THE COSMIC BALLET

spinning in the web

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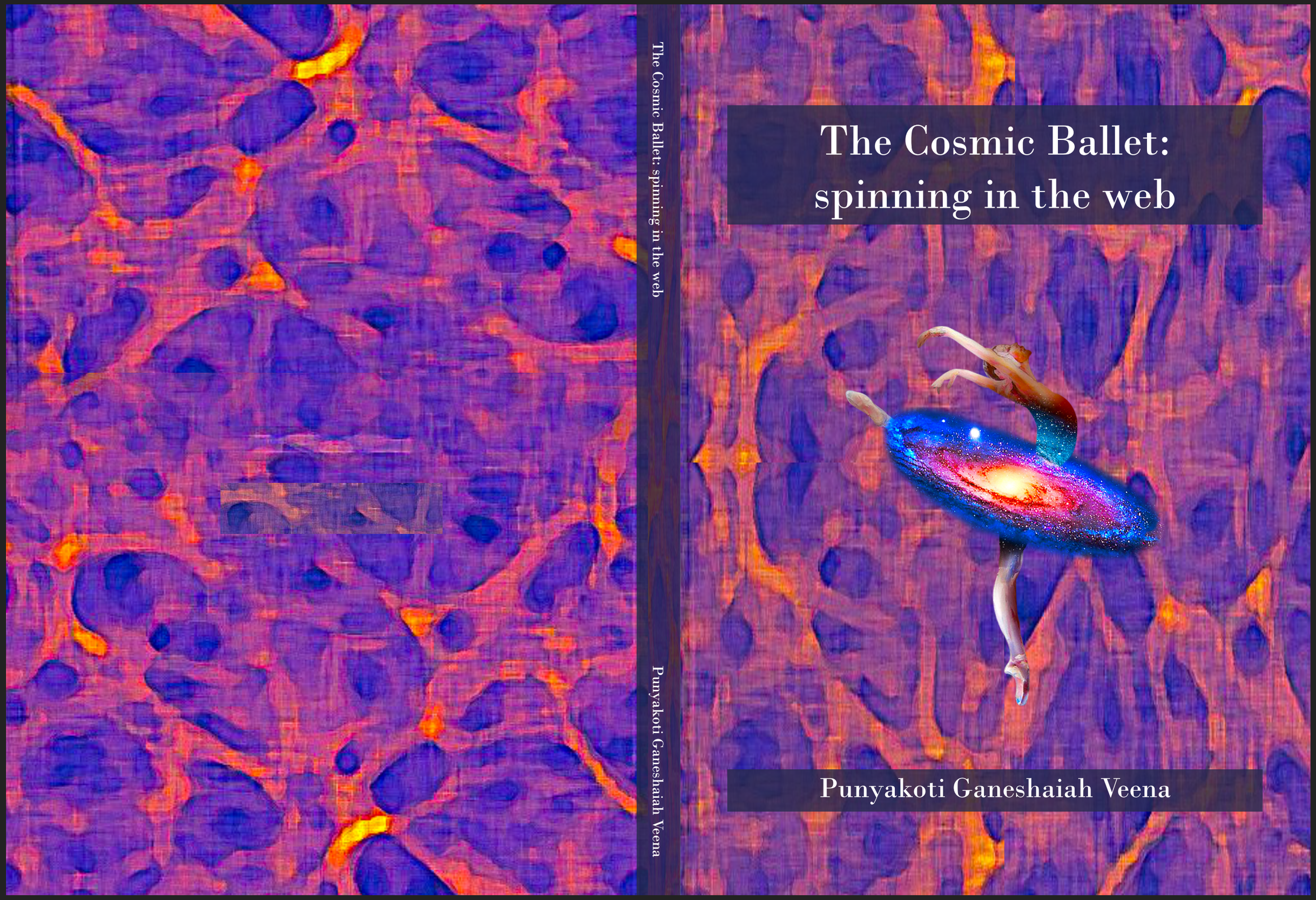
Work done during PhD at Kapteyn Institute, Groningen and Tartu Observatory, Tartu

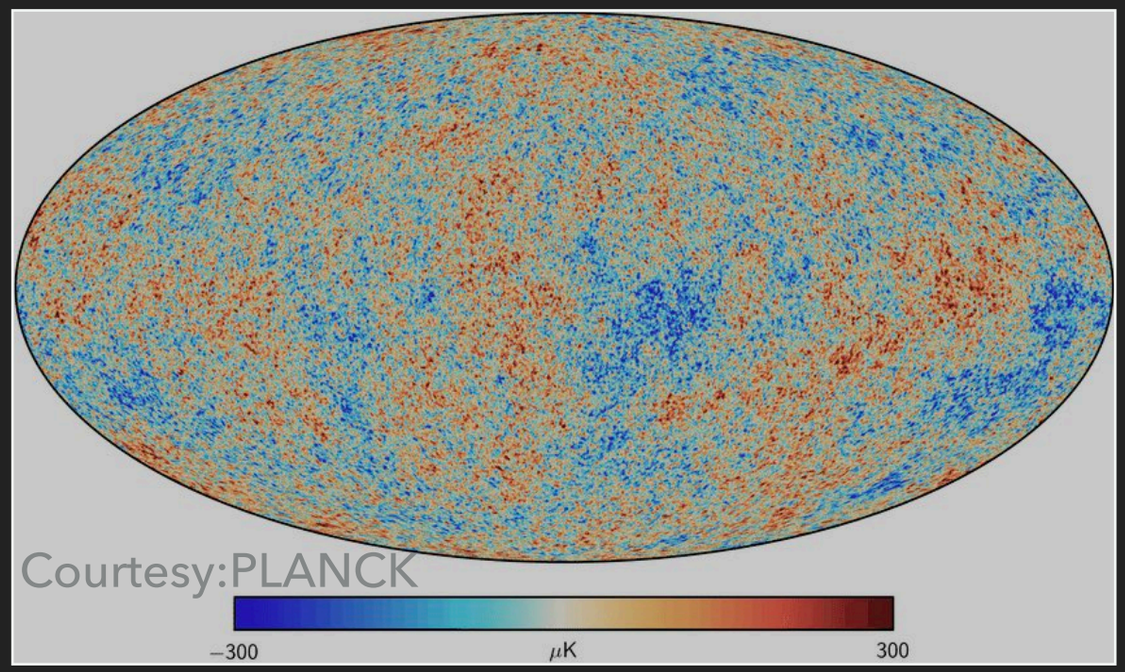
Rien van de Weygaert , Elmo Tempel, Marius Cautun, Carlos Frenk

Recently defended my PhD thesis:

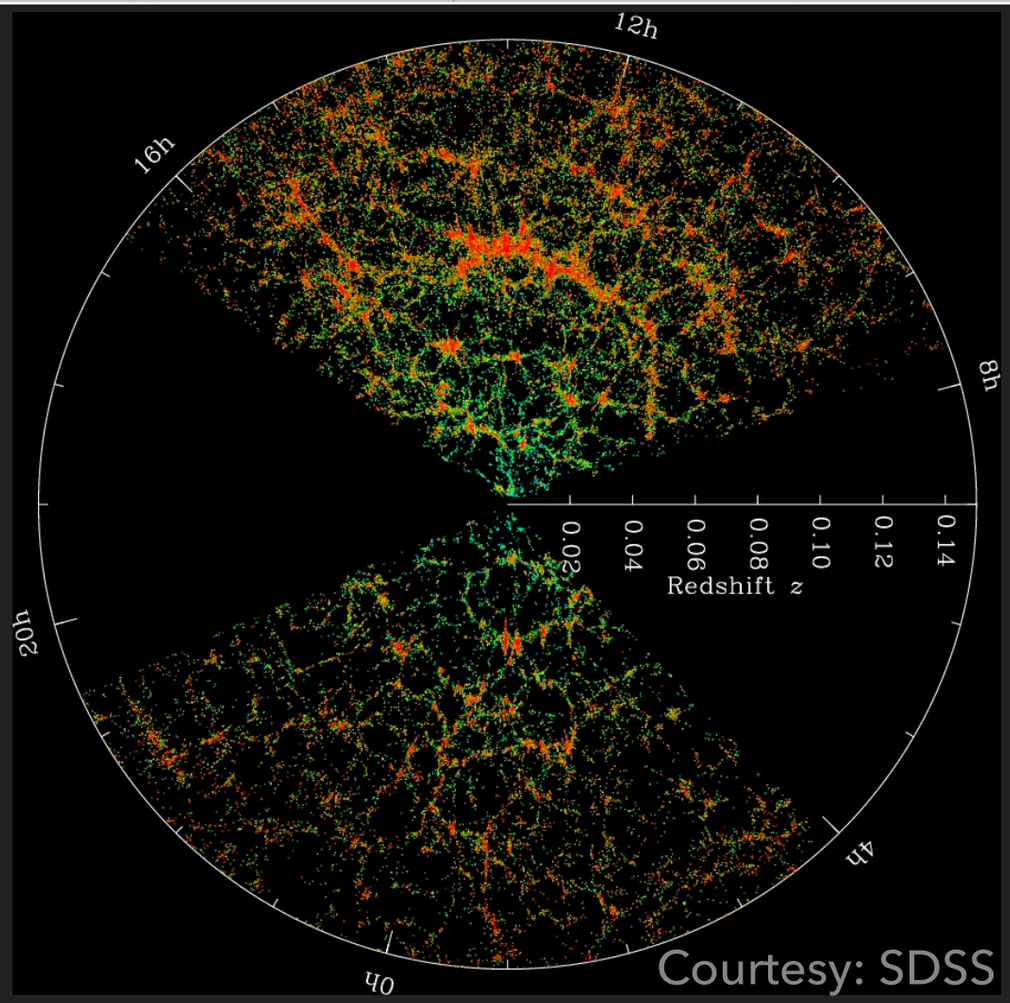


Online version of the thesis: http://hdl.handle.net/11370/e9eeda77-c5ac-451d-8cb5-c66db0e51707

UNIFORM UNIVERSE TO THE COMPLEX COSMIC WEB



Courtesy:PLANCK



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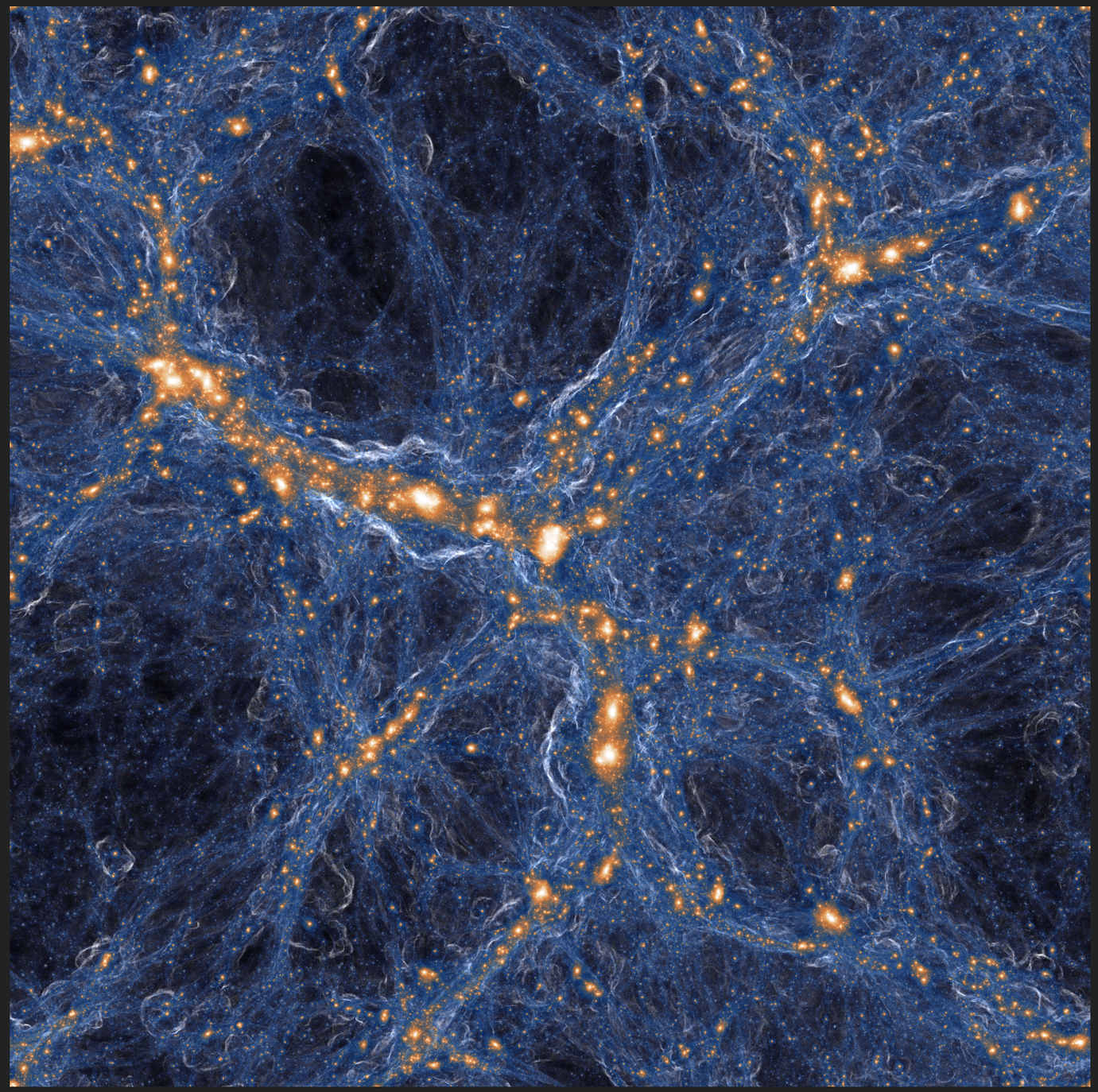

Courtesy: Illustris TNG

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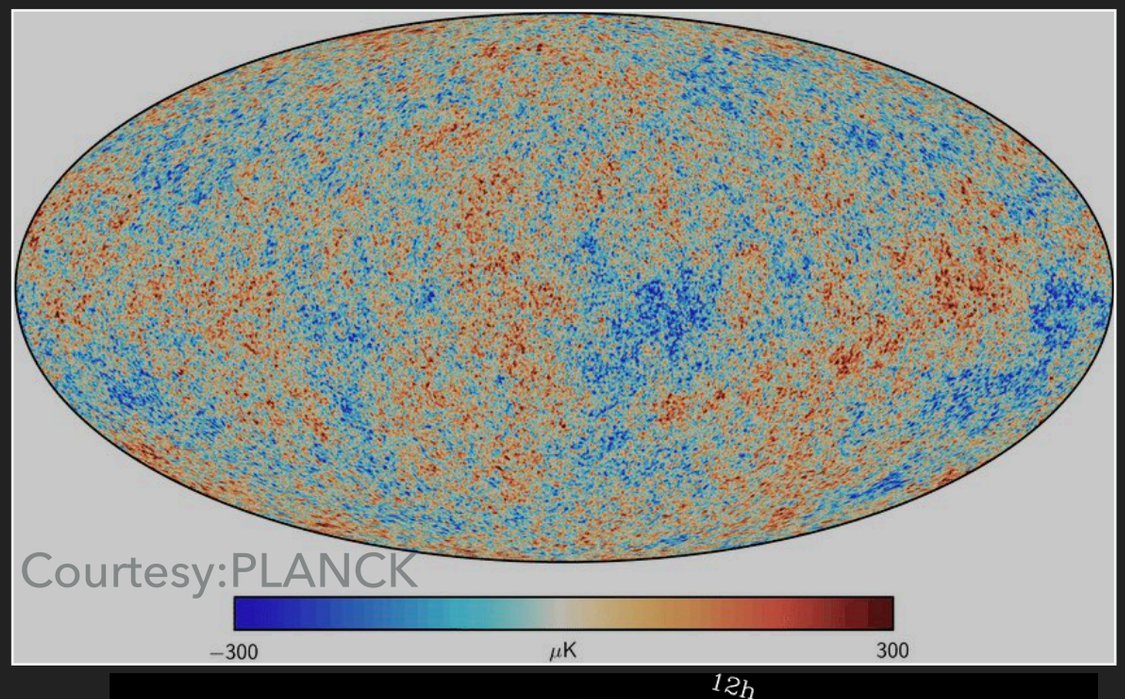

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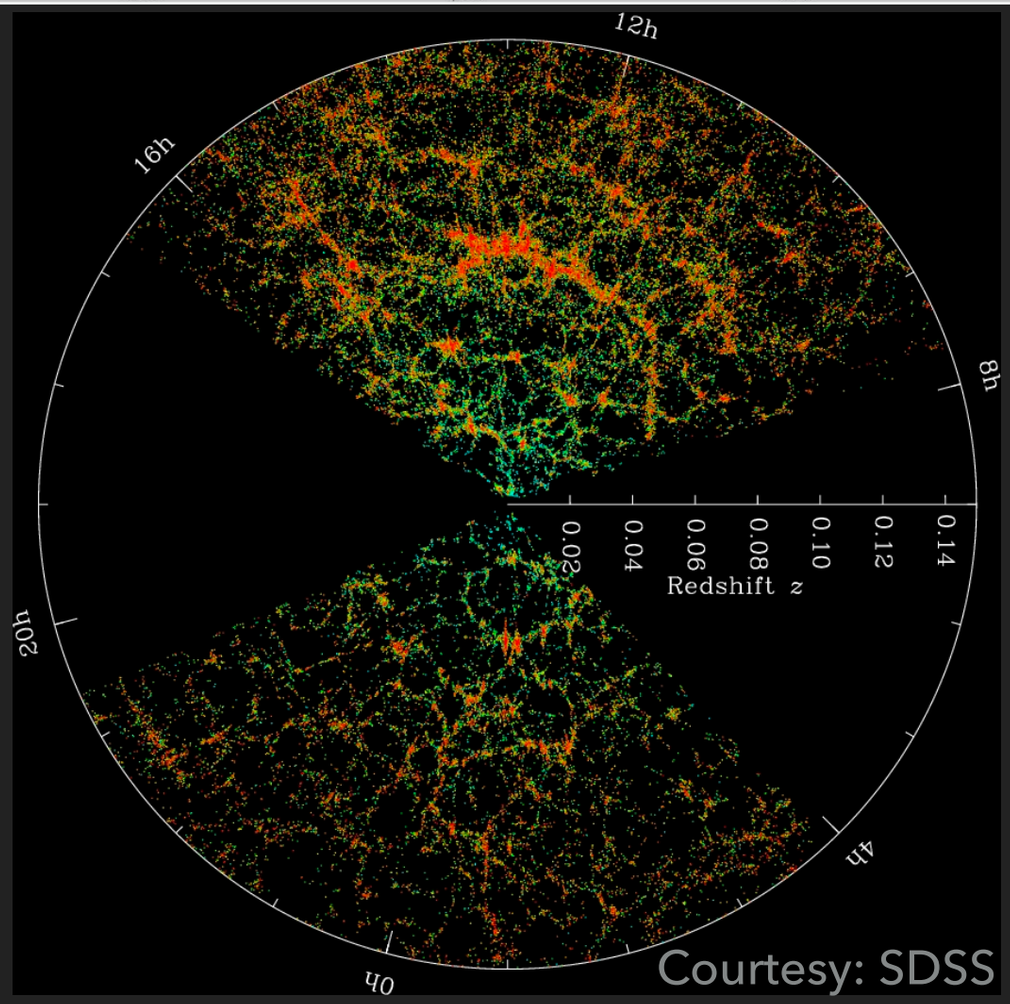

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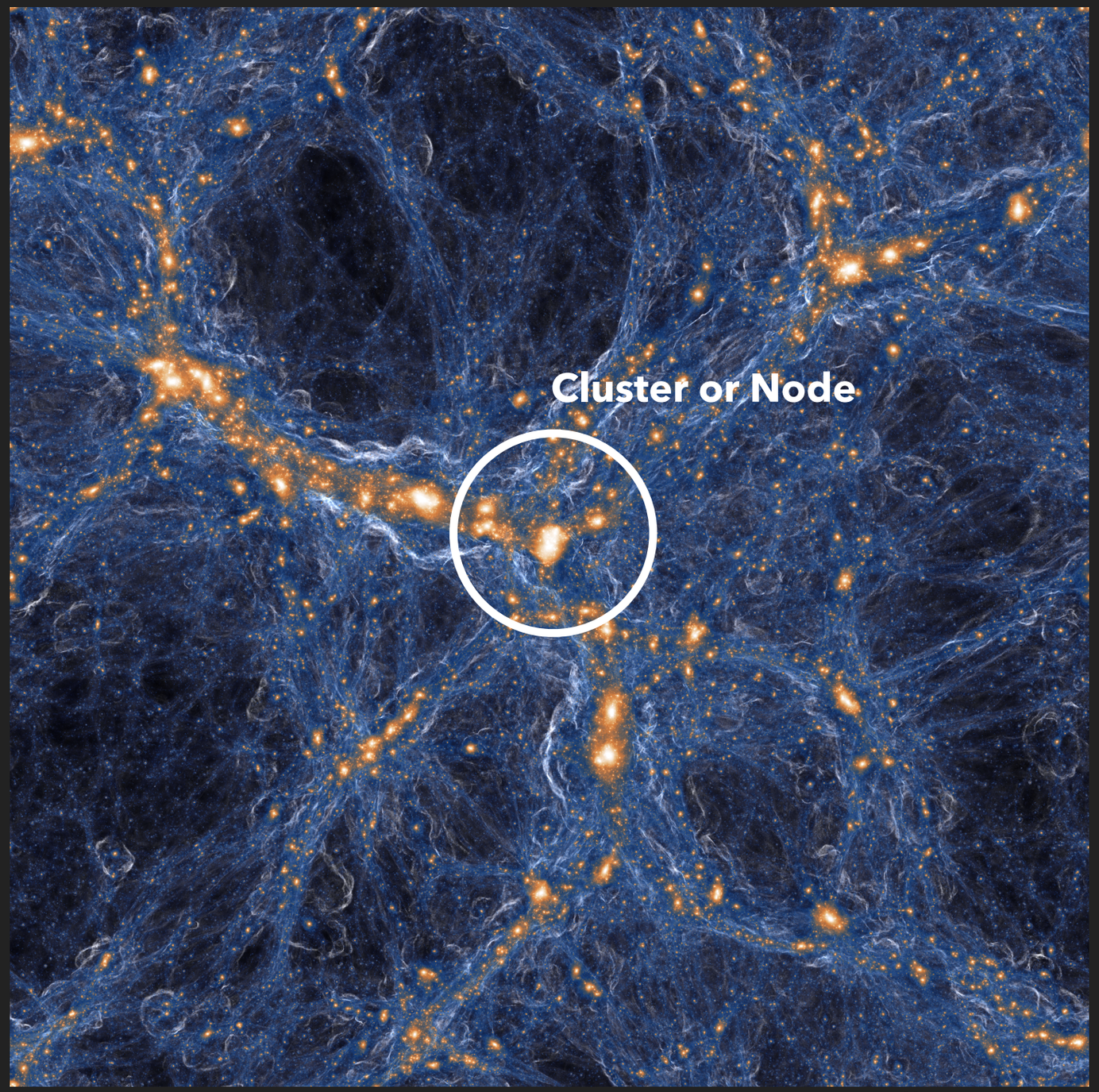

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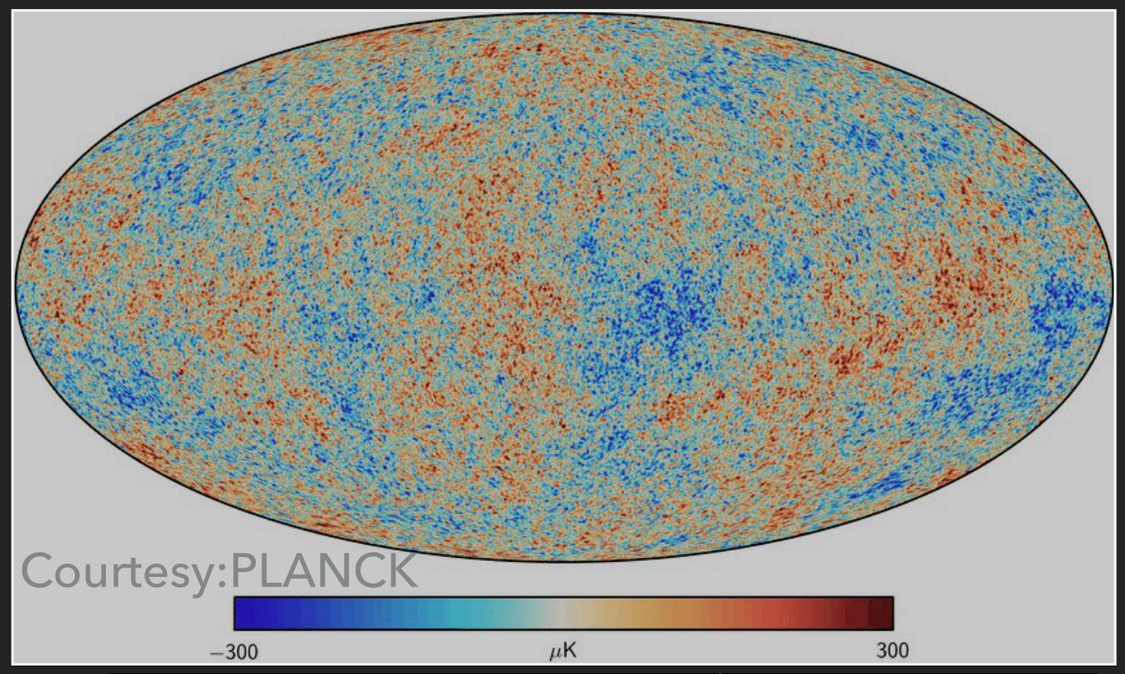

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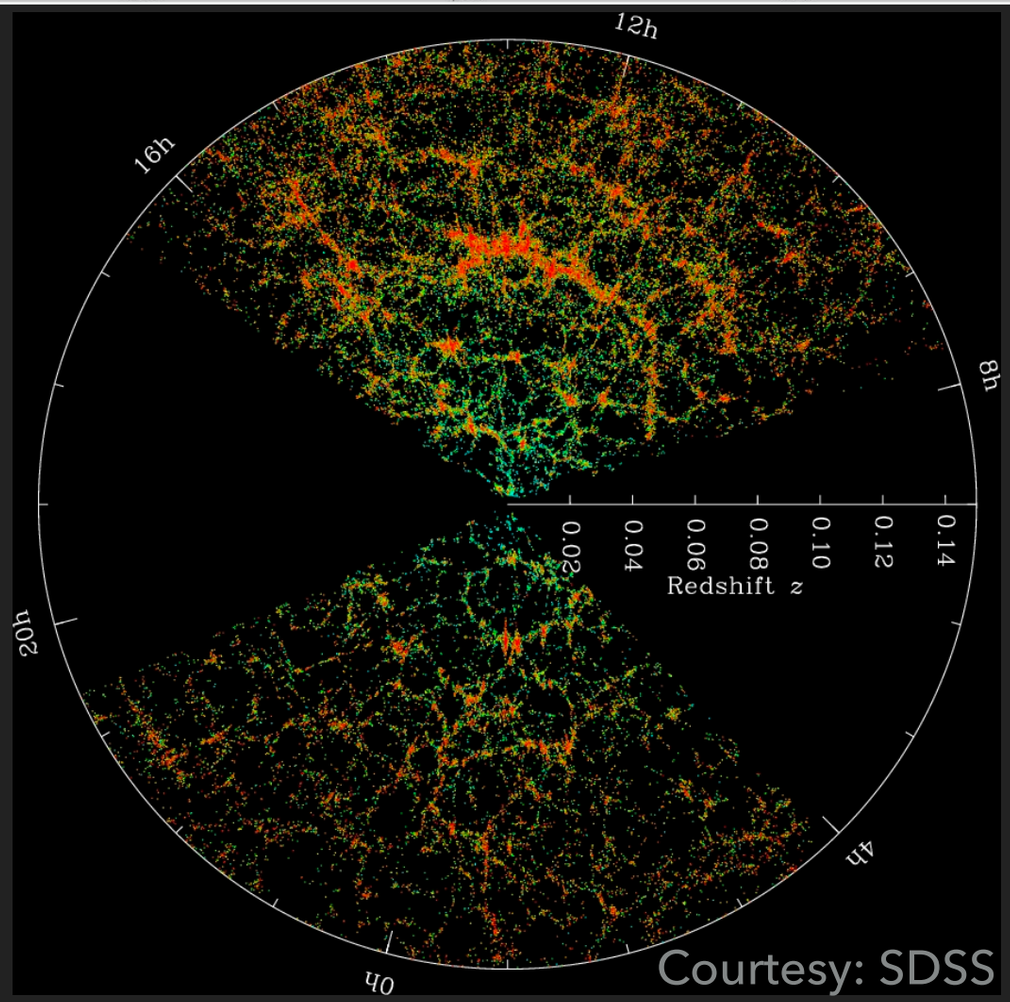

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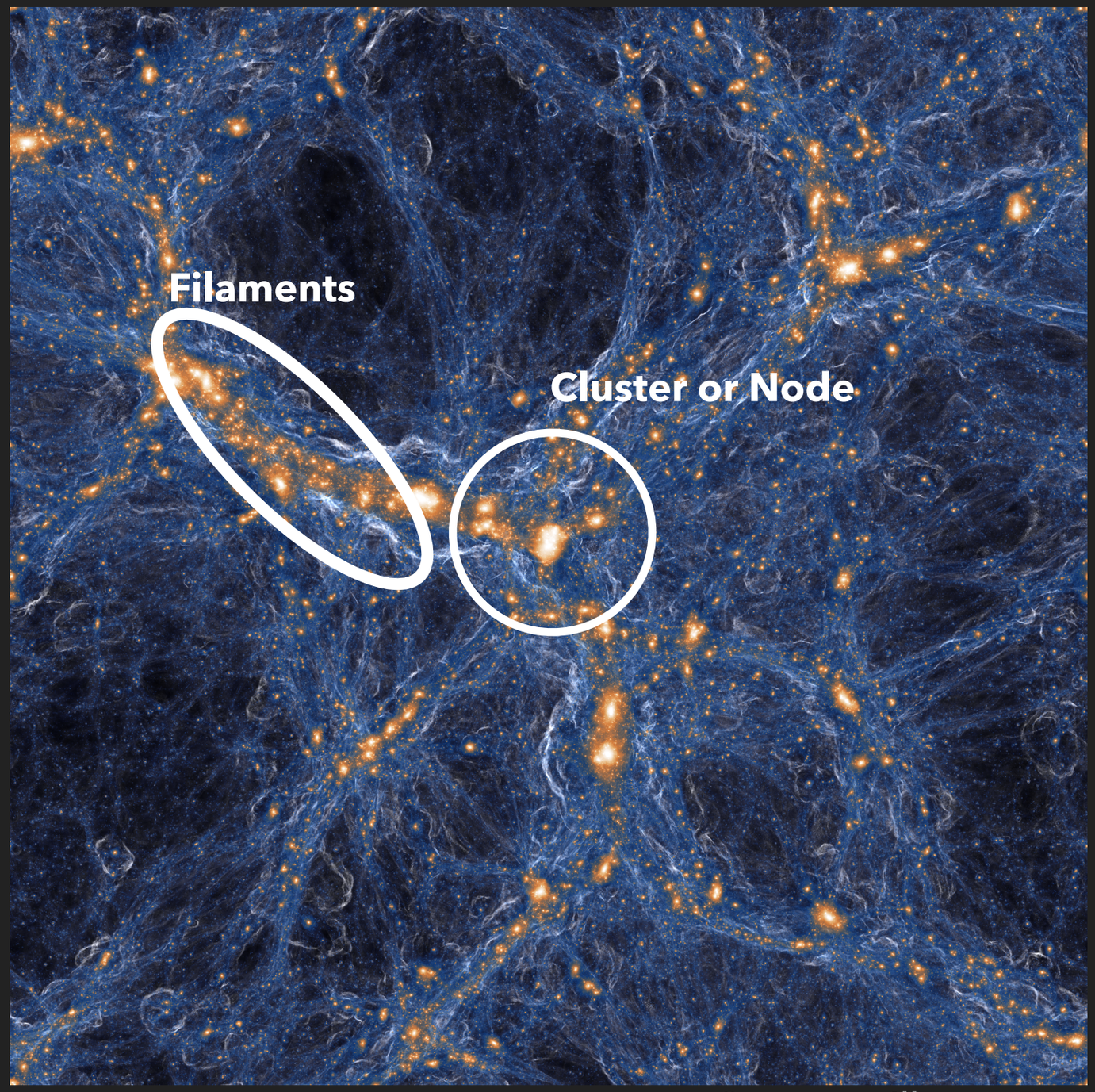

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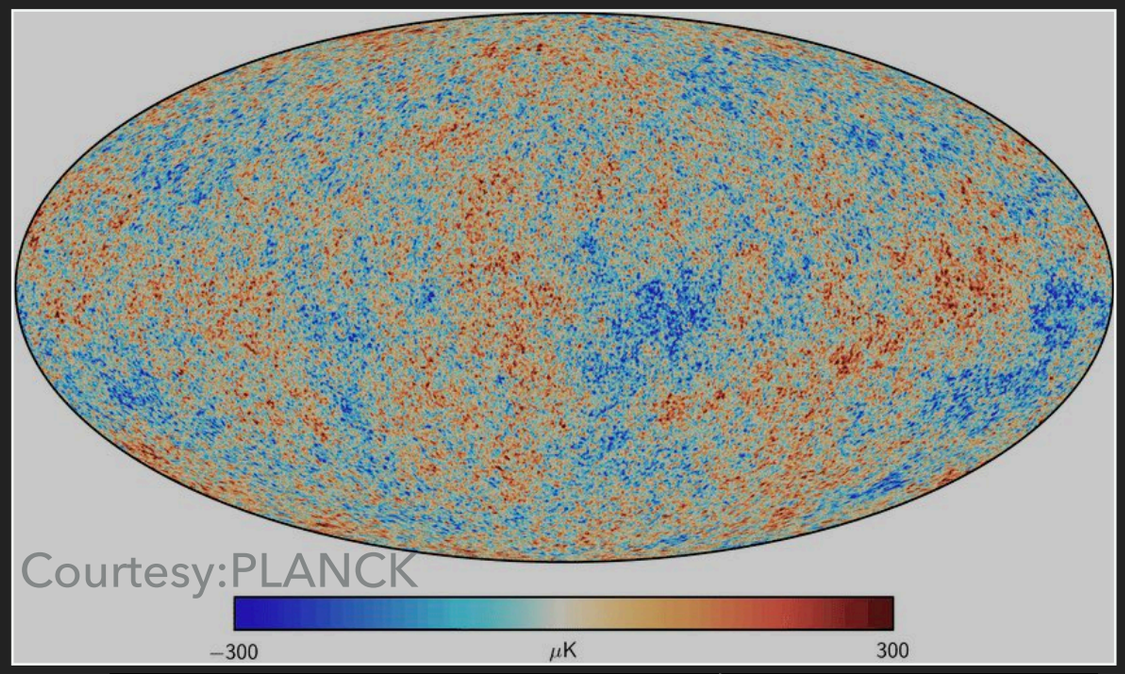

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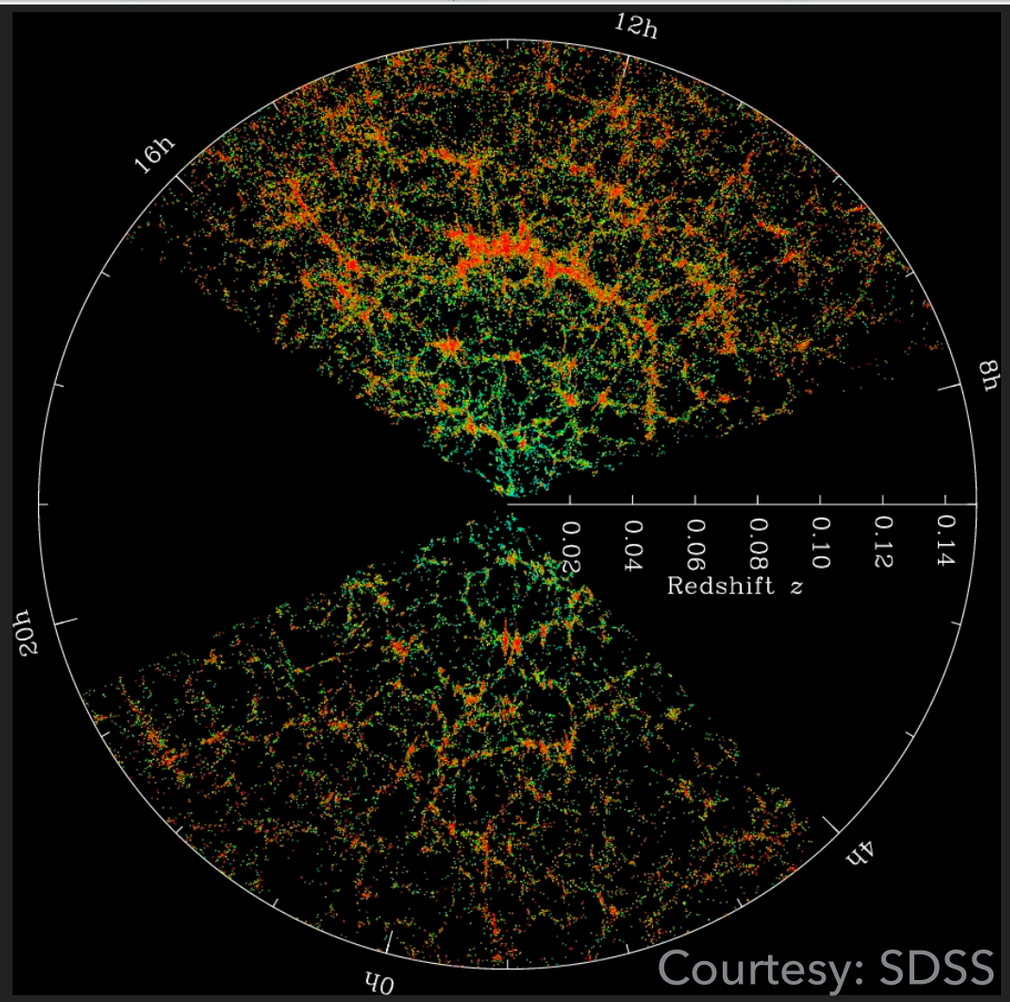

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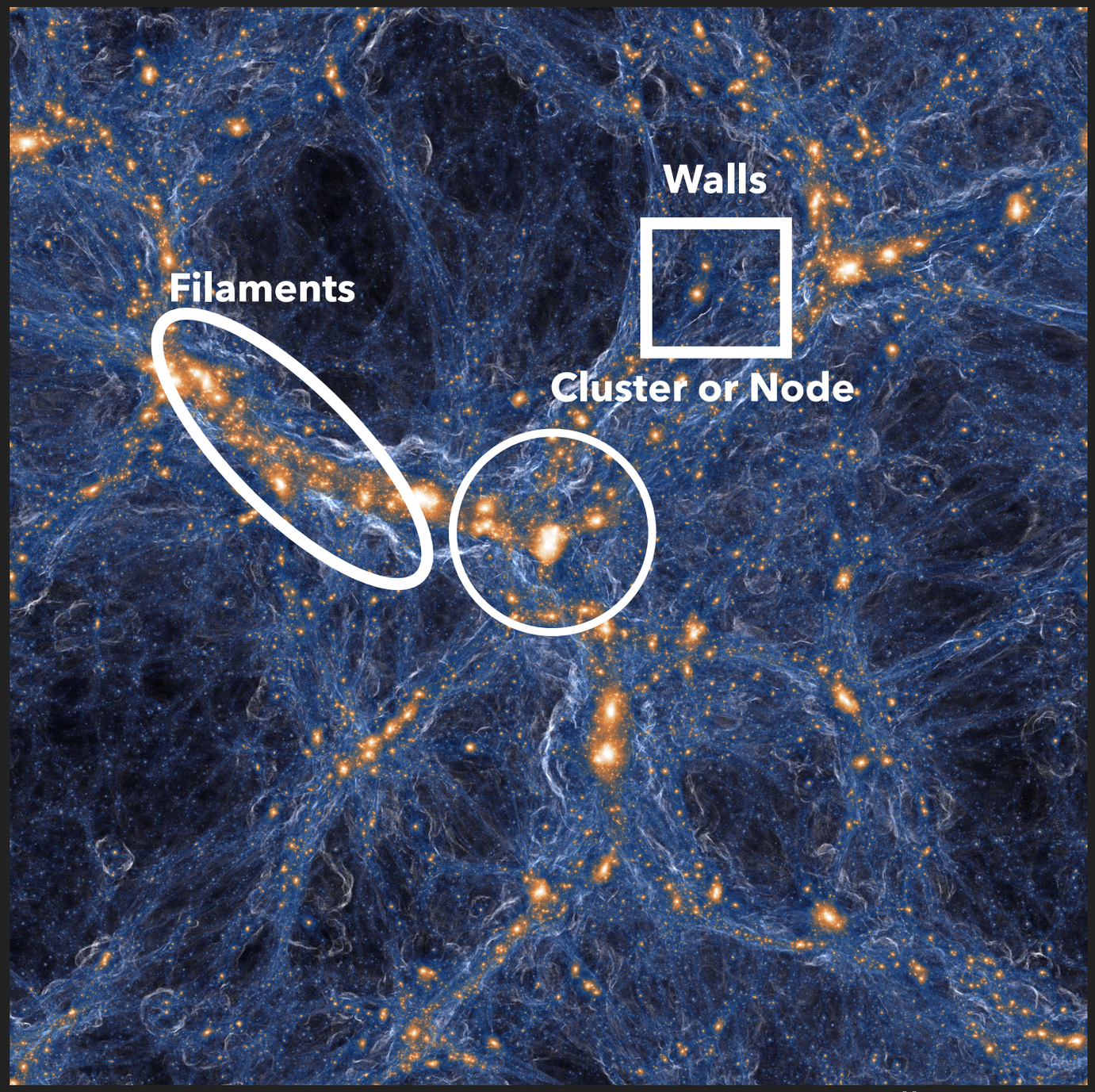

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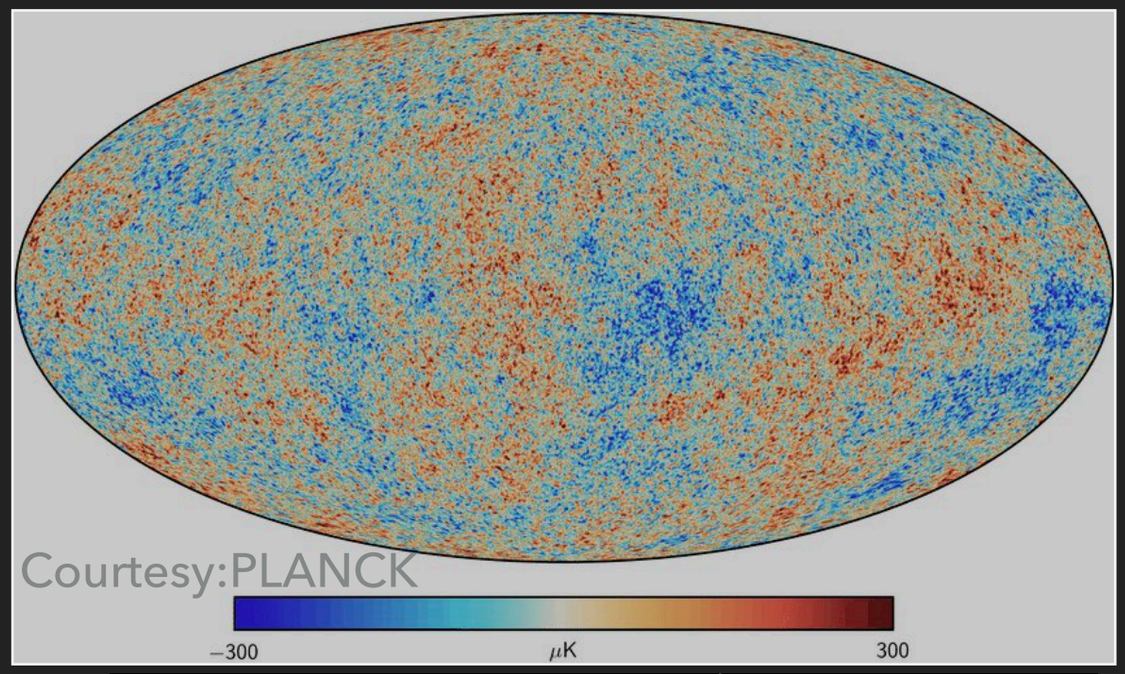

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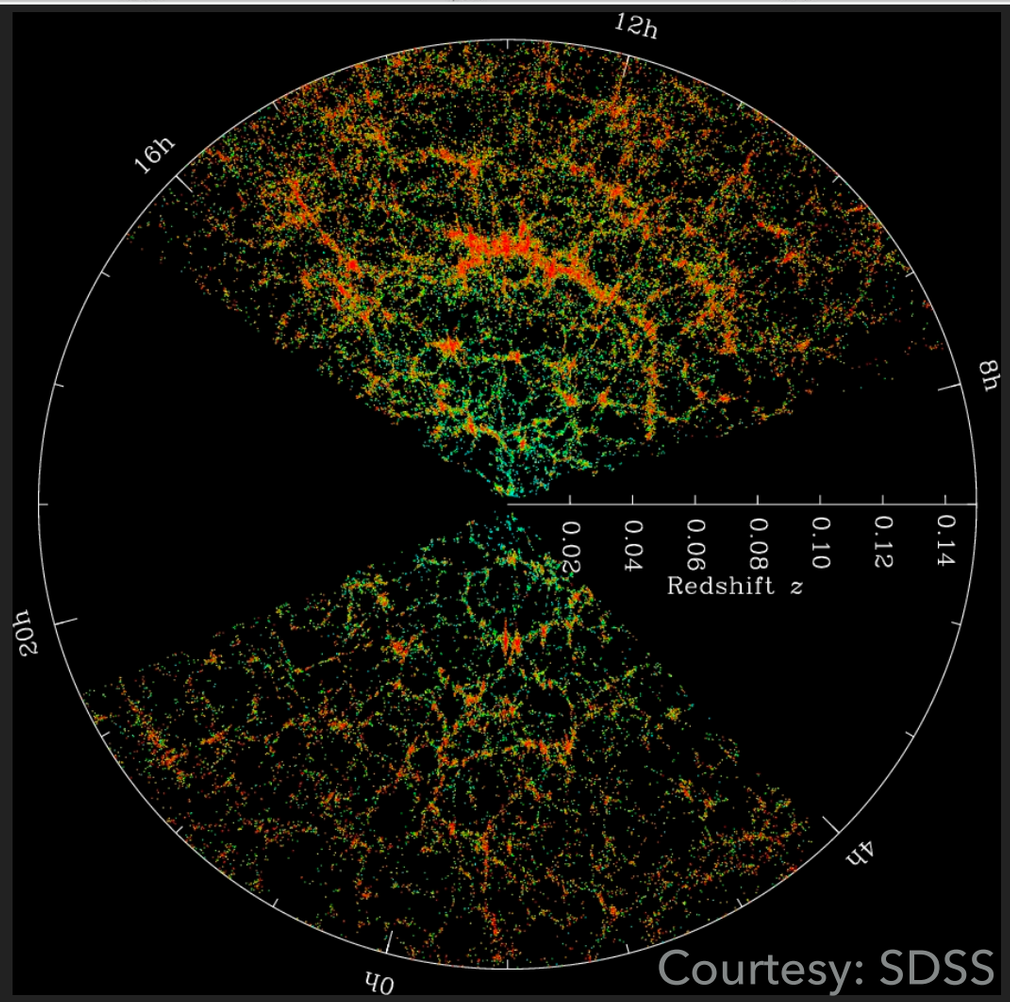

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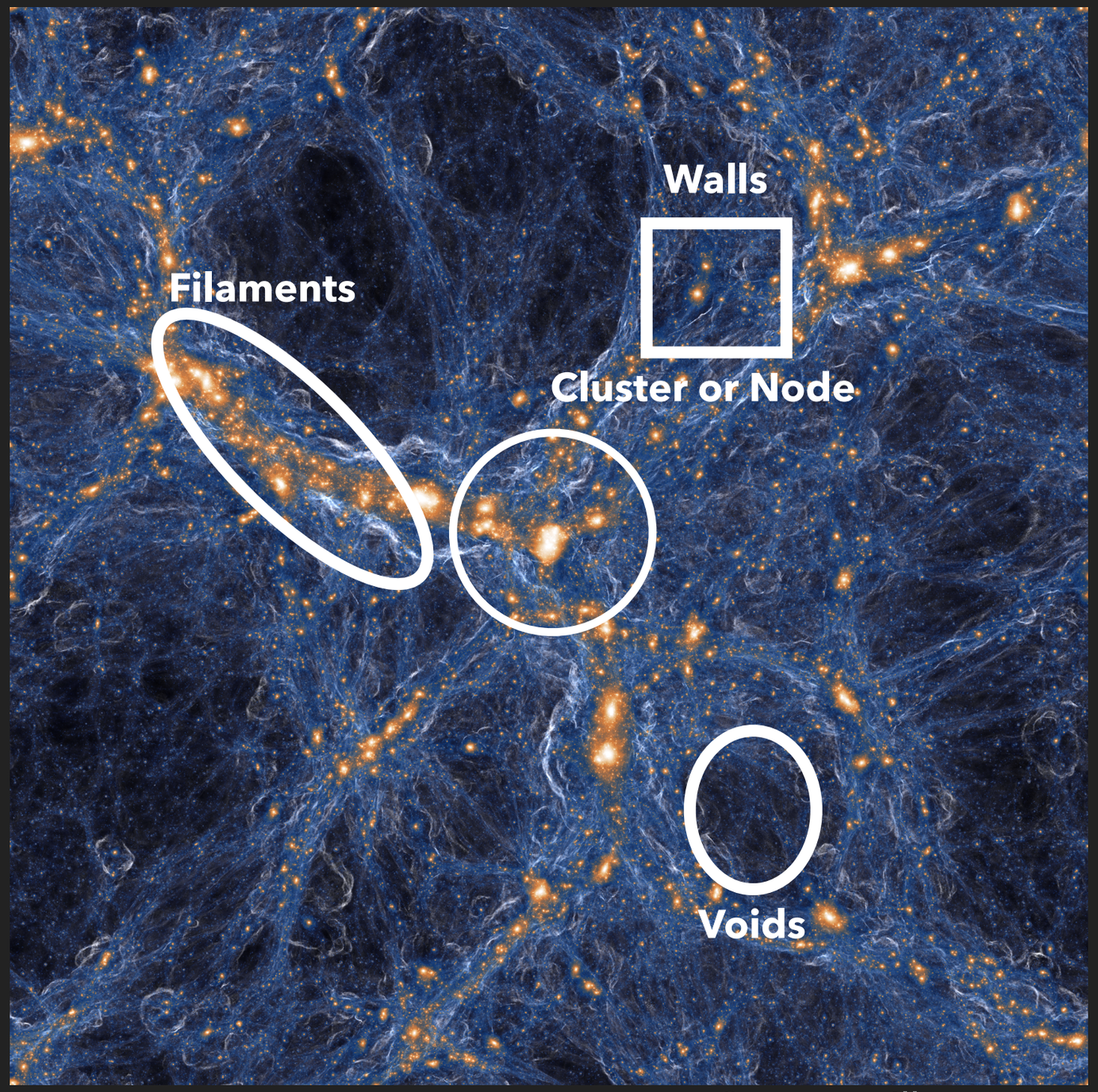

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IN THIS TALK

Explore the interplay between the **cosmic web and halo/ galaxy properties.**

Spin and shape

1. **P. Ganeshaiah Veena,** M. Cautun, R. van de Weygaert, E. Tempel, B.J.T Jones, S. Reider, C.S. Frenk; MNRAS, Volume 481, **2018.**

2. **P. Ganeshaiah Veena,** M. Cautun, E. Tempel, R. van de Weygaert, C.S. Frenk; MNRAS, Volume 487, **2019.**

3. **P. Ganeshaiah Veena,** M. Cautun, R. van de Weygaert, E. Tempel, C. S. Frenk; preprint arXiv:2007.10365, **2020.**

TIDAL FIELDS AND COSMIC WEB – ANISOTROPIC COLLAPSE

$$\Psi_{ij} = \frac{\partial^2 \Psi}{\partial q_i \partial q_j} \qquad \Psi(q) = -\frac{2}{3\Omega_0 H_0^2} \nabla \Phi_0$$

$$\lambda_1 \geq \lambda_2 \geq \lambda_3$$

Cluster	Filament	Wall	Void
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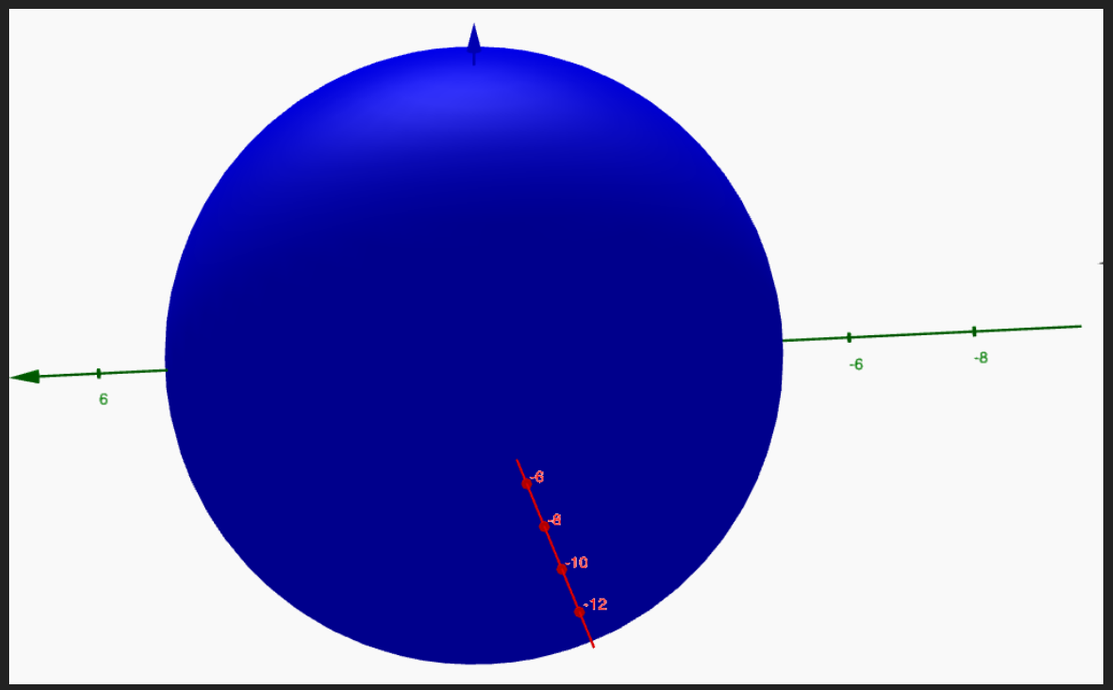

