

Towards a better understanding of the Cosmic Web

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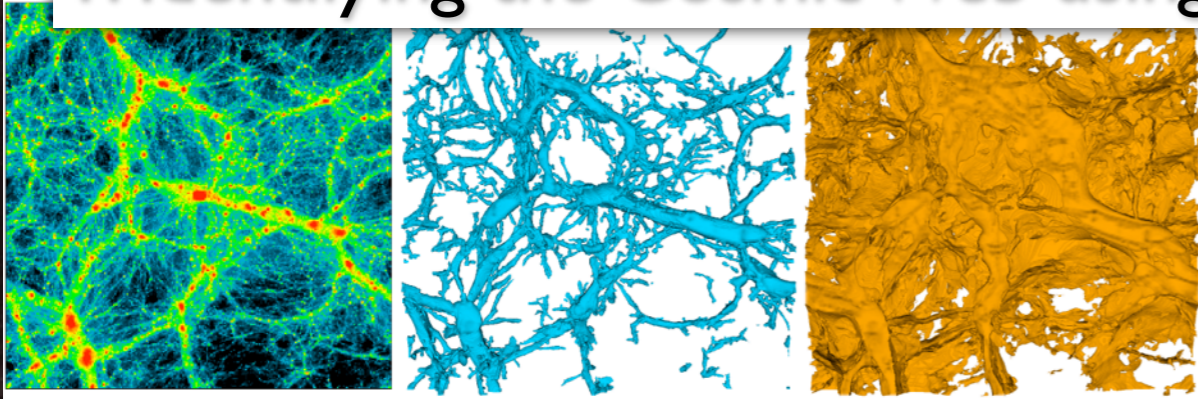
Institute for Computational Cosmology, Durham Univ.

Rien van de Weygaert, Bernard J.T. Jones, Carlos S. Frenk

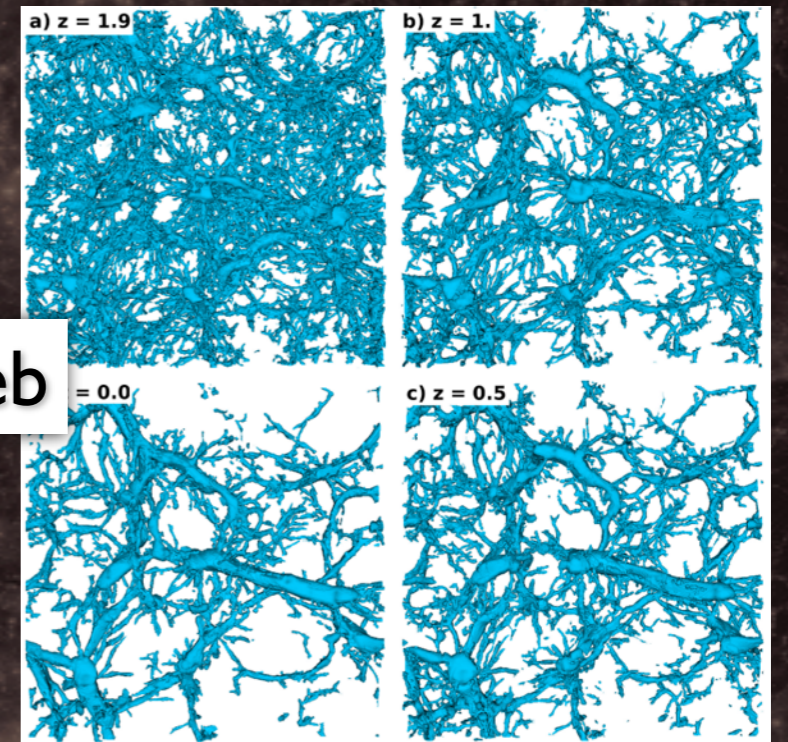
Zeldovich Universe
Tallinn, Estonia
24 June 2014

Outline

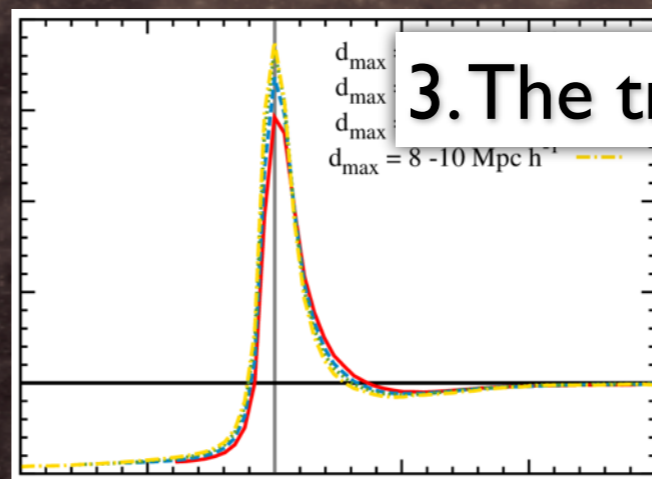
I. Identifying the Cosmic Web using NEXUS



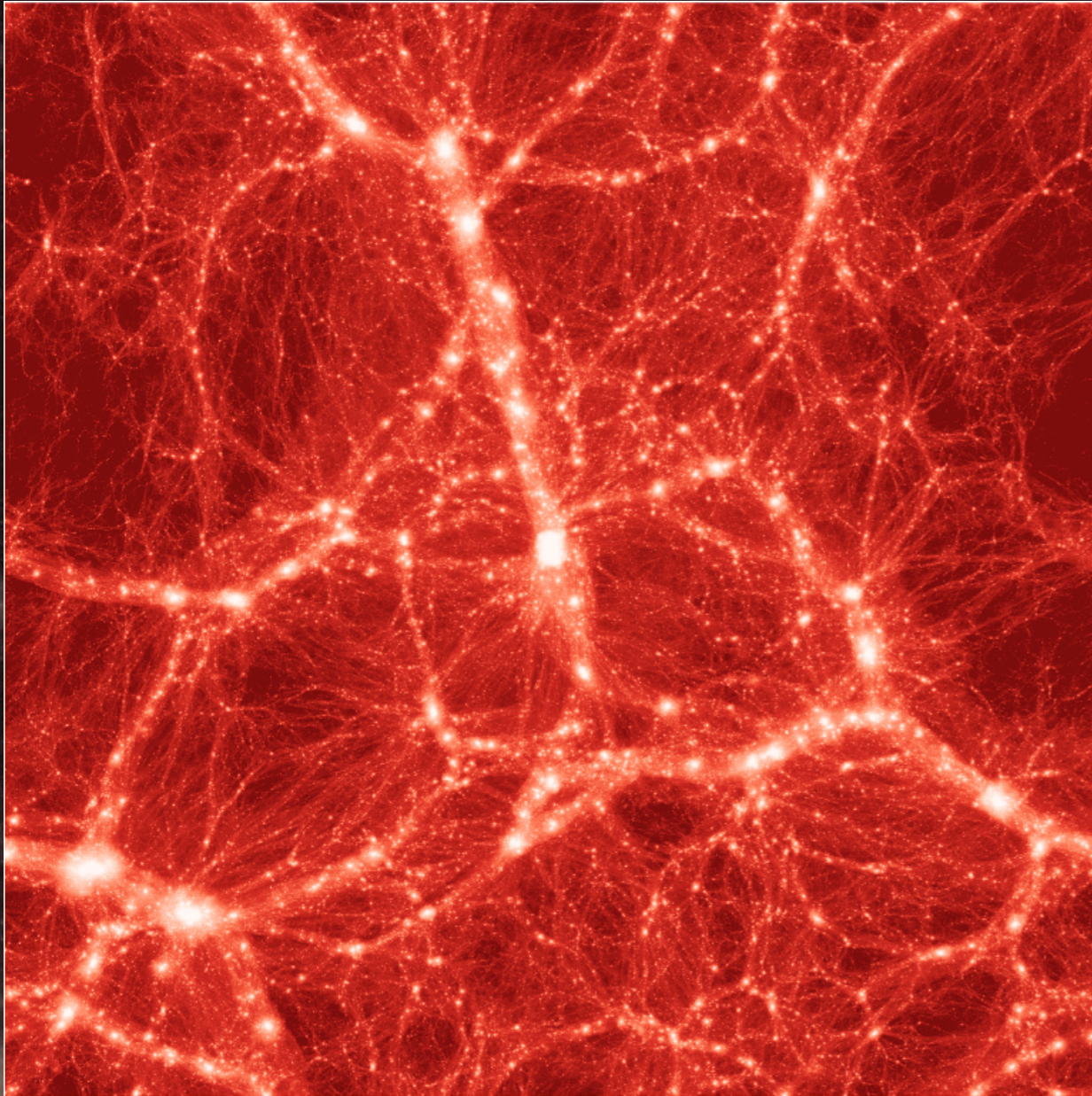
2. Evolution of the Cosmic Web



3. The true profile of voids



The complex Cosmic Web

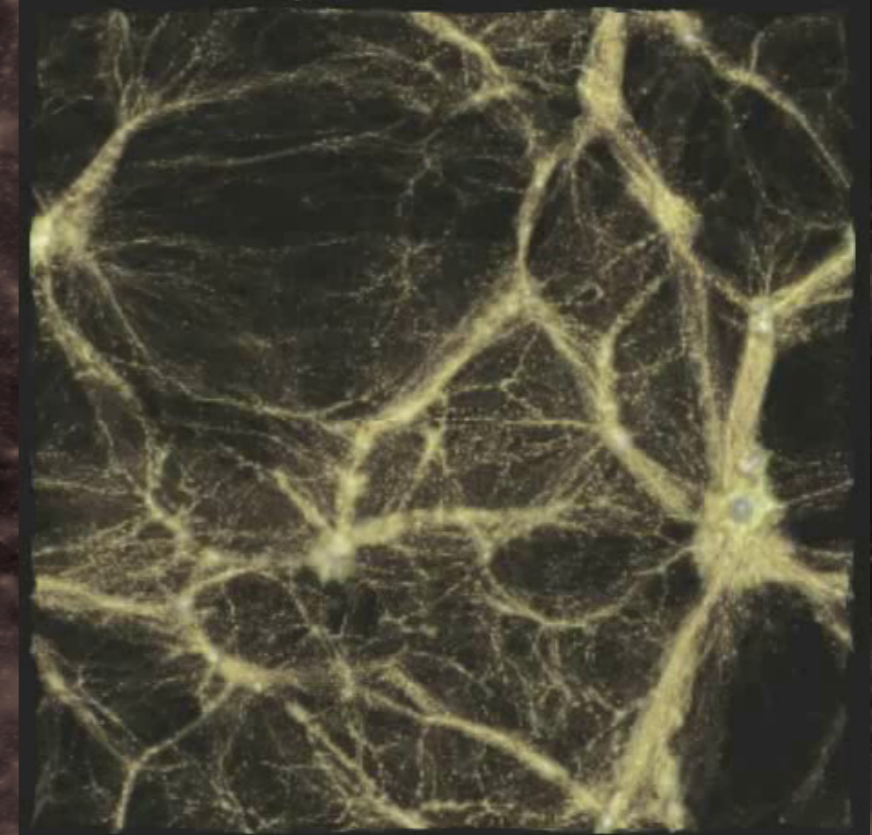
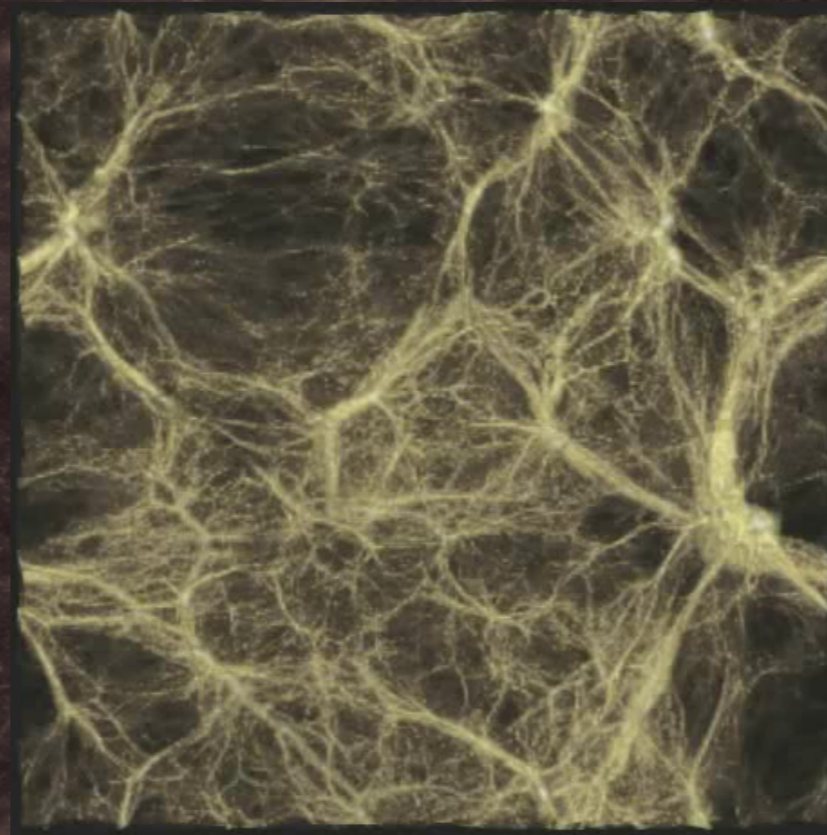
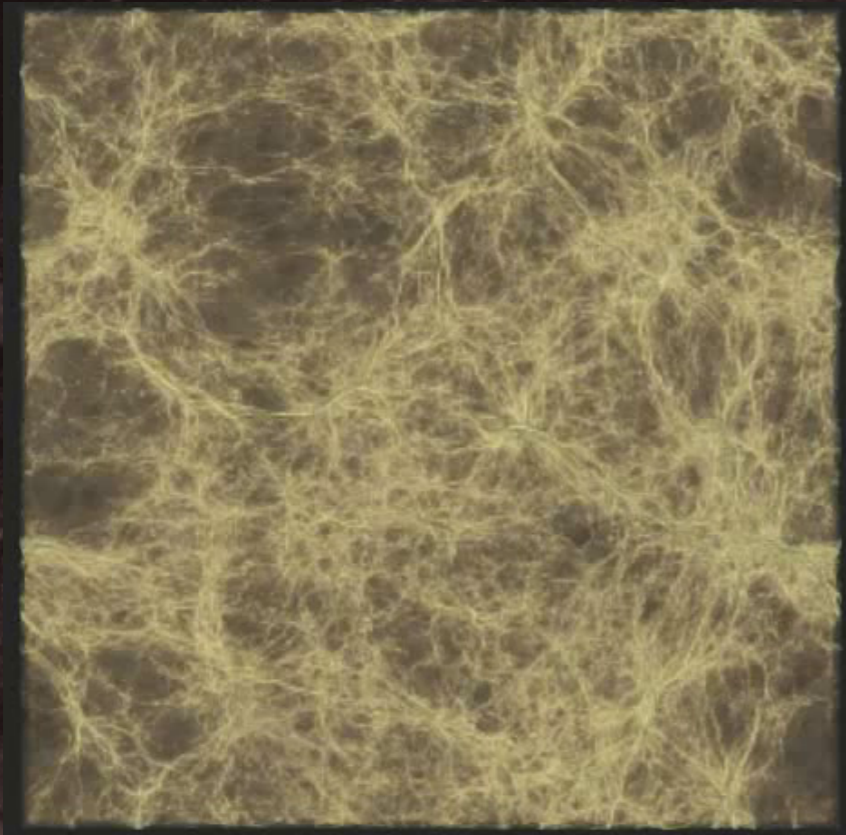


