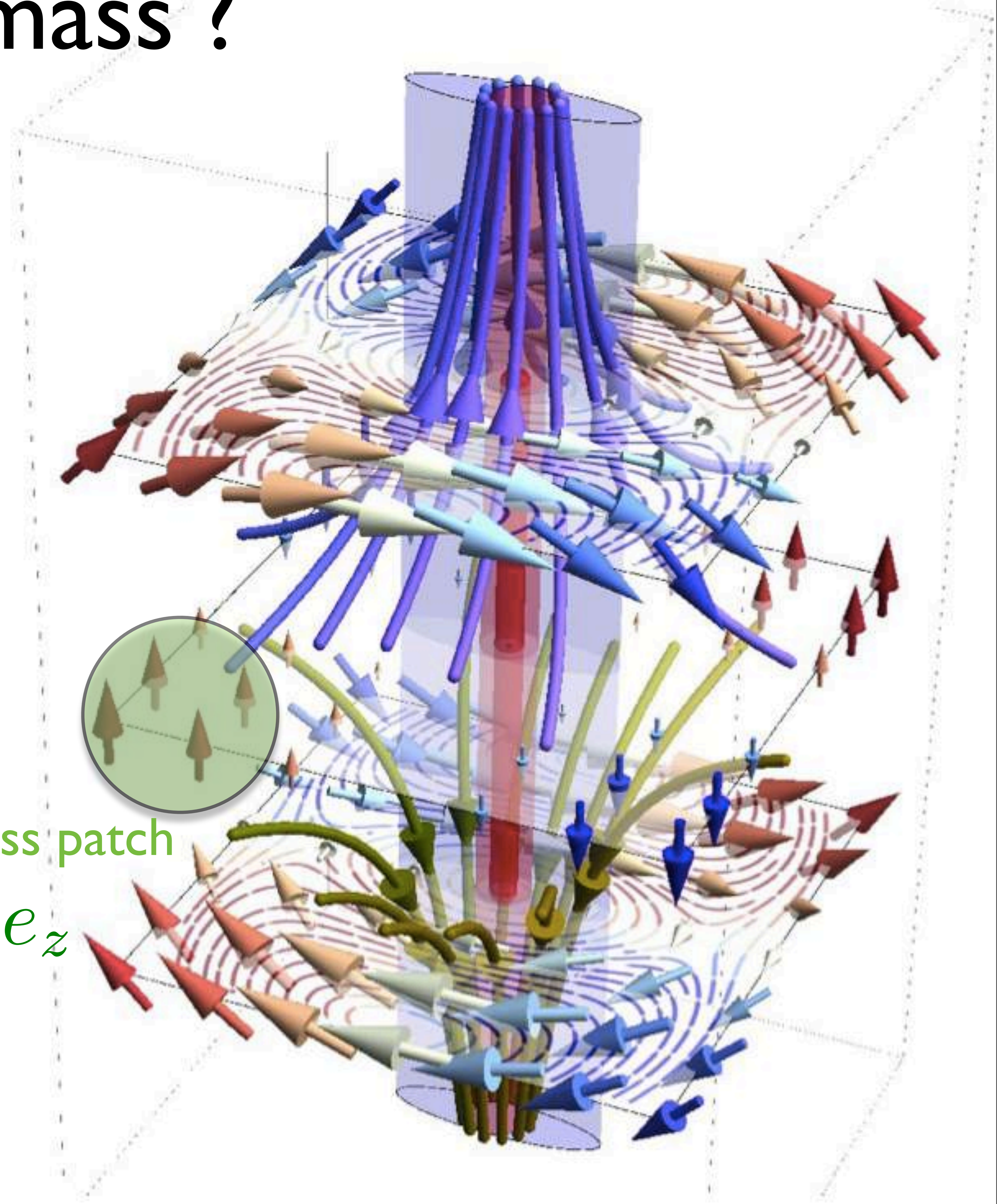
where $\mathbf{L}^{(1)}$ depends on height, ν, and on the trace of the Hessian I_1 but not on orientation

$$\mathbf{L}^{(1)}(r) = \Bigg(\frac{\nu}{1-\gamma^2}\left[(\xi_{\phi\phi}^{\Delta+}+\gamma\xi_{\phi\delta}^{\Delta+})\xi_{\delta\delta}^{\times\times}-(\xi_{\phi\delta}^{\Delta+}+\gamma\xi_{\delta\delta}^{\Delta+})\xi_{\phi\delta}^{\times\times}\right] + \frac{I_1}{1-\gamma^2}\left[(\xi_{\phi\delta}^{\Delta+}+\gamma\xi_{\phi\phi}^{\Delta+})\xi_{\delta\delta}^{\times\times}-(\xi_{\delta\delta}^{\Delta+}+\gamma\xi_{\phi\delta}^{\Delta+})\xi_{\phi\delta}^{\times\times}\right]\Bigg)\mathbb{I}_3,$$

and $\mathrm{L}^{(2)}(\mathbf{r})$ now depends on $\overline{\mathbf{H}}$ and on orientation:

$$\mathbf{L}^{(2)}(\mathbf{r}) = -\frac{5}{8}\Big[2((\xi_{\phi\delta}^{\Delta+}-\xi_{\phi\delta}^{\Delta\Delta})\xi_{\delta\delta}^{\times\times}-(\xi_{\delta\delta}^{\Delta+}-\xi_{\delta\delta}^{\Delta\Delta})\xi_{\phi\delta}^{\times\times})\overline{\mathbf{H}} + ((7\xi_{\delta\delta}^{\Delta\Delta}+5\xi_{\delta\delta}^{\Delta+})\xi_{\phi\delta}^{\times\times}-(7\xi_{\phi\delta}^{\Delta\Delta}+5\xi_{\phi\delta}^{\Delta+})\xi_{\delta\delta}^{\times\times})(\hat{\mathbf{r}}^{\mathrm{T}}\cdot\overline{\mathbf{H}}\cdot\hat{\mathbf{r}})\mathbb{I}_3\Big],$$

3D Transition mass ?



Lagrangian theory capture spin flip !

Transition mass associated with **size** of quadrant

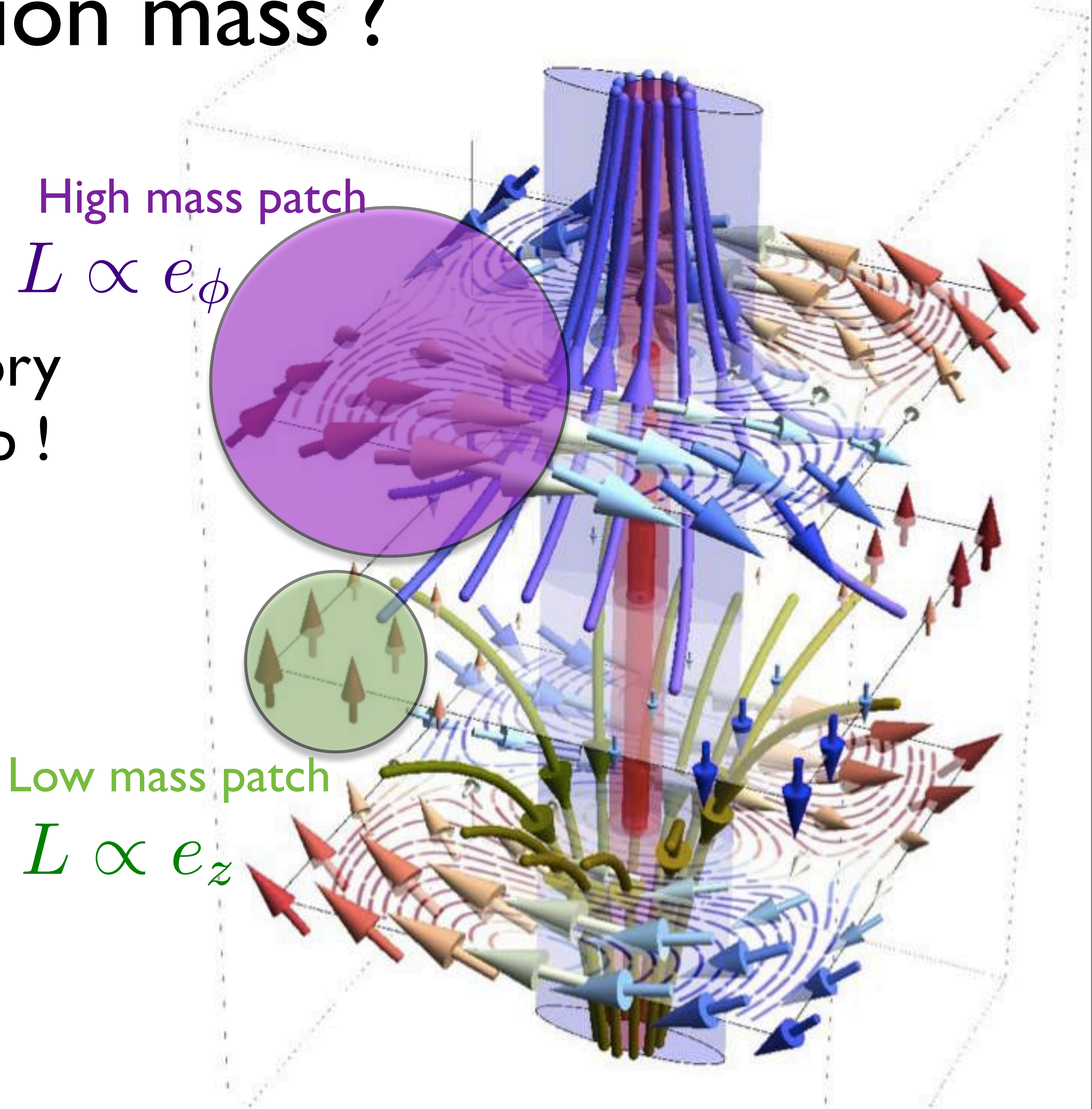
Low mass patch

$L \propto e_z$

3D Transition mass ?

Lagrangian theory capture spin flip !

Transition mass associated with **size** of quadrant



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

Cloud in cloud effect

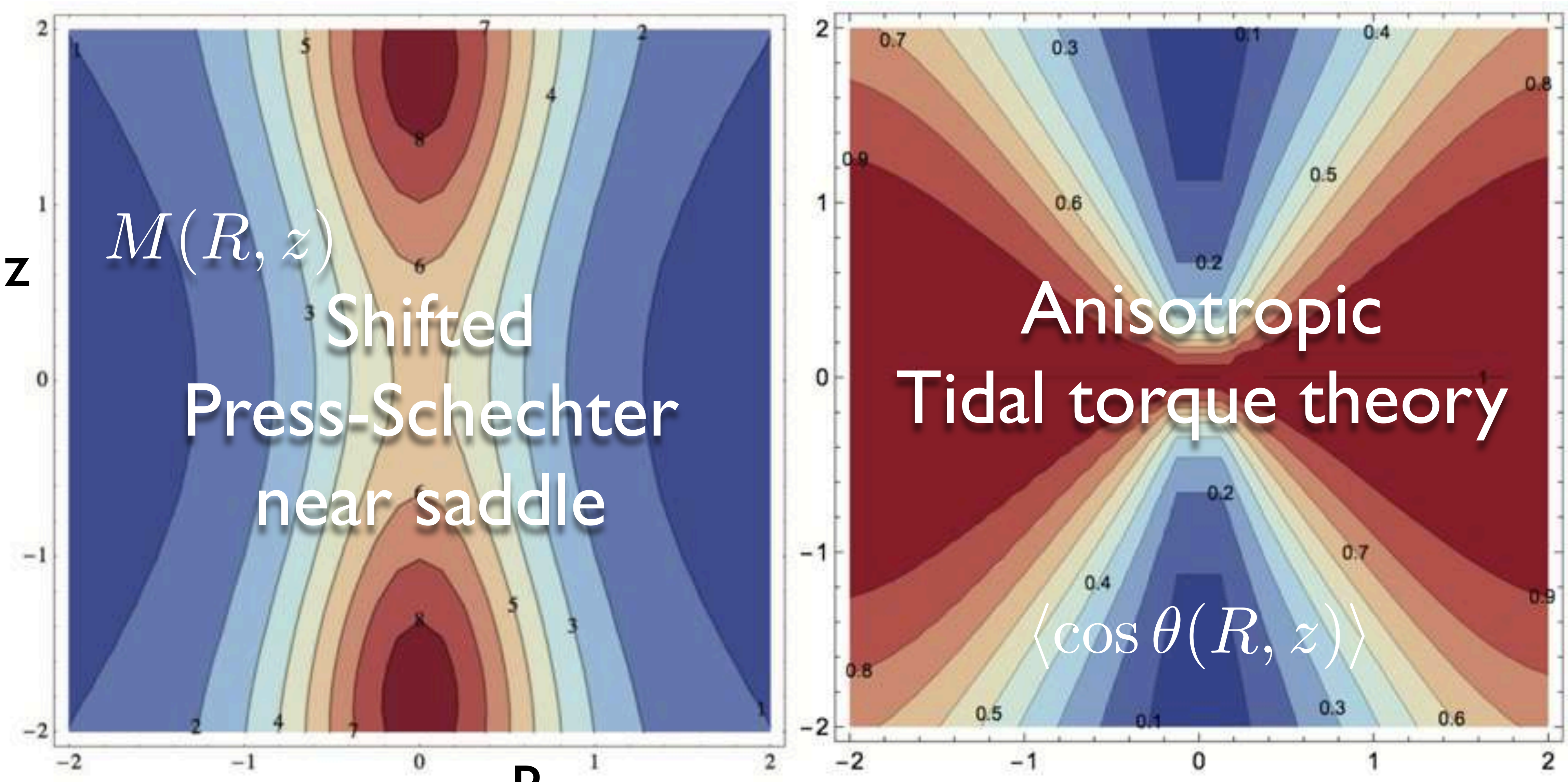


Figure 5. *Left:* logarithmic cross section of $M_p(r, z)$ along the most likely (vertical) filament (in units of $10^{12} M_\odot$). *Right:* corresponding cross section of $\langle \cos \hat{\theta} \rangle(r, z)$. The mass of halos increases towards the nodes, while the spin flips.

geometric split ⟶ mass split

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

Cloud in cloud effect

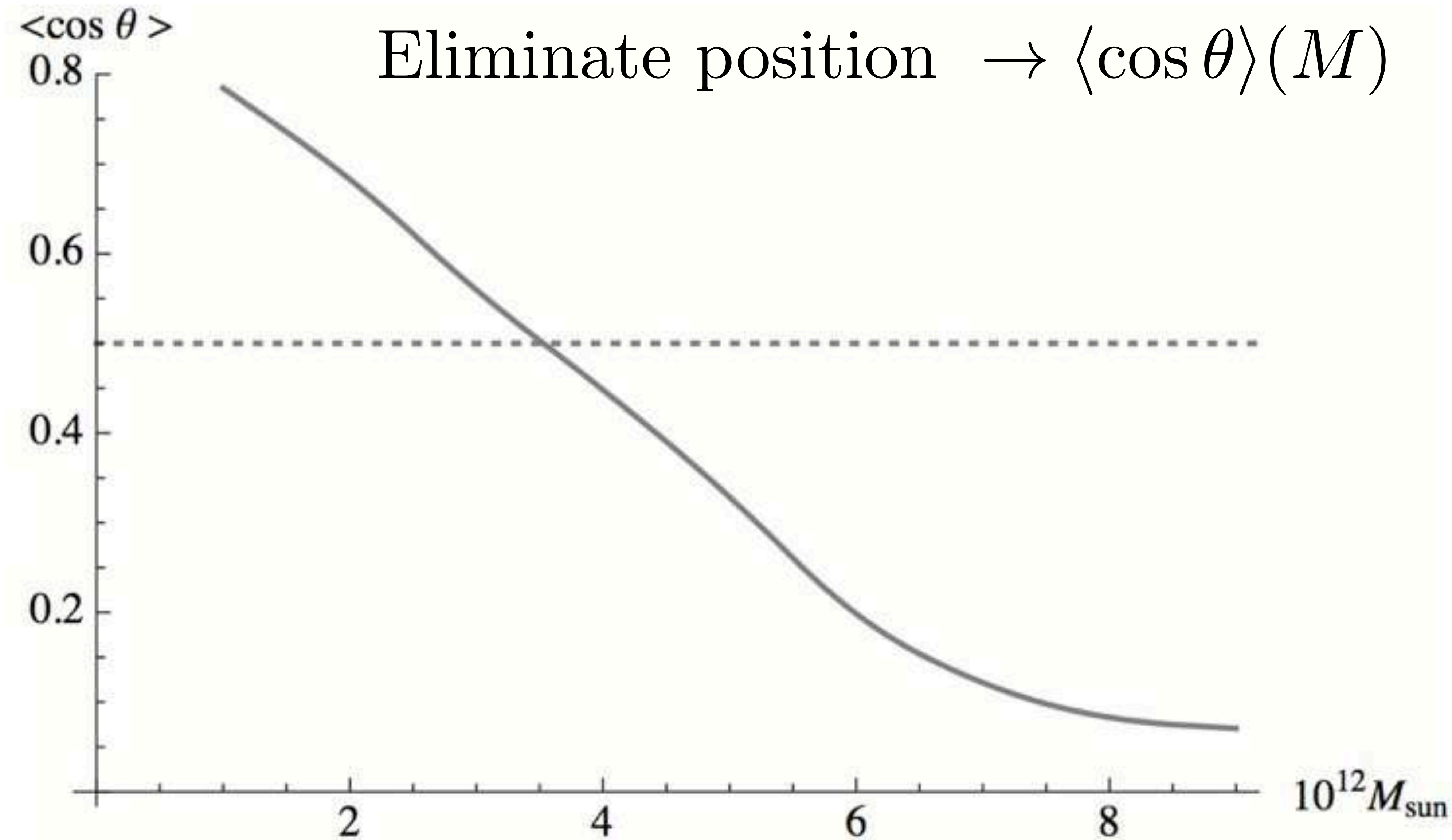


Figure 6. Mean alignment between spin and filament as a function of mass for a filament smoothing scale of 5 Mpc/h. The spin flip transition mass is around $4\,10^{12} M_\odot$.

geometric split ⟶ mass split

Link with Eulerian vorticity?

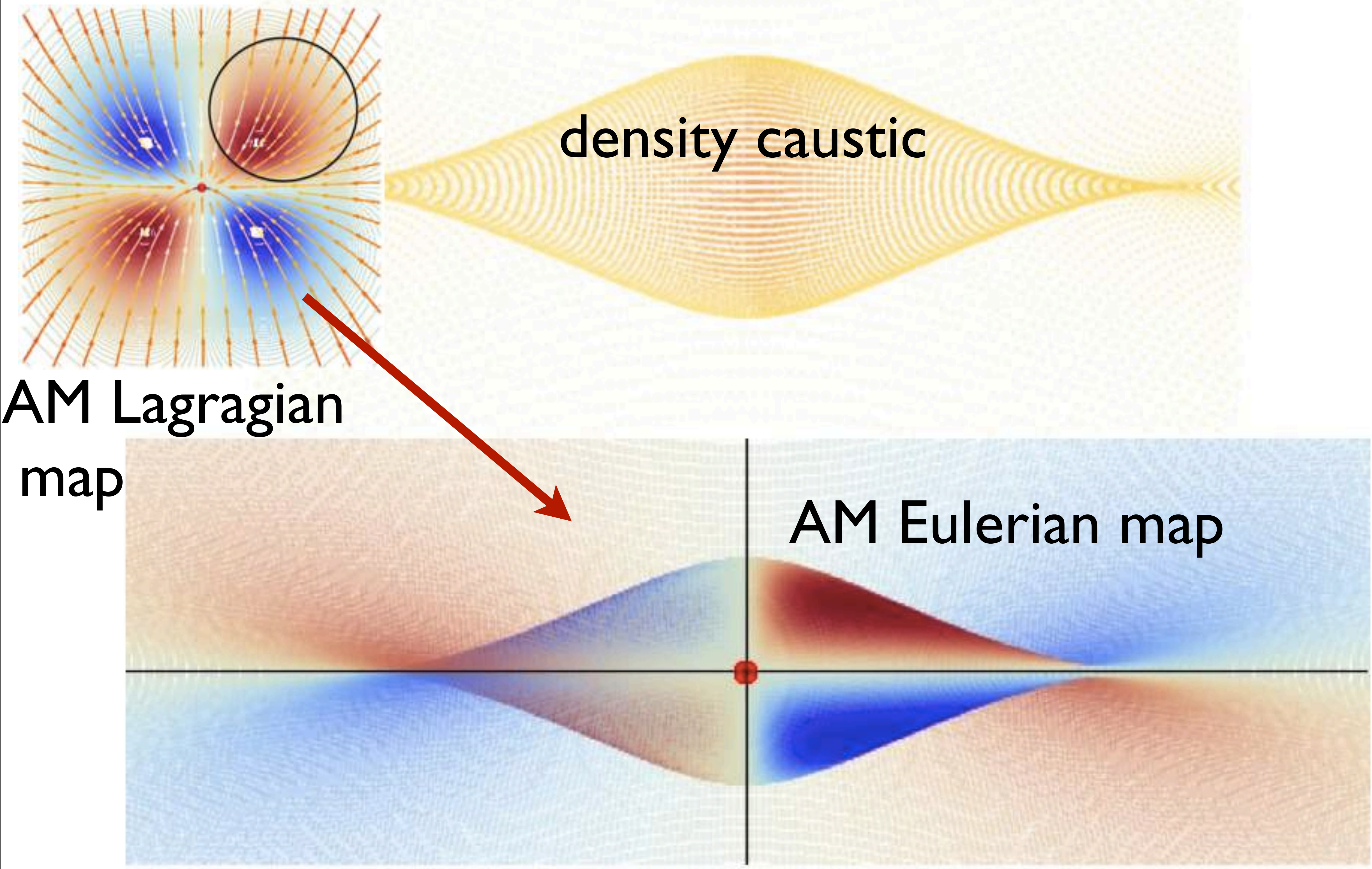
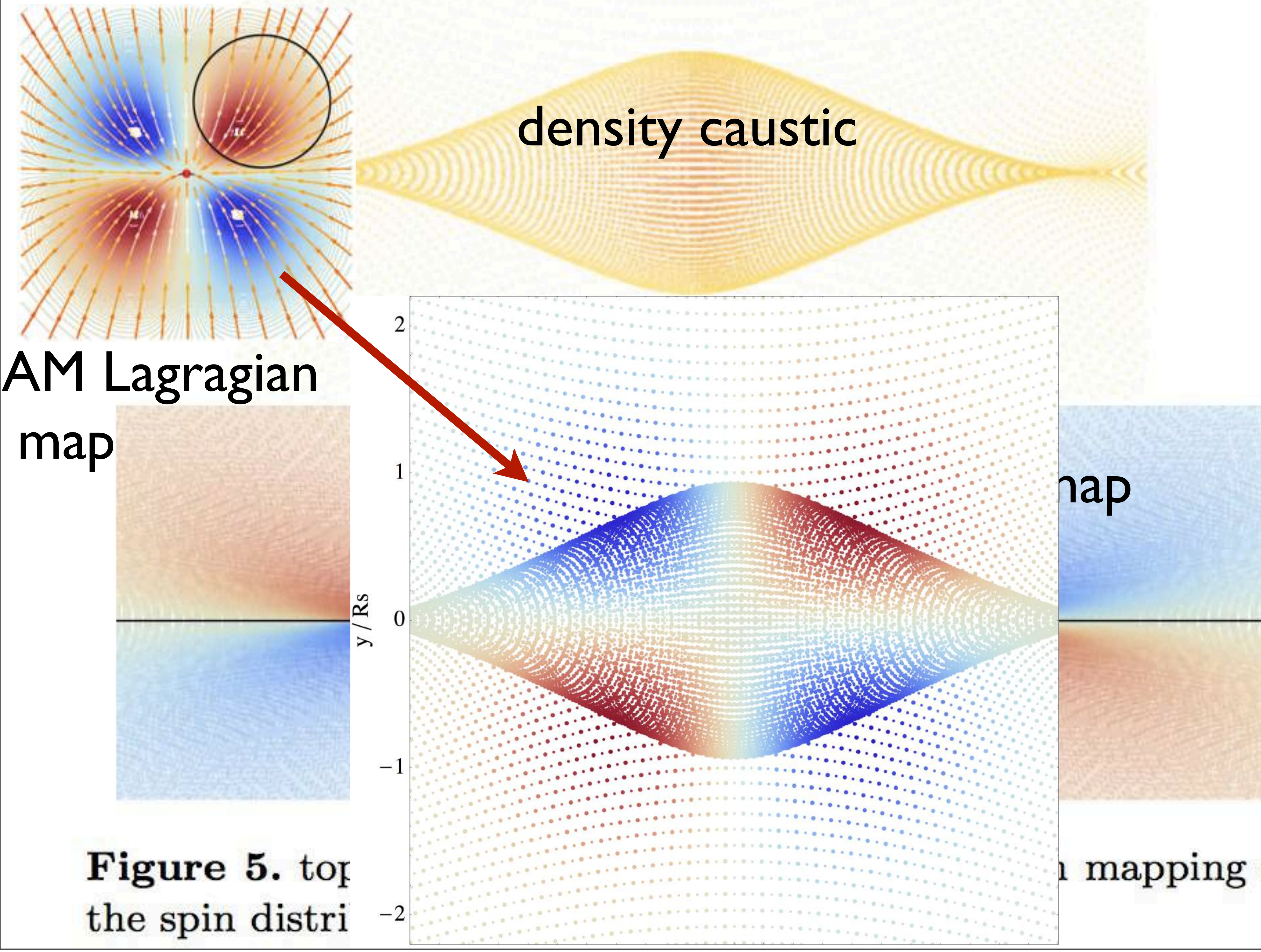
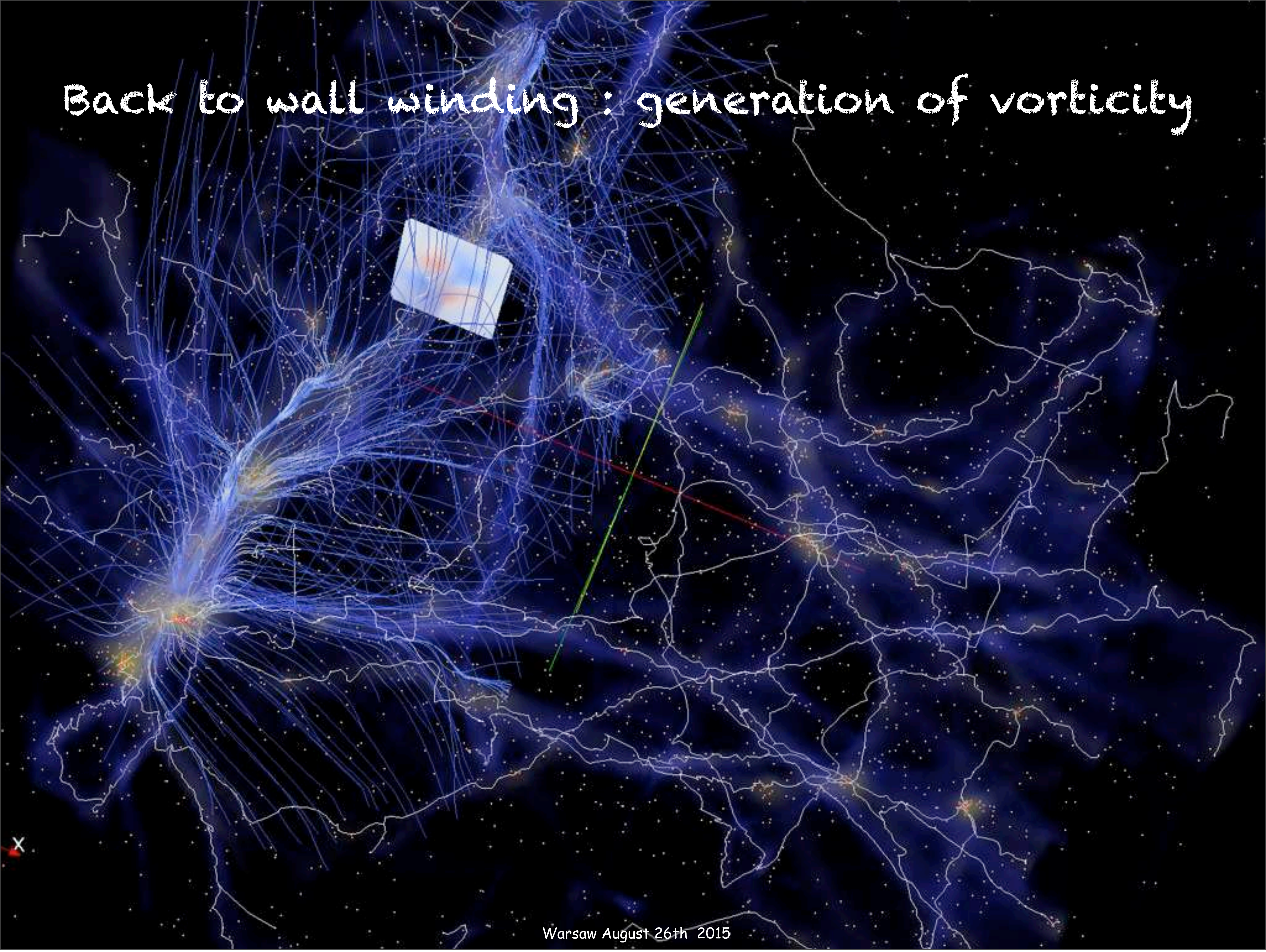


