Quantifying the Flow of Matter through Cosmic Web

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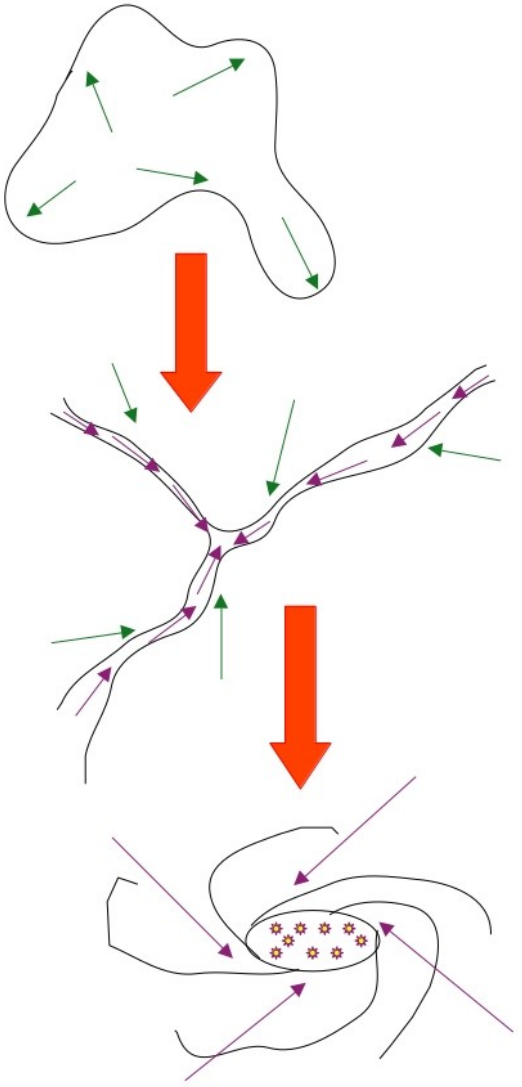

Zeldovich's Formalism of Structure Formation

Zel'Dovich, Y. B. (1970)

- Lagrangian analysis of density perturbation.
- No assumption of shape of overdensity.
- Approximation : Linear Mapping from initial to final positions.

  --> Particles move in the direction of their initial displacement.

$$\vec{r} = \vec{q} + D(t)\vec{p}(\vec{q})$$

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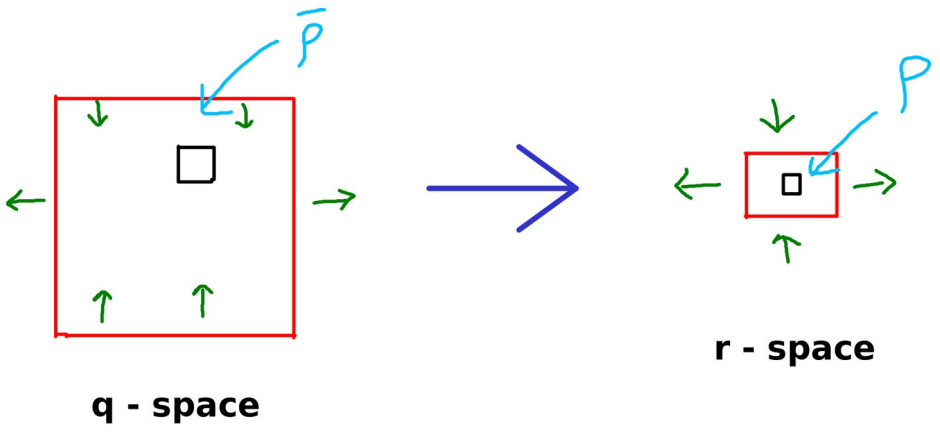

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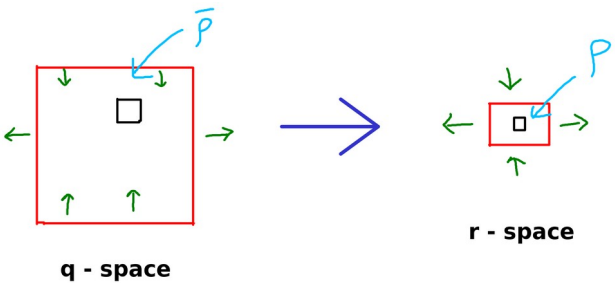

- **Deformation Tensor --**

$$D_{ik} = \frac{\partial r_i}{\partial q_k} = \delta_{ik} + D(t)\frac{\partial p_i}{\partial q_k}$$

$$D = \begin{Vmatrix} 1 - \alpha D(t) & 0 & 0 \\ 0 & 1 - \beta D(t) & 0 \\ 0 & 0 & 1 - \gamma D(t) \end{Vmatrix}$$

Zeldovich's Formalism of Structure Formation

- Using the conservation of mass,

$$\rho = \bar{\rho} \left| \left| \frac{\partial r_i}{\partial q_k} \right| \right|^{-1}$$