Density field in the Millennium II simulation.

Characteristics:

- Hierarchical
- Highly anisotropic geometry
- Interconnected
- Orders of magnitude variation in density

Evolution of cosmic structure

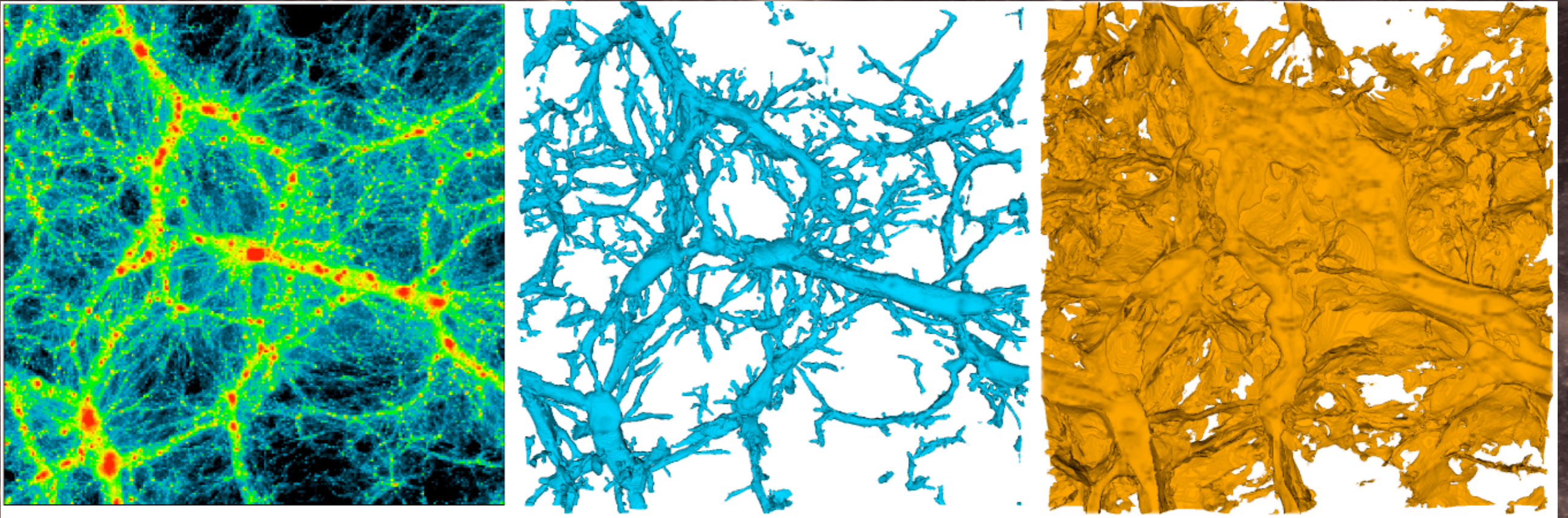


Time evolution



The NEXUS method

MC, van de Weygaert & Jones (2013)



Cosmic Web identification

Multiscale Morphology Filter (Aragon-Calvo+ 2007)

Tidal Tensor (Hahn+ 2007, Forero-Romero+ 2009)

Skeleton (Sousbie+ 2008)

Bisous processes (Stoica+ 2005,2007, Tempel+ 2014)

NEXUS / NEXUS+ (MC+ 2013)

Origami / Phase space sheet (Falck+ 2012, Shandarin+ 2012)

Spine Web (Aragon-Calvo+ 2010)

DisPerSE (Sousbie+ 2011)

Velocity Shear (Hofmann+ 2012, Libeskind+ 2012)

Limitations:

- One web environment
- Single scale
- Subjective parameters
- Not applicable to observations