Figure 5. top: Density caustic; Bottom: Zeldovitch mapping of the spin distribution

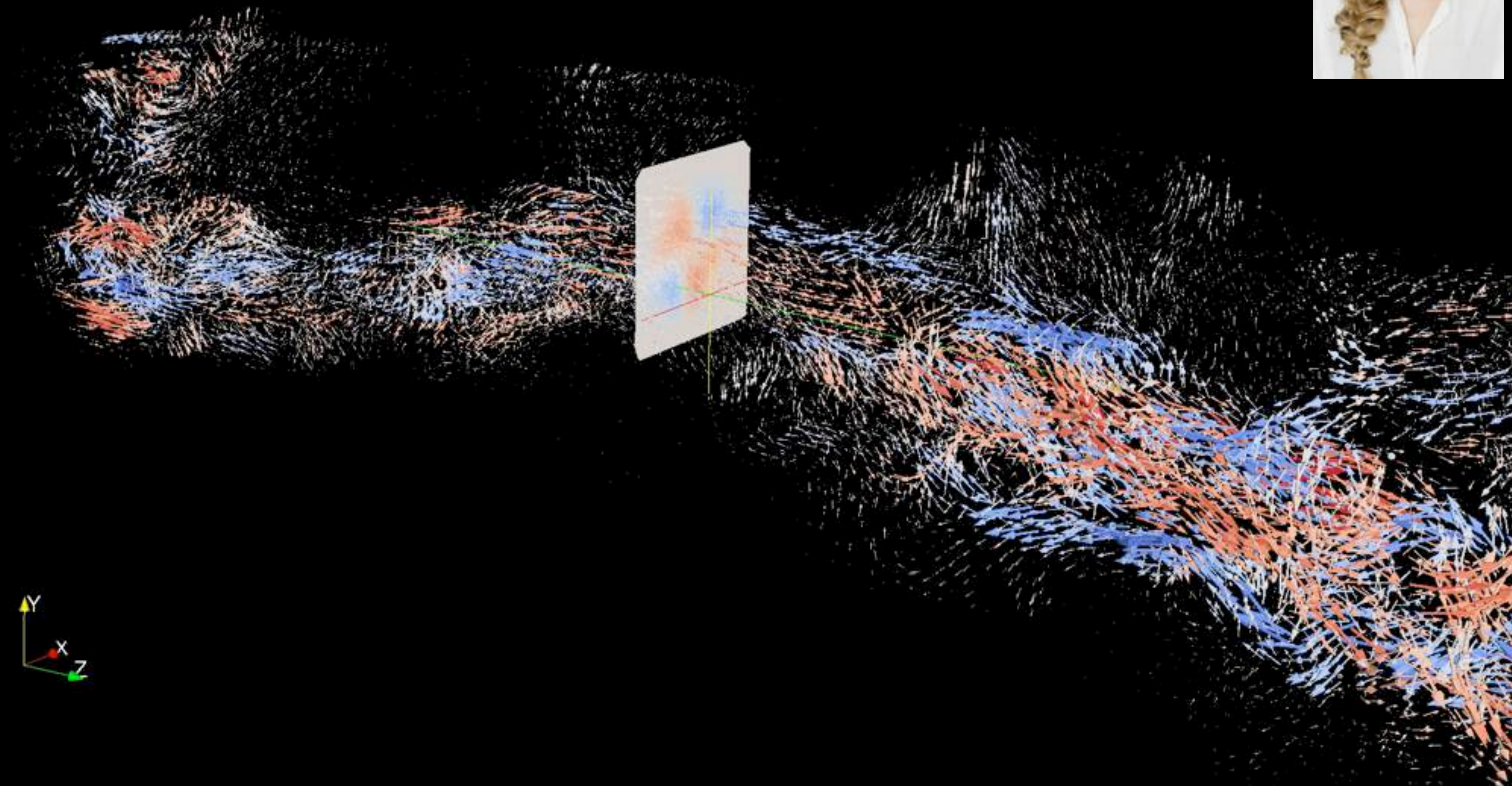
Link with Eulerian vorticity?



Back to wall winding : generation of vorticity



Alignement of vorticity with cosmic web

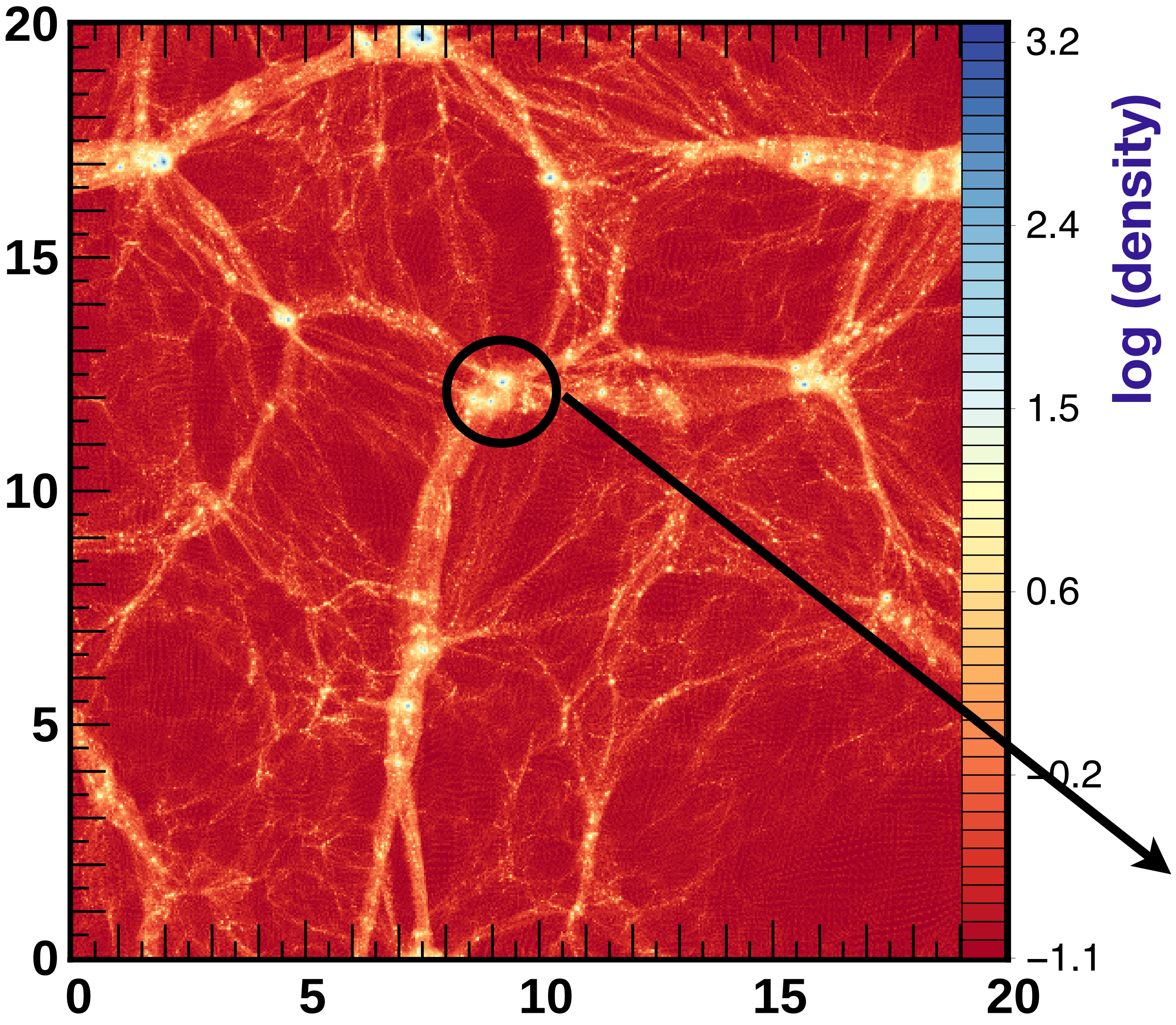


braids structure of vorticity.

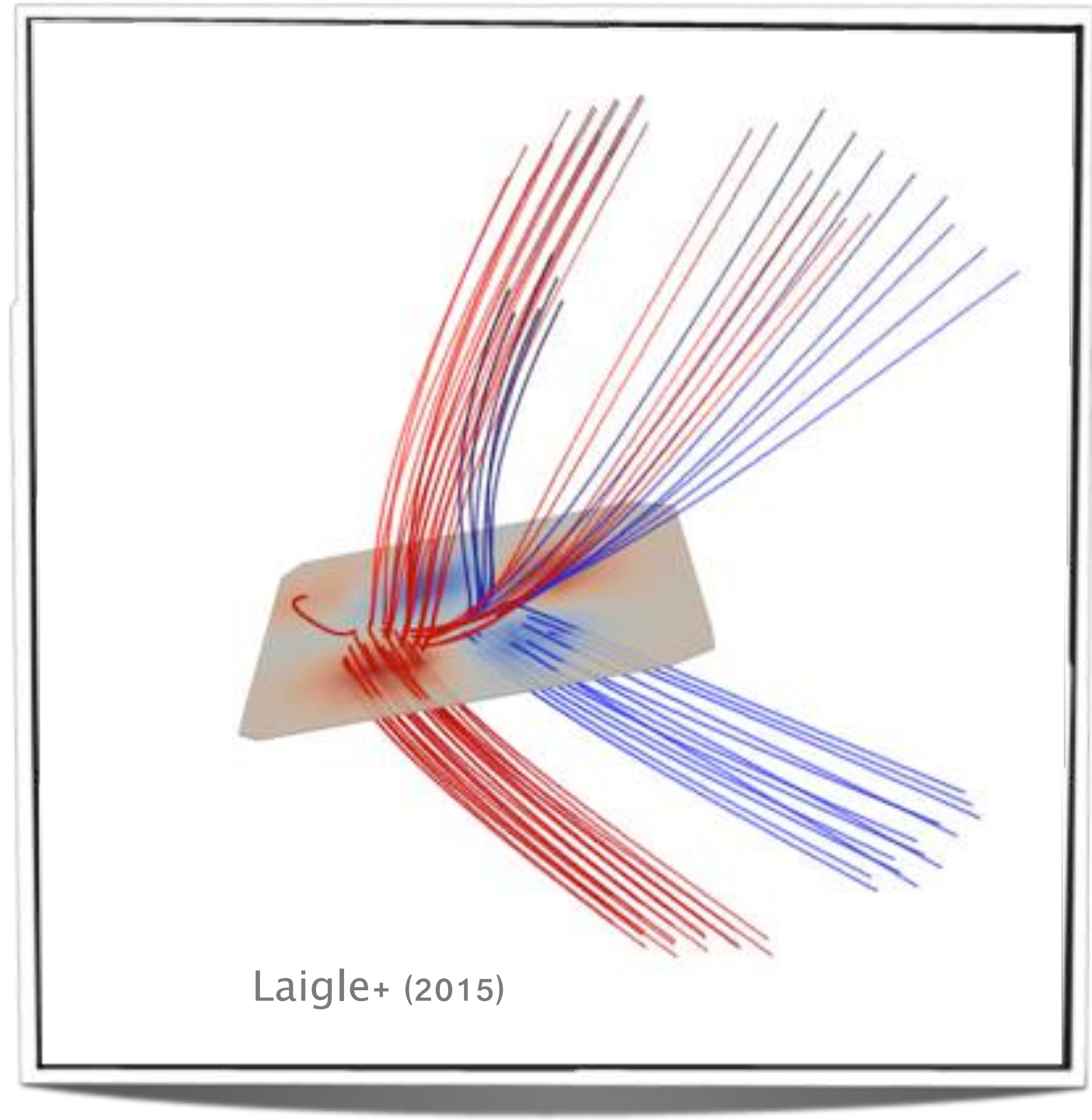
Growth of large-scale structure

In the initial phase of structure formation, **flows are laminar and curl-free.**
This is no longer valid **at the shell-crossing.**

Thin slice of a DM simulation at z=0.



Laigle+ (2015)



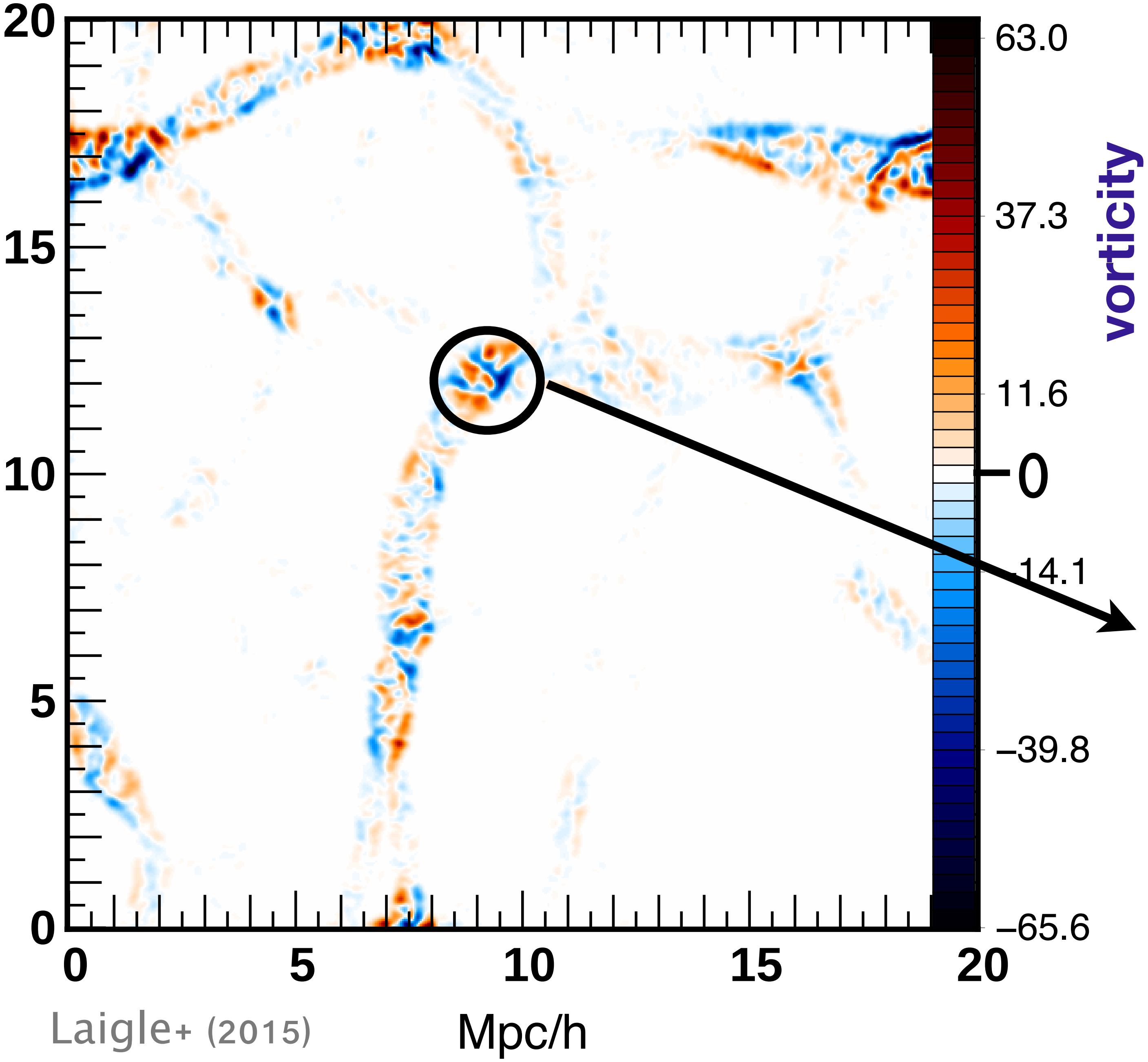
Laigle+ (2015)

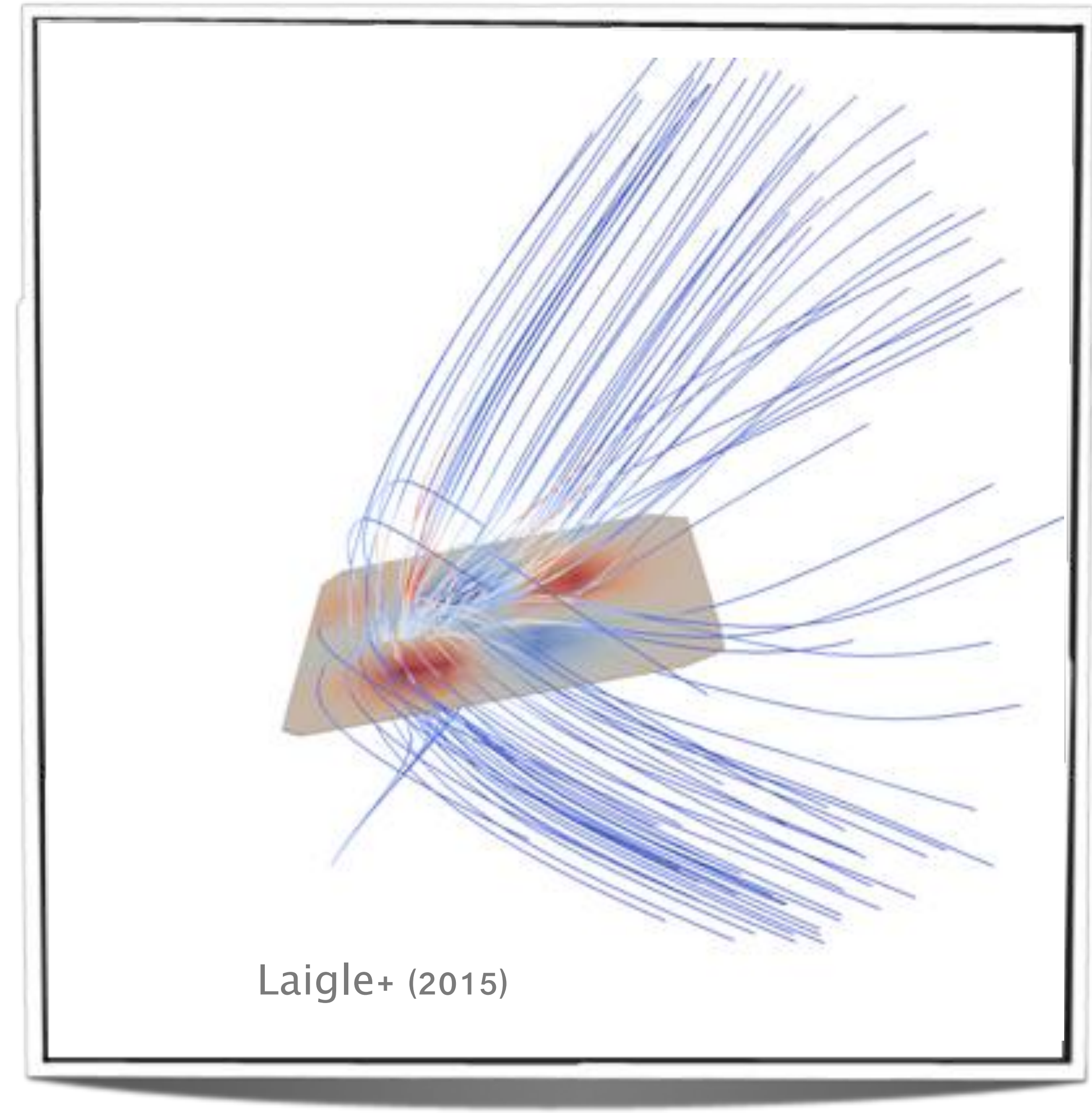
What happens when cosmic flows cross?

Vorticity generation

In the initial phase of structure formation, **flows are laminar and curl-free.**
This is no longer valid **at the shell-crossing.**

Thin slice of a DM simulation at z=0.

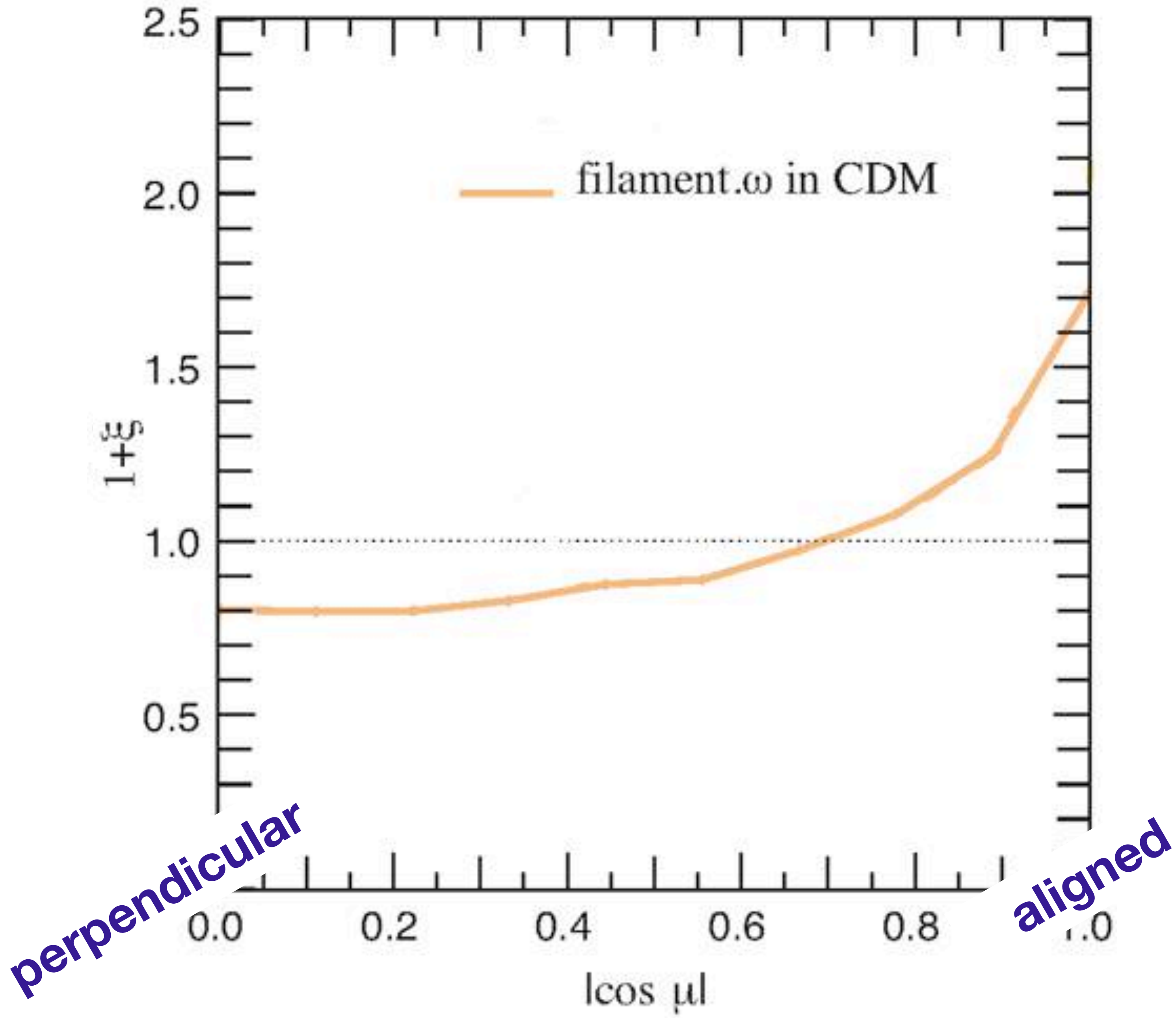


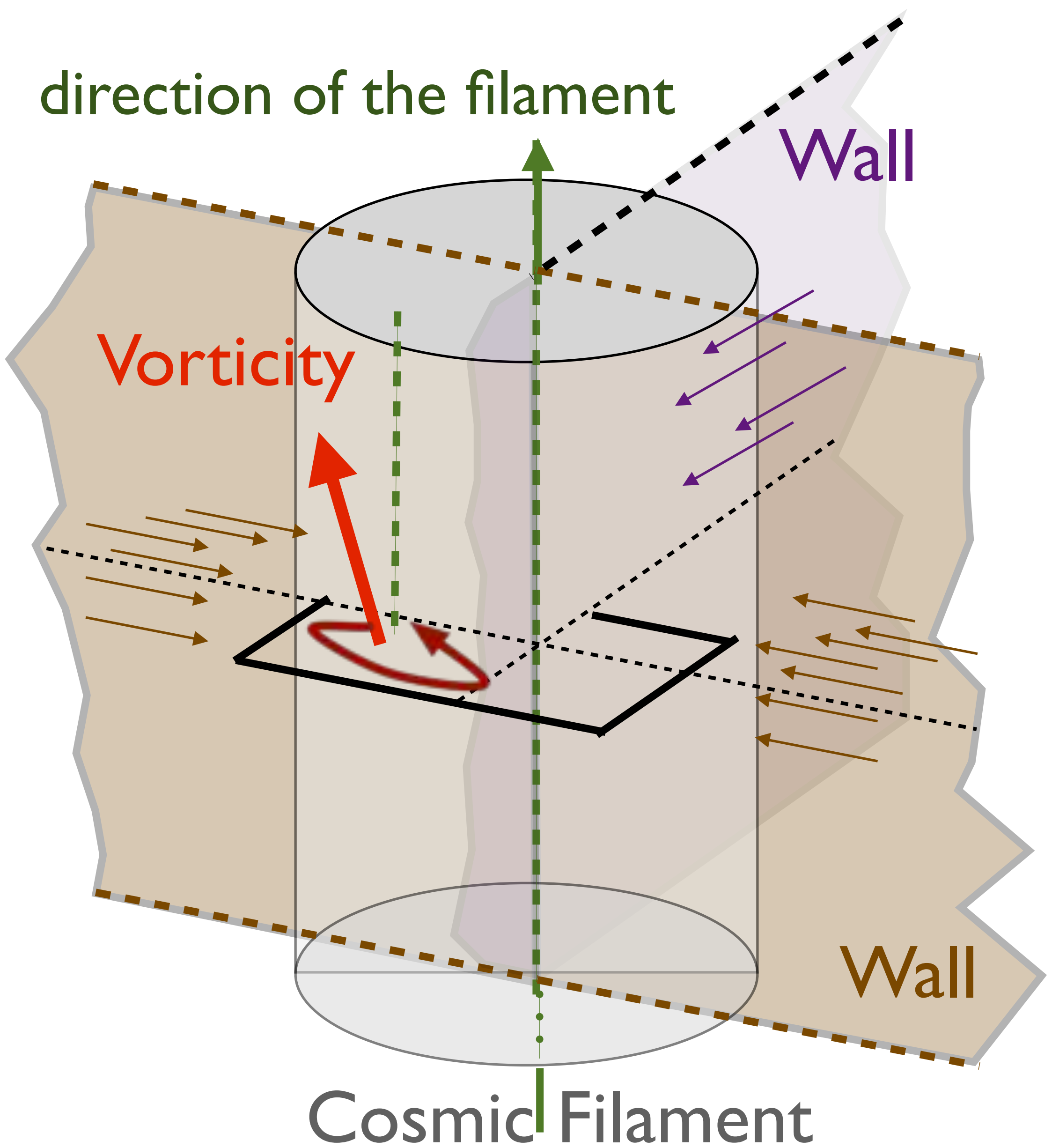


Vorticity is generated and is confined in the filaments.

Vorticity is aligned with the filaments.