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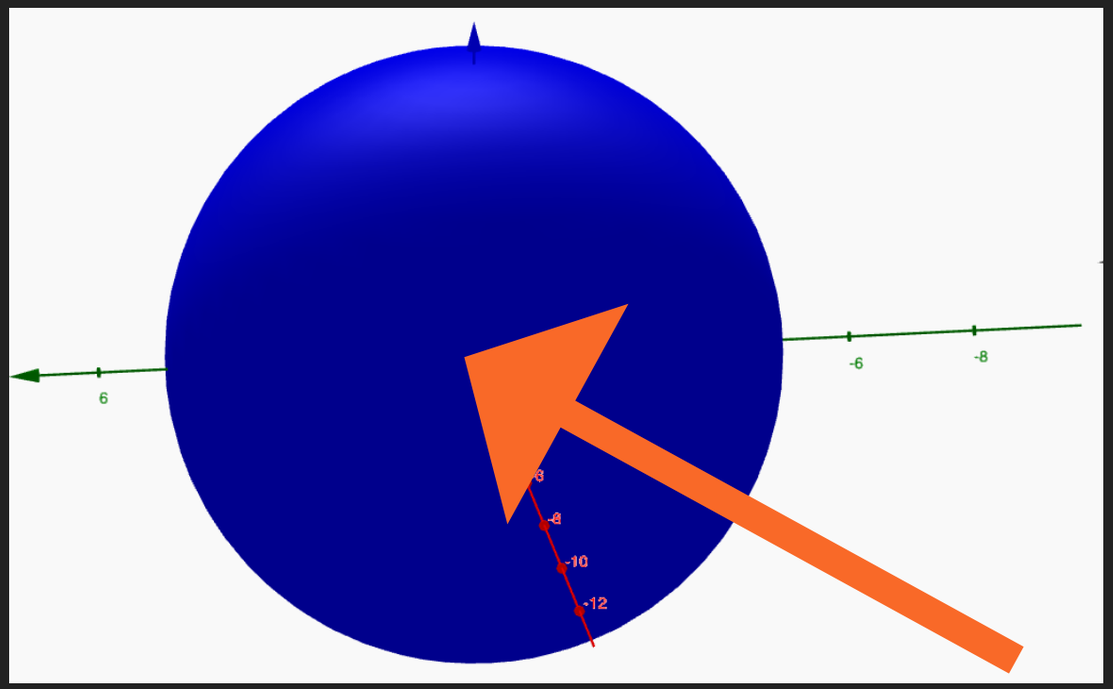

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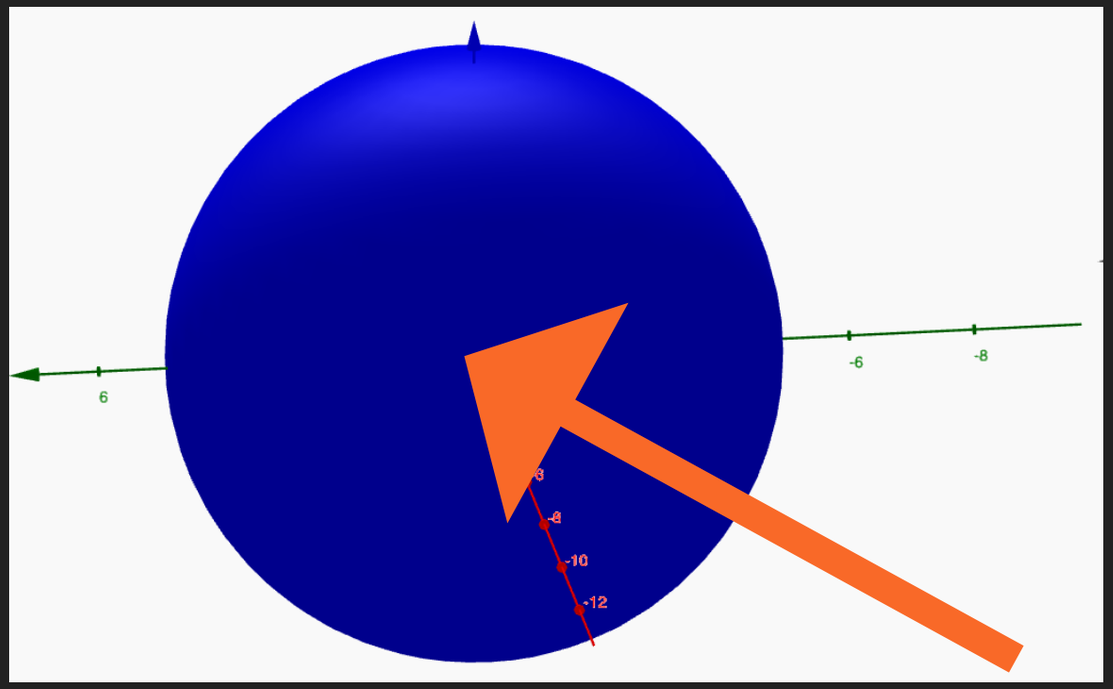

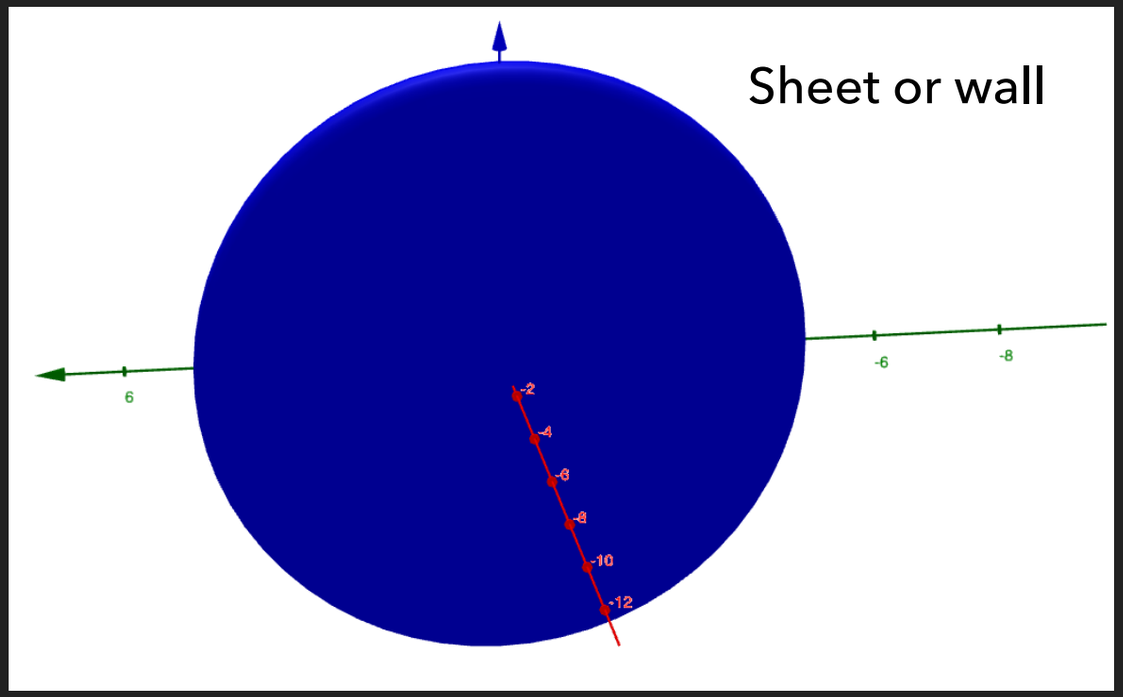

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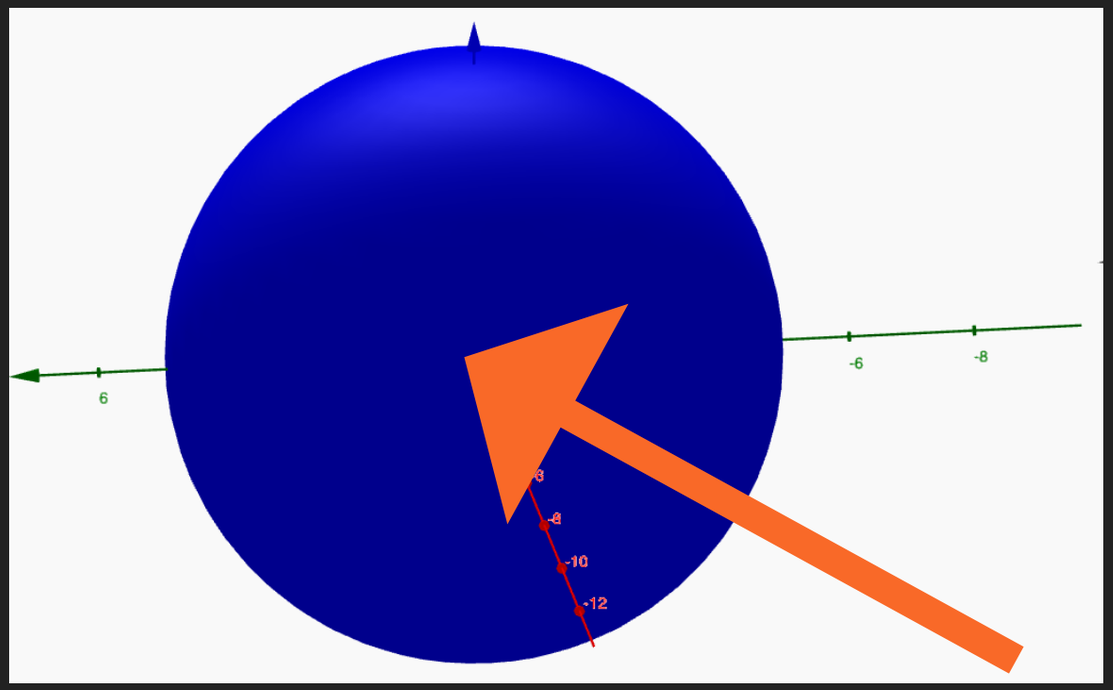

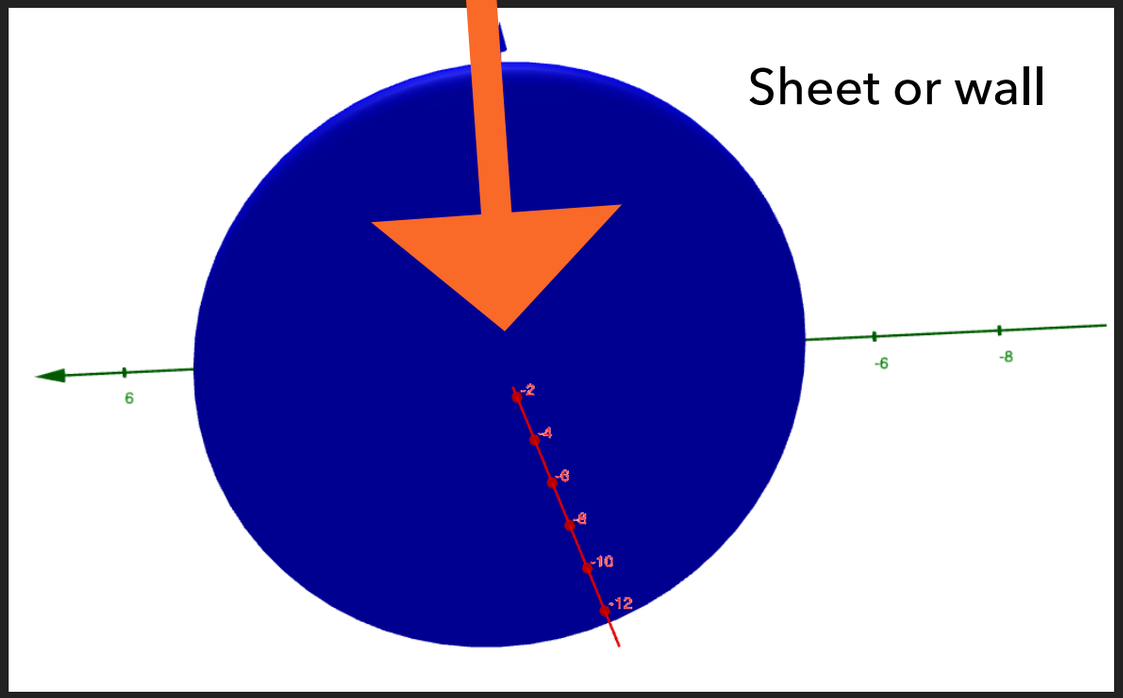

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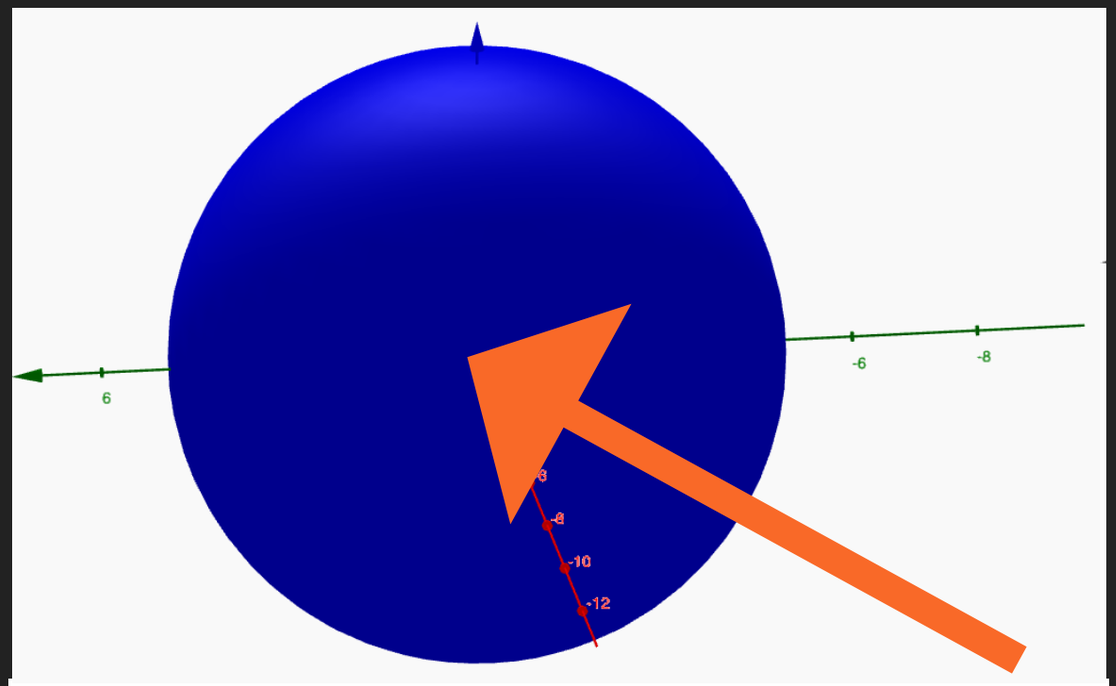

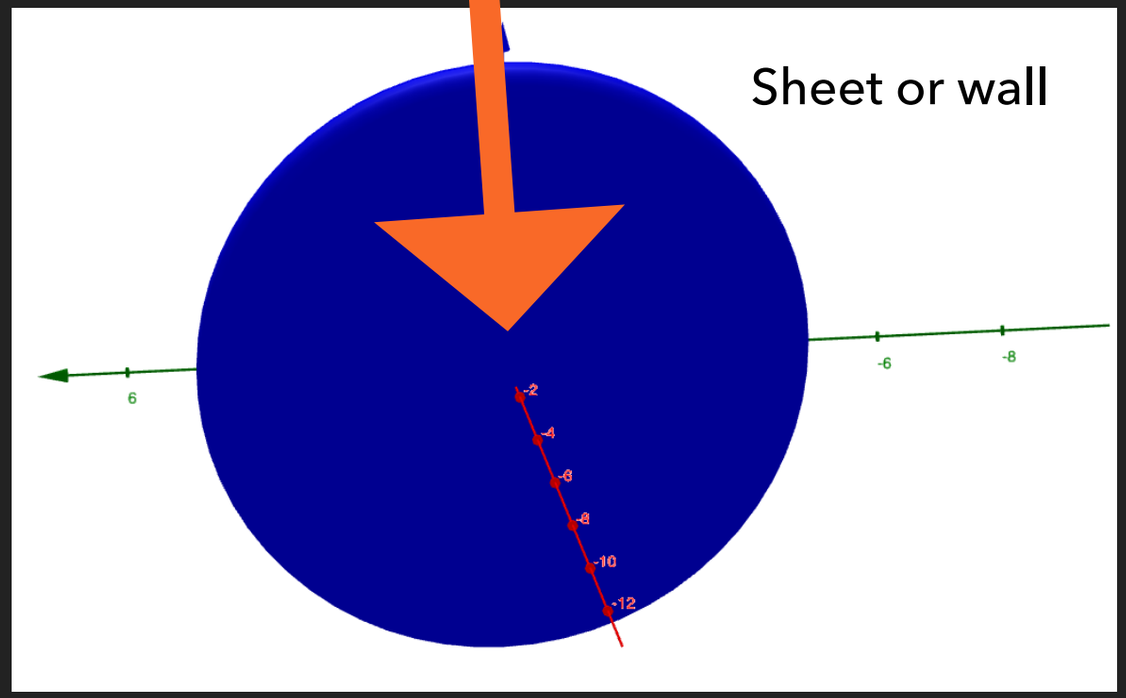

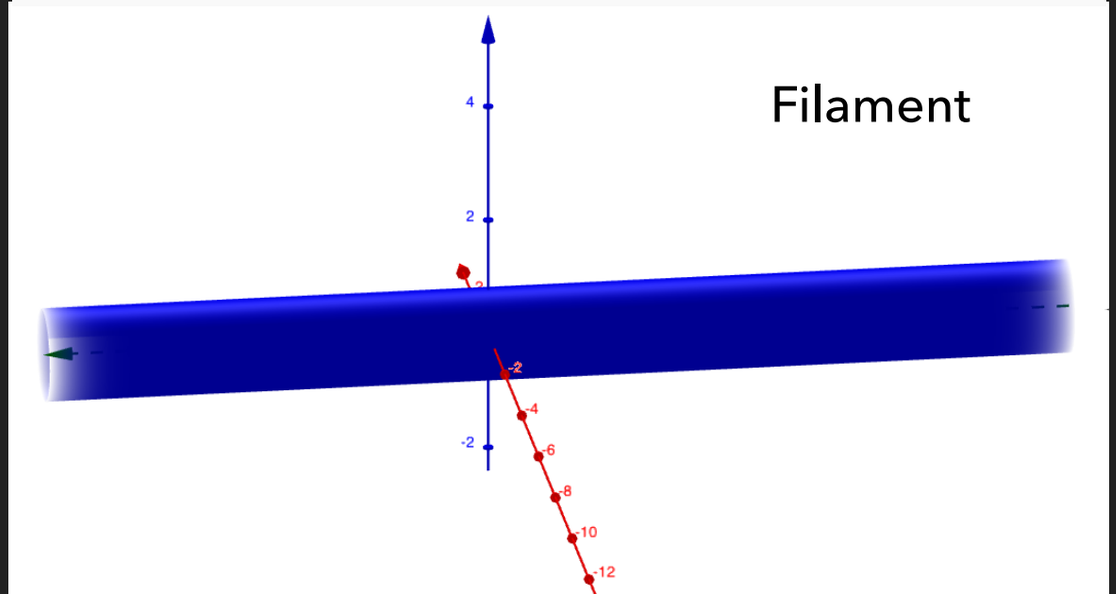

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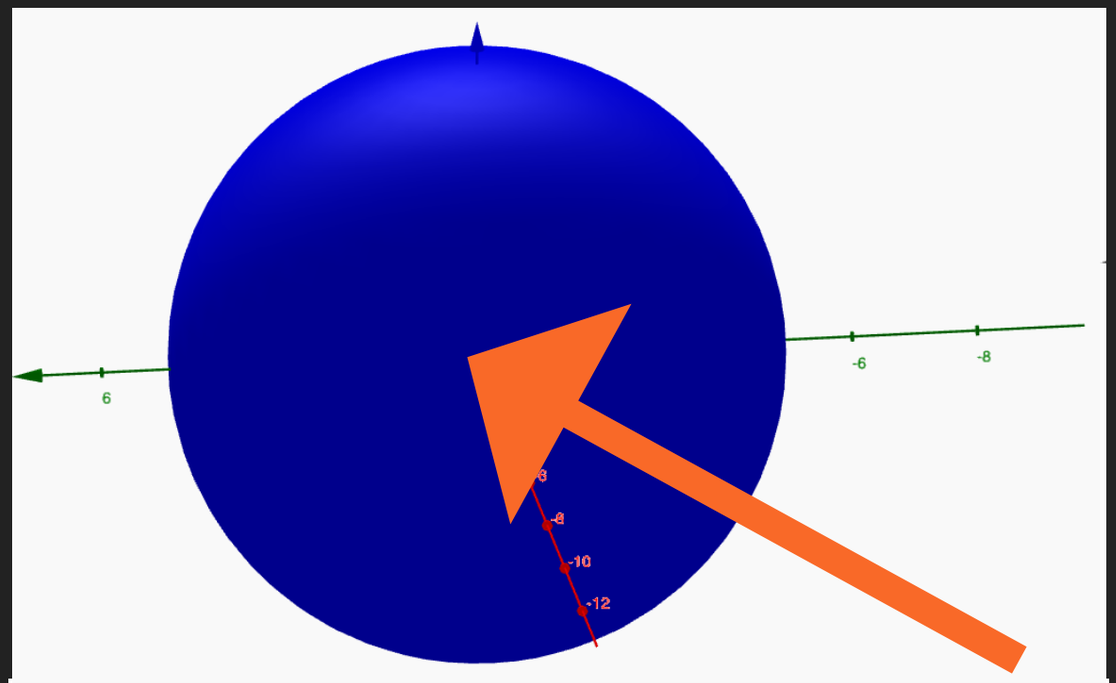

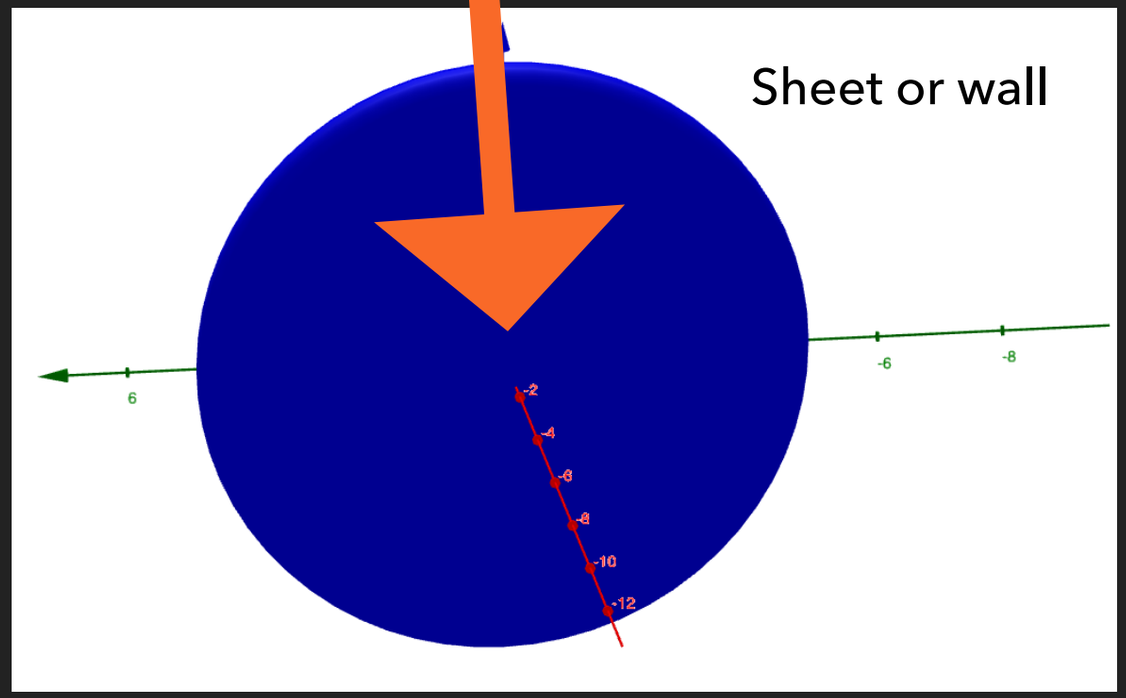

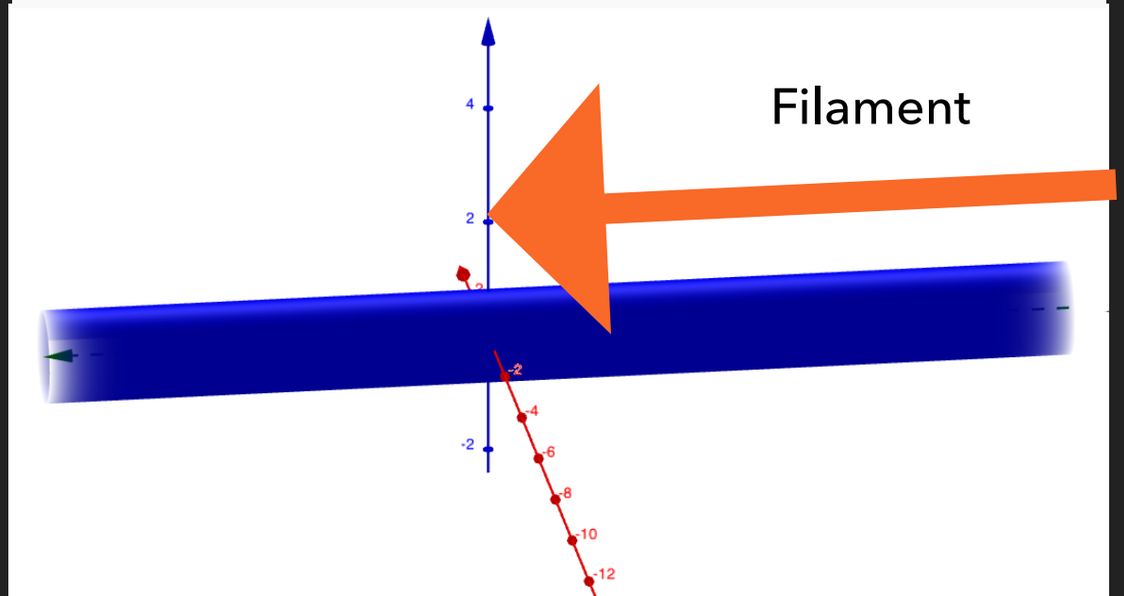

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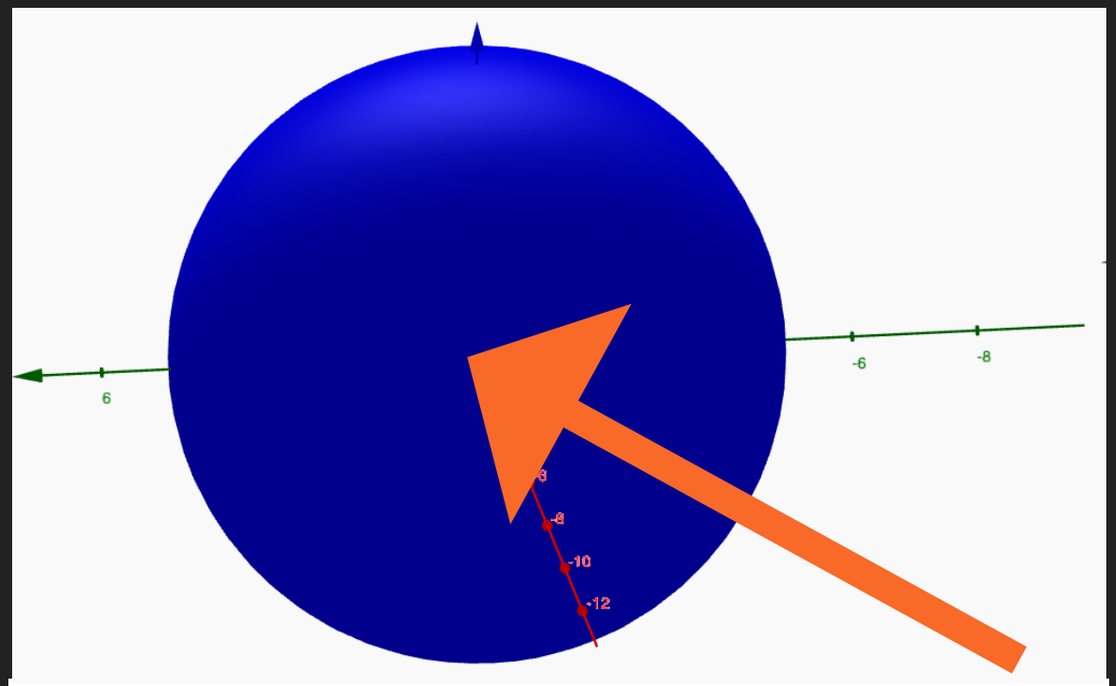

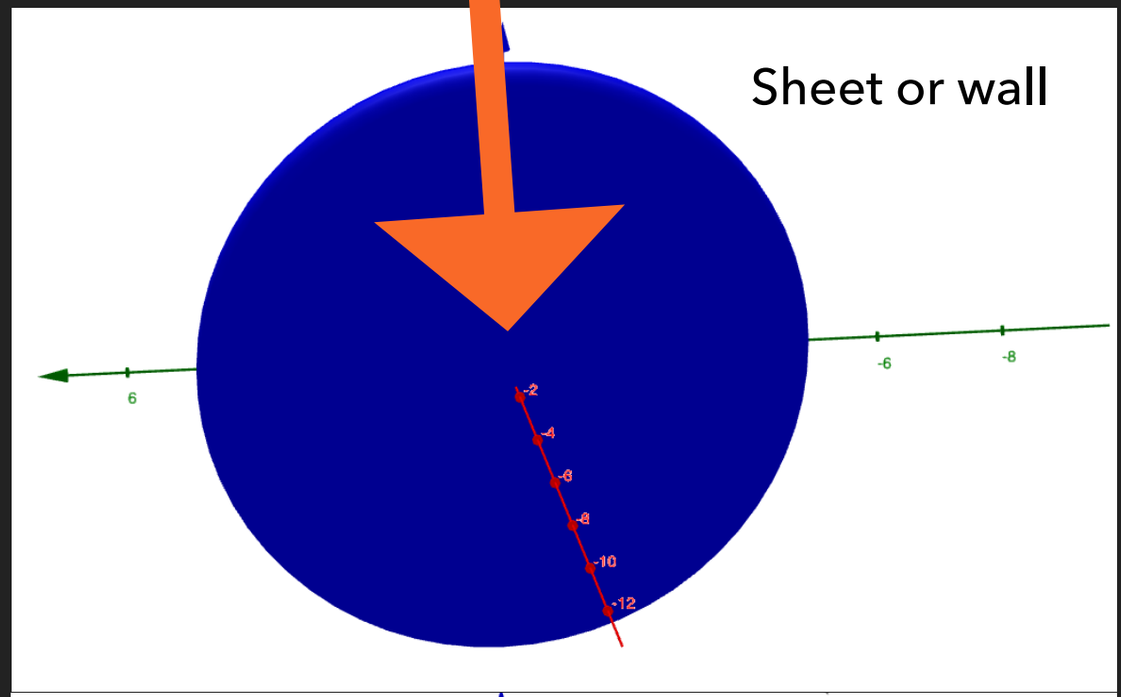

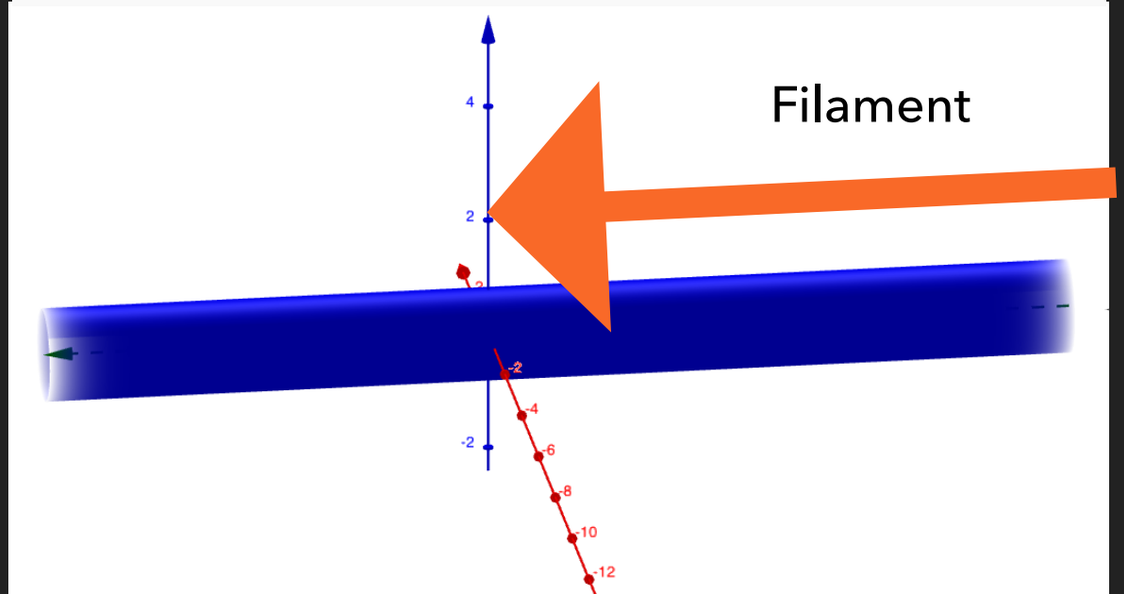

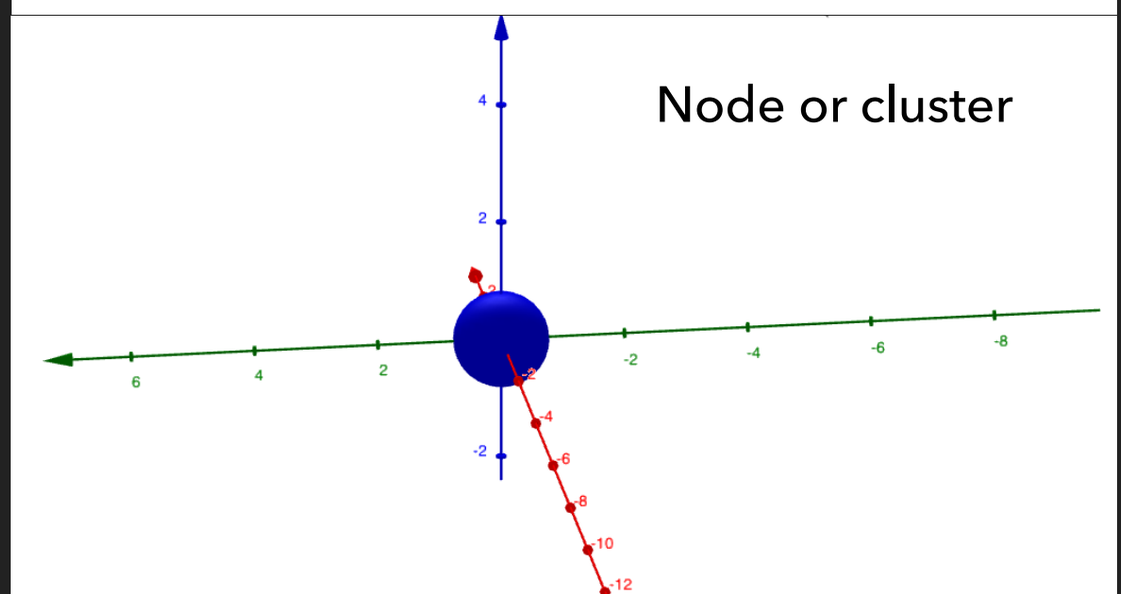

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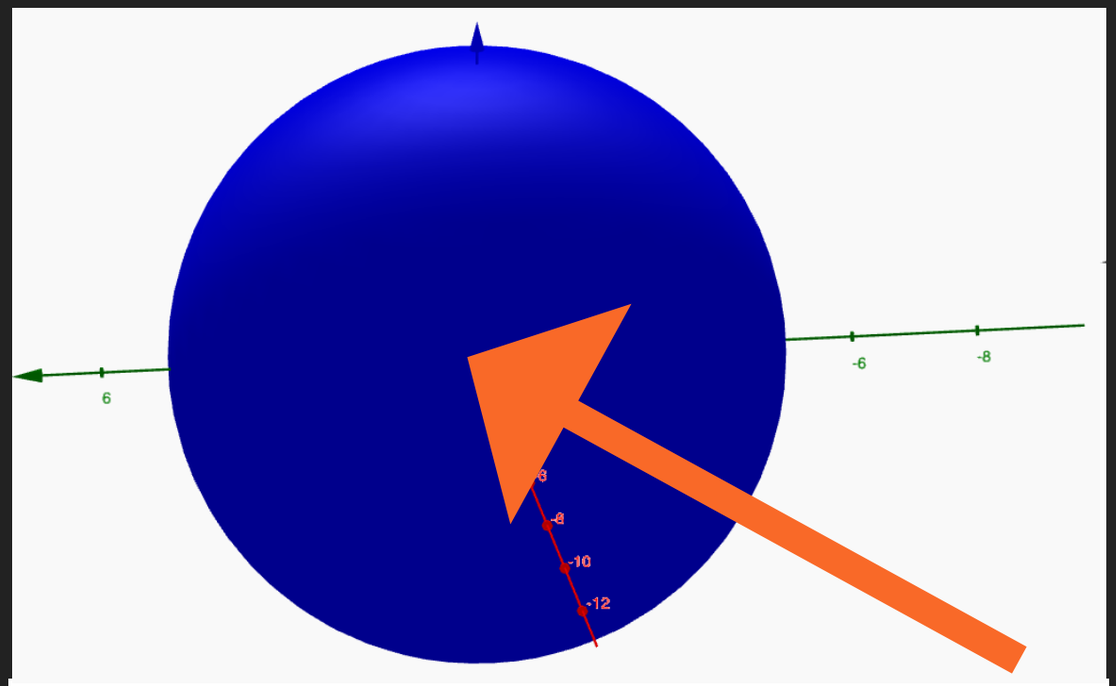
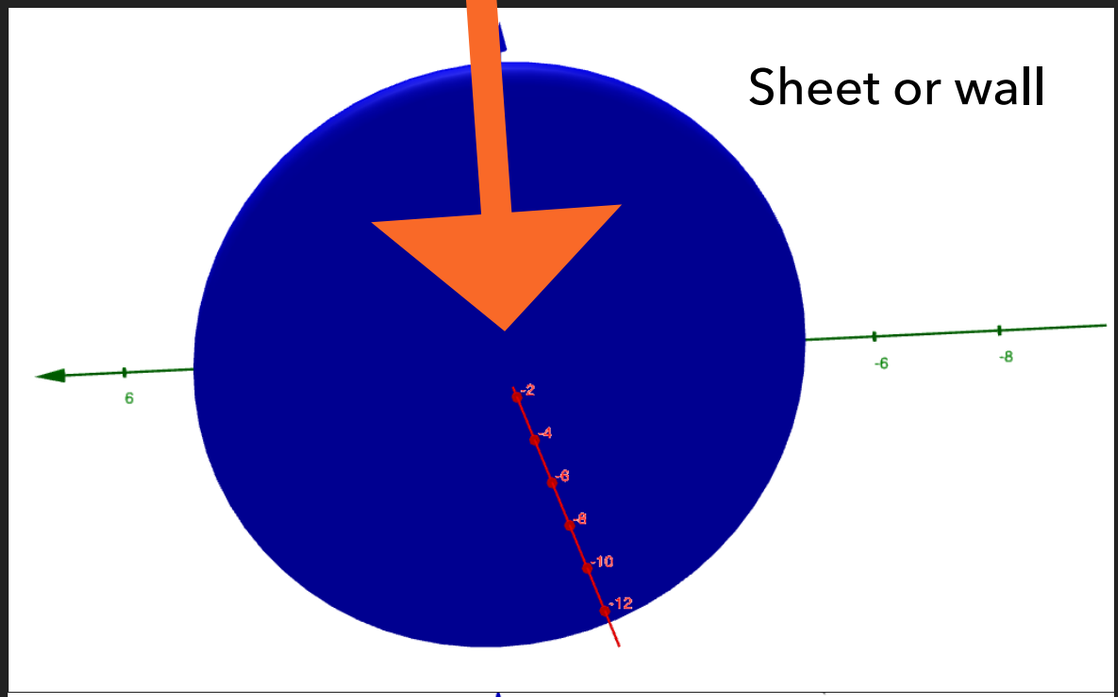
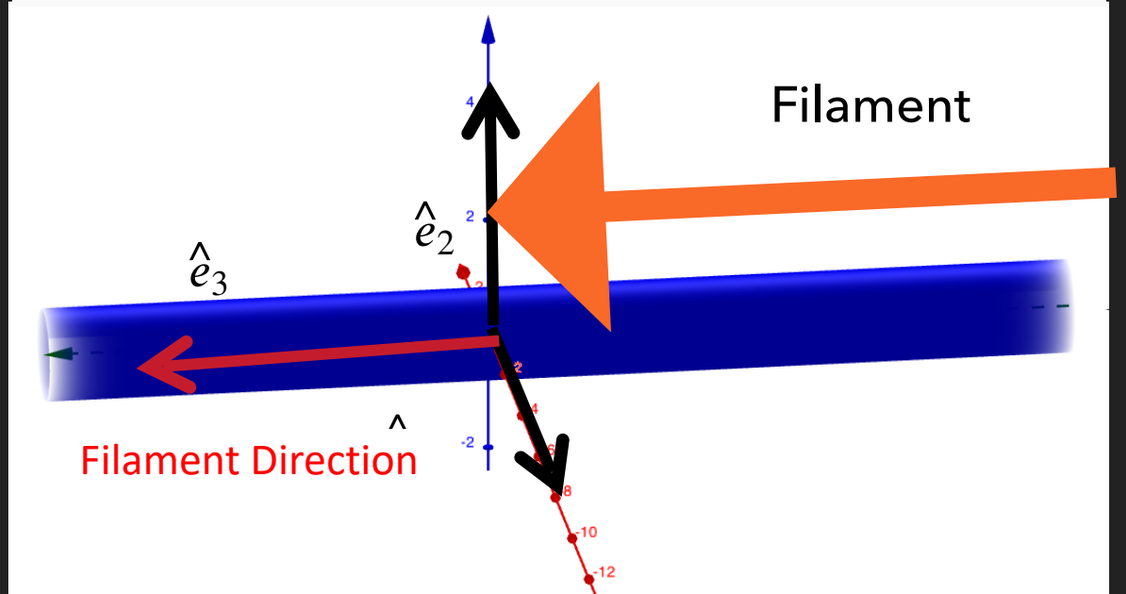
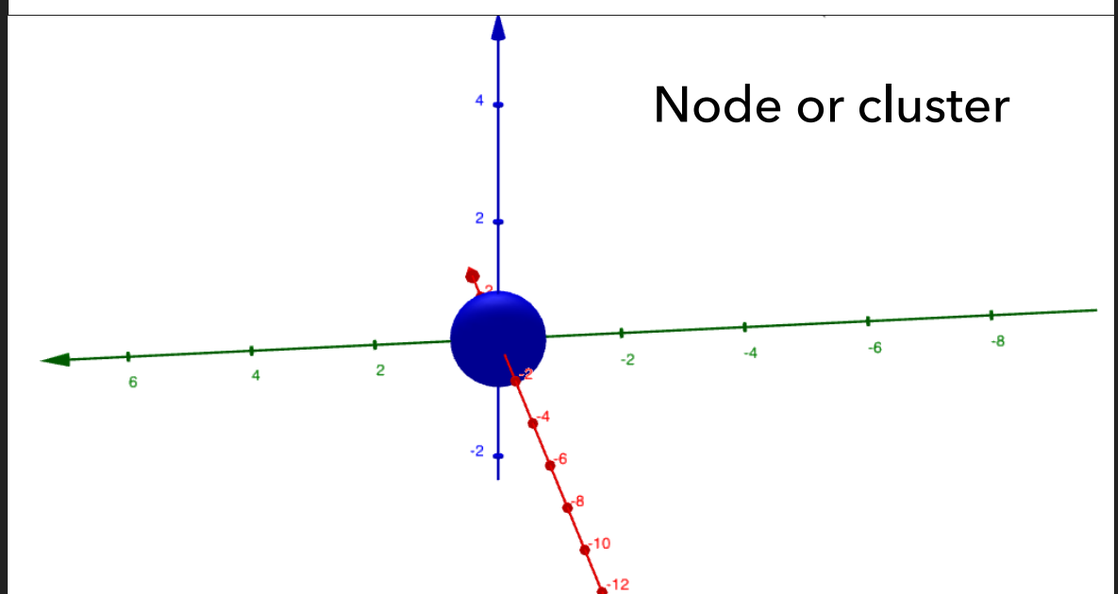
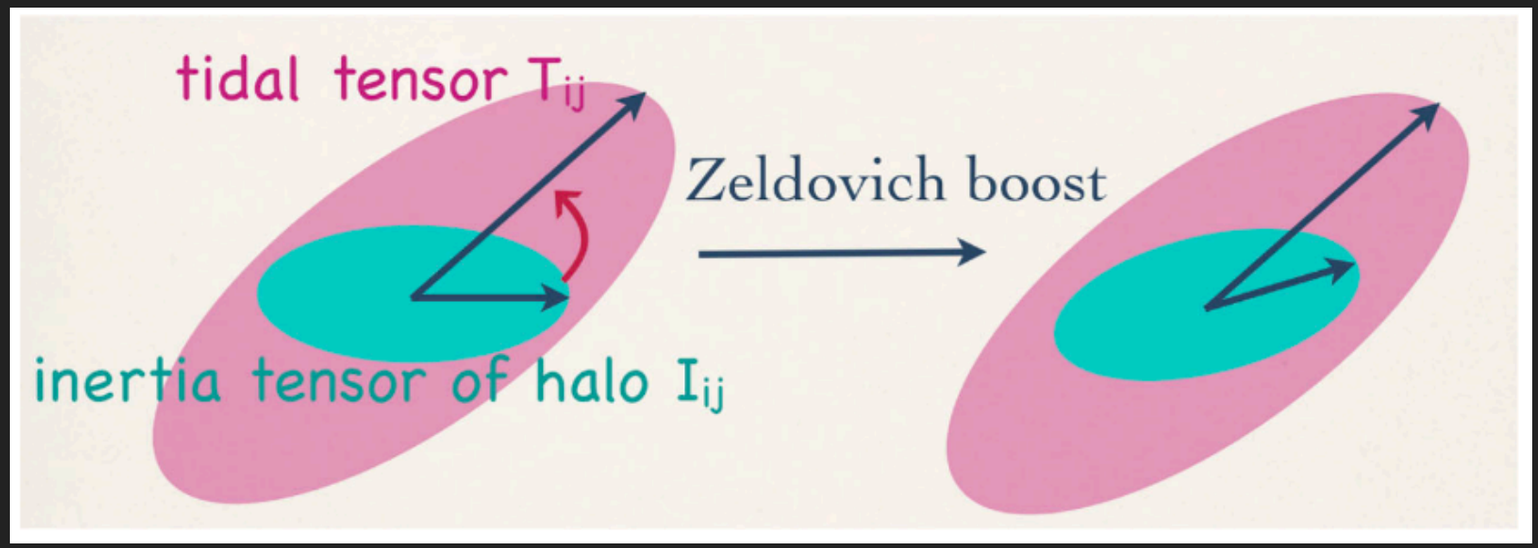








TIDAL TORQUING



Codis et al 2015

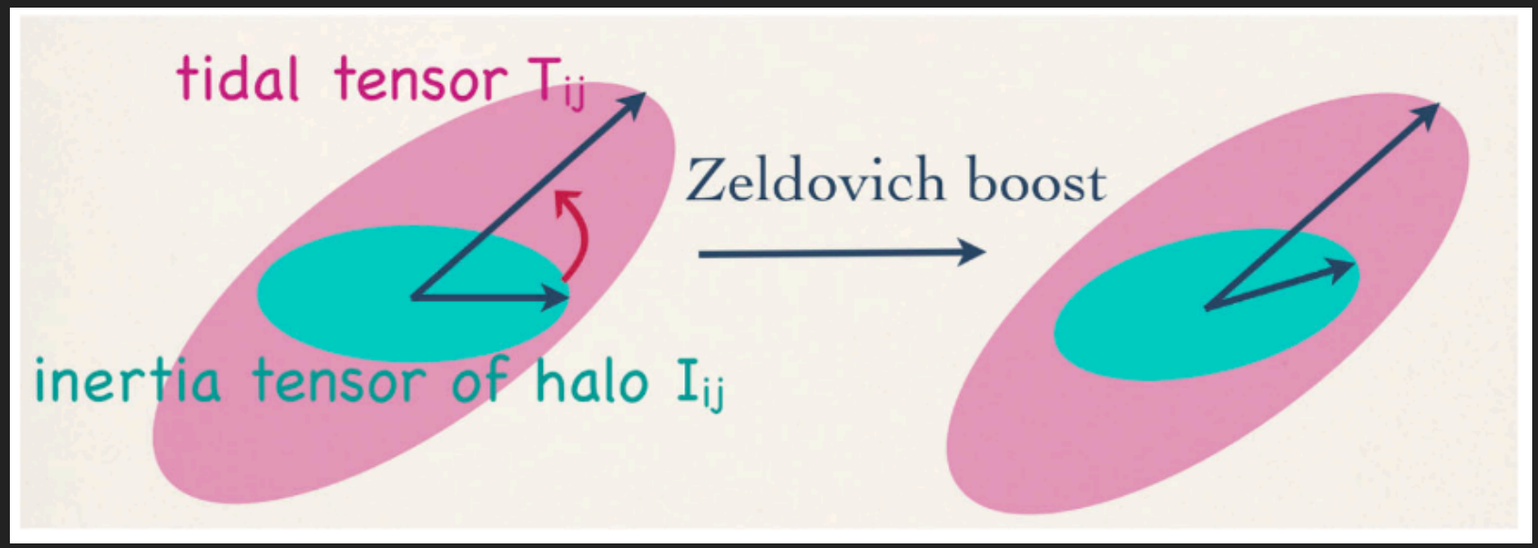
$$J_i(t) = a^2 \dot{D}(t) \epsilon_{ijk} \, T_{jl} \, I_{lk}$$

$$T_{jl} = \frac{\partial^2 \phi(\mathbf{q})}{\partial q_j \partial q_l} \qquad I_{lk} = \int_{V_L} d^3\mathbf{q} \rho(q) q_l q_k$$

Angular momentum grows linearly until turn-around.

Tidal Torque Theory: Hoyle 1949, Peebles 1969, Doroshkevich 1970, White 1984, Catalan & Theuns 1996, Porciani et al 2002, Schäfer 2009

TIDAL TORQUING



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$$J_i(t) = a^2 \dot{D}(t) \epsilon_{ijk} T_{jl} I_{lk}$$

Tidal fields that give rise to the large-scale structures are also giving rise to galaxy spin.

