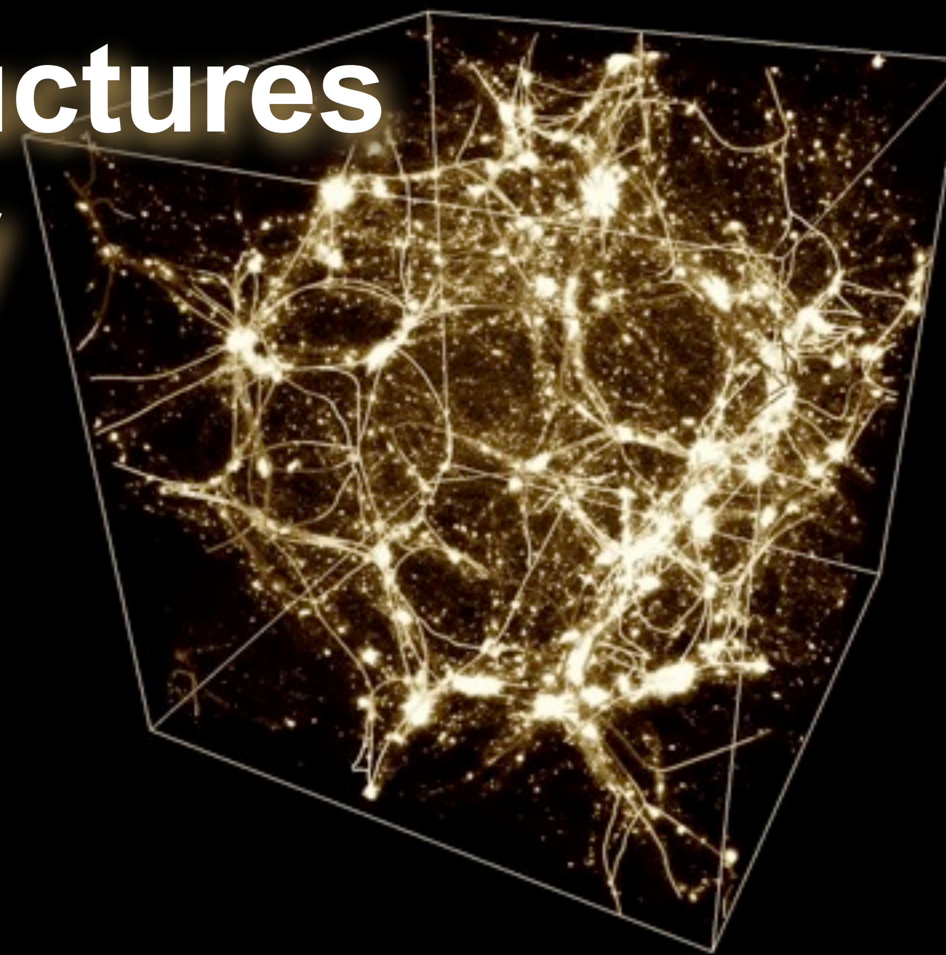
Connecting Large Scale Structures to Galaxy morphology

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

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



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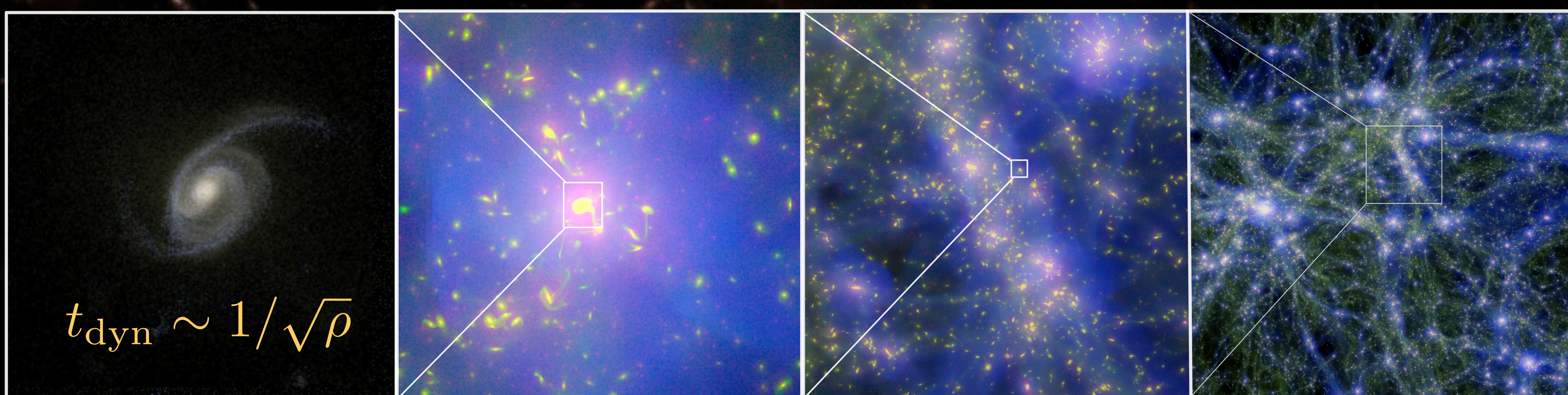

~20 kpc — Galaxy

~600 kpc — Halo

~ 8000 kpc — Filaments

~ 50 000 kpc — Large Scale Structures

IAP June 27th 2013

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?

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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.

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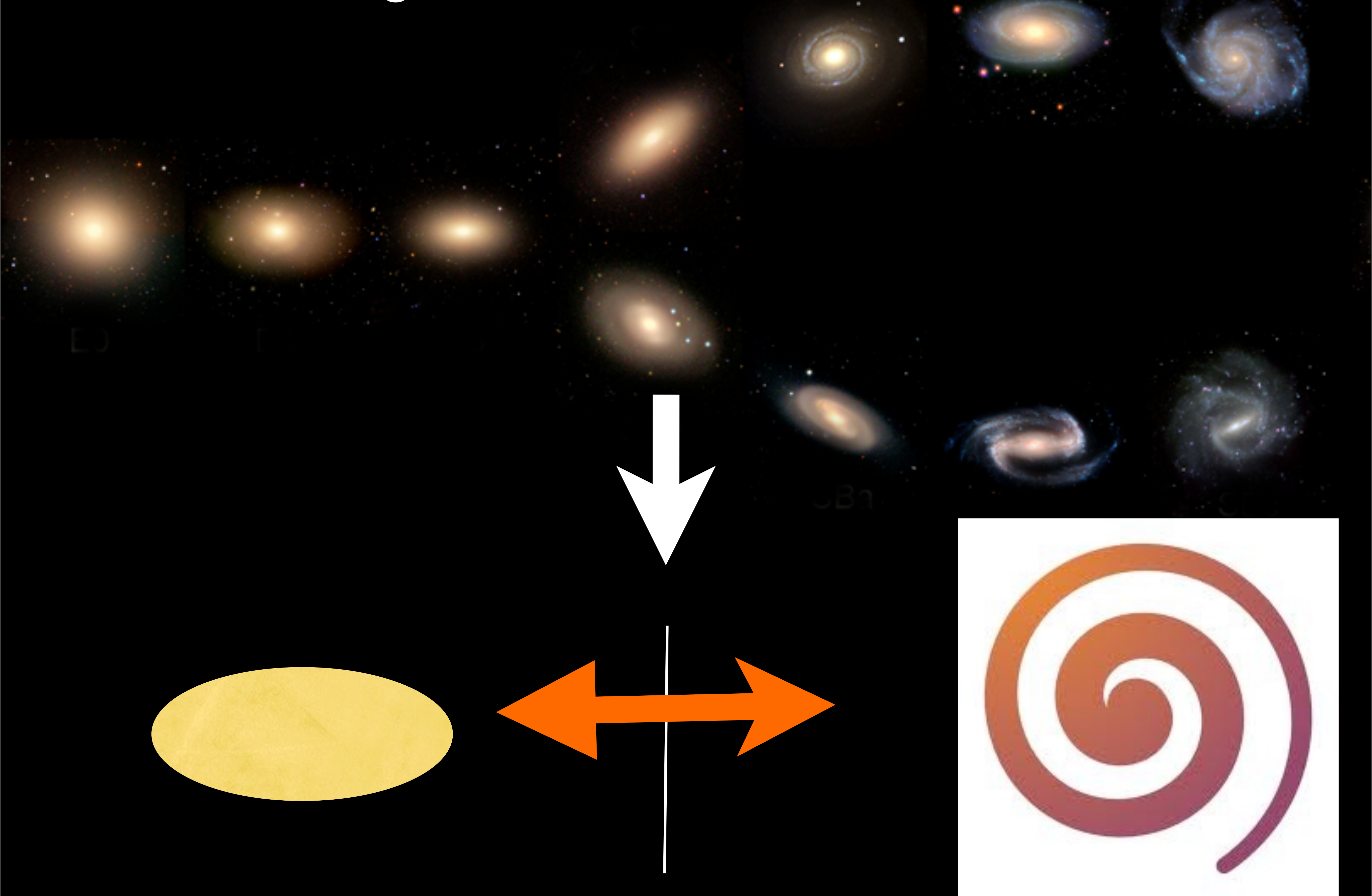
Galactic morphology is driven by AM acquisition through anisotropic secondary infall,
coming from larger scales, which are less dense, hence more steady;
cold flows provide the link.

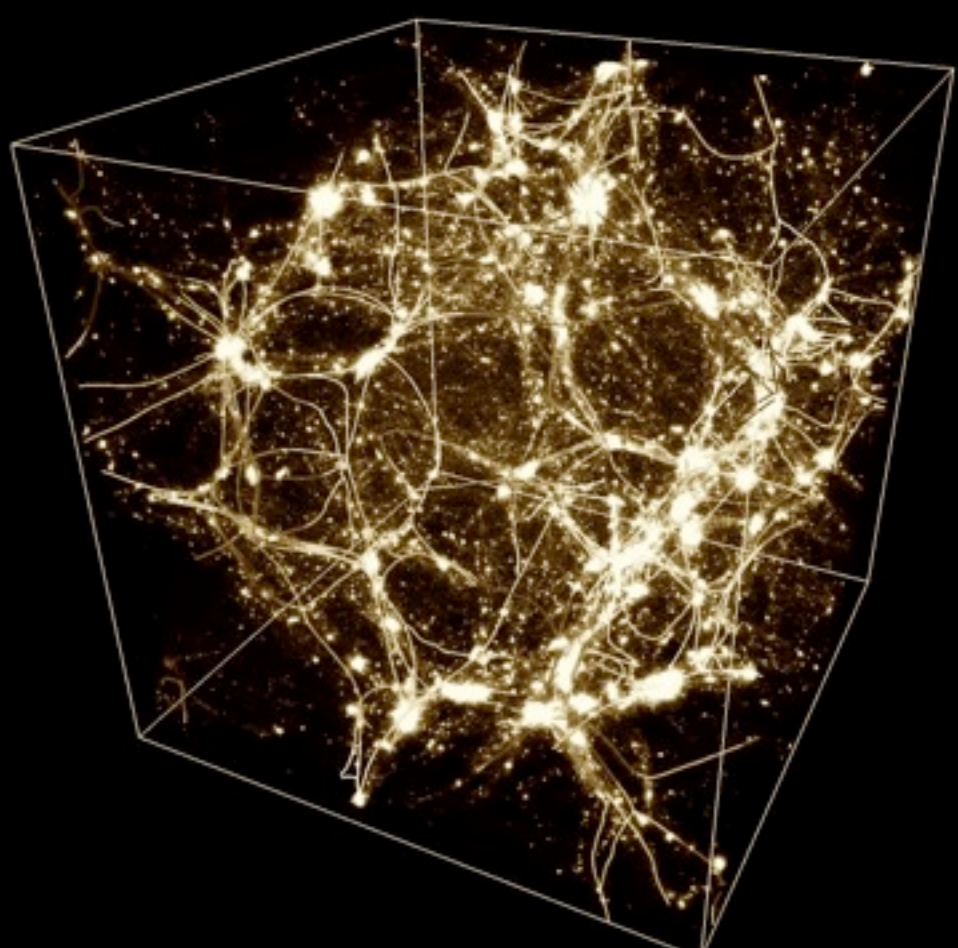
Where *galaxies form does* ***matter****, and can be* ***traced back to ICs***
Flattened filaments generate point-reflection-symmetric AM/vorticity distribution:
they induce the observed spin transition mass & helicity of cold flows

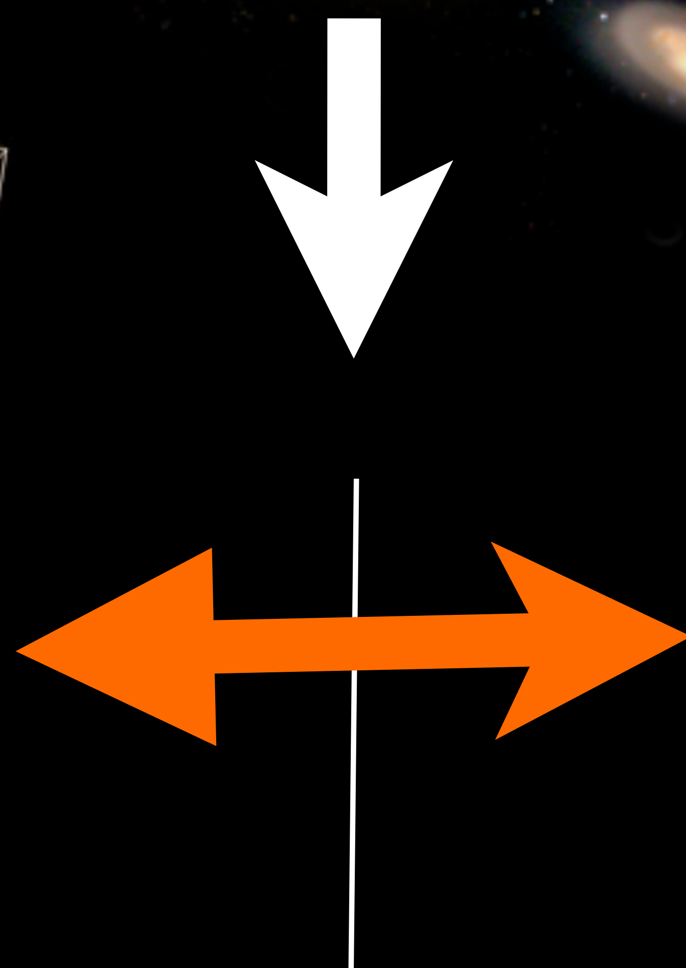
The Hubble diagram: a crude theorist's view



What drives coherent secondary infall?

The Hubble diagram: a crude theorist's view





What drives coherent secondary infall?

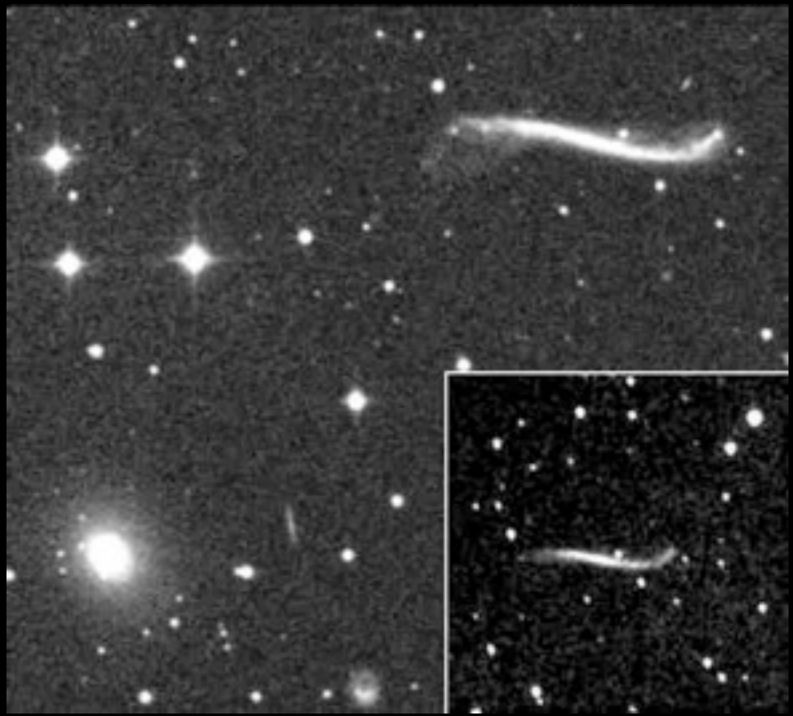
Context

- It's the **angular momentum** "stupid"

Something **beyond** mass function

- @ z>>1 : **nurture** versus **nurture**

- **warps** 1991 ??
- **thick disks** 2001 ??



Part I outline

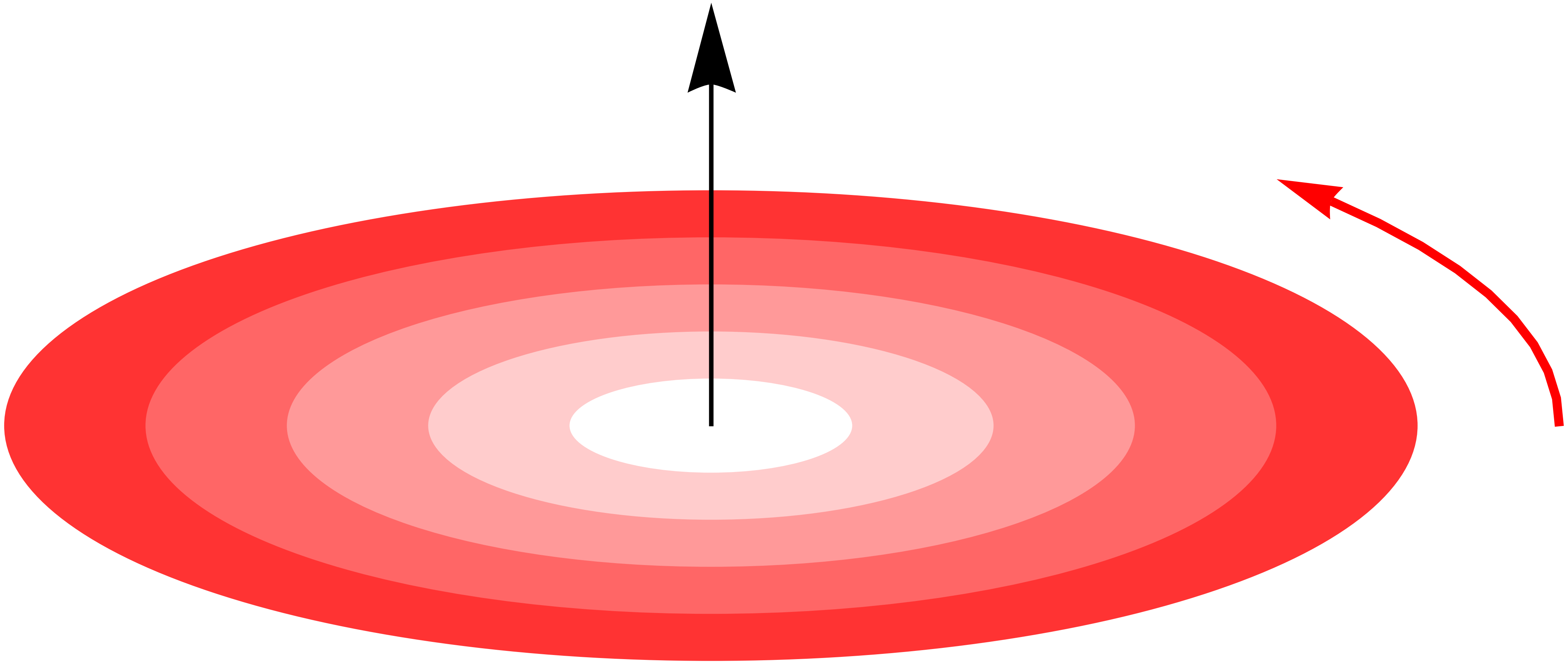
- 4 trivial facts about galaxies in their web
- the proposition
- various proofs of various value?

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:

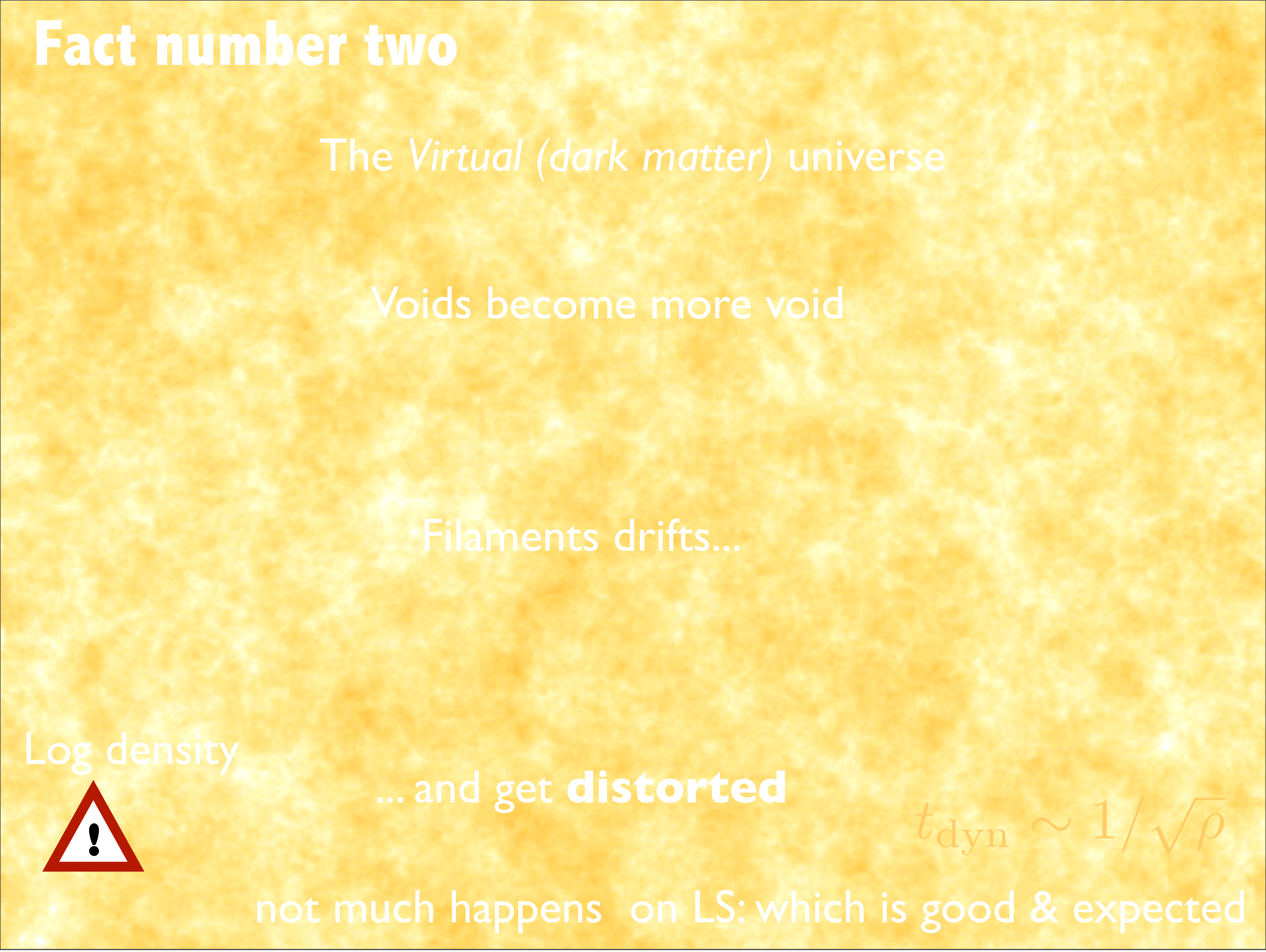


An ensemble of ring made of gas,

- 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**

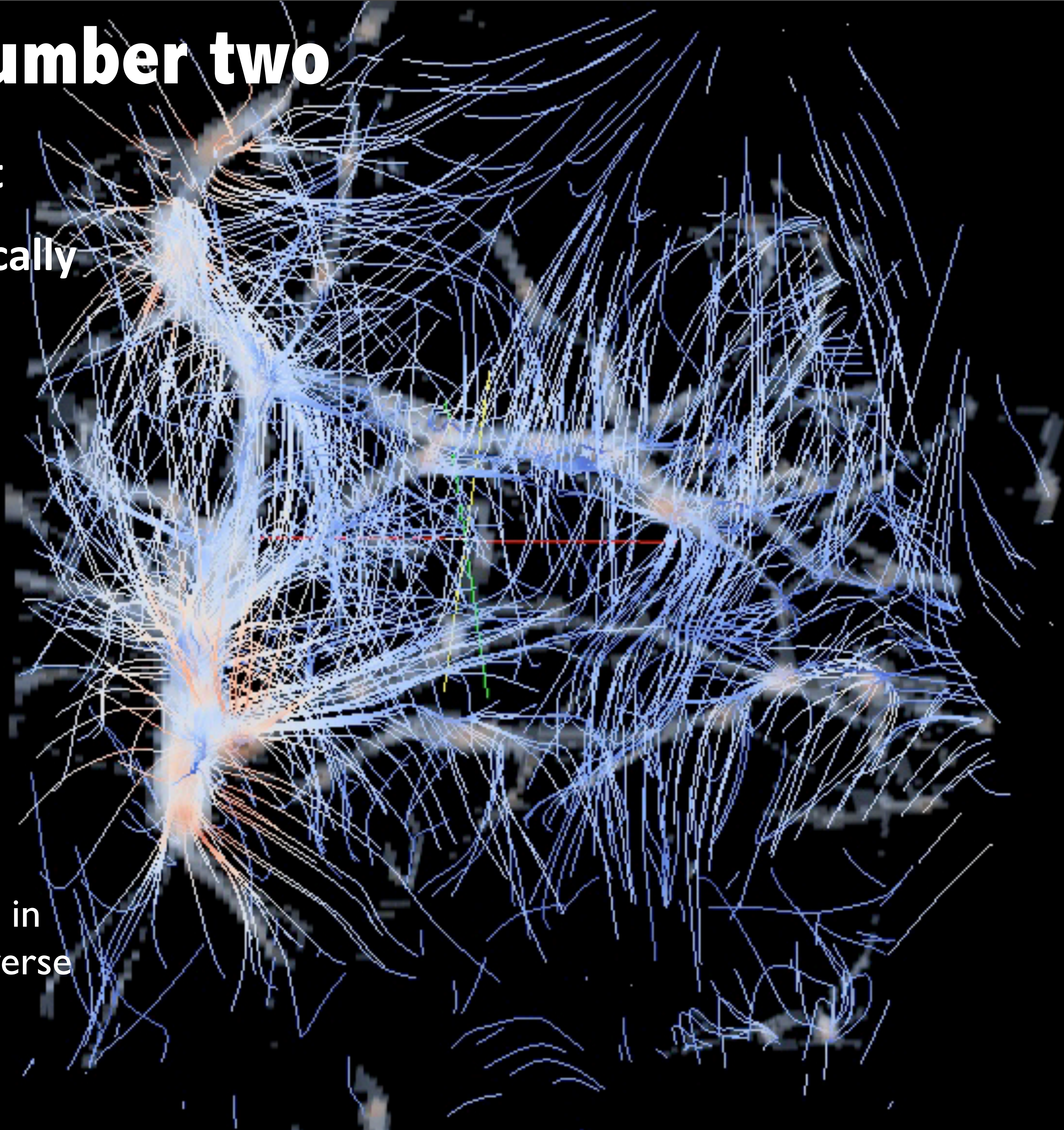
$t_{\rm dyn} \sim 1/\sqrt{\rho}$

not much happens on LS: which is good & expected

Fact number two

Peak attract

catastrophically

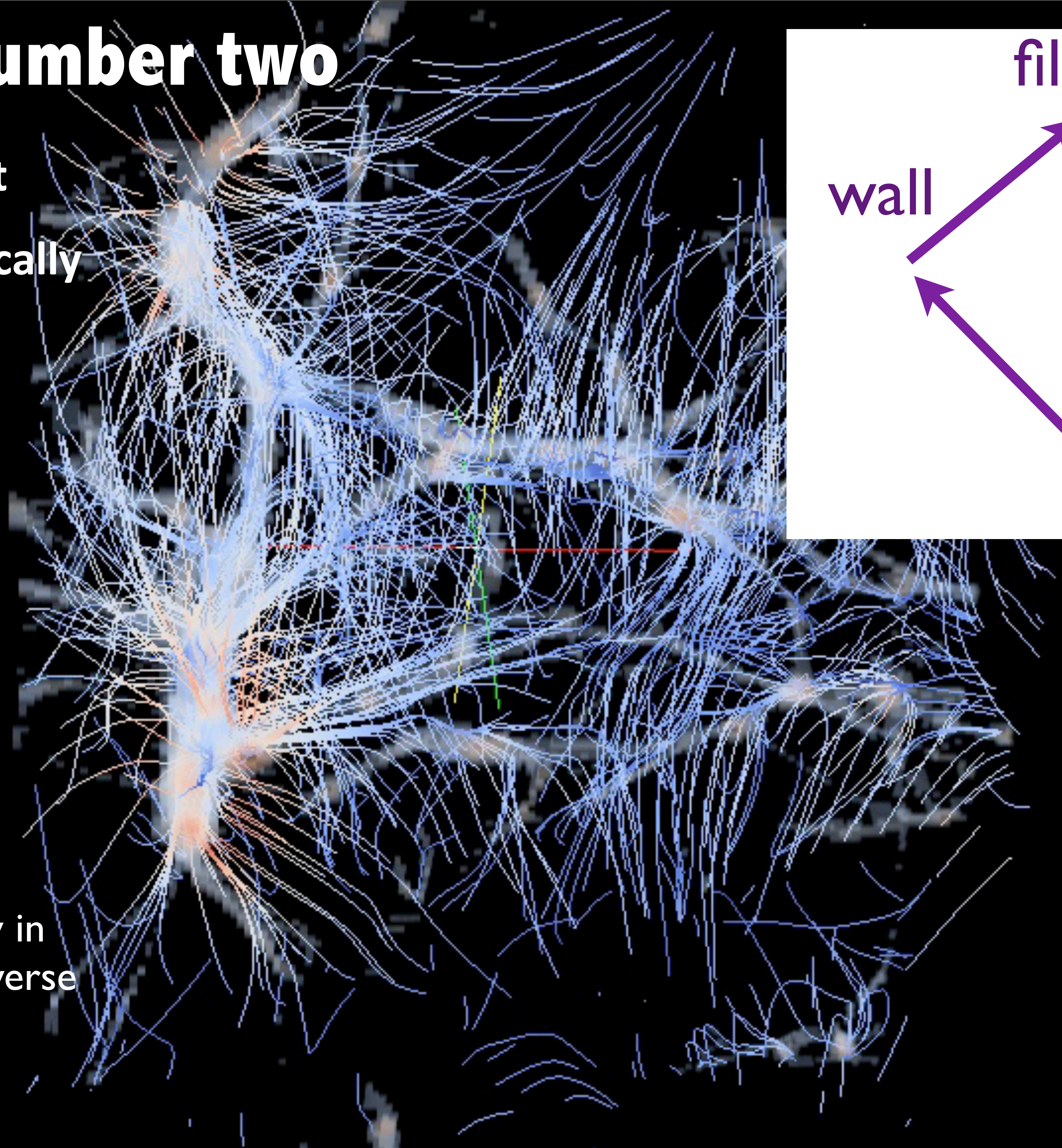


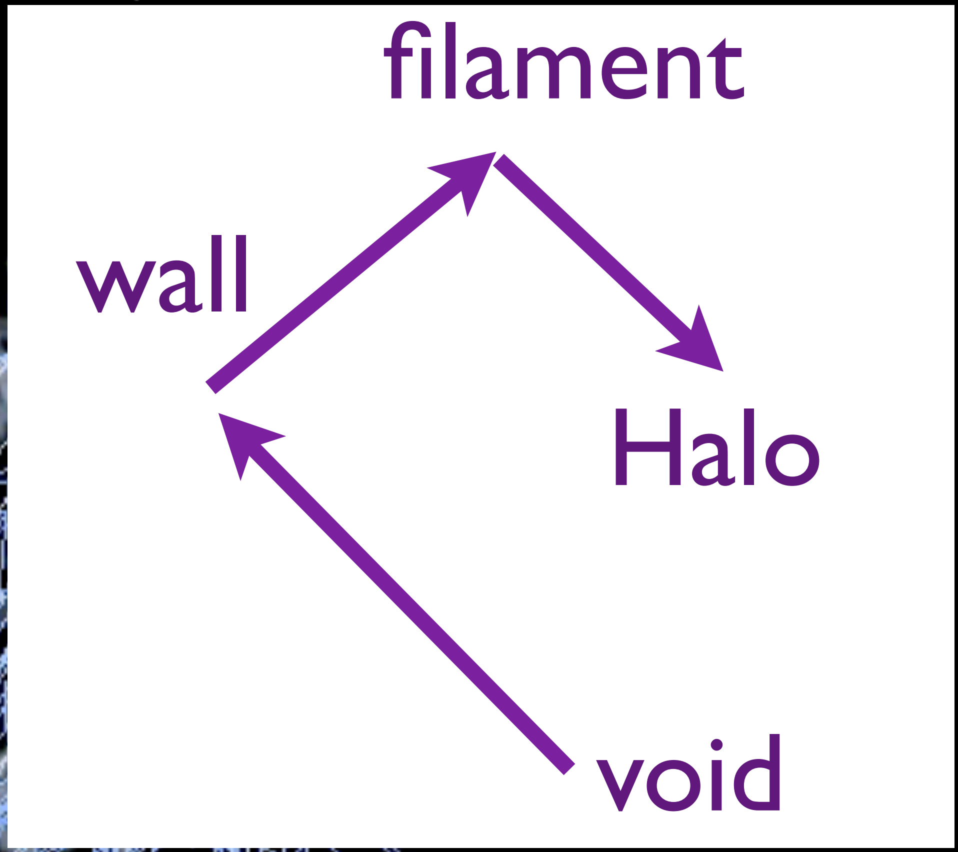
Velocity flow in
expanding universe

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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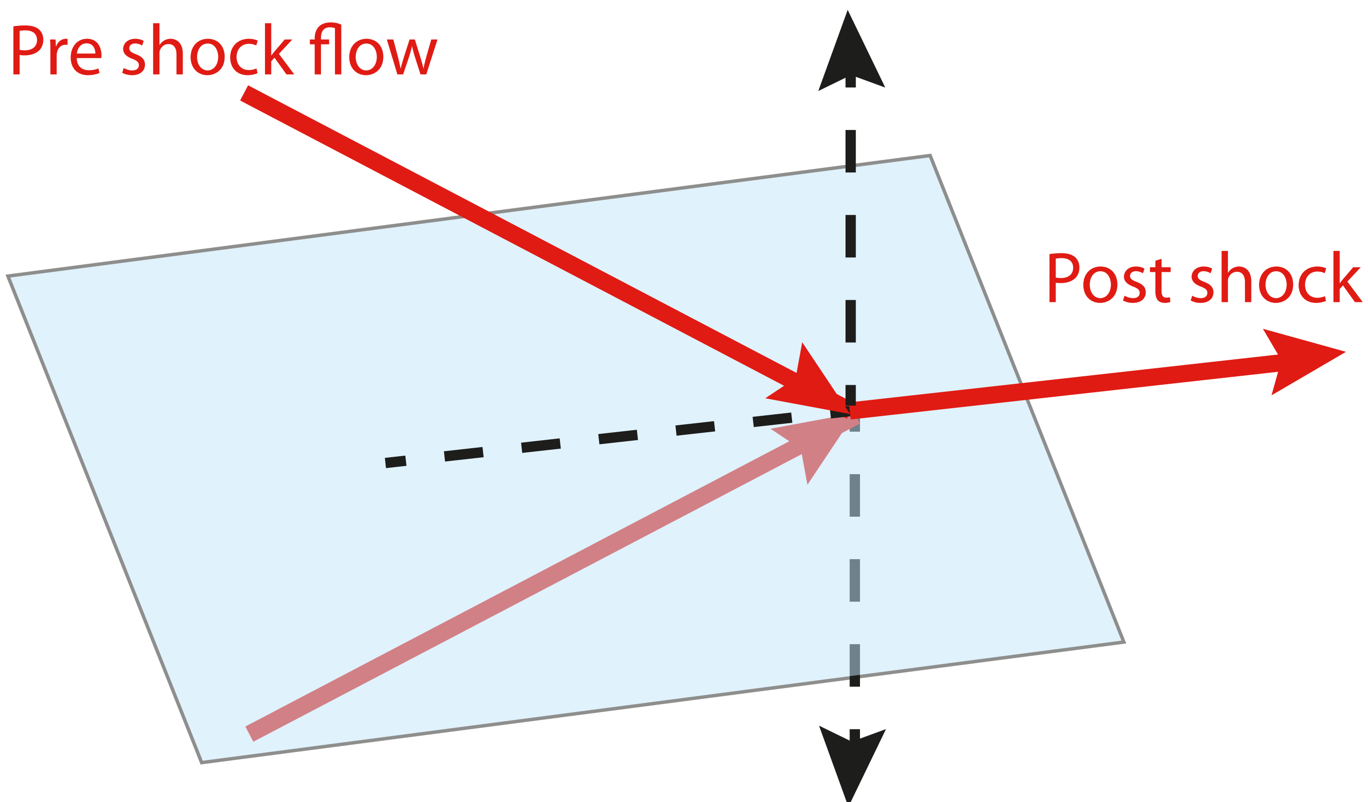
Fact number three

"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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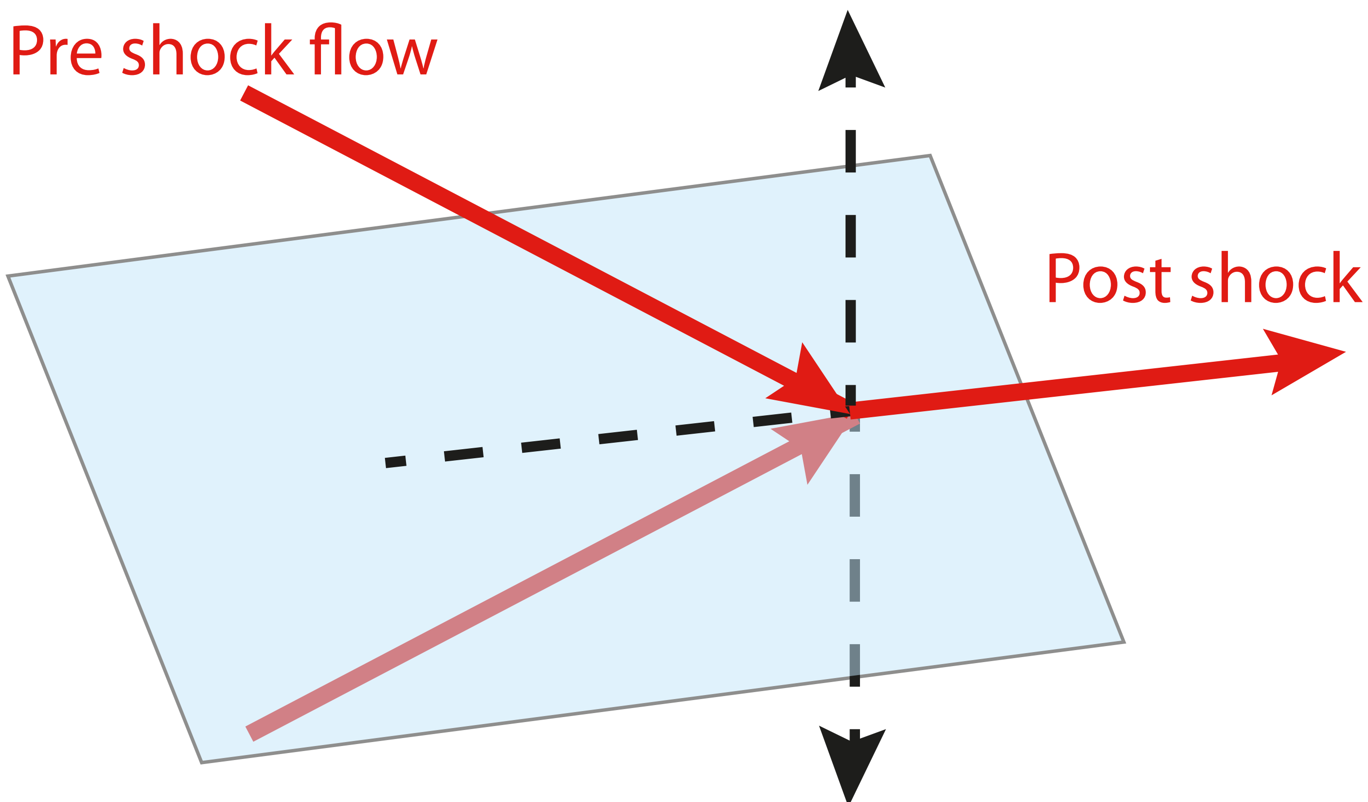

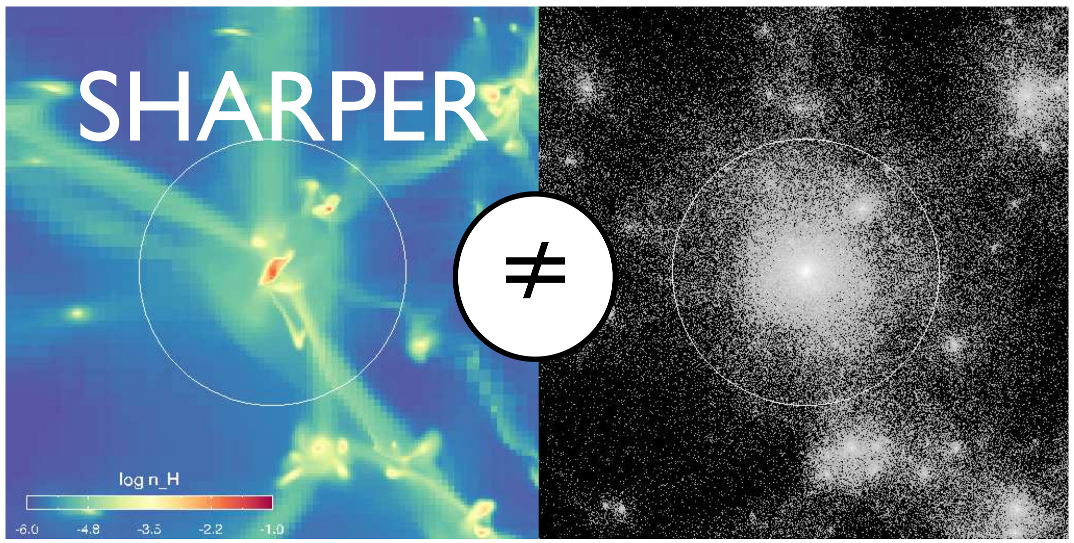

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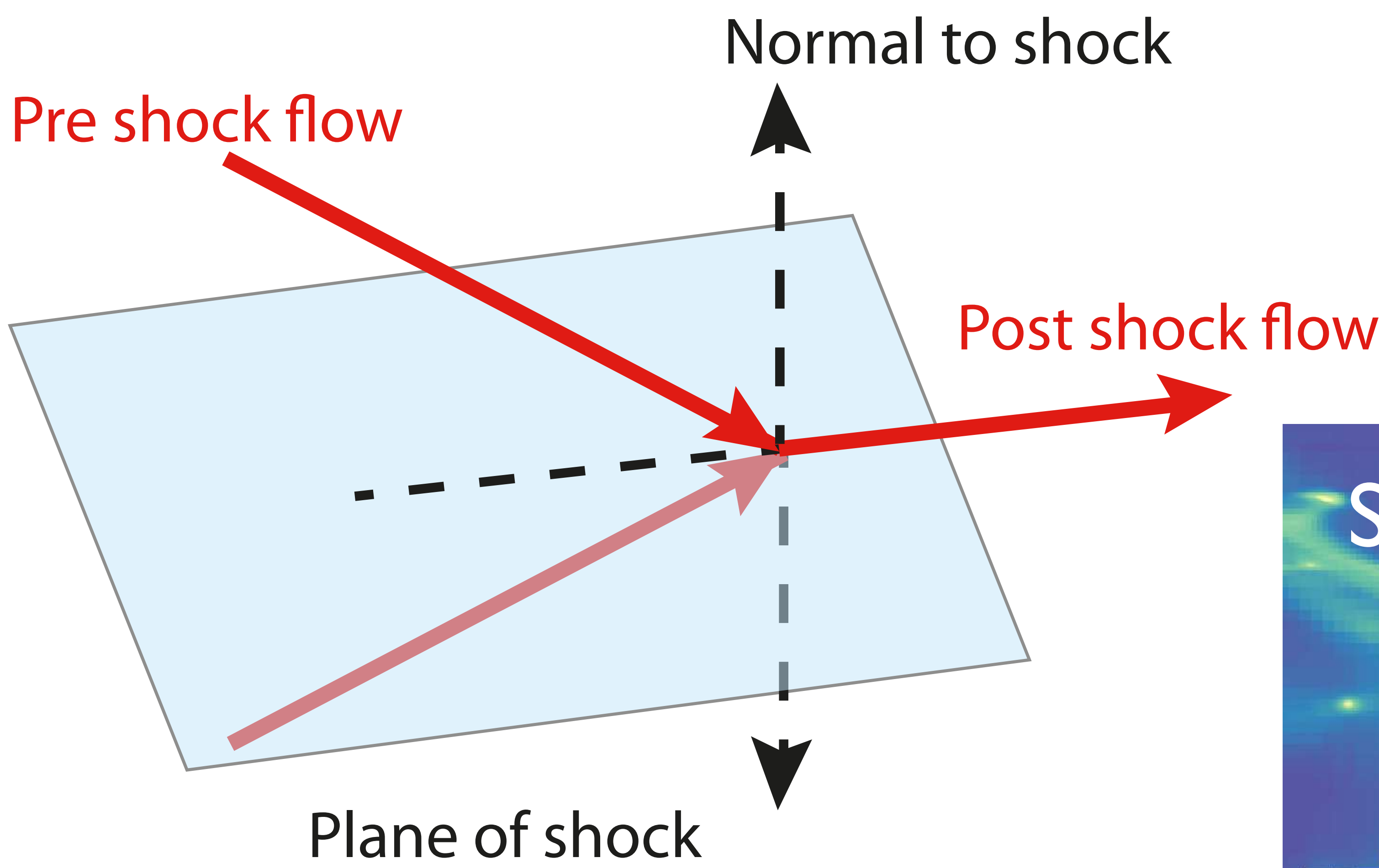

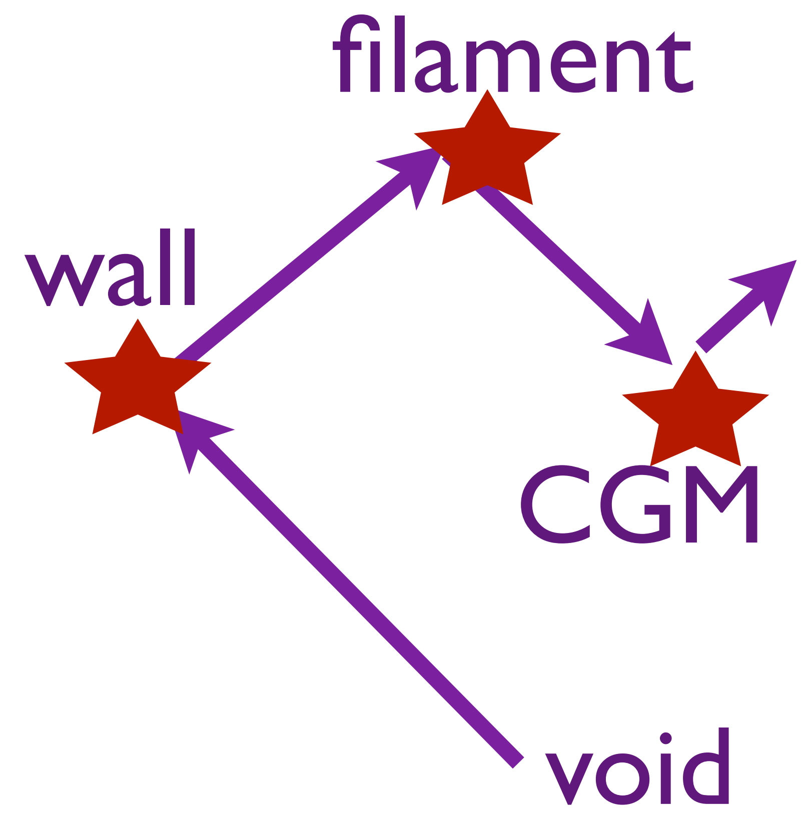

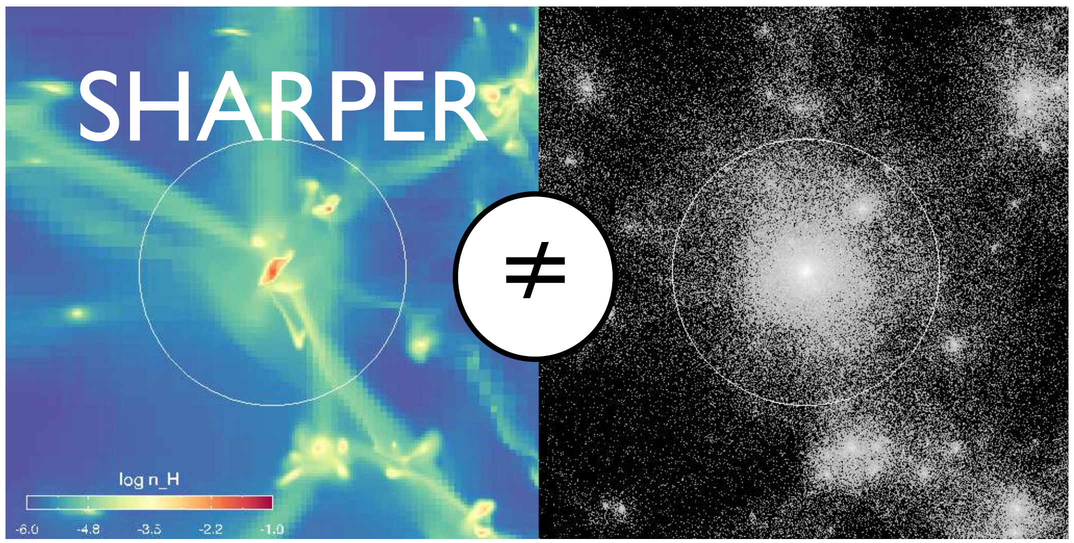

Gas, unlike dark matters, shocks (iso-T) and

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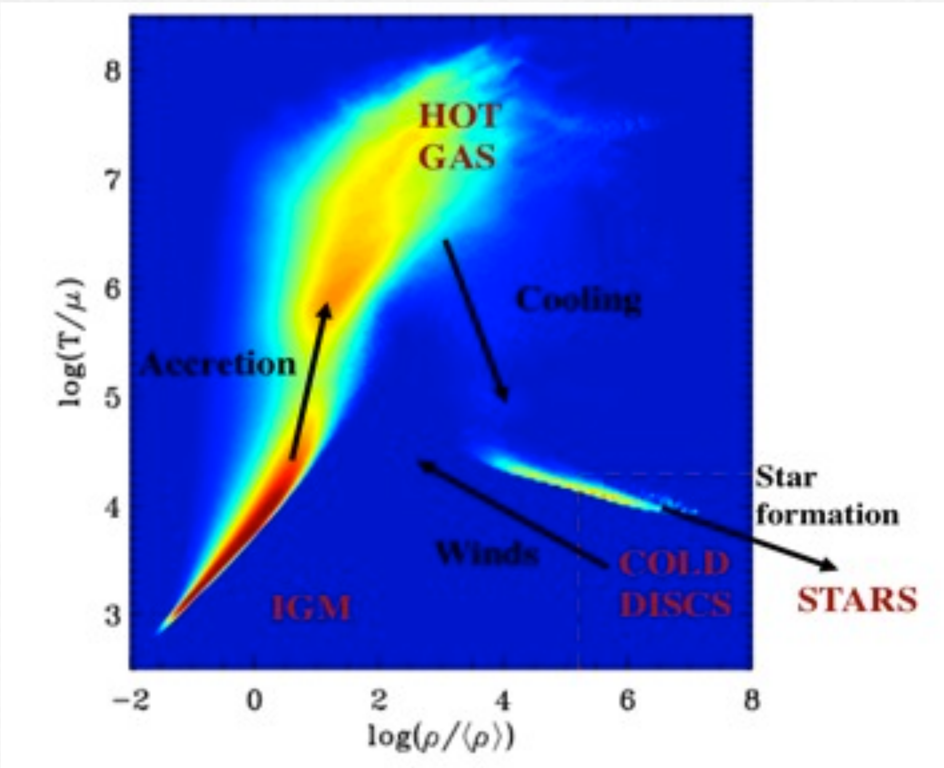
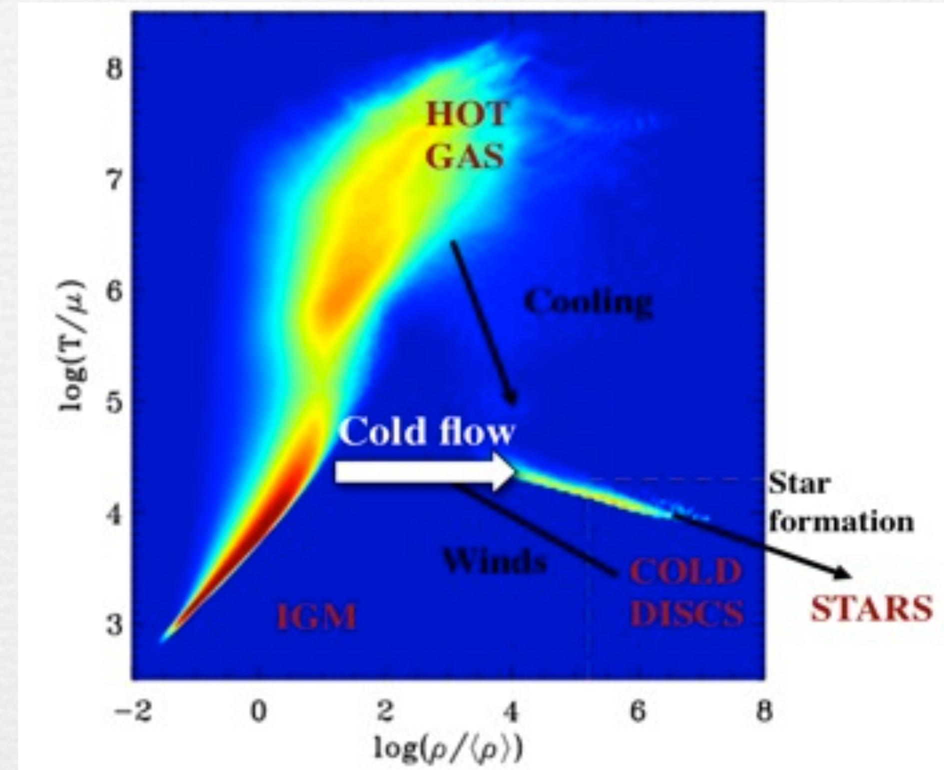
→ **cosmic web** is important **for galaxy morphology**

@ high z / low mass



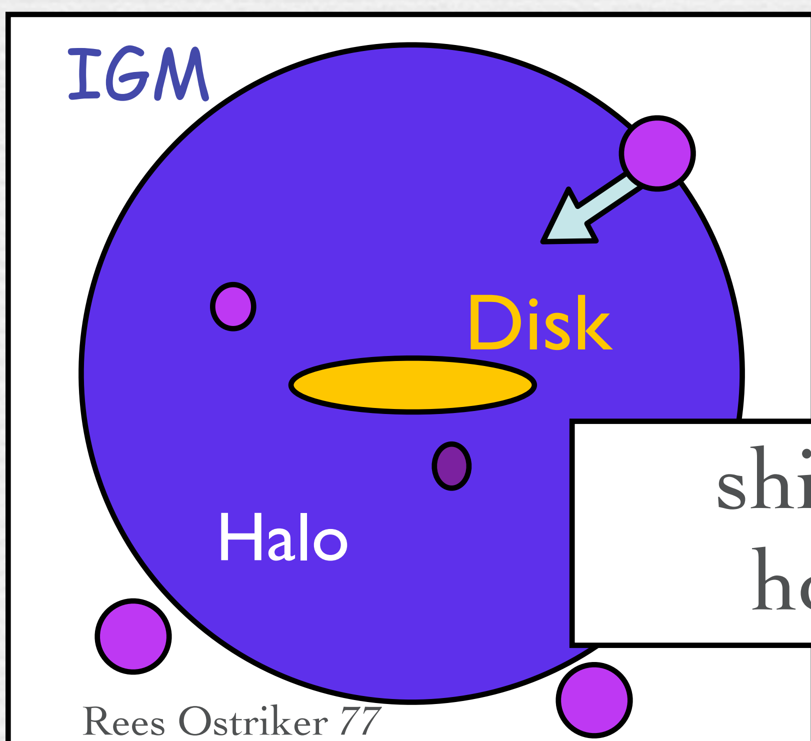
Paradigm
shift

cf Binney 77 !!