The NEXUS / NEXUS+ methods

Anisotropic geometry

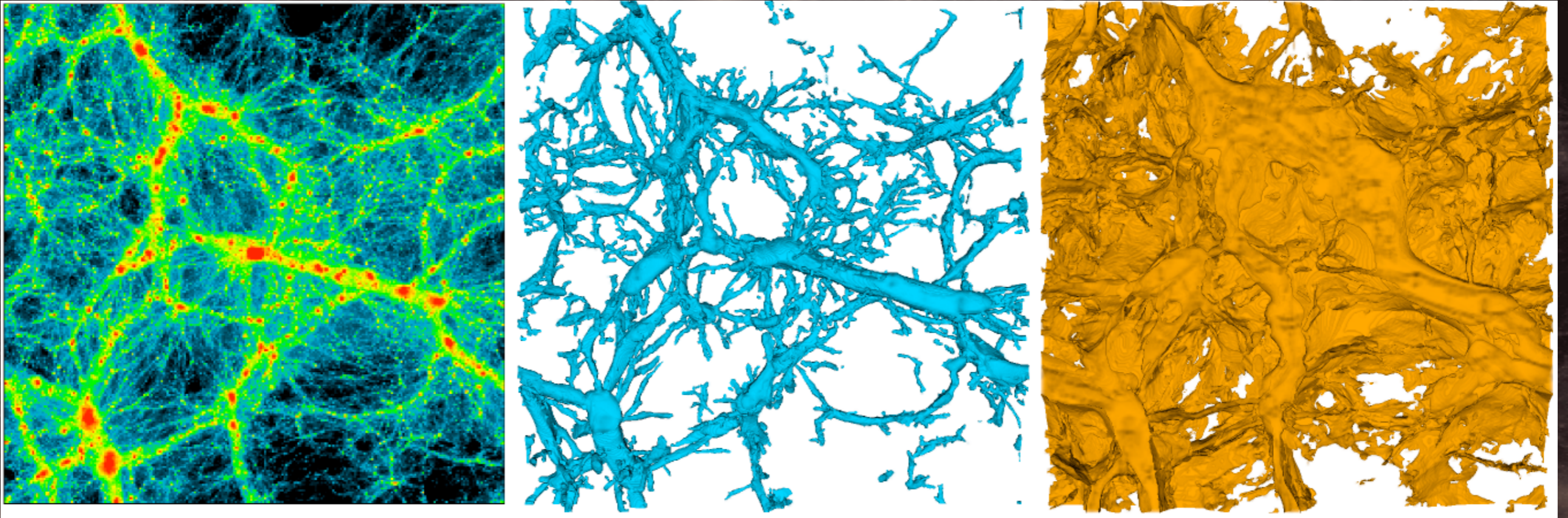
No subjective parameter

Applied to a multitude of web tracers

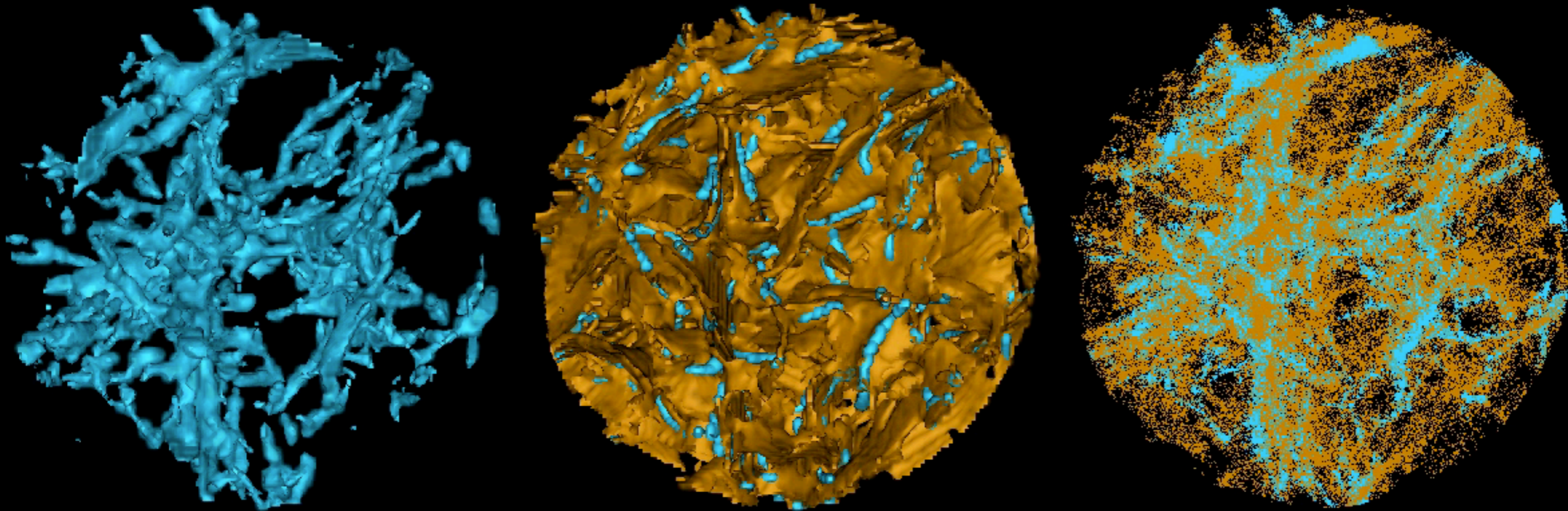
Hierarchical

Orders of magnitude variation

NEXUS+ results

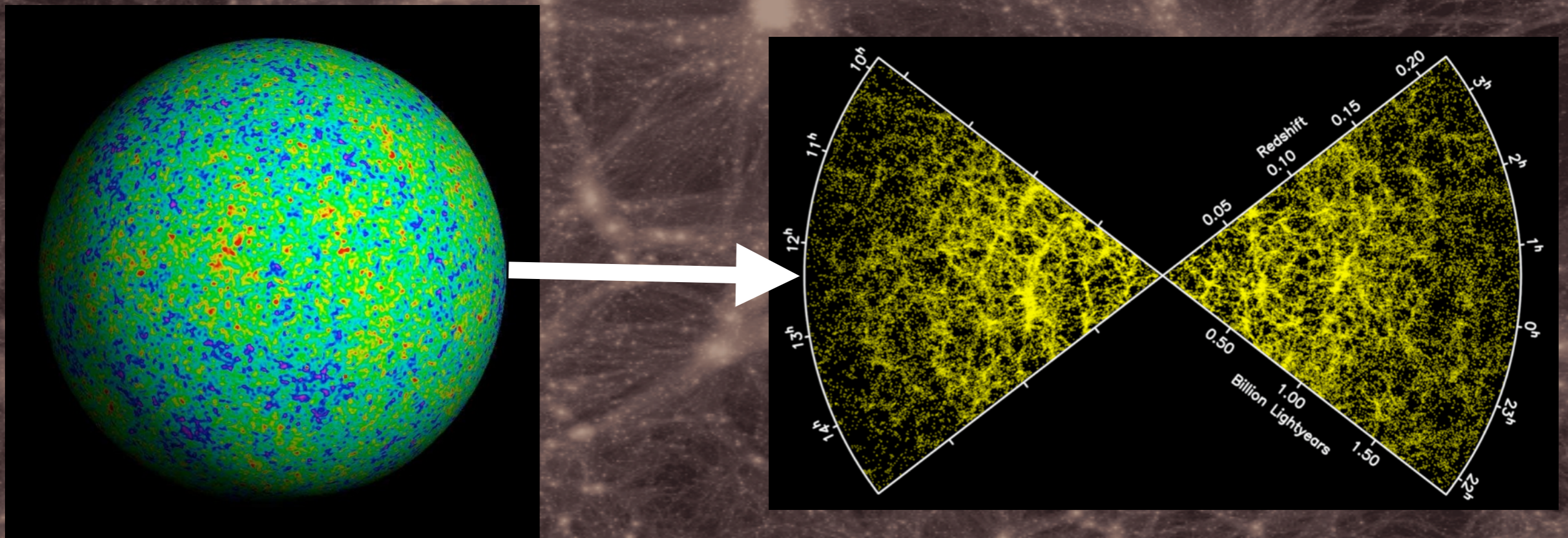


Cosmic Web complexity



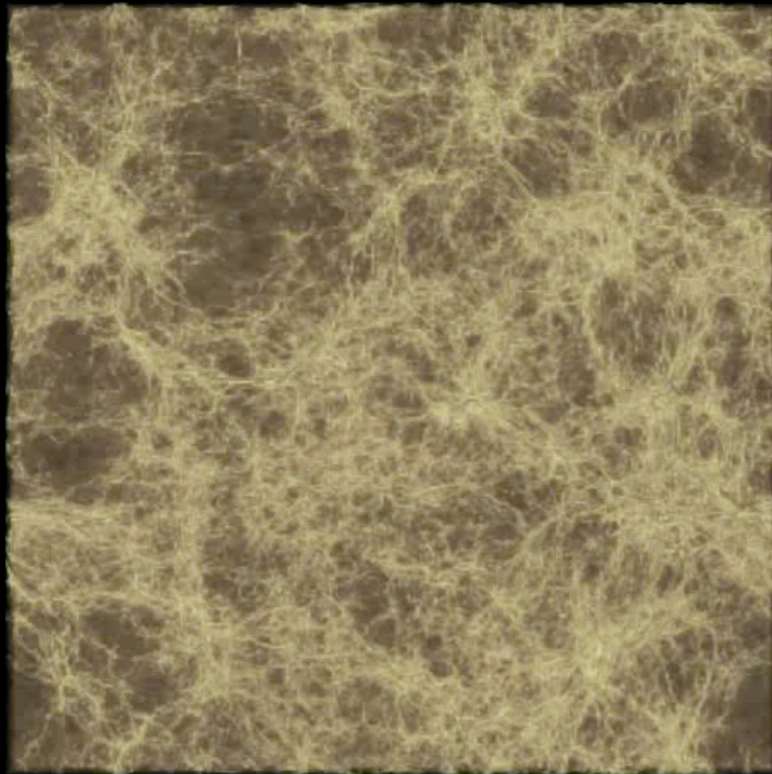
Evolution of the cosmic web

MC, van de Weygaert, Jones & Frenk (2014)

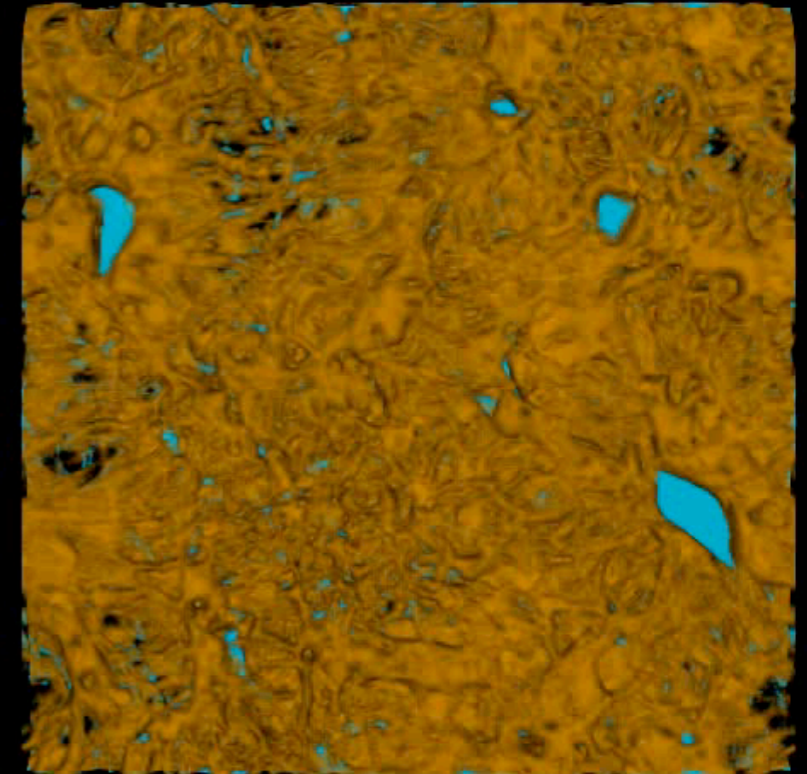
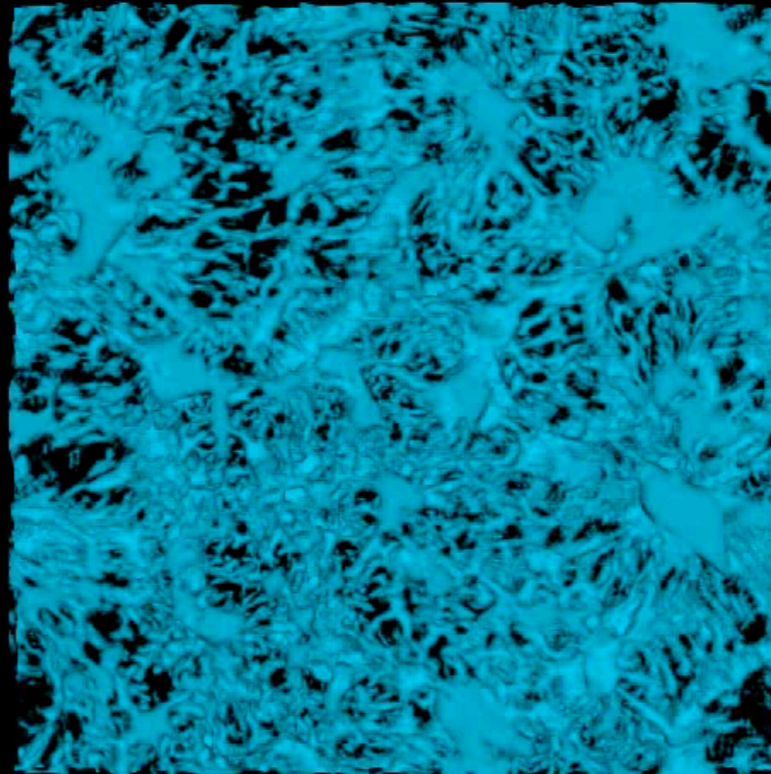


Cosmic web evolution

$t = 0.56$ Gyrs

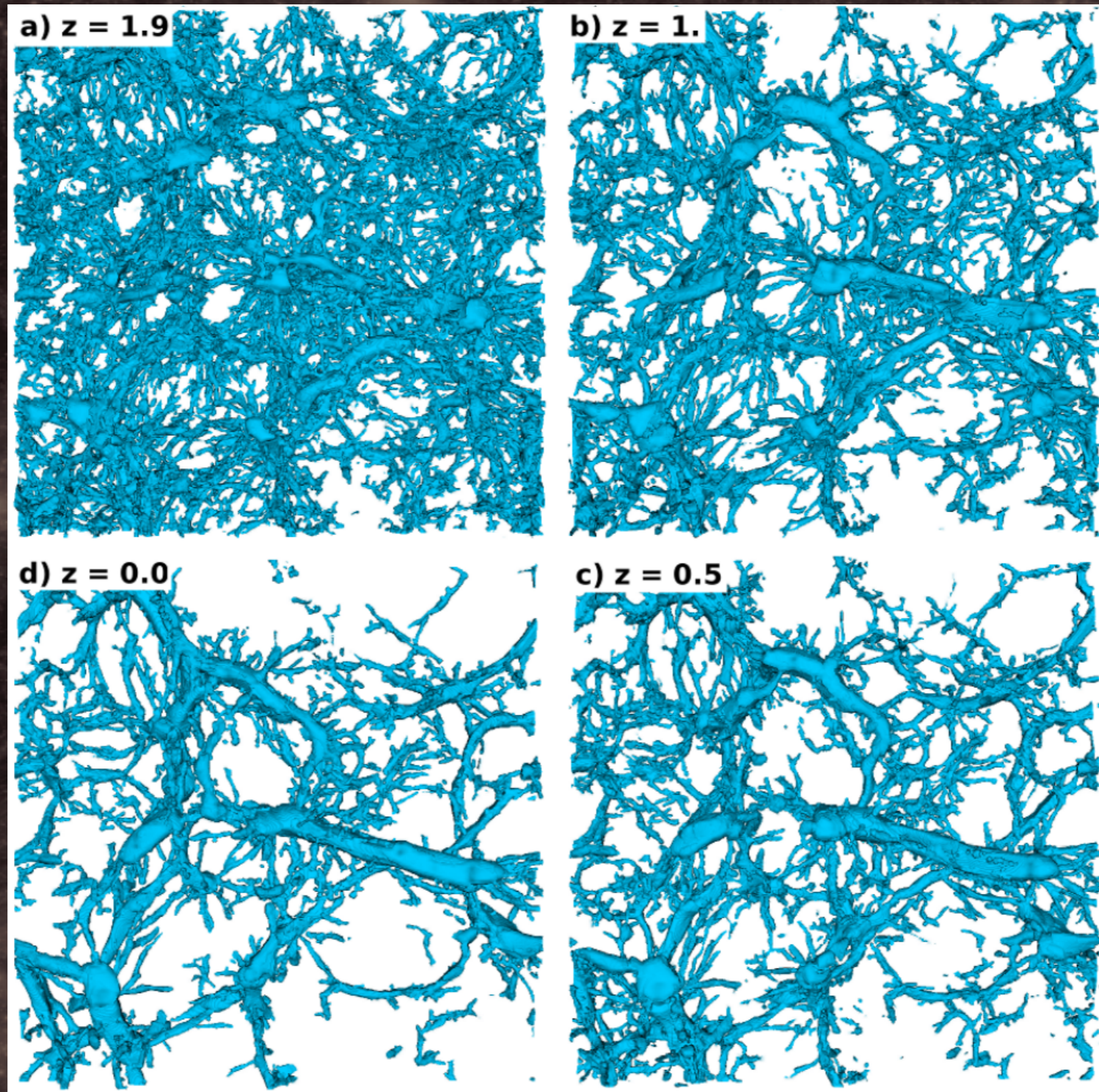


$z = 8.70$

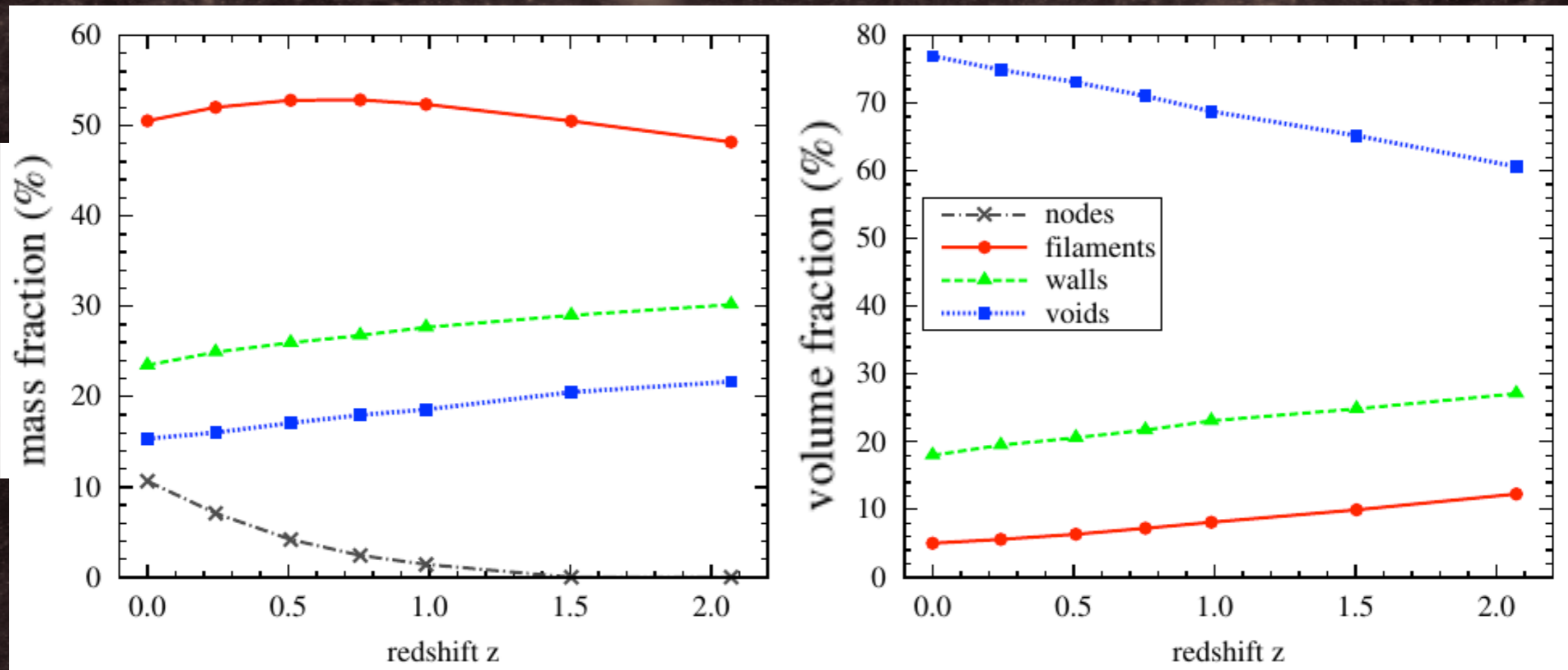


Thanks to Steven Rieder and the CosmoGrid simulation team.