We expect a **correlation between halo/galaxy spins and the cosmic web.**

Tidal Torque Theory: Hoyle 1949, Peebles 1969, Doroshkevich 1970, White 1984, Catalan & Theuns 1996, Porciani et al 2002, Schäfer 2009

TIDAL TORQUE THEORY

Halo formation from a CDM simulation

Credit: https://www.youtube.com/watch?v=jAwDgUInq8Y

IN THIS TALK – COSMIC WEB AND HALO/GALAXY SPIN

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1. Does the cosmic web environment influence **halo spin magnitude and orientation?** How are spins aligned with the underlying geometry of the cosmic web**?**

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2. How does the halo/galaxy spin alignments depend on the **filament properties?**
3. How do spin-alignments **evolve with time?**

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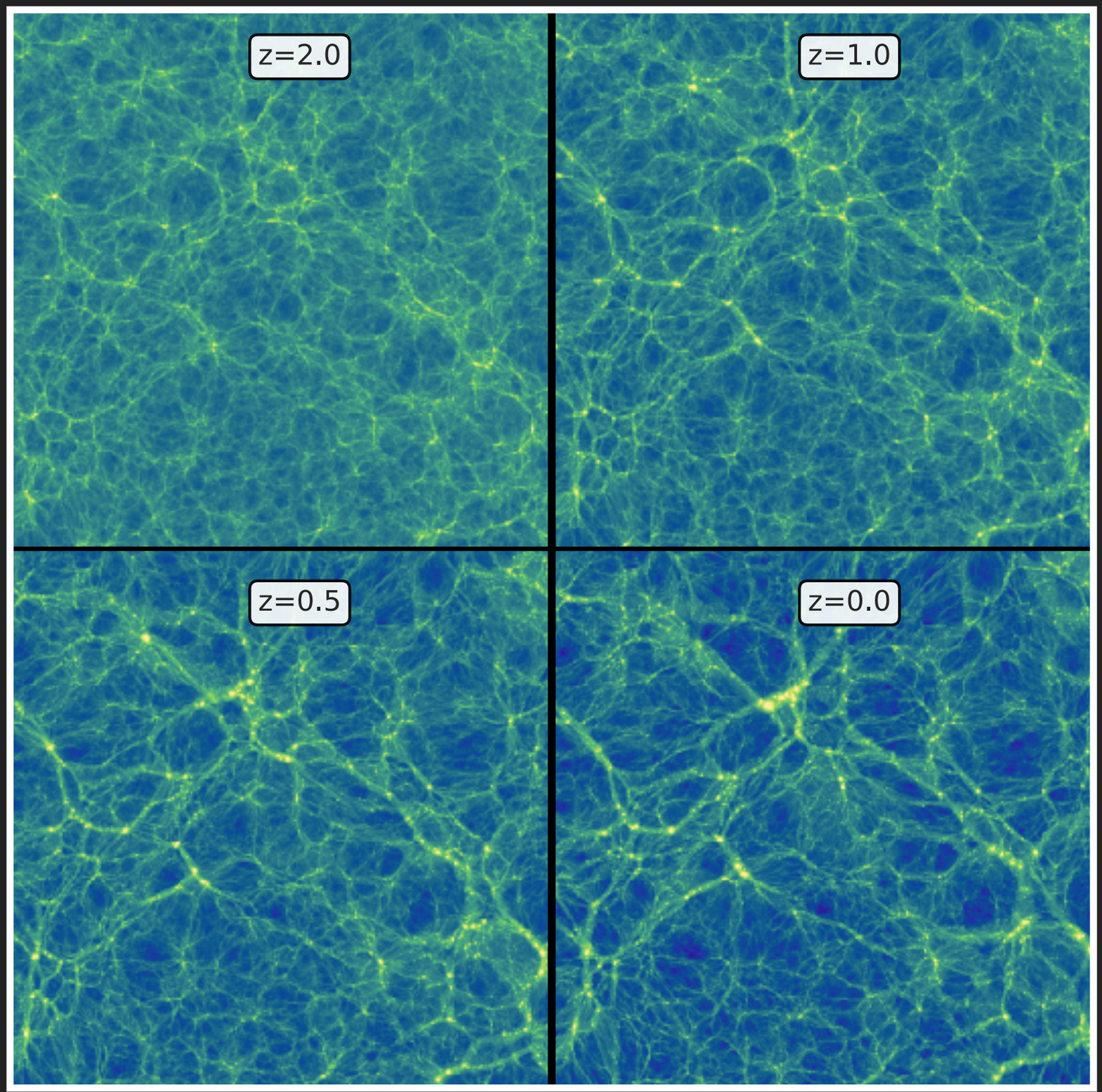
1. Does the cosmic web environment influence **halo spin magnitude and orientation?** How are spins aligned with the underlying geometry of the cosmic web**?**

2. How does the halo/galaxy spin alignments depend on the **filament properties?**

3. How do spin-alignments **evolve with time?**

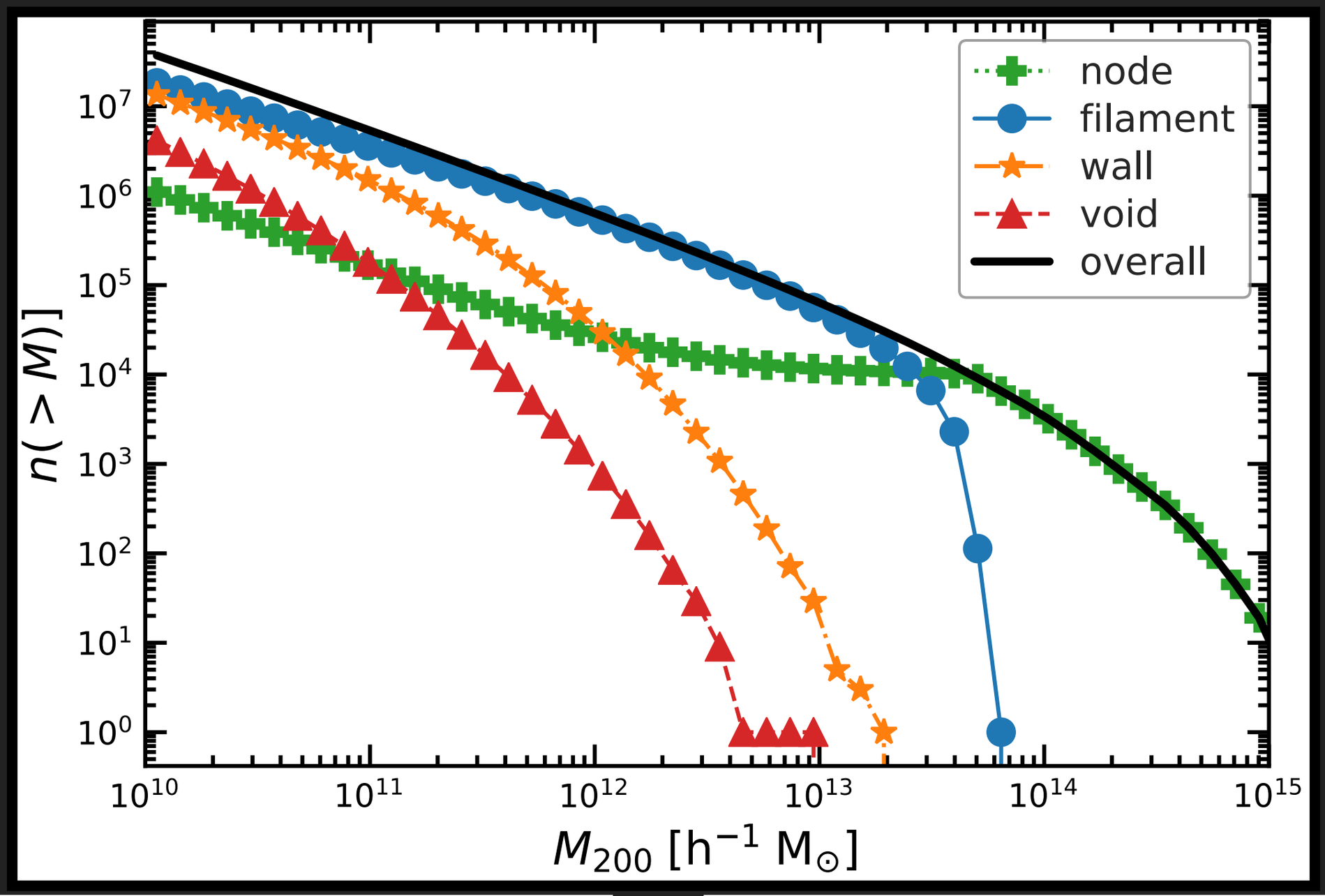
4. **Halo-galaxy connection**: How does galaxy alignment compare to its halo spin alignment? How does it relate to galaxy **morphology?**

PLANCK-MILLENNIUM SIMULATION



- Planck cosmology run in ICC, Durham
- 800 Mpc box
- 128 billion dm particles
- Particle mass ~ $10^8 M_\odot/h$
- Large number of haloes

PLANCK–MILLENNIUM SIMULATION – MASS FUNCTION



~36 million haloes at z=0

~2.8 million haloes chosen for this study

IN THIS TALK – COSMIC WEB AND HALO/GALAXY SPIN

1. Does the cosmic web environment influence **halo spin magnitude and orientation?** How are spins aligned with the underlying geometry of the cosmic web**?**
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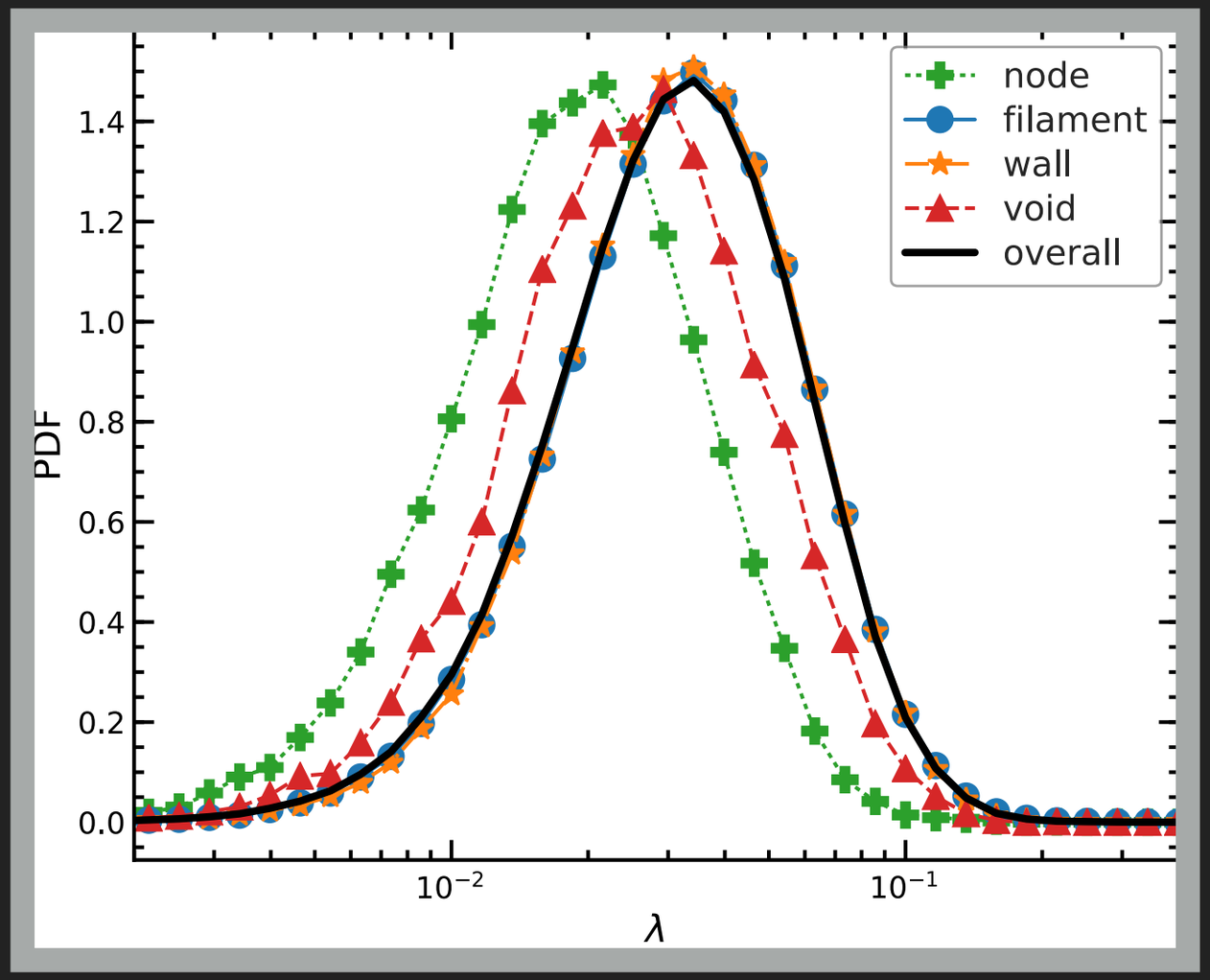
PLANCK–MILLENNIUM SIMULATION – SPIN PARAMETER

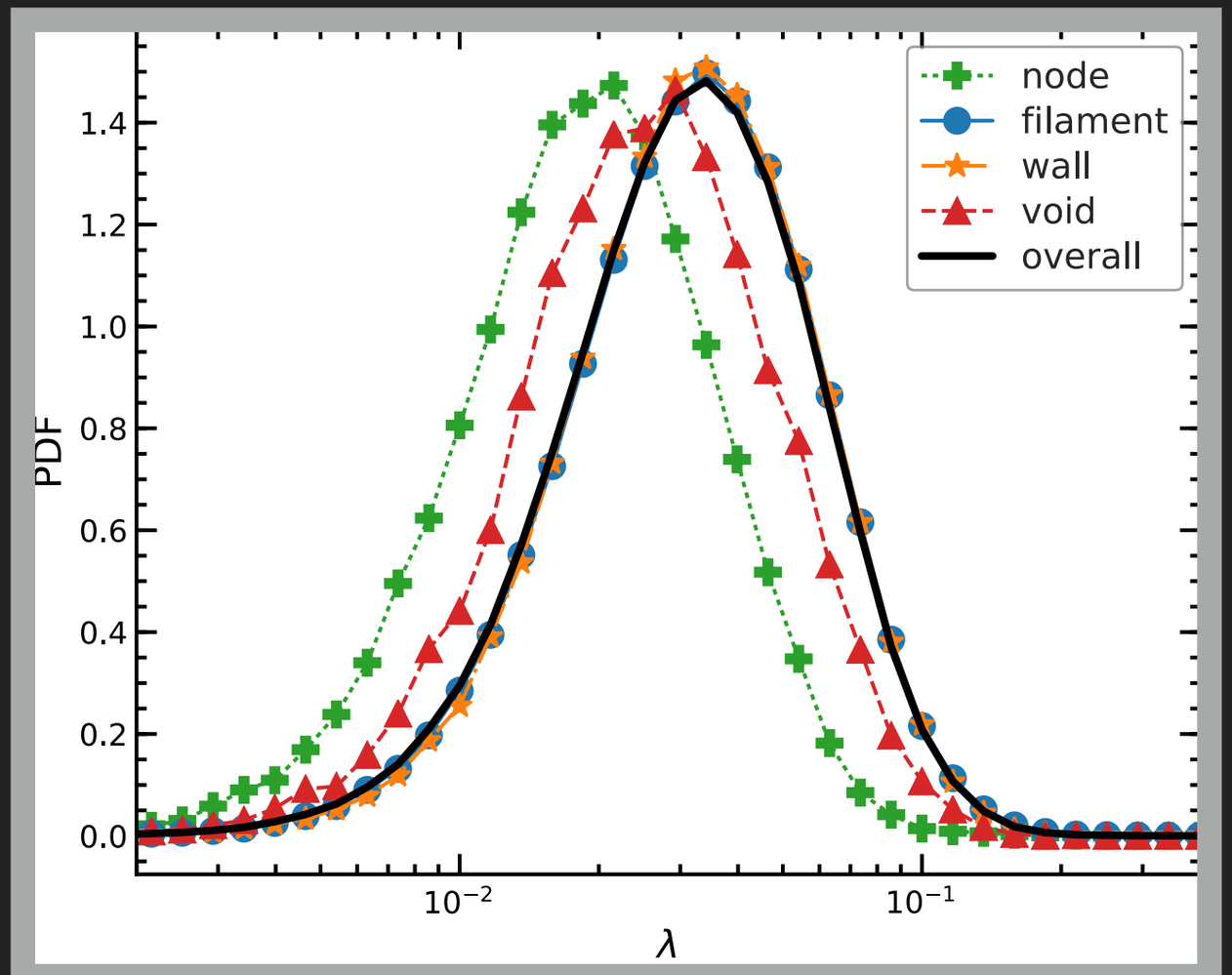


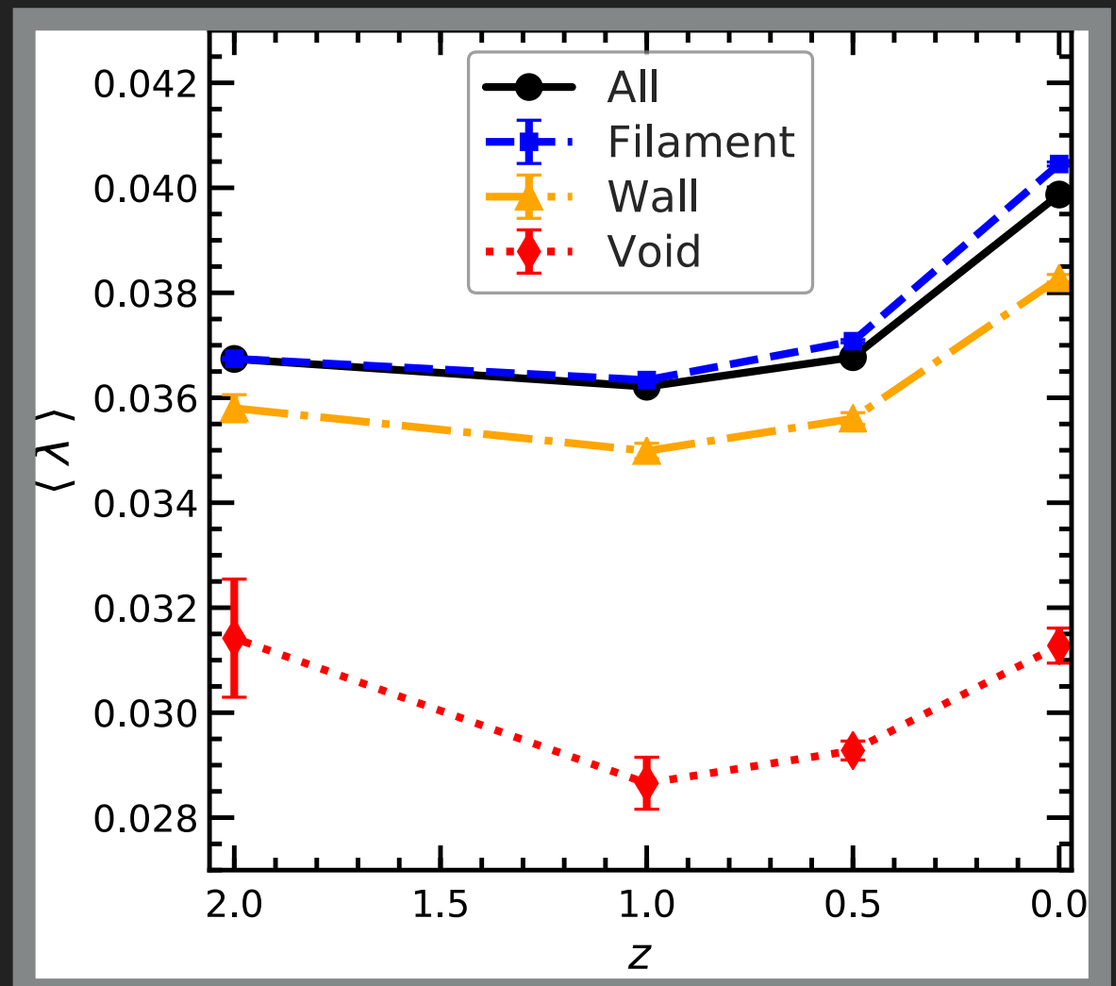
$$\lambda = \frac{J}{\sqrt{2}MVR}$$

$\lambda = 0 \longrightarrow$ dispersion supported

$\lambda = 1 \longrightarrow$ rotation supported

PLANCK–MILLENNIUM SIMULATION – SPIN PARAMETER





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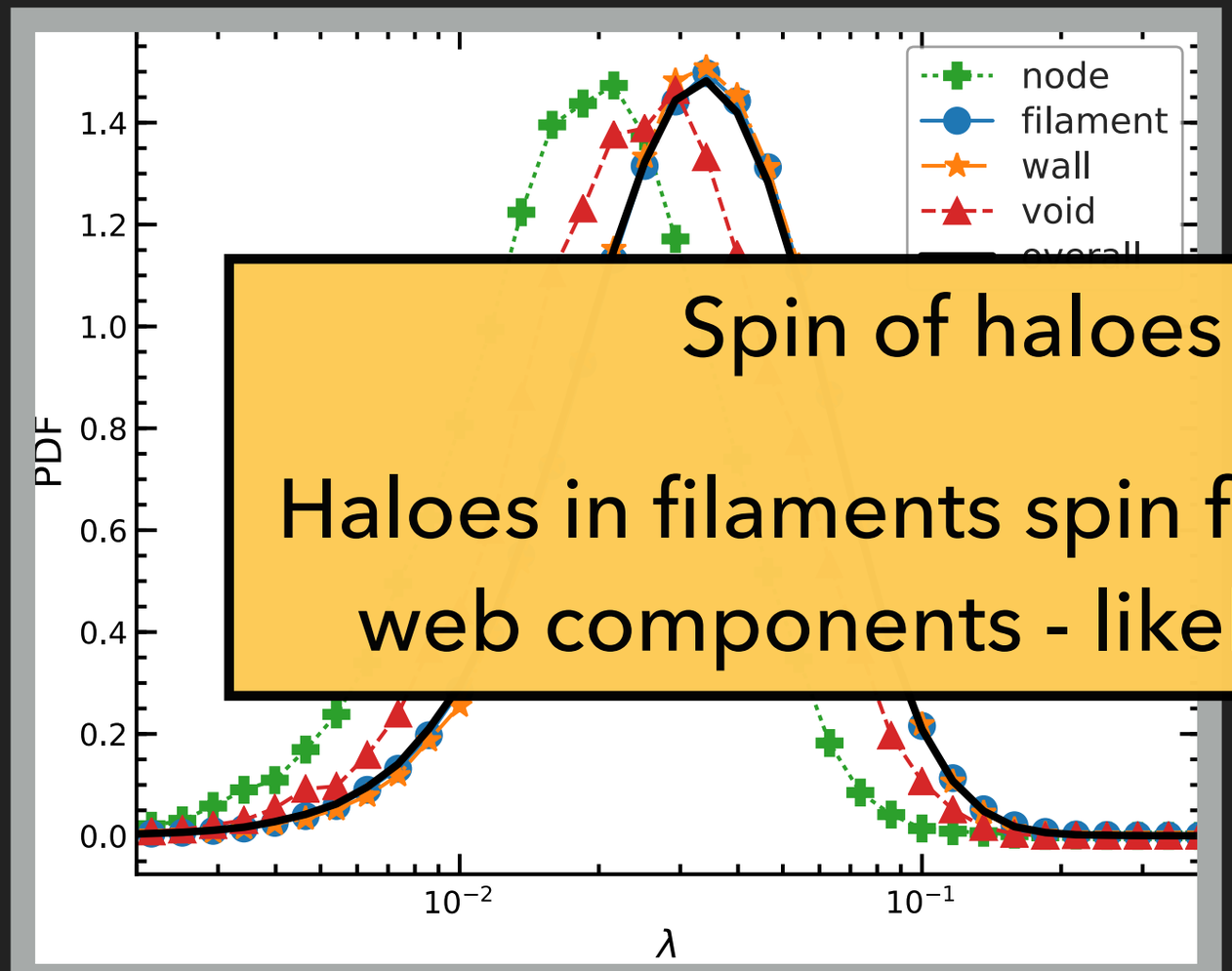

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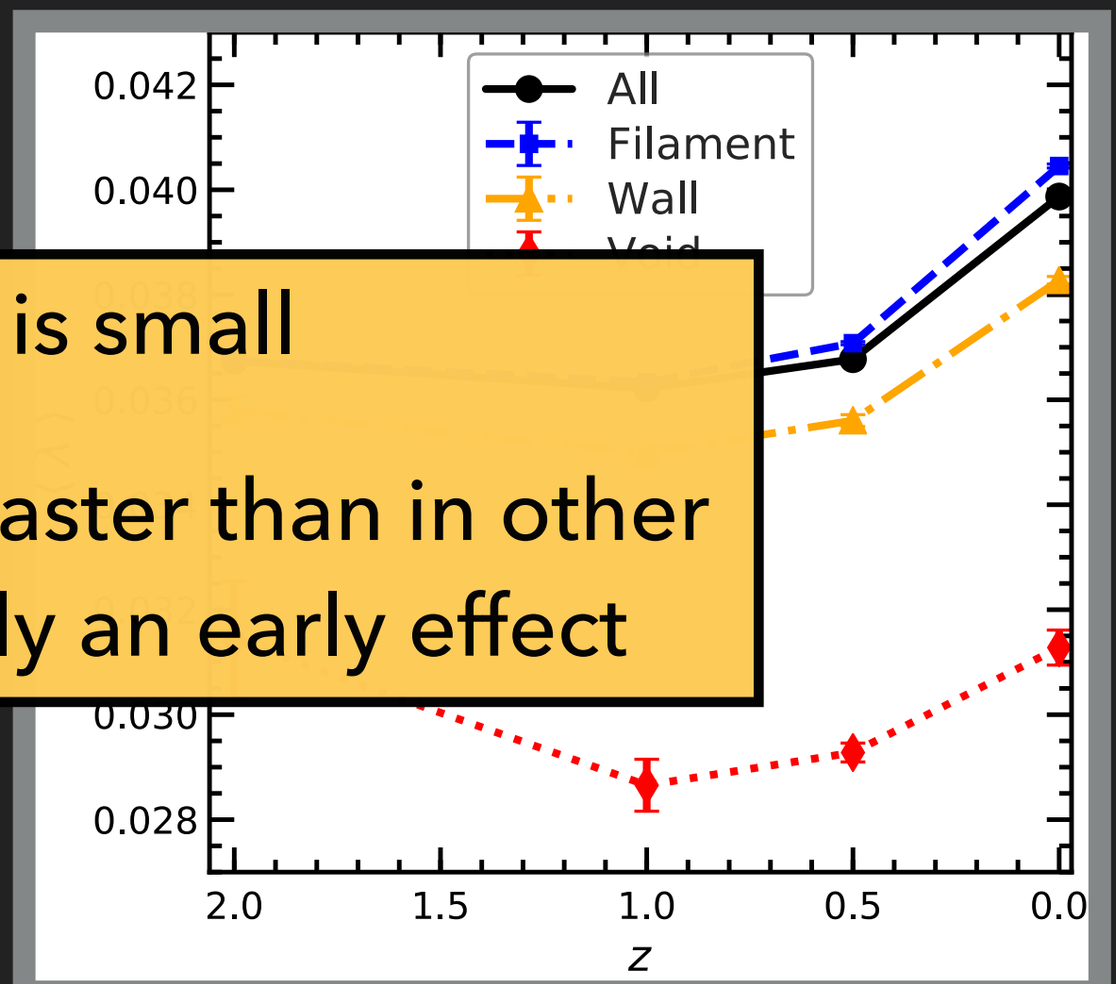

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Spin of haloes is small

Haloes in filaments spin faster than in other web components - likely an early effect

$$\lambda = \frac{J}{\sqrt{2}MVR}$$

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NEXUS +

- Input tracer field - density field
- Geometry of matter distribution

NEXUS VELOCITY SHEAR

- Velocity shear
- Dynamical signature

Morphology: eigenvalue conditions

Multiscale detection

Spine of filament or last collapse: $\hat{e}_3$

NEXUS – ***Multiscale cosmic web detection formalism developed at Kapteyn Institute, Groningen [Aragon-Calvo et al 2007; Cautun et al 2013]***

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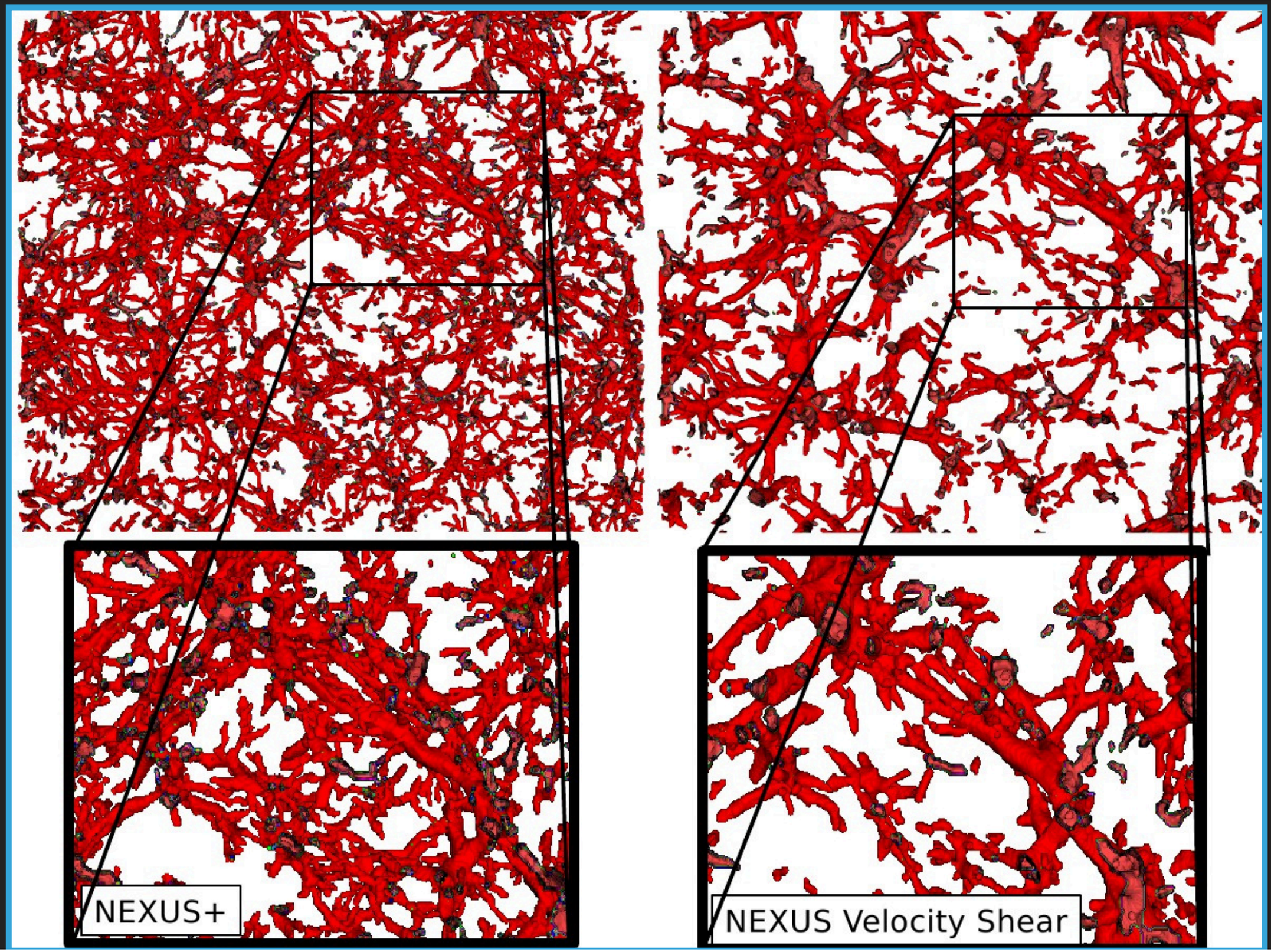
NEXUS+ NEXUS VELOCITY SHEAR



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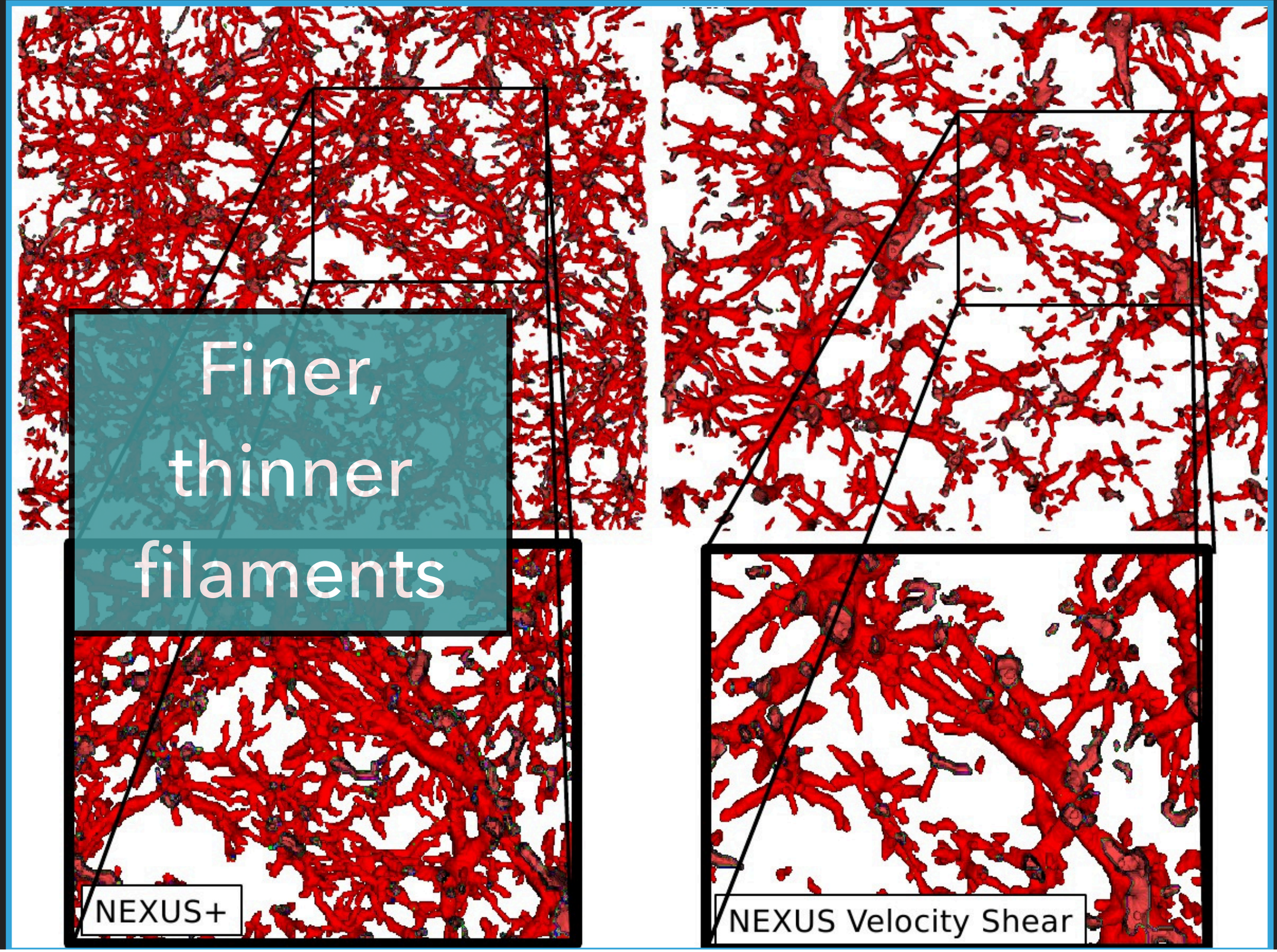
MMF/NEXUS – Multiscale cosmic web detection formalism developed at Kapteyn Institute, Groningen [Aragon-Calvo et al 2007; Cautun et al 2013]



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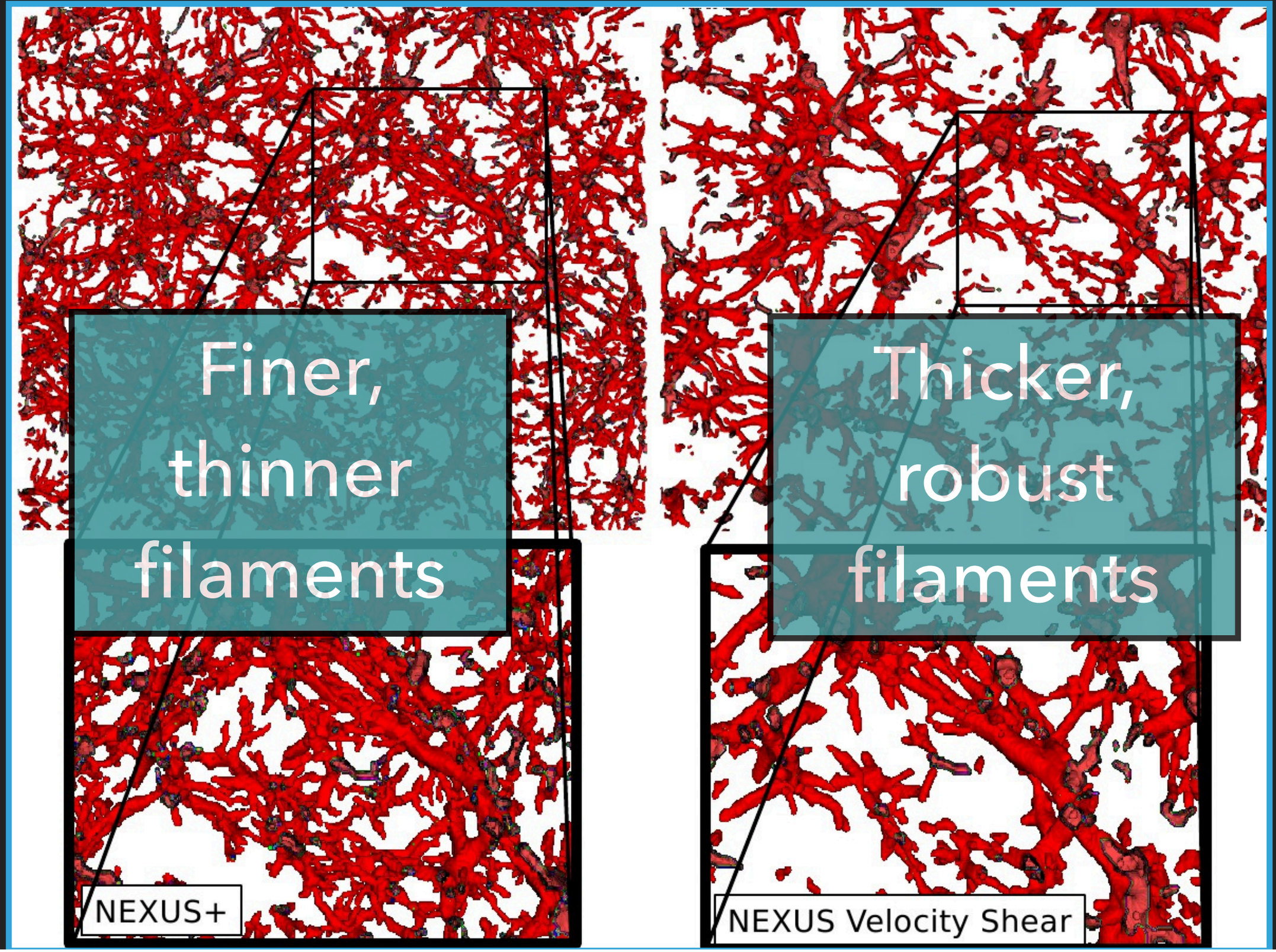

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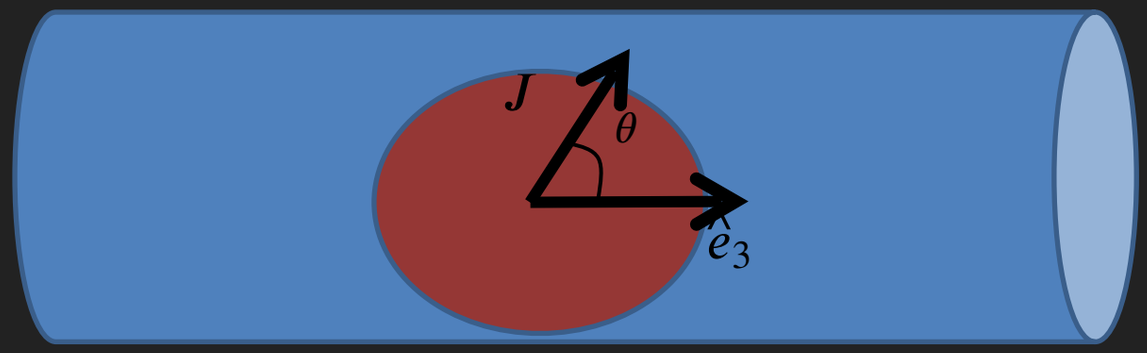


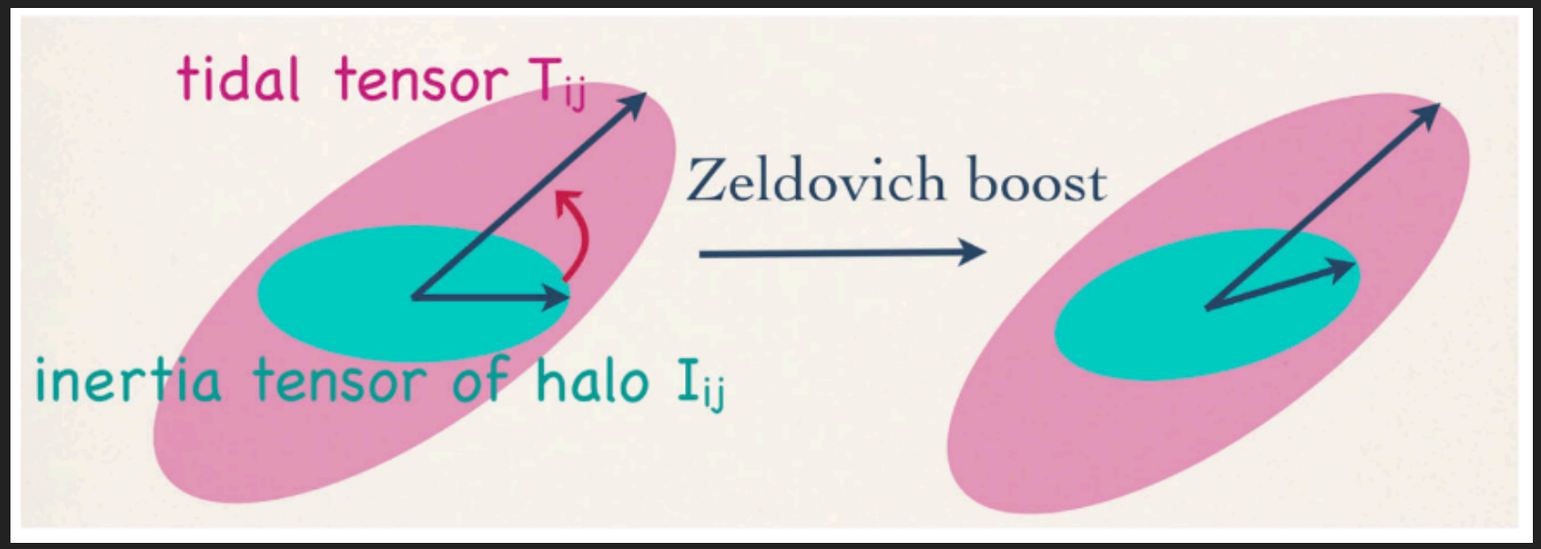
$$\cos\theta_{\mathbf{J},\mathbf{e}_3} = \left| \frac{\mathbf{J} \cdot \mathbf{e}_3}{|\mathbf{J}||\mathbf{e}_3|} \right|$$

$$\cos(\theta) = 1 \quad \longrightarrow \text{Parallel}$$

$$\cos(\theta) = 0.5 \quad \longrightarrow \text{No preferential alignment}$$

$$\cos(\theta) = 0 \quad \longrightarrow \text{Perpendicular}$$

TIDAL TORQUE – ALIGNMENTS



Codis et al 2015

$$J_i(t) = a^2 \dot{D}(t) \epsilon_{ijk}\, T_{jl}\, I_{lk}$$

$$J_1 \propto (\lambda_2 - \lambda_3) I_{23}$$
$$J_2 \propto (\lambda_3 - \lambda_1) I_{31} \qquad \lambda_1 \geq \lambda_2 \geq \lambda_3$$
$$J_3 \propto (\lambda_1 - \lambda_2) I_{12}$$

Tidal Torque Theory: Hoyle 1949, Peebles 1969, Doroshkevich 1970, White 1984, Catalan & Theuns 1996, Porciani et al 2002, Schäfer 2009

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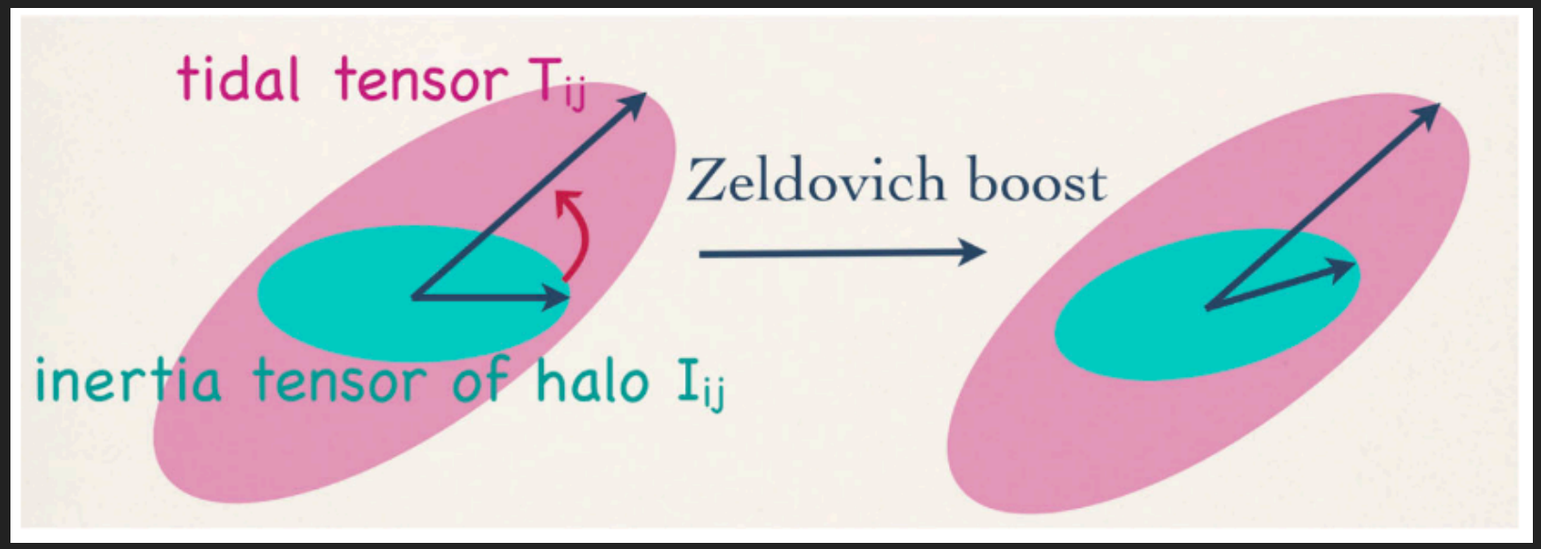

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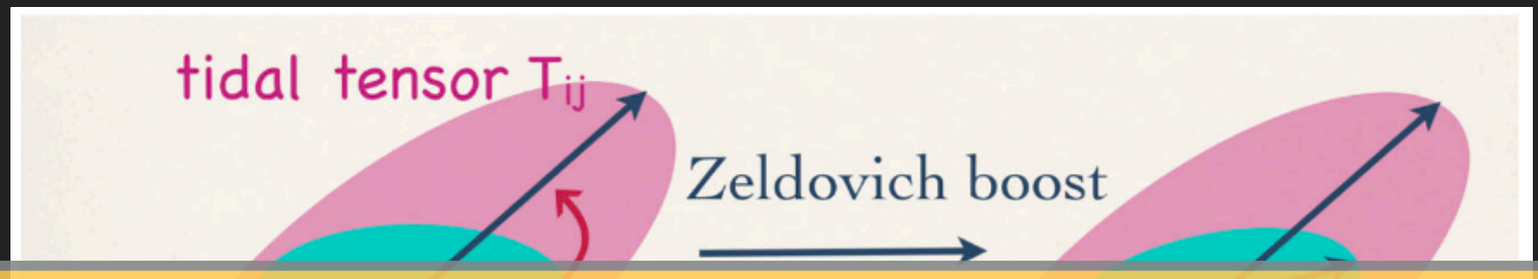

If the **tidal tensor** and the **inertia tensor** are **initially uncorrelated**, then we expect that haloes/galaxies are spinning **perpendicular to the filament spine**.