$$\rho = \frac{\bar{\rho}}{(1 - \alpha D)(1 - \beta D)(1 - \gamma D)}$$

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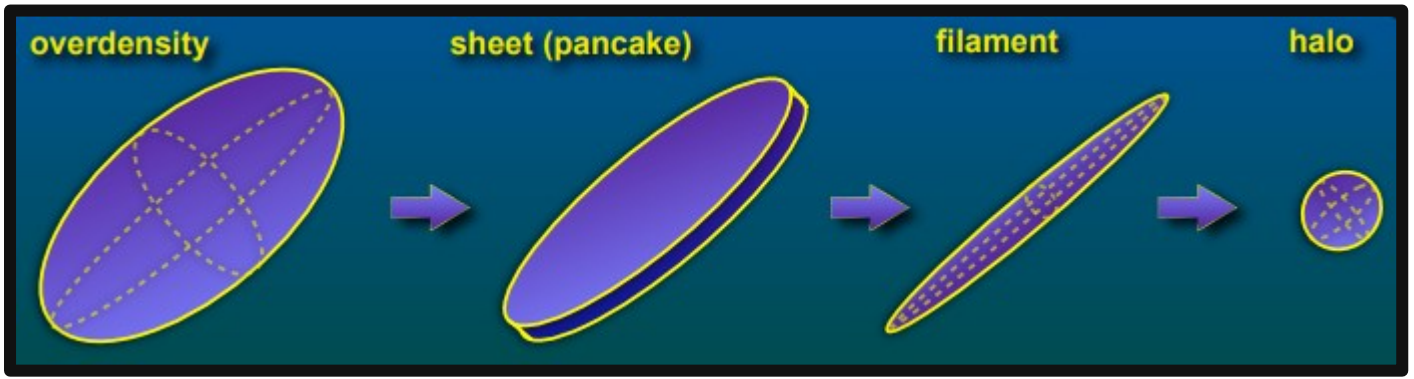
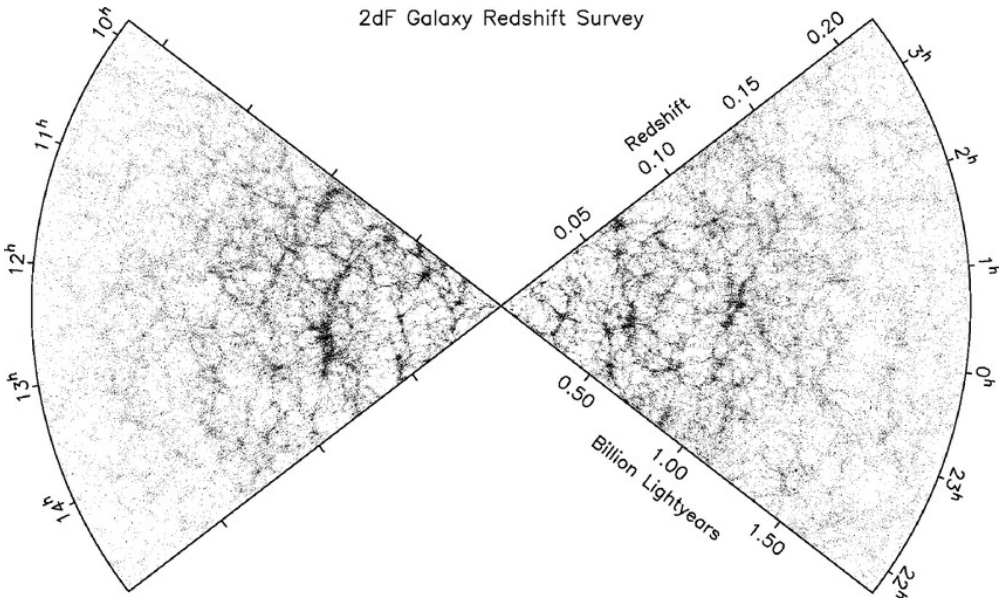
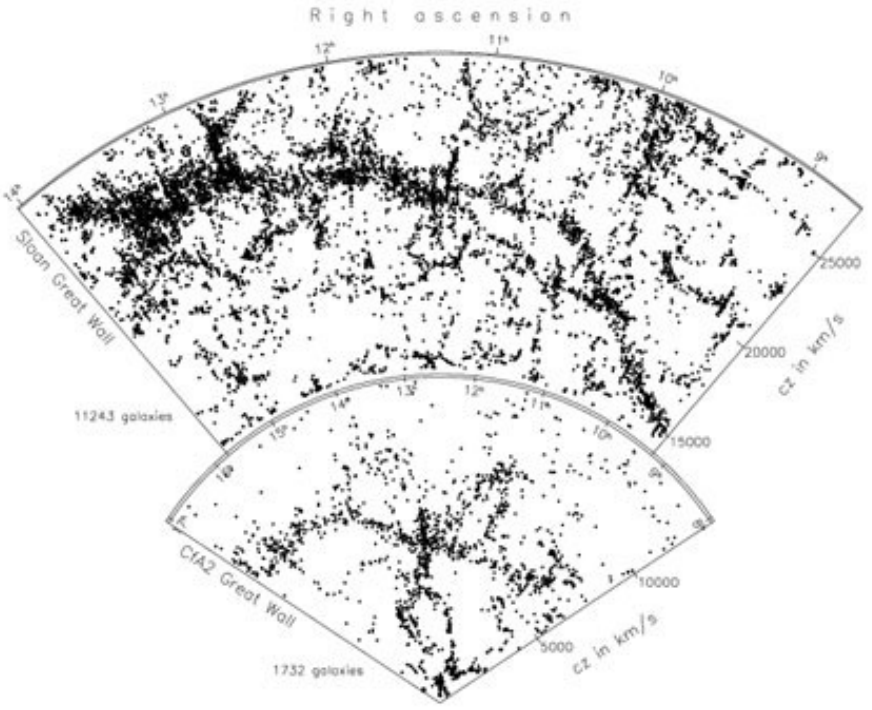
- The unilateral compression transforms a **3D ellipsoid** in q-space into a **flat 2D ellipse** in r-space --> **Zeldovich's Pancakes**