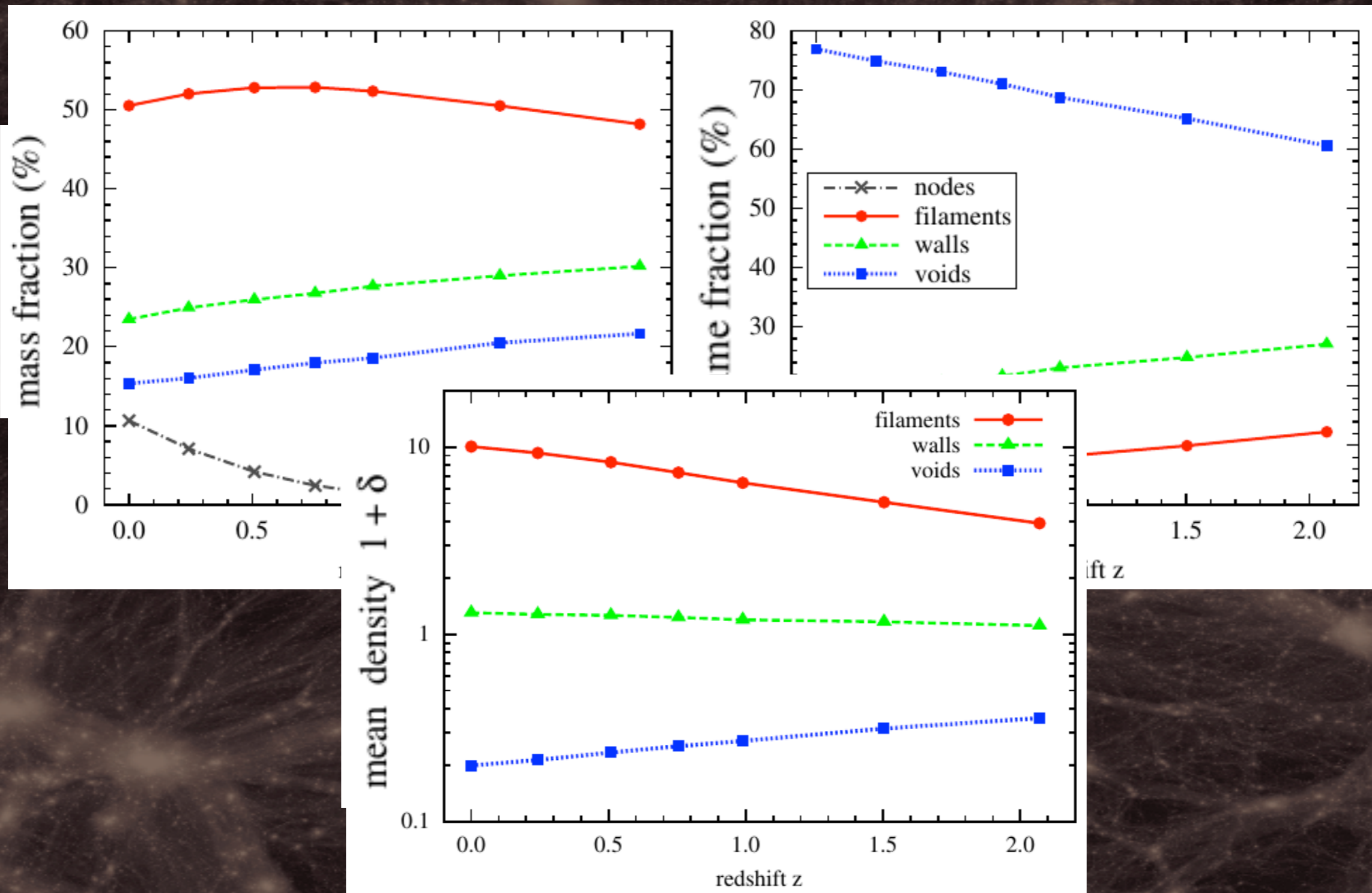
Filament evolution



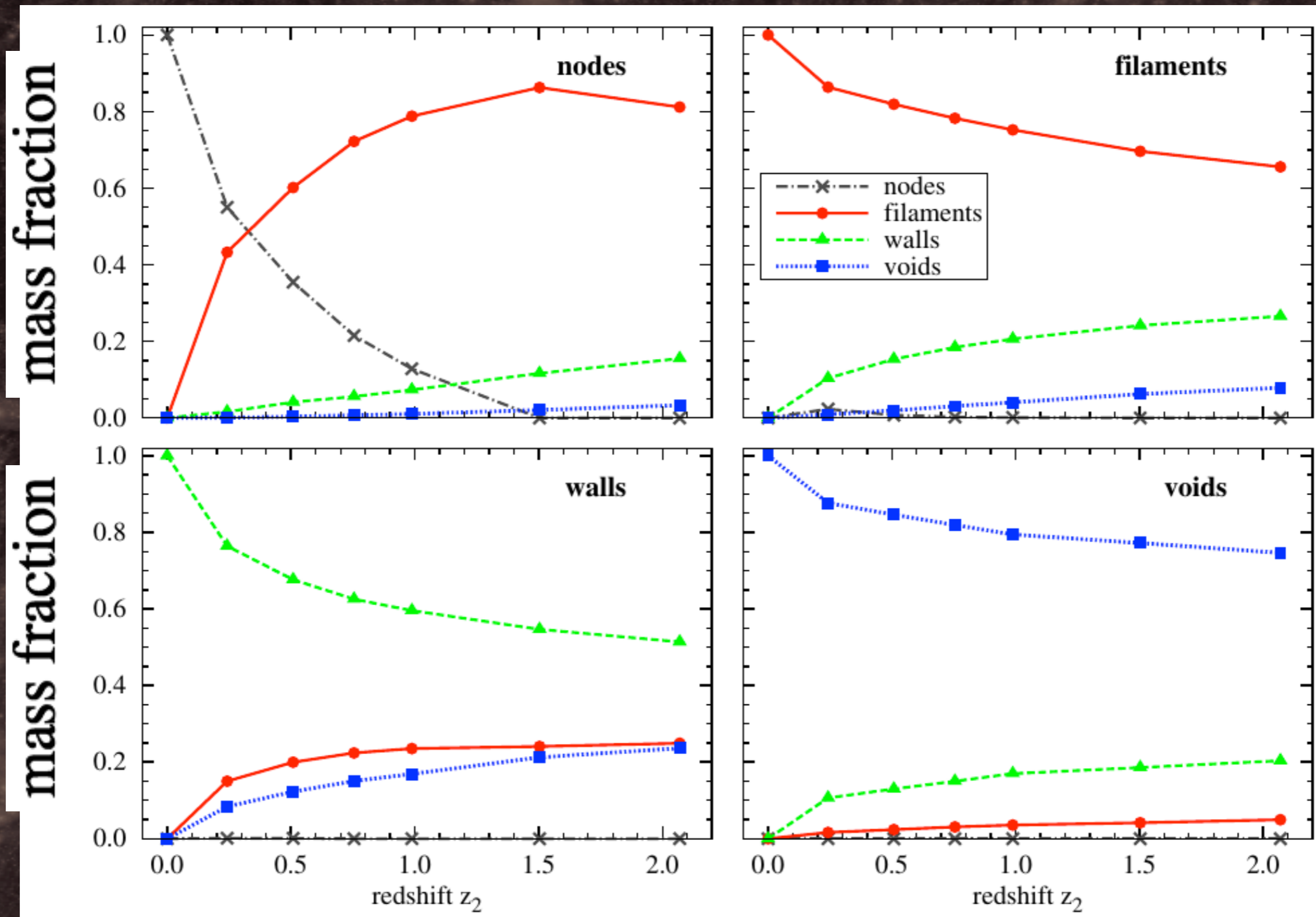
Mass and volume content



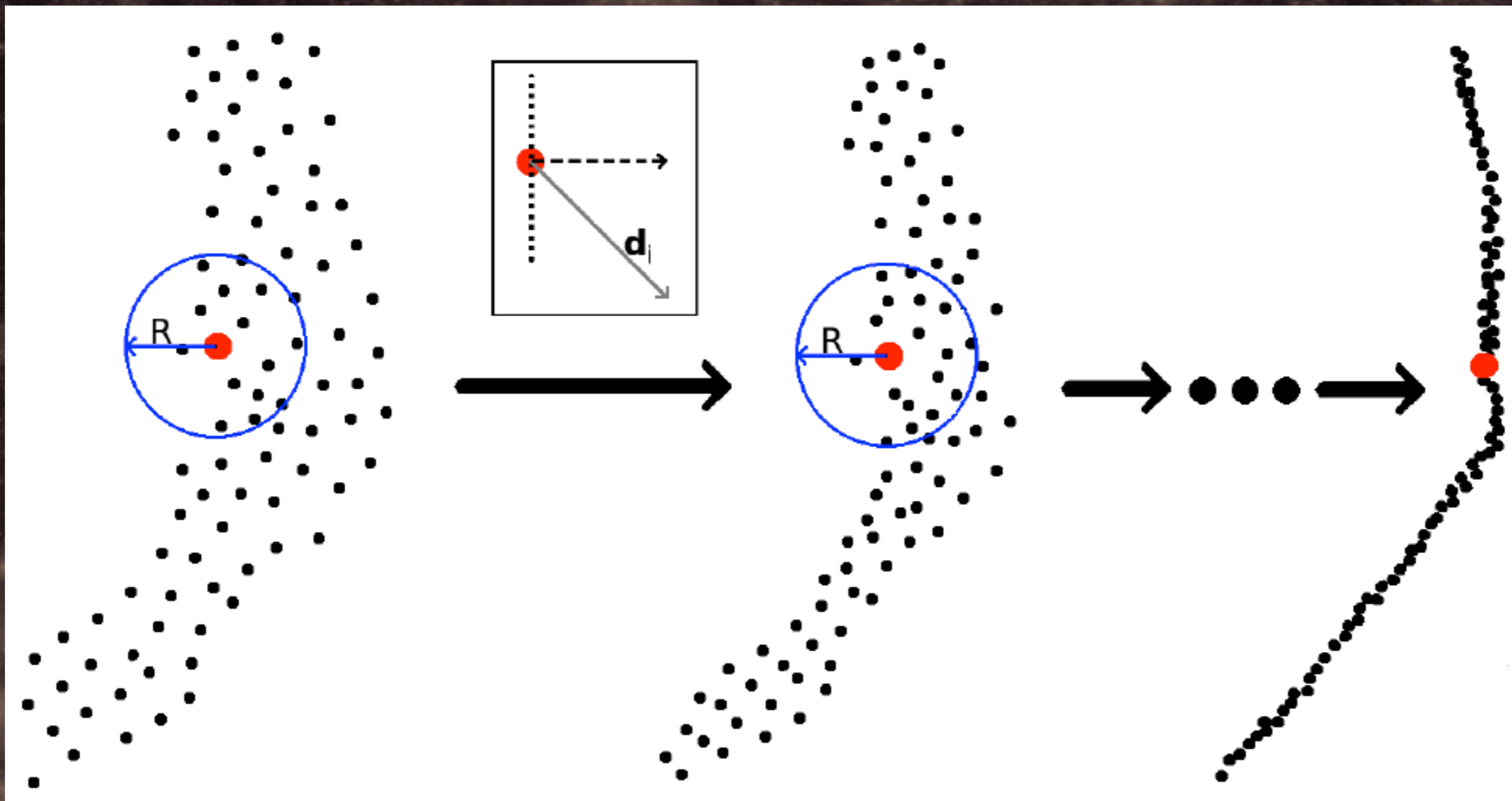
Mass and volume content



Mass transport across the Cosmic Web

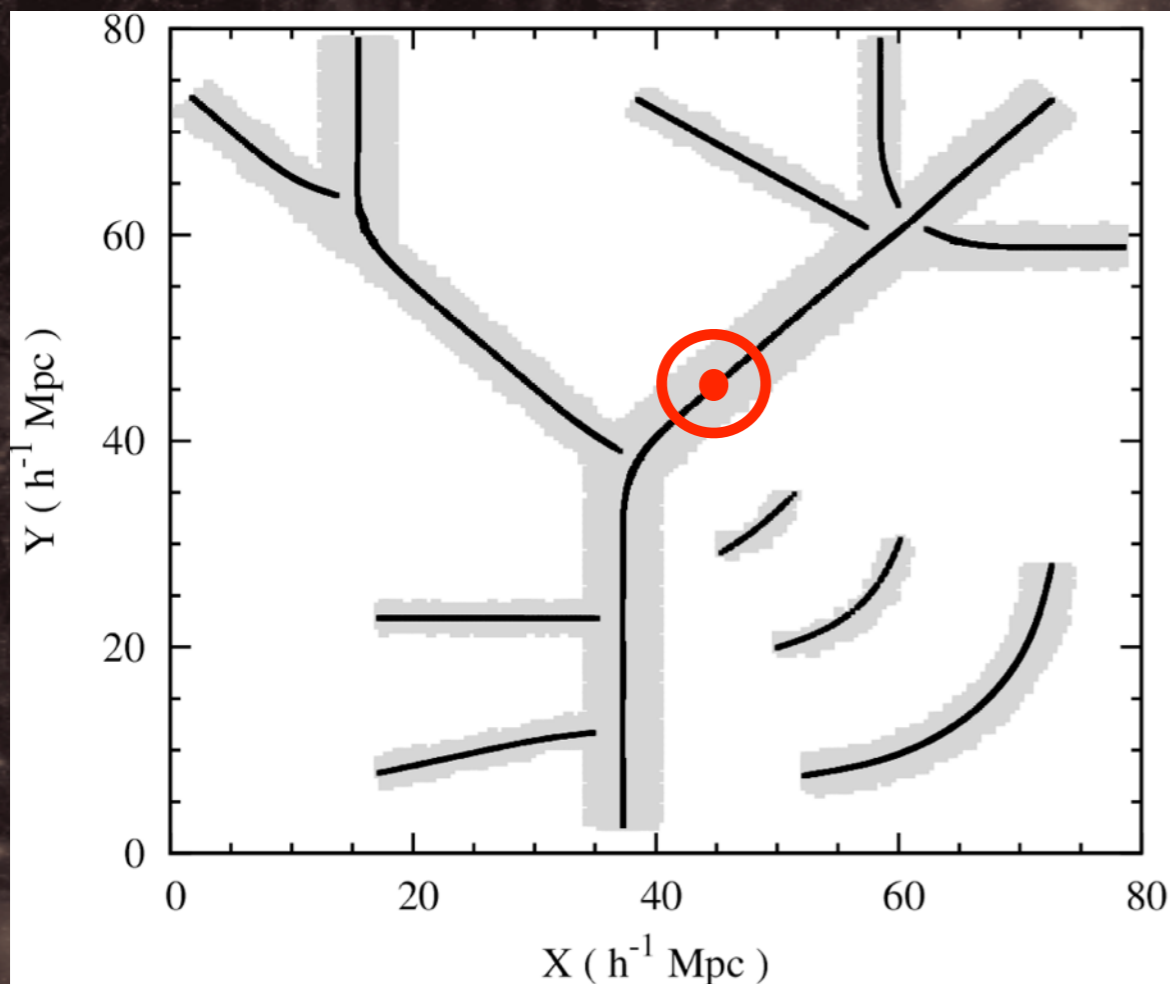


Filament compression



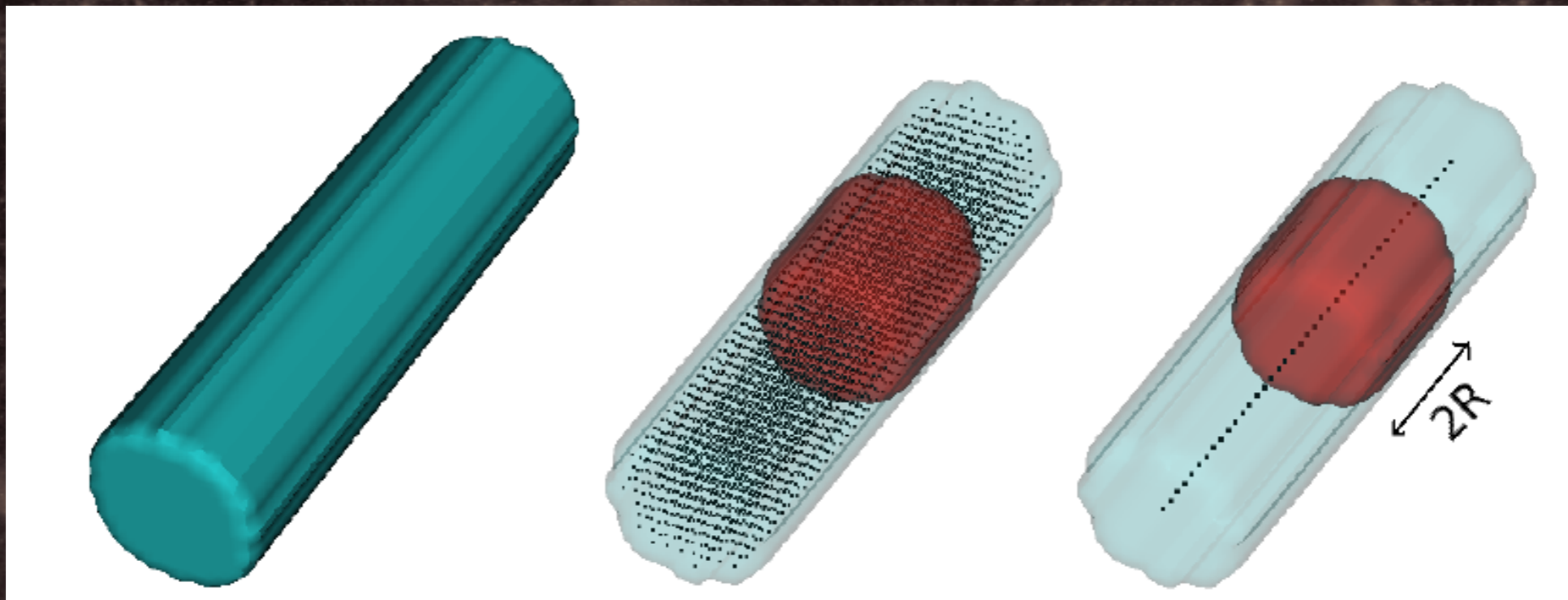
See also Aragon-Calvo+ 2010.

Filament properties



- Length of filaments.
- Local diameter.