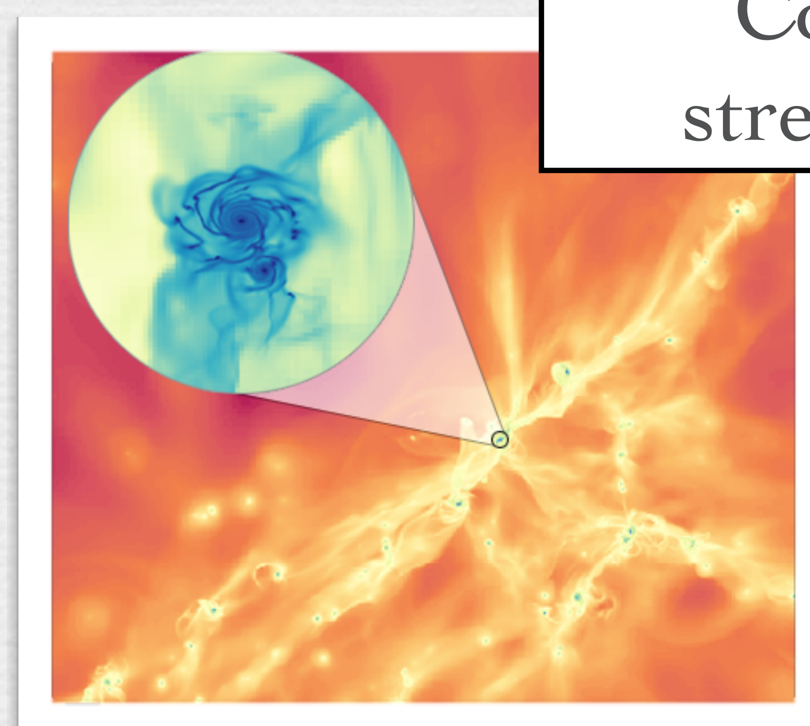
Gas shocks
isothermally
in LSS

« Interface » @ Virial Radius



shielding (?)
hot corona

Cold
streams



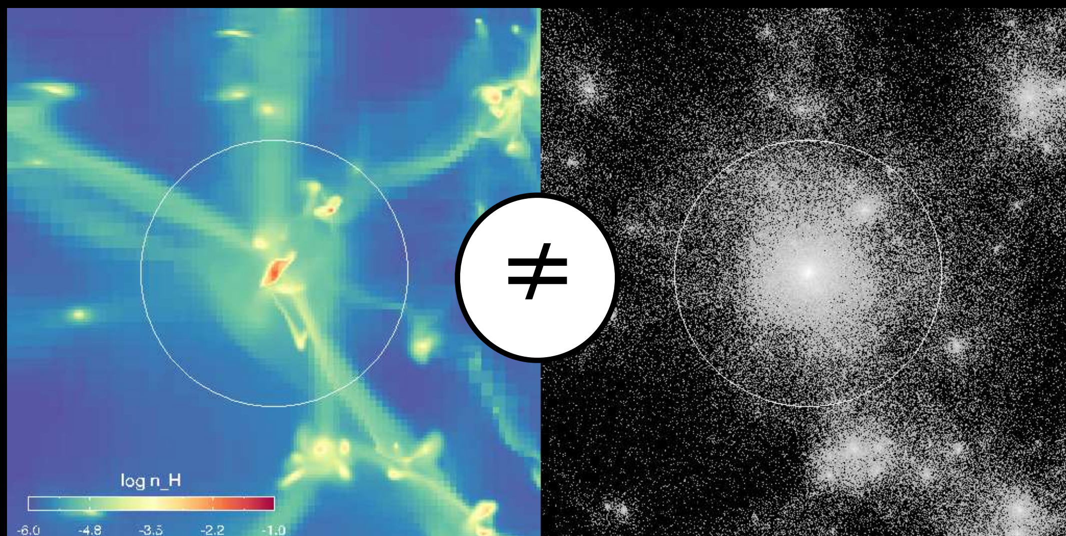
Katz 2002

@ 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

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

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

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?
    - robust statistics?
    - lots of hand waving ??

Clues from LSS

"Proof by halo centric environment"

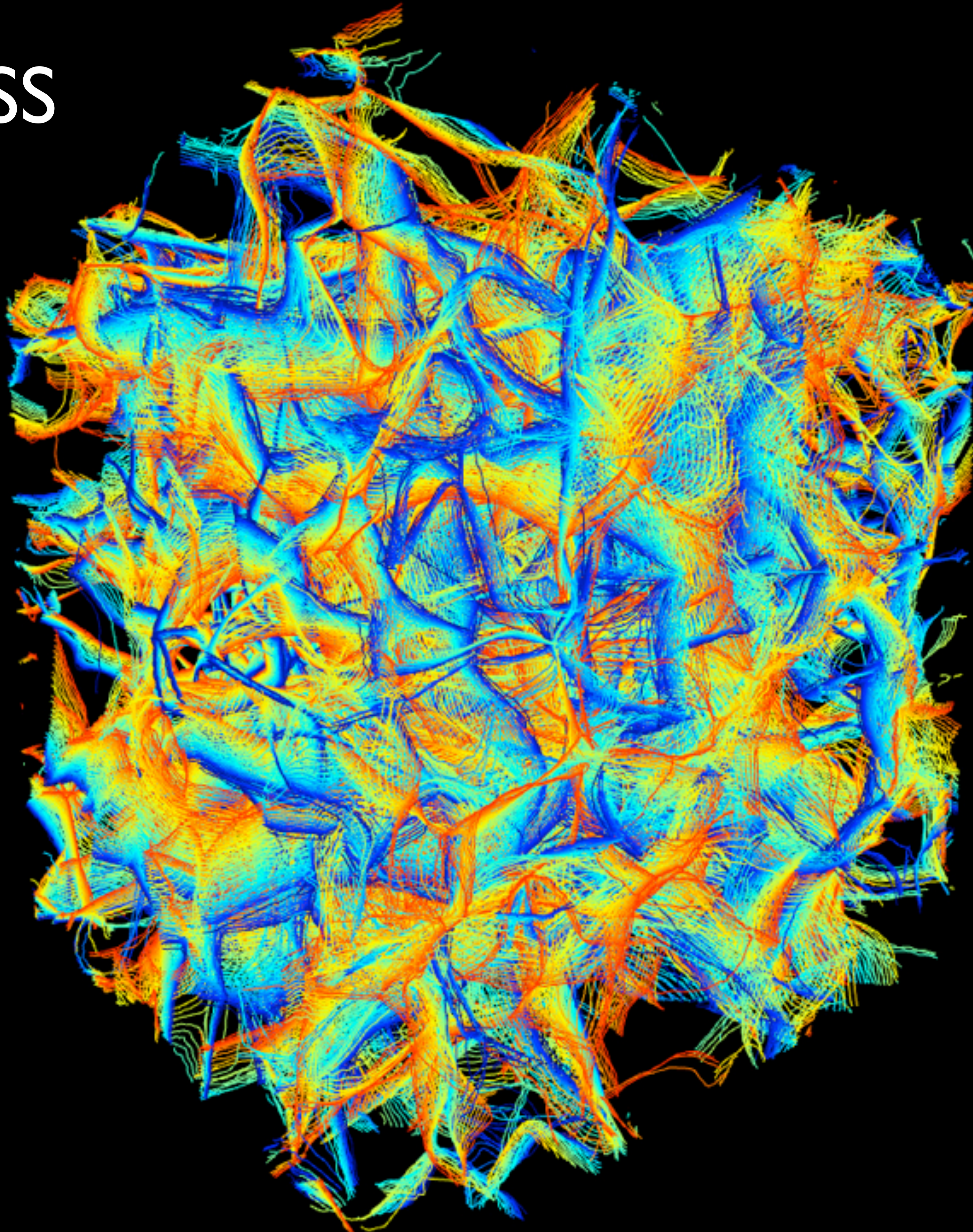
a.k.a

proof by hypnosis,

fishy analogy &

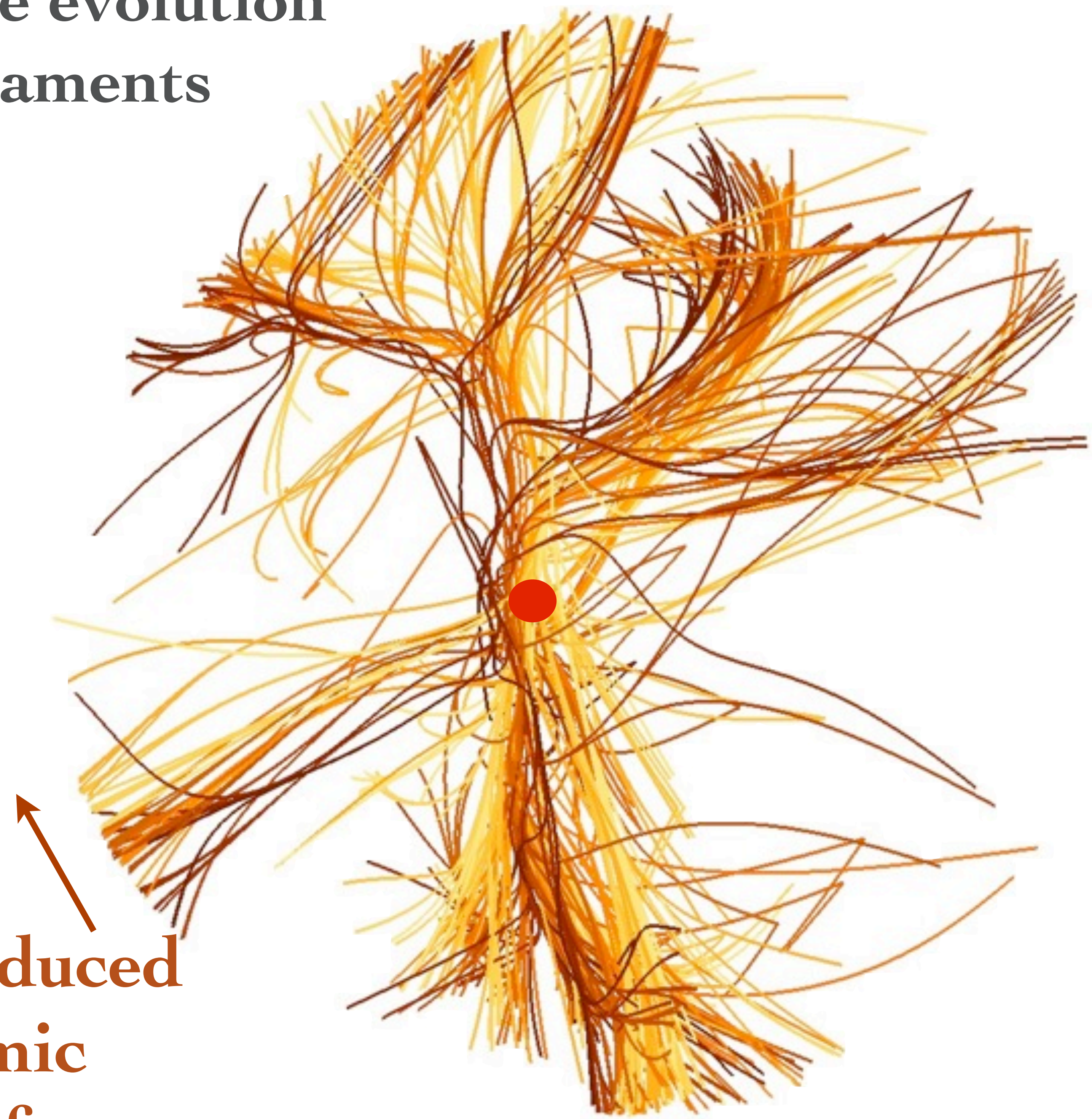
mathematical jargon

Time line of LSS



Drift of filaments

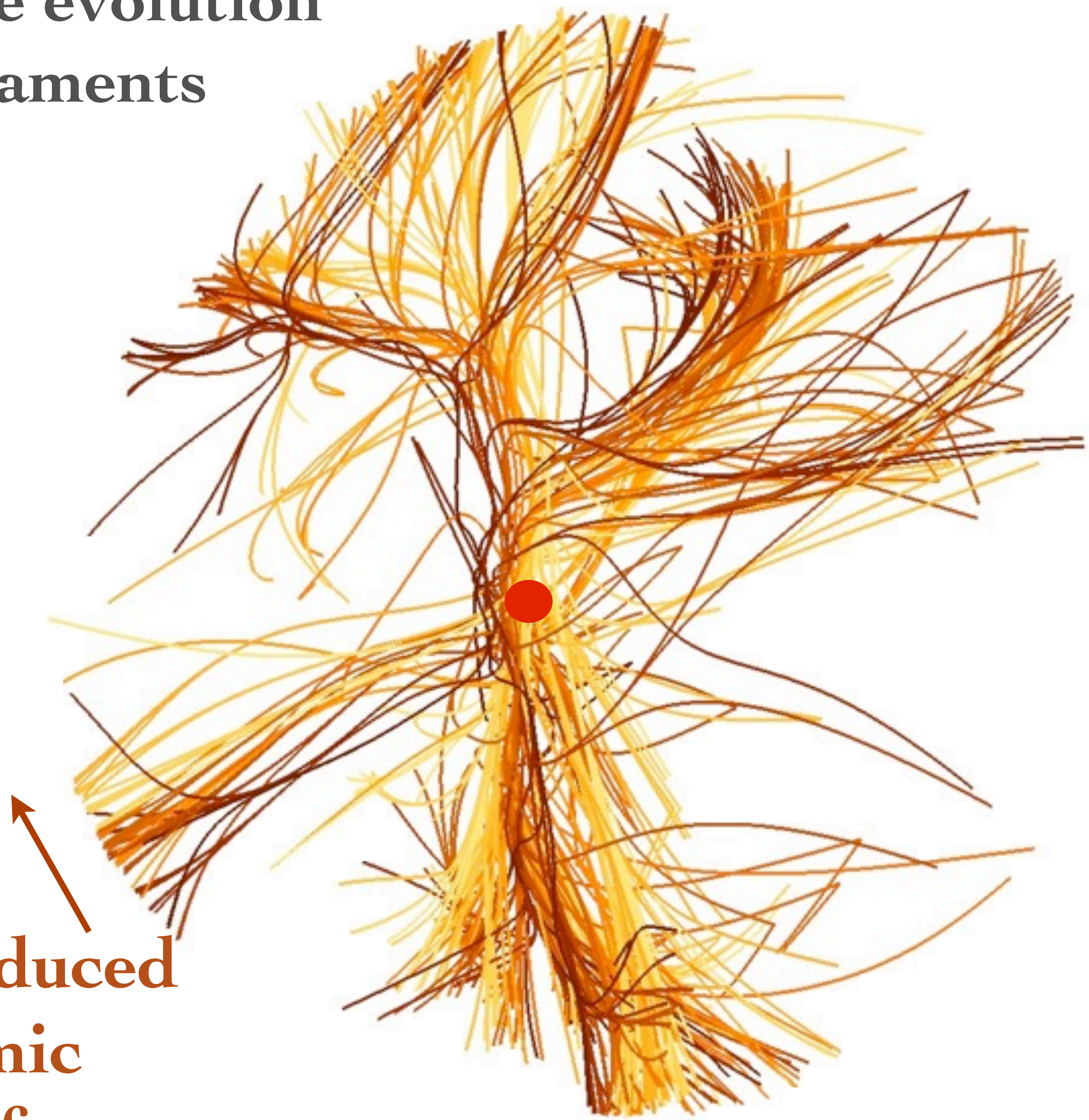
Time-line evolution of filaments

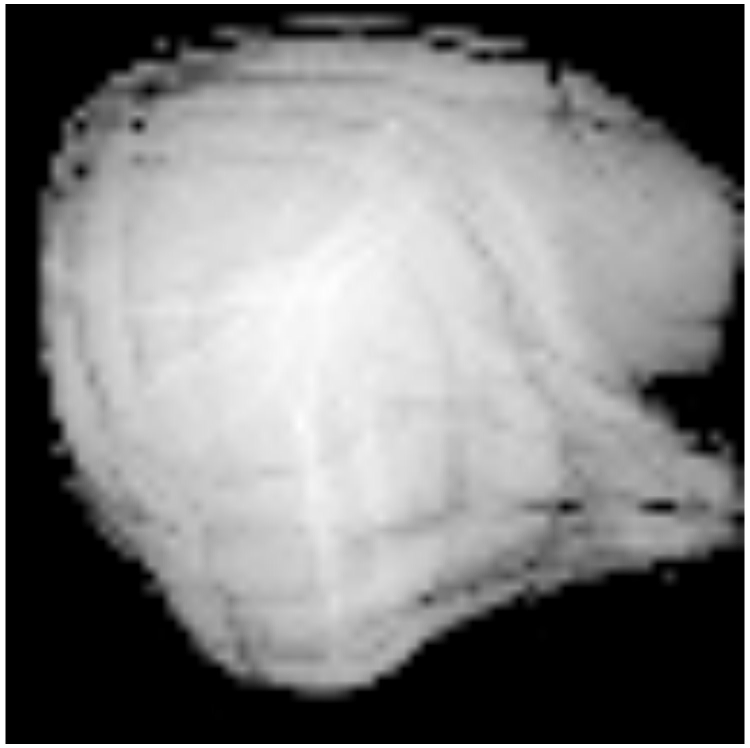


void induced cosmic drift

Drift of filaments

Time-line evolution of filaments





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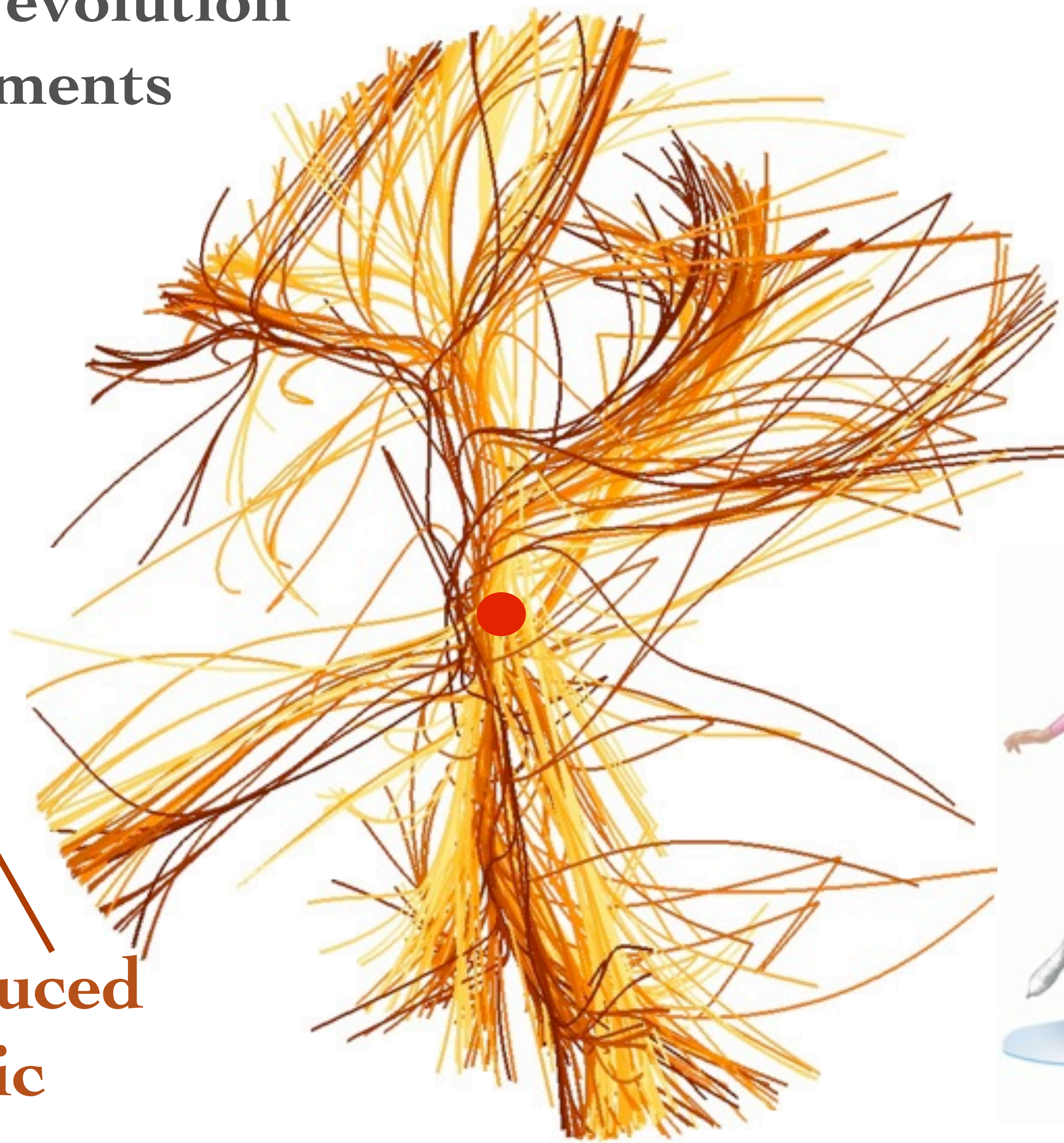
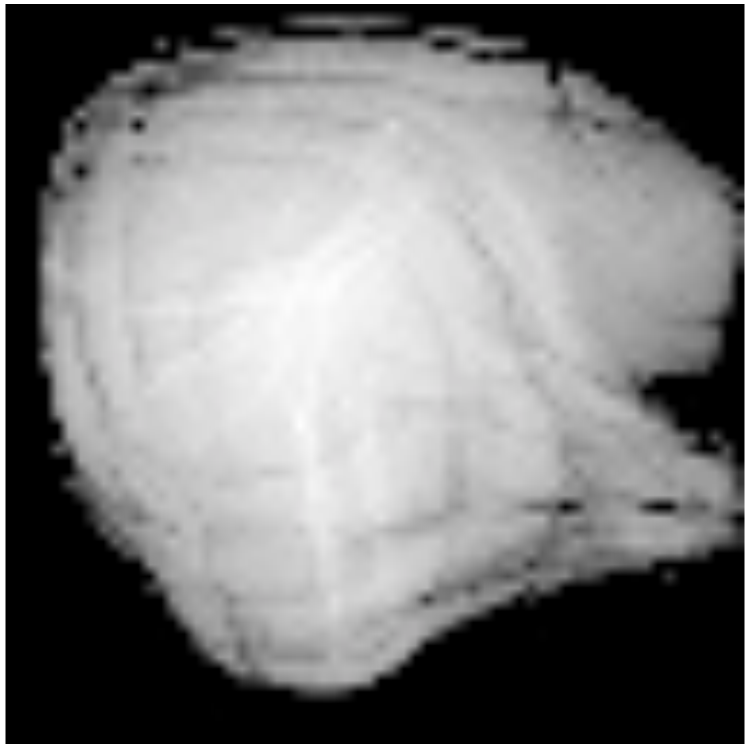
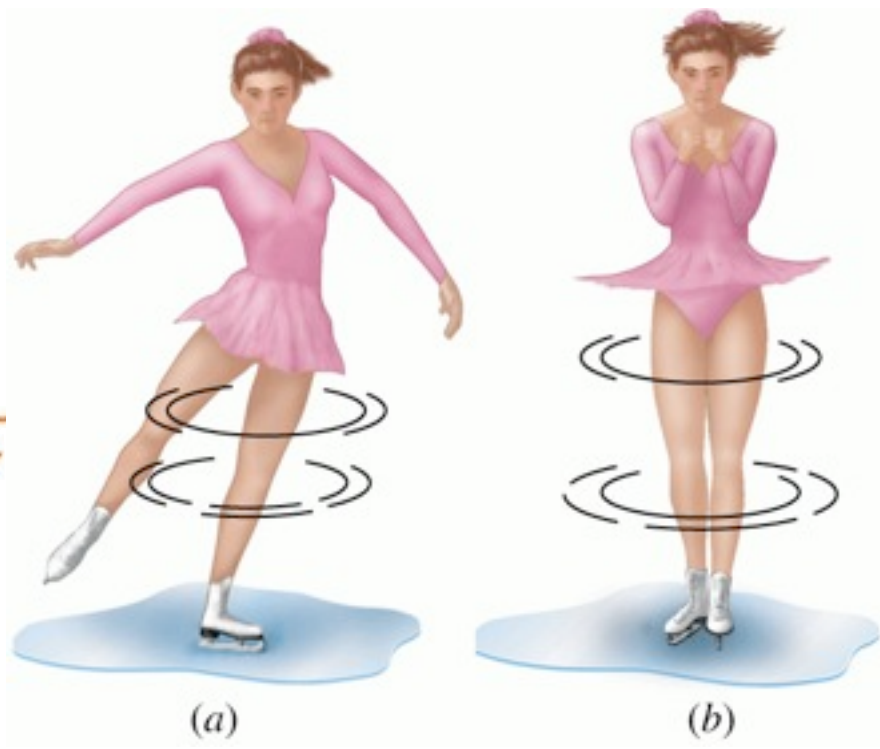


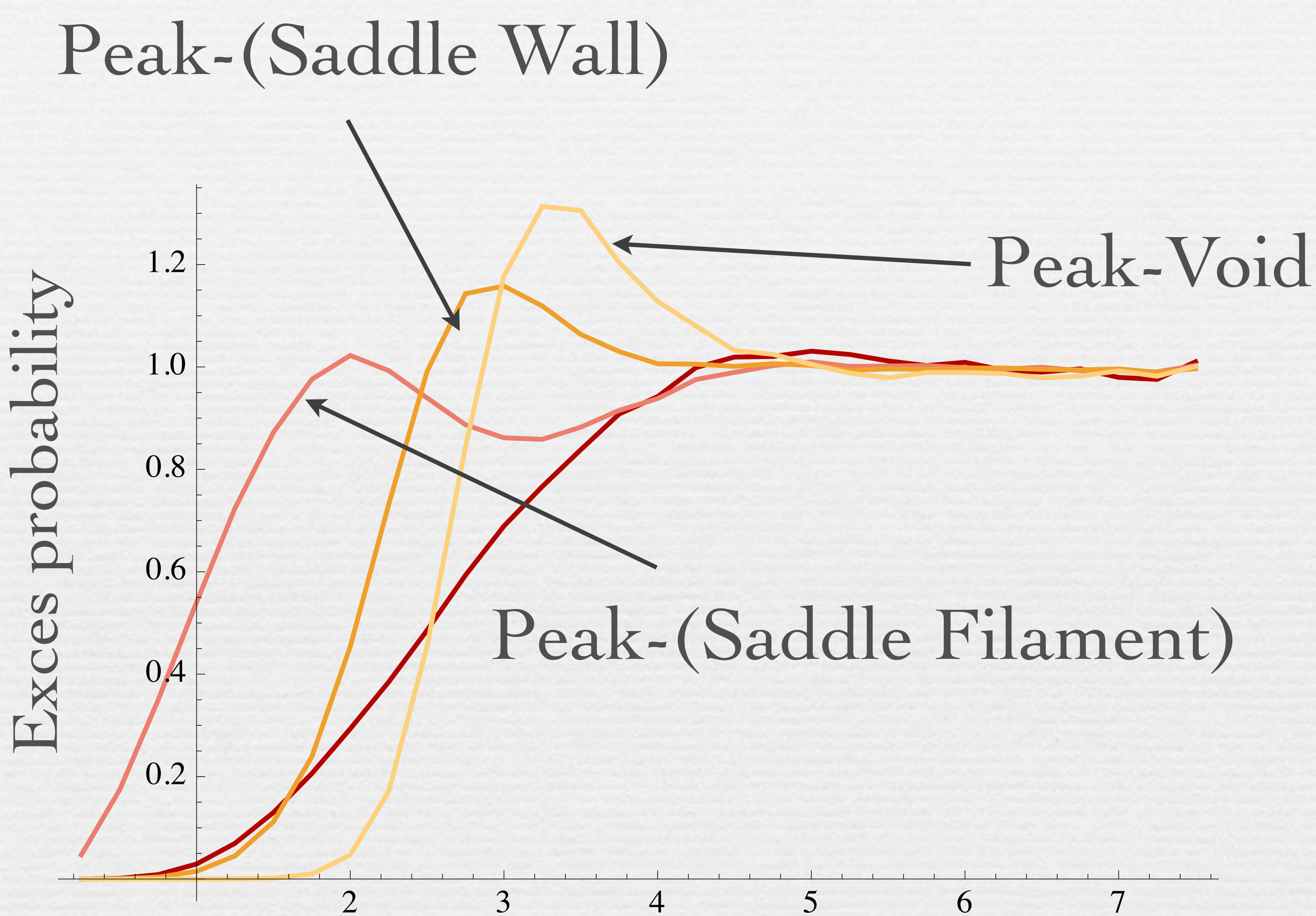


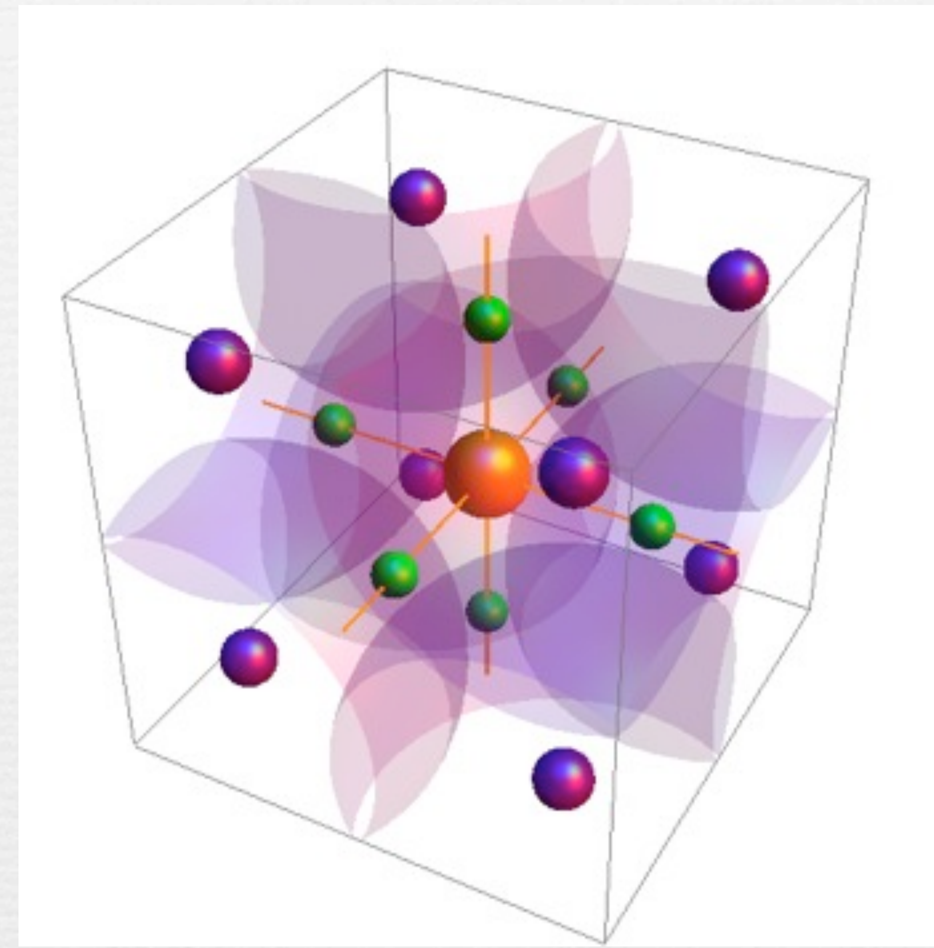


void induced cosmic drift

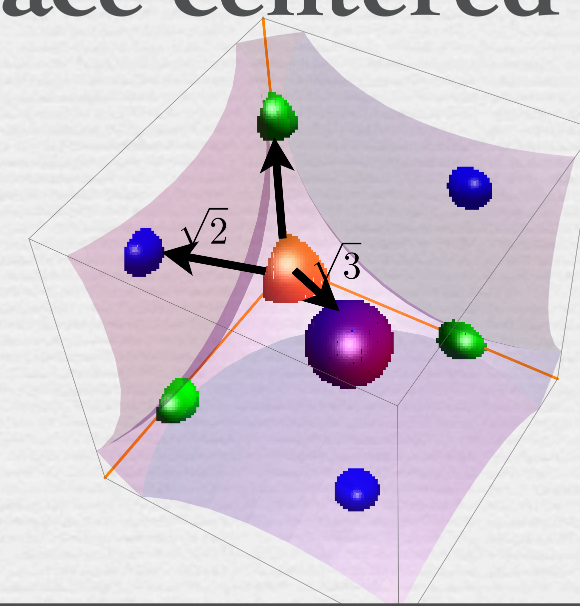
Two pts correlation of critical pts defines cosmic cristal

From first principles...





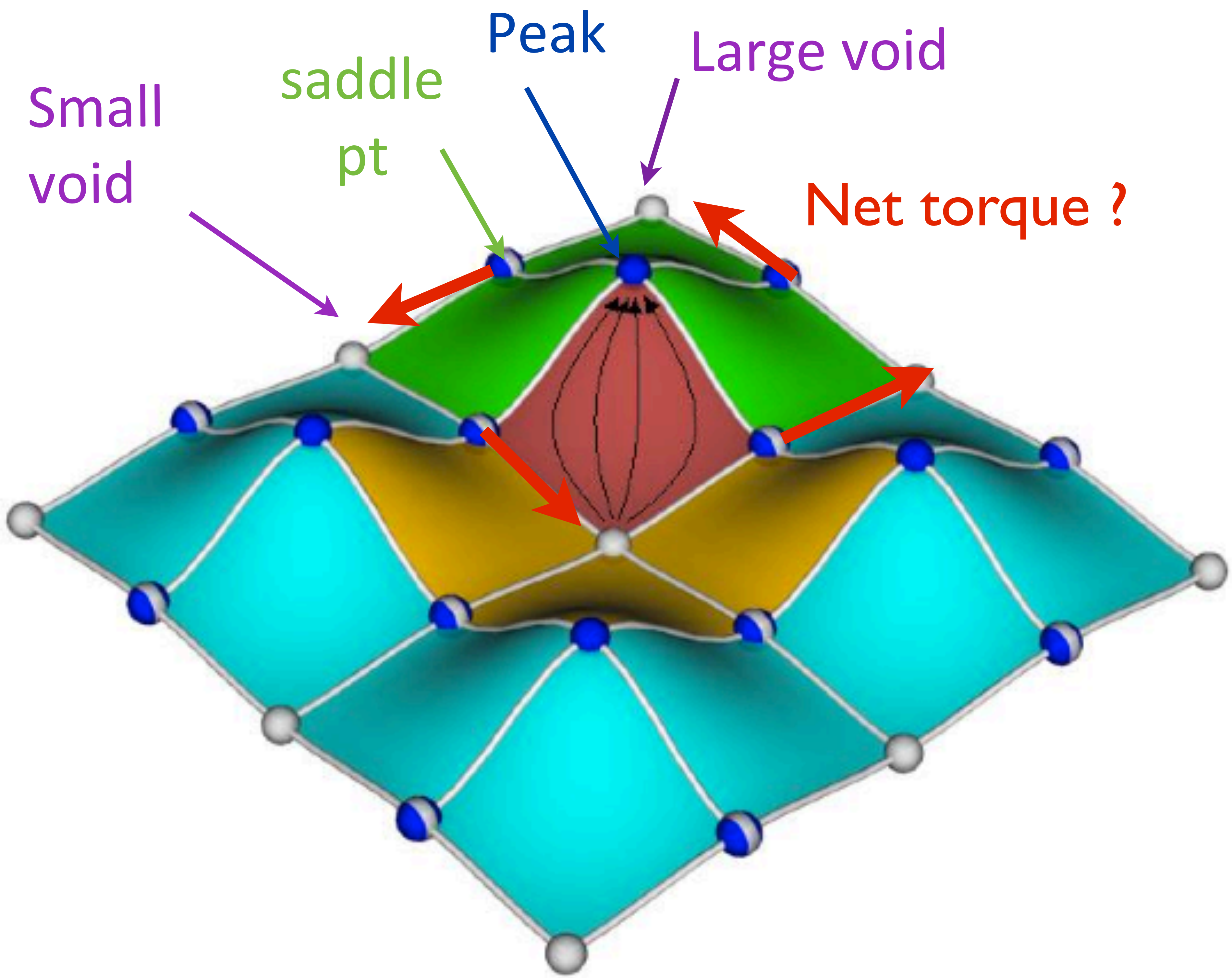
Cosmic "crystal" is *homeomorphic* to cubic face centered



$L_{sad,1}/L_s = 2$ $\qquad L_{\rm sad,2}/L_{\rm sad,1} = \sqrt{2}$

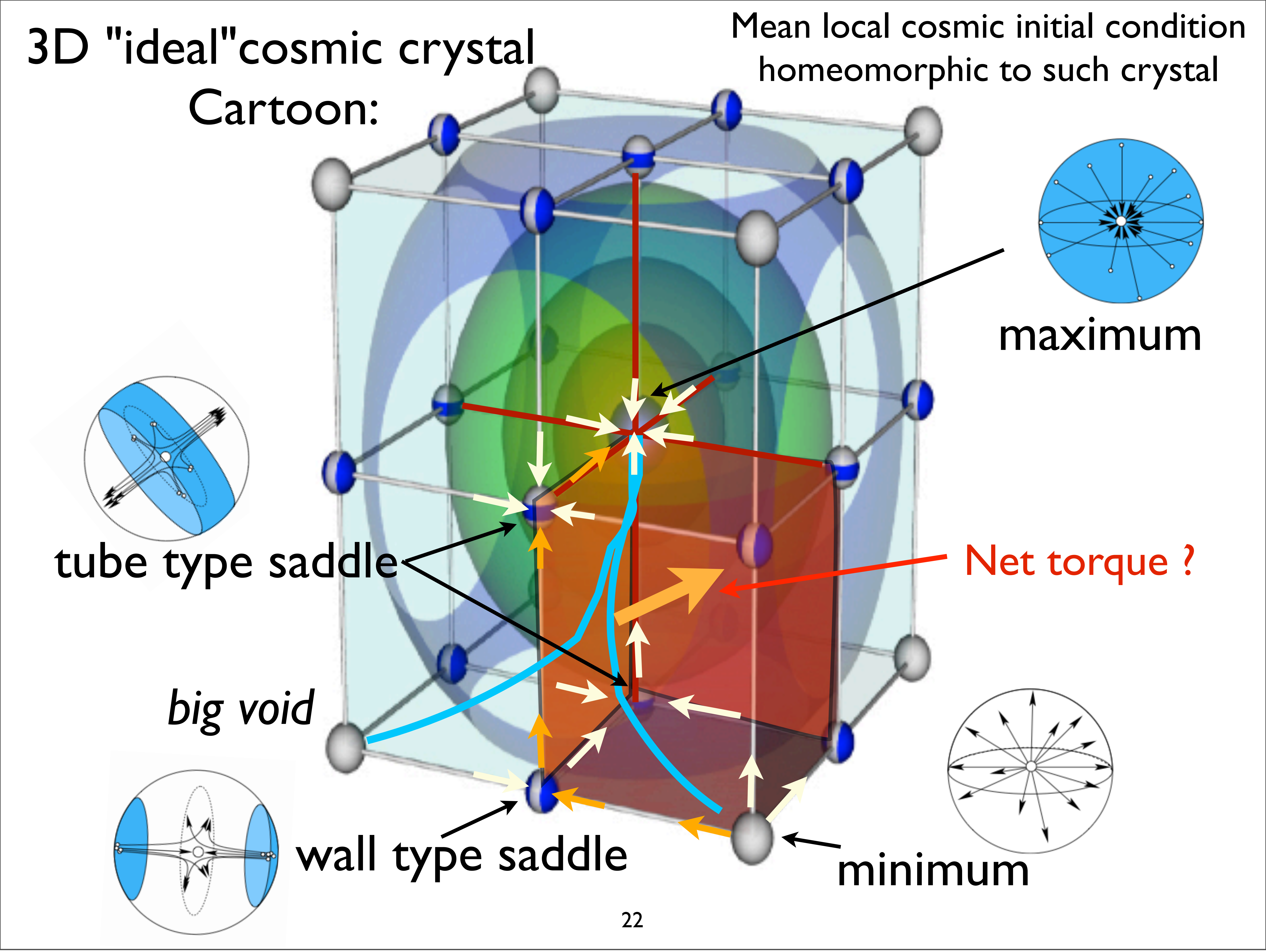
$$L_{\rm vod}/L_{\rm sad,1} = \sqrt{3}$$

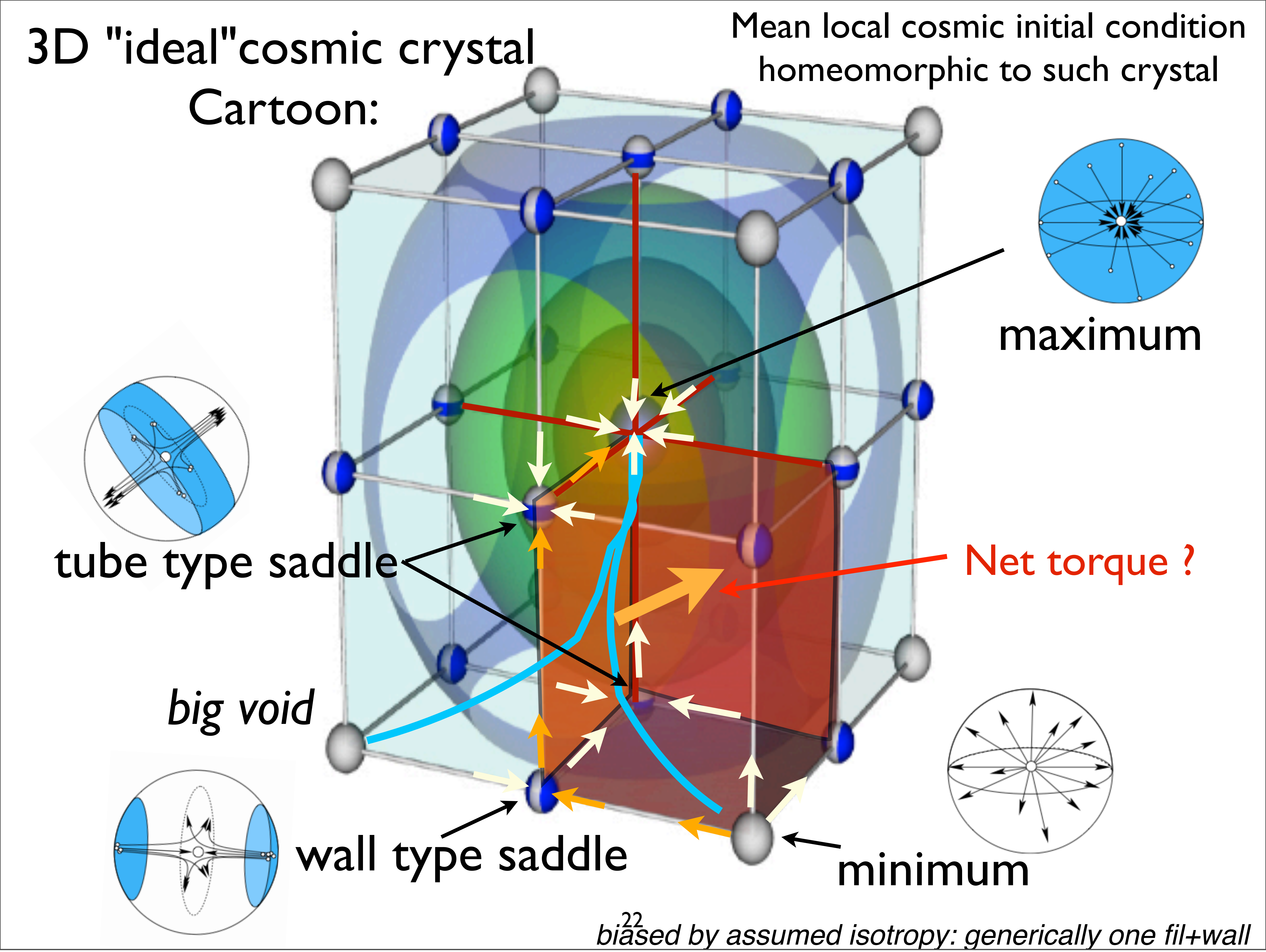
2D Cartoon of "ideal" cosmic environment :



Mean local cosmic initial condition homeomorphic to such crystal

21


3D "ideal"cosmic crystal
Cartoon:
Mean local cosmic initial condition
homeomorphic to such crystal
maximum
tube type saddle
Net torque ?
big void
wall type saddle
minimum
22



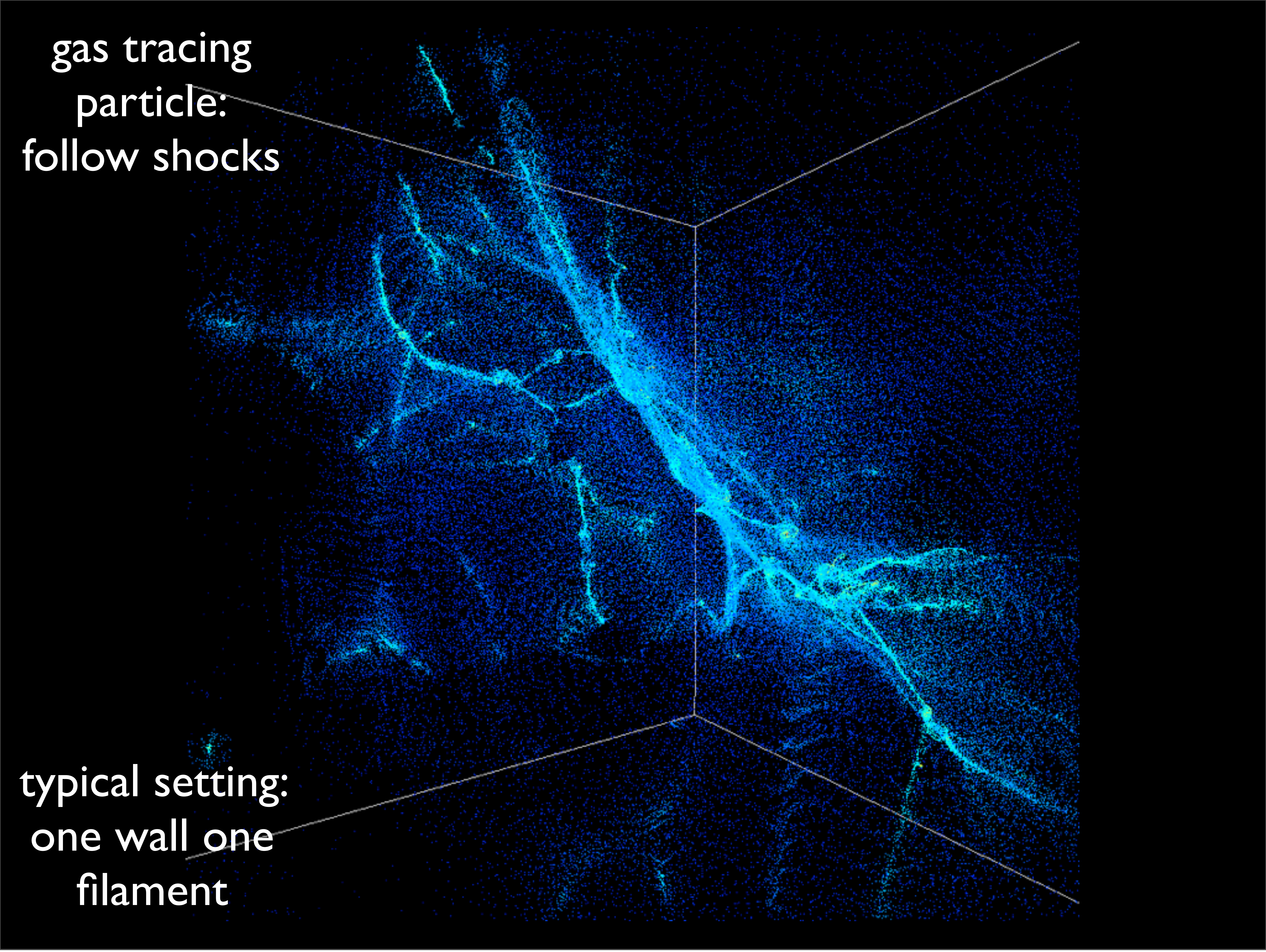
3D "ideal"cosmic crystal
Cartoon:
Mean local cosmic initial condition
homeomorphic to such crystal
maximum
tube type saddle
Net torque ?
big void
wall type saddle
minimum
22
biased by assumed isotropy: generically one fil+wall

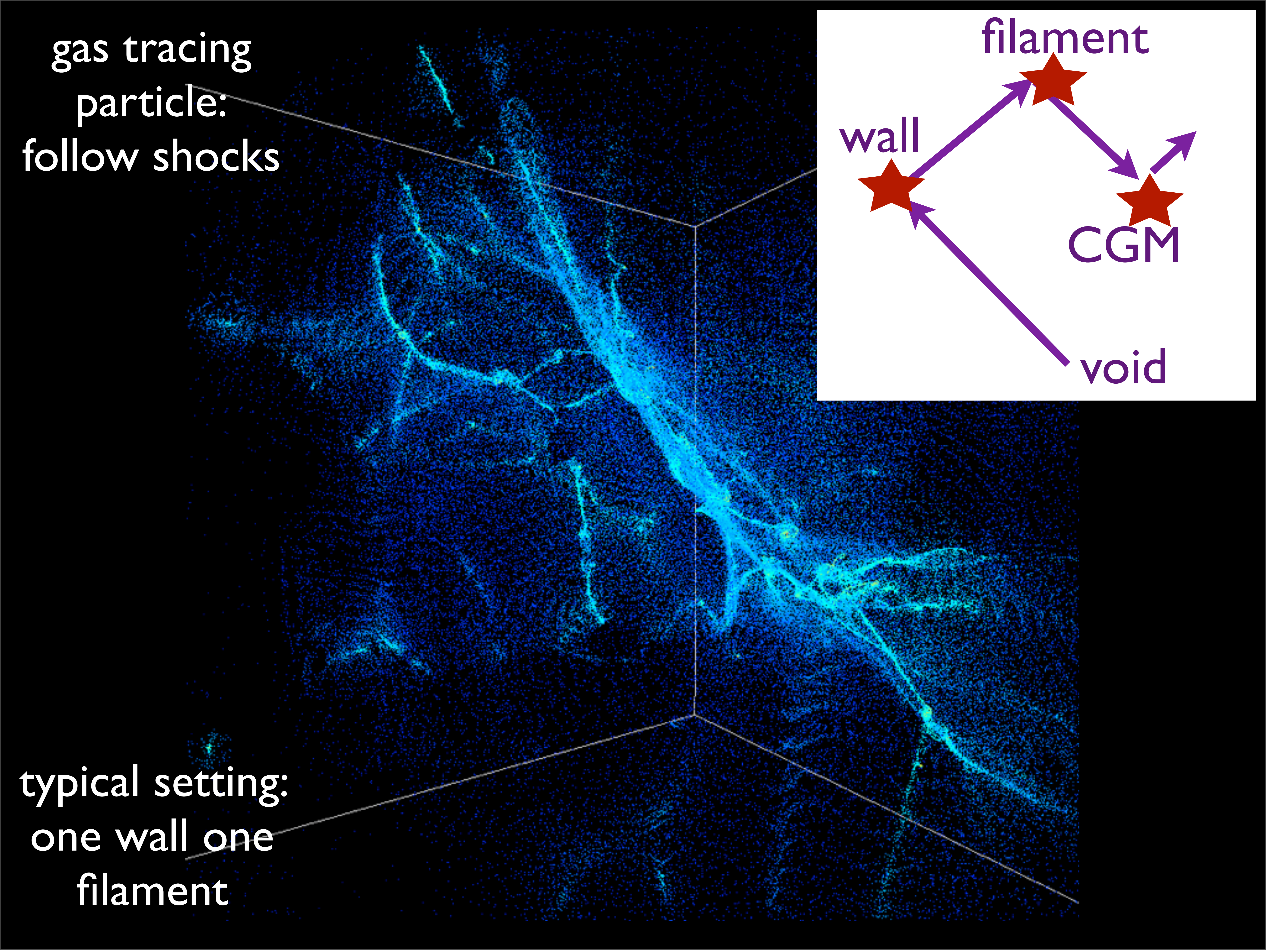
Do we see this?