Credit : Frank van den Bosch

Cosmic Web in Observations





Credit: 2dF, CfA2 and SDSS galaxy redshift surveys

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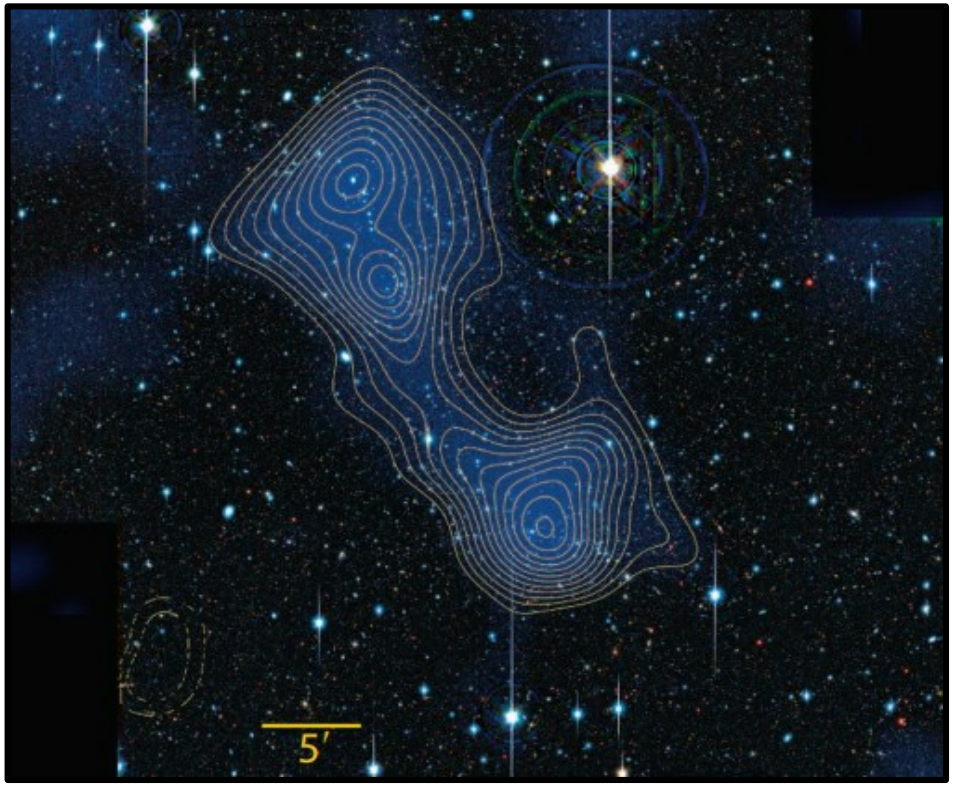
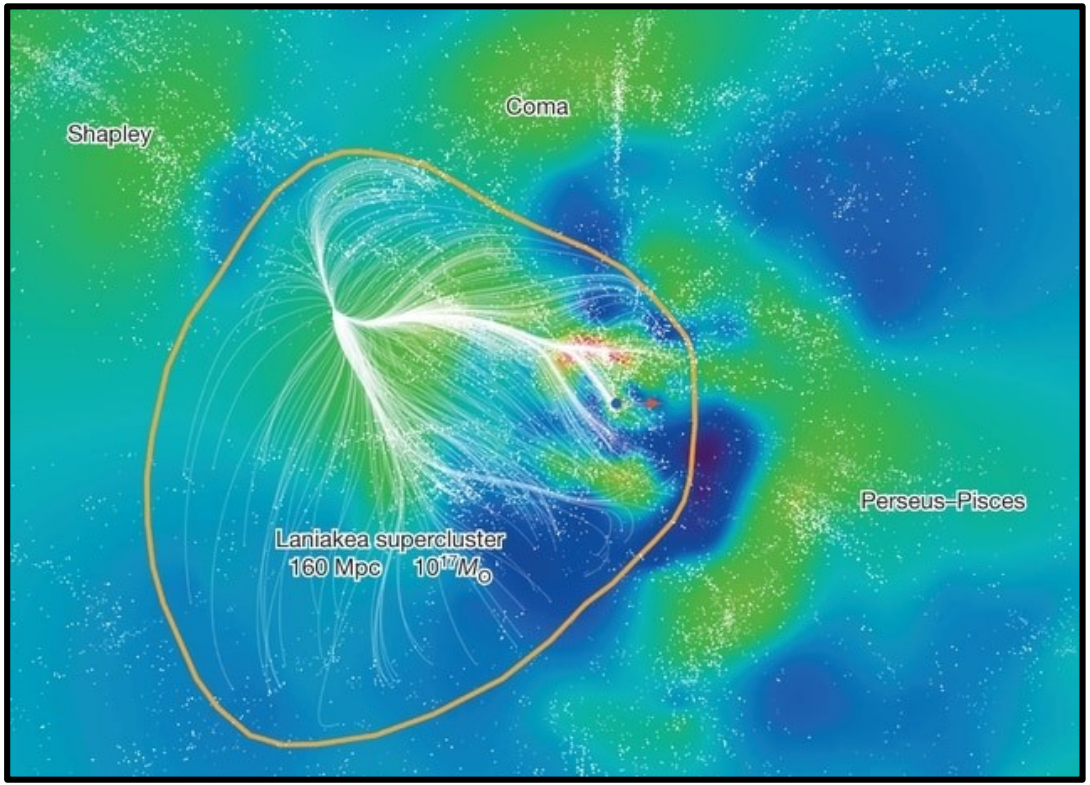
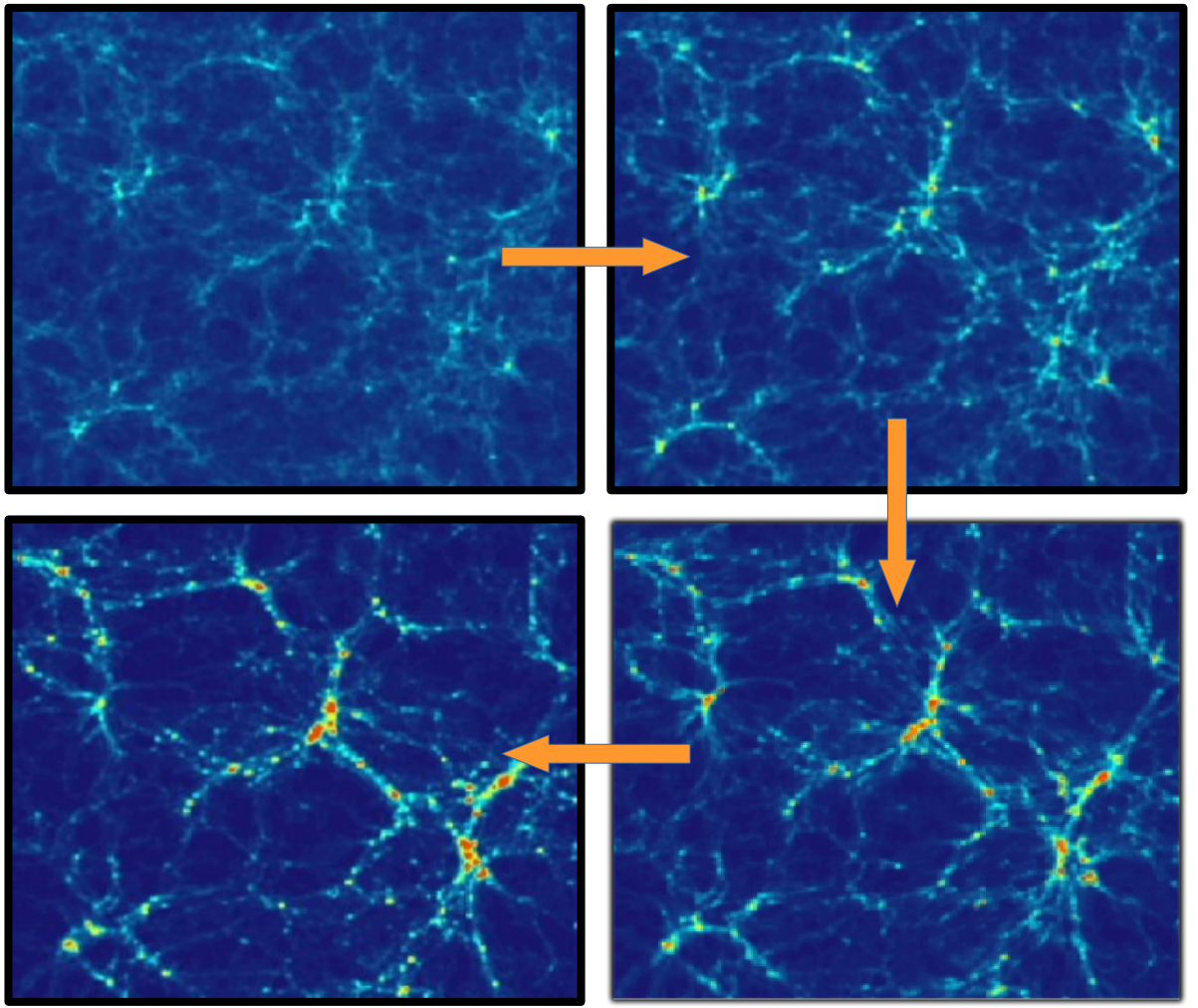


