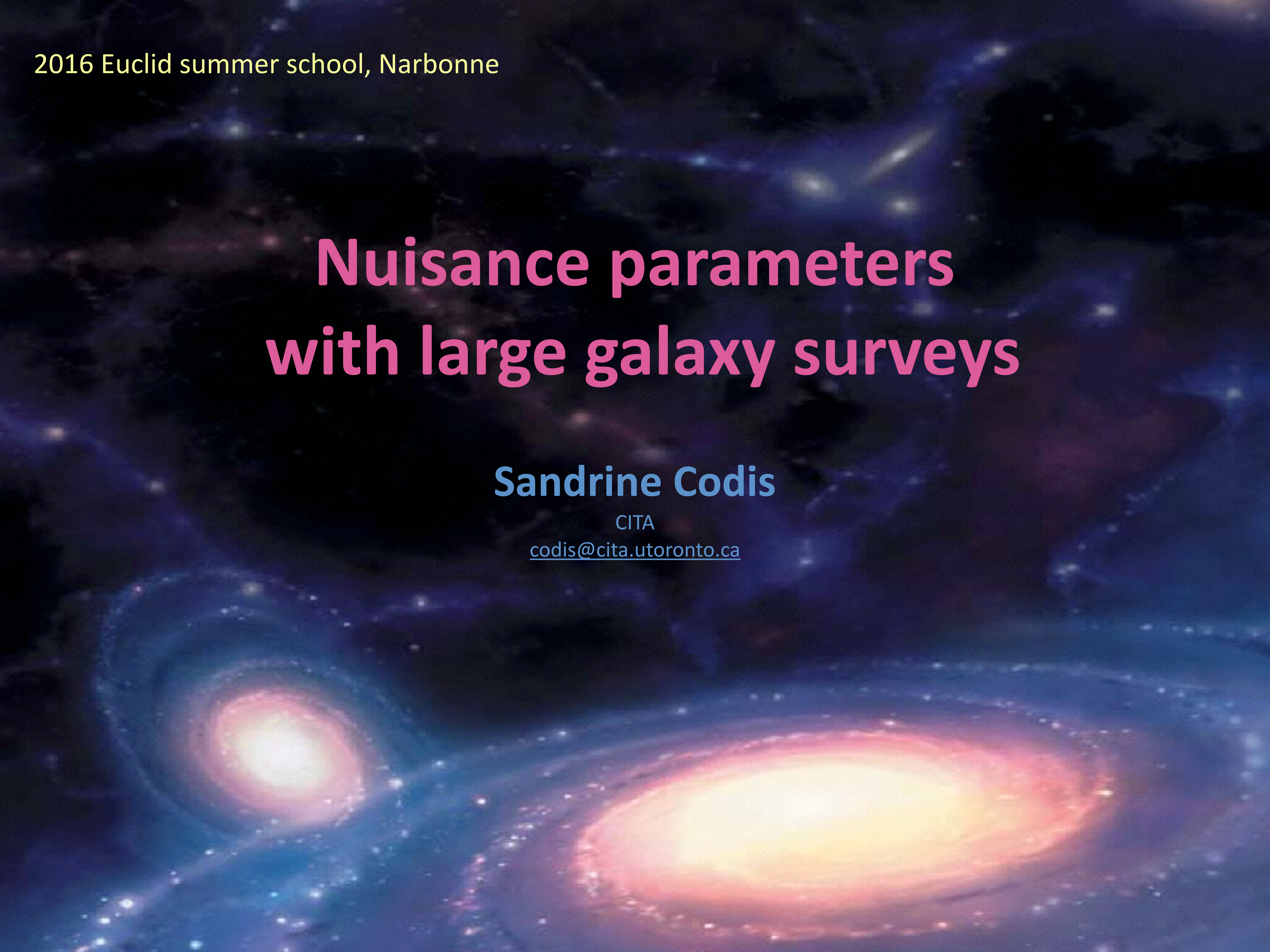
2016 Euclid summer school, Narbonne



Nuisance parameters with large galaxy surveys

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Outline

I. Nuisance parameters in Bayesian analysis

What do you know about Bayesian analysis?

1) I’ve never heard this word before
2) I have a vague understanding
3) I know the concepts well but have never really practiced
4) I am a Bayesian

I. Nuisance parameters in Bayesian analysis

I.1. Statistical inference

The Bayesian point of view interprets probabilities as a **degree of belief** (frequentist have a different epistemological interpretation : probabilities are frequencies of occurence but our Universe is unique).

Bayes' theorem allows us to compute the probability of the parameters of a model given some data (statistical inference):

$$\underset{\text{posterior distribution}}{\mathcal{P}(\theta|d,m)} = \frac{\overset{\text{likelihood}}{\mathcal{P}(d|\theta,m)}\,\overset{\text{prior}}{\mathcal{P}(\theta|m)}}{\underset{\substack{\text{Bayesian evidence}\\ \text{(=normalization)}}}{\mathcal{P}(d|m)}}$$

$m = \text{model}$

$\theta = \text{model parameter}$

$d = \text{data}$

Trivial if you remember that $P(A\&B) = P(A|B)P(B)$.

For instance, m=Lambda-CDM, d is some data (CMB, clustering,…), θ is the set of parameters of the models (Ω_m, σ_8, …).

Visualisation: How to draw figures of merit, compute means, variances, etc?

Once crucial point is to set the **prior**: huge literature on this issue (e.g ignorance priors).

Then, compute the **likelihood**. It can be computationally very challenging - expect for e.g low-dimension Gaussian settings - in which case one has to rely on sampling of the posterior distribution (Markov Chain Monte Carlo, Approximate Bayesian Computation, …). In many applications, a Gaussian approximation (**Fisher matrix** approach) gives a reasonable answer.

→ **see TD tomorrow!**

I. Nuisance parameters in Bayesian analysis

I.1. Statistical inference

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$m = \text{model}$

$\theta = \text{model parameter}$

$d = \text{data}$

I.2. Nuisance parameters

How to deal with nuisance parameters?

$$\theta=(\underset{\substack{\downarrow\\ \text{parameters of interest}}}{\alpha},\beta) \searrow \text{nuisance parameters}$$

Marginalize the posterior distribution over β to infer the parameters of interest:

$$\mathcal{P}(\alpha|d,m) = \int \mathcal{P}(\alpha,\beta|d,m)\mathrm{d}\beta$$

It is not equivalent to slicing the posterior at the most likely value for β!

I.3. Modelling the unknown with nuisance parameters

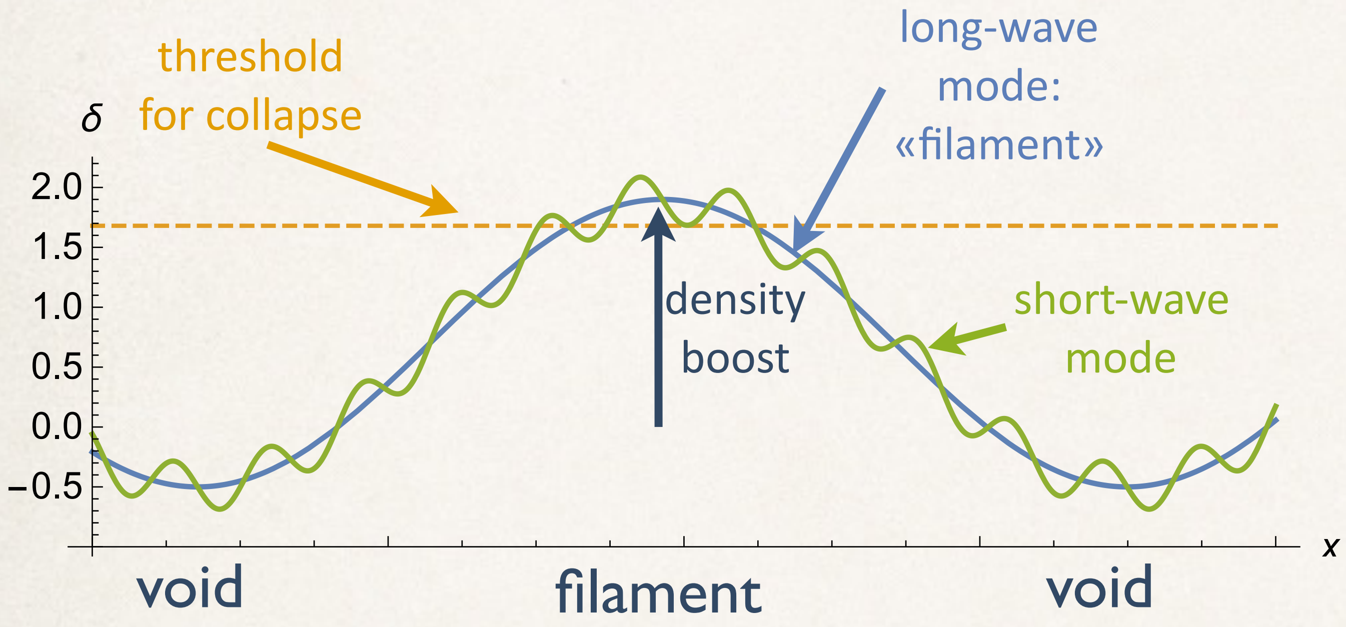
Some examples (see also Francis Bernardeau and Martin Kilbinger's lectures):

-from the instrument: calibrations, …

-physical unknown:

- ☆ galaxy biasing (peak bias, halo bias, baryonic physics)

Galaxies form at the peaks of the initial density field



The most massive objects (high peaks) tend to form in the densest environments (dense filaments and nodes) and are more clustered.

But:

The peak model is an approximation: 30% of halos in DM simulation do not correspond to a peak in the initial condition (Porciani&Ludlow11);

Baryonic physics/galaxy formation: on what scales (if any) are we safe from baryonic effects (feedback can have an influence on somewhat large scales)? van Daalen++11, Schneider++15

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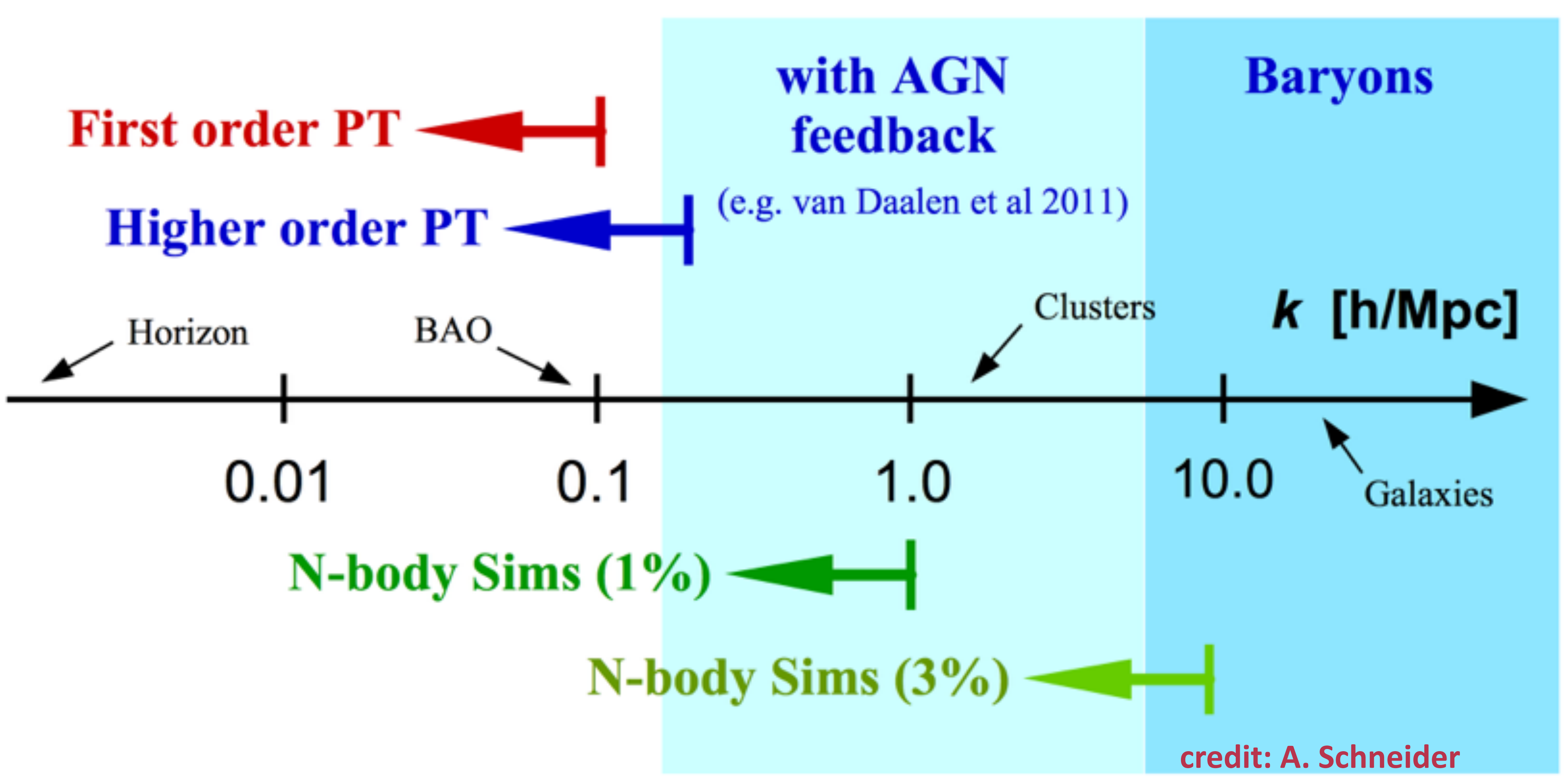


credit: A. Schneider

Baryonic physics/galaxy formation: on what scales (if any) are we safe from baryonic effects (feedback can have an influence on somewhat large scales)? van Daalen++11, Schneider++15

Problem: Hydro simulations are not predictive. Can we still parametrize baryonic physics?

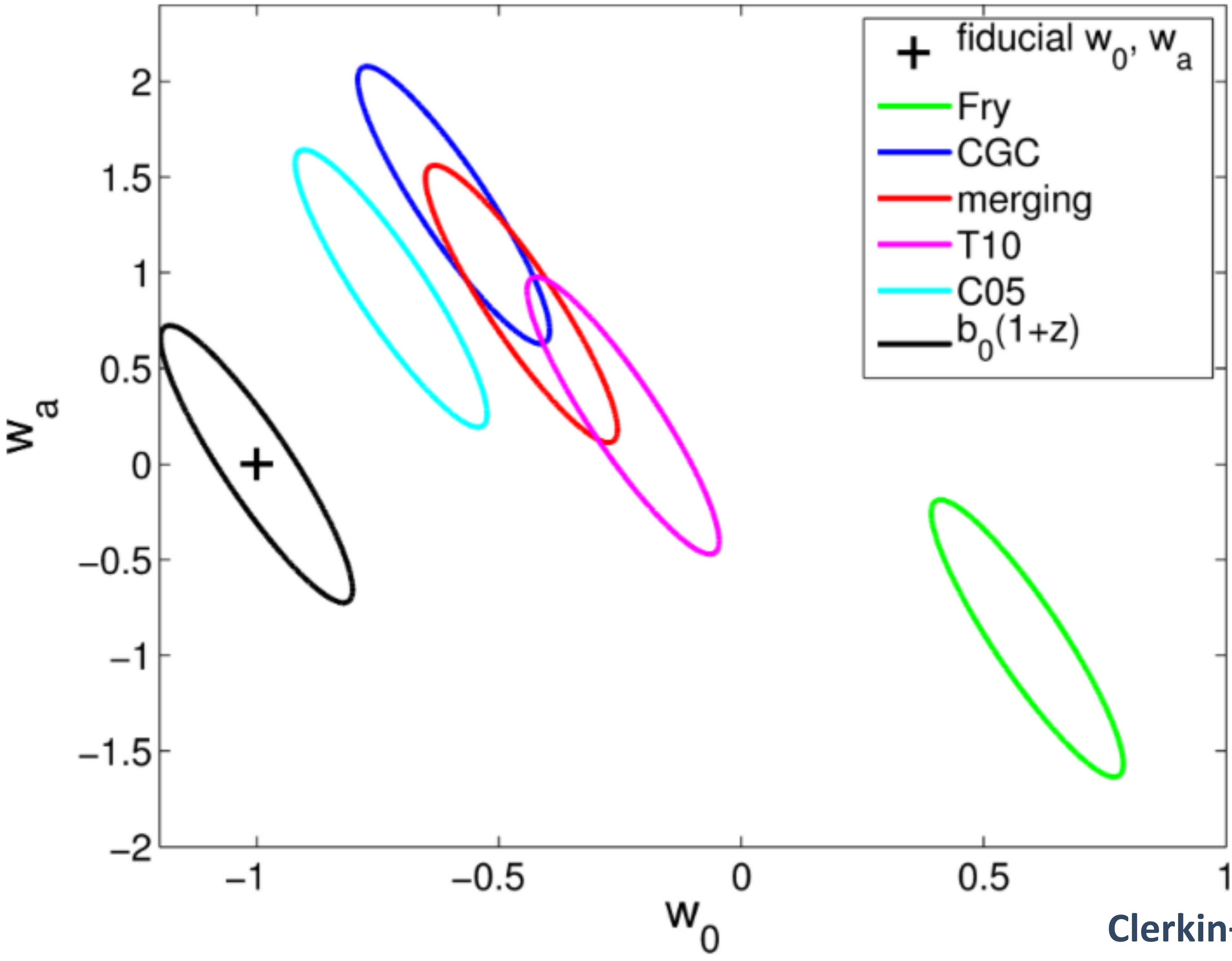
I.3. Modelling the unknown with nuisance parameters

Some examples (see also Francis Bernardeau and Martin Kilbinger's lectures):

-from the instrument: calibrations

-

impact of having a wrong model for b(z) on the eos of DE



Clerkin++15

-

effects

der++15

sics?

I.3. Modelling the unknown with nuisance parameters

Some examples (see also Francis Bernardeau and Martin Kilbinger's lectures):

-from the instrument: calibrations, …

-physical unknown:

- galaxy biasing (peak bias, halo bias, baryonic physics)
- redshift space distortions

Different models e.g TNS (see FB's talk). Probably valid below k about 0.2 h/Mpc.

$$P(k,\mu) = D_{\mathrm{f}}(k\,\mu\,f\sigma_{\mathrm{v}})$$

damping

$$\times \Big[P_{\delta\delta}(k) + 2\,f\mu^2 P_{\delta\theta}(k) + f^2\mu^4 P_{\theta\theta}(k)$$

« extended Kaiser »

$$+\underline{A(k,\mu;f) + B(k,\mu;f)}\Big]$$

I.3. Modelling the unknown with nuisance parameters

Some examples (see also Francis Bernardeau and Martin Kilbinger’s lectures):

-from the instrument: calibrations, …

-physical unknown:

- galaxy biasing (peak bias, halo bias, baryonic physics)
- redshift space distortions,
- non-linearities (effective field theory?)

$$P_{\text{EFT-2-loop}} = P_{11} + P_{\text{1-loop}} + P_{\text{2-loop}} - 2\,(2\pi)(c^2_{s(1)} + c^2_{s(2)})\frac{k^2}{k^2_{\text{NL}}}P_{11} + (2\pi)c^2_{s(1)}P^{(c_s,p)}_{\text{1-loop}} + (2\pi)^2 c^4_{s(1)}\frac{k^4}{k^4_{\text{NL}}}P_{11}$$

I.3. Modelling the unknown with nuisance parameters

Some examples (see also Francis Bernardeau and Martin Kilbinger's lectures):

-from the instrument: calibrations, …

-physical unknown:

- ☆ galaxy biasing (peak bias, halo bias, baryonic physics)
- ☆ redshift space distortions,
- ☆ non-linearities (effective field theory?)
- ☆ intrinsic alignments of galaxies
- ☆ …

Issues: model-dependent constraints, number of d.o.f., …

Marginalizing over parameters of a given model does not guarantee that this model fits well the data ⟶ model comparison.

Possible alternatives: try different parametrizations, e.g form filling function (Kitching++09)

It is important to have multiple observables having different biases and sensitivities (e.g alternative probes like extrema counts, Minkowski functionals, count-in-cell PDF, voids, …)!

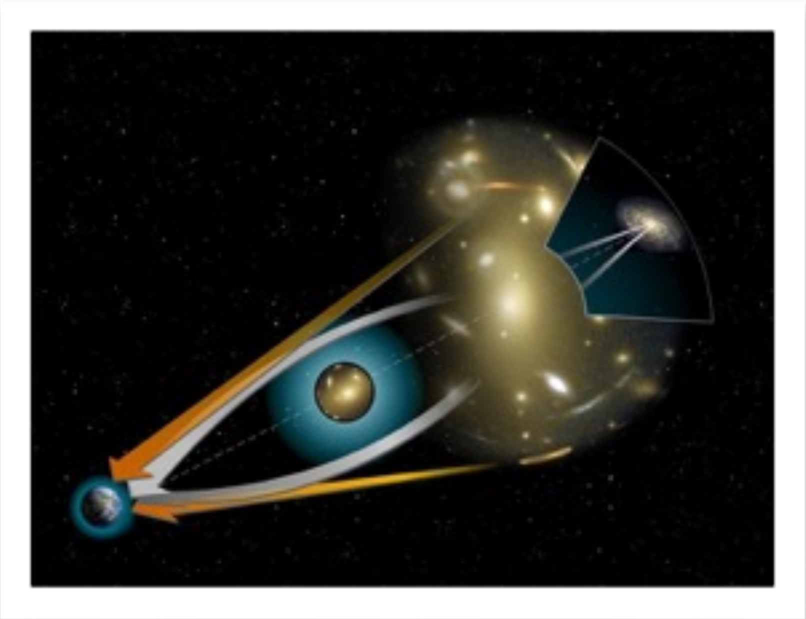
ANY QUESTIONS?

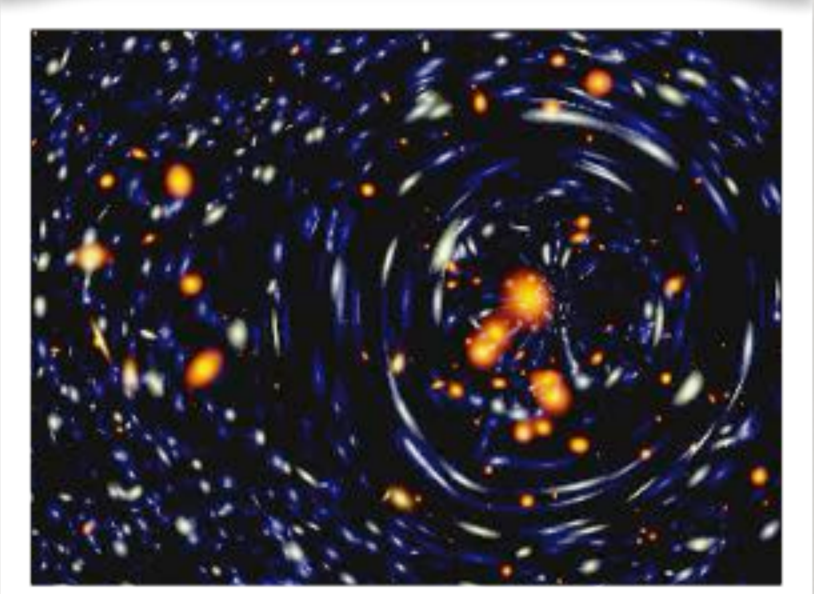
II. Intrinsic alignments

What do you know about intrinsic alignments?

1) I’ve never heard this word before
2) I have a vague understanding
3) I know some concepts but would like to hear more
4) I know everything

Intrinsic alignments contaminate weak lensing!

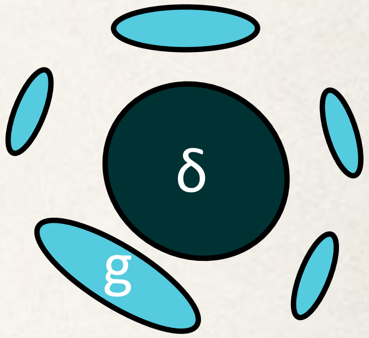




credit: LSST

Weak lensing creates **tangential distorsions** of galaxy shapes.

small effect (~1%)!



$$\underset{\text{apparent ellipticity}}{\epsilon} = \overset{\text{shear}}{\gamma} + \underset{\text{intrinsic ellipticity}}{\epsilon^s}$$

Measure coherent distortions:

$$\langle \epsilon_i \epsilon_j \rangle = \langle \gamma_i \gamma_j \rangle + \left\langle \epsilon_i^s \epsilon_j^s \right\rangle + \langle \epsilon_i^s \gamma_j \rangle + \left\langle \gamma_i \epsilon_j^s \right\rangle$$

intrinsic ellipticity correlations (II term)

shear-ellipticity correlations (GI term)

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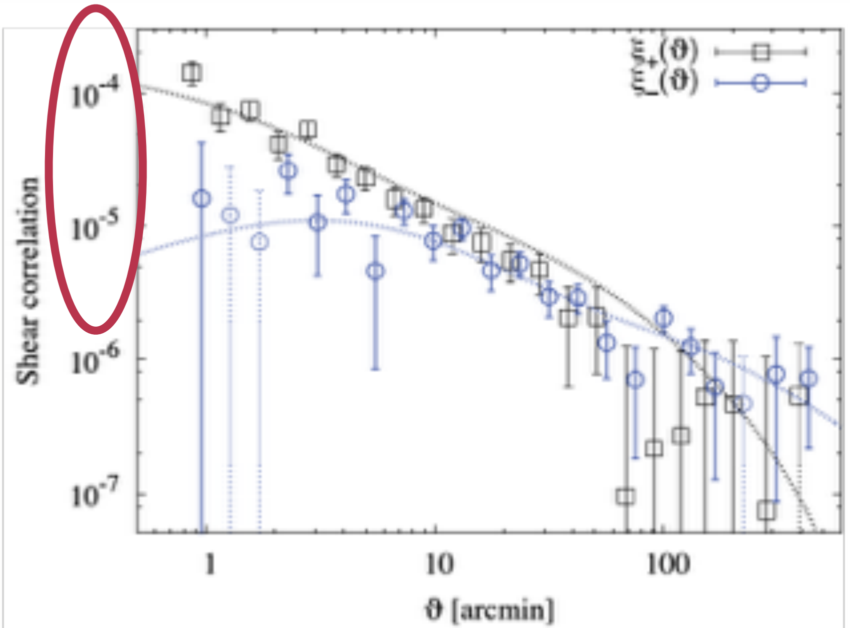
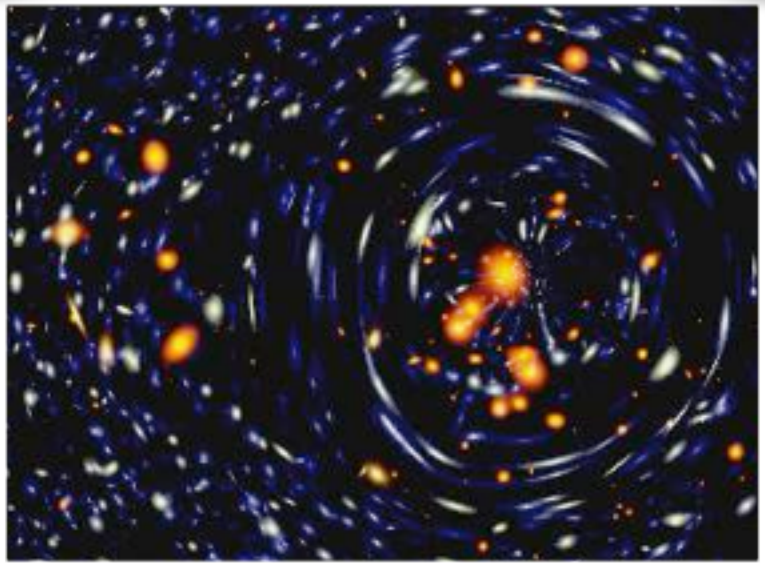


CFHTLenS data, Kilbinger '13



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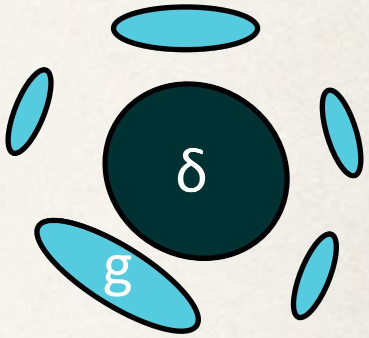

shear

$$\epsilon = \gamma + \epsilon^s$$

apparent ellipticity

intrinsic ellipticity

Measure coherent distortions:

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intrinsic ellipticity correlations (II term)

shear-ellipticity correlations (GI term)

At order zero :

II and GI are **neglected** because galaxy's shapes are uniformly distributed in the Universe.

