Title: The Cosmic Web: Structural Complexity and Dynamics of the Megaparsec Universe

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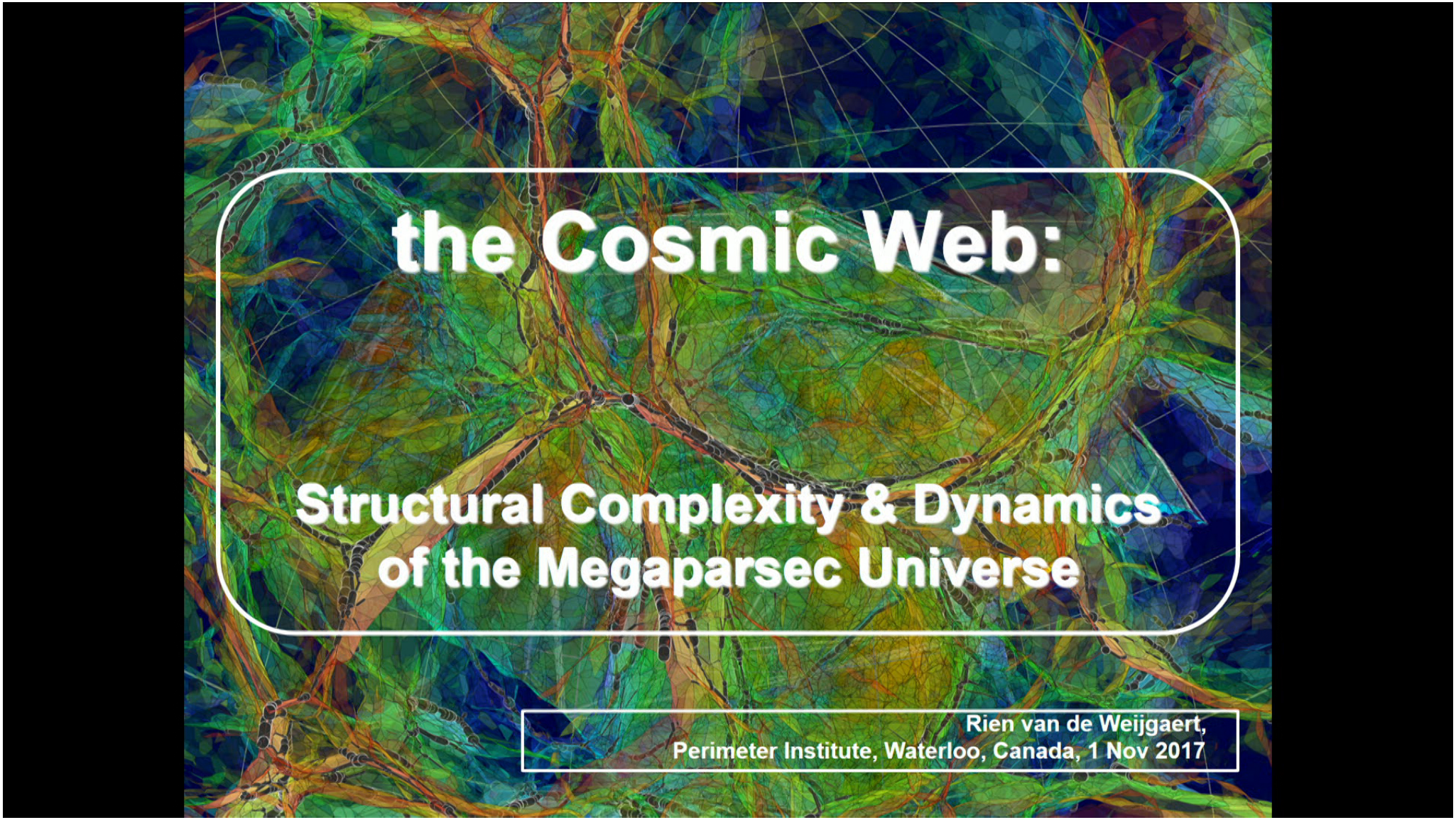
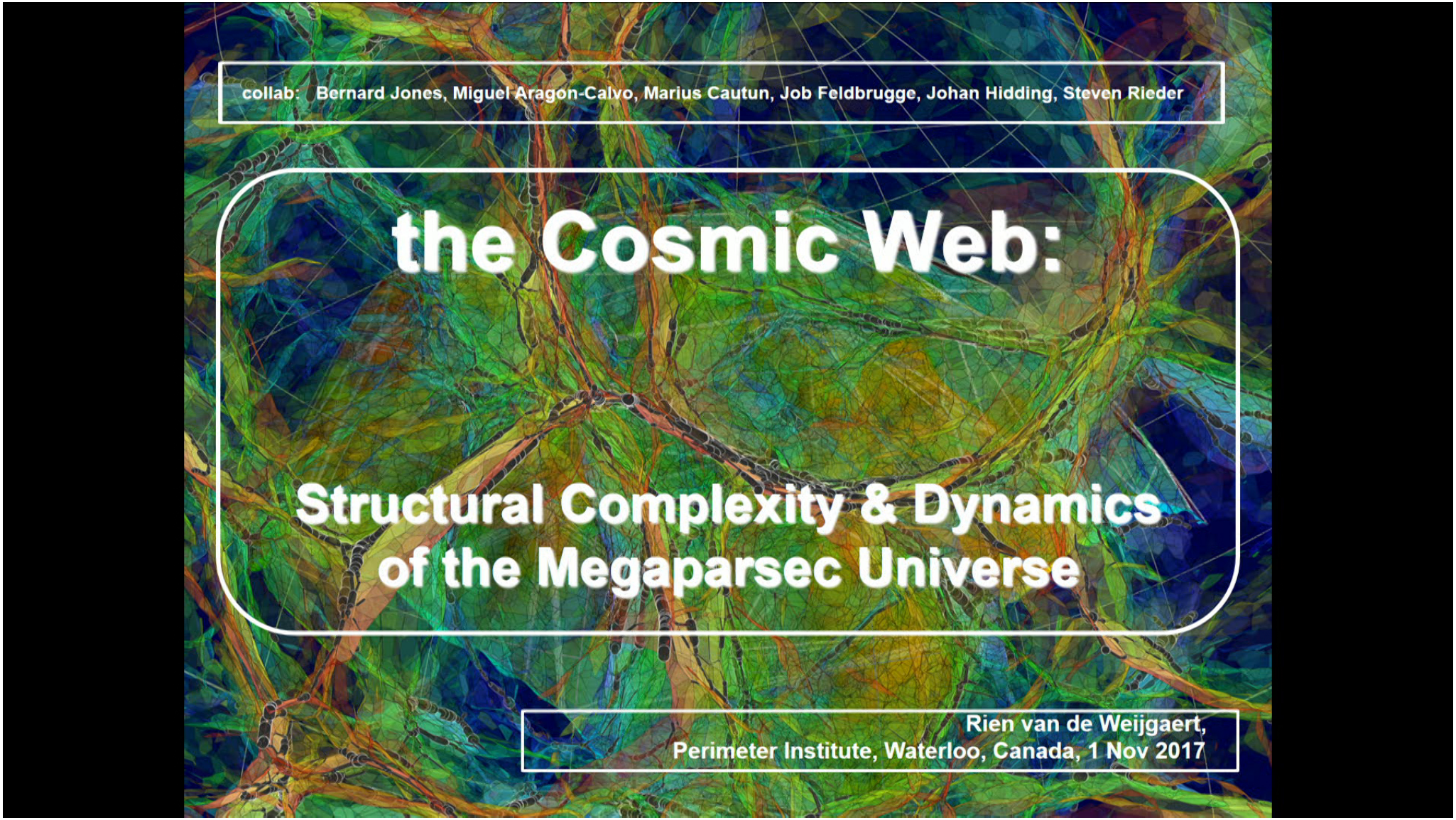
Abstract: The Cosmic Web is the fundamental spatial organization of matter in the Universe on scales of a few up to a hundred Megaparsec, scales at which the Universe still resides in a state of moderate dynamical evolution. Galaxies, intergalactic gas and dark matter exist in a wispy weblike spatial arrangement consisting of dense compact clusters, elongated filaments, and sheetlike walls, amidst large near-empty void regions. The weblike pattern is marked by prominent anisotropic features, a distinct multiscale character, a complex spatial connectivity of its various morphological components and a clear asymmetry between voids and overdense regions.

