



---

---

# Galaxy assembly in the cosmic web: a multi-scale tidal analysis



Work in progress...



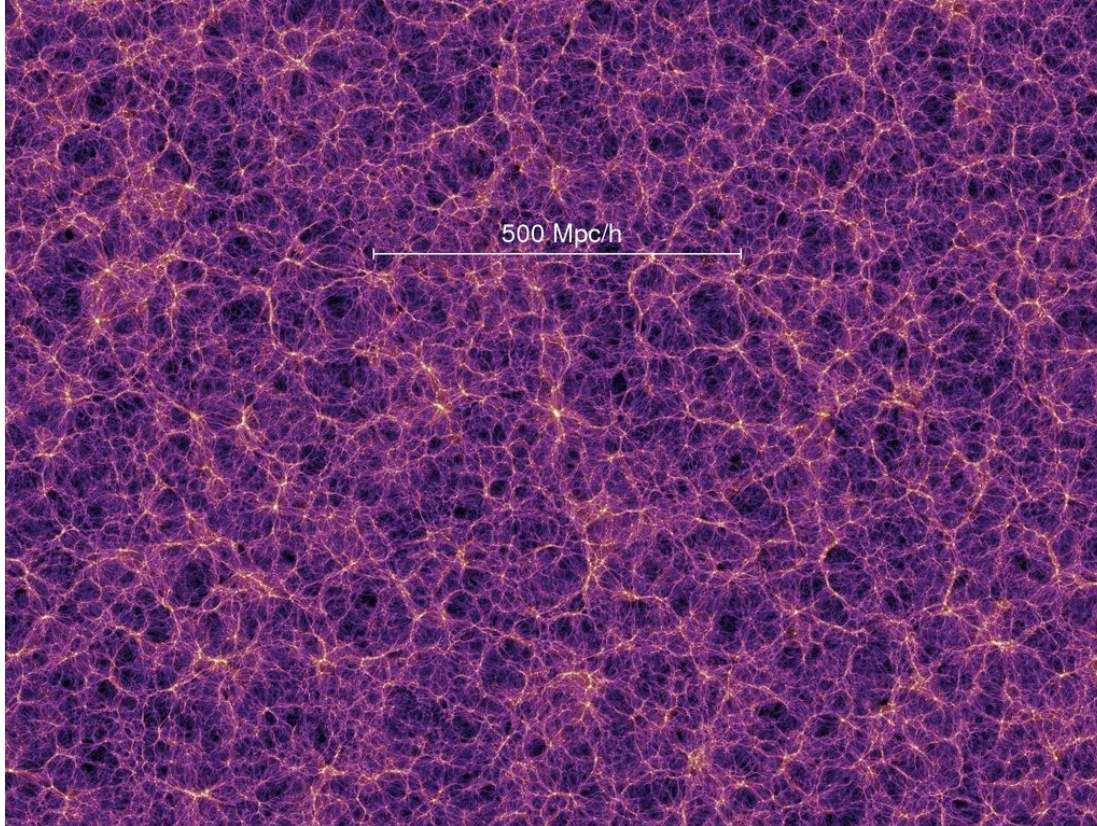
LOADING...

---

---

Yeimy D. Camargo C.- Universidad Nacional de Colombia.  
Rigoberto A. Casas-M. - Universidad Nacional de Colombia.

# Cosmic Web

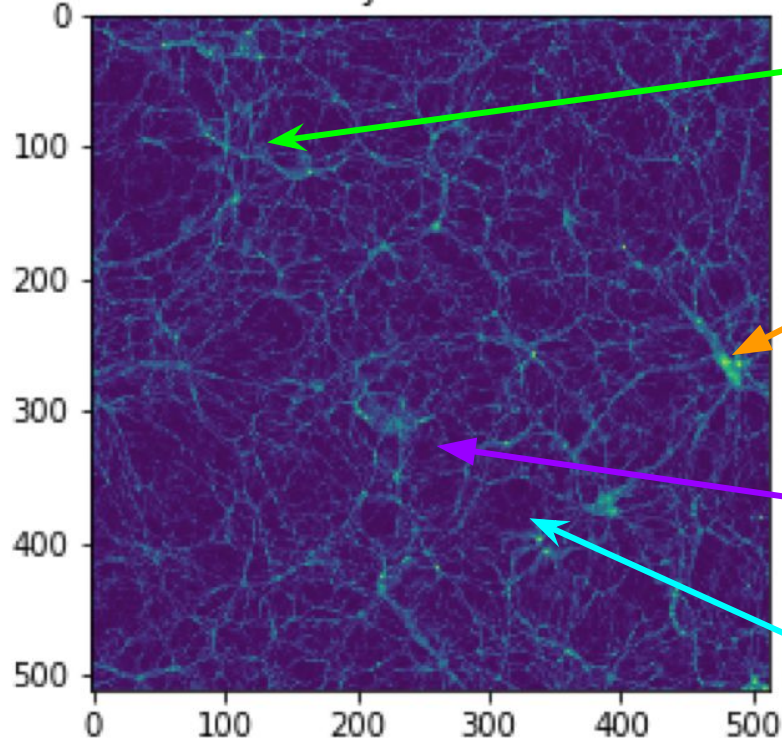


Millennium simulation -  $z = 0$

# Cosmic Web



Density Dark Matter



Filaments

web-like pattern

Nodes

Sheets

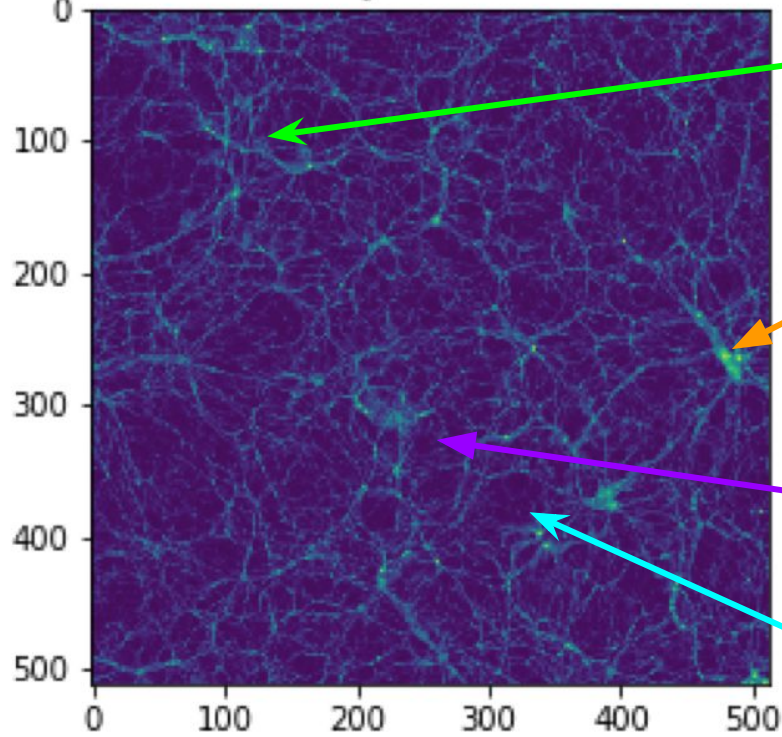
Voids

Interpolate Density Field CIC TNG300-2  
Nmesh= 512<sup>3</sup>

# Cosmic Web



Density Dark Matter



Filaments

web-like pattern

Clusters

The cosmic web shapes the flow of matter and affects the formation and evolution of galaxies.