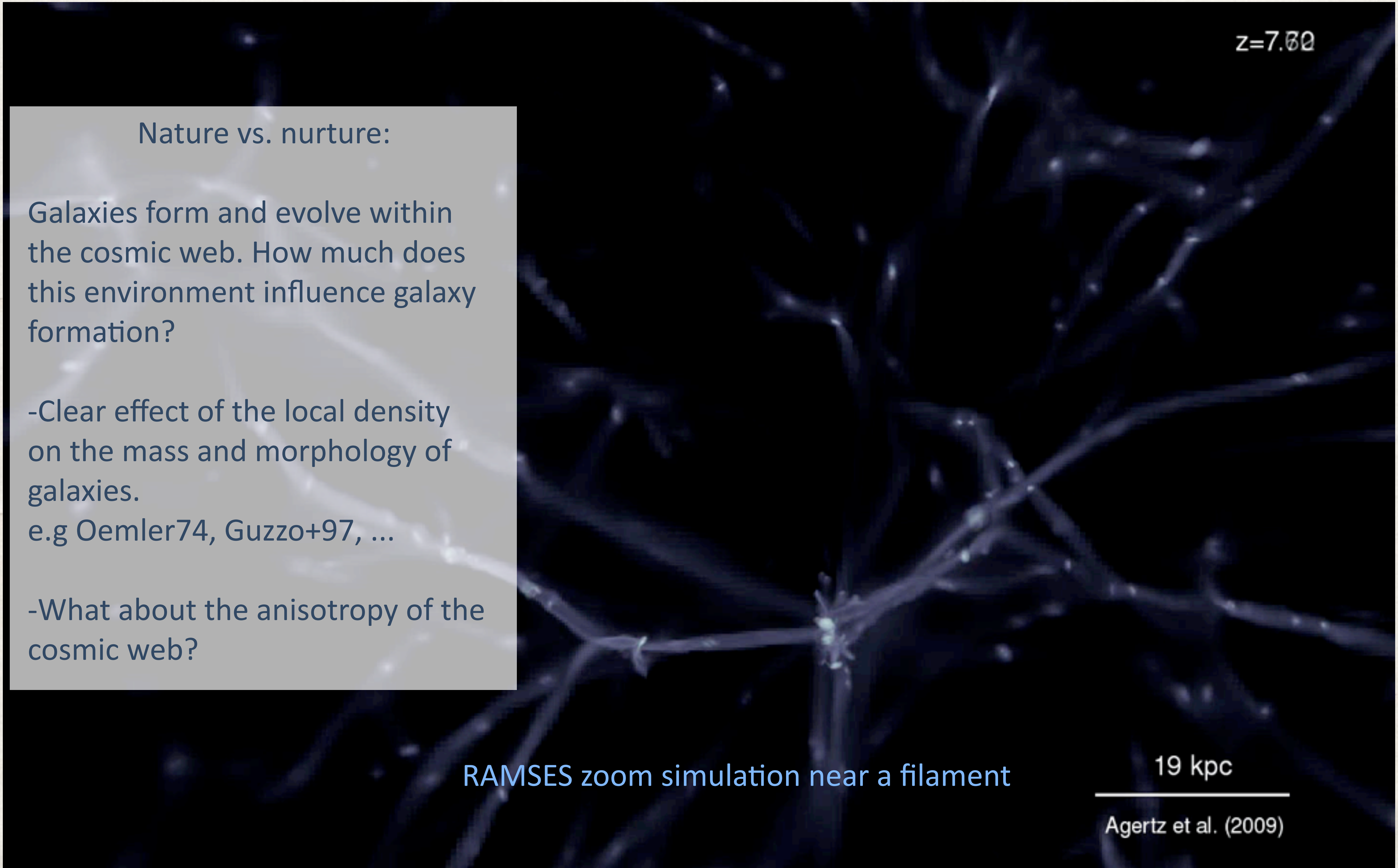
But :

Galaxies are correlated with the cosmic web through dynamics!

II. Intrinsic alignments

I.1. Physical origin

LSS is the birthplace of galaxies:



Nature vs. nurture:

Galaxies form and evolve within the cosmic web. How much does this environment influence galaxy formation?

-Clear effect of the local density on the mass and morphology of galaxies.
e.g Oemler74, Guzzo+97, ...

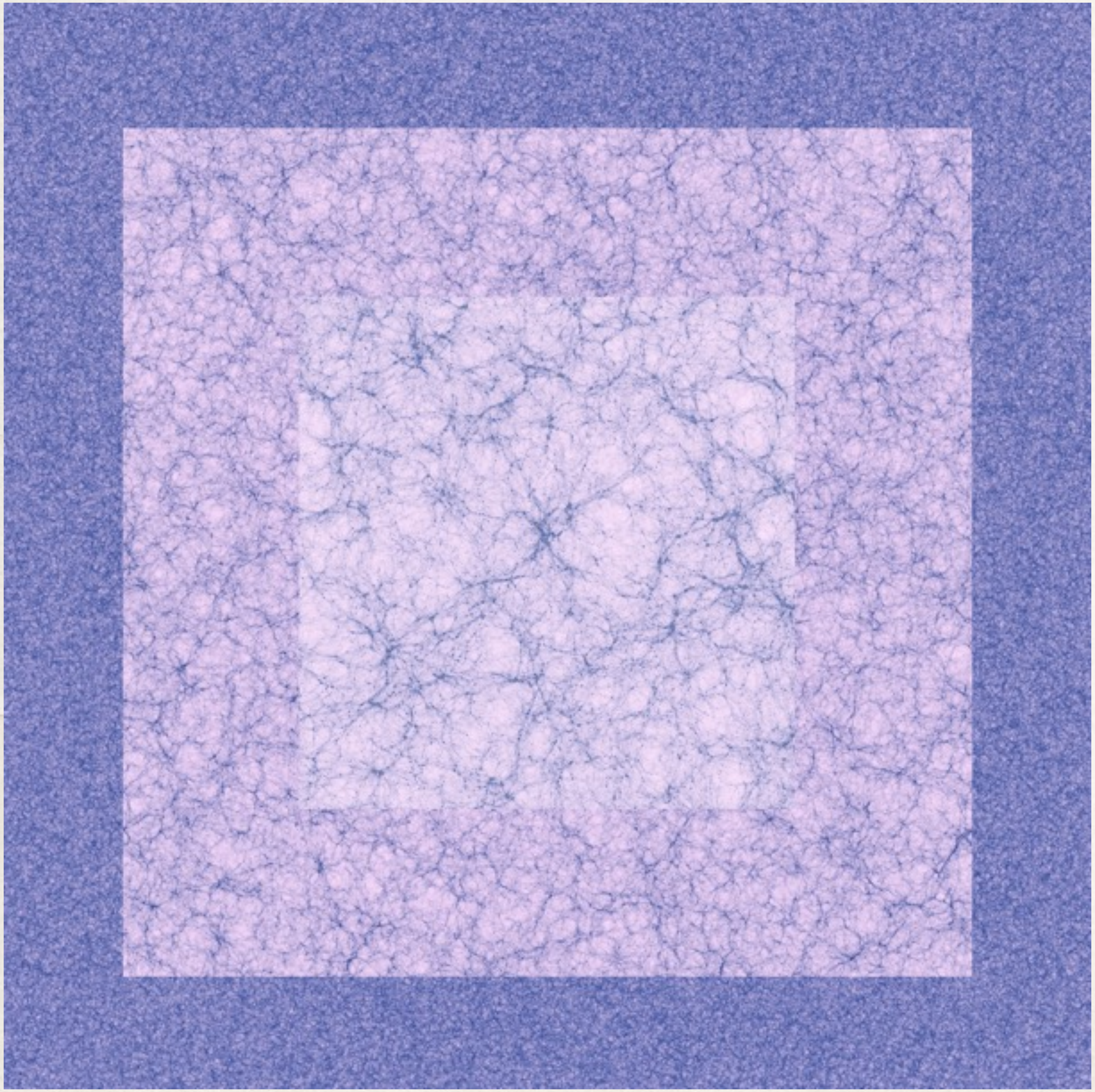
-What about the anisotropy of the cosmic web?

RAMSES zoom simulation near a filament

Agertz et al. (2009)

Codis+12

Morphology of halos is correlated to the LSS

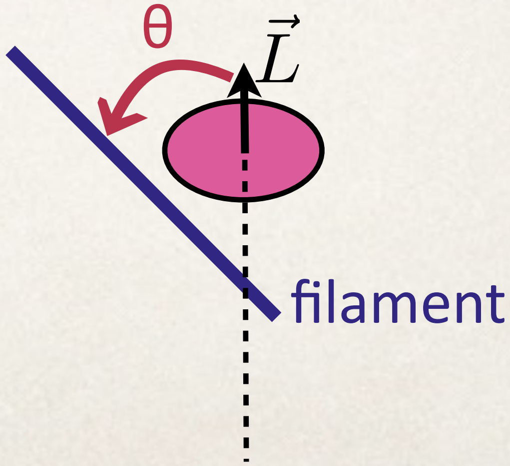


Horizon-4π simulation
DM only
2 Gpc/h periodic box
73 millions halos @ z=0
Teyssier+09

filaments extracted using the *skeleton*
Sousbie+09

spin are defined as

$$\vec{L} = m\sum_i (\vec{r}_i - \vec{r}_0)(\vec{v}_i - \vec{v}_0)$$



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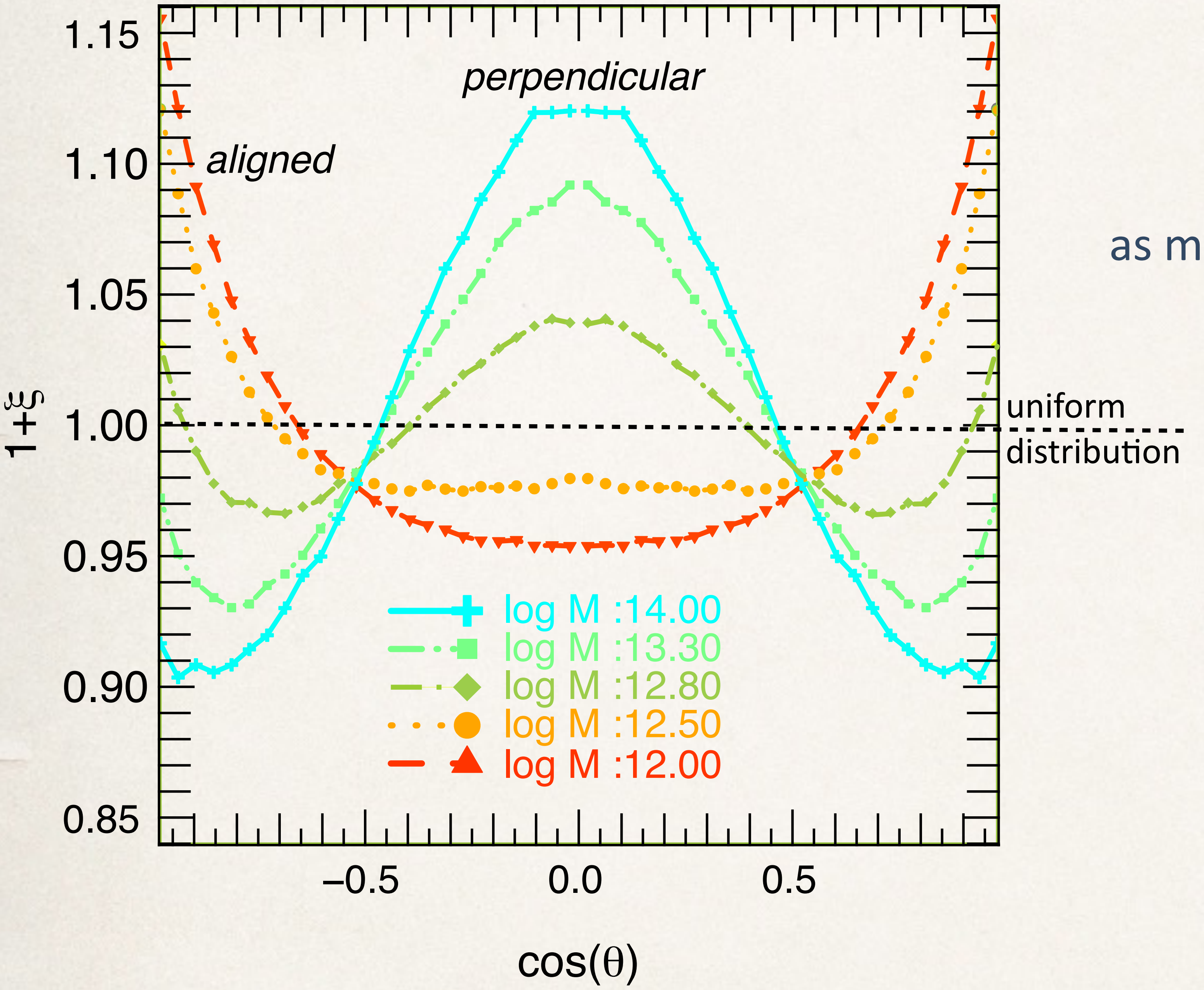


spin-filament alignment
as measured in the Horizon-4π simulation (DM)

mass transition: $M_{tr}=5.10^{12}M_{sun}$

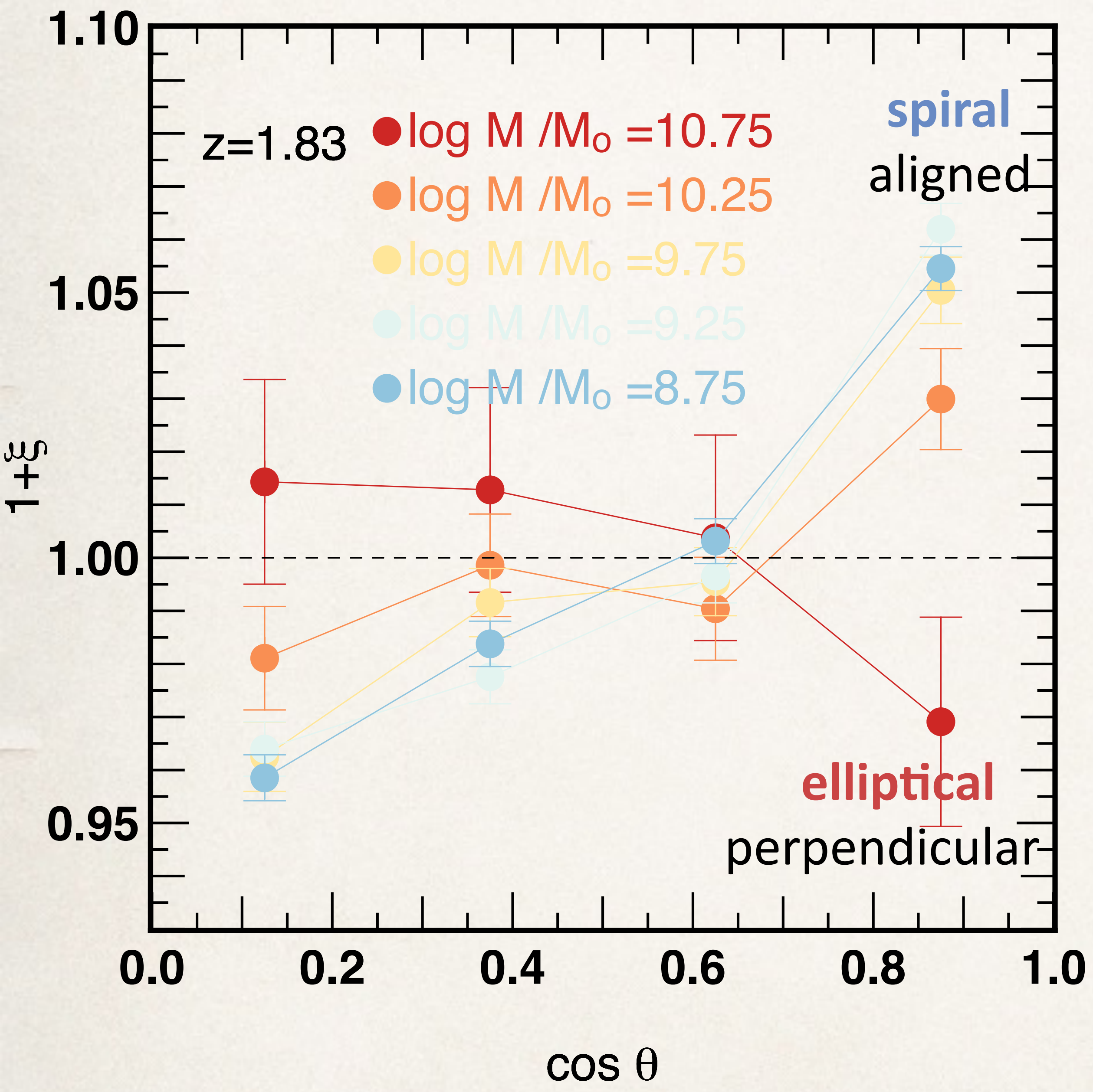
$M<M_{tr}$: aligned

$M>M_{tr}$: perpendicular

Broad literature on this topic e.g Aubert+04, Bailin+05; Aragon-Calvo+07,13; Hahn+07; Paz+08...

Dubois+14

Morphology of galaxies is correlated to the LSS



→ *of stars*

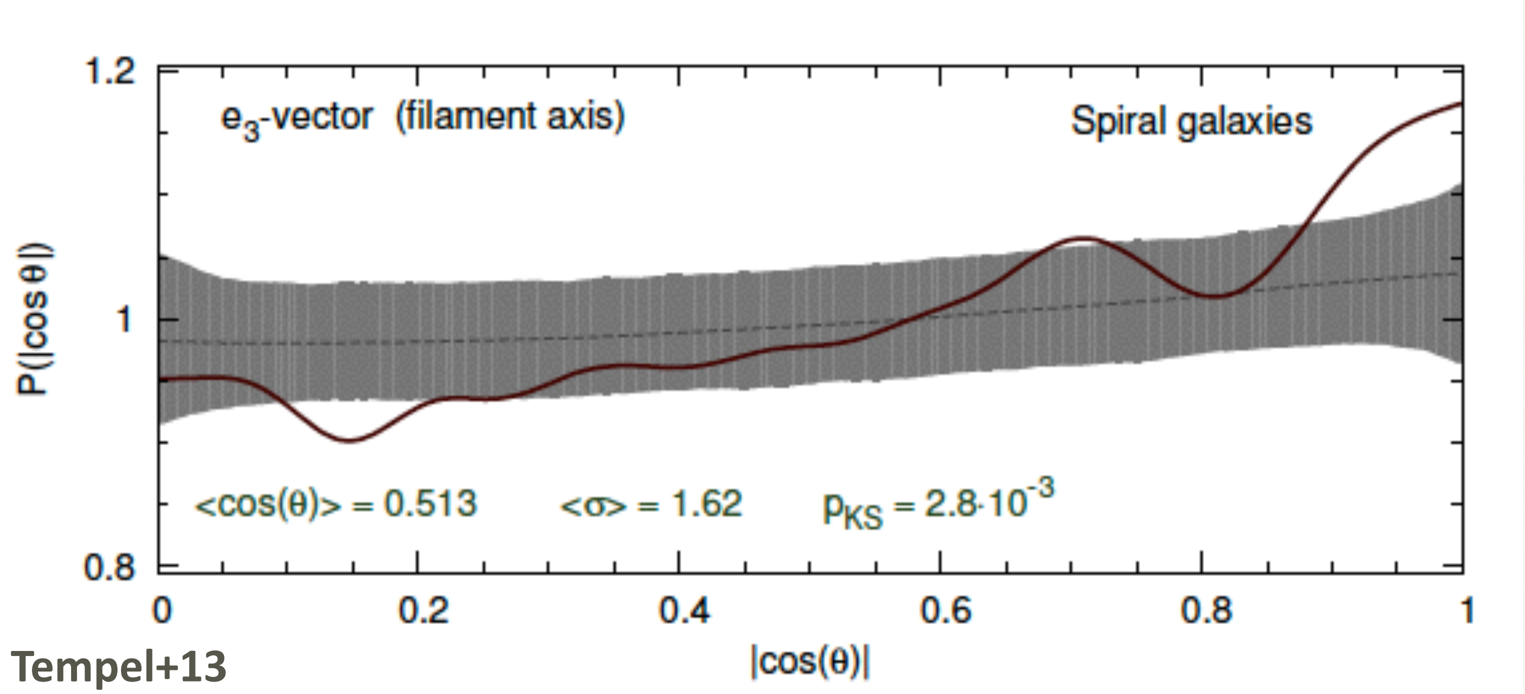
spin-filament alignment
as measured in the Horizon-AGN simulation

mass/colour/age/... transition:

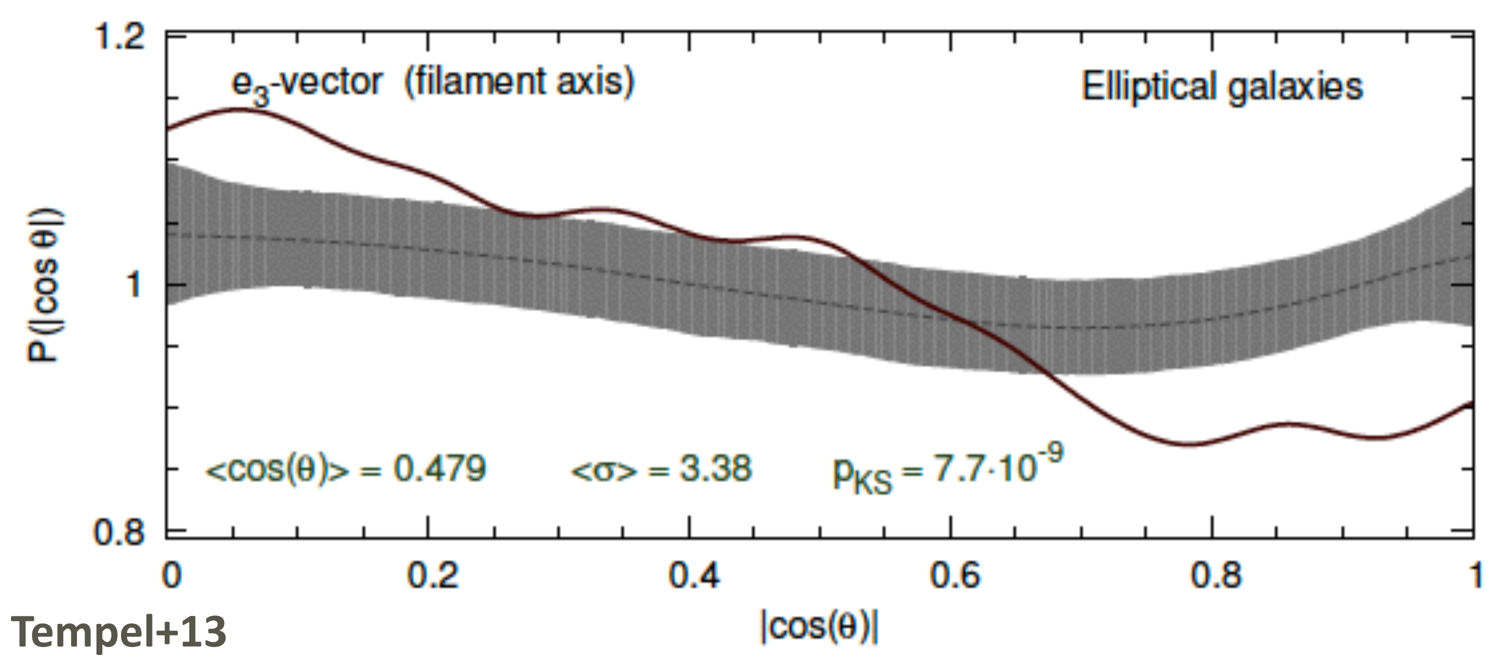
low-mass, star forming, blue, high v/σ → aligned

massive, quiescent, red, low v/σ → perpendicular

Morphology of galaxies is correlated to the LSS in the SDSS

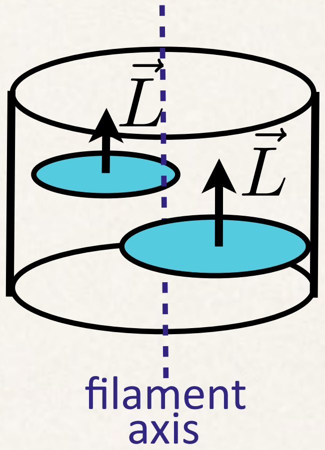


Tempel+13

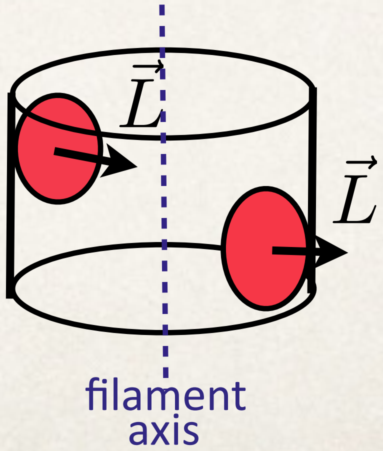


Tempel+13

spirals tend to have a spin **aligned** with filaments



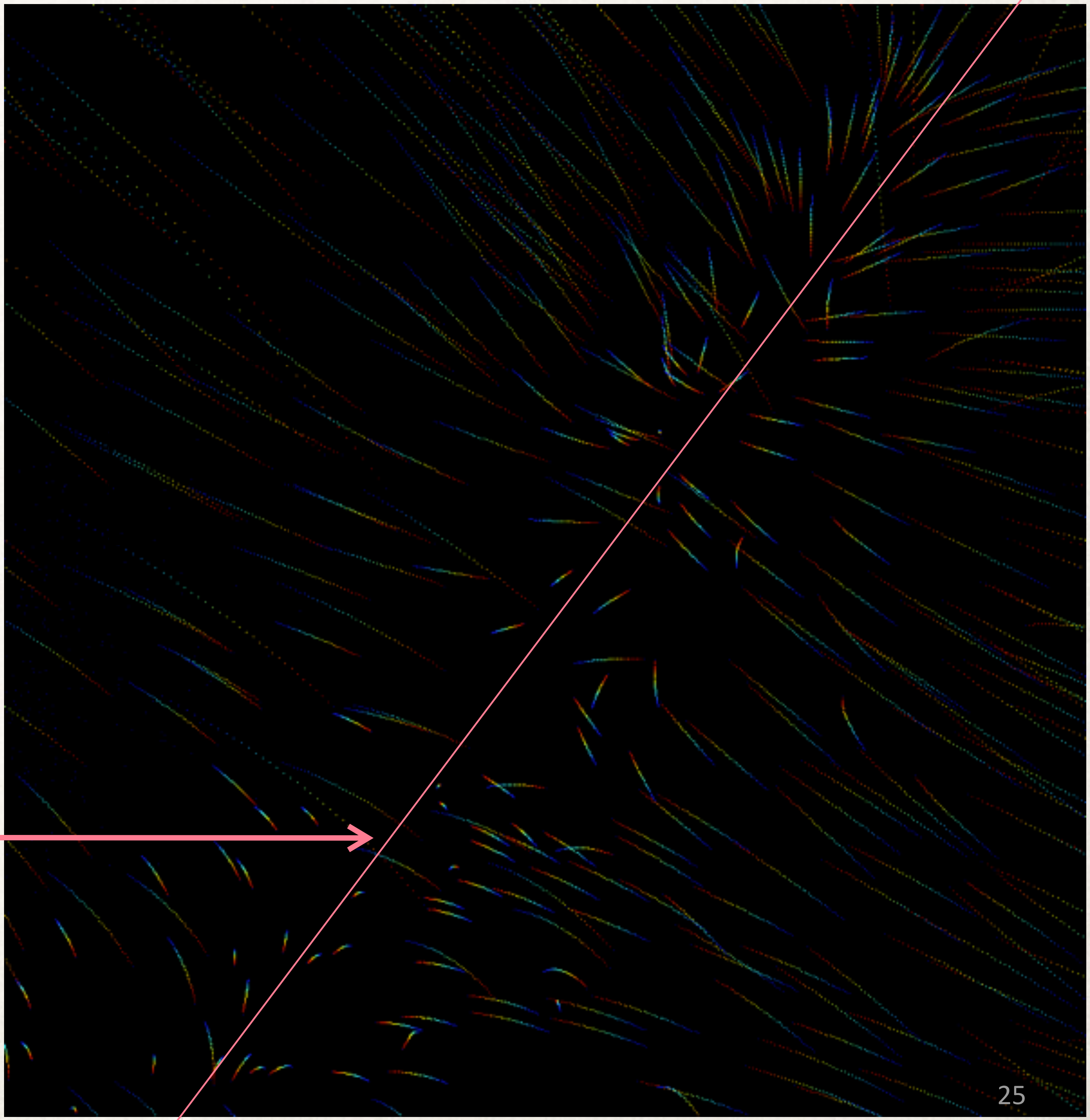
«ellipticals» tend to have a spin **perpendicular** to filaments



in agreement with simulations!