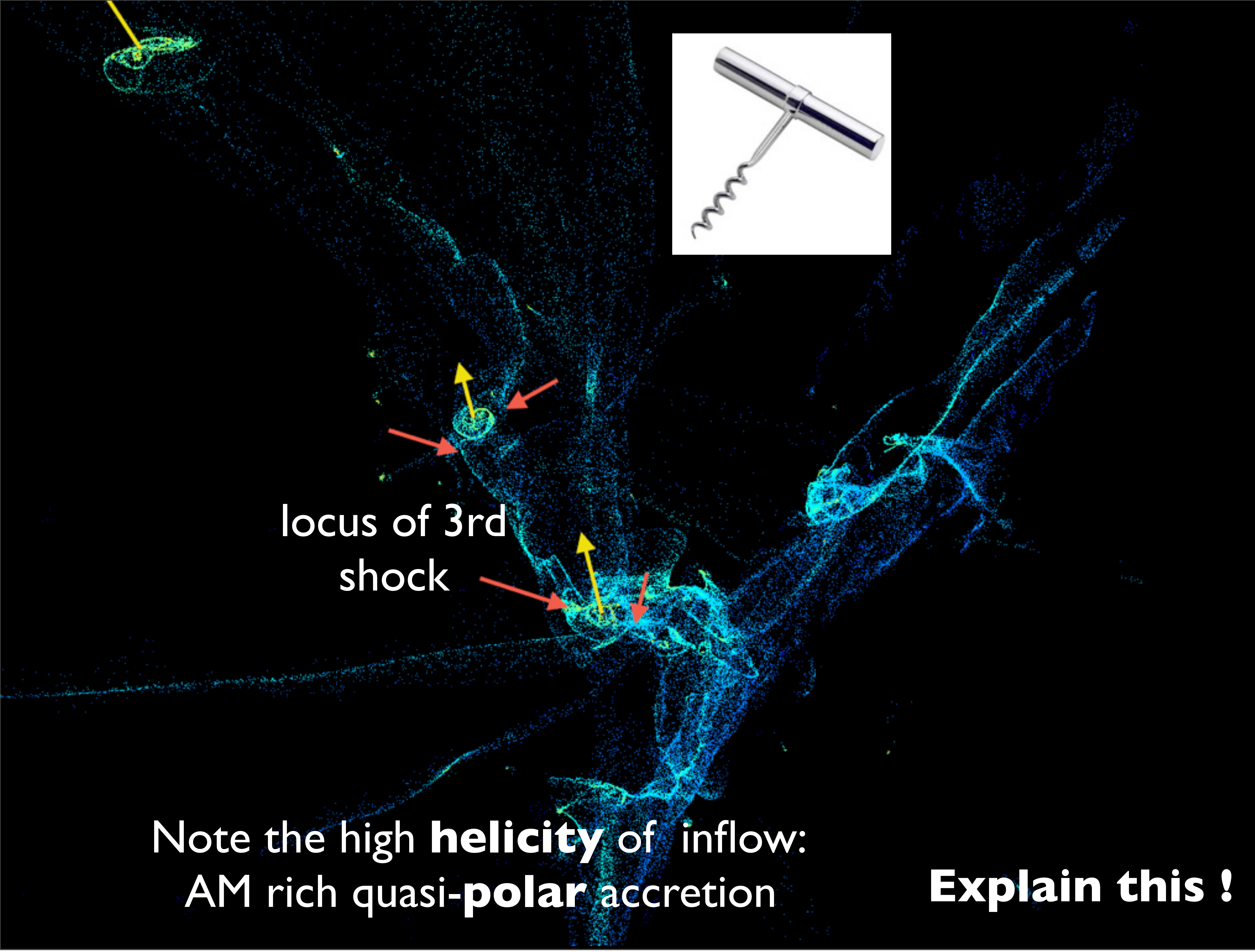
"Proof" by visualisation of hydrodynamical simulation

a.k.a

proof by pretty pictures


gas tracing particle: follow shocks
typical setting: one wall one filament


gas tracing particle: follow shocks
typical setting: one wall one filament
filament
wall
CGM
void



Note the high **helicity** of inflow:
AM rich quasi-**polar** accretion

Explain this !

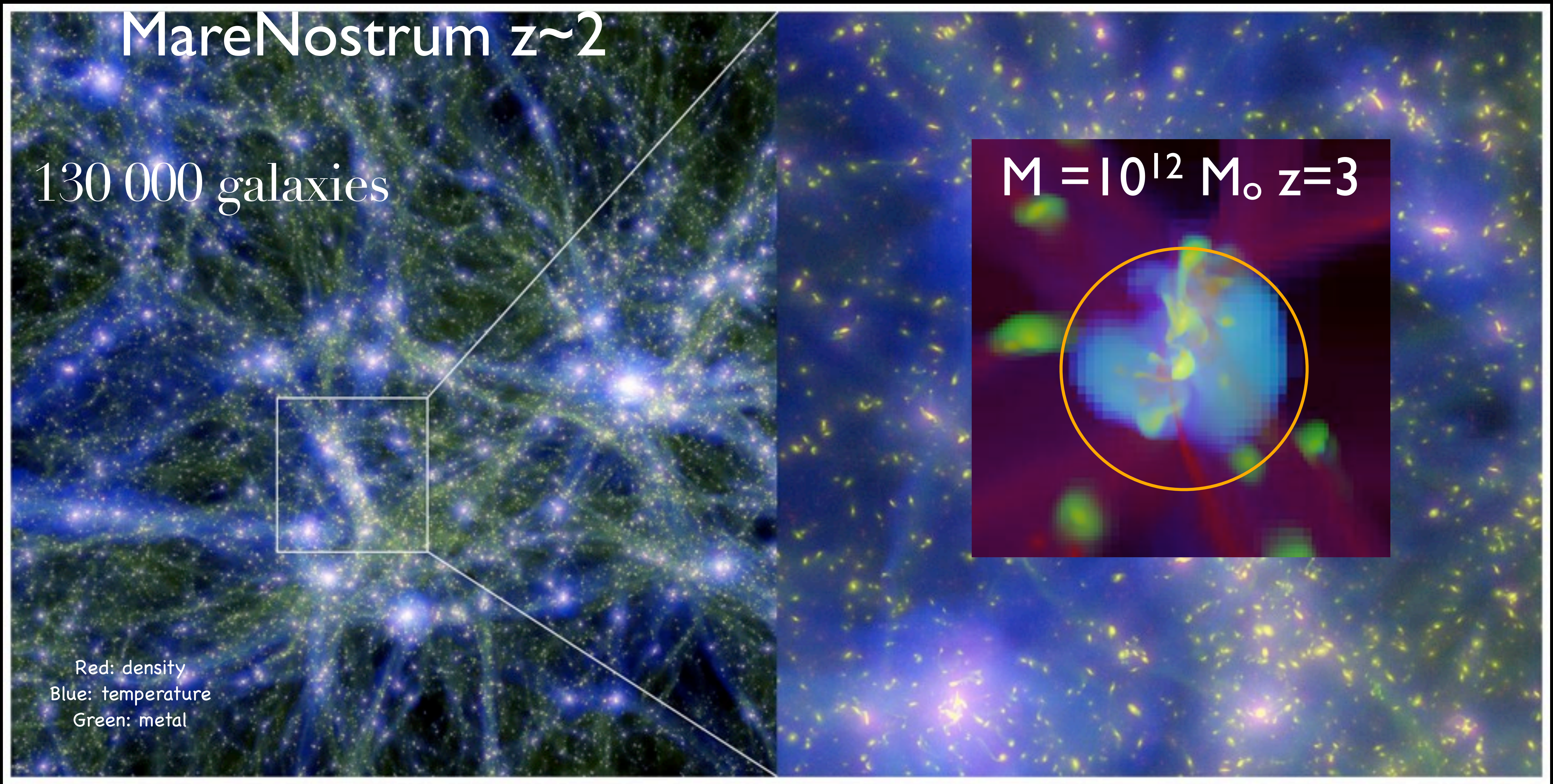
Can it be made quantitative?

"Proof" by robust statistical analysis

a.k.a

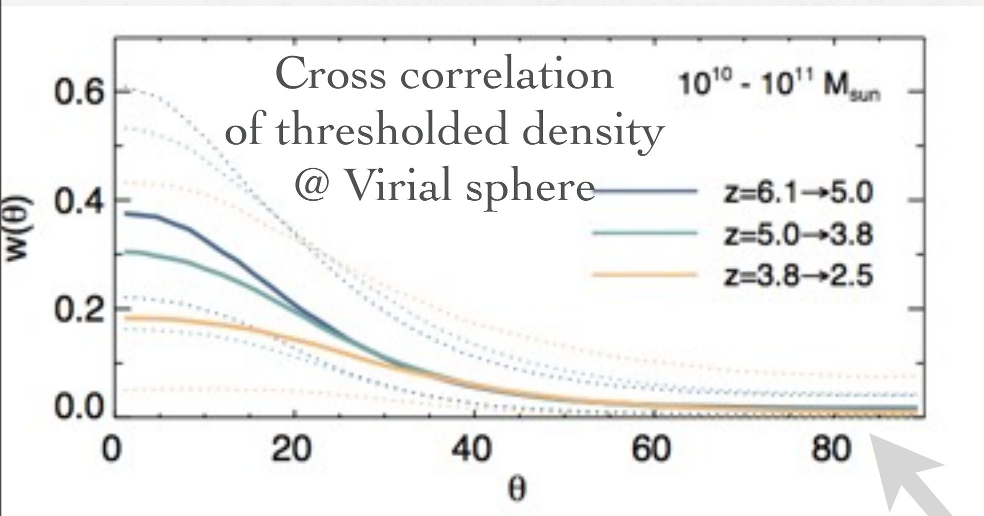
lies, damn lies and statistics

Anisotropic accretion: cold flows driven by LSS

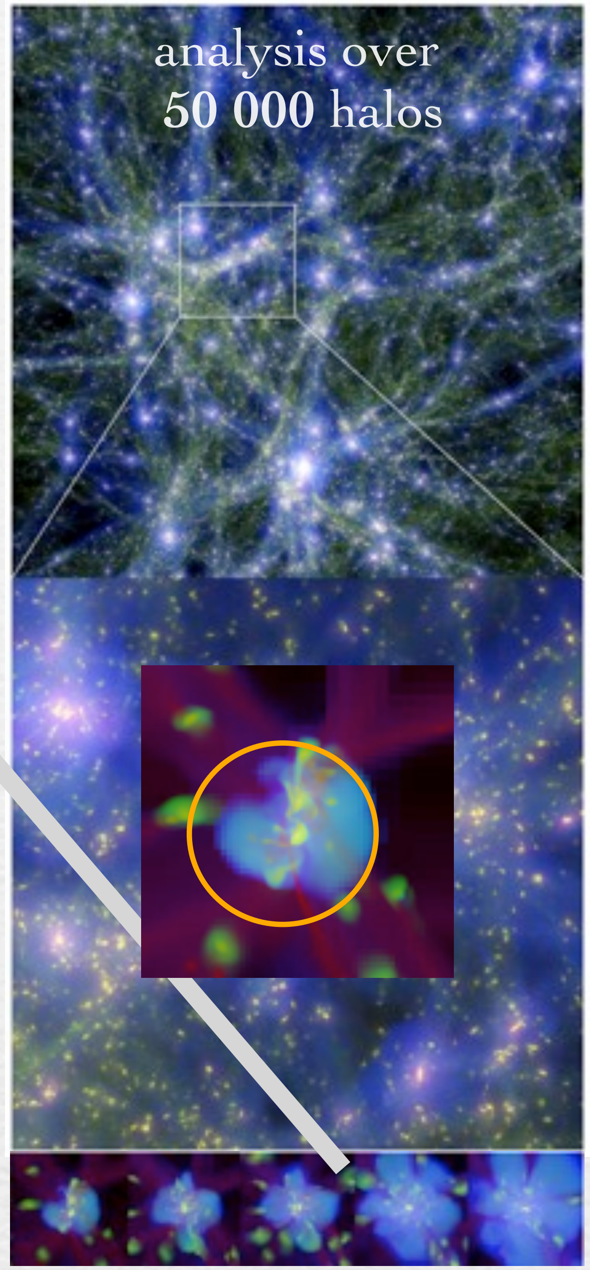


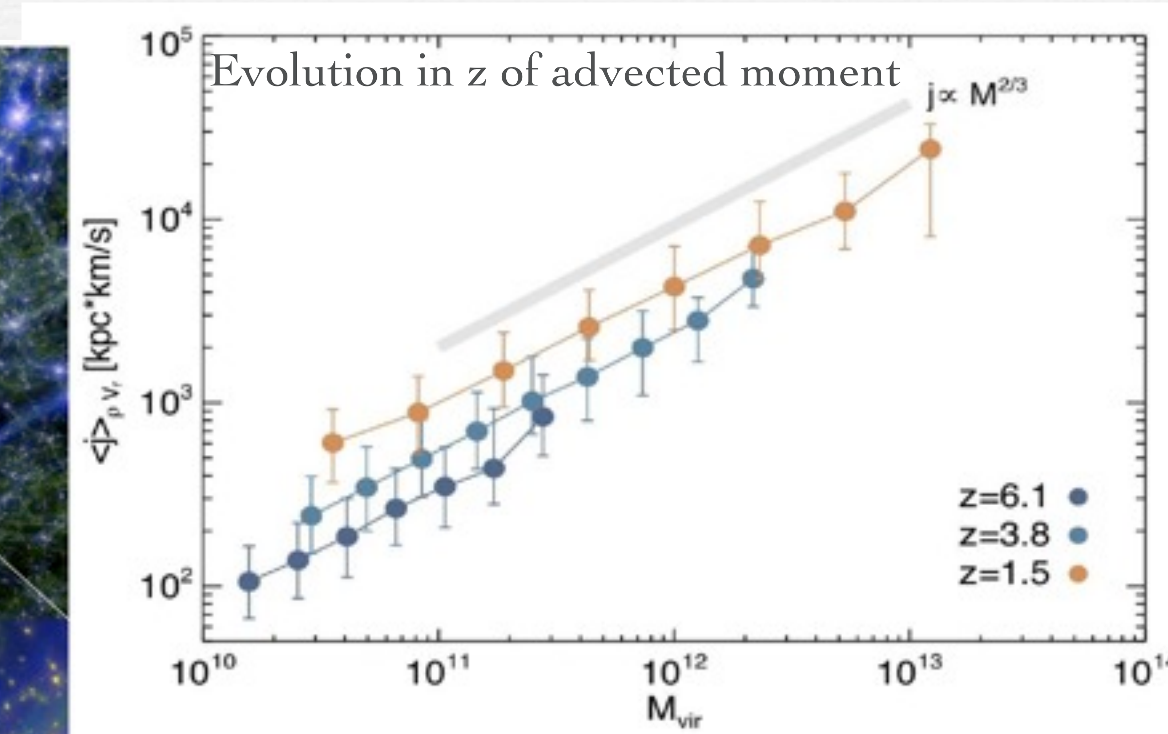
- Use LSS dynamics to statistically analyse AM infall @ Rvir

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



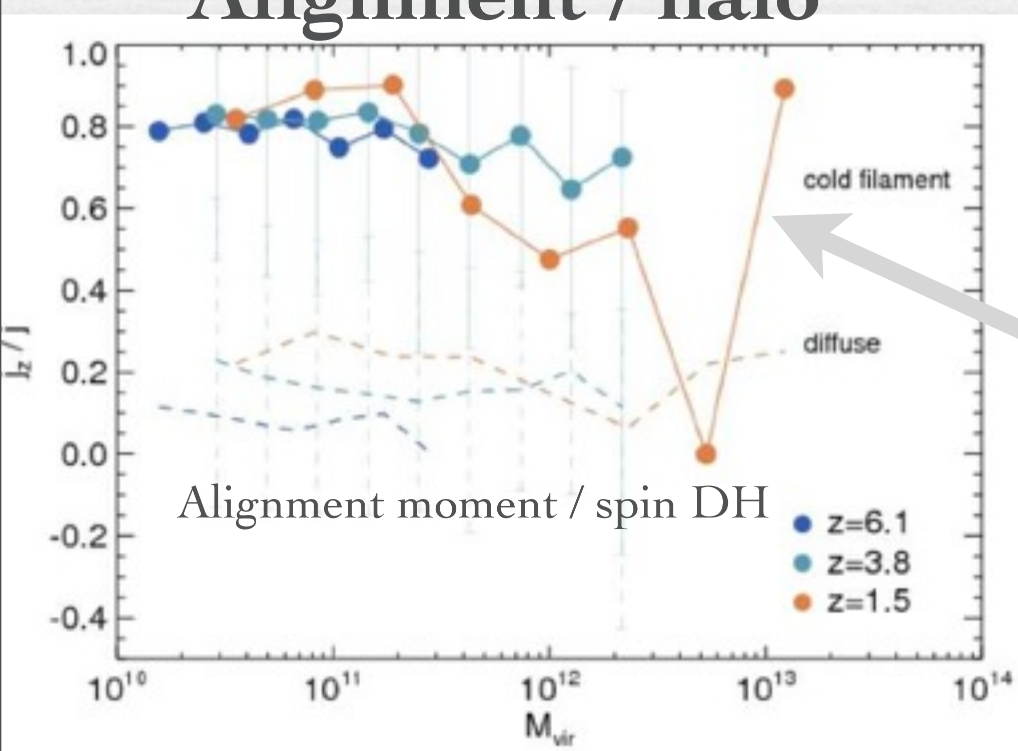
Filamentary Accretion: coherent orientation

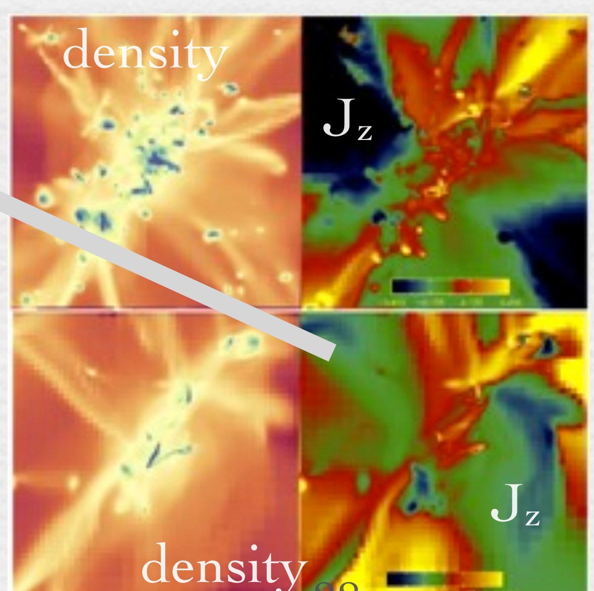




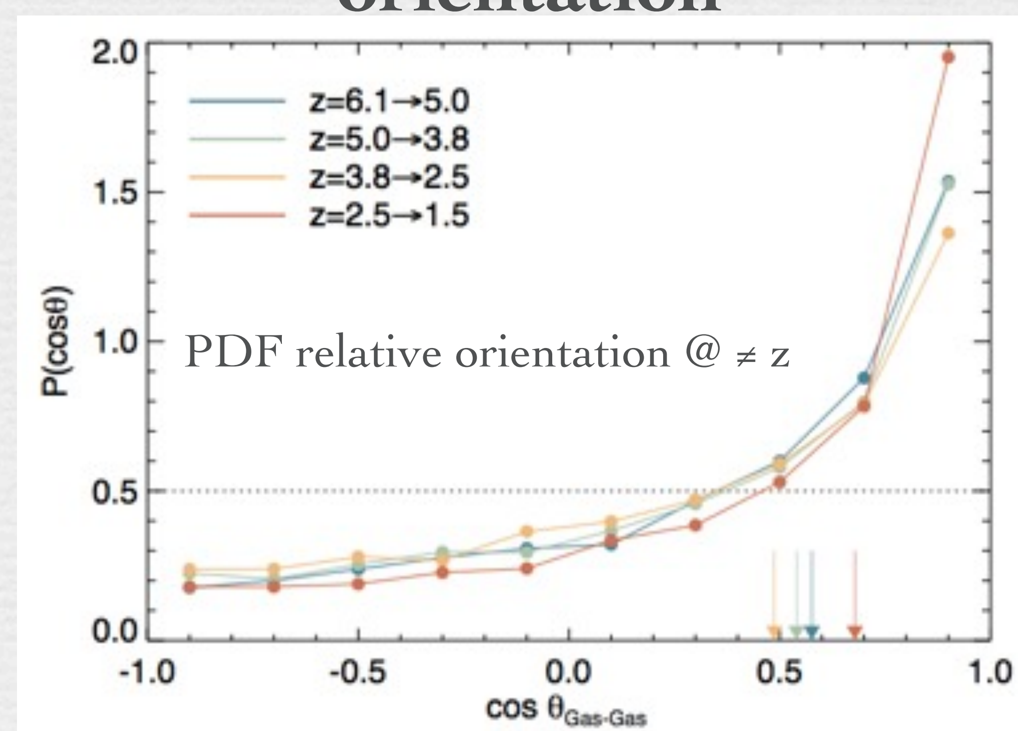
growth of |ang moment|

Advected Ang Moment Alignment / halo





Coherent ang. moment orientation

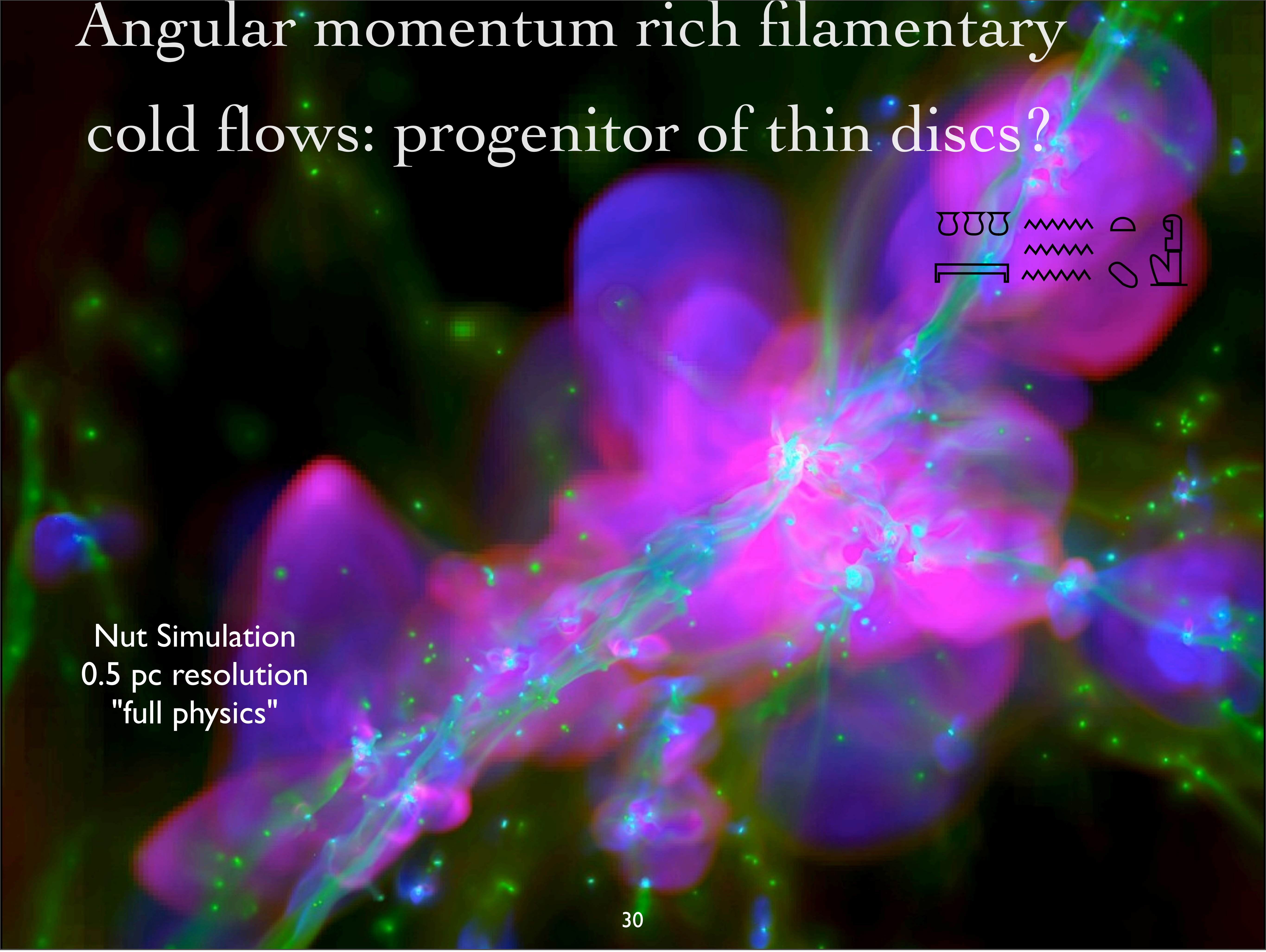


Can we trace this back in time?

"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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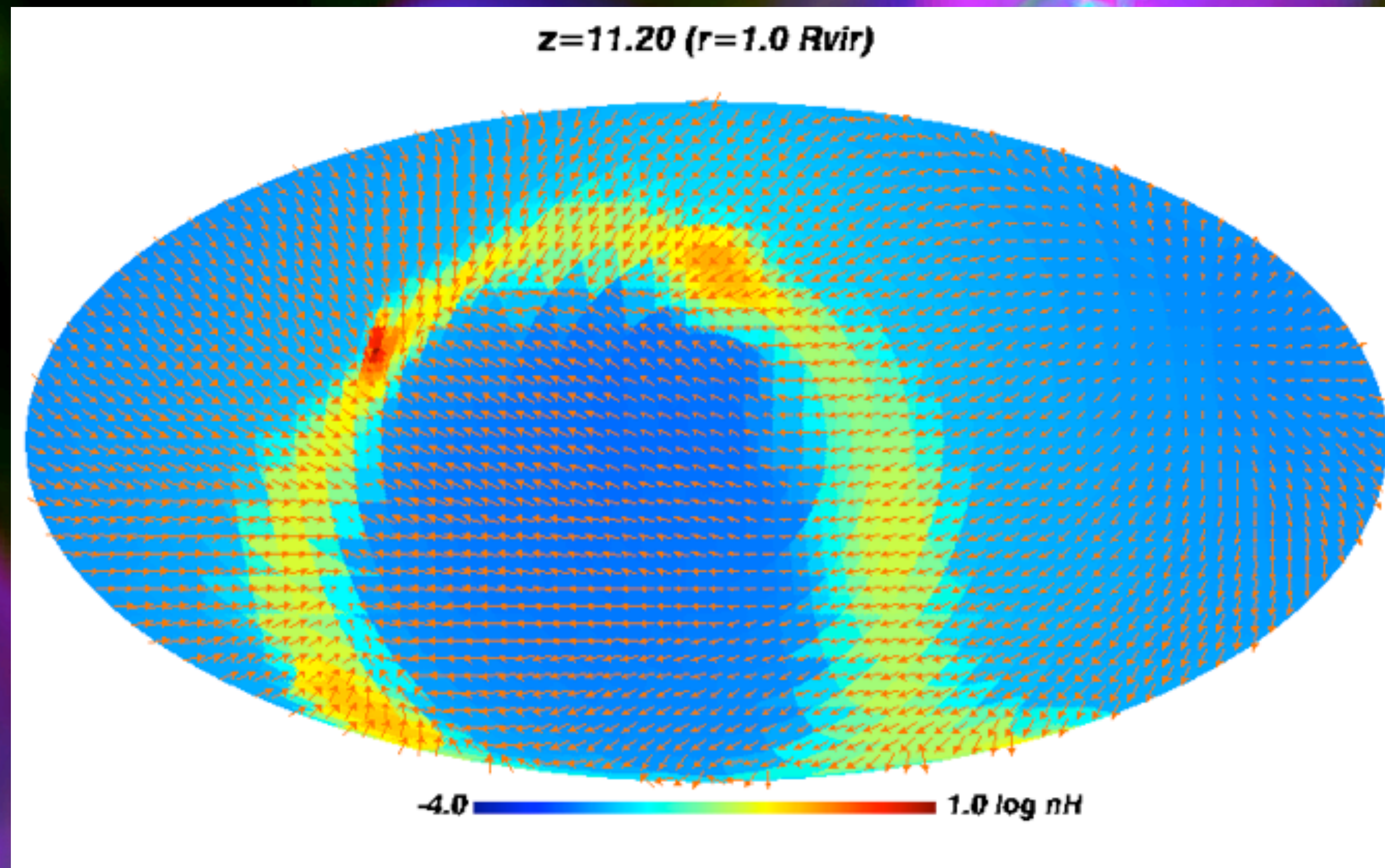
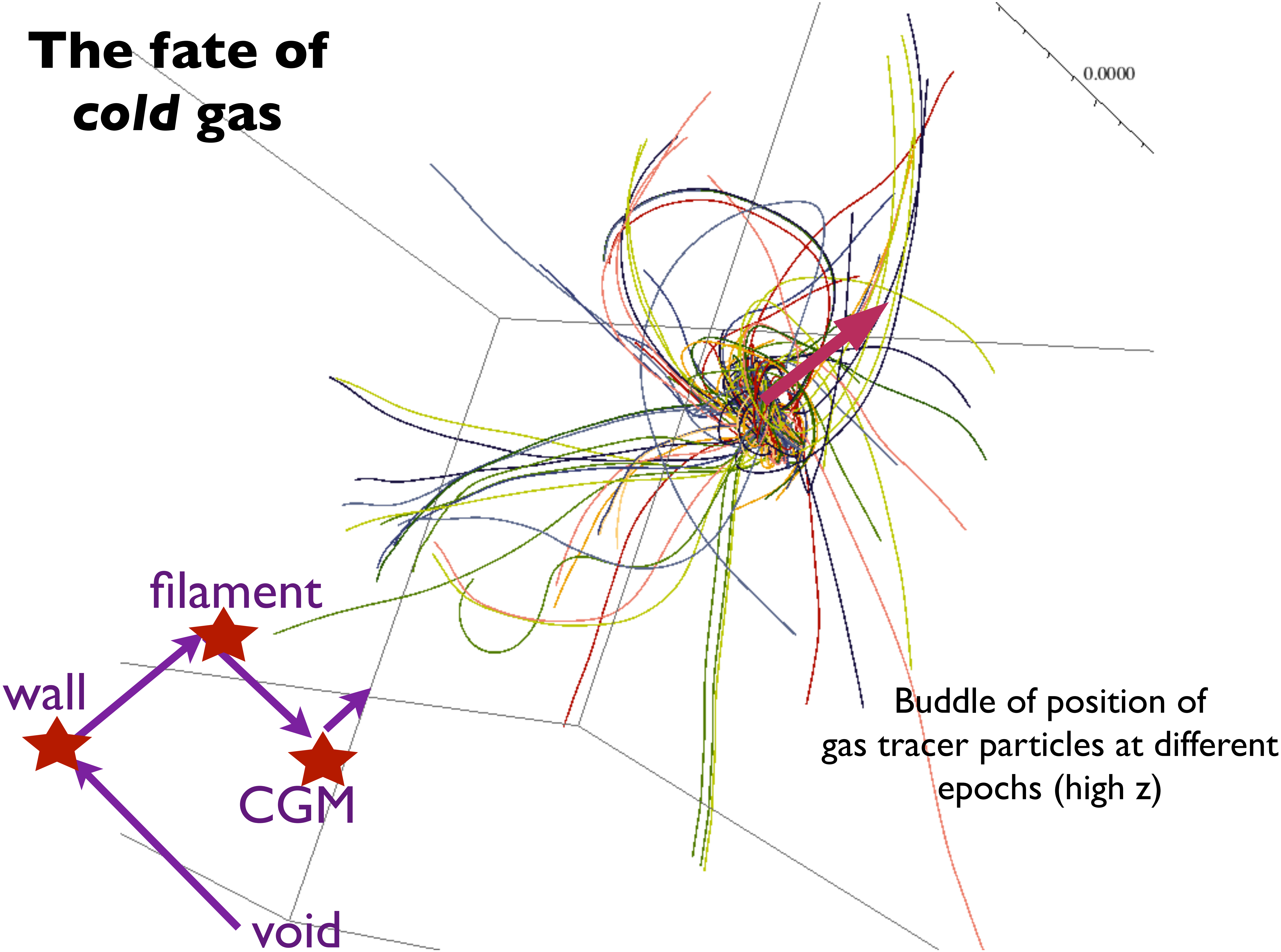
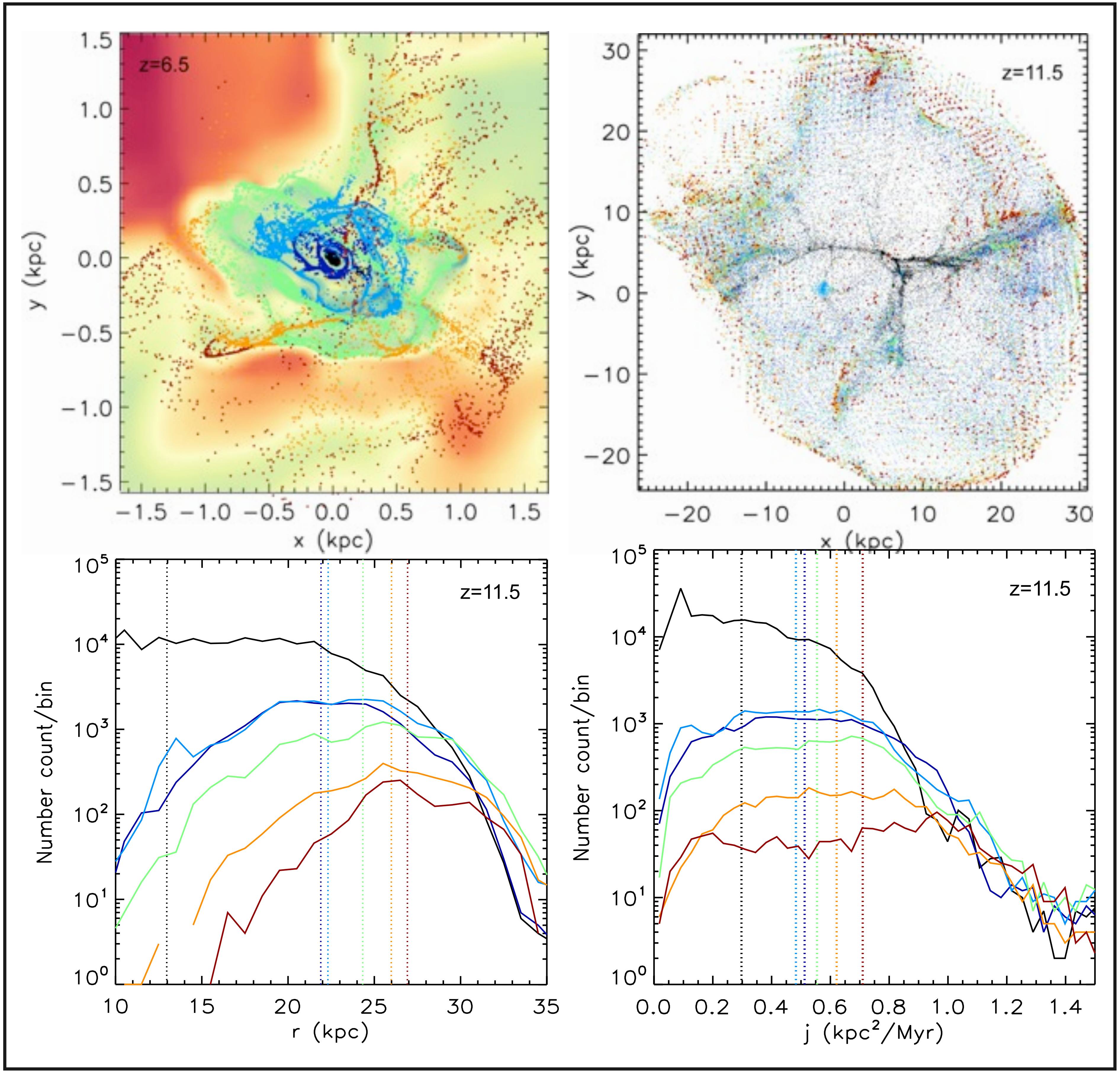


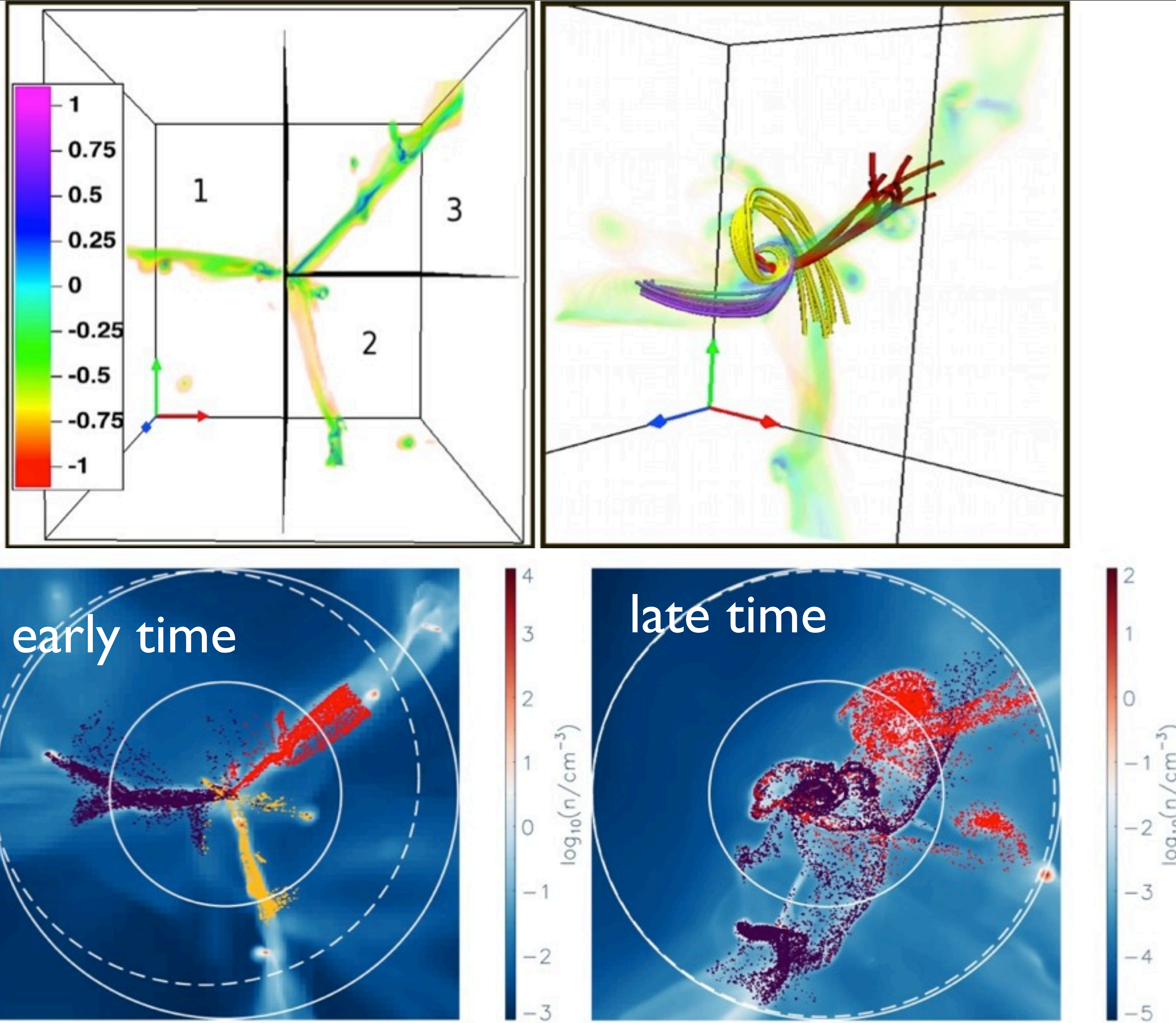
Nut Simulation
0.5 pc resolution
"full physics"

The fate of *cold* gas

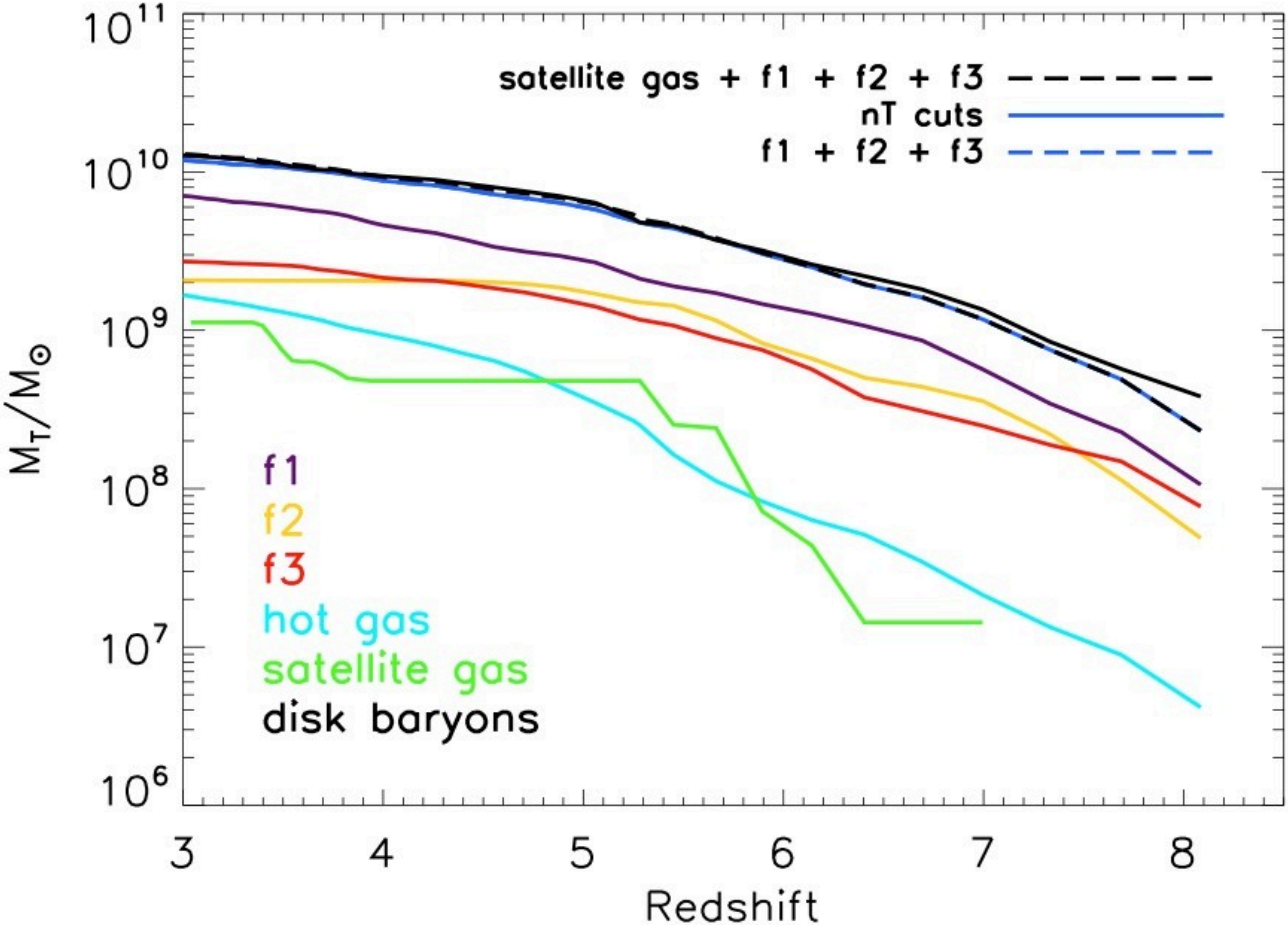


Stratified mass and momentum

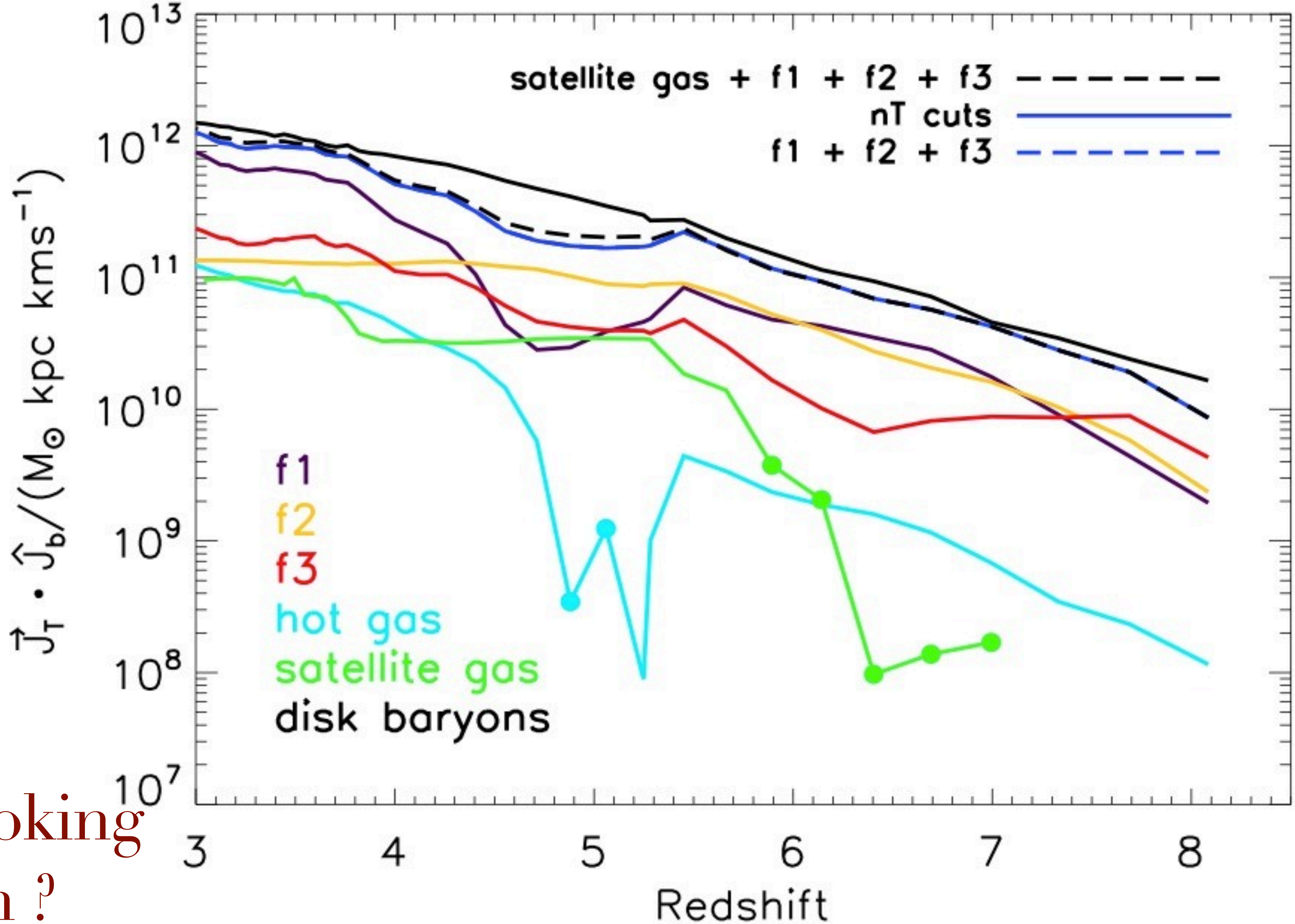



1
0.75
0.5
0.25
0
-0.25
-0.5
-0.75
-1
1
2
3
early time
late time
4
3
2
1
0
−1
−2
−3
$\log_{10}(n/cm^{-3})$
2
1
0
−1
−2
−3
−4
−5
$\log_{10}(n/cm^{-3})$

Mass in disc originate from filaments



Angular momentum in disc originate from filaments



Smoking gun ?

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
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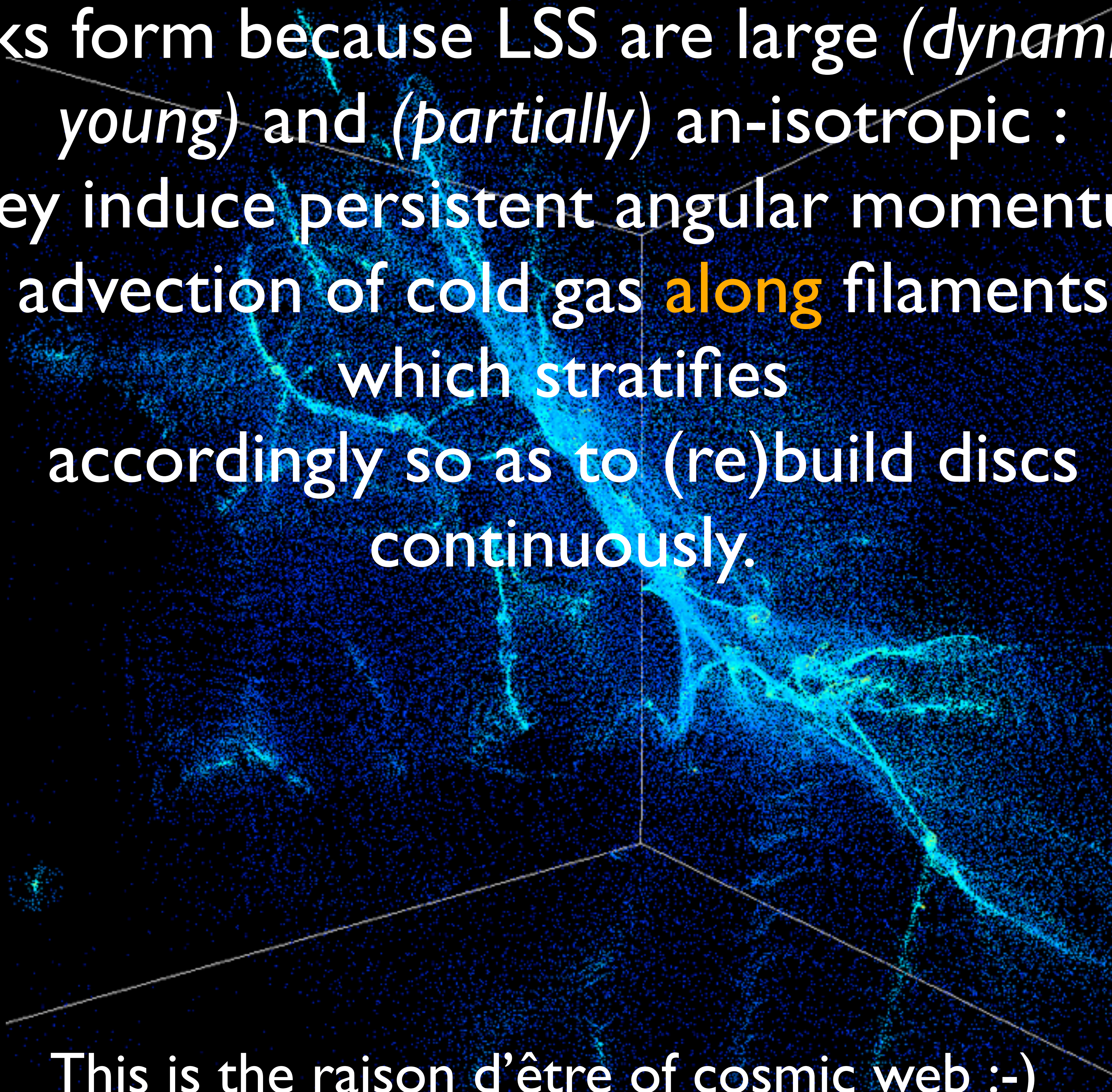


This is the raison d’être of cosmic web :-)

- 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?
- What is the corresponding Lagrangian theory?

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?

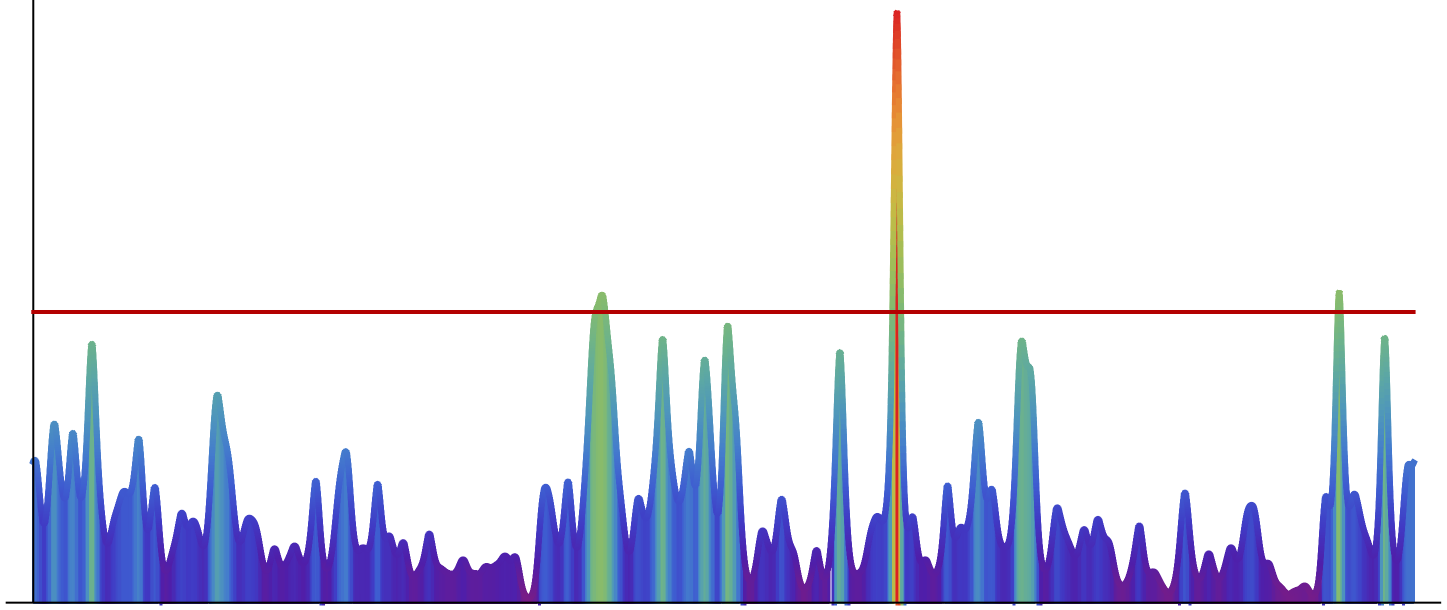
Part II Outline

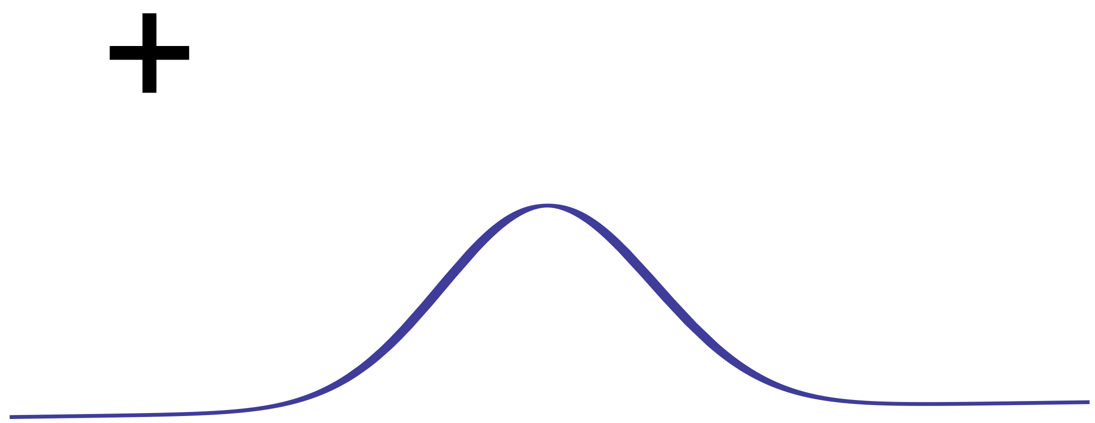
Nick+ anisotropy

- Where do galaxies form?
- What is the spin orientation w.r.t. cosmic web
- What do low mass galaxies do?
- What do high mass galaxies do?