If they are correlated, then it is more complex.

$$J_i(t) = a^2 D(t) \epsilon_{ijk} T_{jl} I_{lk}$$

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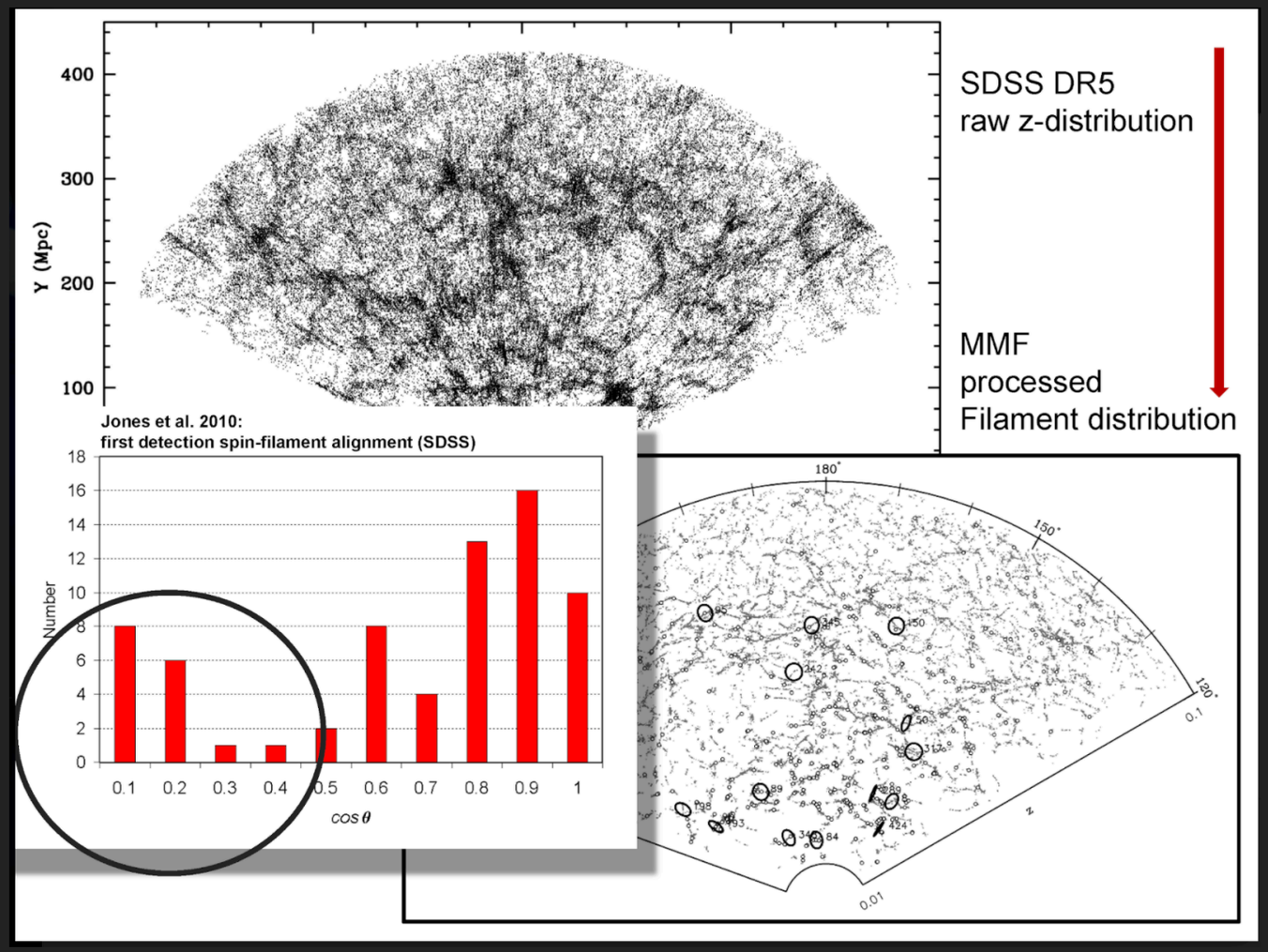
GALAXY ALIGNMENTS IN OBSERVATIONS

Slide courtesy: Rien van de Weygaert



Jones et al 2010; Tempel et al 2013; Welker et al 2020

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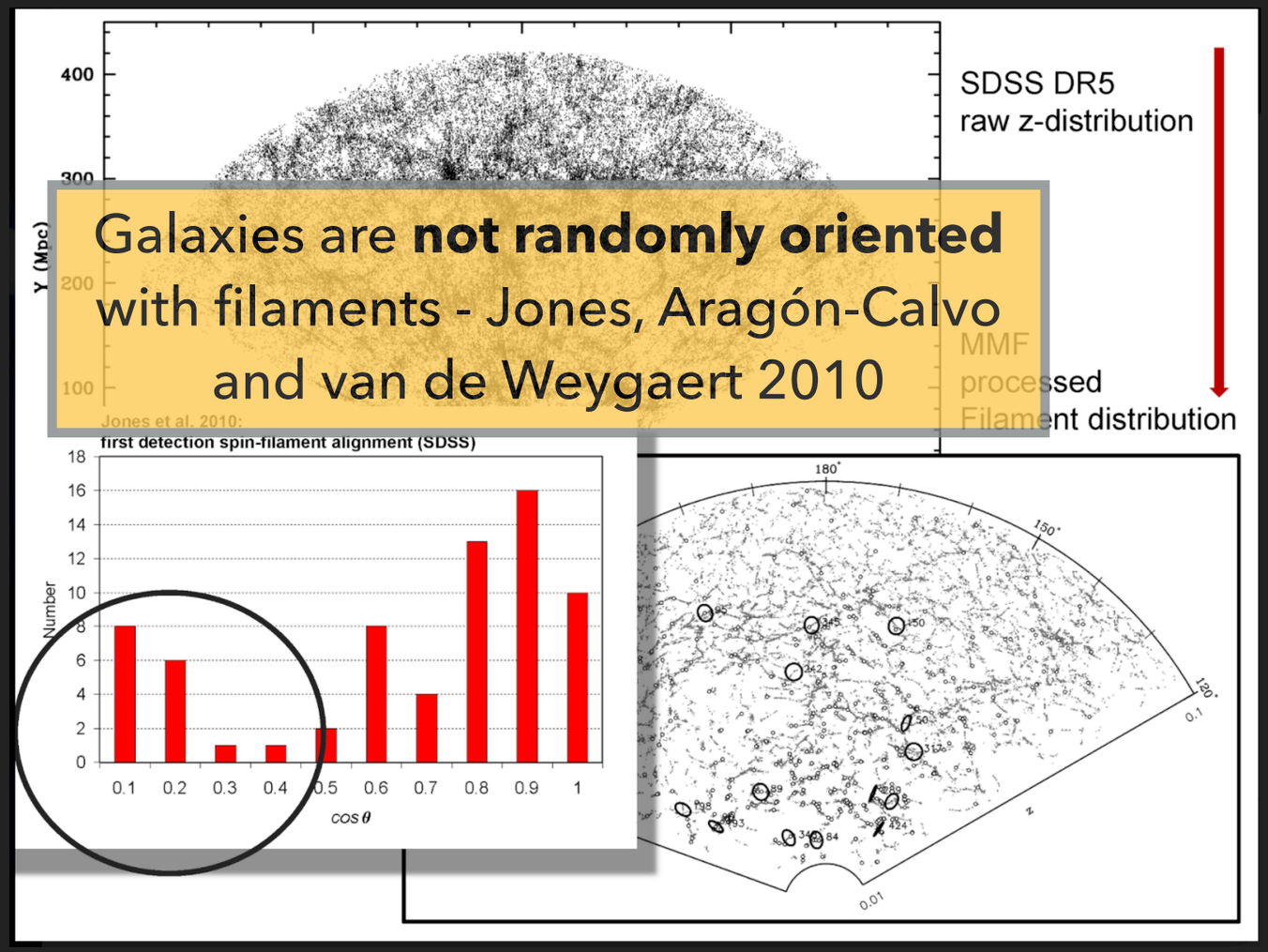

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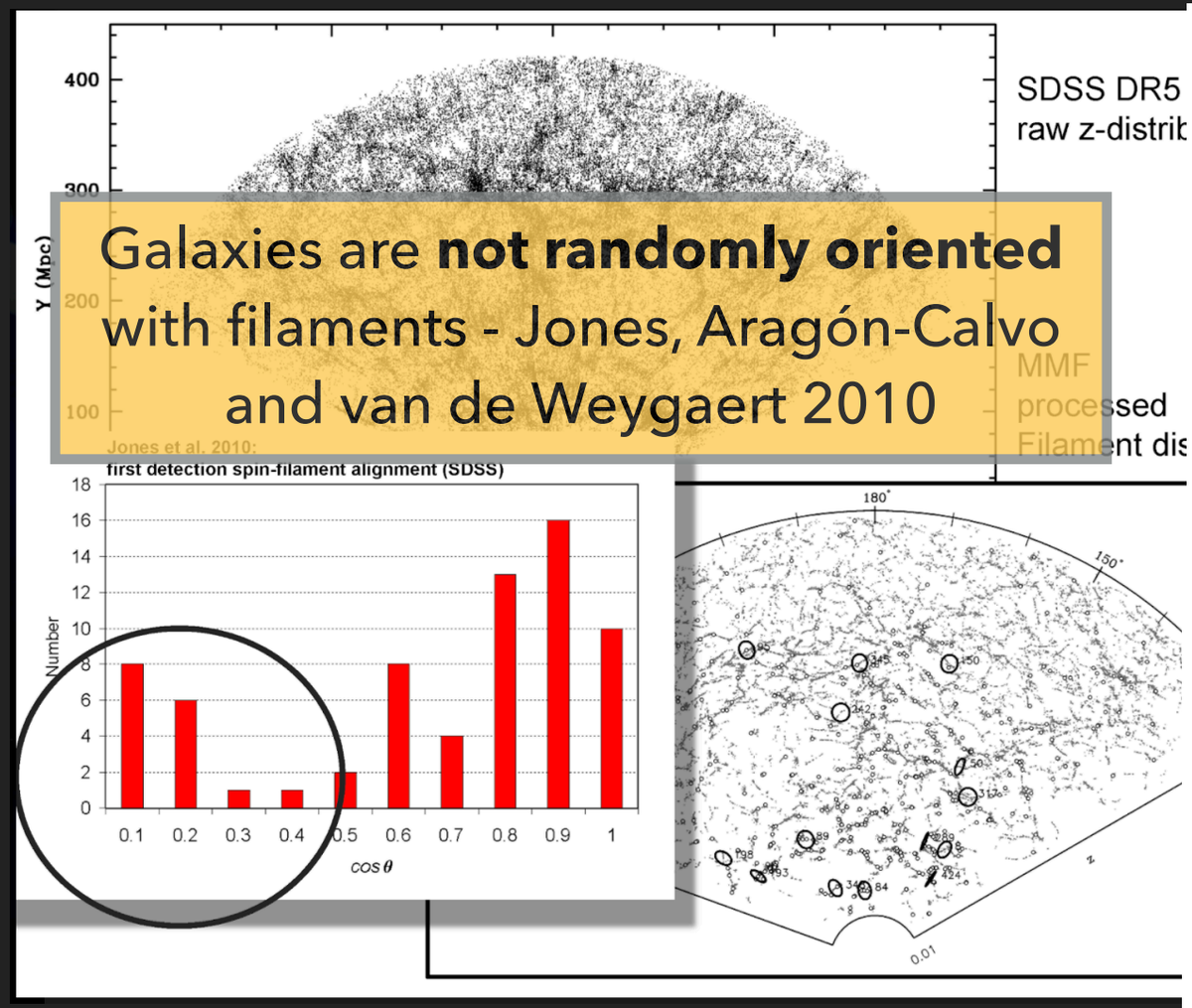
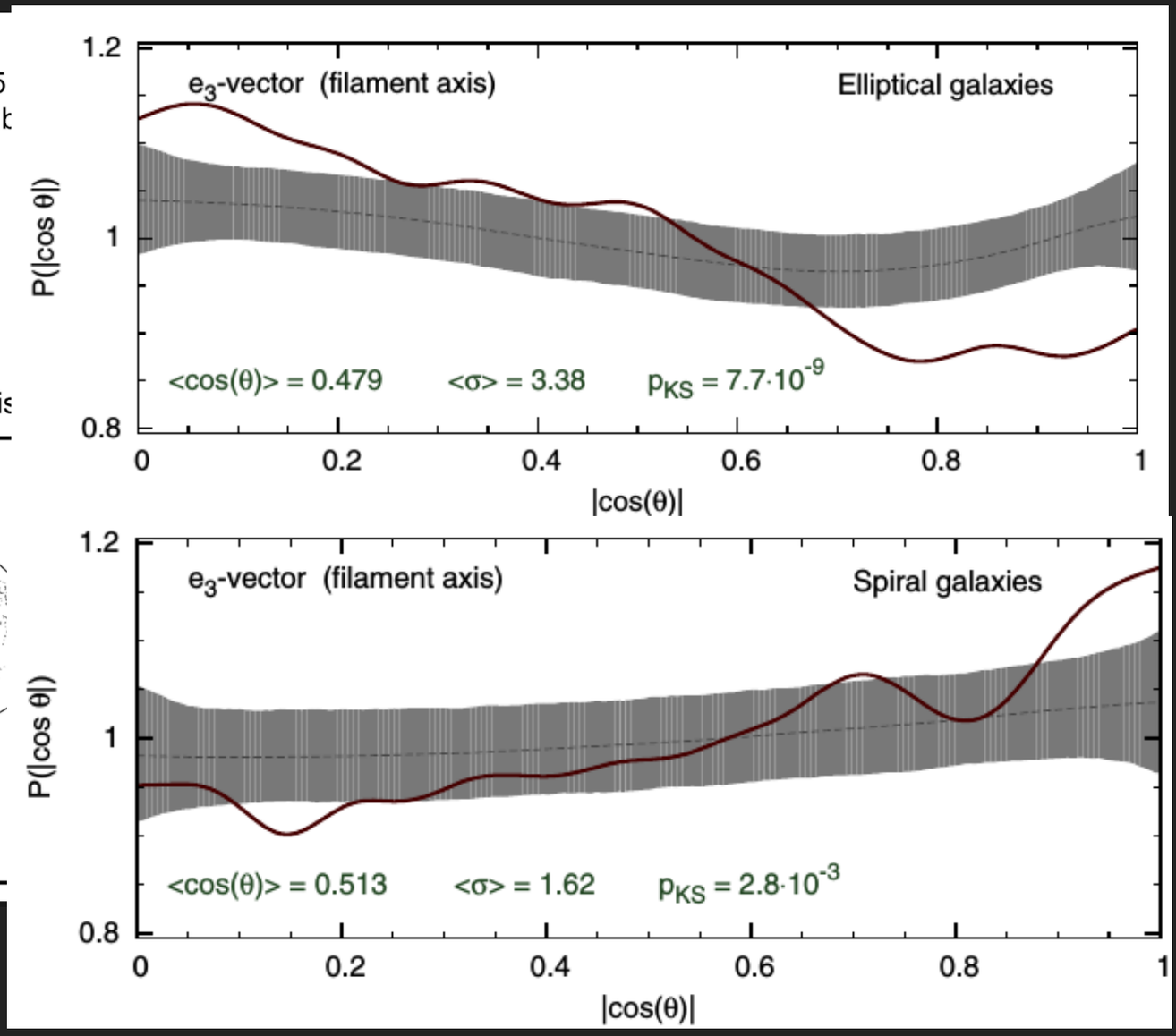


Galaxies are **not randomly oriented** with filaments - Jones, Aragón-Calvo and van de Weygaert 2010



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GALAXY ALIGNMENTS IN OBSERVATIONS

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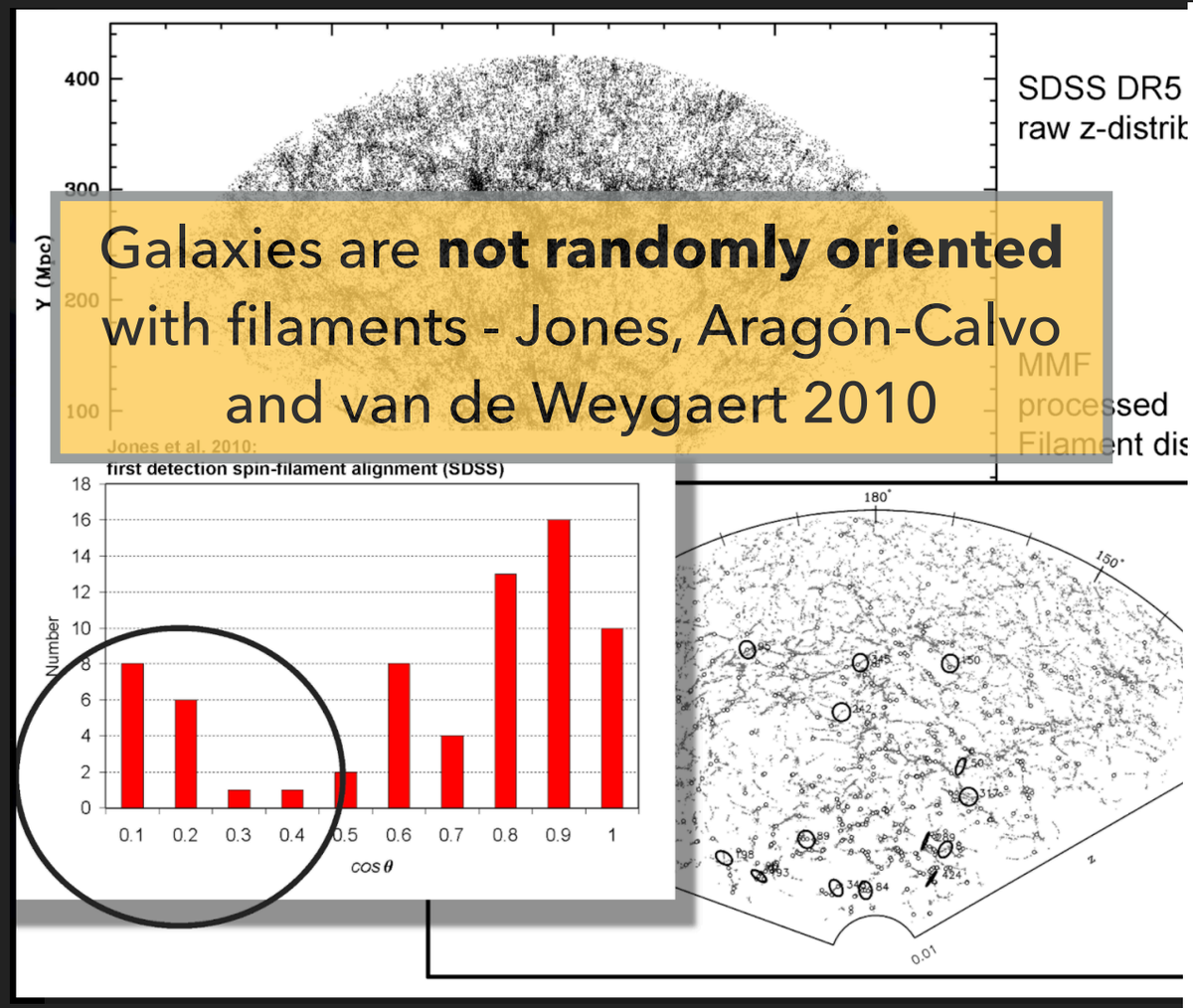

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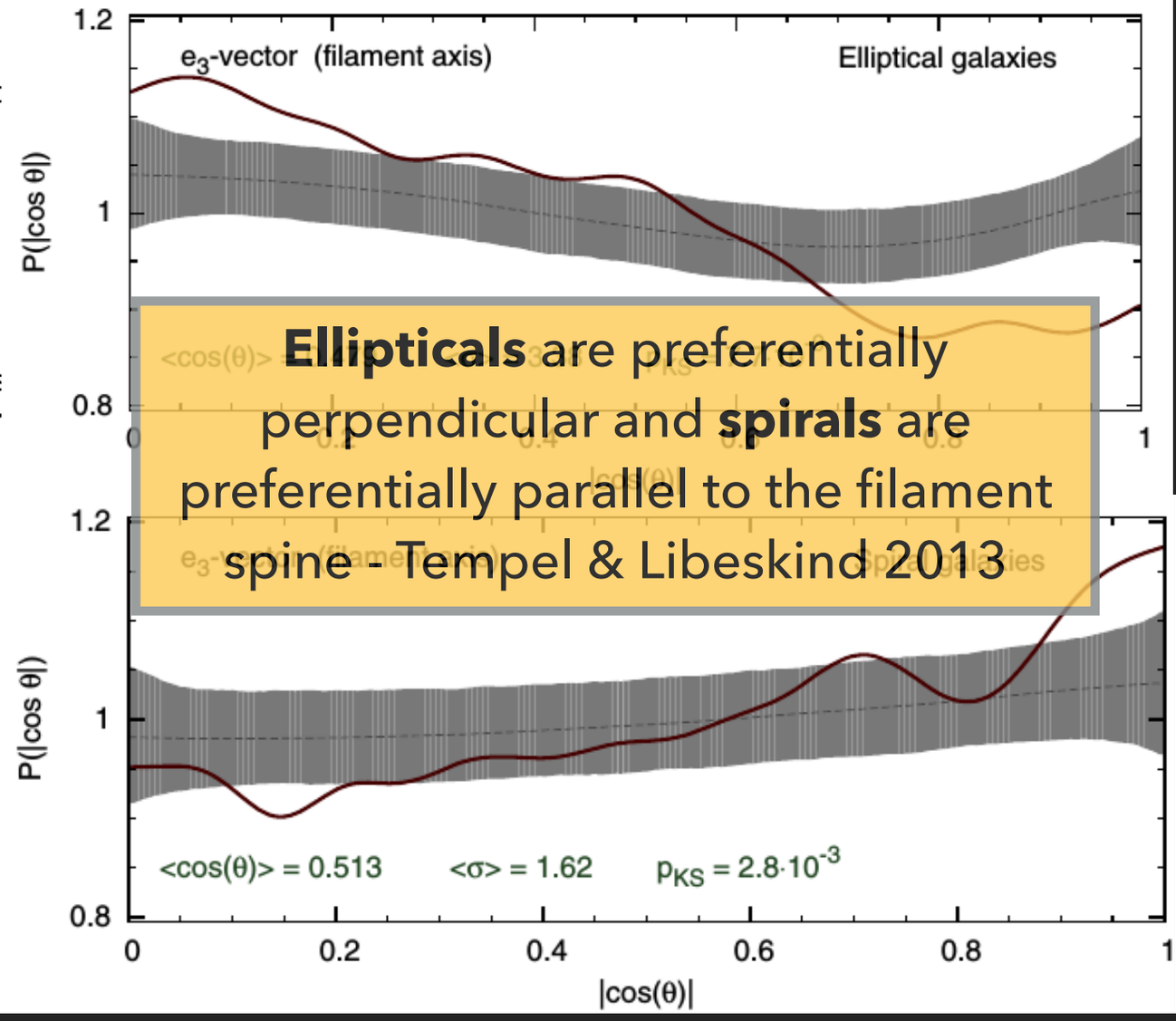

Ellipticals are preferentially perpendicular and **spirals** are preferentially parallel to the filament spine - Tempel & Libeskind 2013

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GALAXY ALIGNMENTS IN OBSERVATIONS

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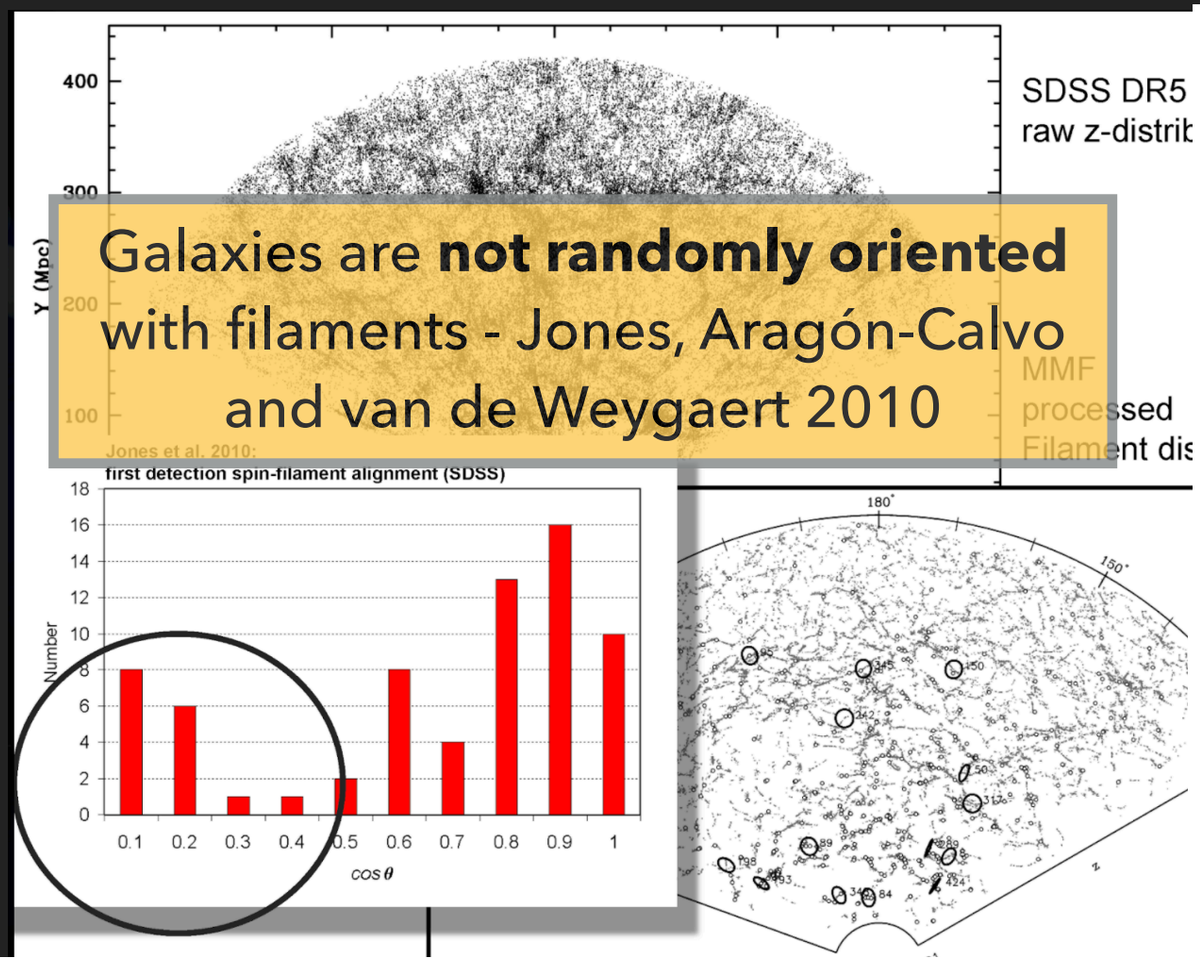

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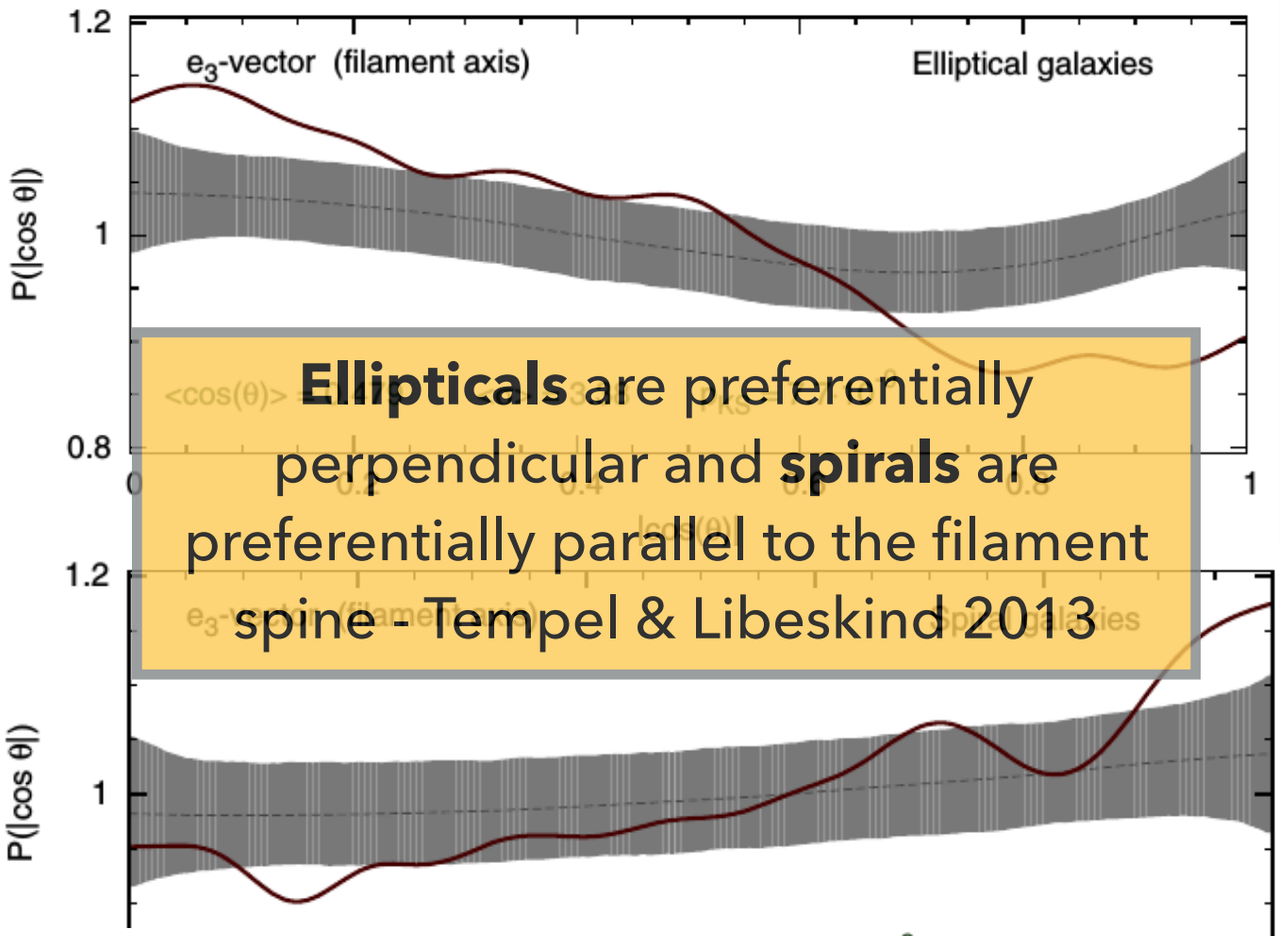

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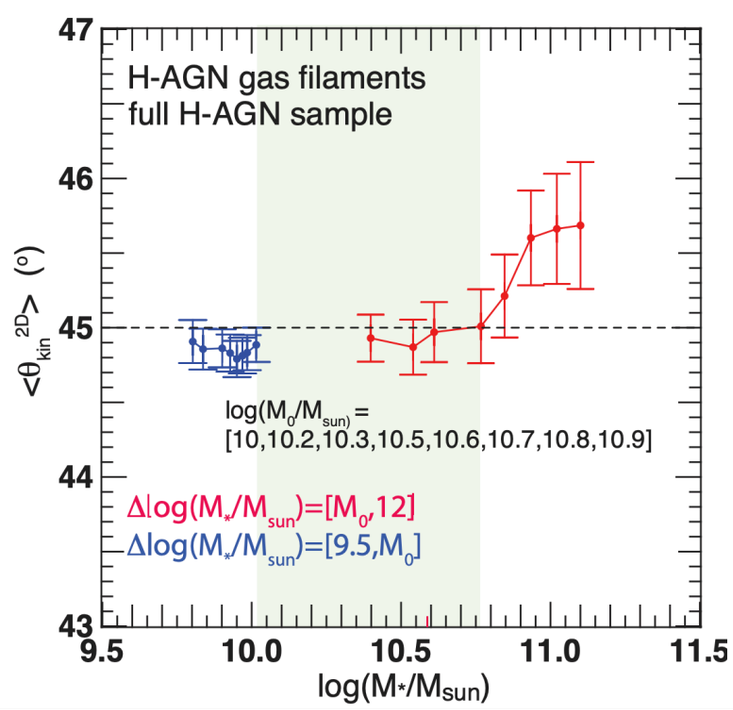

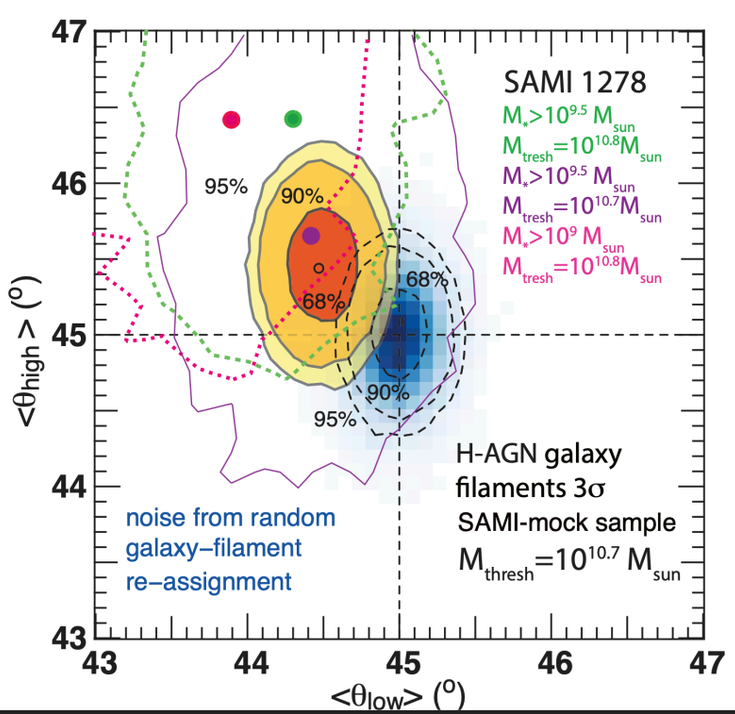

Jones et al 2010; Tempel et al 2013; Welker et al 2020

GALAXY ALIGNMENTS IN OBSERVATIONS

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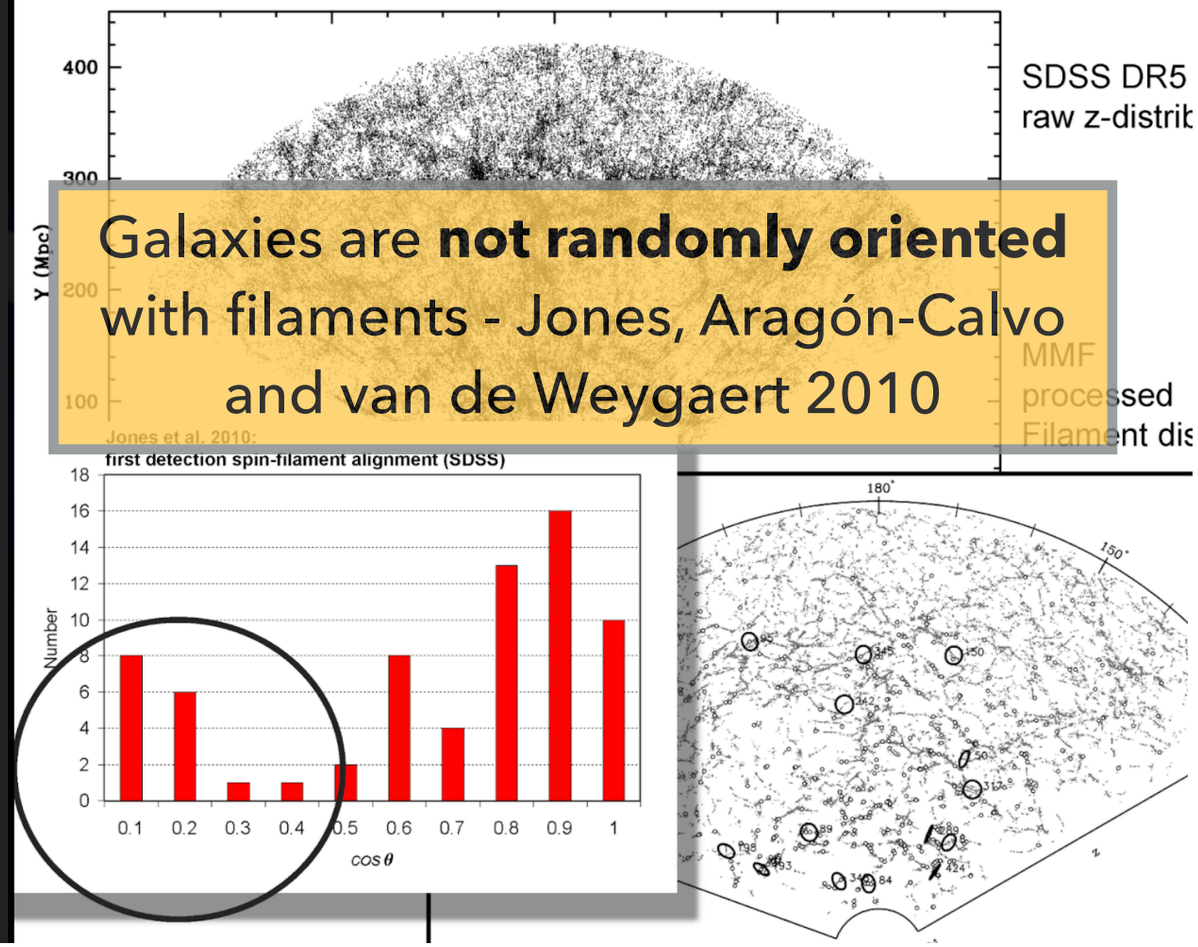

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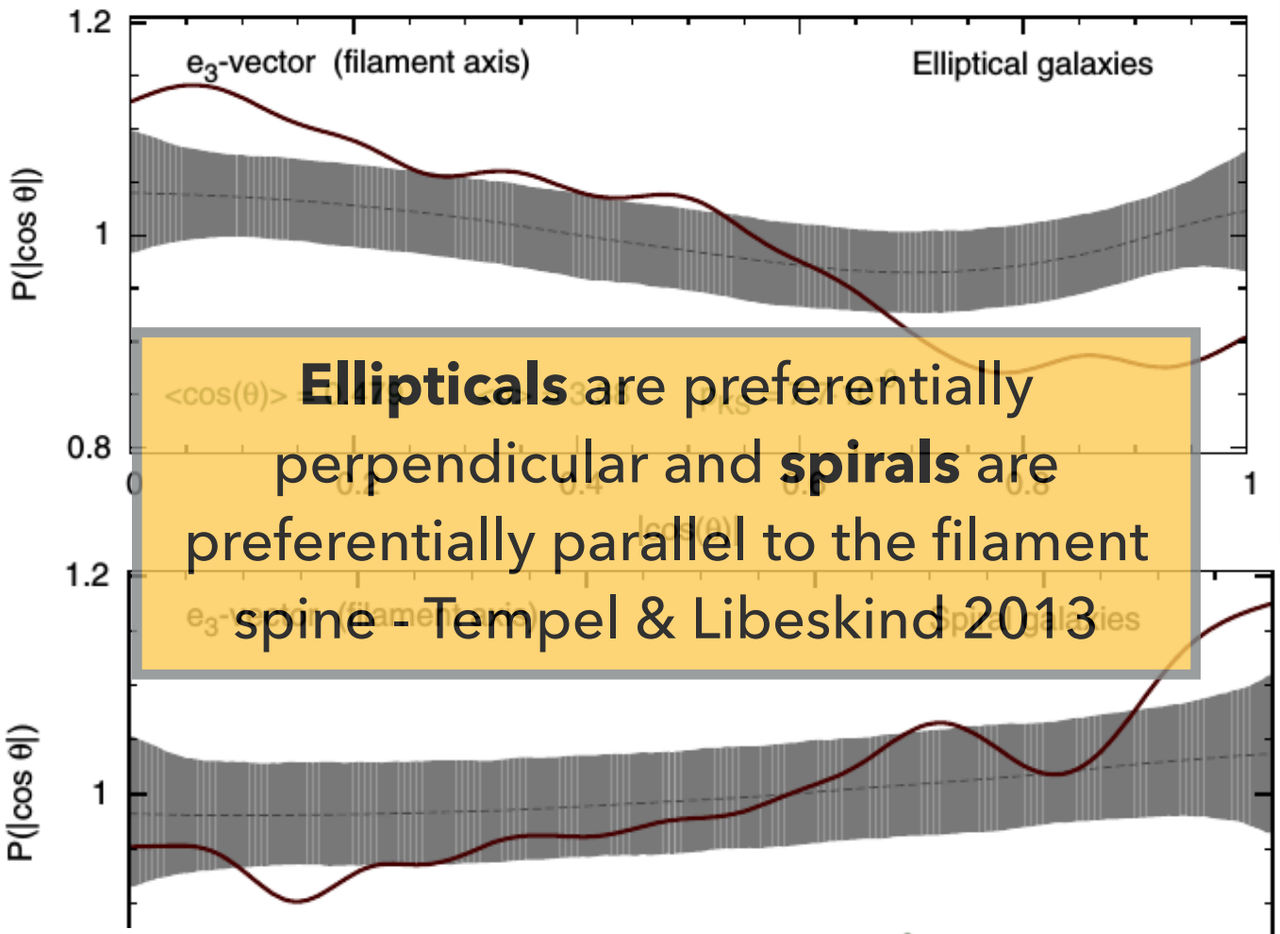

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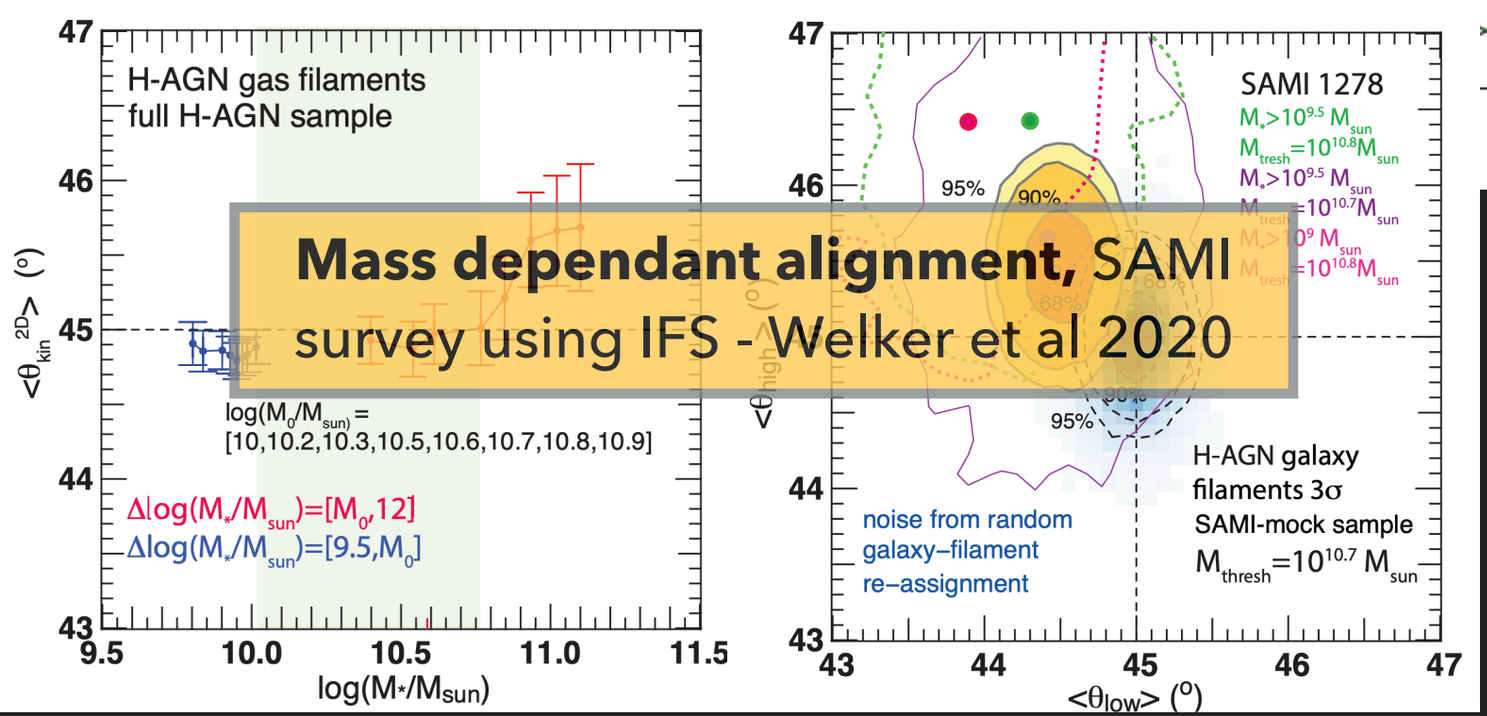
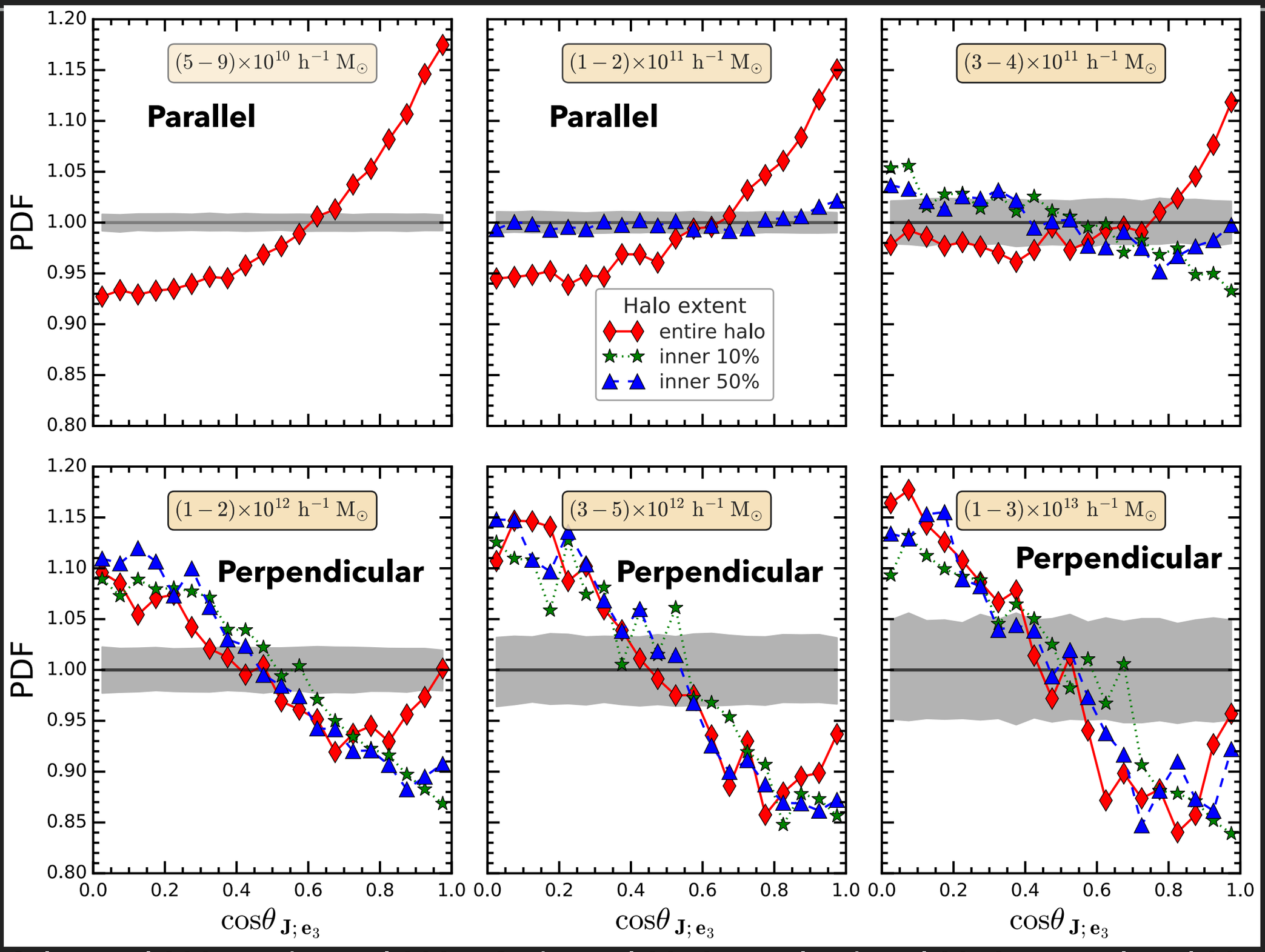


Mass dependant alignment, SAMI survey using IFS - Welker et al 2020

Jones et al 2010; Tempel et al 2013; Welker et al 2020

HALO MASS DEPENDENT ALIGNMENT - PLANCK MILLENNIUM SIMULATION



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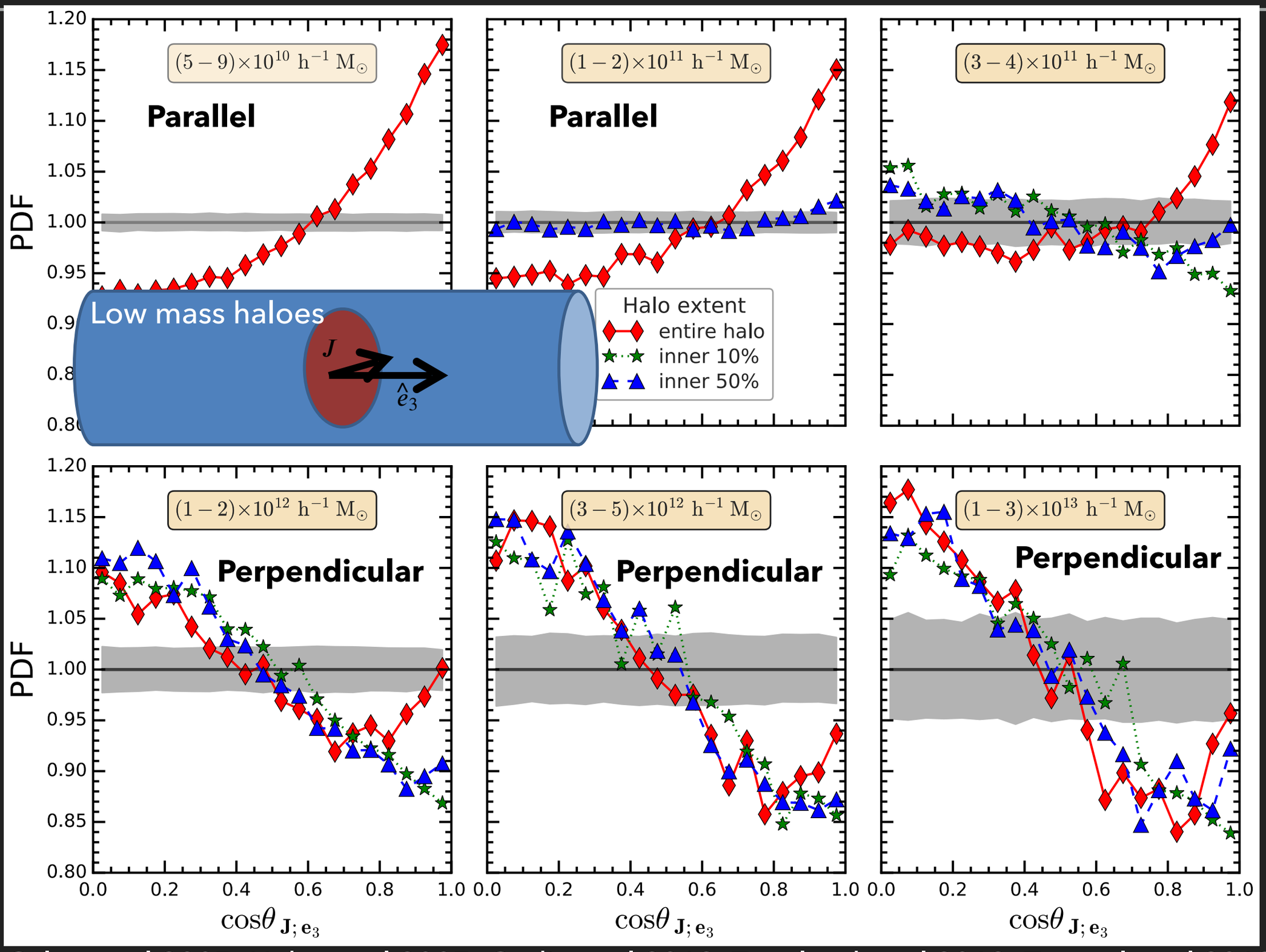

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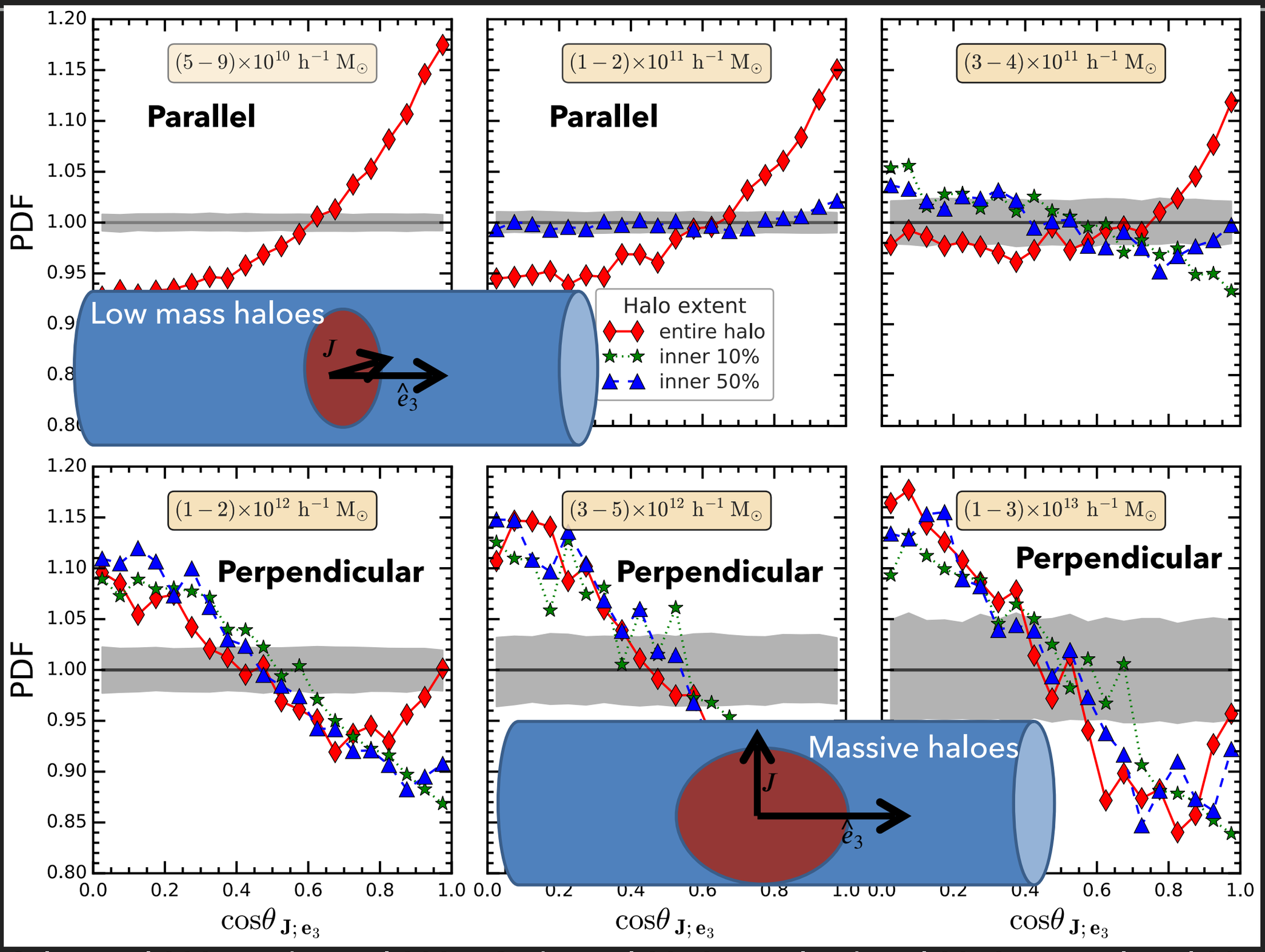

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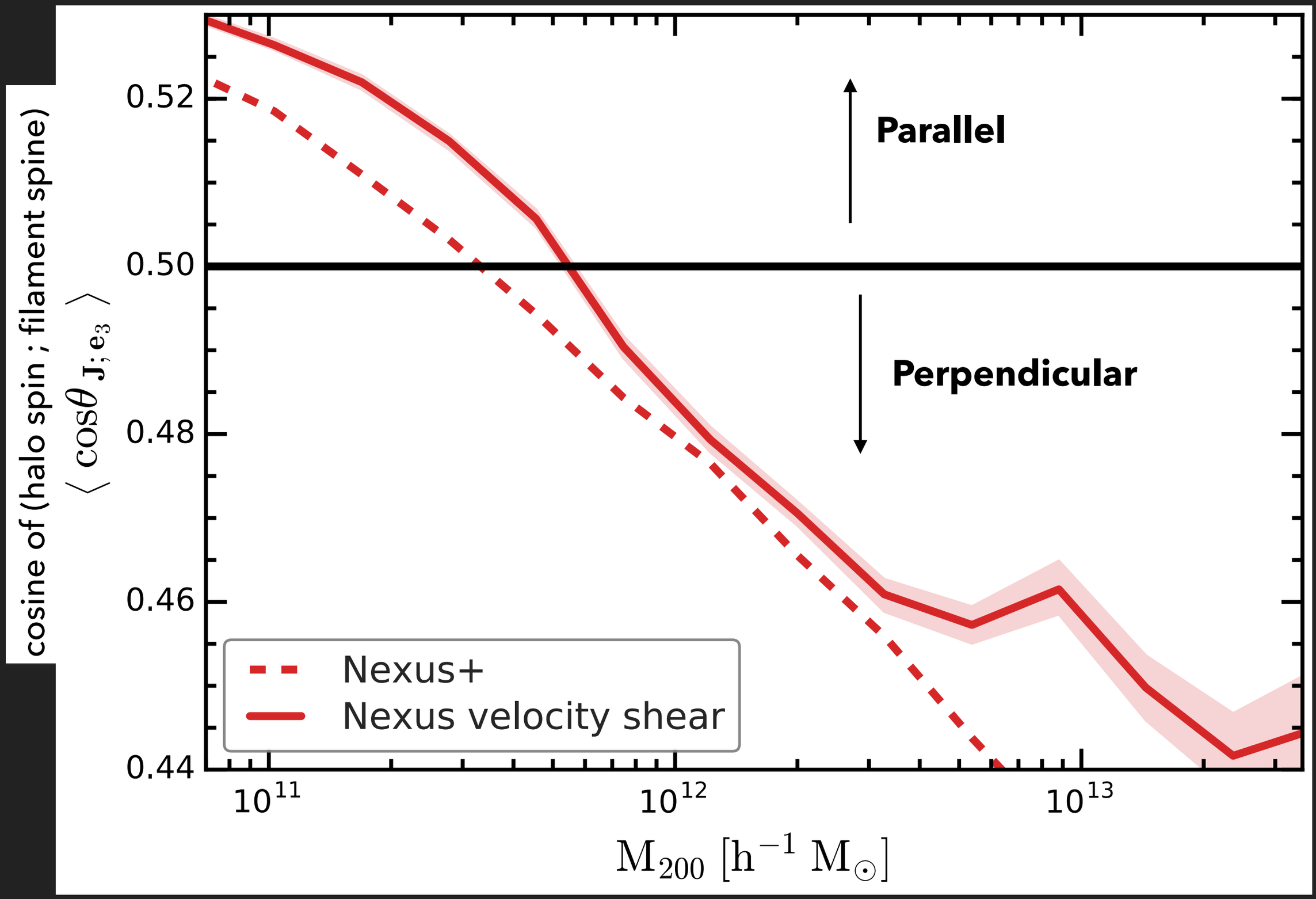
NEXUS + VELOCITY SHEAR