This seminar will describe recent work on the structure and dynamics of the Cosmic Web. For the analysis of its complex and multiscale structural pattern, we invoke concepts from computational topology and computational geometry. We apply the explicit multi-scale -- parameter-free and scale-free -- Nexus/MMF Multiscale Morphology formalism to dissect the cosmic mass distribution into clusters, filaments, walls and voids. This results in a systematic study ofthe evolving size and volume distribution of these structural components. Subsequently, we assess the mass and halo distribution in the filaments and walls, and follow their evolution.

To study the dynamical evolution of the cosmic web, we describe our adhesion model of cosmic structure formation based on Voronoi and Delaunay tessellations. Subsequently, we will shortly describe how a full phase-space analysis allows us to understand the growth of structural complexity in terms of the emergence and spatial connectivity of singularities and caustics. Finally, we will discuss the migration flows of matter and galaxies along the cosmic web and prospects of using voids to constrain dark energy and dark matter.


the Cosmic Web:
Structural Complexity & Dynamics
of the Megaparsec Universe
Rien van de Weijgaert,
Perimeter Institute, Waterloo, Canada, 1 Nov 2017


collab: Bernard Jones, Miguel Aragon-Calvo, Marius Cautun, Job Feldbrugge, Johan Hidding, Steven Rieder
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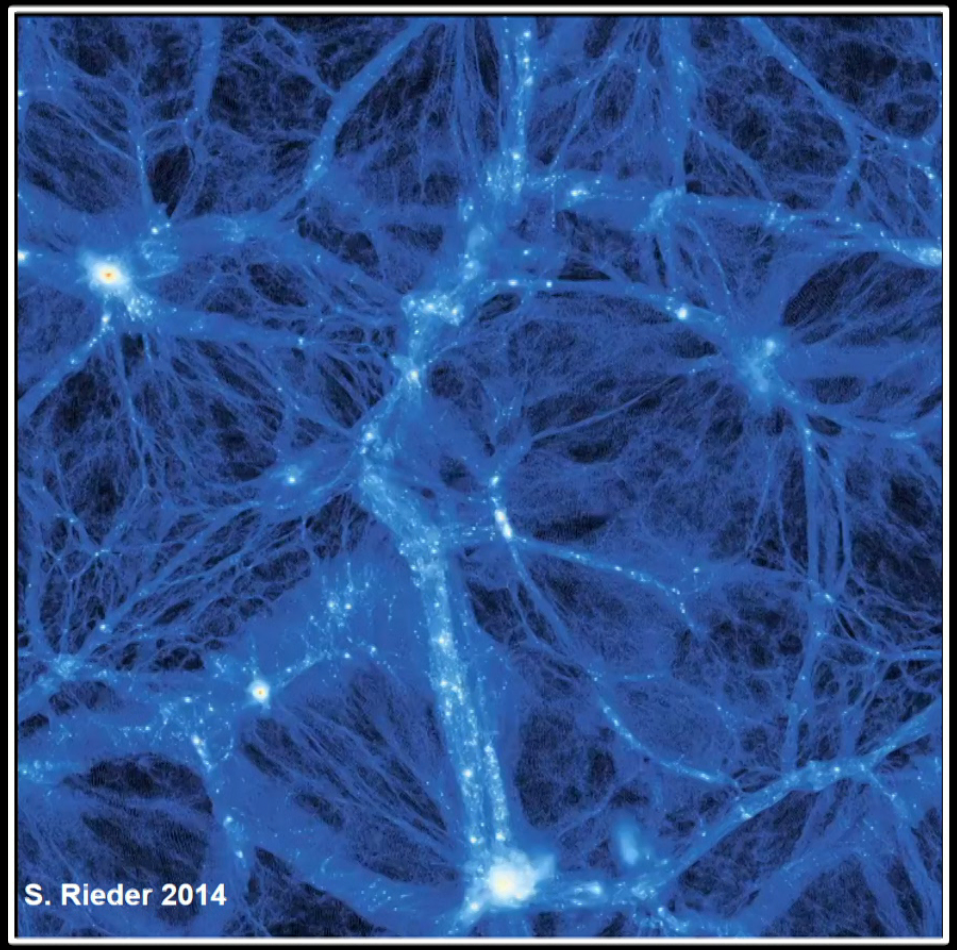


on scales of ~0.1-500
millions of lightyears

complex weblike pattern

in which
matter, gas & galaxies
are organized in

- compact clusters,
- elongated filaments
- flattened walss

around

- cosmic voids

Cosmic Web

Cosmic Web:

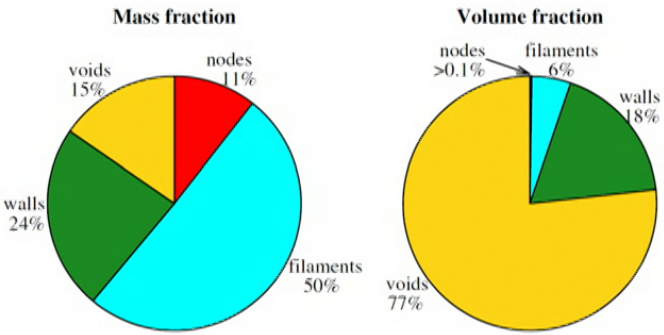
Density-Morphology Connection

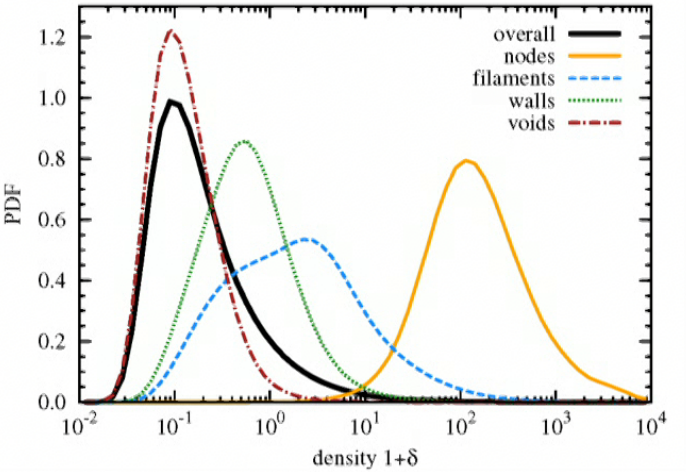
Mass & Volume content

Web morphologies

Density distribution

Individual morphologies



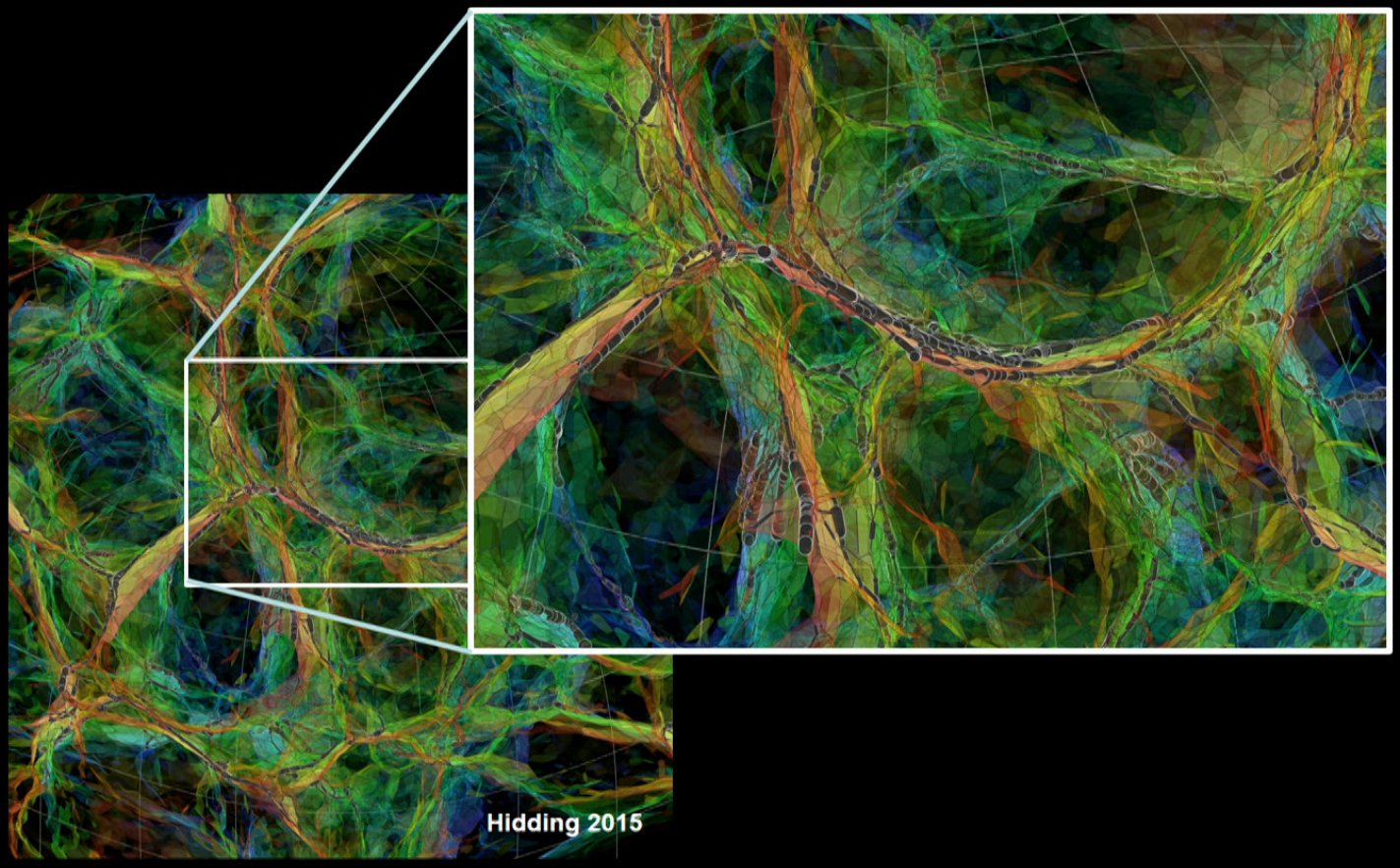


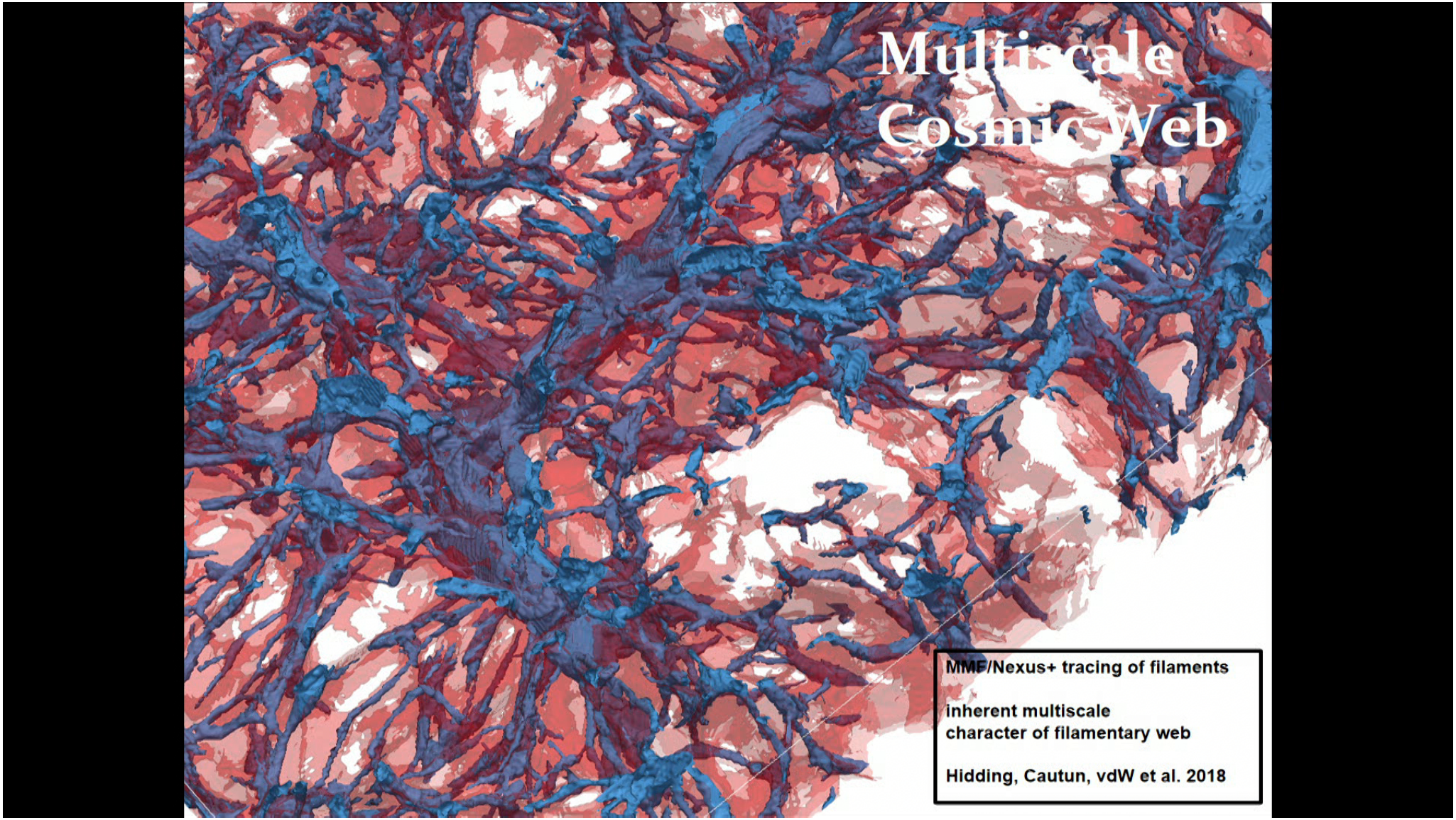
Cautun et al. 2014

Cosmic Web Characteristics

- **anisotropic structure:**
