PART 1- THE COSMIC BALLET

spinning in the web

Punyakoti Ganeshaiah Veena

with Rien van de Weygaert , Elmo Tempel, Marius Cautun

PART 2 - Unmasking the Universe with neural nets

arXiv: 2212.06439

with Robert Lilow and Adi Nusser
Technion, Haifa, Israel.

IN PART - 1

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.**

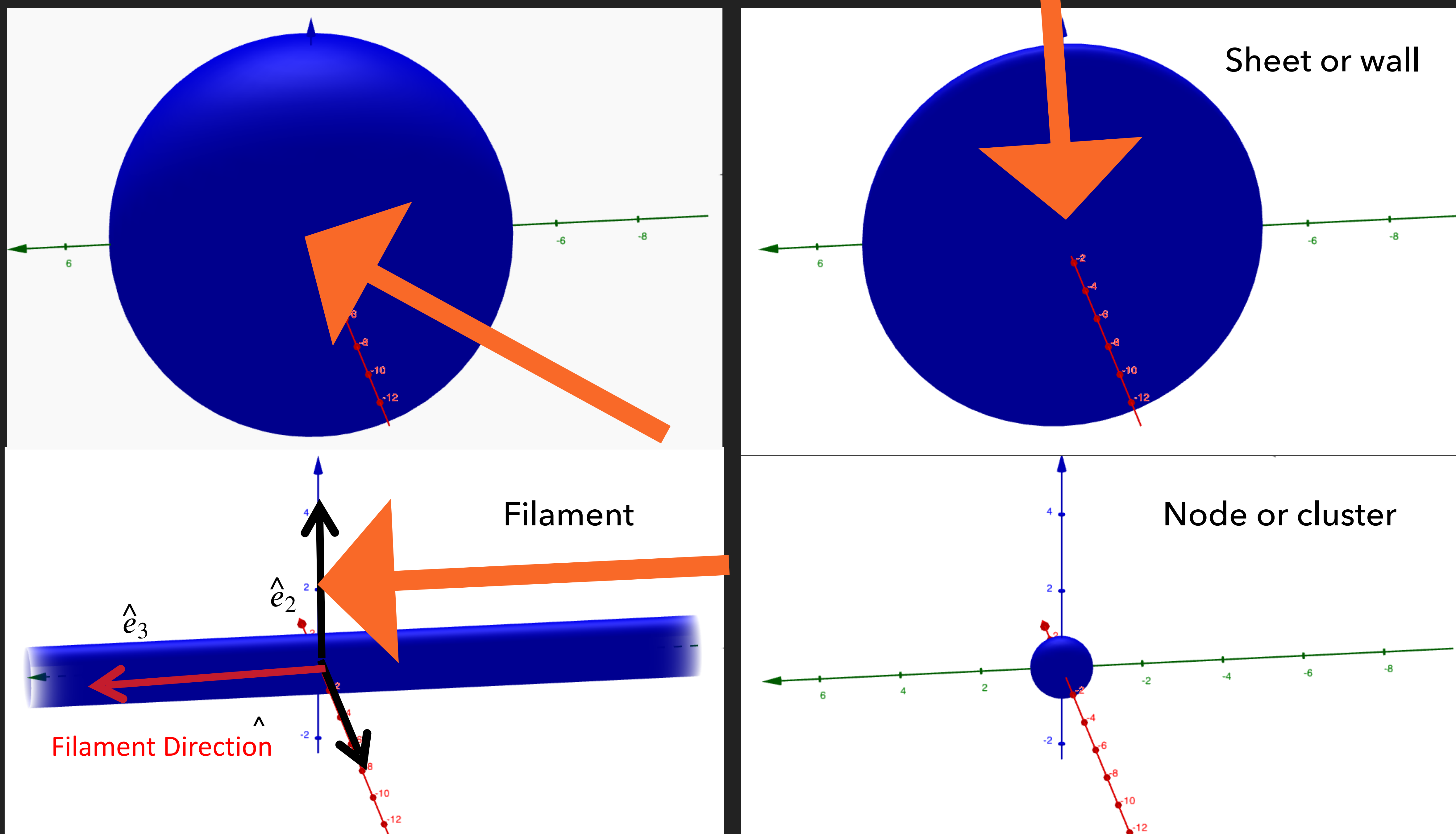
3. **P. Ganeshaiah Veena,** M. Cautun, R. van de Weygaert, E. Tempel, C. S. Frenk; MNRAS, **2021.**

TIDAL FIELDS AND COSMIC WEB – ANISOTROPIC COLLAPSE

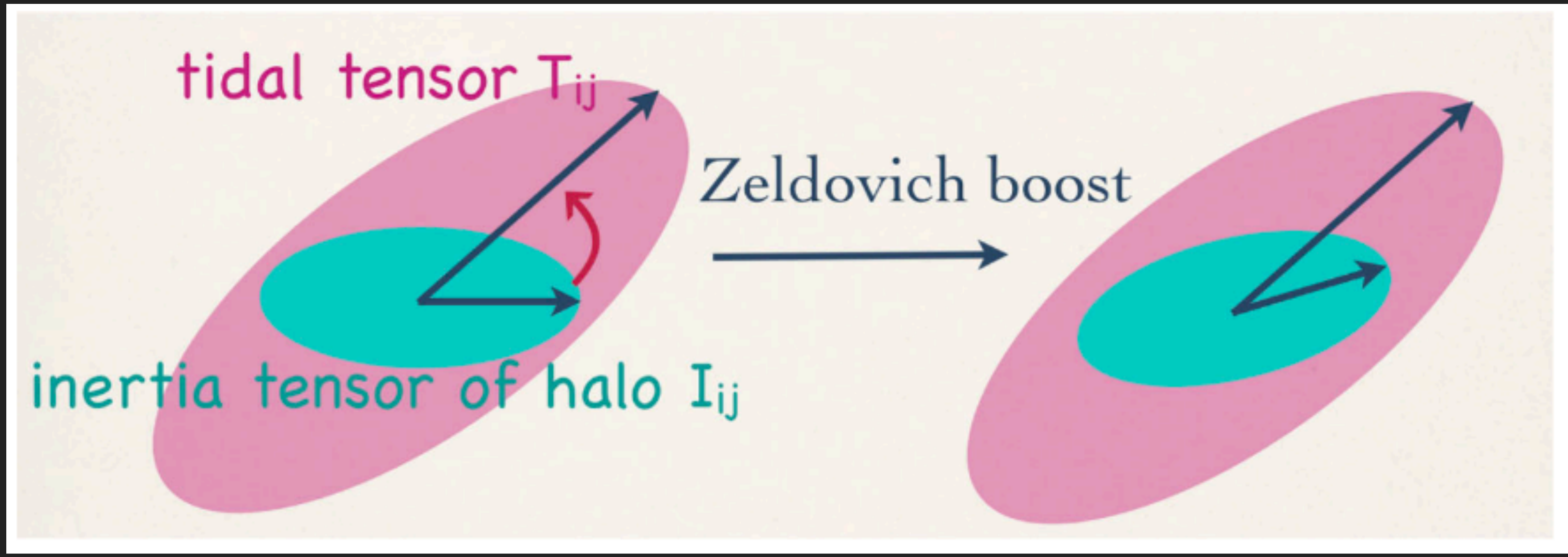
$$\Psi_{ij} = \frac{\partial^2 \Psi}{\partial q_i \partial q_j} \qquad \Psi(q) = -\frac{2}{3\Omega_0 H_0^2}\Phi_0$$

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

Cluster	Filament	Wall	Void
$\lambda_1 > 0$	$\lambda_1 > 0$	$\lambda_1 > 0$	$\lambda_1 < 0$
$\lambda_2 > 0$	$\lambda_2 > 0$	$\lambda_2 < 0$	$\lambda_2 < 0$
$\lambda_3 > 0$	$\lambda_3 < 0$	$\lambda_3 < 0$	$\lambda_3 < 0$



TIDAL TORQUING



Codis et al 2015

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

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

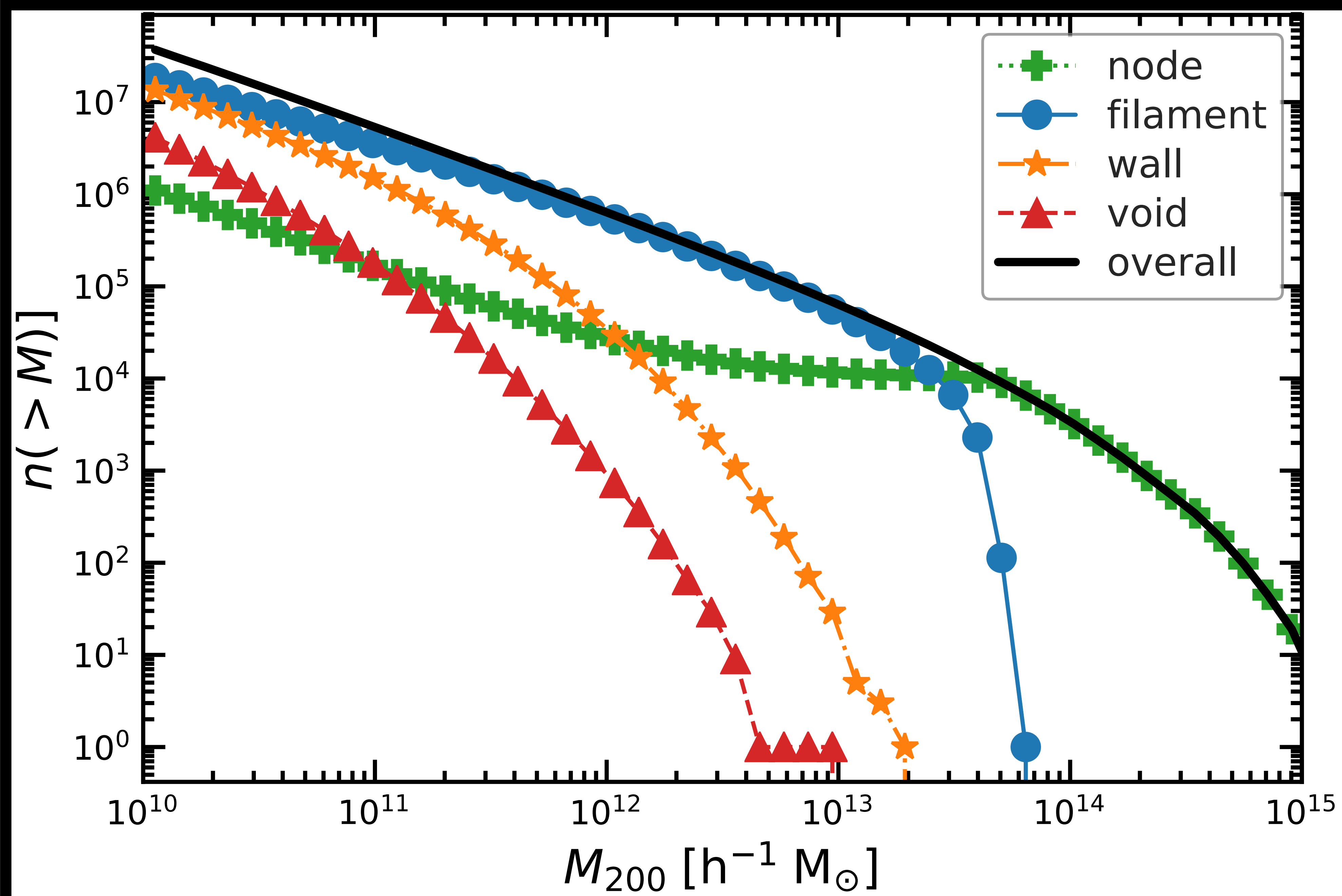
Angular momentum grows linearly until turn-around.

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

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**?**
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 – MASS FUNCTION