- Local mass content (i.e. linear mass density).
- Similar quantities for sheet environments too.

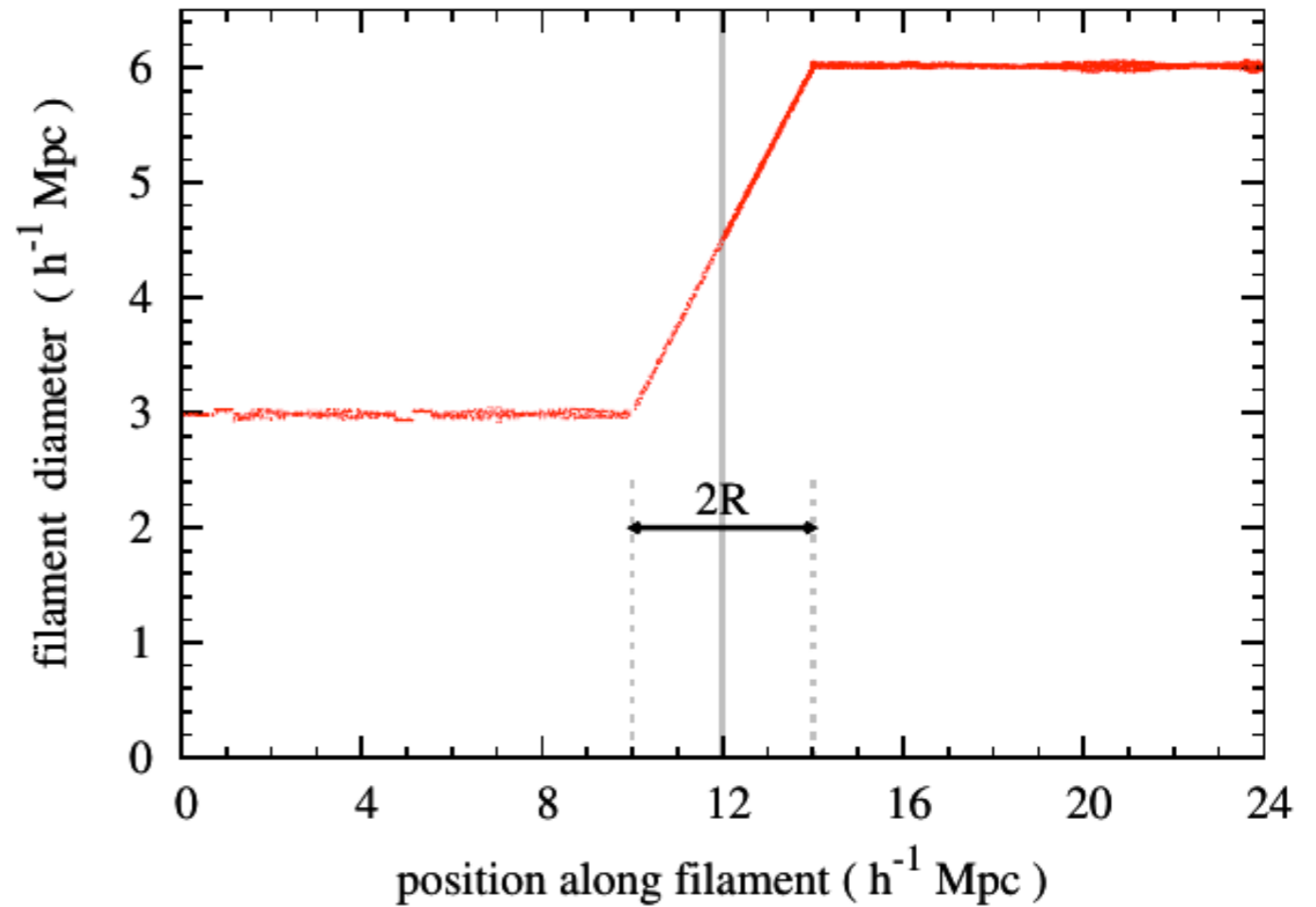
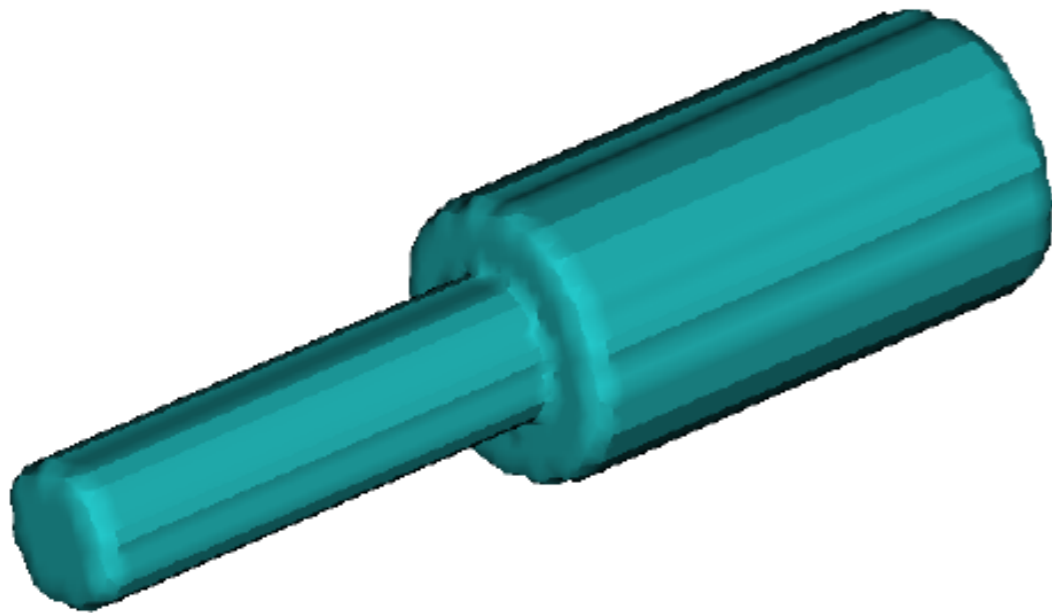
Filament properties



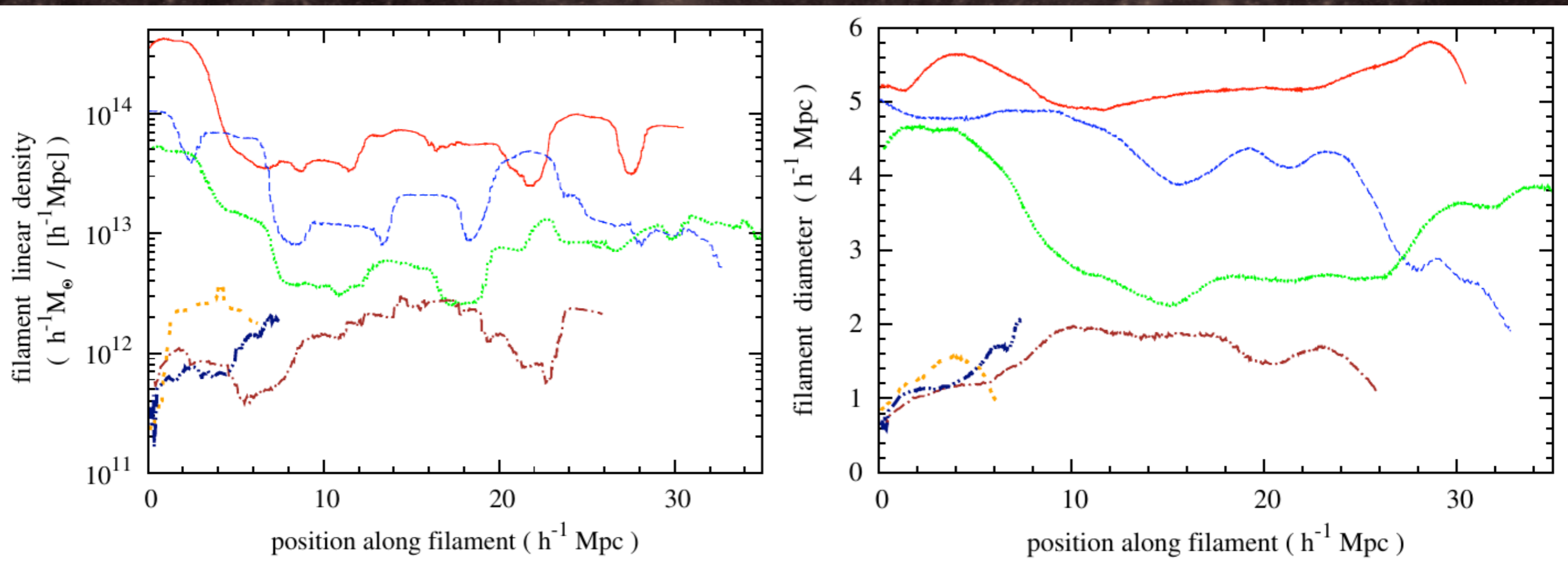
$$\begin{aligned} V_{\text{shaded area}} &= N_{\text{cells}} V_{\text{cell}} \\ &= \frac{\pi}{4} LD^2 \end{aligned}$$

$$\begin{aligned} M_{\text{shaded area}} &= \sum_{i=1}^{N_{\text{cells}}} M_{\text{cell},i} \\ &= L\zeta \end{aligned}$$