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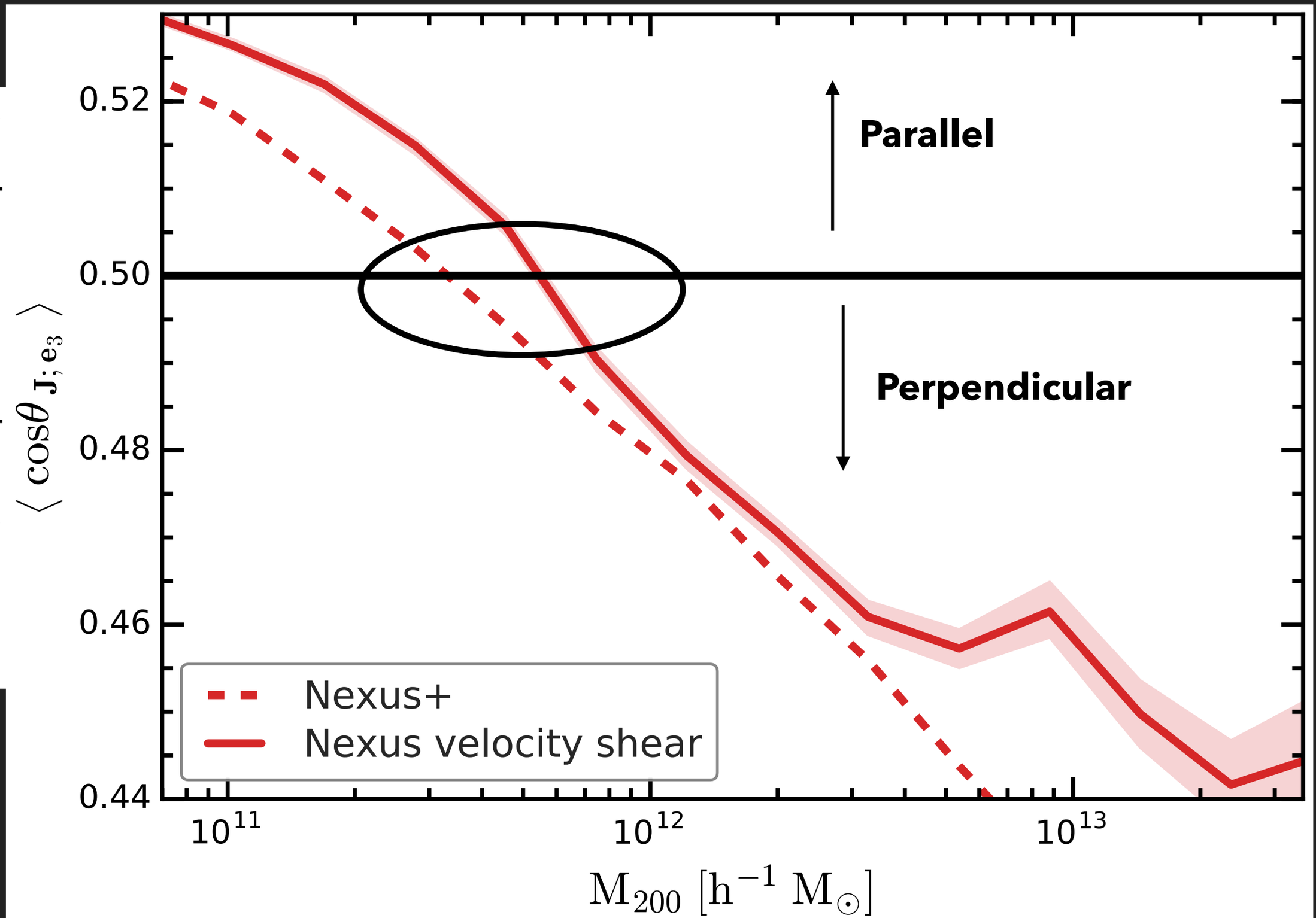

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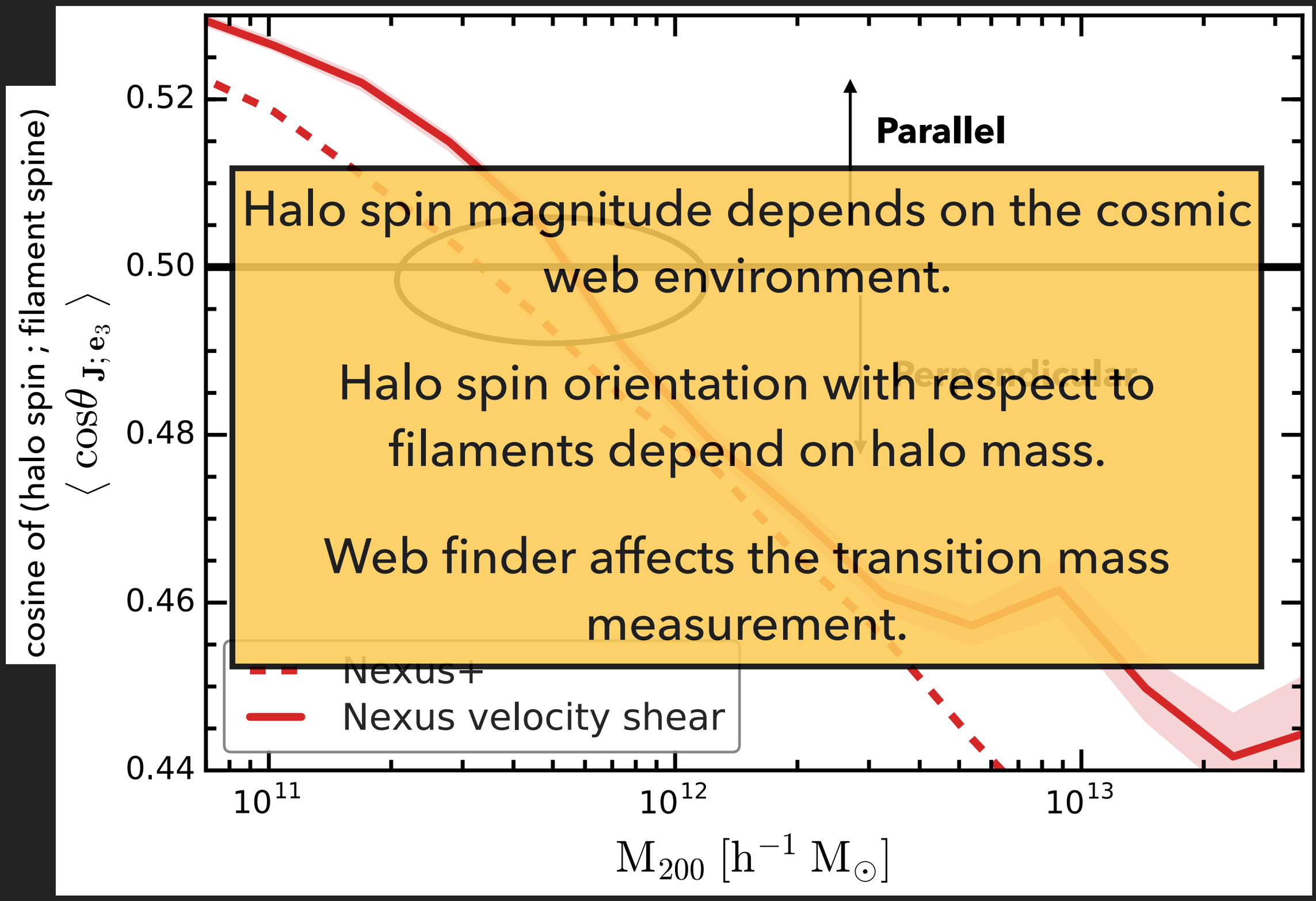

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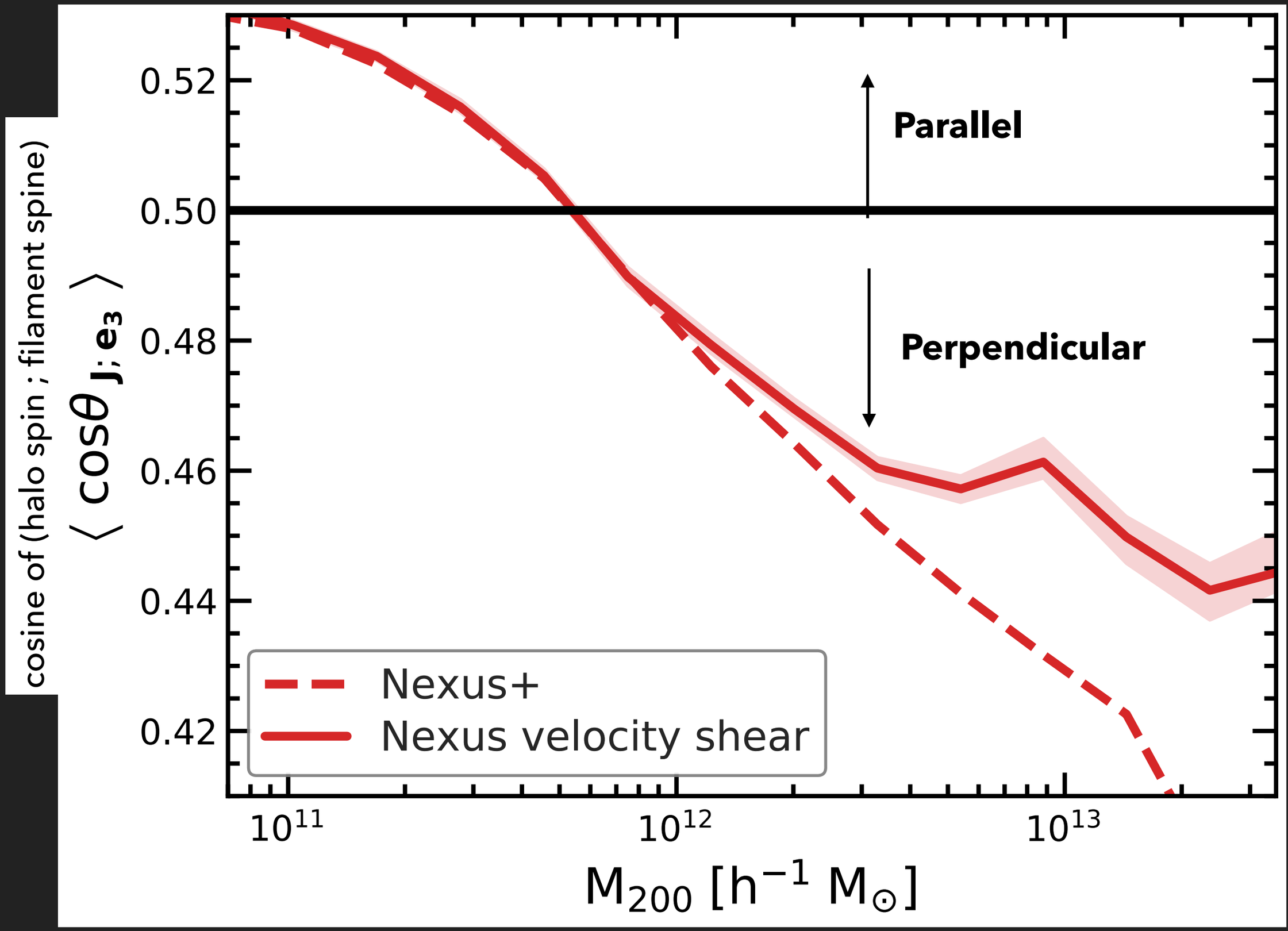
COMMON HALOES



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TRANSITION MASS AND WEB FINDERS

Table 1: Halo spin alignments in simulations

Work by	Simulation box length [h^{-1} Mpc]	Cosmic web detection	Transition mass ($\times 10^{12} h^{-1} M_\odot$)
Aragón-Calvo et al. (2007b)	150	MMF	~ 1
Hahn et al. (2007a)	180	tidal tensor	–
Codis et al. (2012)	2000	DISPERSE	~ 3.5
Libeskind et al. (2012)	64	velocity shear tensor	–
Trowland et al. (2013)	300	density Hessian	~ 1.2
Forero-Romero et al. (2014)	250	T-Web	1
		V-Web	2
Aragon-Calvo & Yang (2014)	32	MMF-2	
Wang & Kang (2018b)	200	tidal tensor	0.5 - 1.4
Ganeshaiah Veena et al. (2018)	542	NEXUS+	0.3
		NEXUS_VEL_SHEAR	0.5
Lee (2019)	400	tidal tensor	–

Table from: P. Ganeshaiah Veena thesis, table 1, page number 34

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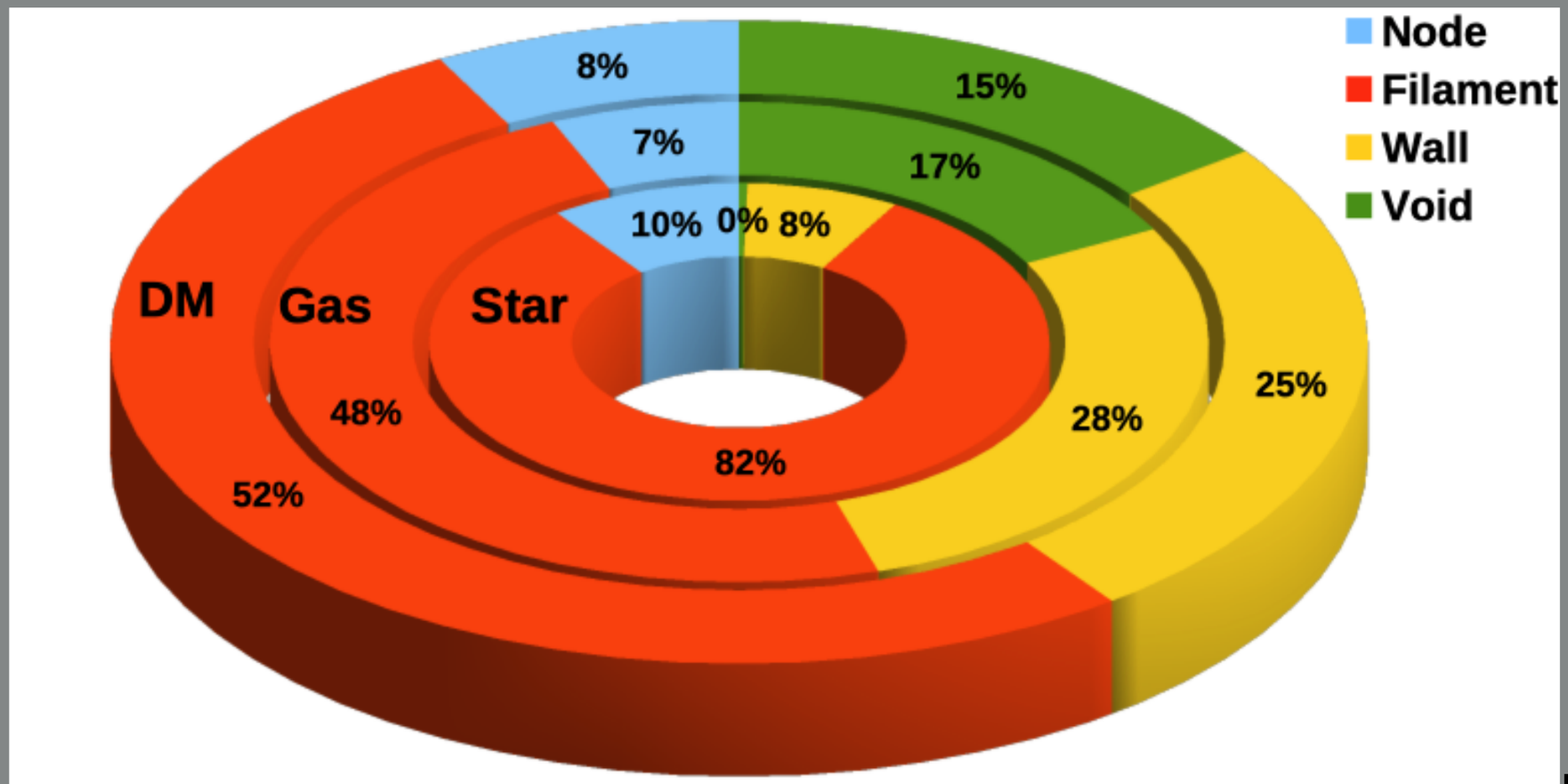
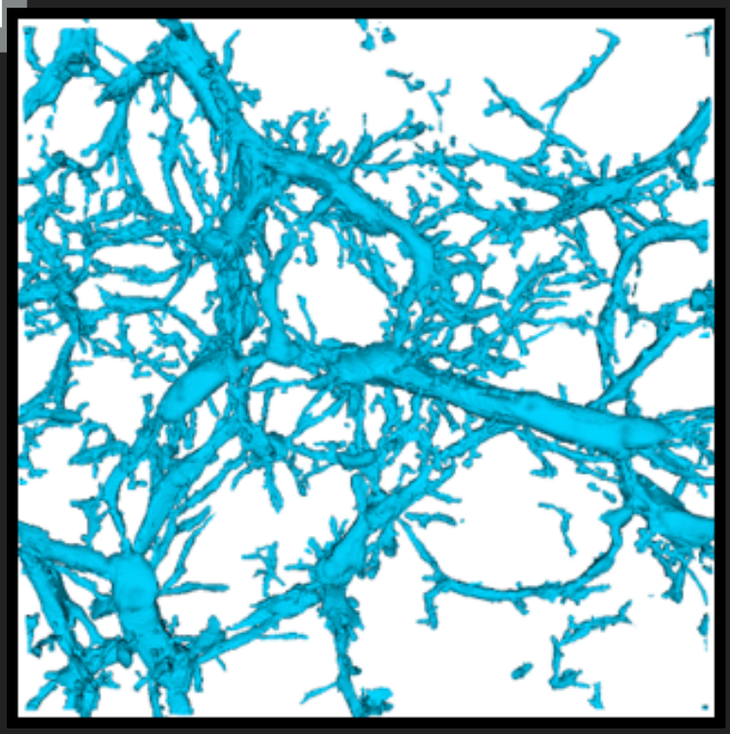
MASS FRACTION IN THE UNIVERSE – EAGLE SIMULATION

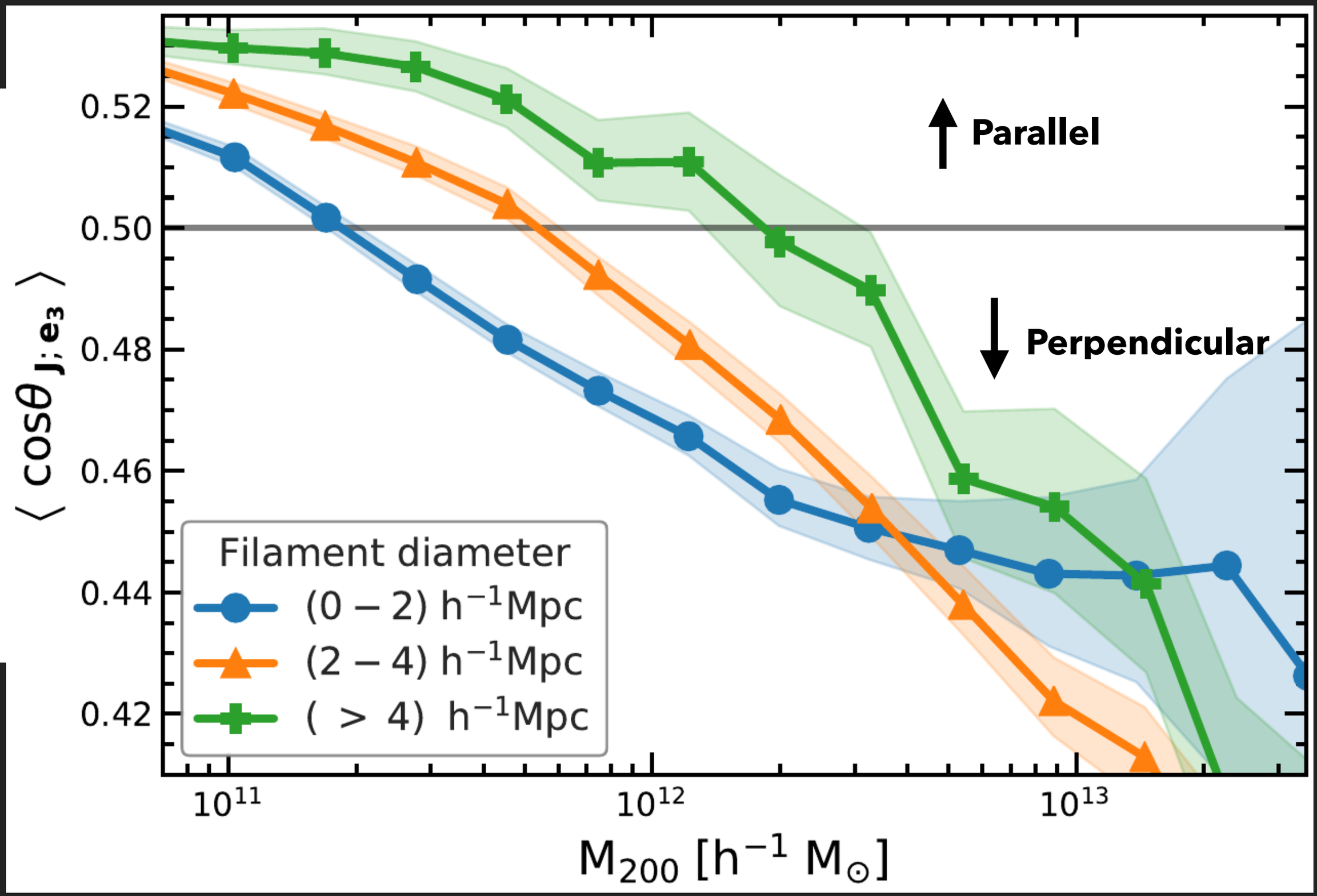


P. **Ganeshaiah Veena,** M. Cautun, E. Tempel, R. van de Weijgaert and C. Frenk, 2019.



Nexus+ filaments, from Cautun et al 2014.

FILAMENT THICKNESS



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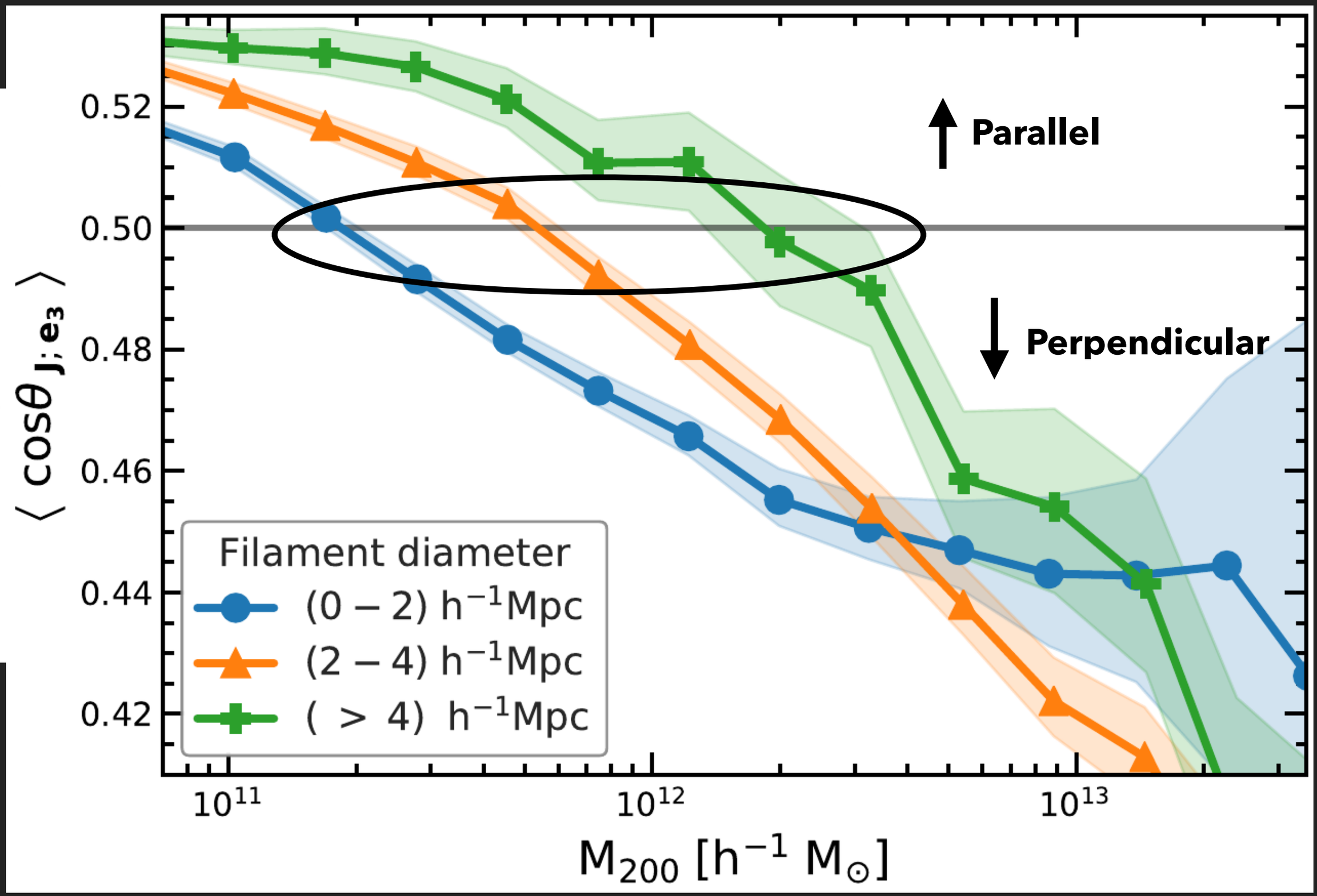
FILAMENT THICKNESS



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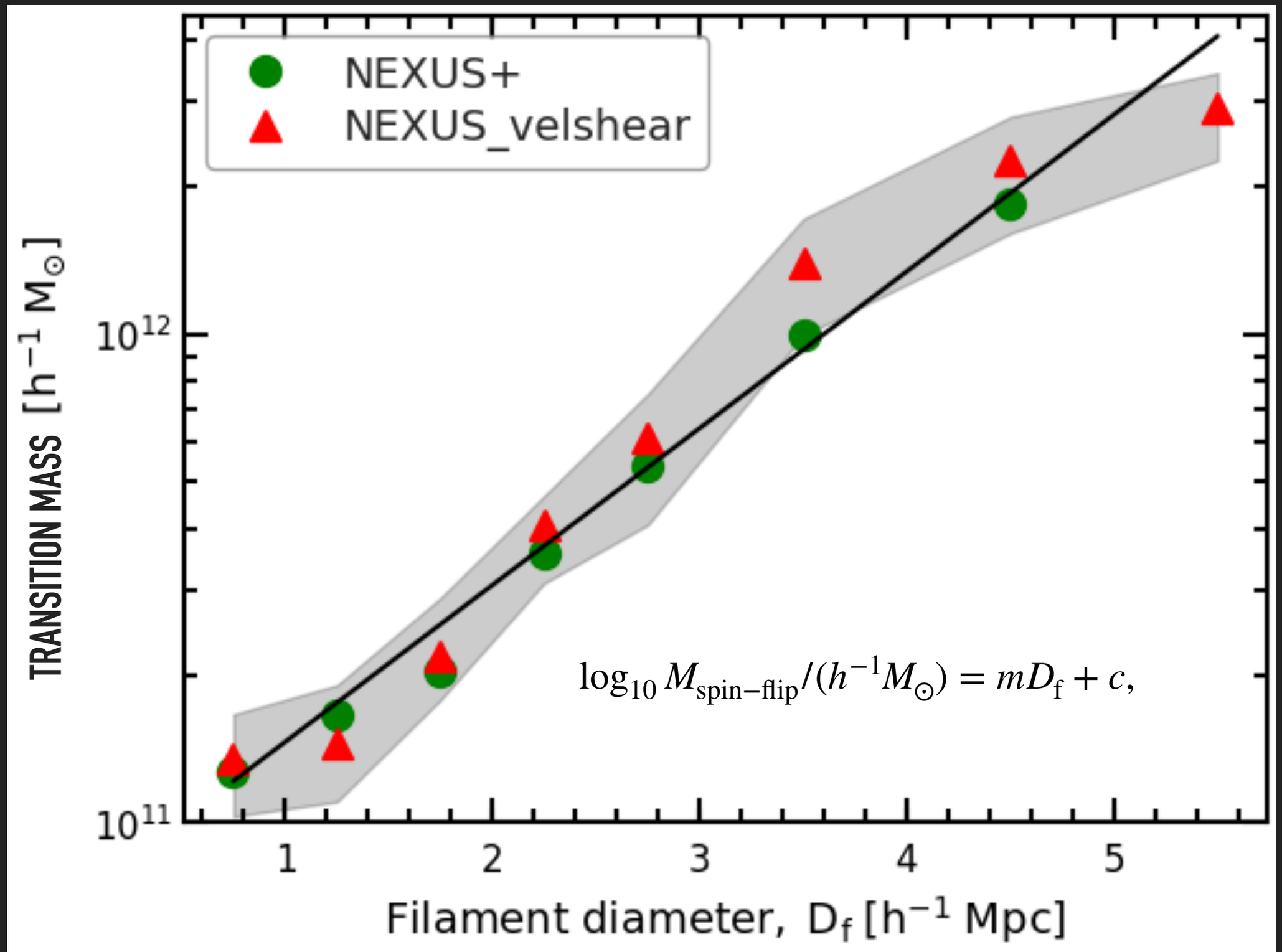
FILAMENT THICKNESS



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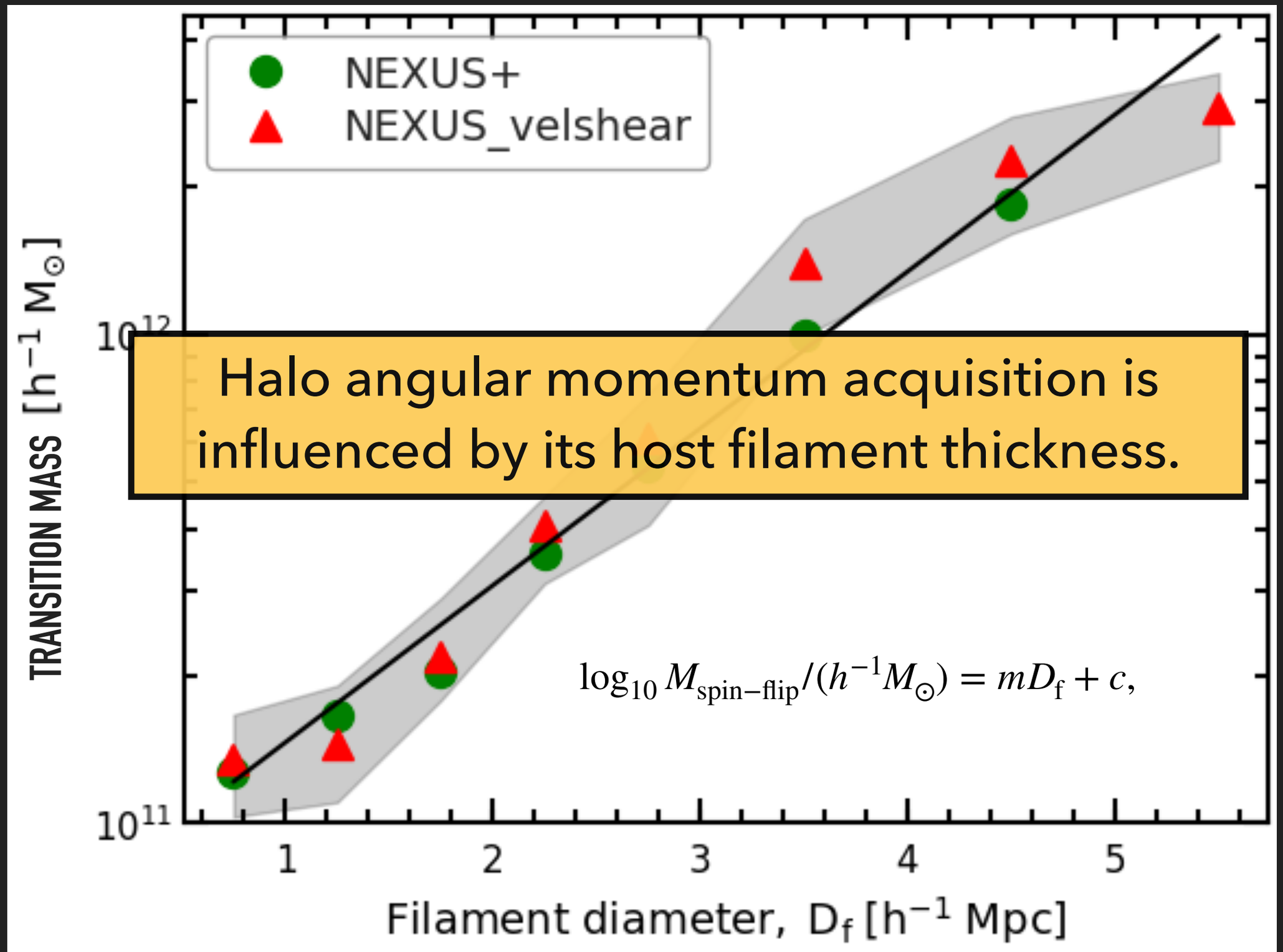
FILAMENT THICKNESS



Halo angular momentum acquisition is influenced by its host filament thickness.

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IN THIS TALK – COSMIC WEB AND HALO/GALAXY SPIN

1. Does the cosmic web environment influence **halo spin magnitude and orientation?** How are spins aligned with the underlying geometry of the cosmic web**?**
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WEB FINDER

TRANSITION MASS

FILAMENT PROPERTIES - THICKNESS

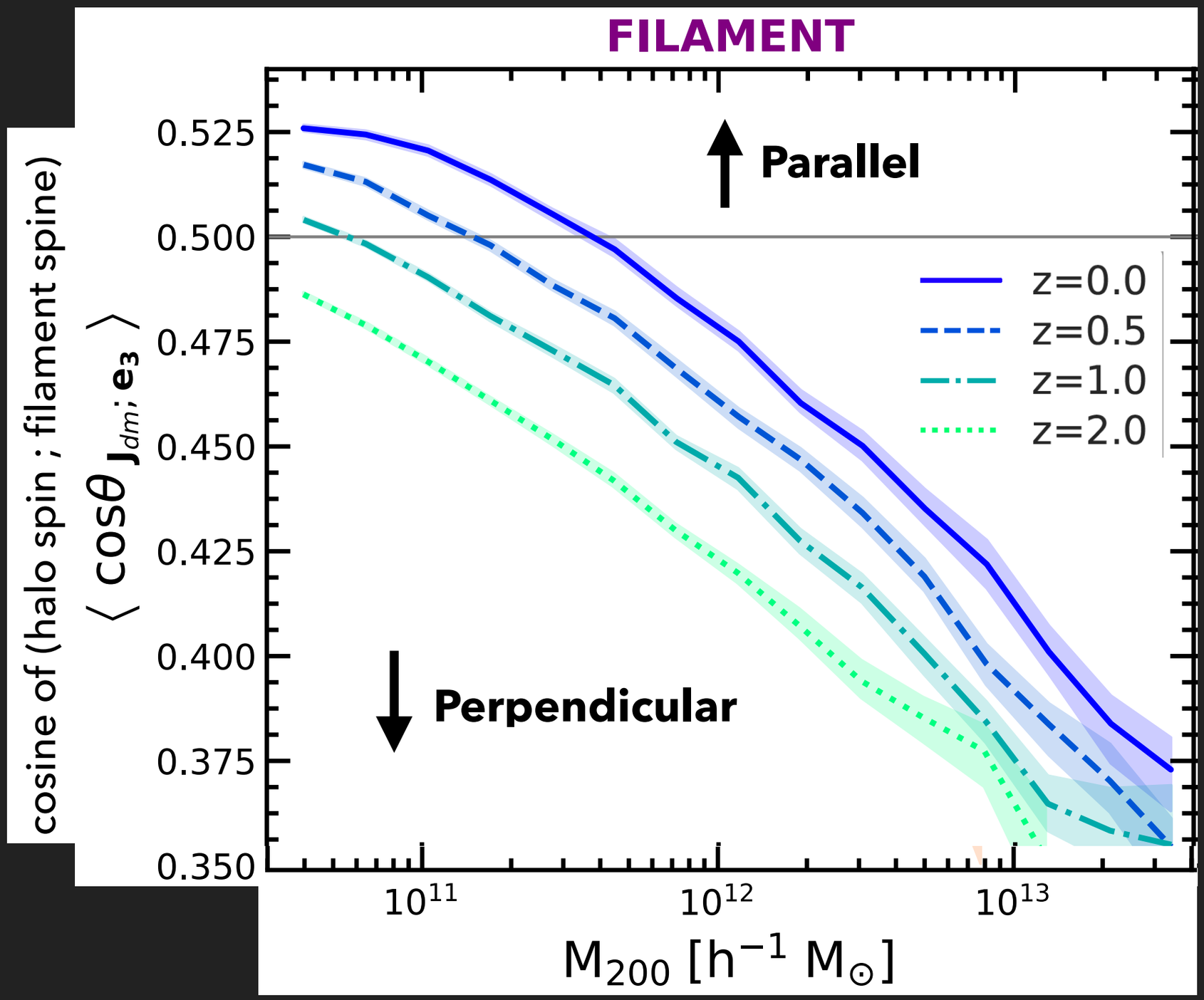
EVOLUTION WITH TIME

WEB FINDER

TRANSITION MASS

FILAMENT PROPERTIES – THICKNESS

SPIN ALIGNMENT EVOLUTION



EVOLUTION WITH TIME

TRANSITION MASS

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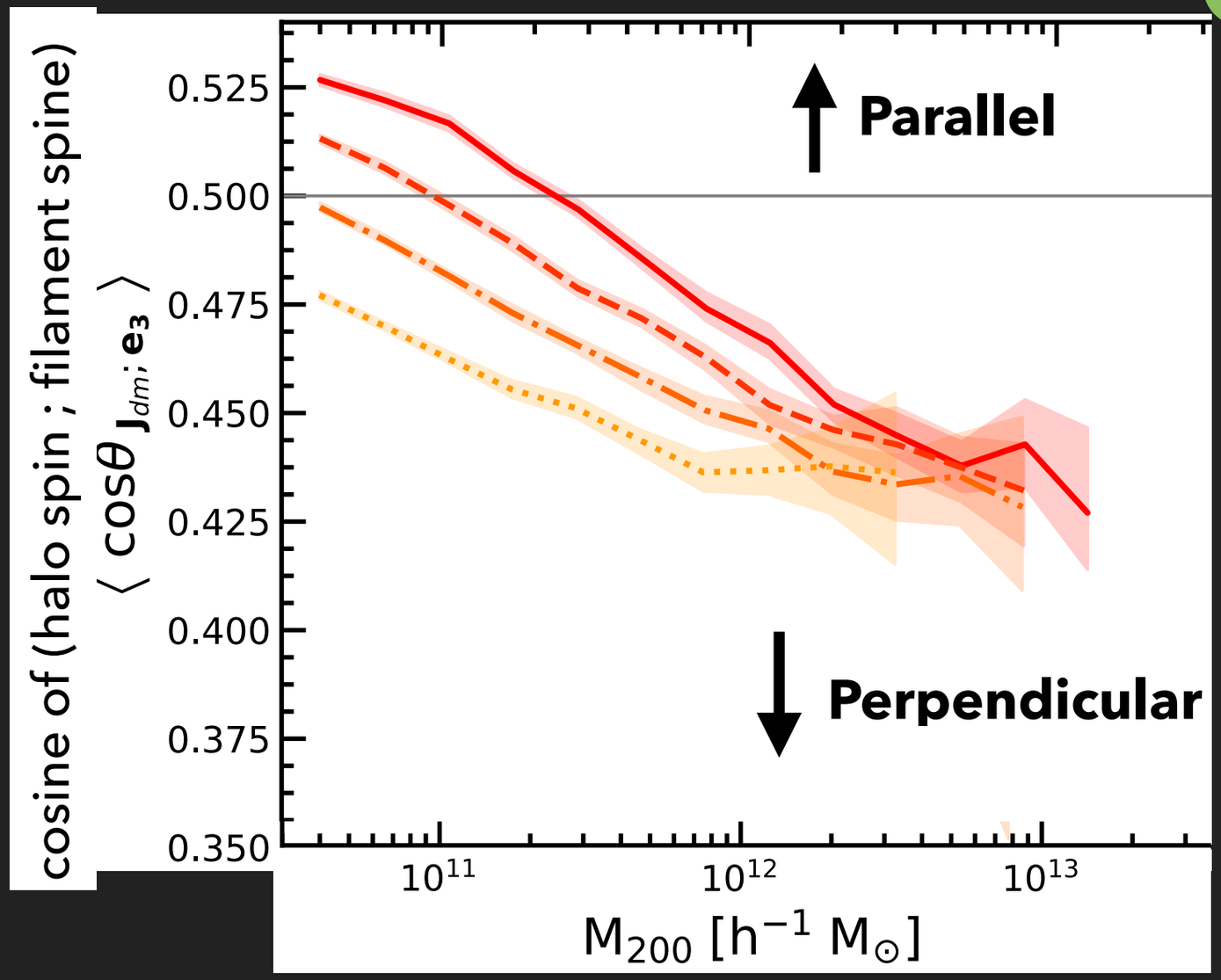
THIN FILAMENTS



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EVOLUTION WITH TIME

TRANSITION MASS

FILAMENT PROPERTIES - THICKNESS

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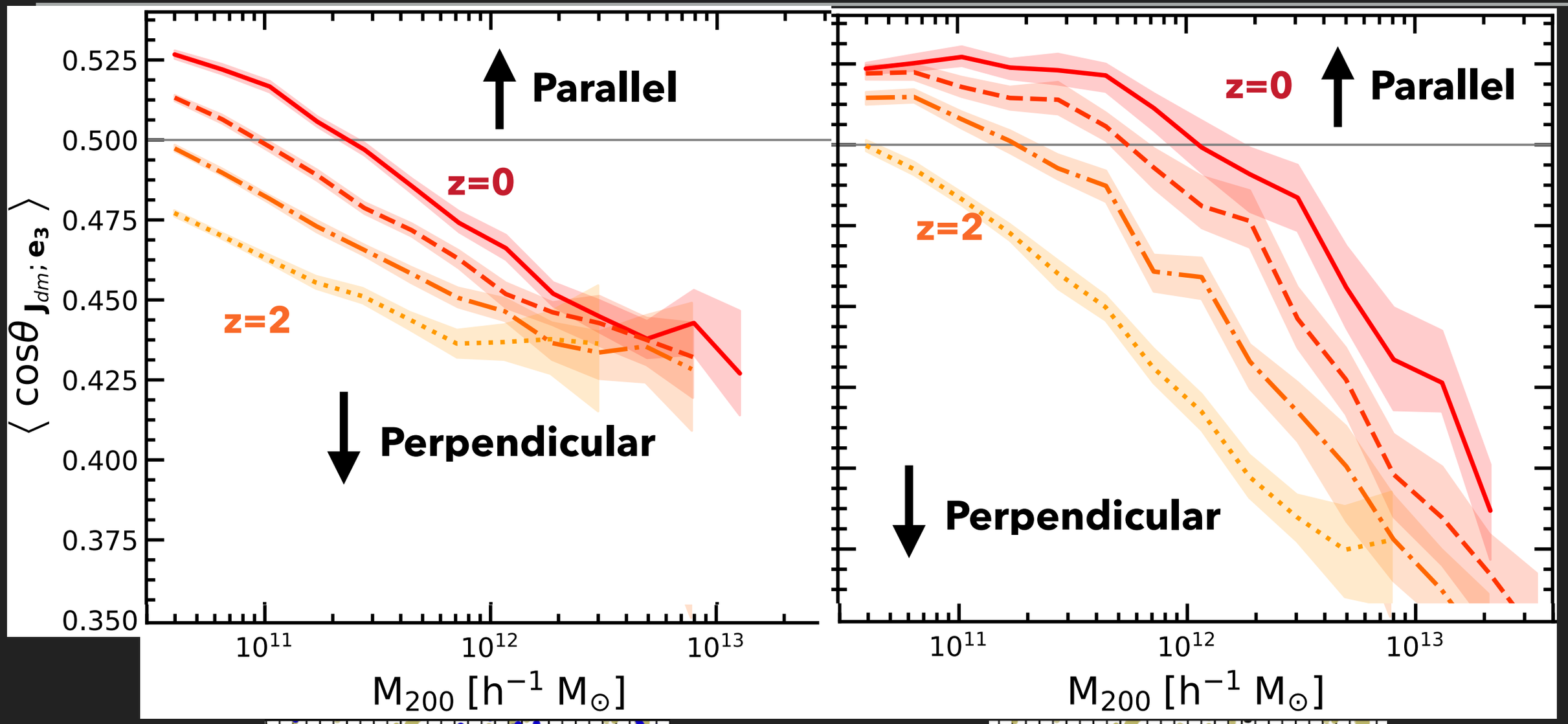
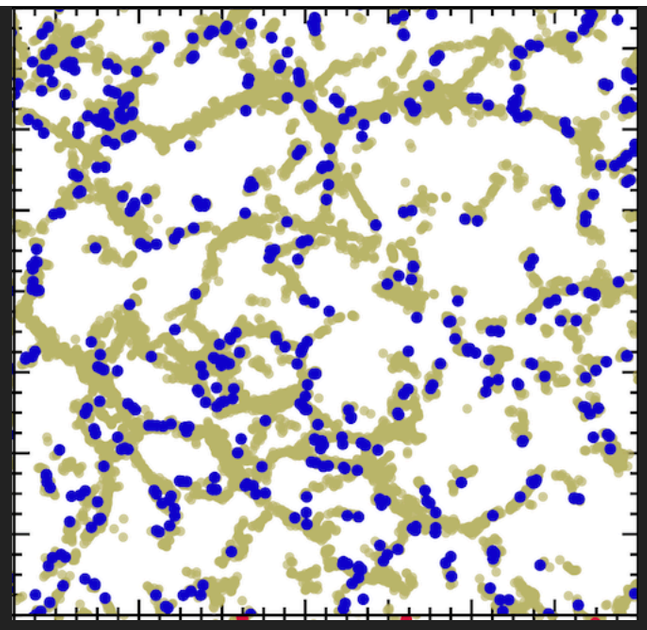
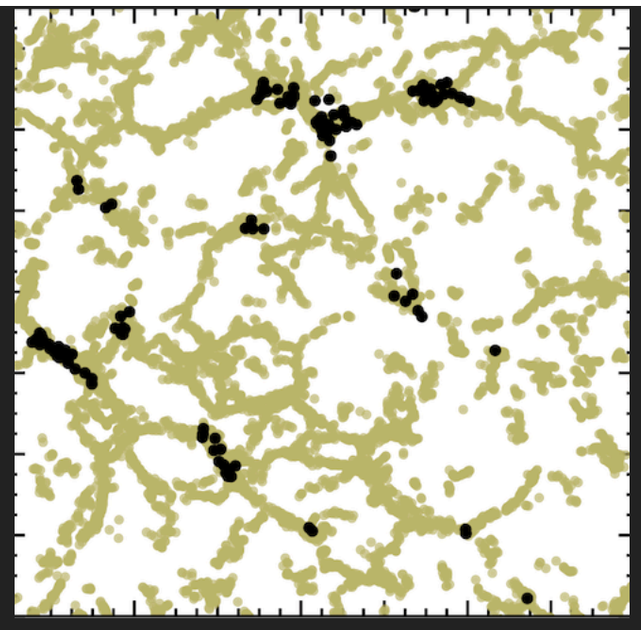
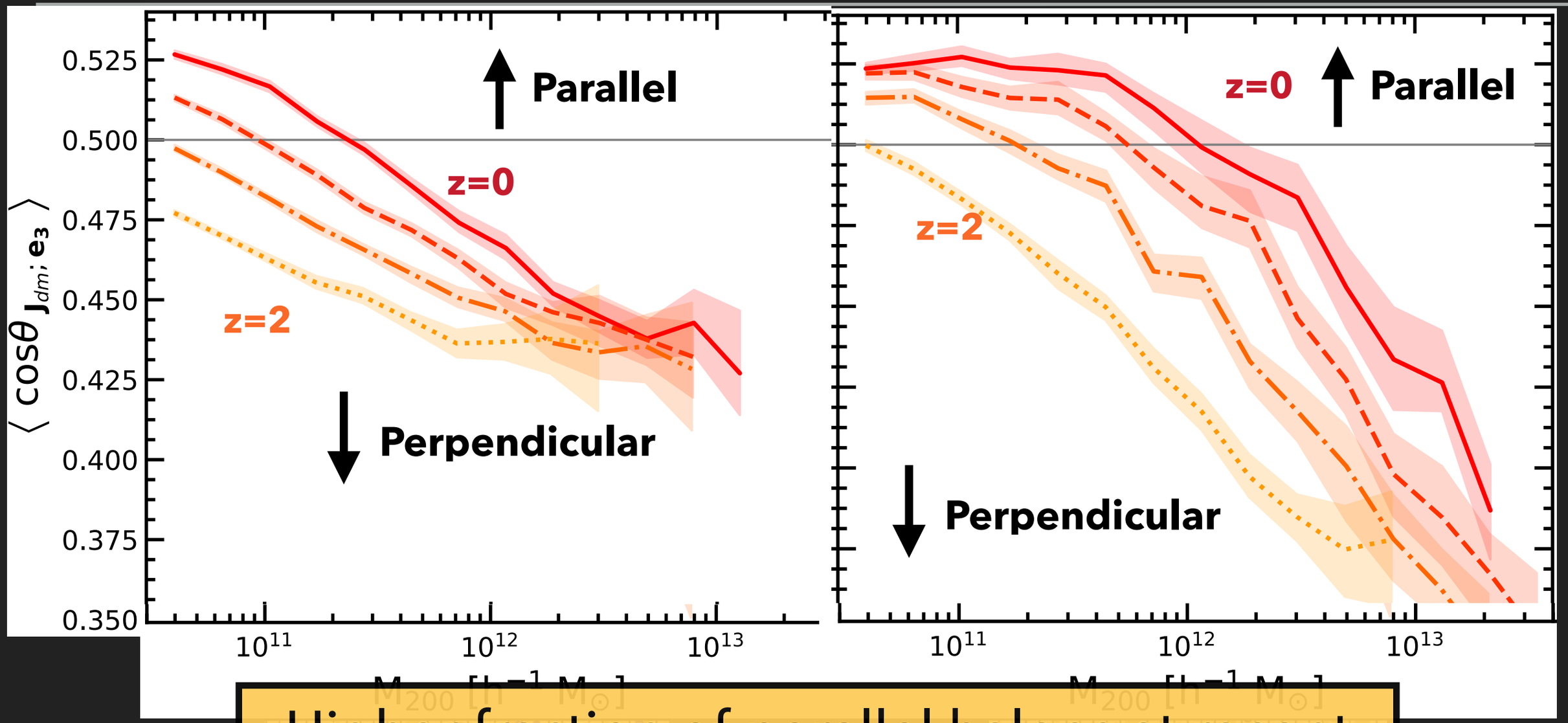






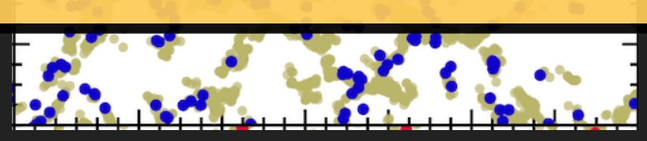
THIN FILAMENTS

THICK FILAMENTS



Higher fraction of parallel haloes at recent times.

Transition mass increases with filament thickness and also time.



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EVOLUTION WITH TIME

INCREASES WITH TIME

WEB FINDER

TRANSITION MASS

FILAMENT PROPERTIES – THICKNESS

INCREASES WITH FILAMENT THICKNESS

EVOLUTION WITH TIME

INCREASES WITH TIME

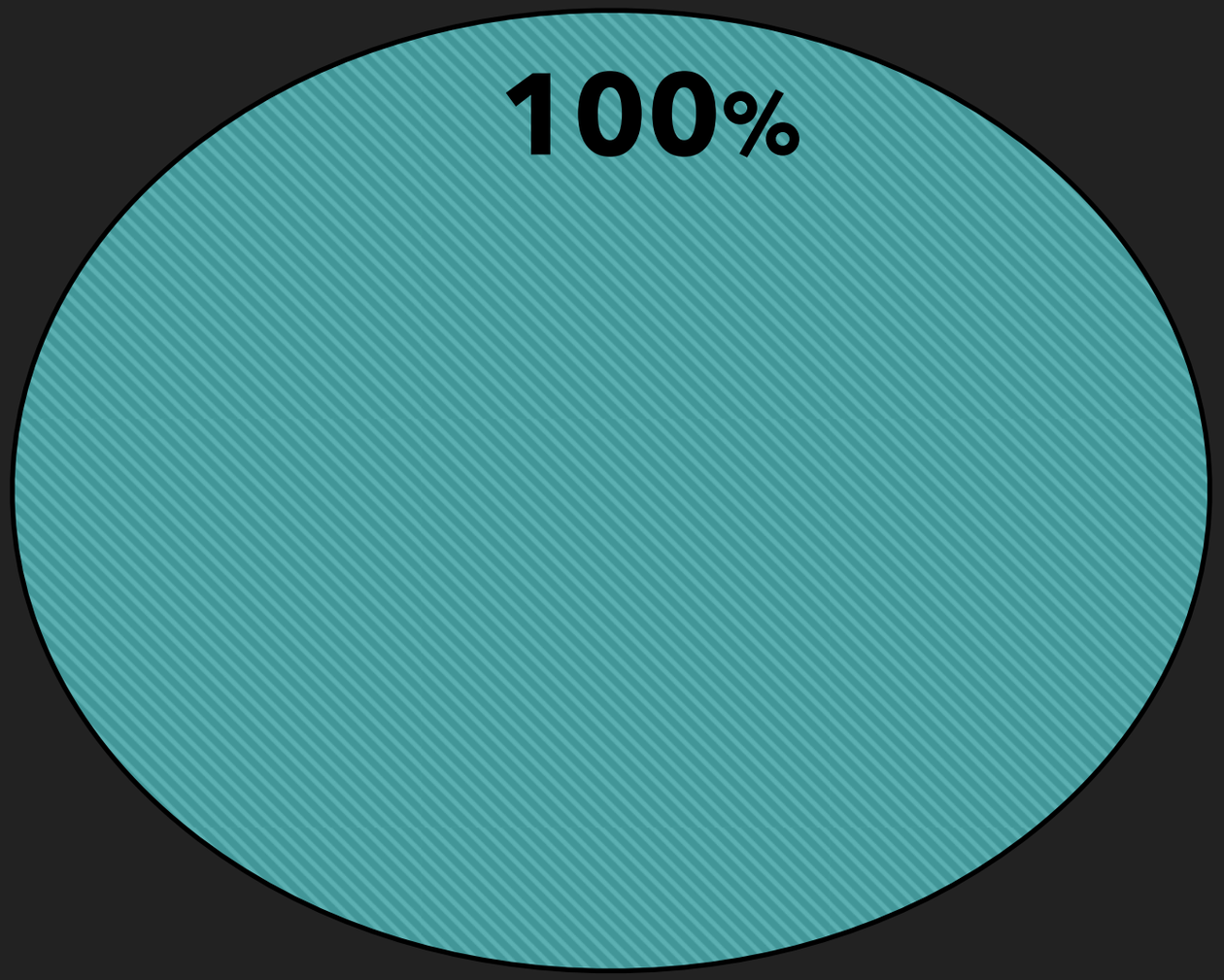
WEB FINDER

TRANSITION MASS

What could be the physical mechanism?