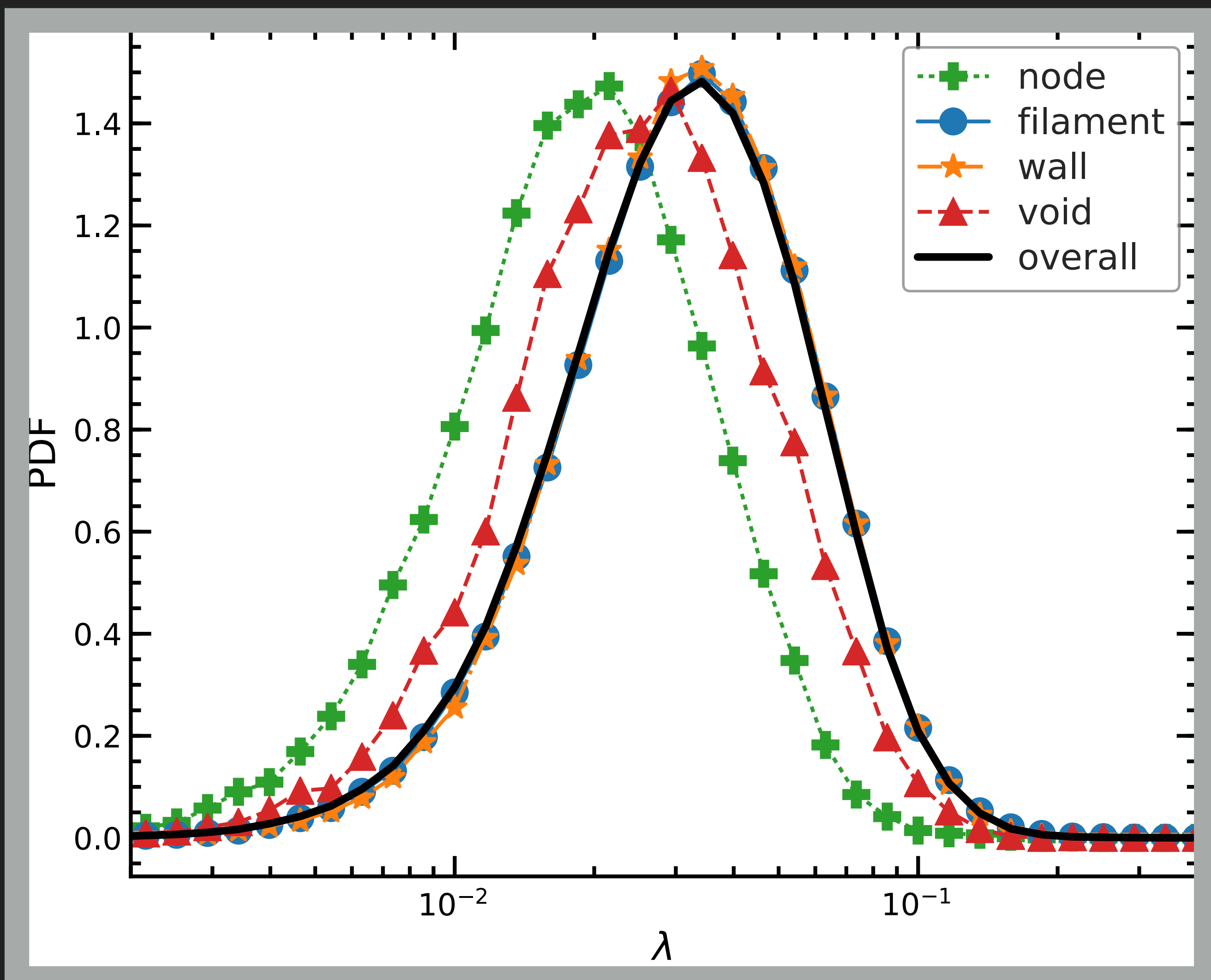
P. Ganeshaiah Veena et al 2018

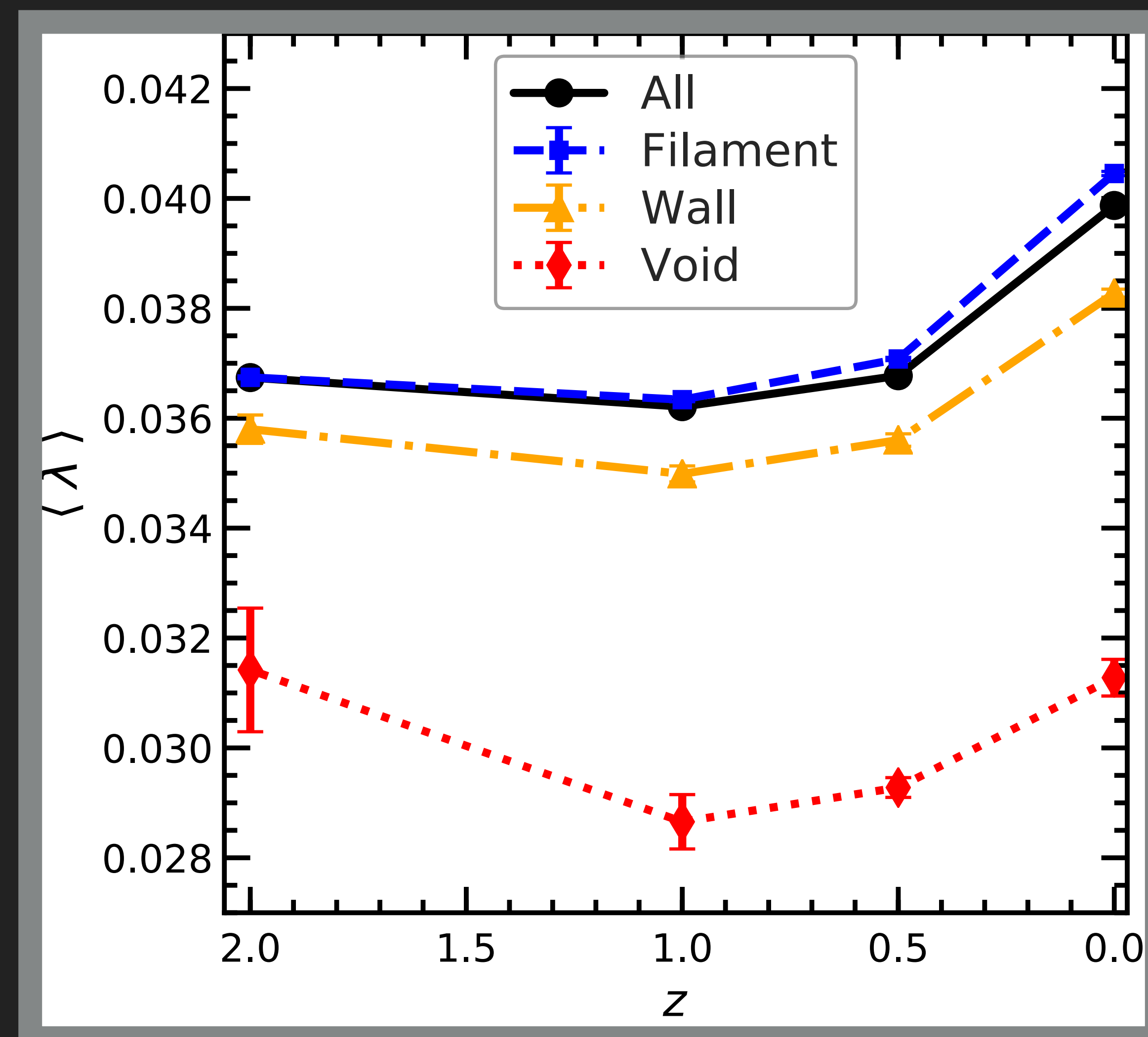
~36 million haloes at z=0

~2.8 million haloes chosen for this study

PLANCK-MILLENNIUM SIMULATION – SPIN PARAMETER

PGV et al 2018





PGVa et al 2021

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

$\lambda = 0 \longrightarrow$ dispersion supported

$\lambda = 1 \longrightarrow$ rotation supported

NEXUS +

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

NEXUS VELOCITY SHEAR

- Velocity shear
- Dynamical signature

Morphology: eigenvalue conditions

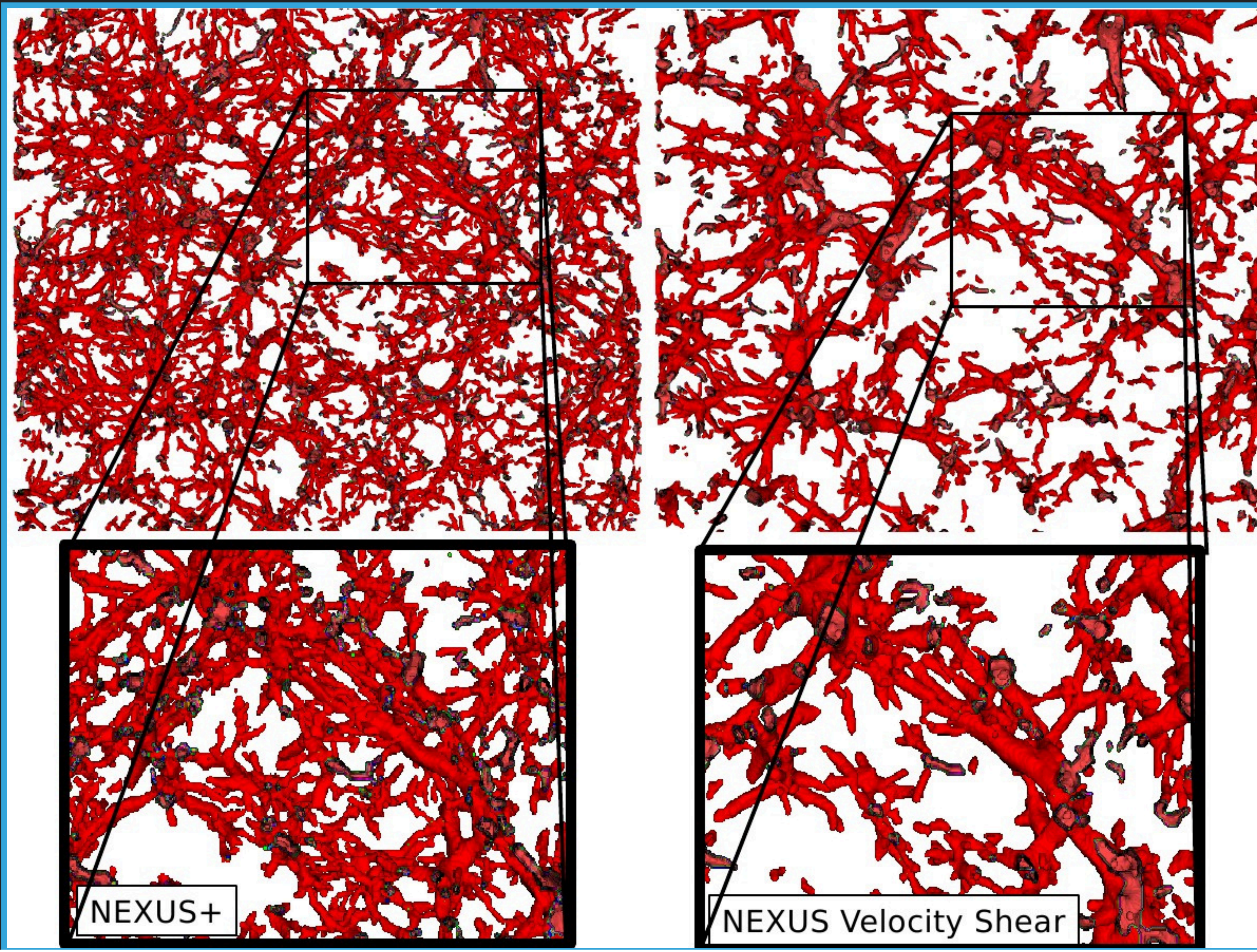
Multiscale detection

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

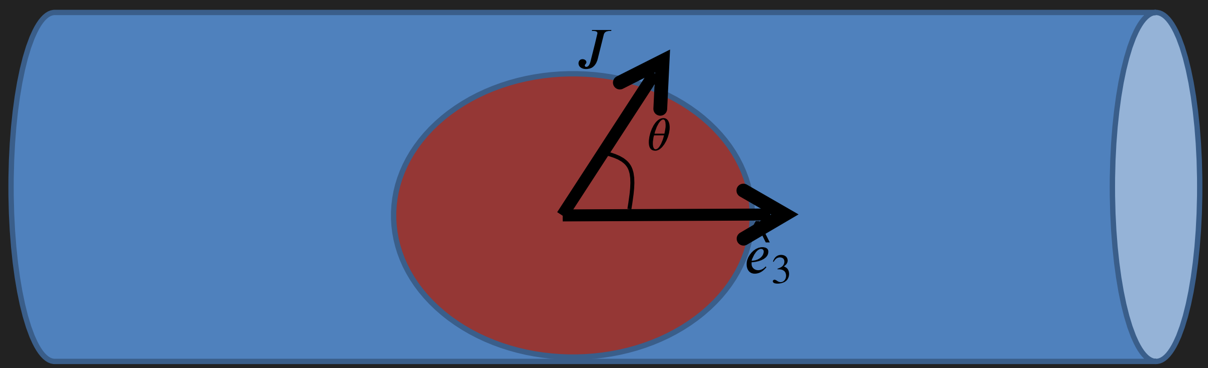
NEXUS *– Multiscale cosmic web detection formalism developed at Kapteyn Institute, Groningen [Aragon-Calvo et al 2007; Cautun et al 2013]*

WEB FINDERS

NEXUS+ | NEXUS VELOCITY SHEAR



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



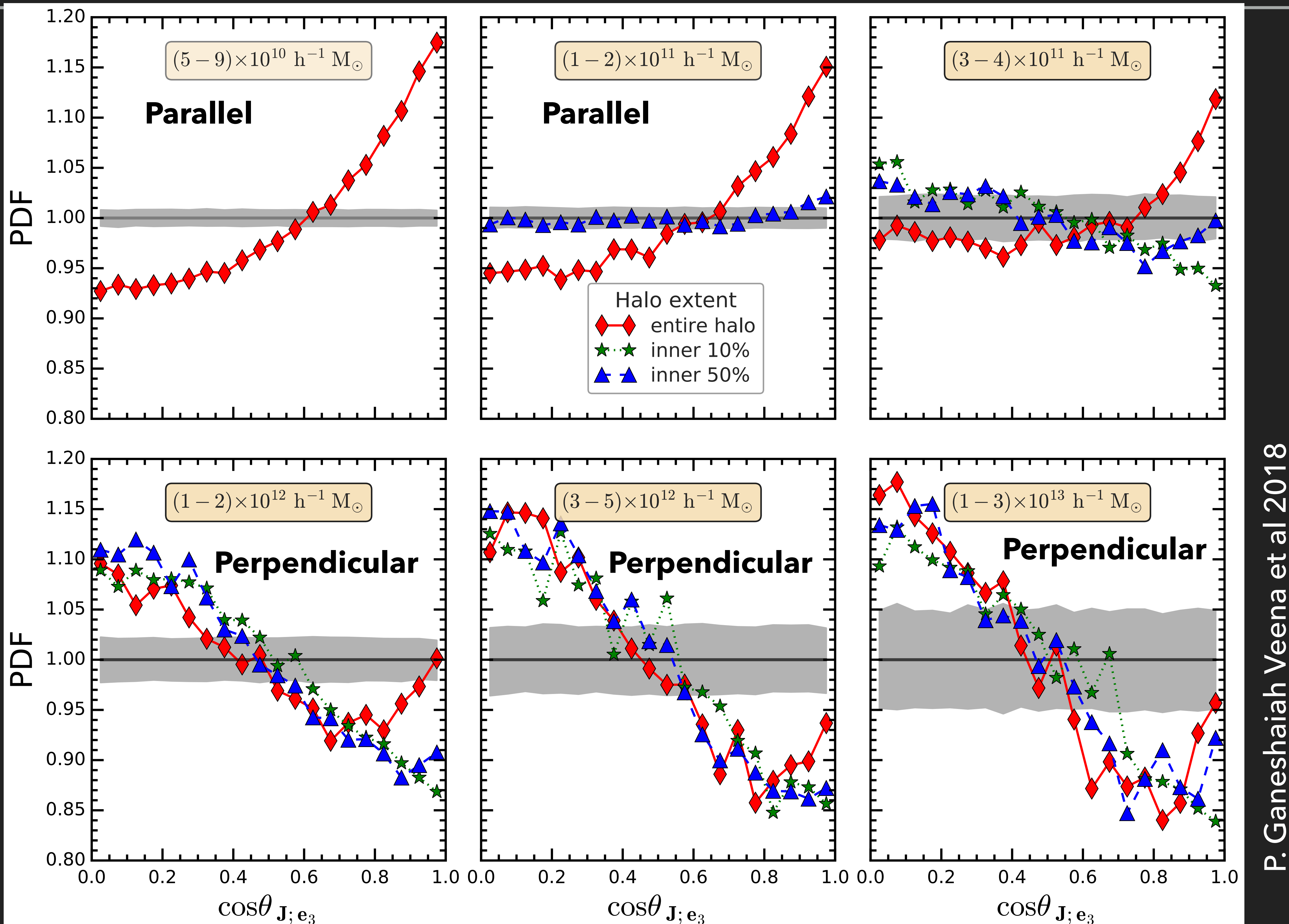
$$\cos\theta_{\mathbf{J},\mathbf{e}_3} = \left| \frac{\mathbf{J}\cdot\mathbf{e}_3}{|\mathbf{J}||\mathbf{e}_3|} \right|$$

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

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

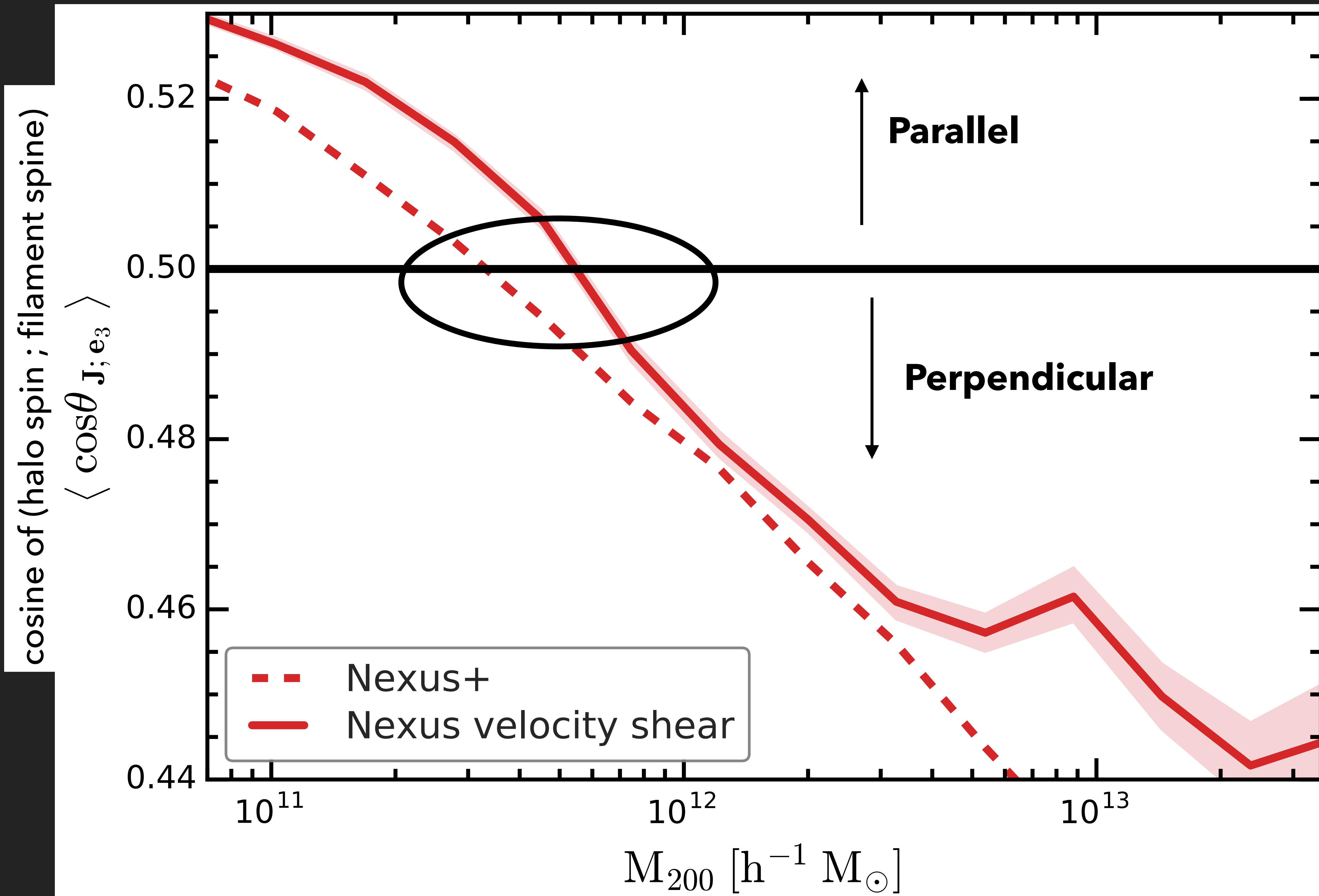
$$\cos(\theta) = 0 \longrightarrow \text{Perpendicular}$$

HALO MASS DEPENDENT ALIGNMENT - PLANCK MILLENNIUM SIMULATION



Aragón-Calvo et al 2007; Hahn et al 2007; Codis et al 2012; Trowland et al 2013; Tempel et al 2013; Forero-Romero et al 2014; Welker et al 2014; Wang et al 2017, 2018; Ganeshaiah Veena et al 2018; Kraljic et al 2019; Lee et al 2019.

NEXUS + VELOCITY SHEAR



P. Ganeshaiah Veena et al 2018

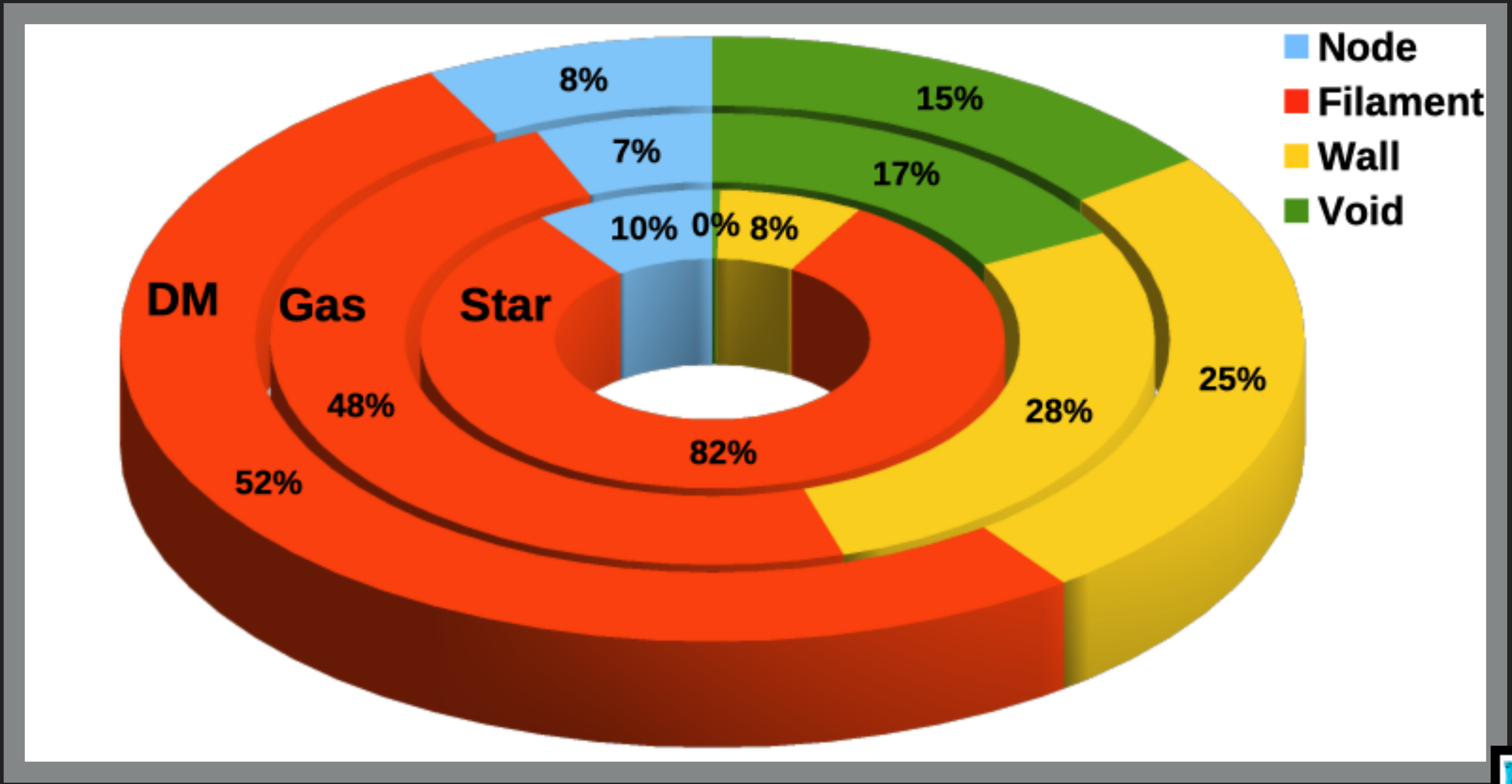
TRANSITION MASS AND WEB FINDERS

Table 1: Halo spin alignments in simulations

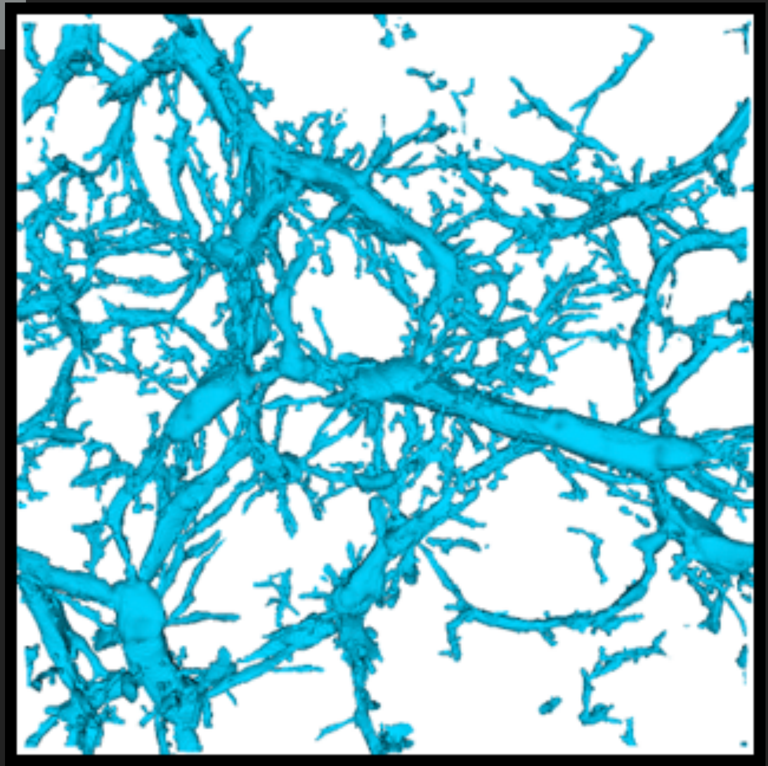
Work by	Simulation box length [h^{-1} Mpc]	Cosmic web detection	Transition mass ($\times 10^{12} h^{-1} \mathrm{M}_{\odot}$)
Aragón-Calvo et al. (2007b)	150	MMF	~ 1
Hahn et al. (2007a)	180	tidal tensor	–
Codis et al. (2012)	2000	DISPERSE	~ 3.5
Libeskind et al. (2012)	64	velocity shear tensor	–
Trowland 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: PGV thesis, table 1, page number 34