Sheets

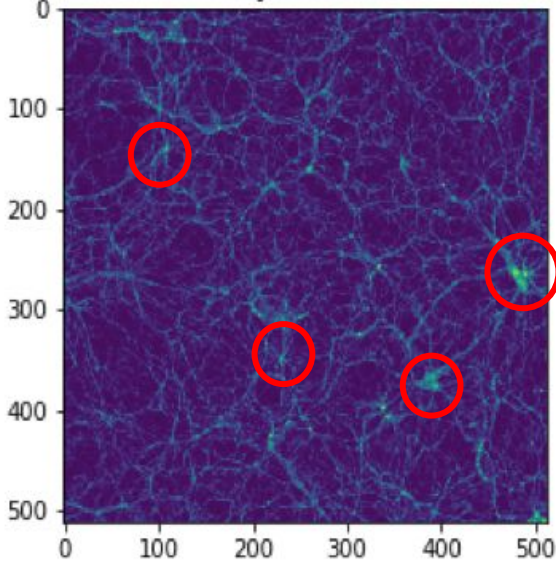
Voids

Matter flows from regions of low density to regions of high density, the galaxies are concentrated inside of dark halos in the regions highly dense and relatively cold

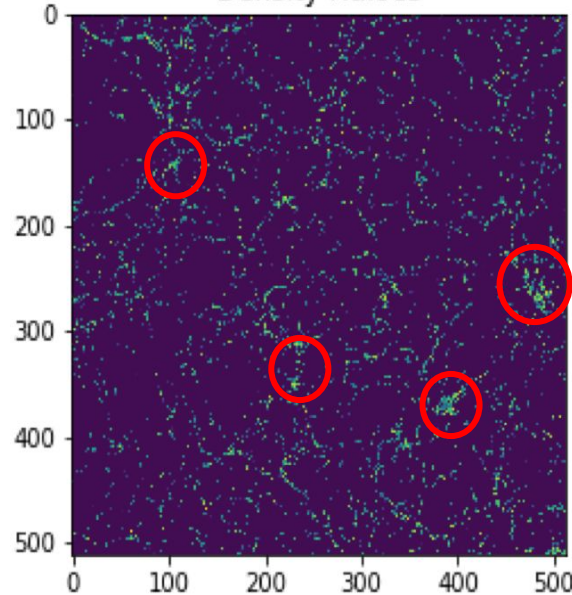
# Bias



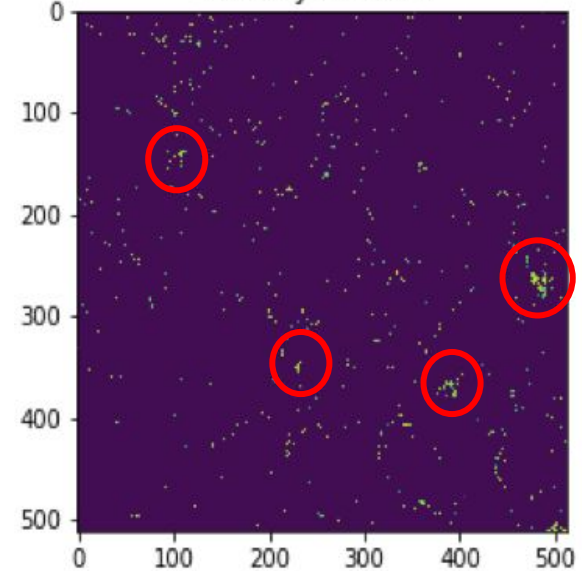
Density Dark Matter



Density Haloes



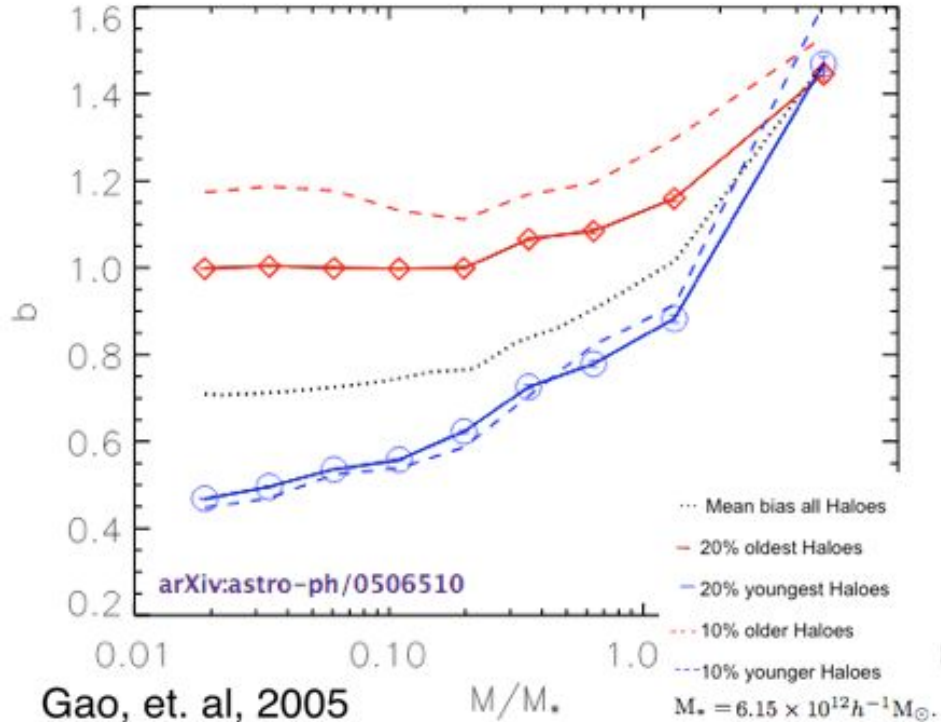
Density Galaxies



Interpolate Density Field CIC TNG300-2  
Nmesh= 512<sup>3</sup>

**How the Galaxy Distribution is related with underlying matter distribution?**

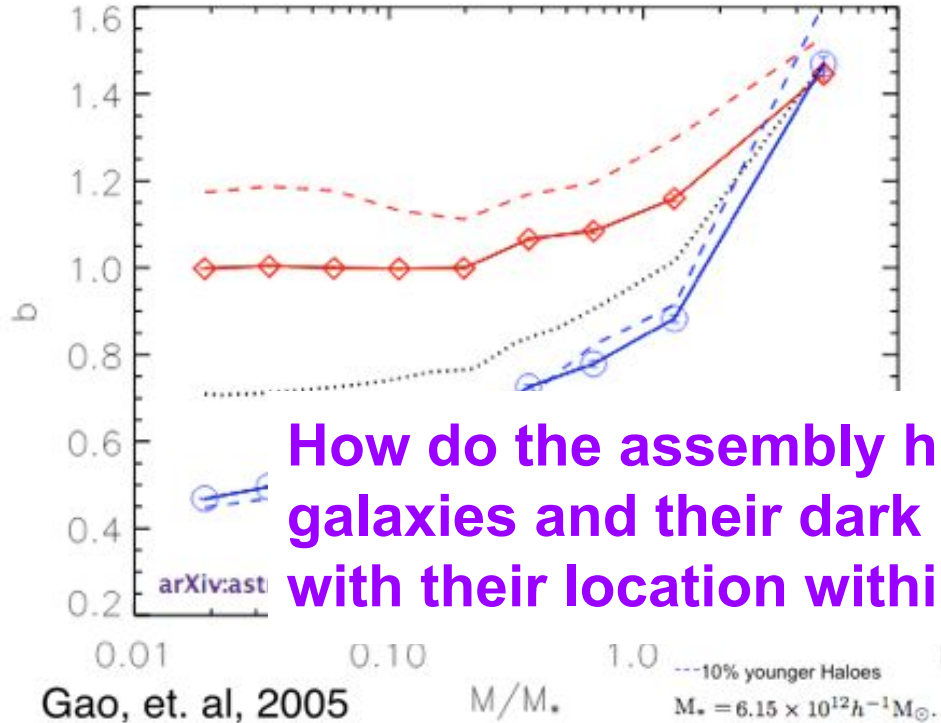
# Halo Assembly Bias



Gao, et. al, 2005

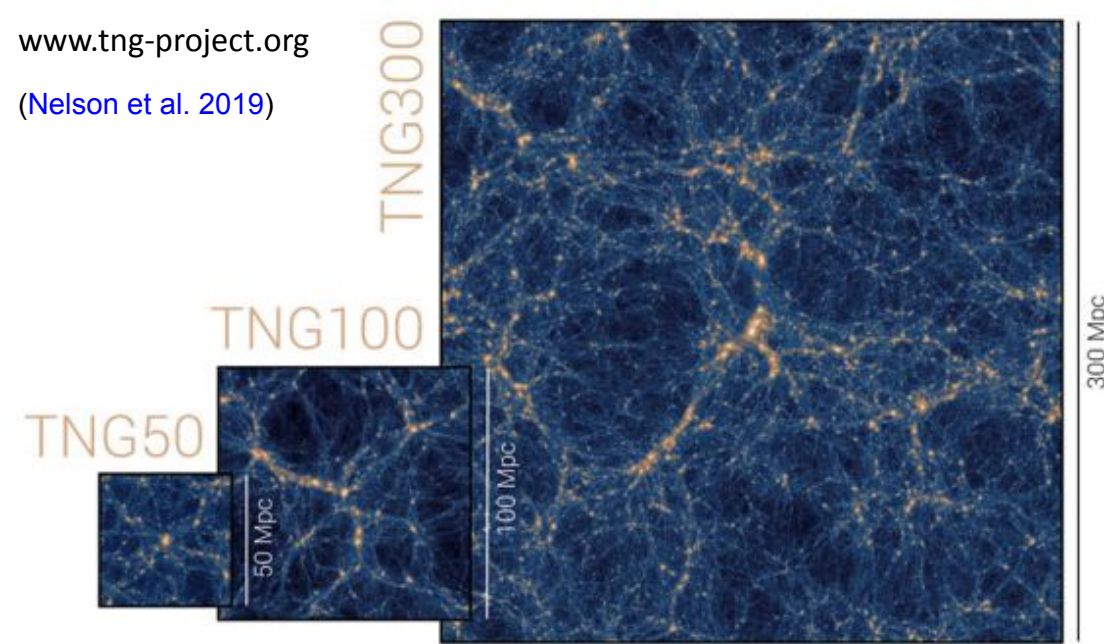
**Halo Assembly Bias:** Older halos are found in more clustered environments, while more recent halos (late assembly) are found in more uniform environments.

# Halo Assembly Bias



**Halo Assembly Bias:** Older halos are found in more clustered environments, while more recent halos (late assembly) are found in more uniform environments.

How do the assembly histories of central galaxies and their dark matter haloes correlate with their location within the cosmic web?



TNG300-2	$302.6^3$
$N_{DM}$	$1250^3$

$\Lambda$ CDM cosmology:

$\Omega_m = 0.2726, \Omega_b = 0.0456,$   