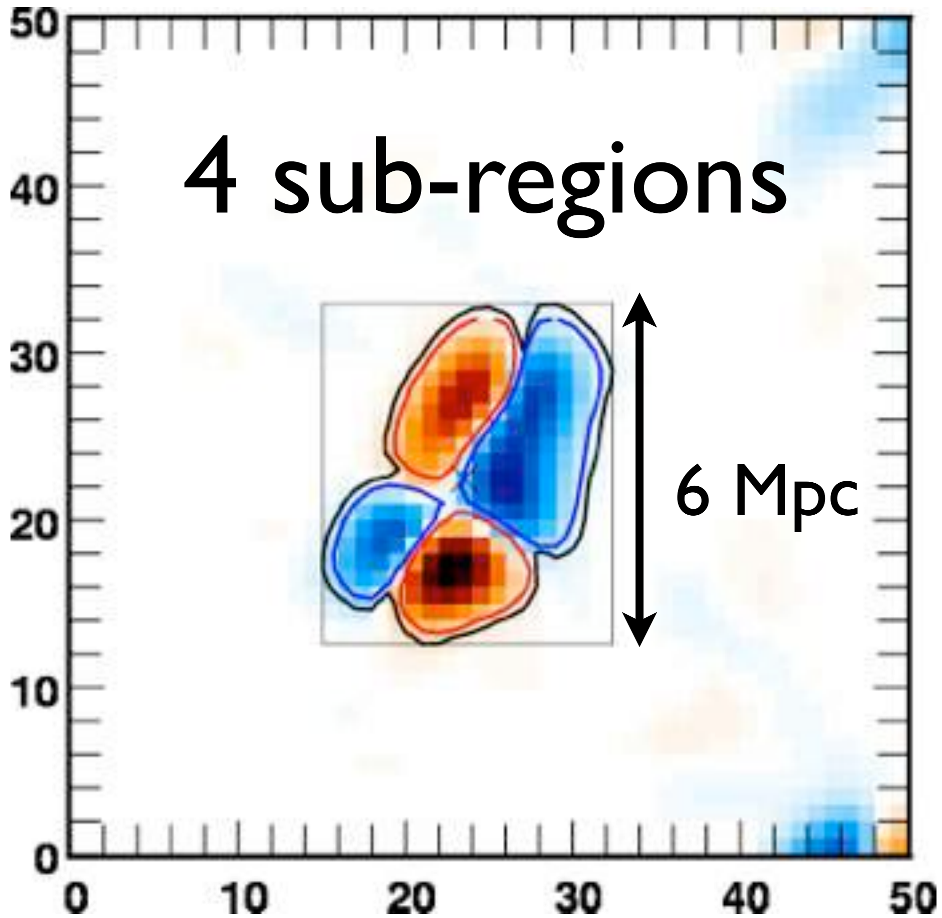
Laigle+ (2015)

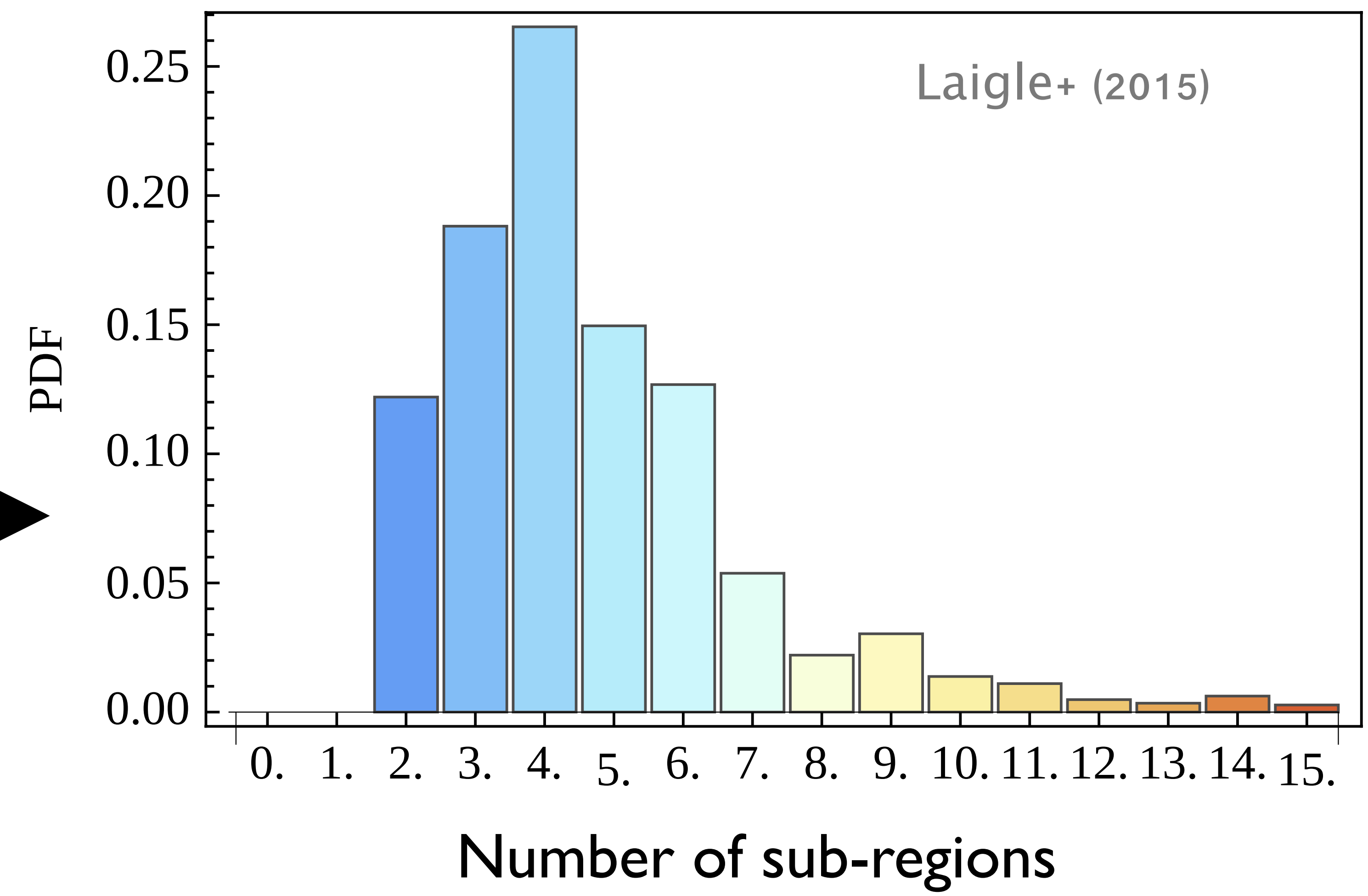




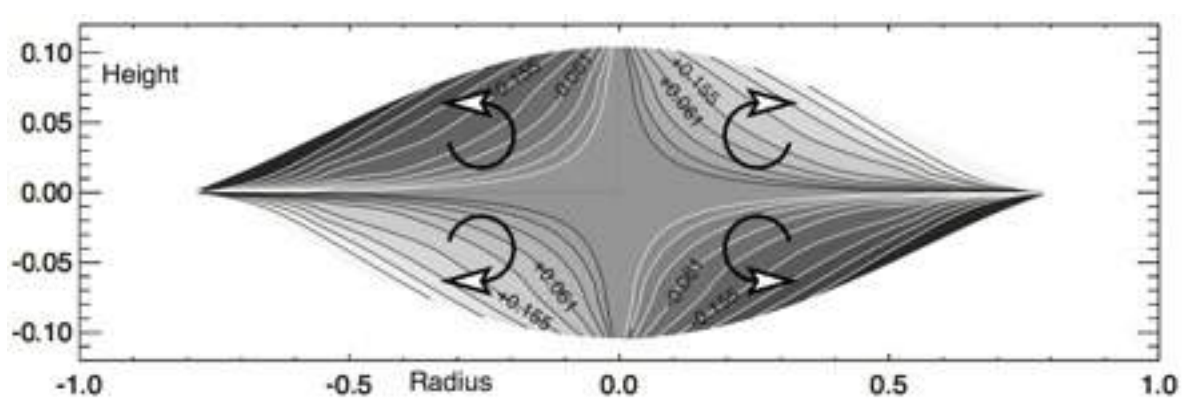
Filaments and walls are identified with DISPERSE: Sousbie+ (2011).

Geometry of the vorticity cross-section





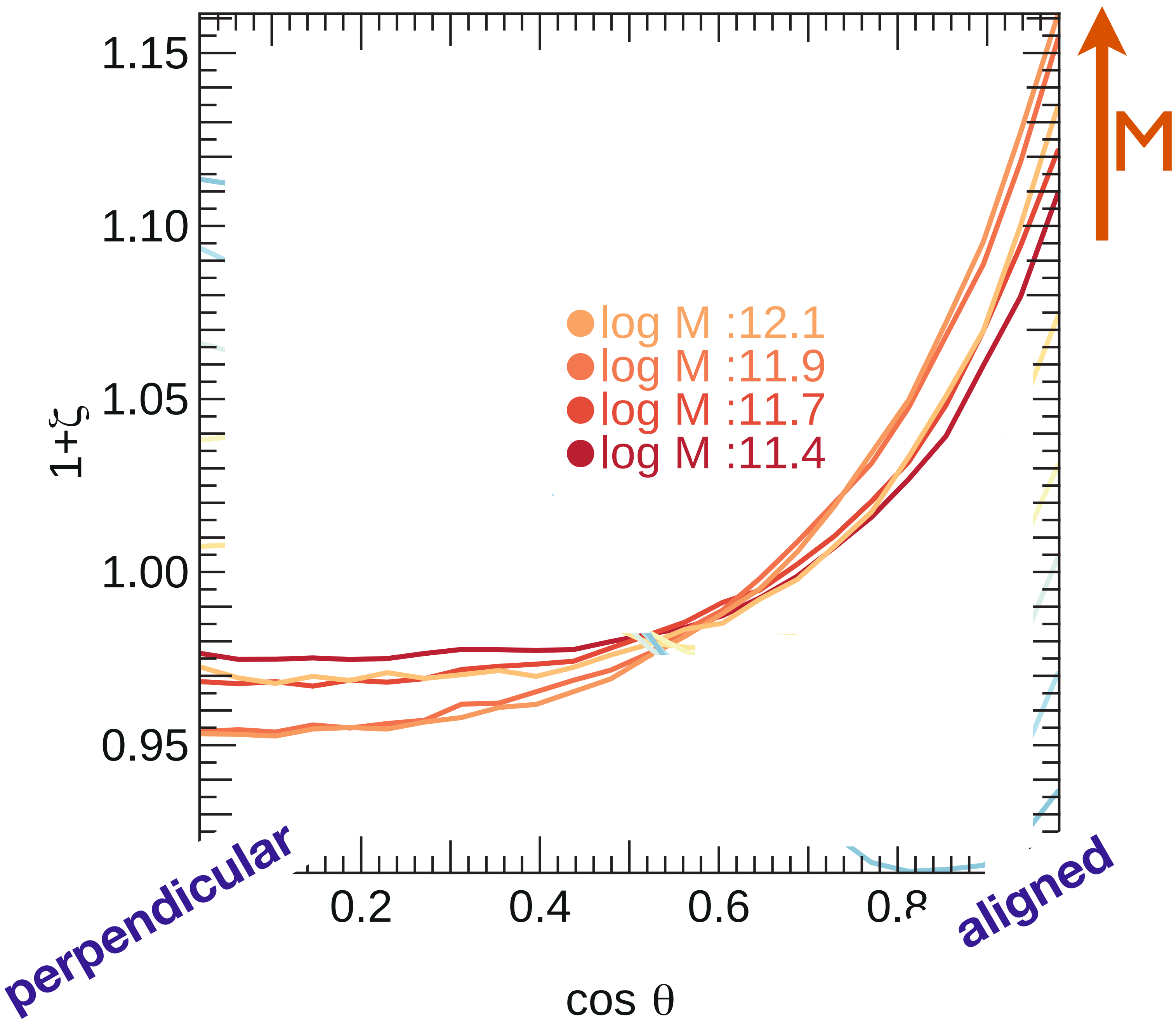
Pichon & Bernardeau (1999)



Cross-sections are typically divided in 4 quadrants.

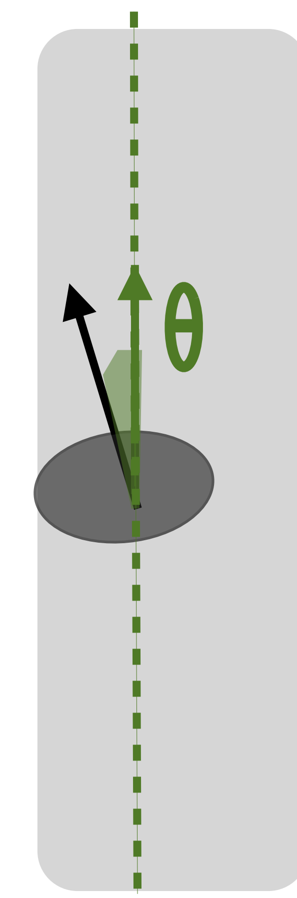
Theoretical prediction from Pichon & Bernardeau 1999

Low-mass halos are aligned with the filament

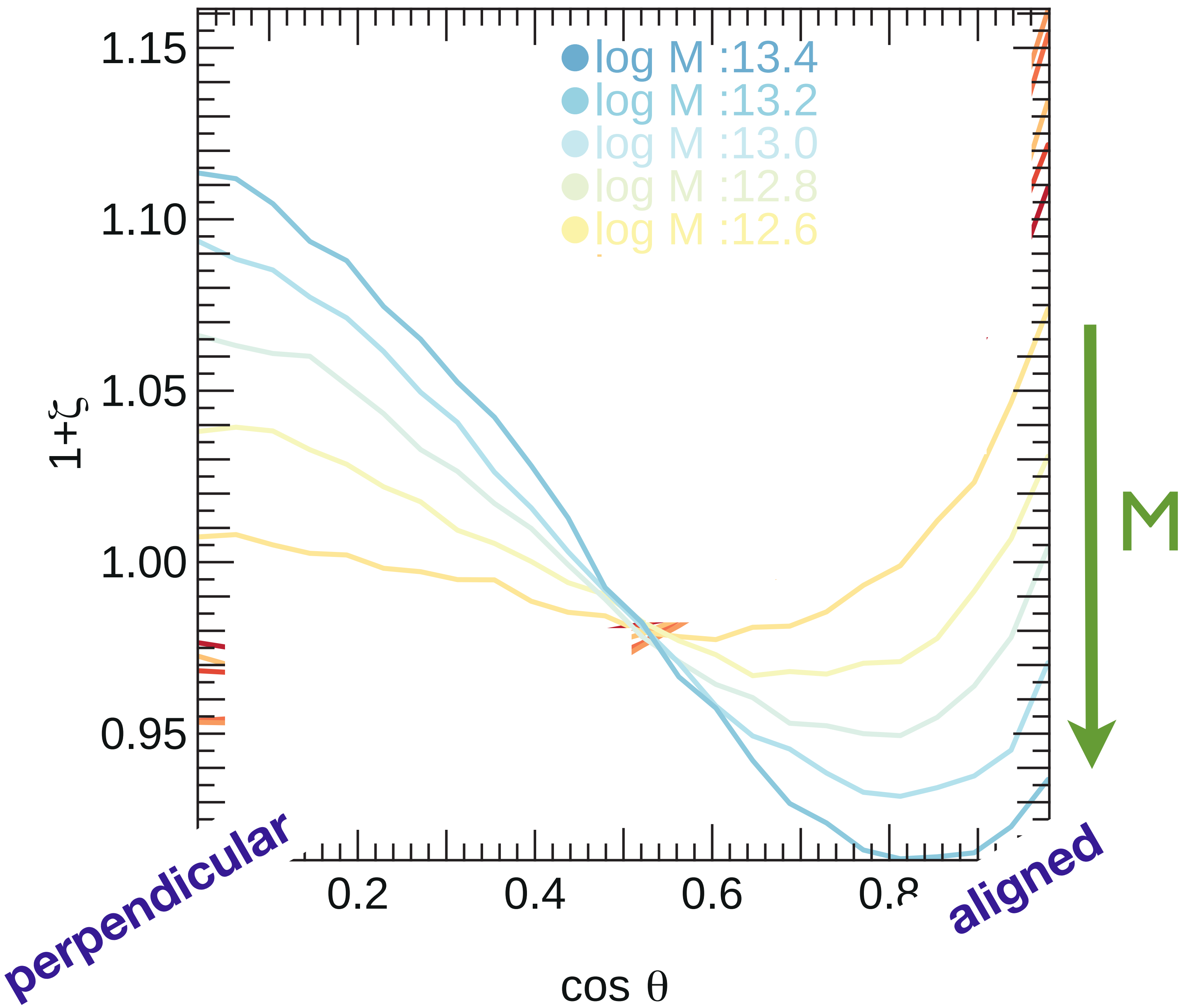


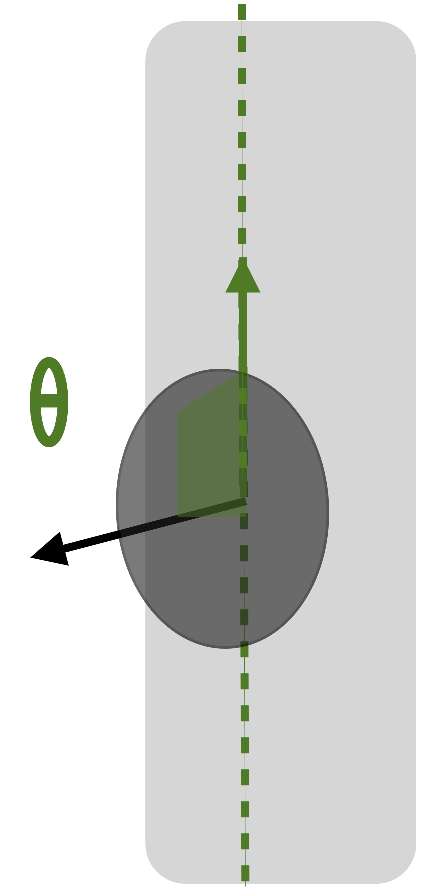
Laigle+ (2015)
in DM simulation (10^5 haloes)

- M_{halo} < M_{crit}
  alignment of halo spin with filament increases with mass.
- M_{crit}



High-mass halos are perpendicular

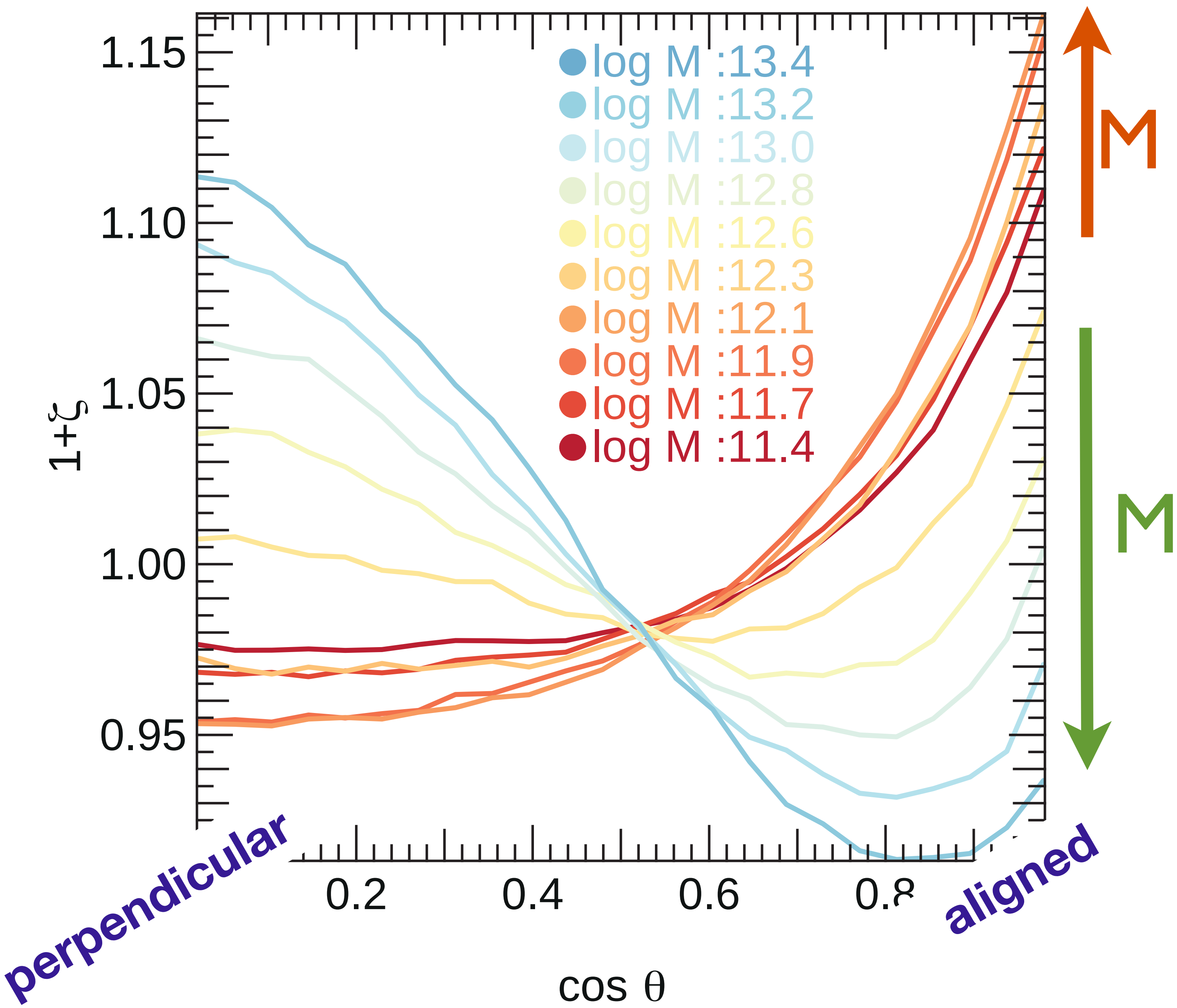




- M_{crit}
- $M_{halo} > M_{crit}$
  halo spin tends to be perpendicular to the filament.

Laigle+ (2015)
in DM simulation (10^5 haloes)

Mass dependent Halo spin - filament alignment



Laigle+ (2015)
in DM simulation (10^5 haloes)

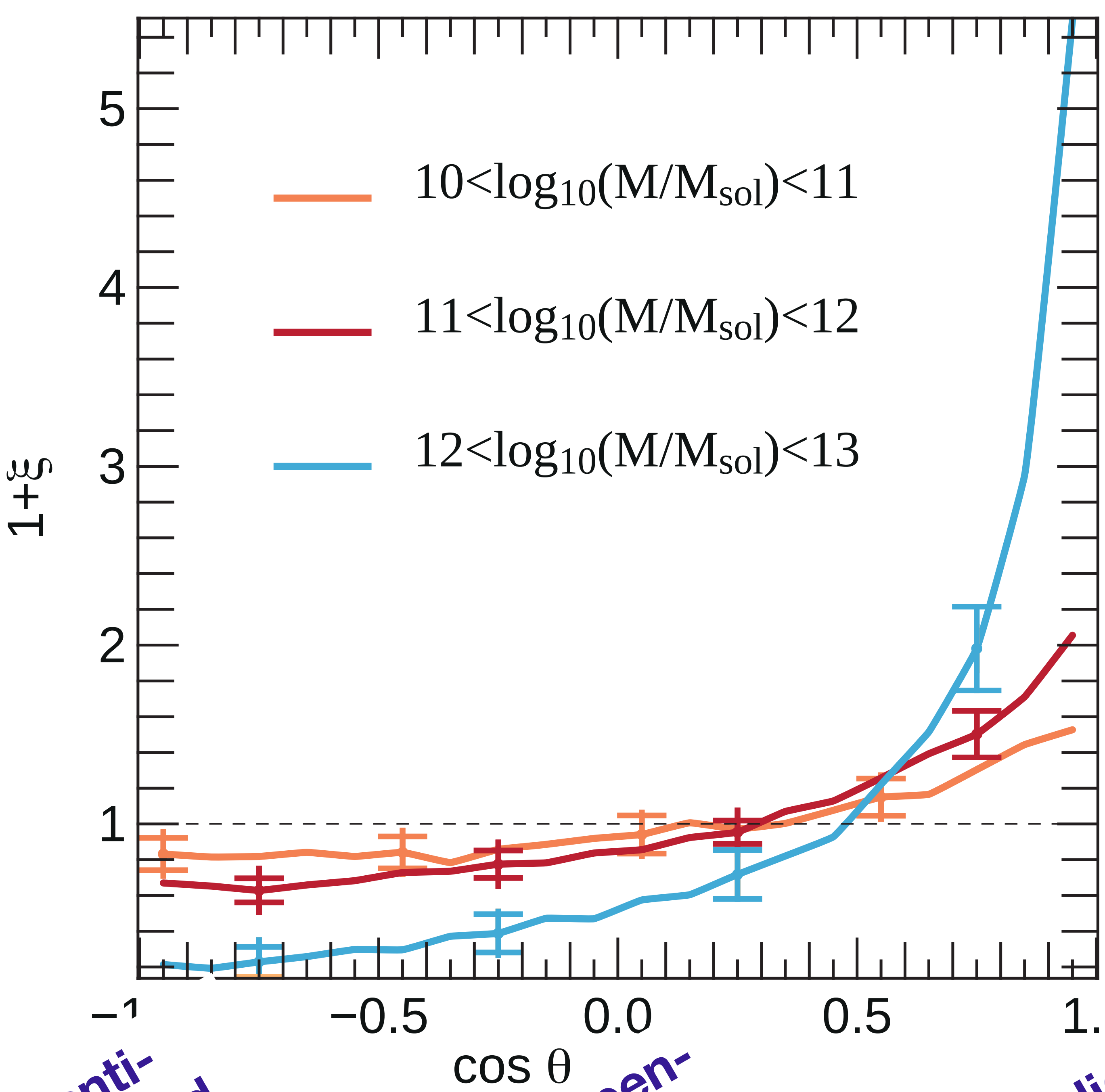
- $M_{halo} < M_{crit}$ alignment of halo spin with filament increases with mass.
- M_{crit}
- $M_{halo} > M_{crit}$ halo spin tends to be perpendicular to the filament.

Why?

When?

Why?