Dark-matter filament connecting the two main components of the Abell 222/223 (Dietrich et al. 2012)



A slice of the Laniakea supercluster in the supergalactic equatorial plane (Tully et al. 2014)

Cosmic Web in 21-cm simulations



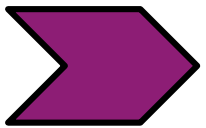
Simulation: Debanjan Sarkar

Flow of matter through Cosmic Web

Cosmic Web → **Anisotropic Collapse**

Gravitational Instability
Matter flows of low-density regions to high-density regions

Underdense (δ < 0)
Voids



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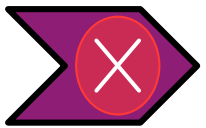

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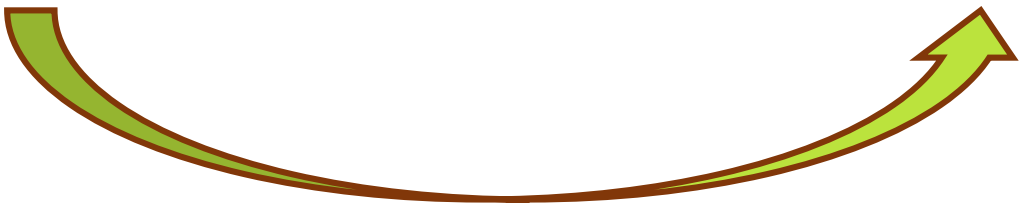
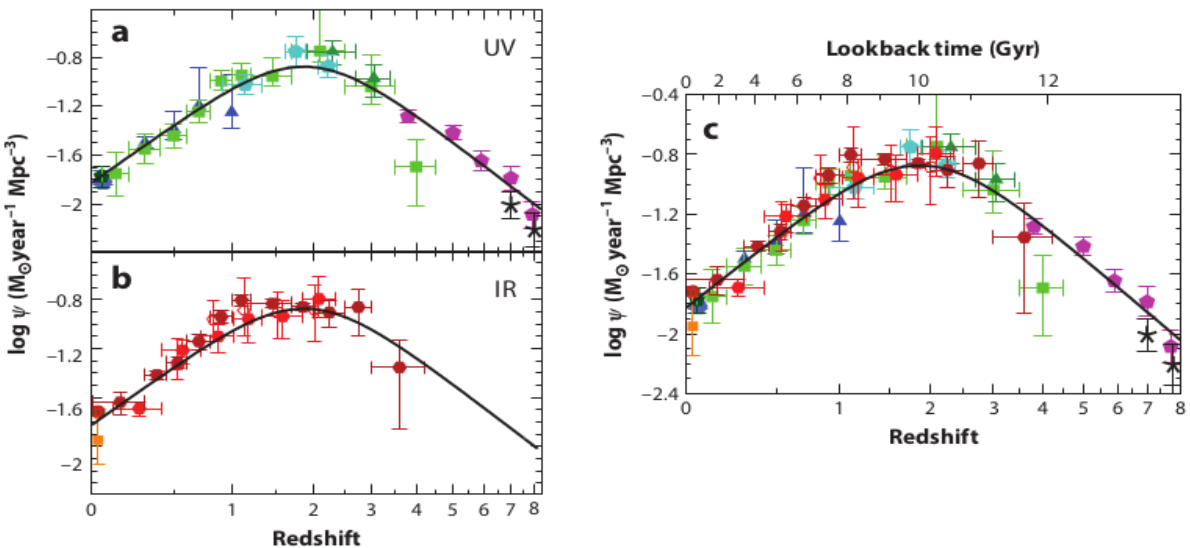


Channels
Sheets & Filaments

Cosmic Star Formation History

SFRD : total mass turned into stars per unit time per unit volume at a redshift



Madau & Dickinson (2014)

Quenching of Cosmic Star Formation

Matter Flow through Cosmic Web

Simulation

Mondal et al. (2015)

N-body simulation

V = $(256\ \text{Mpc})^3$

$(1536)^3$ grid points

Resolution = 0.1667 Mpc.