MASS FRACTION IN THE UNIVERSE – EAGLE SIMULATION

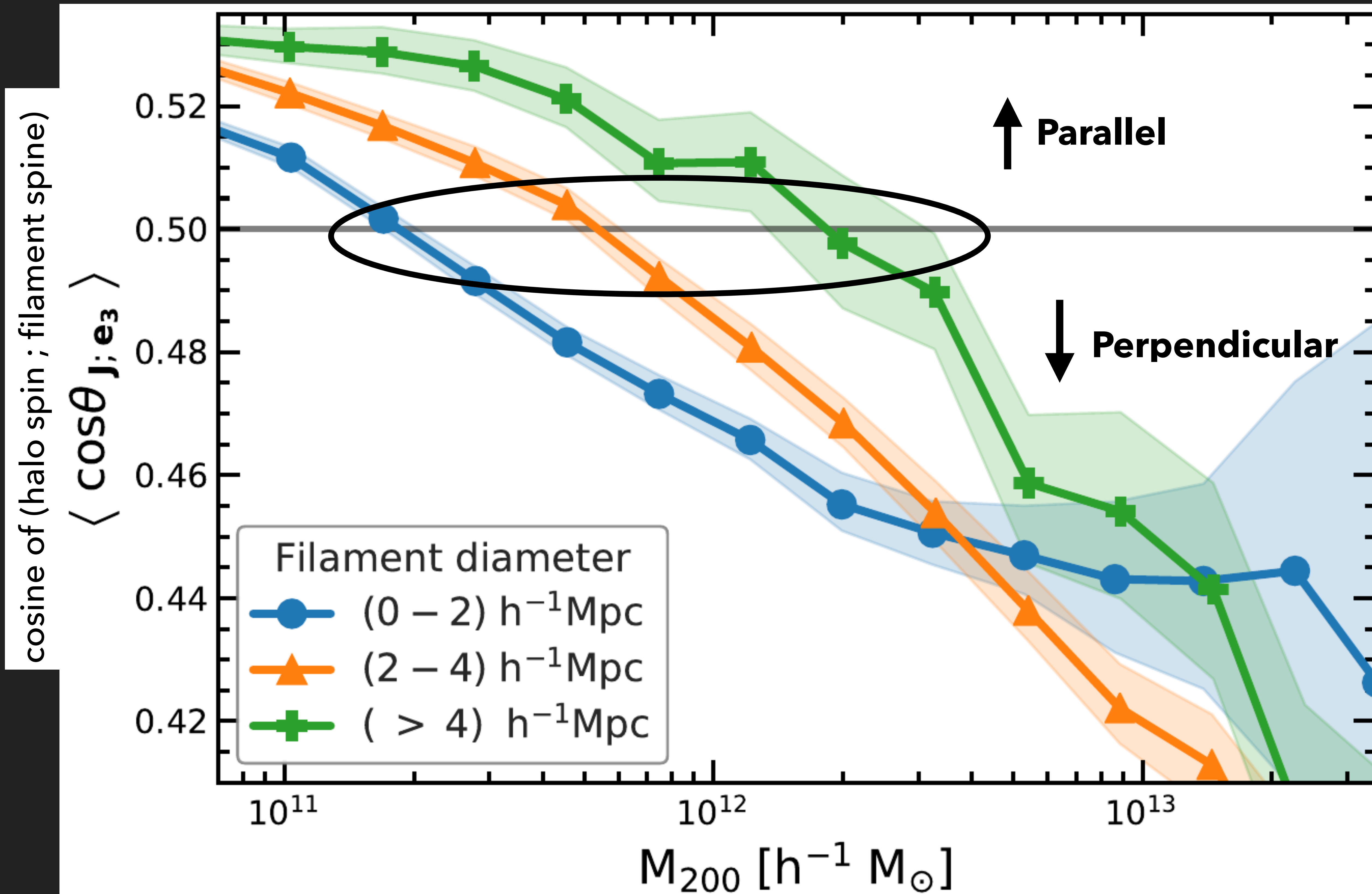


P. **Ganeshaiah Veena,** M. Cautun, E. Tempel, R. van de Weijgaert and C. Frenk, 2020.



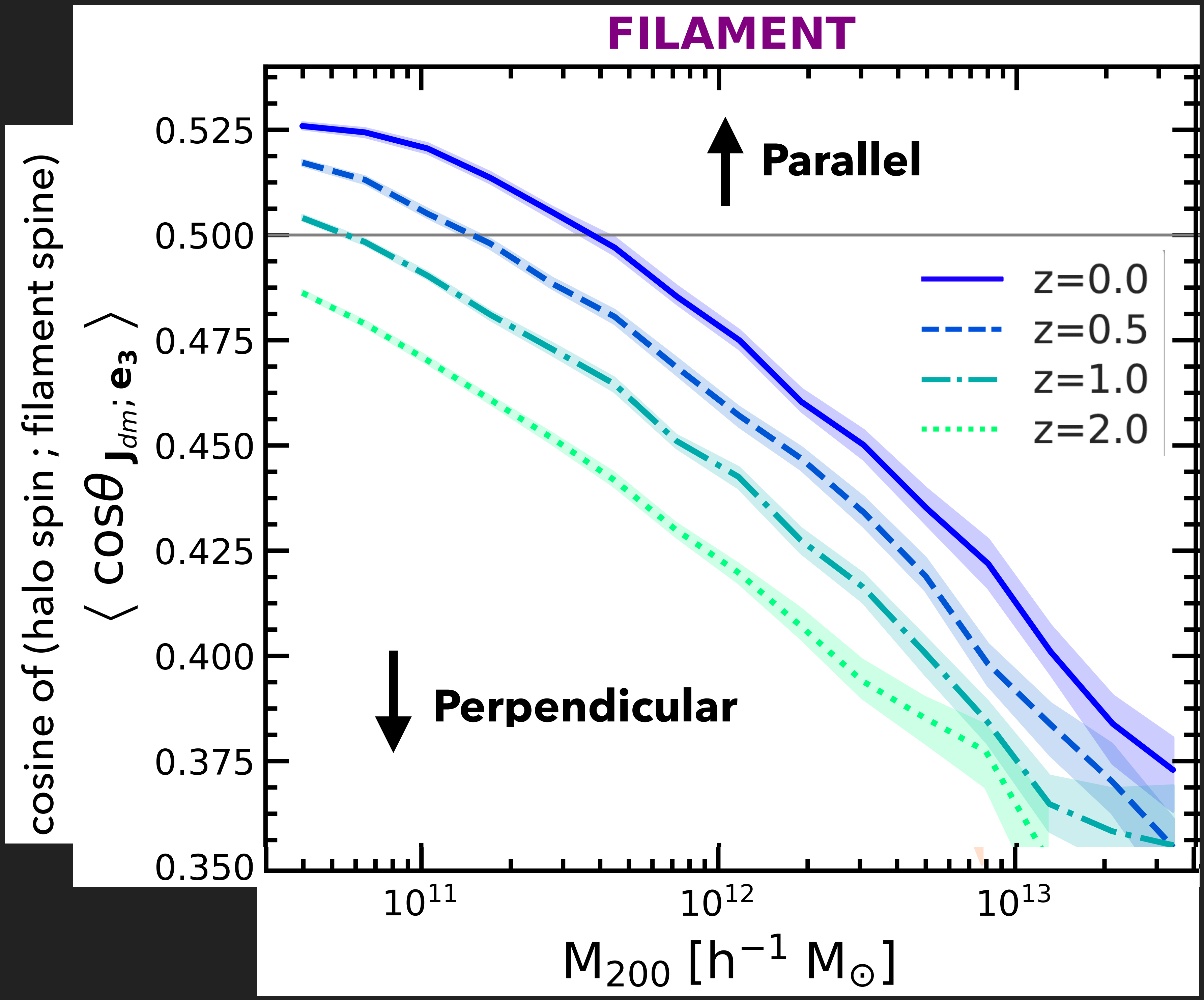
Nexus+ filaments, from Cautun et al 2014.

FILAMENT THICKNESS

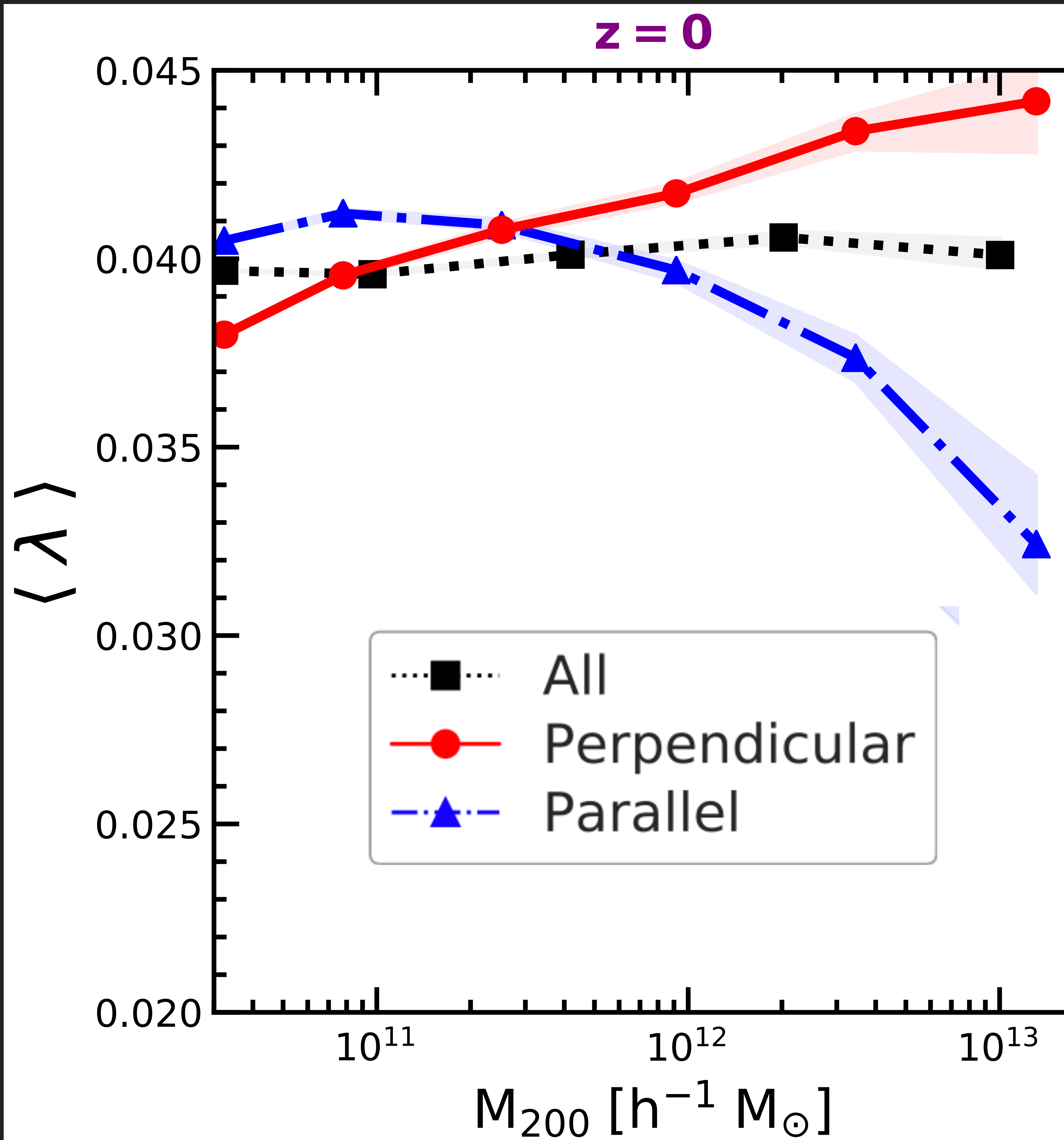


P. Ganeshaiah Veena et al 2018

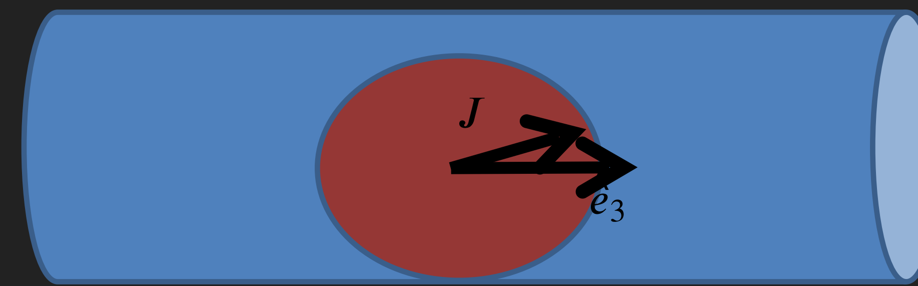
SPIN ALIGNMENT EVOLUTION



P. Ganeshaiah Veena et al 2021



PGV et al 2021

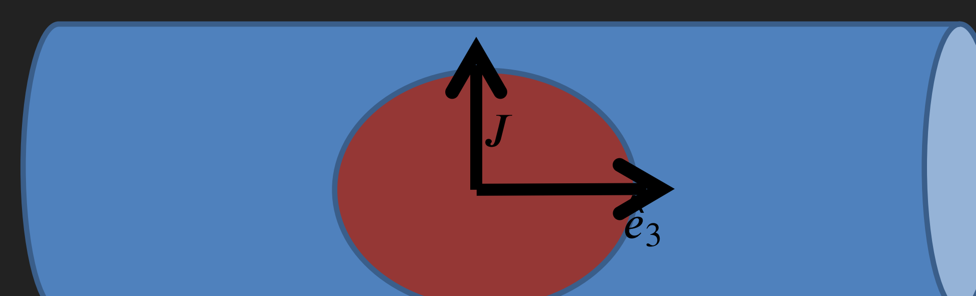


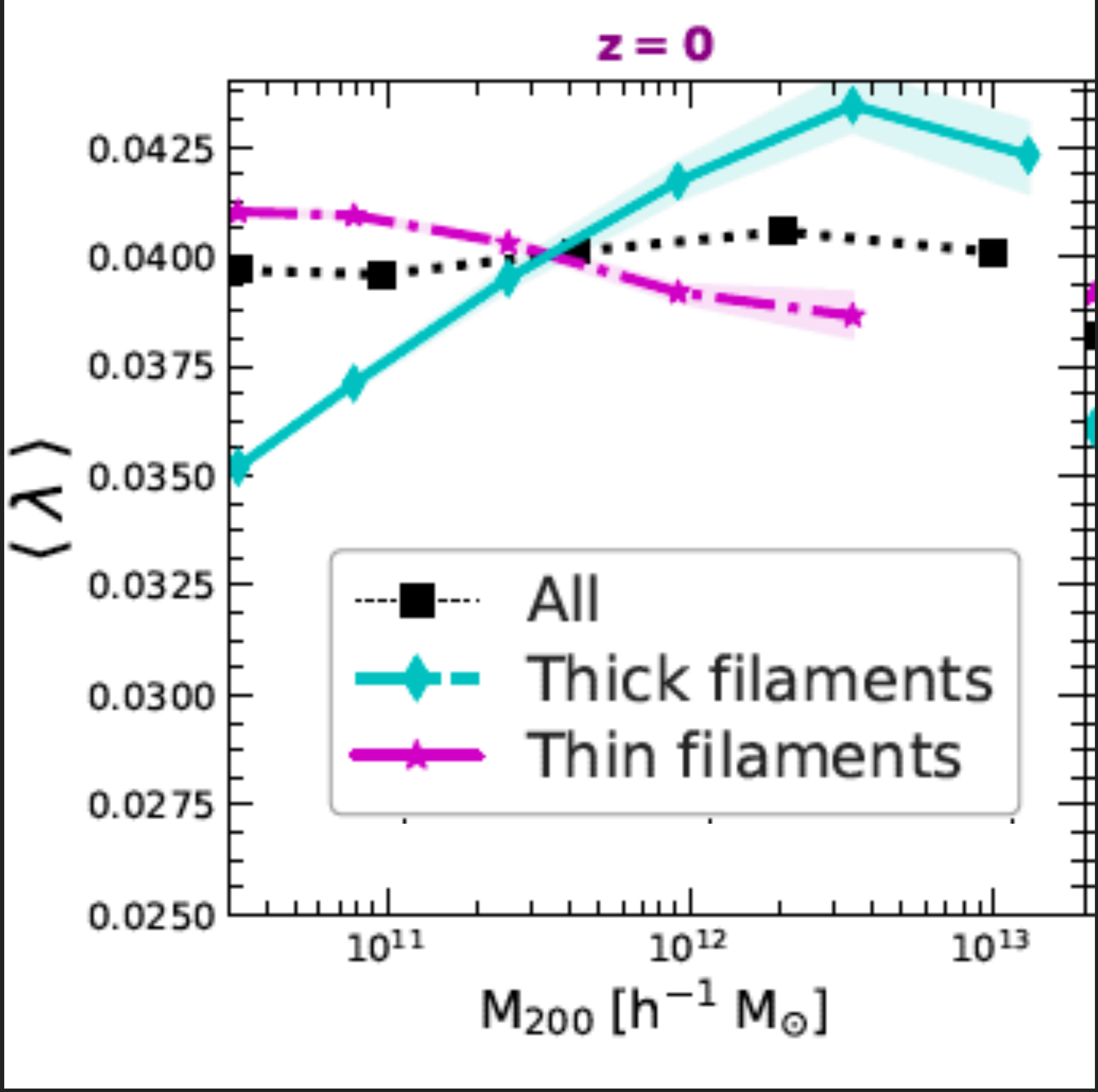
$\cos(\theta) \geq 0.8 \longrightarrow$ Parallel to fila…