How to understand this spin-filament alignment?

trajectories of DM particles from the walls to the forming filaments



first generation
of small halos by
winding of the walls

vorticity is created in the **multi-flow** region defining the filament

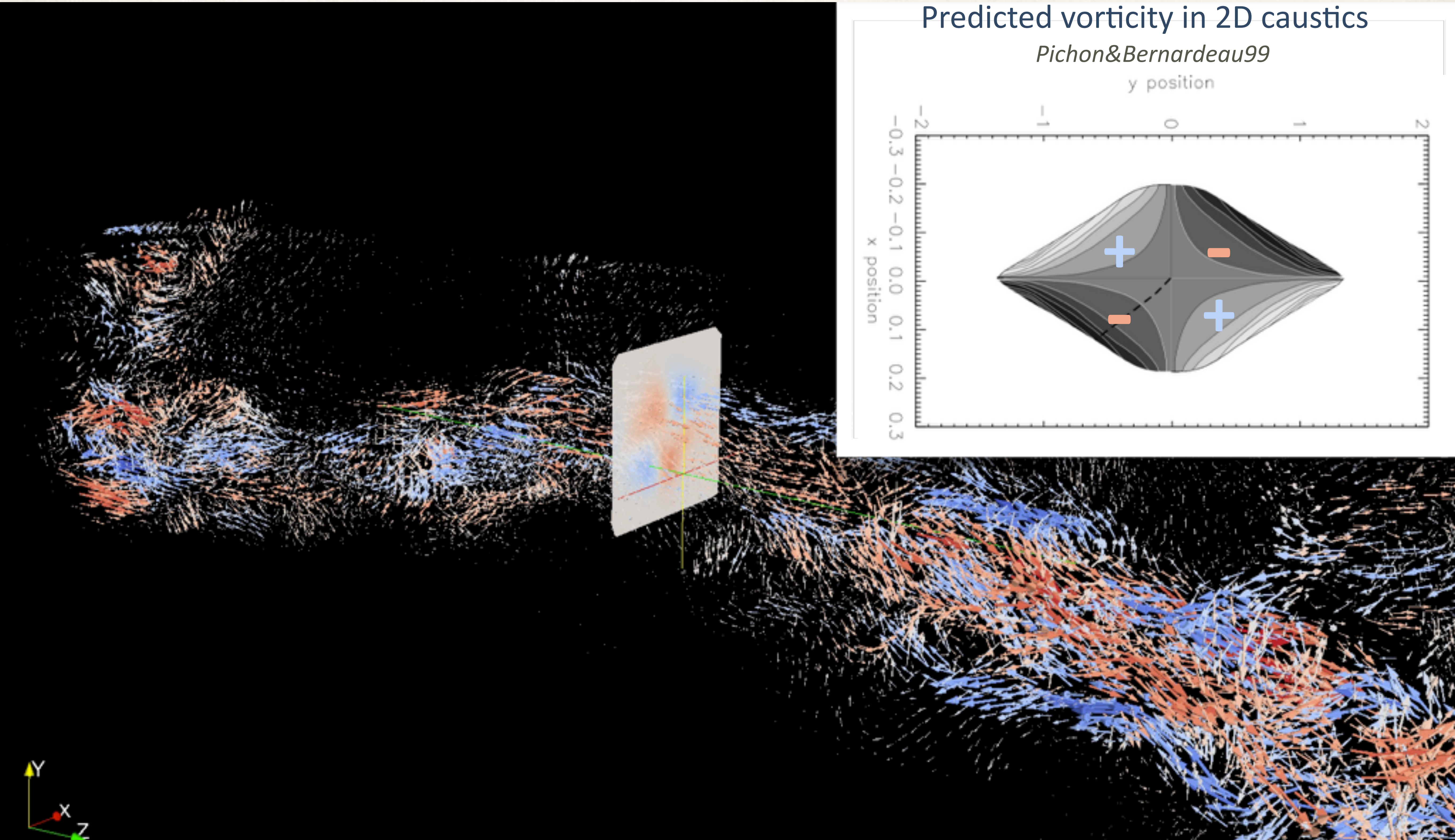
forming filaments

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

vorticity = curl of velocity

Laigle+15

Alignment of vorticity with the cosmic web



Predicted vorticity in 2D caustics

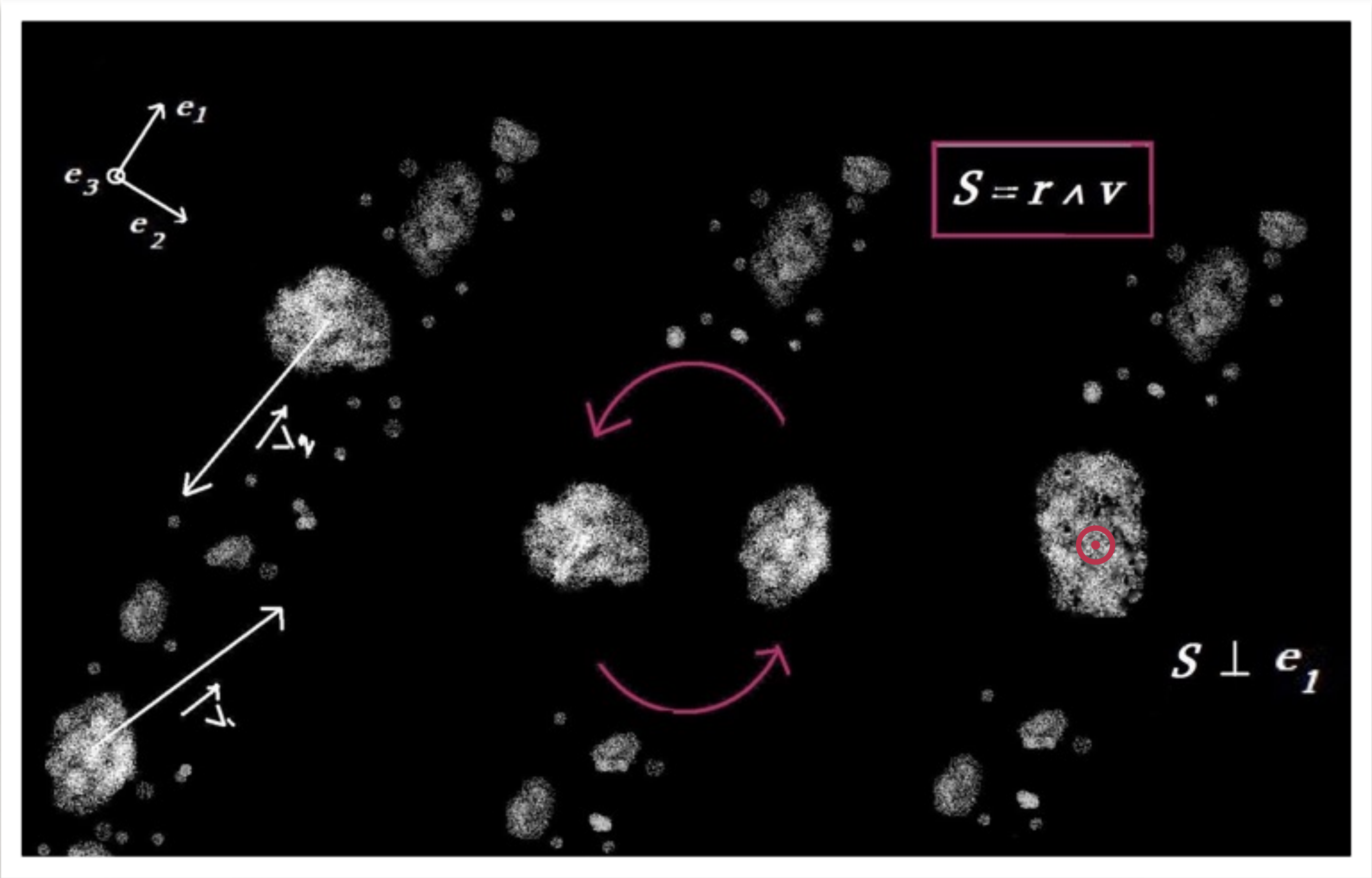
Pichon&Bernardeau99

braids structure of vorticity

Generation of massive halos

halos catch up with each other along the filaments

generation of a population of massive halos with a spin perp. to filaments



Quick questions:

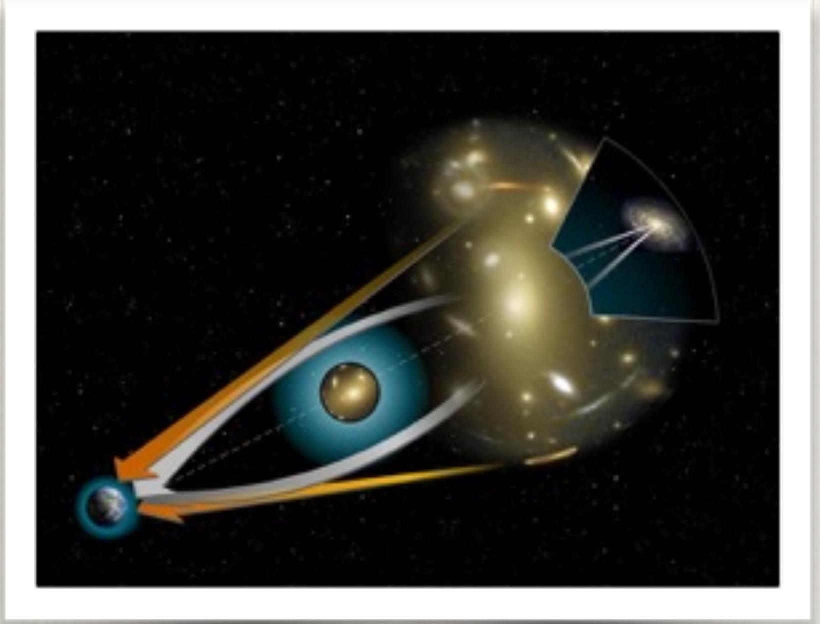
Have you understood why galaxy's spin is correlated to the cosmic web?

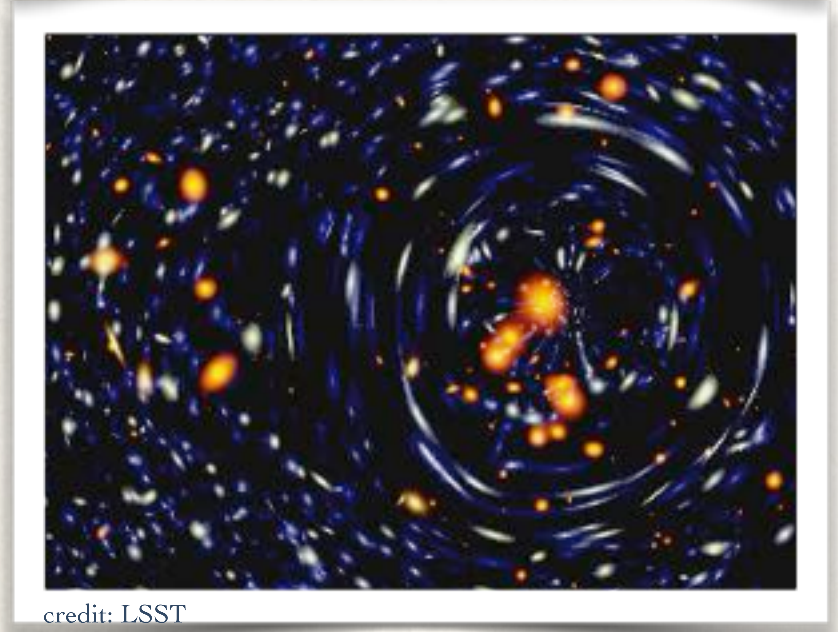
1) Not at all
2) I understood the global idea but not the transition from alignment to orthogonality
3) Yes perfectly!

Where do we have non-zero vorticity?

1) Nowhere, vorticity is diluted by the expansion
2) only in filaments
3) only inside halos
4) none of the above

Intrinsic alignments contaminate weak lensing!





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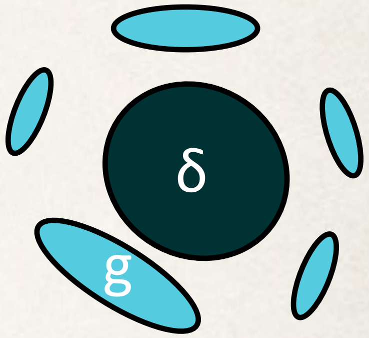

shear

$$\epsilon = \gamma + \epsilon^s$$

apparent ellipticity

intrinsic ellipticity

Measure coherent distortions:

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intrinsic ellipticity correlations (II term)

shear-ellipticity correlations (GI term)

How to handle them?

I.2. Modelling IA

galaxy-galaxy

galaxy-tidal shear

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intrinsic ellipticity correlations (II term)

shear-ellipticity correlations (GI term)

Two separate mechanisms:

Discs are dominated by their spin which was acquired at their formation time by tidal torquing

Ellipticals are stretched by the tidal field and/or subject to anisotropic accretion

I.2. Modelling IA

galaxy-galaxy

galaxy-tidal shear

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intrinsic ellipticity correlations (II term)

shear-ellipticity correlations (GI term)

★ linear theory *Crittenden+01, Hirata+04* → need to account for biased clustering? non-linearities?

★ semi-analytical modelling of galaxy formation *Joachimi+13* → gaz dynamics, anisotropy of accretion?

★ hydrodynamical simulations *Codis+15a, Tenneti+15, Chisari+15, Velliscig+15*

Intrinsic alignments : perturbative models

Discs are dominated by their spin which was acquired at their formation time by tidal torquing

↓

Quadratic model (in the tidal field)

Tidal torque theory states that at linear order, the spin is acquired gradually until the time of maximal extension (before collapse) and is proportional to the misalignment between the inertia tensor of the protogalaxy and the surrounding tidal tensor (see [Schaefer, 2009] for a review) :

inertia tensor

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

tidal tensor

From spins, Lee and Pen 2001 computed the corresponding shape correlation functions assuming that shapes are induced by the projection of a circular disk perpendicular to the spin.

Missing ingredients: biased clustering (galaxies do not form anywhere but in filaments and nodes inducing constraints on the tidal field), non-linear evolution, baryons.

Ellipticals are stretched by the tidal field and/or subject to anisotropic accretion

↓

Linear model (in the tidal field)

In the linear model ([Catelan et al., 2001, Hirata and Seljak, 2004]), the intrinsic ellipticity of a (typically elliptical) galaxy is proportional to the tidal field, i.e second derivatives of the gravitational potential smoothed on some scale Ψ, with a coefficient C_1 that measures the strength of the alignment occurring at redshift z_{IA}

$$\begin{pmatrix} e_s^+ \\ e_s^\times \end{pmatrix} = -\frac{C_1}{4\pi G}\begin{pmatrix} \nabla_x^2 - \nabla_y^2 \\ 2\nabla_x\nabla_y \end{pmatrix}\Psi(z_{\rm IA})\,,$$

as it is assumed that stars and dark matter are in dynamical equilibrium and therefore the stellar distribution follows the distortion of the galaxy halo spheroid which is tidally distorted.

Improvements: try to go beyond linear dynamics with the **NLA model** ([Bridle and King, 2007]) by accounting for the non-linear matter power spectrum, build halo model, etc. Still not accurate in the intermediate regime.

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Linear model (in the tidal field)

$$P_{\delta +}(\mathbf{k}, z) = -A_I \frac{C_1 \rho_{\mathrm{crit}} \Omega_m}{D(z)} \frac{k_x^2 - k_y^2}{k^2} P_\delta(\mathbf{k}, z)$$

occurring at redshift z_{IA}

$$\begin{pmatrix} e_s^+ \\ e_s^\times \end{pmatrix} = -\frac{C_1}{4\pi G}\begin{pmatrix} \nabla_x^2 - \nabla_y^2 \\ 2\nabla_x\nabla_y \end{pmatrix}\Psi(z_{\mathrm{IA}}),$$

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Quick questions:

Do you want to see the calculations for the spin generated by TTT (only 4 equations!)?

1) Yes!
2) Not interested, I know it already
3) Too difficult so no
4) I am bored so no

Tidal torque theory

Discs are dominated by their spin which was acquired at their formation time by tidal torquing

↓

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

tidal tensor

From spins, Lee and Pen 2001 computed the corresponding shape correlation functions assuming that shapes are induced by the projection of a circular disk perpendicular to the spin.

Missing ingredients: biased clustering (galaxies do not form anywhere but in filaments and nodes inducing constraints on the tidal field), non-linear evolution, baryons.

Tidal torque theory :

The spin of a protogalaxy contained in a volume V and with center of gravity located at position r can be written

$$\mathbf{L} = \int_V \mathrm{d}^3\mathbf{r}(\mathbf{r}-\bar{\mathbf{r}})\times(v(\mathbf{r})-v(\bar{\mathbf{r}}))\rho(\mathbf{r})\,,$$

where the implicitly time-dependent velocity field is denoted v(r) and the mass density ρ(r). Once expressed in Lagrangian coordinates:

$$\mathbf{L} = \rho_0 a^5 \int_{V_L} \mathrm{d}^3\mathbf{q}(\mathbf{x}-\bar{\mathbf{x}})\times(\dot{\mathbf{x}}(\mathbf{q})-\dot{\mathbf{x}}(\bar{\mathbf{q}}))$$

In the Zel'dovich approximation where $x = q - D_+\nabla\Psi(q)$ and $x' = -D_+'(t)\nabla\Psi$, Ψ being the displacement field (such that $\Delta\Psi = \delta$), and assuming that the gradient of the displacement field is almost constant across the proto-object of Lagrangian volume V_L, a second-order Taylor expansion of L gives

$$\mathbf{L} \approx -\dot{D}_+\rho_0 a^5 \int_{V_L} \mathrm{d}^3\mathbf{q}(\mathbf{q}-\bar{\mathbf{q}})\times[T\cdot(\mathbf{q}-\bar{\mathbf{q}})]$$

where T is the tidal shear tensor $T_{ij} = \partial_i\partial_j\Psi_{ij}$ at the center of gravity. Let us define the inertia tensor I

$$I_{ij} = \rho_0 a^3 \int_{V_L} \mathrm{d}^3\mathbf{q}(q_i-\bar{q}_i)(q_j-\bar{q}_j)$$

so that

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

Intrinsic alignments : perturbative models

Discs are dominated by their spin which was acquired at their formation time by tidal torquing

↓

Quadratic model (in the tidal field)

Tidal torque theory states that at linear order, the spin is acquired gradually until the time of maximal extension (before collapse) and is proportional to the misalignment between the inertia tensor of the protogalaxy and the surrounding tidal tensor (see [Schaefer, 2009] for a review) :

$$L_i = a^2(t)\dot{D}_+(t)\sum_{j,k,l}\epsilon_{ijk}\overset{\substack{\textbf{inertia tensor}\\ \downarrow}}{I_{jl}}\underset{\substack{\nwarrow\\ \textbf{tidal tensor}}}{T_{lk}}$$

From spins, Lee and Pen 2001 computed the corresponding shape correlation functions assuming that shapes are induced by the projection of a circular disk perpendicular to the spin.

Missing ingredients: biased clustering (galaxies do not form anywhere but in filaments and nodes inducing constraints on the tidal field), non-linear evolution, baryons.

Ellipticals are stretched by the tidal field and/or subject to anisotropic accretion

↓

Linear model (in the tidal field)

In the linear model ([Catelan et al., 2001, Hirata and Seljak, 2004]), the intrinsic ellipticity of a (typically elliptical) galaxy is proportional to the tidal field, i.e second derivatives of the gravitational potential smoothed on some scale Ψ, with a coefficient C_1 that measures the strength of the alignment occurring at redshift z_{IA}

$$\begin{pmatrix} e_s^+ \\ e_s^\times \end{pmatrix} = -\frac{C_1}{4\pi G}\begin{pmatrix} \nabla_x^2 - \nabla_y^2 \\ 2\nabla_x\nabla_y \end{pmatrix}\Psi(z_{\rm IA}),$$

as it is assumed that stars and dark matter are in dynamical equilibrium and therefore the stellar distribution follows the distortion of the galaxy halo spheroid which is tidally distorted.

Improvements: try to go beyond linear dynamics with the **NLA model** ([Bridle and King, 2007]) by accounting for the non-linear matter power spectrum, build halo model, etc. Still not accurate in the intermediate regime.

Intrinsic alignments : perturbative models

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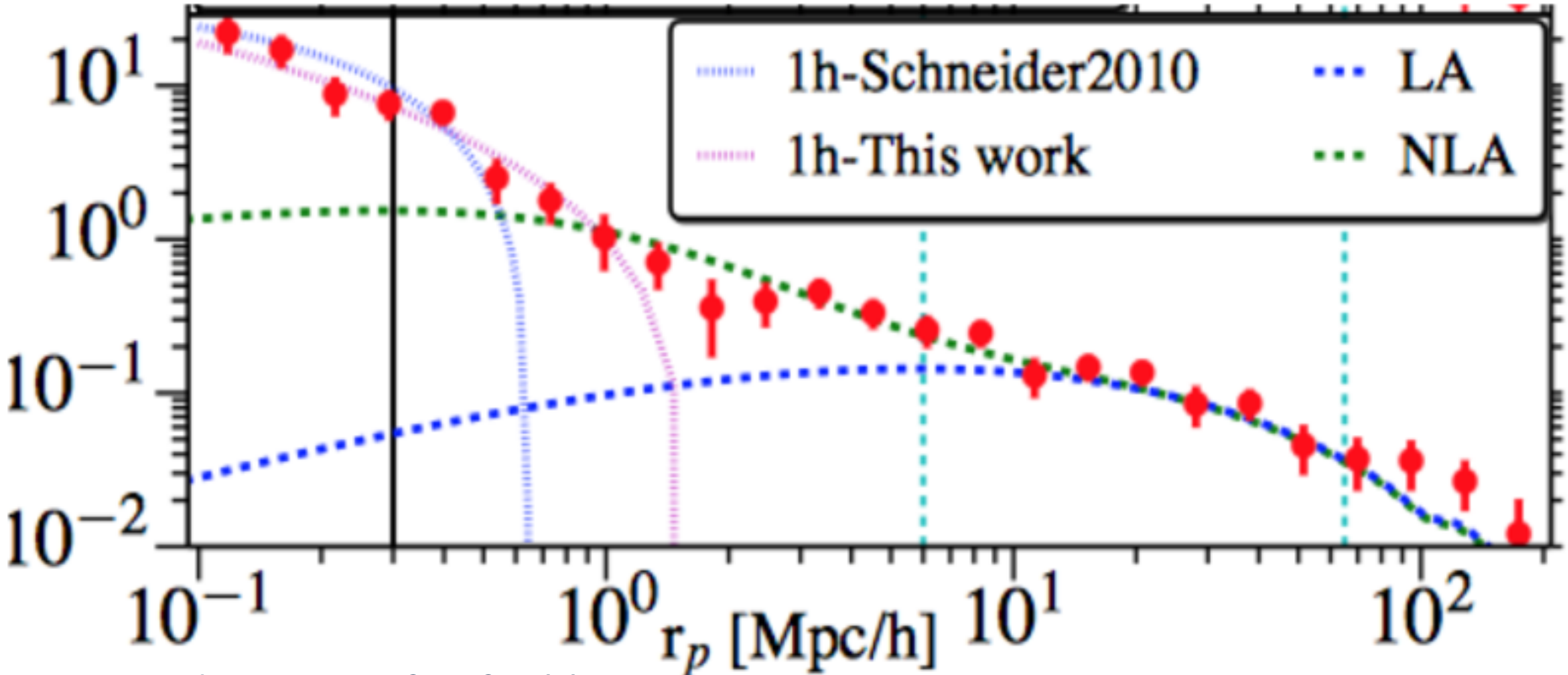
the tidal fie , non-linear evolution, baryons.

with the **NLA**
the non-linear
matter power spectrum, build halo model, etc. Still not accurate
in the intermediate regime.