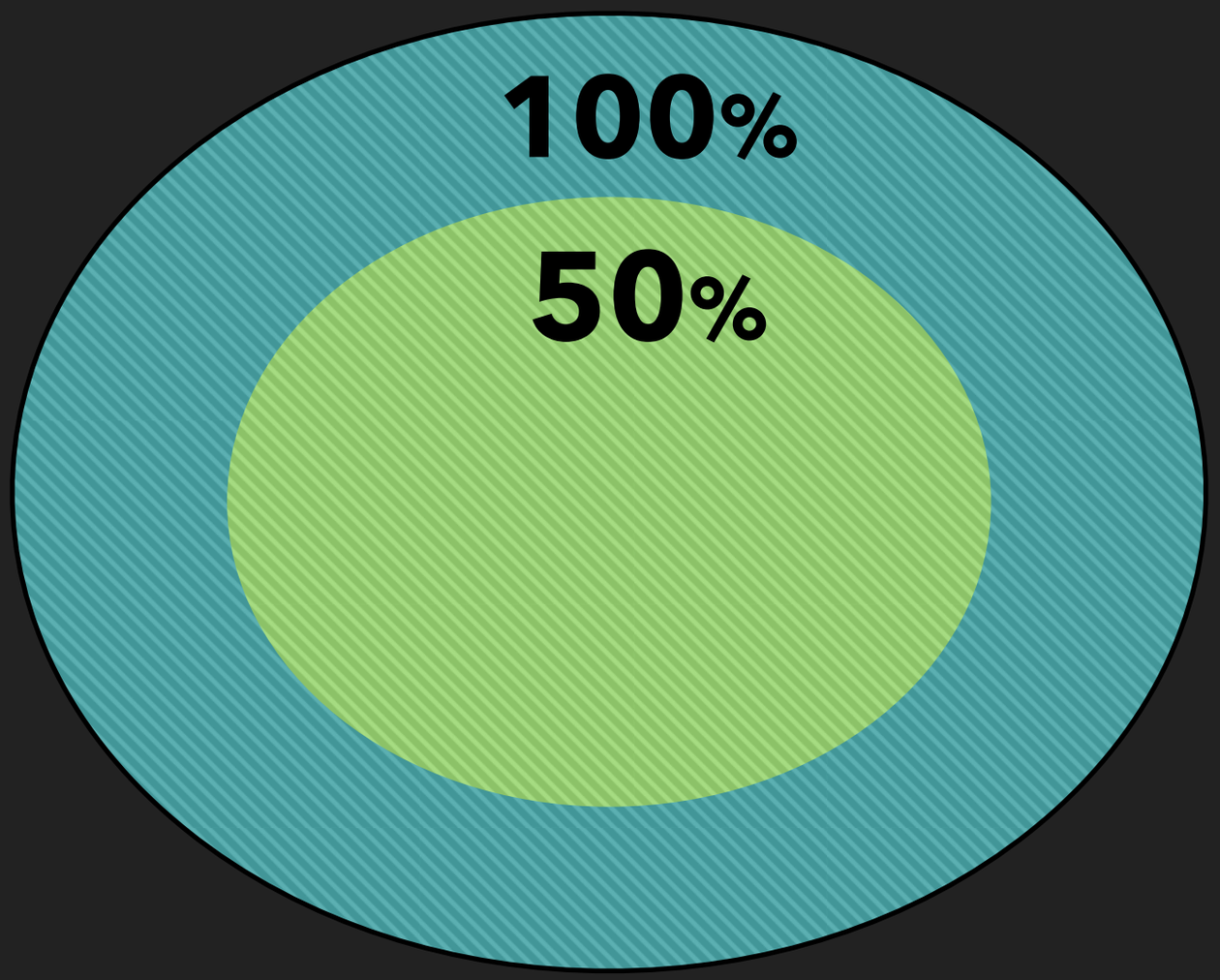
FILAMENT PROPERTIES - THICKNESS

INCREASES WITH FILAMENT THICKNESS



$$\mathbf{J} = \sum_{k=1}^{N} m_k \left(\mathbf{r}_k \times \mathbf{v_k} \right)$$

$$\cos \theta_{\mathbf{J},\mathbf{e}_3} = \left| \frac{\mathbf{J} \cdot \mathbf{e}_3}{|\mathbf{J}||\mathbf{e}_3|} \right|$$



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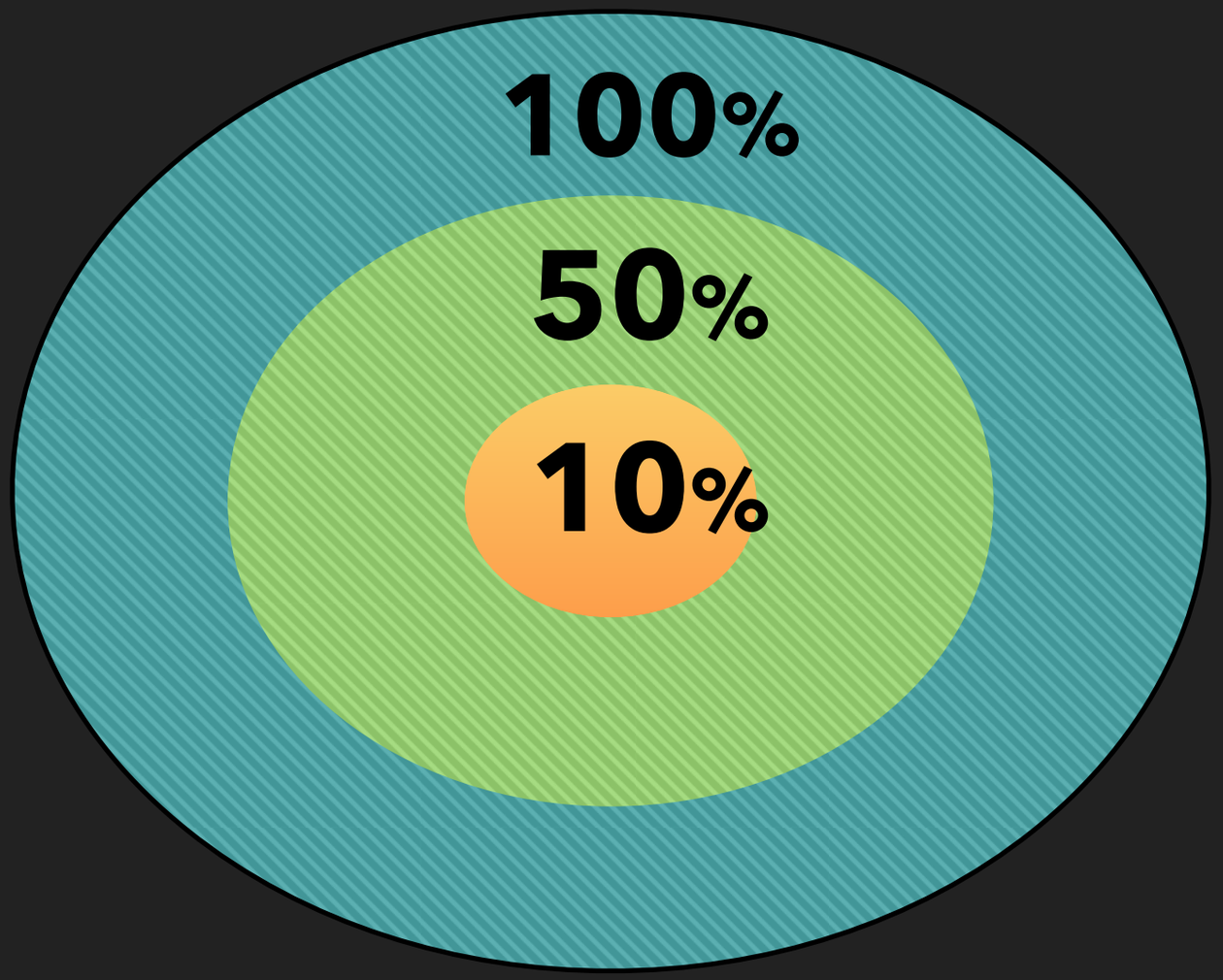

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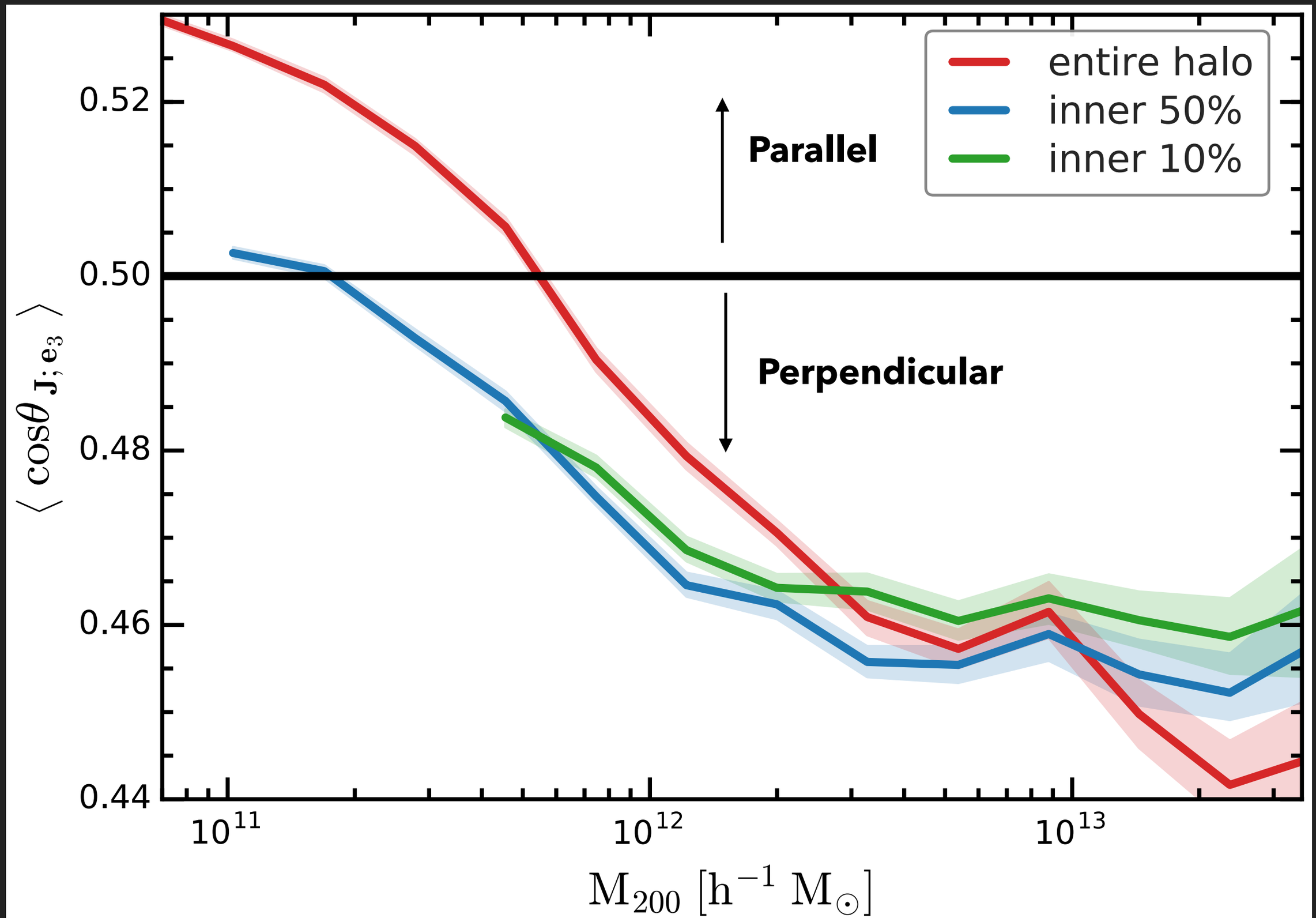
INNER HALO FRACTIONS



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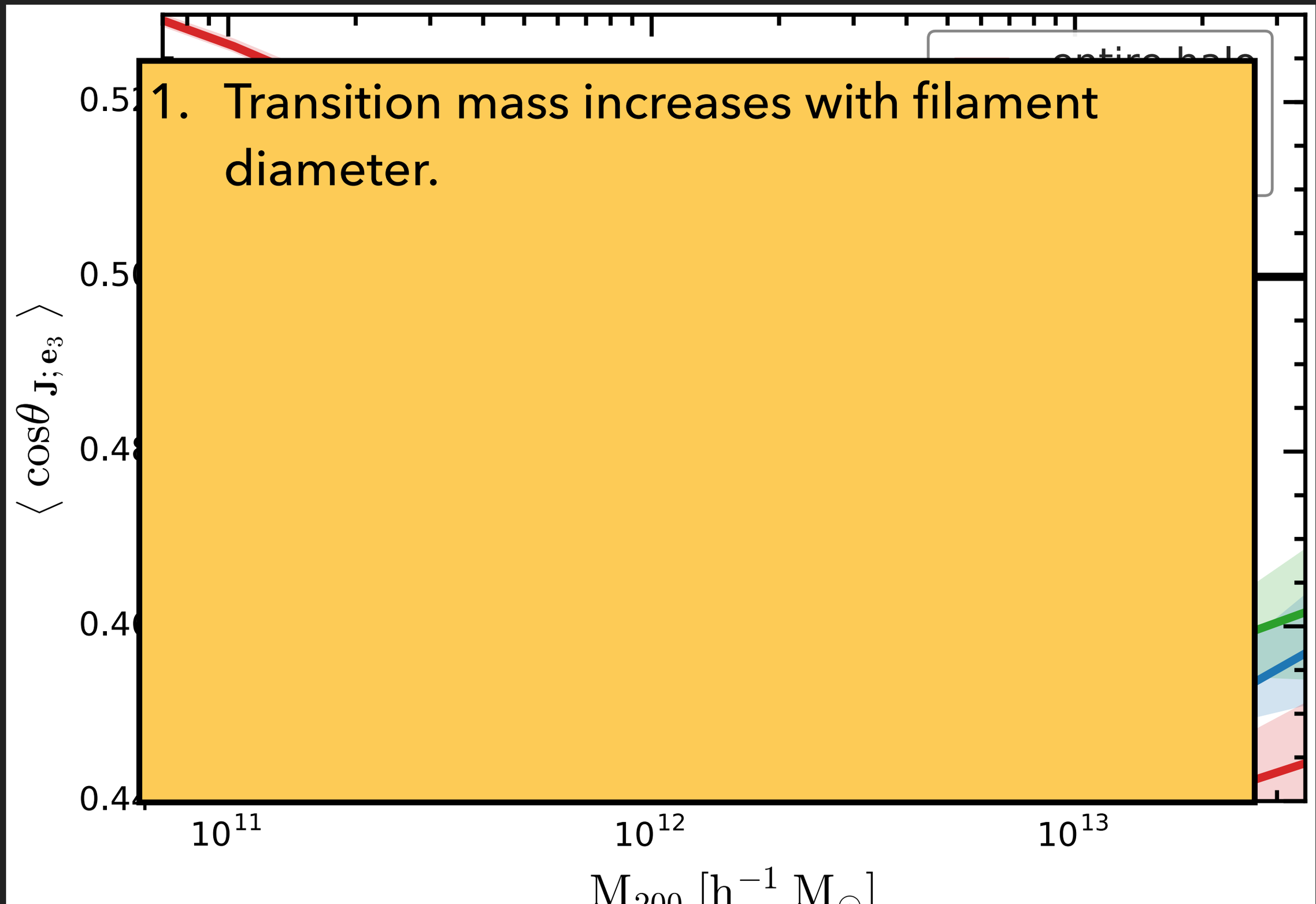
INNER HALO FRACTIONS

1. Transition mass increases with filament diameter.



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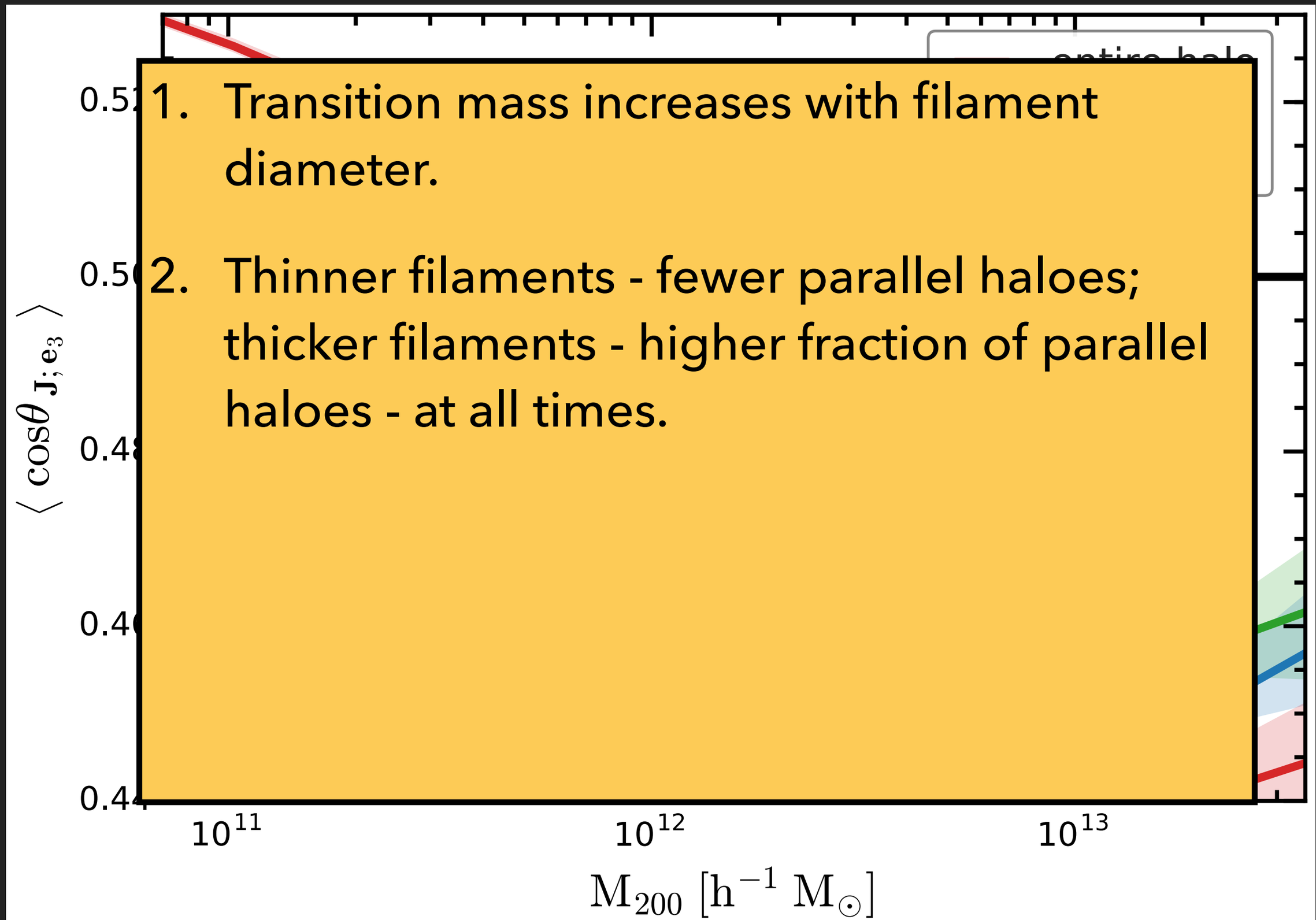
INNER HALO FRACTIONS

1. Transition mass increases with filament diameter.
2. Thinner filaments - fewer parallel haloes; thicker filaments - higher fraction of parallel haloes - at all times.



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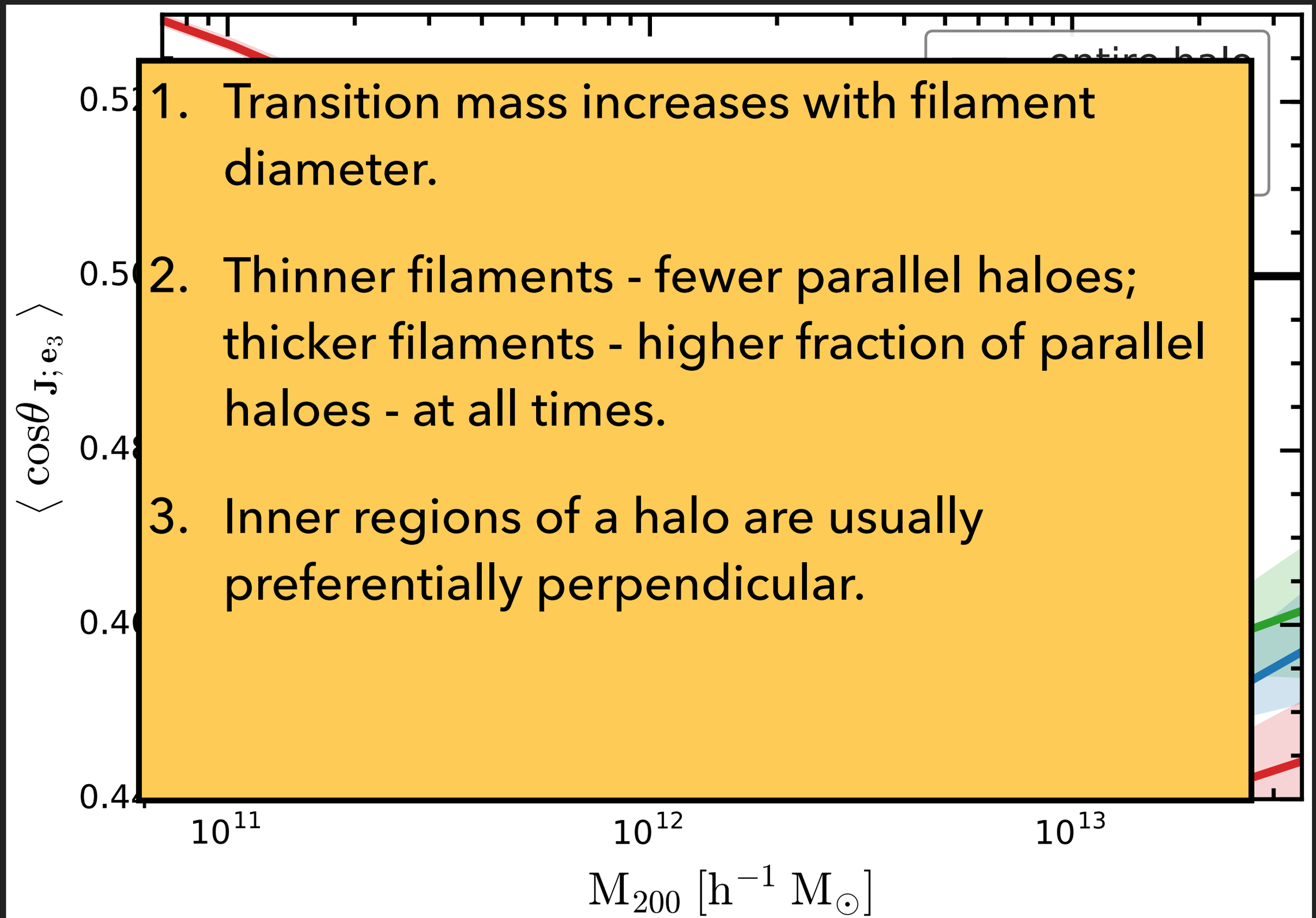

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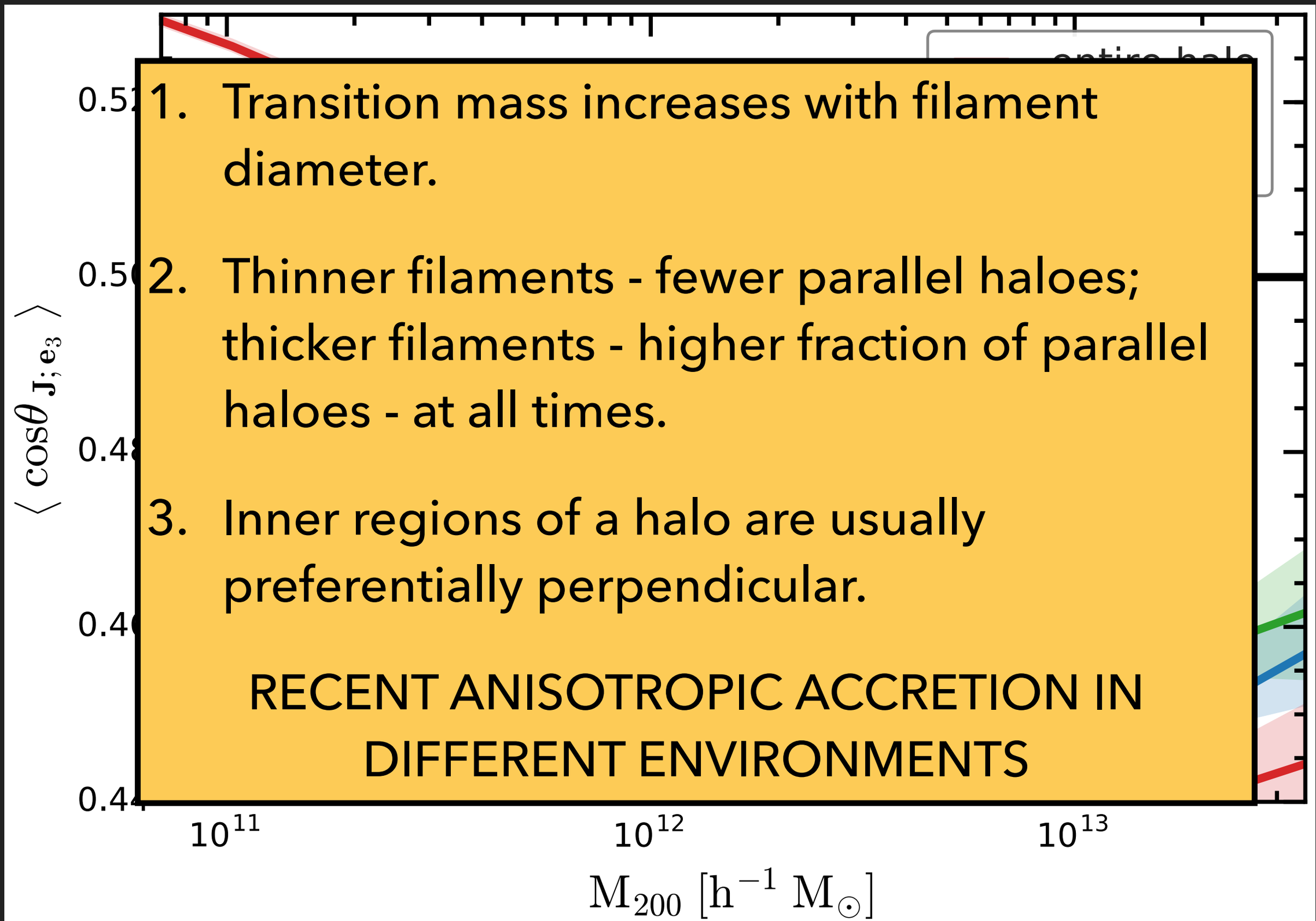
RECENT ANISOTROPIC ACCRETION IN DIFFERENT ENVIRONMENTS



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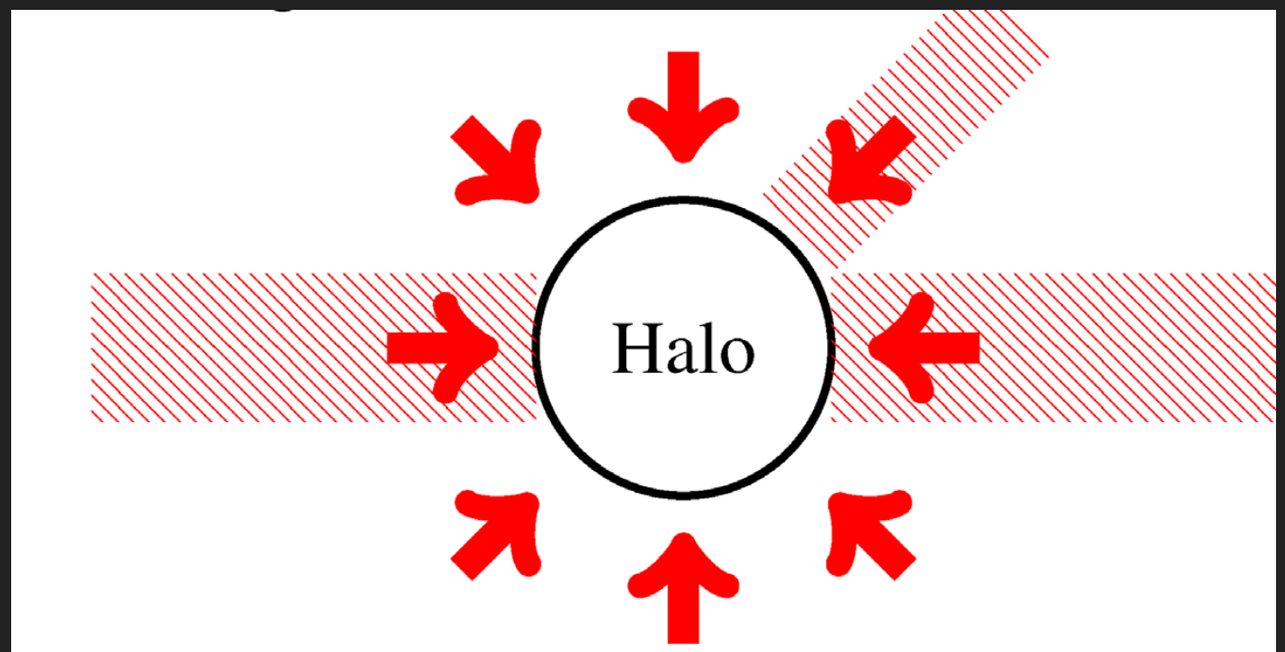
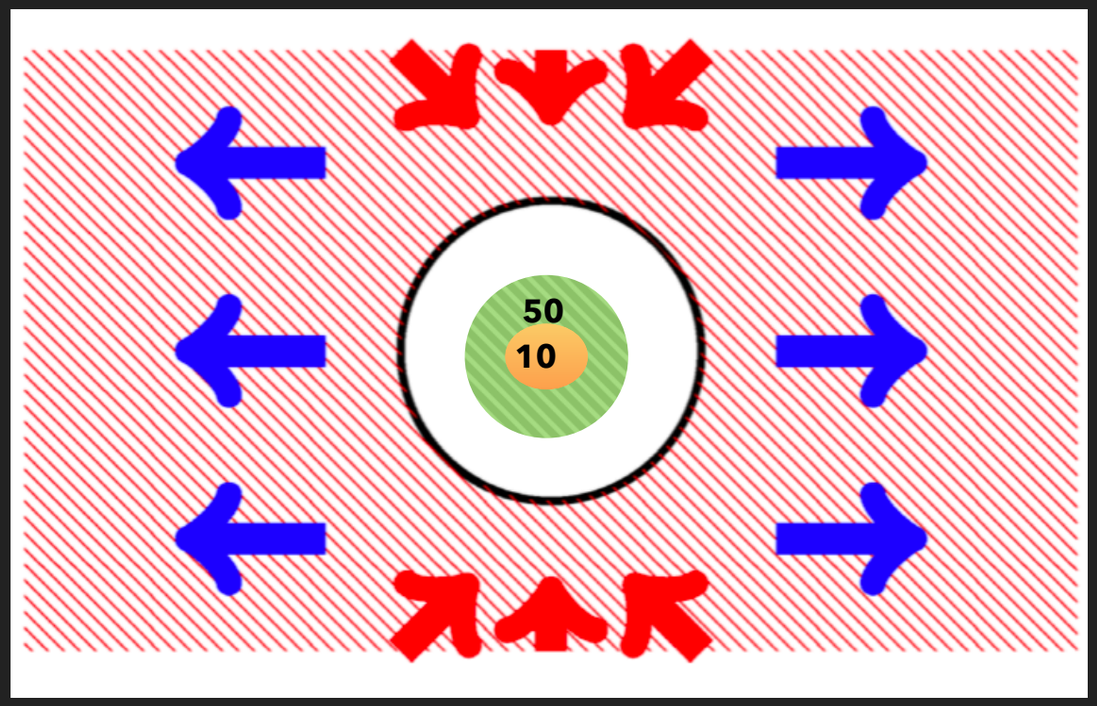
THE CAUTUN HYPOTHESIS

ACCRETING HALO



- Thin filaments
- Accretion - perpendicular spin
- Isotropic

STALLED HALO



- Thick filament
- Accretion - parallel spin
- Anisotropic

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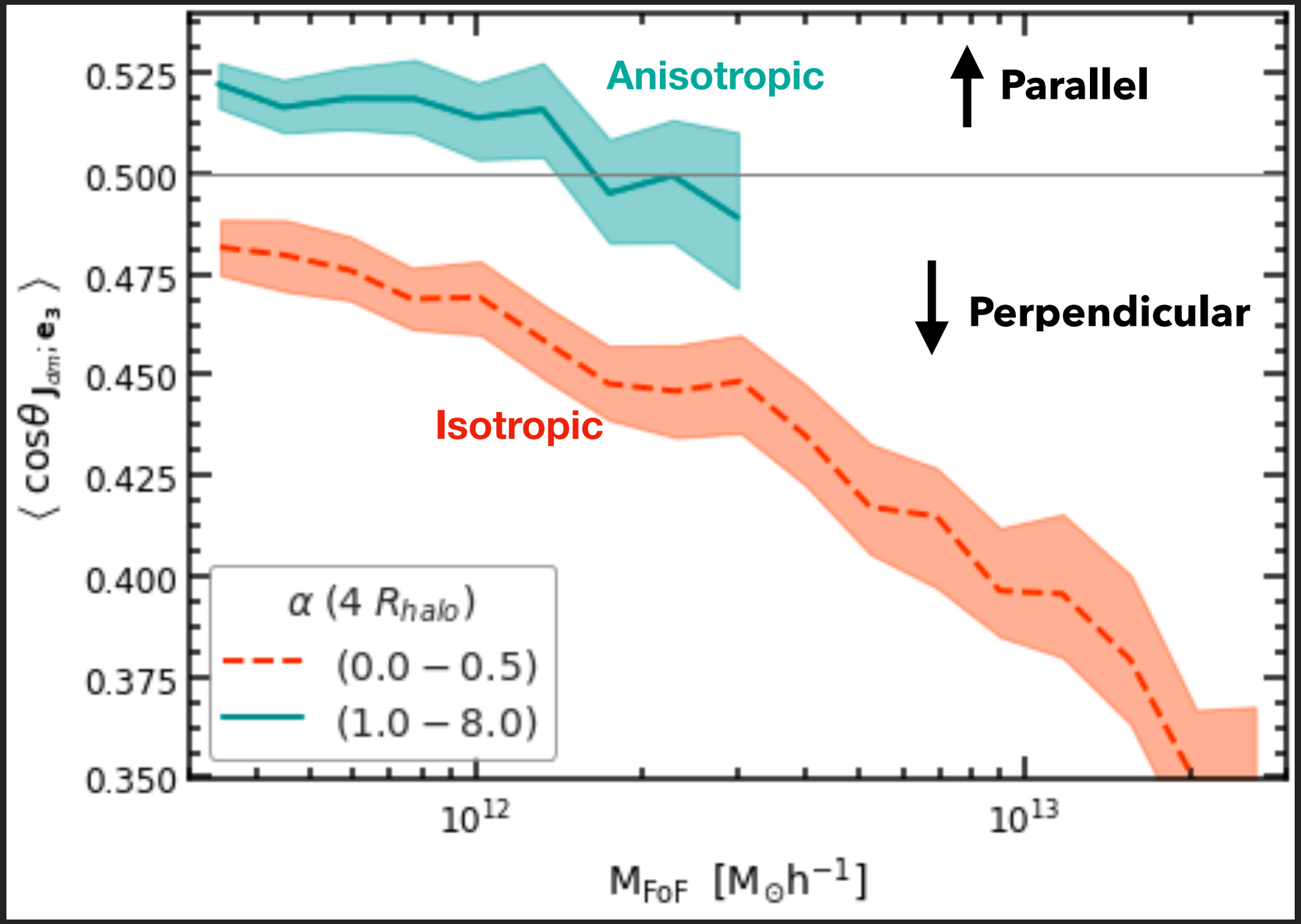
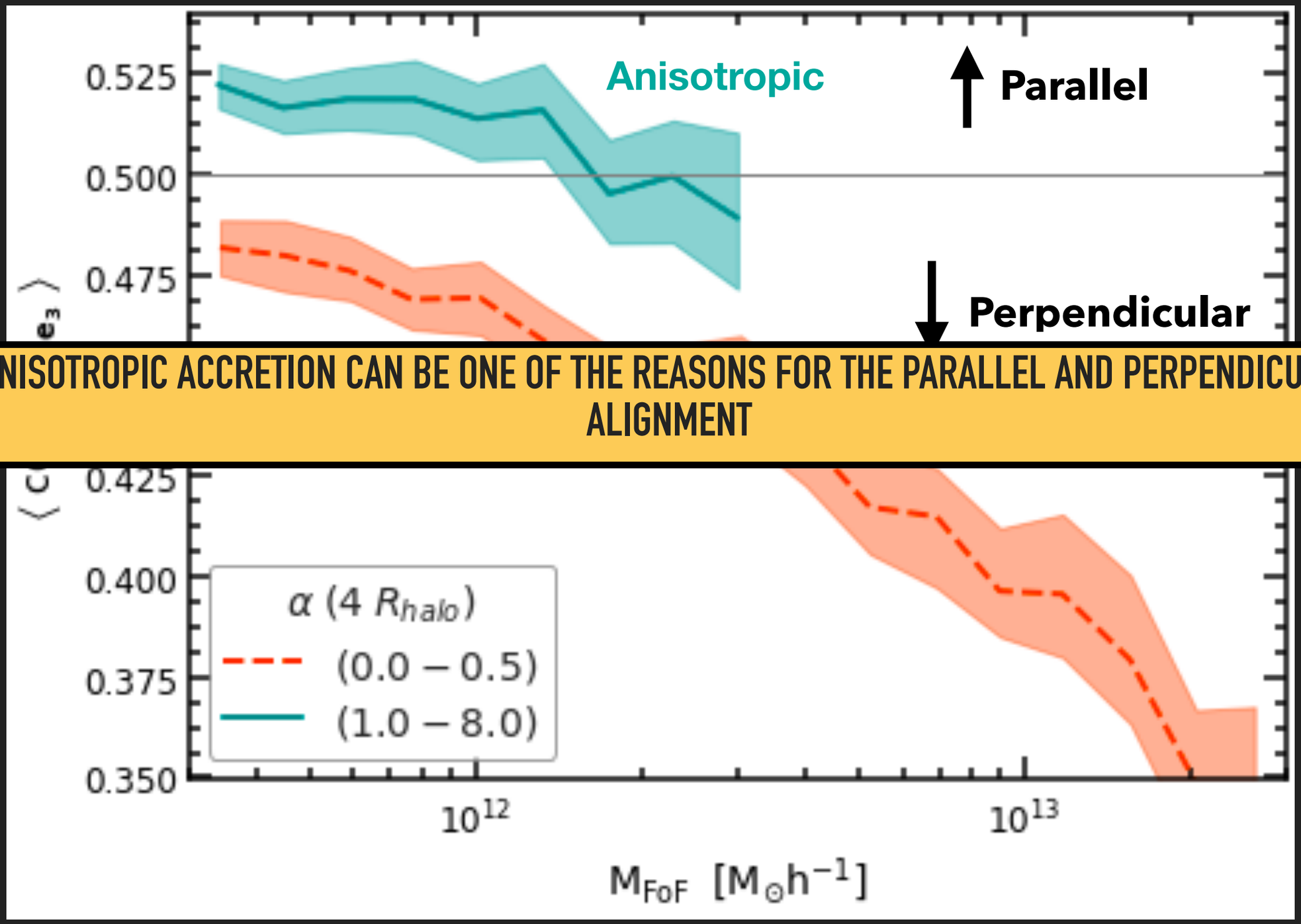
Tidal anisotropy - preliminary results



Special thanks to Pablo Lopez, Aseem Paranjape

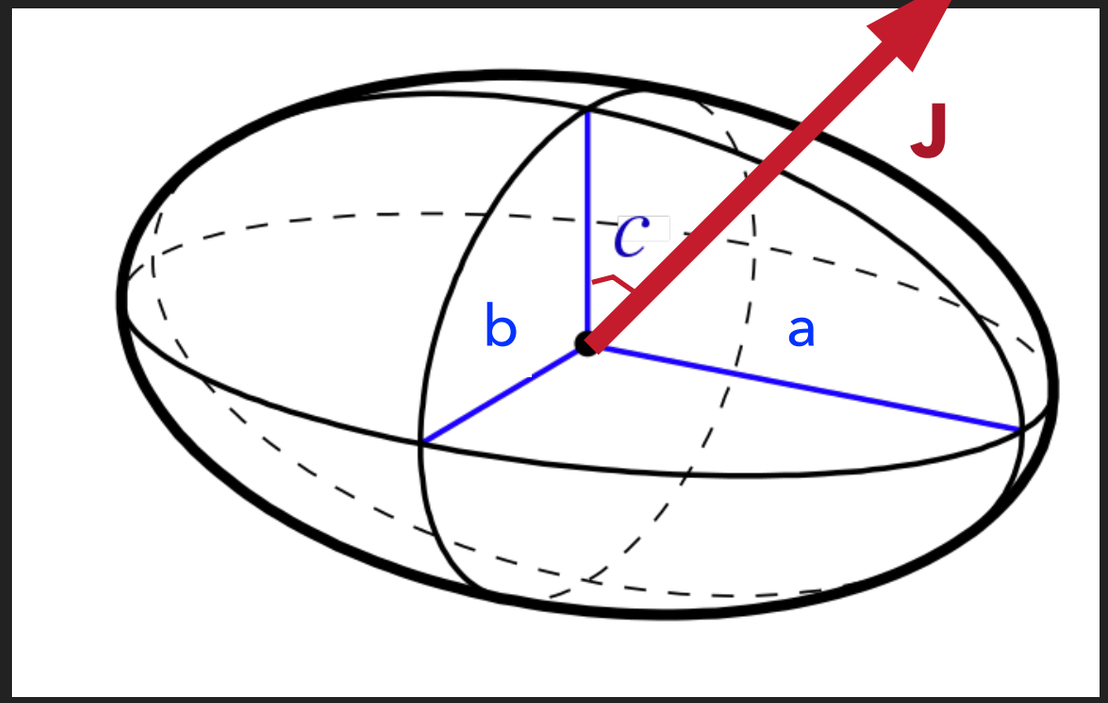
Tidal anisotropy - preliminary results



ANISOTROPIC ACCRETION CAN BE ONE OF THE REASONS FOR THE PARALLEL AND PERPENDICULAR ALIGNMENT

Special thanks to Pablo Lopez, Aseem Paranjape

HALO SPIN AND SHAPE



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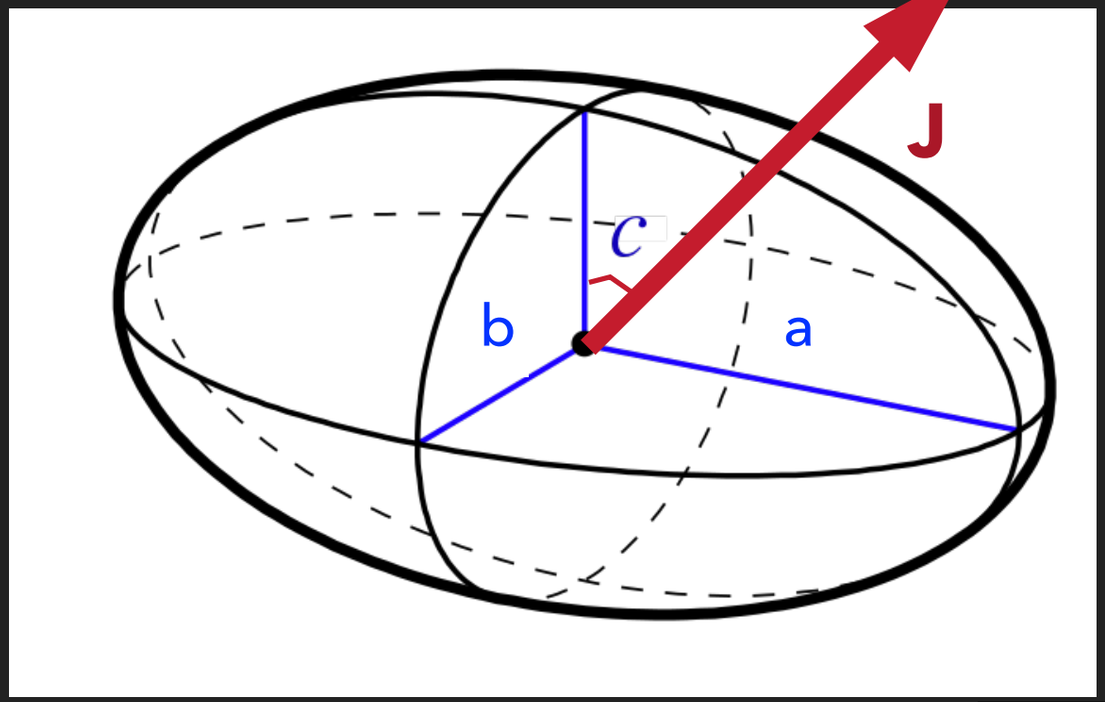

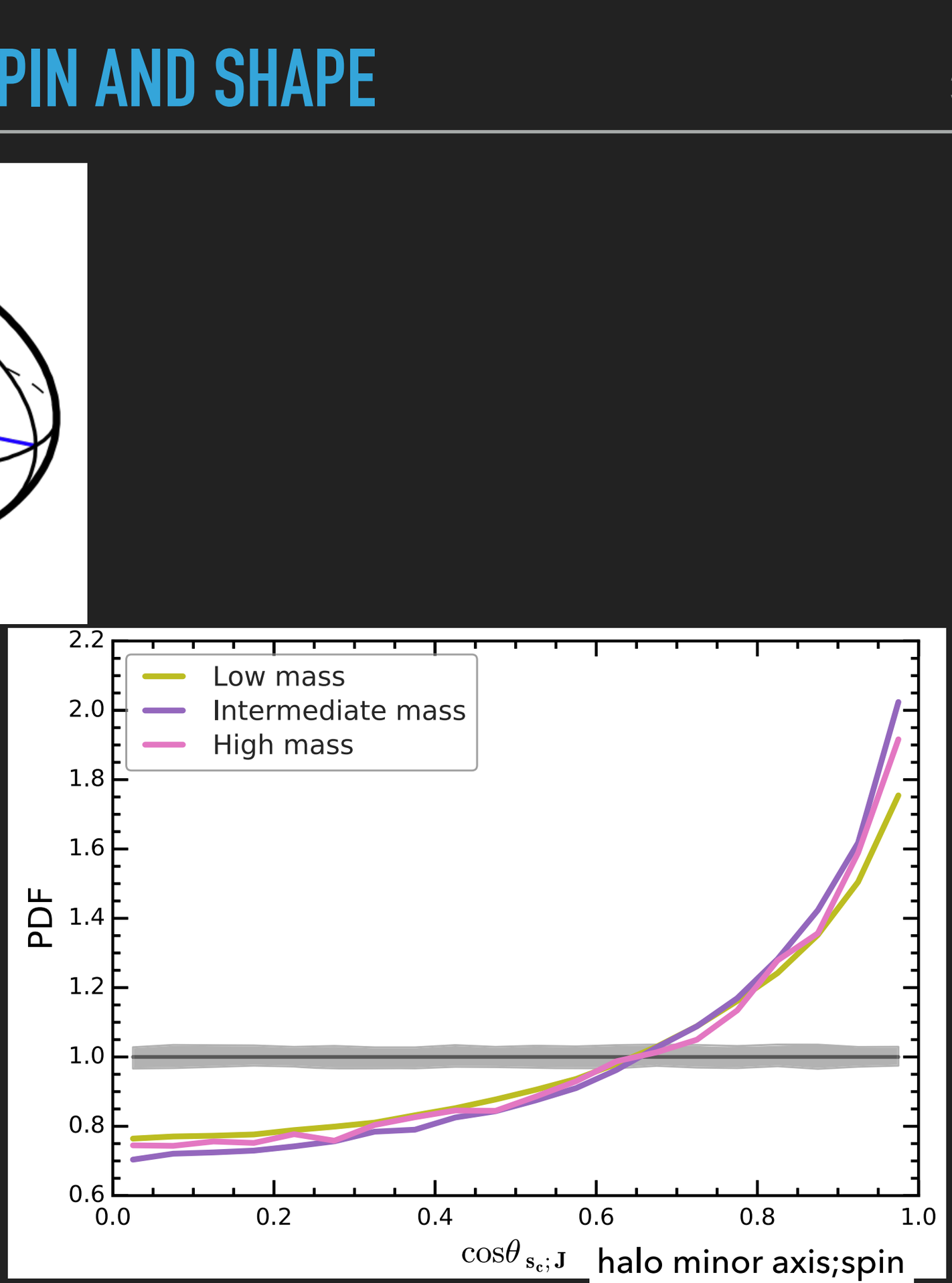

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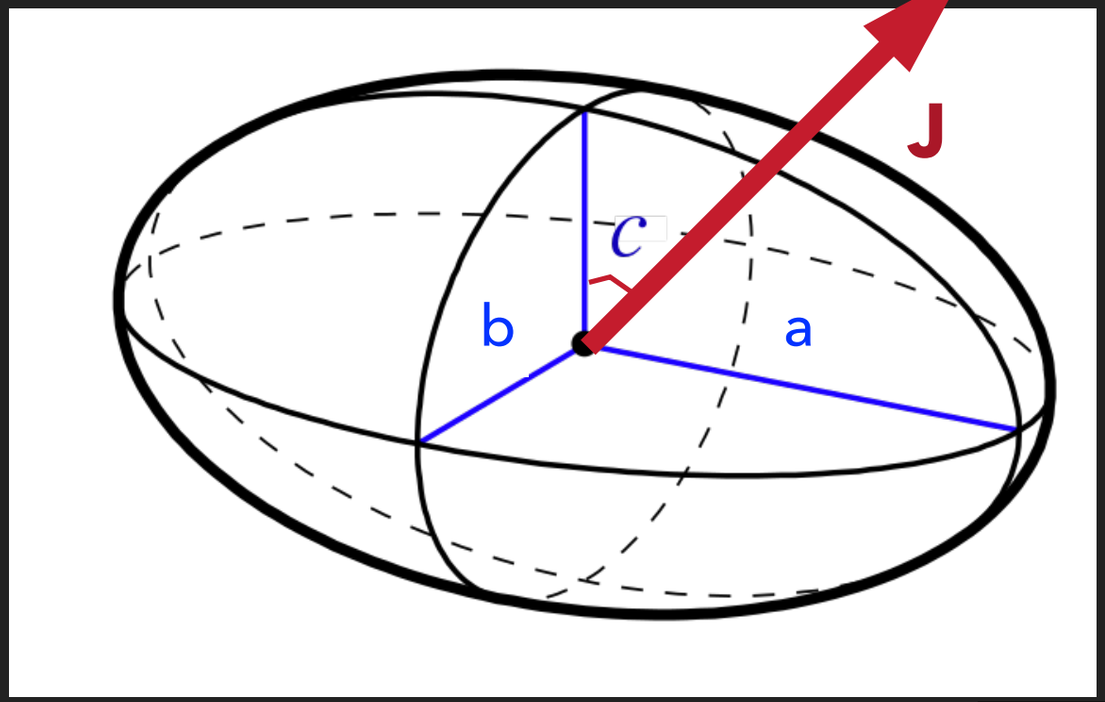