4.53×10^8 particles

$m_p = 1.47 \times 10^9\ M_\odot$

Cloud-in-cell (CIC) gridding

$(512)^3$ points at 0.5 Mpc

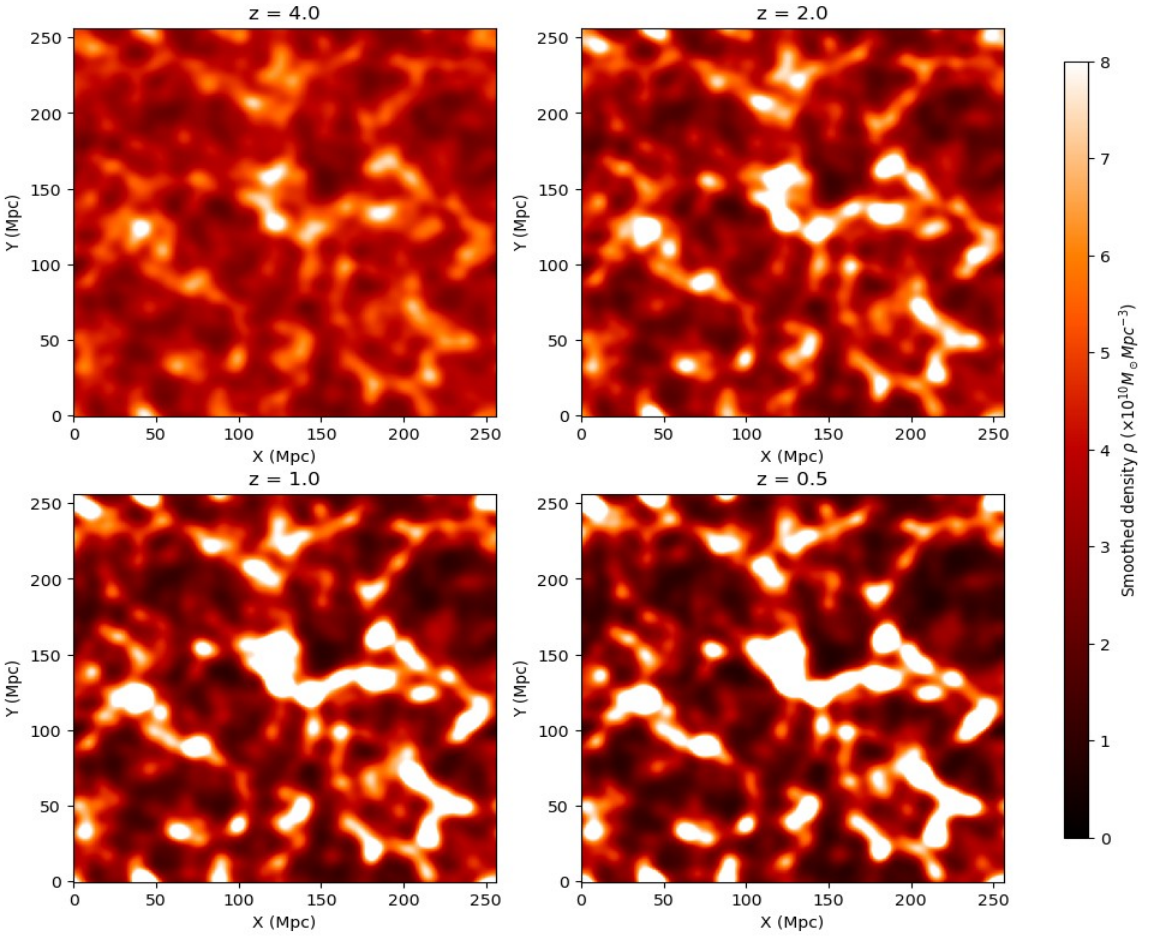
Position : numder density (ρ)

Velocity : momentum density (ρv)

Smoothing

Gaussian filter

Radius = 2 h^{-1} Mpc

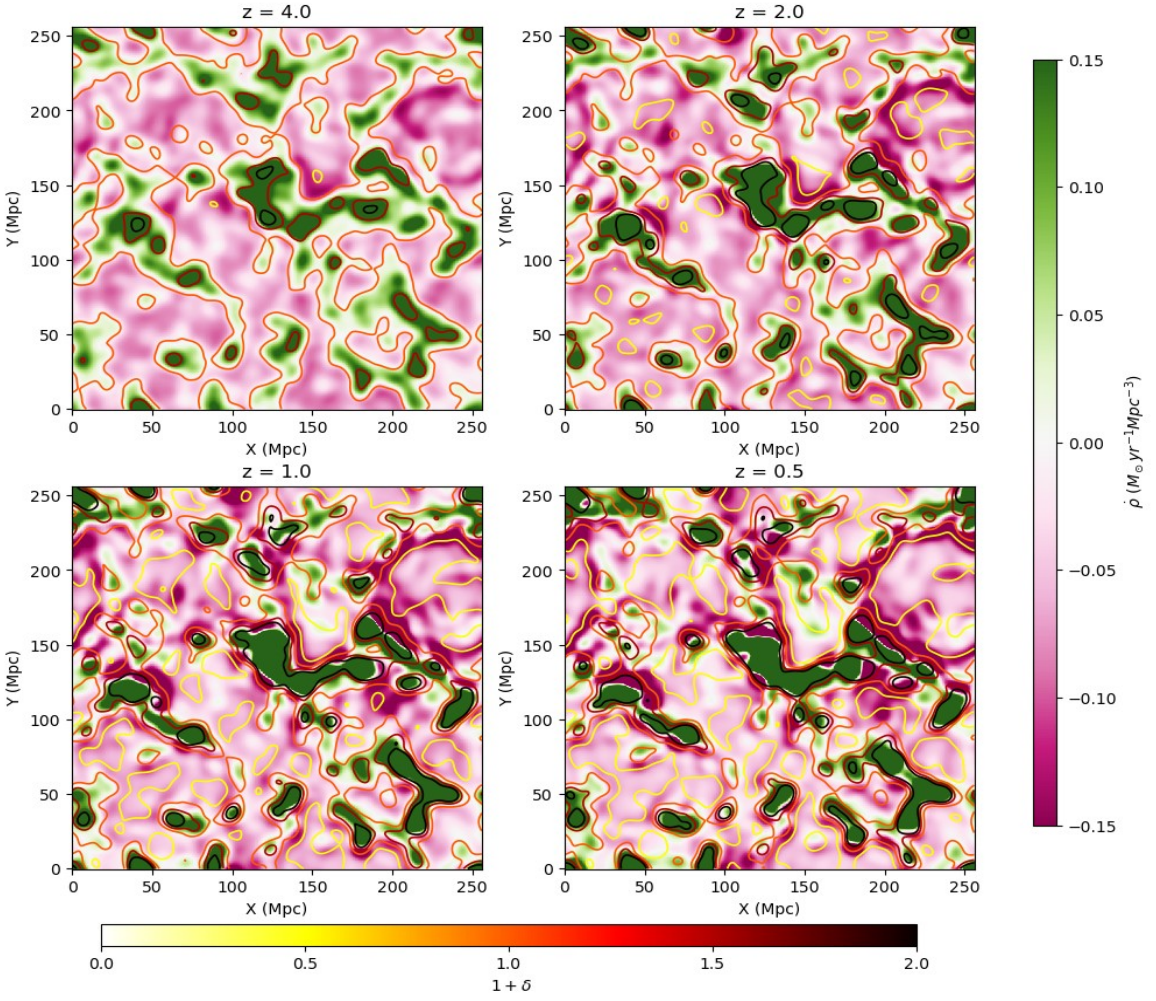


Rate of Matter Flow

Continuity equation :