Alignment of red galaxies in SDSS:

Singh et al. (2014)



No detection of IA for blue galaxy

Intrinsic alignments from simulations

Recently, several cosmological « full physics » hydro simulations have been run:

	code	paper	size	resolution
Cosmo-OWLS/ Eagle	GADGET-3 (Nbody)	Shaye++15	100 Mpc/h	1504^3
Horizon-AGN	RAMSES (AMR)	Dubois++14	100Mpc/h	1024^3
Illustris	AREPO (moving mesh)	Vogelsberger++14	75 Mpc/h	1820^3
MassiveBlack II	P-GADGET (Nbody)	Khandai++15	100 Mpc/h	1792^3

all with different subgrid physics:
cooling
star formation
SN feedback
AGN feedback
…

Dubois+14

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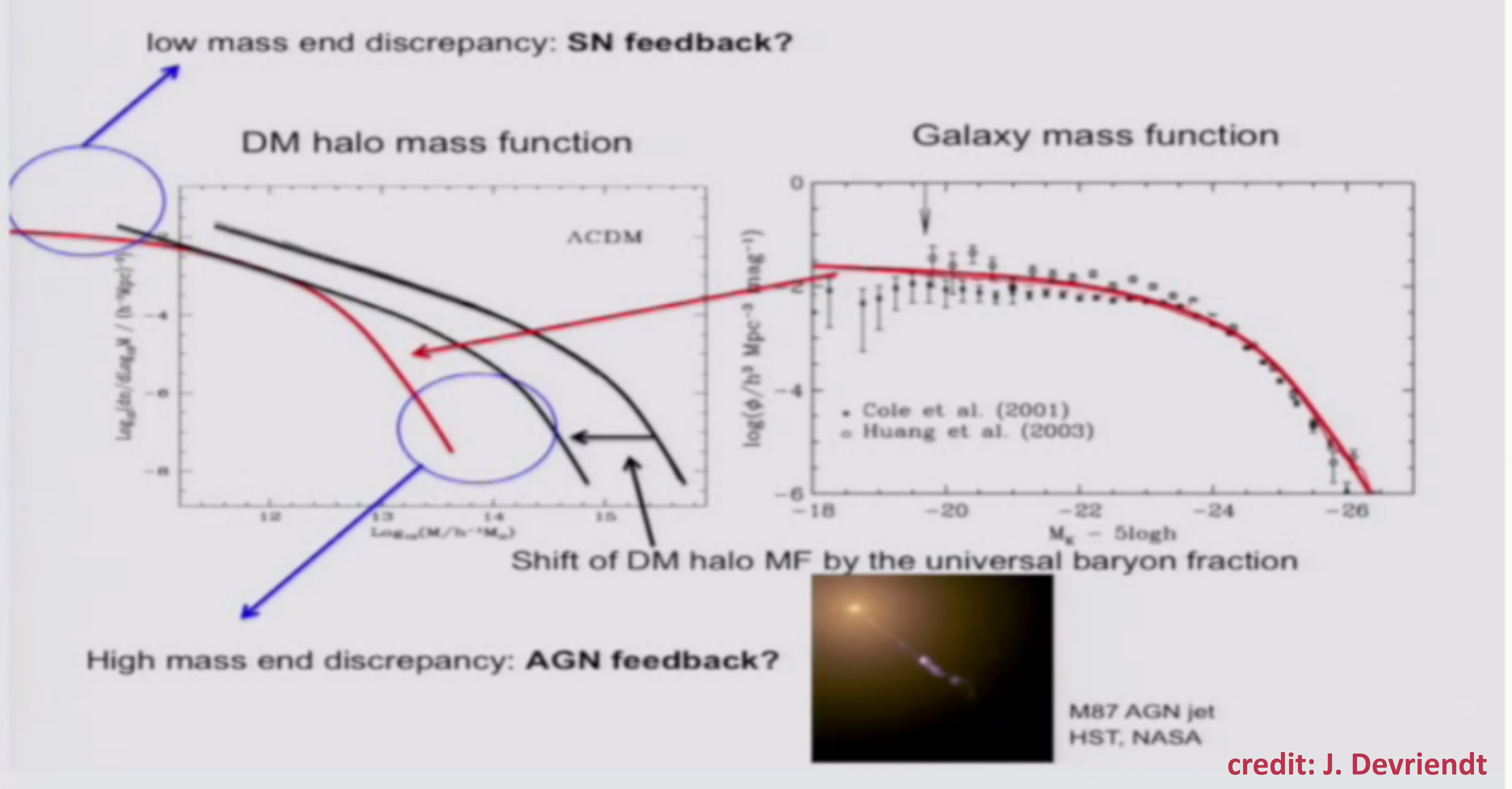

credit: J. Devriendt

all with different
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cooling
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Intrinsic alignments from simulations

Dubois+14

Horizon-AGN, a full-physics hydro simulation:

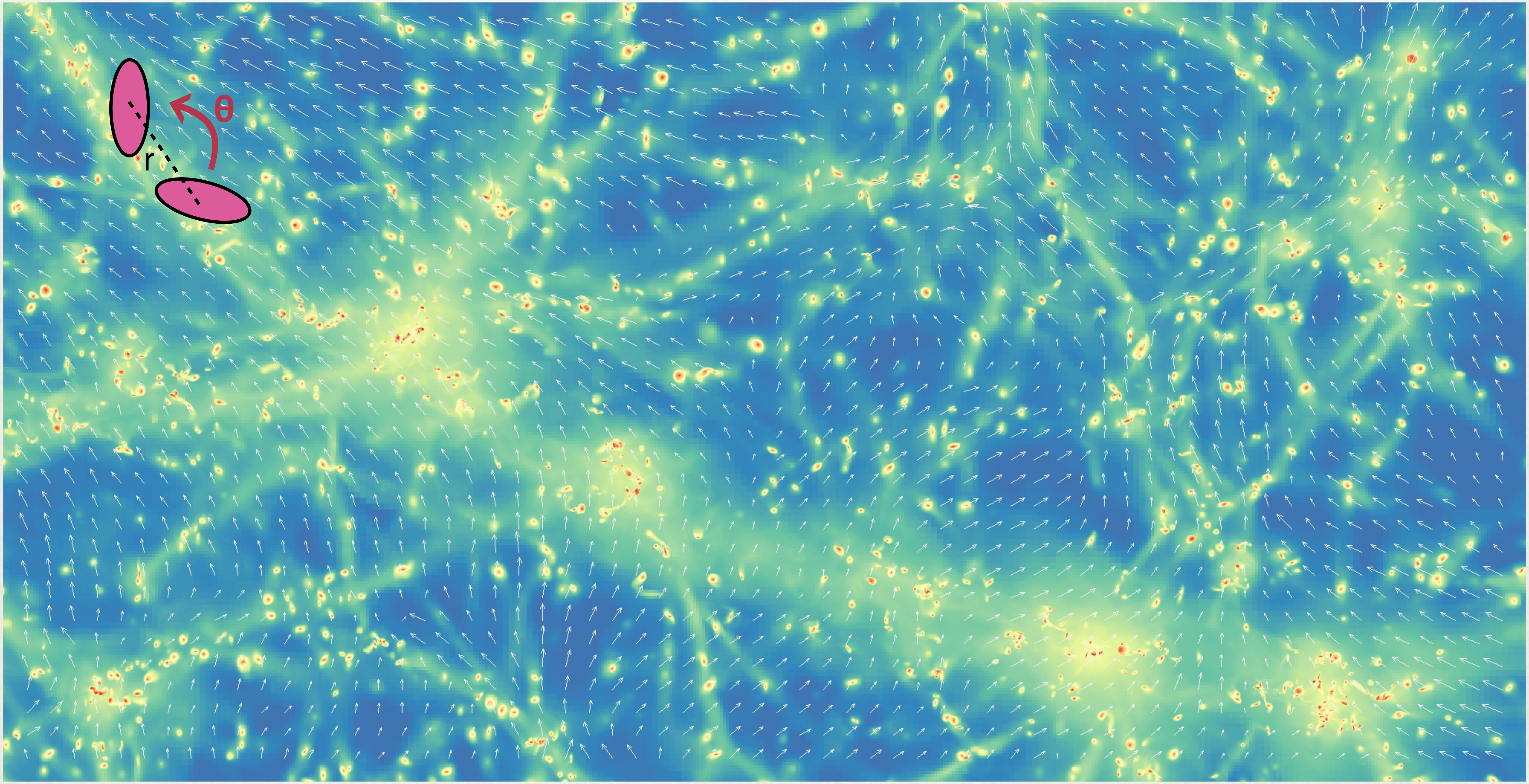
*AMR code RAMSES

*volume: (100 Mpc/h)^3

*165 000 galaxies at z=1.2

*subgrid physical recipes including AGN feedback

*resolution : 1024^3, 8.10^7 M$_s$, Δx=1 kpc and 7.10^9 gas resolution elements



12.5 Mpc/h comoving

Intrinsic alignments from simulations

Dubois+14

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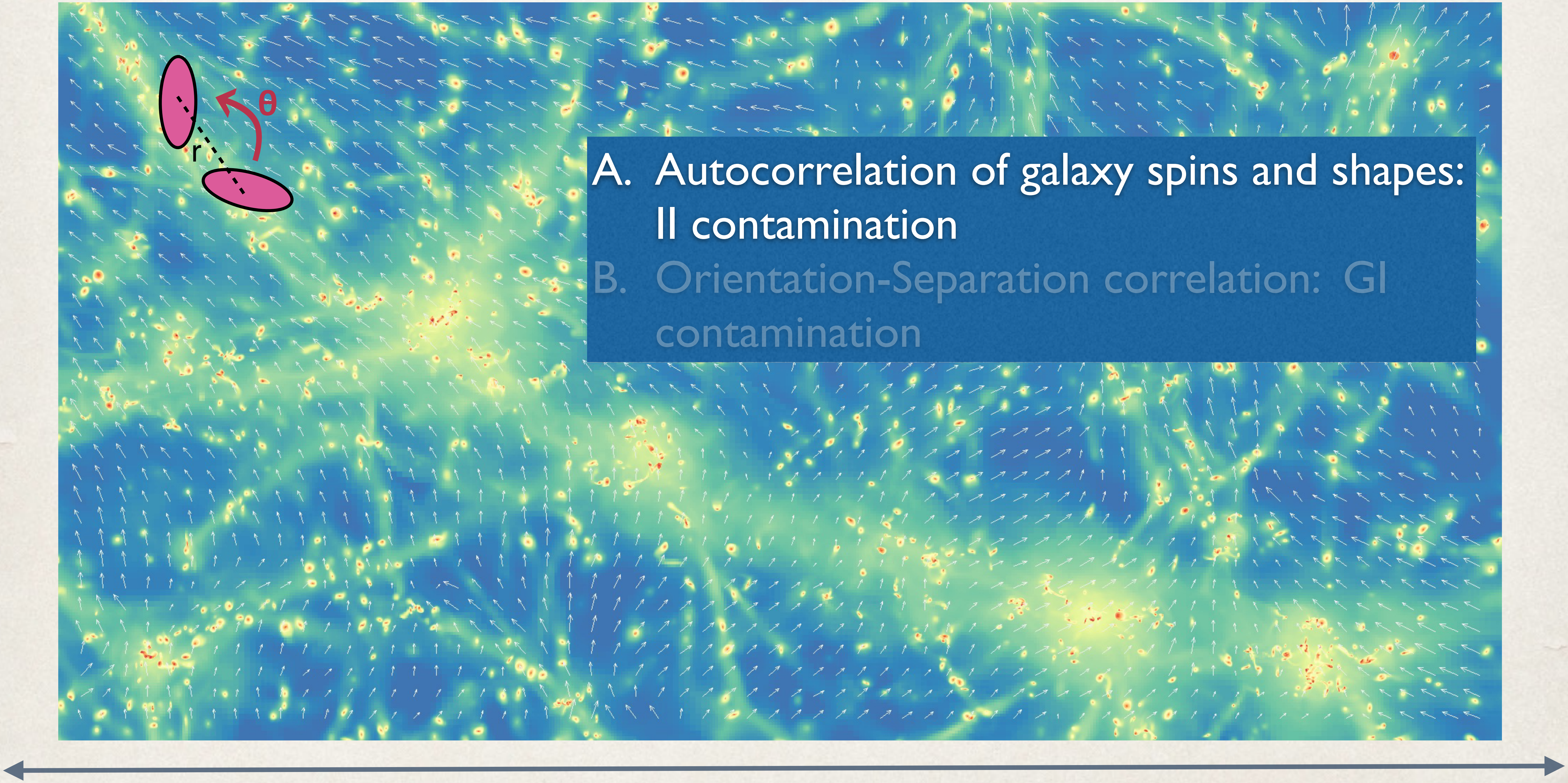
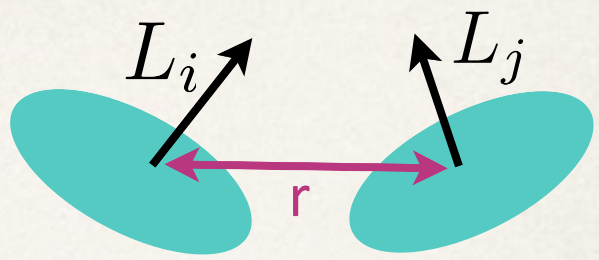


A. Autocorrelation of galaxy spins and shapes: II contamination

B. Orientation-Separation correlation: GI contamination

Codis+15a

Projected ellipticities correlations from spins



- 3D spins L=(L_x,L_y,L_z) are measured.
- We infer projected ellipticities ϵ:

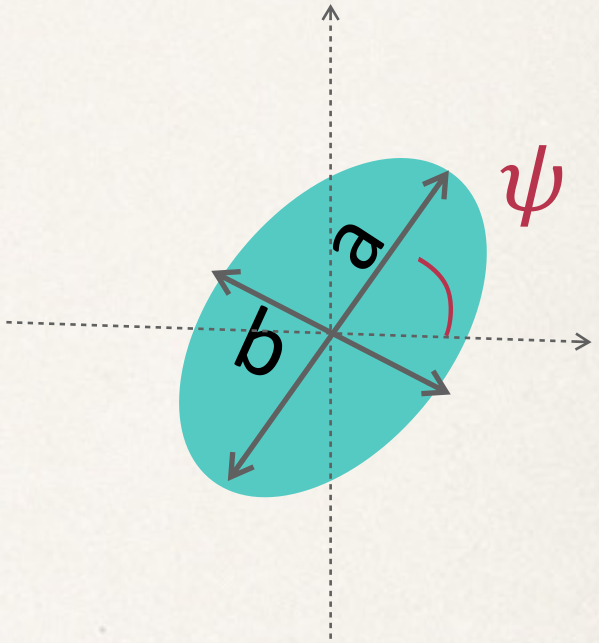
$$\epsilon = \frac{1-q_p}{1+q_p} e^{2i\psi}$$

where the axis ratio q_p = b/a of a **thin disk** reads

$$q_p = \frac{|L_z|}{||L||} + q_d \sqrt{1 - \frac{L_z^2}{L^2}}$$

z=line-of-sight

disk thickness

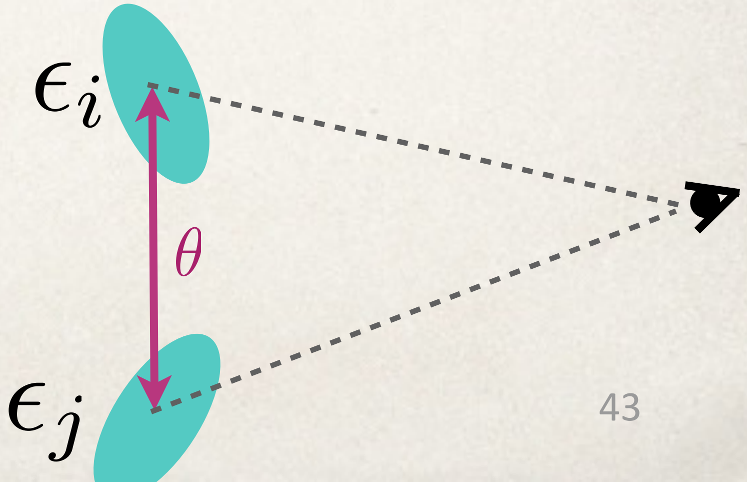


and the orientation of the ellipse is

$$\psi = \frac{\pi}{2} - \arctan\left(\frac{L_y}{L_x}\right)$$

- We compute the ellipticity correlation

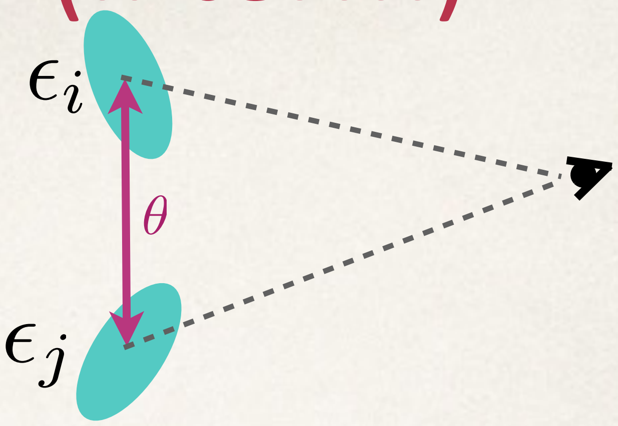
$$\xi_+^{\rm II} = \left\langle \epsilon_i^s \cdot \epsilon_j^s \right\rangle$$

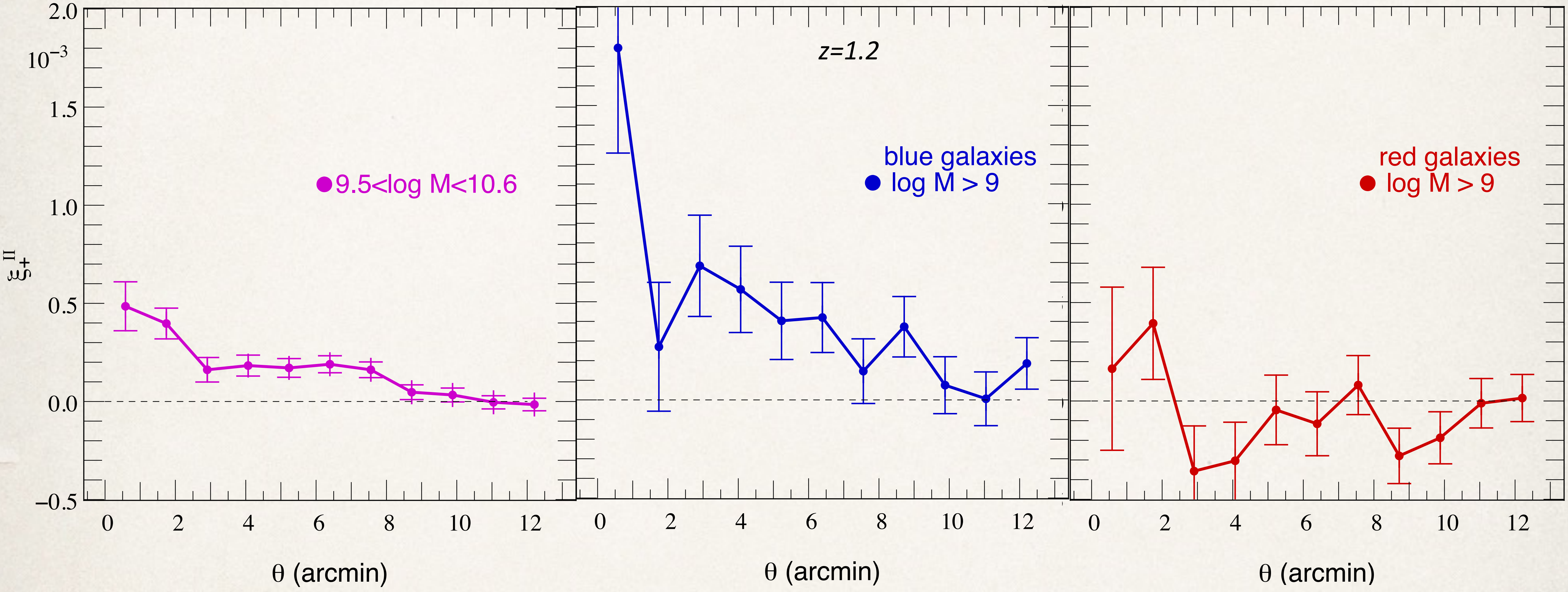


Projected ellipticities correlations (II term)

Codis+15a

$$\xi_+^{\mathrm{II}} = \left\langle \epsilon_i^s \epsilon_j^s \right\rangle$$





* blue/mid-mass galaxies are correlated on scales about 10’

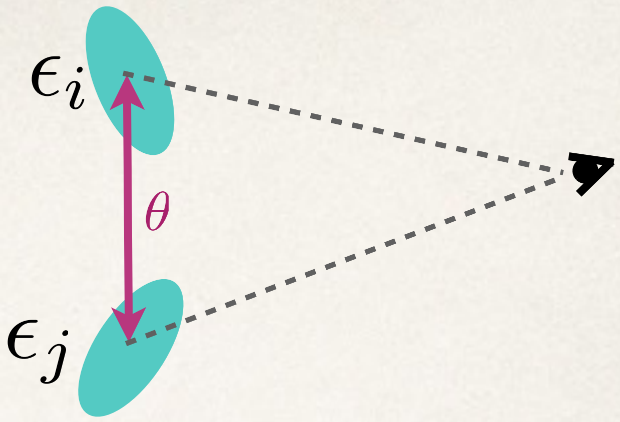
* no correlation for red galaxies

Possible significant contamination of cosmic shear measurements.

Limitations

Codis+15a

$$\xi_{+}^{\mathrm{II}} = \left\langle \epsilon_i^s \epsilon_j^s \right\rangle$$



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In the observations:

* no significant alignment of blue galaxies (Mandelbaum+11),

* but detection of alignments of red galaxies (Okumura&Jing09).

Contradiction?

Limitations

Codis+15a

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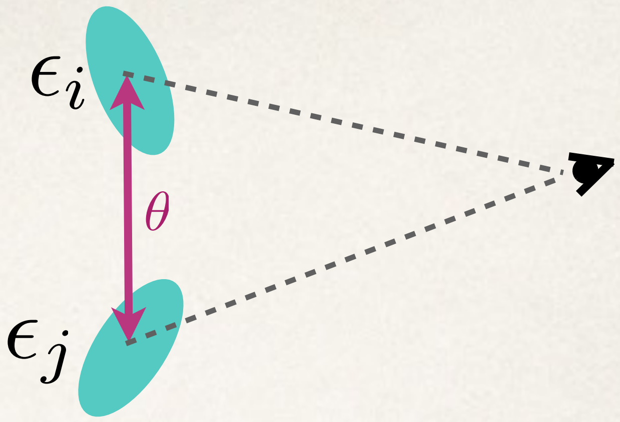

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In the observations:

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Contradiction?

Not necessarily because:

★ our measurements are done at higher redshift (z=1.2)

★ spin is a bad proxy for elliptical (...red) galaxies

★ observations often rely on the separation-orientation correlation function ...

Horizon-AGN, a full-physics hydro simulation

Dubois+14

*AMR code RAMSES

*volume: (100 Mpc/h)^3

*165 000 galaxies at z=1.2

*subgrid physical recipes including AGN feedback

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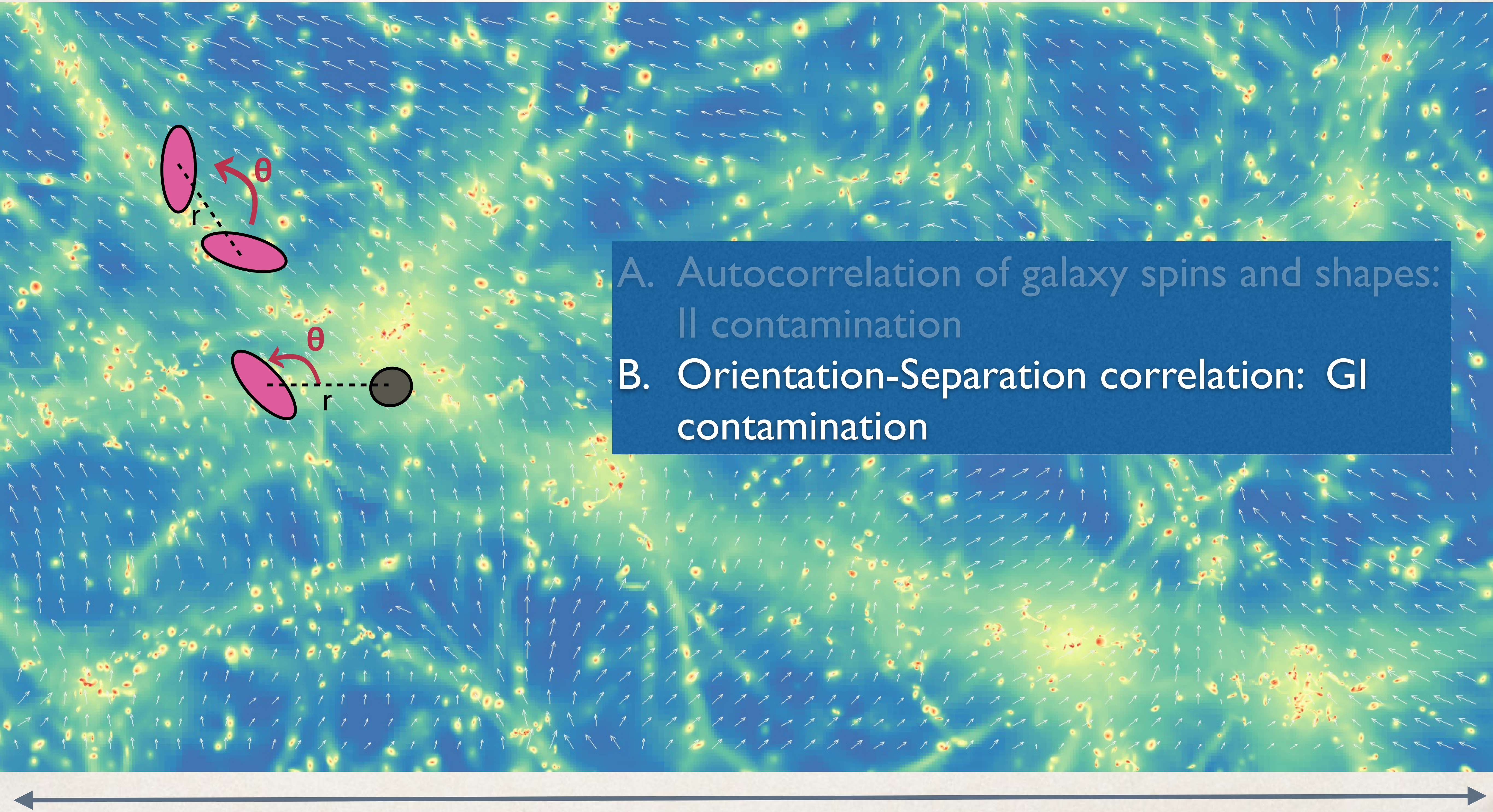


A. Autocorrelation of galaxy spins and shapes: II contamination

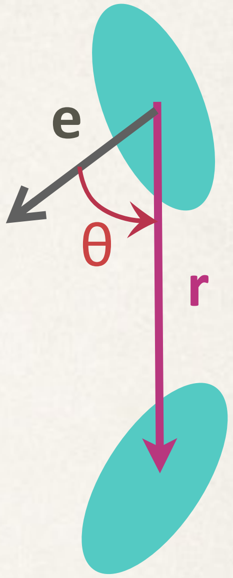
B. Orientation-Separation correlation: GI contamination

12.5 Mpc/h comoving

Separation-Orientation correlations

Chisari+15

Standard observable in the field of intrinsic alignments, defined as

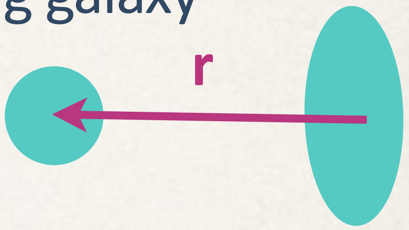


$$\eta_e(r) = \langle|\overset{\text{unit separation vector}}{\hat{\mathbf{r}}} \cdot \overset{\text{orientation of inertia minor axis}}{\hat{\mathbf{e}}}(\mathbf{x}+\mathbf{r})|^2\rangle - 1/3$$

$$= \left\langle\cos^2\theta\right\rangle - 1/3$$

It measures the correlations between the ellipticity of a galaxy and the surrounding galaxy distribution.

>0 : galaxies are elongated tangentially wrt the other galaxies



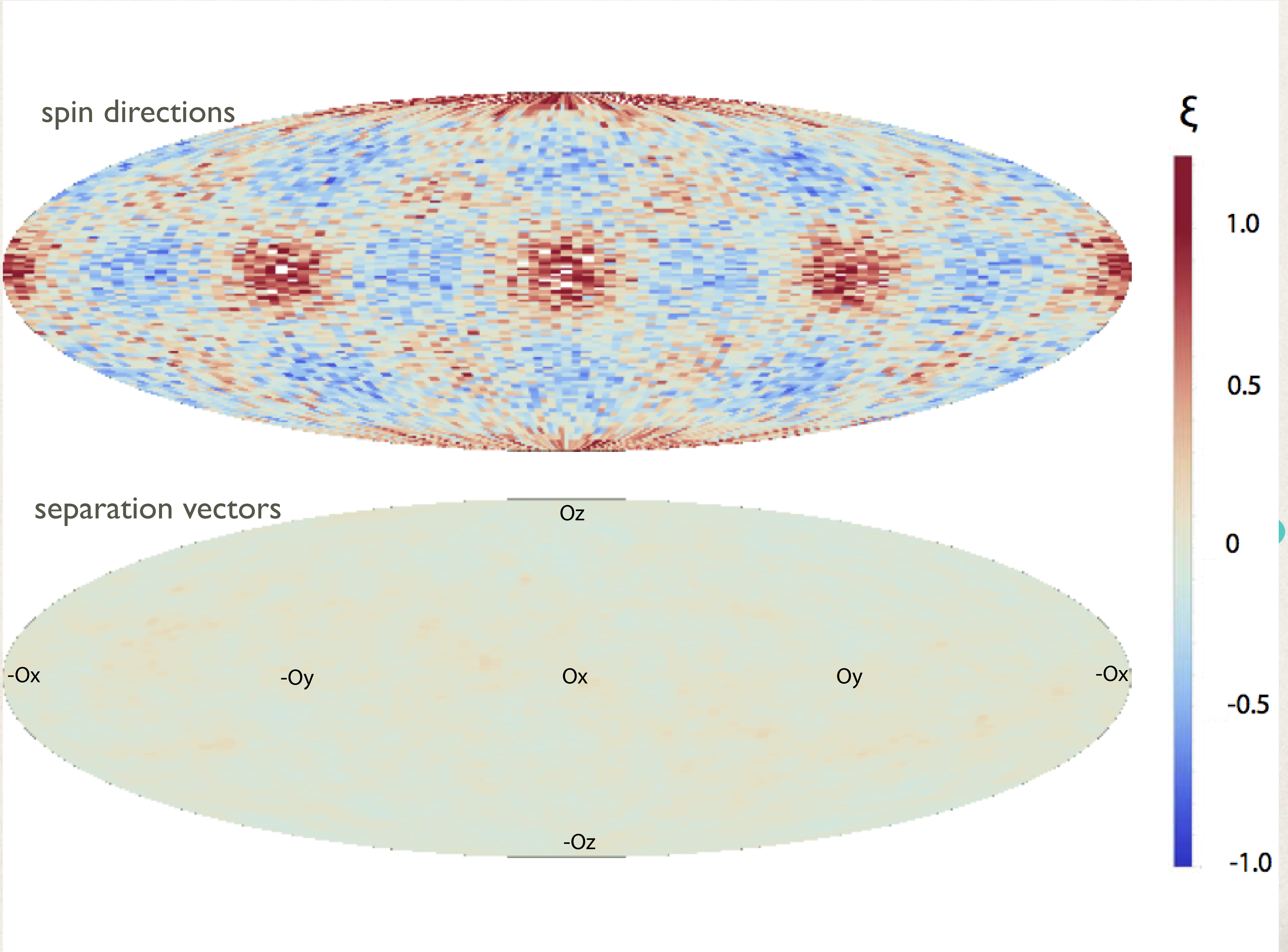
<0 : galaxies are elongated radially towards other galaxies

No grid locking!