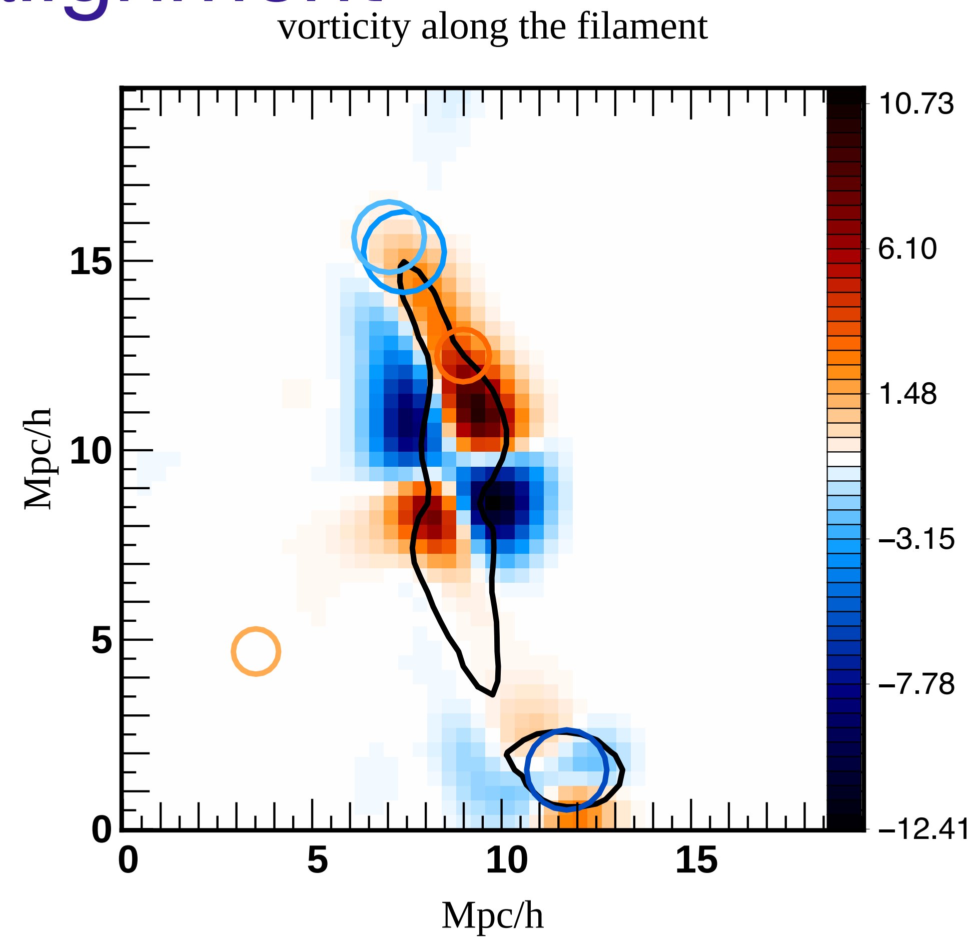
Halo-spin vorticity alignment

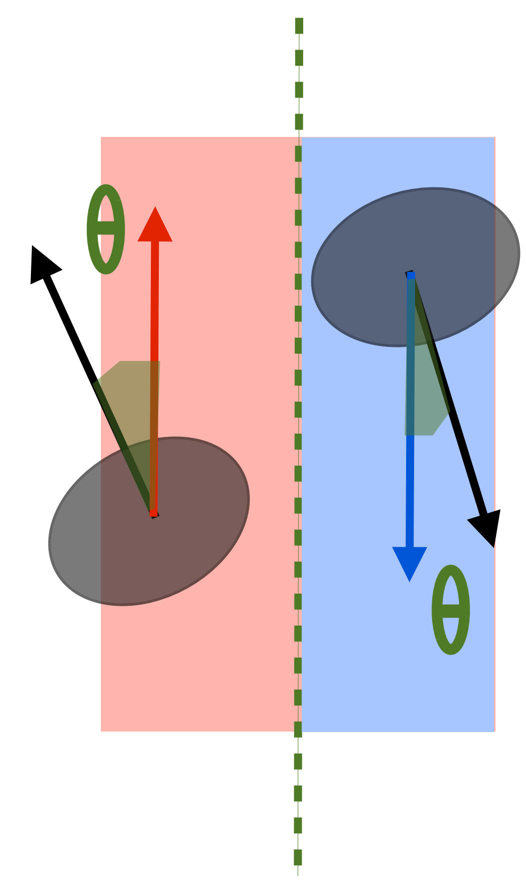


anti-aligned

perpen-dicular

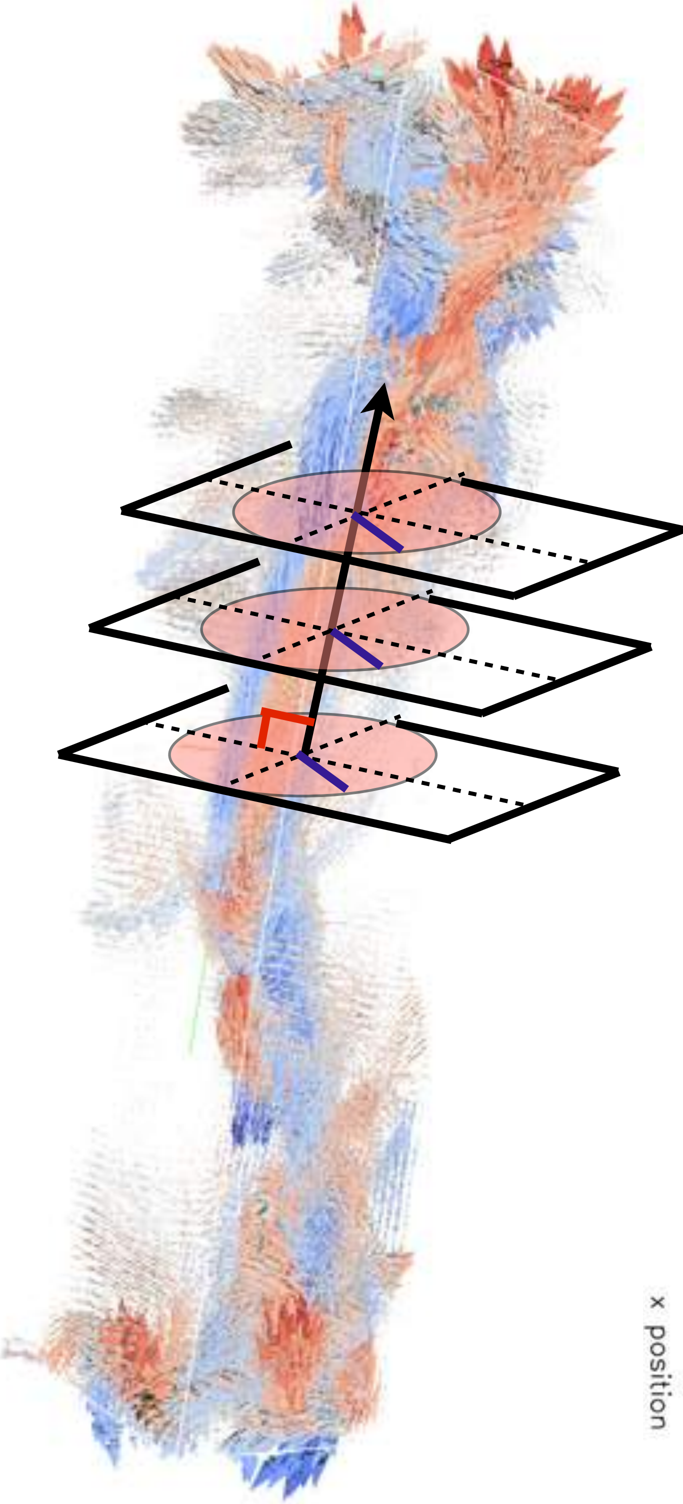
aligned



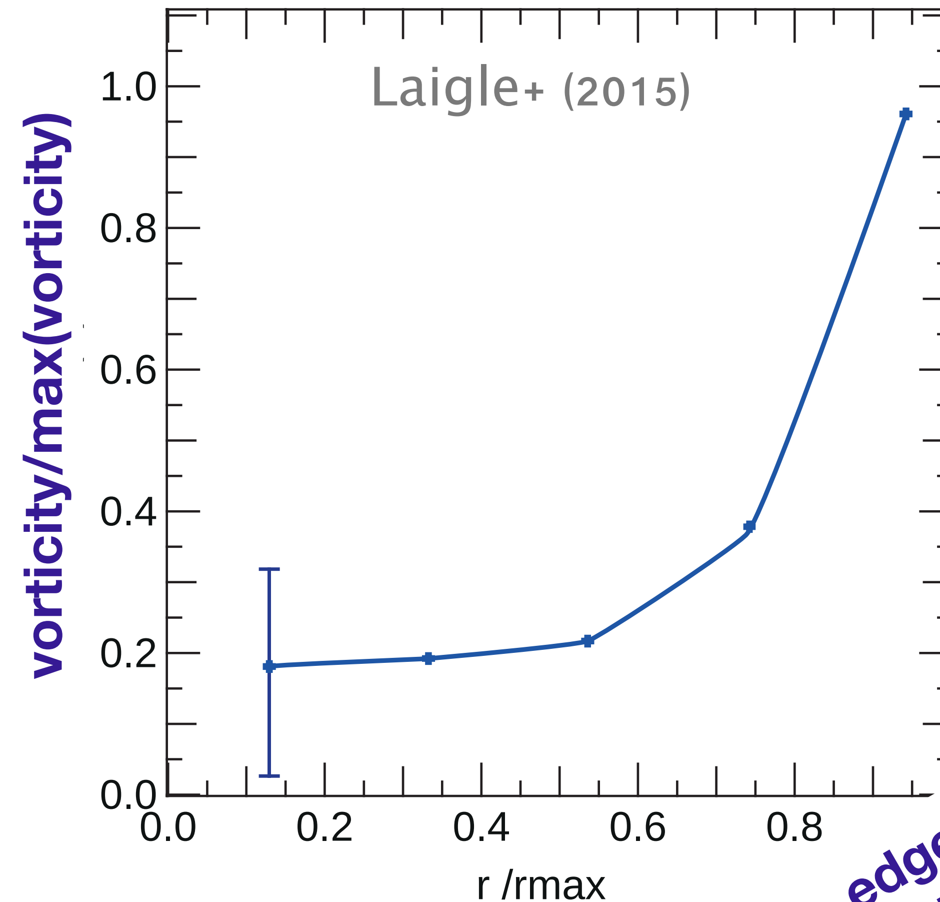


Halo spins are aligned with the vorticity in quadrants.

Geometry of the vorticity cross-section

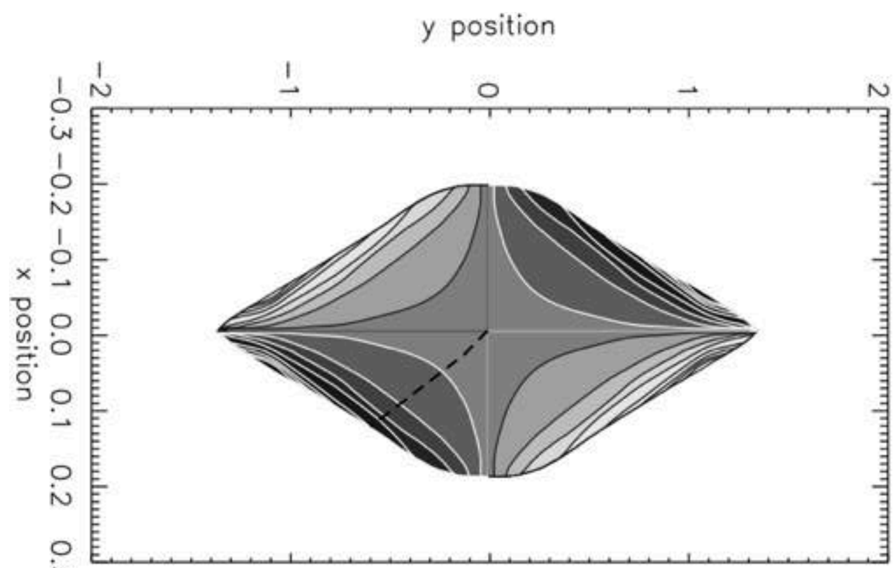


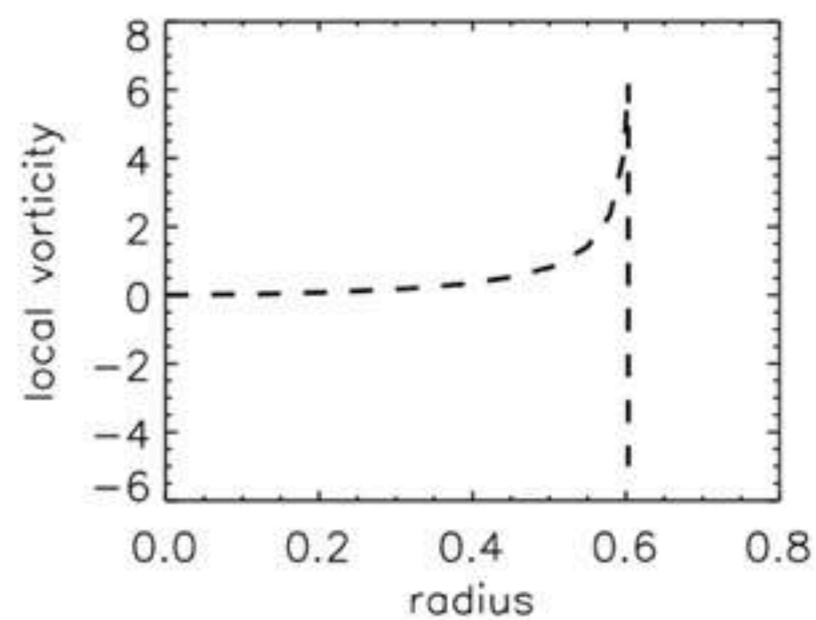
Stacked profile →



edge of the filament

Pichon & Bernardeau (1999)

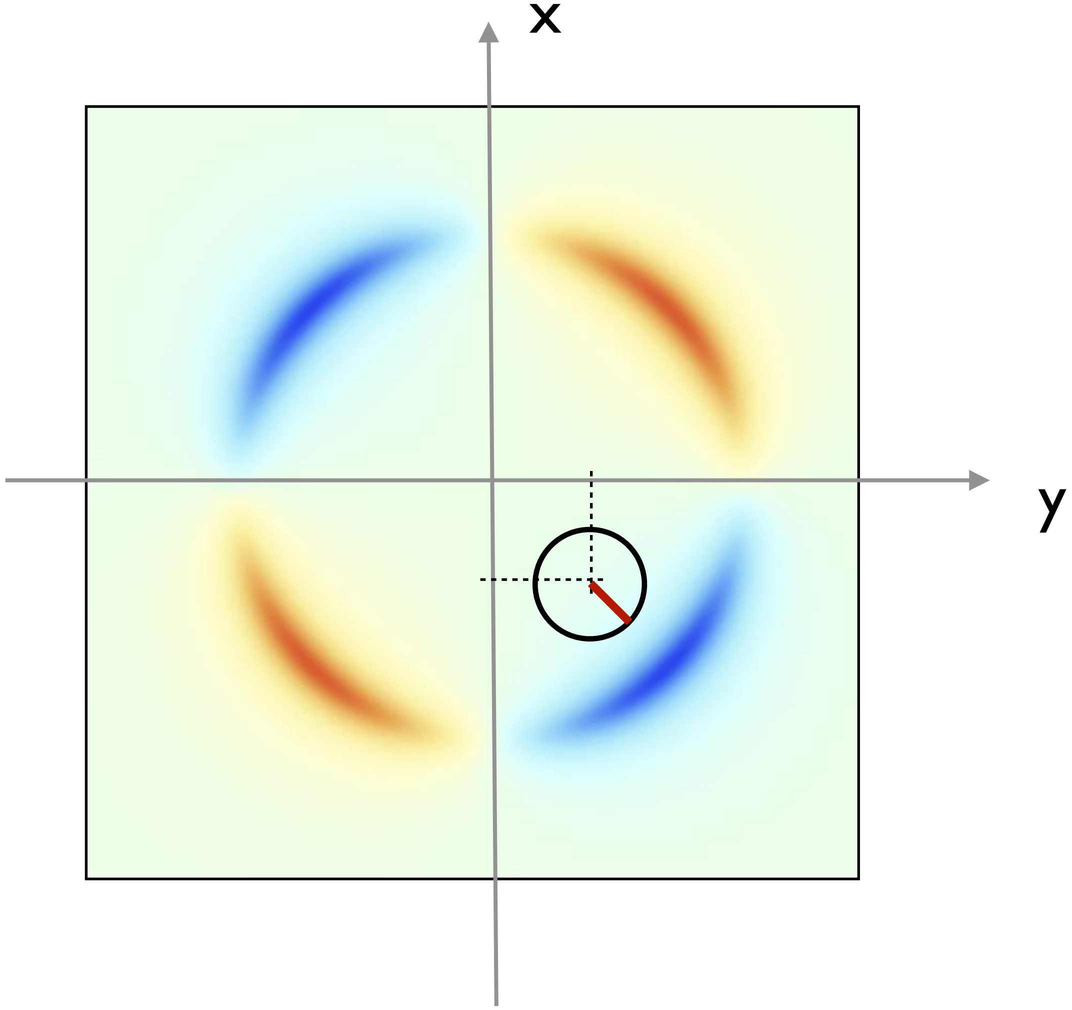


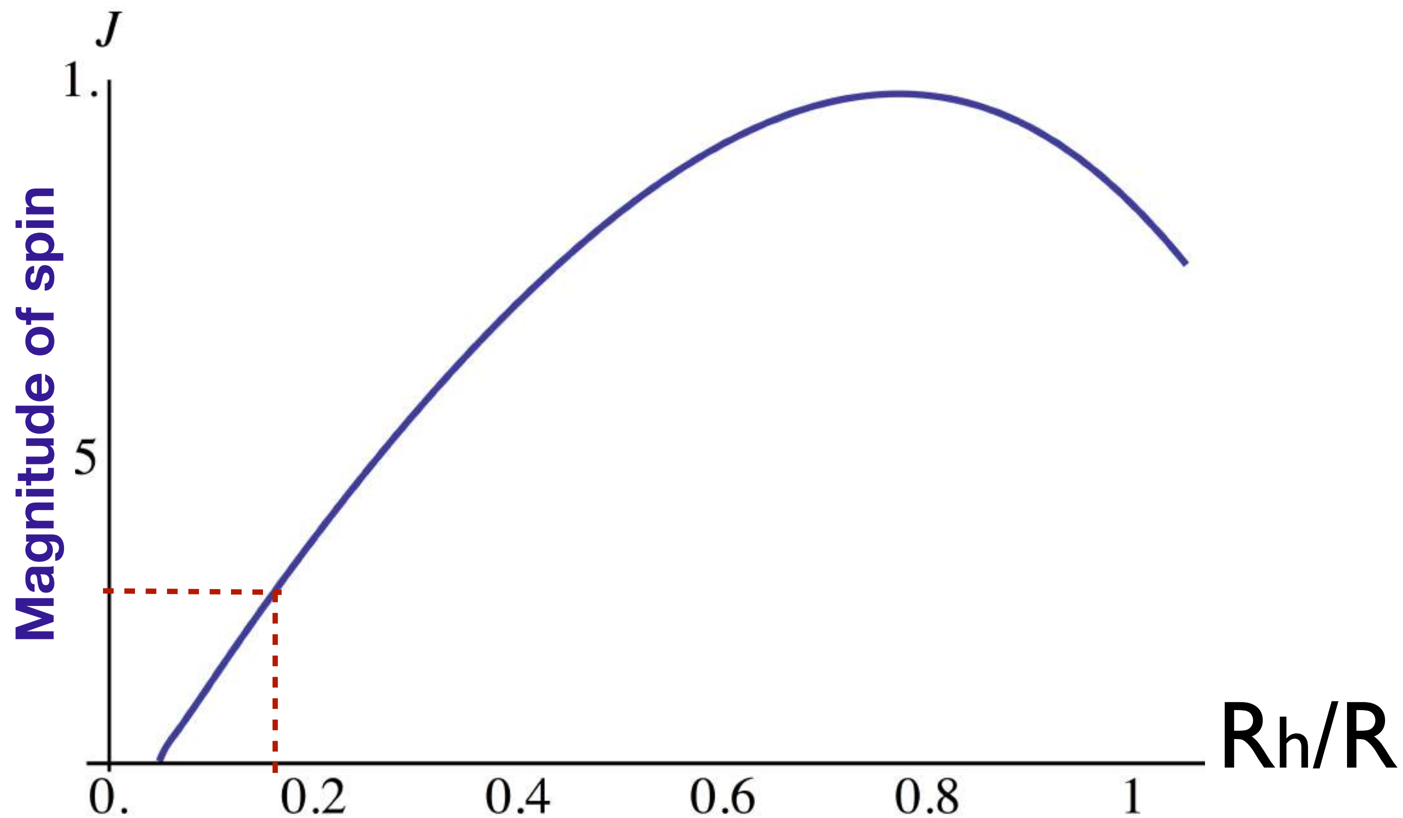


High vorticity regions are located at the edges of the filament.

Mass transition for spin alignment

Idealized **toy model**: The position is fixed and the radius of the halo increases:

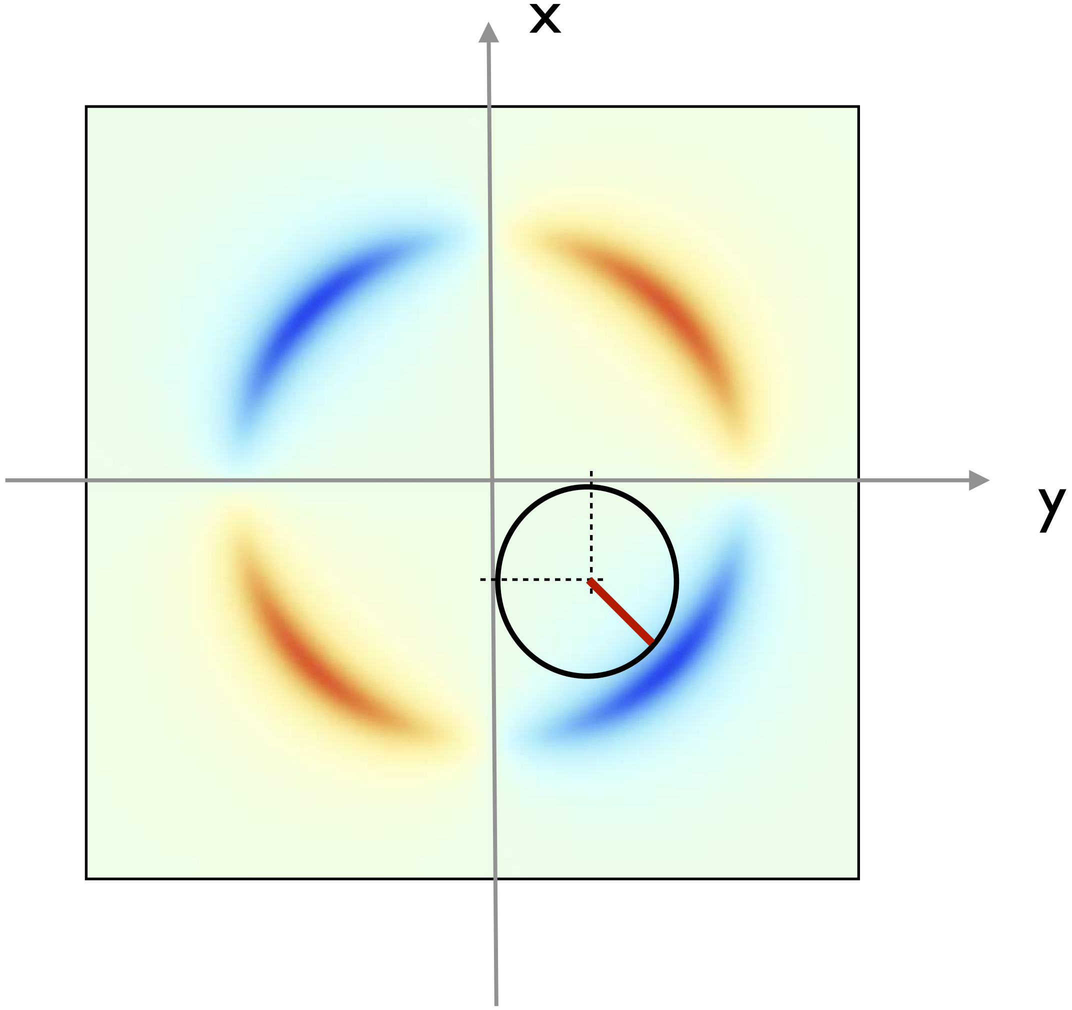


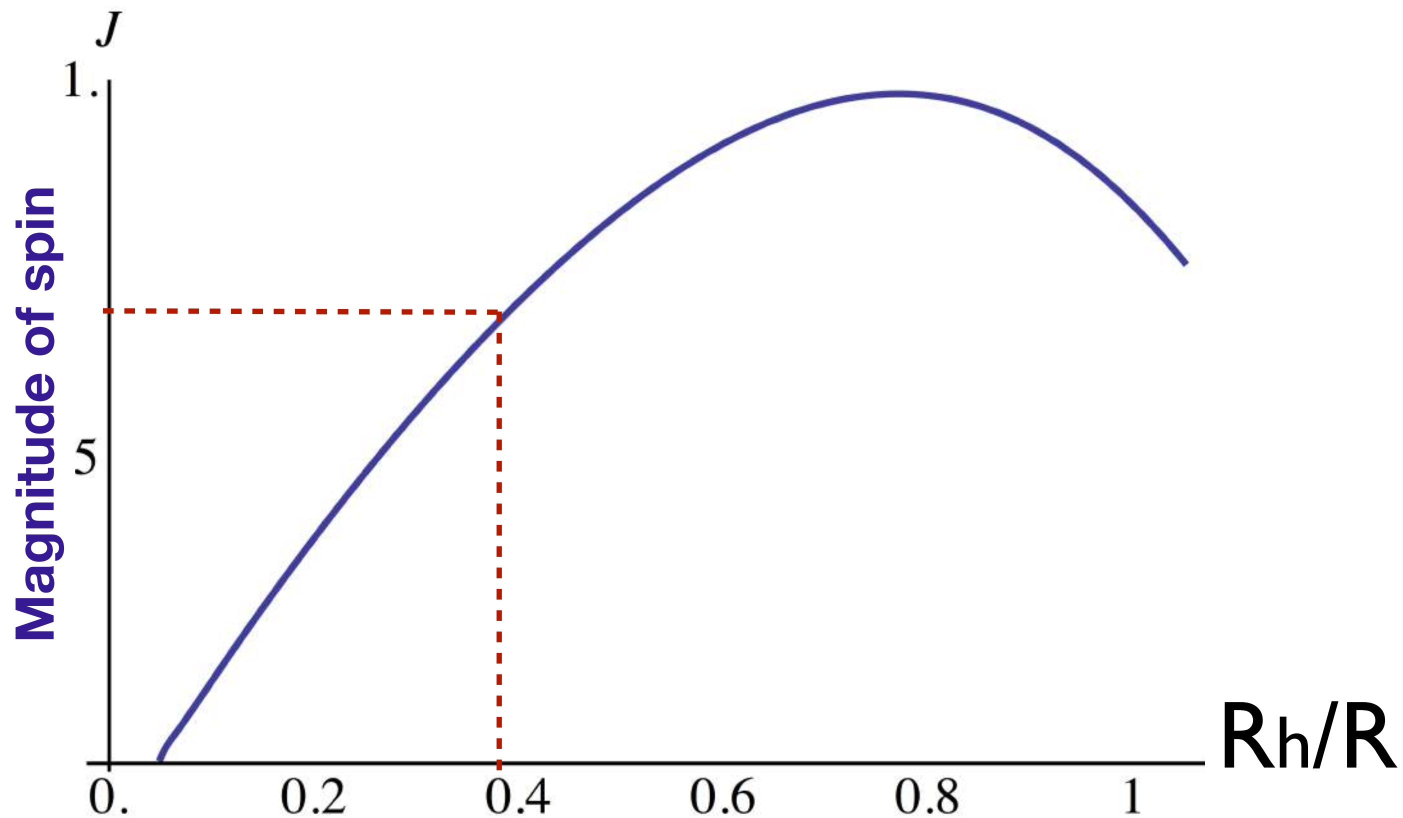


Transition mass is correlated with the size of the quadrants.