 $\Omega_\Lambda = 0.7274, \sigma_8 = 0.809$   
 $h = 0.704$ . (Vogelsberger, et al. 2014)

Illustris TNG:

$\Omega_m = 0.38089, \Omega_b = 0.0486,$   
 $\Omega_\Lambda = 0.6911, h = 0.6774$   
 (Planck Collaboration, et al. 2016)

- ★ The Illustris project is a suite of state-of-the-art cosmological galaxy formation simulations. Each simulation in IllustrisTNG evolves a large swath of a mock Universe from soon after the Big-Bang until the present day while taking into account a wide range of physical processes that drive galaxy formation.
- ★ TNG300, hydrodynamical simulations have reached a sufficient volume and resolution to study clustering of all matter components in The Universe on the relevant scales.
- ★ **Free Data access.**

# Cosmic Web Classification: General Methodology



1. Use CIC scheme to obtain the density field interpolated.
2. Apply Gaussian smoothing at a given scale.
3. Obtain the eigenvalues of for the Hessian matrix of the potential.

$$T_{\alpha\beta} = \frac{\partial^2 \phi}{\partial r_\alpha \partial r_\beta} \longrightarrow \text{Tidal Tensor}$$

4. The cosmic web classification is based on the signs of the eigenvalues of the Hessian of the potential, evaluated at the positions of halos/galaxies with early and late assembly times:

Voids: All eigenvalues are negative.