It does not suffer from grid locking…

Separation-Orientation correlations

Chisari+15



Separation-Orientation correlations

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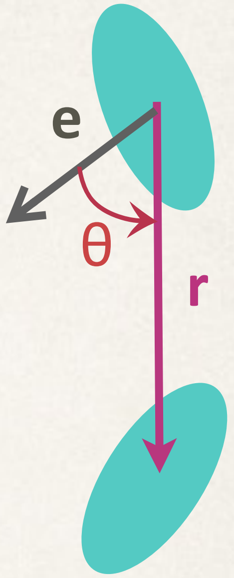
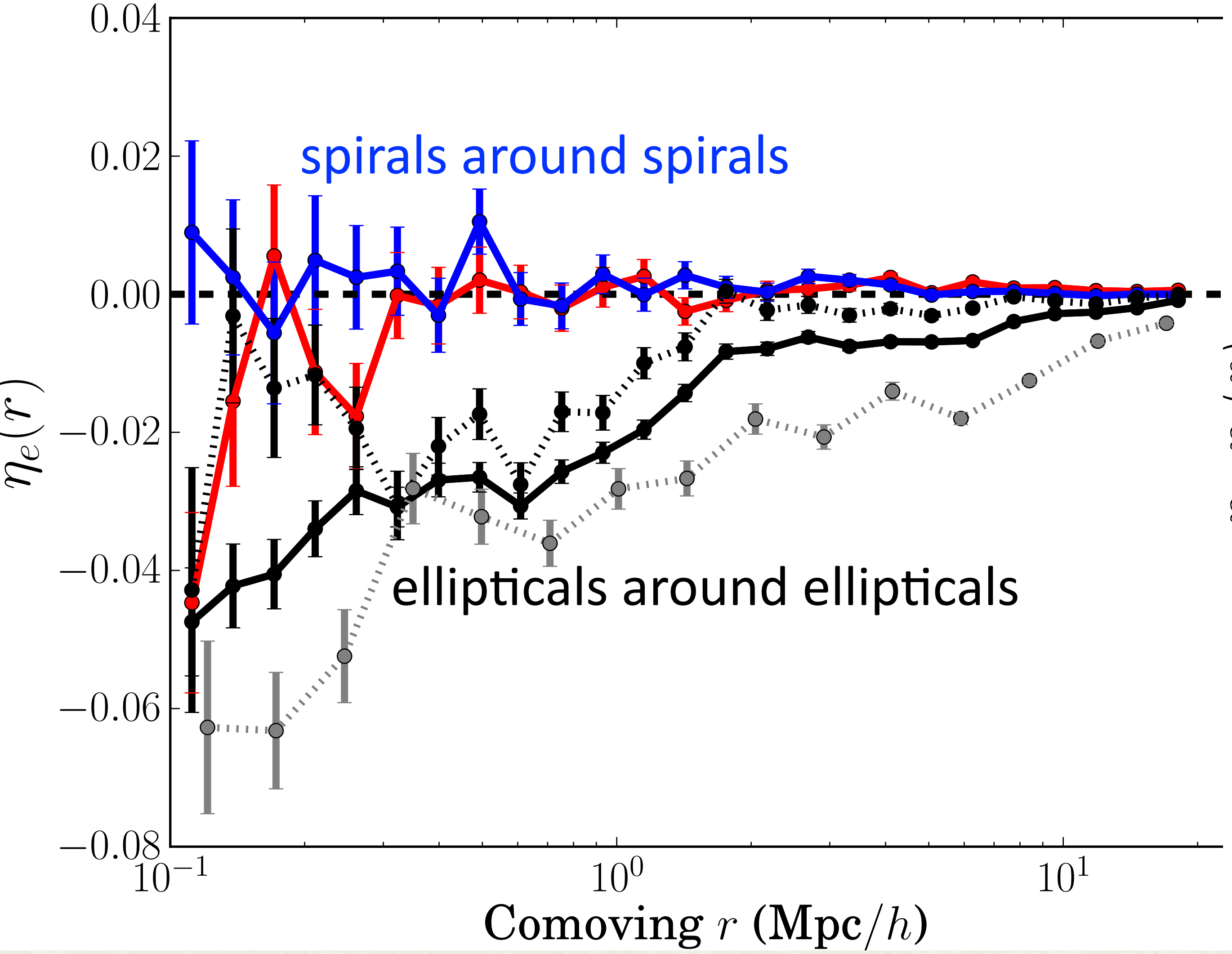
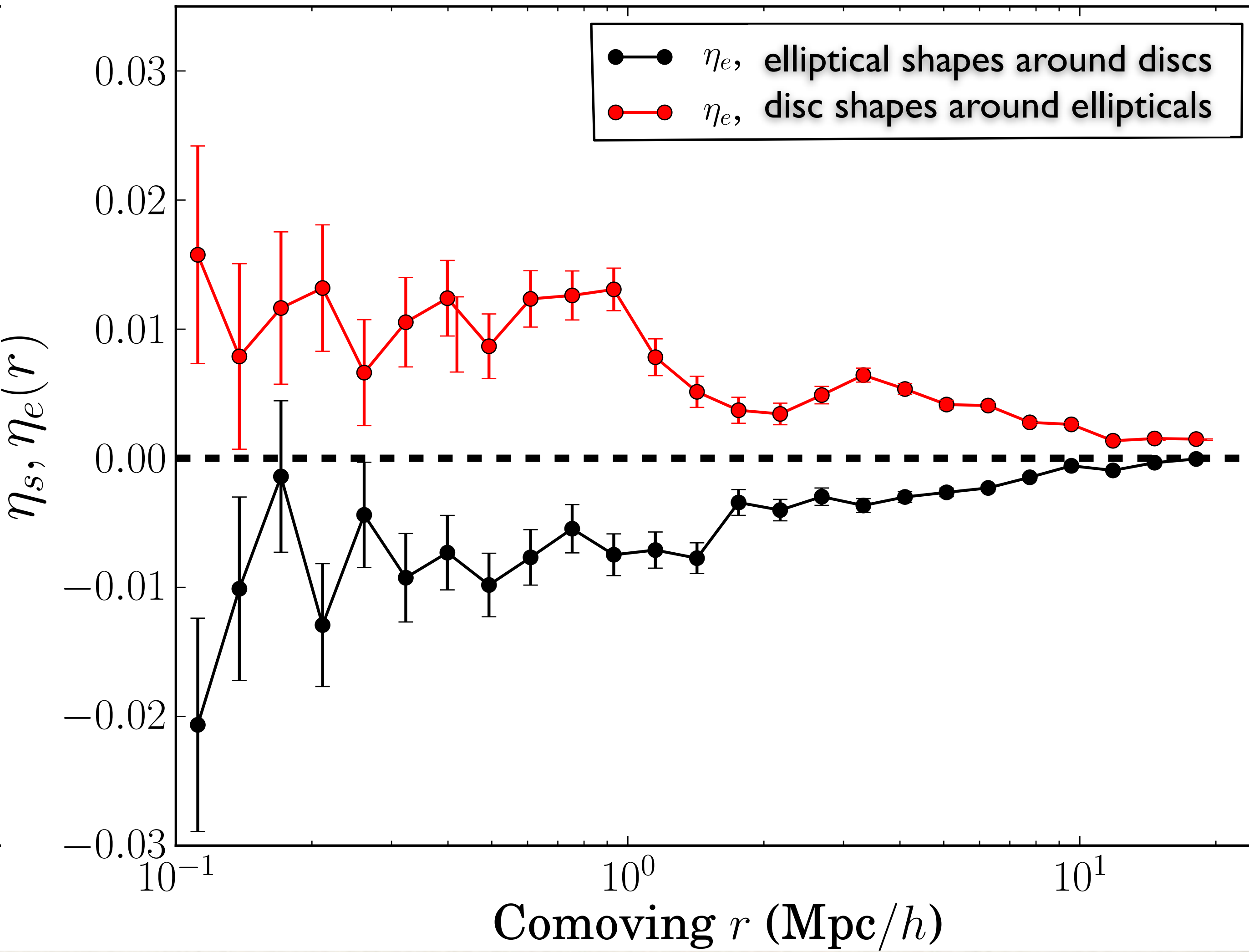




ellipticals are elongated radially towards all galaxies



spirals are elongated tangentially wrt ellipticals

Separation-Orientation correlations

Chisari+15

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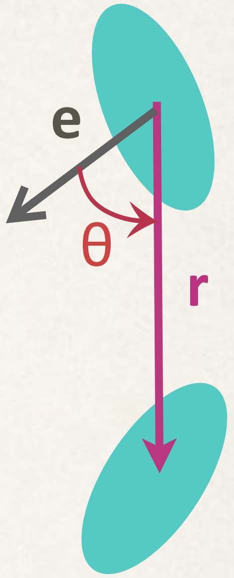

ellipticals are elongated radially towards all galaxies

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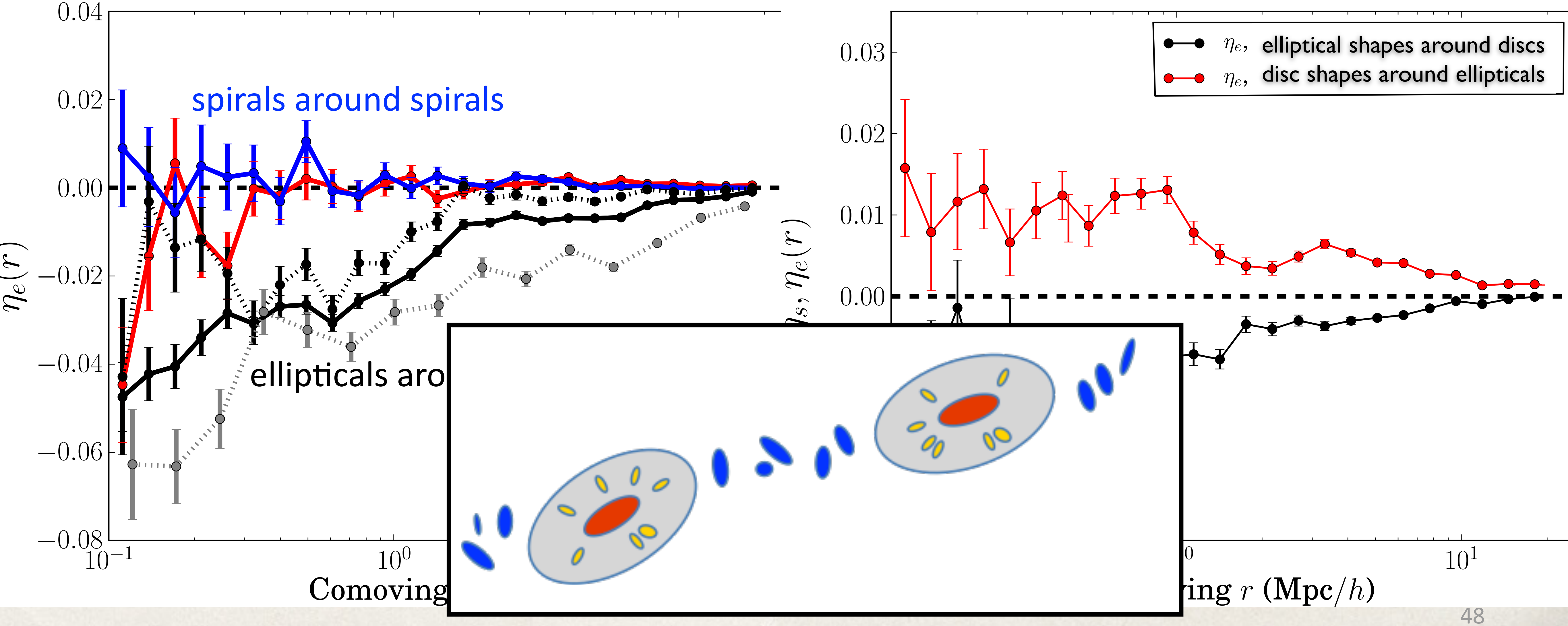
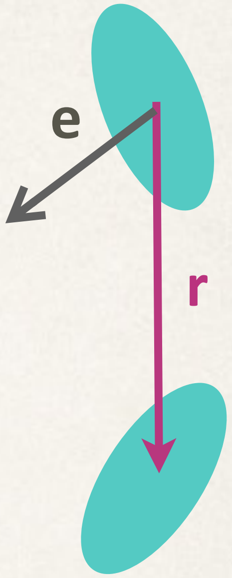


Separation-Orientation correlations in projection

Chisari+15



proxy for the tidal tensor

Correlation between projected ellipticity and density tracers via a Landy-Szalay estimator:

projected pair separation

ellipticity

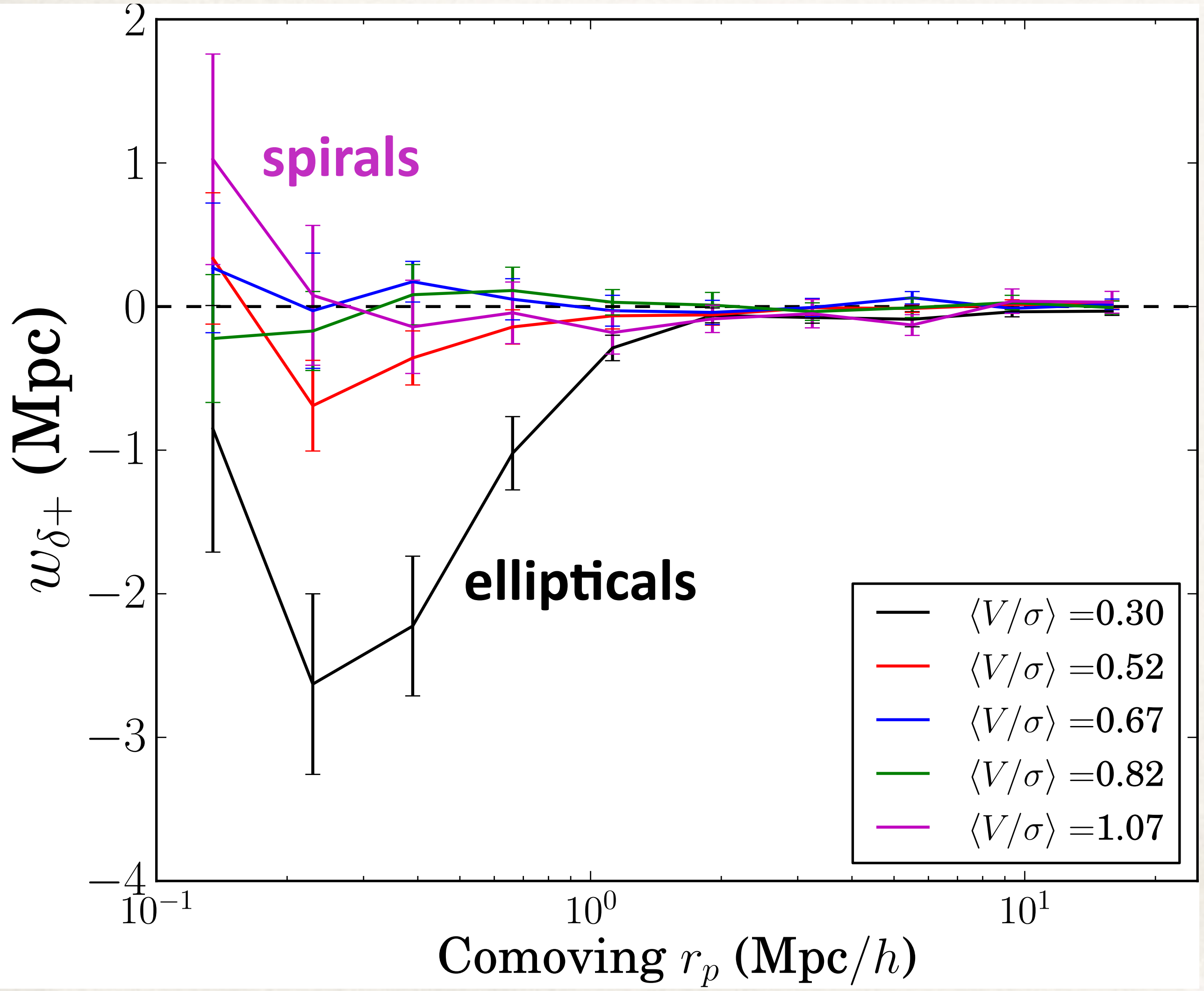
data

random

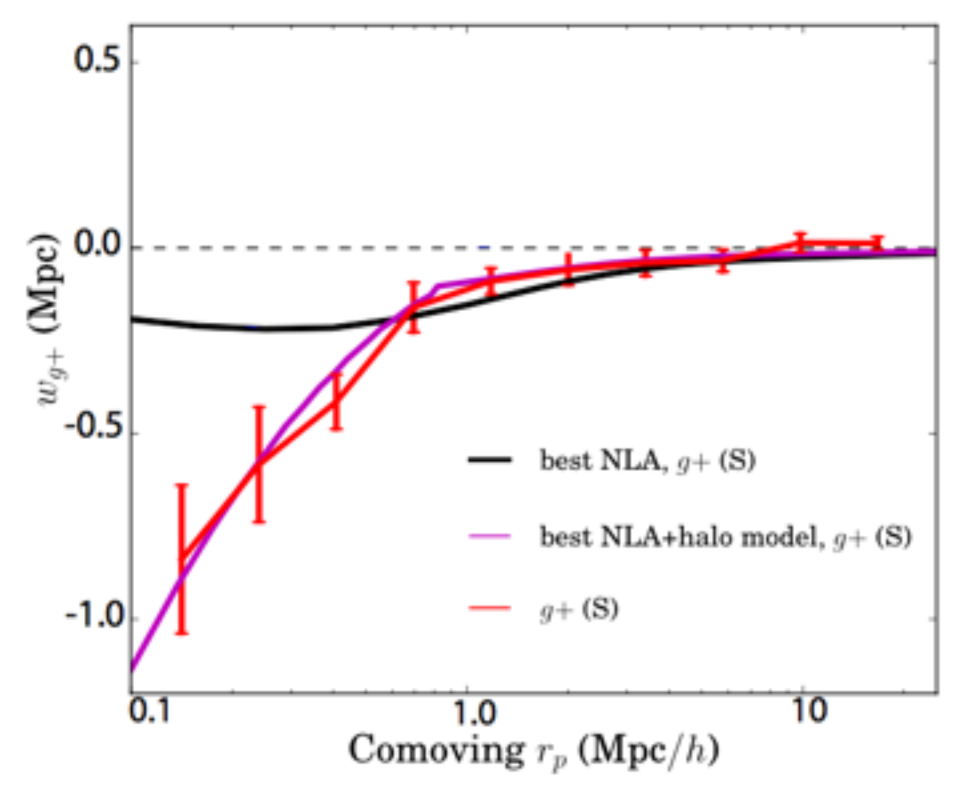
$$w_{g,+}(r_p) = \frac{S_+D - S_+R}{RR}$$

where

$$S_+D = \sum_{j \text{ at fixed } r_p} \frac{e_{+,j}}{2(1-\langle e^2\rangle)}$$

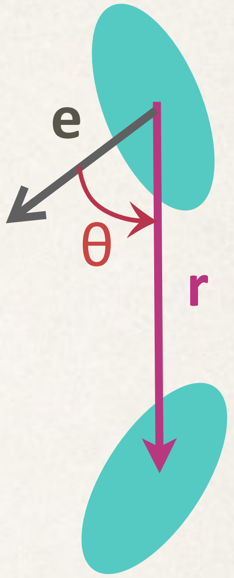


Ellipticals *are* correlated to the density field (less significantly for spirals)



Redshift evolution?

Chisari+16



Standard observable in the field of intrinsic alignments, defined as

unit separation vector

orientation of inertia minor axis

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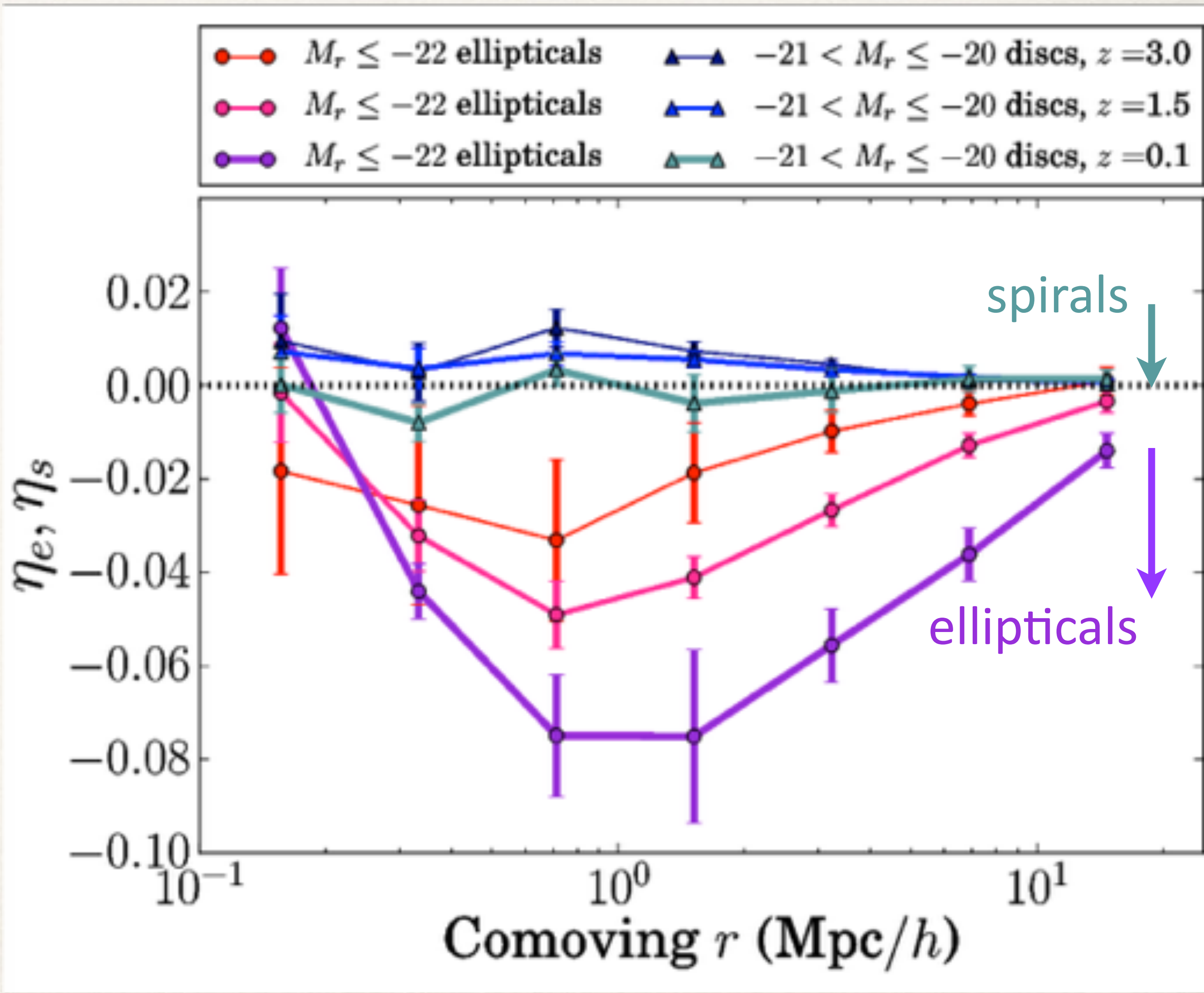
$$= \left\langle \cos^2\theta \right\rangle - 1/3$$

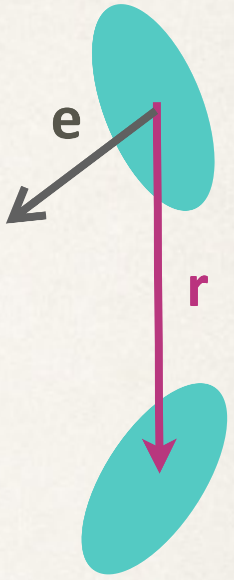
Elliptical radial alignment increases at low-redshift
Spiral tangential alignment increases at high redshift



Redshift evolution?

In projection….