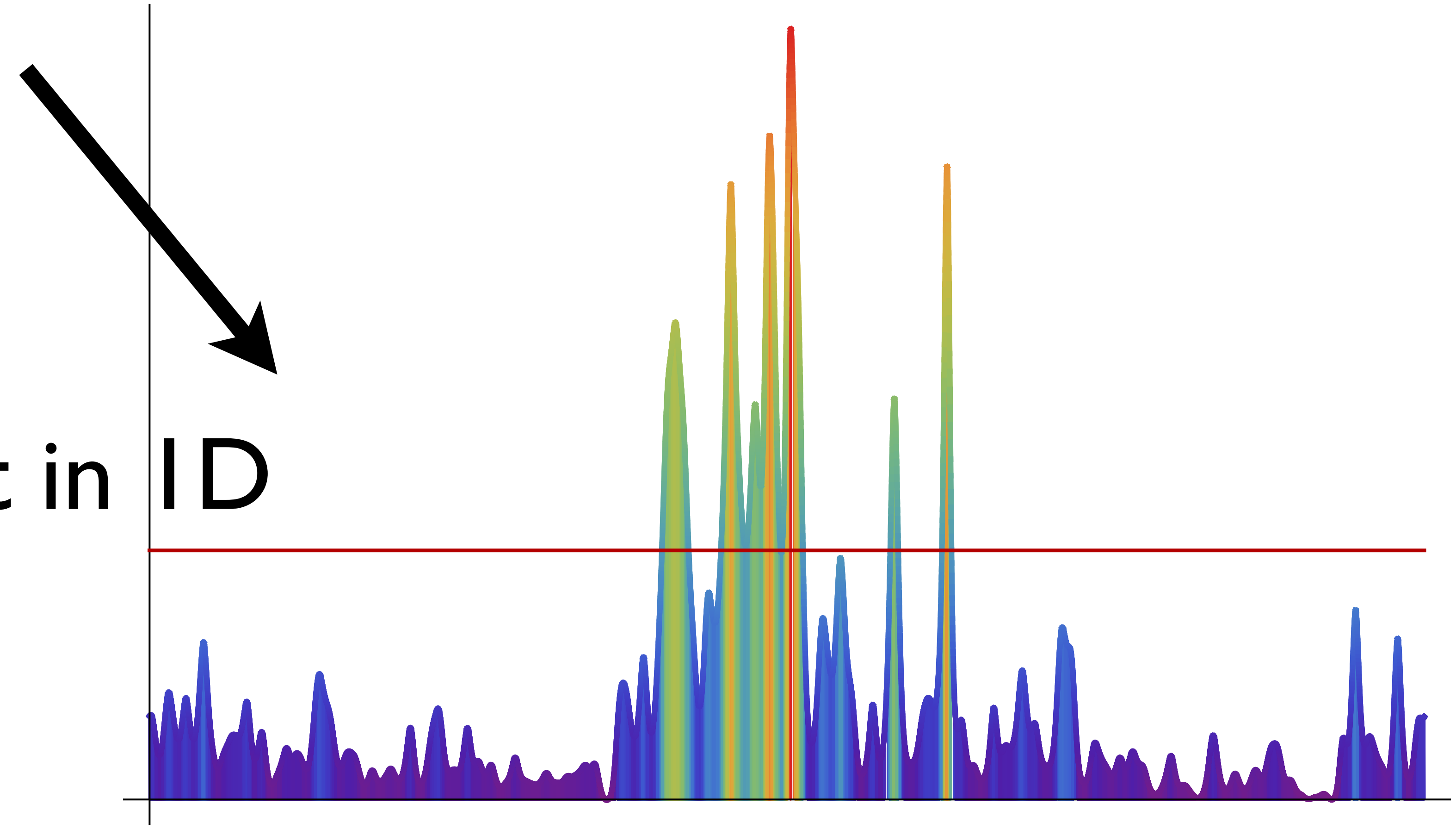
The Eulerian view of spin/LSS connection

dark halos don't form anywhere

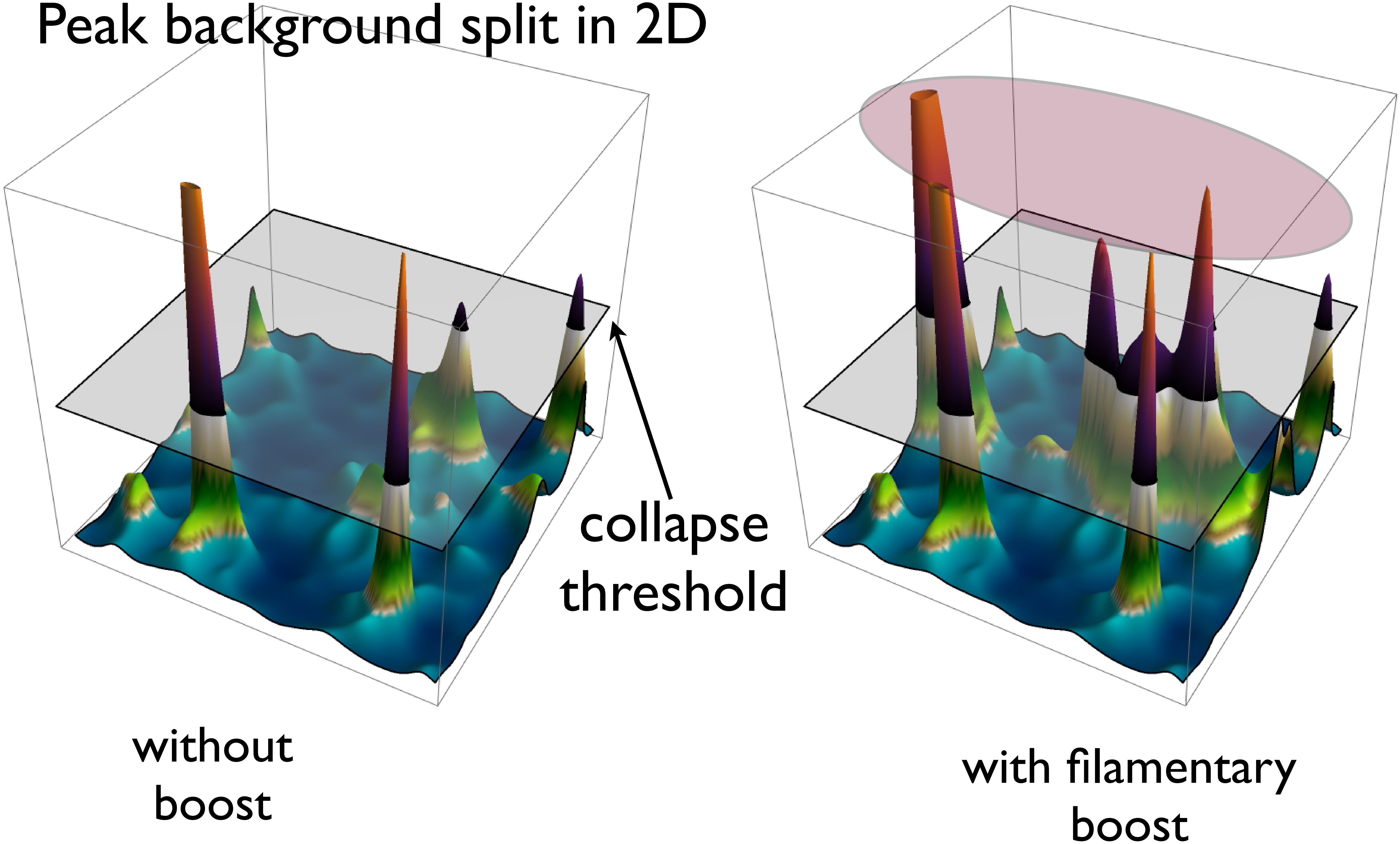




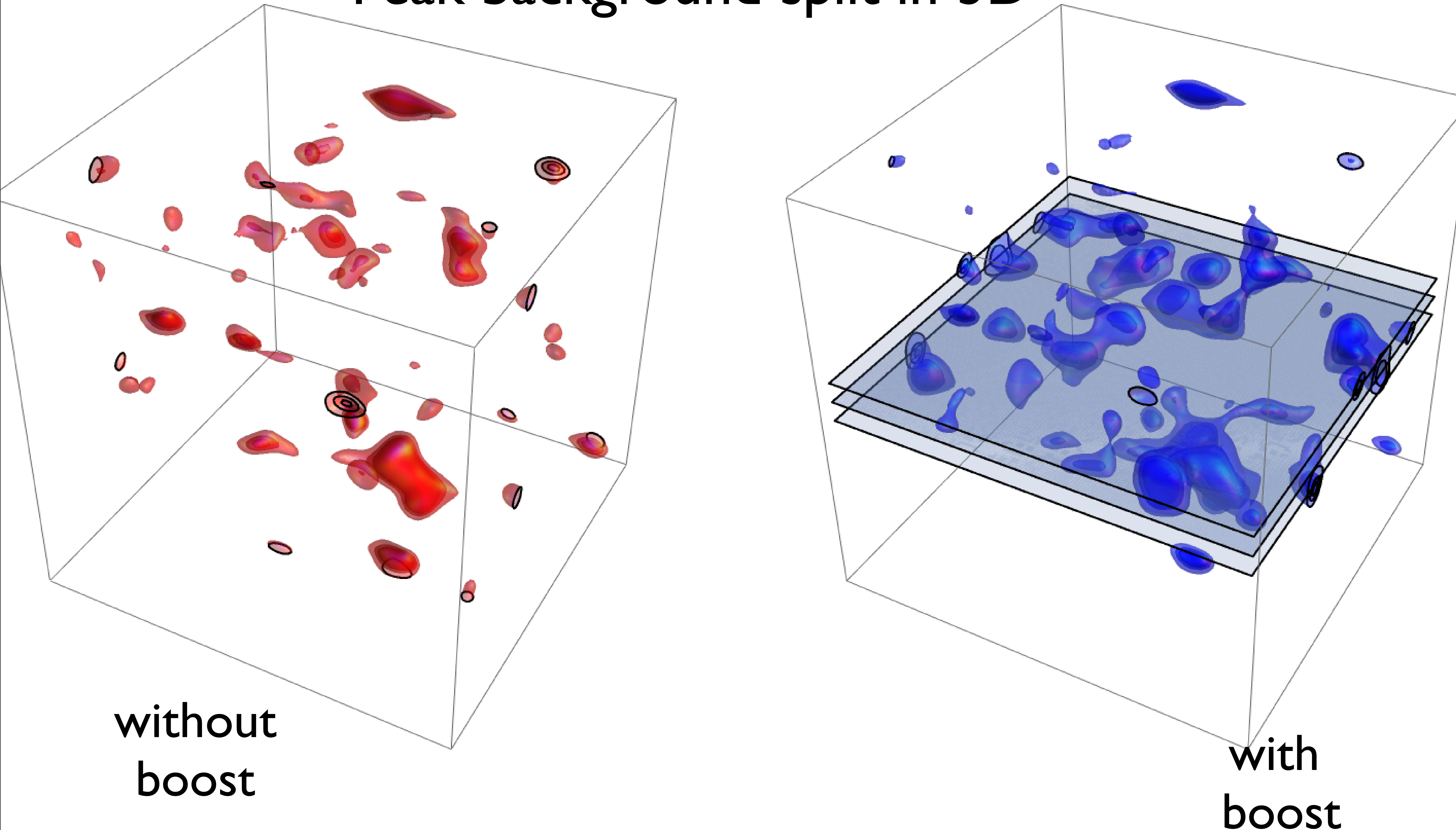
Peak background split in 1D



Peak background split in 2D

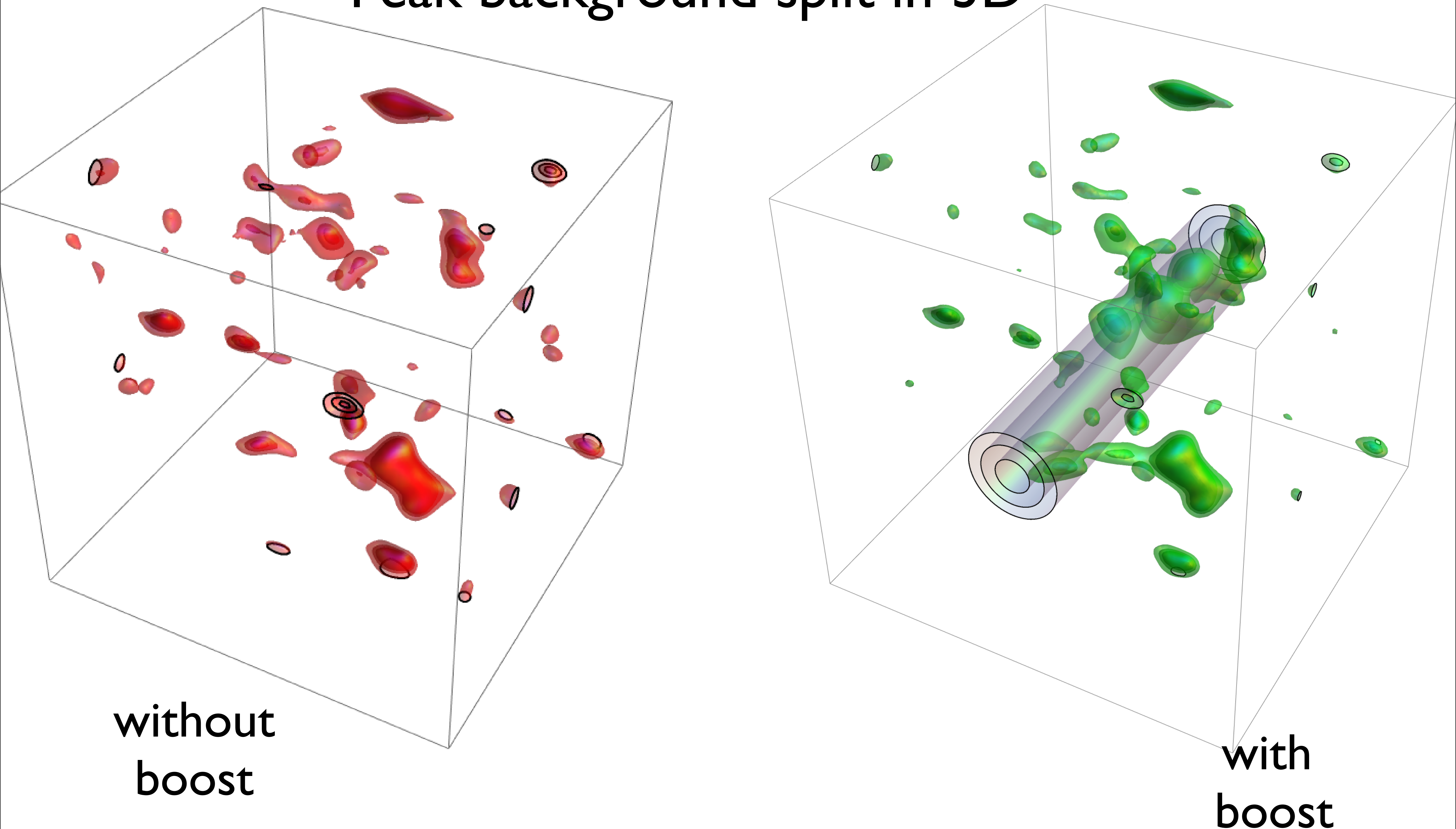


Peak background split in 3D



Does this anisotropic biassing have a dynamical signature? yes!

Peak background split in 3D



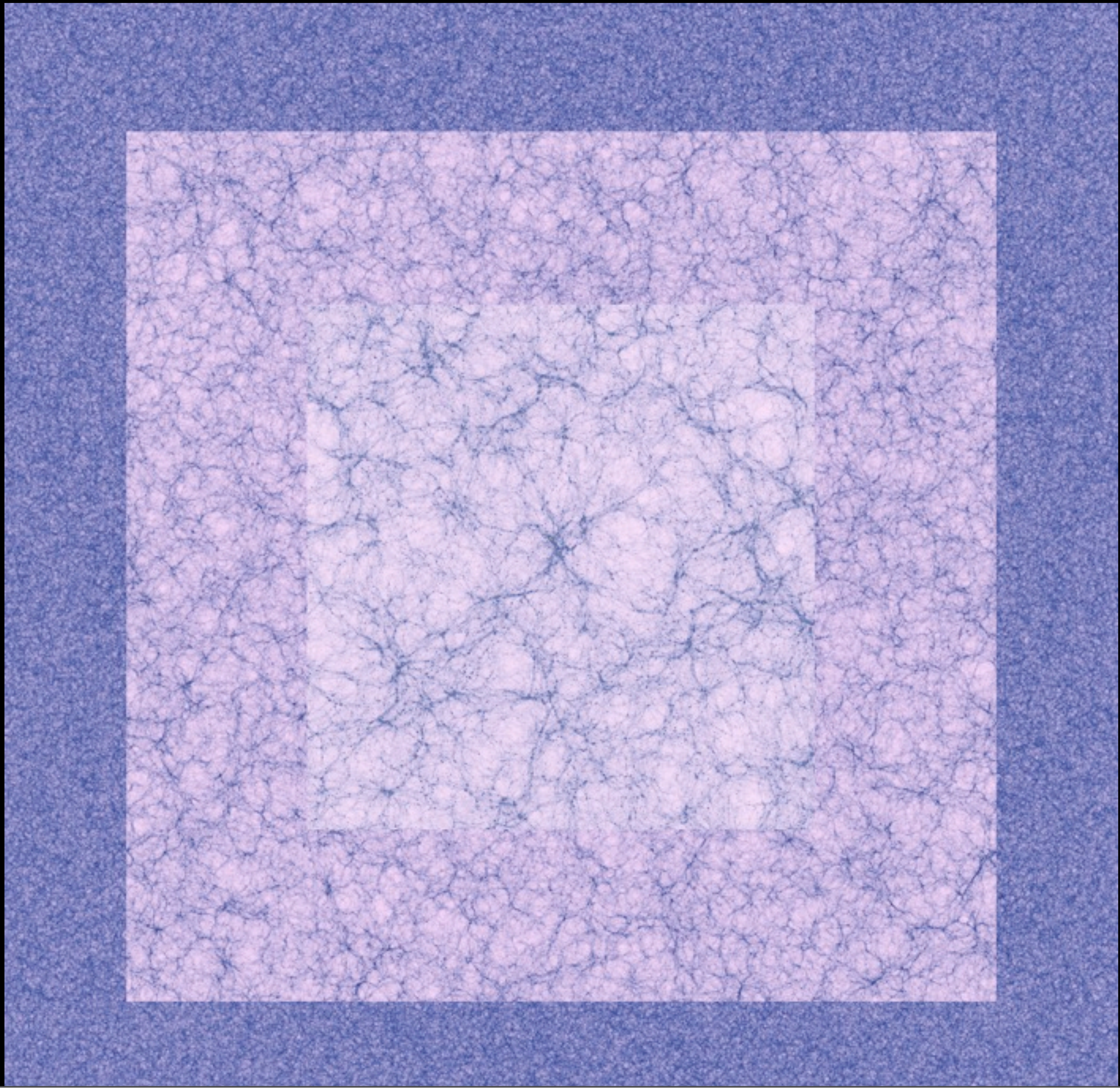
Does this anisotropic biassing have a dynamical signature? yes!

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)



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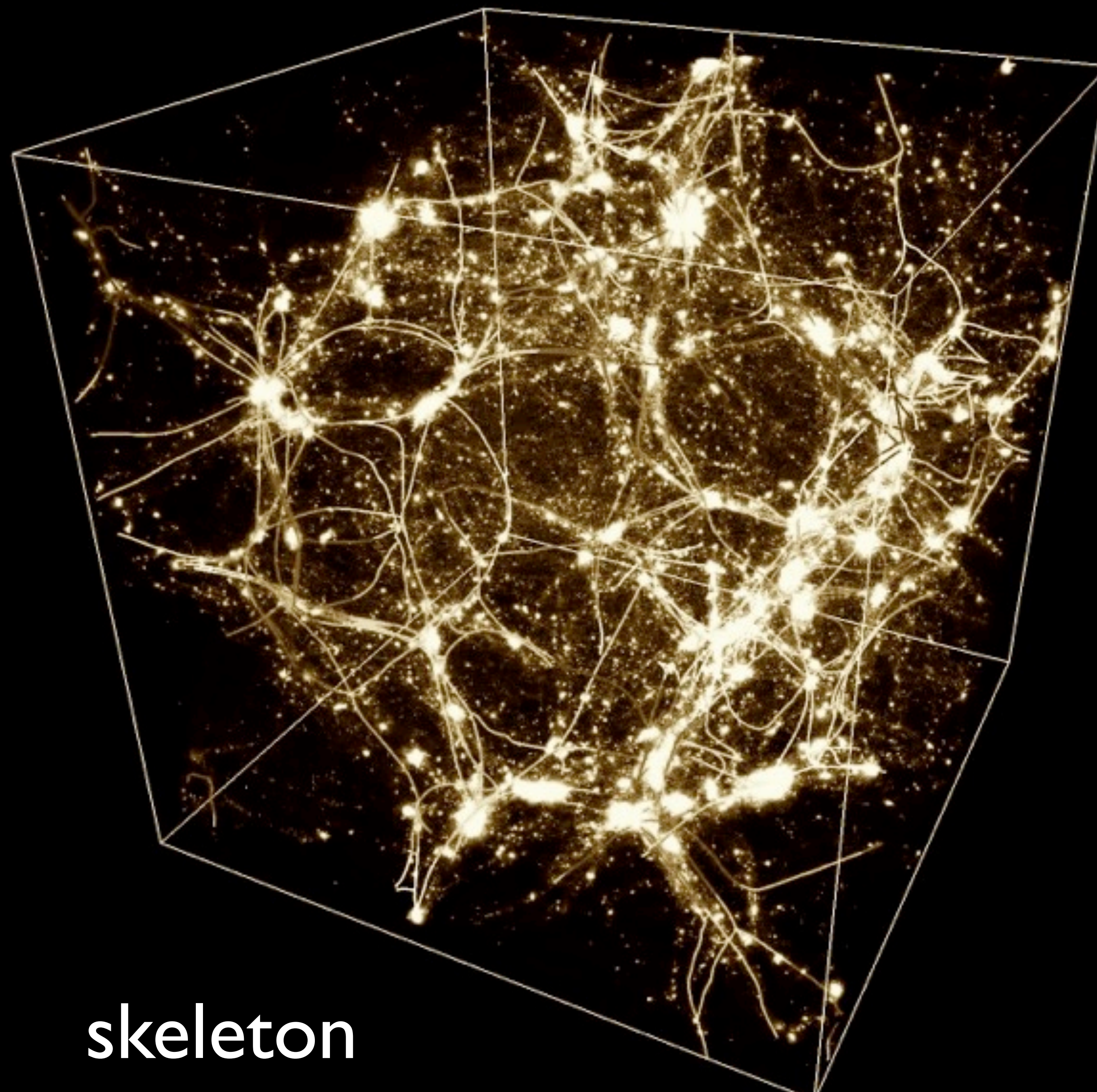

skeleton
follow filaments

Orientation of the spins w.r.t the filaments

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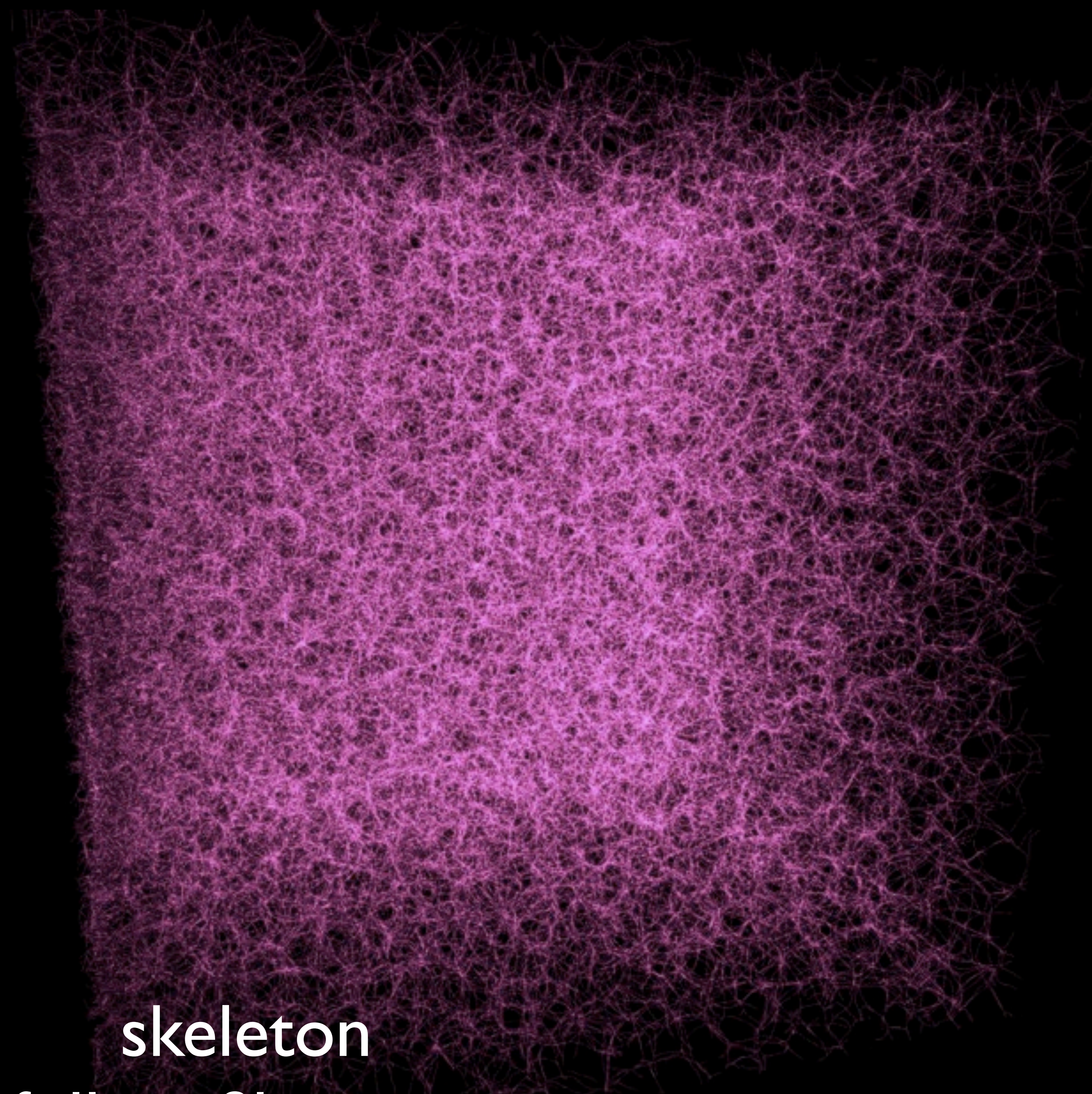


skeleton
follow filaments

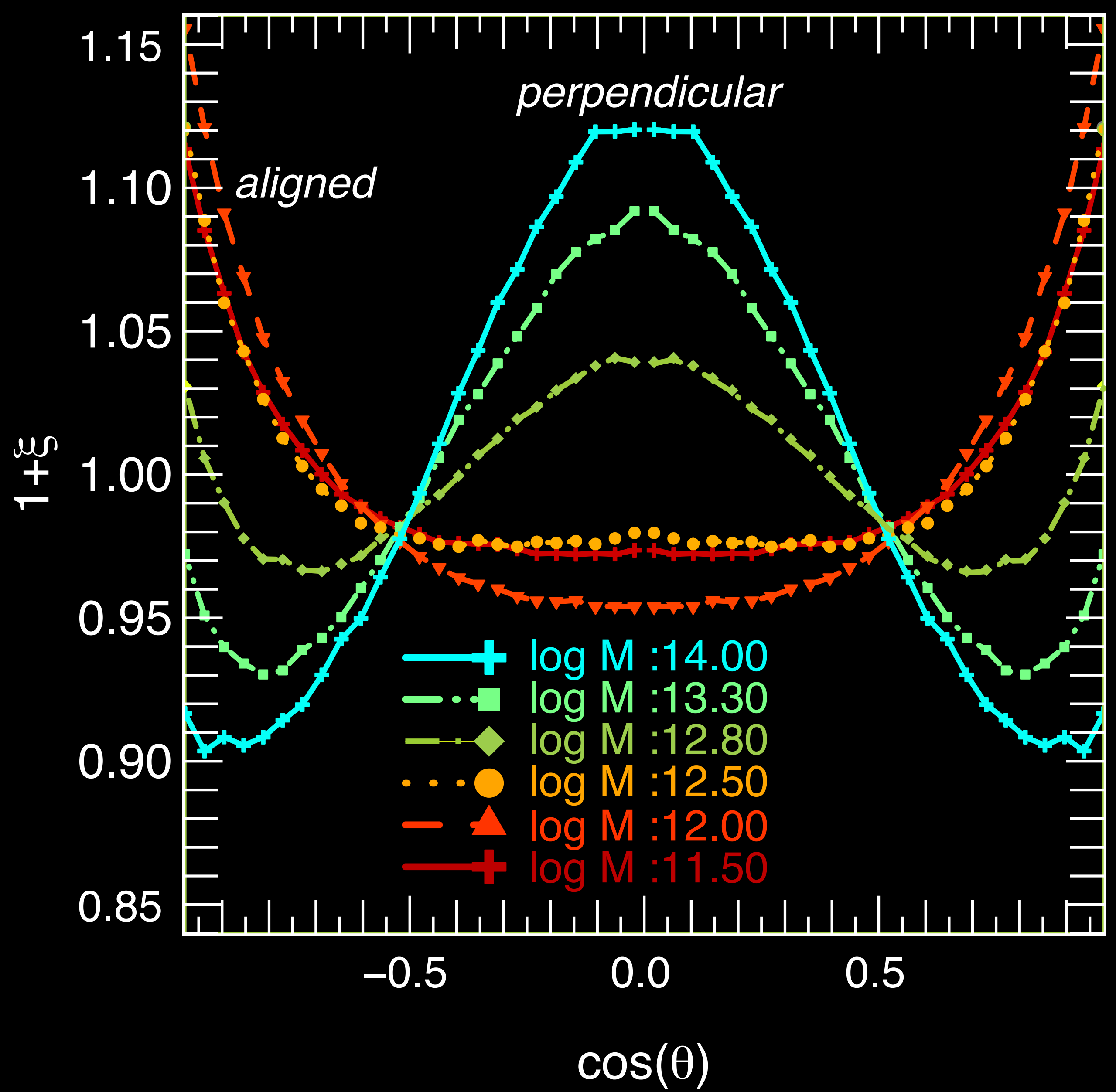
Excess probability of alignment between the spins and their host filament

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:

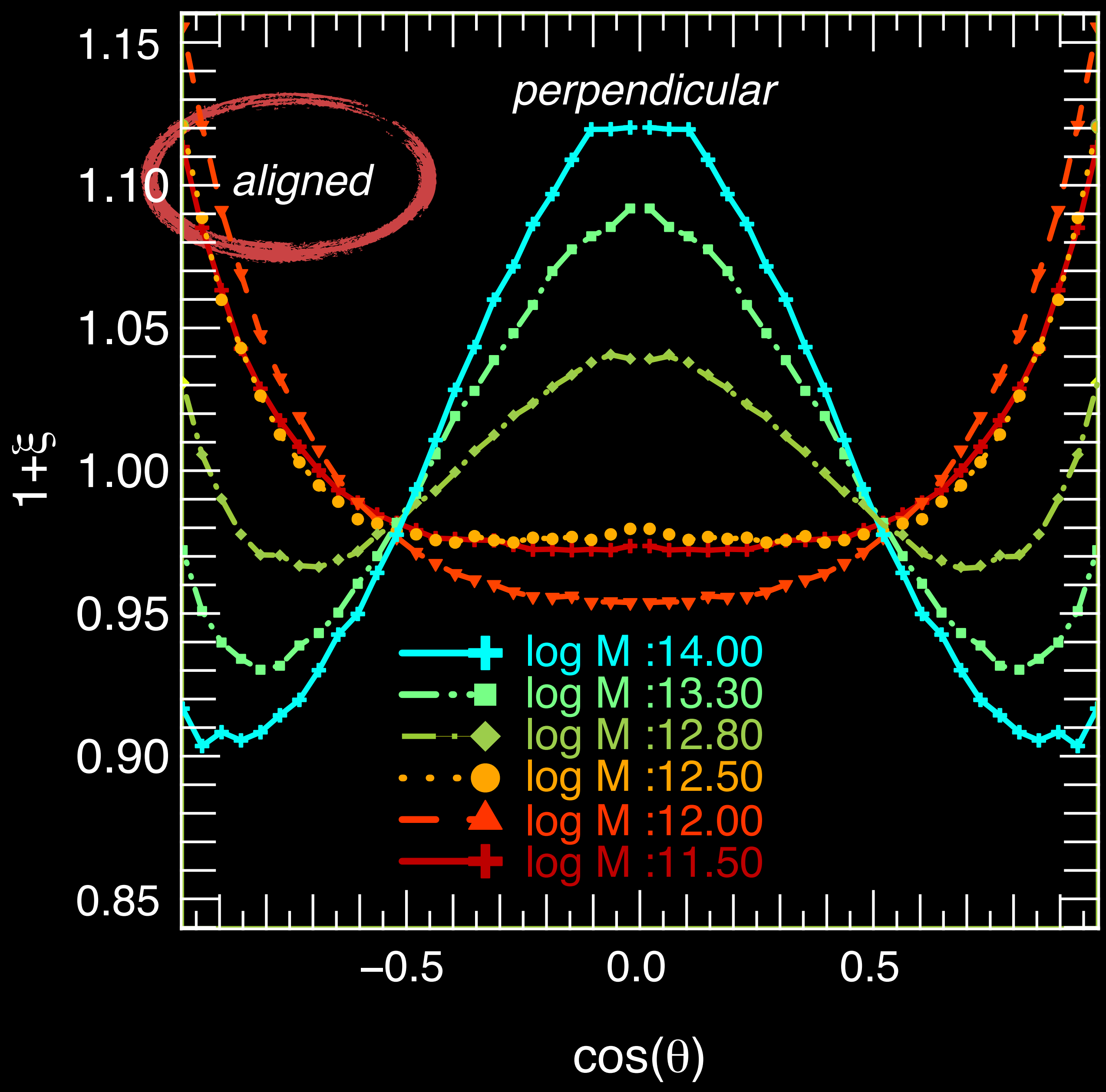
$$M_{\rm crit} = 4 \cdot 10^{12} M_{\odot}$$

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

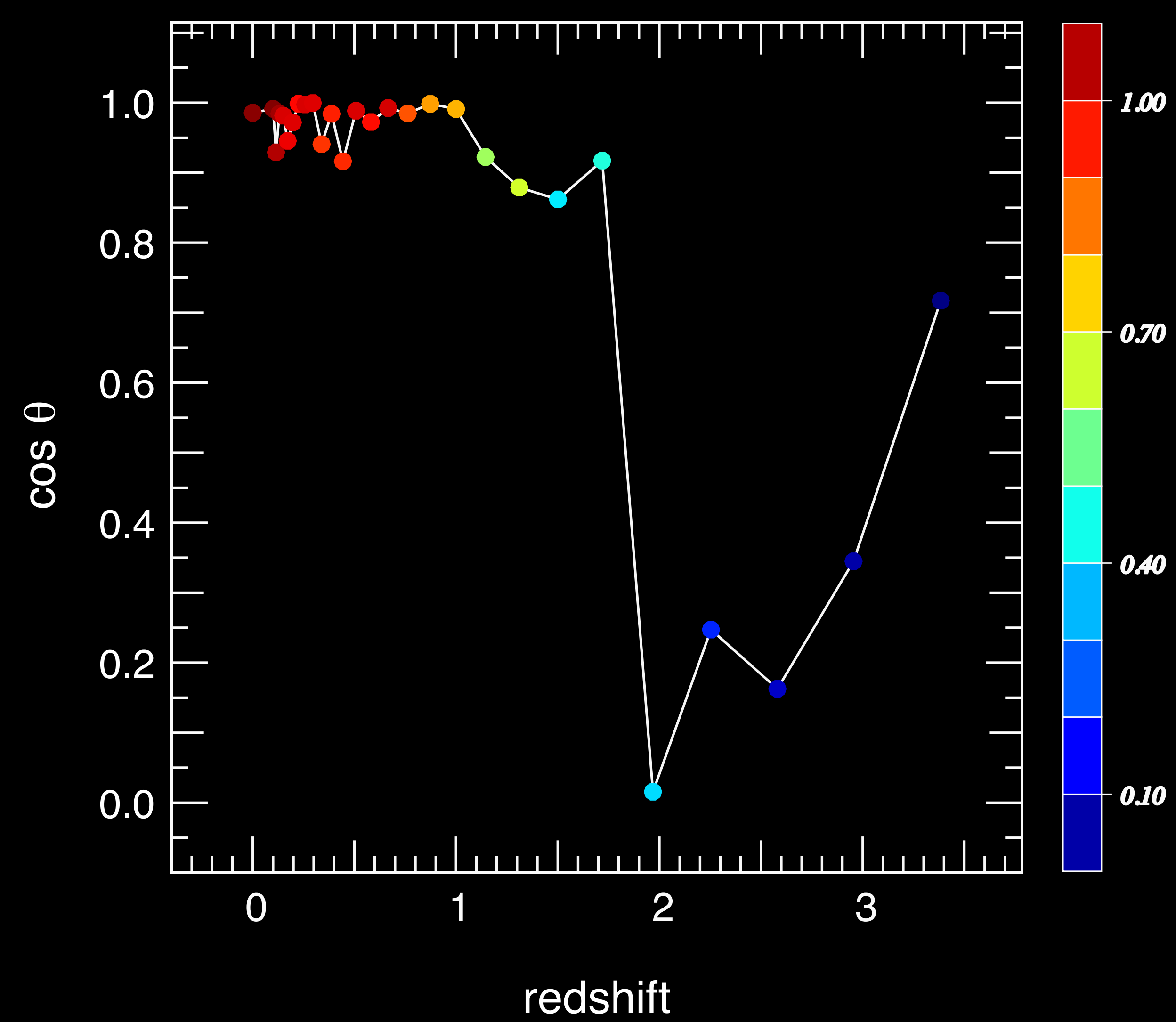


$$M_{\rm crit} = 4 \cdot 10^{12} M_\odot$$

mass transition:

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

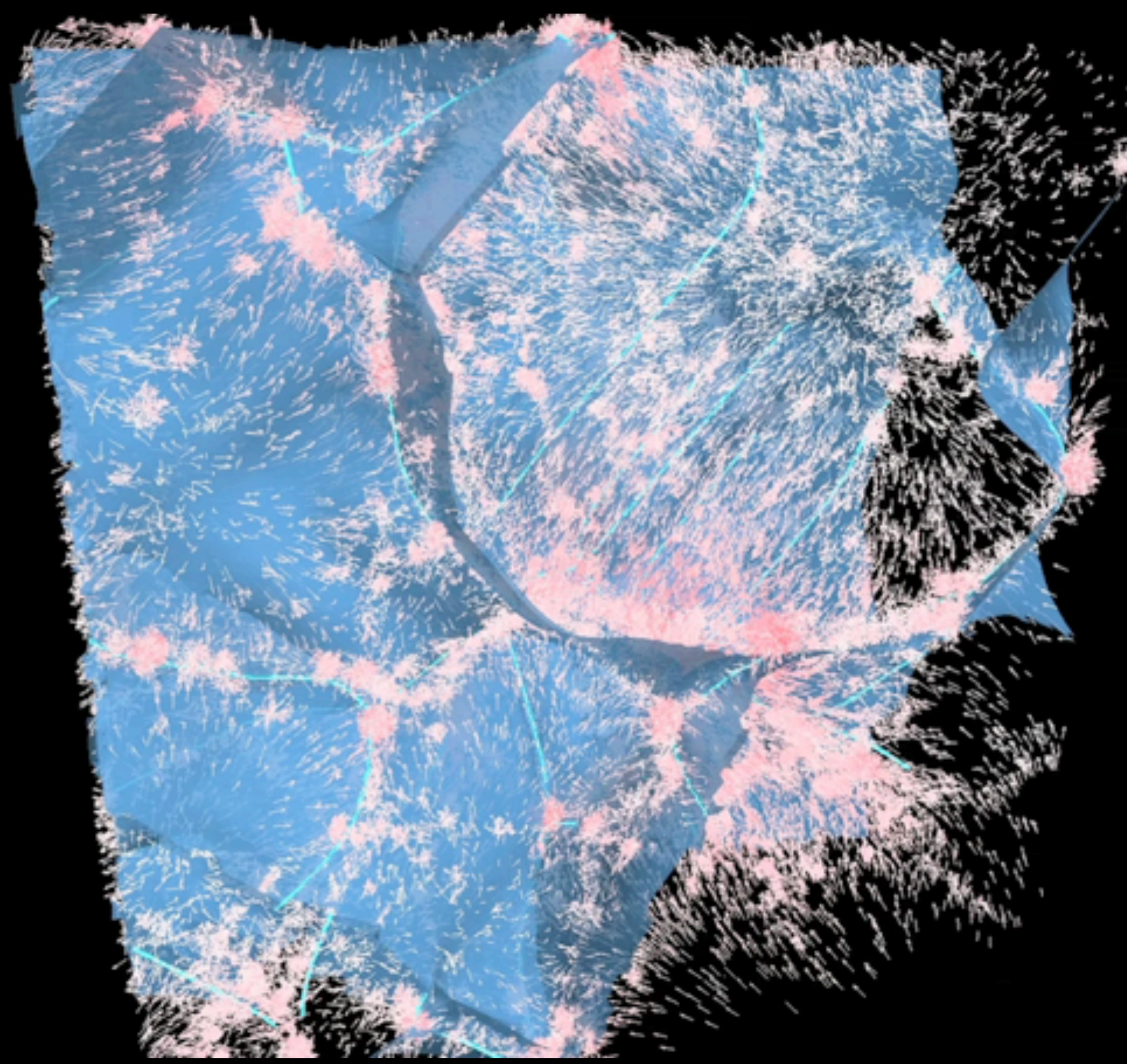
mass %



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

Voids/wall saddle repel...

winding of walls



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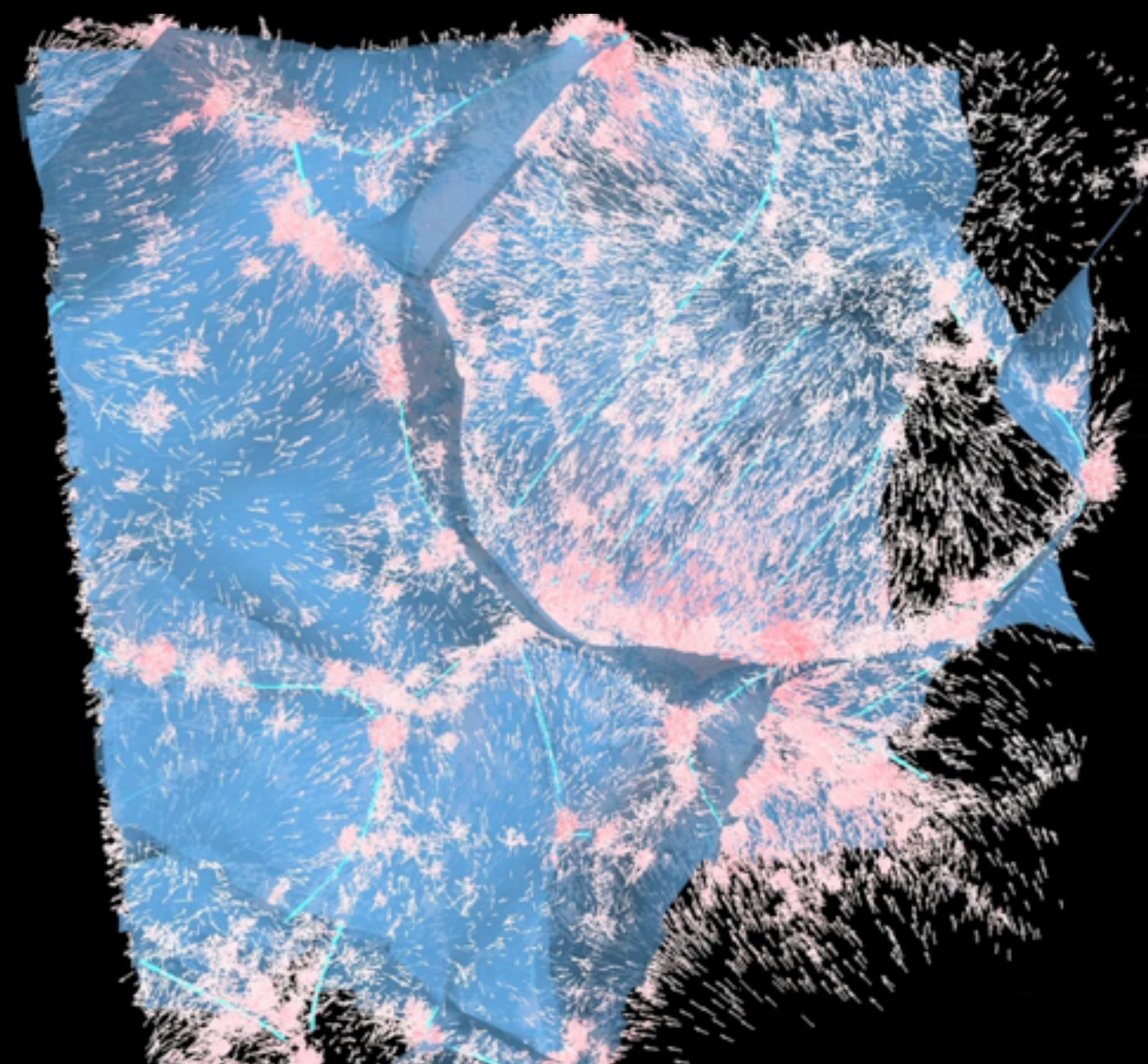

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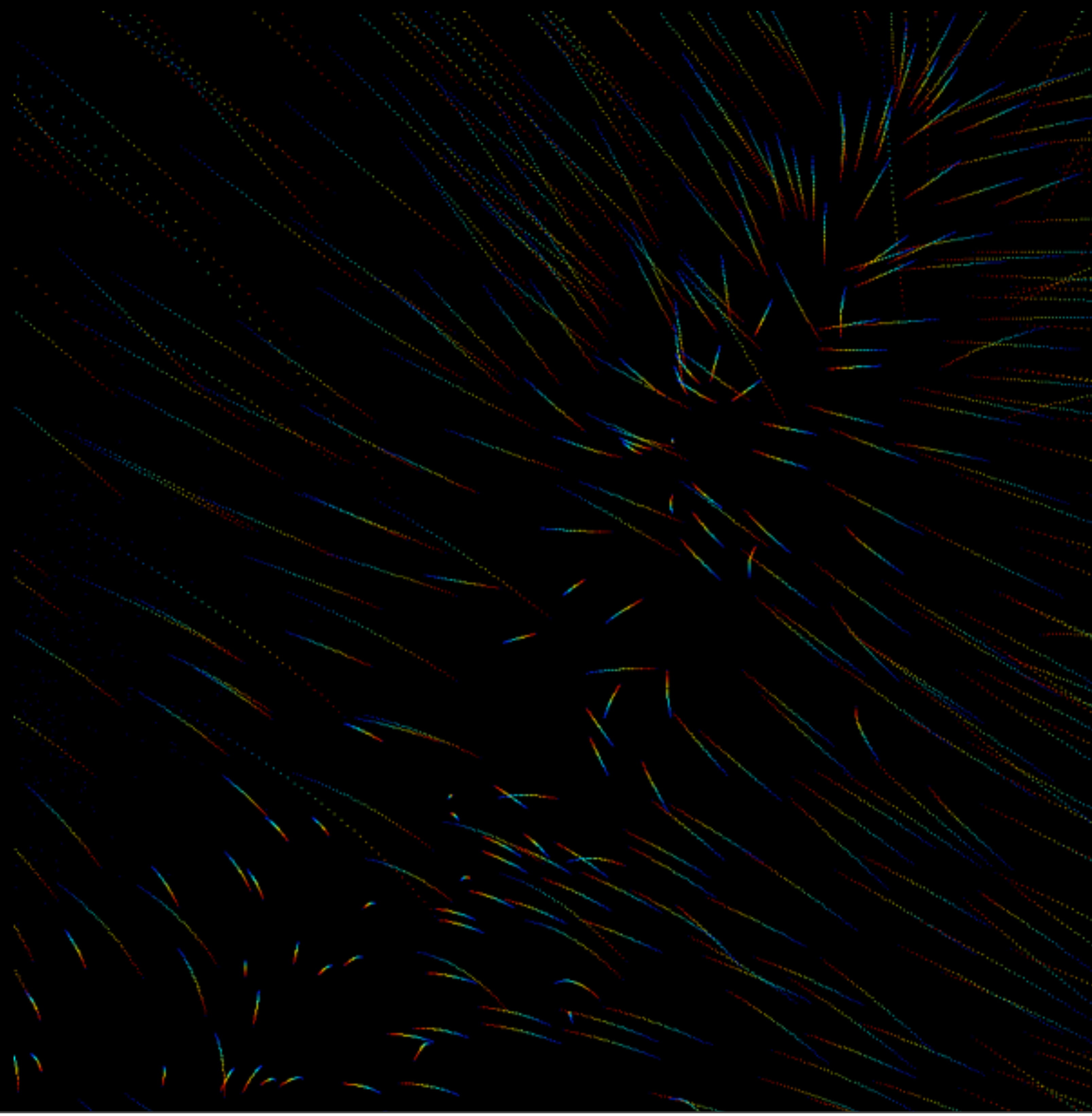
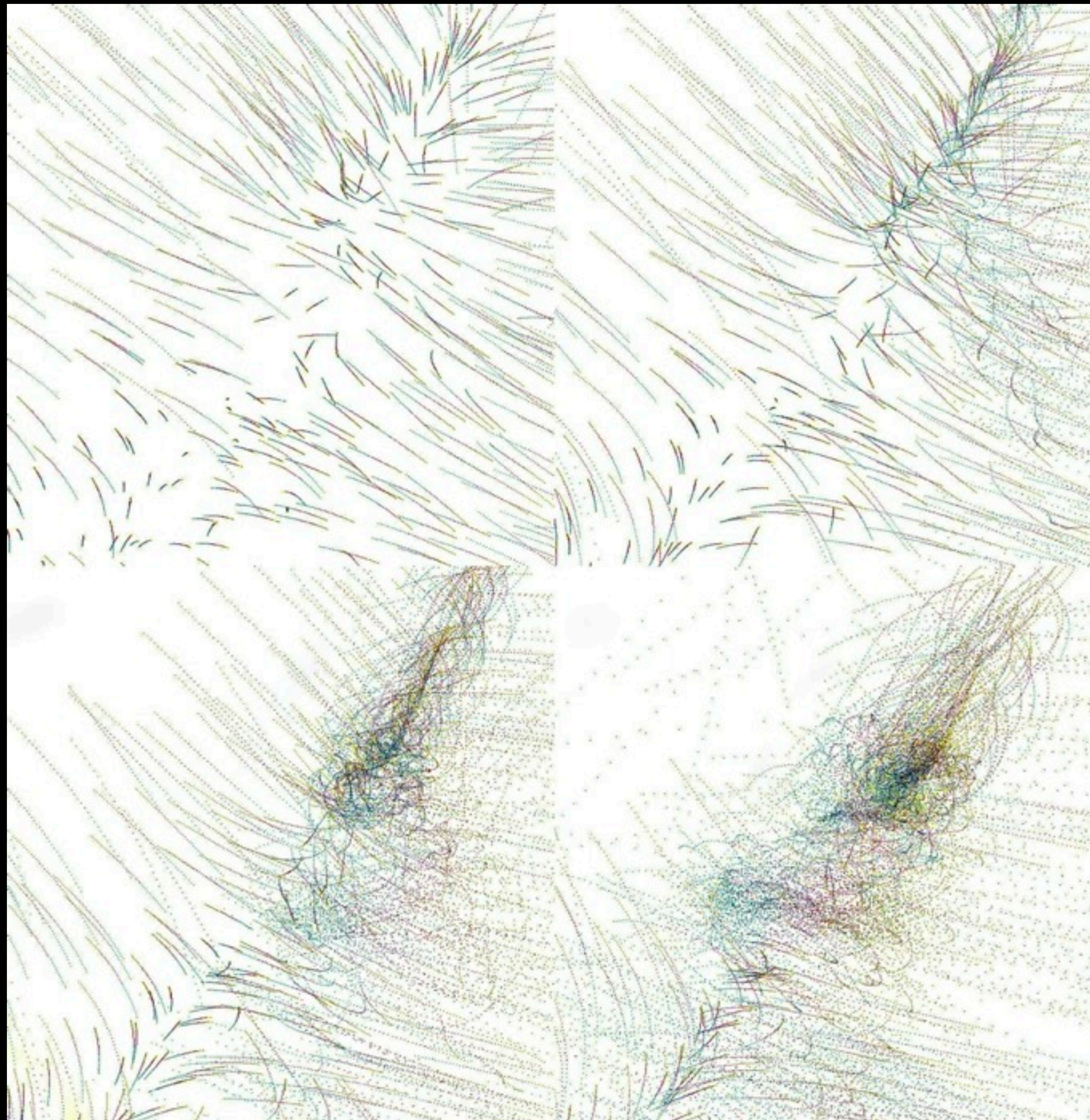


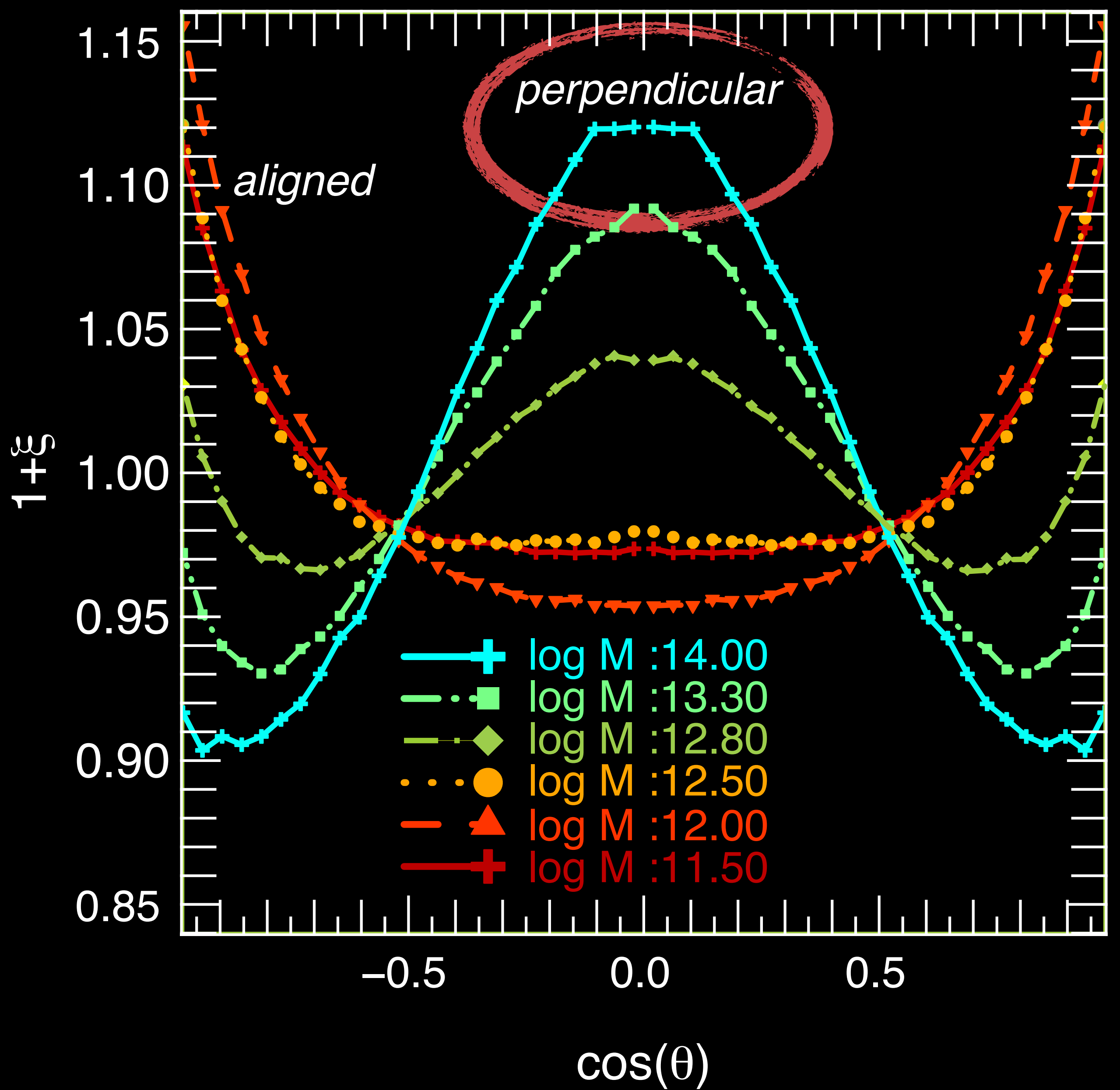
Winding of walls
onto filaments
generate spin
//
to filament

->

Vorticity?