  - filaments dominant structural feature - elongated
  - sheets/walls - flattened
- **multiscale nature**
  - structure on wide range of scales
  - structures have wide range of densities
- **overdense-underdense asymmetry**
  - voids: underdense, large & roundish
  - filaments & walls: overdense, flattened/elongated
  - clusters: dense, massive & compact nodes
- **complex spatial connectivity**
  - all structural features connected in a complex, multiscale weblike network

Pisces-Perseus Supercluster

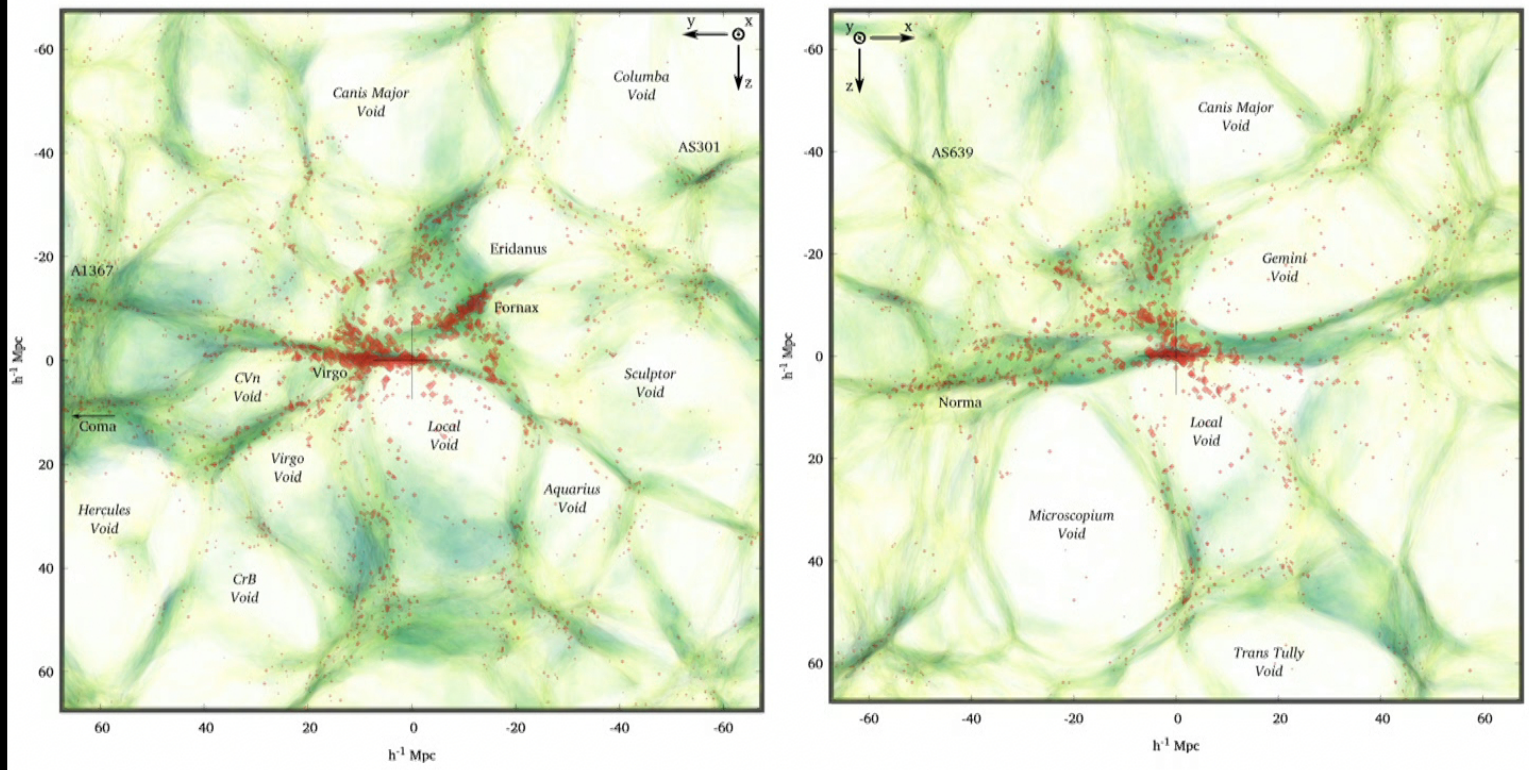



Multiscale
Cosmic Web
MMF/Nexus+ tracing of filaments
inherent multiscale
character of filamentary web
Hidding, Cautun, vdW et al. 2018