Mass transition for spin alignment

Idealized toy model: The position is fixed and the radius of the halo increases:





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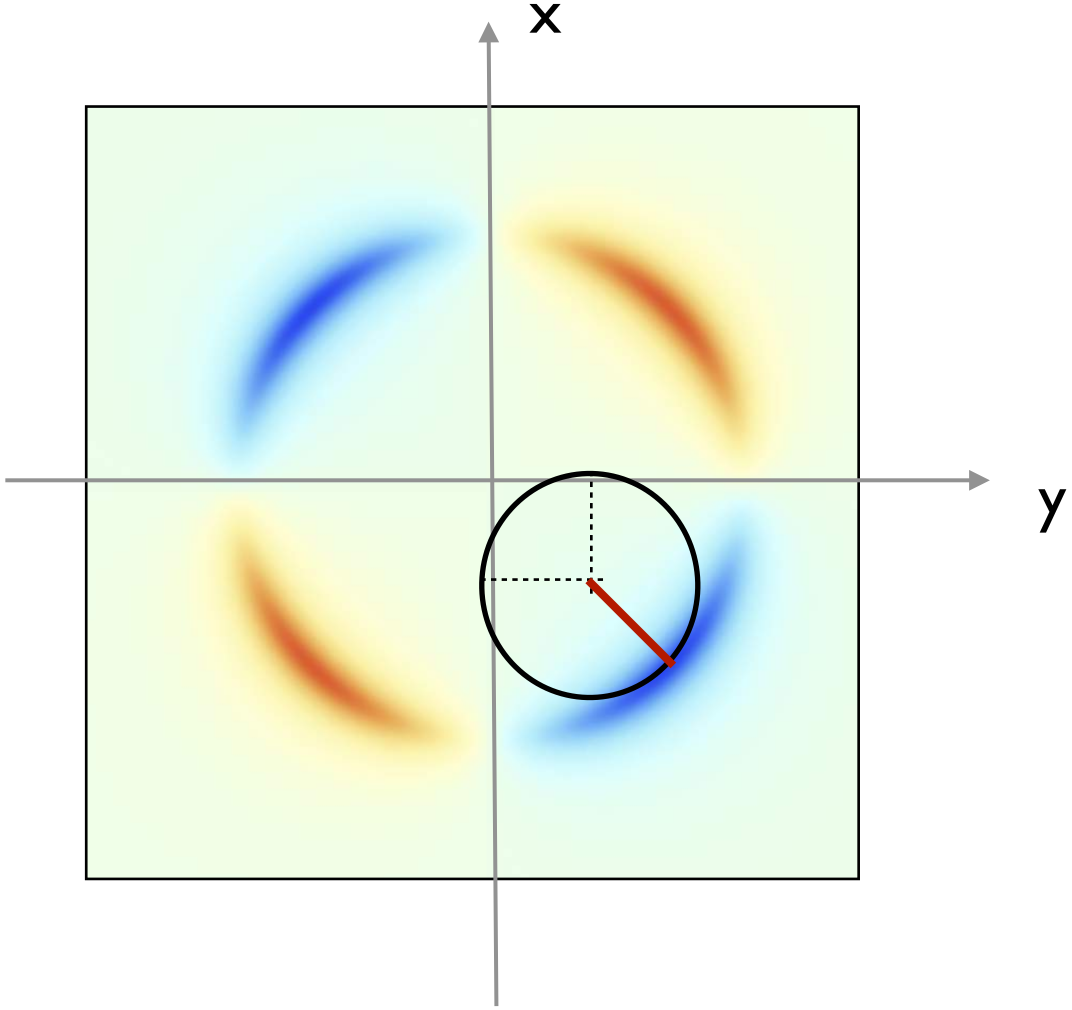

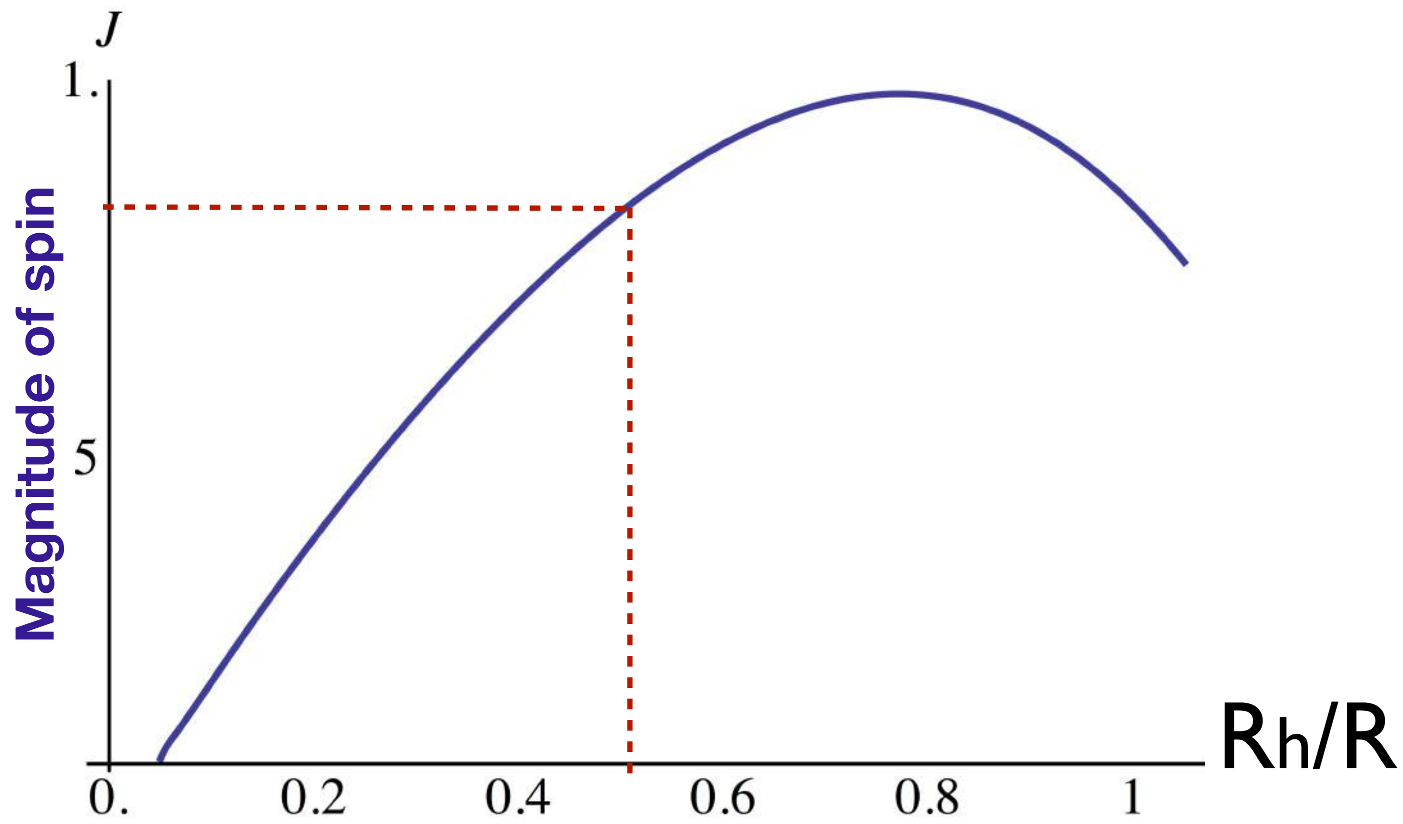

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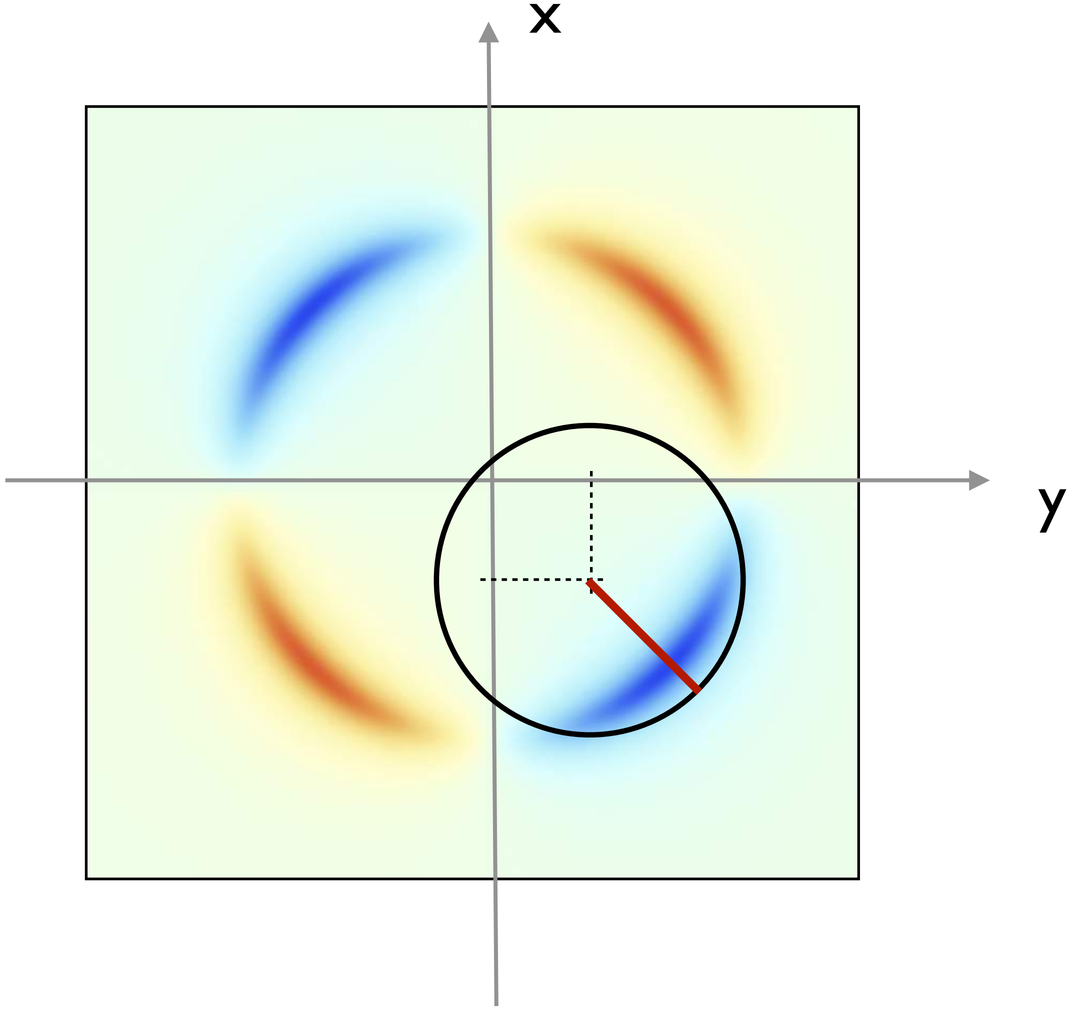

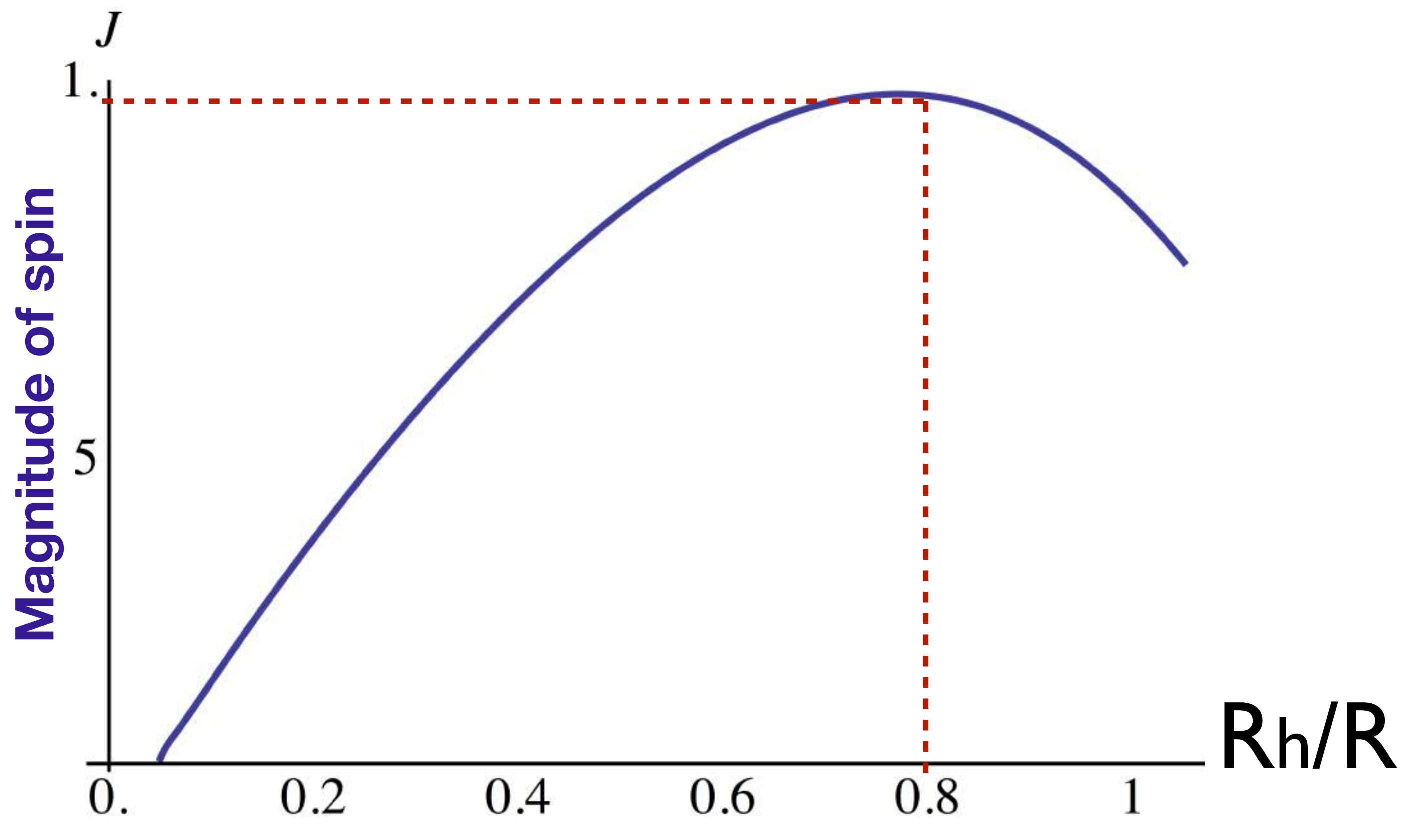

Transition mass is correlated with the size of the quadrants.

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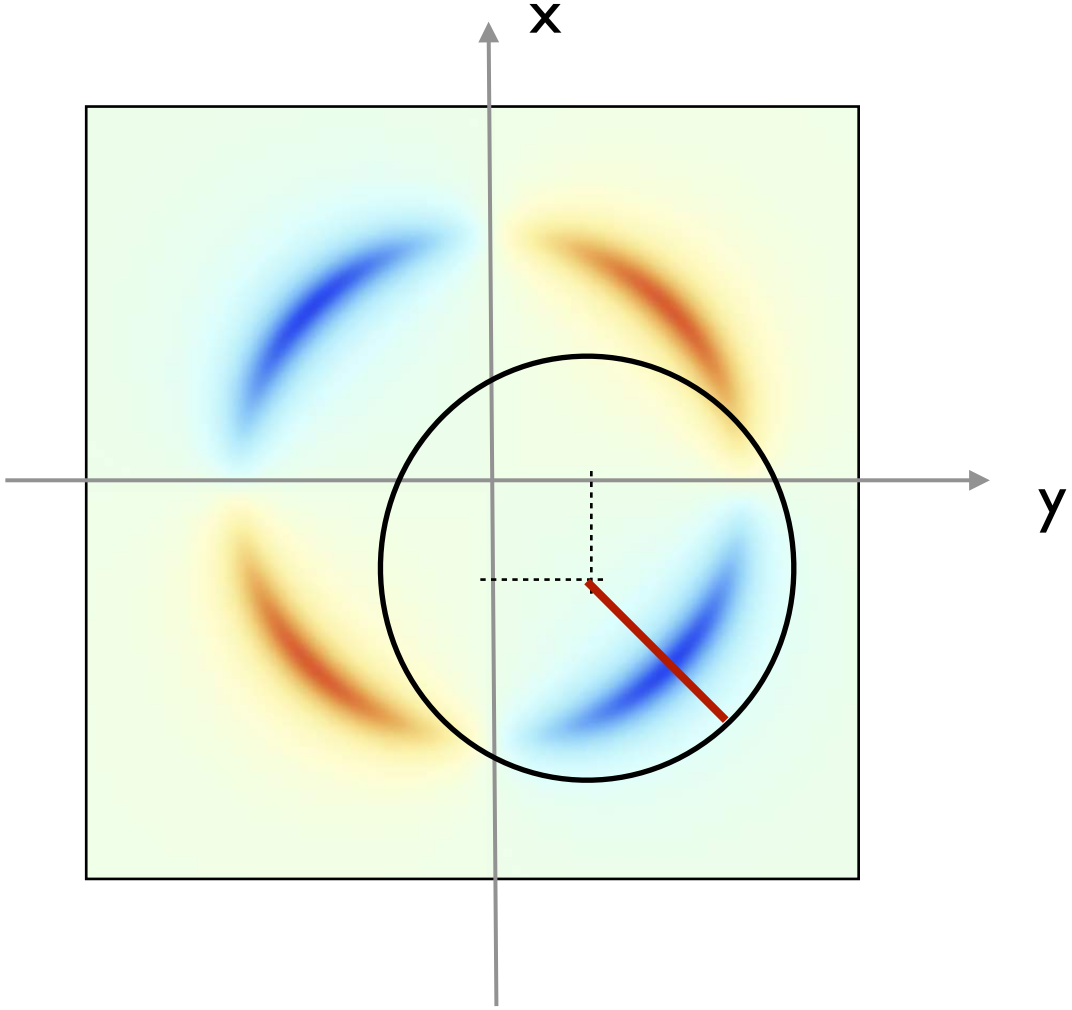

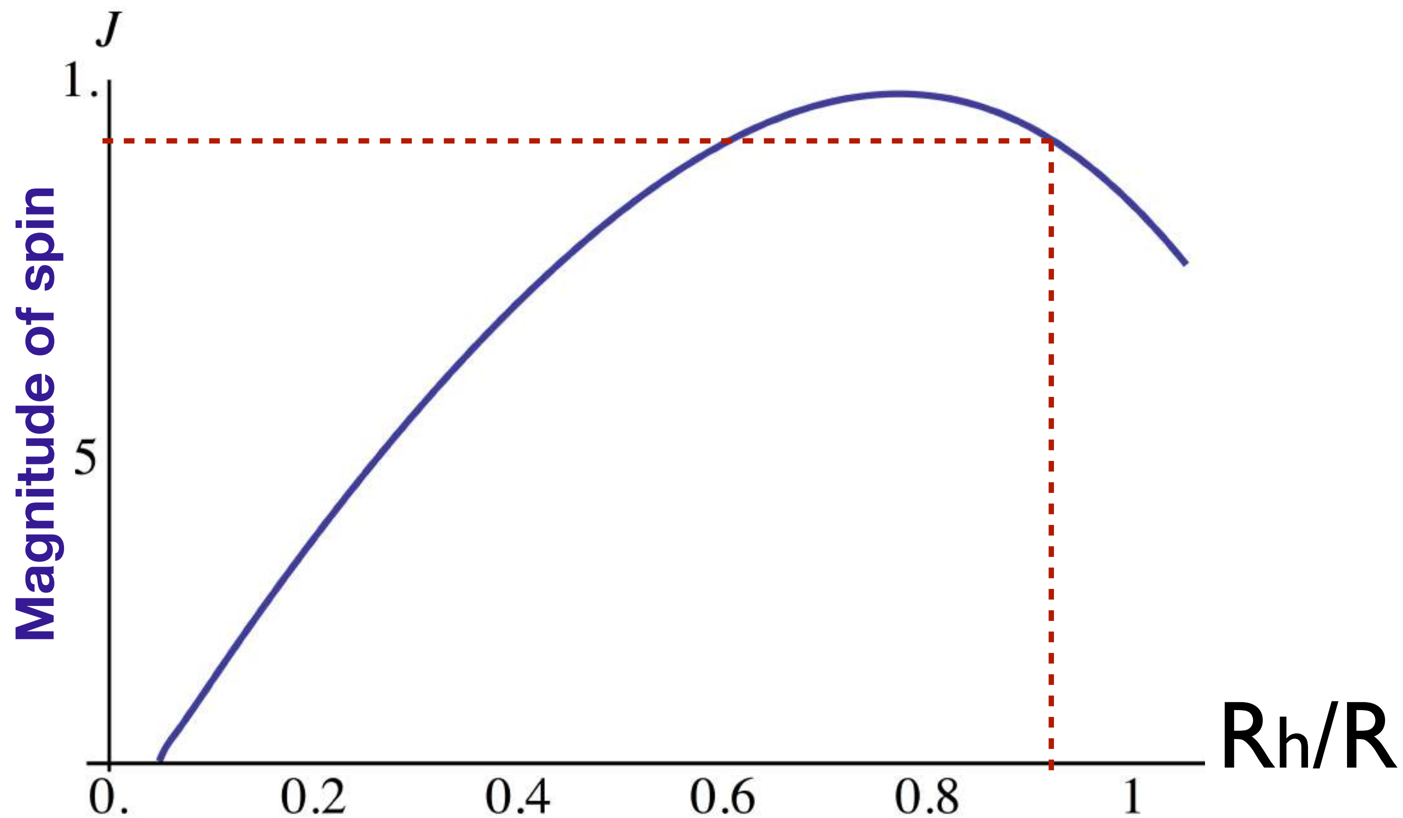

Transition mass is correlated with the size of the quadrants.

Mass transition for spin alignment

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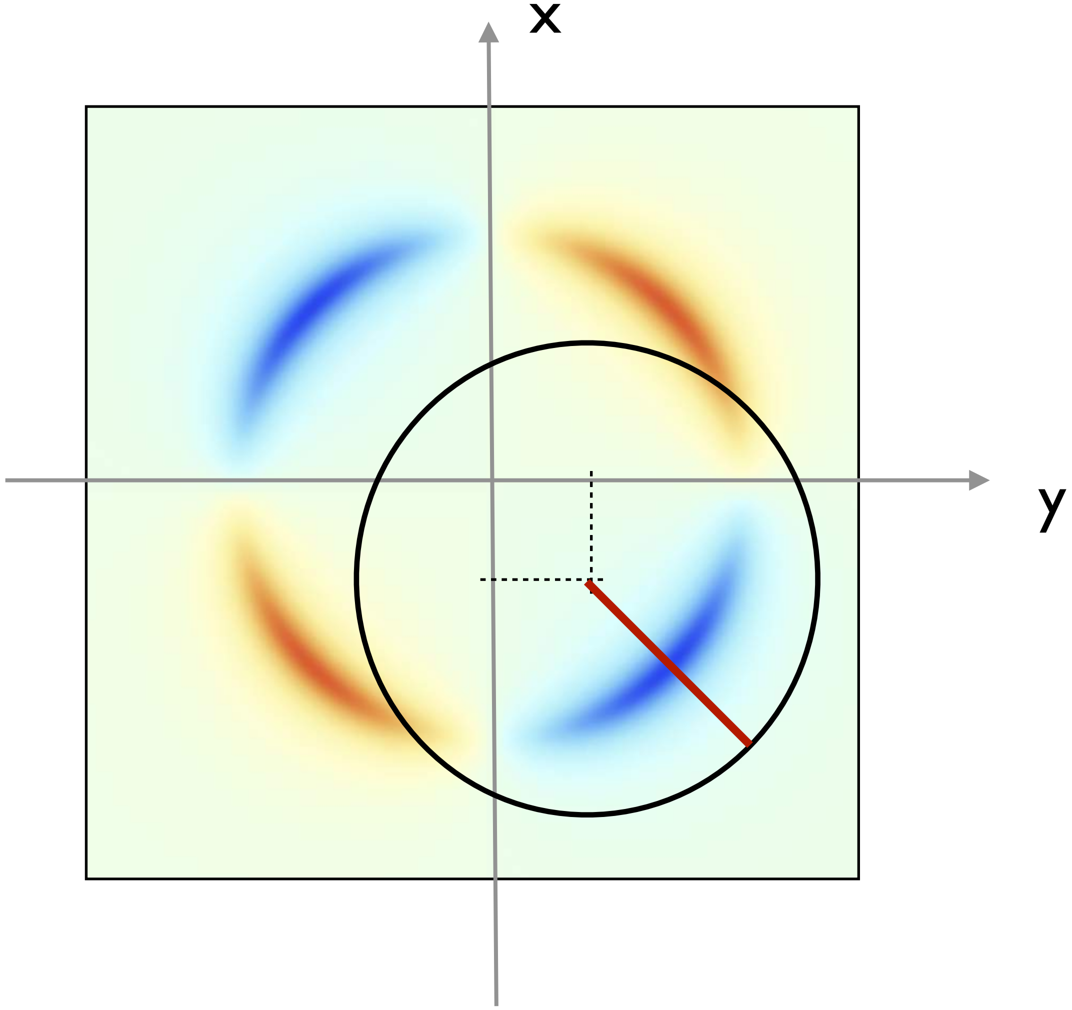
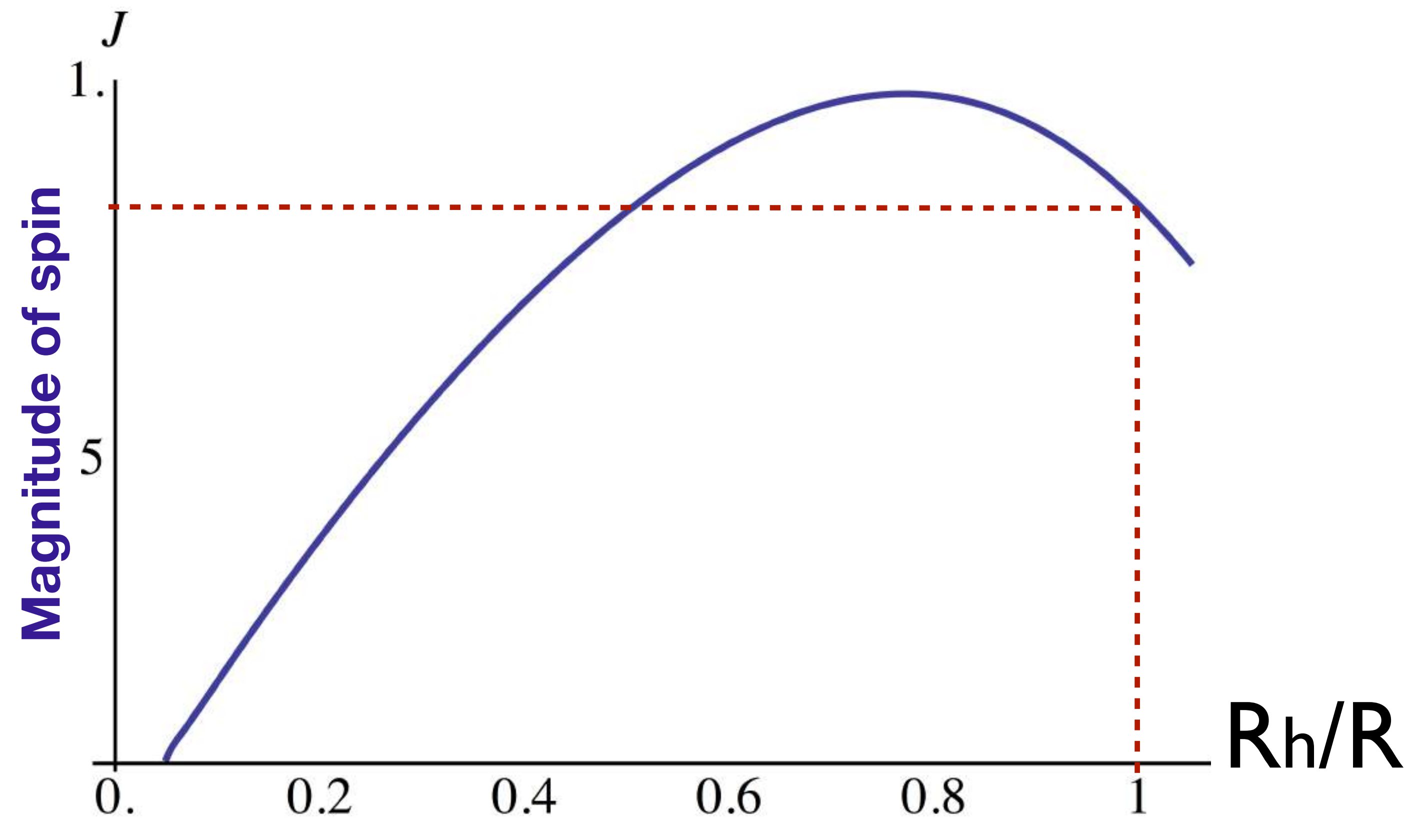
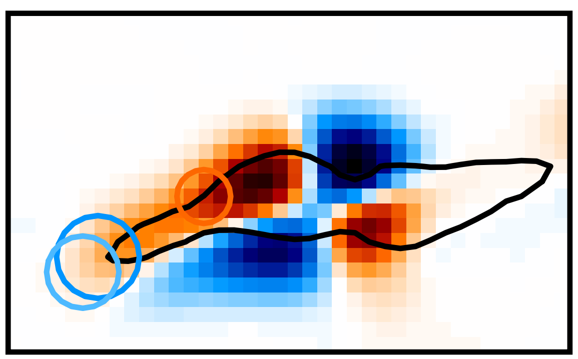




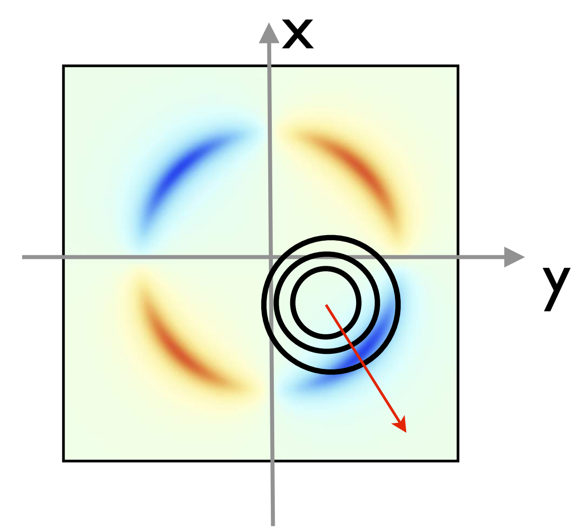
Transition mass is correlated with the size of the quadrants.

in short...