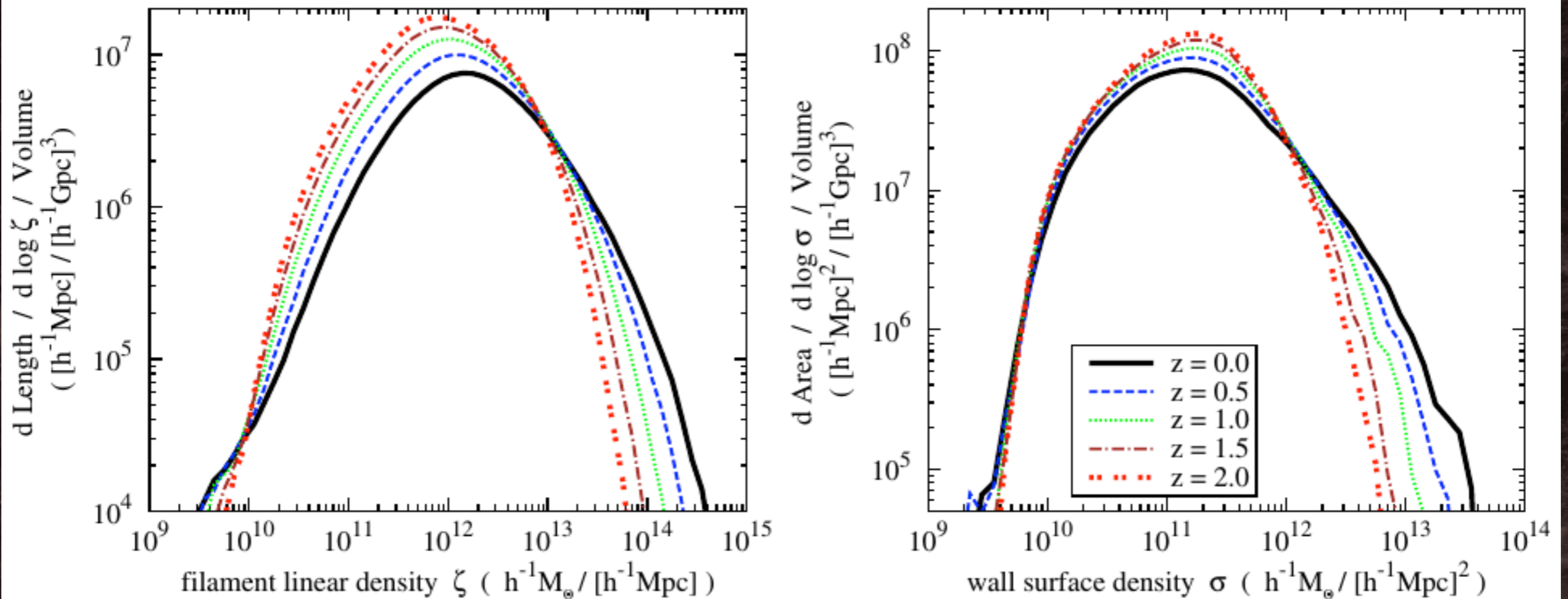
Filament properties



Filament linear mass density

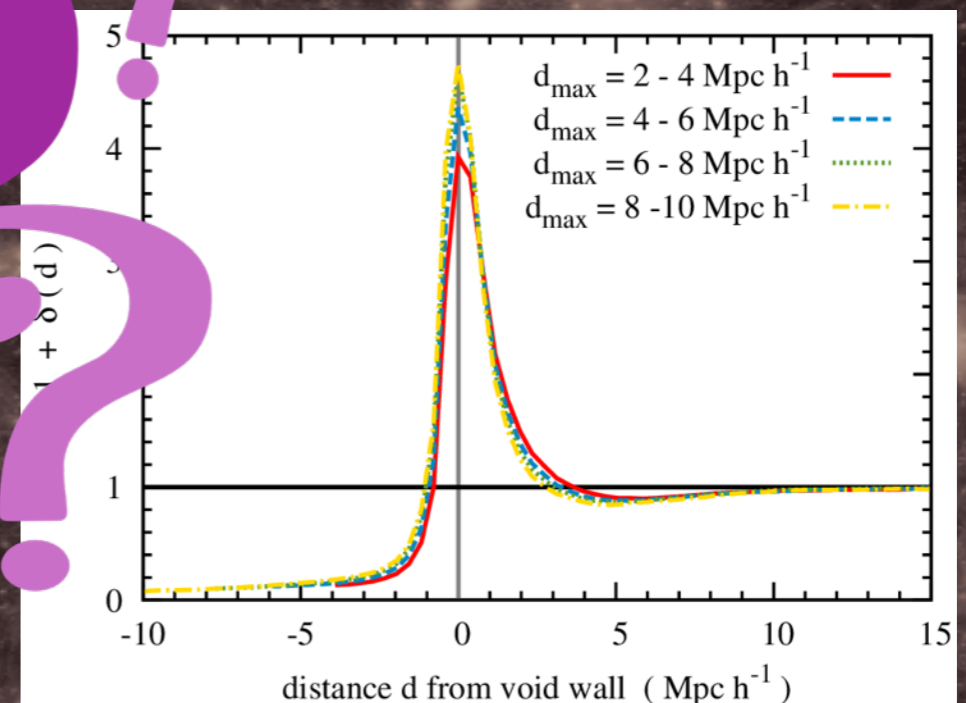
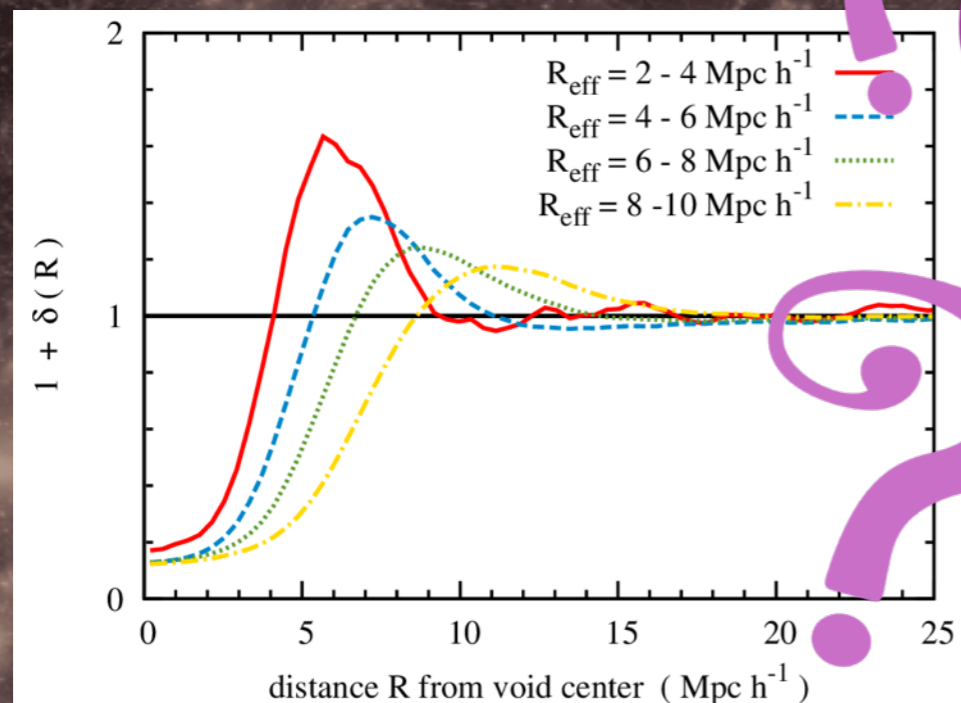