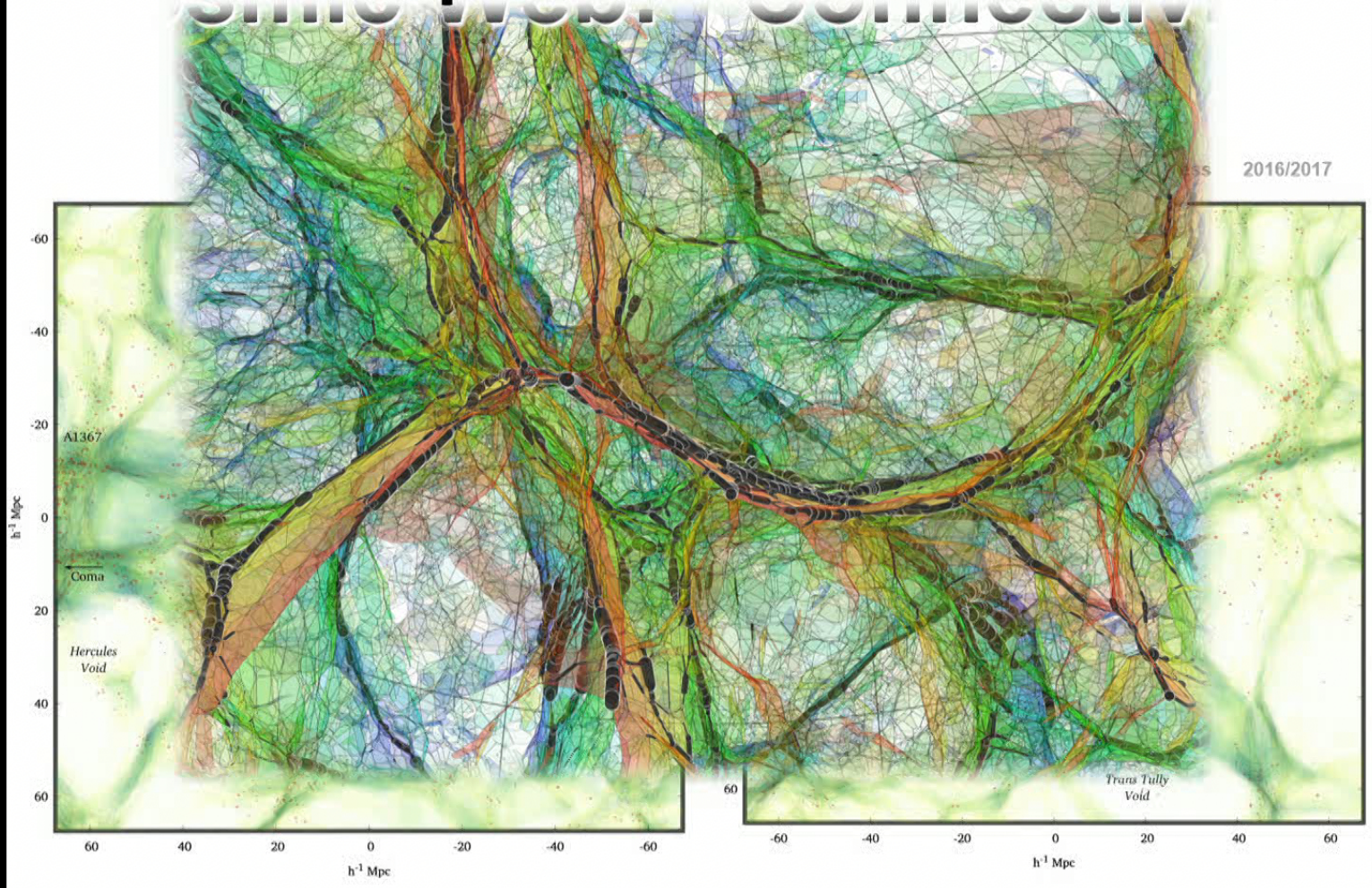
Void Population Local Universe

mean KIGEN-adhesion reconstruction (2MRS)

Hidding, Kitaura, vdW & Hess 2016/2017



Void Population Local Universe



The Cosmic Web

Physical Significance:

- **Manifestation mildly nonlinear clustering:**
  Transition stage between linear phase
  and fully collapsed/virialized objects