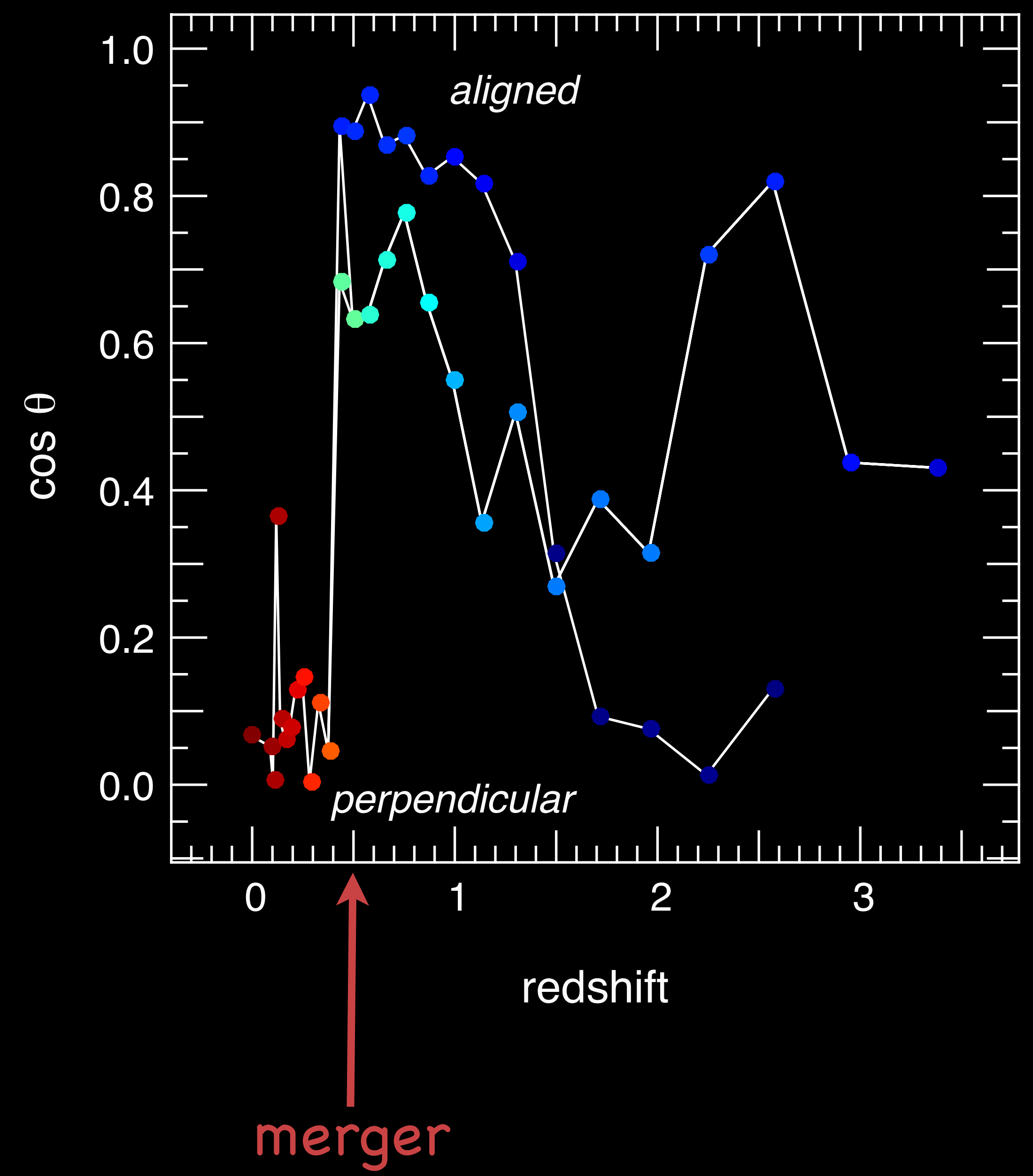


High-mass haloes: $M > M_{crit}$



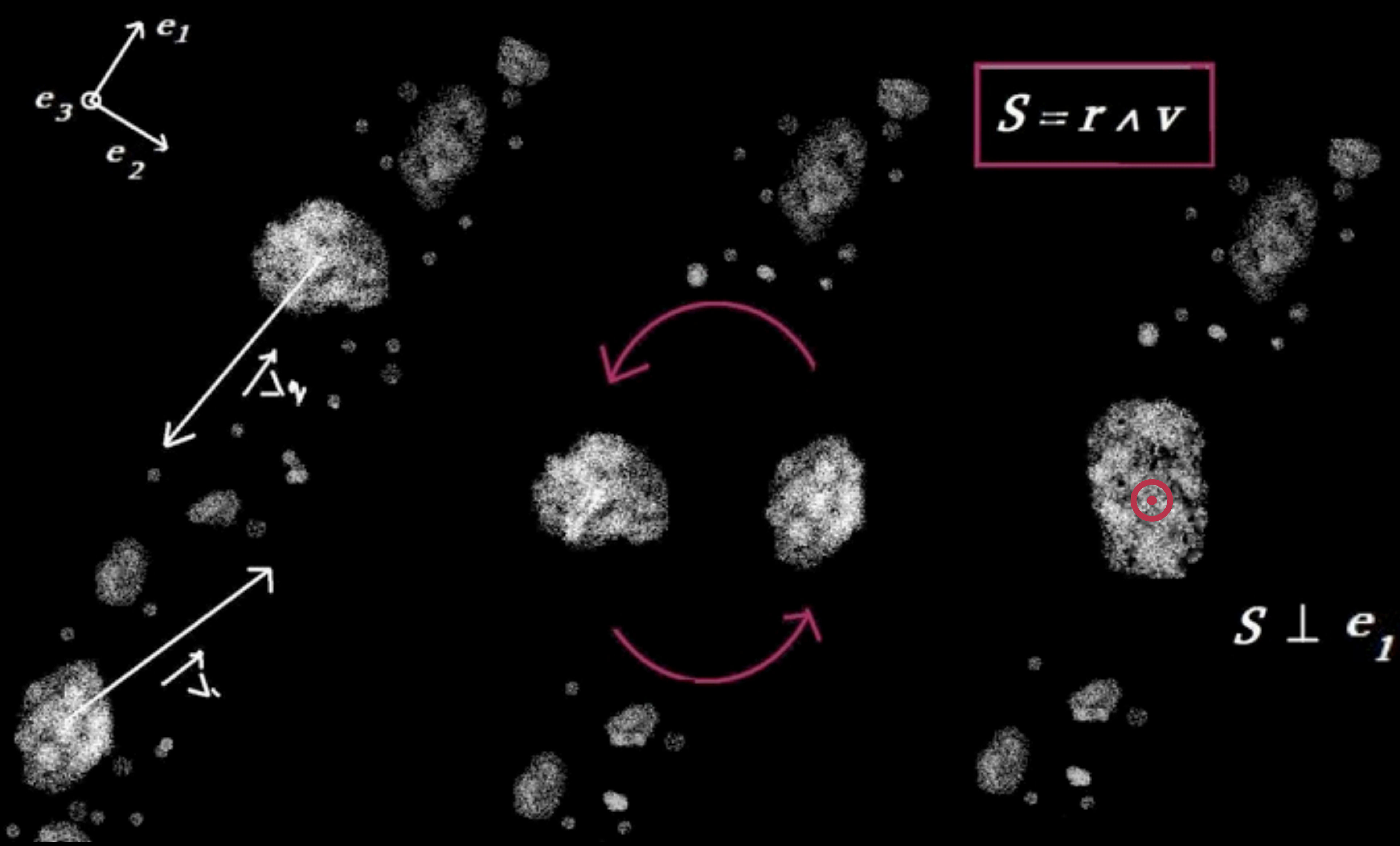
$$M_{crit} = 4 \cdot 10^{12} M_{\odot}$$

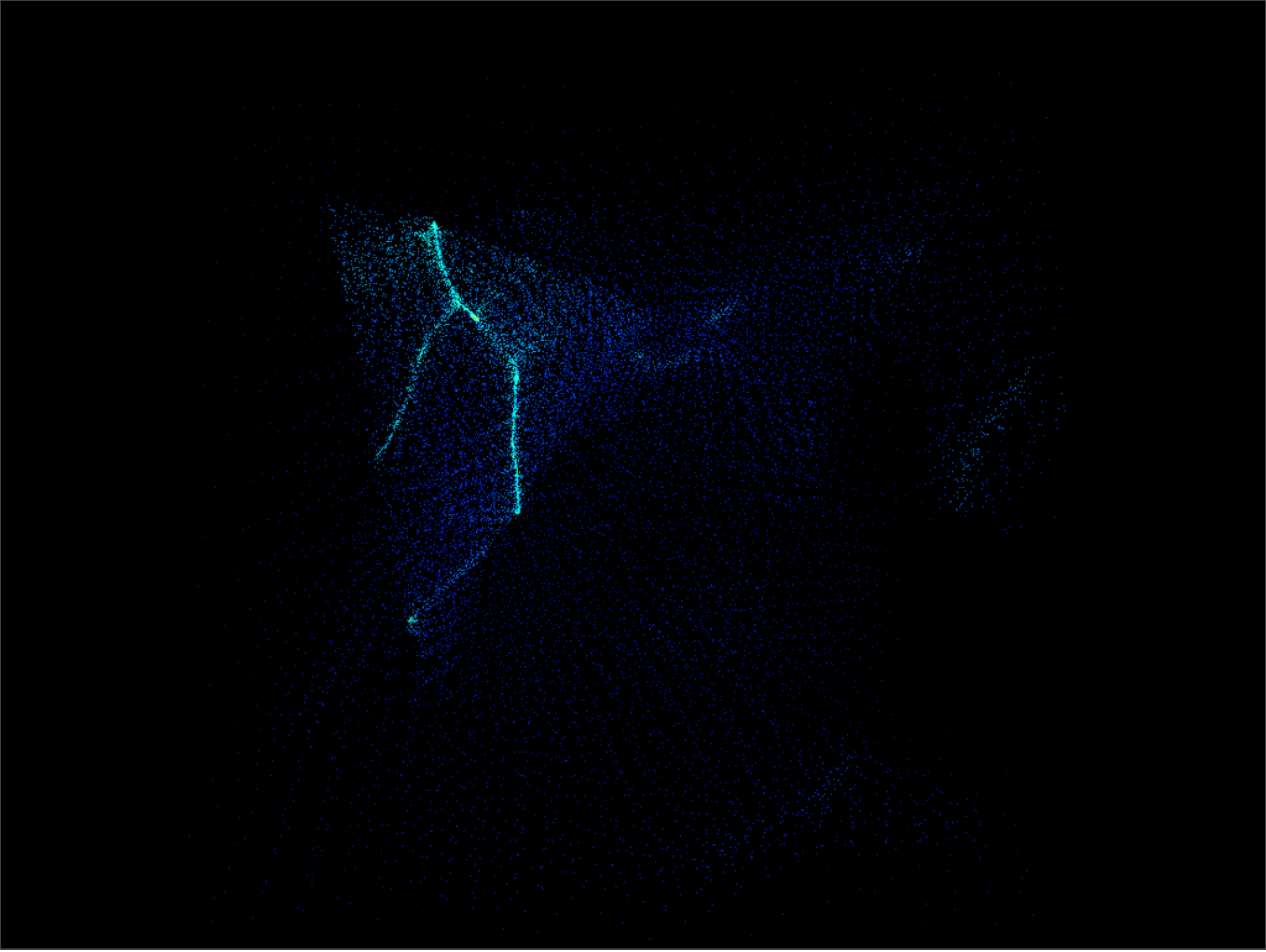
formed at low z by mergers inside the filaments



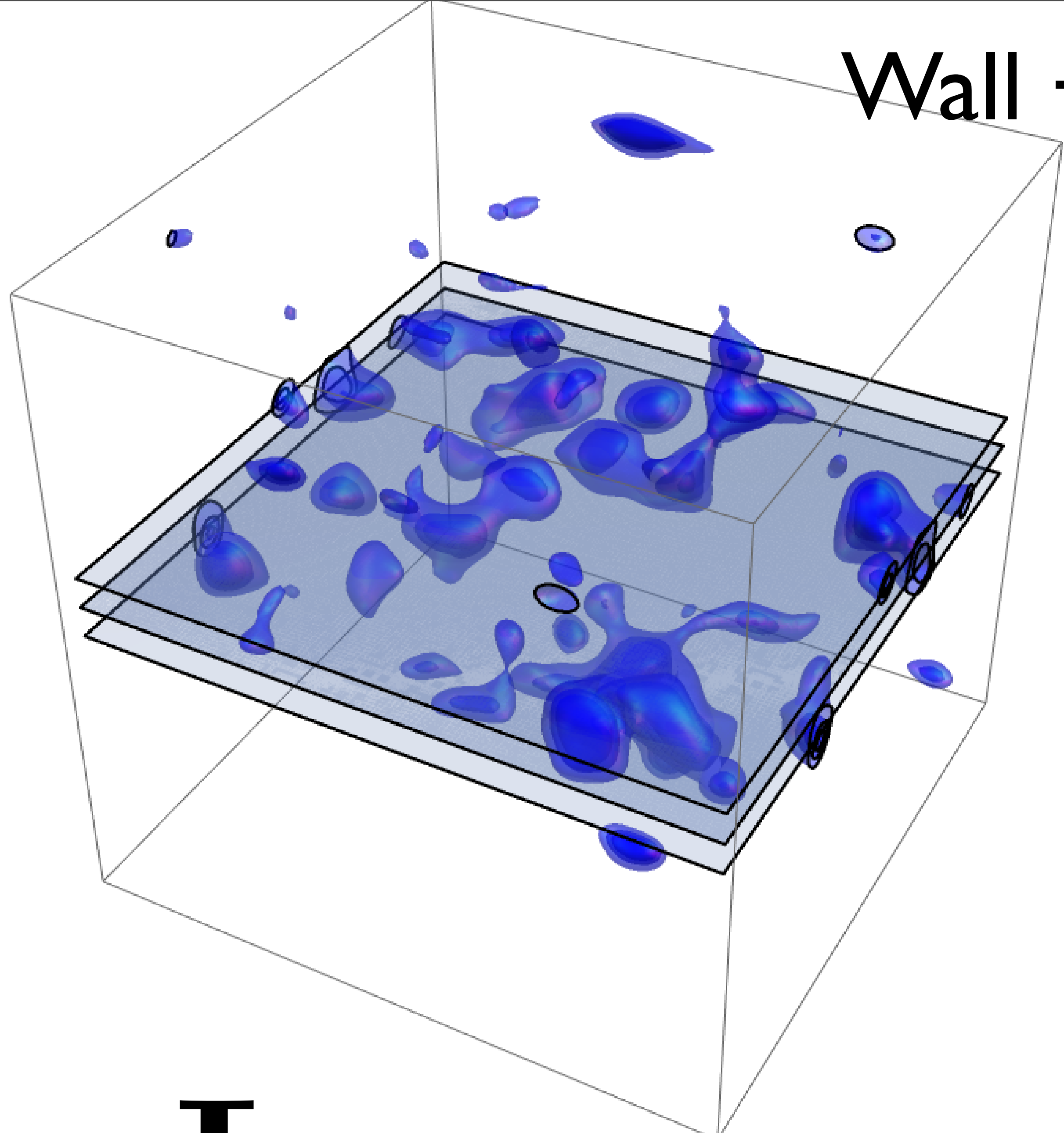
How do mergers along the filaments create spin perpendicular to them?

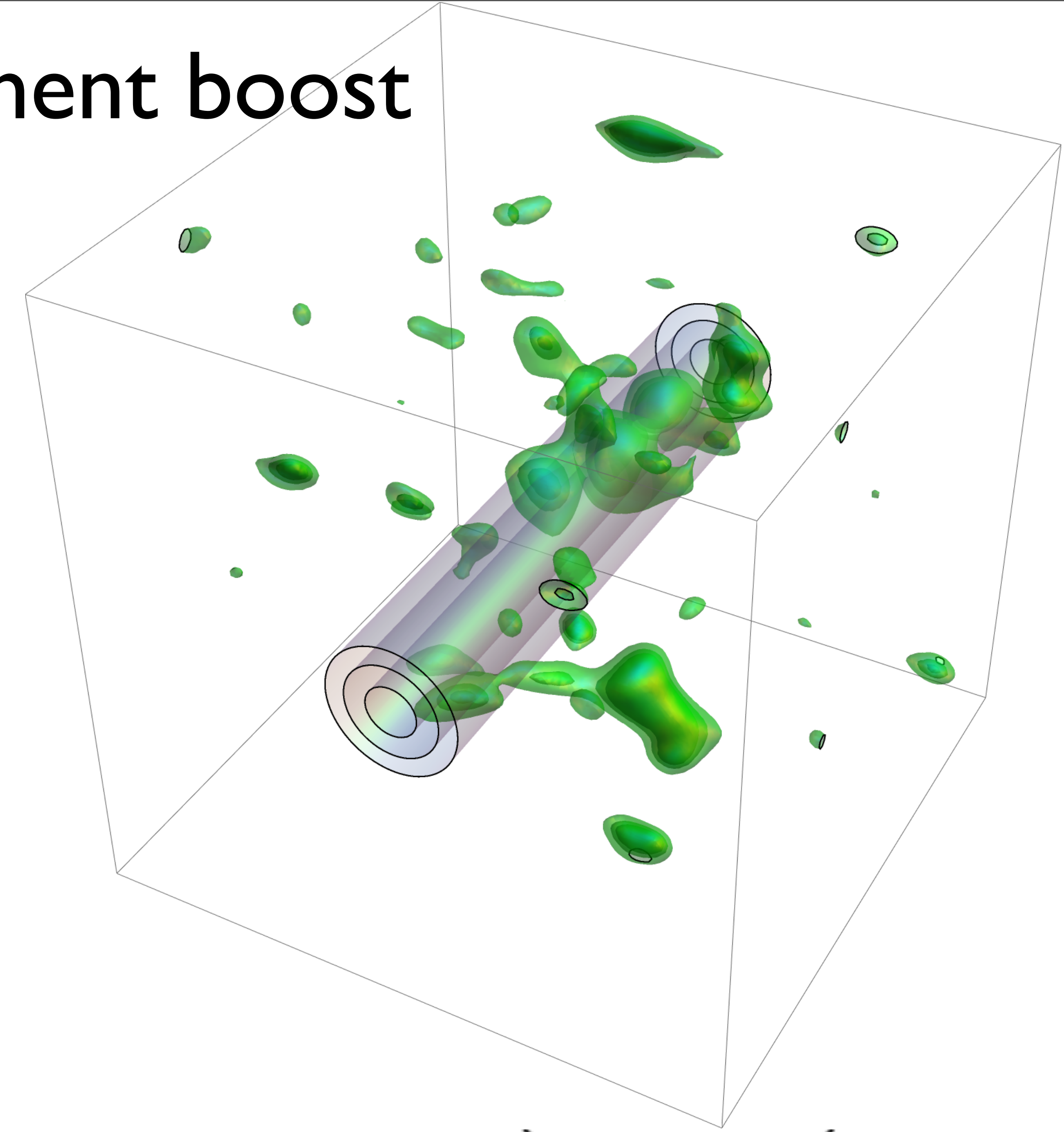
halos catch up with each other along the filaments





Wall + filament boost

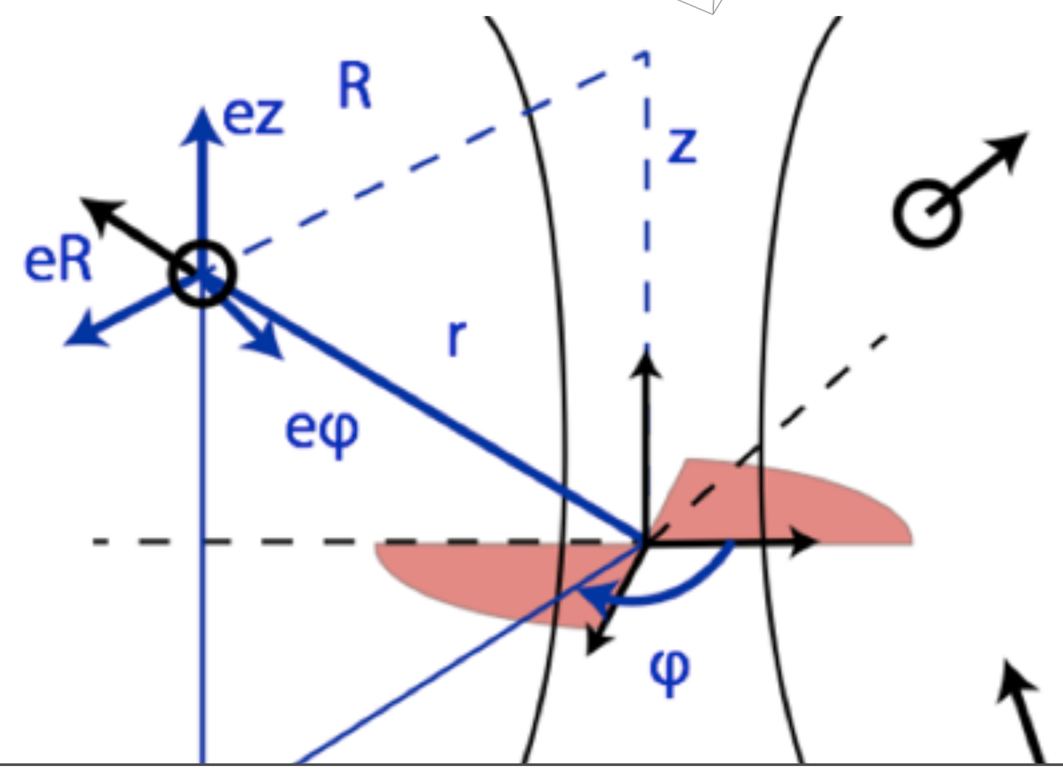




$$\mathbf{L} = \mathbf{r} \times \mathbf{v}$$

If pancake $\ni$ filament

$\longrightarrow$ mergers along e_ϕ



- 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

Swirling around filaments:

Are large-scale structure spinning up low mass halos?

Vorticity of cosmic flow

$$\omega = \nabla \times \mathbf{v}$$

The Eulerian view of spin/LSS connection

La nuit étoilée, Van Gogh, 1989

Part III Outline

- Where is the vorticity/helicity ?
- How is it distributed across a filament?
- What does it do to the spin low mass galaxies ?
- What is its relation to the transition mass ?

The Eulerian view of spin/LSS connection

Problematic

Why is the spin of low mass **halos preferentially aligned with cosmic web ?**

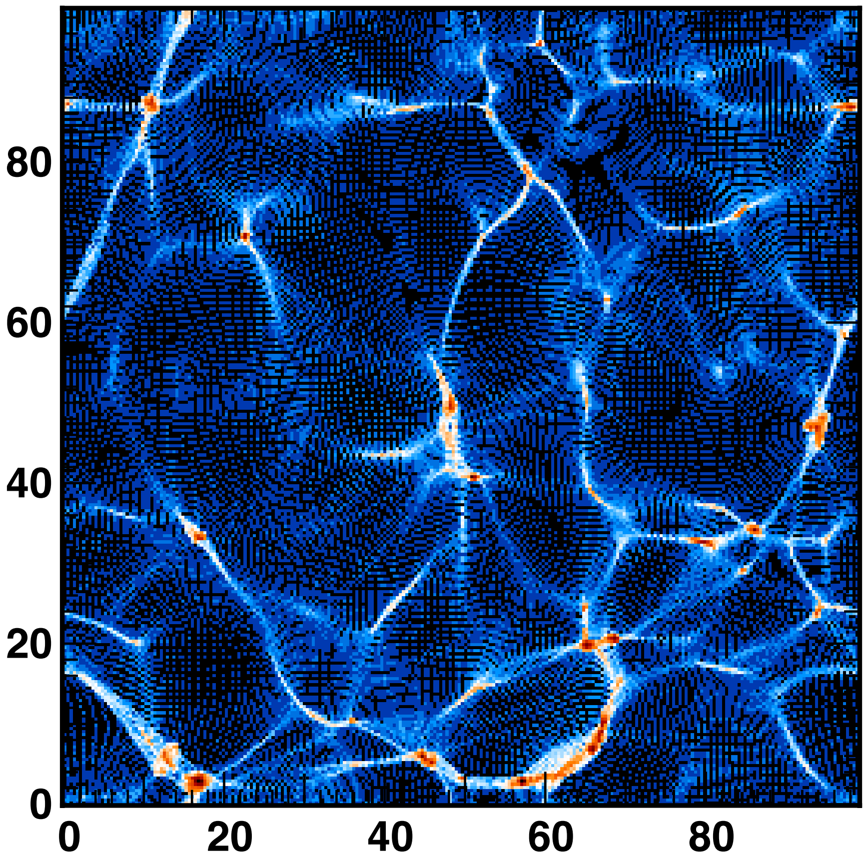
Strategy

- Identify the geometric locus of vorticity & its alignment with cosmic web.
- Understand vorticity generation within cosmic web.
- Study alignment of vorticity & spin of halos.

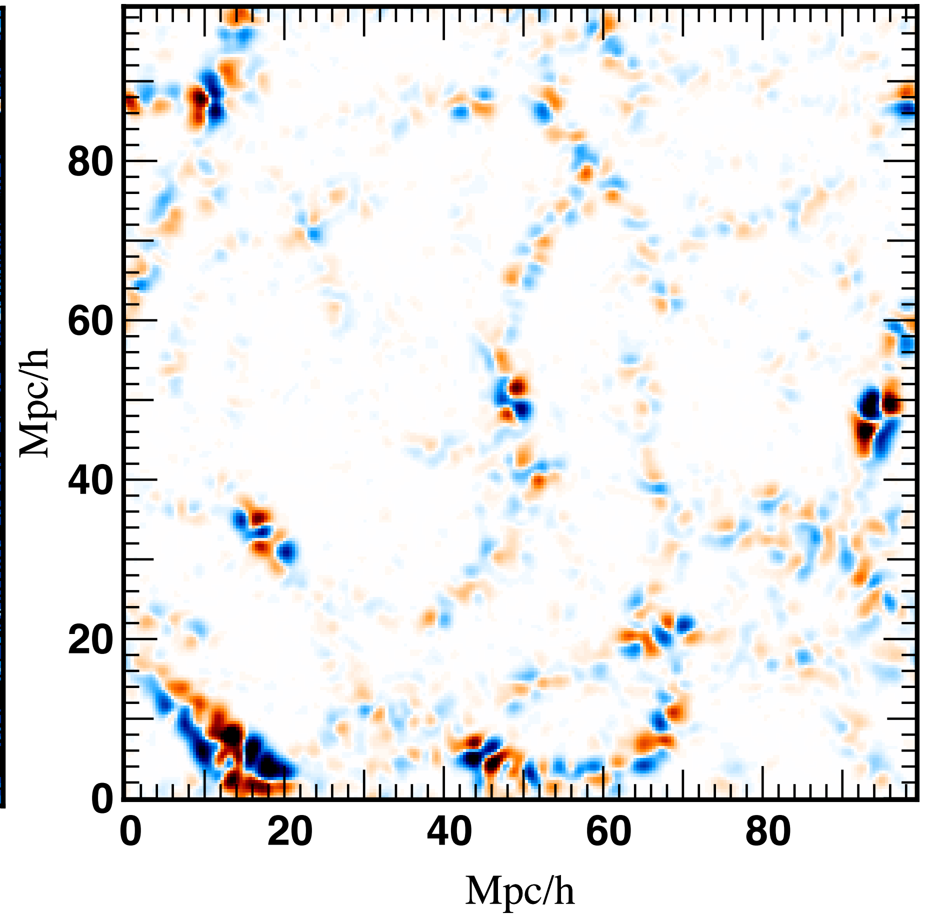
indeed

- In the perfect fluid approximation, on large scales, flow is laminar without vorticity.
- Vorticity is generated when the stress tensor becomes non zero during shell crossing.

Locus of vorticity



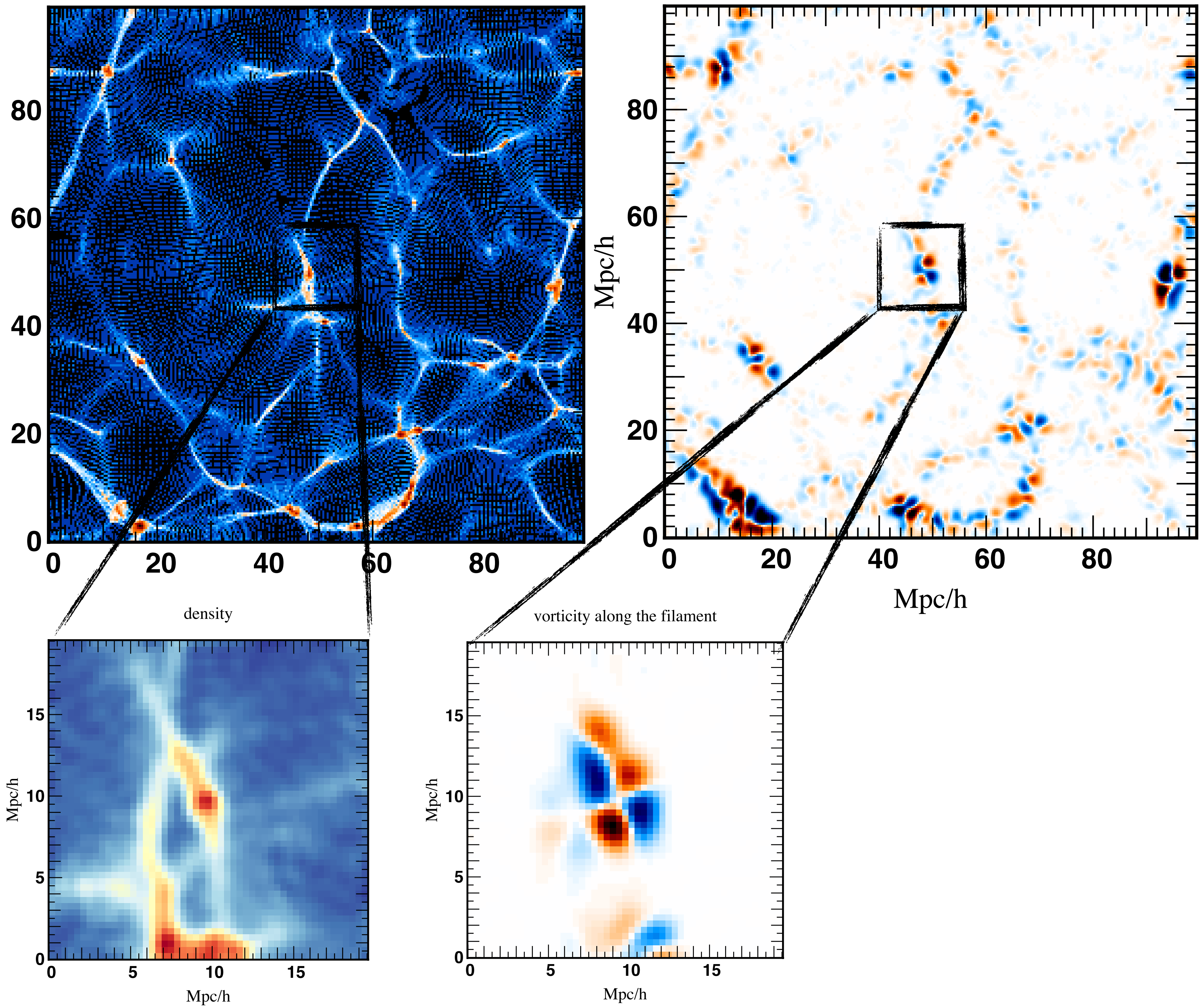
Density



Vorticity

Density & vorticity slice in a DM simulation.

Locus of vorticity

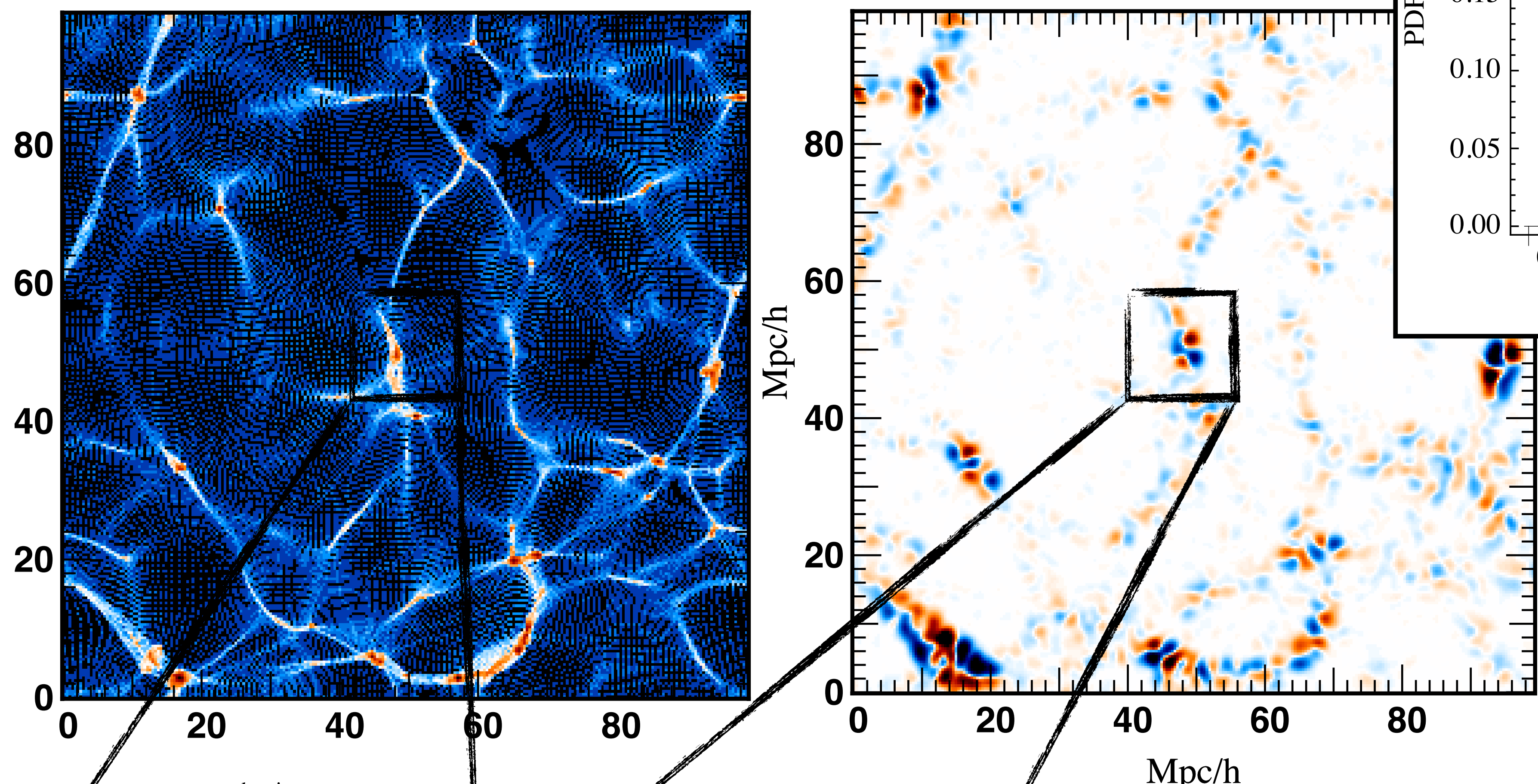


density

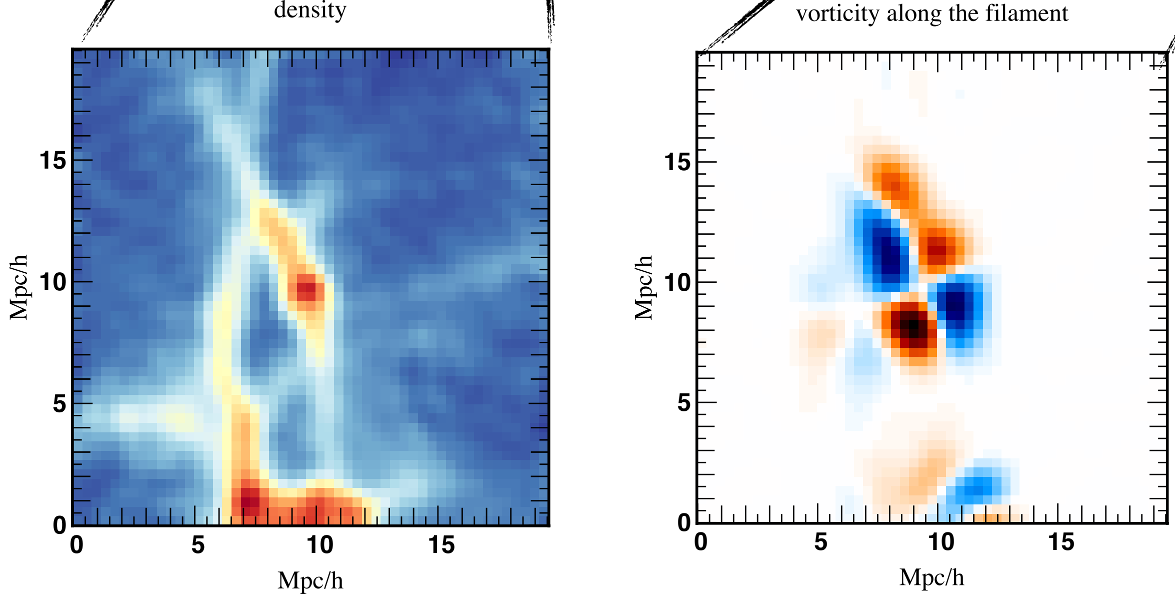
vorticity

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

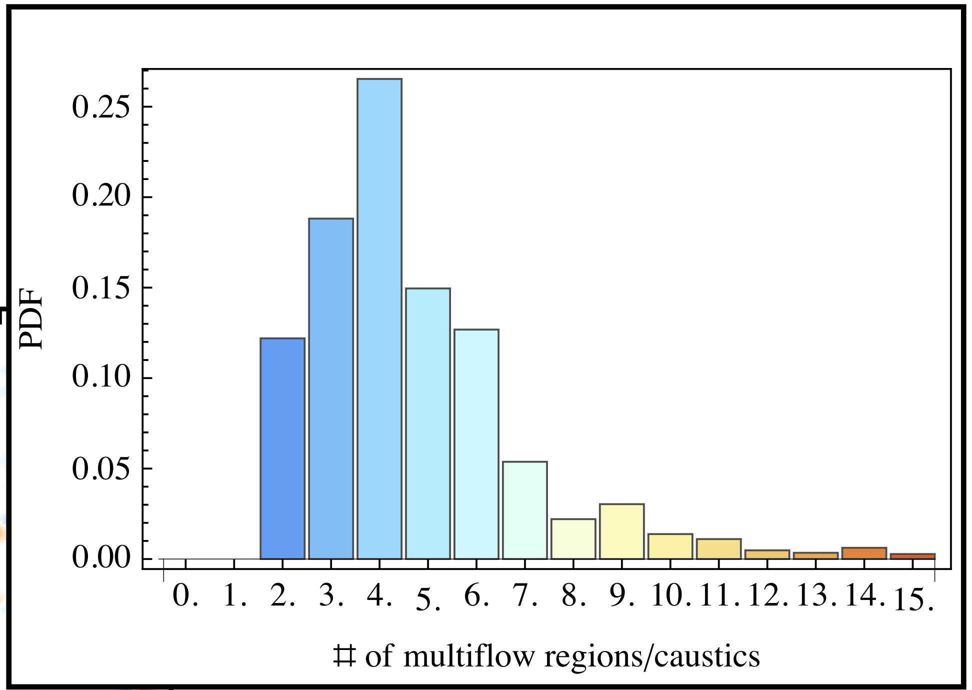
Locus of vorticity



density

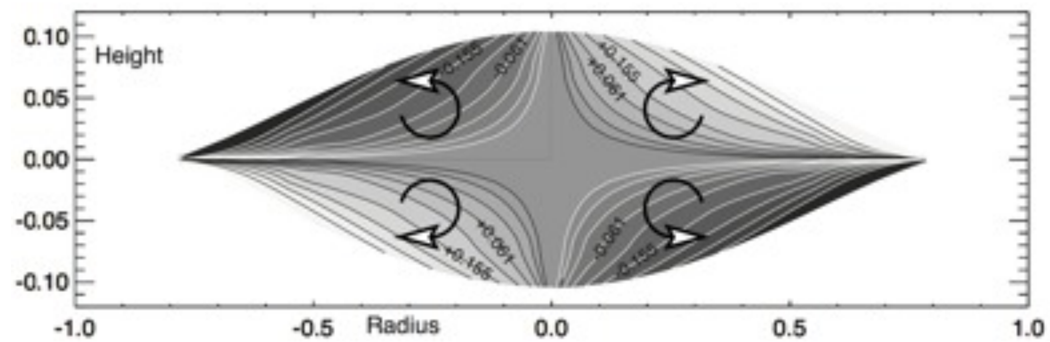


vorticity

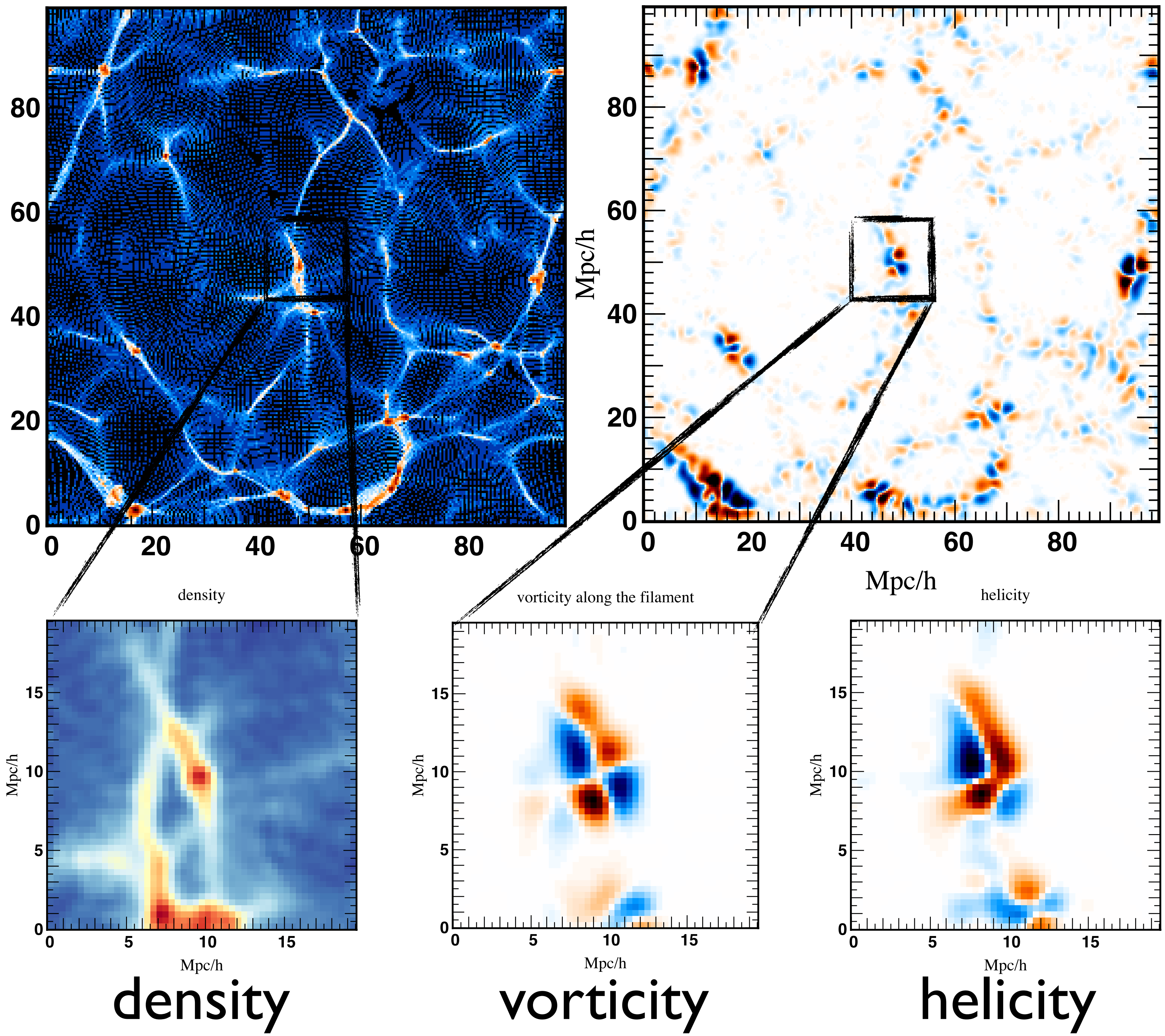


- ✴ vorticity is confined to filaments.
- ✴ Vorticity is aligned with filament

✴caustics are ~ quadripolar



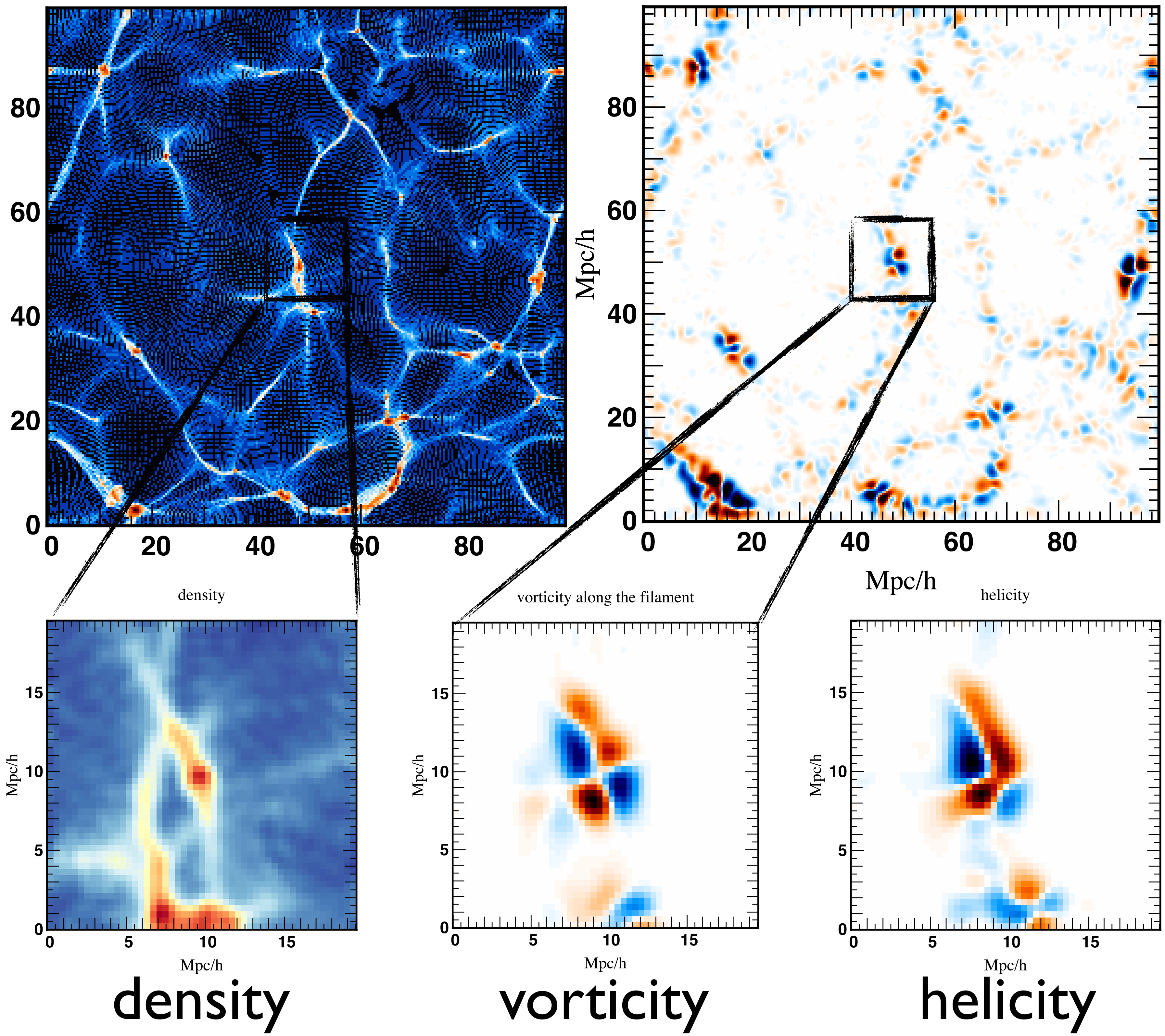
Locus of vorticity



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

- In the filament, **velocity** is along the filament (**helicity**).