Filament (sheet) linear (surface) mass density

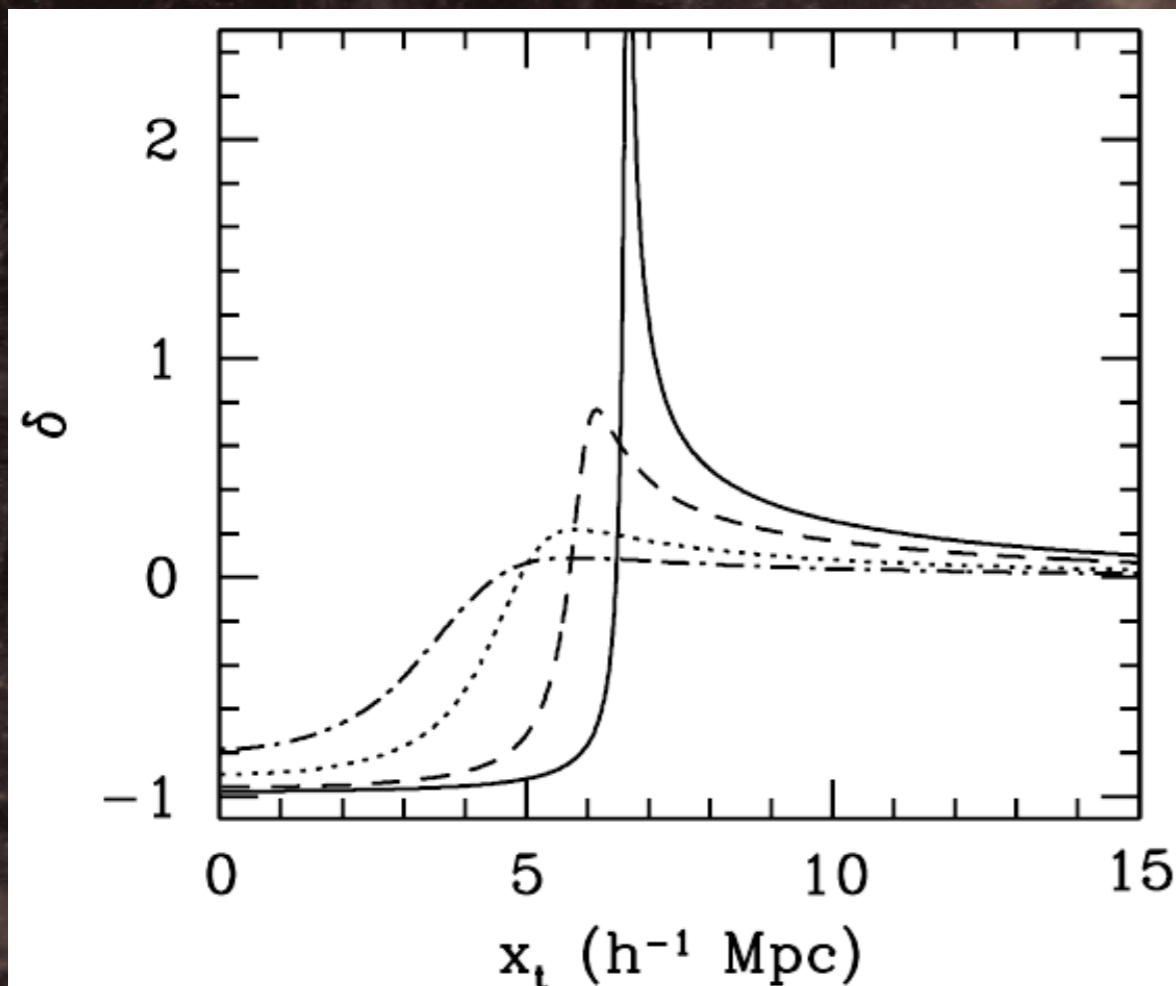


The true profile of voids

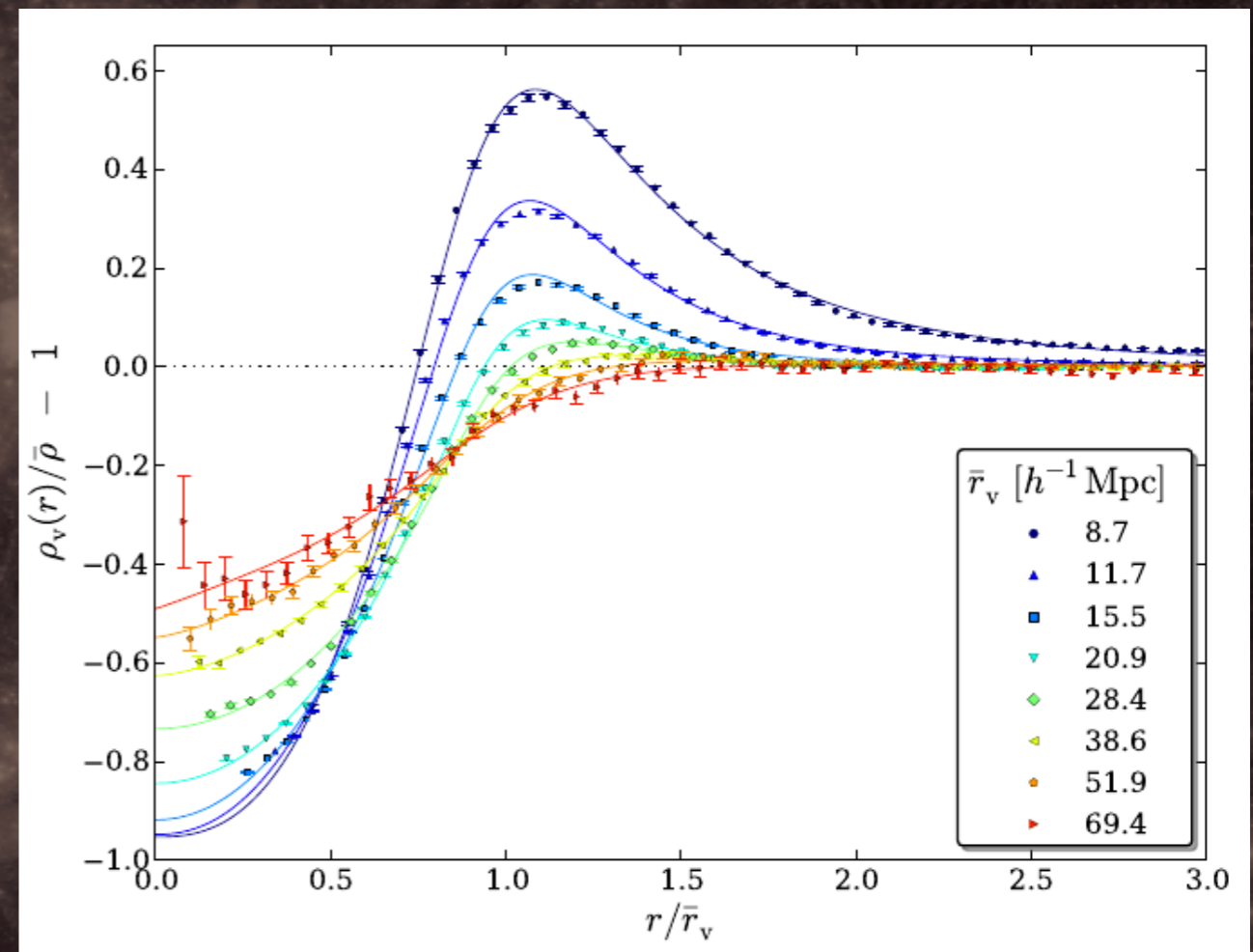
MC et al., in preparation



Void profile: theory versus simulations

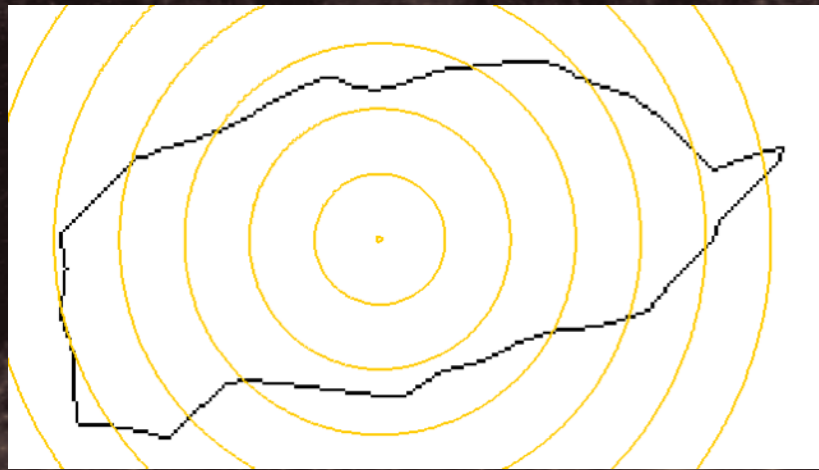


Spherical model for void evolution
(Seth & van de Weygaert 2004)

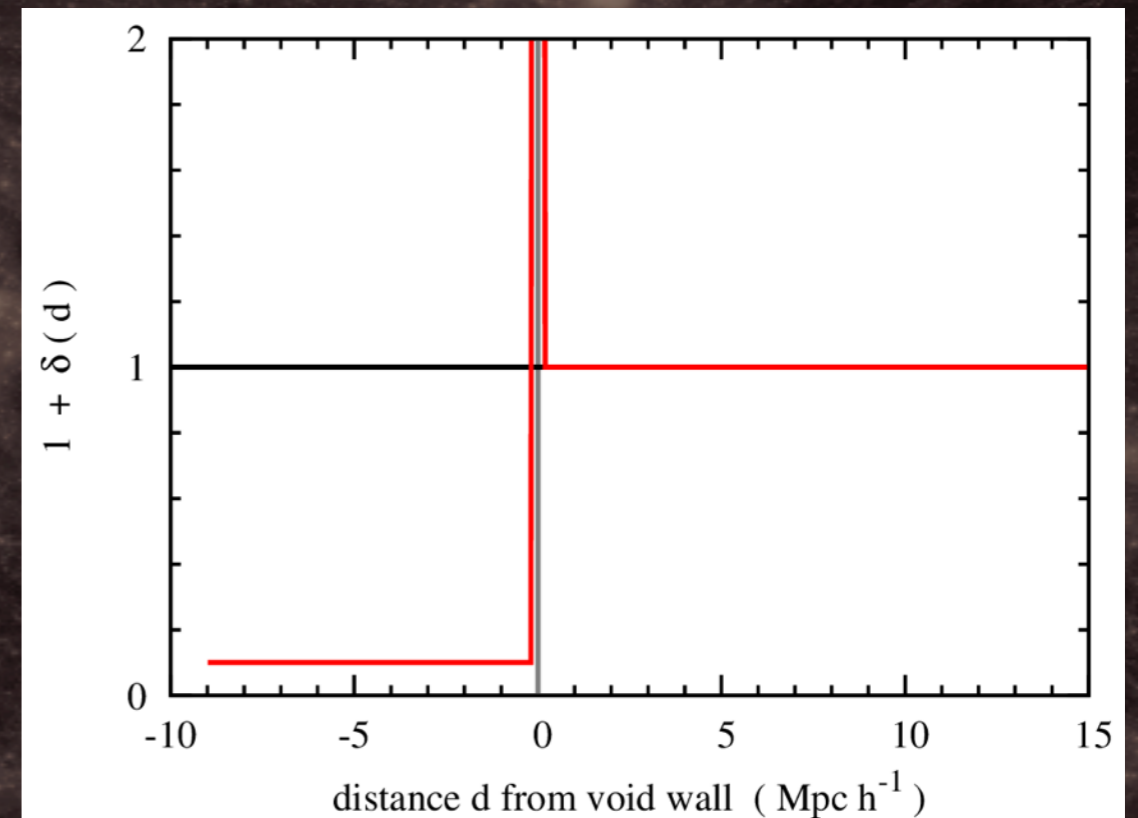
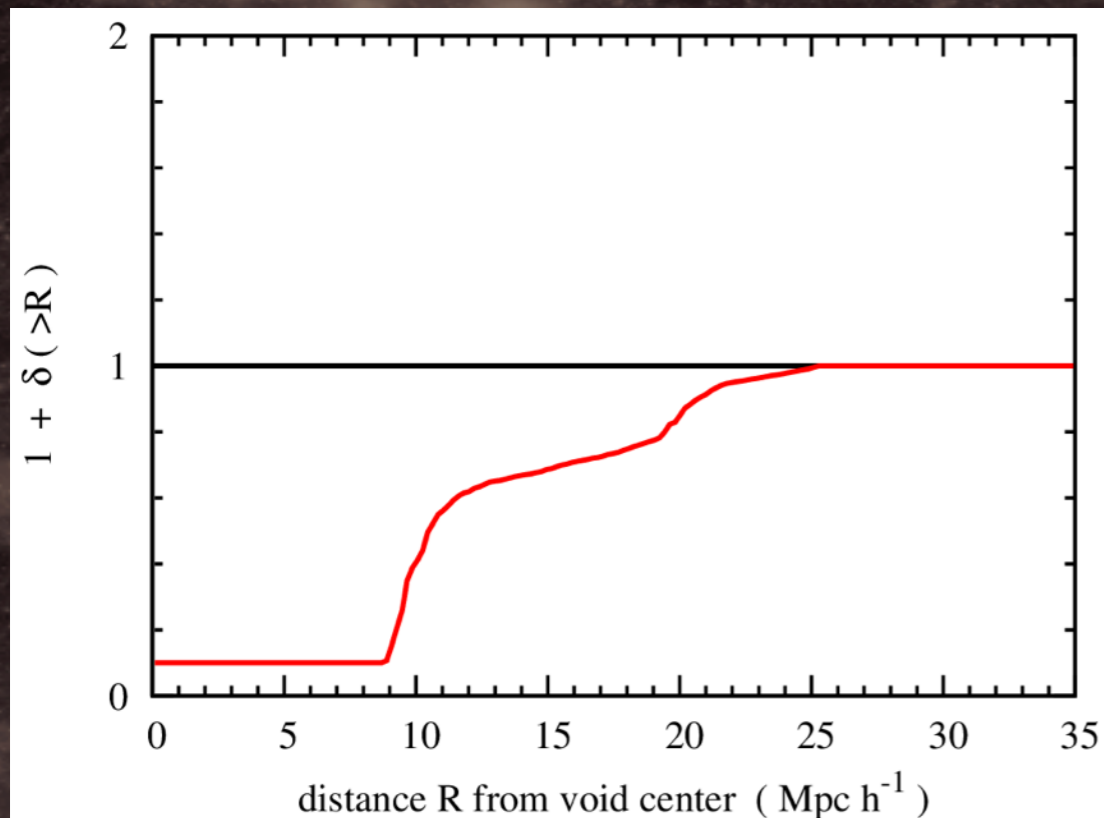
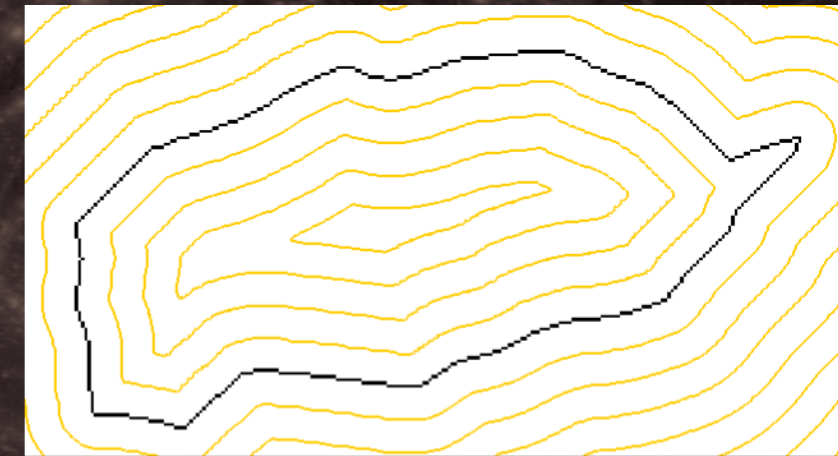
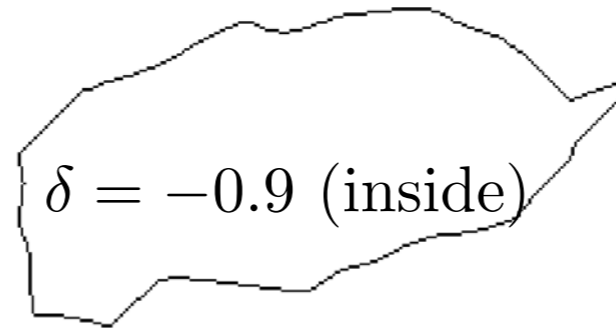


Measured in simulations & data (Hamaus+ 2014,
Padilla+ 2005, Ricciardelli+ 2013, 2014, Paz+ 2013)