- Vorticity is confined in the filaments, and aligned with them. The cross-section with a plane perpendicular to the filament is typically quadripolar.



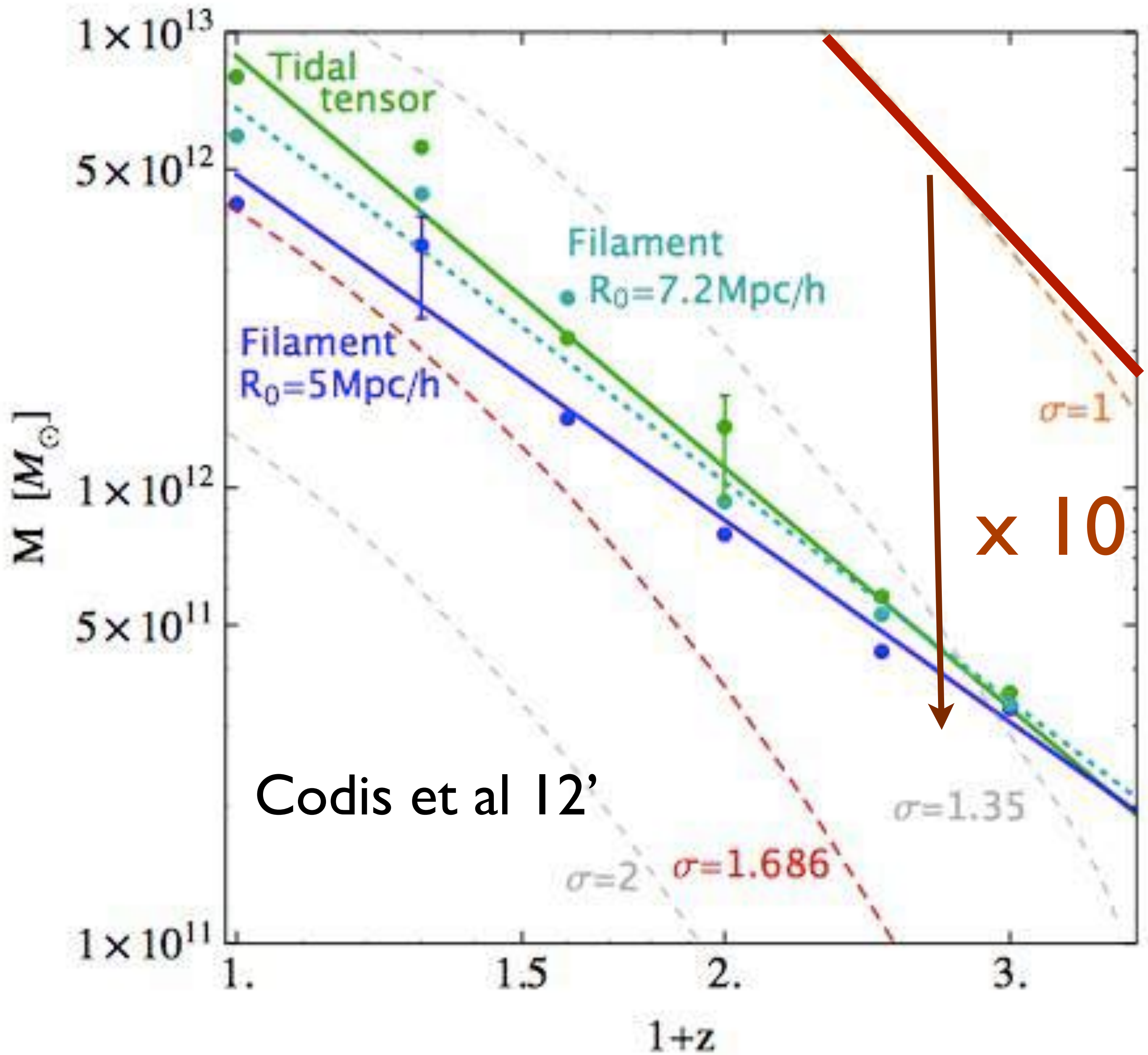
- Halo spins are aligned with the same polarity than vorticity in quadrants.



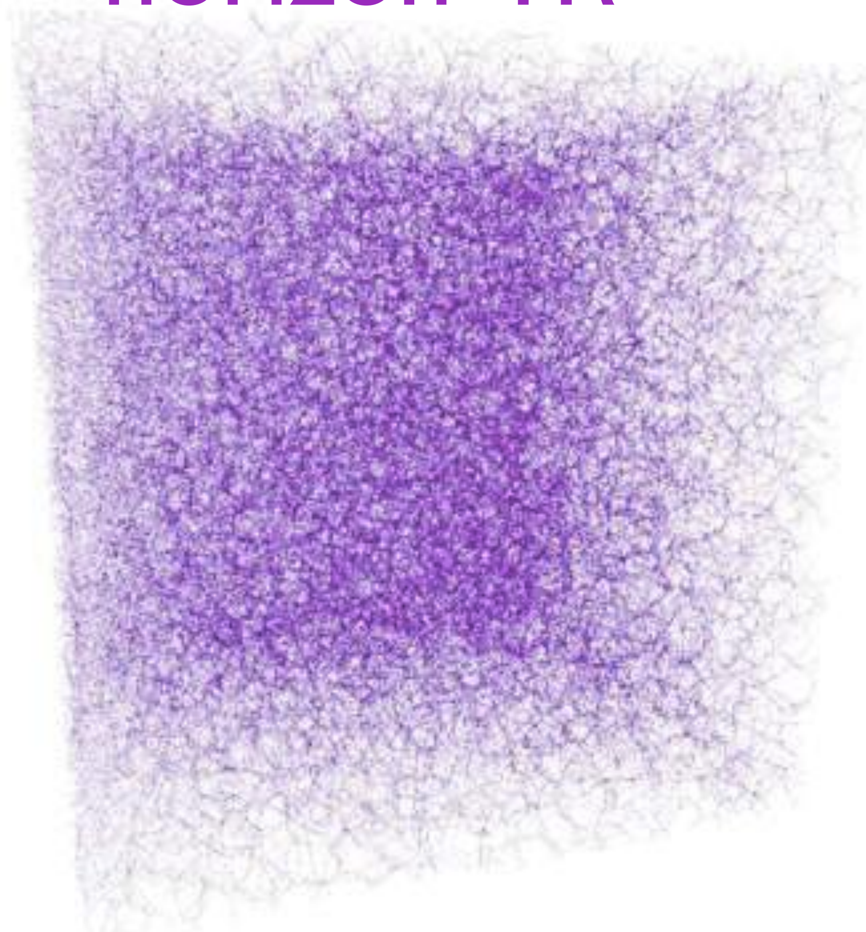
- Qualitatively, the transition mass in the alignment could be correlated with the size of the quadrant.

Explain transition mass? YES!

Transition mass versus redshift



horizon 4π

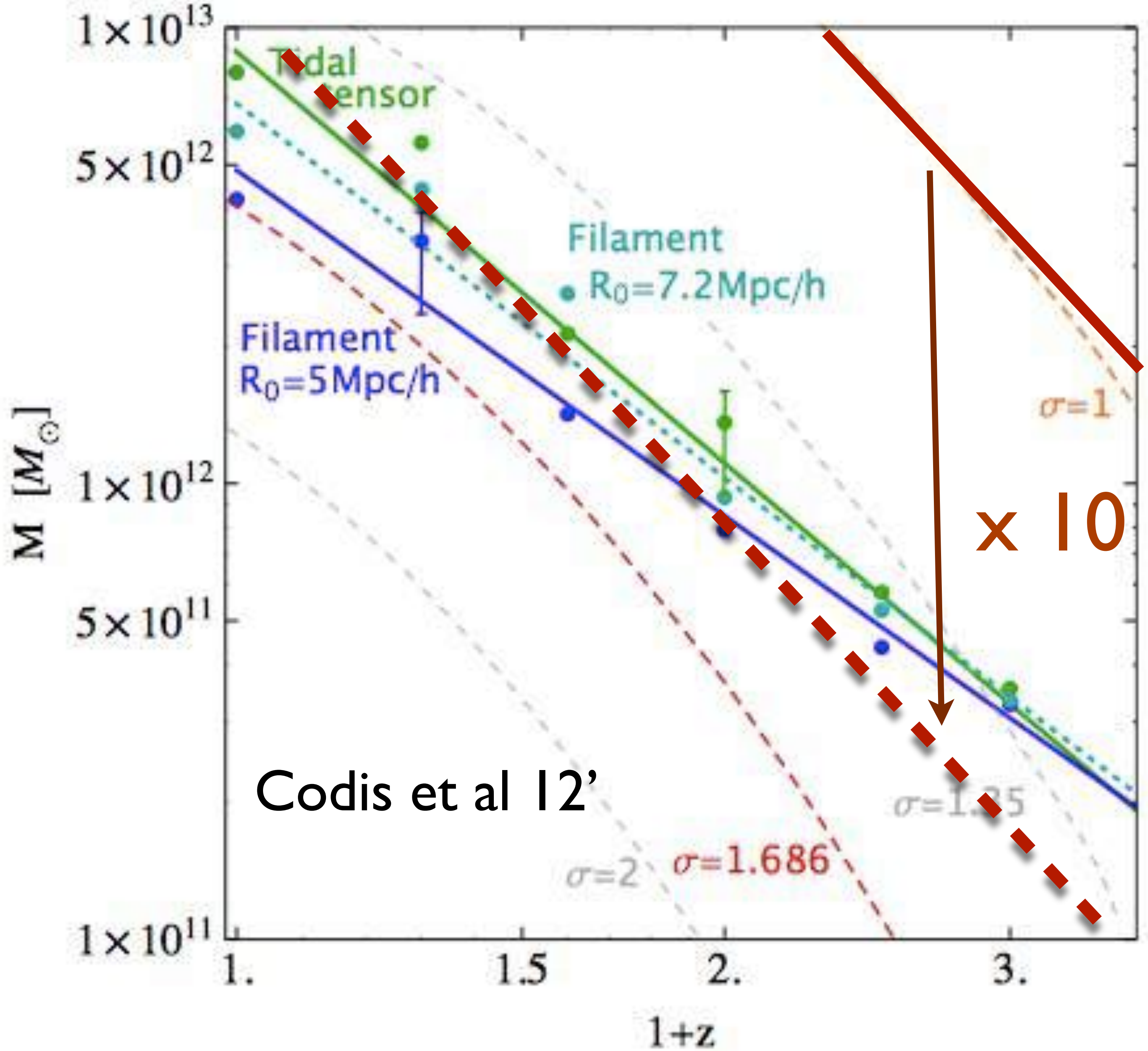


skeleton of LSS

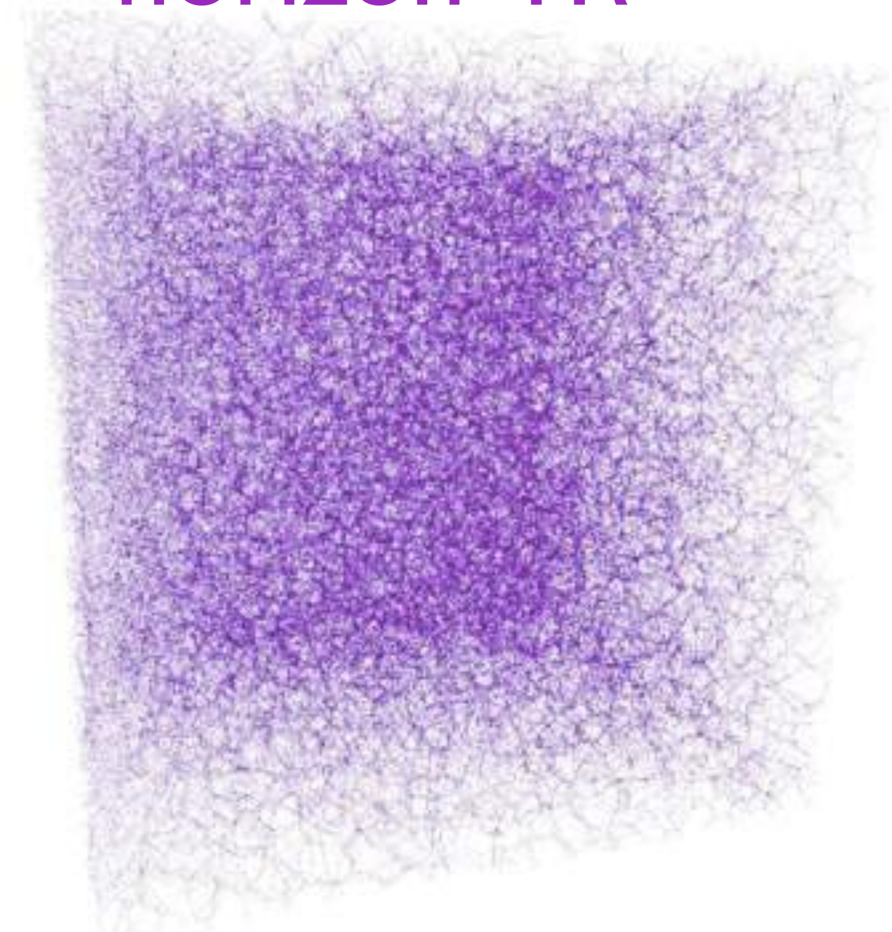
Only 2 ***ingredients***: a) spin is spin one b) filaments flattened

Explain transition mass? YES!

Transition mass versus redshift

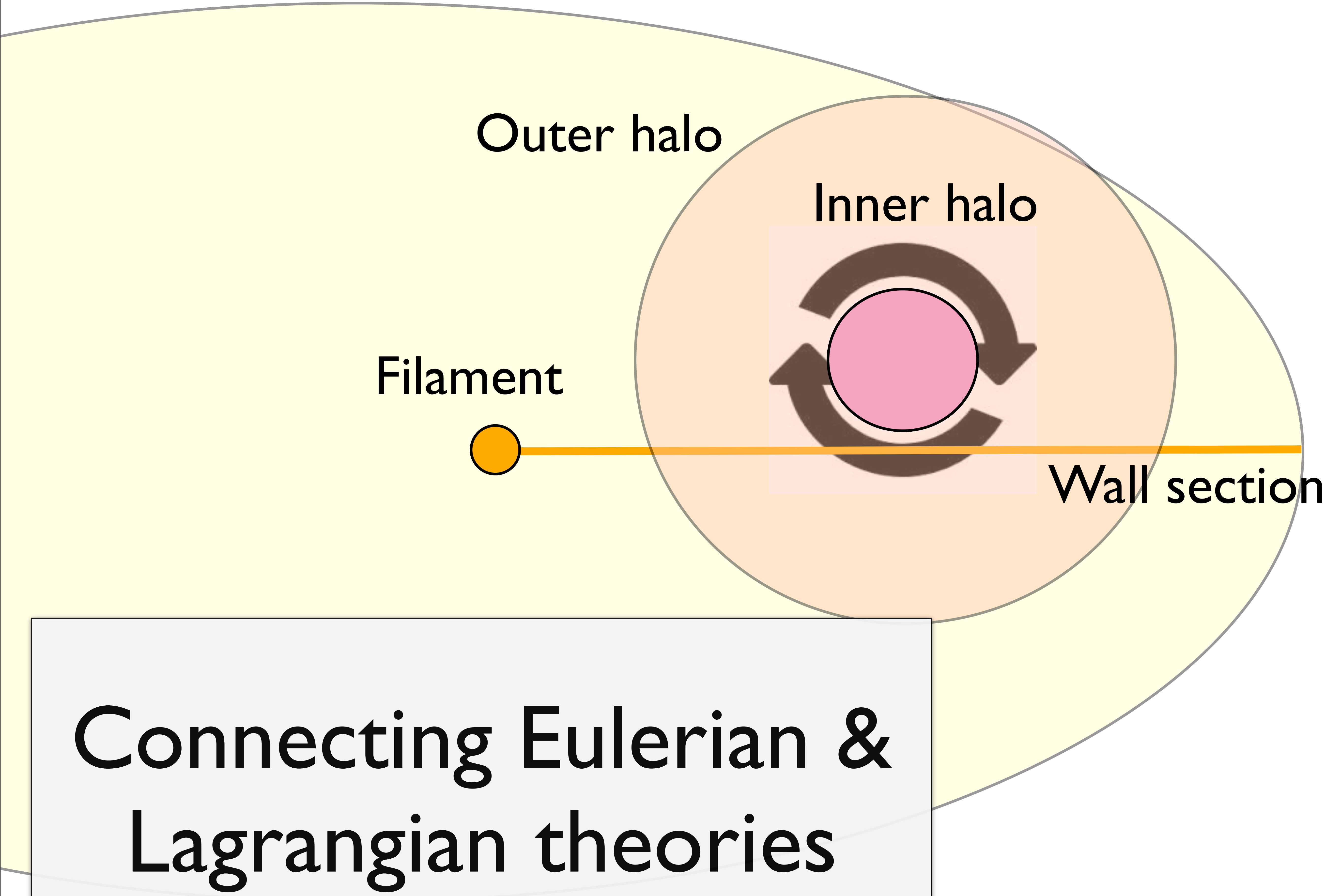


horizon 4π

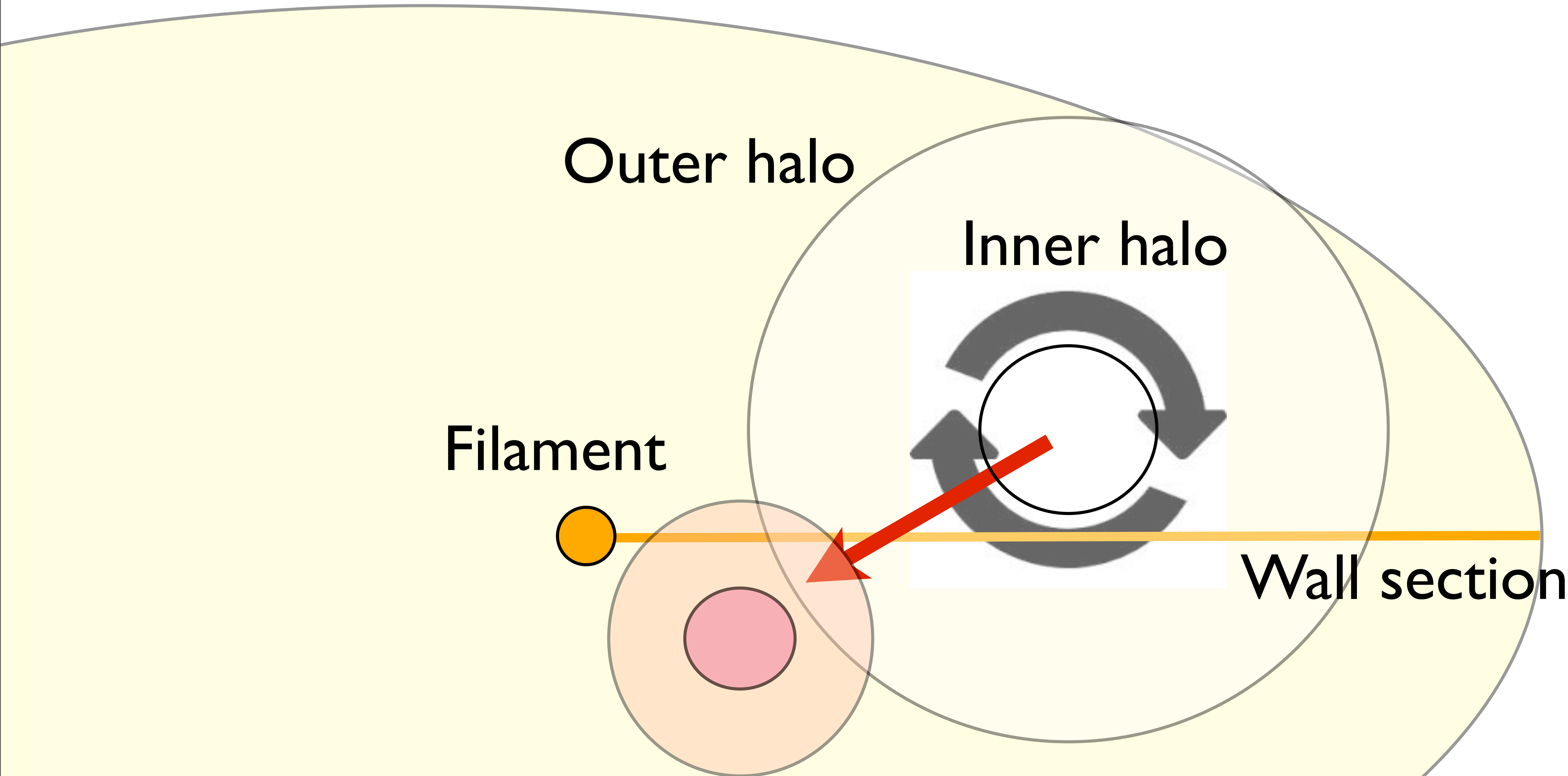


skeleton of LSS

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

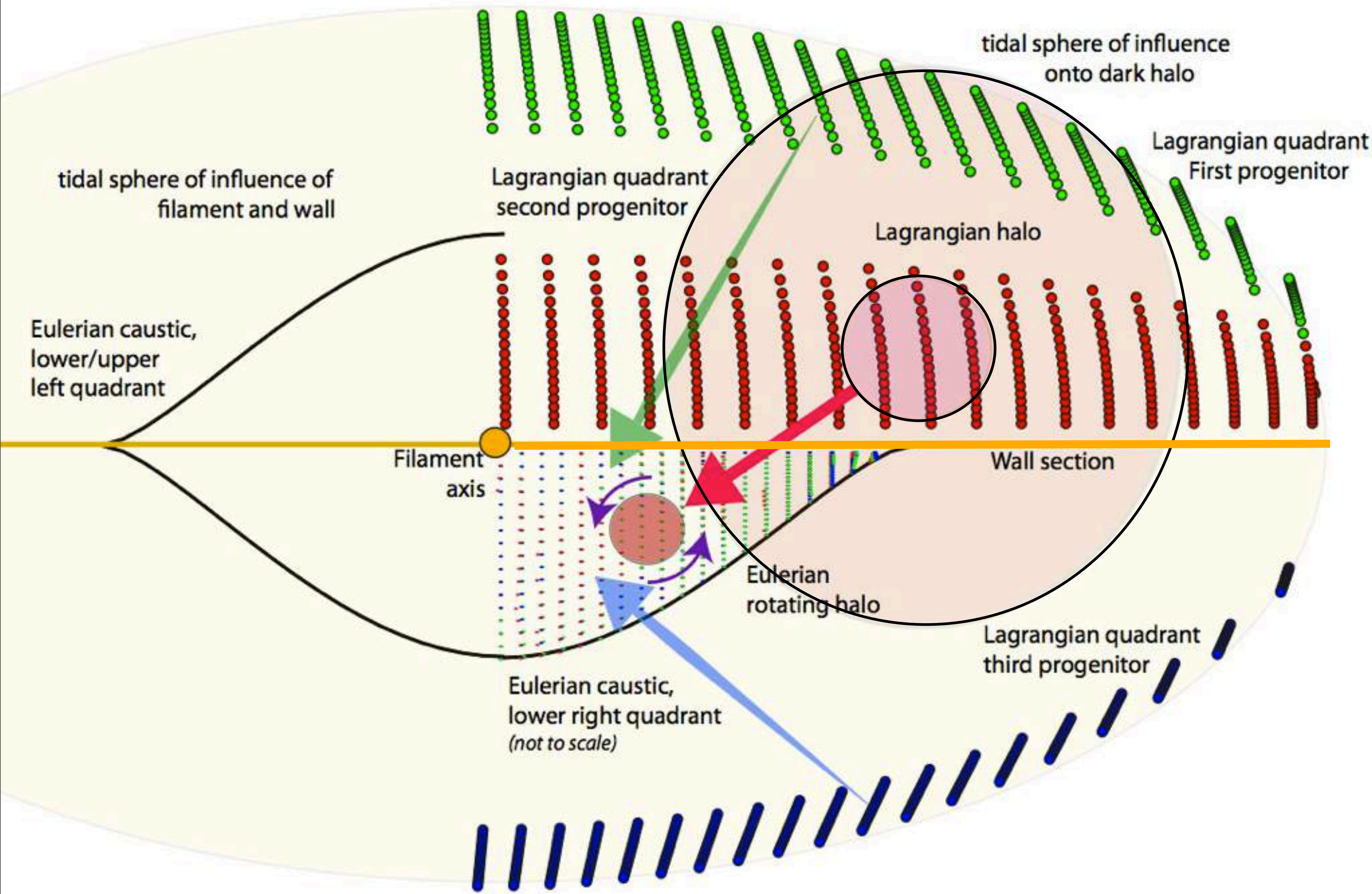


Connecting Eulerian & Lagrangian theories



+Zeldovitch boost

BUT in // from the pt of view of LSS



Complementary vorticity advection view

Take home message...