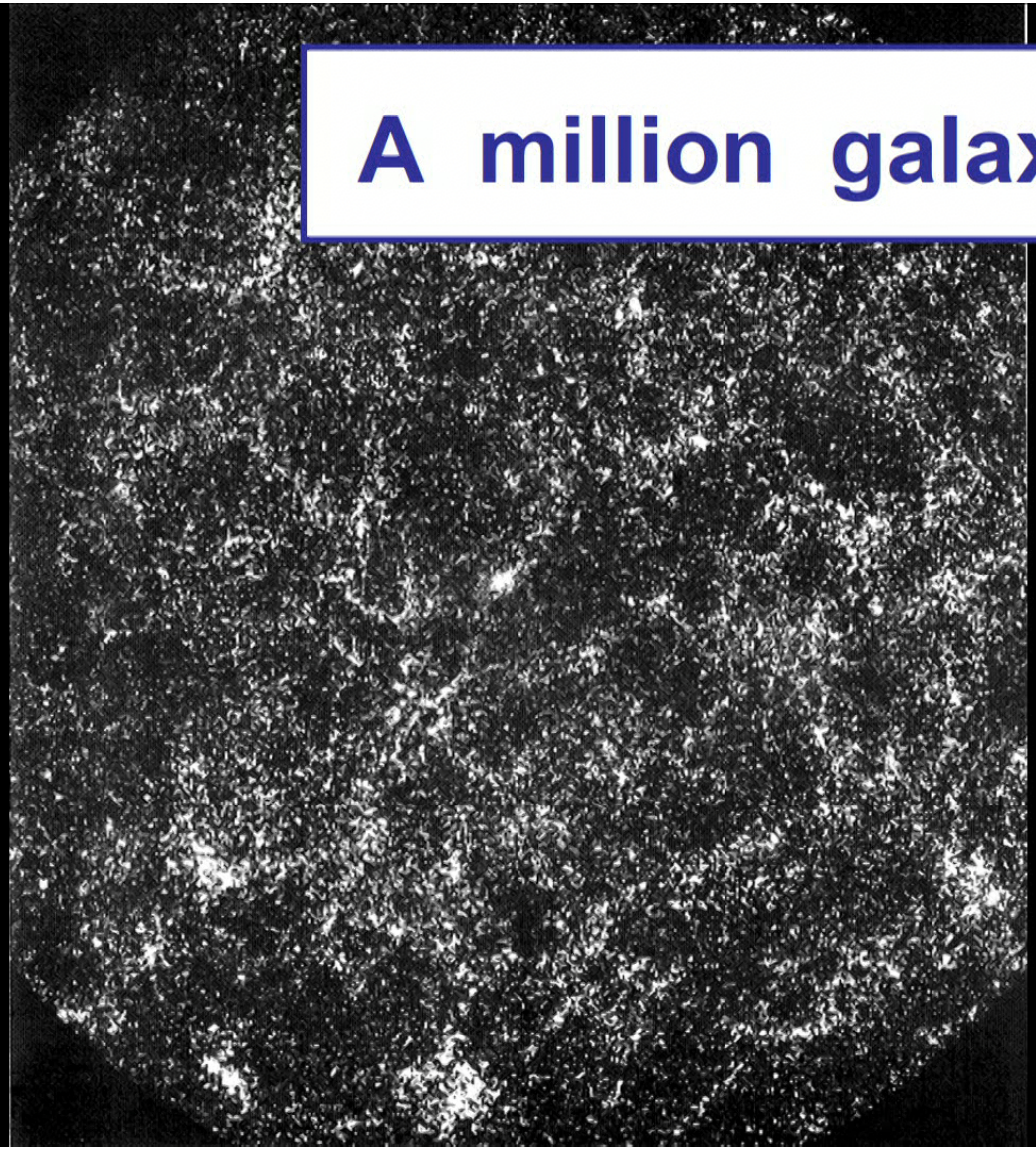
- **Weblike configurations contain**
  cosmological information:
  eg. *Void shapes & Alignments*

- **Cosmic environment within which to understand**
  the formation of galaxies.

Cosmic Web

Observational Reality

A million galaxies



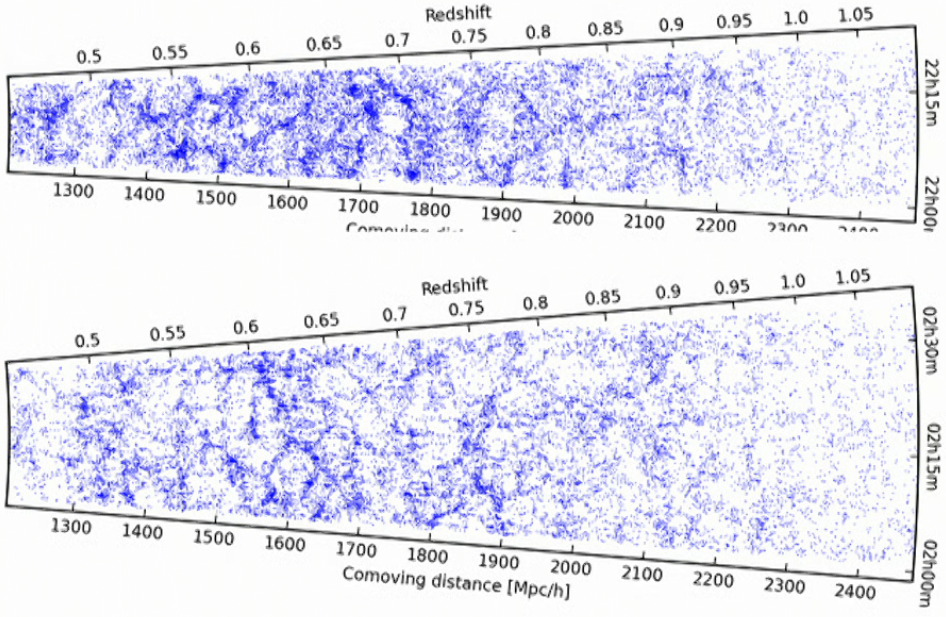
Shane-Wirtanen map:

On the basis of the Shane-Wirtanen counts,

P.J.E. Peebles produced a map of the sky distribution of 1 million galaxies on the sky:

- Clearly visible are clusters
- hint of filamentary LSS features, embedding clusters