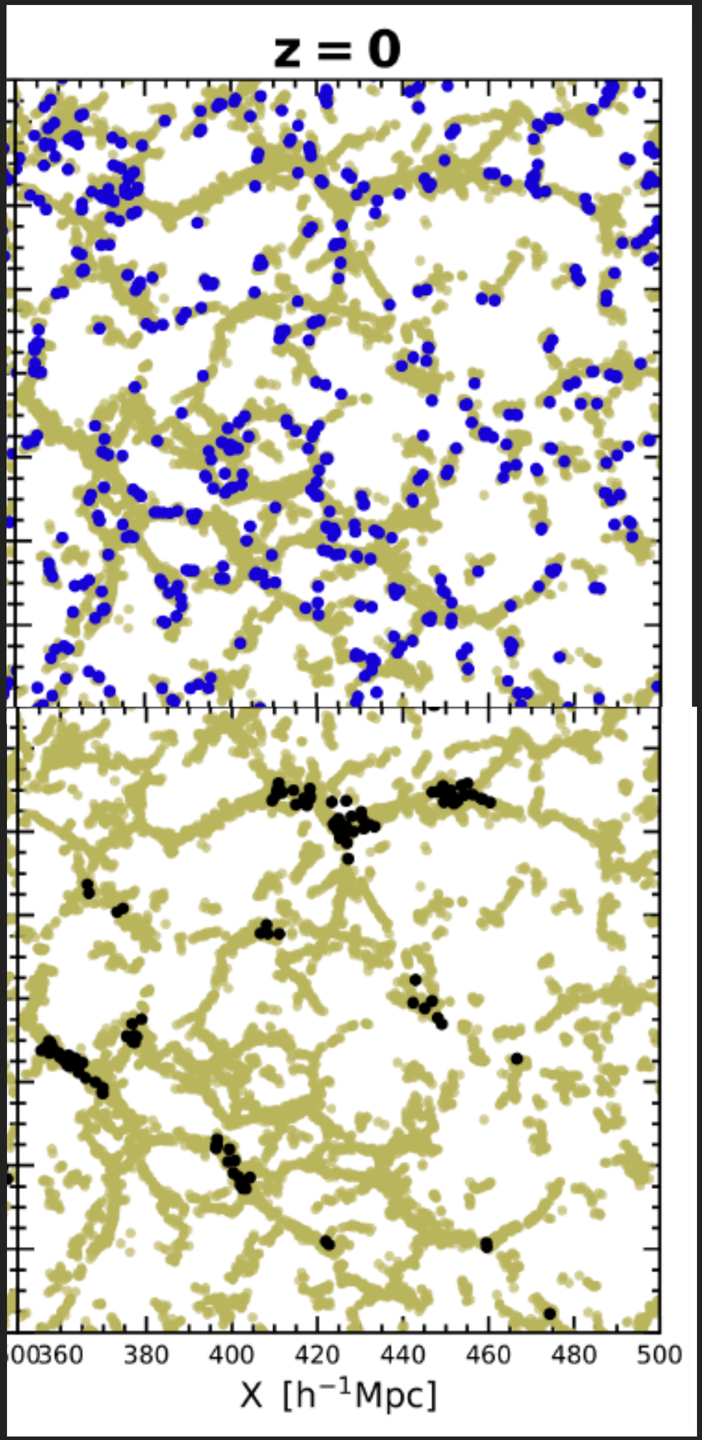
$\theta \leq 36^\circ$

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

$\theta \geq 80^\circ$

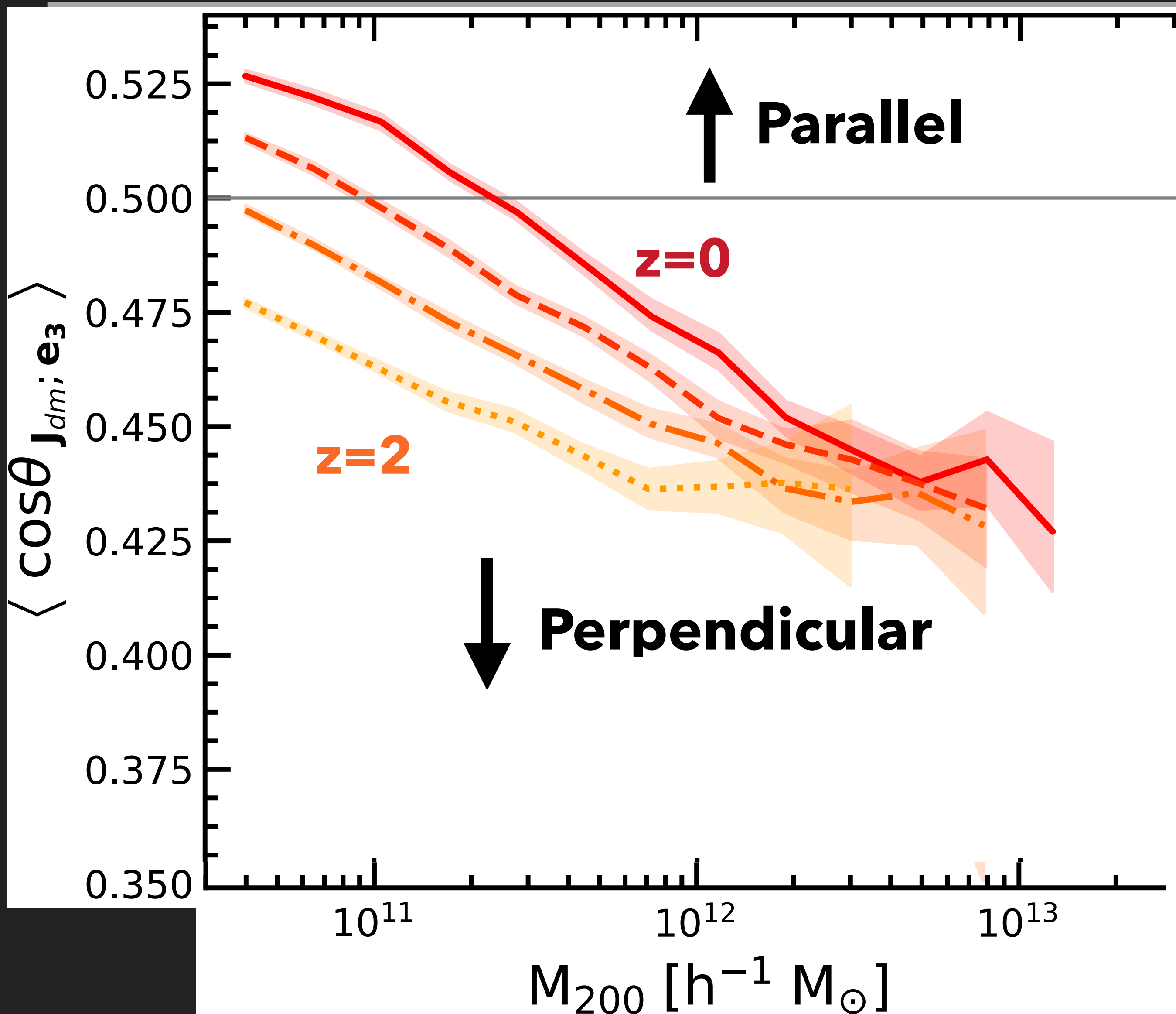


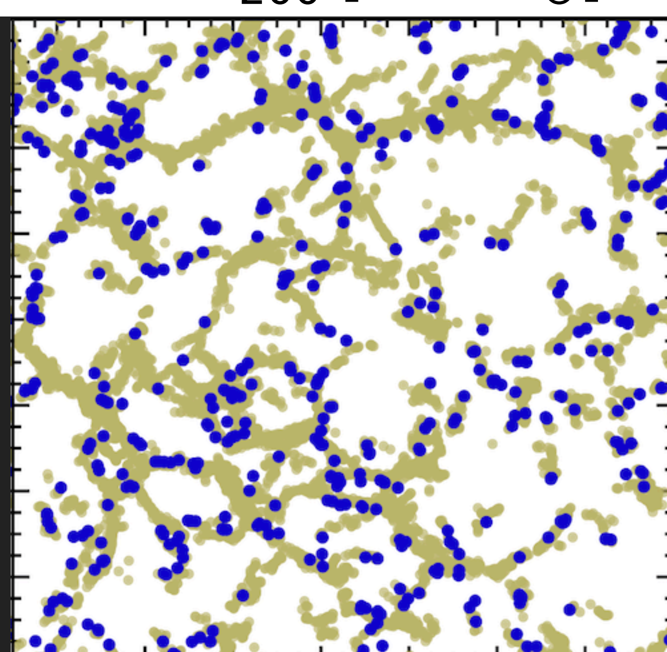




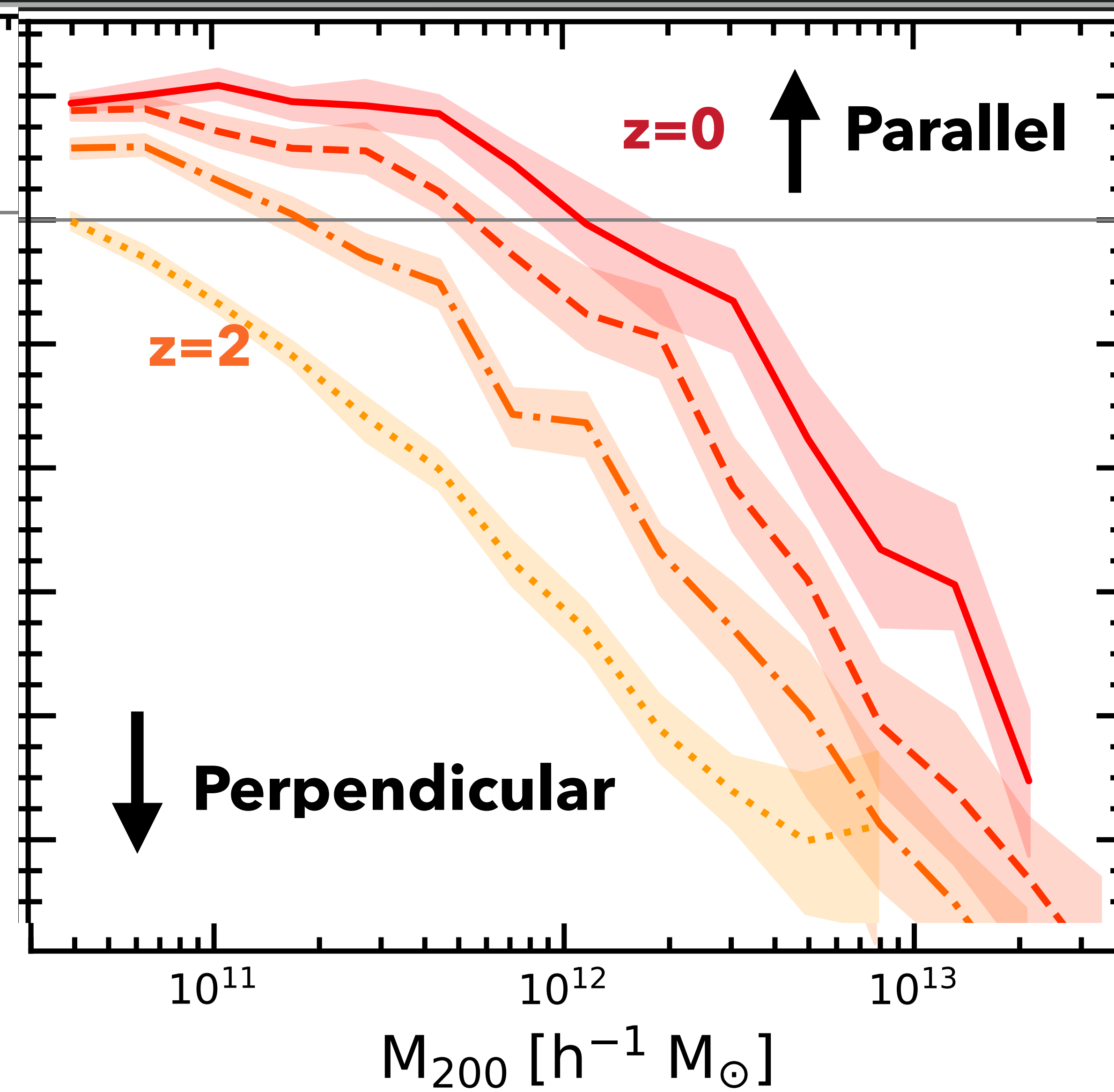
P. Ganeshaiah Veena et al 2021

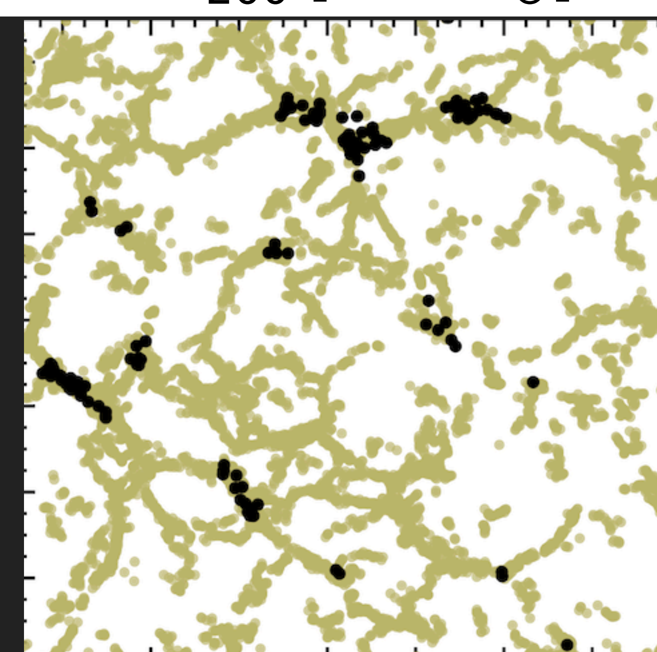
THIN FILAMENTS



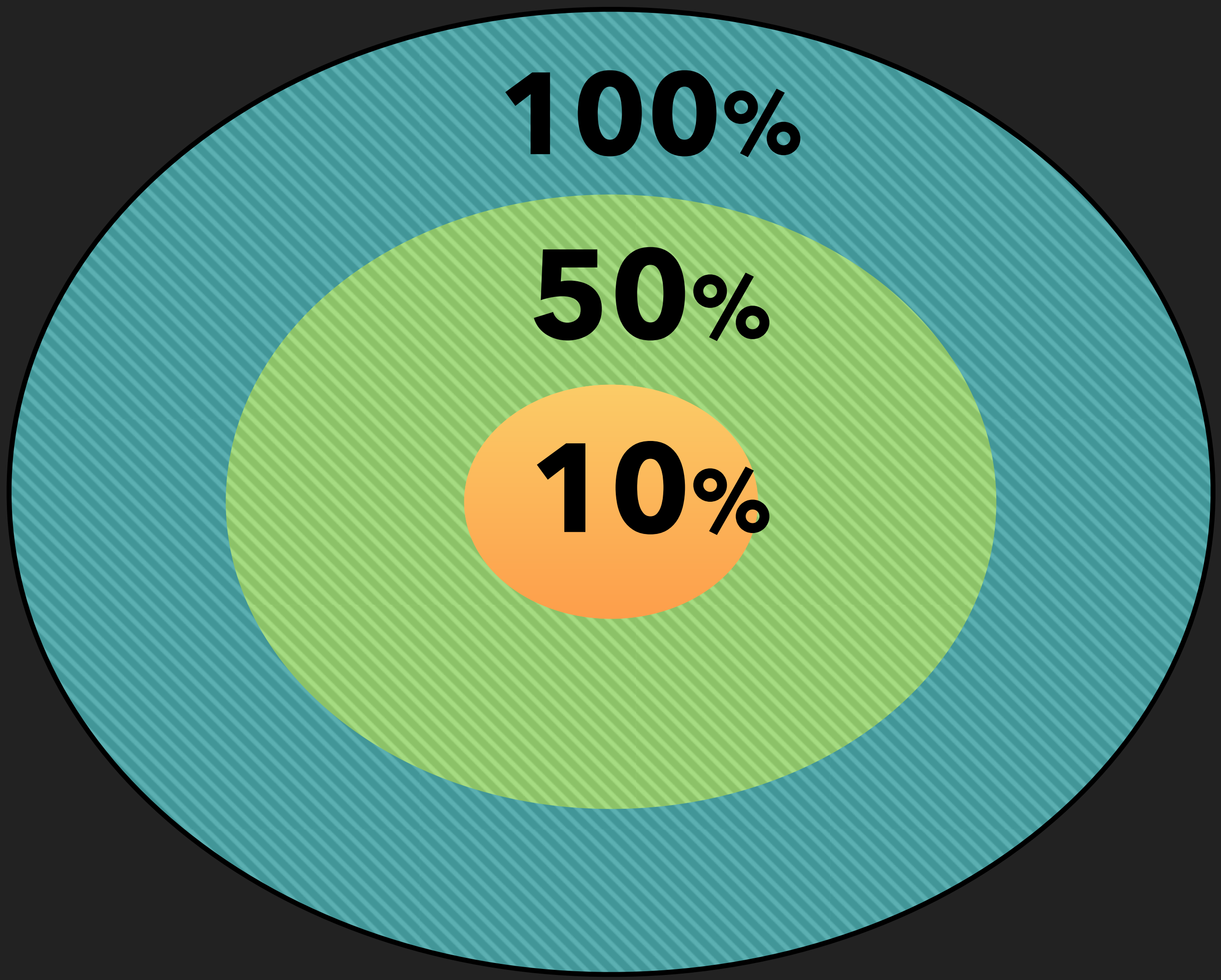


THICK FILAMENTS





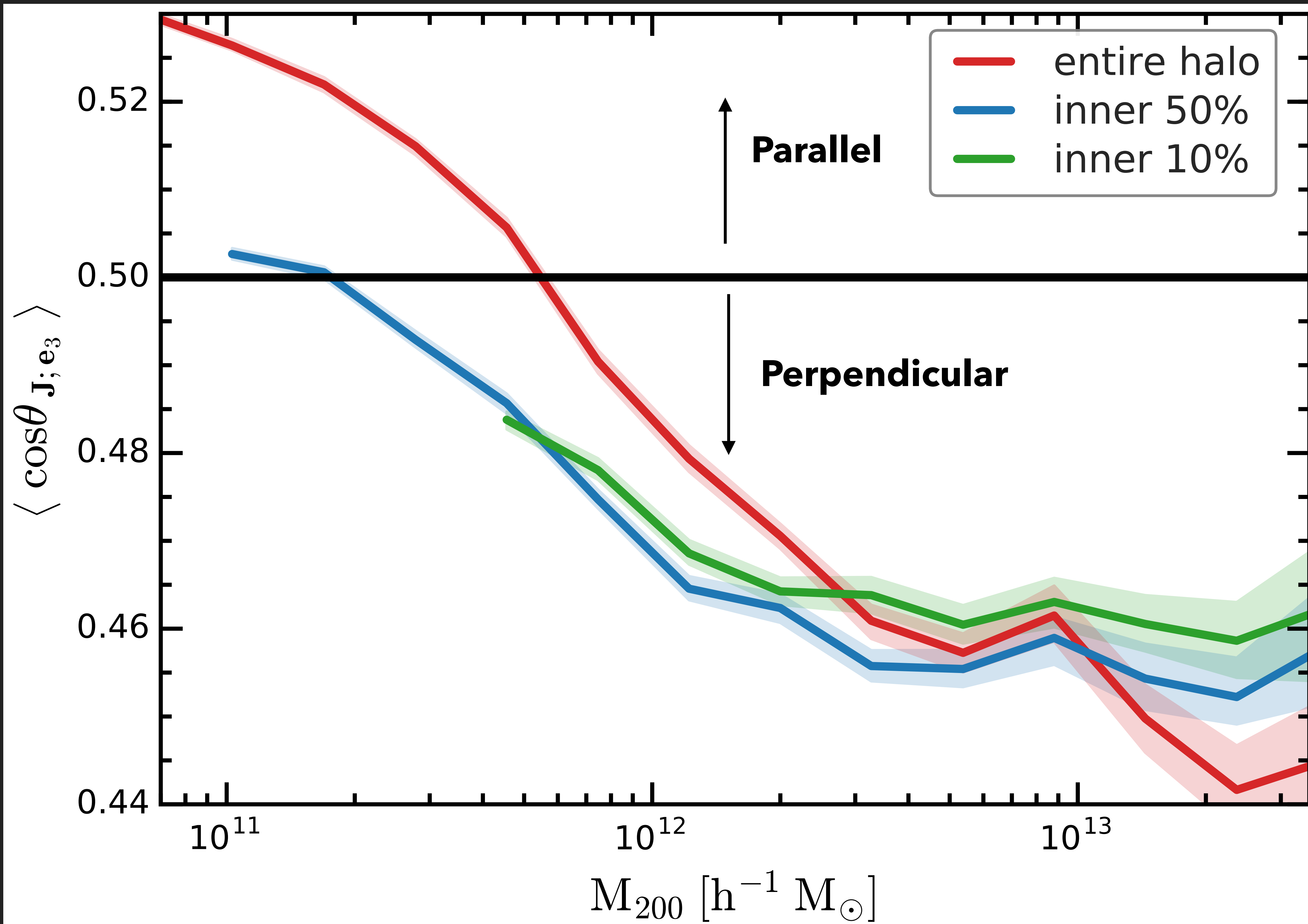
P. Ganeshaiah Veena et al 2020



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

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

INNER HALO FRACTIONS

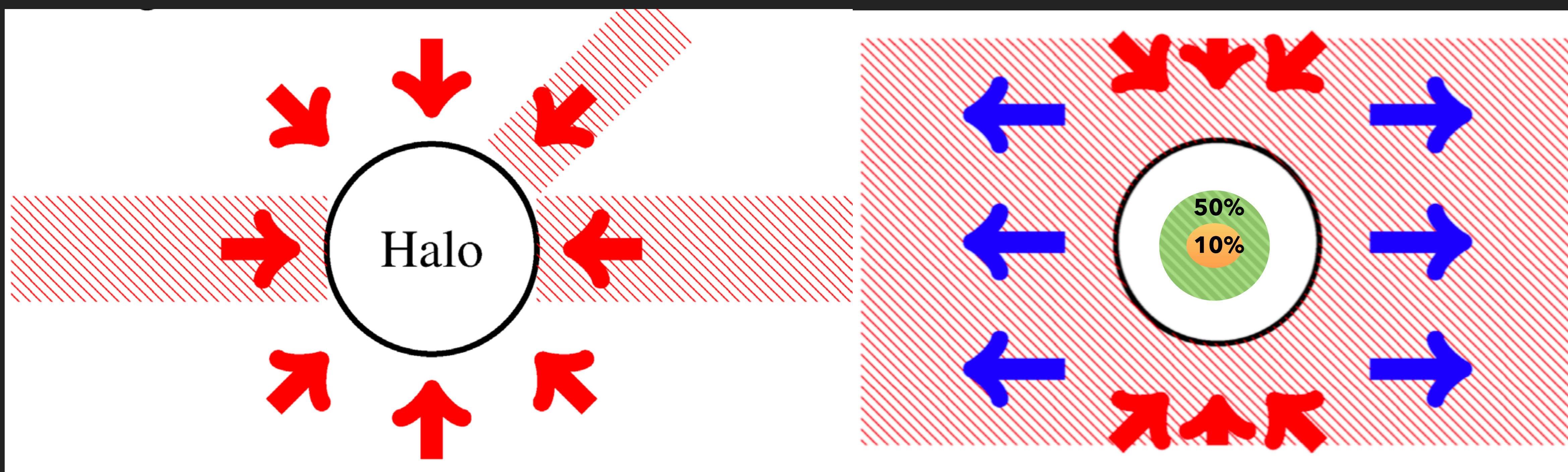


P. Ganeshaiah Veena et al 2018

POSSIBLE CAUSE:

ACCRETING HALO

STALLED

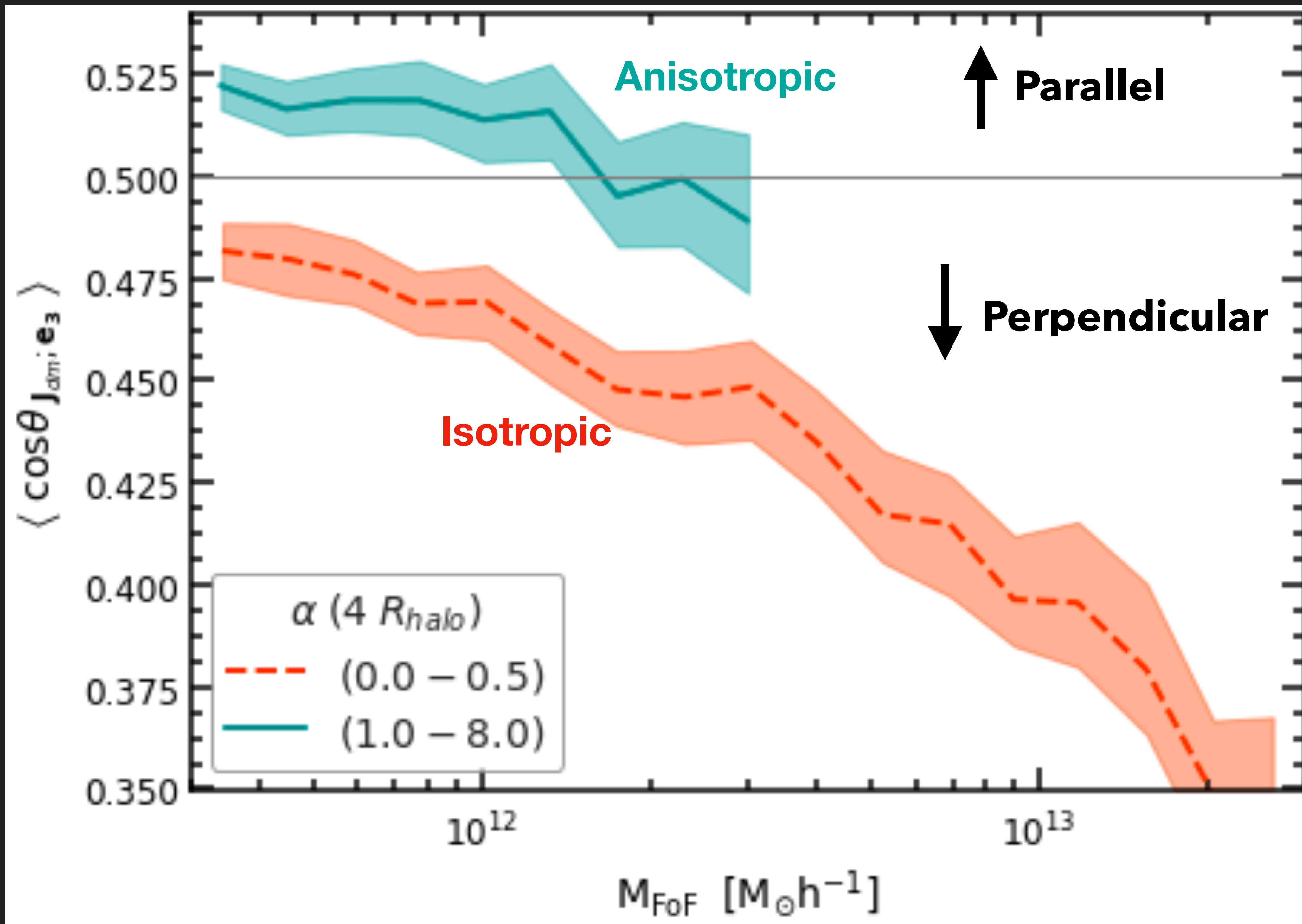


P. Ganeshaiah Veena et al 2021

- Thin filaments
- Accretion - perpendicular spin
- Isotropic

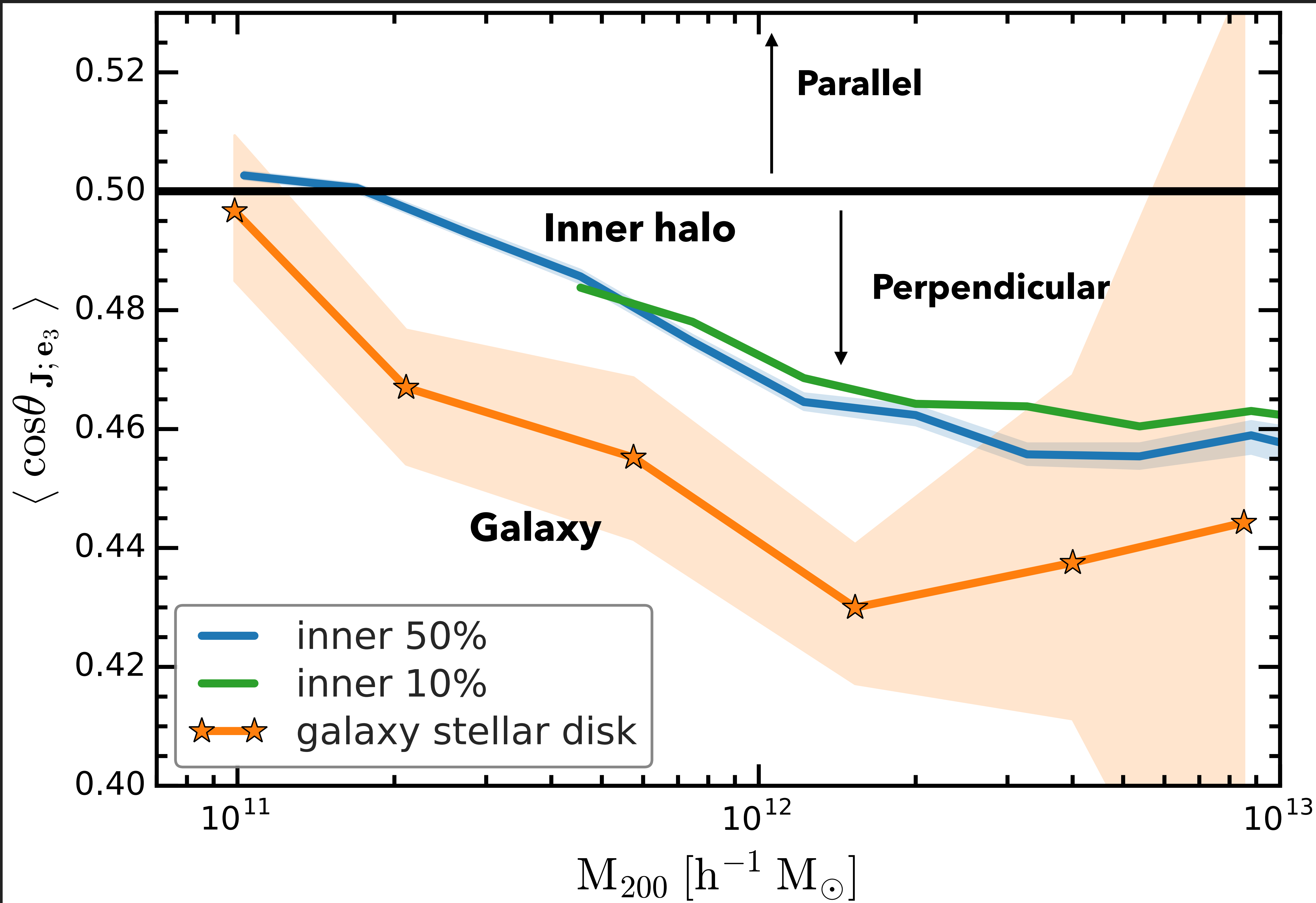
- Thick filament
- Accretion - parallel spin
- Anisotropic

Tidal anisotropy - preliminary results



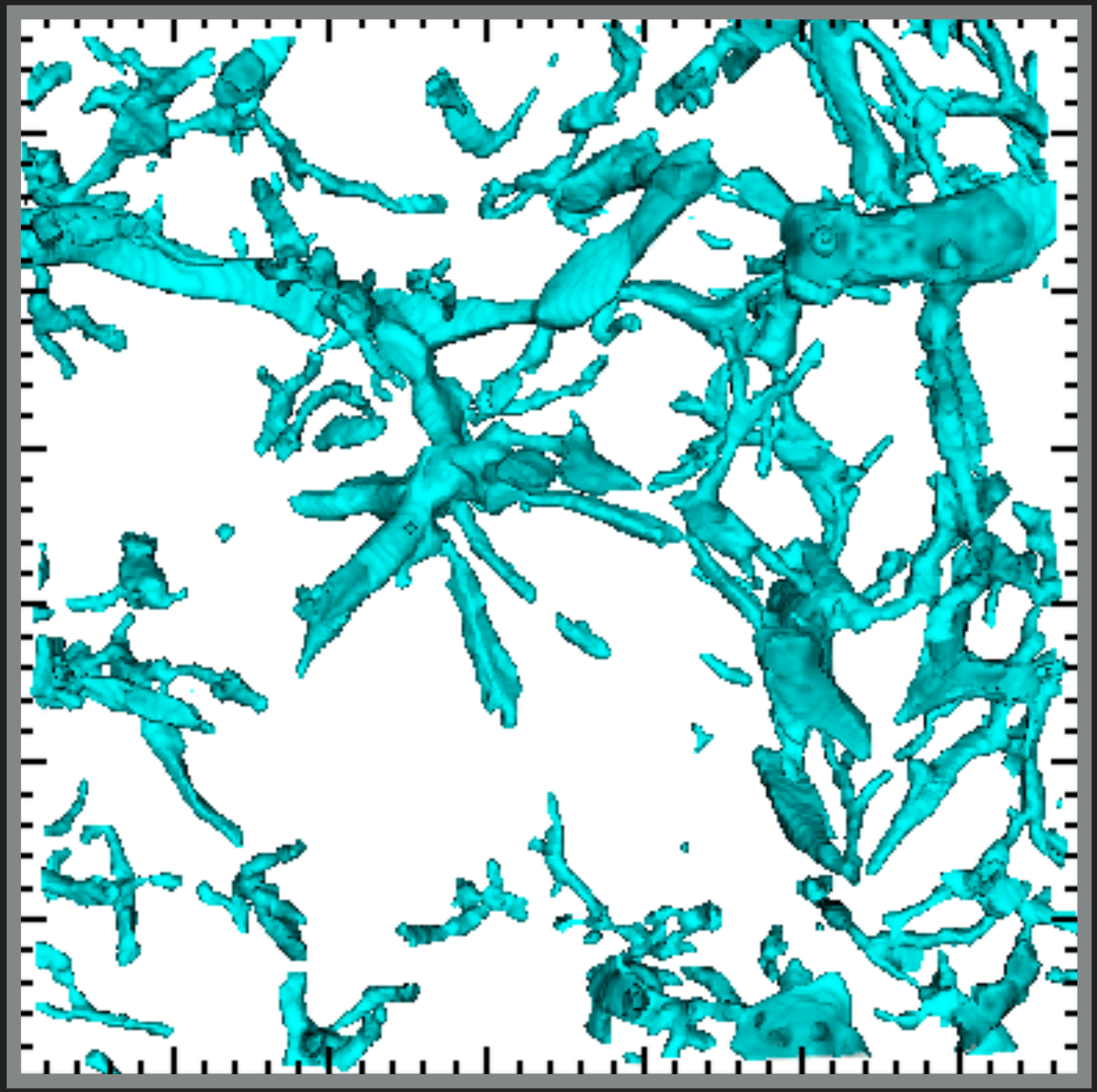
Thanks to Pablo Lopez for sharing the data and Aseem Paranjape for the discussion.

QUESTION: HOW ARE GALAXIES ALIGNED COMPARED TO INNER HALOES?

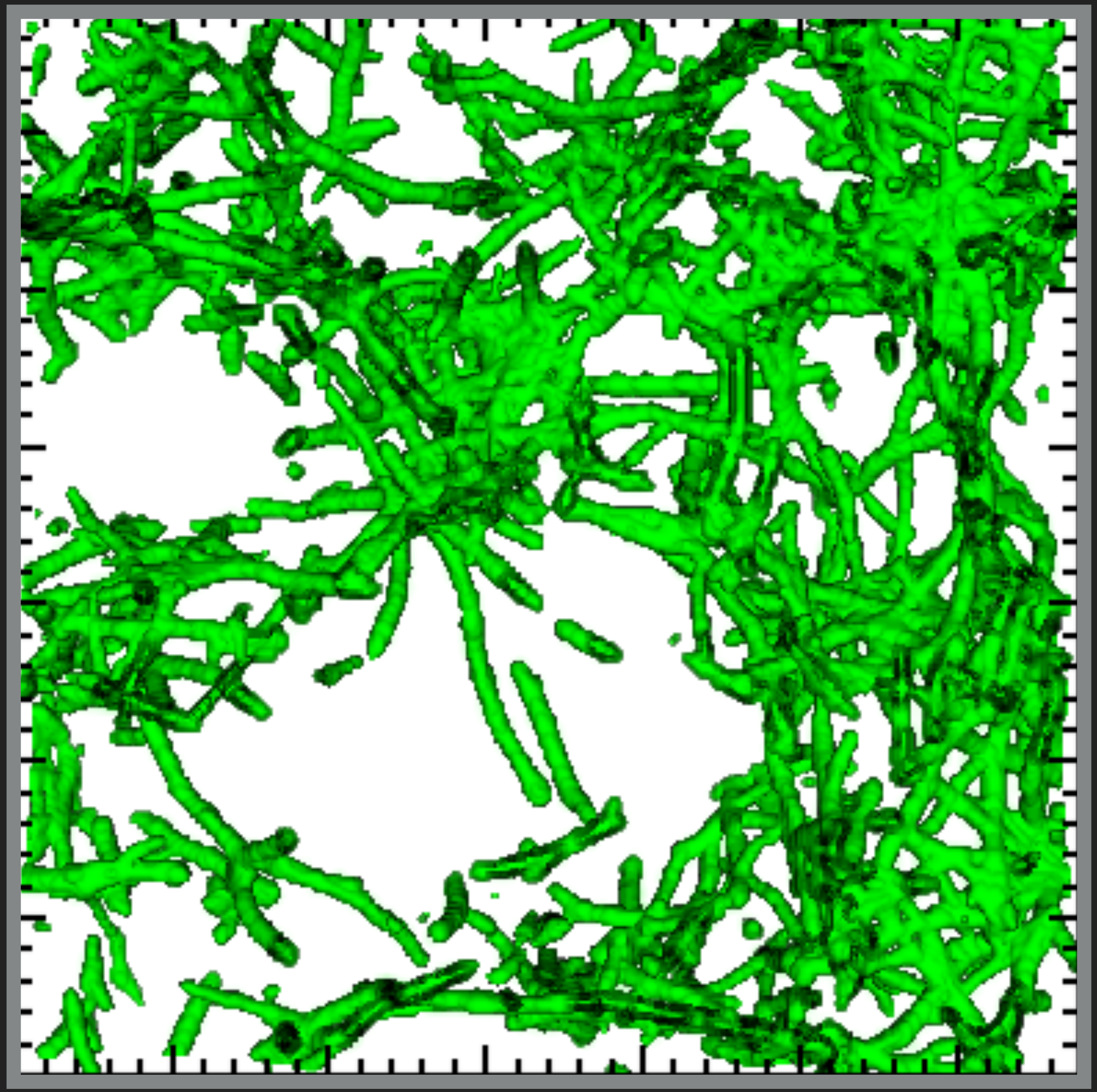


P. Ganeshaiah Veena et al 2019

NEXUS + FILAMENTS

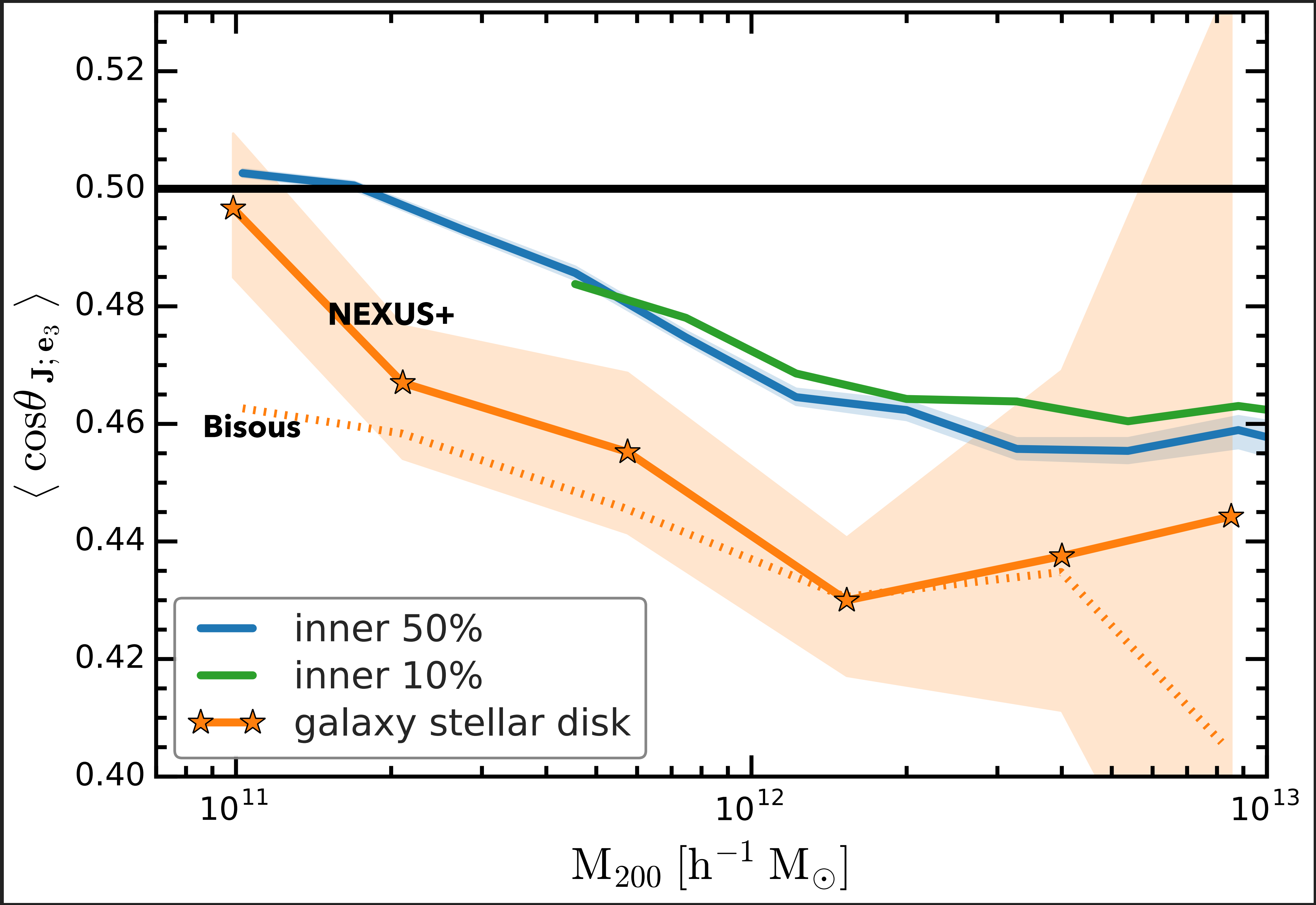


BISOUS FILAMENTS



P. Ganeshaiah Veena et al 2019

BISOUS AND NEXUS +



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

KEY CONCLUSIONS

- Cosmic web environment influences halo/galaxy spin magnitude and orientation.
- Definition of filament or filament detection method is crucial when dealing with weak signals.
- 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.