- Morphology (= AM stratification) driven by LSS in cosmic web: it explains Es & Sps where, how & why from **IC**s
- Signature in correlation between *spin* and *internal* kinematic structure of cosmic web on larger scales.
- Process driven by simple PBS/biassed clustering dynamics:

  - requires updating TTT to **saddles**: simple theory :-)
  - can be expressed into an Eulerian theory via vorticity

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*

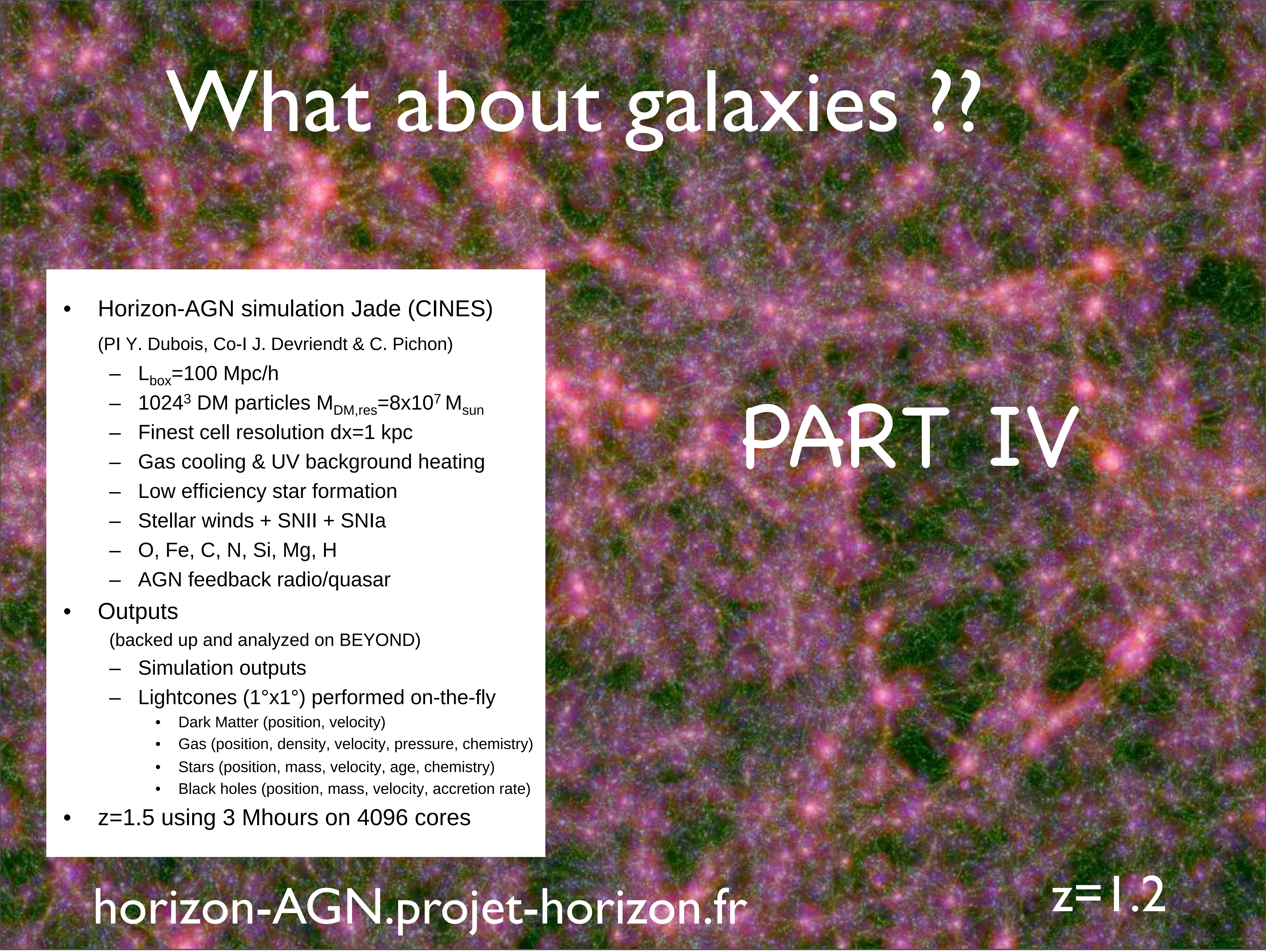
- which is why the δ-Web is the best :-)

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

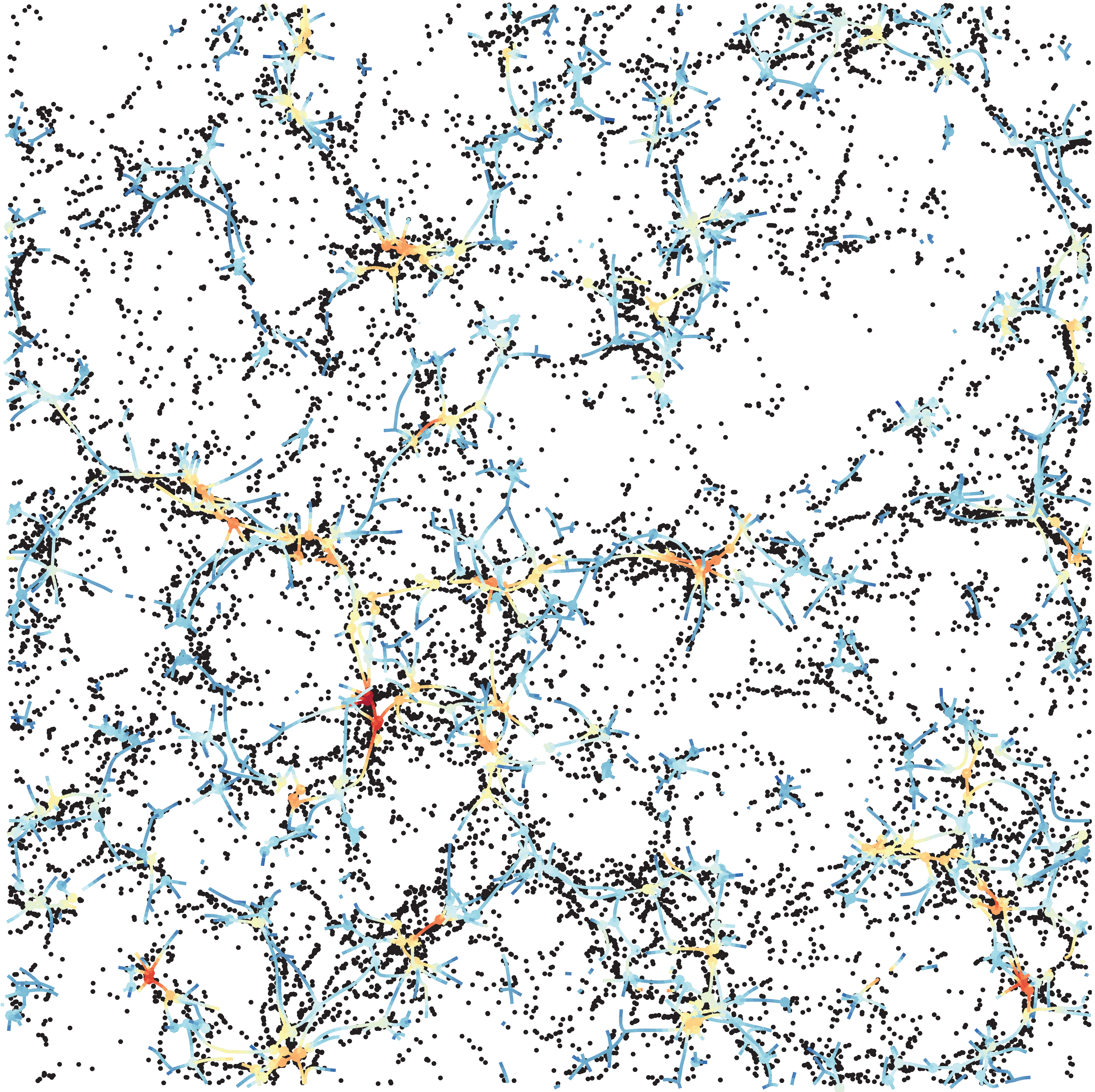


horizon-AGN.projet-horizon.fr

Part V Outline

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

Galaxies versus dense filaments



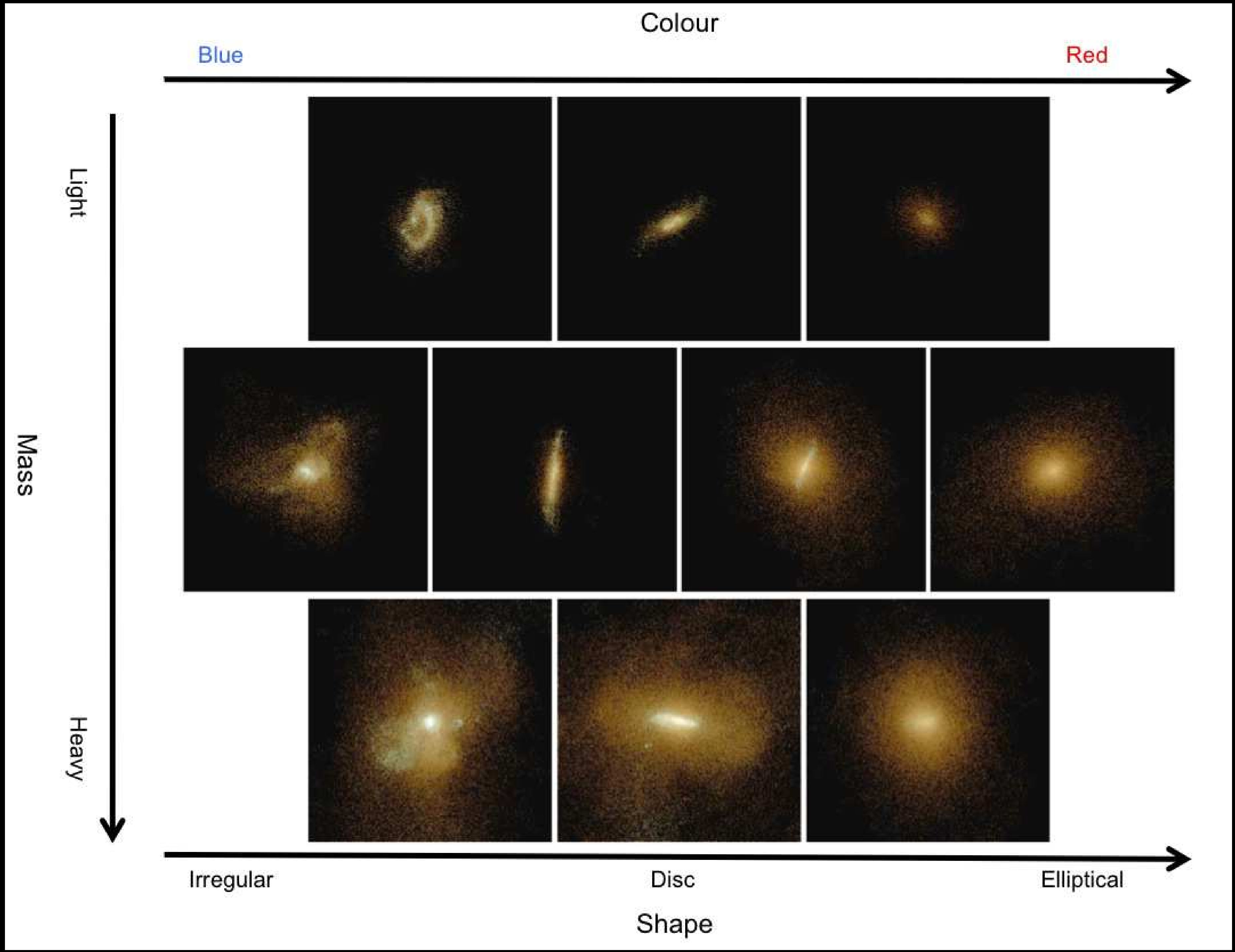
Galaxies are strongly

clustered

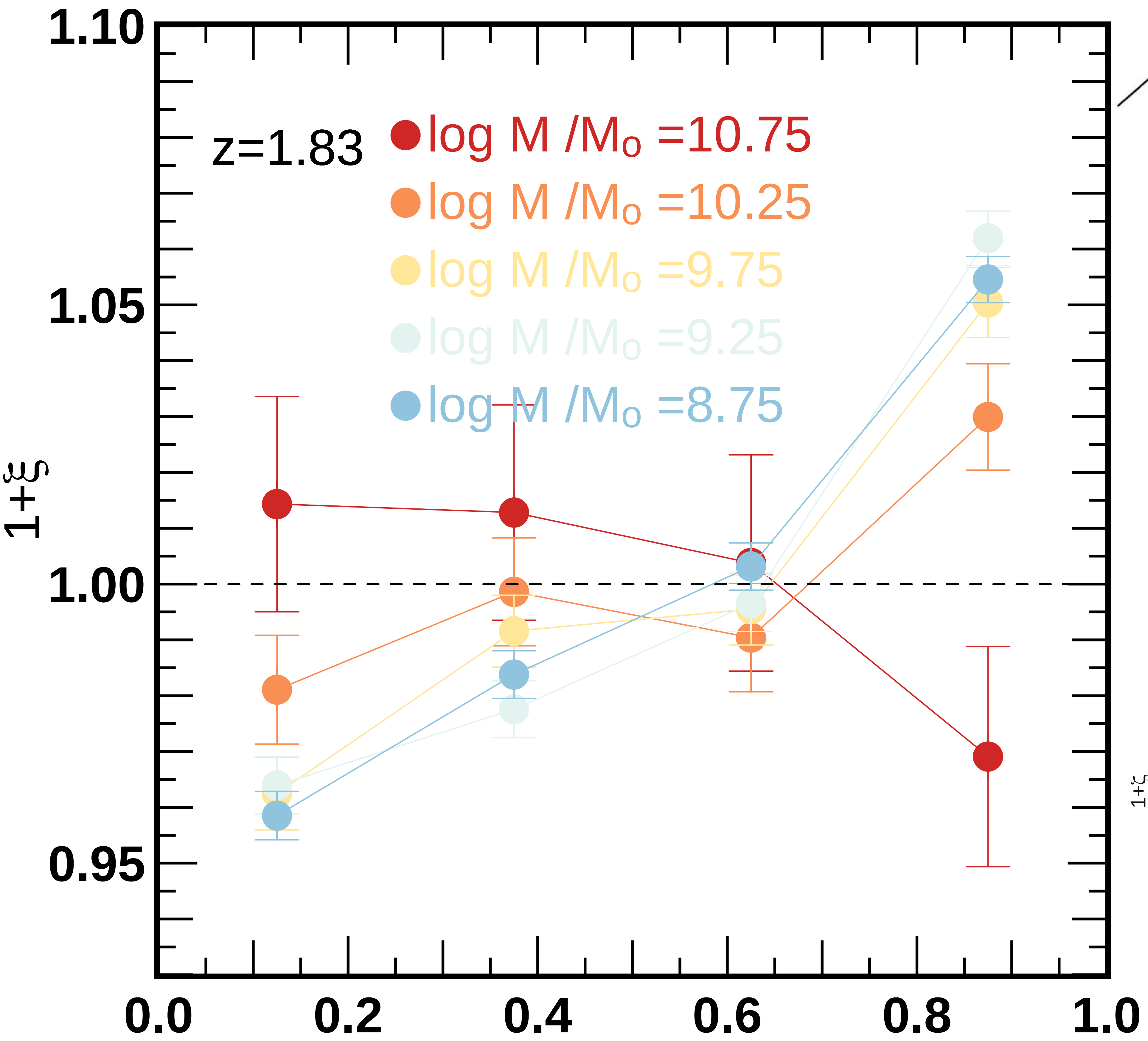
near filaments

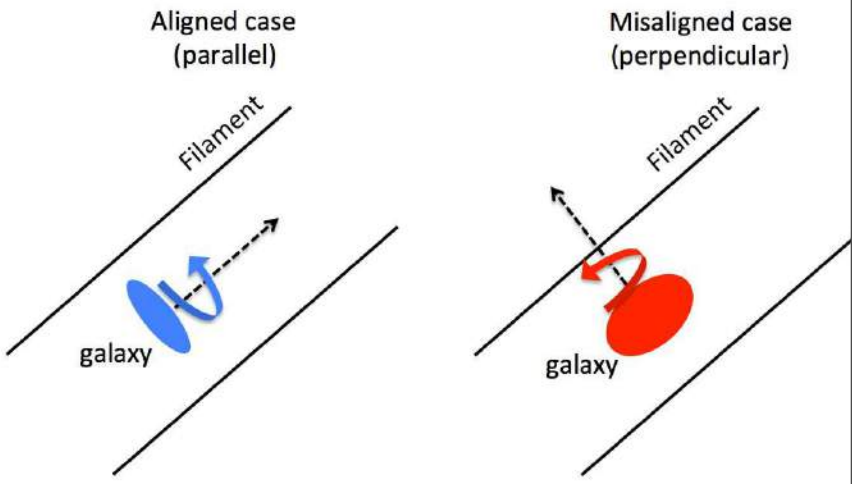
can morphology trace spin flip ?

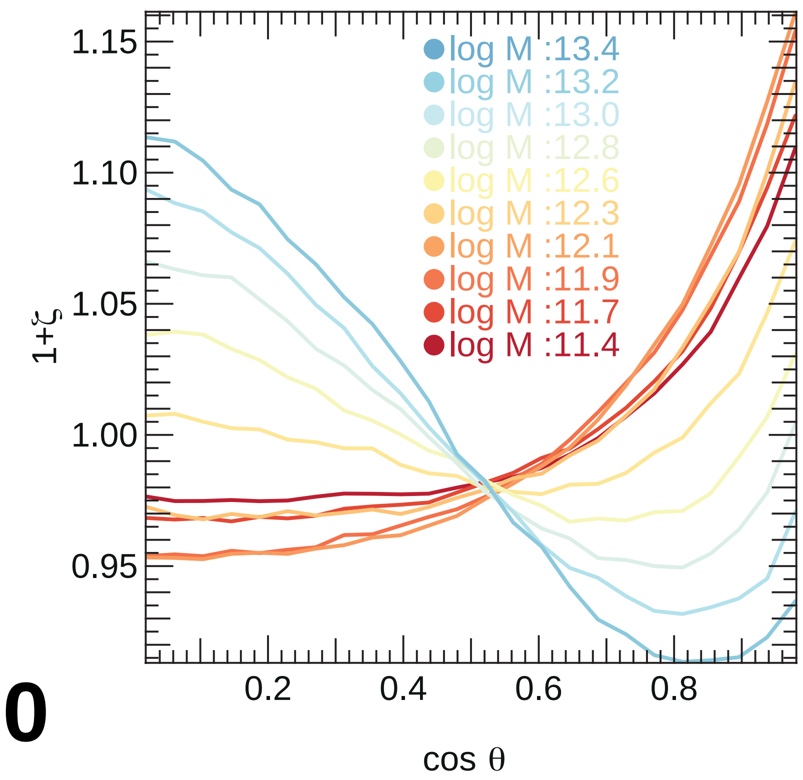
- thanks to AGN feedback we have morphological diversity


Colour
Blue
Red
Mass
Light
Heavy
Irregular
Disc
Elliptical
Shape

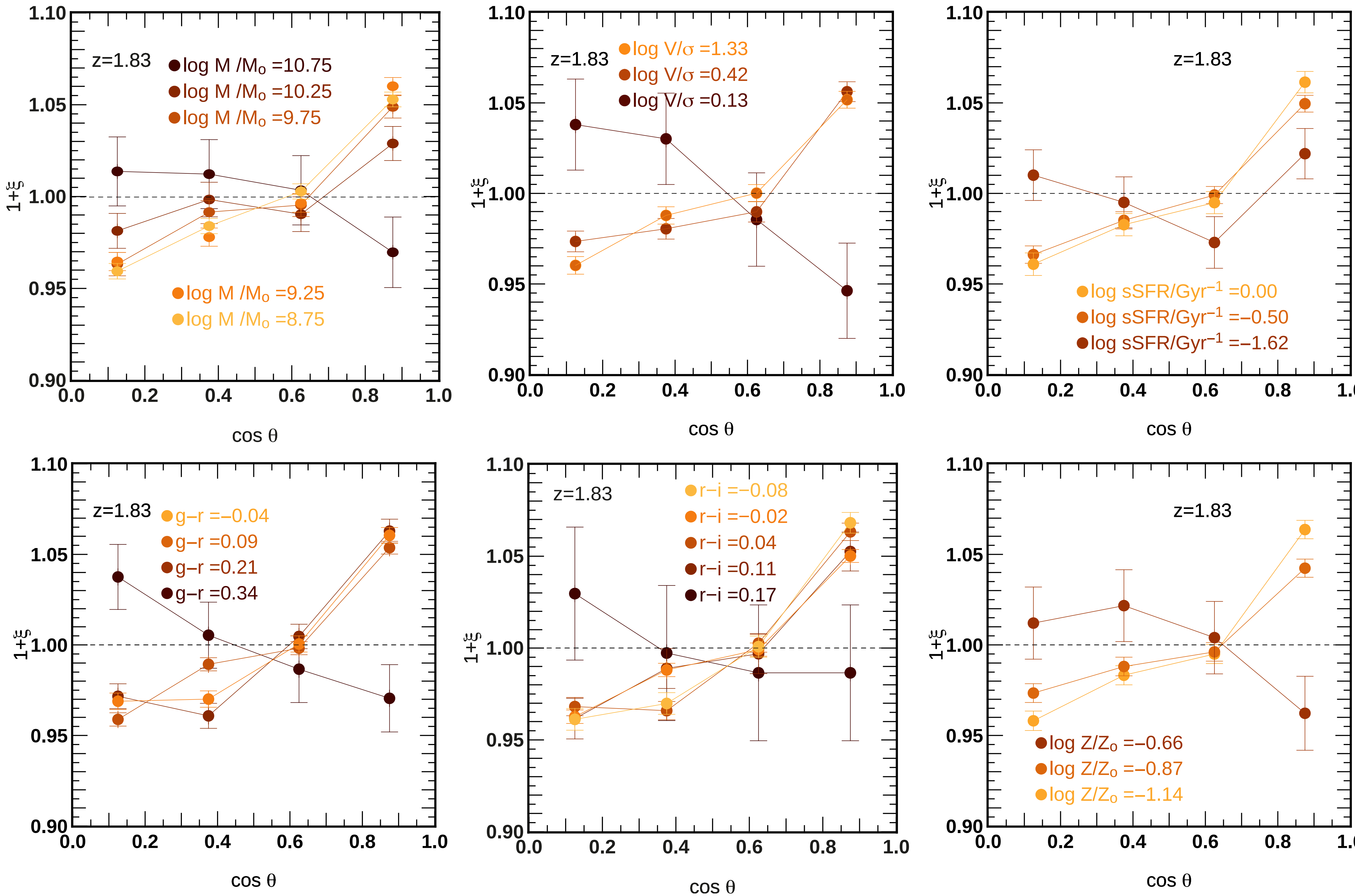
Filament-galactic spin & mass







Can morphological/physical properties of galaxies trace spin flip?

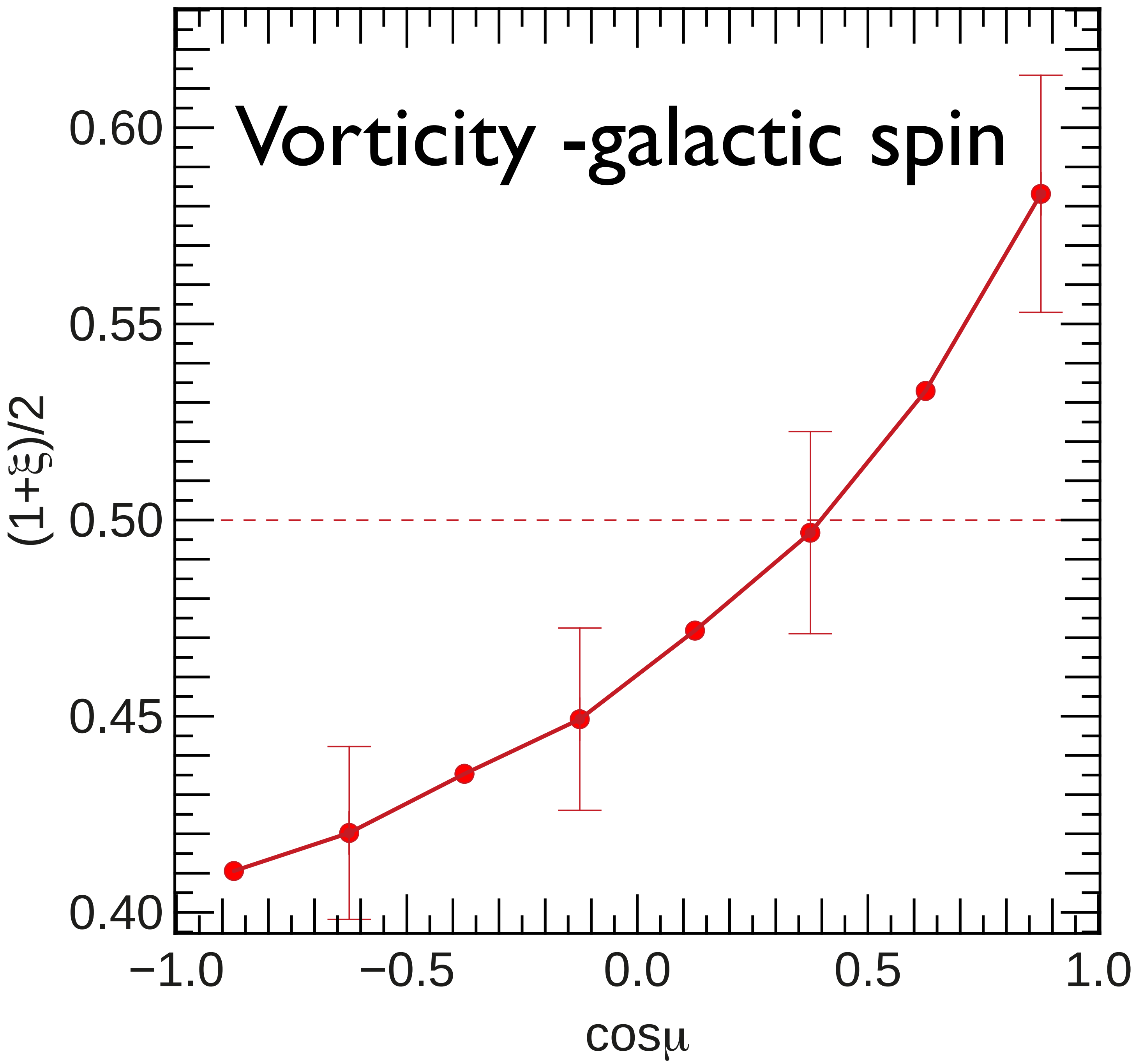


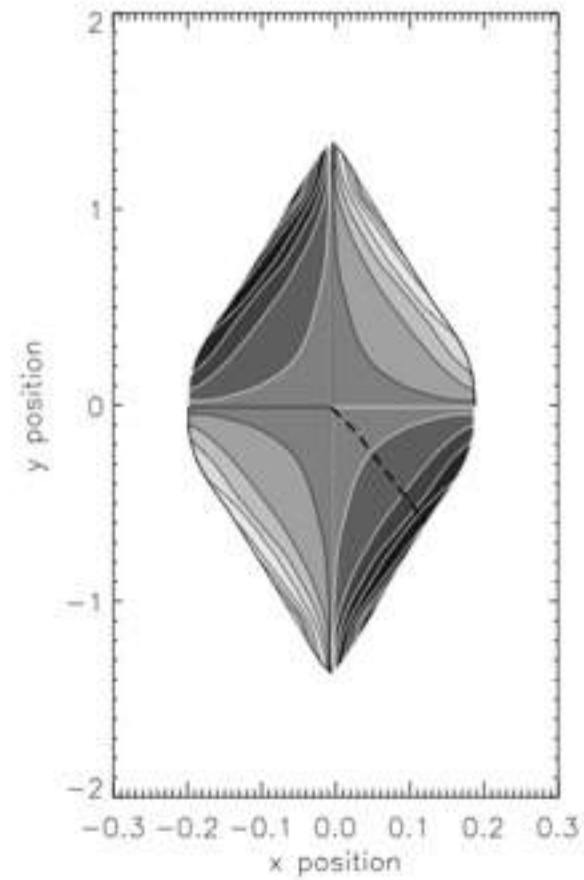
is morphometric transition mass consistent with DM ?

Final point 1/2:
low mass galaxies

What is the *physical* origin of low mass **galaxies** spin-filament alignment ?

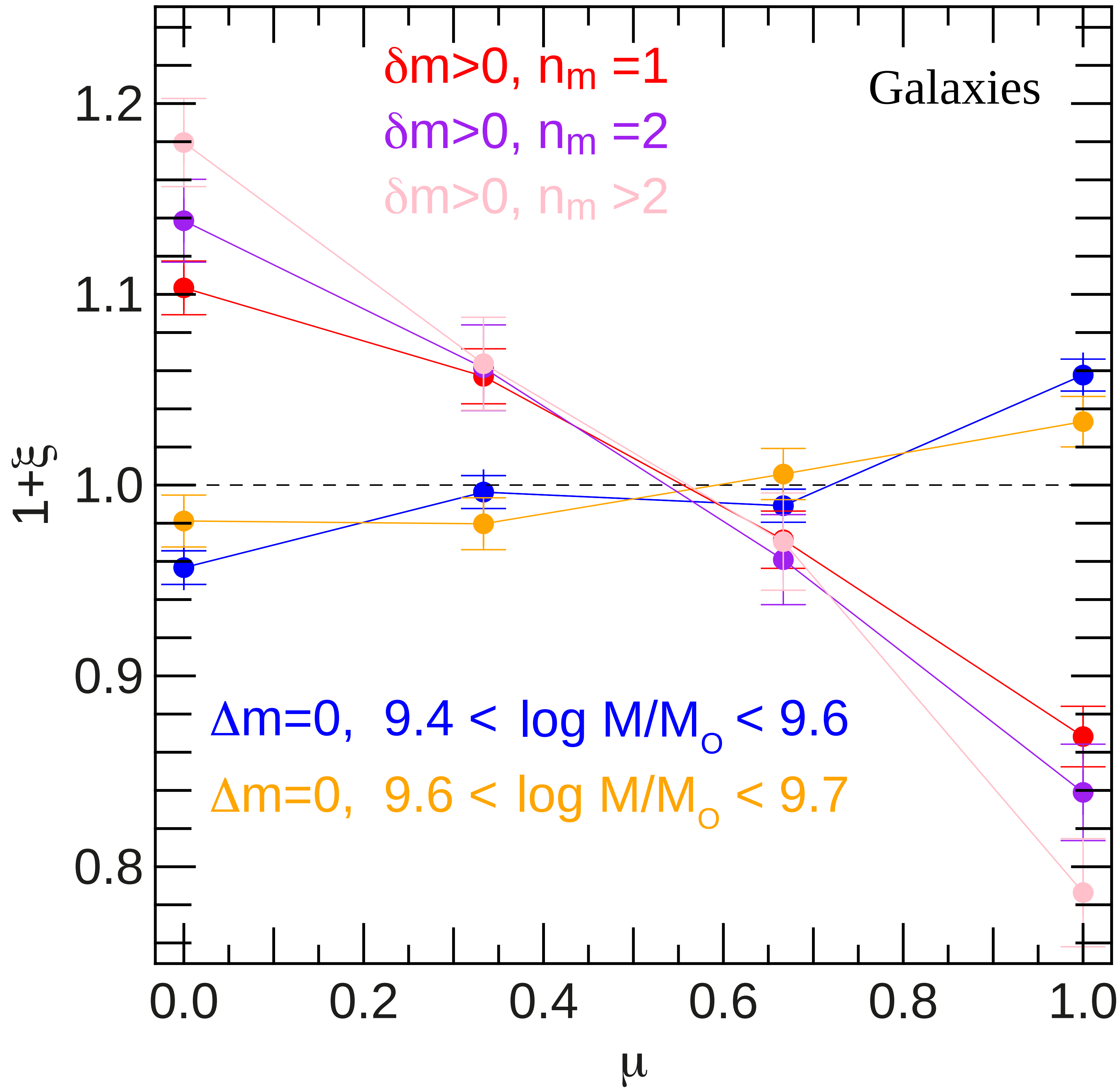
Vorticity arising from kin. structure of filament!