Chisari+16



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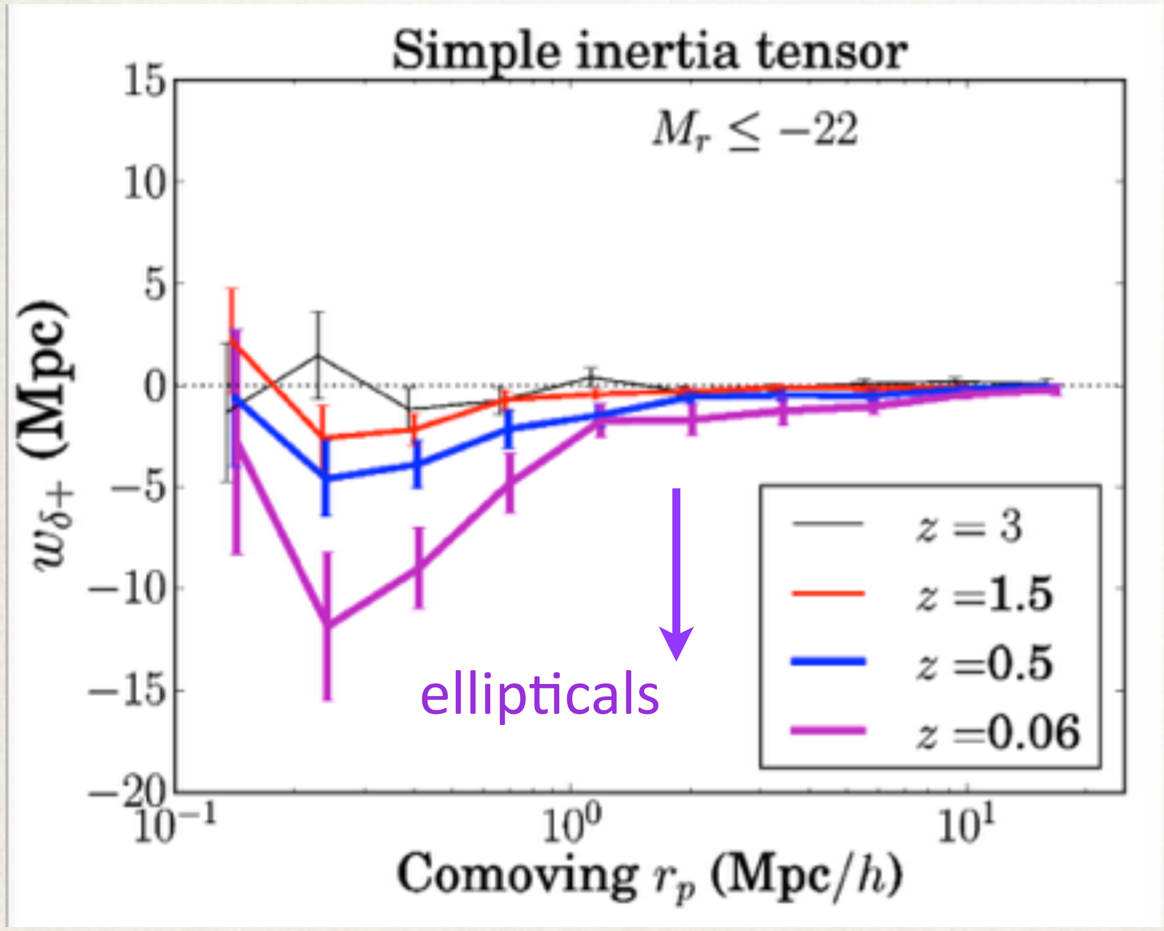

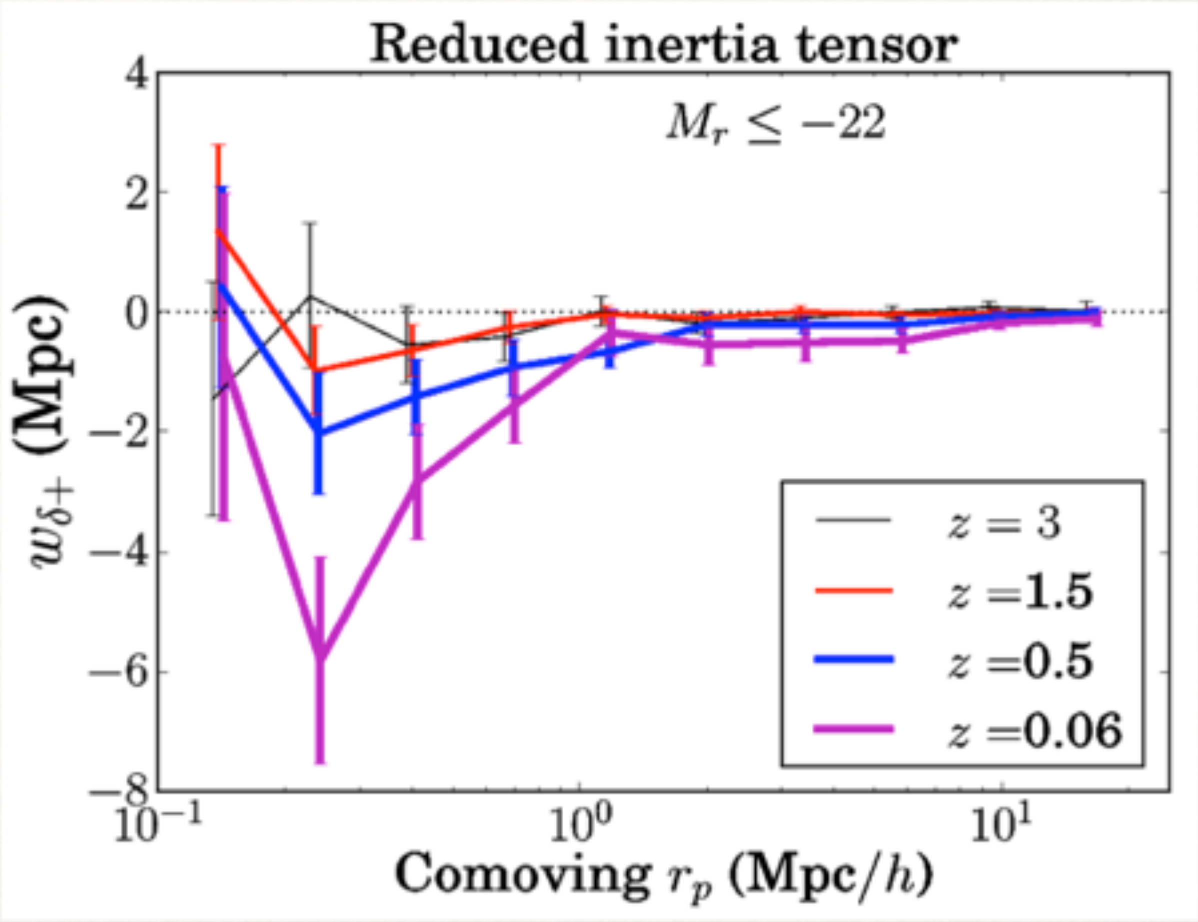

Elliptical radial alignment increases at low-redshift

Shape measurements method matters…

Comparison with other simulations and observations….

Chisari+16

Consistent with current observations BUT:

-Illustris and Massive Black II do not predict the **tangential alignment** of disc-like galaxies and the increased radial alignment at low-redshift (Tenneti+15). The amplitude of IA in Massive-Black II is about a factor of 2 larger than Horizon-AGN, Illustris and observations.

-Theoretical models of IA (including NLA + halo model) do not completely reproduce the measurements in Horizon-AGN in particular on **small scales** (<1Mpc/h) and for the transition from radial (high luminosity) to tangential (low luminosity) alignments.

Open questions:
impact of baryonic physics ? numerical schemes ? observational systematics like dust attenuation, shape measurements, galaxy selections?

Those questions are essential as IA can have a drastic impact on cosmological contraints from weak lensing…

Comparison with other simulations and observations….

Chisari+16

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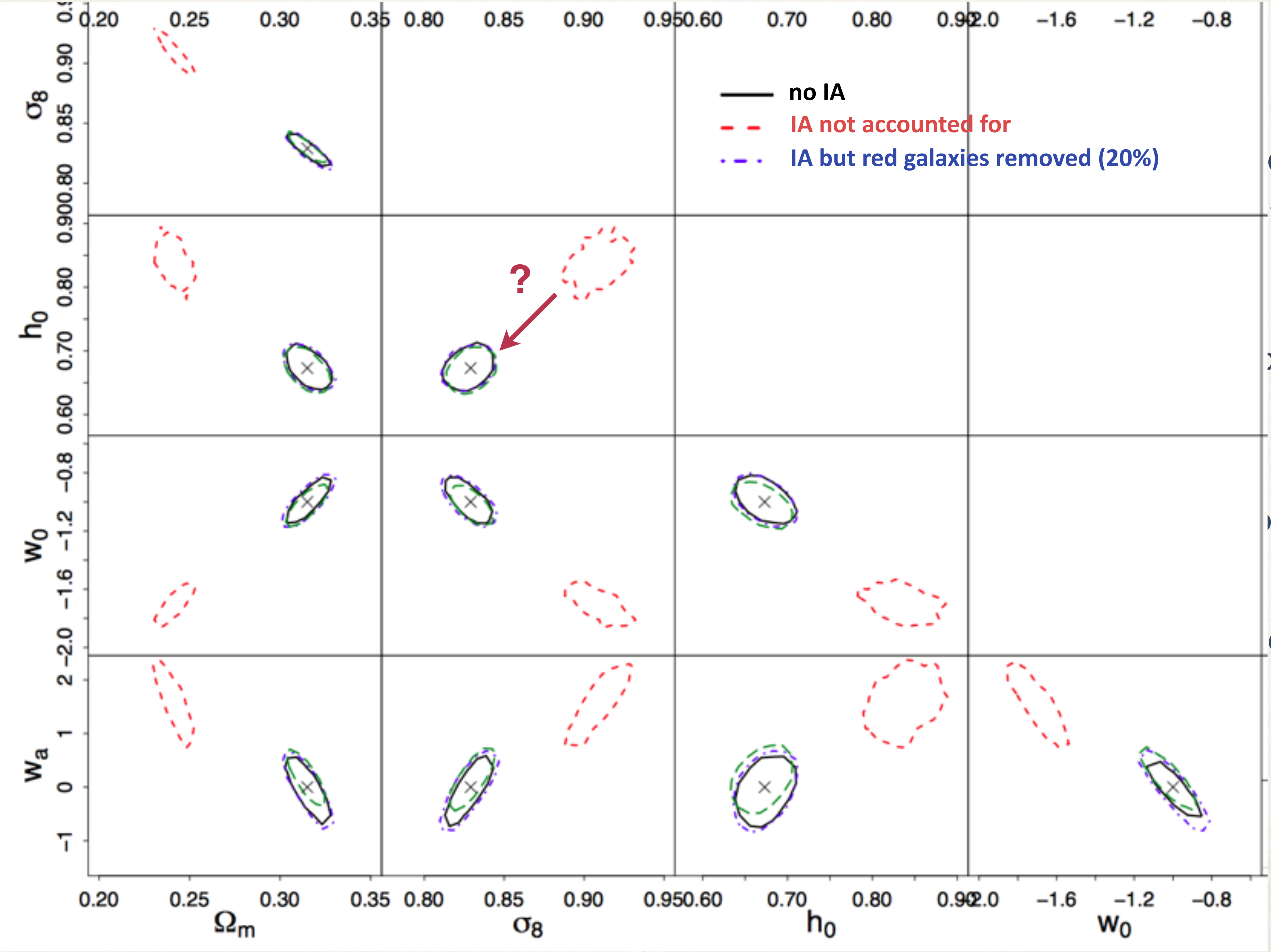
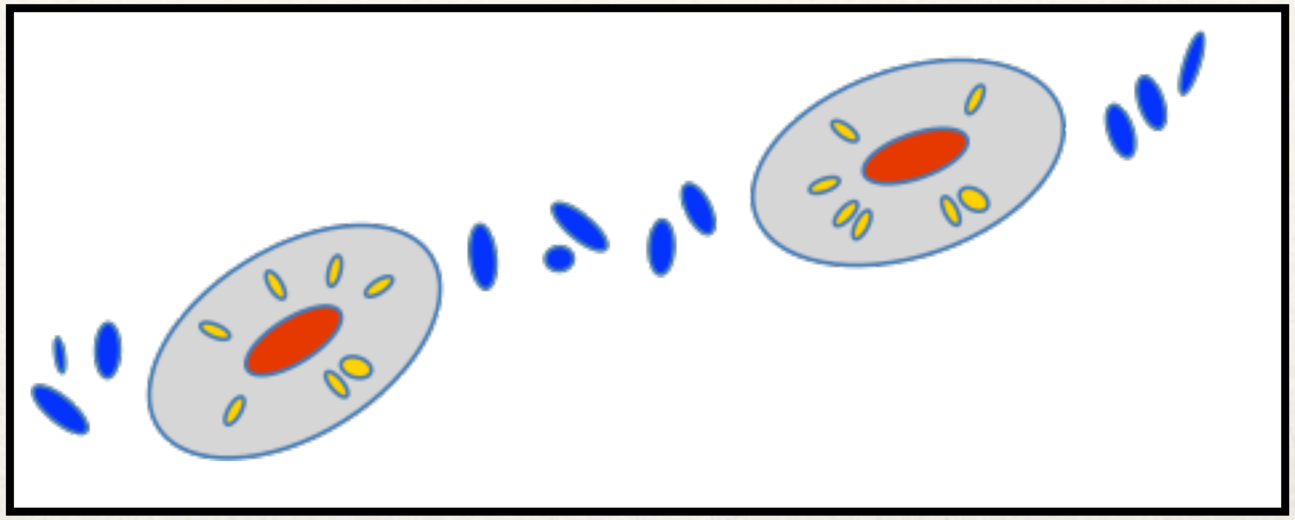
Impact of IA modelisation for Euclid (Krause 2015):



Current status and perspectives

- ★ Galaxy morphology is correlated with the LSS and induces IA
- ★ Parametrizing IA is a difficult issue, not yet satisfactory enough. One idea could be to incorporate biased clustering in the picture.
- ★ Induced IA contamination can be investigated with hydro simulations which account for non-linear gas dynamics, baryonic physics, selection effects, ...
- ★ In order to improve our knowledge about IAs, further works are necessary: match shape measurement and galaxy selection done in observations, study the impact of numerical codes, sub-grid physics, ...
- ★ Find the optimal strategy for Euclid (select a sample less prone to IA, design a parametrized model in agreement with galaxy formation simulations?)



Additional materials: more on anisotropic spin acquisition

Can we understand, from a **Lagrangian** point of view, where spin alignments come from?

Additional materials:
more on anisotropic spin acquisition

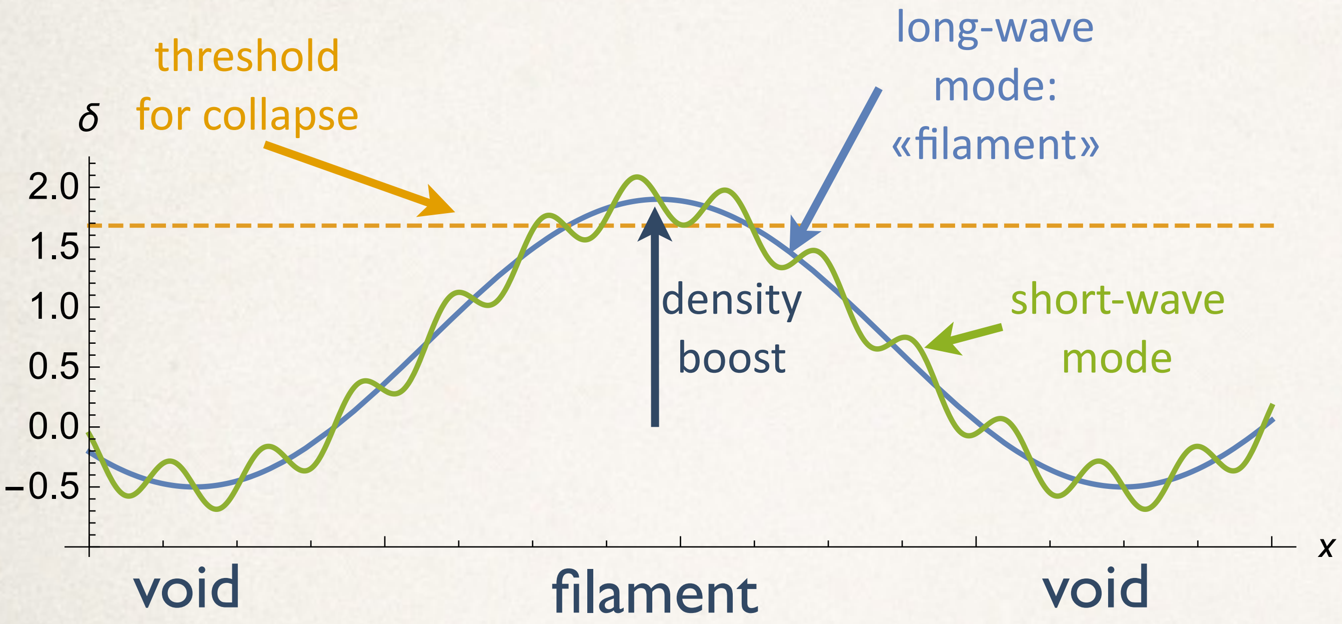
Can we understand, from a **Lagrangian** point of view, where spin alignments come from?

Do you know about peak theory/BBKS?

1) Not at all
2) I’ve already heard about it but would like to hear more
3) I know everything about peaks/I am an aficionado of BBKS

Biased clustering
The peak (or filament) background split

Kaiser84
Cole&Kaiser89
Sheth+01 ...



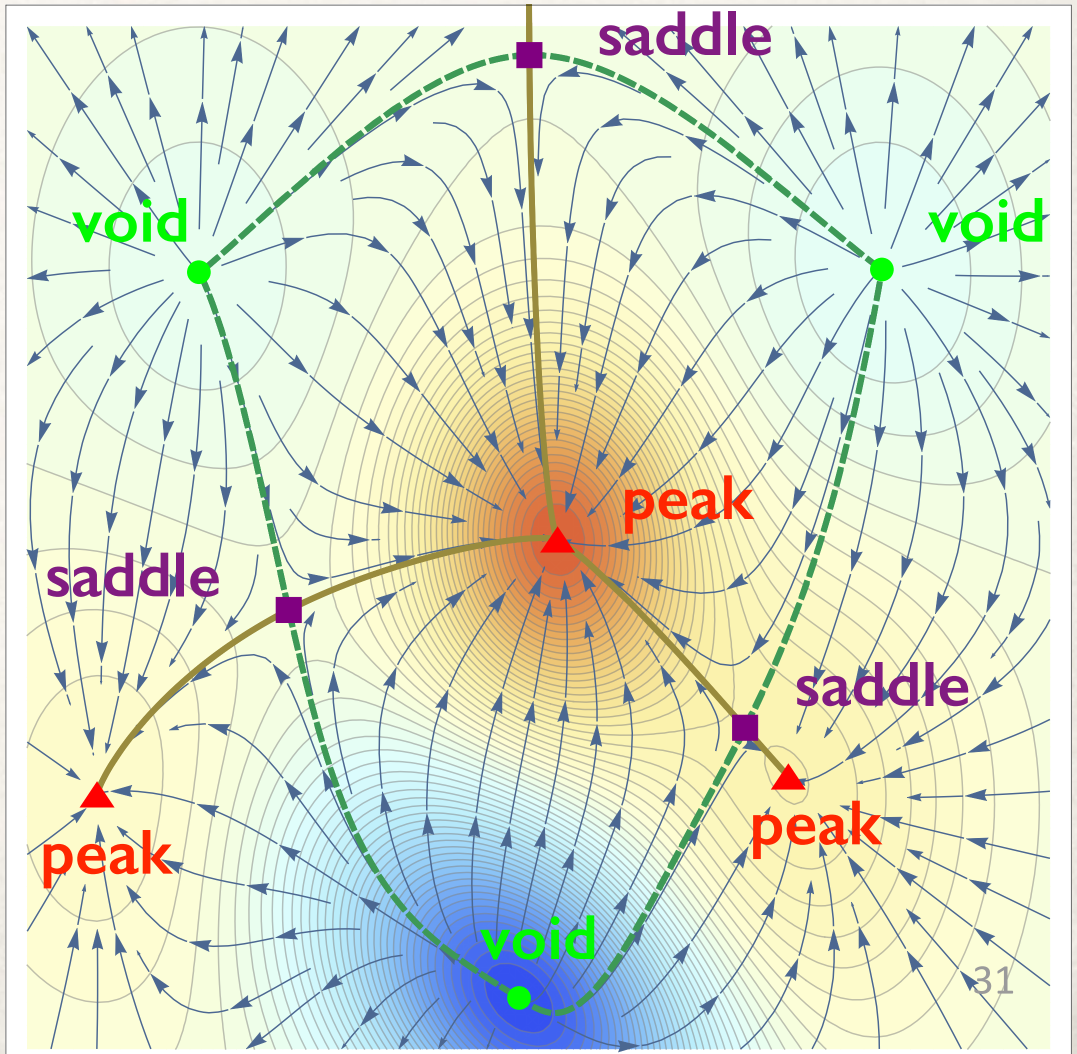
Filaments is the interference pattern on which proto-galaxies form.

The most massive halos tend to form in the densest environments (dense filaments and nodes).

Filaments are the field lines joining the maxima through saddle points.

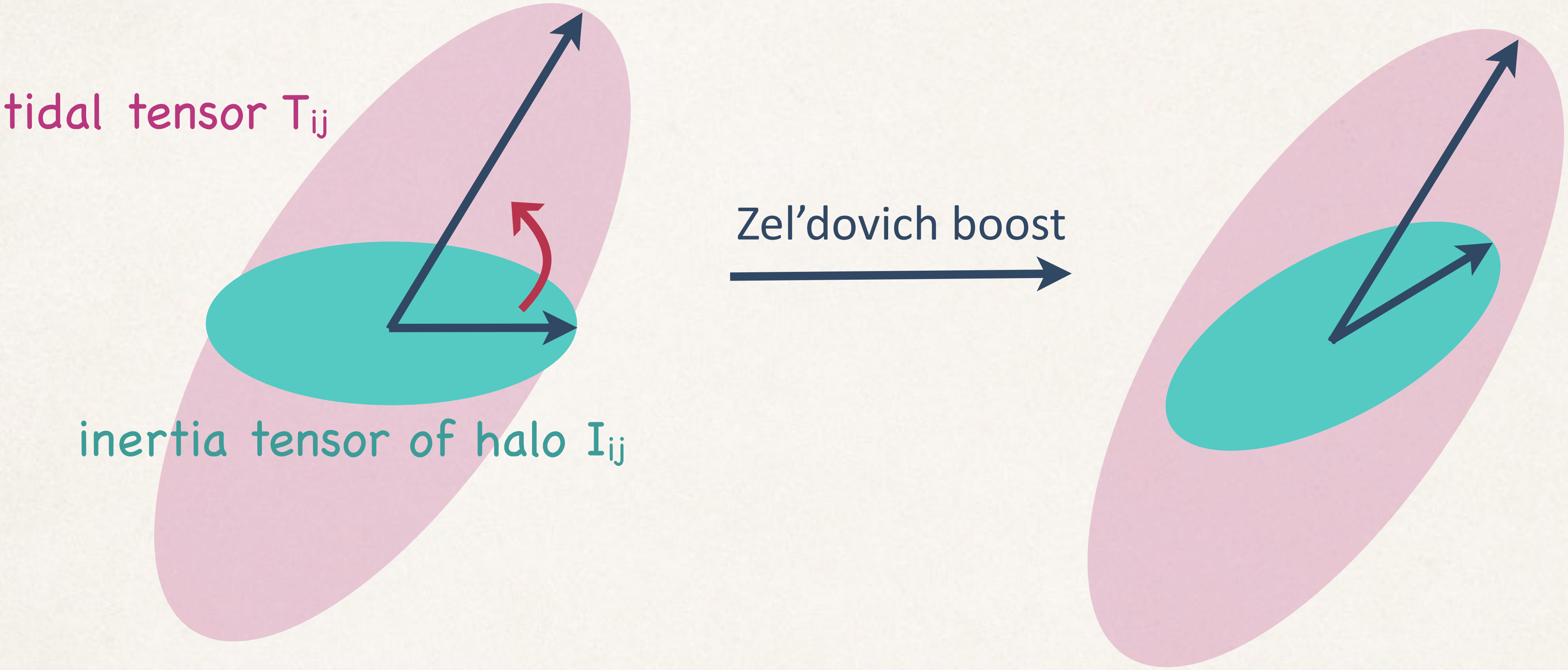
Pogosyan+09

We will therefore focus on the vicinity of saddle points.



Standard theory of tidal torquing

Hoyle49, Doroshkevich70,
White 84, Heavens+88,
Catelan+96, Crittenden+01
Schafer09,...



tidal tensor T_{ij}

inertia tensor of halo I_{ij}

Zel'dovich boost

The force field acts as a torque and generates spin proportionally to the misalignment between I and T:

$$L_k \propto \epsilon_{ijk} I_{li} T_{lj}$$

Can we understand where spin alignments come from?

★ usual tidal torque theory (TTT)

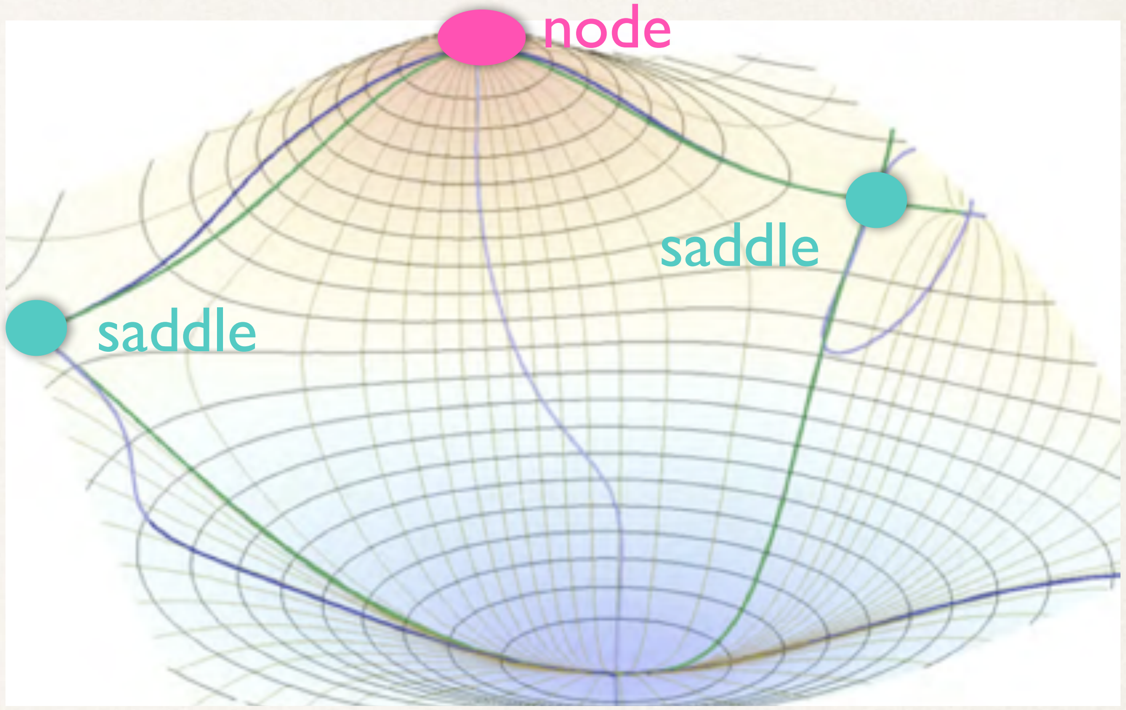
$$L_k = \varepsilon_{ijk} I_{li} T_{lj}$$

+

★ anisotropy of the cosmic web

=

TTT constrained to
the vicinity of a saddle point



Basic idea: I is sensitive to smaller scales than T.
In the plane of the saddle : the proto-halo mainly feels the gravitational influence of the nearby wall and therefore acquire spin aligned with the filament.
Closer from the nodes : it mainly feels the filaments and therefore acquires spin perpendicular to the filament.
Key ingredient: the saddle point is anisotropic (=flattened)!

Spin acquisition near saddle points : analytics

Spin generated by linear TTT:

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

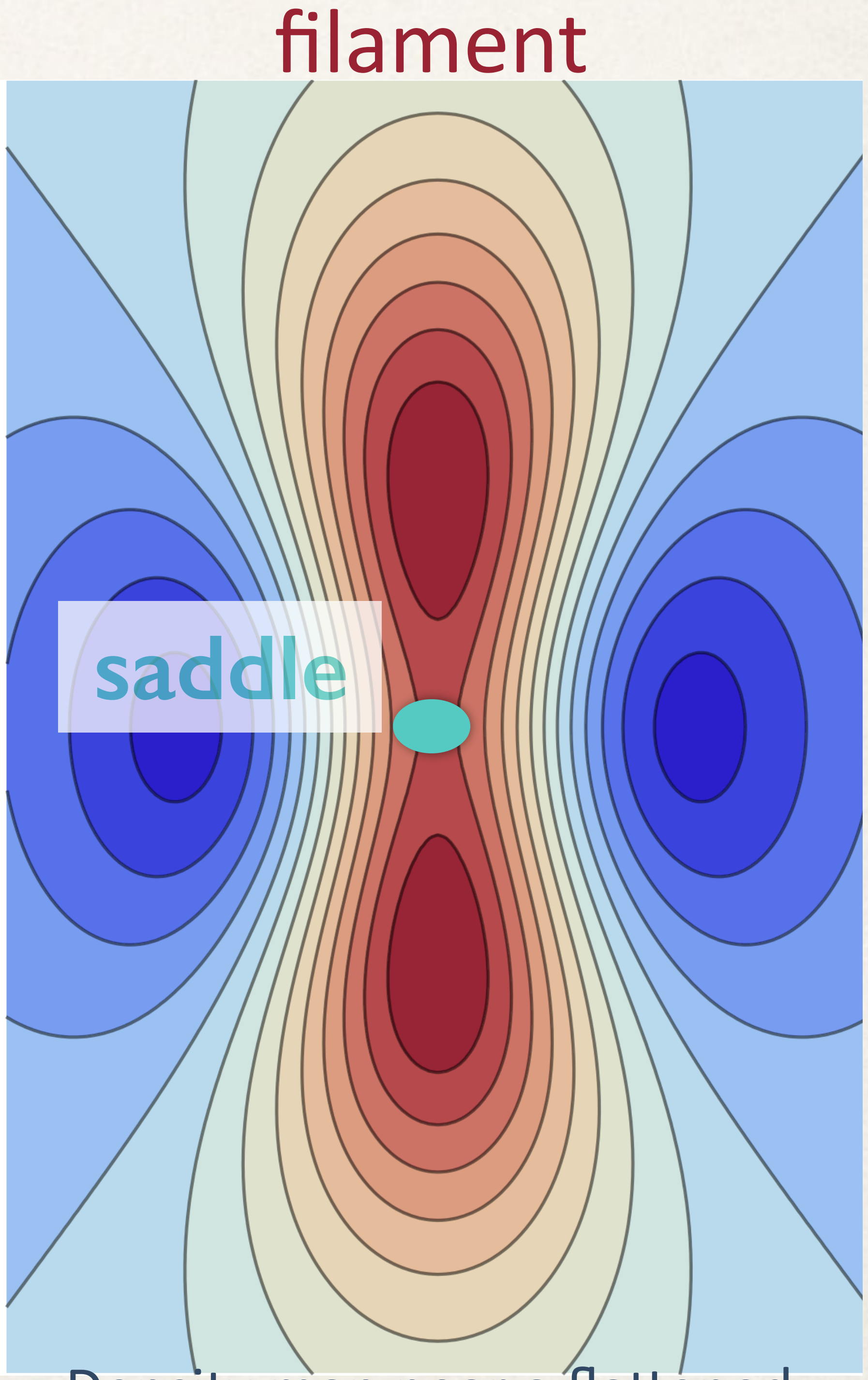
$$\approx \varepsilon_{ijk}\, H_{li}\, T_{lj}$$

Tidal tensor $\partial_{lj}\Phi$

density Hessian $\partial_{aali}\Phi$

<L>=0 (no preferred direction)

<L|saddle>?