Sheets: Two eigenvalues are negative, and one is positive.

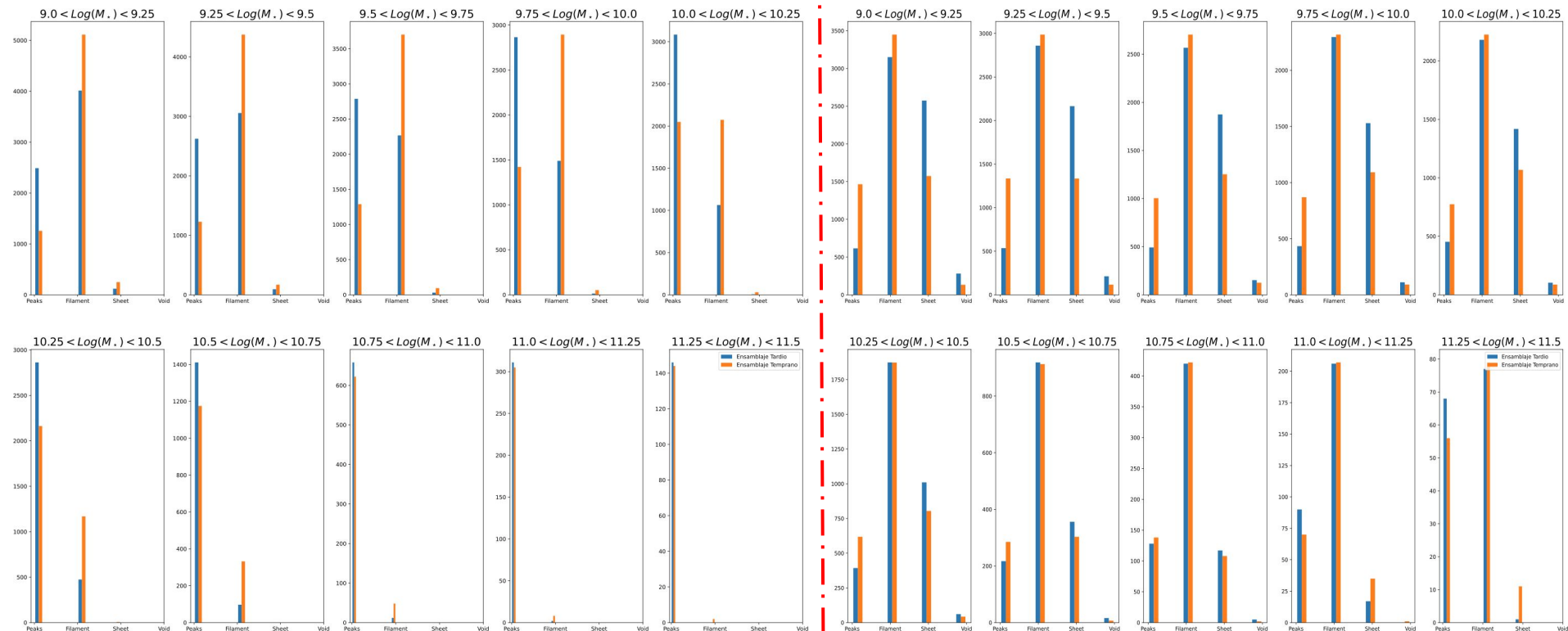
Hahn et al (2007)

Filaments: Two eigenvalues are positive, and one is negative.

Nodes: All eigenvalues are positive.

## Halos smooth scale: 1UC

## Halos smooth scale:12.5 UC



Orange: Early Assembly Halos  
Blue: Late Assembly Halos

# Cosmic Web: Tidal Anisotropy

$$q_R^2 = \frac{1}{2} [(\lambda_3 - \lambda_1)^2 + (\lambda_3 - \lambda_2)^2 + (\lambda_2 - \lambda_1)^2]$$

Tidal Shear

Similar to [Aseem Paranjape et al \(2018\)](#) we use the Tidal Anisotropy ( $\alpha$ ) to characterize the tidal environment

$$\alpha_R \equiv (1 + \delta_R)^{-1} \sqrt{q_R^2}$$

$q^2 = 0$   $\longrightarrow$  Isotropy.

$q^2 > 0$   $\longrightarrow$  Anisotropy.

Small  $\alpha$  values correspond to isotropic regions (voids, clusters).  
Large  $\alpha$  values correspond to highly anisotropic regions (filaments).

# Cosmic Web: Tidal Anisotropy

$$q_R^2 = \frac{1}{2}[(\lambda_3 - \lambda_1)^2 + (\lambda_3 - \lambda_2)^2 + (\lambda_2 - \lambda_1)^2]$$

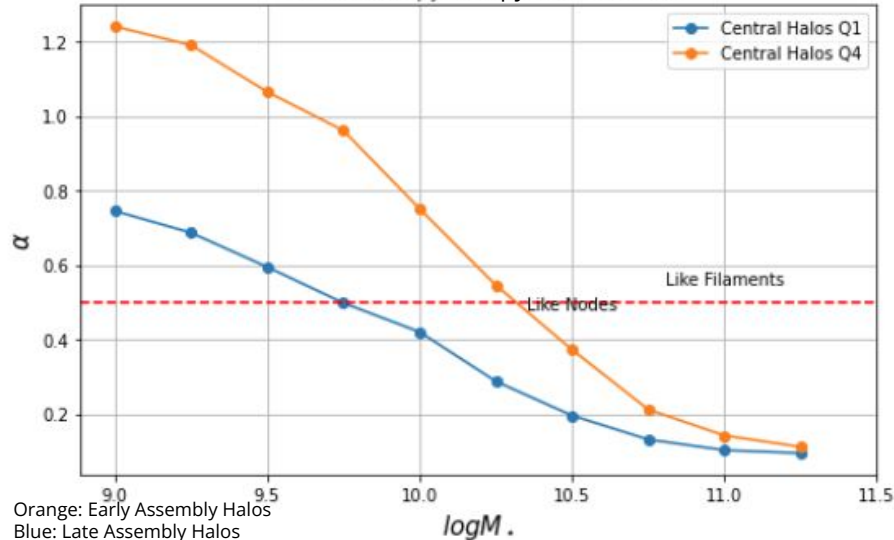
tidal torque

Similar to [Aseem Paranjape et al \(2018\)](#) We use the Tidal Anisotropy ( $\alpha$ ) to characterize the tidal environment