PART 2 - Unmasking the Universe with neural nets

arXiv: 2212.06439

Punyakoti Ganeshaiah Veena

with Robert Lilow and Adi Nusser

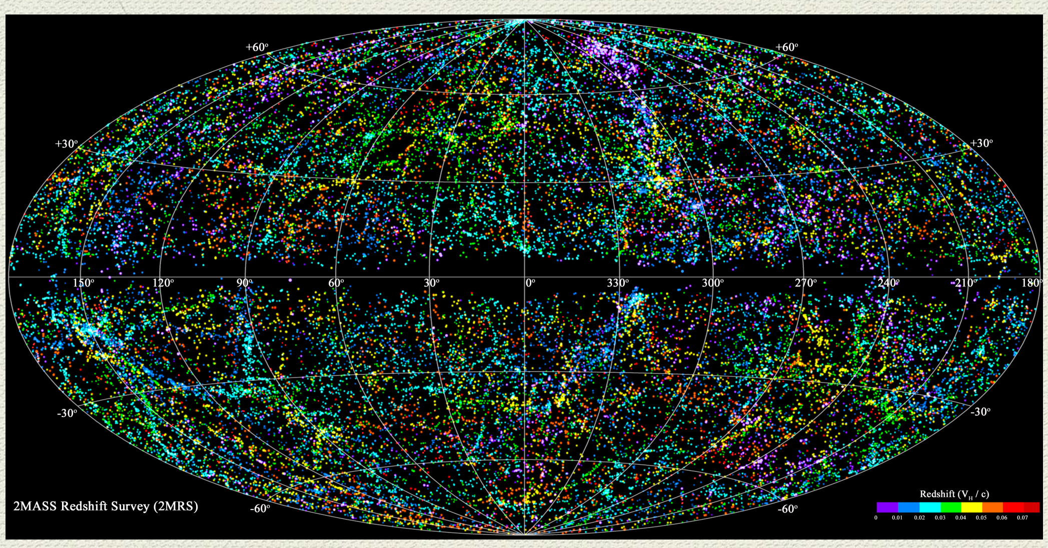
Technion, Haifa, Israel.

Mapping the Universe

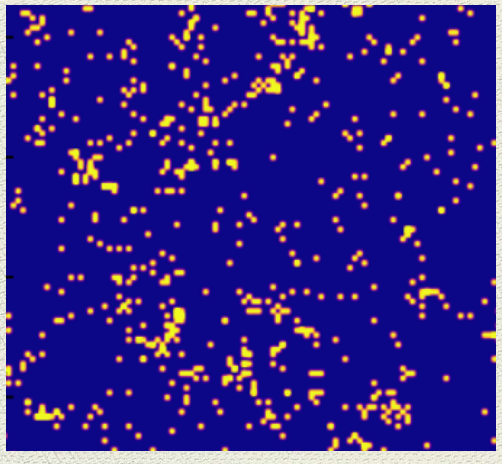
- 3D positions of galaxies - trace the underlying dark matter distribution.

- Infer the matter density and 3D flows - constraints on the cosmological parameters.

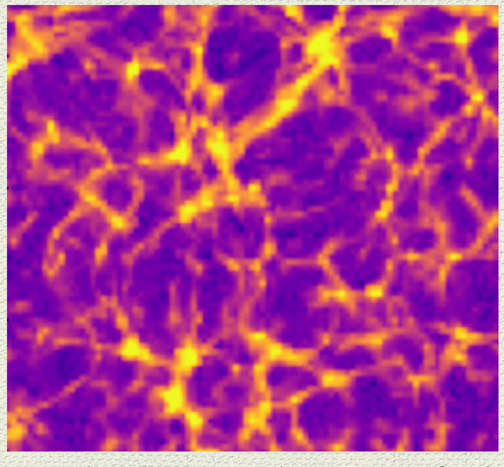
- $-\frac{1}{H}\vec{\nabla}_r . \vec{v}_{lin} = f\sigma_8\delta \quad f \approx \Omega_m^{0.55}$



2MRS



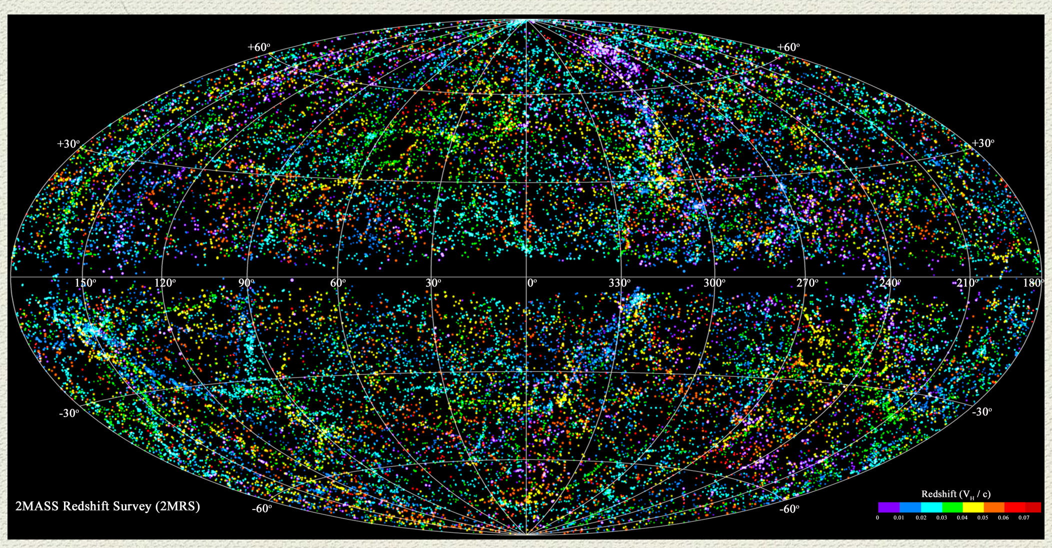
galaxy distribution



underlying density field

Noisy, missing and incomplete data

- Discrete sampling.
- Redshift space distortions - structures are elongated along the line-of-sight.
- Gaps in the data - eg. galaxies in the ZoA are obscured by star, dust and gas.
- In optical wavelengths, this covers almost 20% of the sky.



Other methods used so far for reconstructing LSS?

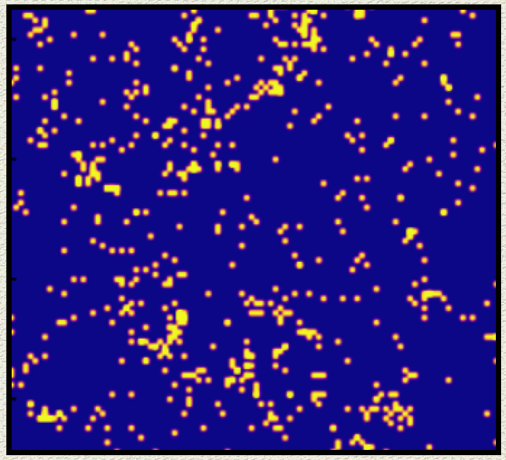
- **Wiener filter** - linear reconstruction - e.g *Zaurobi et al 1994, Lilow et al 2021*
- **Other reconstruction methods** - e. g. *Bertschinger & Dekel 1989; Yahil et al. 1991; Nusser & Davis 1994; Fisher et al. 1995; Bistolas & Hoffman 1998; Zaroubi et al. 1999; Kitaura et al. 2010; Jasche et al. 2010; Courtois et al. 2011; Kitaura 2013; Jasche & Wandelt 2013; Wang et al. 2013; Carrick et al. 2015; Lavaux 2016; Jasche & Lavaux 2019; Graziani et al. 2019; Kitaura et al. 2020; Zhu et al. 2020*

What did we do in this paper?

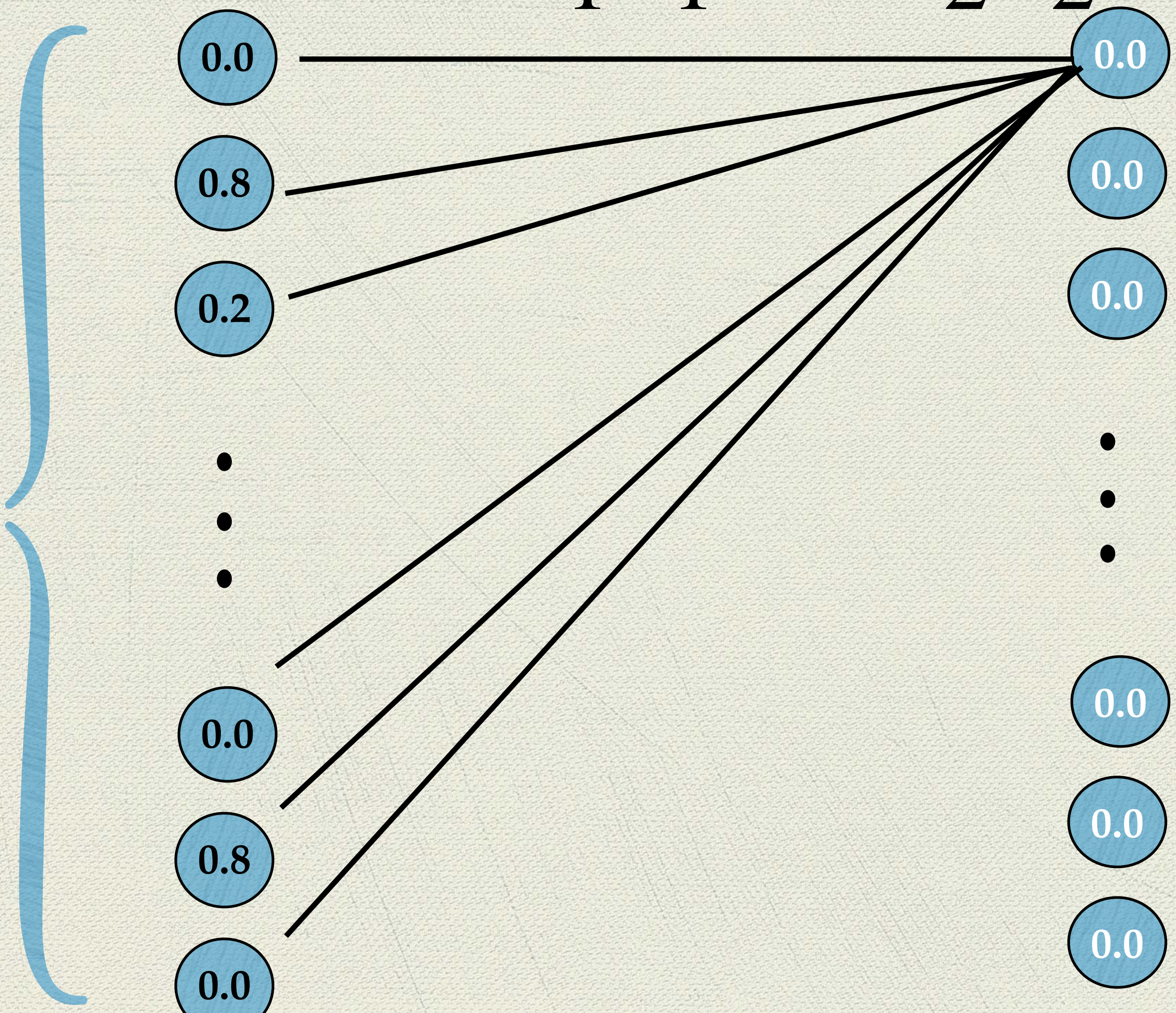
- Reconstruct **underlying density and velocity fields** from galaxy distributions using neural networks.
- In the process, demystify machine learning:
  - understand the black-box
  - can we recreate what the machine does using known statistical techniques?
- What are the **advantages and caveats** of using neural nets over the traditional techniques for such reconstructions? And why so?
- Can we recover Wiener Filter from neural network methods?

A simple network (3Blue1Brown - youtube channel)

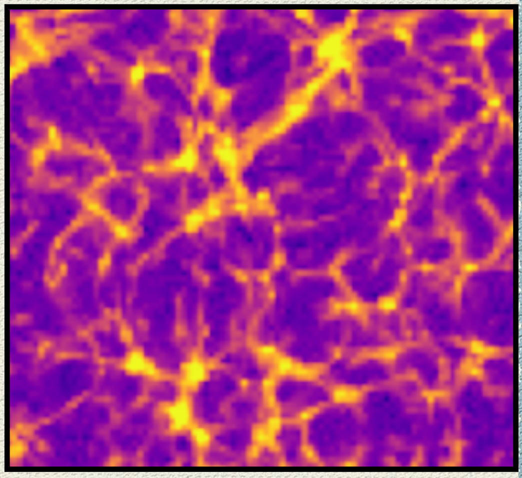
$$w_1 a_1 + w_2 a_2 + w_3 a_3 + \ldots w_n a_n$$



δ^{obs}



δ^{obs} δ^{recon}

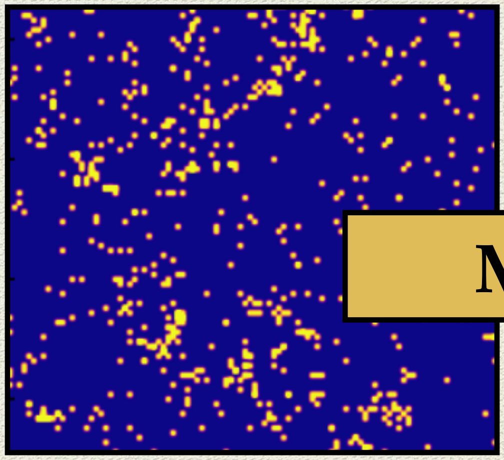


δ^{true}

$$\mathrm{MSE}(\hat{\delta}) = \frac{1}{N} \sum_{j=1}^{N} \left(\delta_j^{recon} - \delta_j^{true} \right)^2$$

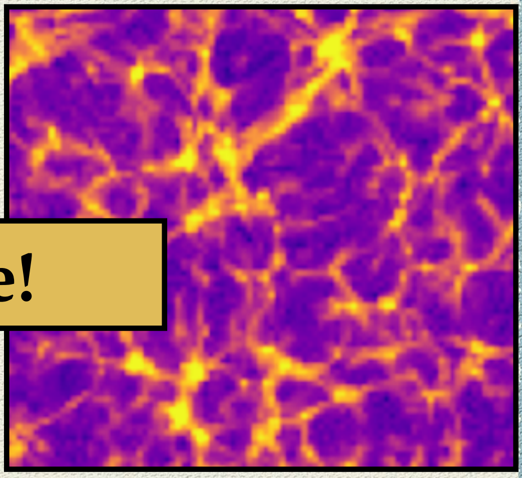
Non-linear network + MSE loss = Mean posterior estimate

$$L^{\mathrm{MSE}}(\hat{\mathbf{T}}[\lambda]) = \frac{1}{MN}\sum_{\alpha=1}^{M}\sum_{j=1}^{N}\left(T_j^{\alpha} - \hat{T}_j[\lambda](\mathbf{I}^{\alpha})\right)^2$$



Input field : I_j

Minimising MSE gives the mean posterior estimate!



Target field : T_i

$$\boxed{\hat{\mathbf{T}}_i^{\mathrm{MSE}}(\mathbf{I}) = \sum_{T} P(\mathbf{T}\,|\,\mathbf{I})\,T_i = \langle T_i\,|\,\mathbf{I}\rangle,}$$

Wiener filtering for galaxy distributions

[Zaroubi et al 1994]

- Observed density field —-> True density field
- Assume a prior for the true fields
- Reconstructed field is a linear combination of the observed field. $$\hat{T}_i^{WF(I)} = \sum_j w_{ij}^{WF} I_j + b_i^{WF} ,$$
- Minimum variance estimator: minimise MSE.
- $T^{WF} = \langle TI \rangle \langle II \rangle^{-1} I$

Wiener filtering for galaxy distributions

[Zaroubi et al 1994]

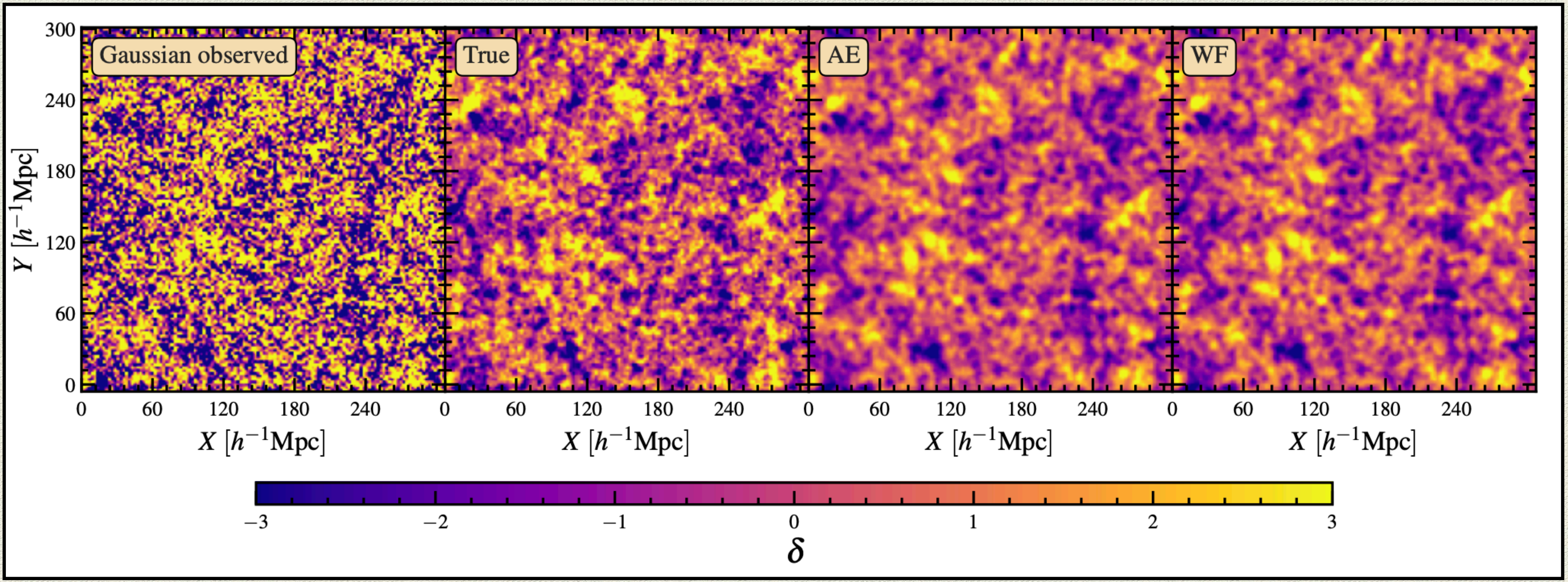
1. A **neural network** with an input and output layer and **linear activation** is equivalent to a **WF**.

2. When the field is **Gaussian**, WF and NN estimates should both be the mean posterior estimates.

- Minimum variance estimator: minimise MSE.