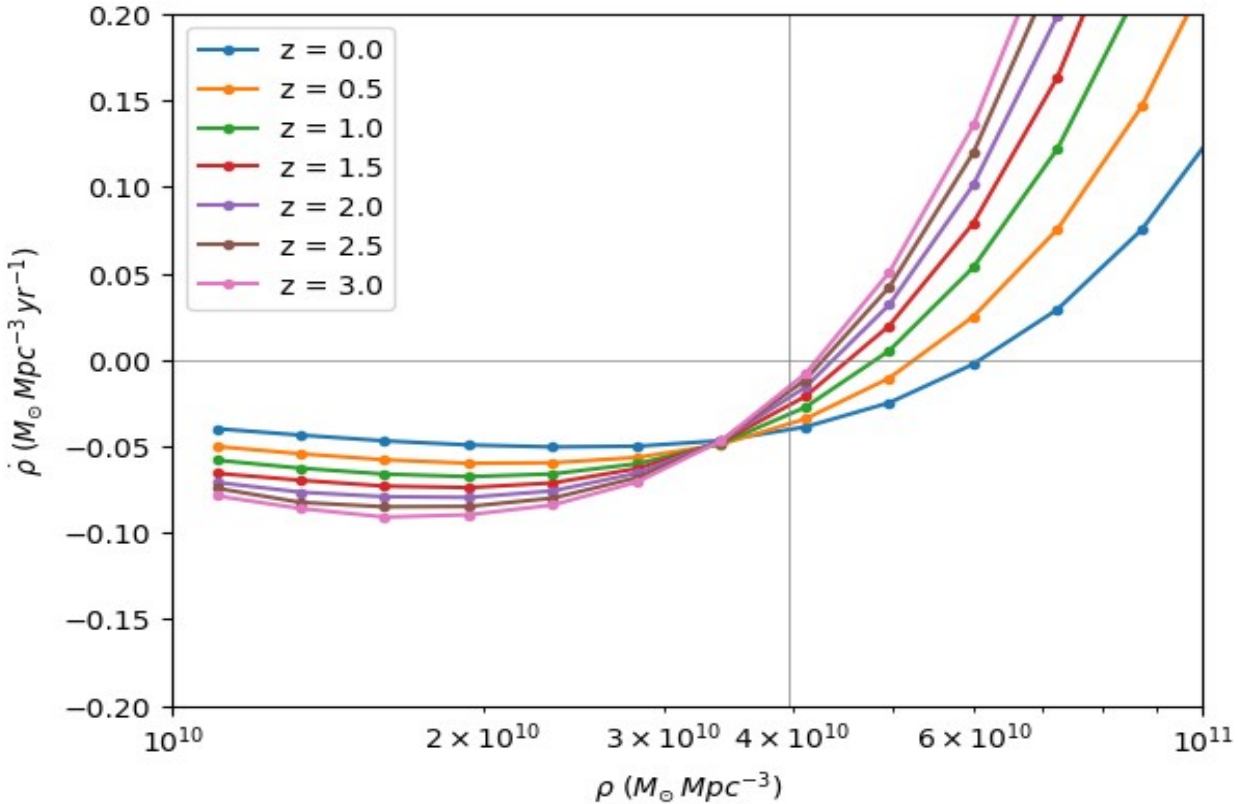
$$\frac{d\rho}{dt} = -\frac{1}{a}\nabla \cdot (\rho \vec{v})$$

Available from gridding of velocities in the simulation!



1.

Density vs its rate of change



Environment Classification : T-Web

Hahn et al. (2007)

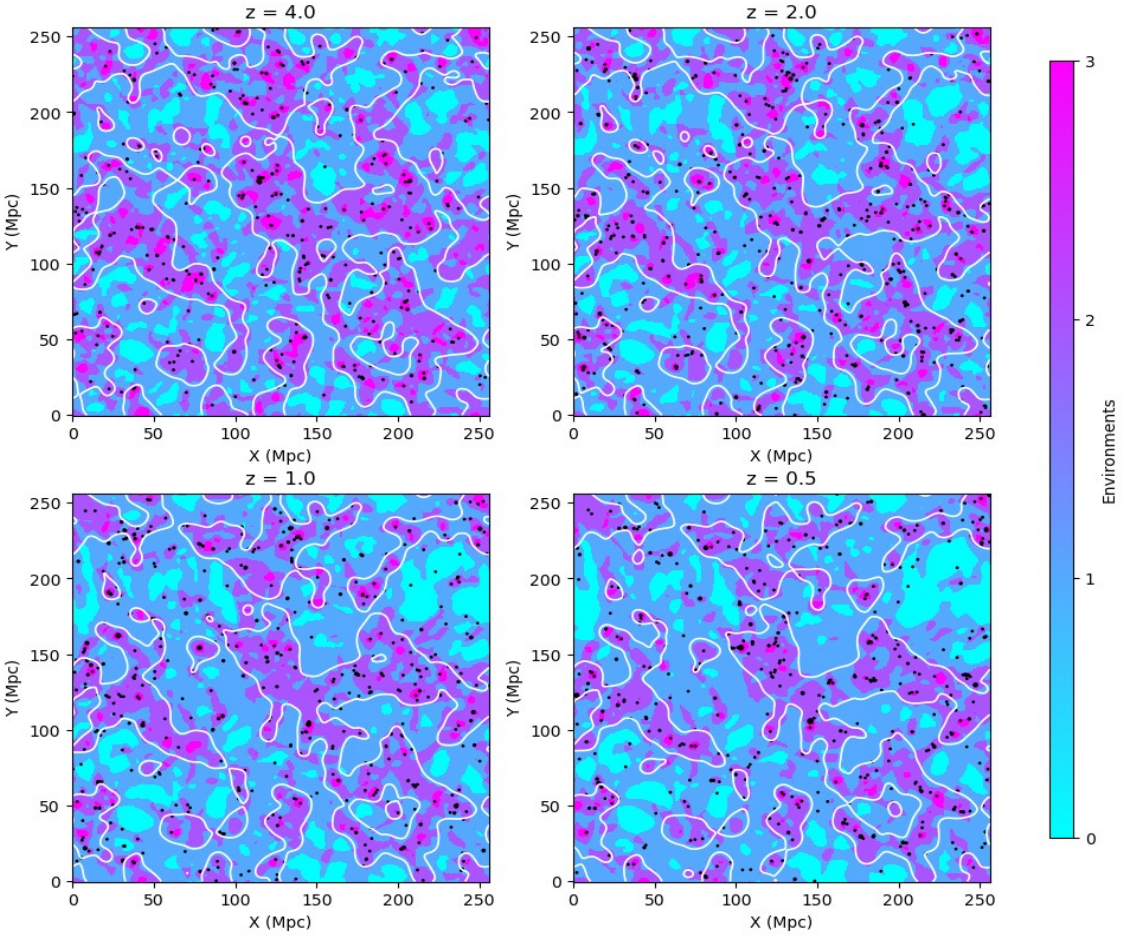
Tidal Field (Hessian of gravitational potential) :