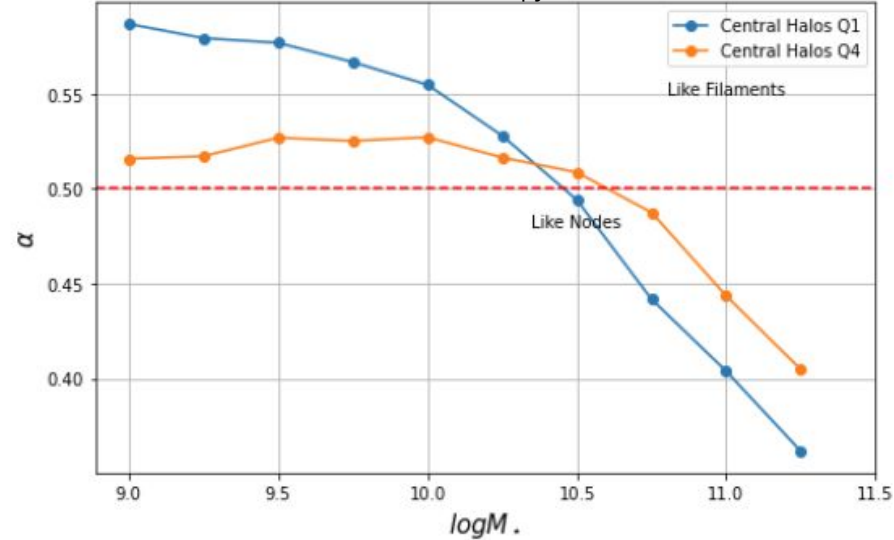
$$\alpha_R \equiv (1 + \delta_R)^{-1} \sqrt{q_R^2}$$

----- Aseem Paranjape et al (2018)

Tidal Anisotropy 1 UC



Tidal Anisotropy 12.5 UC



# Cosmic Web: Tidal Anisotropy

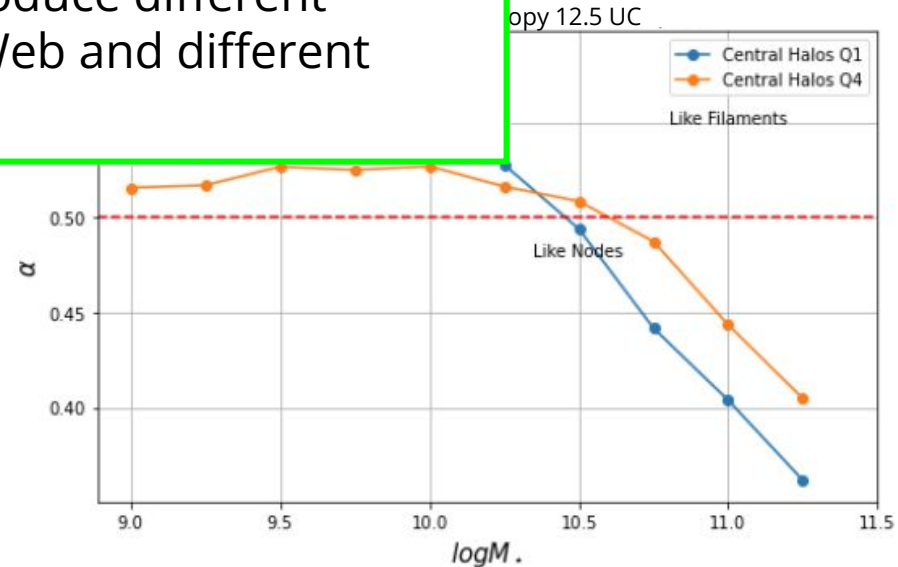
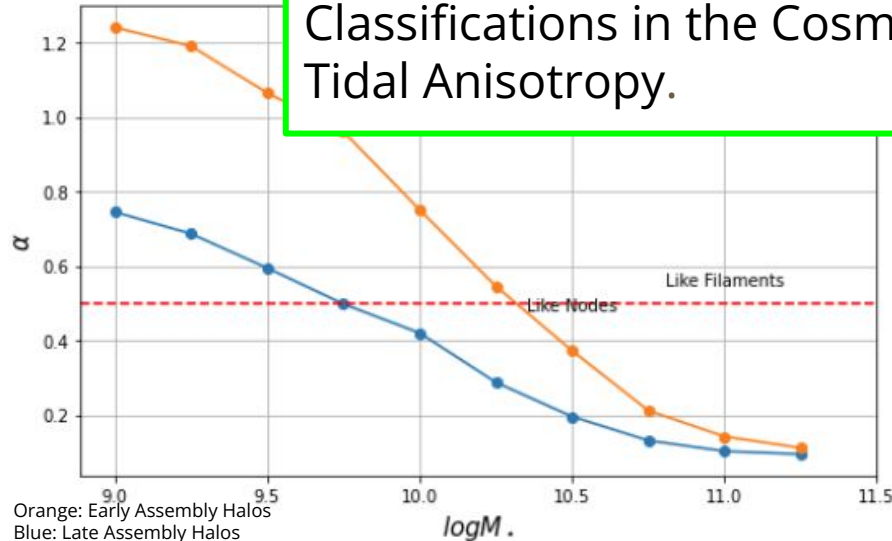
$$q_R^2 = \frac{1}{2}[(\lambda_3 - \lambda_1)^2 + (\lambda_3 - \lambda_2)^2 + (\lambda_2 - \lambda_1)^2]$$

tidal torque

Similar to [Aseem Paranjape et al \(2018\)](#) We use the Tidal Anisotropy ( $\alpha$ ) to characterize the tidal environment

$$\alpha_R \equiv (1 + \delta_R)^{-1} \sqrt{q_R^2}$$

Different smoothing scales produce different Classifications in the Cosmic Web and different Tidal Anisotropy.



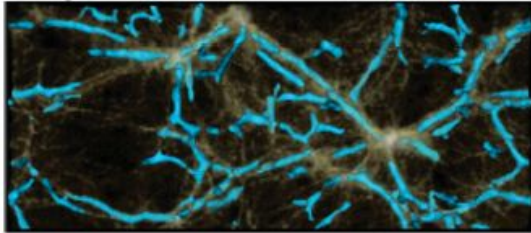
Orange: Early Assembly Halos  
Blue: Late Assembly Halos

# Cosmic Web: NEXUS - NEXUS+

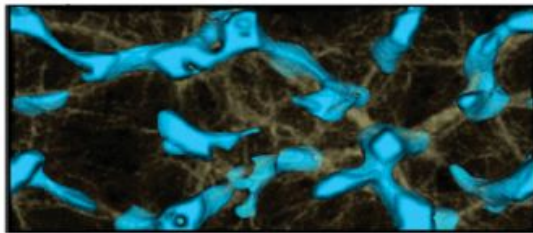


NEXUS is an algorithm for the identification of cosmic web environments: clusters, filaments, walls and voids. This is a multiscale and automatic morphological analysis tool that identifies all the cosmic structures in a scale free way, without preference for a certain size or shape.