Locus of vorticity

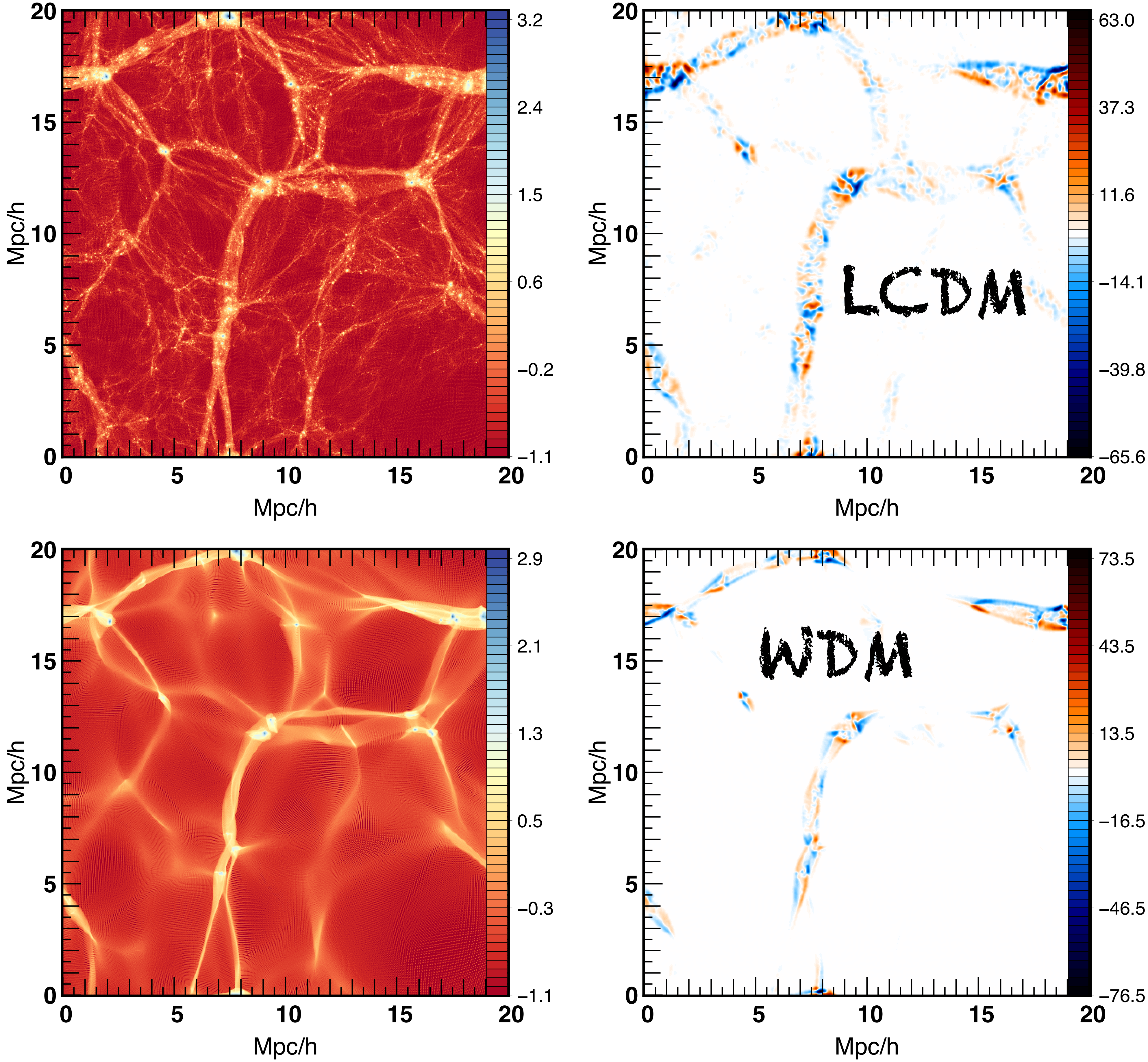


- ✴ vorticity is confined to filaments.
- ✴ Vorticity is aligned with filament

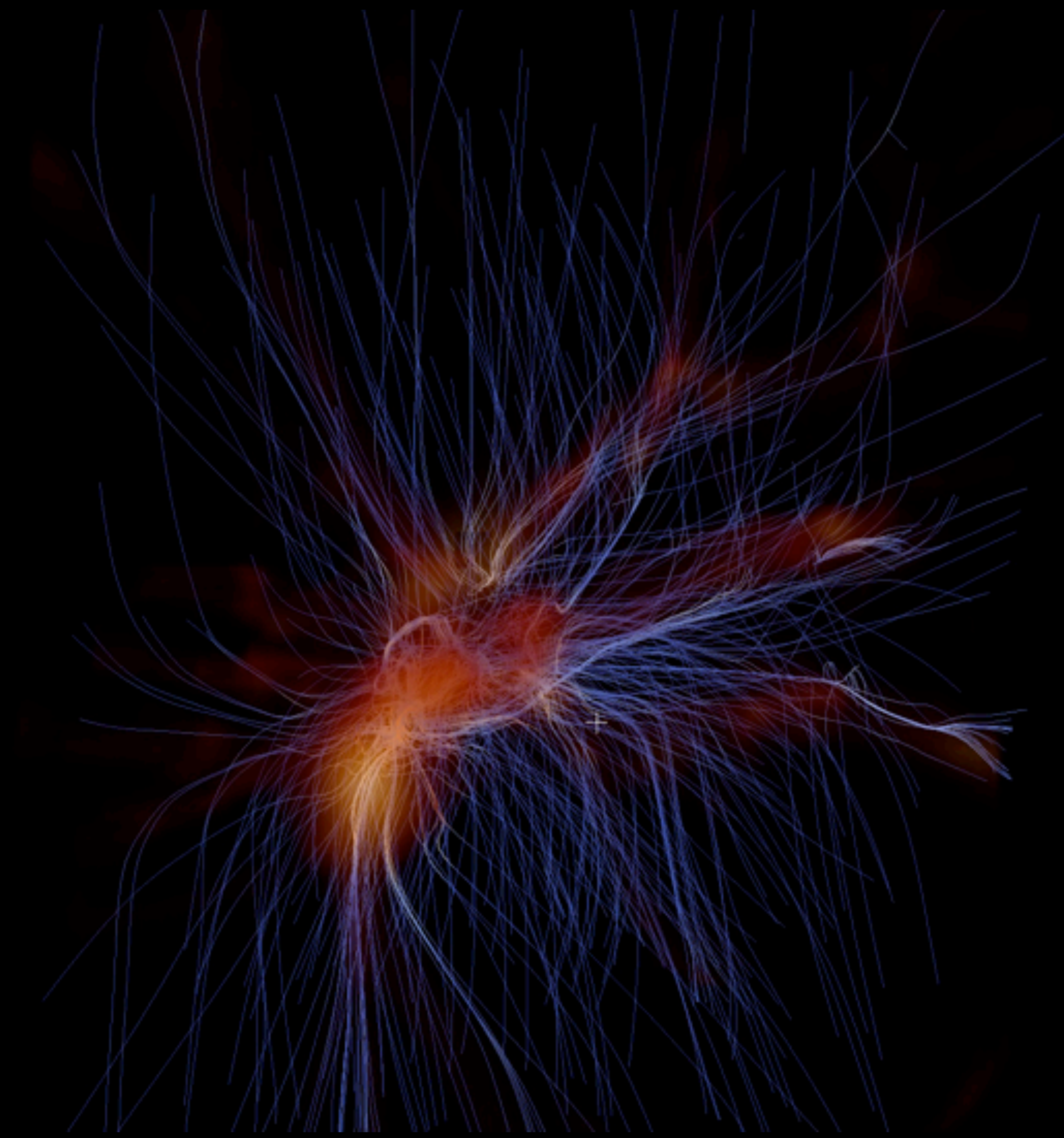
✴ In the filament, **velocity** is along the filament (**helicity**).

important for disc spin up

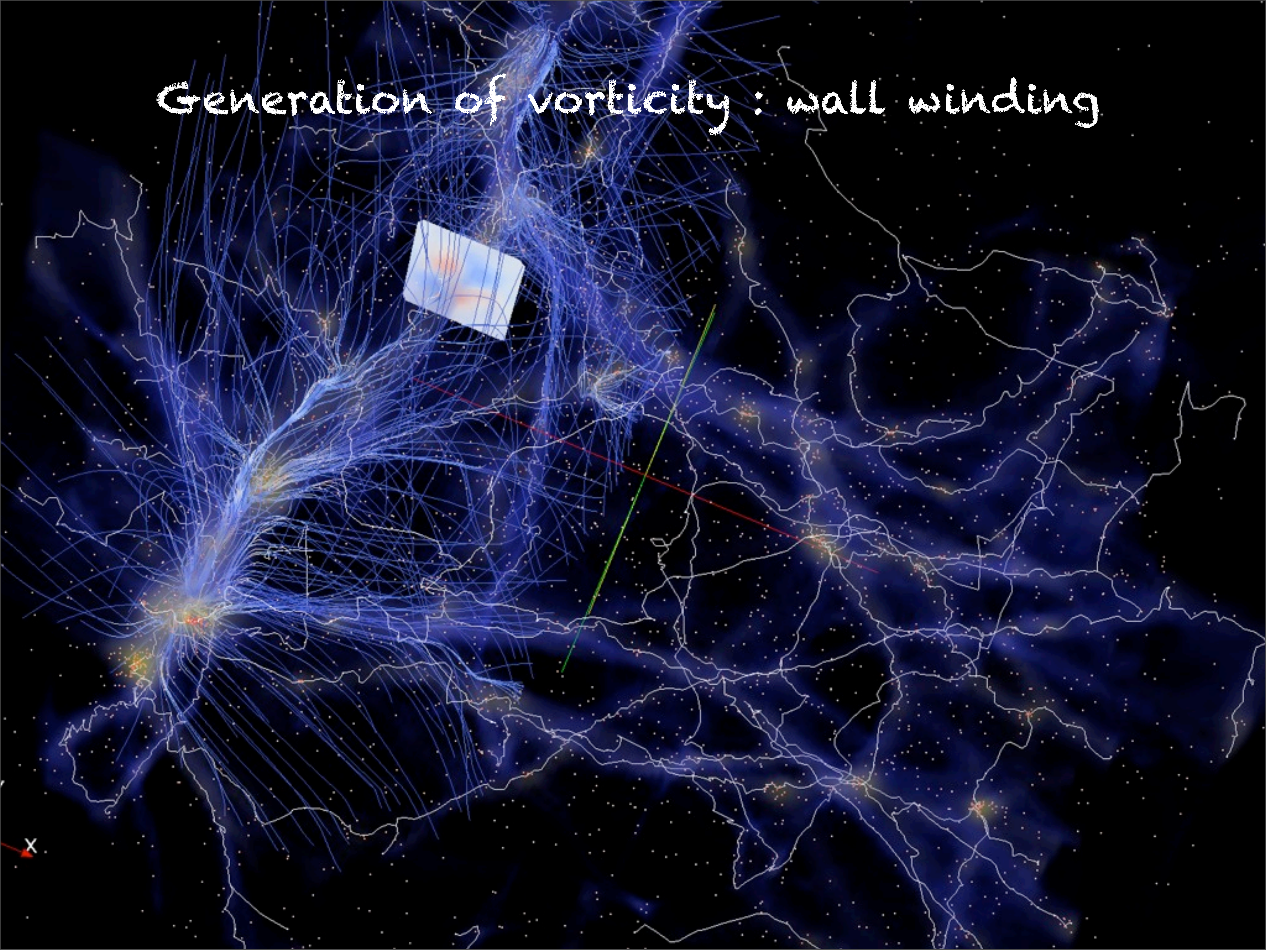
A Qualitative understanding



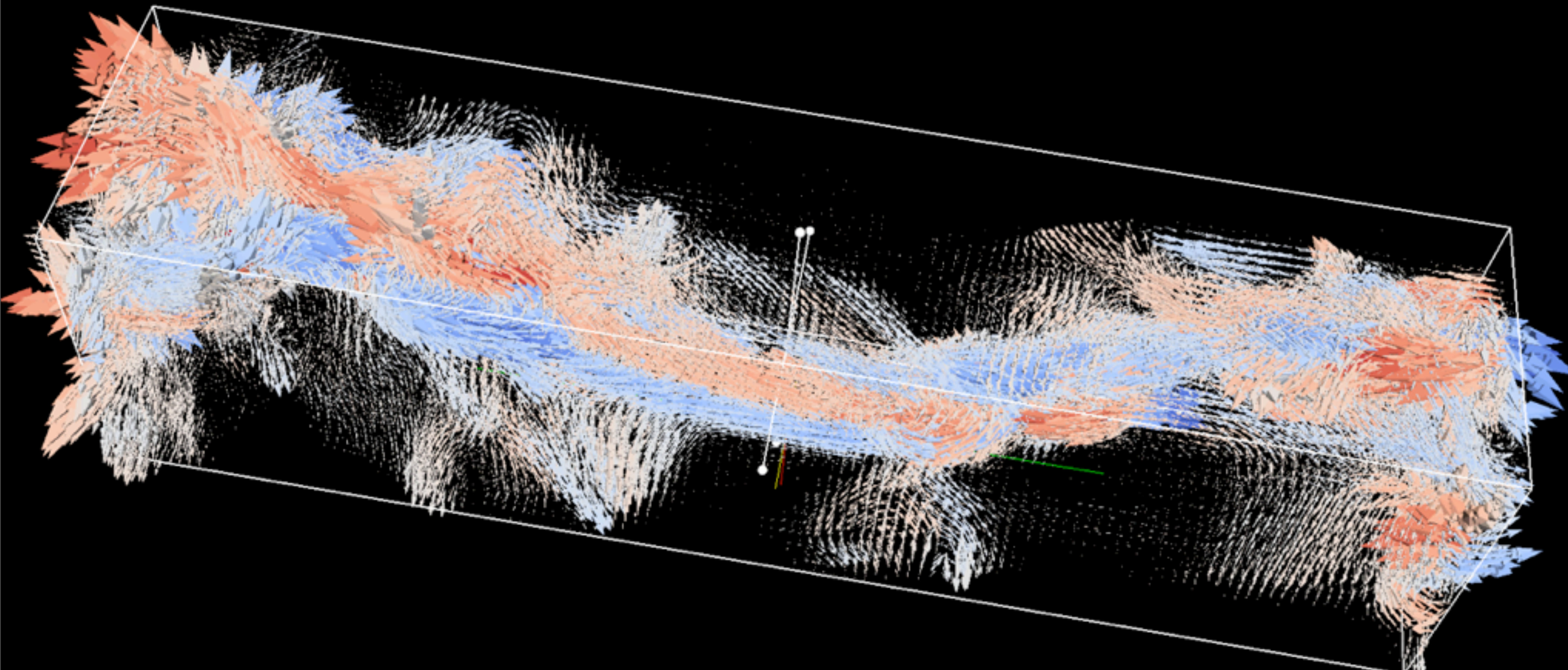
Focussing on main filament

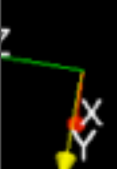


Generation of vorticity : wall winding



Alignement of vorticity with cosmic web





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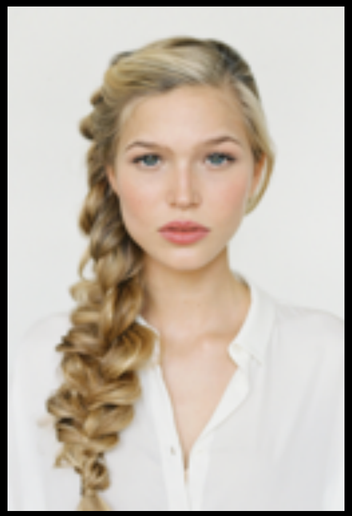
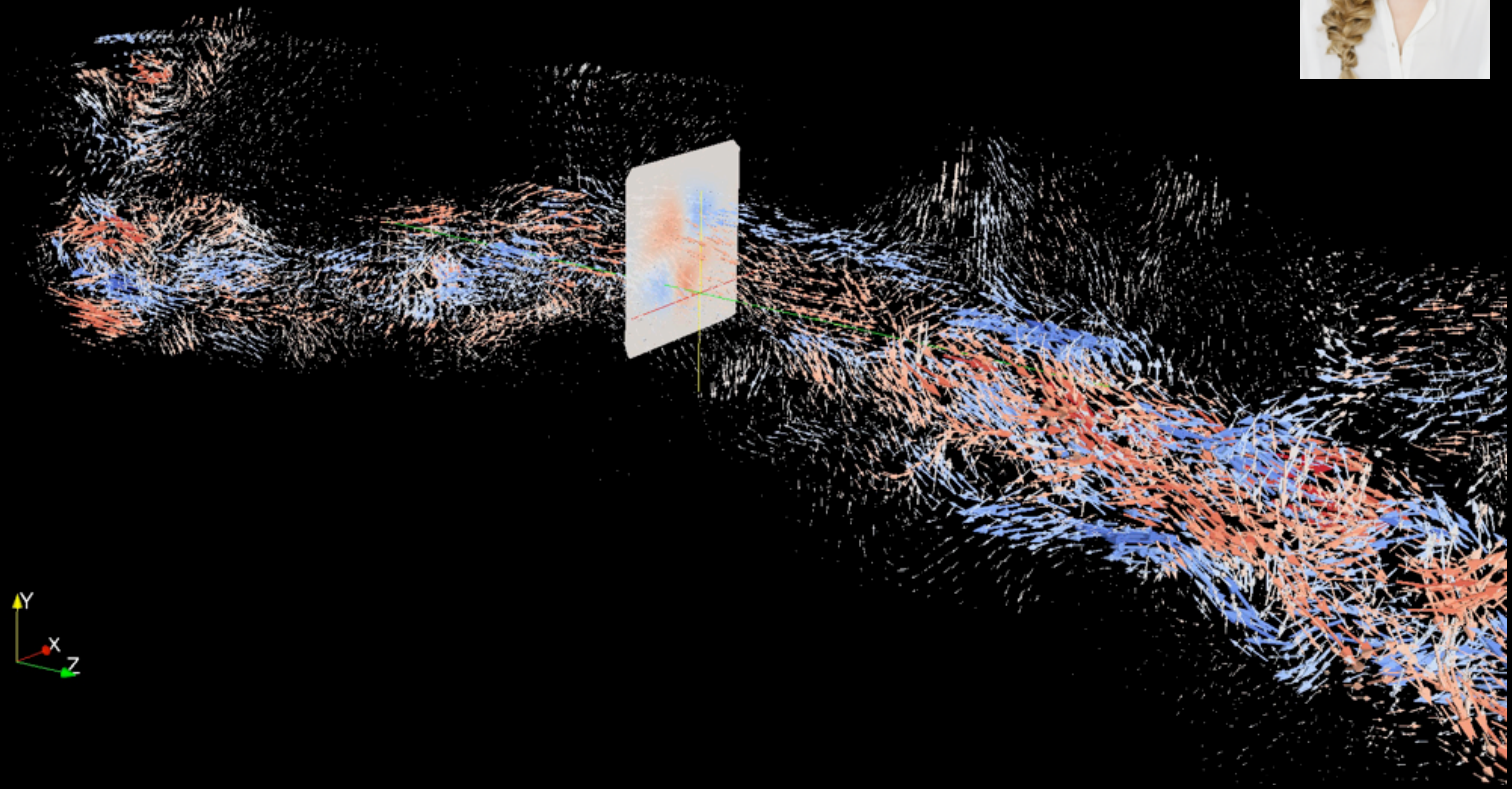


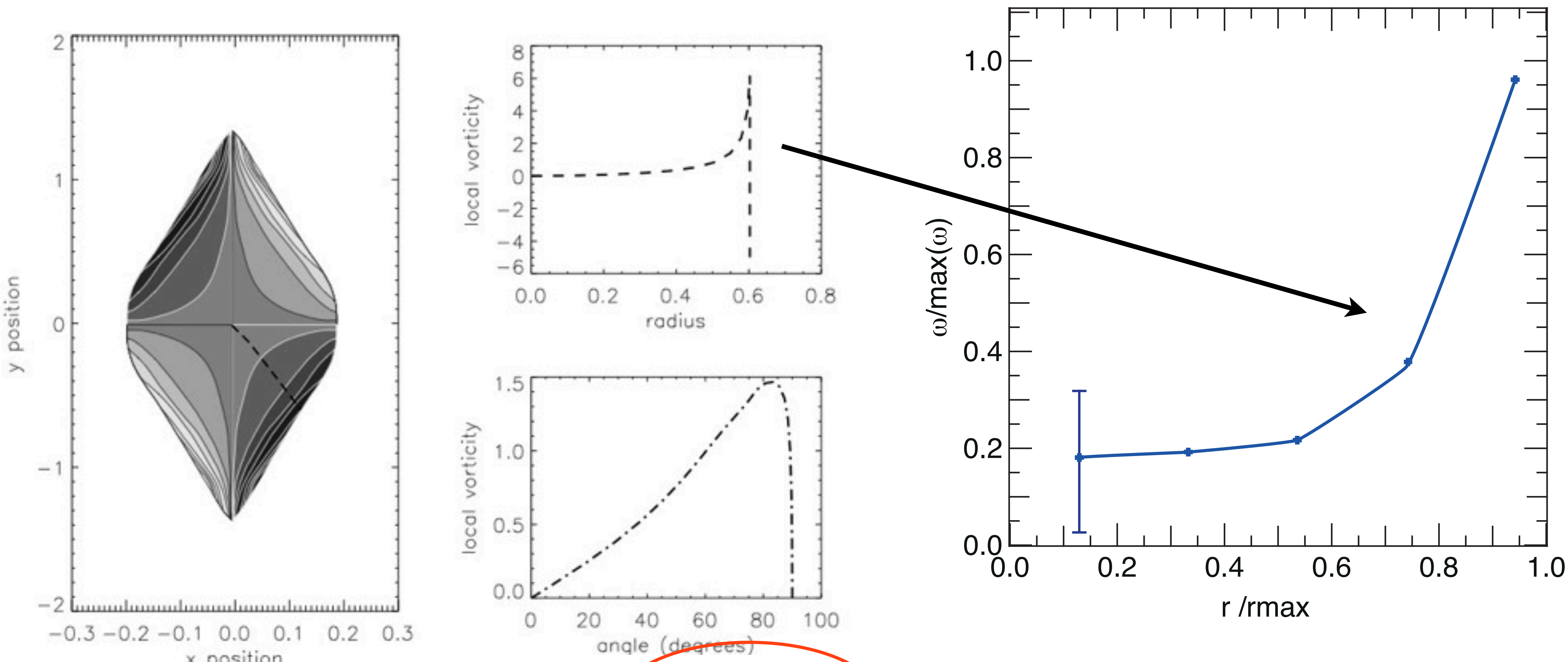


braids structure of vorticity.

Cross section of vorticity in caustic

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

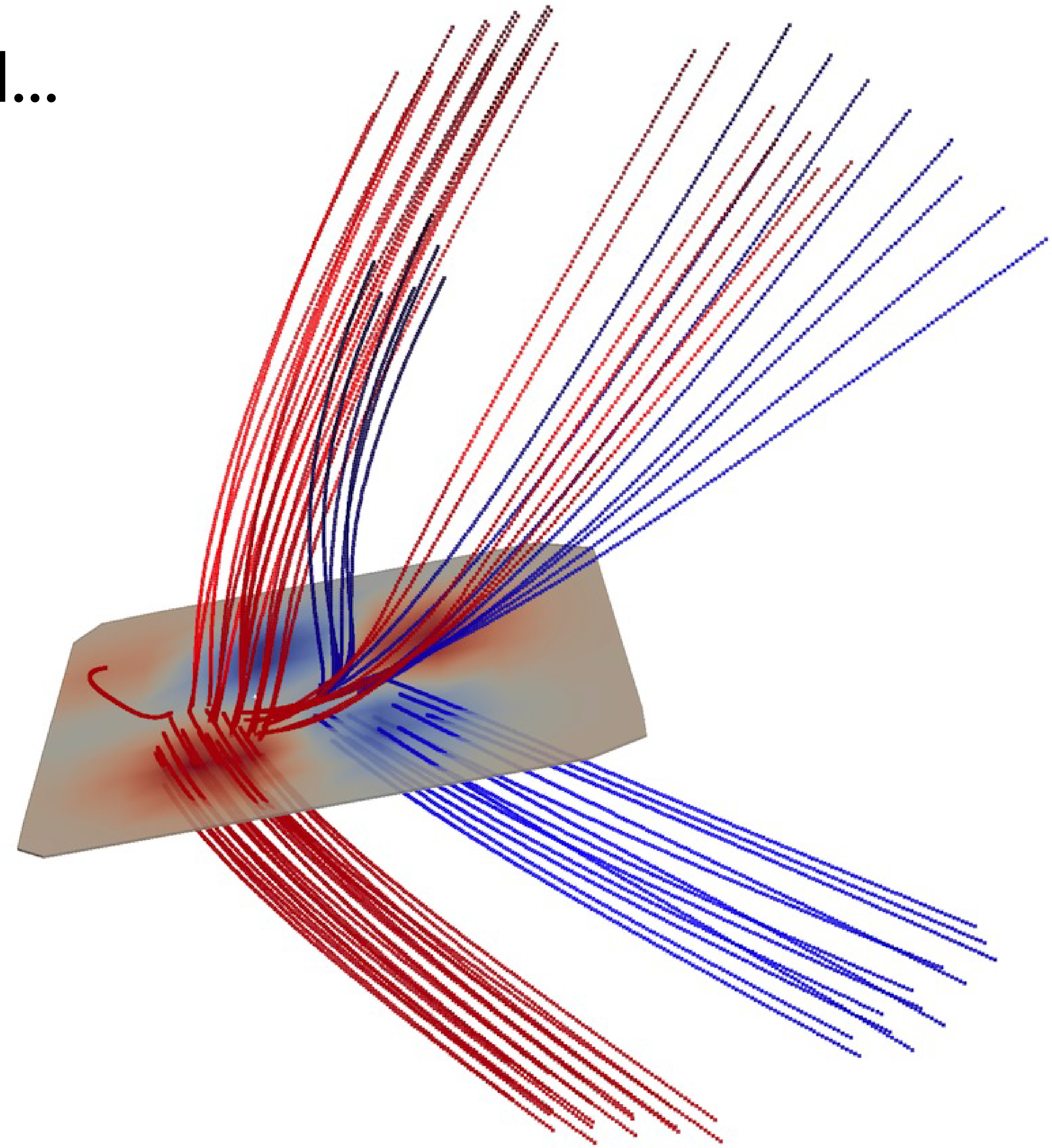
Pichon Bernardeau, 1999



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

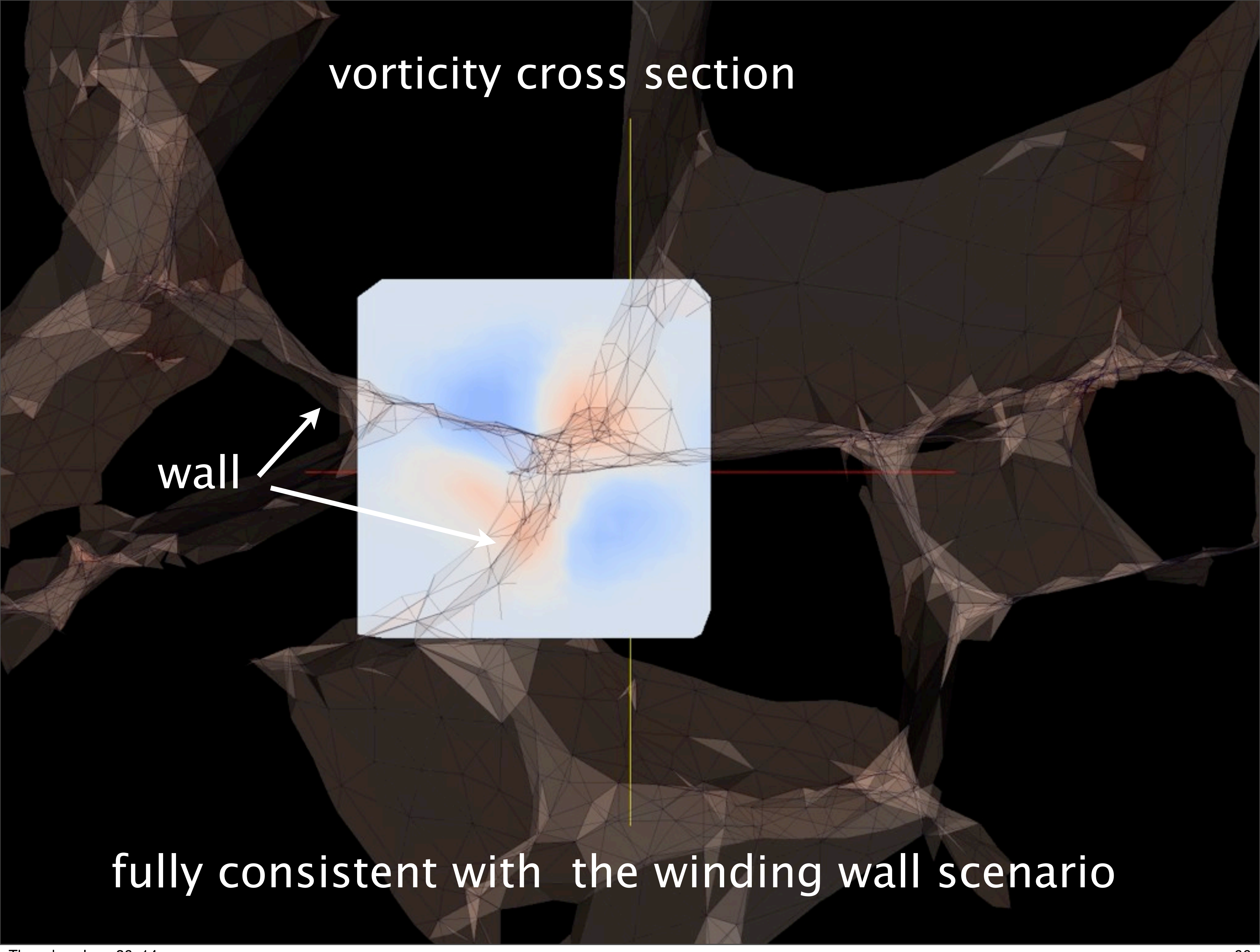
Generation of vorticity : wall winding

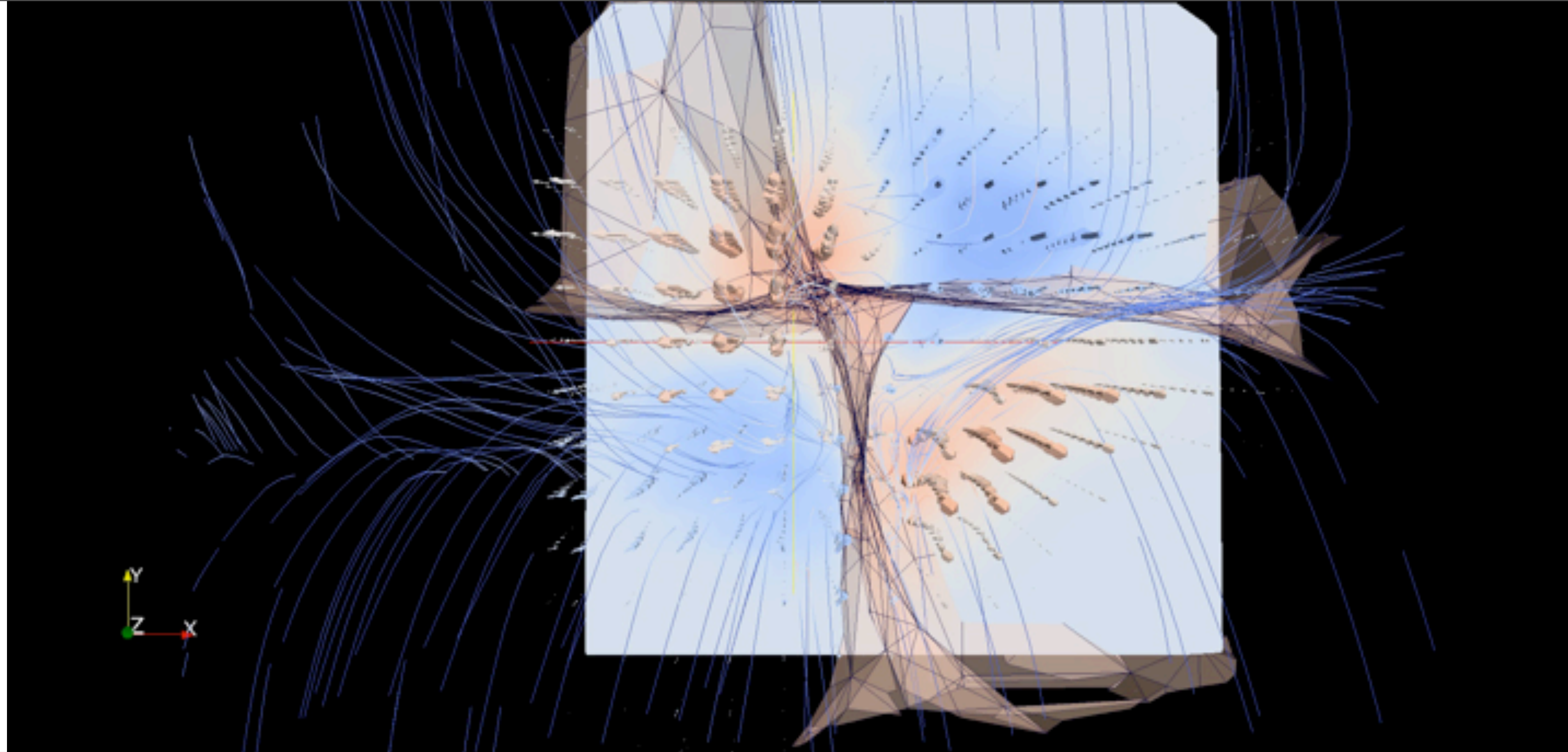
back to WDM...



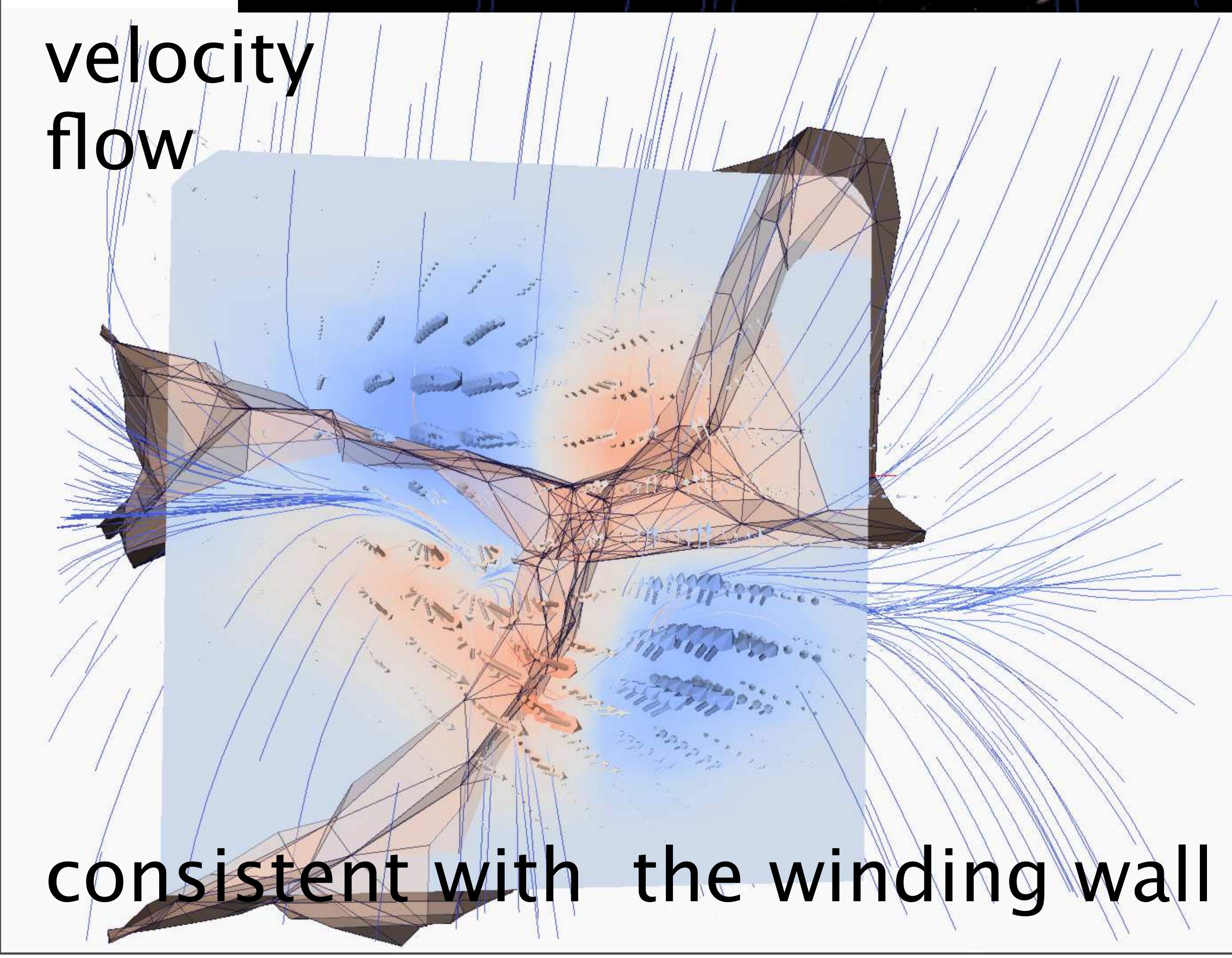
Two sets of trajectories of particles reaching one caustic quad.

3 flows crossing in filaments generate vorticity.

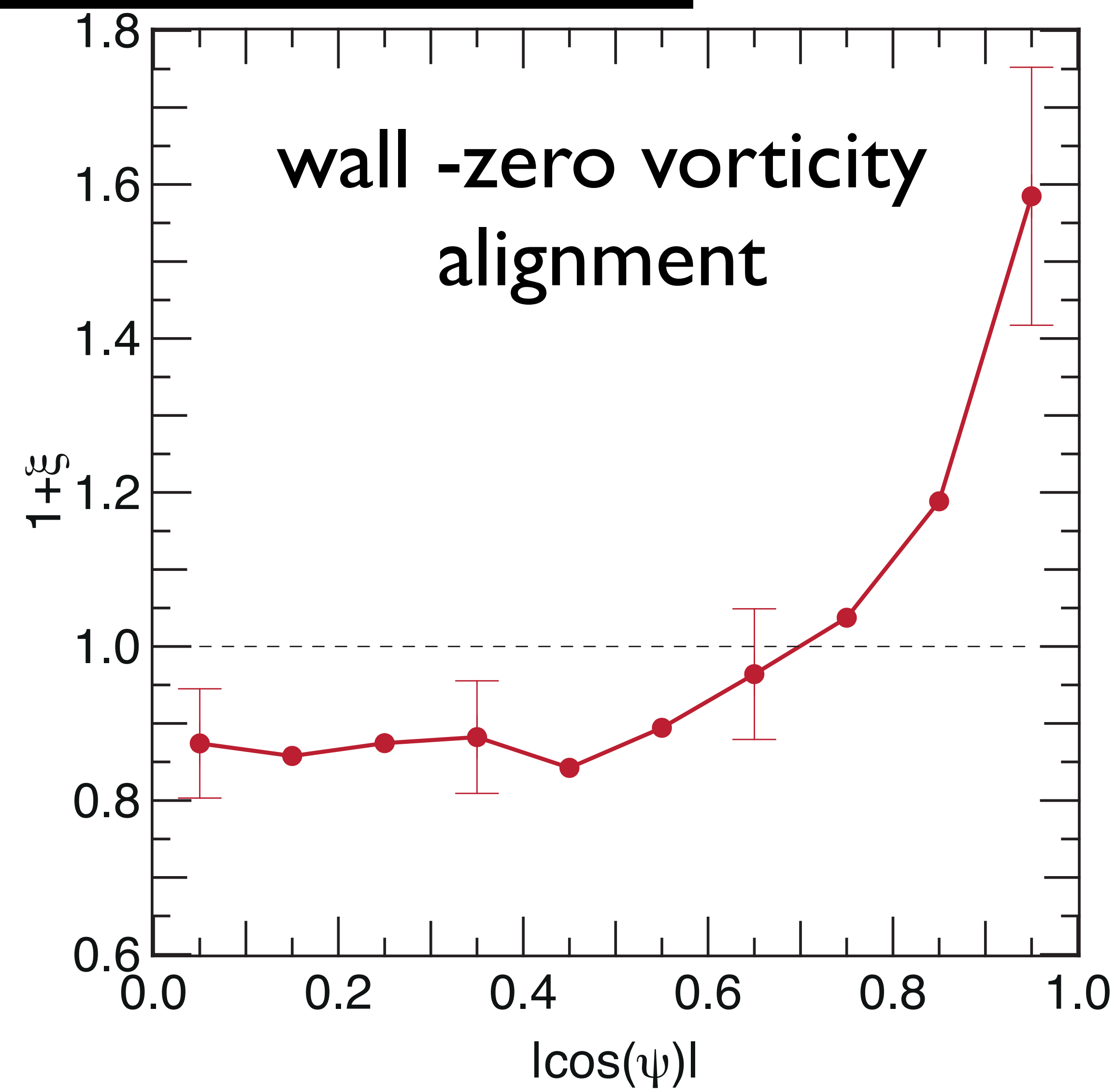

vorticity cross section
wall
fully consistent with the winding wall scenario



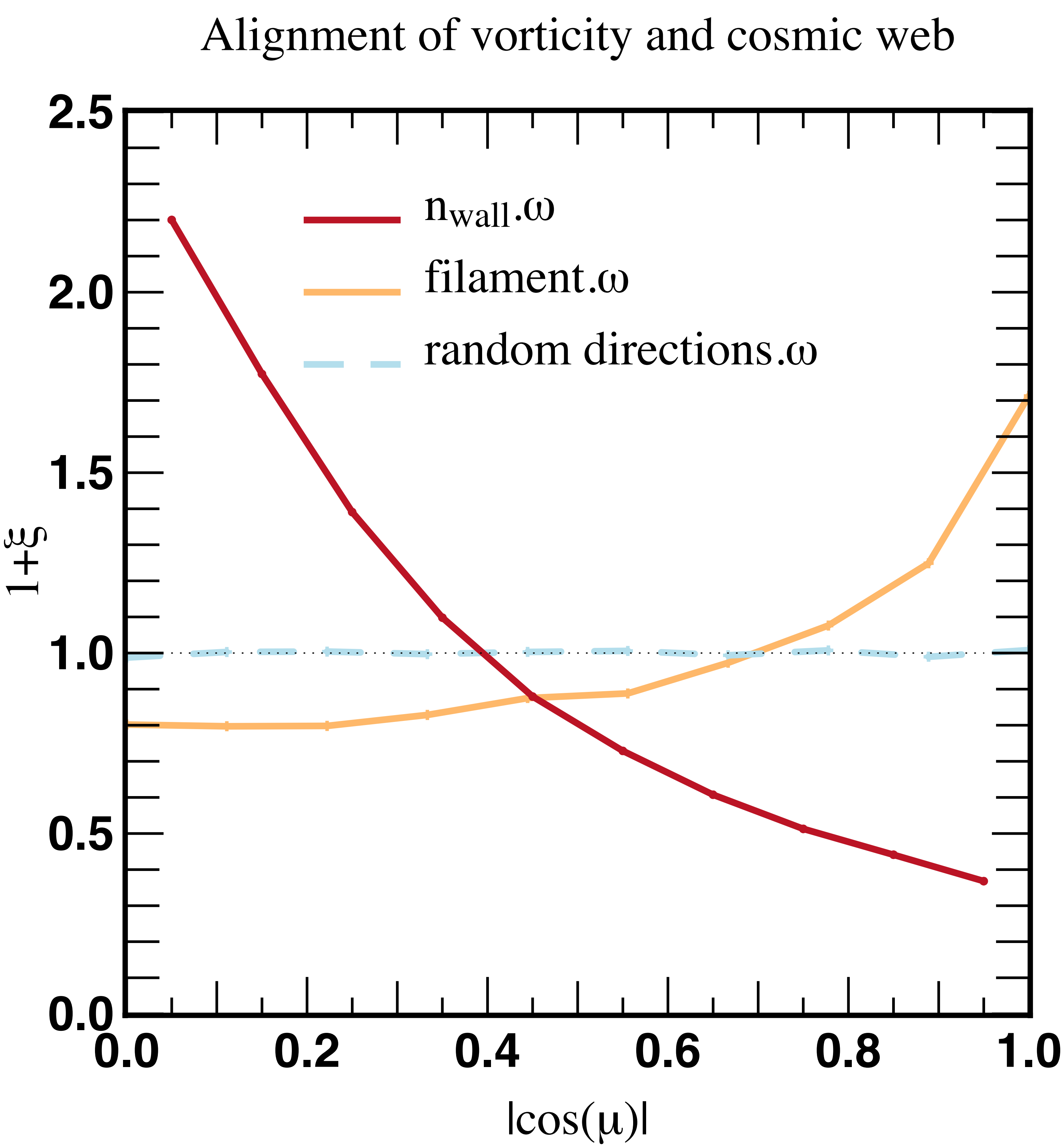
velocity
flow



consistent with the winding wall



Alignement of vorticity with cosmic web



Vorticity is aligned with filaments

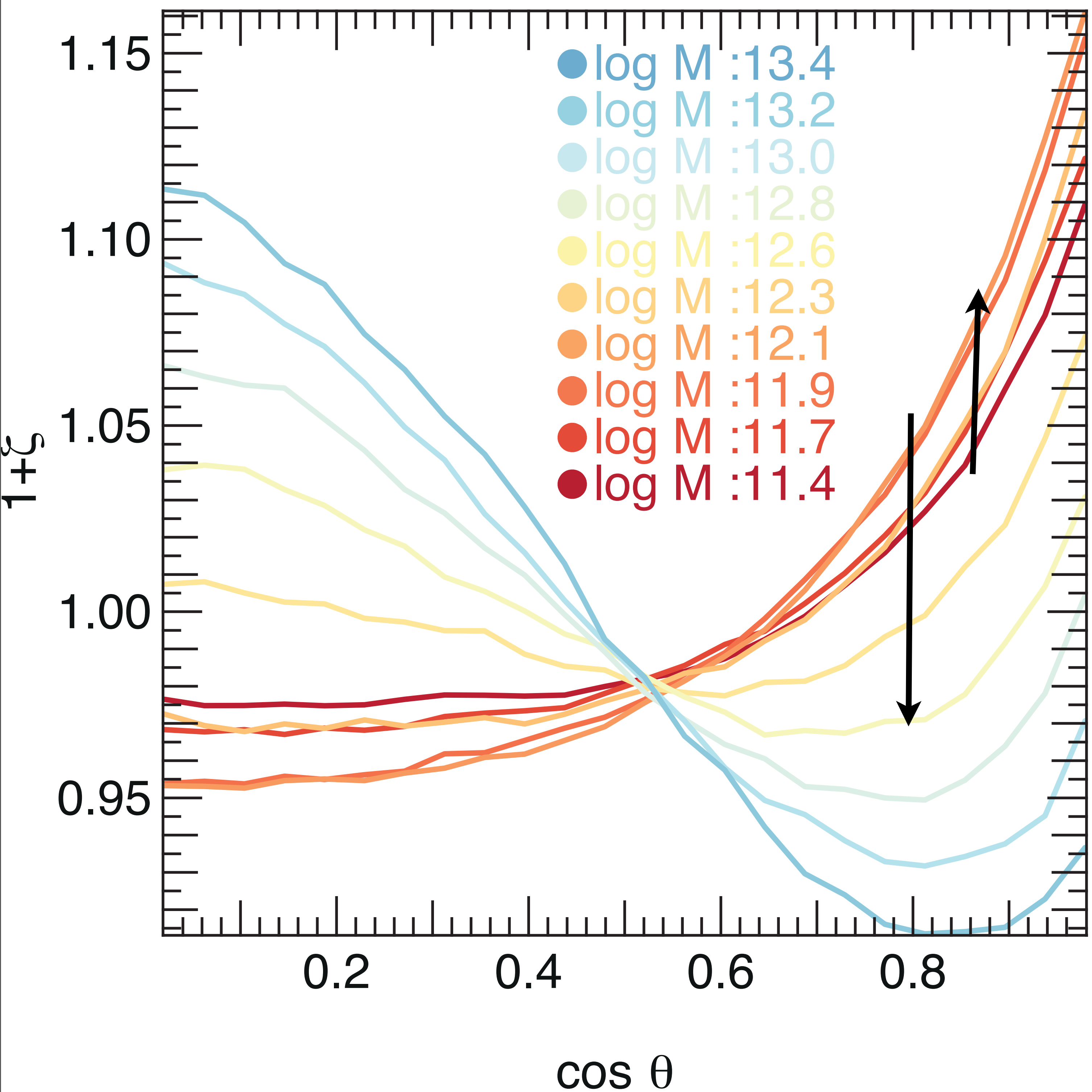
In walls, vorticity is perpendicular to the normal of walls

Revisit

Alignement of spin with cosmic web

vorticity
max on edge

Spin alignment first INCREASES with mass !!!



Revisit

Alignement of spin with cosmic web

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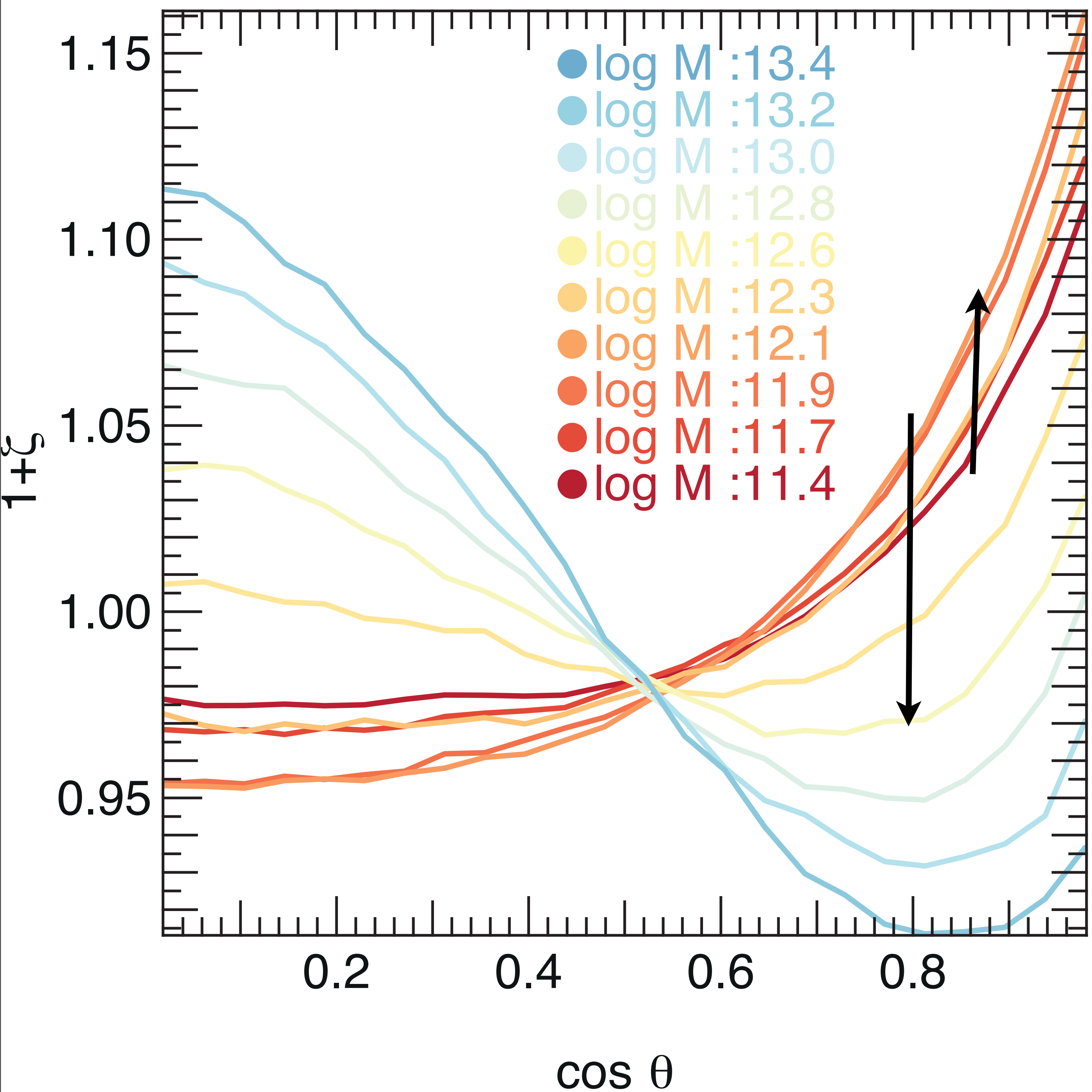
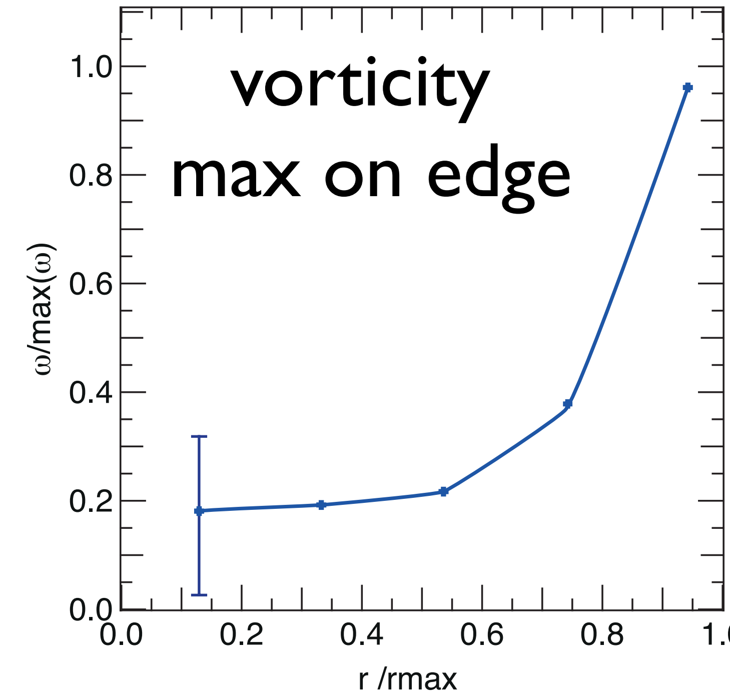
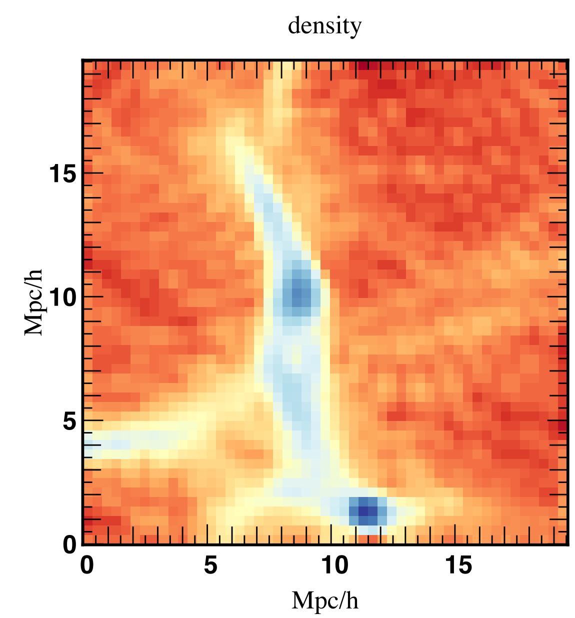
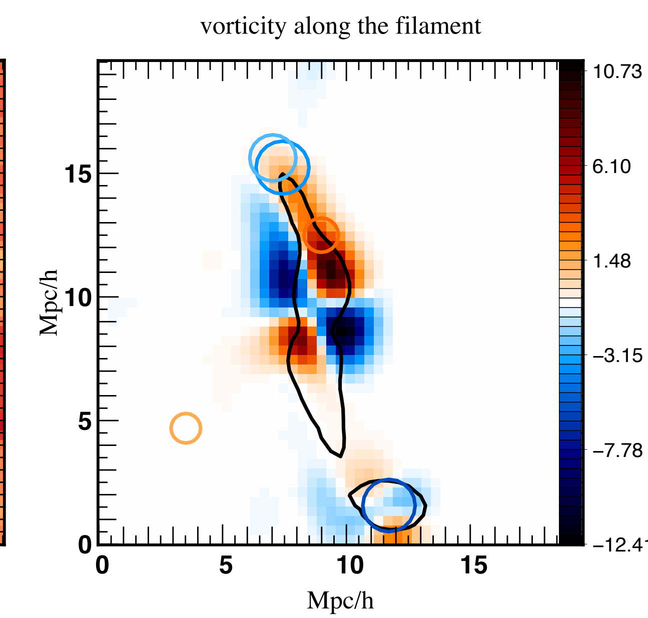
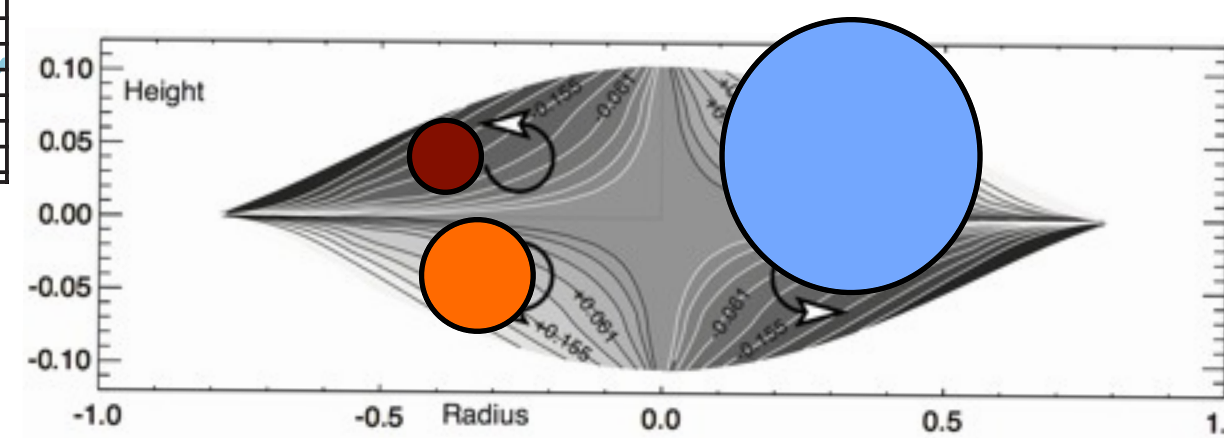