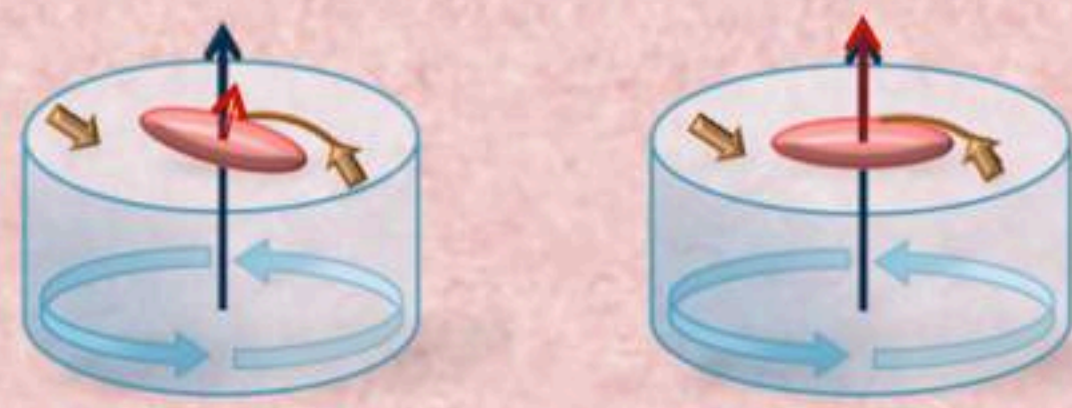
Final point 2/2:
high mass galaxies

What is the *physical* origin of spin flip? high mass **galaxies** merge!

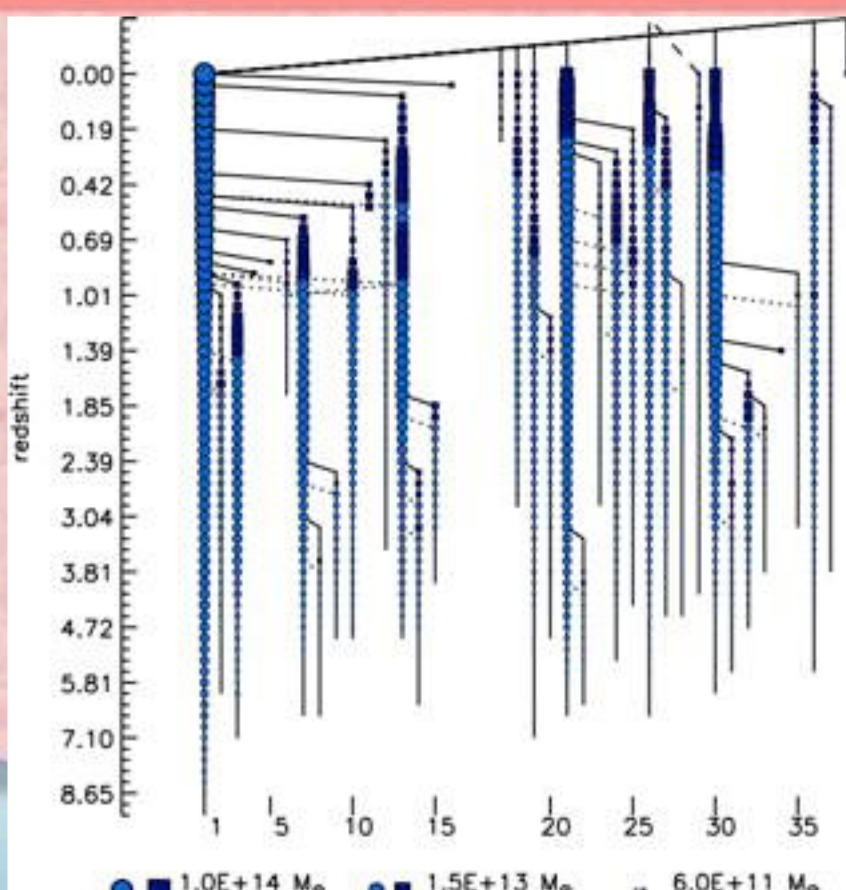


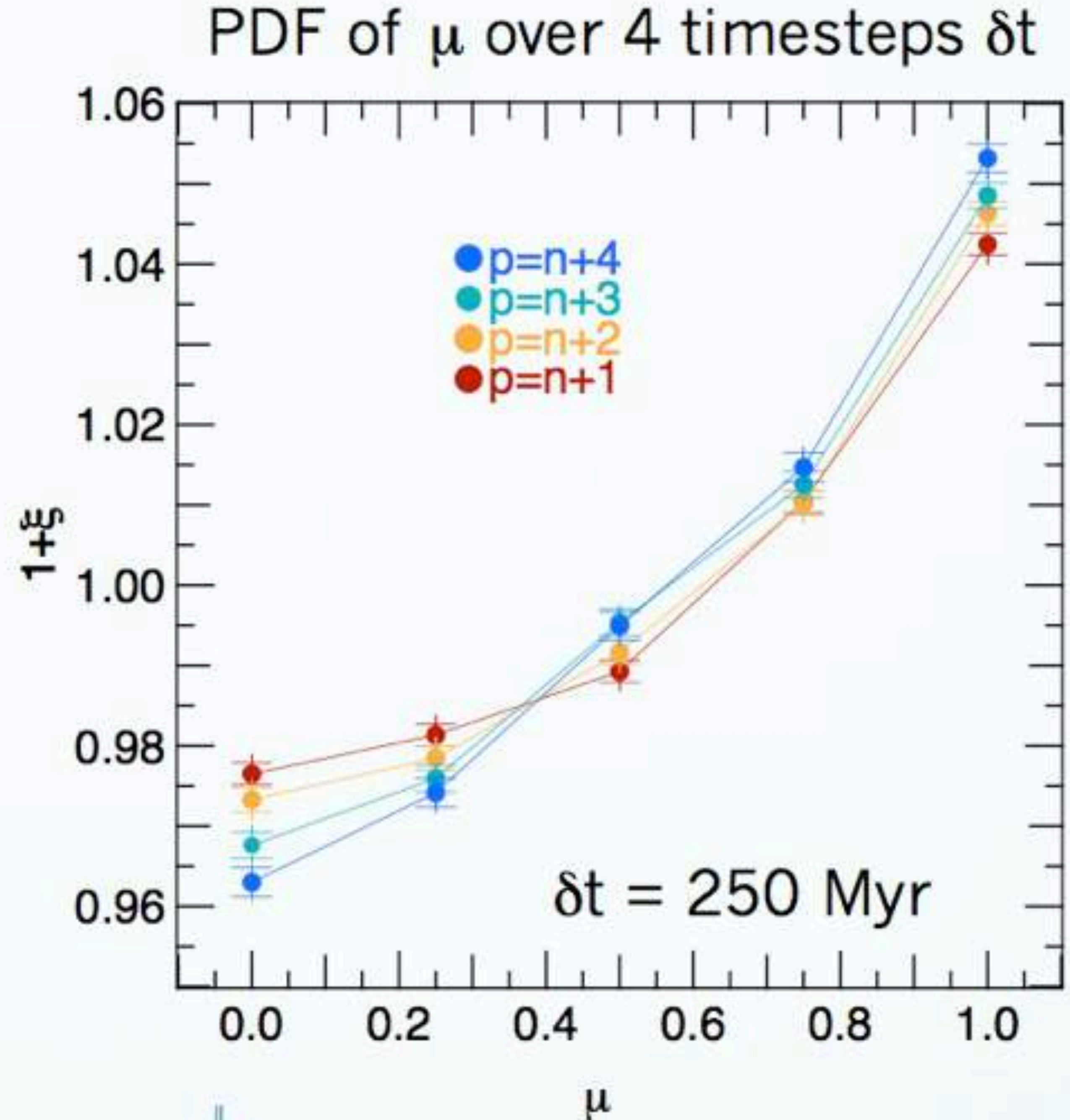
Transition mass versus **merging rate** for galaxies

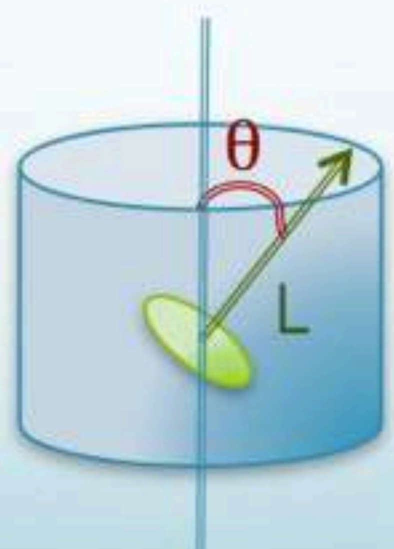
SMOOTH ACCRETION



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







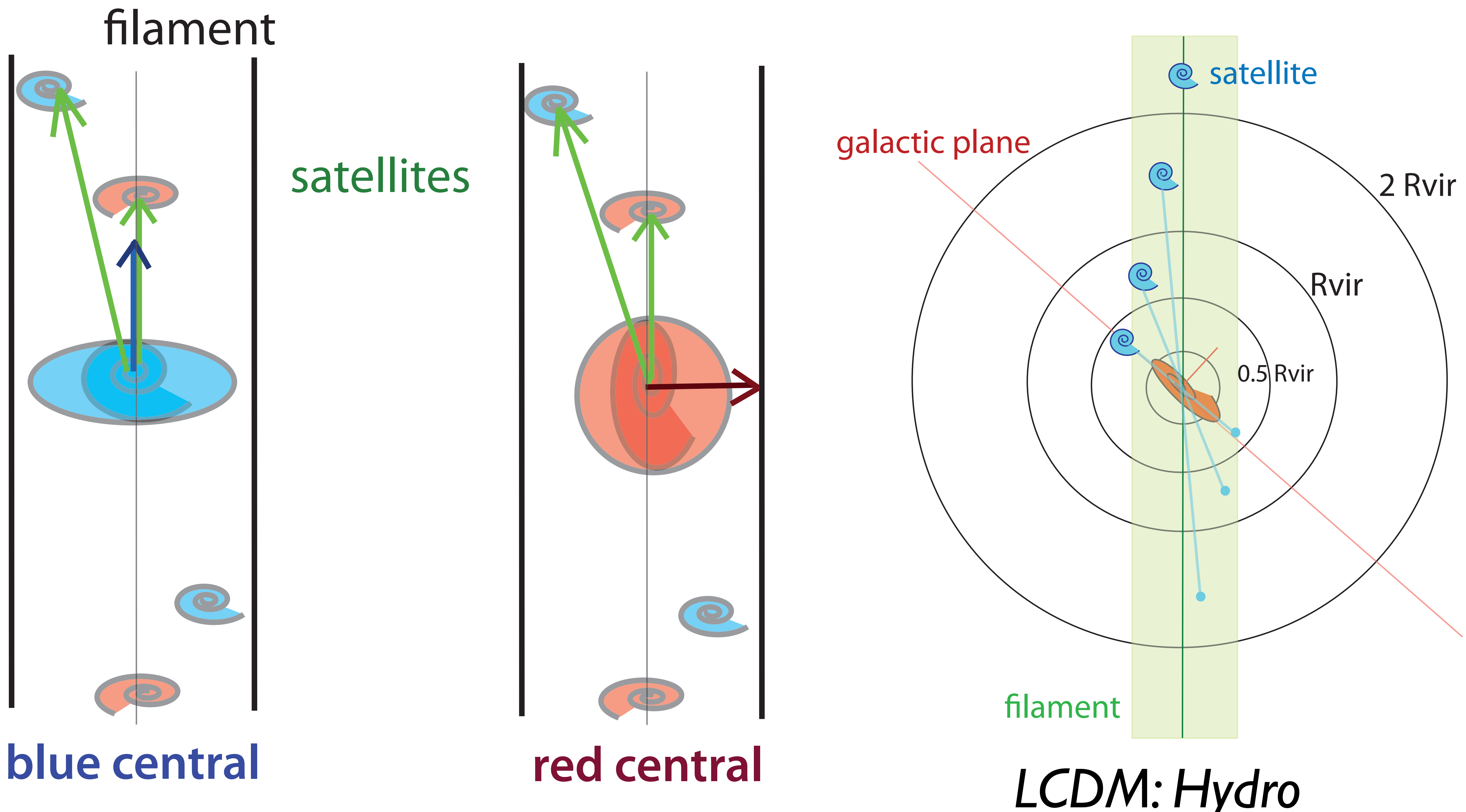
$\mu = |\cos(\theta)|$

- Spin-filament angle
- ξ : excess probability

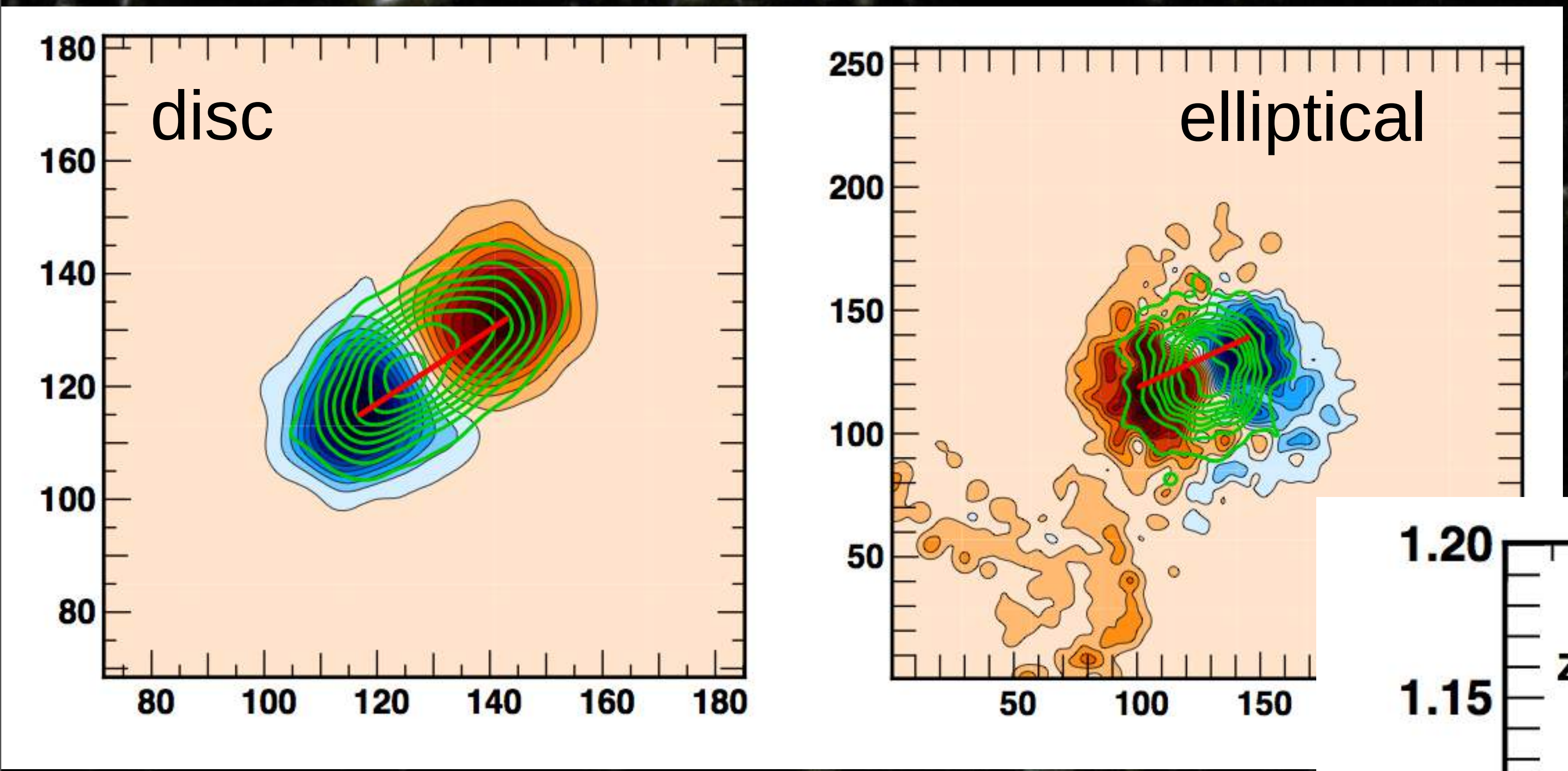
no merger : orientation versus look-back time

Caught in the rhythm: satellites in their galactic plane

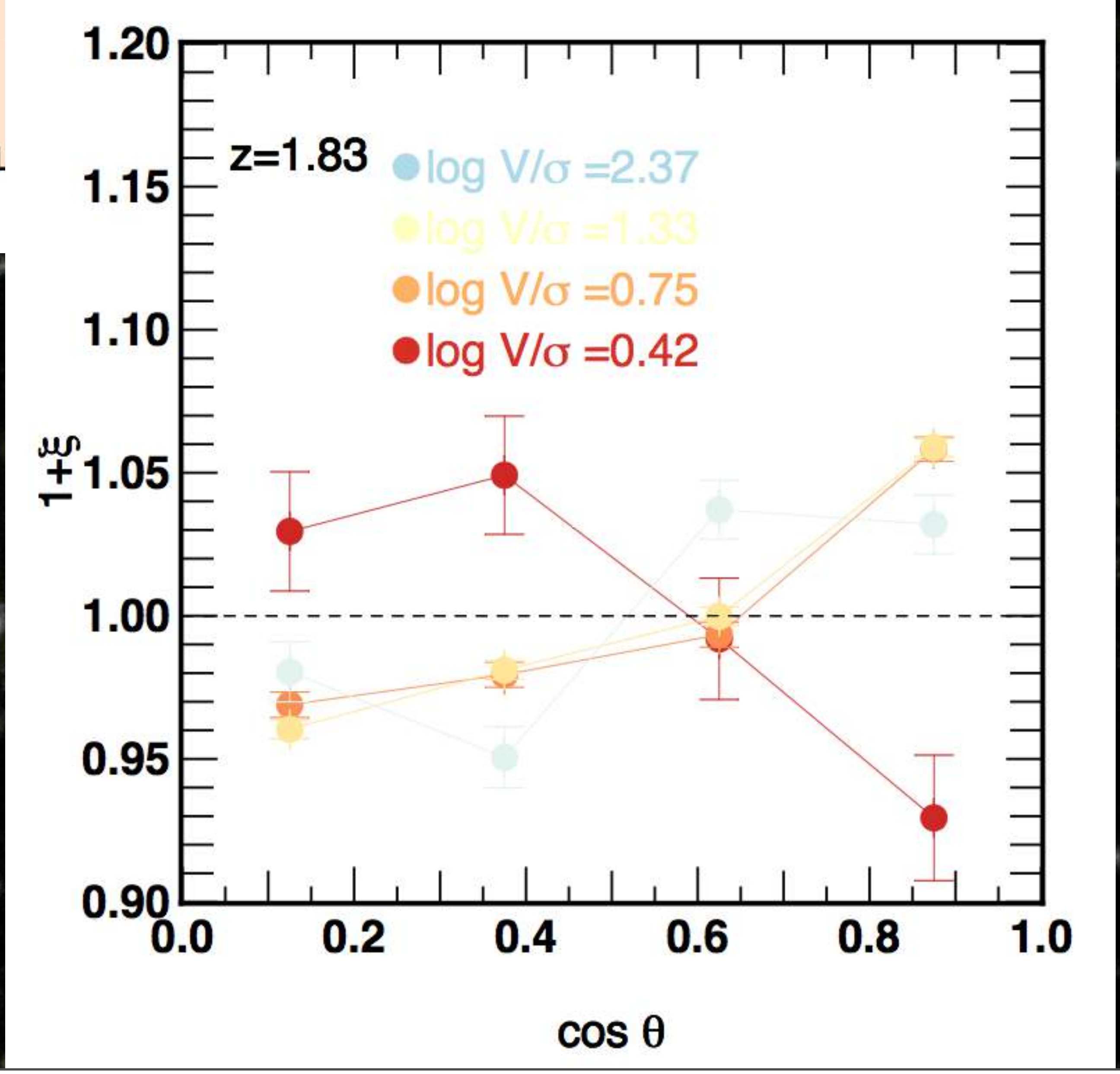
C. Welker[1⋆], Y. Dubois[1], C. Pichon[1,2], J. Devriendt[3,4] and N. E. Chisari[3]



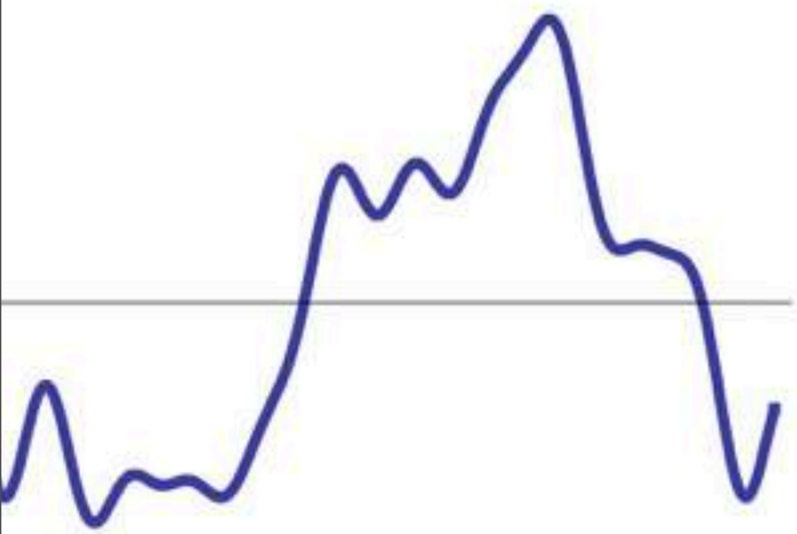
Are the imprints of LSS noticeable on galaxy properties ?

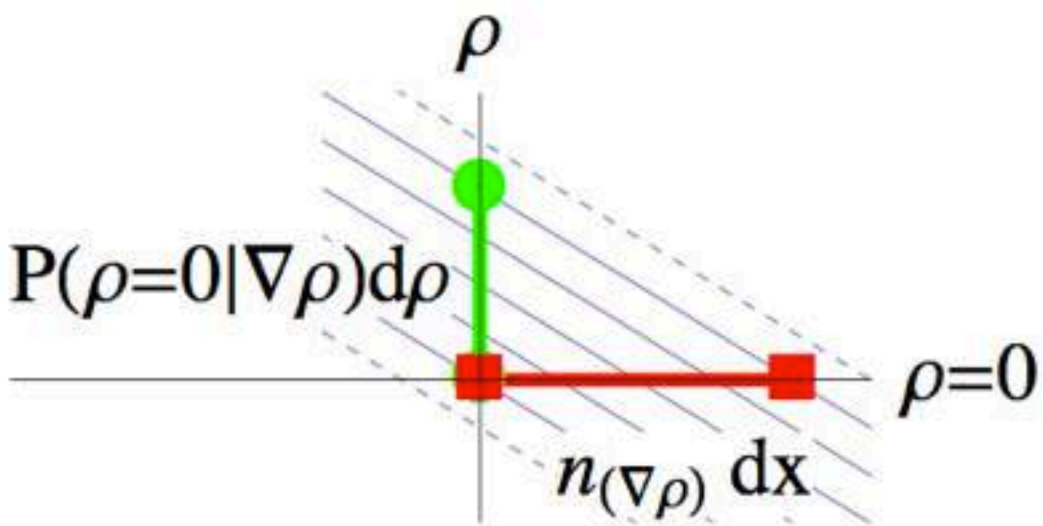


Horizon-AGN
>150 000 galaxies



1D level crossing primer





$$\left.\begin{array}{rcl} n_{\nabla\rho}\,\mathrm{dx} & = & \mathcal{P}(\rho=0|\nabla\rho)\,\mathrm{d}\rho \\ \mathrm{d}\rho & = & -\nabla\rho\,\mathrm{dx} \end{array}\right\} \quad \Rightarrow \quad n_{\nabla\rho} = \mathcal{P}(\rho=0|\nabla\rho)\;|\nabla\rho|$$

r

$$n_{zeroes} = \int_{-\infty}^{\infty} \mathrm{d}\nabla\rho\;|\nabla\rho|\,\mathcal{P}(\rho=0,\nabla\rho) \propto \frac{\sigma_1}{\sigma_0}$$

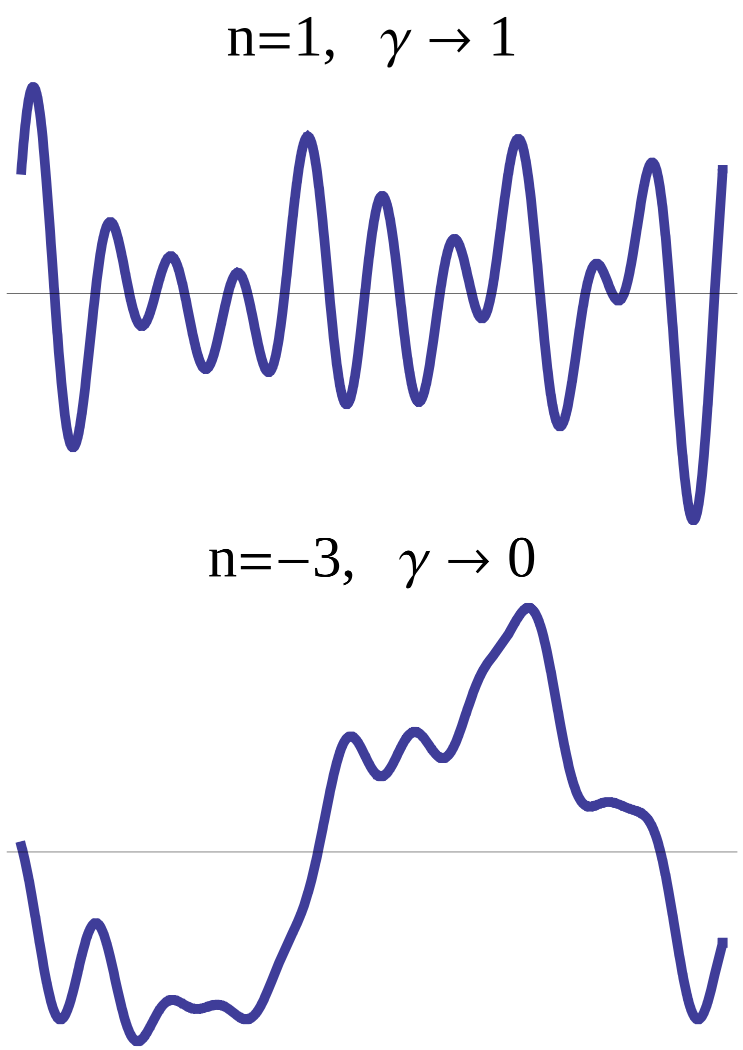
$$n_{extrem} = \int_{-\infty}^{\infty} \mathrm{d}\nabla\nabla\rho\;|\nabla\nabla\rho|\,\mathcal{P}(\nabla\rho=0,\nabla\nabla\rho) \propto \frac{\sigma_2}{\sigma_1}$$

Summary of 1D Gaussian calculations

Fundamental scales R_0, R_*

$$n_{zero} \propto \frac{1}{R_0} = \frac{\sigma_1}{\sigma_0}, \quad n_{maxima} \propto \frac{1}{R_*} = \frac{\sigma_2}{\sigma_1}$$

$$\frac{n_{maxima}}{n_{zero}} = \gamma \equiv \frac{\sigma_1^2}{\sigma_0 \sigma_2} = \frac{R_*}{R_0}, \quad \gamma \in [0, 1]$$



More sophisticated result:
Maxima above threshold $\eta = \rho/\sigma_0$

$$n_{max}(\rho > \eta\sigma_0) = \begin{cases} n_{max}\mathcal{P}(\eta) & \gamma \to 0 \\ n_{max}\mathcal{P}(\eta)(\gamma\eta) & \gamma \to 1 \end{cases}$$

back to 2D Theory without Hessian approximation