$$T_{i,j} \equiv \partial_i \partial_j \phi_{grav}$$

Eigenvalues : $\lambda_1 > \lambda_2 > \lambda_3$

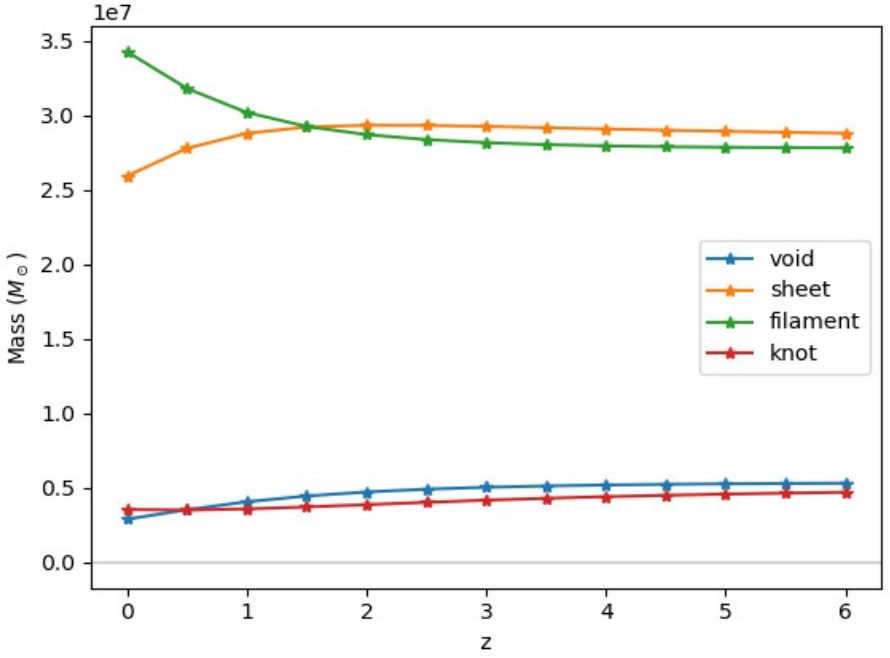
- n = 0: Void (unstable orbits)
- n = 1: Sheet (1D stable manifold)
- n = 2: Filament (2D stable manifold)
- n = 3: Knot (Attractive fixed point)

Halos :
Friends-of-Friends Halo Finder



2.

Mass vs redshift



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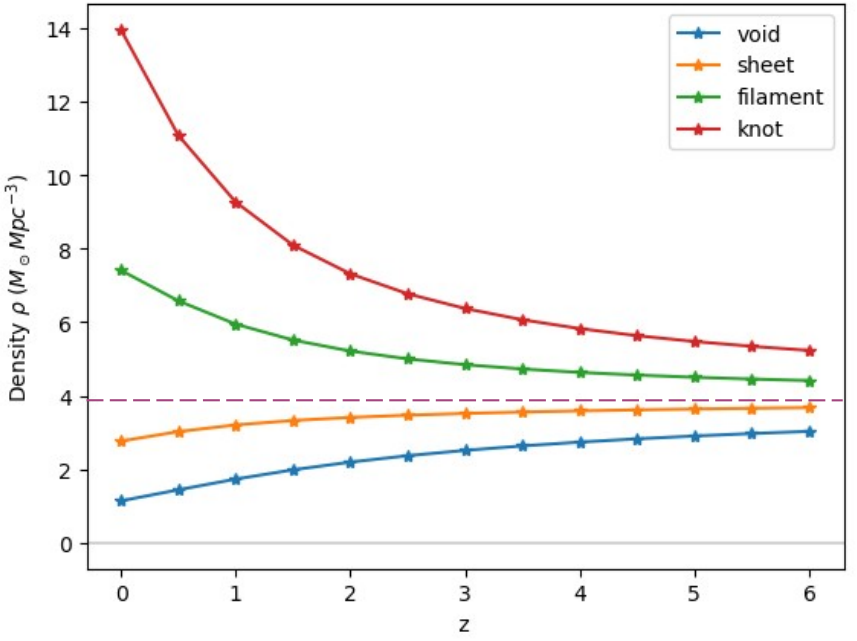

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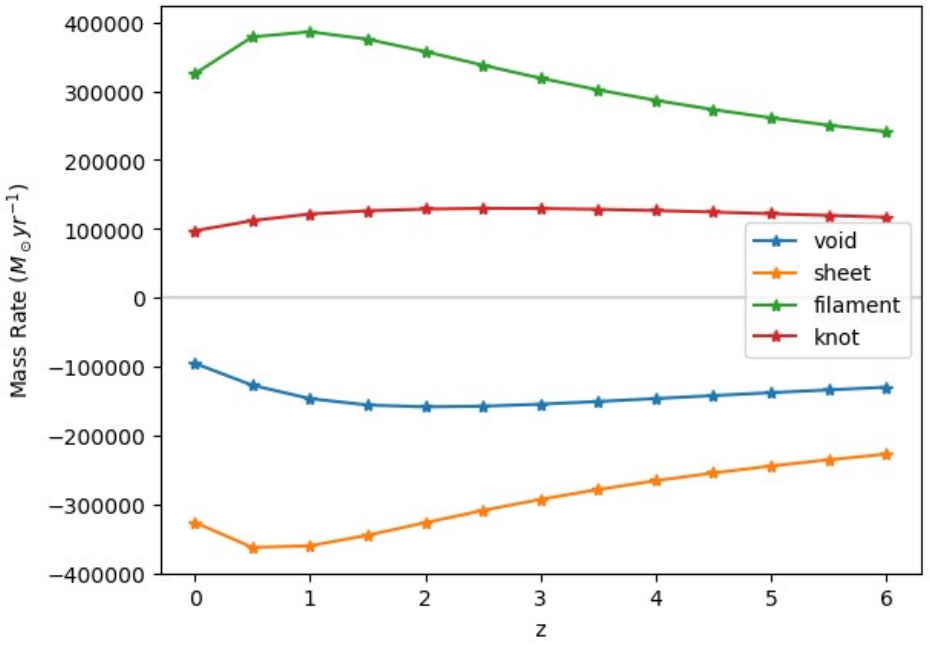
Mass-rate vs redshift