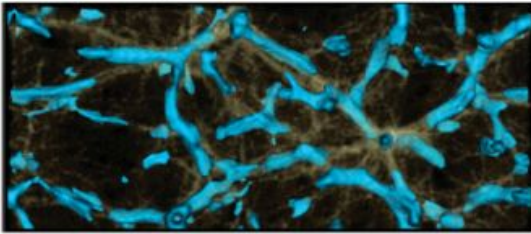
1 Mpc/h smoothing



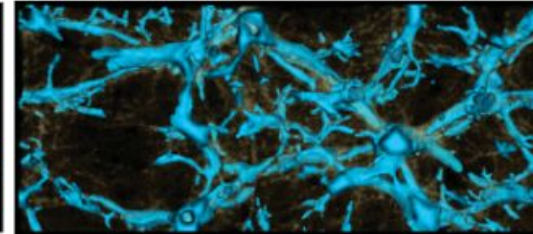
4 Mpc/h smoothing



2 Mpc/h smoothing



Combining all scales



**NEXUS: tracing the cosmic web connection**

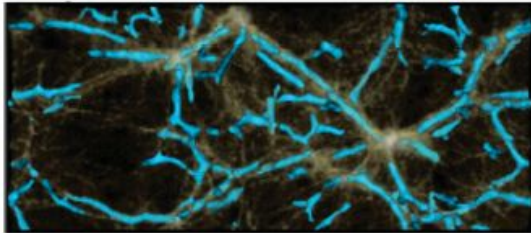
Marius Cautun et al (2012)

The paper provides a description of the algorithm but does not provide the associated code, requiring independent re-implementation

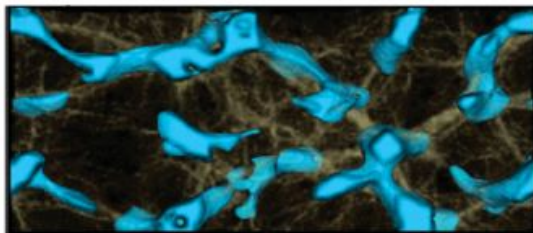
# Cosmic Web: NEXUS - NEXUS+



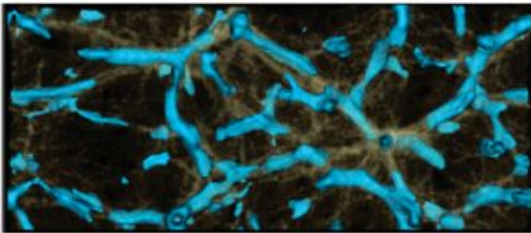
1 Mpc/h smoothing



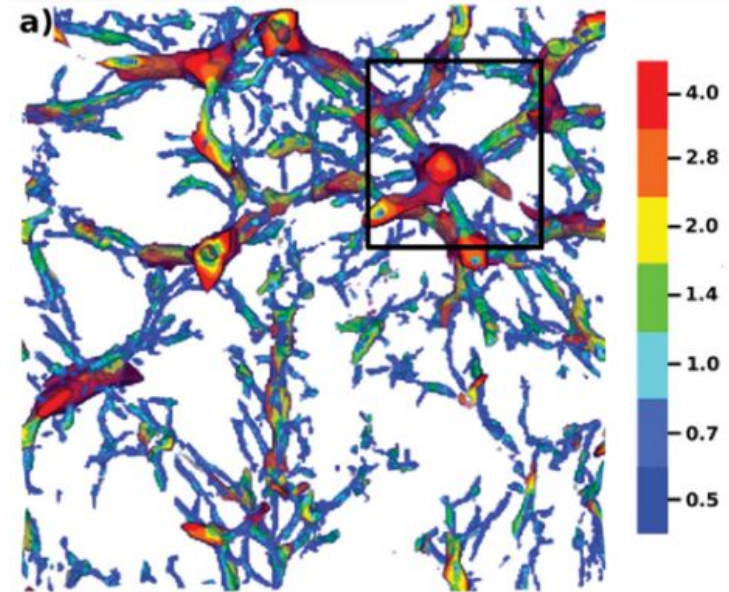
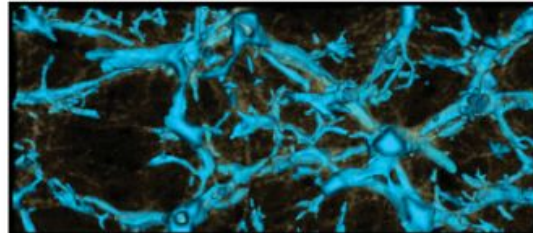
4 Mpc/h smoothing



2 Mpc/h smoothing



Combining all scales



# NEXUS: Cosmic Web Detection



The NEXUS algorithm detects the point, line- and sheet-like structures for a generic input field  $f$ . For large-scale structure, these features correspond to clusters, filaments and walls. The NEXUS algorithm consists of the following six steps.

1. Applying a Gaussian filter of width  $R_n$  to the input field.
2. Computing the Hessian matrix eigenvalues for the filtered field.
3. Assigning to each point a cluster, filament and wall signature using the Hessian eigenvalues.

$$\mathbf{H}_{ij,R_n}(\mathbf{x}) = R_n^2 \frac{\partial^2 f_{R_n}(\mathbf{x})}{\partial x_i \partial x_j},$$

$$\lambda_1 \leq \lambda_2 \leq \lambda_3$$

$$\mathcal{S} = \mathcal{I} \times \begin{cases} |\lambda_3| \theta(-\lambda_1)\theta(-\lambda_2)\theta(-\lambda_3) & \text{cluster,} \\ |\lambda_2| \theta(-\lambda_1)\theta(-\lambda_2) & \text{filament,} \\ |\lambda_1| \theta(-\lambda_1) & \text{wall,} \end{cases}$$

$$\mathcal{I} = \begin{cases} \left| \frac{\lambda_3}{\lambda_1} \right| & \text{cluster,} \\ \left| \frac{\lambda_2}{\lambda_1} \right| \Theta \left( 1 - \left| \frac{\lambda_3}{\lambda_1} \right| \right) & \text{filament,} \\ \Theta \left( 1 - \left| \frac{\lambda_2}{\lambda_1} \right| \right) \Theta \left( 1 - \left| \frac{\lambda_3}{\lambda_1} \right| \right) & \text{wall,} \end{cases}$$

# NEXUS: Cosmic Web Detection



The NEXUS algorithm detects the point, line- and sheet-like structures for a generic input field  $f$ . For large-scale structure, these features correspond to clusters, filaments and walls. The NEXUS algorithm consists of the following six steps.