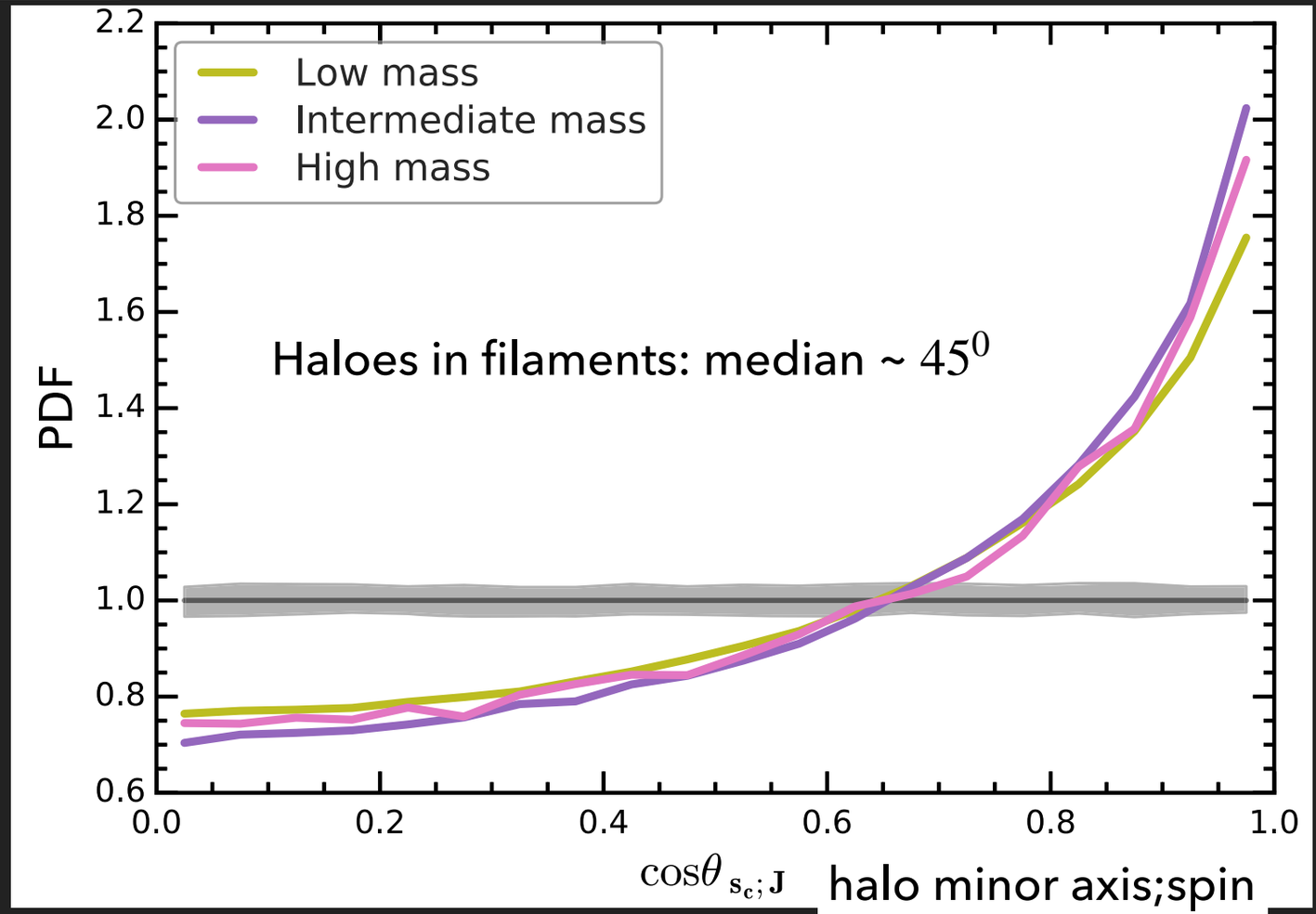

P. Ganeshaiah Veena et al 2018

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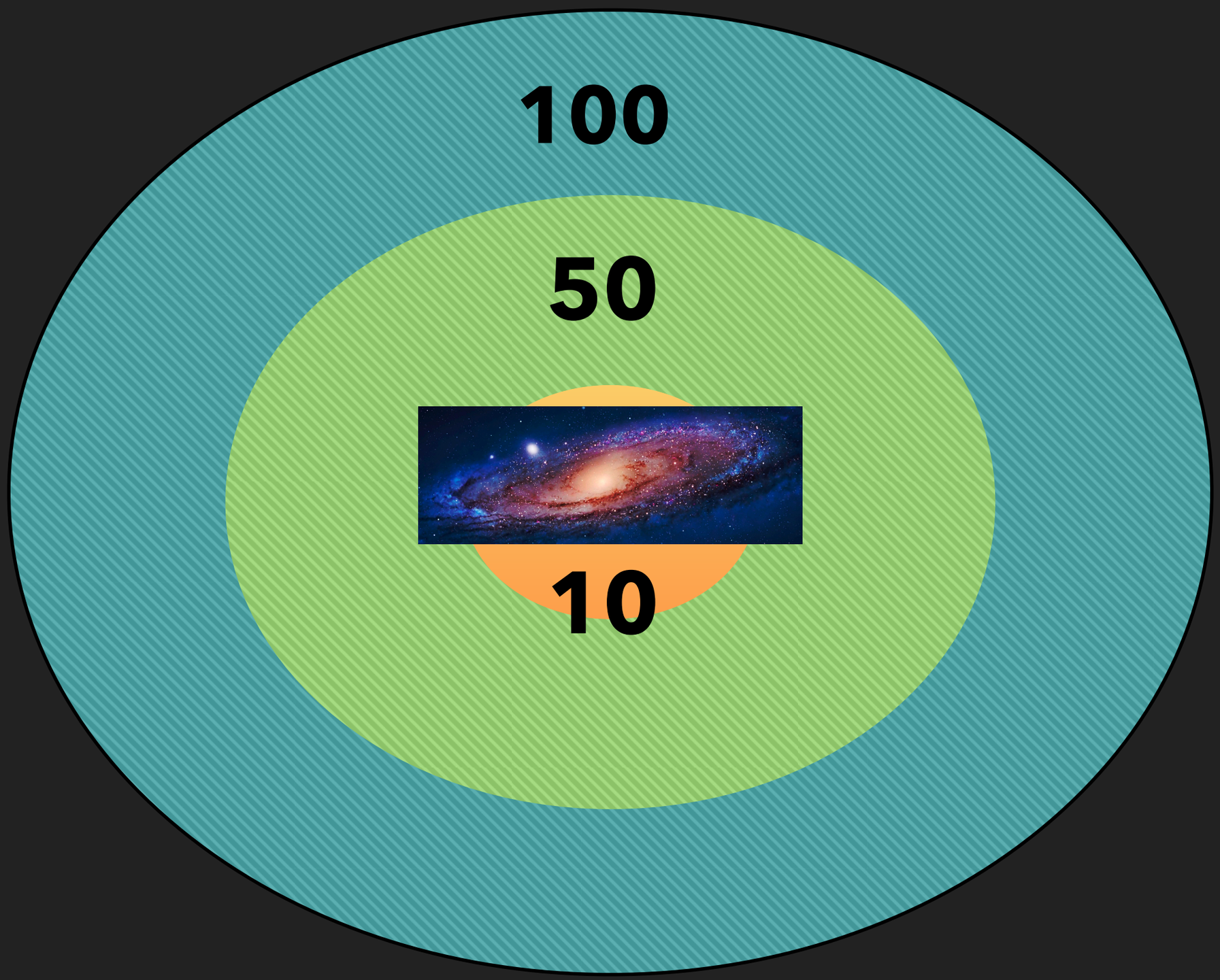

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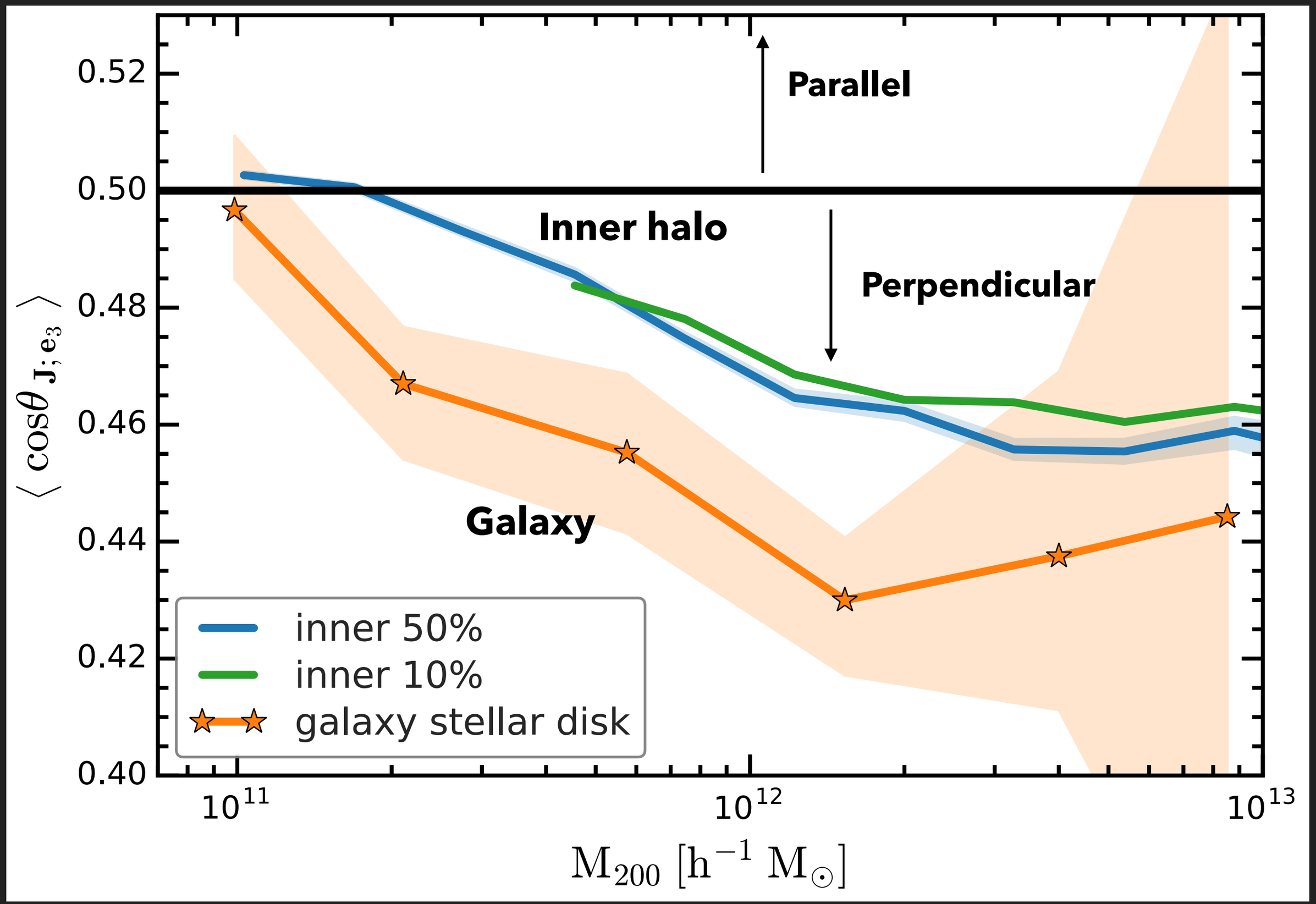

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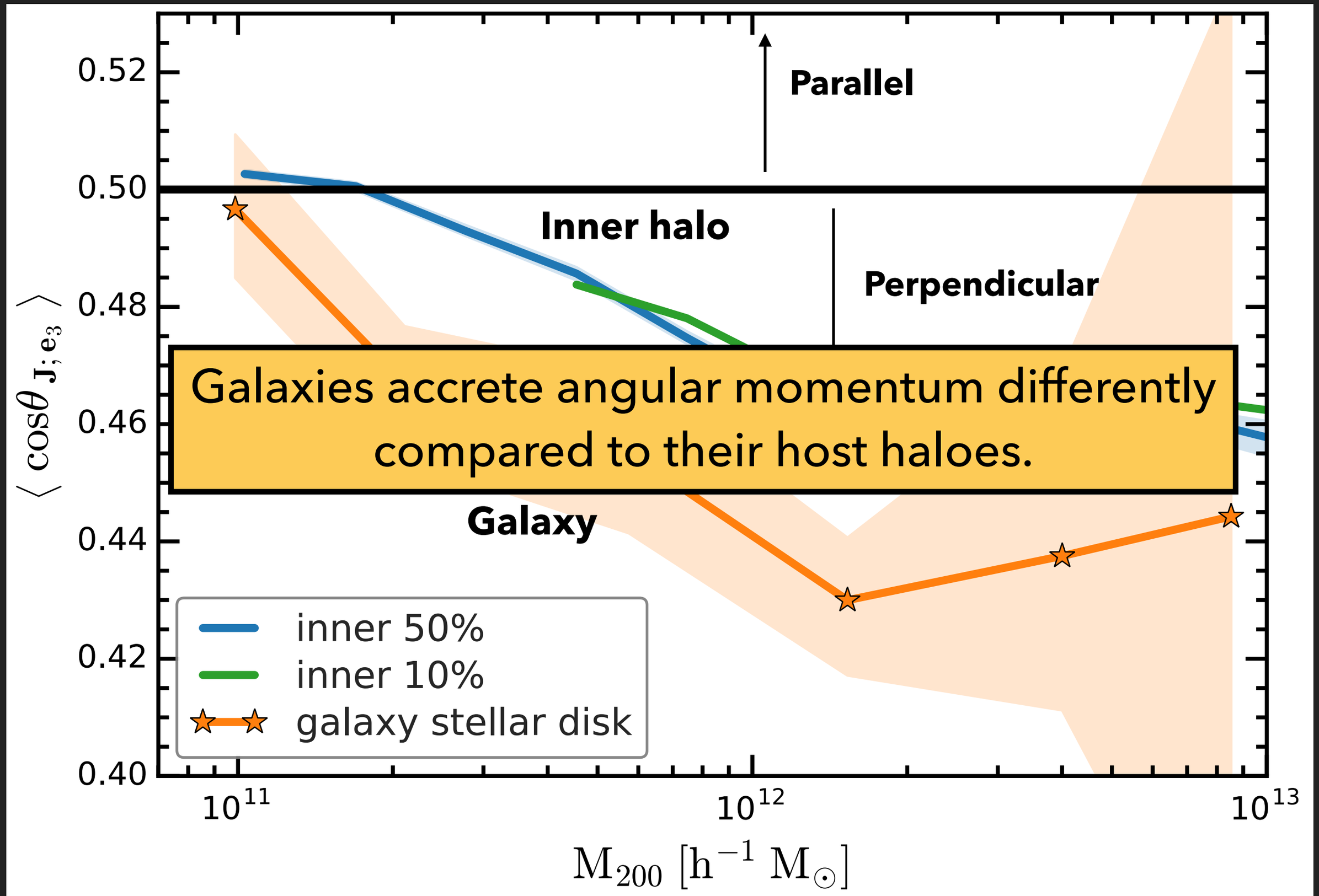

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NEXUS +

- Input tracer field - dark matter
- Geometry of matter distribution

Morphology: eigenvalue conditions

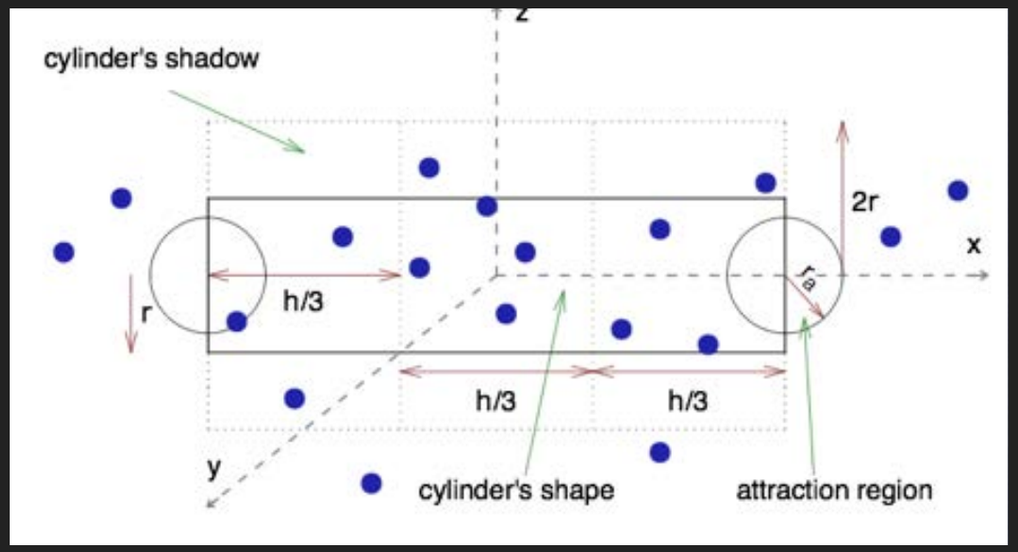
Multiscale detection

Direction of filament: $\hat{e}_3$

NEXUS – [Cautun et al 2012]

BISOUS

- Galaxy distribution
- Filamentary network is seen as a object point process
- Cylinders and their connectivity



Bisous – Algorithm developed at Tartu Observatory by Enn Saar, Elmo Tempel [Tempel et al 2013]

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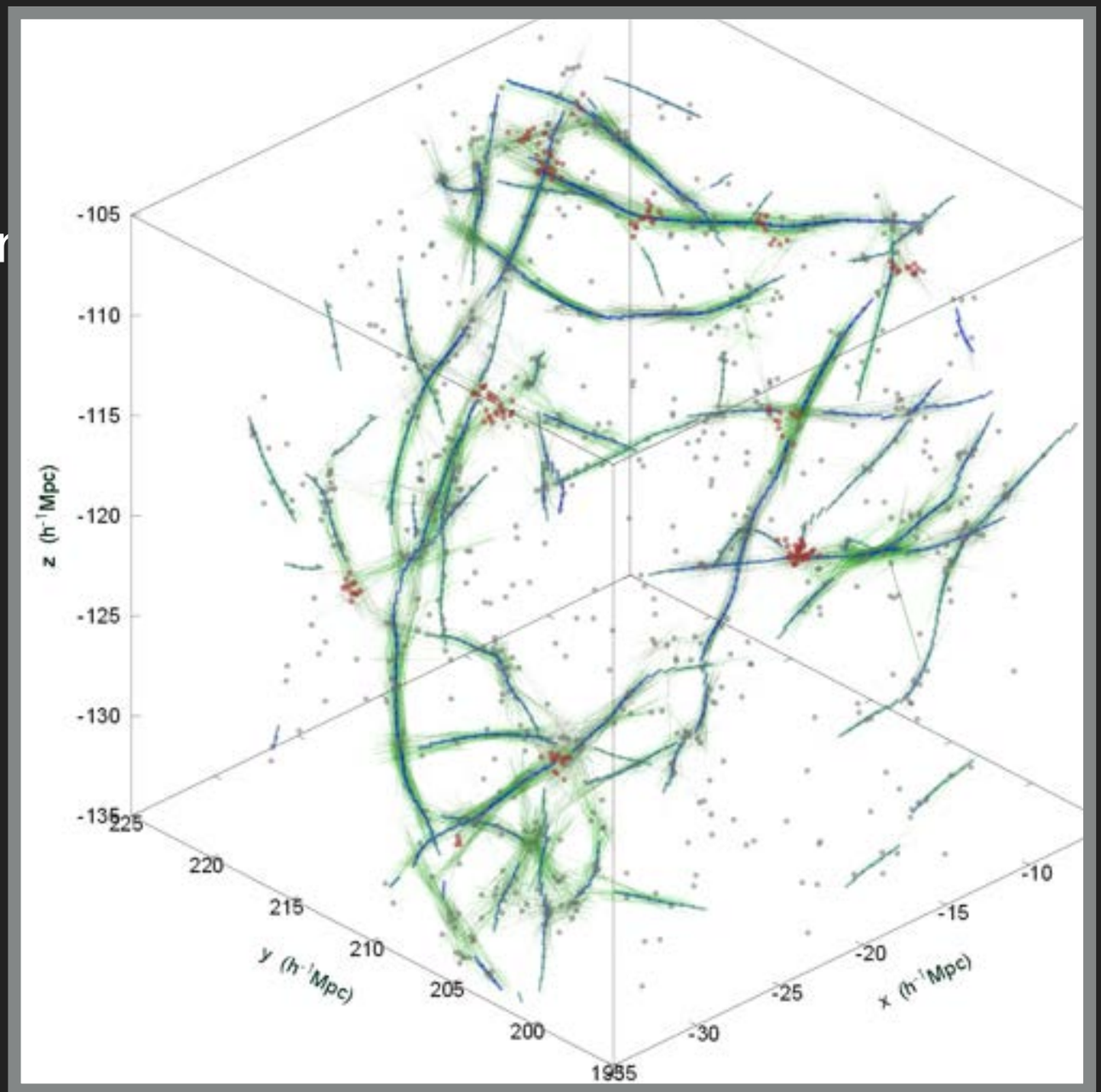
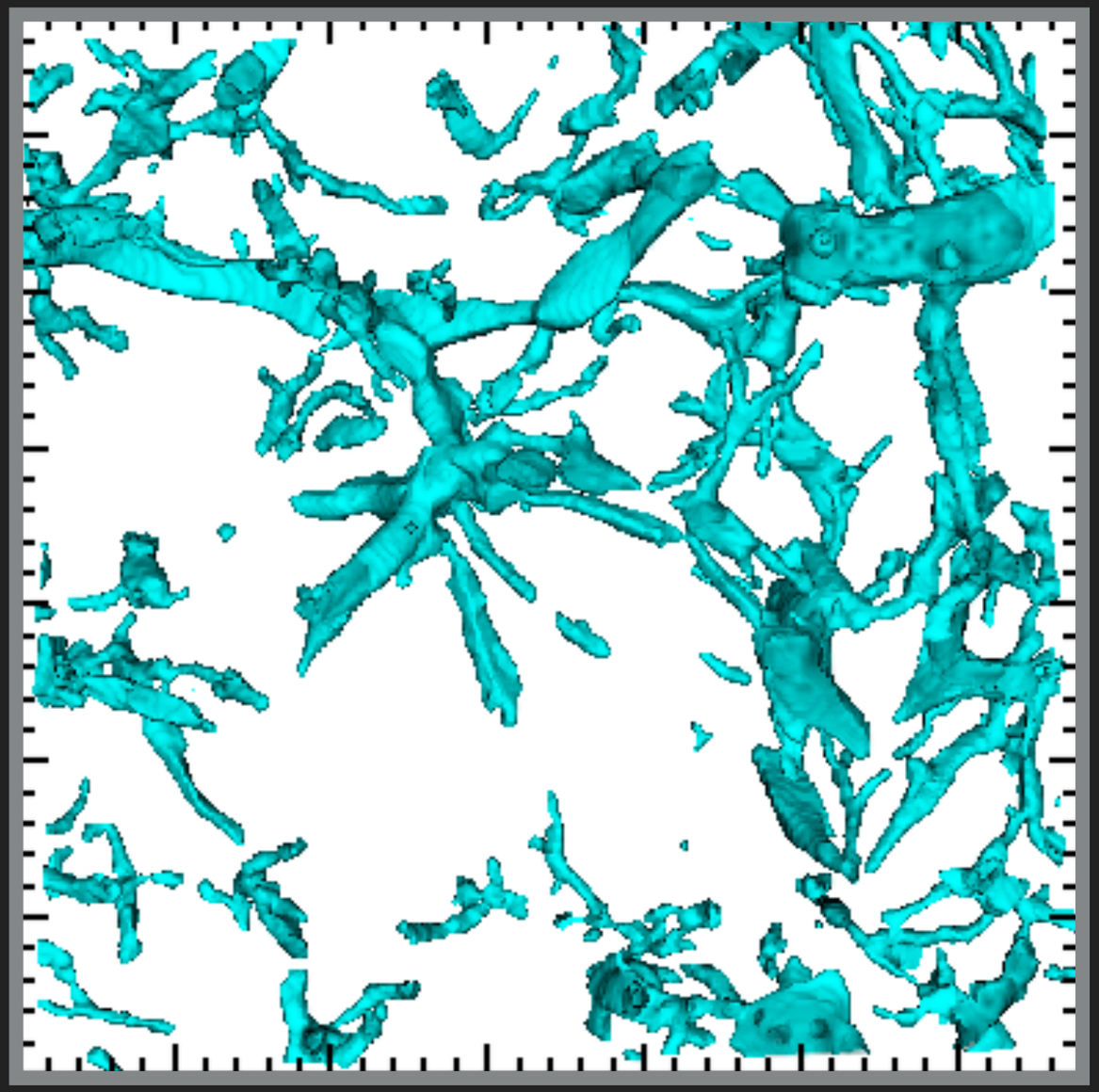
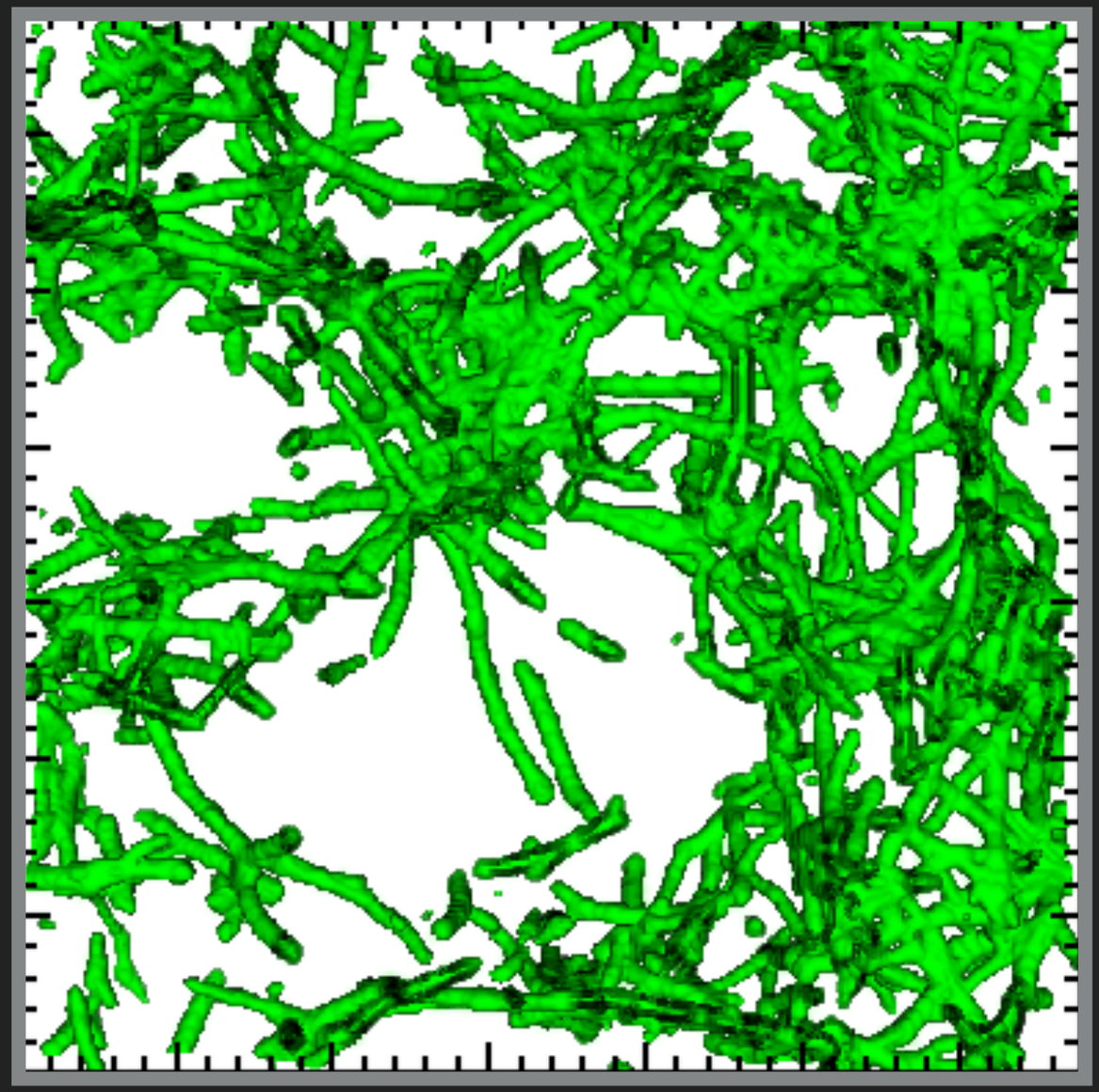


Tartu Observatory by Enn Saar, Elmo Tempel [Tempel et al 2013]

NEXUS + FILAMENTS



BISOUS FILAMENTS



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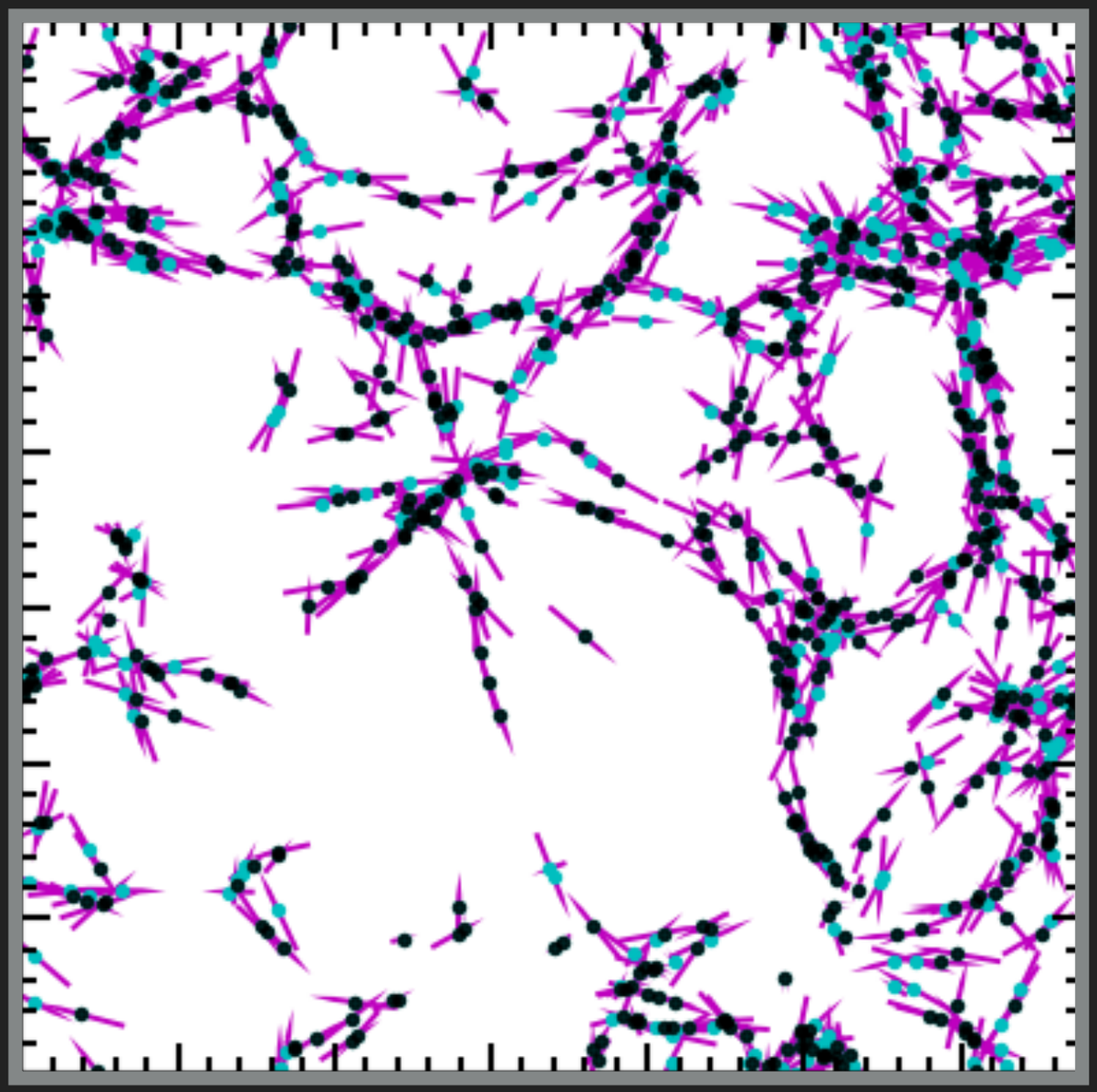
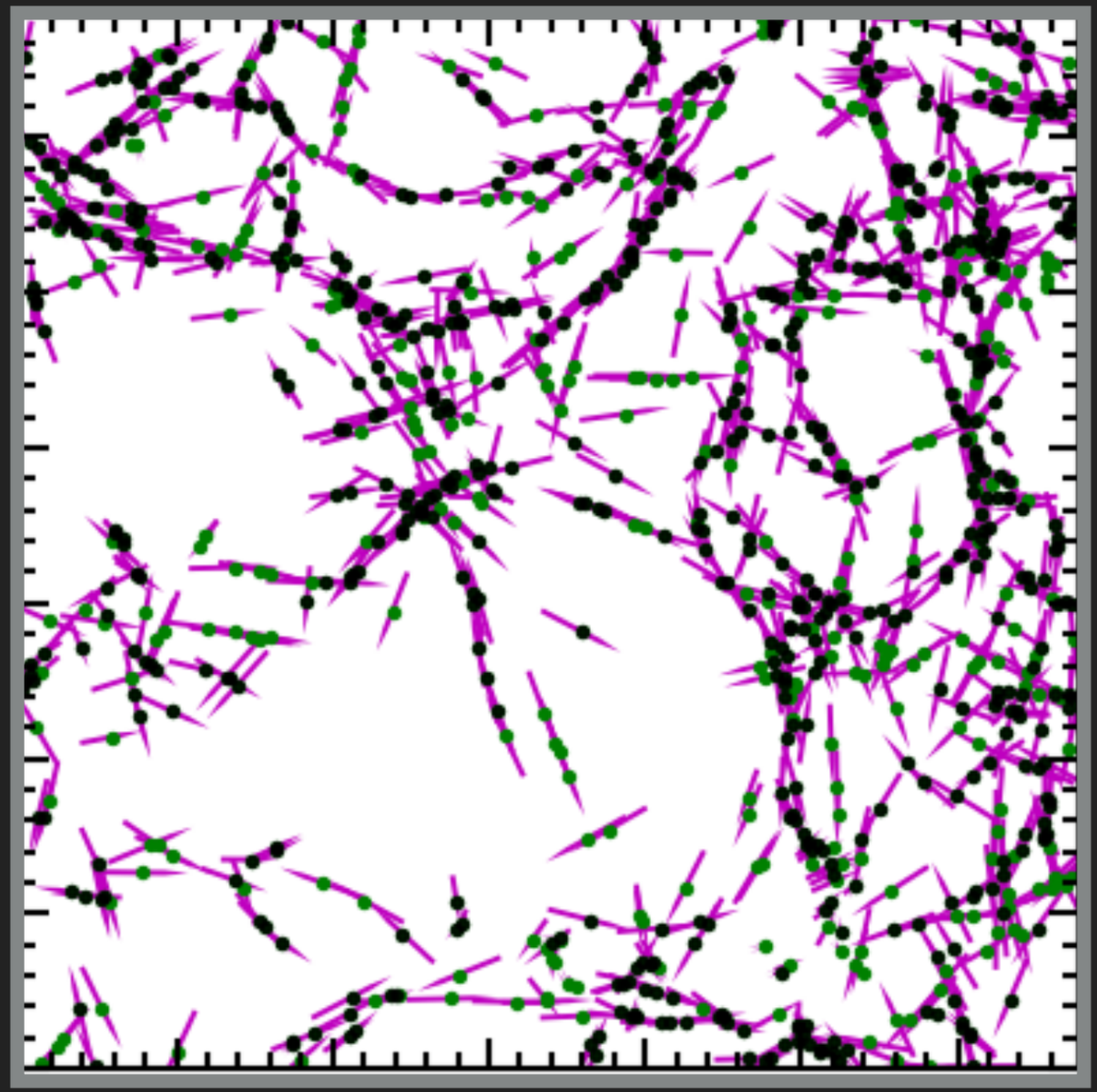
NEXUS + GALAXIES



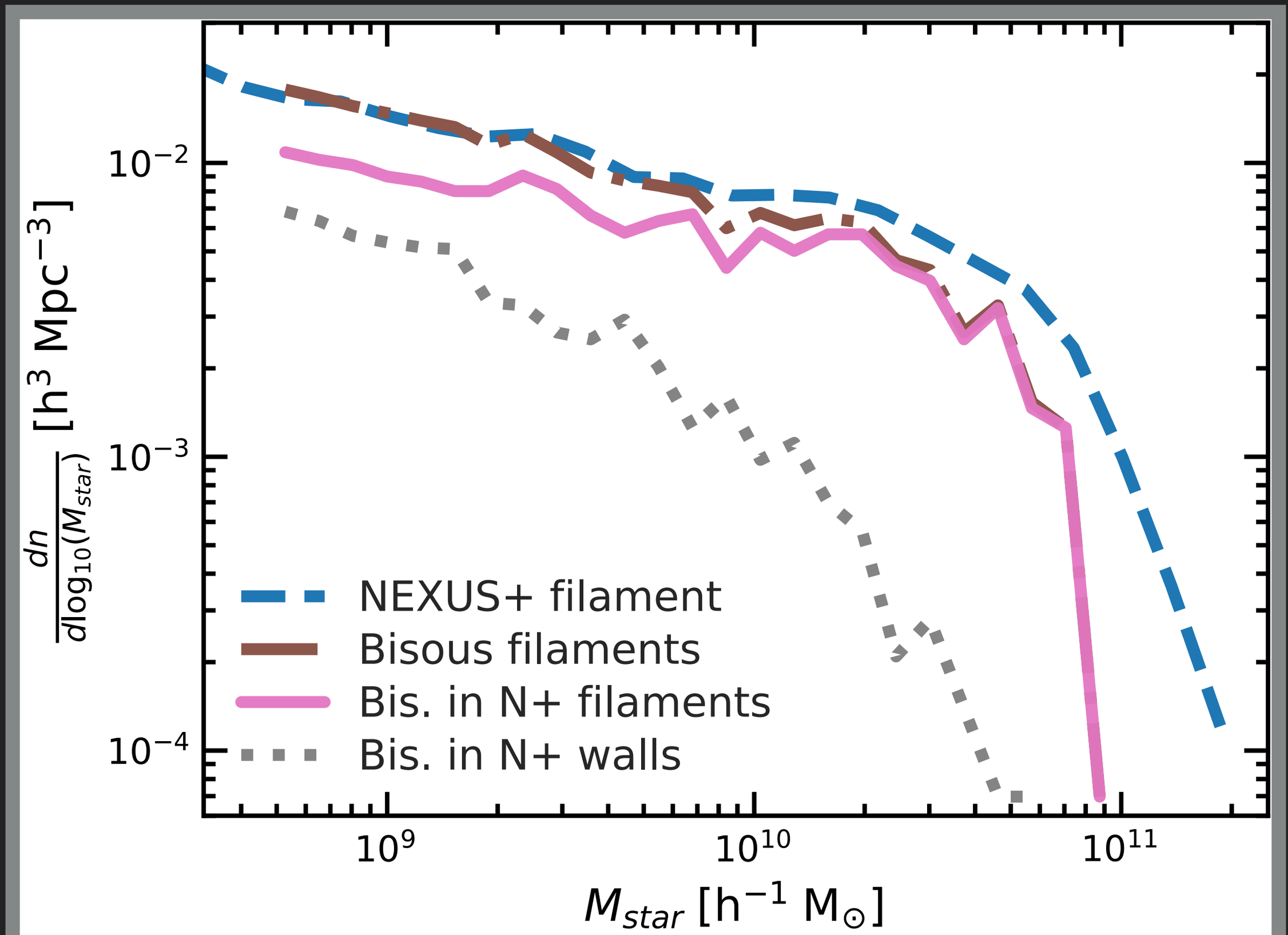
BISOUS GALAXIES



P. Ganeshaiah Veena et al 2019.

Median alignment between Nexus and Bisous is 21 degrees.

GALAXY STELLAR MASS FUNCTION



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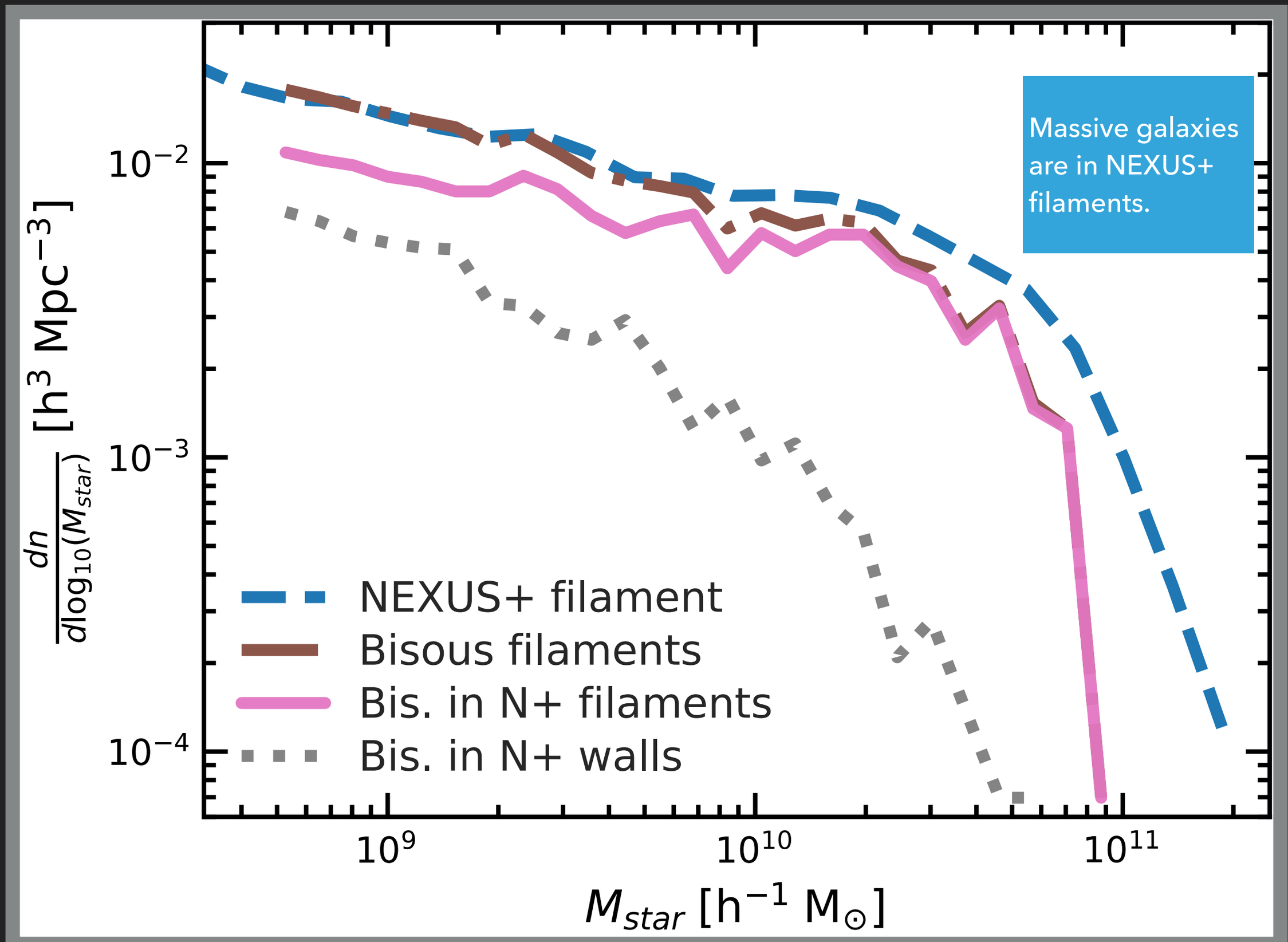
GALAXY STELLAR MASS FUNCTION



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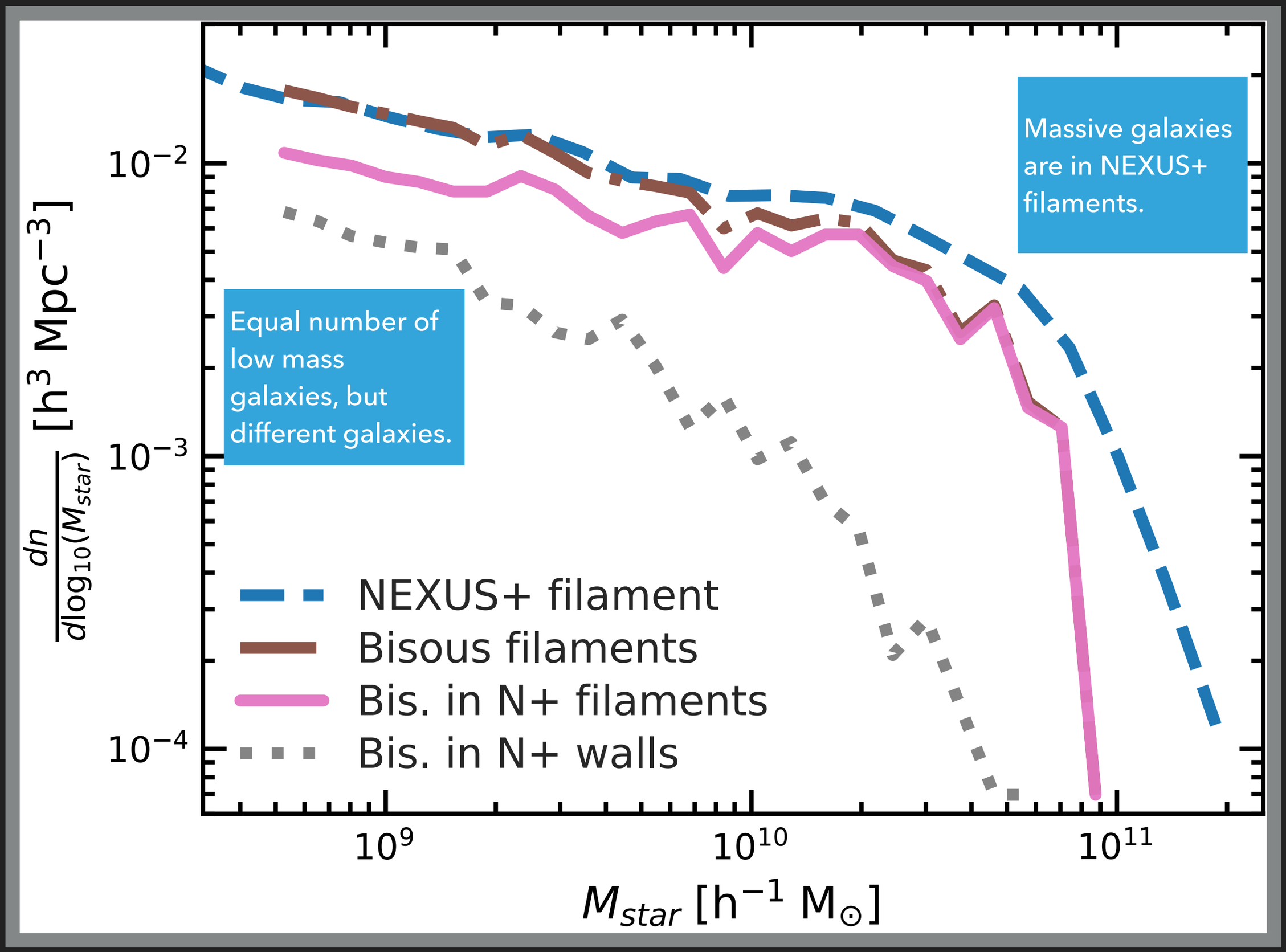

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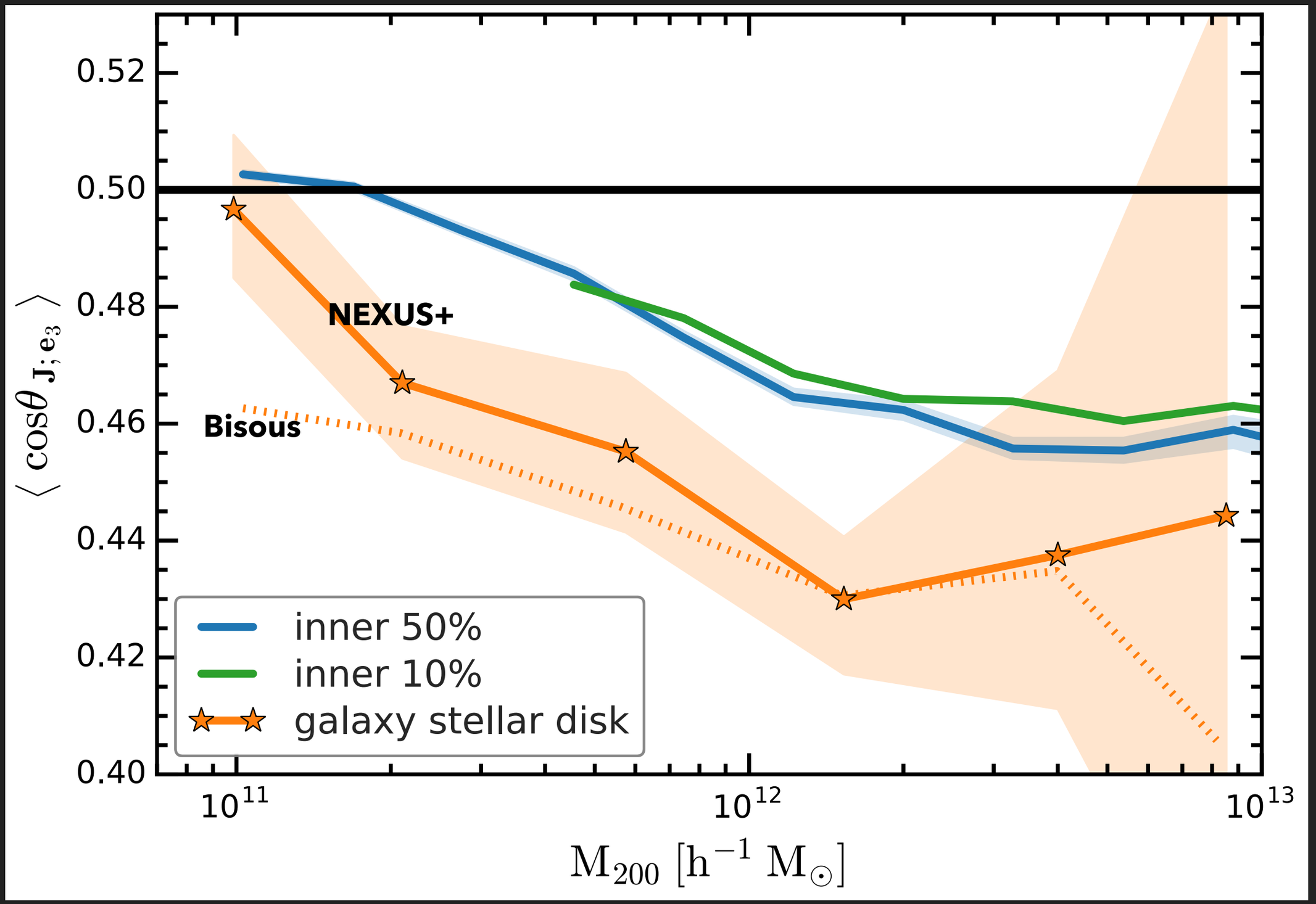
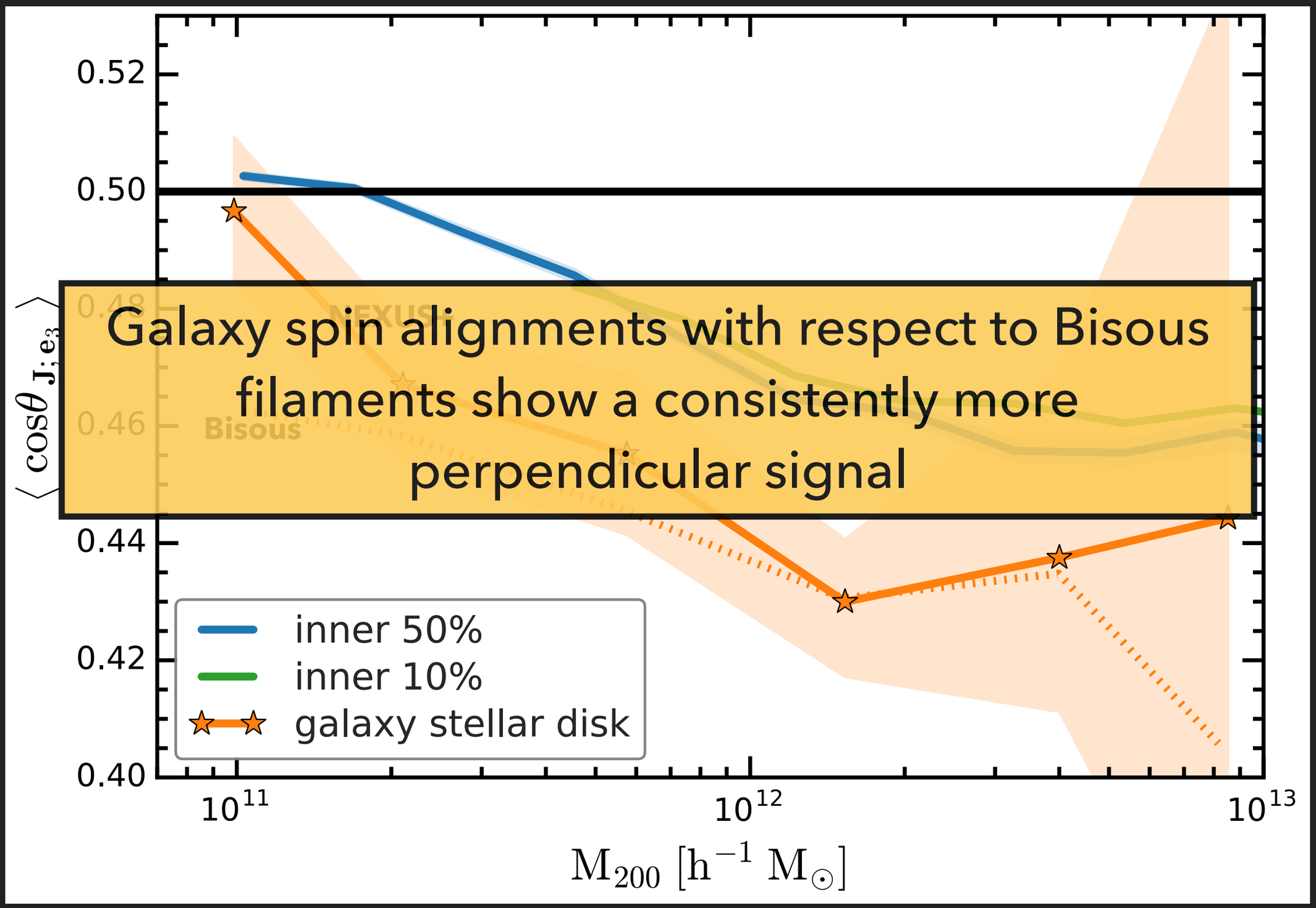
BISOUS AND NEXUS +