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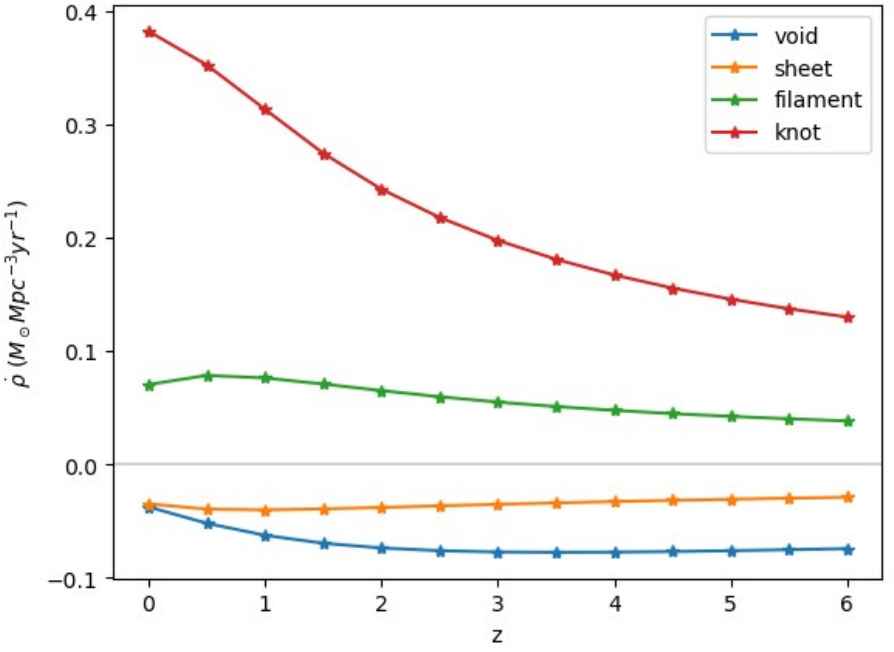
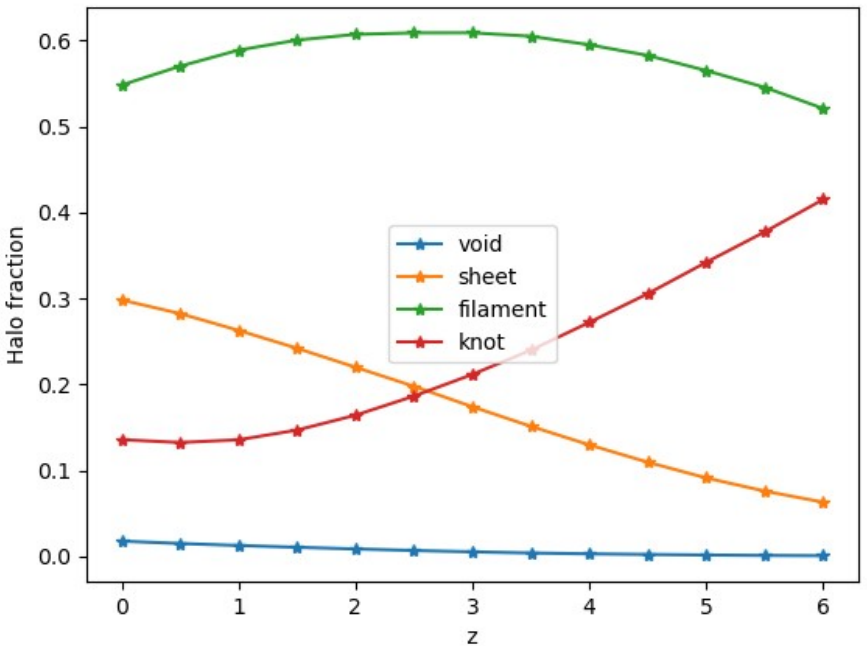
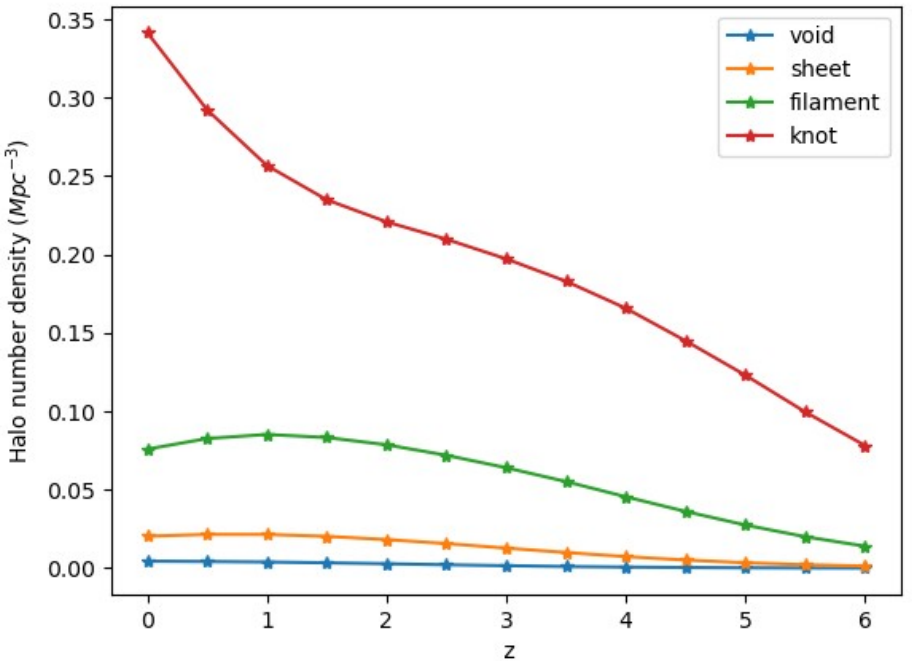


4.

Halo fraction vs redshift



Halo density vs redshift



Summary

- Large-scale structure → Cosmic Web
- Matter flow through the cosmic web → cosmic Star formation History
- Density and its rate of flow → N-body simulation
- Environment classification → T-Web Scheme

- Transition from matter outflow to inflow does NOT happen at mean-ρ.
- Most mass resides in sheets & filaments. But, sheets are underdense at all redshifts.
- Rate of mass flow increases at z ~ 2 and declines at low redshifts.
- Filaments host the most number of halos – most impact on cosmic SFH.

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