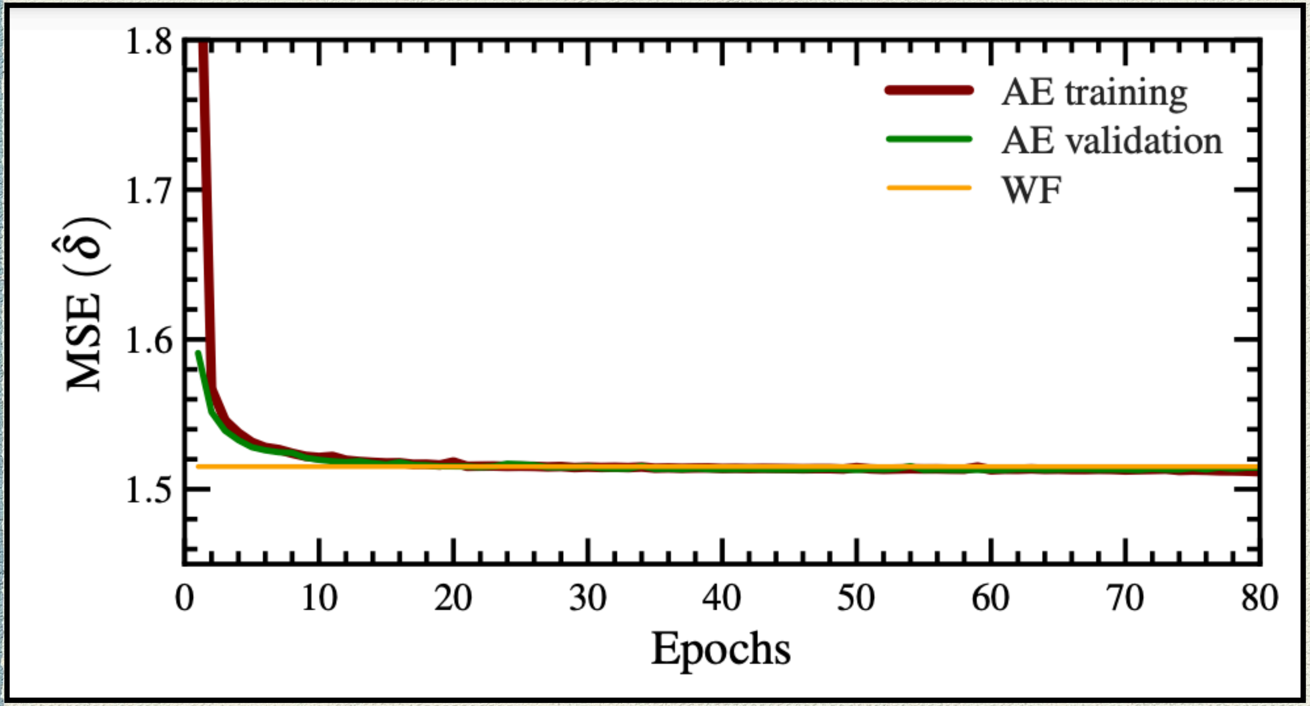
- $T^{WF} = \langle TI \rangle \langle II \rangle^{-1} I$

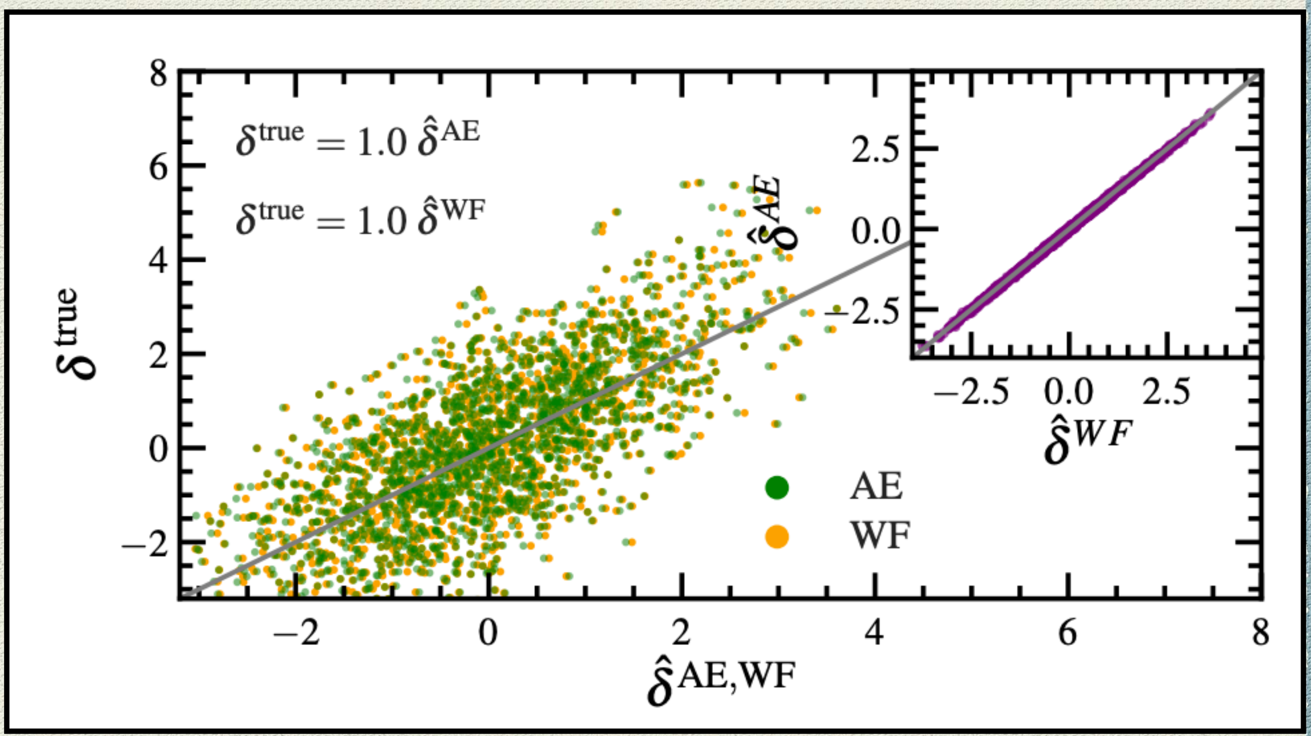
Gaussian fields



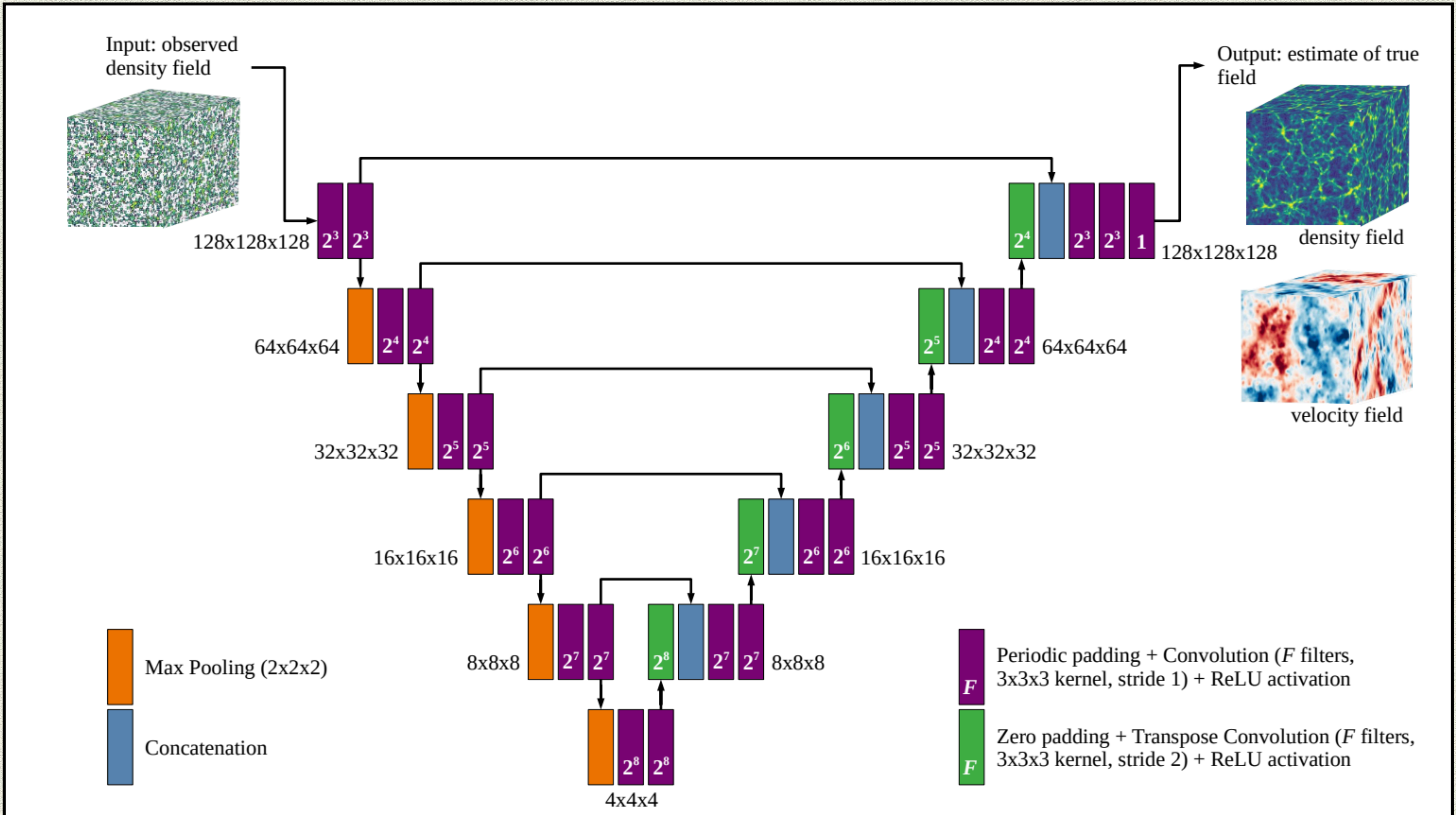
WF and AE are minimum variance solutions and give the same result for Gaussian fields.

Gaussian fields

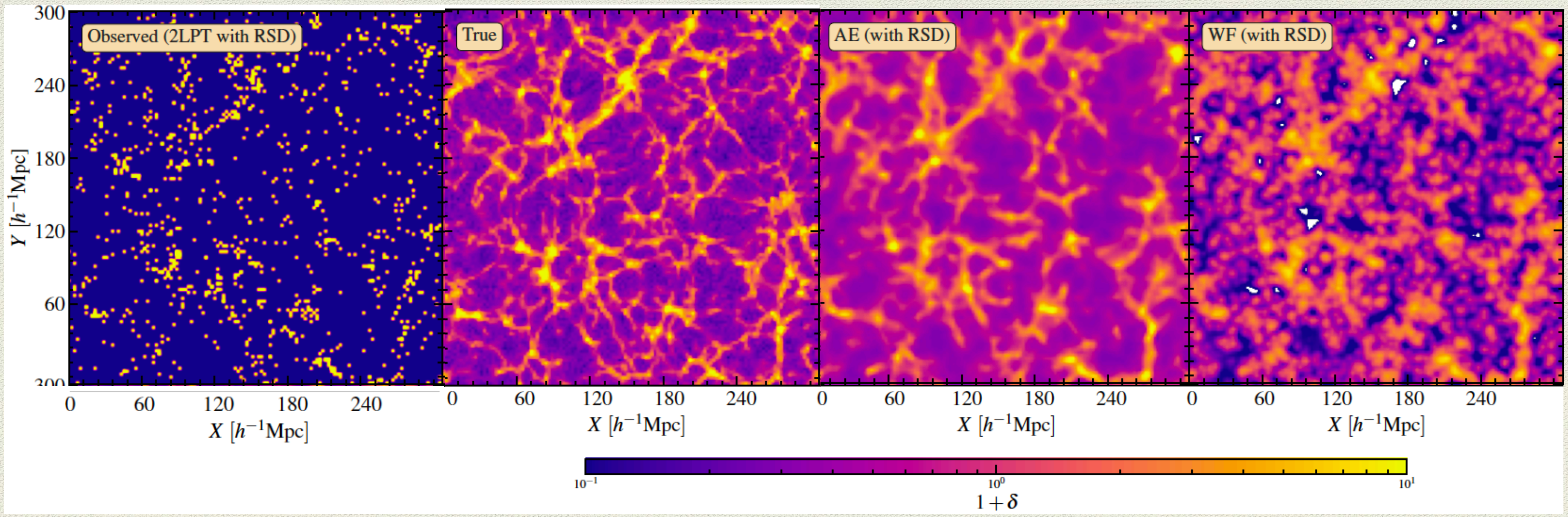




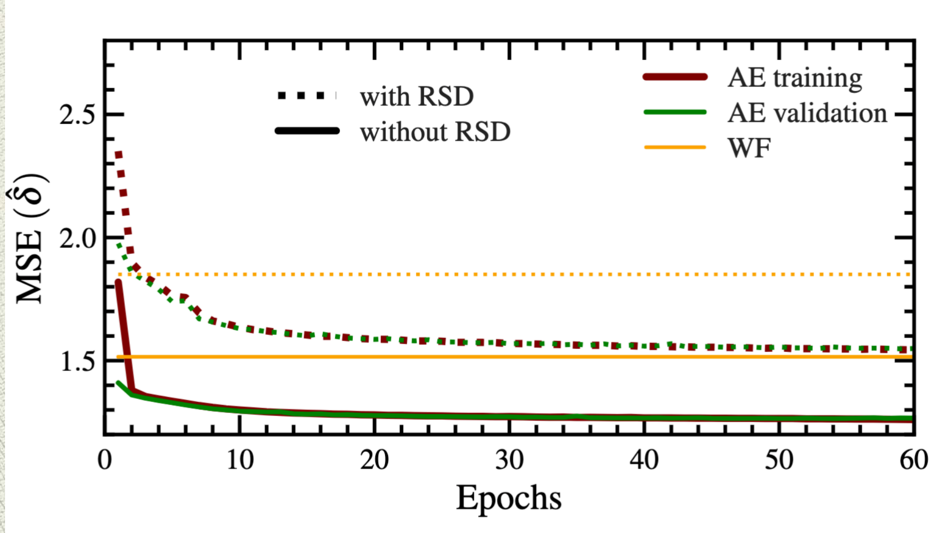
For 3D data, use convolutions: Autoencoder



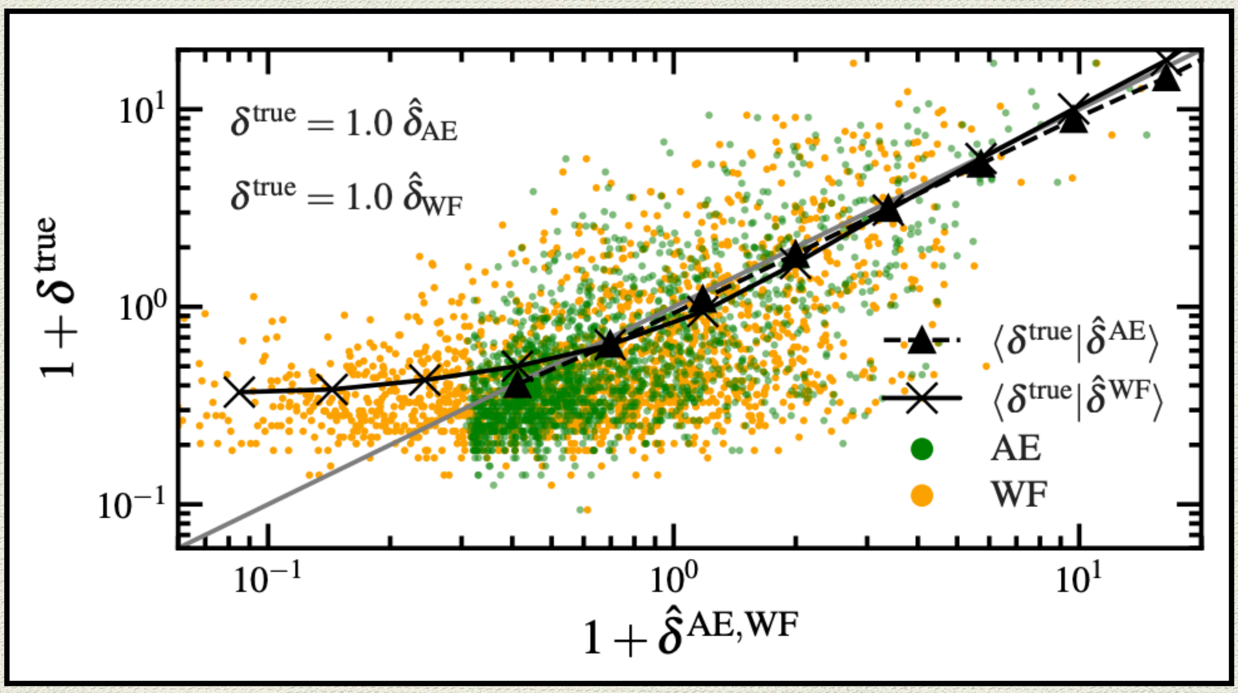
Density field reconstructions.

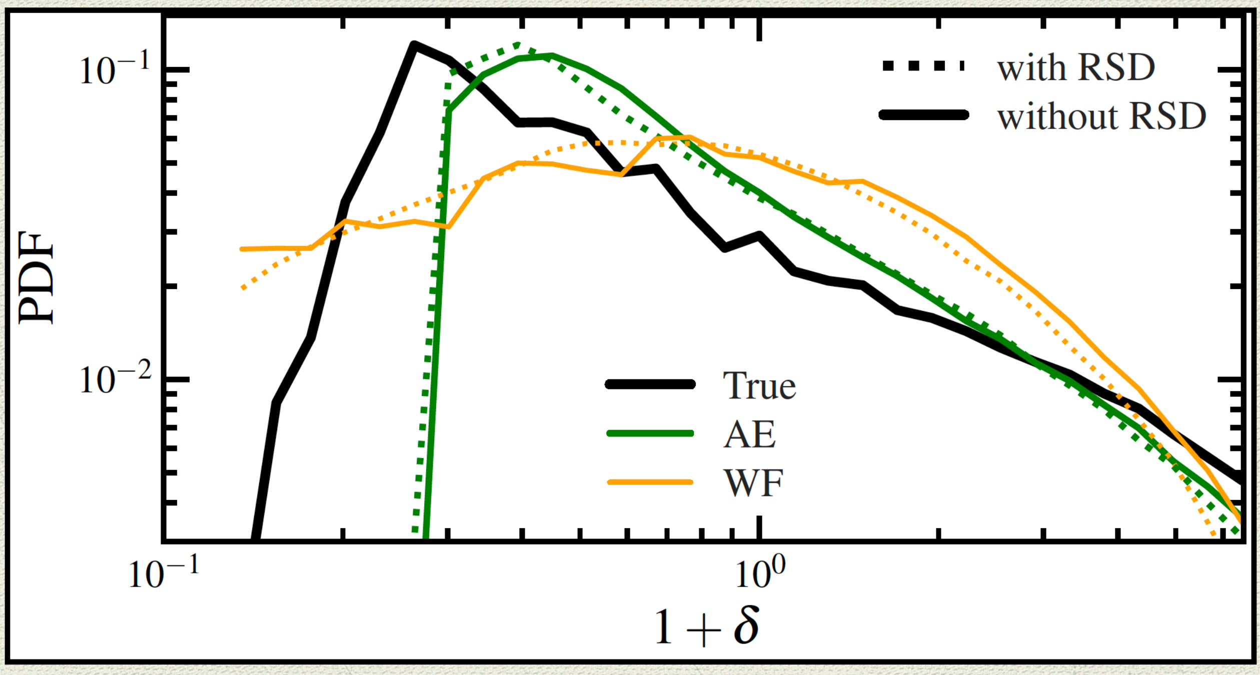


$$\delta(x) = \frac{\rho(x) - \bar{\rho}}{\bar{\rho}}$$



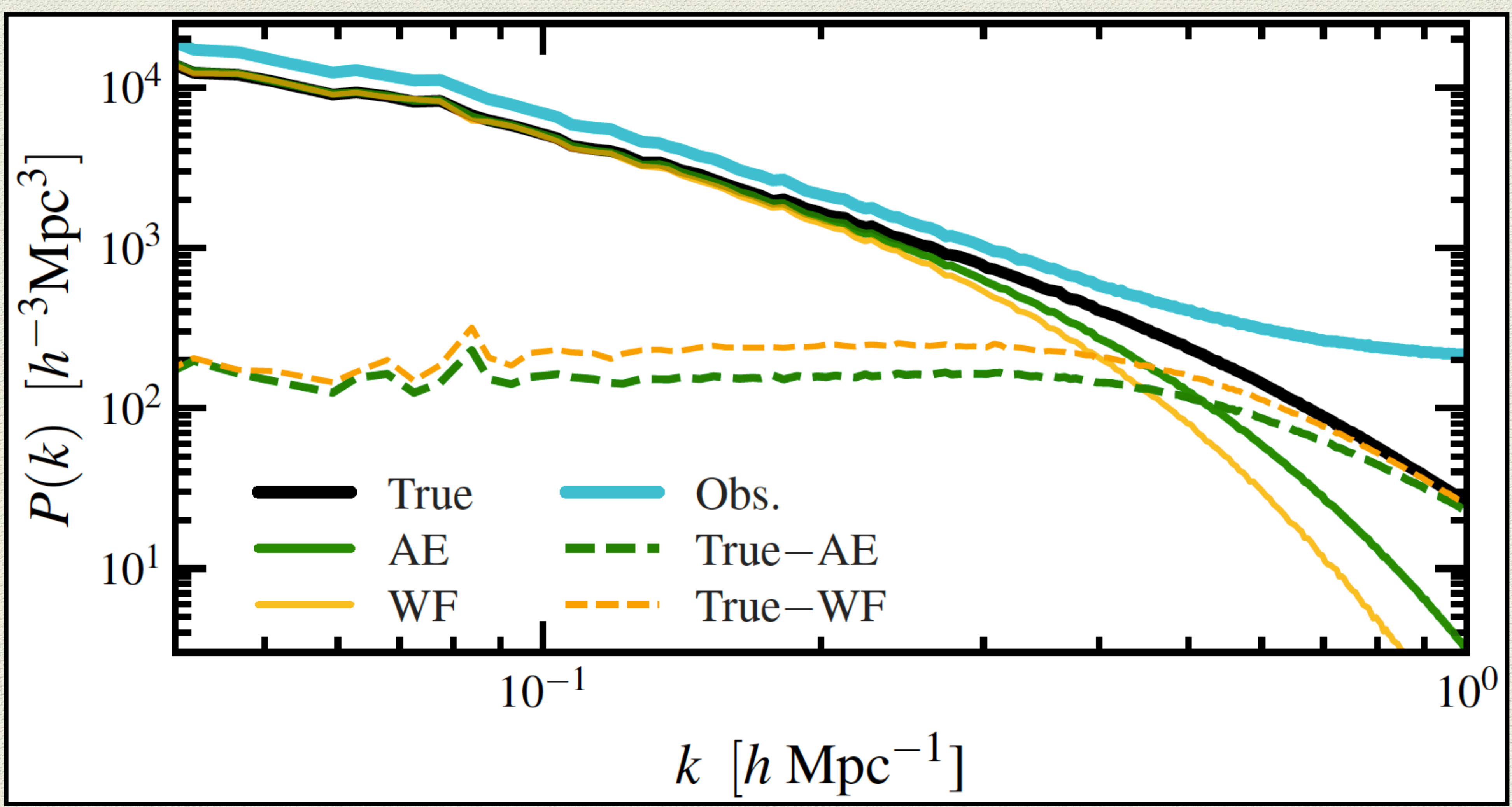
Density field reconstructions.