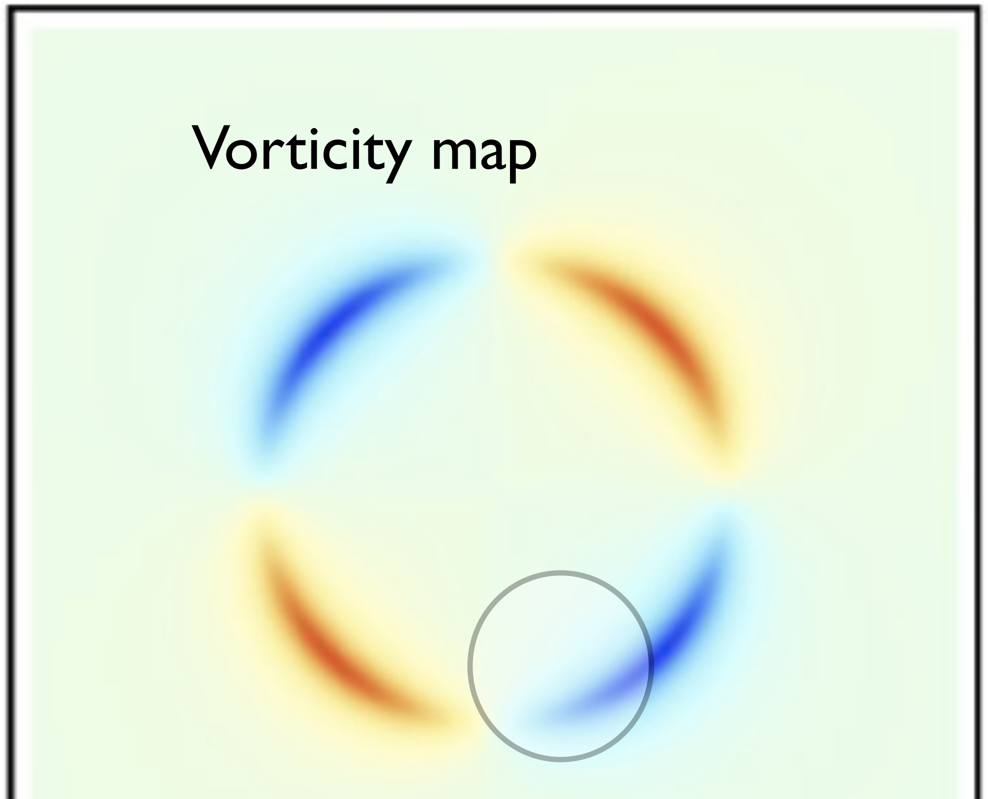




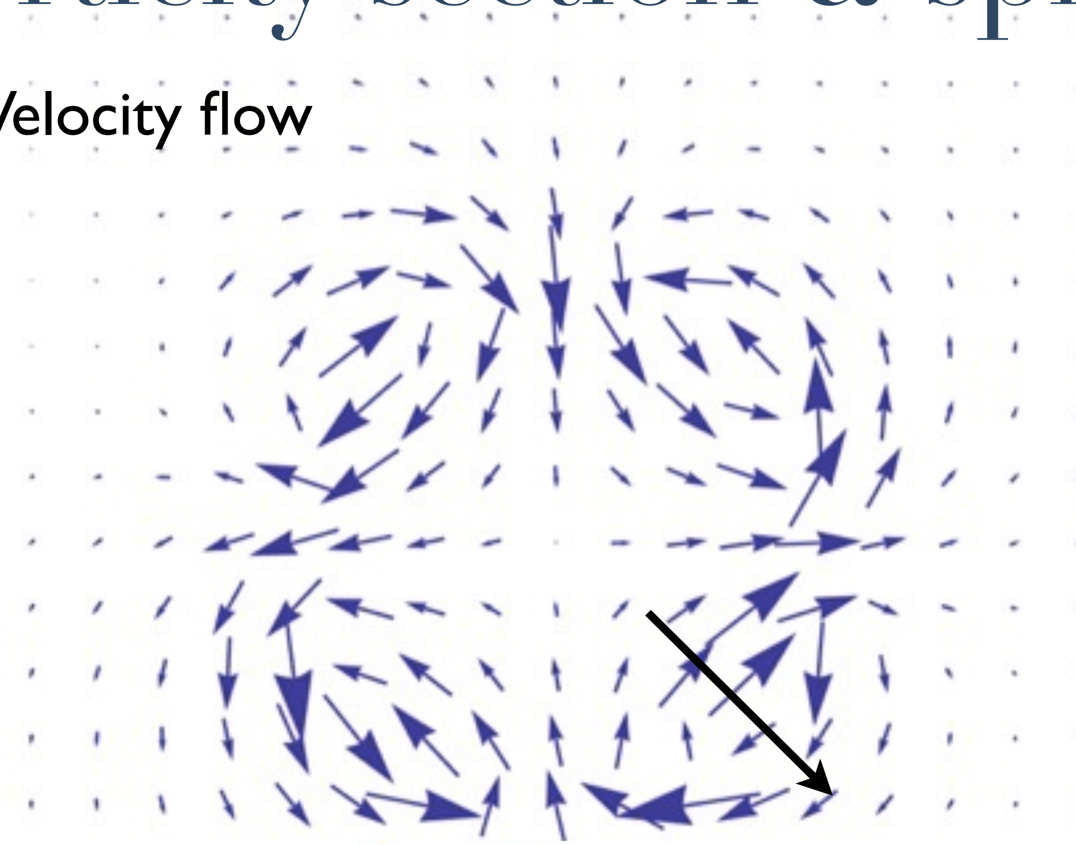


Spin flip imposed by caustic size

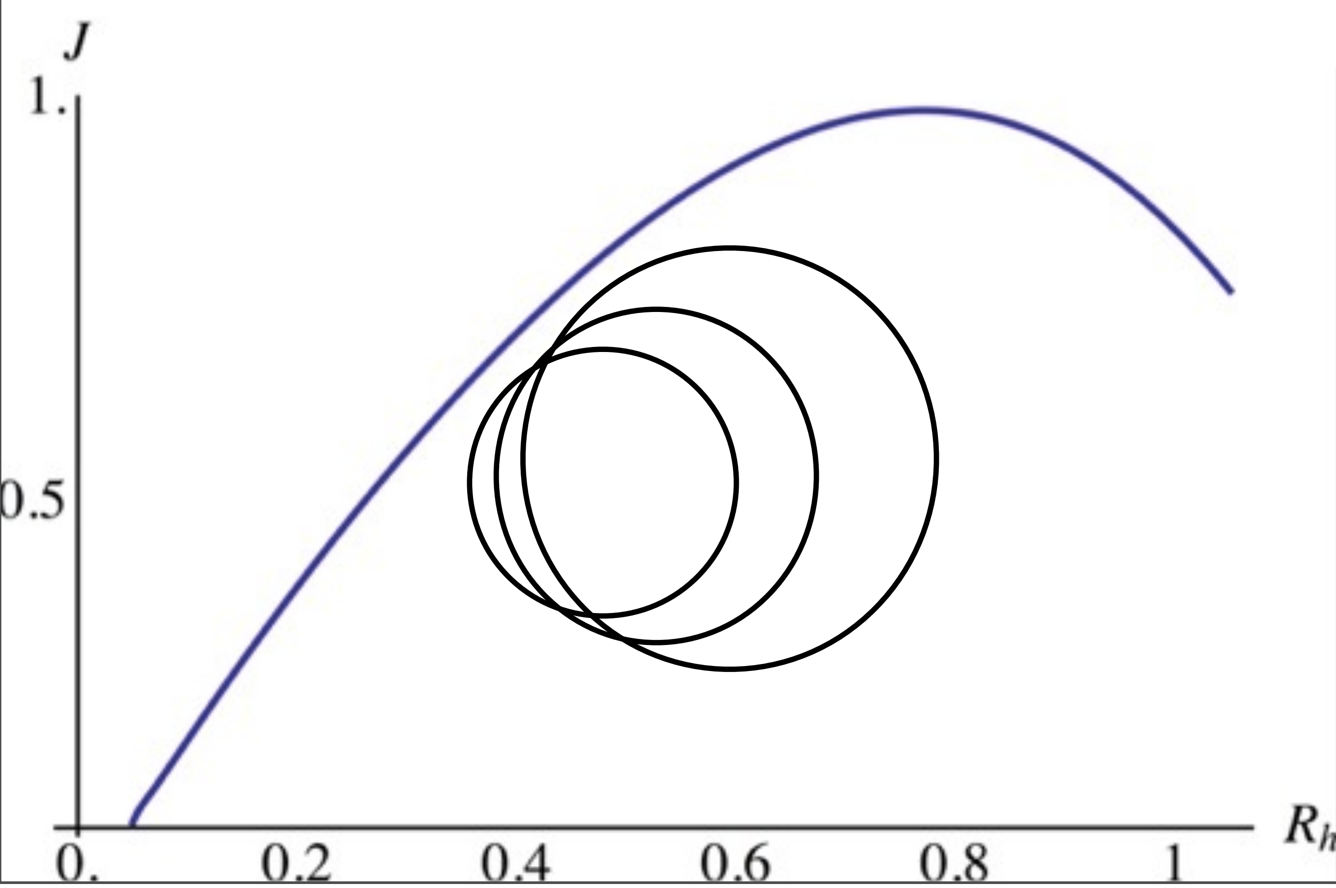
A toy model for vorticity section & spin flip

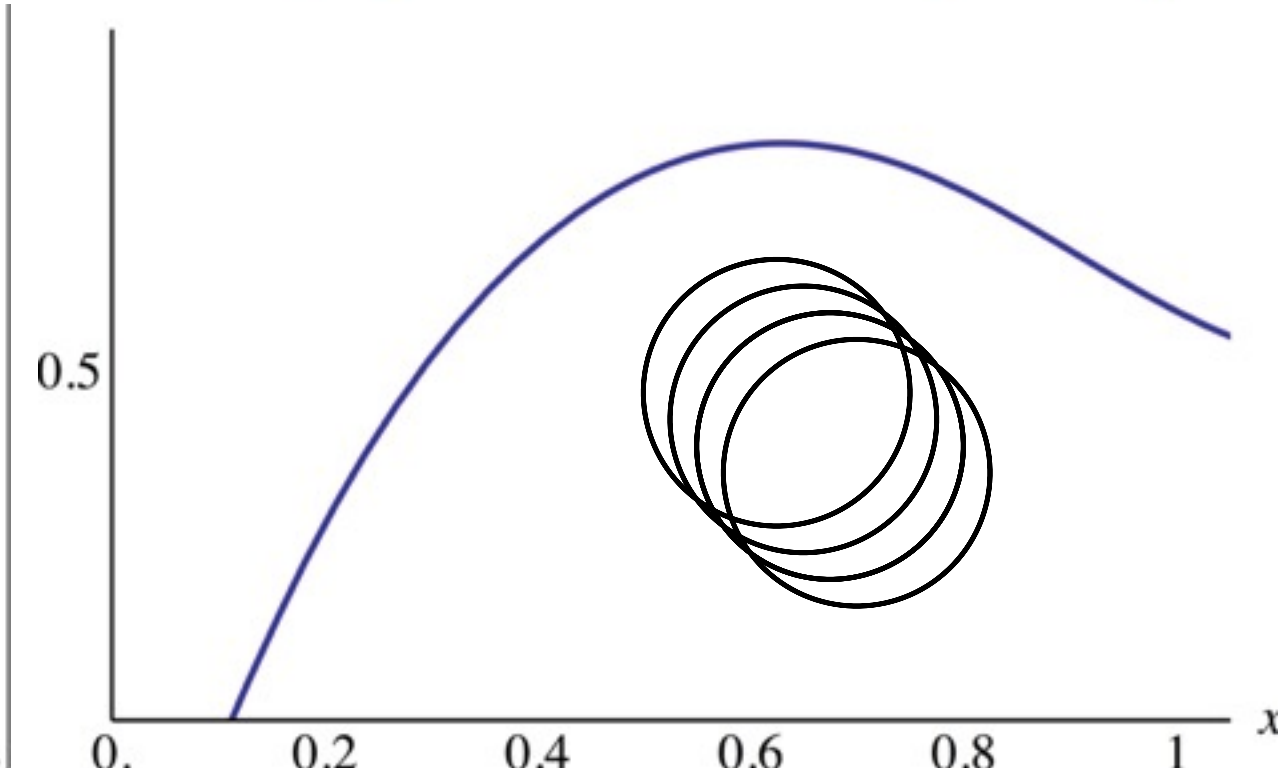


$$\boldsymbol{\Omega}(\mathbf{r},\theta) = C\epsilon \sin(2\theta)\frac{1}{(\epsilon^2 + (r-R)^2)}\mathbf{e}_z\,,$$



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

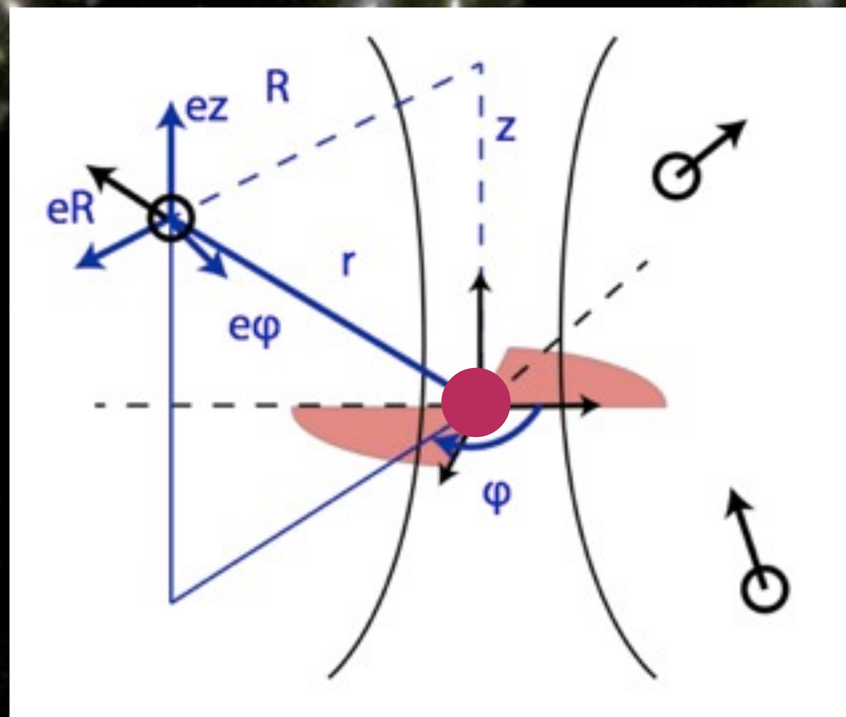




- How discs build up from persistent cosmic web?
- **How dark halo's spin flip relative to filament?**
- **Why are they initially aligned with filaments? Why the transition mass? Eulerian view**
- **What is the corresponding Lagrangian theory?**

Part IV

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

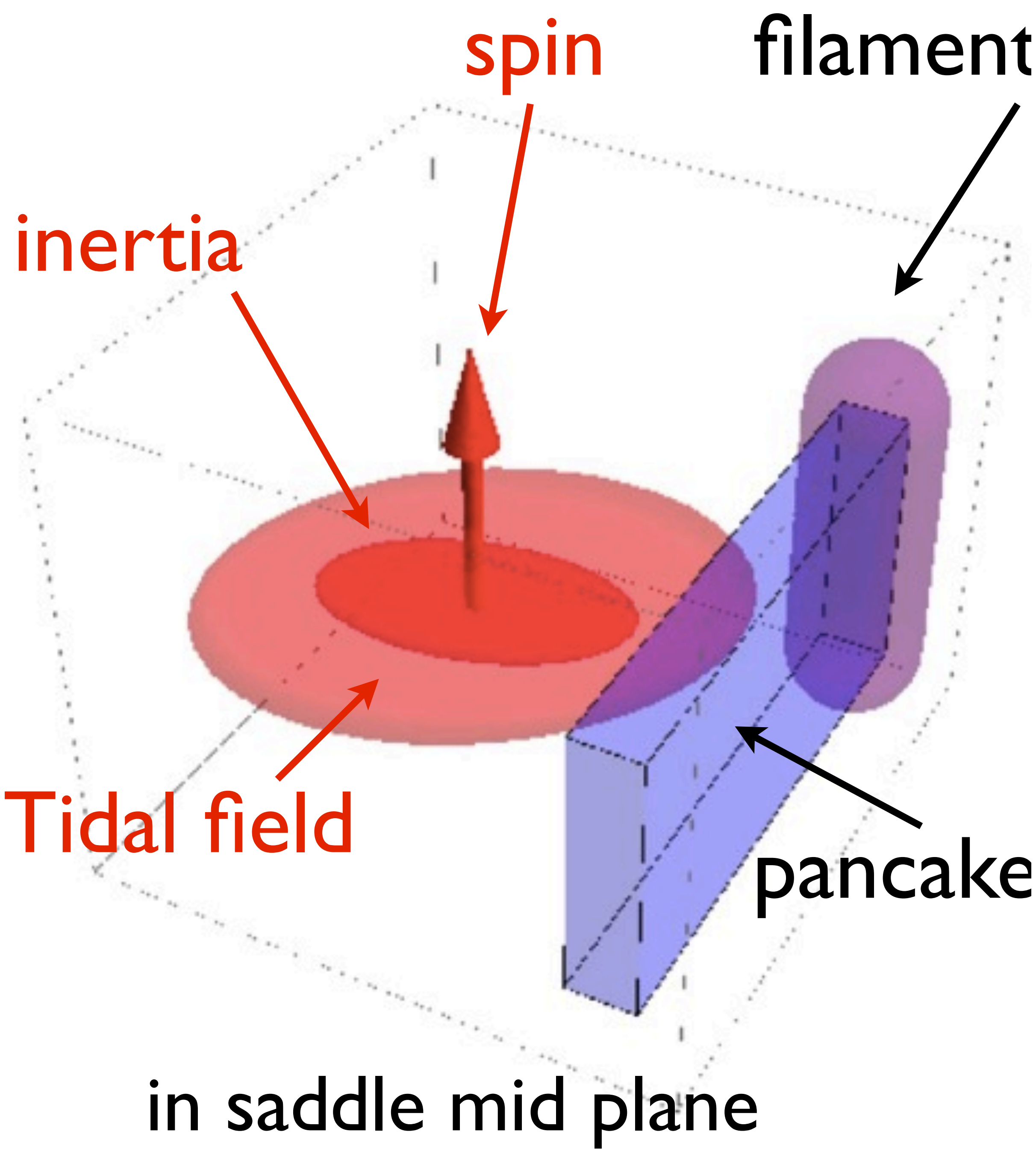


Part IV Outline

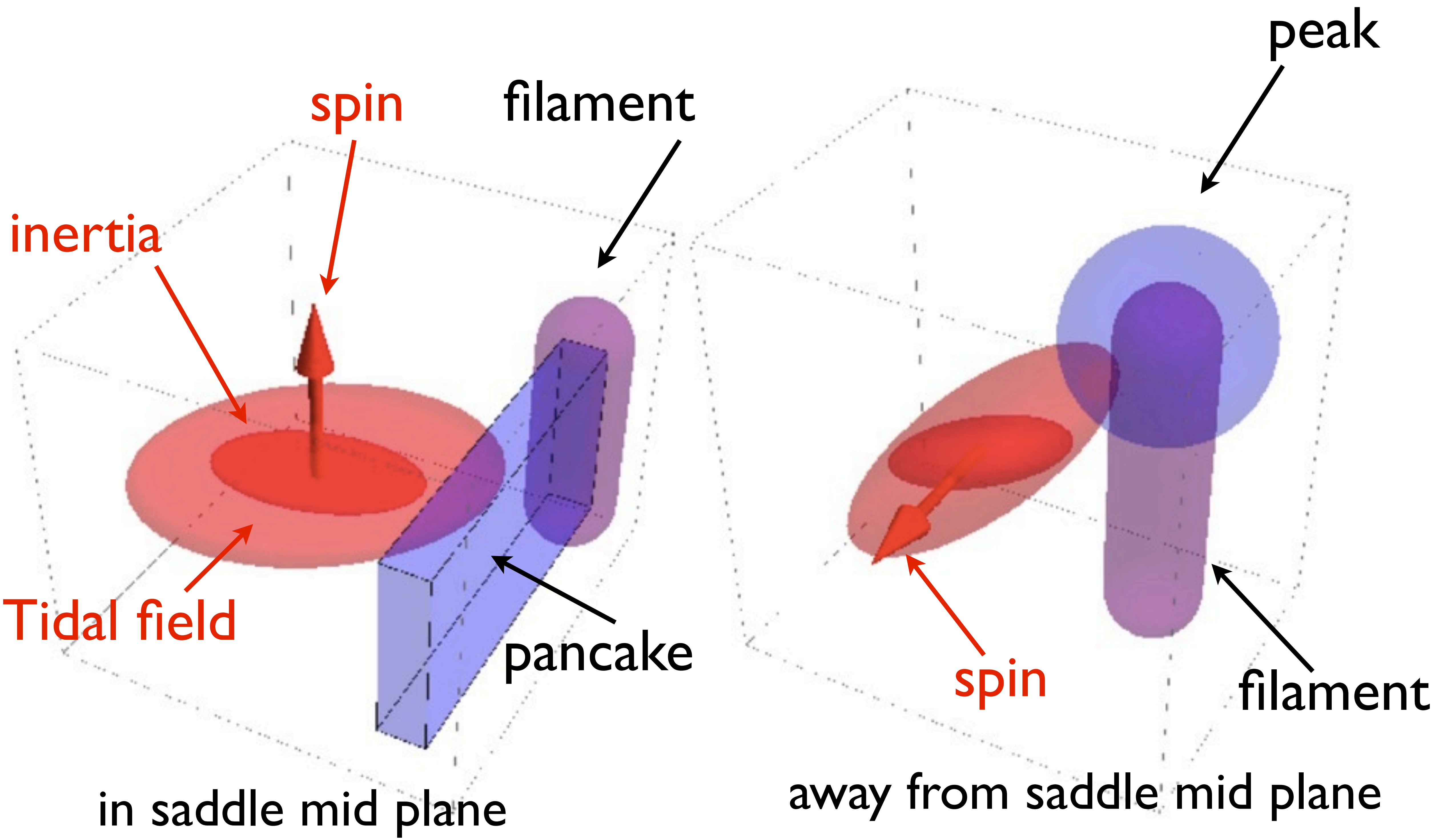
- The Idea
  - walls/filament/peak locally bias differentially tidal and inertia tensor: spin alignment reflect this
- The picture
  - Geometry of spin near saddle: point reflection symmetric distribution
- The Maths
  - Very simple **ab initio** prediction for mass transition + **helicity**

The Lagrangian view of spin/LSS connection

Tidal/Inertia mis-alignment



Tidal/Inertia mis-alignment

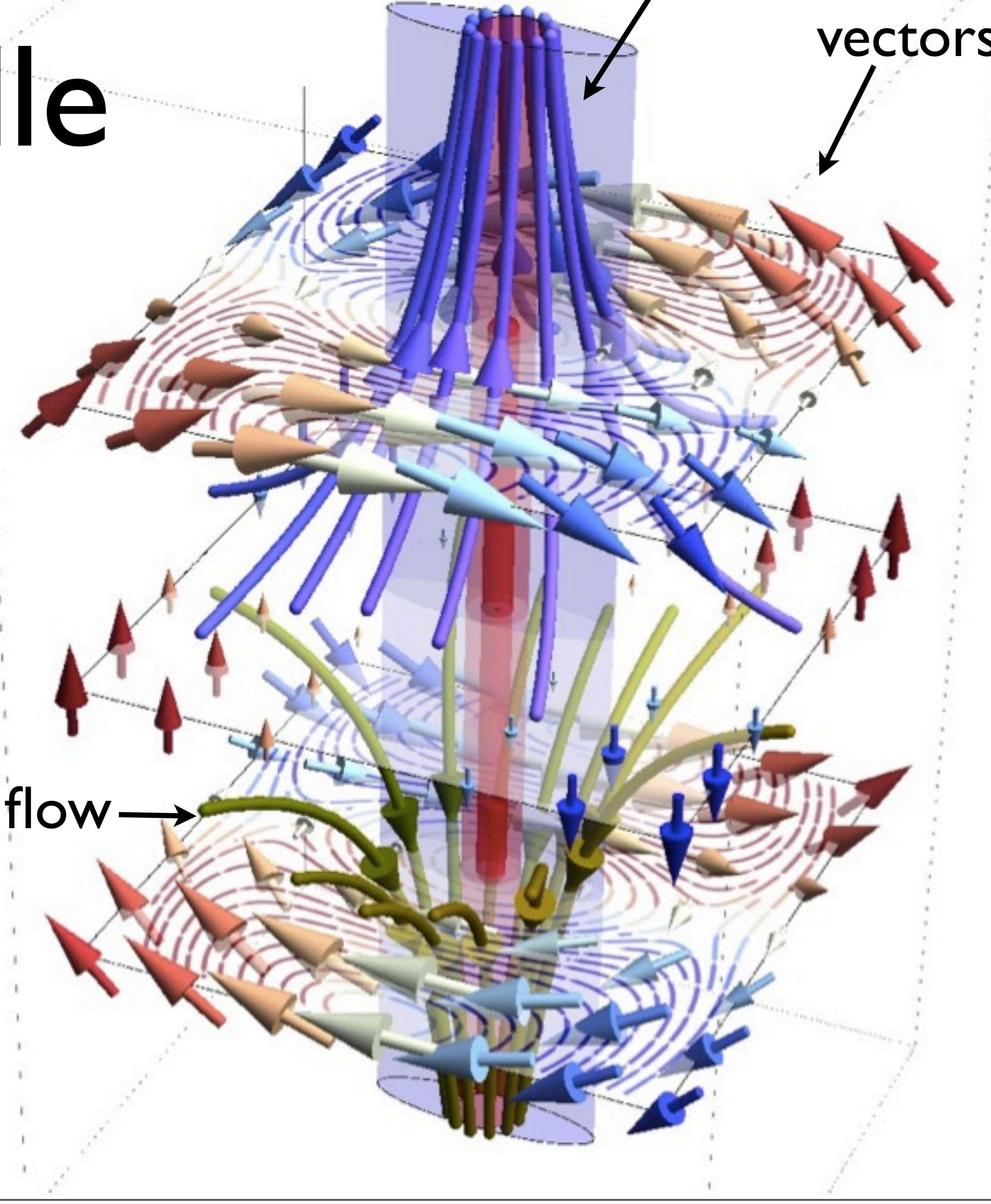


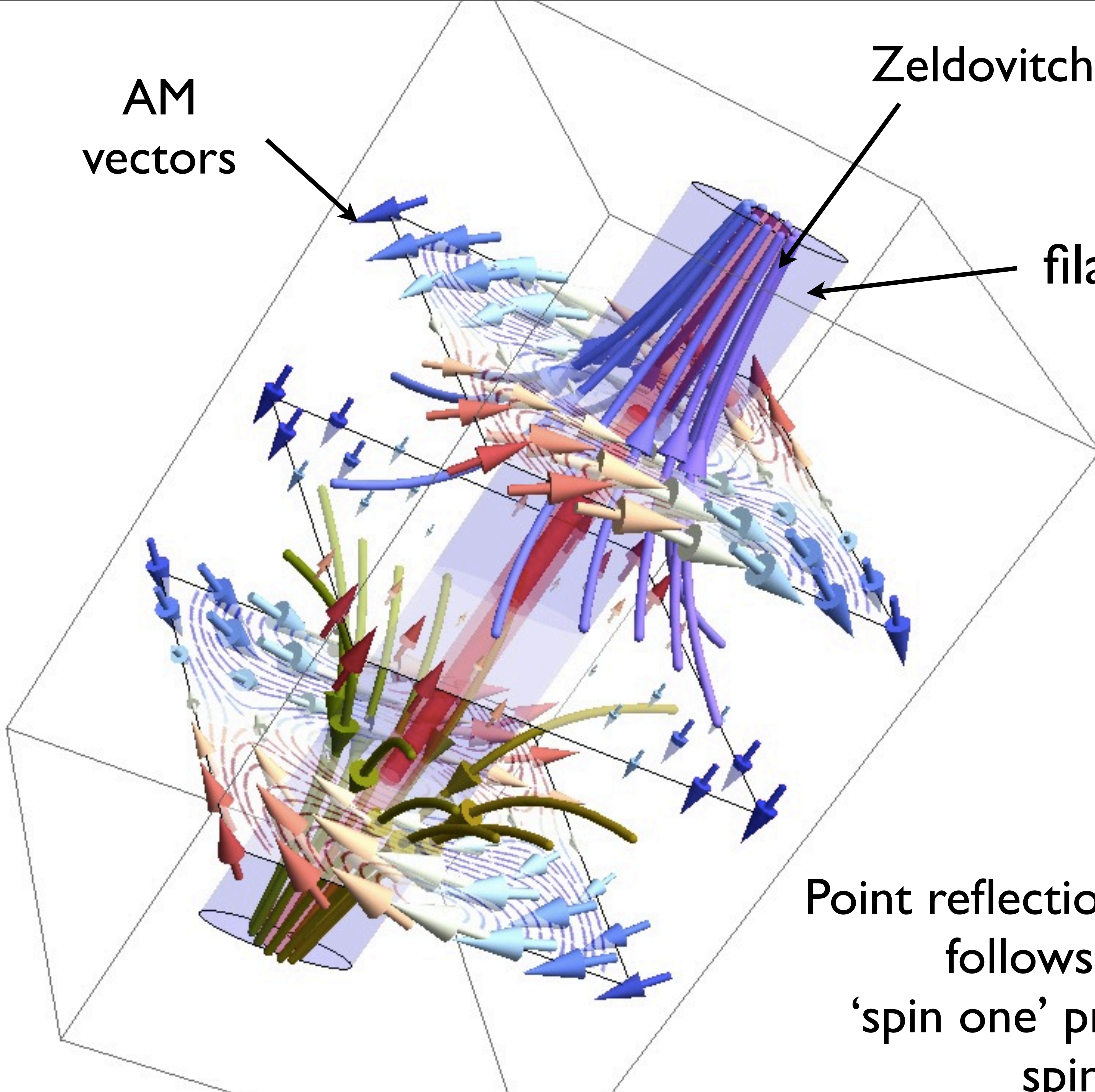
Spin structure near Saddle

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

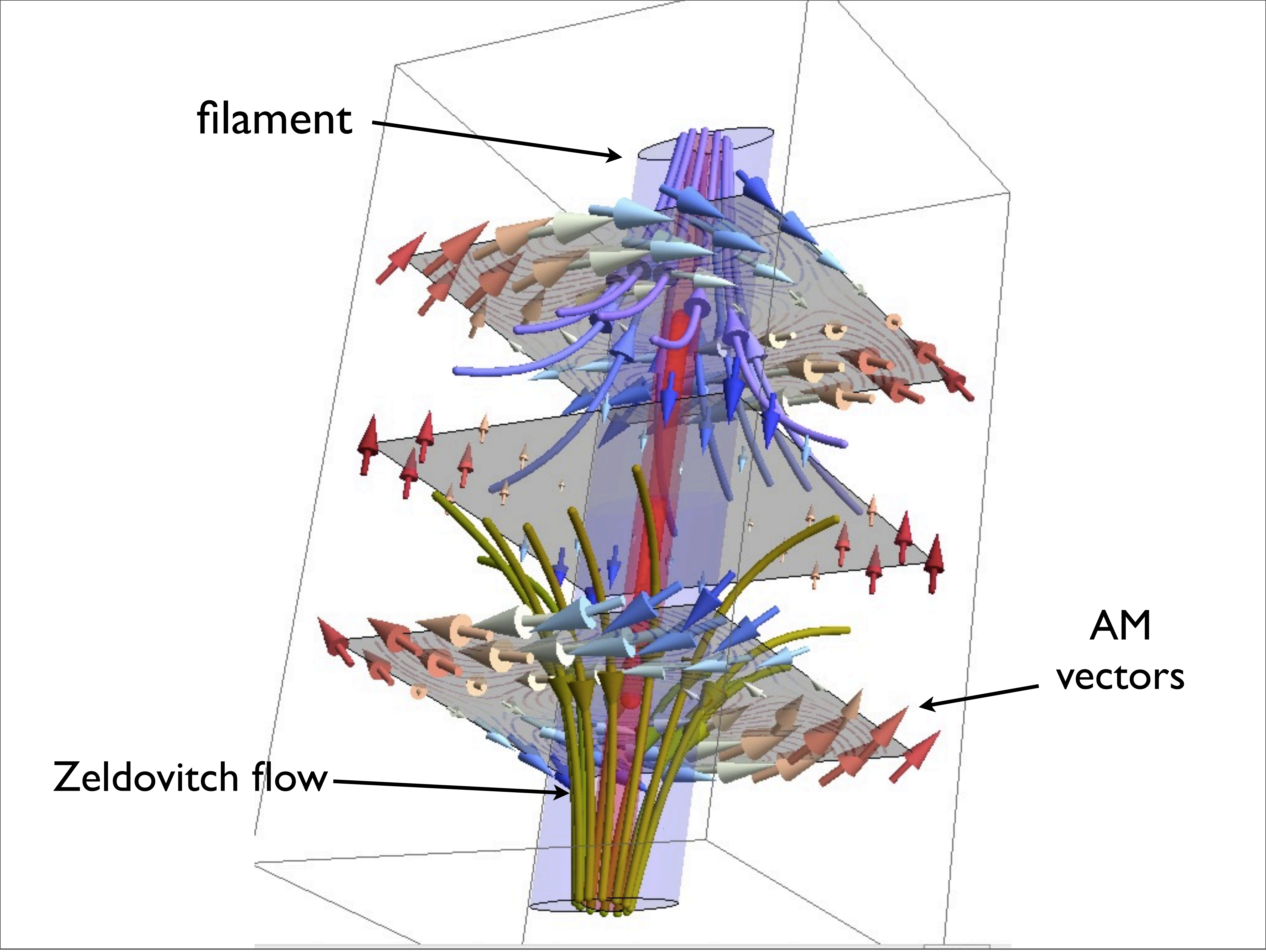
Hessian

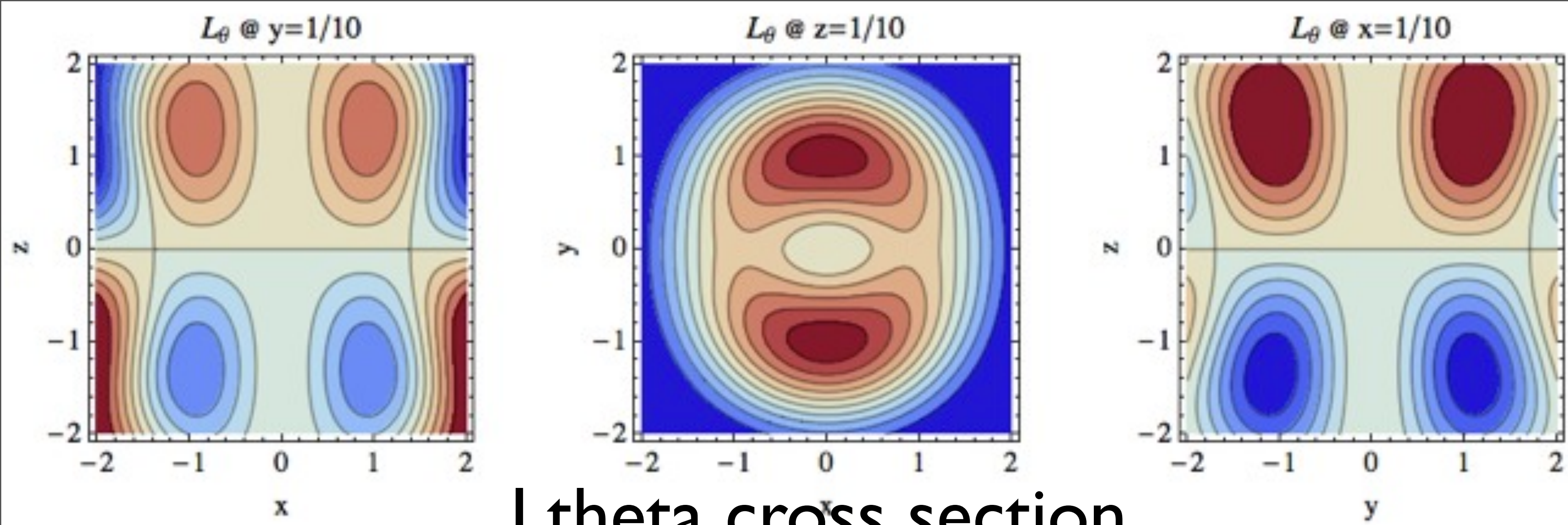
Tidal





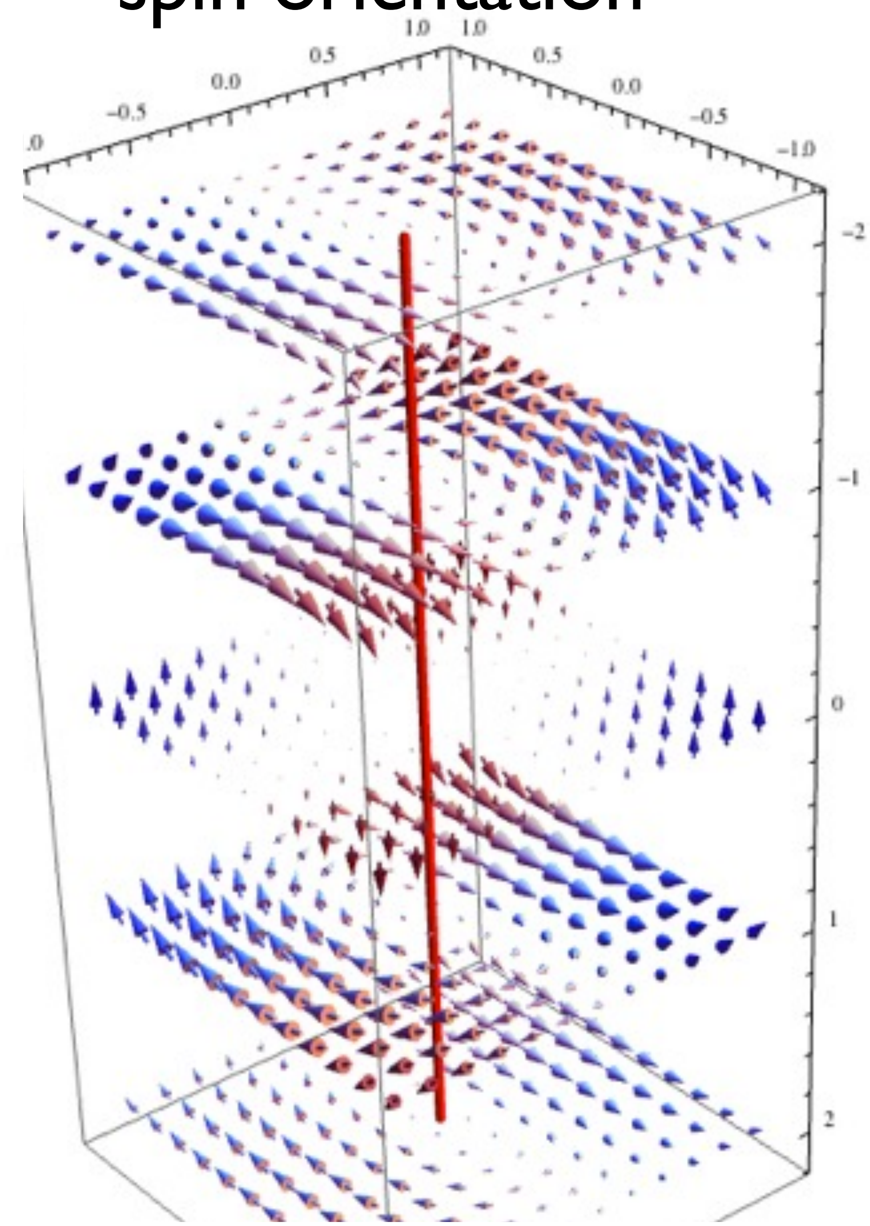
Point reflection symmetry
follows from
'spin one' property of
spin !

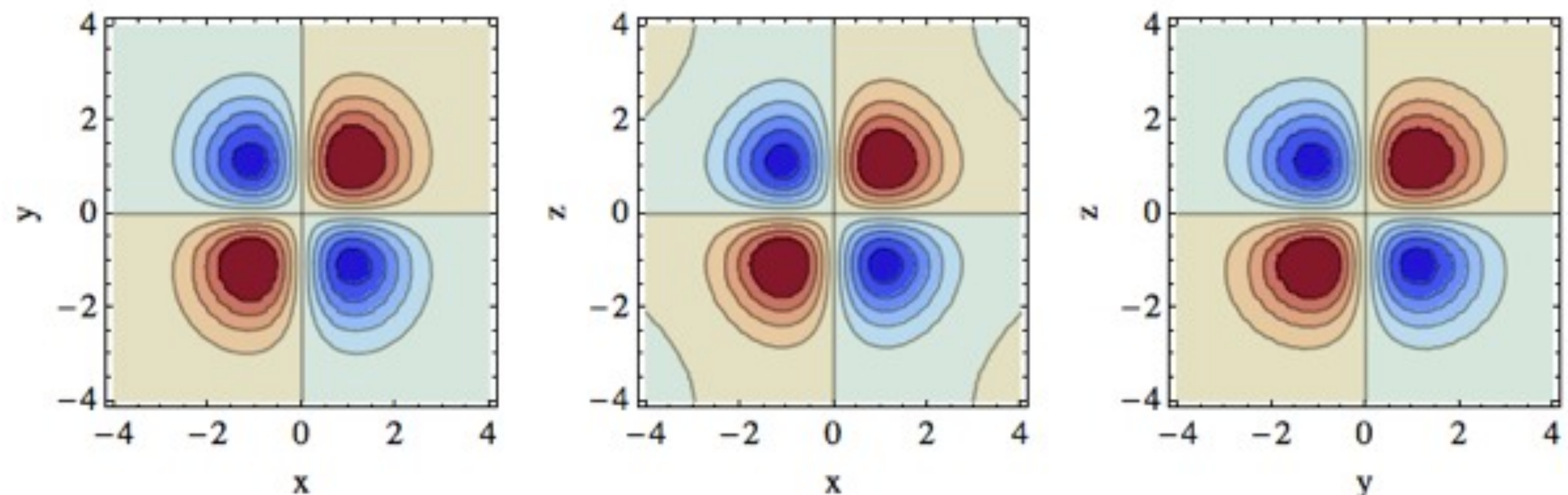

filament
AM
vectors
Zeldovitch flow



Ltheta cross section

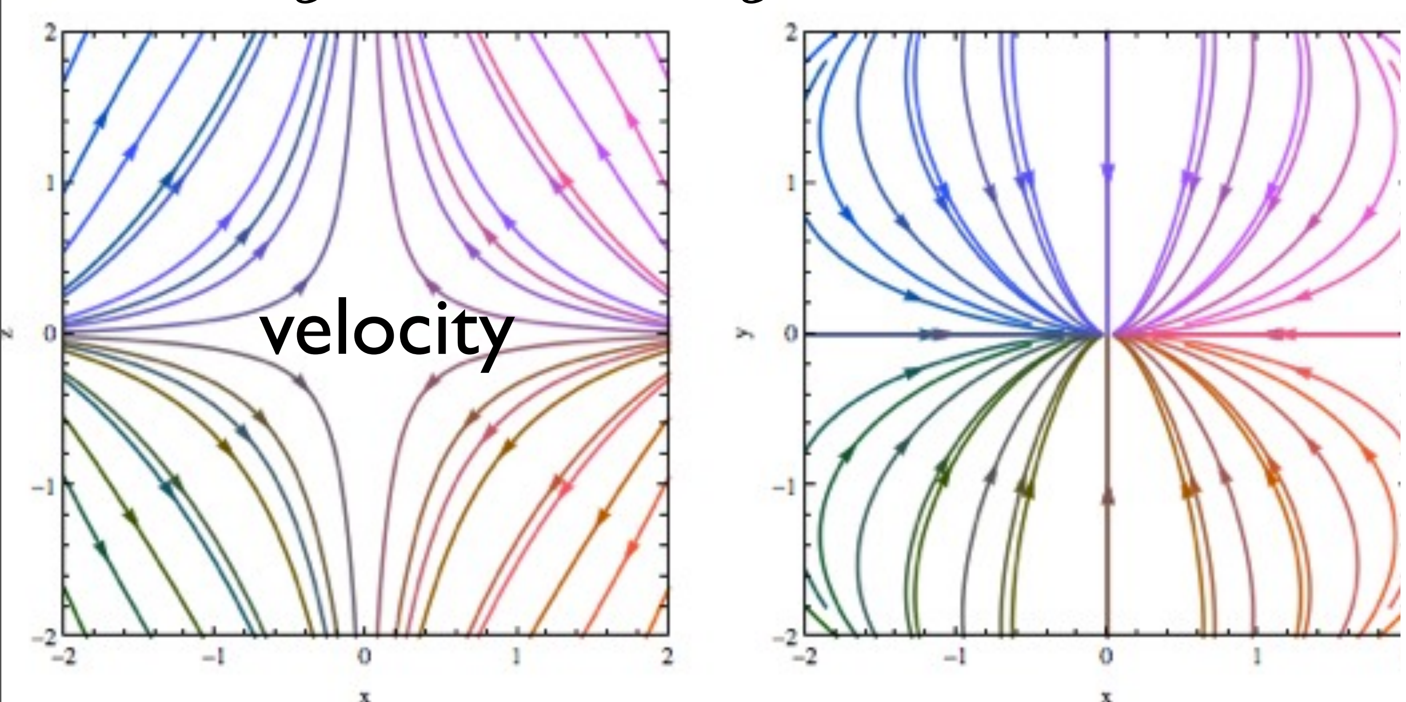
spin orientation



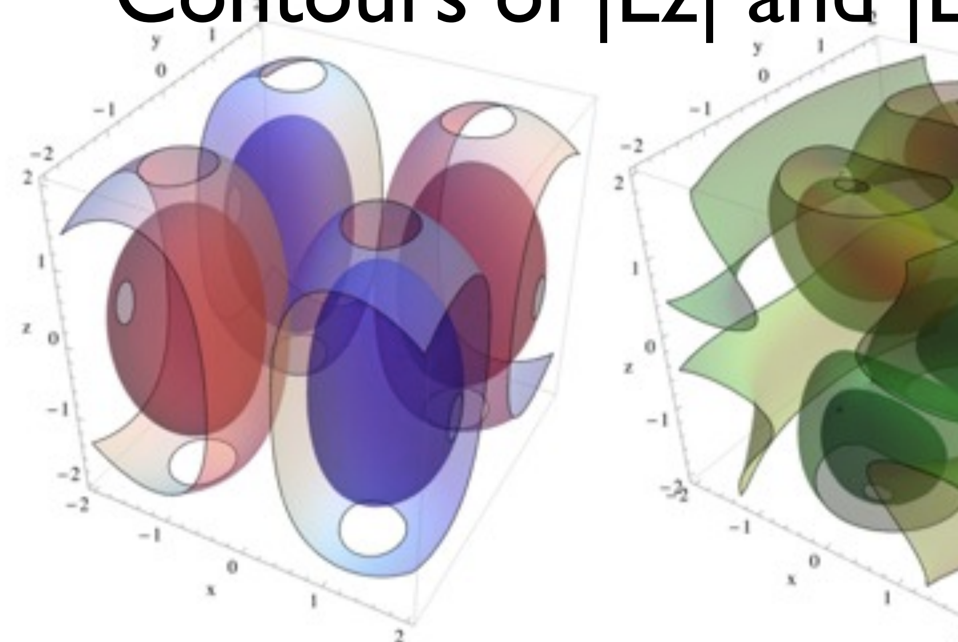


$$\varepsilon_{ijk}\,\delta_{li}\,\psi_{lj}\,\psi_k$$

helicity cross section



Contours of |Lz| and |Lphi|



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

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

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

3D

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

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)

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

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

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

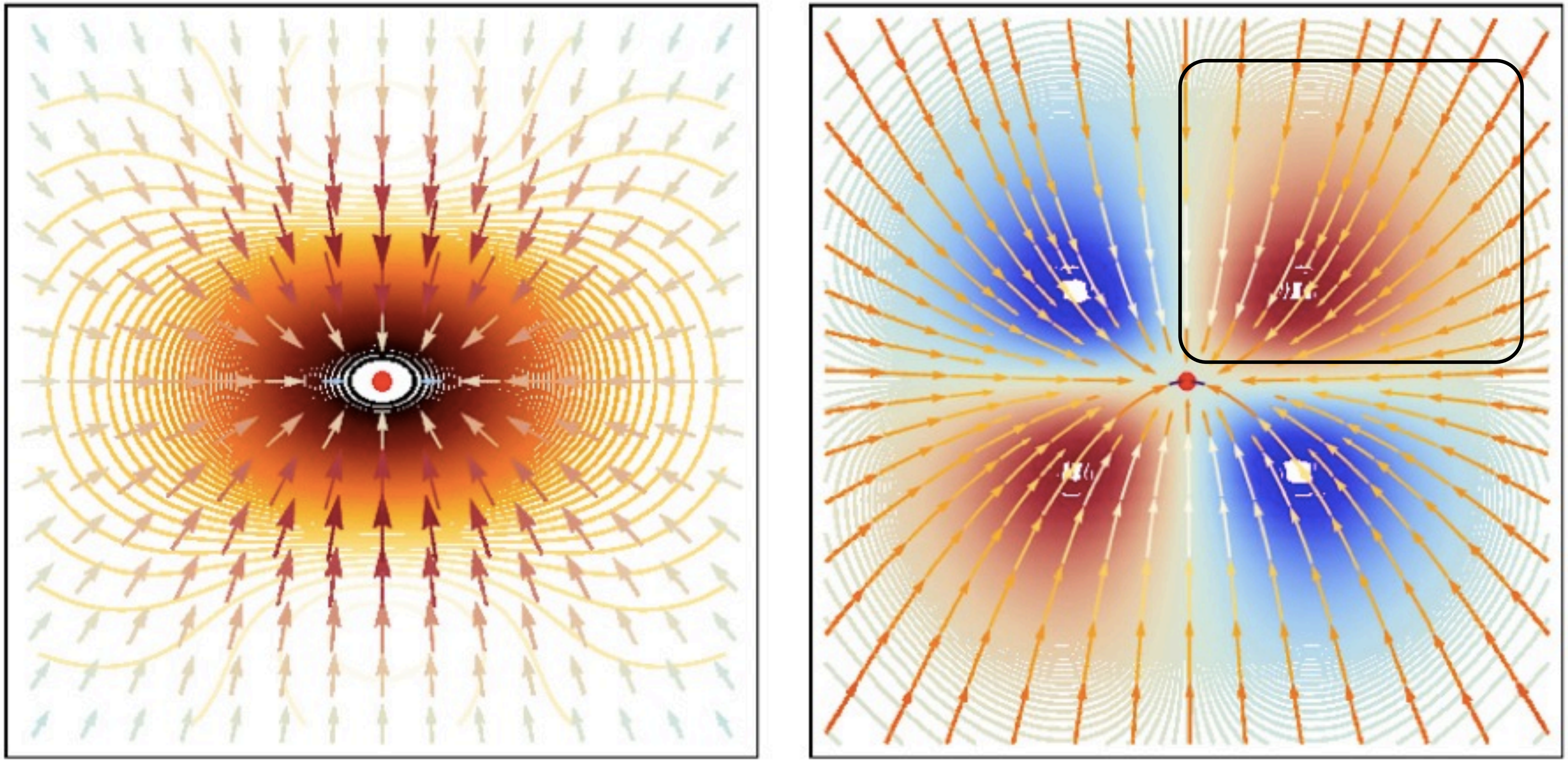


Figure 4. left: cross section of 2D Lagrangian patch near a saddle point; right: corresponding momentum (colour coded) and transverse velocity flow.

Link with Eulerian vorticity?

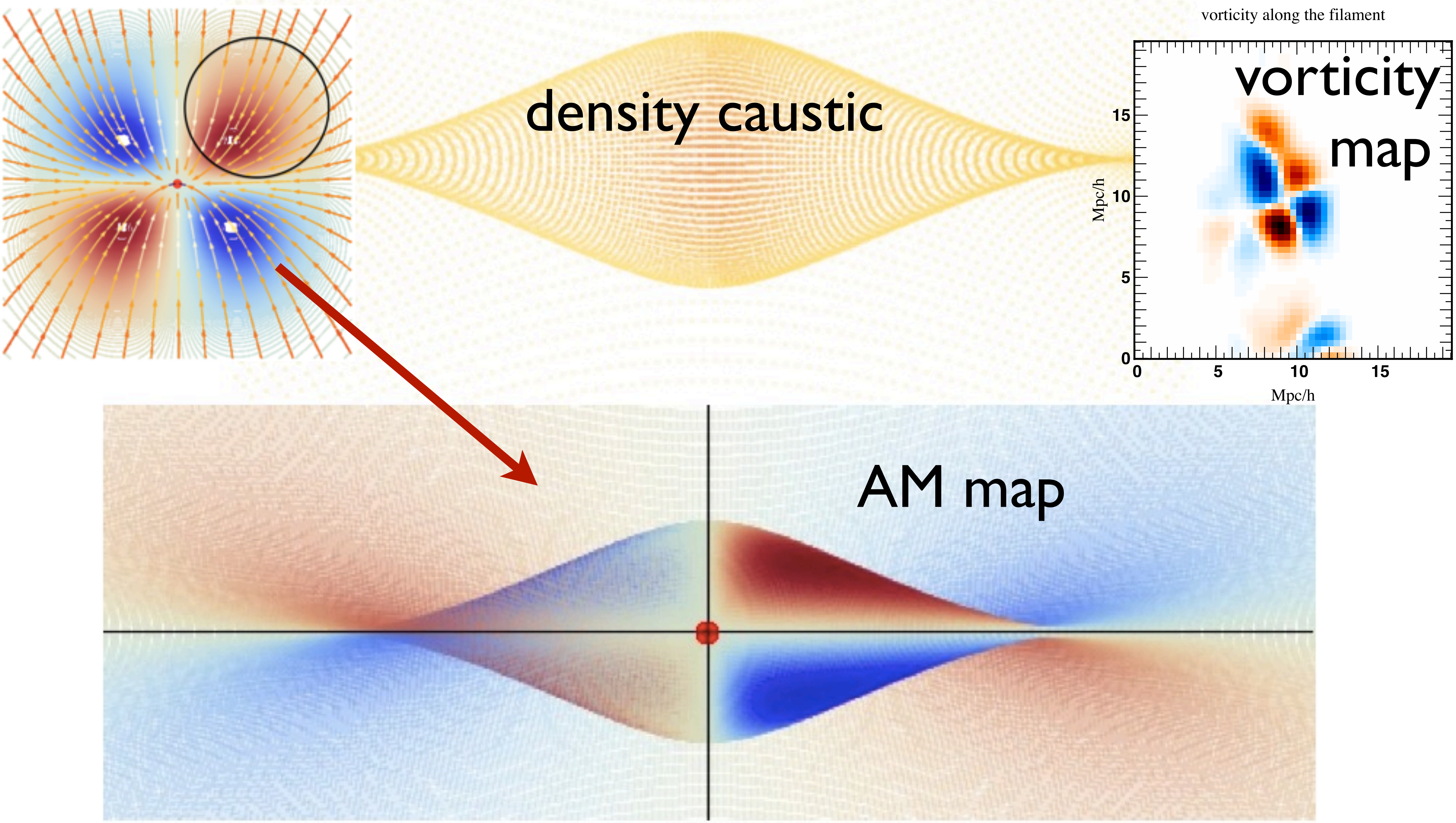
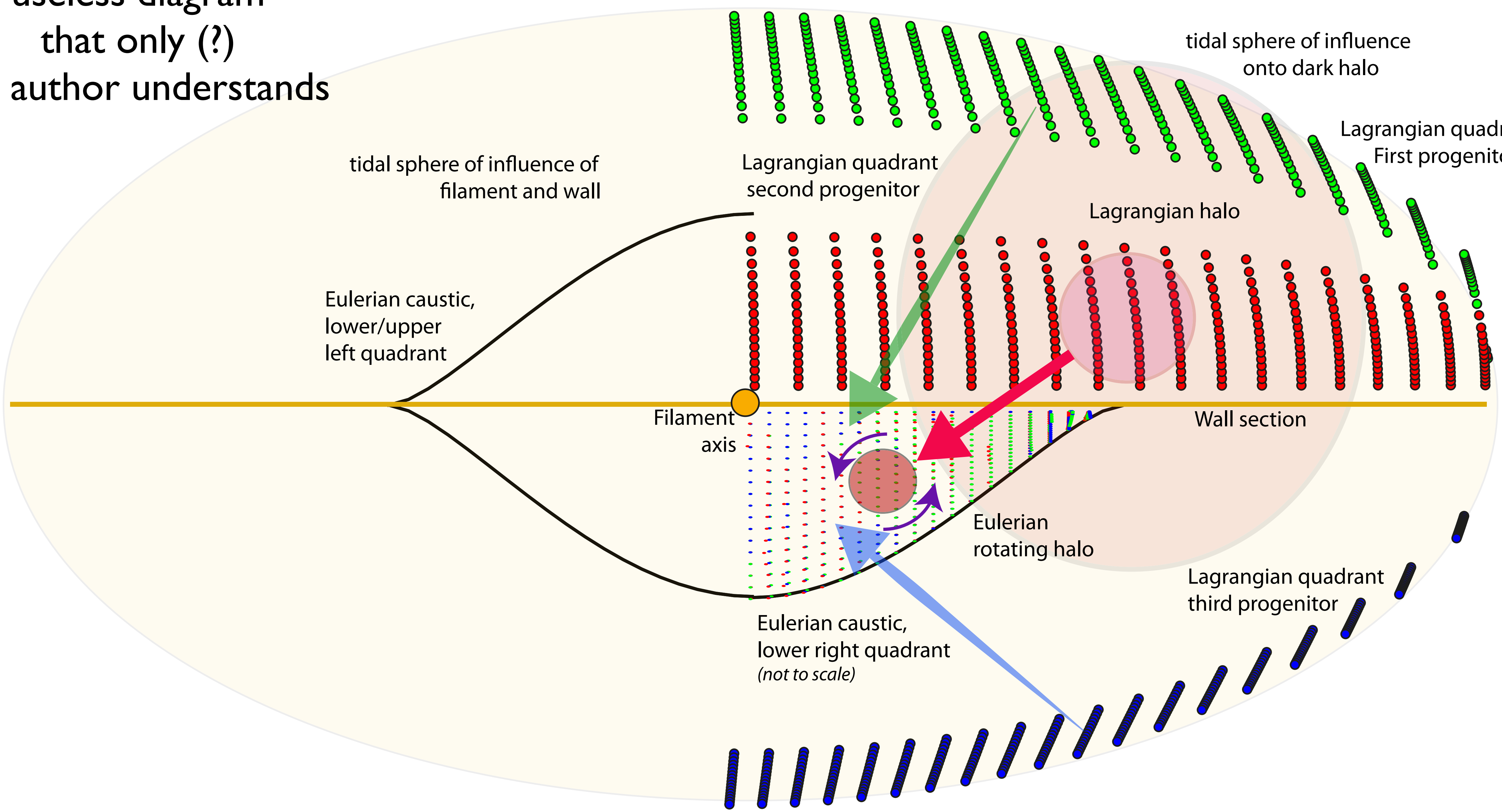


Figure 5. top: Density caustic; Bottom: Zeldovitch mapping of the spin distribution

Eulerian versus Lagrangian theory?