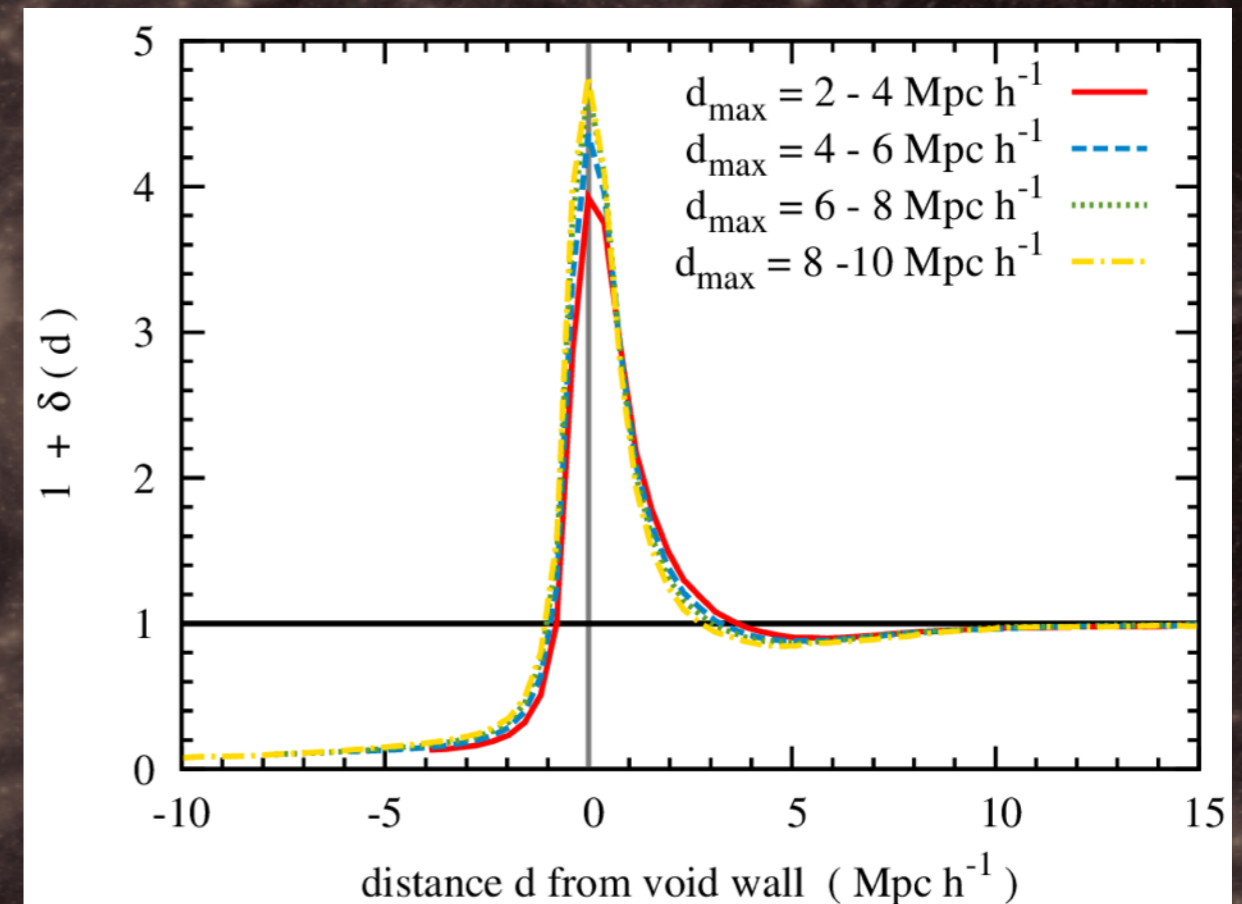
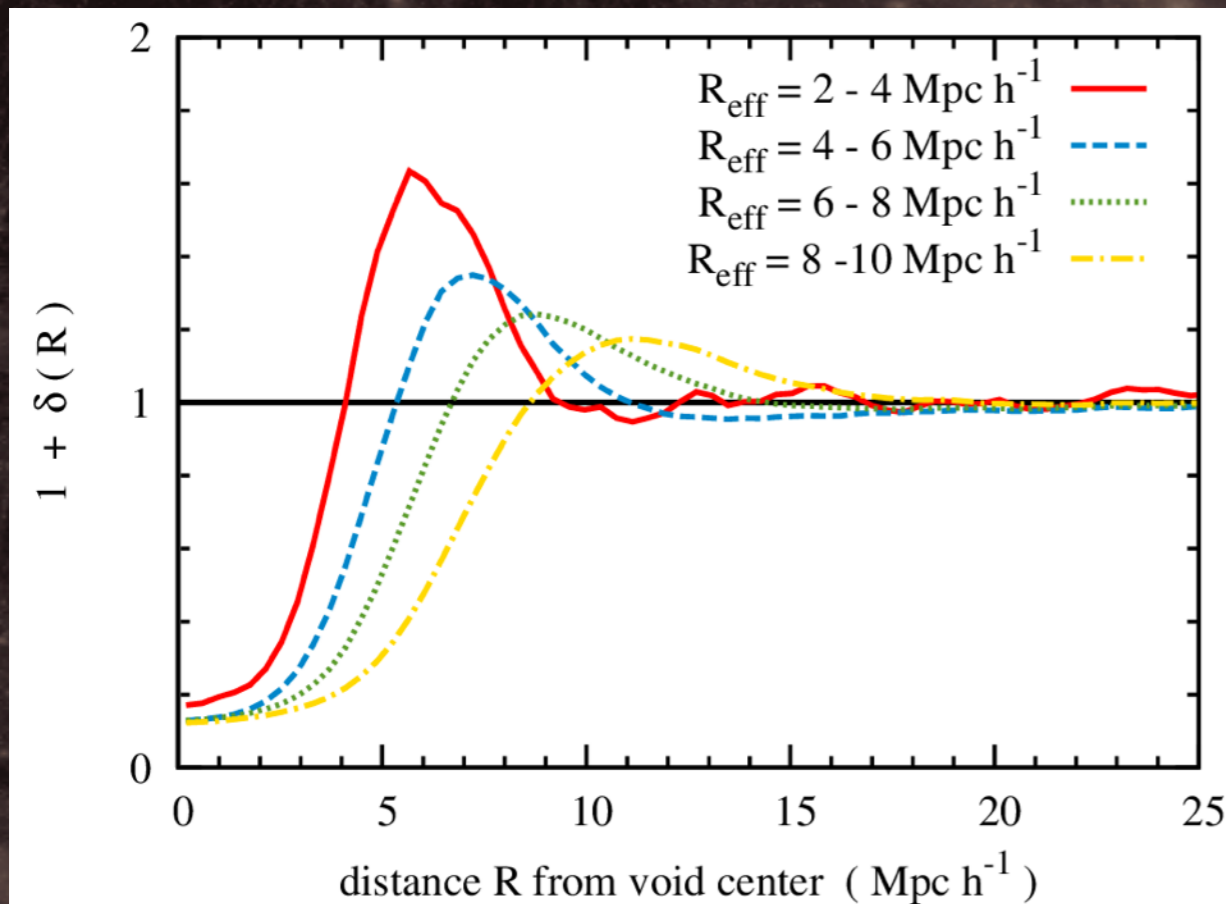
Void profile: toy example



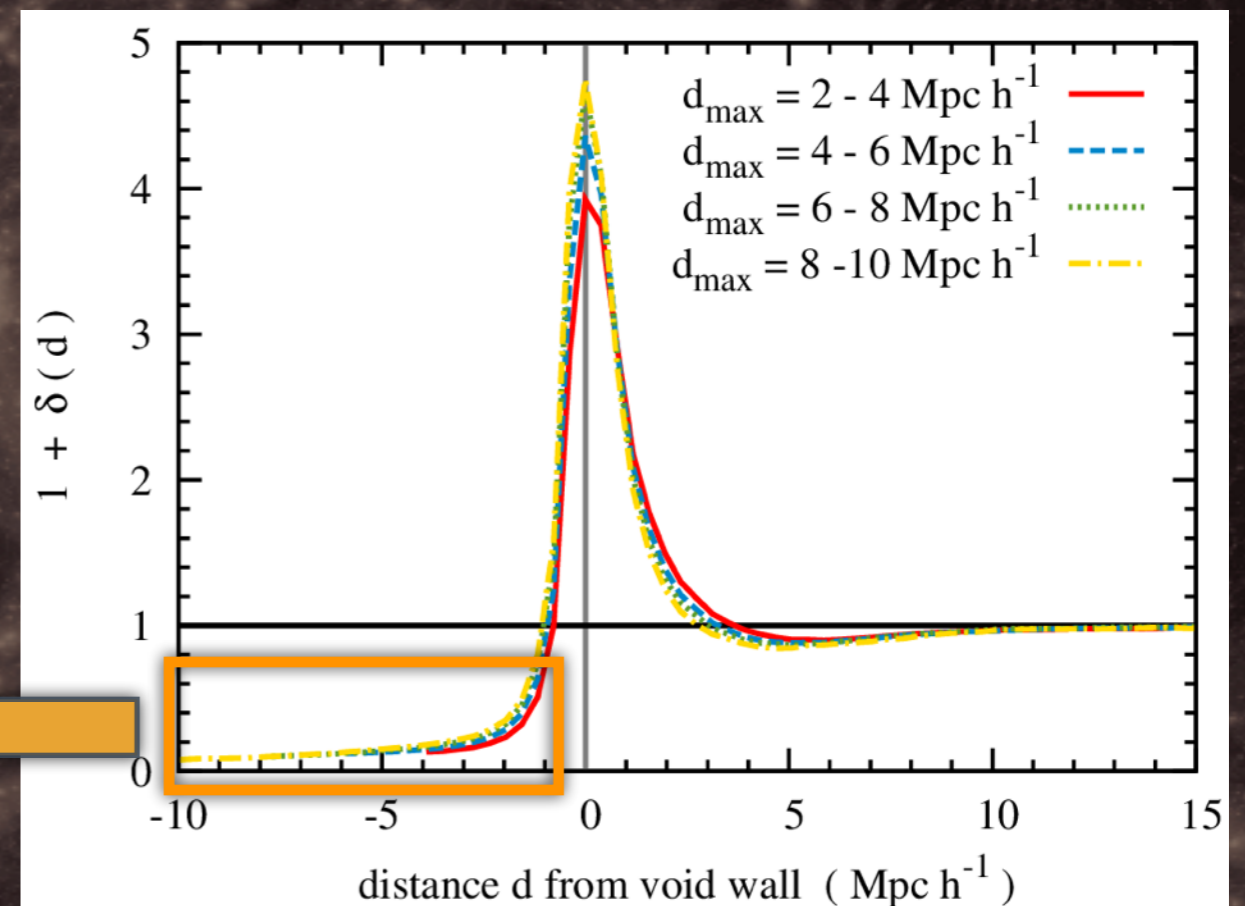
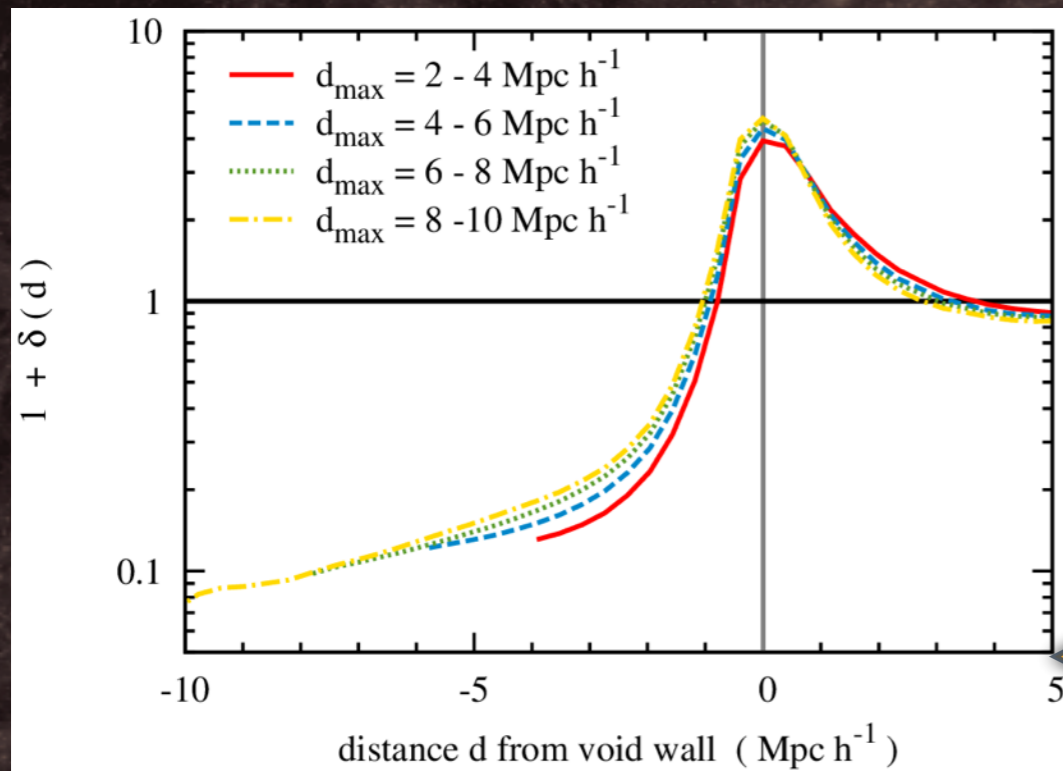
$\delta = 0$ (outside)



Void profile



Void profile



Void profile

What is it good for?

- Better understanding of voids
- A more sensitive probe of non-standard cosmologies (e.g. $f(R)$: Clampitt+ 2013)
- Maximises weak lensing signal from voids (void weak lensing: Melchior+ 2013, Clampitt & Jain 2014)

Conclusions

- We need new analysis methods to fully understand the Cosmic Web in all its complexity and beauty.
- A multi-scale web identification method, like NEXUS / NEXUS+, is crucial for detecting and characterising the cosmic environments.
- While global quantities are useful to obtain an overview of the web, local quantities as width or mass density offer better insights into the structure and evolution of the Cosmic Web.
- Voids are highly non-spherical structures. Taking this into account is essential for understanding voids.

Thank you!