P. Ganeshaiah Veena, M. Cautun, R. van de Weygaert, E. Tempel et al 2019.

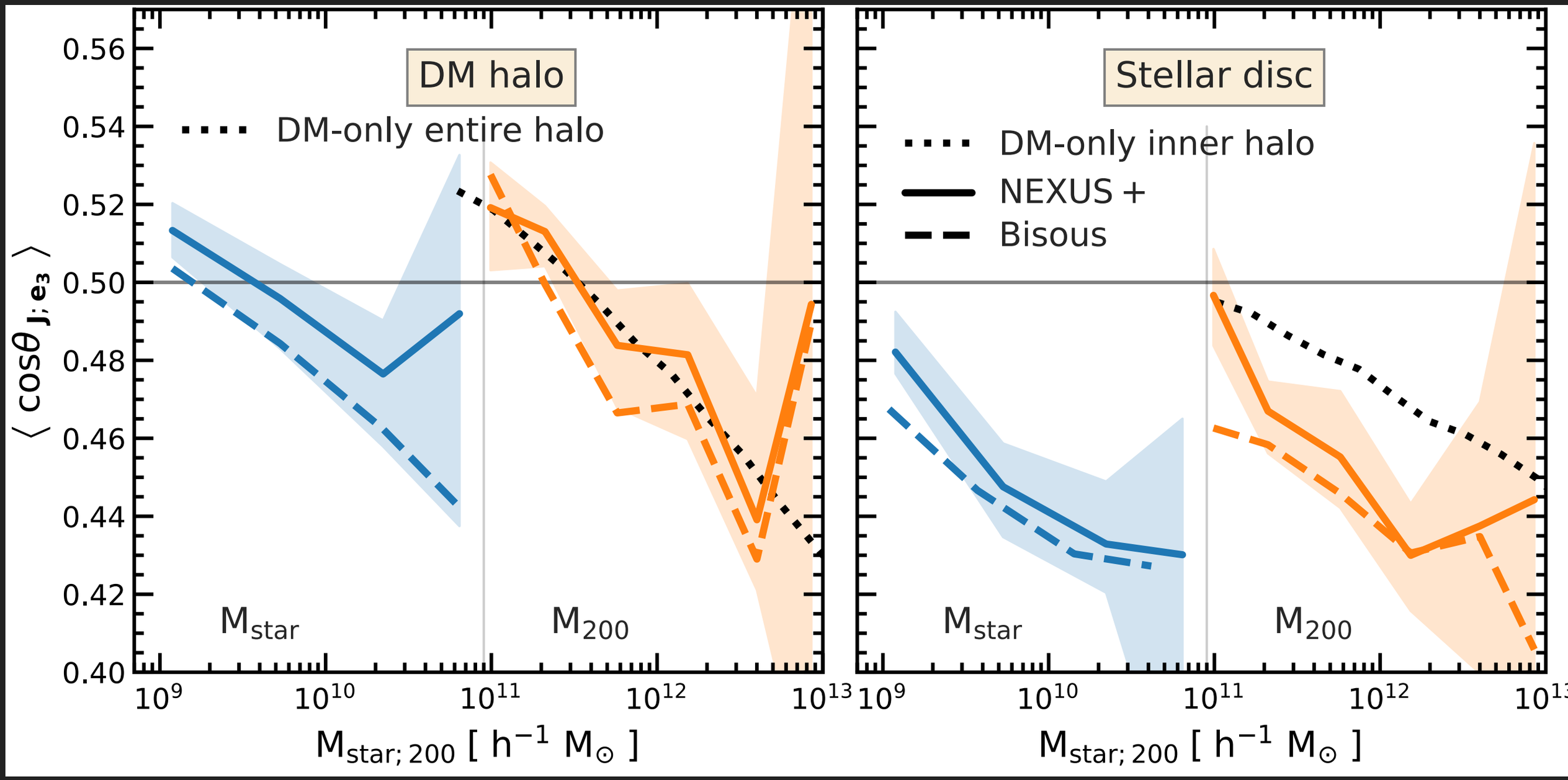
BISOUS AND NEXUS +



Galaxy spin alignments with respect to Bisous filaments show a consistently more perpendicular signal

P. Ganeshaiah Veena, M. Cautun, R. van de Weygaert, E. Tempel et al 2019.

BISOUS AND NEXUS+



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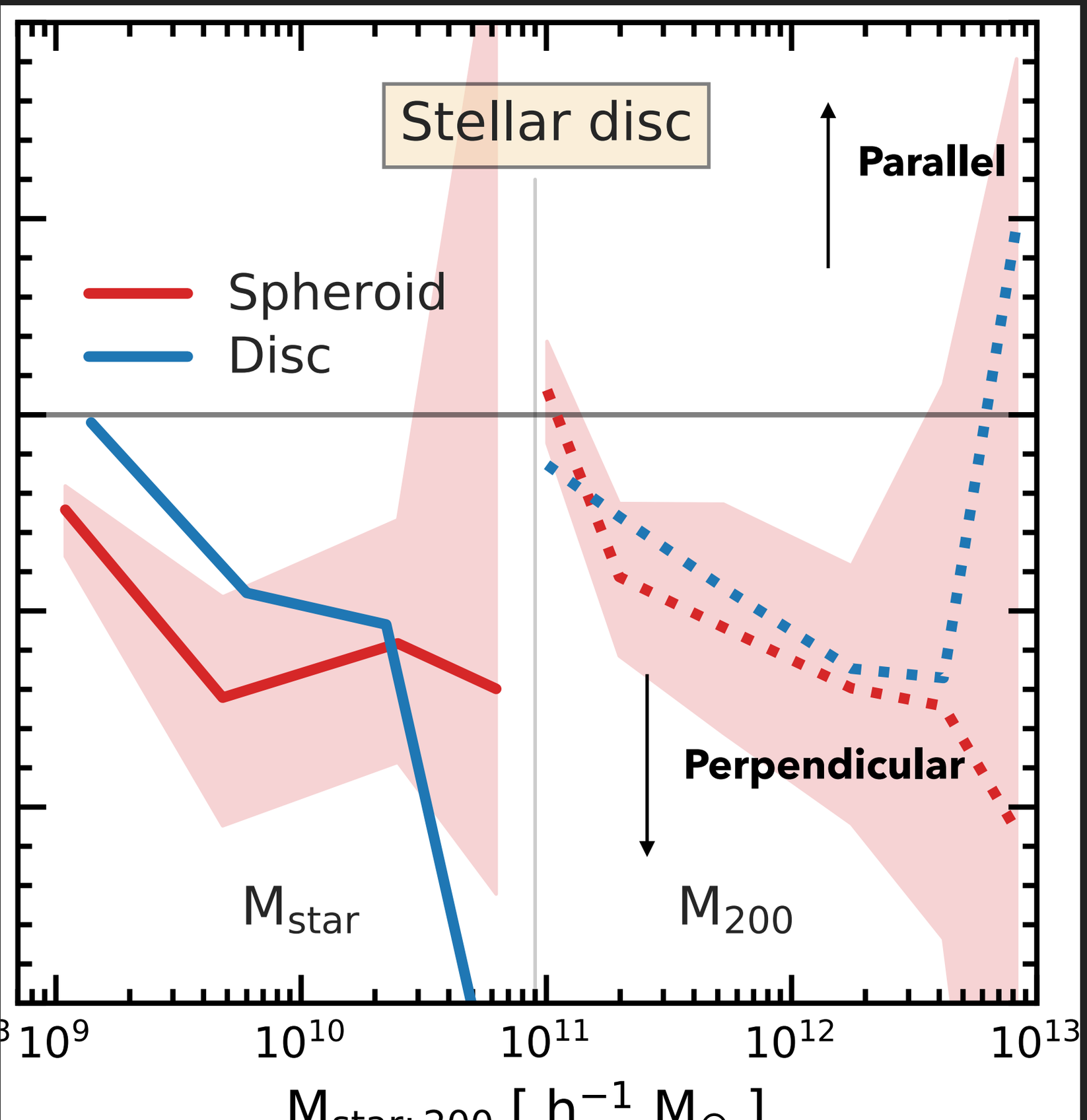

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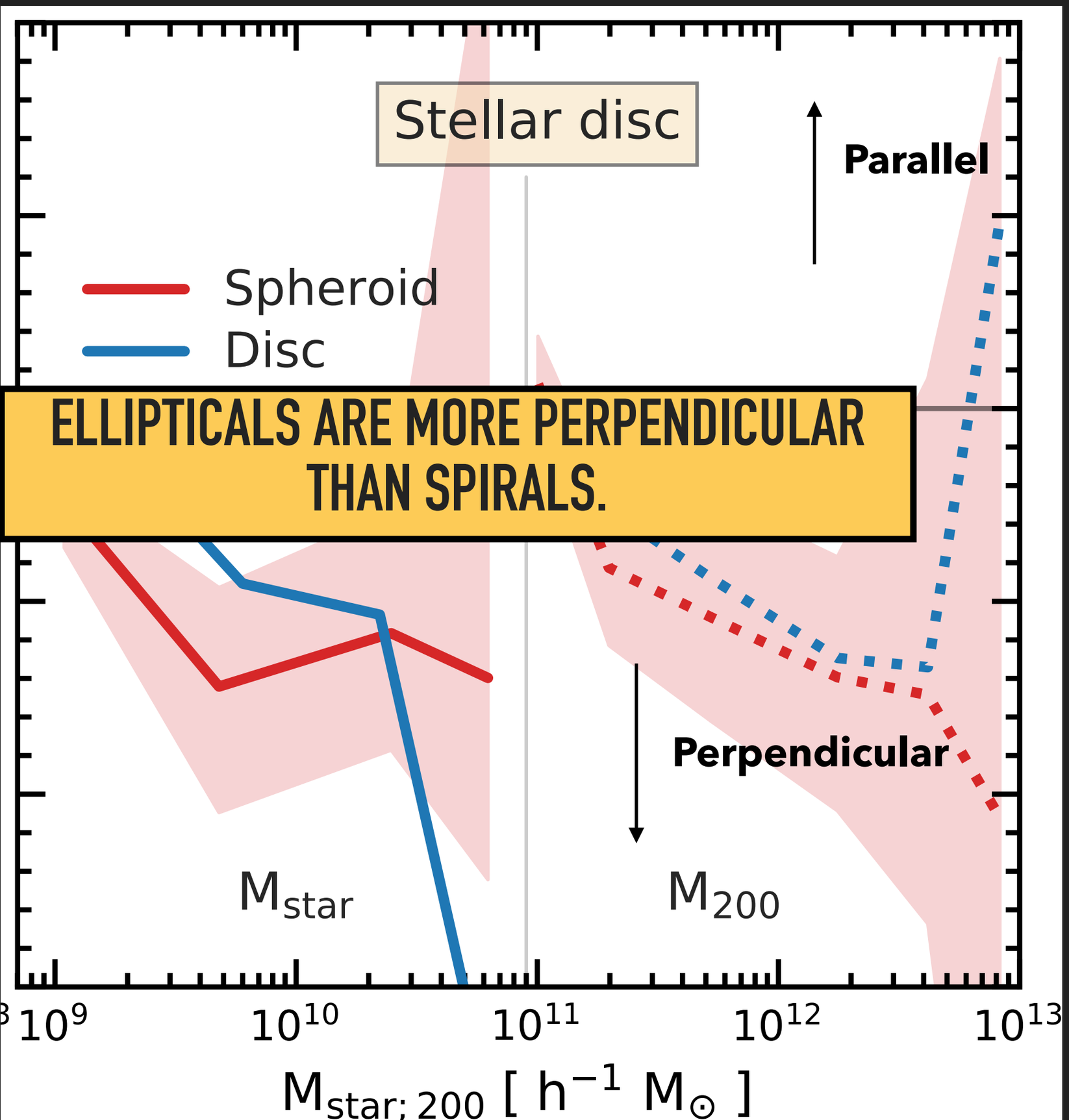
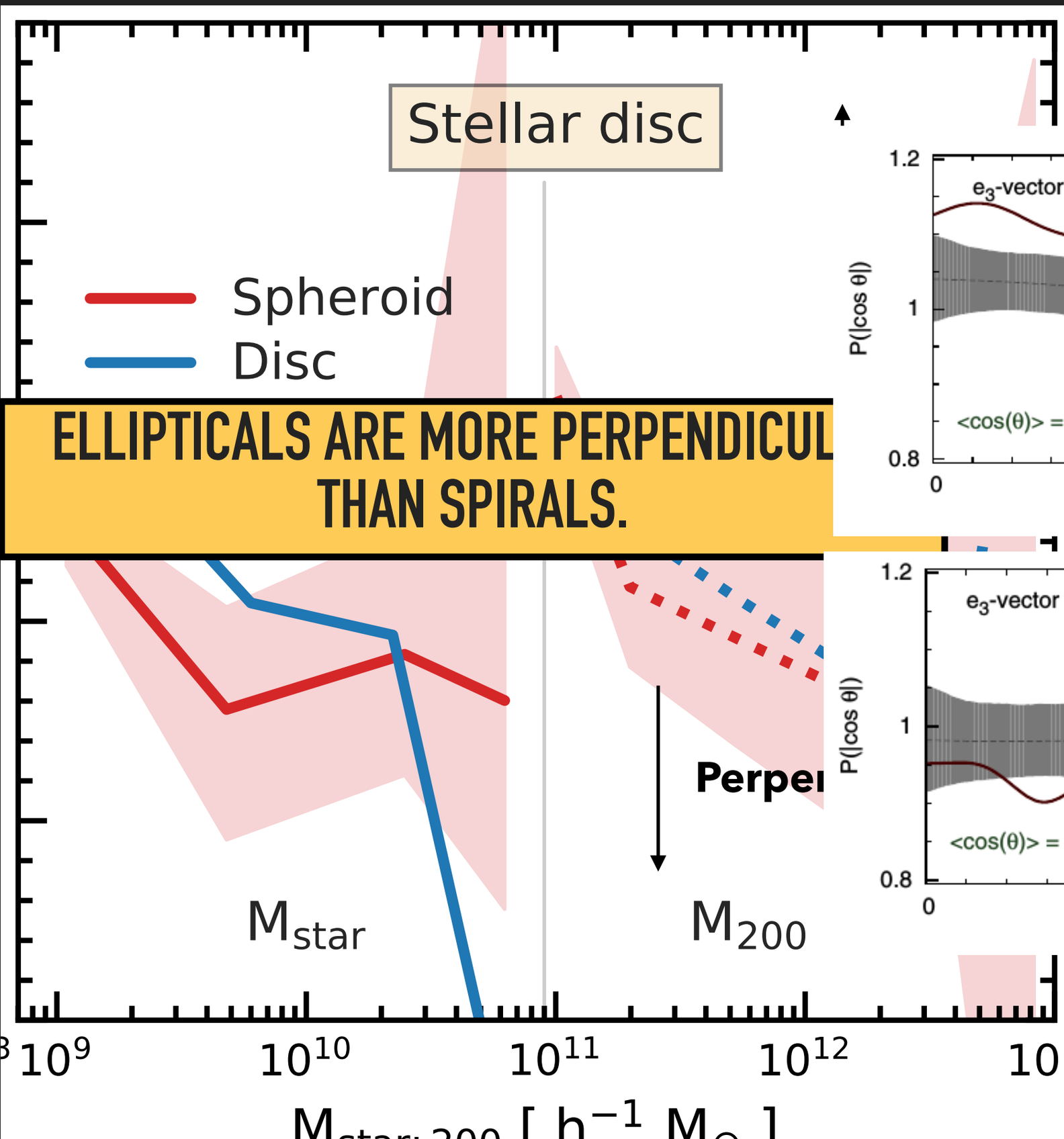
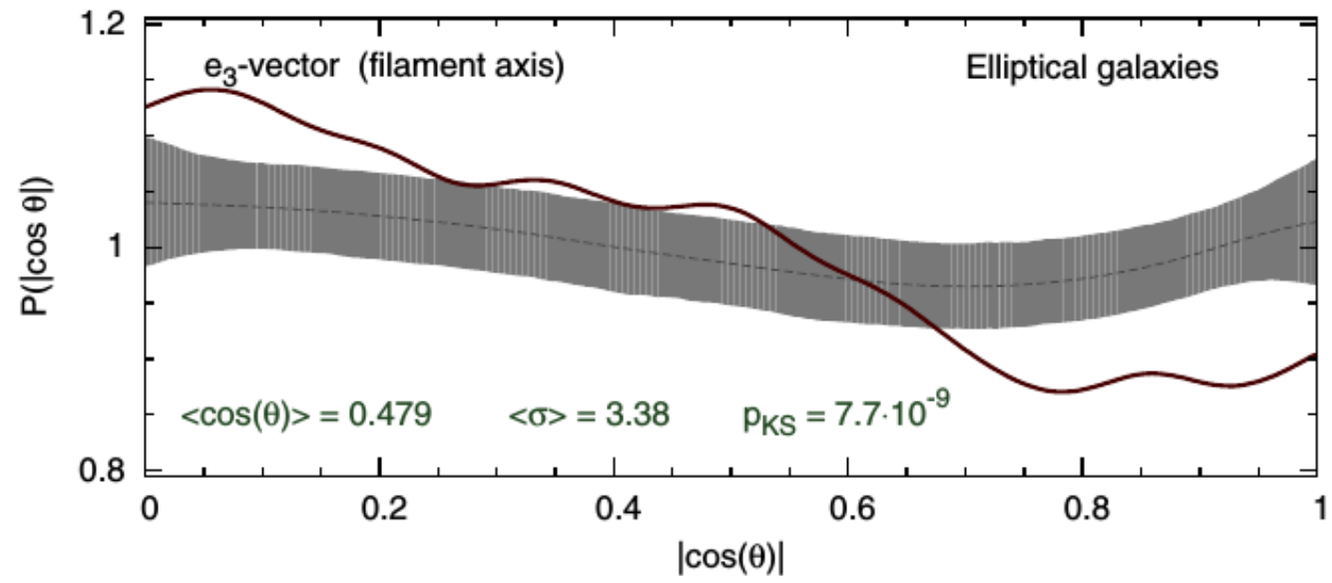


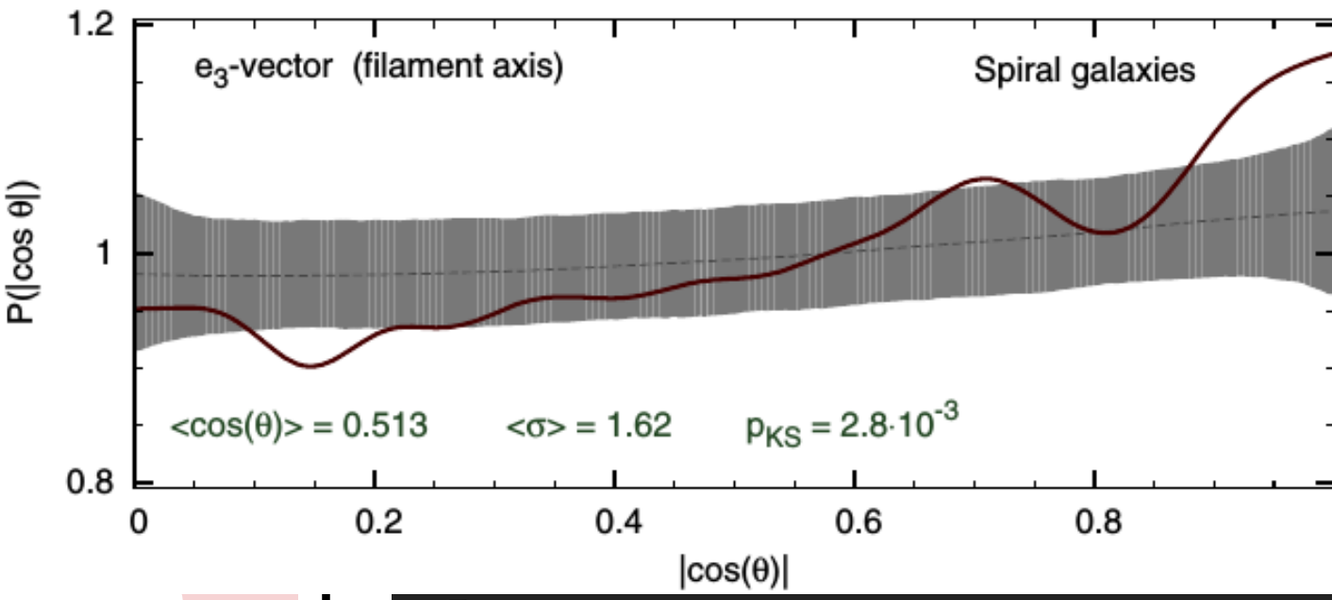
P. Ganeshaiah Veena et al 2019

SDSS



ELLIPTICALS ARE MORE PERPENDICUL THAN SPIRALS.

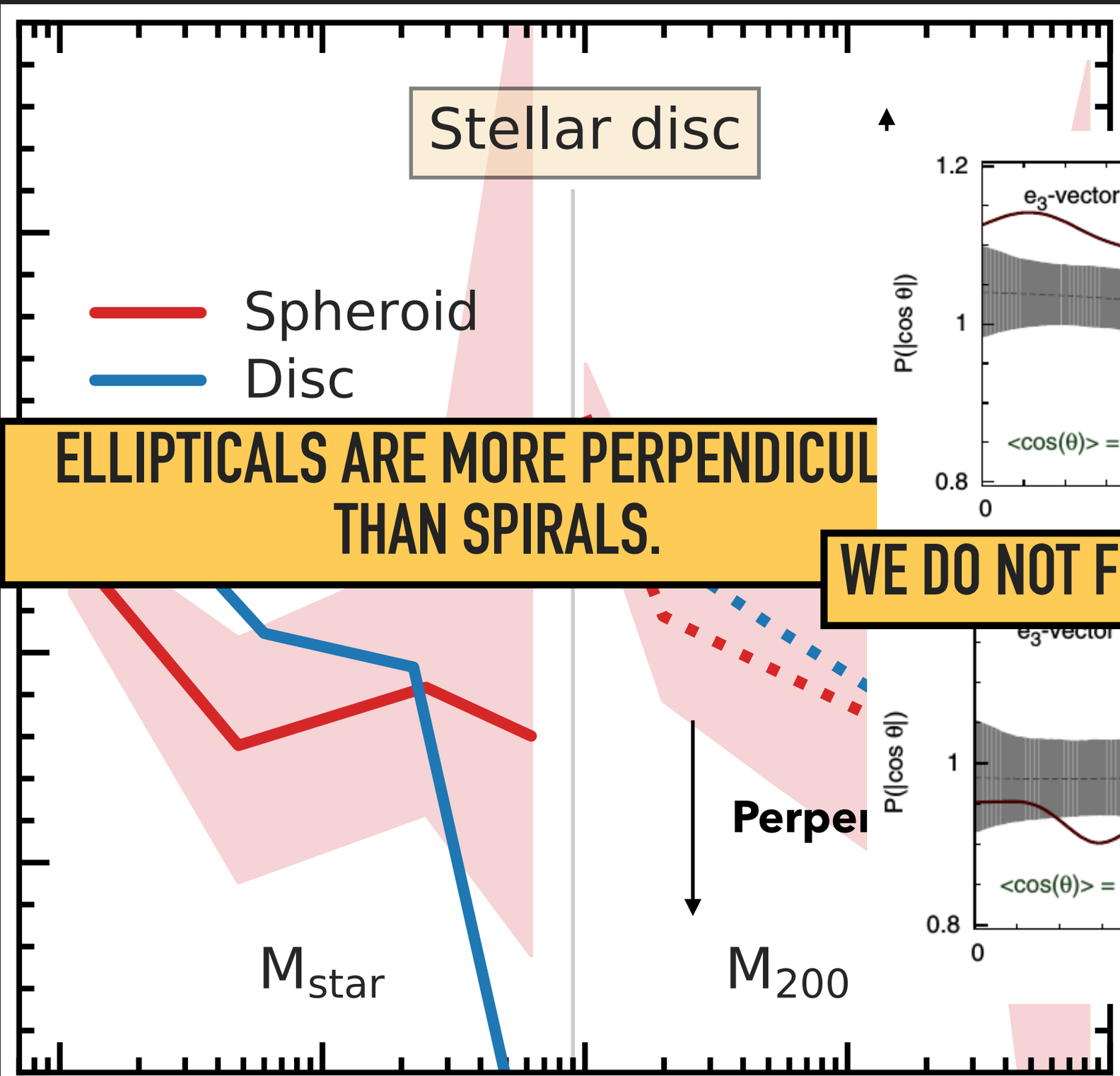




P. Ganesha

Tempel & Libeskind 2013

SDSS



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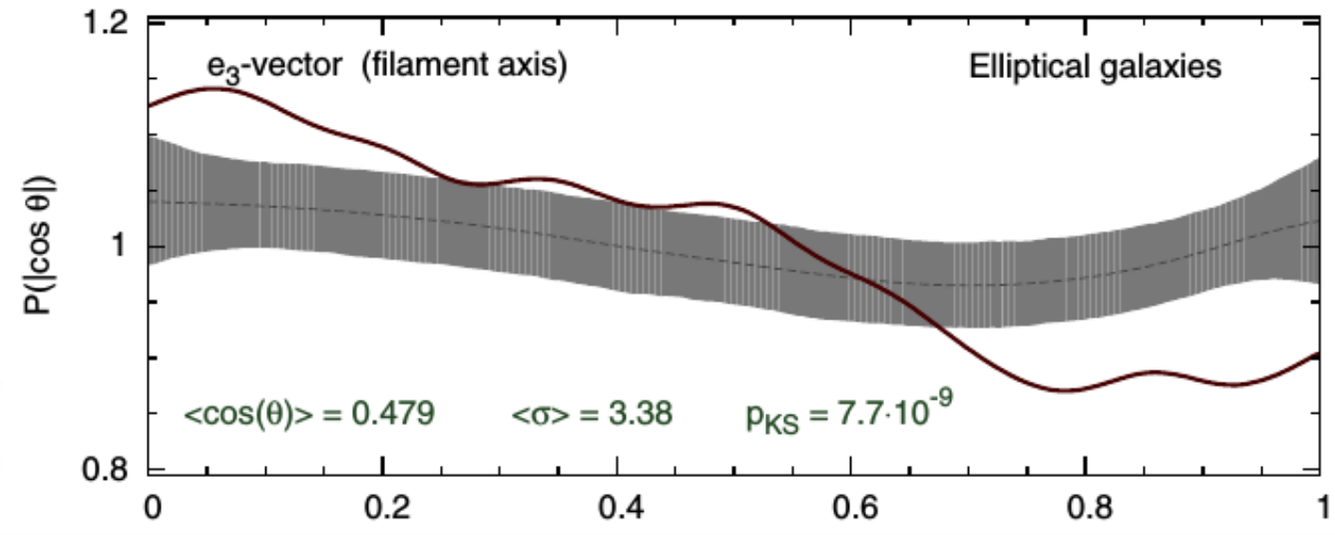
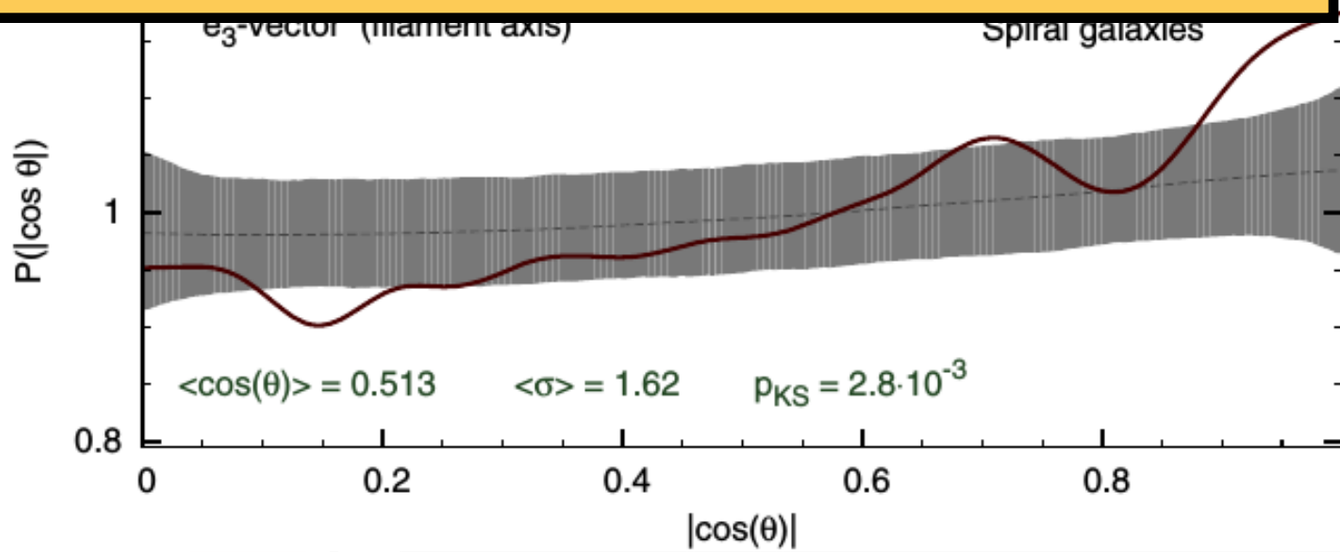


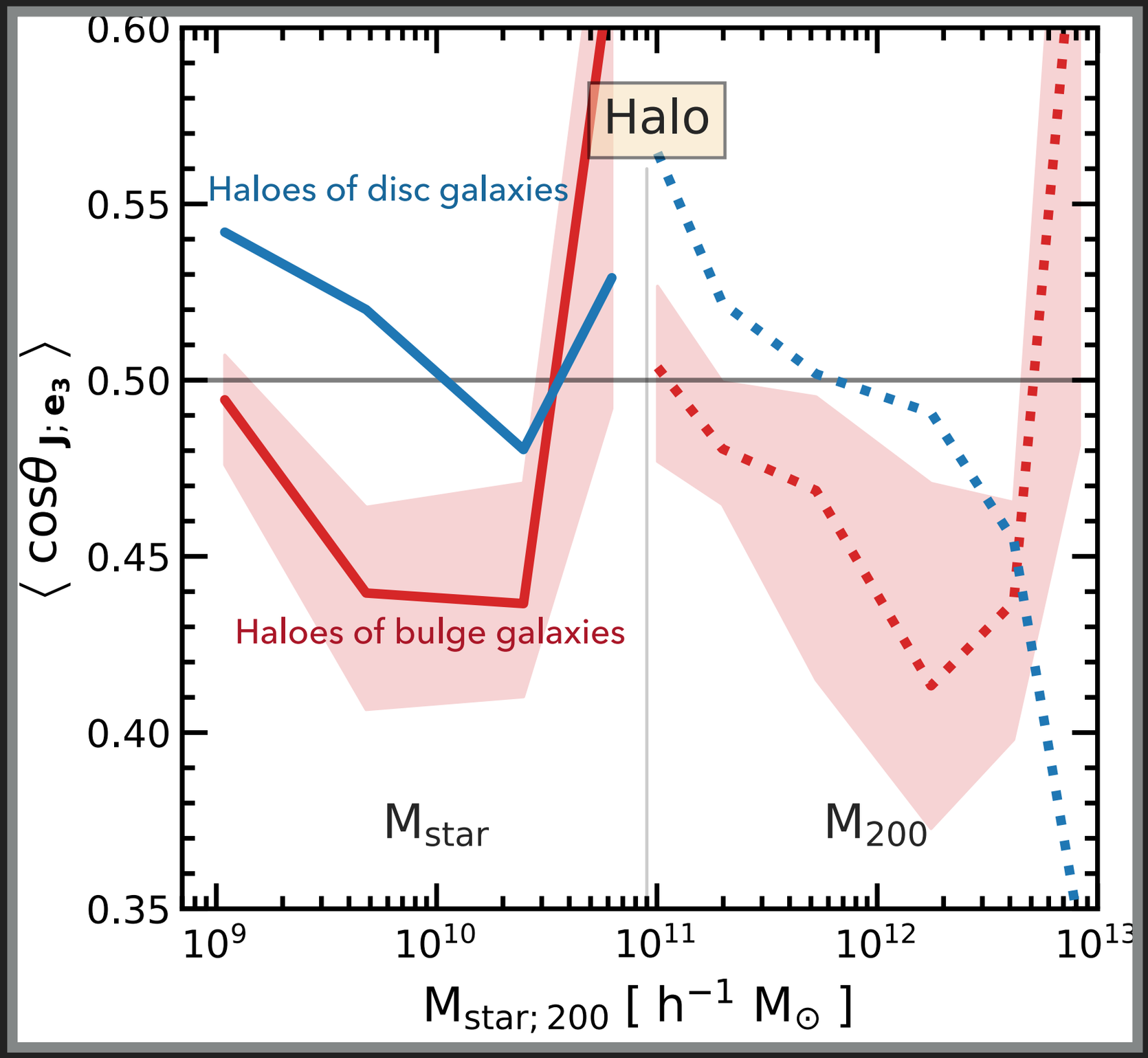
WE DO NOT FIND DISCS PARALLEL IN EAGLE!



P. Ganesha

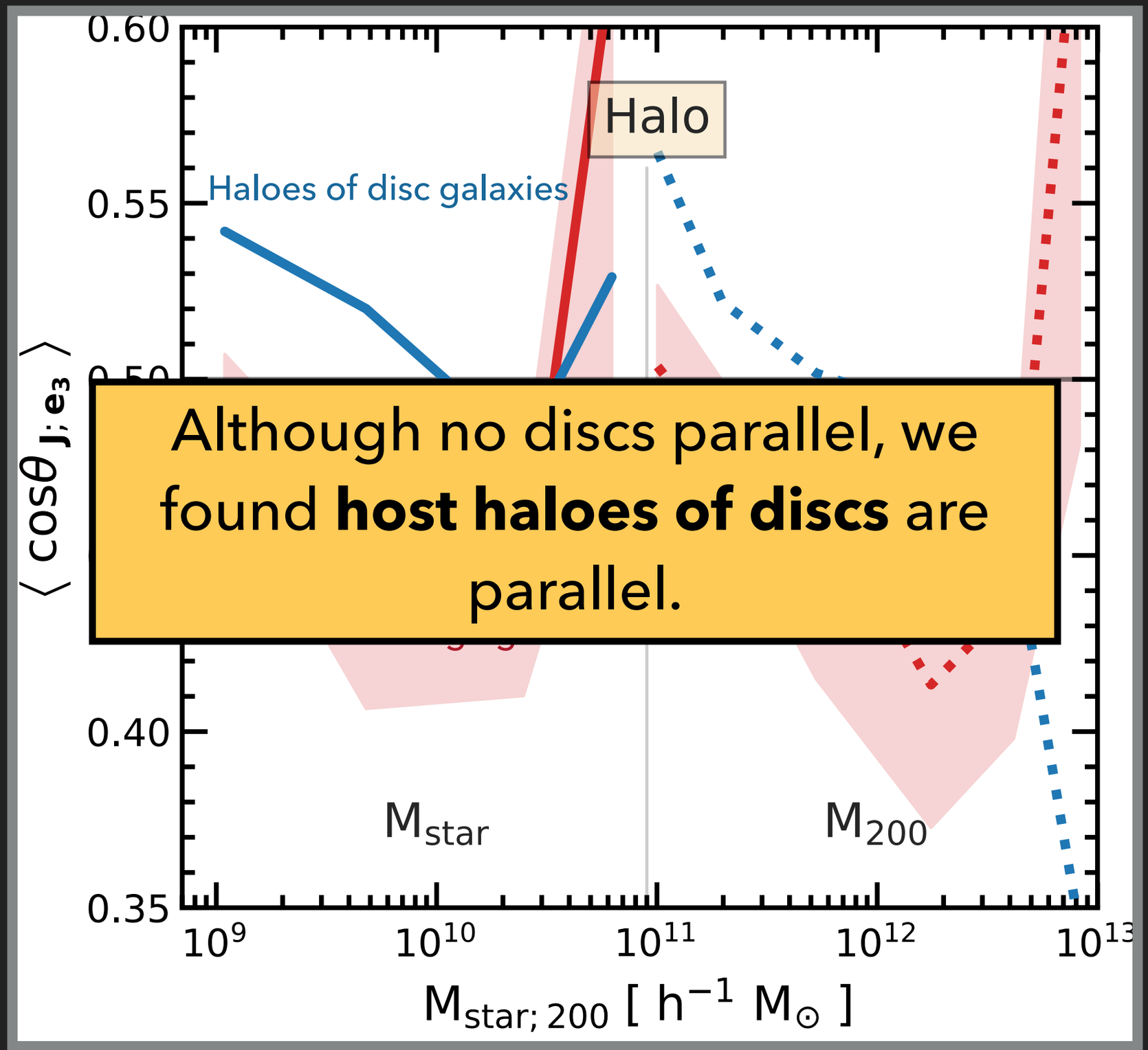
Tempel & Libeskind 2013

DISC AND BULGE DOMINATED



P. Ganeshaiah Veena et al 2019

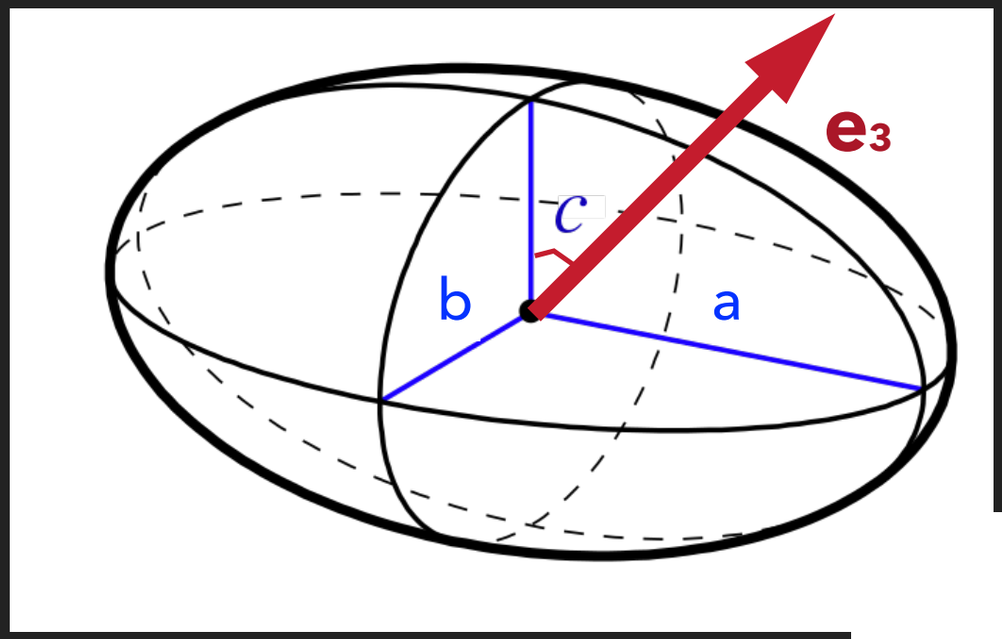
DISC AND BULGE DOMINATED

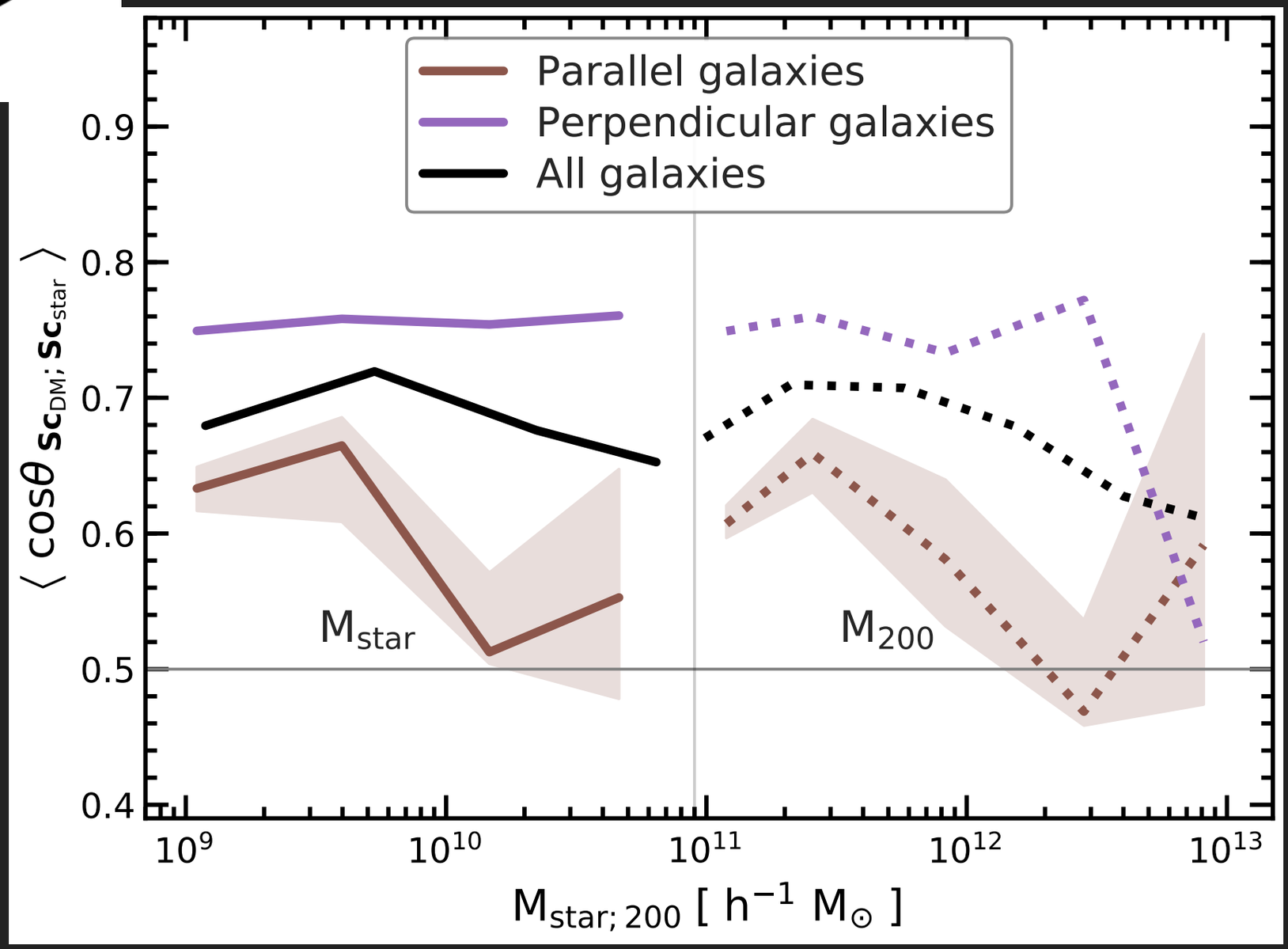


Although no discs parallel, we found **host haloes of discs** are parallel.

P. Ganeshaiah Veena et al 2019

QUESTION: HALO-GALAXY CONNECTION- IS IT POSSIBLE TO PREDICT HOW HALOES ARE ALIGNED IF WE KNOW HOW THEIR GALAXIES ARE ALIGNED?





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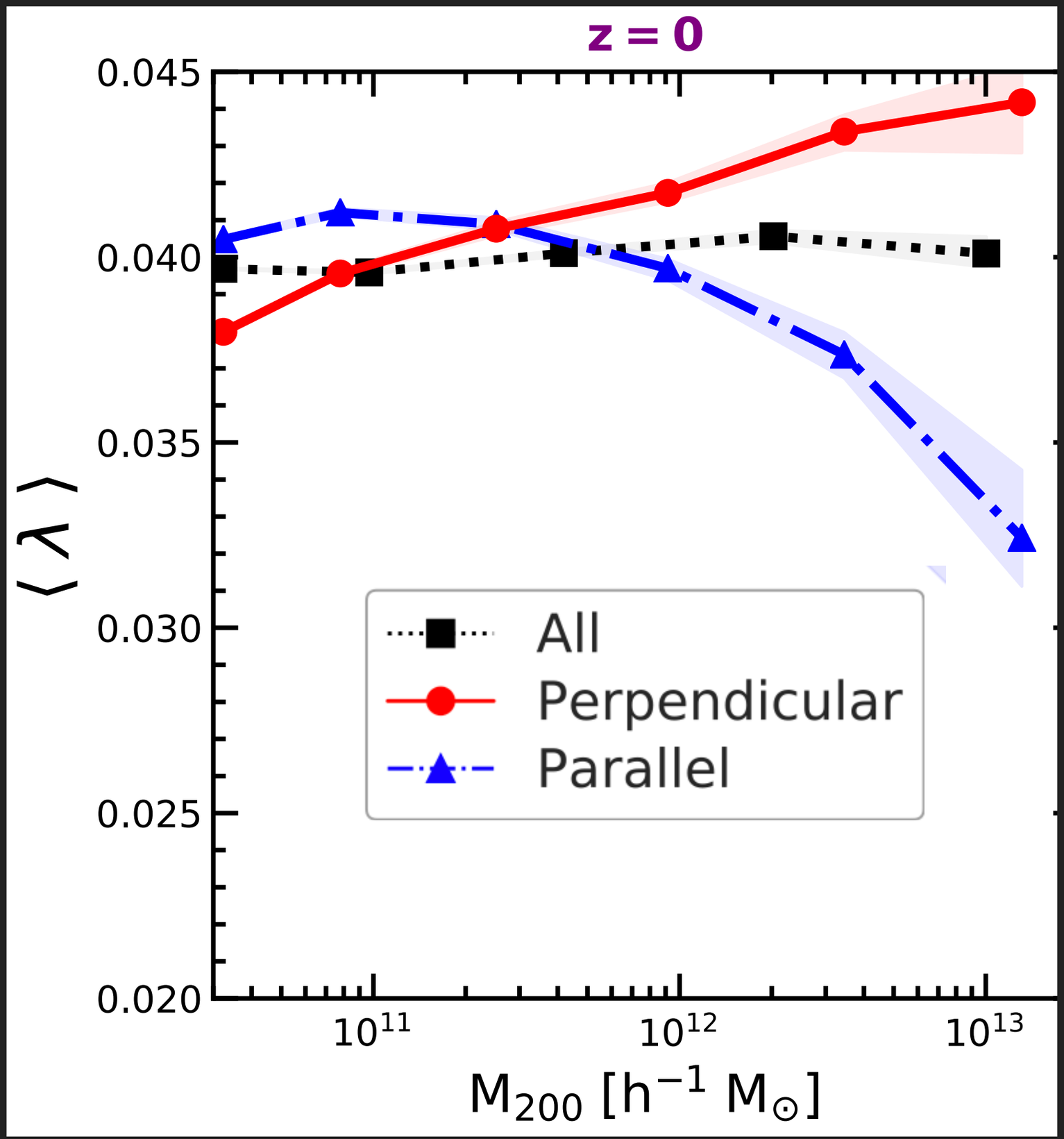
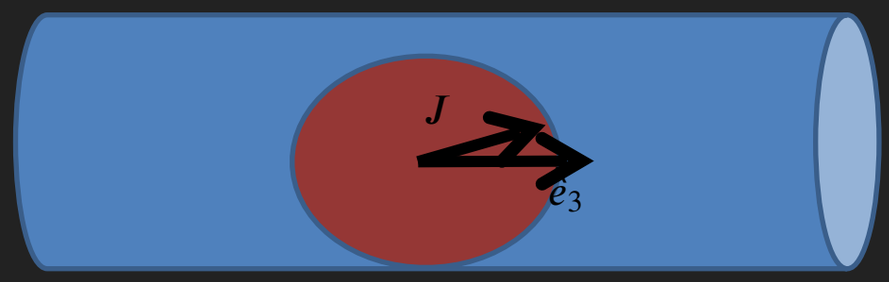


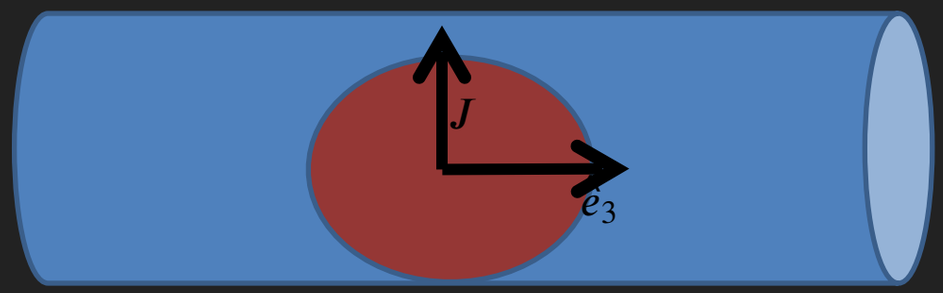


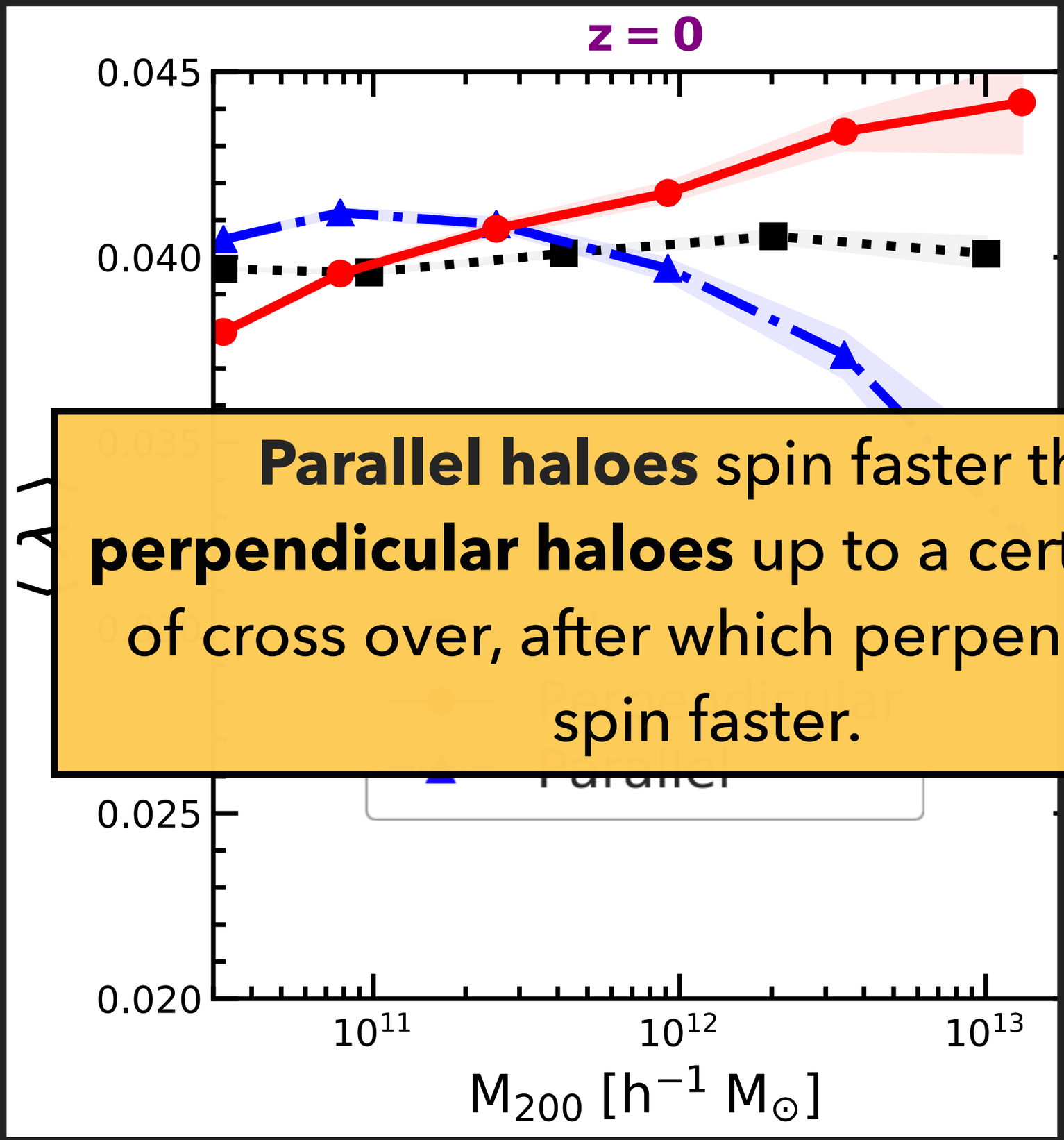
$\cos(\theta) \geq 0.8 \longrightarrow$ Parallel

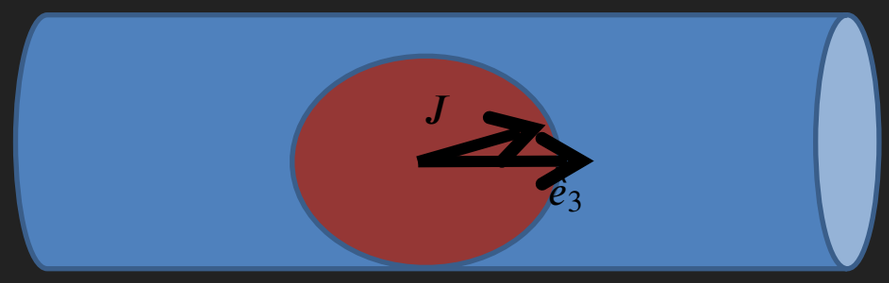
$\theta \leq 36^{\circ}$

$\cos(\theta) \leq 0.2 \longrightarrow$ Perpendicular

$\theta \geq 80^{\circ}$







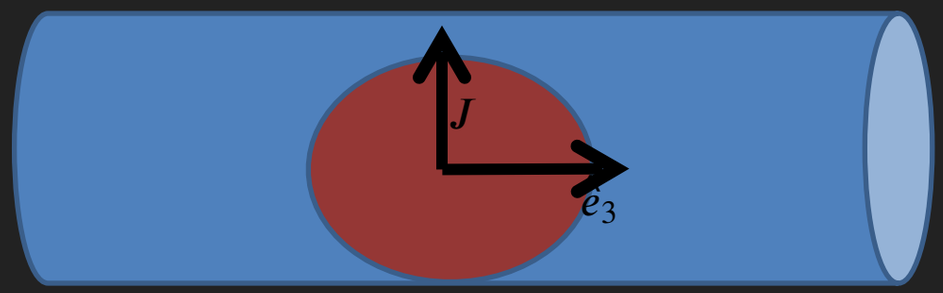
$\cos(\theta) \geq 0.8 \longrightarrow$ Parallel

$\theta \leq 36^\circ$

Parallel haloes spin faster than **perpendicular haloes** up to a certain mass of cross over, after which perpendiculars spin faster.

$\cos(\theta) \leq 0.2 \longrightarrow$ Perpendicular

$\theta \geq 80^\circ$



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- Transition mass is influenced by several factors such as host filament properties, cosmic time and anisotropy of the web environment.
- Galaxies are more perpendicular to filaments than their host haloes and their spin alignments depends on their mass and morphology.
- Host haloes of parallel and perpendicular galaxies show different degree of alignments with their galaxies.

RELEVANCE

- **Dark matter halo - galaxy connection:** How does galaxy alignment compare to its halo spin alignment?

- **A window into galaxy formation?** Spirals and ellipticals show different alignments with respect to large scale filaments in observations.
- Spin alignments **hold information of the early Universe** and also help in **correct interpretation of weak lensing measurements.**
- How do **different filament properties** influence halo/galaxy evolution?

WHAT I CAN OFFER FOR THE GROUP HERE

- If you wish to test how your results vary with the cosmic web environment, then I have techniques to extract cosmic web information - best work for filaments.
- Any predictions related to the properties of LSS, I can help test it in simulations - eg. neutrinos, fuzzy dark matter etc.
- Can we use H1 21cm and/or Ly-alpha as tracers to detect cosmic filaments?
- Interested in exploring the galaxy spins as relics of early Universe - looking for ideas and collaborations.
- Also interested in applying deep learning techniques to detect the cosmic web.

Thank you!

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