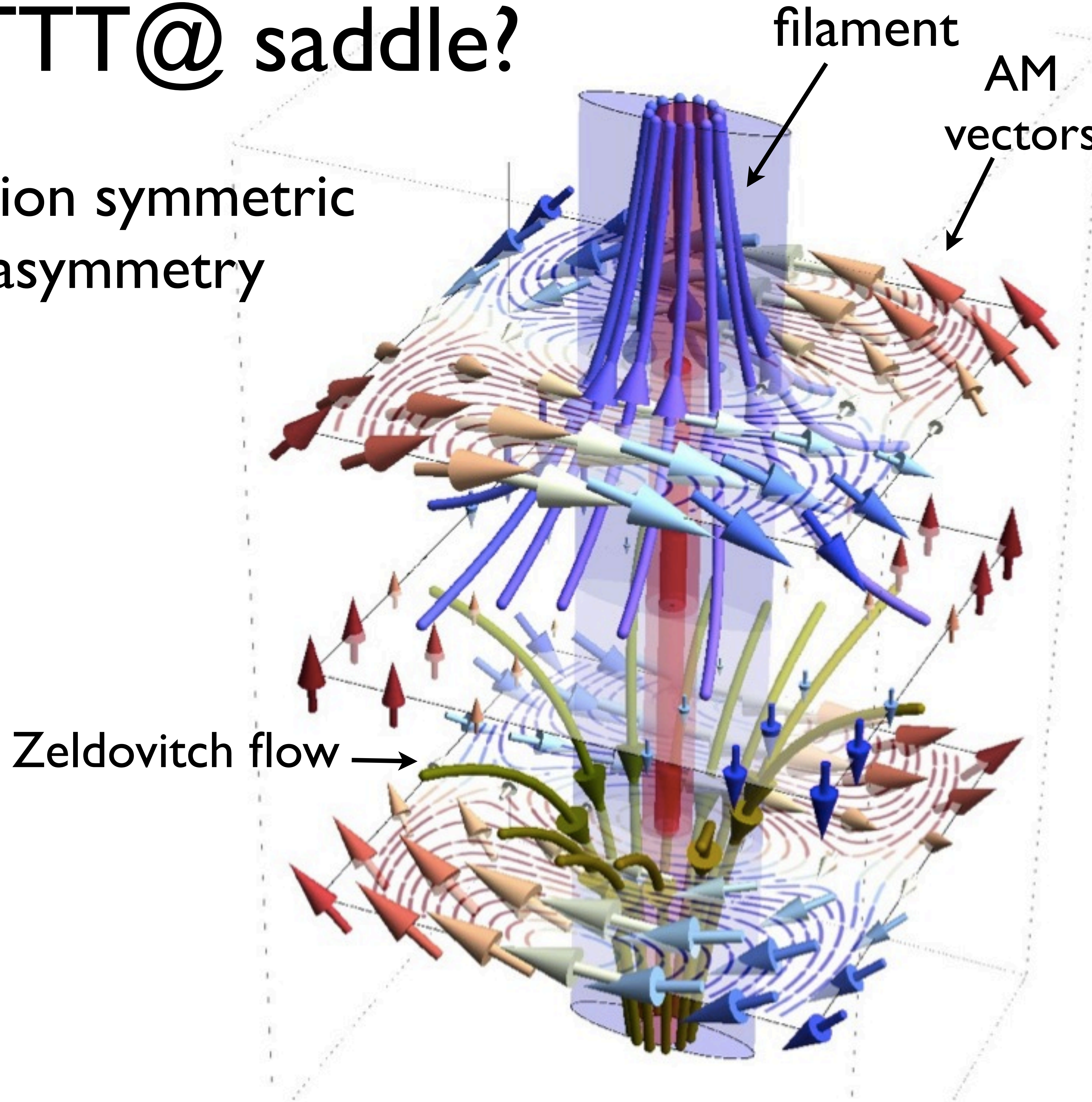
Yet another completely
useless diagram
that only (?)
the author understands



TTT can be reconciled with quadrant dependent vorticity spin alignment if it is extended to account for the tides of the filament.
Then spin-filament alignment can be interpreted both ways.

3D TTT@ saddle?

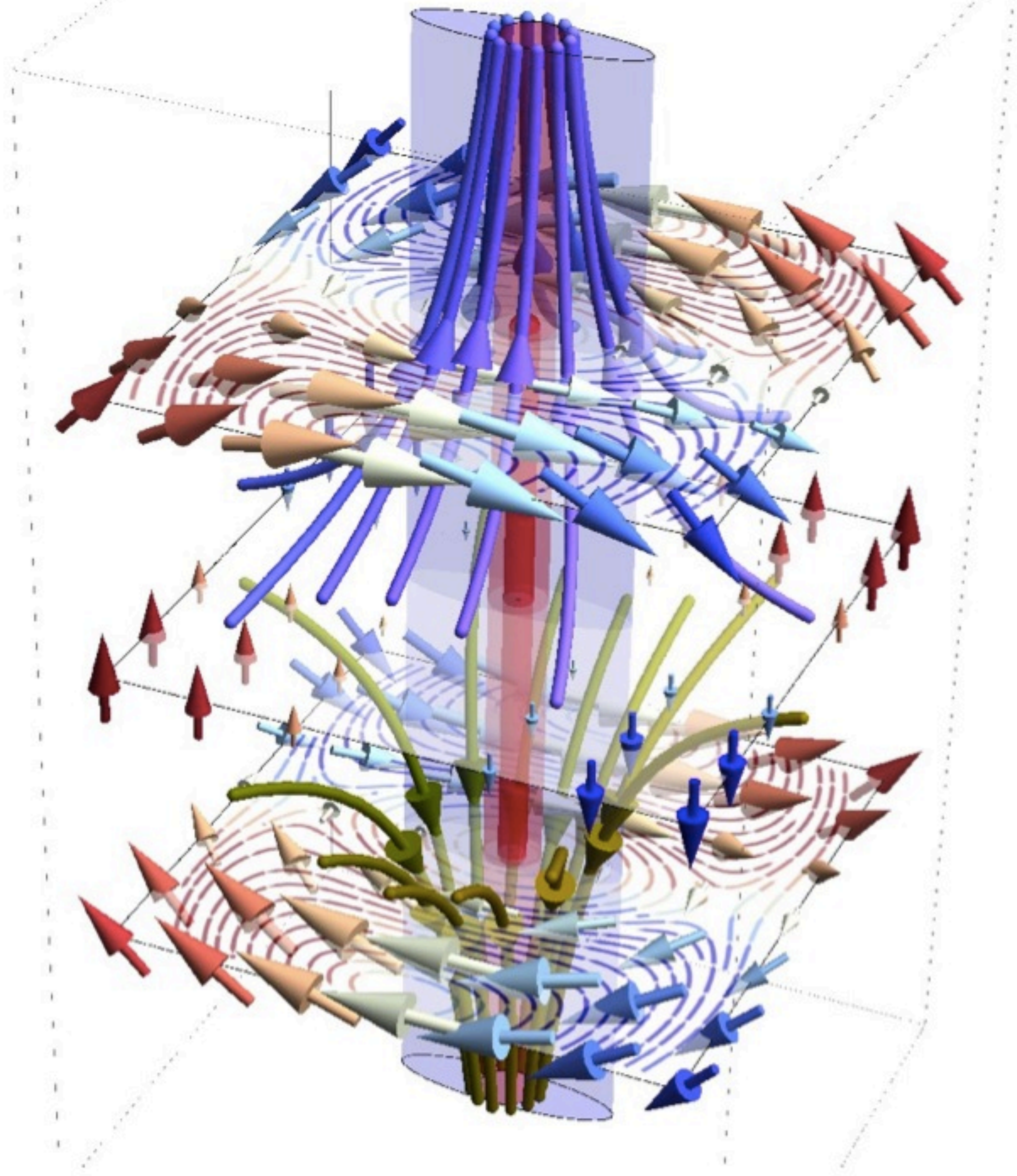
- point reflection symmetric
- vanish if no asymmetry



3D Transition mass ?

Lagrangian theory capture spin flip !

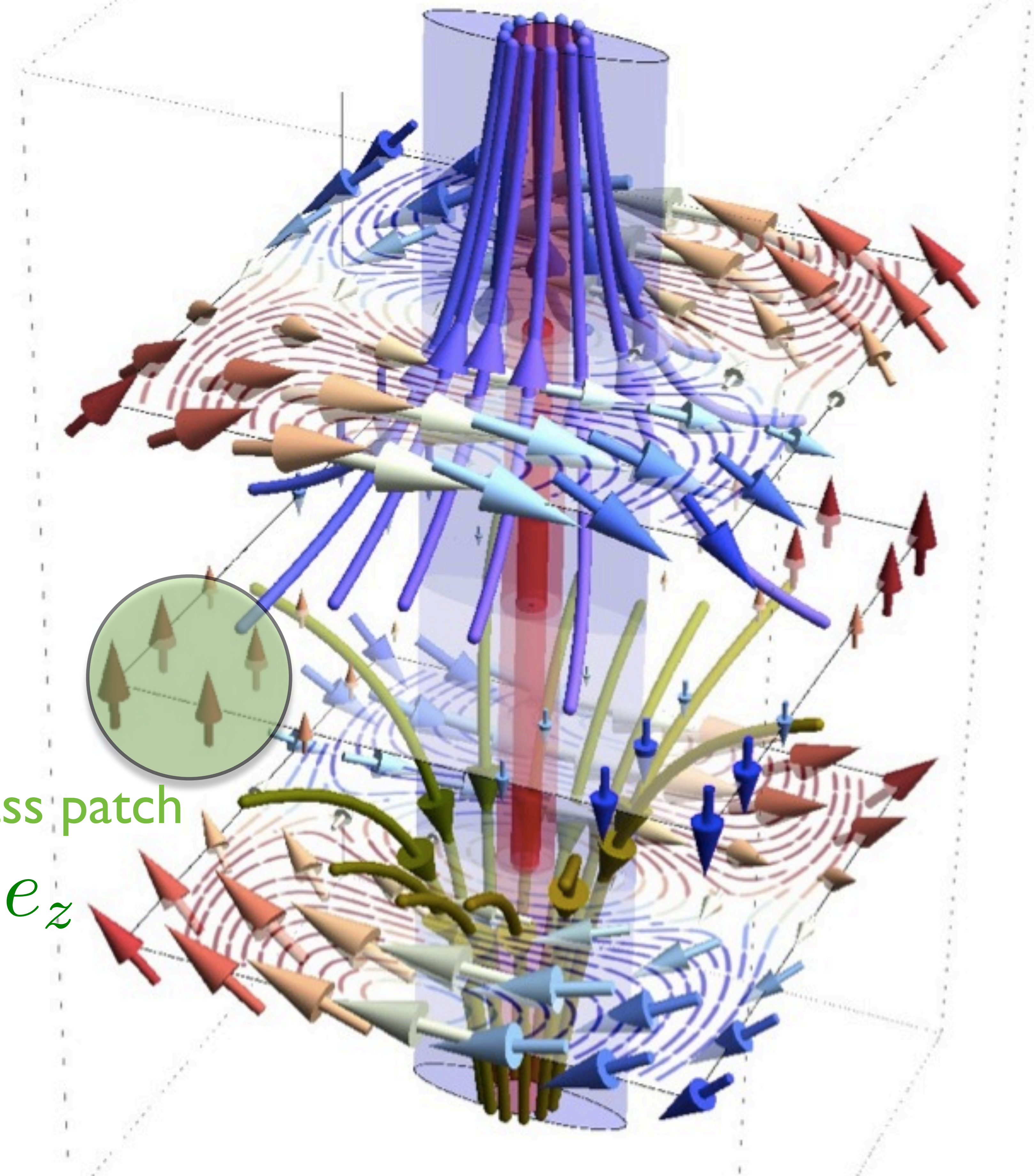
Transition mass associated with **size** of quadrant



3D Transition mass ?

Lagrangian theory
capture spin flip !

Transition mass
associated
with **size**
of quadrant



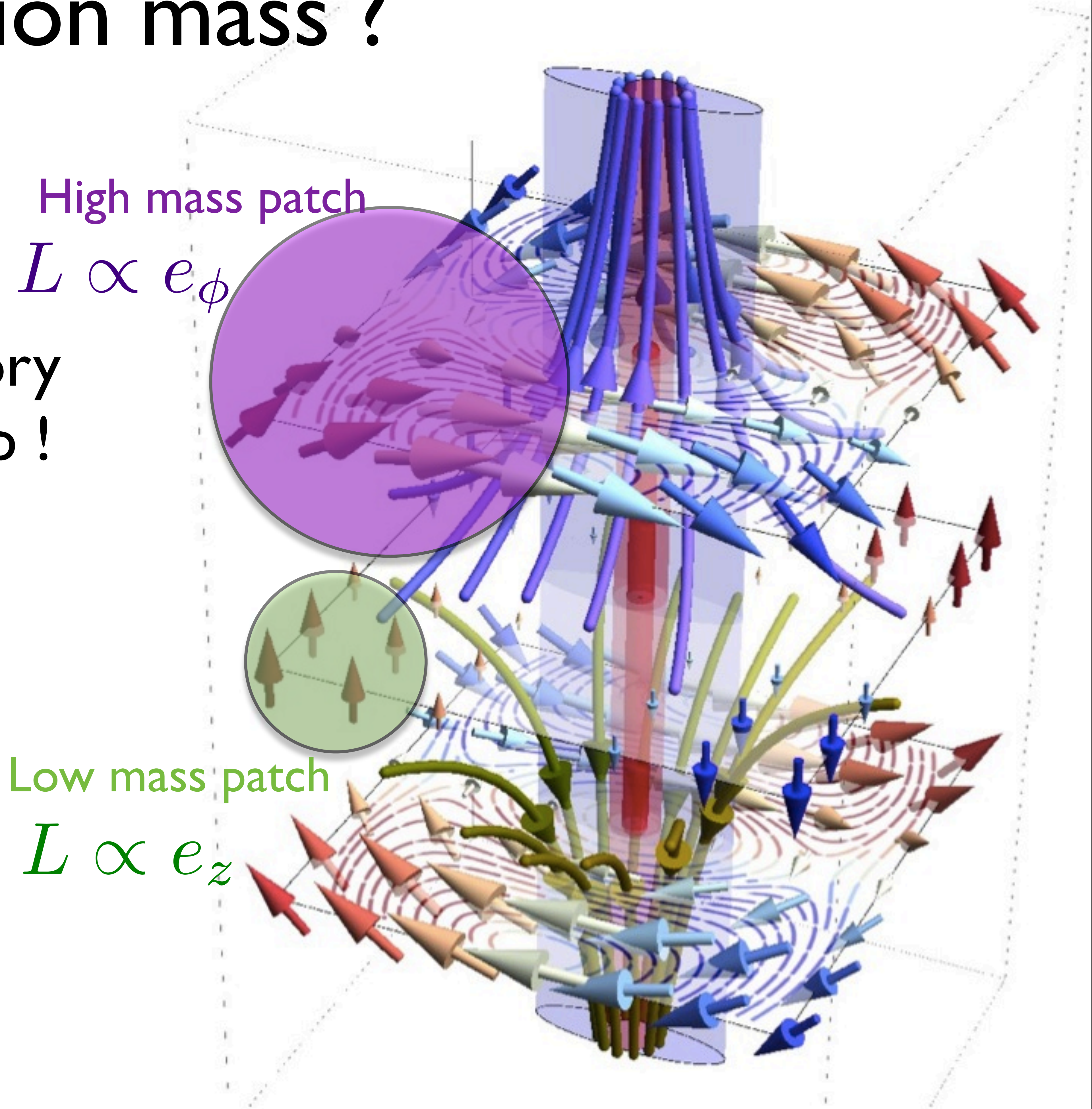
Low mass patch

$L \propto e_z$

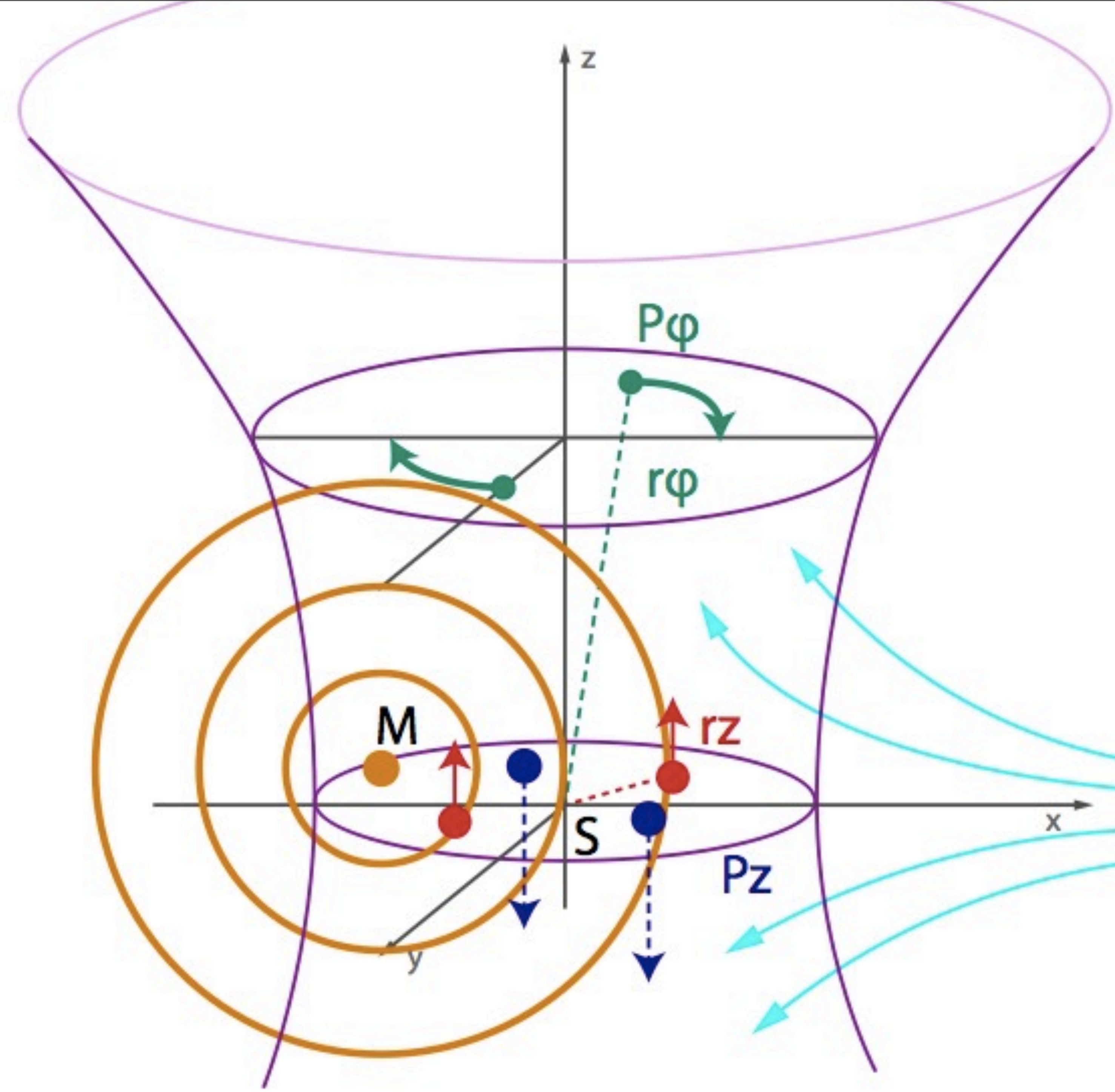
3D Transition mass ?

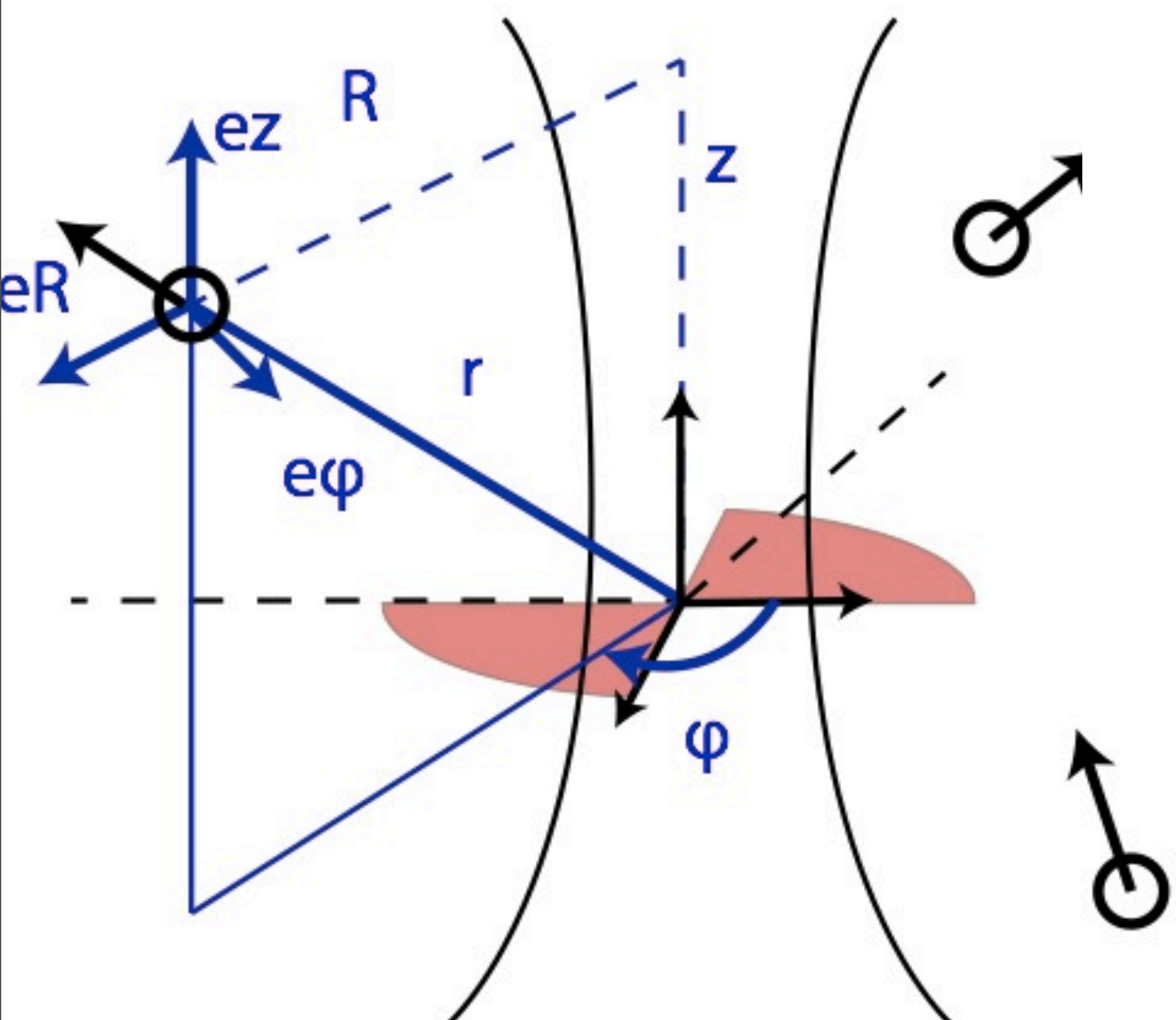
Lagrangian theory capture spin flip !

Transition mass associated with **size** of quadrant

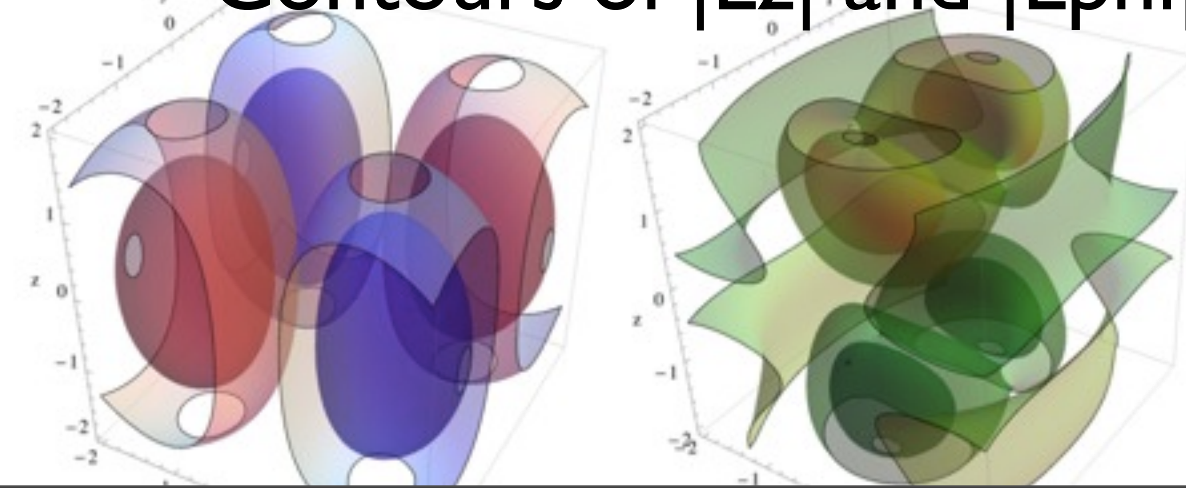


Geometry of AM @ saddle



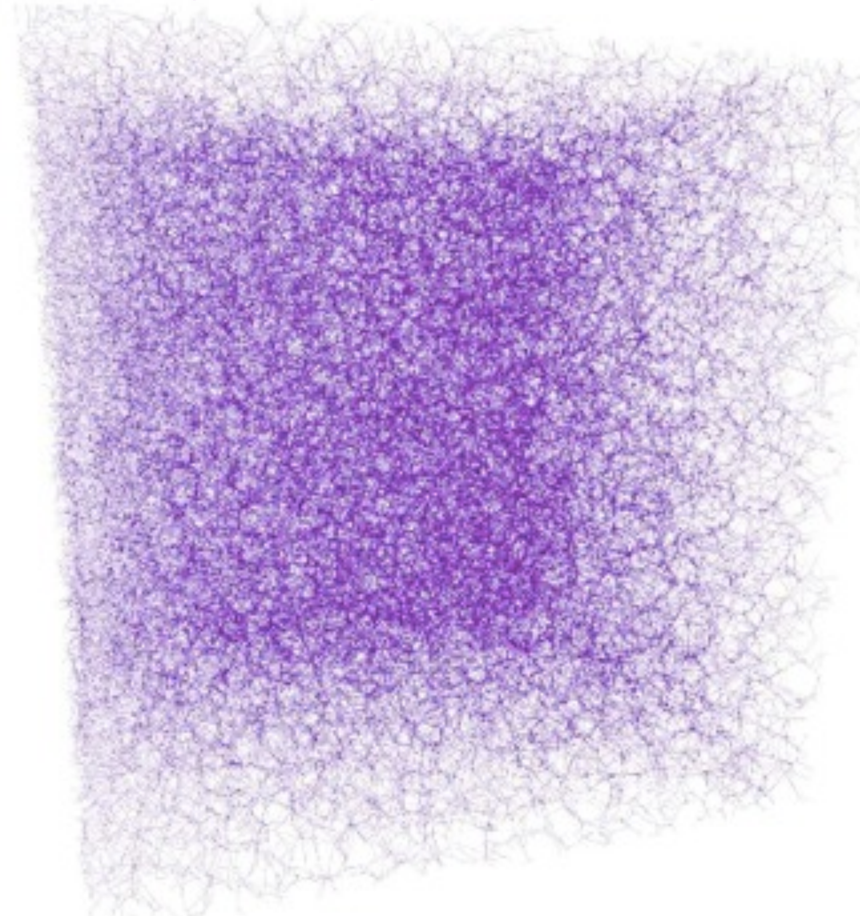


Contours of |Lz| and |Lphi|

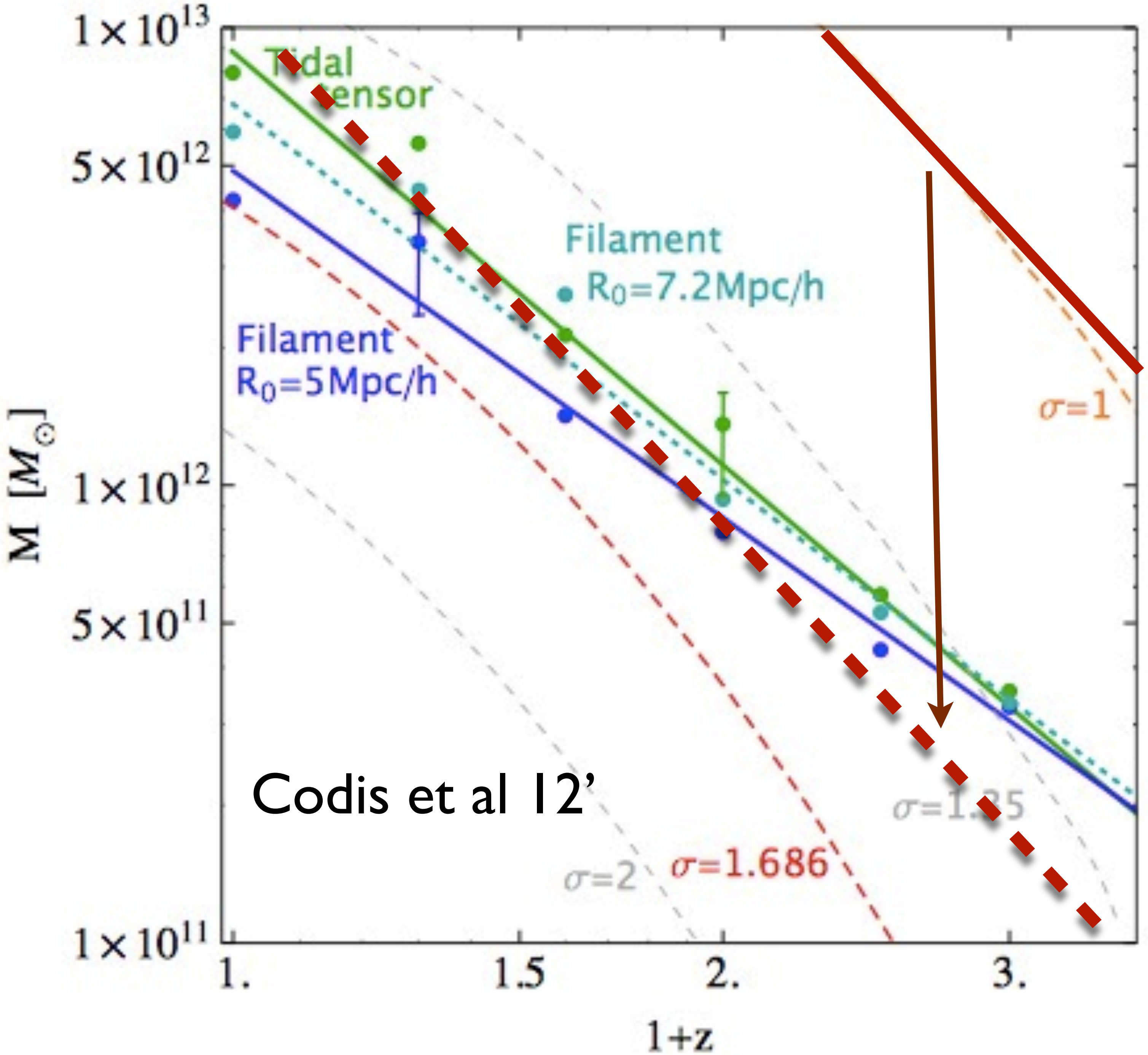


Explain transition mass?

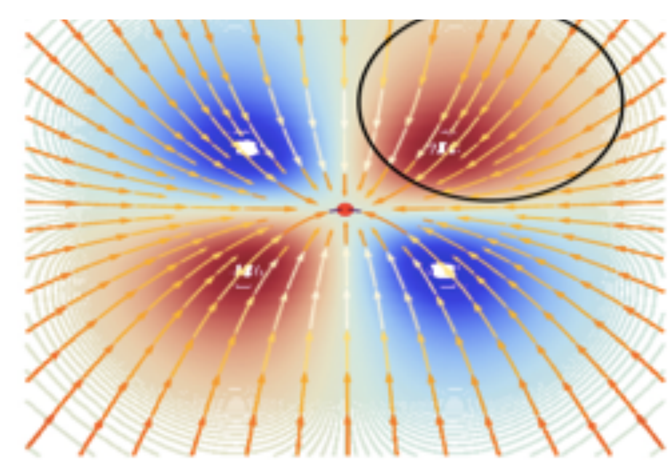
horizon 4π



Transition mass versus redshift



$$\alpha_{3D} = \Delta N \frac{\lambda_2}{\lambda_3}\frac{\lambda_3}{\lambda_1}\left(\frac{r_{\star,z}}{L_s}\right)^2 \frac{r_{\star,\phi}}{L_s}.$$

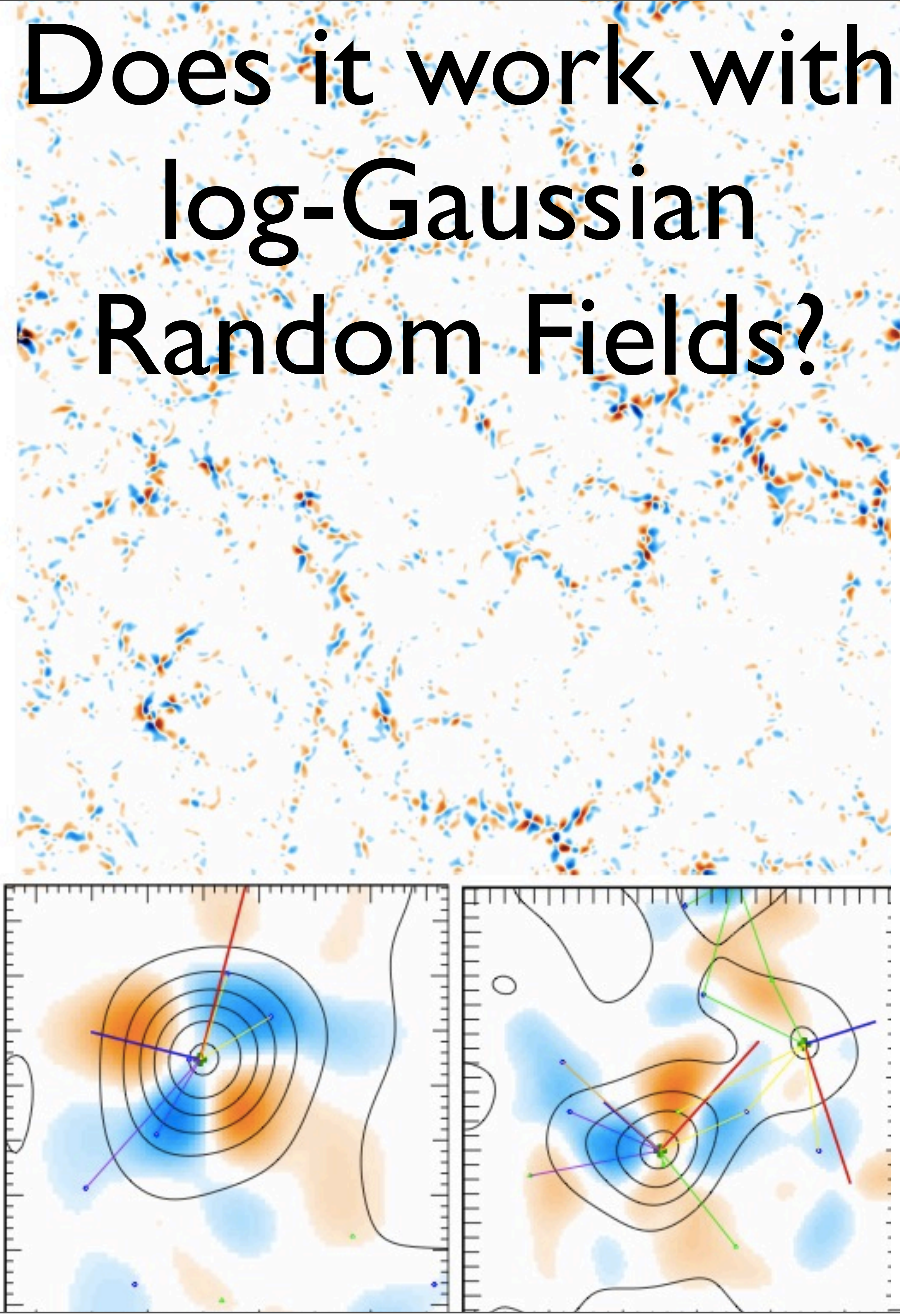


Only 2 ingredients: a) spin is spin one b) filaments flattened

Does it work with log-Gaussian Random Fields?

2D

point reflection symmetry for realistic sets of saddles from log GRF



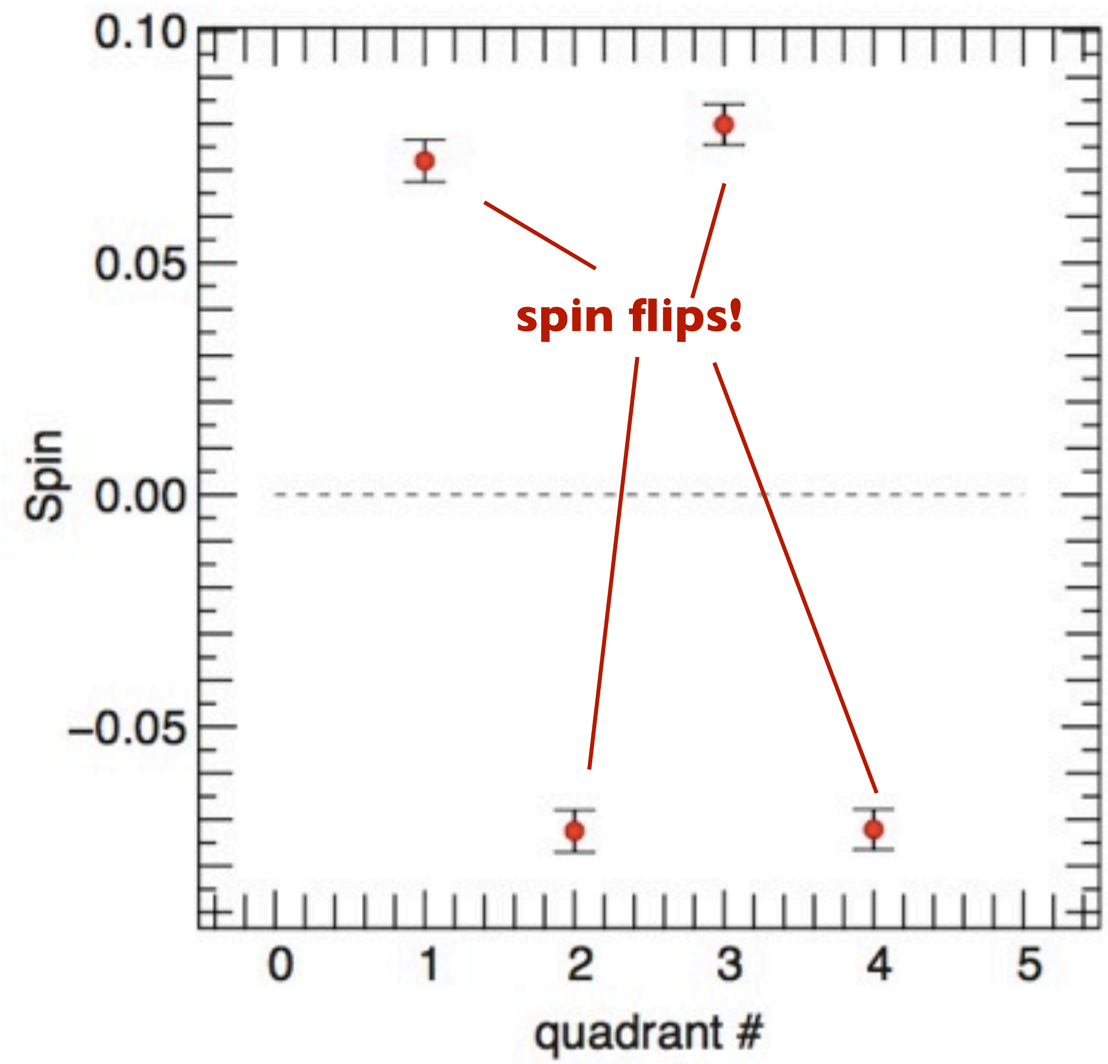
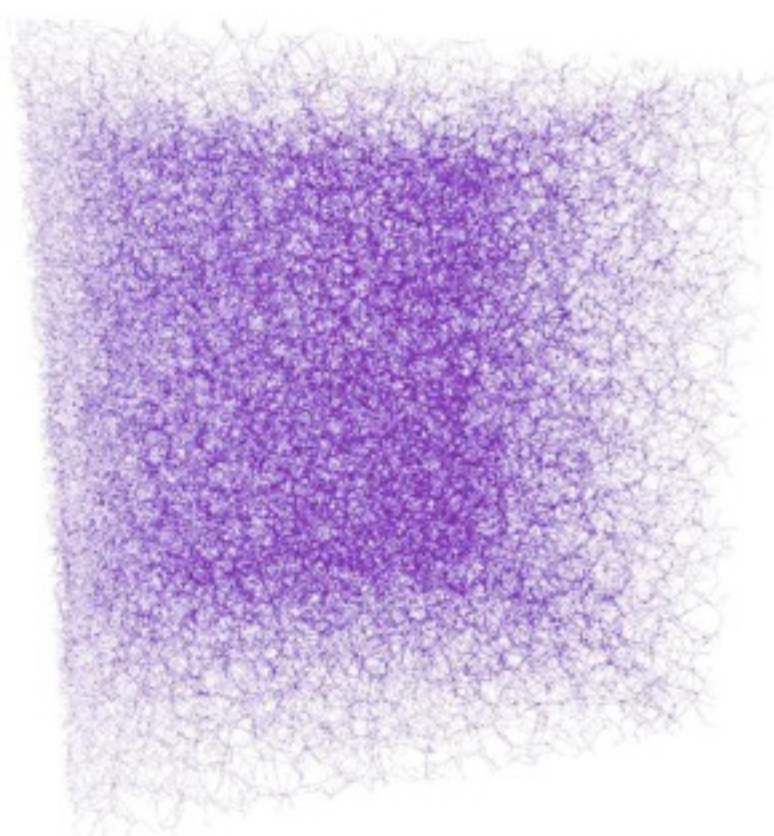
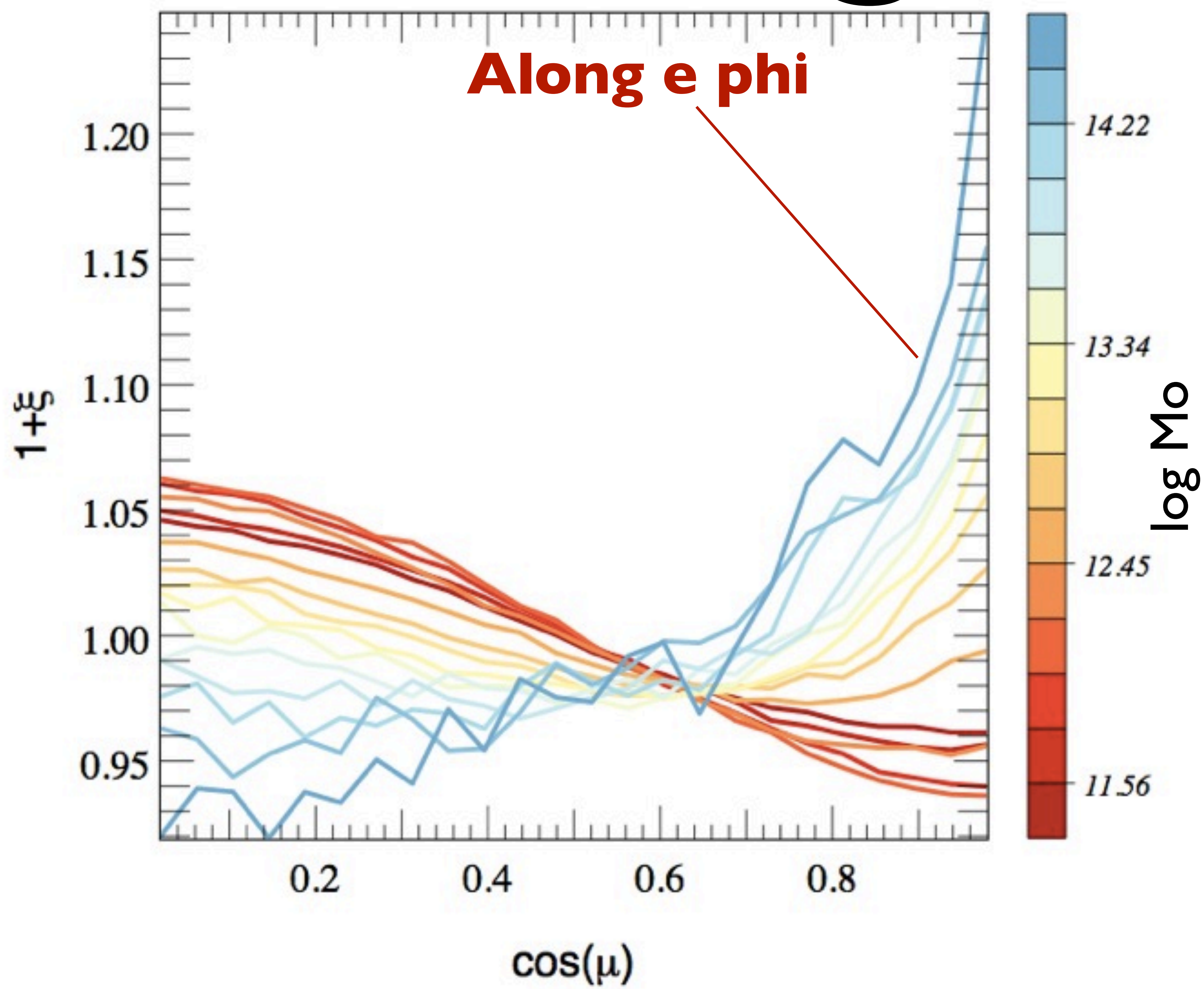


Figure 11. Alignment of 'spin' along $\mathbf{e}_z$ in 2D as a function of quadrant rank, clockwise. As expected, from one quadrant to the next, the spin is flipping sign.

... and with DM simulation @z=0?

Horizon 4Pi:





As predicted,
the physical flip occurs along ephi !

Figure 12. Alignment of 'spin' along $\mathbf{e}_\phi$ in horizon-4π simulation. Low mass galaxies are increasingly perpendicular up to the transition mass, while high mass galaxies parallel to $\mathbf{e}_\phi$.

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!

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

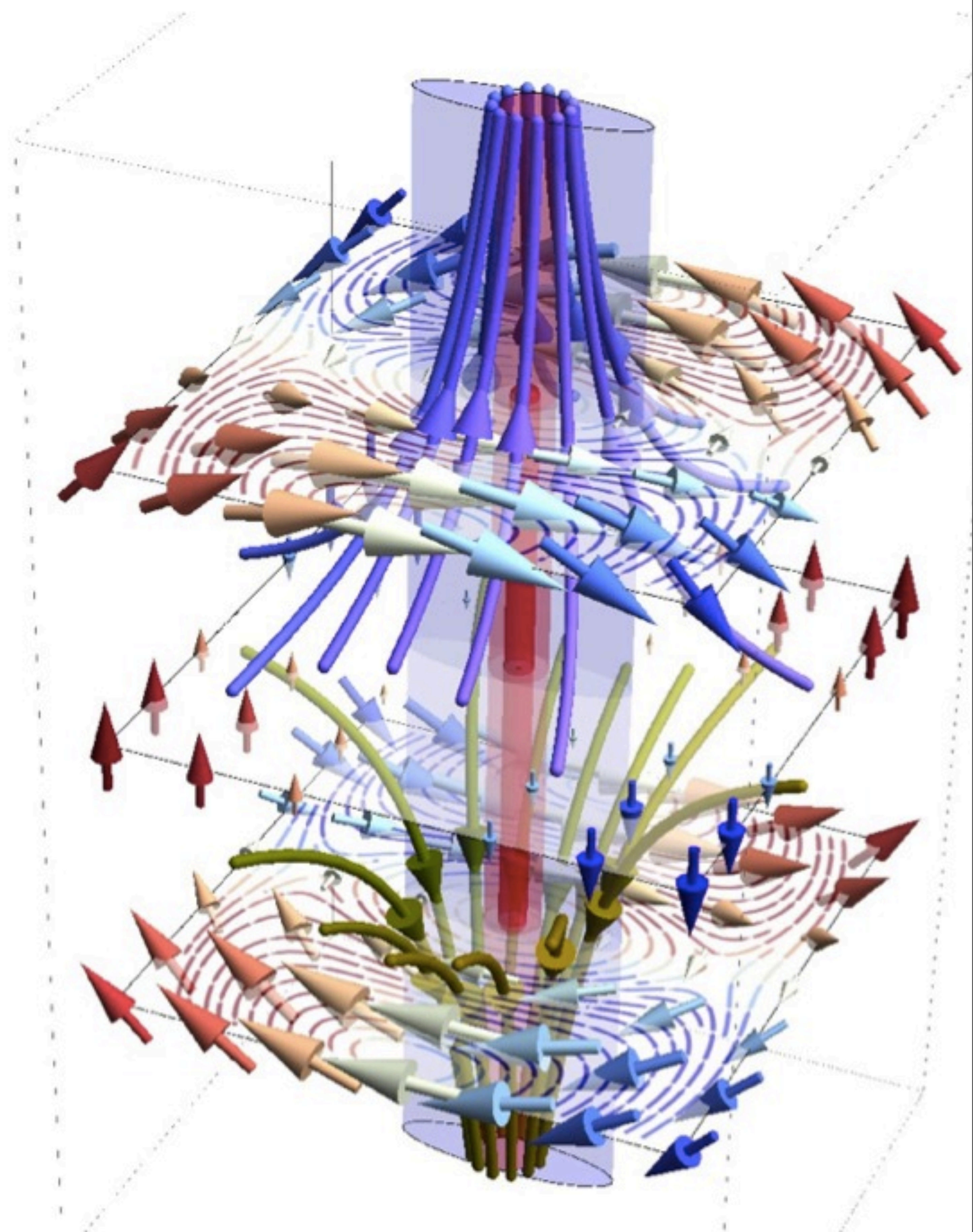


Figure 8
near sadd
away fron

in fact helicity gradient is key

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!

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

predicted Lagrangian extrema of 'helicity'

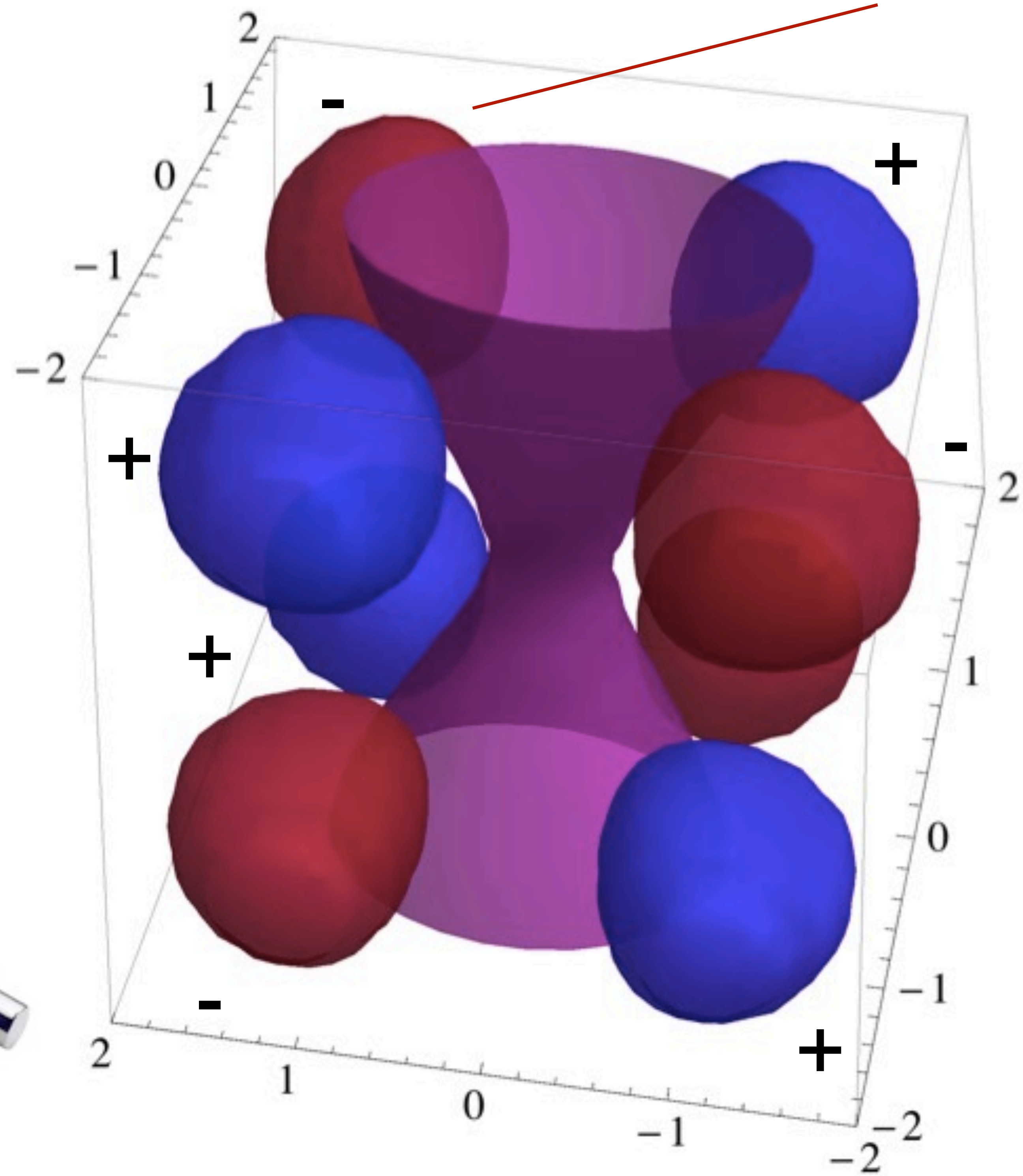


Figure 8. Helicity (colour coded by sign) around density contour near saddle point. Note that Helicity is largest at some distance away from the mid plane.

in fact helicity gradient is key

Take home message...

- Morphology (= AM stratification) driven by LSS via *cold flows* in cosmic web: it explains Es & Sps where, how & why from **ICs**
- Signature in correlation between *morphology* and *internal* kinematical 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
  - Forget about voids: saddles is hype! :-)

- Cosmic web is important because it produces beautiful galaxies

  See Also CODIS + WELKER's talk for implications after coffee

For more details: Pichon et al. 2011 Codis et al 2012, Tillson et al 2012, Laigle et al 2013 Dubois et al 2014 Welker et al 2014, Codis et al. 2014