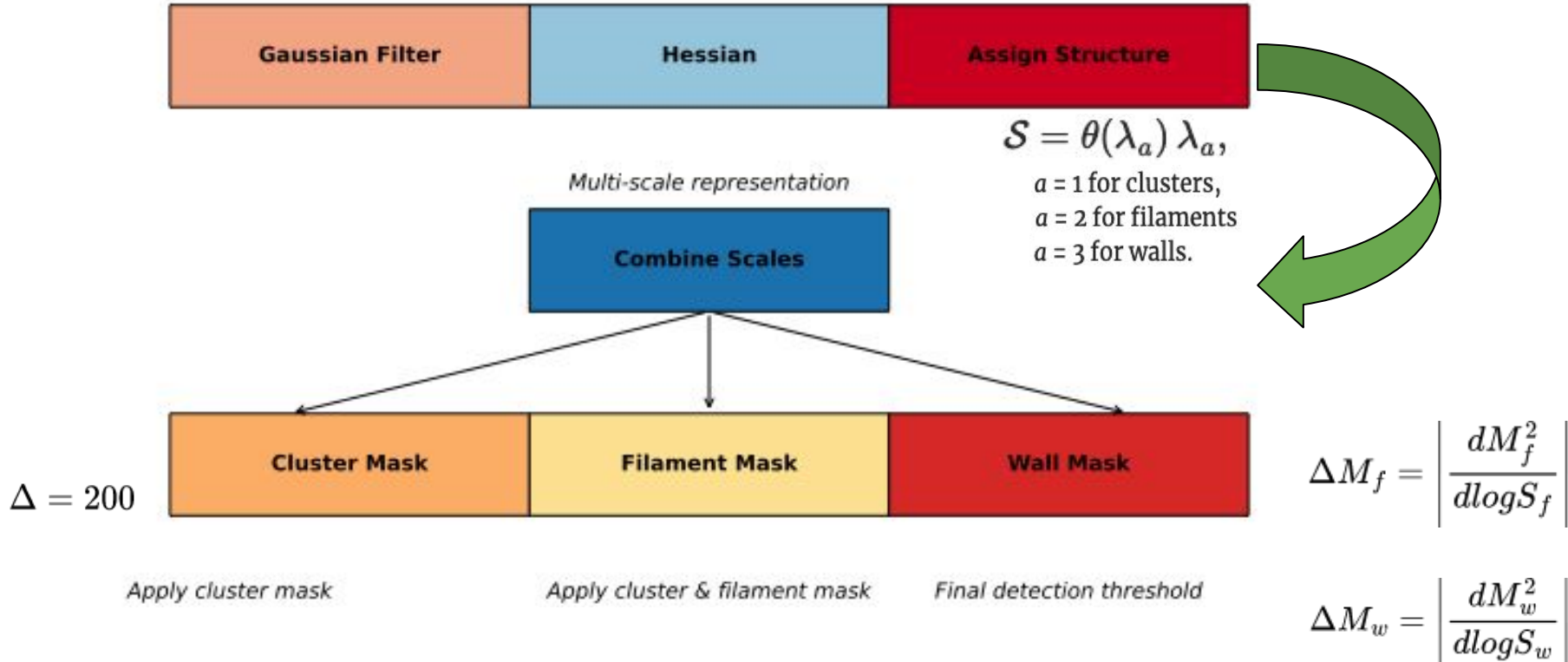
1. Applying a Gaussian filter of width  $R_n$  to the input field.
2. Computing the Hessian matrix eigenvalues for the filtered field.
3. Assigning to each point a cluster, filament and wall signature using the Hessian eigenvalues.
4. Repeating steps (1) to (3) over a range of smoothing scales to construct the scale-space representation of the field.
5. Combining the results of all scales to obtain a scale-independent cluster, filament and wall signature. 
$$\mathcal{S}(\mathbf{x}) = \max_{\text{levels } n} \mathcal{S}_{R_n}(\mathbf{x}).$$
6. Using physical criteria to determine the detection threshold corresponding to valid environments.

# Cosmic Web: NEXUS\_tidal

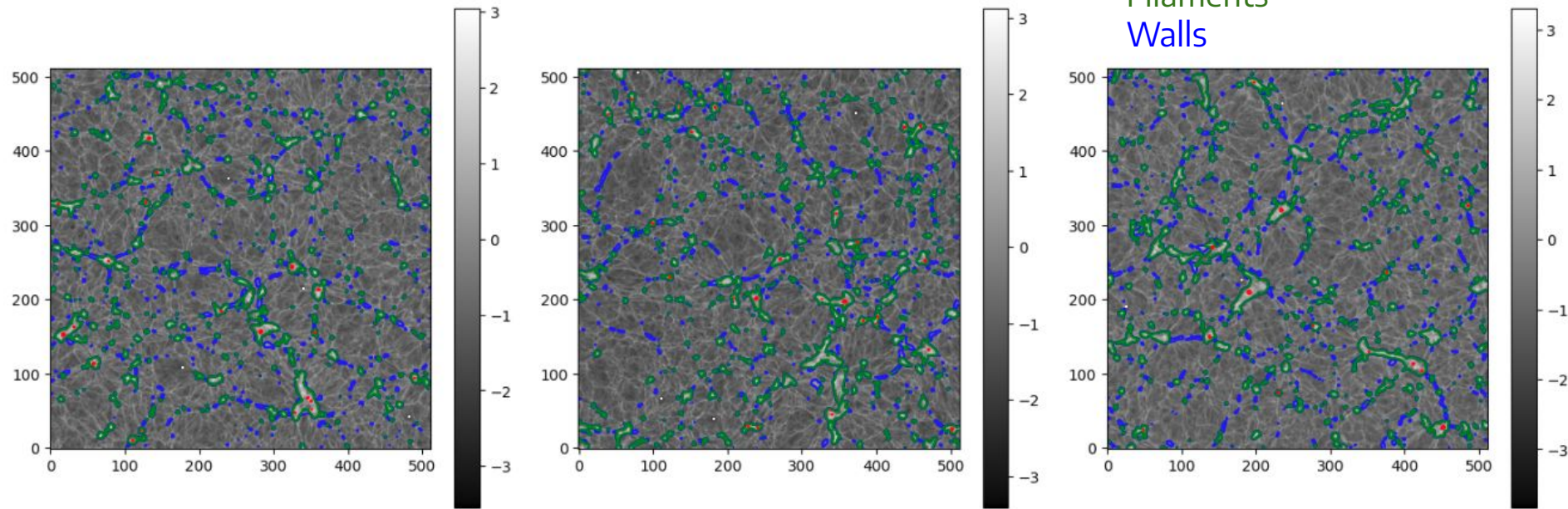


$$\hat{H}_{ij,R_n}(\mathbf{k}) = 4\pi G\bar{\rho} \frac{k_i k_j}{k^2} \hat{\delta}(\mathbf{k}) e^{-k^2 R_n^2/2}.$$