Density map near a flattened saddle point

2D Spin acquisition near peaks

Spin generated by linear TTT:

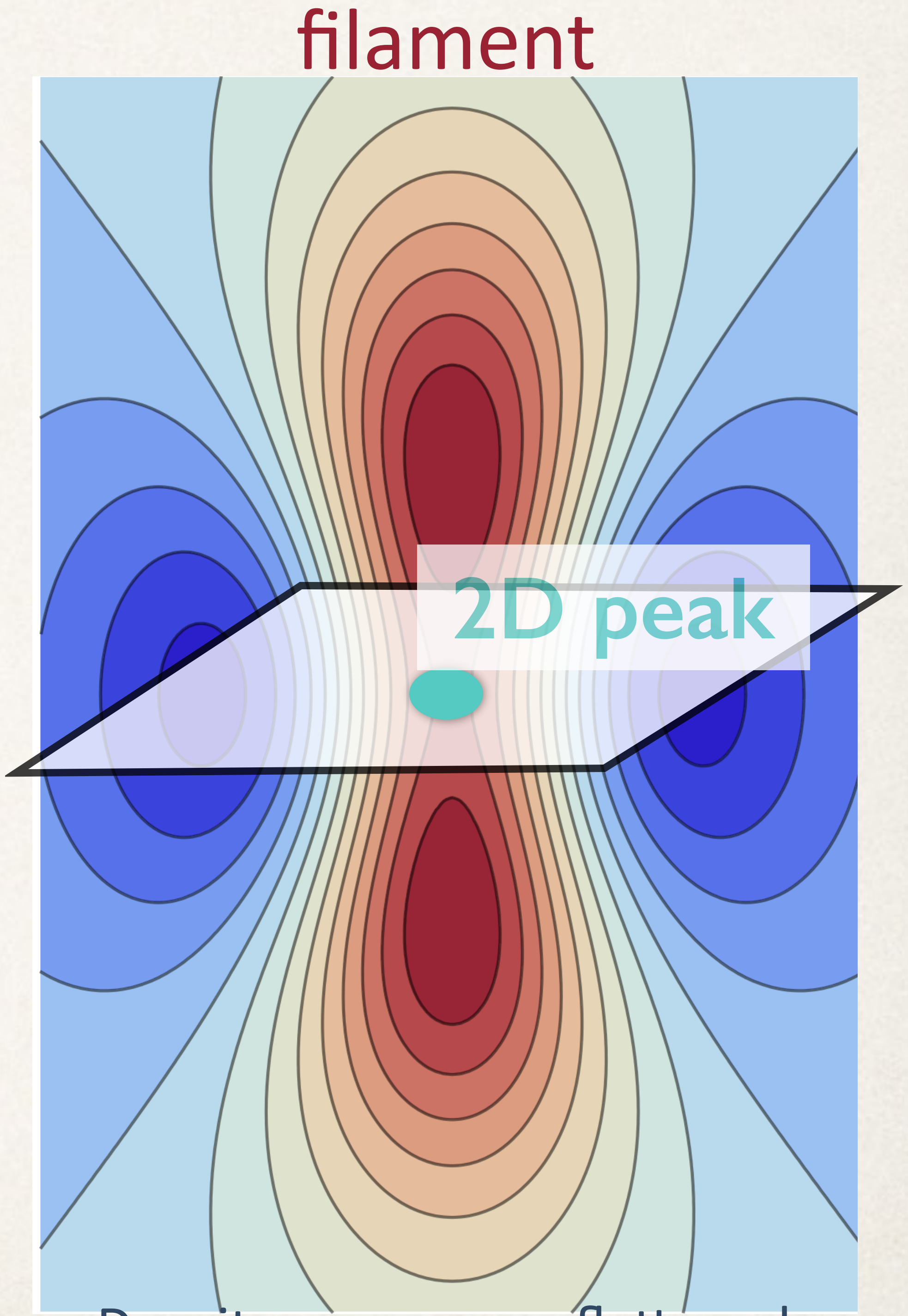
$$\begin{aligned} L_k &= \varepsilon_{ijk}\, I_{li}\, T_{lj} \\ &\approx \varepsilon_{ijk}\, H_{li}\, T_{lj} \end{aligned}$$

Tidal tensor $\partial_{lj}\Phi$

density Hessian $\partial_{aali}\Phi$

<L>=0 (no preferred direction)

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



Density map near a flattened saddle point *from seminal ideas in BBKS 86*

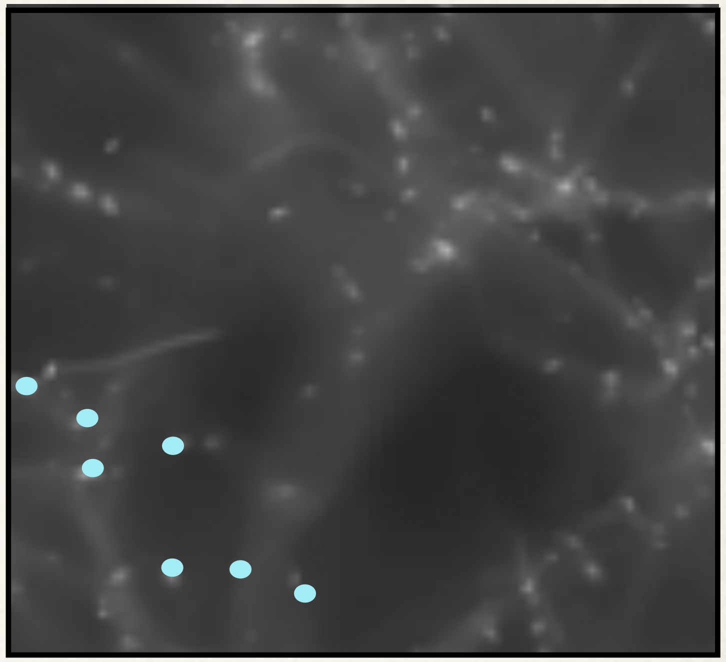
The peak (or saddle) condition

It requires the knowledge of the joint PDF :

$$P(x, x_i, x_{ij})$$

of the **field** x and its first x_i and second x_{ij} derivatives.

peaks = point process



Why?

Let us come back to **peak theory** (*Bardeen et al 86*).
The number density of peaks is:

$$n_{\rm peak}(\vec{r}) = \sum_k \delta_D(\vec{r} - \vec{r}_{{peak}\, k})$$

A Taylor expansion of x_i around a peak *k* reads:

$$\underset{\nabla}{x_i}(\vec{r}) = 0 + \sum_j \underset{\mathcal{H}}{x_{ij}}(\vec{r}_{{\rm peak}\, k}) \times (\vec{r} - \vec{r}_{{\rm peak}\, k})_j$$

which can be inverted : $(\vec{r} - \vec{r}_{{\rm peak}\, k}) = \mathcal{H}^{-1}(\vec{r}_{{\rm peak}\, k}) \cdot \nabla(\vec{r})$

So that $n_{\rm peak} = \sum_k \delta_D(\vec{r} - \vec{r}_{{\rm peak}\ k}) = |\det \mathcal{H}| \delta_D(\nabla)$

Therefore, we get

$$\overline{n}_{\rm peak}(\nu) = \int \frac{{\rm d}^3\vec{r}}{V}\, n_{\rm peak}(\vec{r}) = \langle n_{\rm peak} \rangle = \int {\rm d}x\, {\rm d}^3 x_i\, {\rm d}^6 x_{ij} P(x, x_i, x_{ij}) |\det x_{ij}| \delta_D(x_i)$$

ergodicity!
spatial average=ensemble average

$$\times \Theta(-\lambda_i) \times \Theta(x - \nu)$$

eigenvalues of $\mathcal{H}$ density threshold

The peak (or saddle) condition

from seminal ideas in BBKS 86

It requires the knowledge of the joint PDF :

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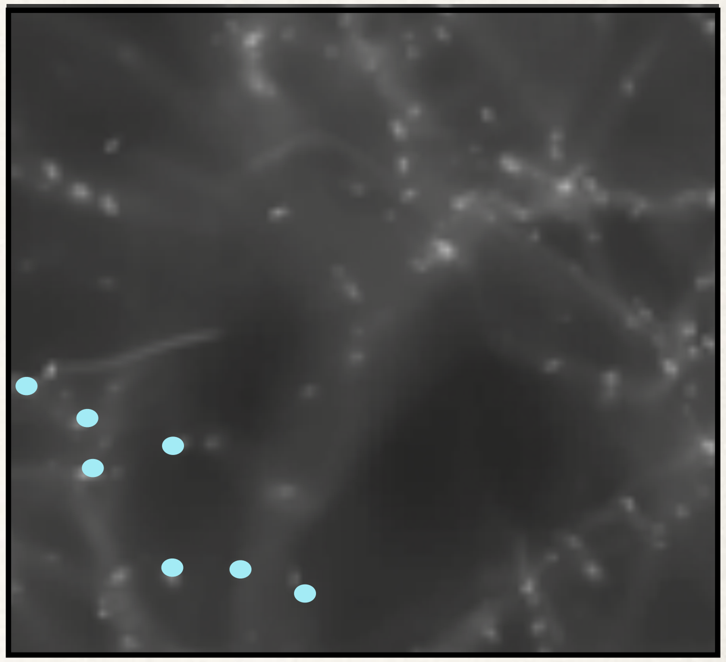
peaks = point process



So that in the end:

1-point

$$\langle n_{\rm peak}\rangle(\nu) = \int {\rm d}x\, {\rm d}^3x_i\, {\rm d}^6x_{ij} P(x, x_i, x_{ij}) |\det x_{ij}| \delta_D(x_i) \Theta(x-\nu)\Theta(-\lambda_i)$$

from seminal ideas in BBKS 86

The peak (or saddle) condition

It requires the knowledge of the joint PDF :

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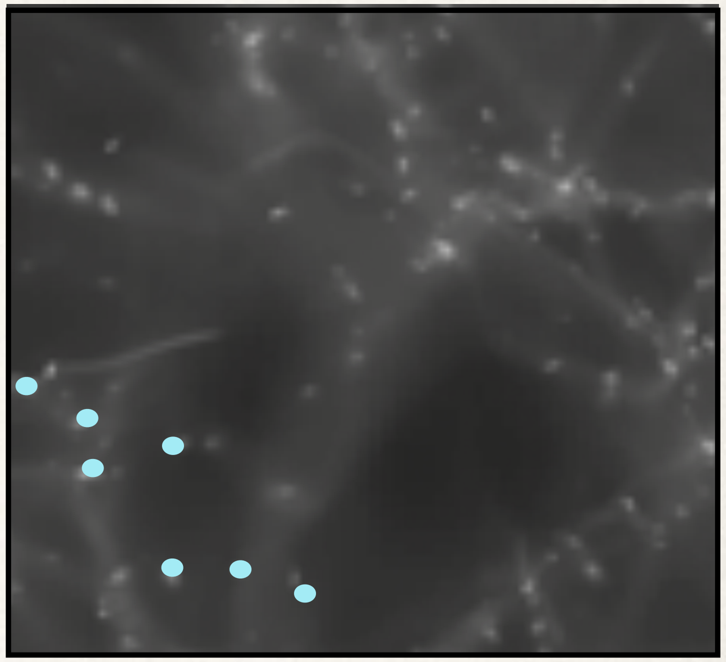

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So that in the end:

1-point

$$\langle n_{\rm peak} \rangle (\nu) = \int {\rm d}x\, {\rm d}^3 x_i\, {\rm d}^6 x_{ij} P(x, x_i, x_{ij}) |\det x_{ij}| \delta_D(x_i) \Theta(x - \nu) \Theta(-\lambda_i)$$

2-point

Similarly, in 2D, the mean spin given a peak with known density height and curvatures reads

$$\langle L_z | pk \rangle (\vec{r}) \propto \int {\rm d}X\, {\rm d}Y\, P(X, Y)\, L_z(Y) \times |\det x_{ij}| \delta_D(x_i) \delta_D(x - \nu) \delta_D(\lambda_1(X) - \overline{\lambda_1}) \delta_D(\lambda_2(X) - \overline{\lambda_2})$$

where $X = \{x, x_i, x_{ij}\}$ and $Y = \{y, y_i, y_{ij}, \dots\}$ in two locations separated by $\vec{r}$.

Joint statistics of a field and its derivatives

Let us think about the joint PDF

$$P(x, x_i, x_{ij})$$

of the field x and its first x_i and second x_{ij} derivatives.

If the statistics is Gaussian (e.g in the initial conditions) then

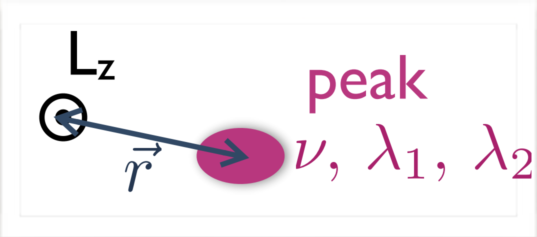
$$P(X) = \frac{1}{\sqrt{\det|2\pi C|}} \exp\left(-\frac{1}{2} X^t \cdot C^{-1} \cdot X\right)$$

where C is the covariance matrix of $X = \{x, x_i, x_{ij}, \ldots\}$.
For instance, in 2D, the covariance matrix of $\{x, x_1, x_2, x_{11}, x_{22}, x_{12}\}$ is given by

$$C \equiv \langle X \cdot X^t \rangle = \begin{pmatrix} 1 & 0 & 0 & -\gamma/2 & -\gamma/2 & 0 \\ 0 & 1/2 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1/2 & 0 & 0 & 0 \\ -\gamma/2 & 0 & 0 & 3/8 & 1/8 & 0 \\ -\gamma/2 & 0 & 0 & 1/8 & 3/8 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1/8 \end{pmatrix}$$

where the spectral parameter $\gamma = \dfrac{\langle \nabla^2 x \rangle}{\sqrt{\langle x^2 \rangle \langle \Delta^2 x \rangle}}$ is built upon the power spectrum.

2D spin acquisition near peaks : analytical result



In 2D, the mean spin given a peak with known density height and curvatures reads

$$\langle L_z|pk\rangle\,(\vec{r}) = -16(\hat{\mathbf{r}}^{\mathrm{T}}\cdot\,\epsilon\cdot\overline{\mathbf{H}}\cdot\hat{\mathbf{r}})\,\left[L_z^{(1)} + 2(\hat{\mathbf{r}}^{\mathrm{T}}\cdot\,\overline{\mathbf{H}}\cdot\hat{\mathbf{r}})L_z^{(2)}\right]$$

unit separation vector

Levi-Civita tensor

detraced Hessian

spin 1 quantity
null if the peak is isotropic

where

$$L_z^{(1)}(r) \quad = \quad \frac{\nu}{1-\gamma^2}\left[(\xi^{\Delta+}_{\phi\phi} + \gamma\xi^{\Delta+}_{\phi x})\xi^{\times\times}_{xx} - (\xi^{\Delta+}_{\phi x} + \gamma\xi^{\Delta+}_{xx})\xi^{\times\times}_{\phi x}\right]$$
$$+\frac{\lambda_1+\lambda_2}{1-\gamma^2}\left[(\xi^{\Delta+}_{\phi x} + \gamma\xi^{\Delta+}_{\phi\phi})\xi^{\times\times}_{xx} - (\xi^{\Delta+}_{xx} + \gamma\xi^{\Delta+}_{\phi x})\xi^{\times\times}_{\phi x}\right]$$

quadrupole ($\propto \sin 2\theta$) coefficient

$$L_z^{(2)}(r) = \left(\xi^{\Delta\Delta}_{\phi x}\xi^{\times\times}_{xx} - \xi^{\times\times}_{\phi x}\xi^{\Delta\Delta}_{xx}\right)$$

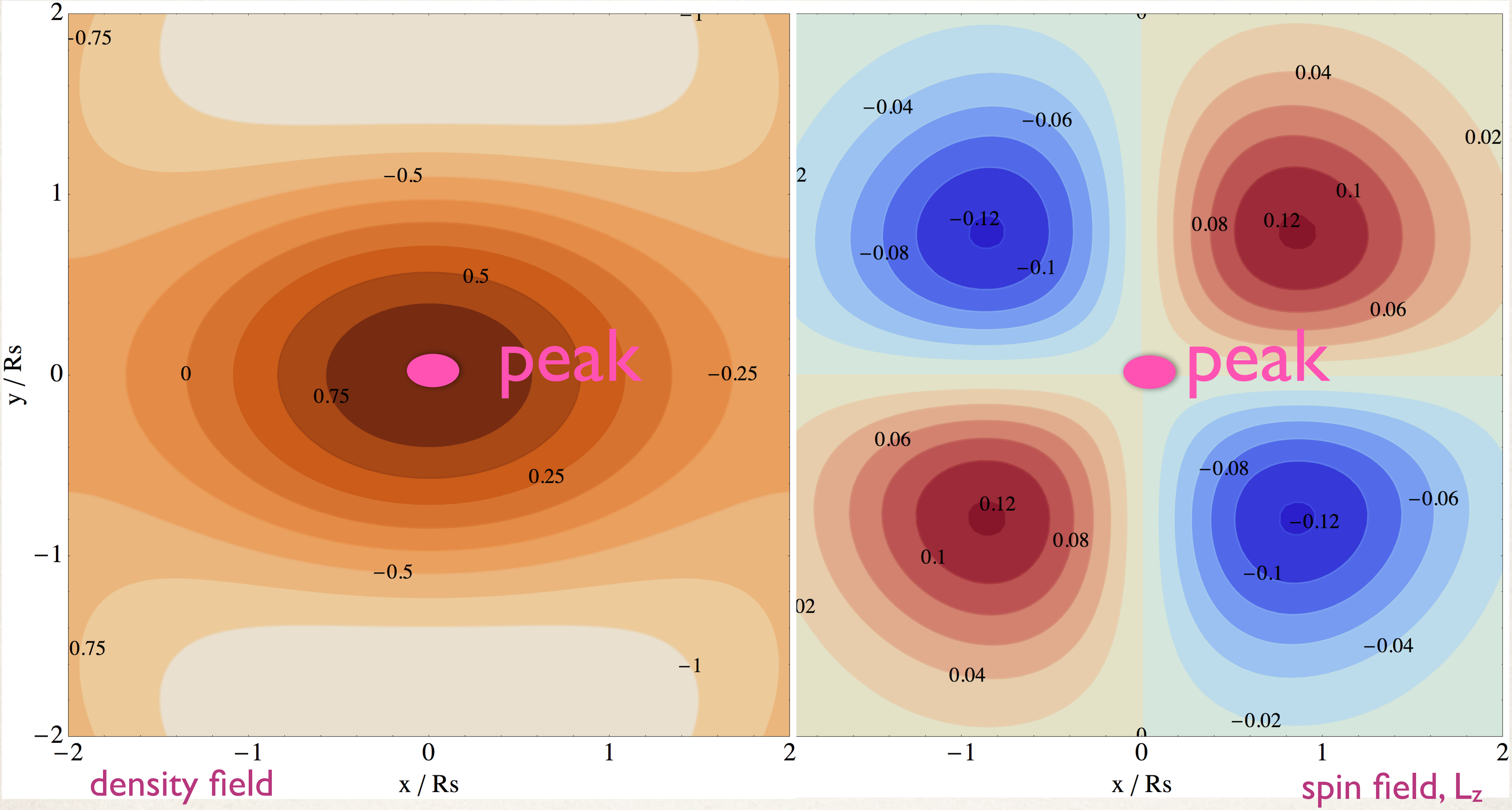
octupole ($\propto \sin 4\theta$) coefficient

and all ξ-functions are known correlation functions that only depends on the distance $\|\vec{r}\|$.
For instance,

$$\xi^{\Delta\Delta}_{\phi x}(r) = \left\langle \Delta\phi(\vec{r'})\Delta x(\vec{r}+\vec{r'})\right\rangle_{\vec{r'}}$$

Codis+15b

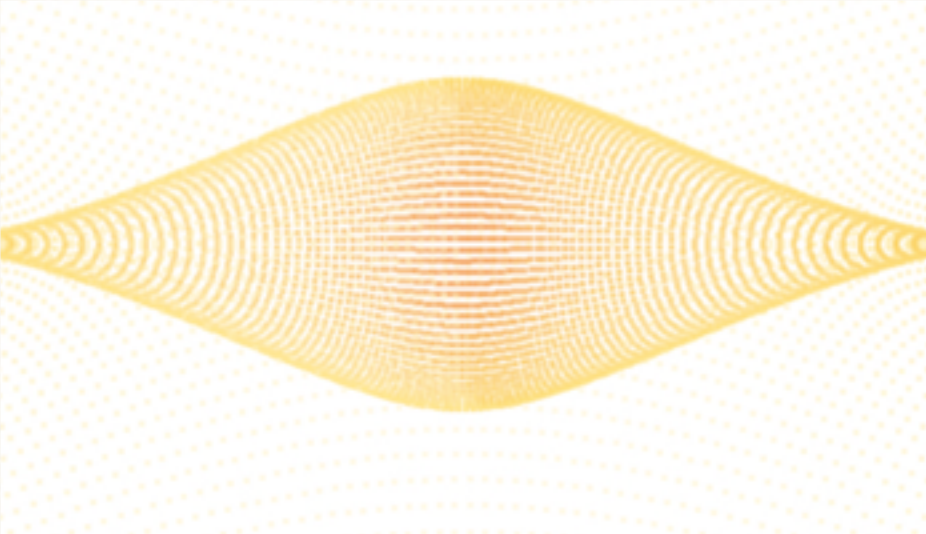
2D spin acquisition near peaks



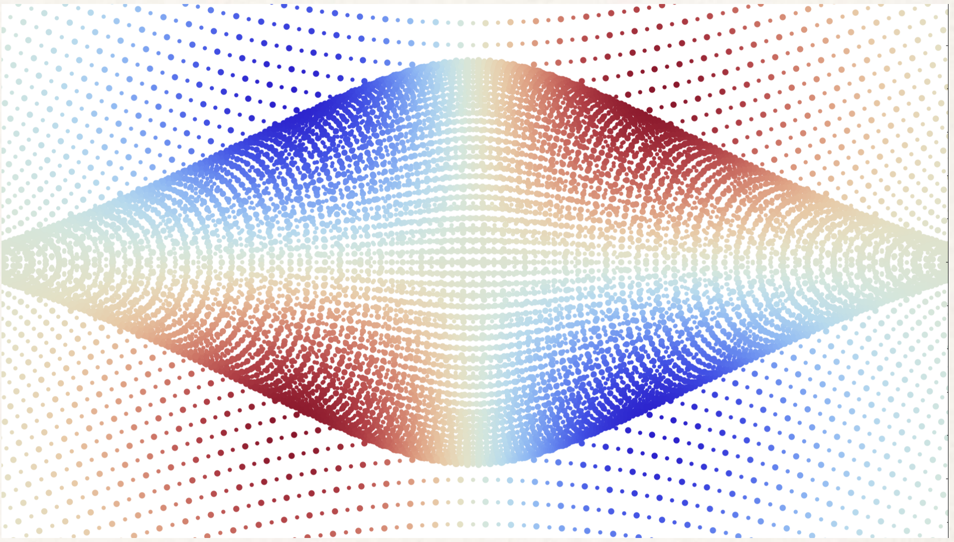
$L_z \propto r^2 \sin 2\theta$ at small radius:

the quadrupole dominates.