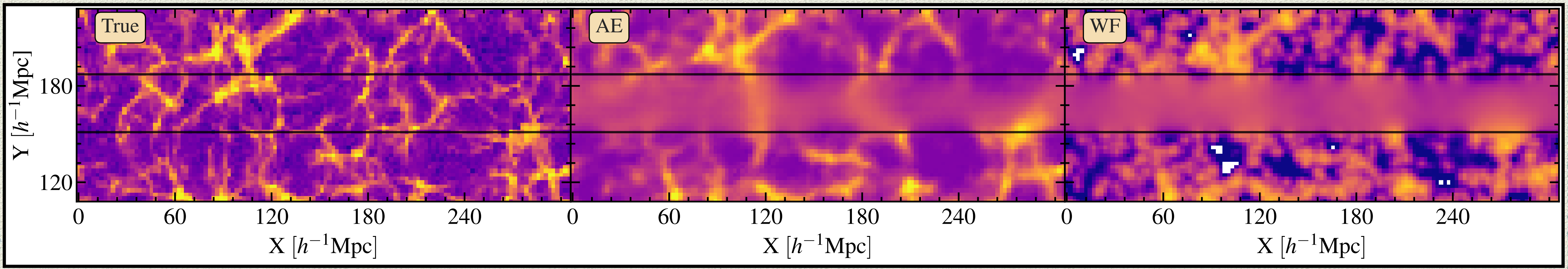


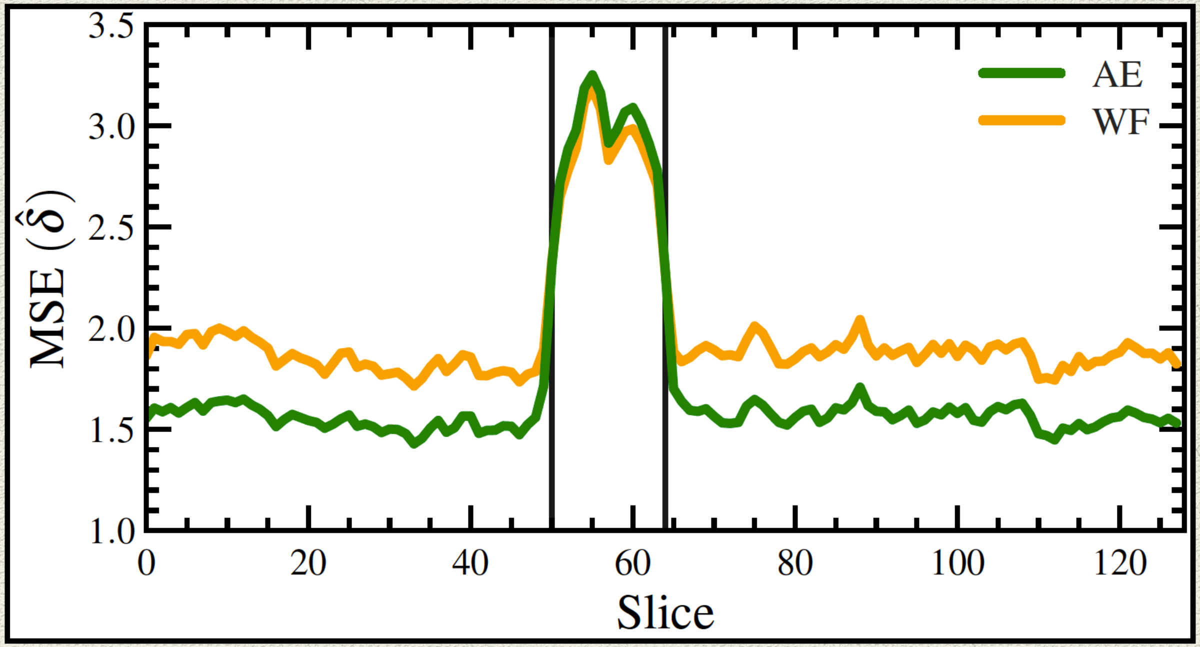
- Floor - is a result of the choice of our loss function and Poisson sampling.
- Towards the tails, NN is better.

Density field reconstructions - with RSD

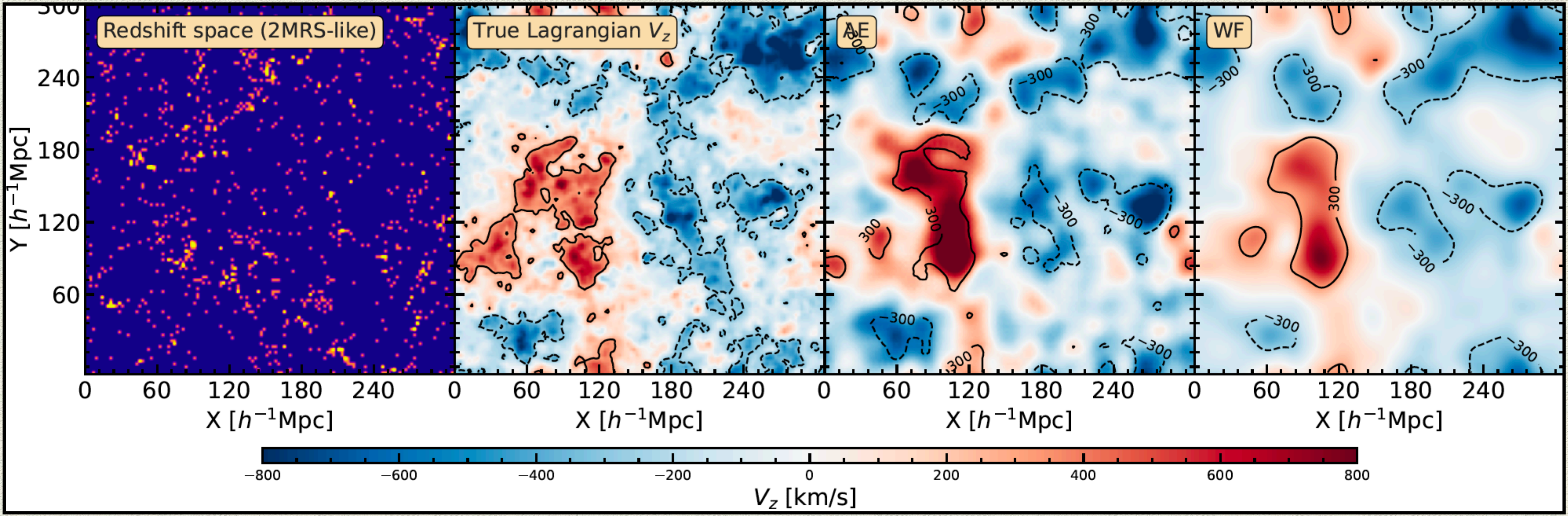


Density field reconstructions - with gap

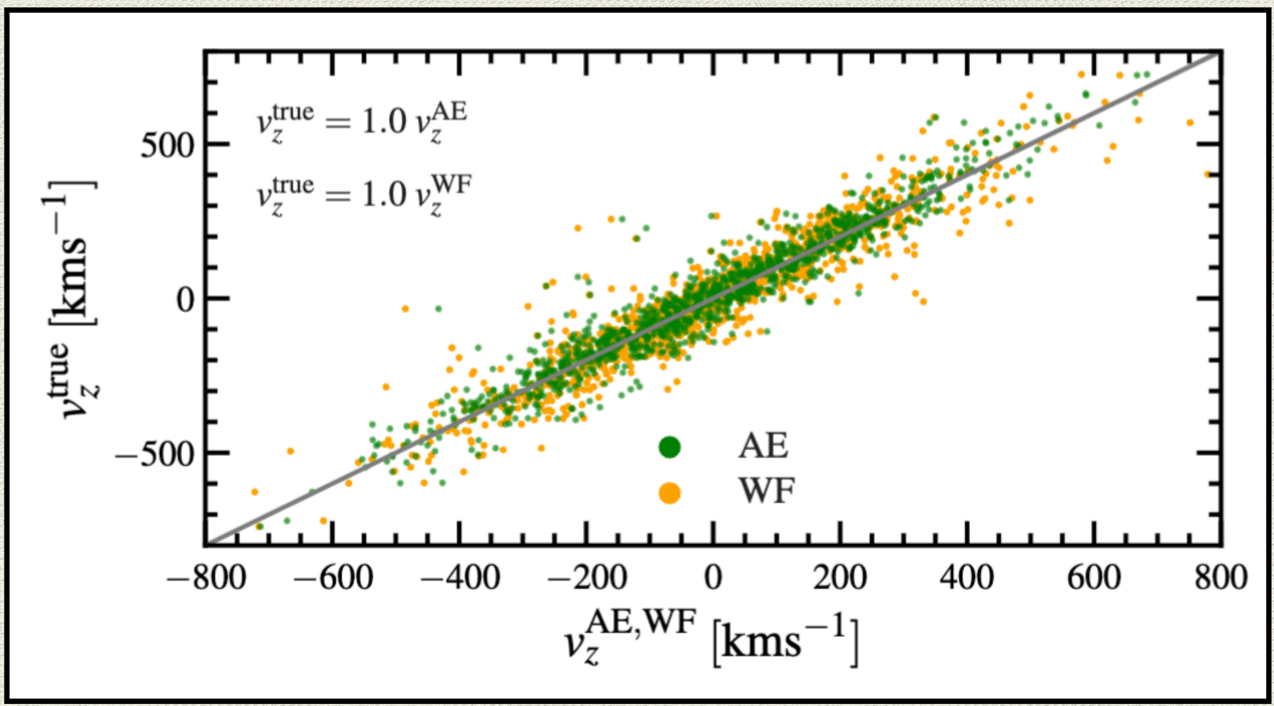


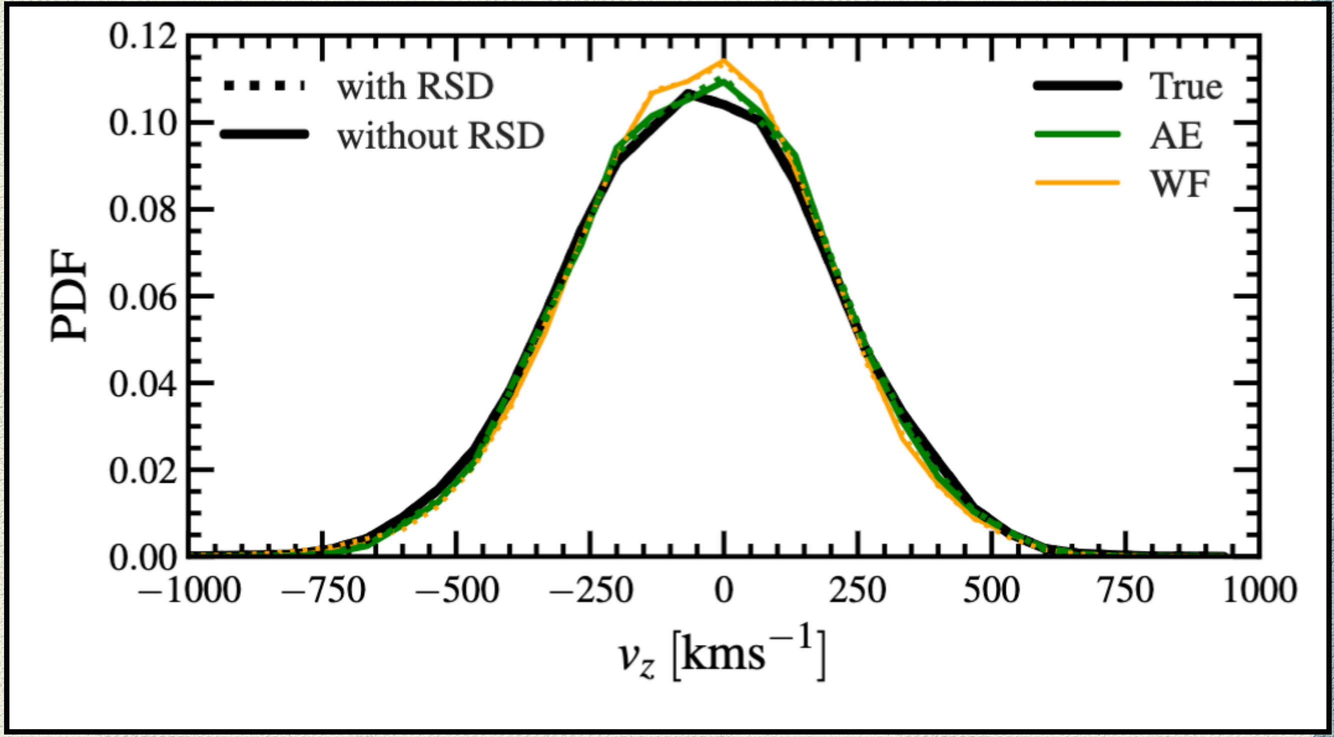


Velocity field reconstructions.

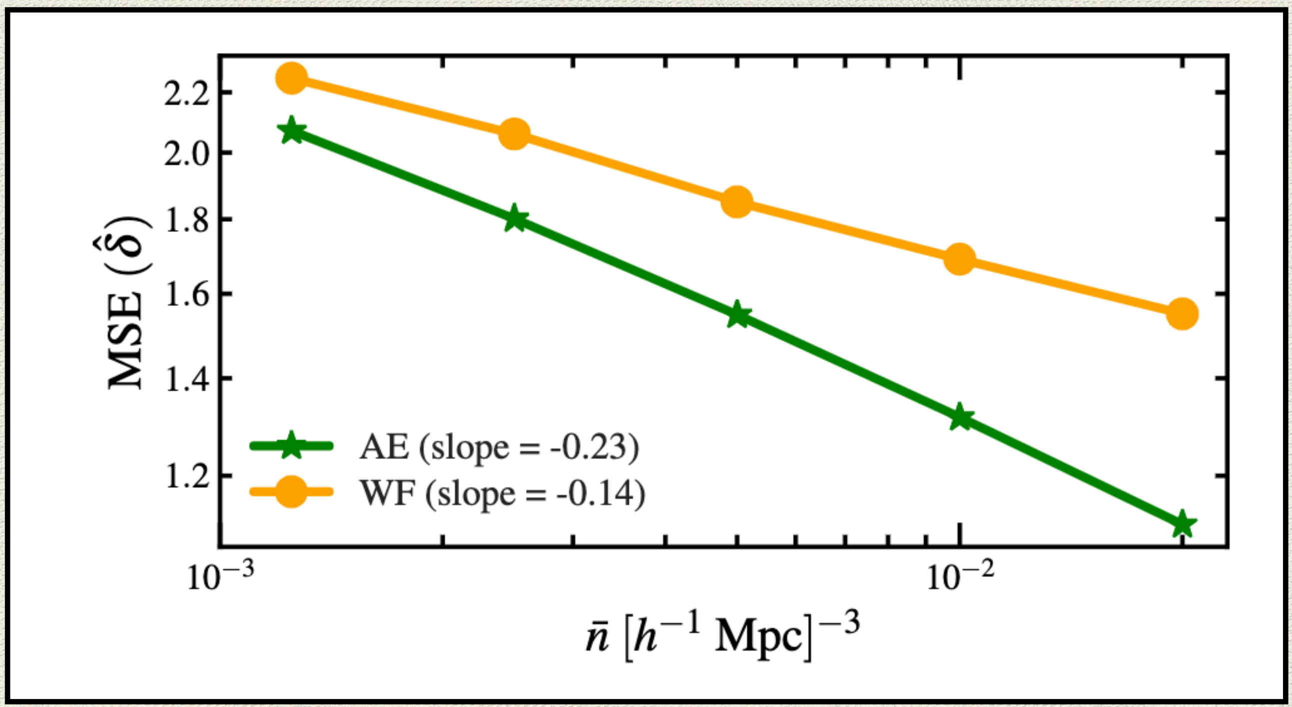


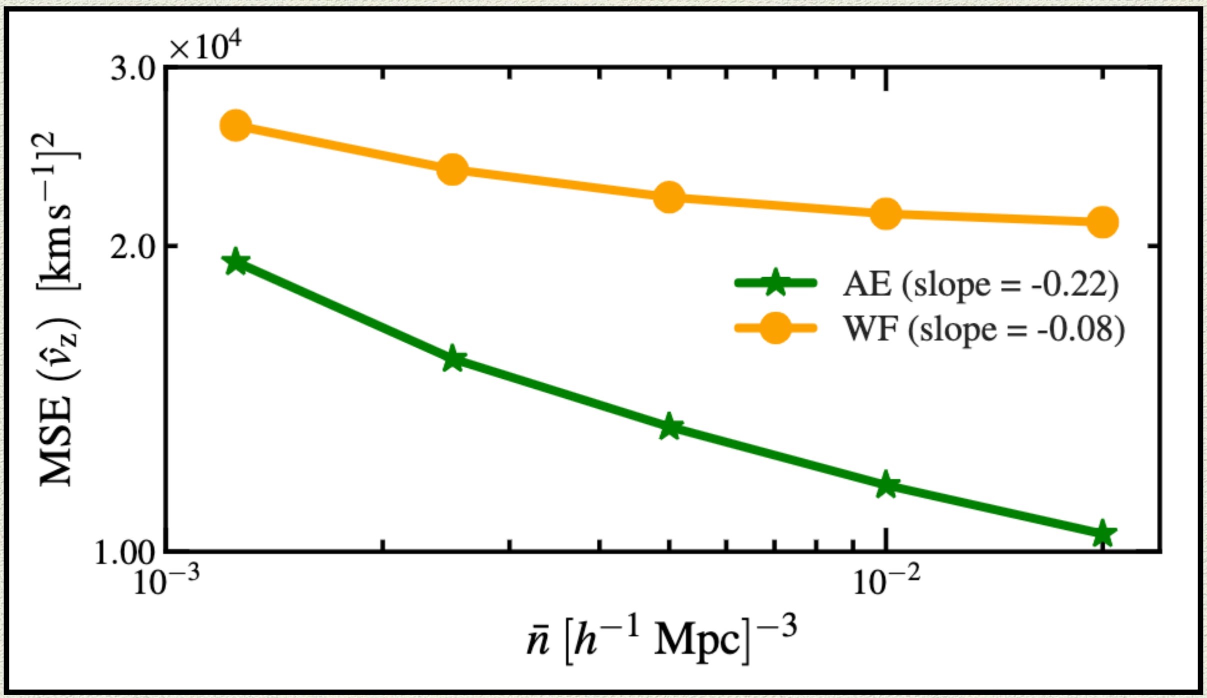
Velocity field reconstructions.





Reconstruction for different galaxy number densities





Thank you!