## NEXUS\_tidal Workflow



# Red Cosmica: NEXUS\_tidal

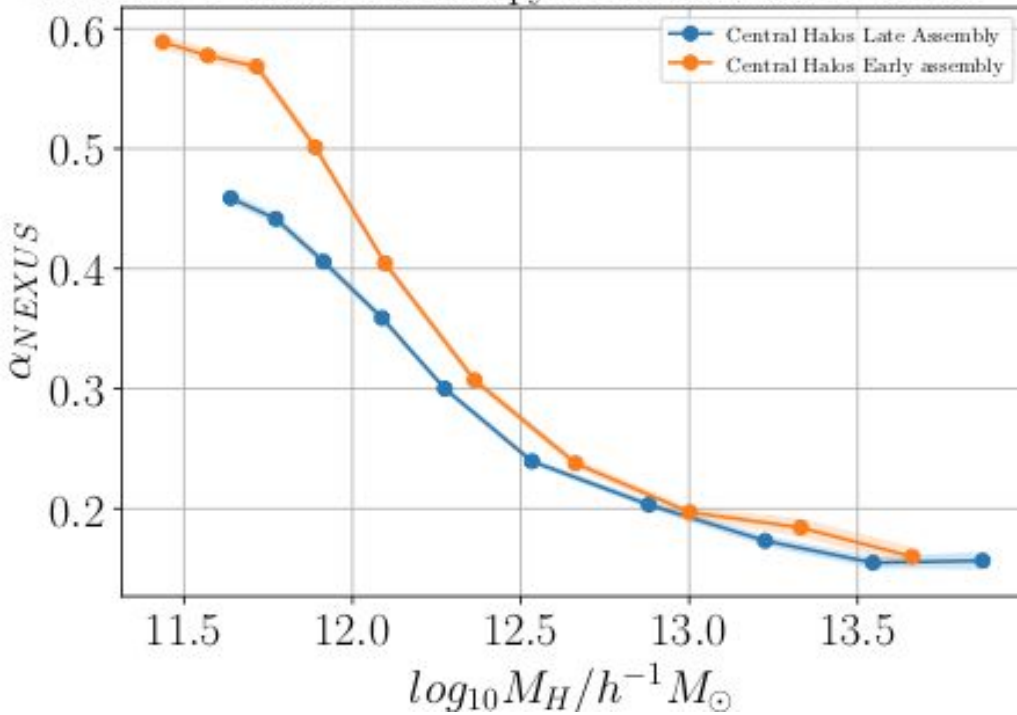


$$L_{cel} = 0.4 \text{ Mpc}/h$$



# Nexus\_Tidal: Tidal Anisotropy

TNG300-2 Tidal Anisotropy NEXUS\_tidal  $N_{mesh} = 512^3$



We found:

1. The detection of the Cosmic Web structures and the calculation of tidal anisotropy in NEXUS depend on the choice of  $L_{Cel}$ .
2. Early-forming halos are found in more anisotropic environments compared to their late-forming counterparts.

small values  $\alpha \rightarrow$  like Node environment  
 large values  $\alpha \rightarrow$  like Filament environment

Work in progress...



LOADING...

# Nexus\_Tidal: Future Work

---



**Improving Resolution:** We plan to enhance the resolution by reducing the smoothing scale  $L_{\text{Cel}}$  to better capture the details of halo structures, improving the detection of cosmic web features.

**Studying Galaxy Properties:** We aim to investigate galaxy properties that correlate with the assembly time of their host halos, further elucidating the connection between galaxy evolution and the underlying large-scale structure.

By refining the resolution and studying these correlations, we hope to gain deeper insights into the role of assembly bias in galaxy formation. Specifically, we will explore how the assembly history of halos influences galaxy properties, and how these properties are spatially distributed within the cosmic web, offering a better understanding of the environmental dependence of galaxy evolution.

Work in progress...



LOADING...

# References



- Paranjape, A., Hahn, O., and Sheth, R. K., “Halo assembly bias and the tidal anisotropy of the local halo environment”, *Monthly Notices of the Royal Astronomical Society*, vol. 476, no. 3, OUP, pp. 3631–3647, 2018. doi:10.1093/mnras/sty496.
- Cautun, M., van de Weygaert, R., and Jones, B. J. T., “NEXUS: tracing the cosmic web connection”, *Monthly Notices of the Royal Astronomical Society*, vol. 429, no. 2, OUP, pp. 1286–1308, 2013. doi:10.1093/mnras/sts416.
- Cautun, M., van de Weygaert, R., Jones, B. J. T., and Frenk, C. S., “Evolution of the cosmic web”, *Monthly Notices of the Royal Astronomical Society*, vol. 441, no. 4, OUP, pp. 2923–2973, 2014. doi:10.1093/mnras/stu768.
- Libeskind, N. I., “Tracing the cosmic web”, *Monthly Notices of the Royal Astronomical Society*, vol. 473, no. 1, OUP, pp. 1195–1217, 2018. doi:10.1093/mnras/stx1976.
- Alam, S., Zu, Y., Peacock, J. A., and Mandelbaum, R., “Cosmic web dependence of galaxy clustering and quenching in SDSS”, *Monthly Notices of the Royal Astronomical Society*, vol. 483, no. 4, OUP, pp. 4501–4517, 2019. doi:10.1093/mnras/sty3477.
- Dome, T., Fialkov, A., Sartorio, N., and Mocz, P., “Cosmic web dissection in fuzzy dark matter cosmologies”, *Monthly Notices of the Royal Astronomical Society*, vol. 525, no. 1, OUP, pp. 348–363, 2023. doi:10.1093/mnras/stad2276.