Link with simulations: from Lagrangian to Eulerian space

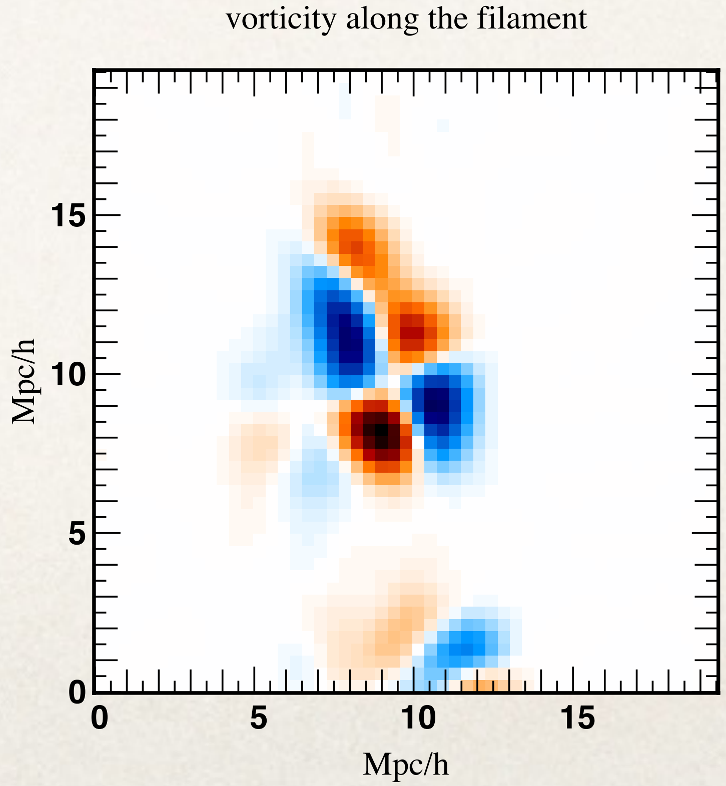


Zel'dovich mapping of the density field



Zel'dovich mapping of the spin field

to be compared with simulations...
Laigle+15



Codis+15b

3D spin acquisition near a saddle point: analytics

In 3D, the mean spin given a saddle point with known density height and curvatures reads

$$\mathbf{L}(\mathbf{r}|\text{saddle}) = -15(\mathbf{L}^{(1)} + \mathbf{L}^{(2)}) \cdot (\hat{\mathbf{r}}^{\mathrm{T}} \cdot \epsilon \cdot \overline{\mathbf{H}} \cdot \hat{\mathbf{r}})$$

spin 1 quantity along e_ϕ if the saddle is isotropic

where

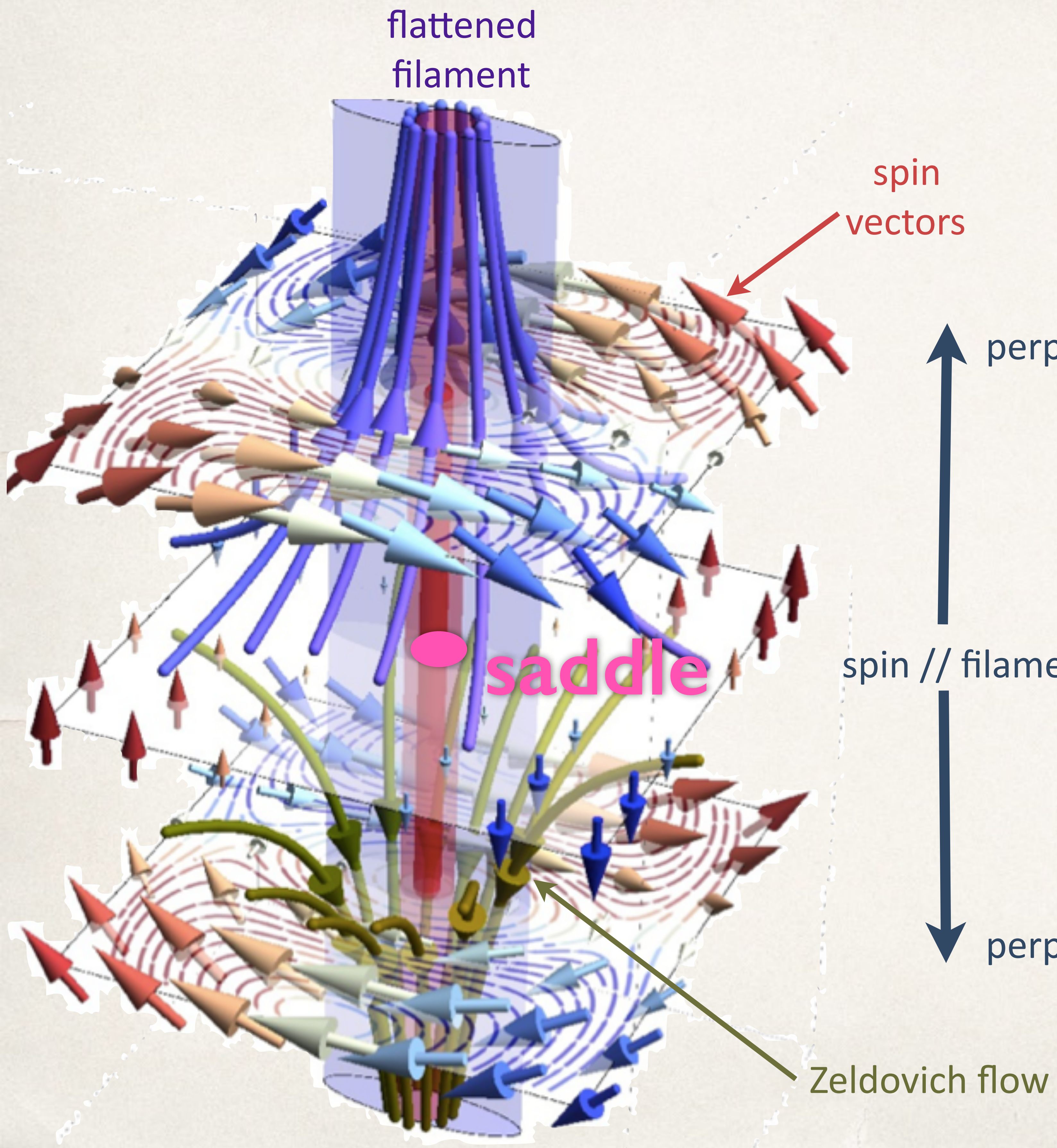
$$\mathbf{L}^{(1)} = \left(\tfrac{\nu}{1-\gamma^2} \left[(\xi_{\phi\phi}^{\Delta+} + \gamma \xi_{\phi x}^{\Delta+}) \xi_{xx}^{\times\times} - (\xi_{\phi x}^{\Delta+} + \gamma \xi_{xx}^{\Delta+}) \xi_{\phi x}^{\times\times} \right] + \frac{I_1}{1-\gamma^2} \left[(\xi_{\phi x}^{\Delta+} + \gamma \xi_{\phi\phi}^{\Delta+})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

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

and all ξ-functions are known correlation functions that only depends on the distance $\|\vec{r}\|$.

3D spin acquisition near a saddle point

Codis+15b



perp.

point-reflexion symmetry:

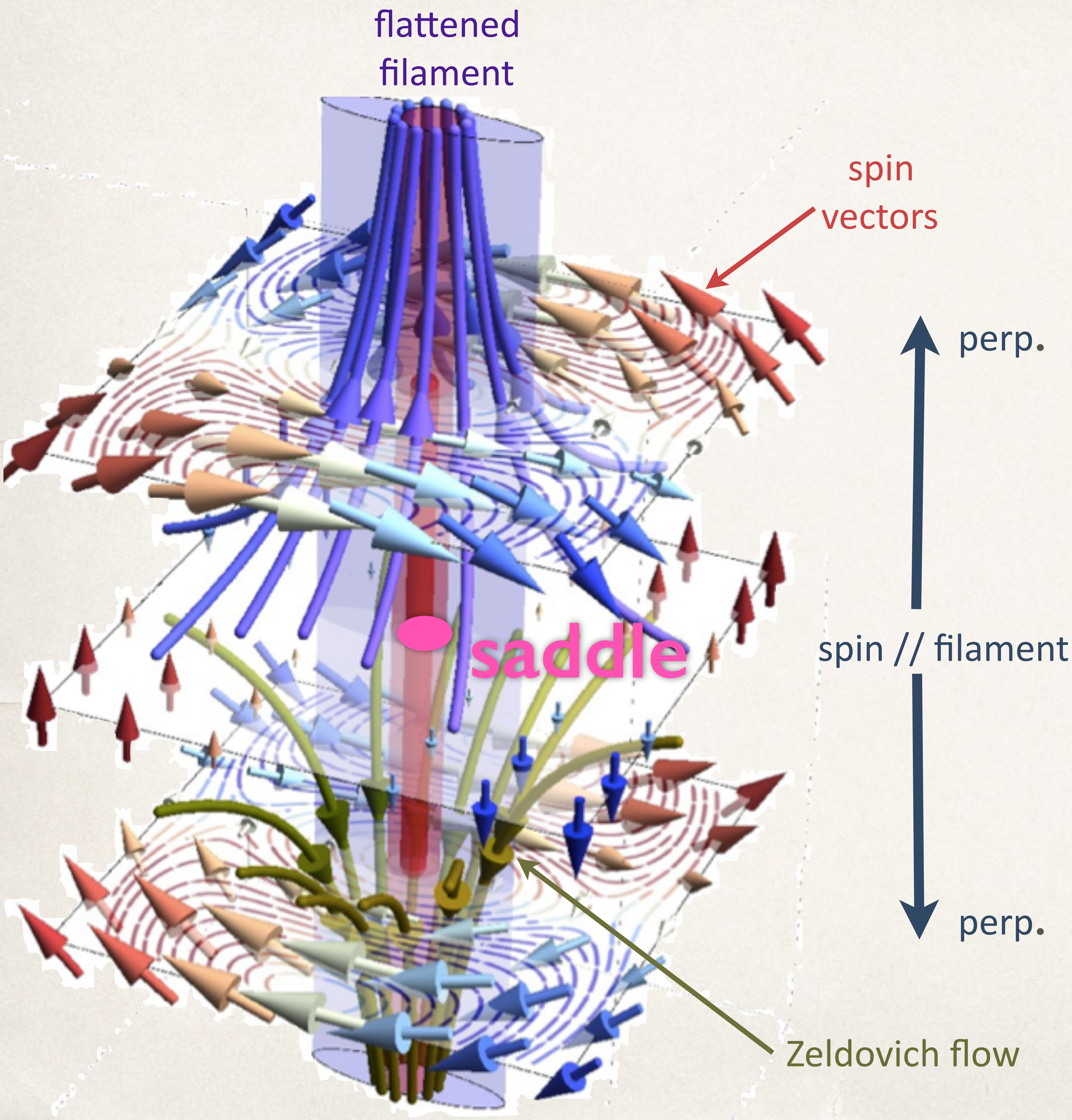
$$\vec{r} \longrightarrow -\vec{r}$$

spin // filament, similar to the «quadrants of vorticity»

perp.

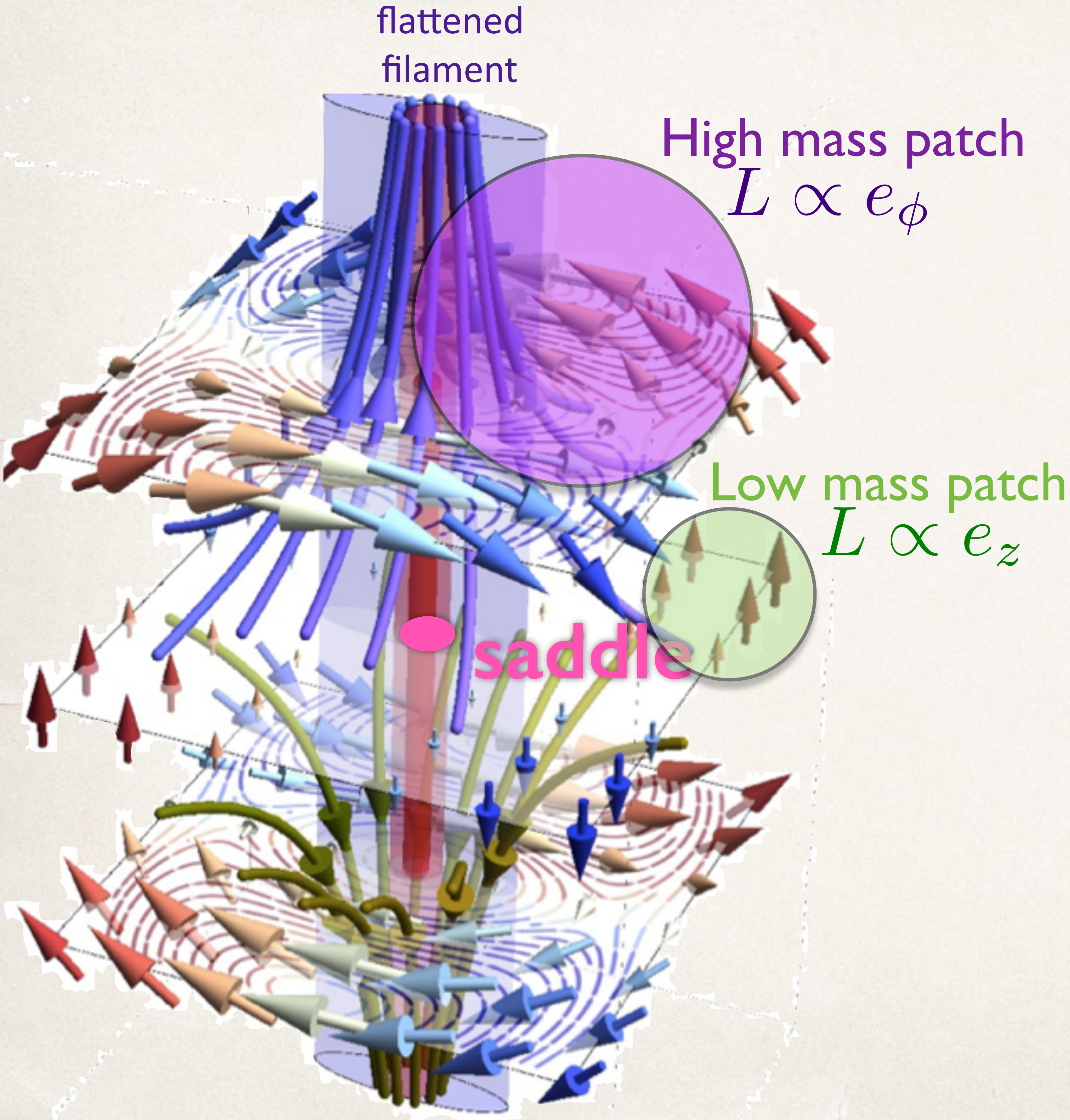
3D spin acquisition near a saddle point

Codis+15b



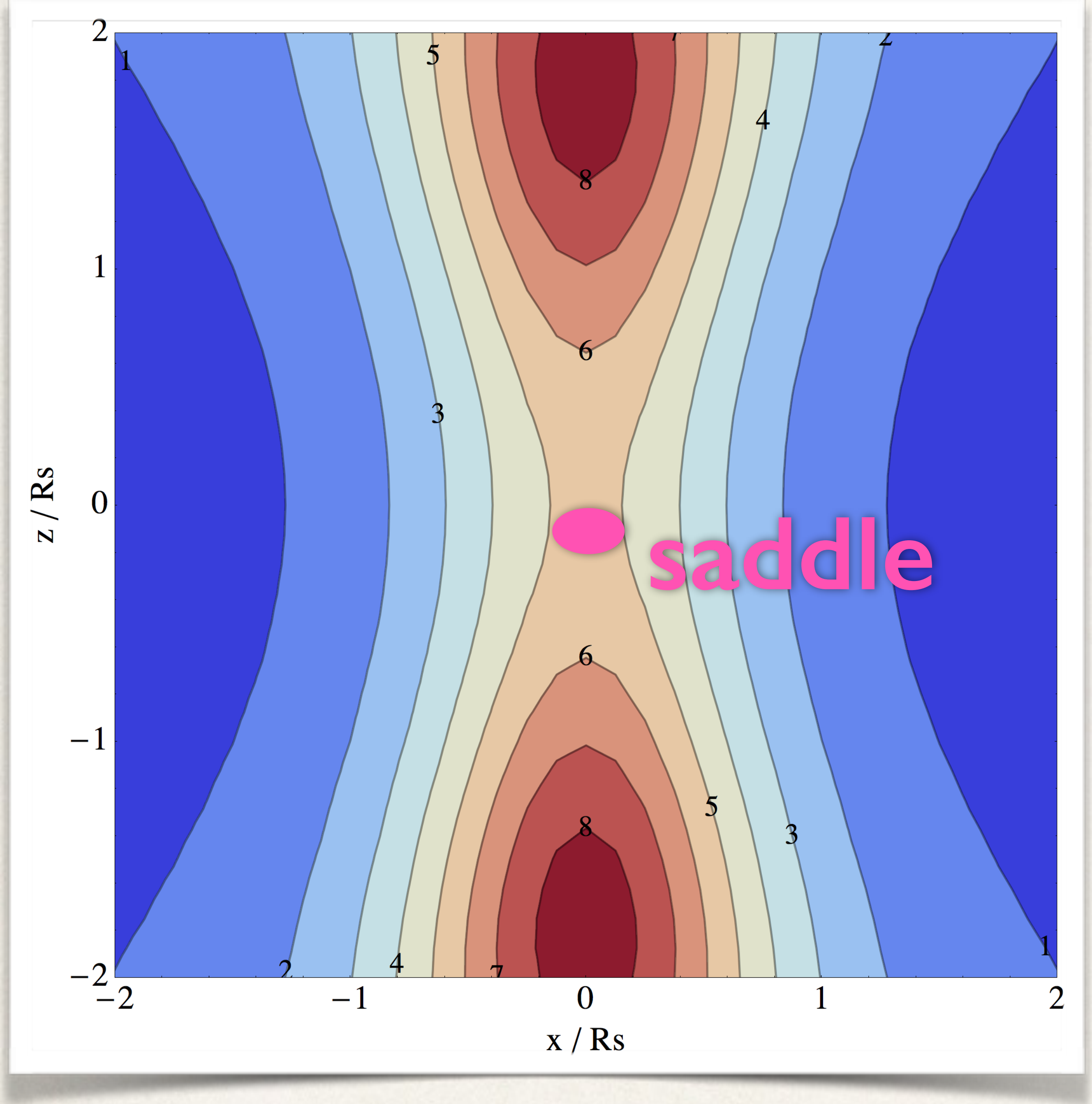
**How to predict
the transition mass?**

3D spin acquisition near a saddle point



- ★predict the mean saddle geometry
- ★compute the expected spin field given such a saddle geometry
- ★compute the most likely mass map as predicted by Press Schechter + filament background split

The transition mass



mass map in units of 10^{12} M_{sun}

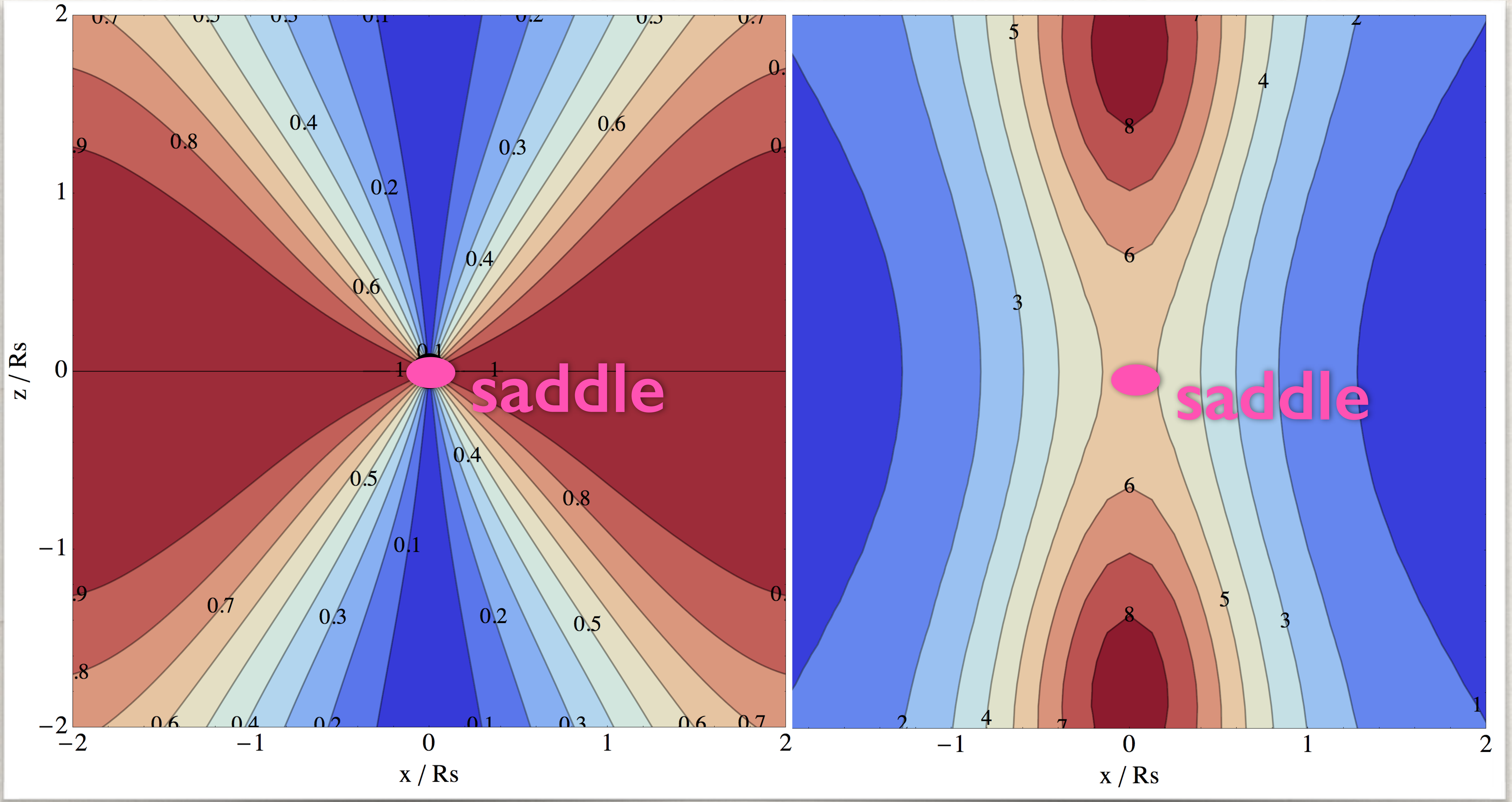
★predict the mean saddle geometry

★compute the expected spin field given such a saddle geometry

★compute the most likely mass map as predicted by Press Schechter + filament background split

Codis+15b

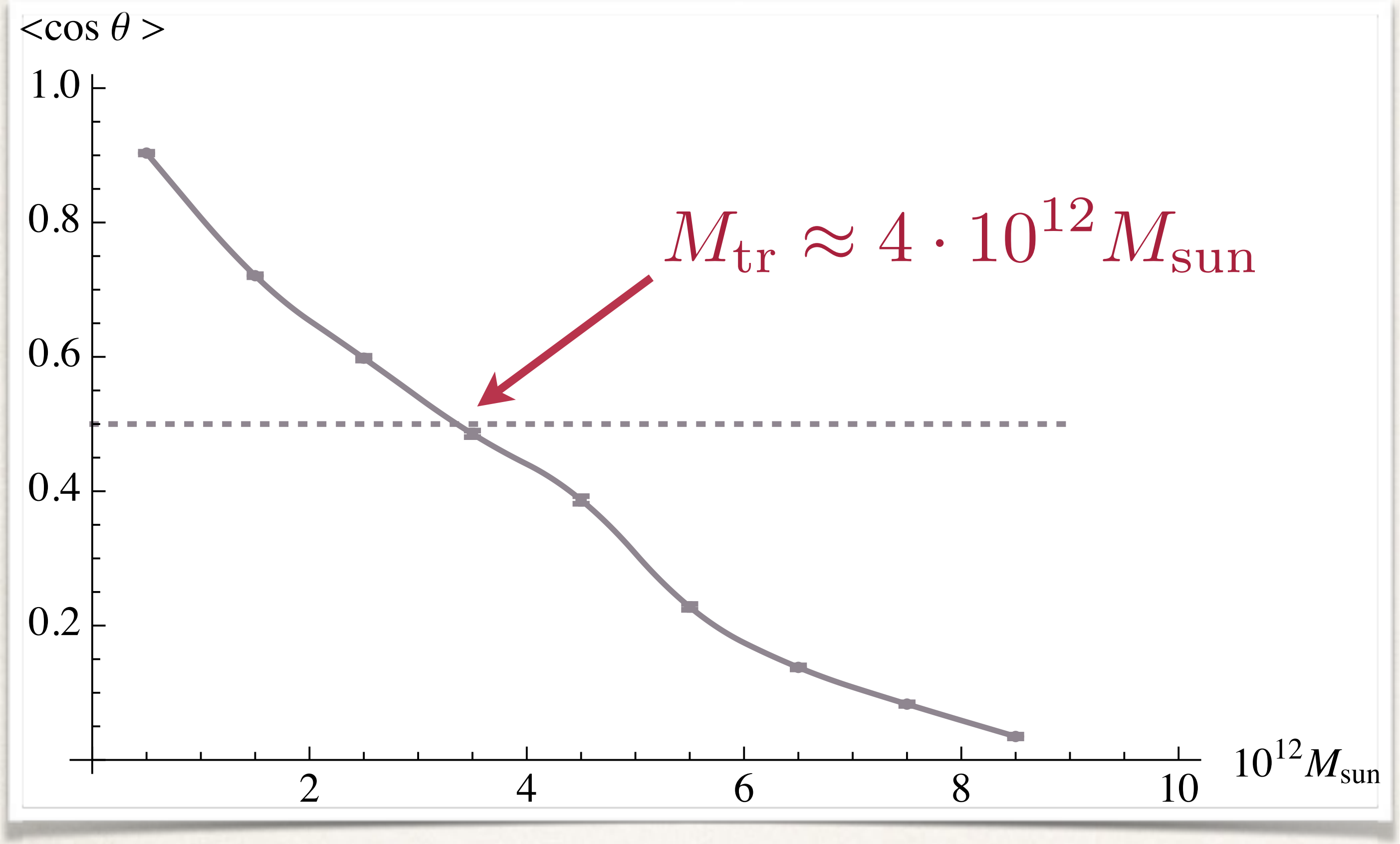
The transition mass



spin alignment (cos θ) map

mass map in units of 10^{12} M_{sun}

The transition mass



★predict the mean saddle geometry

★compute the expected spin field given such a saddle geometry

★compute the most likely mass map as predicted by Press Schechter + filament background split

The transition mass is about 4.10^{12} M_{sun}, in agreement with simulations!

Toward an anisotropic alignment models for IA?

We know that we can predict the orientation of spins w.r.t the cosmic web.

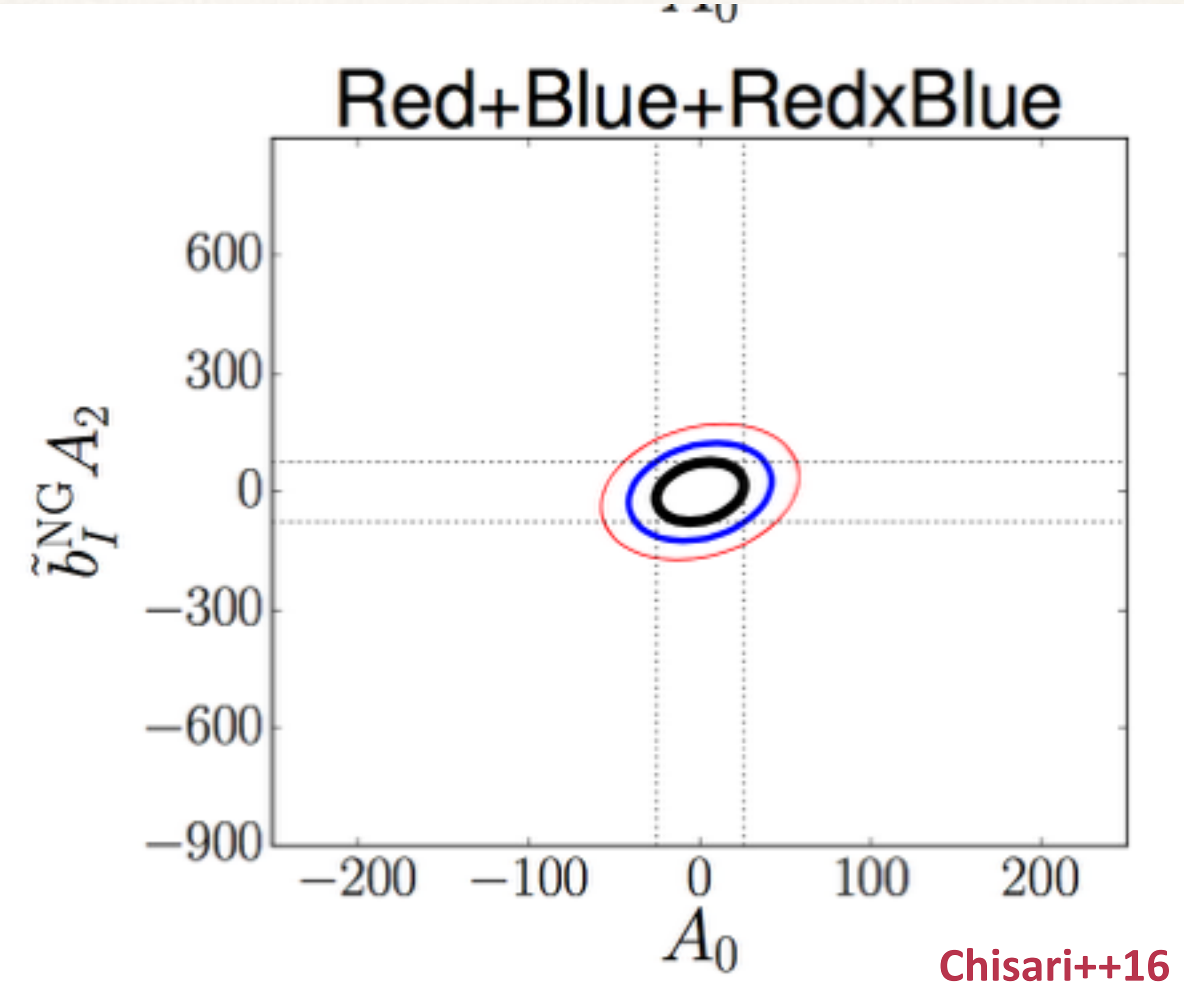
Let’s do the same for IA!

It could either improve the theoretical modelling and/or suggest a way to mitigate the effect of IA.

Last comment:

Le bruit des uns est le signal des autres.

As an example, measuring intrinsic alignments also provides information on galaxy formation and potentially cosmology (Chisari&Dvorkin2013).



Chisari++16