VIPERS: Cosmic Web at High z



VIPERS

deep redshift survey,

z=0.4-1.2

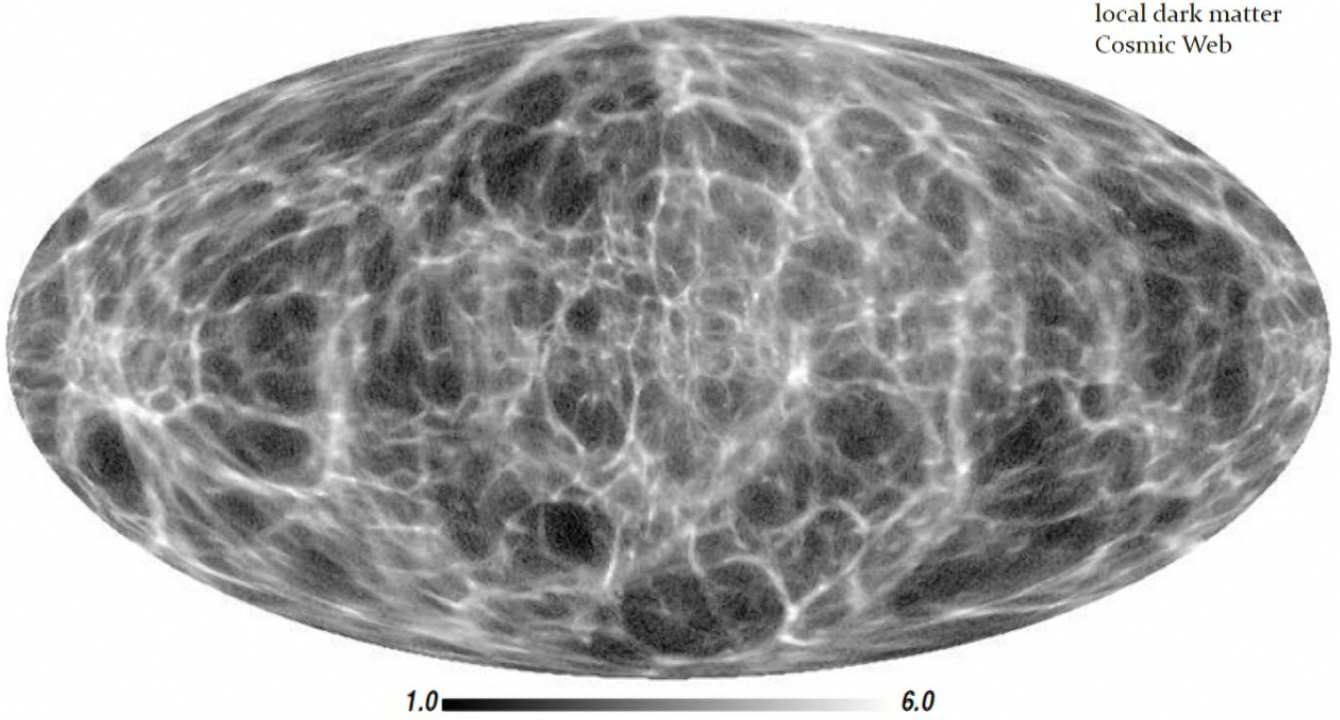
(Guzzo et al. 2014-)

recent galaxy surveys out to high cosmic depths
- eg. DEEP, VIPERS -
establish that the Cosmic Web pervades entire Universe (up to z~5 at least)

local Cosmic Web: 2MRS

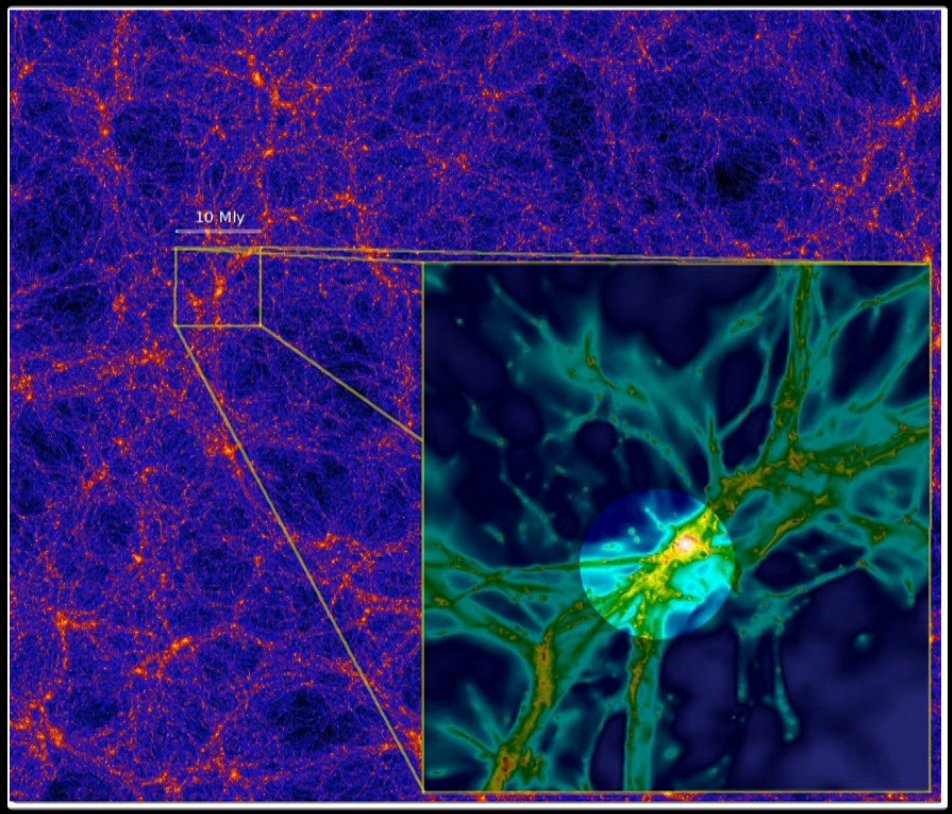
most detailed reconstruction of the

local dark matter Cosmic Web



Courtesy: Francisco Kitaura

the Gaseous Cosmic Web



Gaseous Cosmic Web:

Detection via:

1) Lyα absorption (Lyα forest)
   - neutral hydrogen (cloud)
   - mostly at high redshift
   - absorption against quasar los.
   - possible use as tomographic tool

2) WHIM
   - warm-hot intergalactic medium
   - soft Xray emission of hot gas (10^5 K) very hard to see
   - absorption lines Xray band (eg. OVI)

3) Sunyaev-Zeldovich scattering filaments
   - inverse Compton scattering CMB photons against hot electrons in ICM/IGM
   - has been seen in Planck (80 filam.)

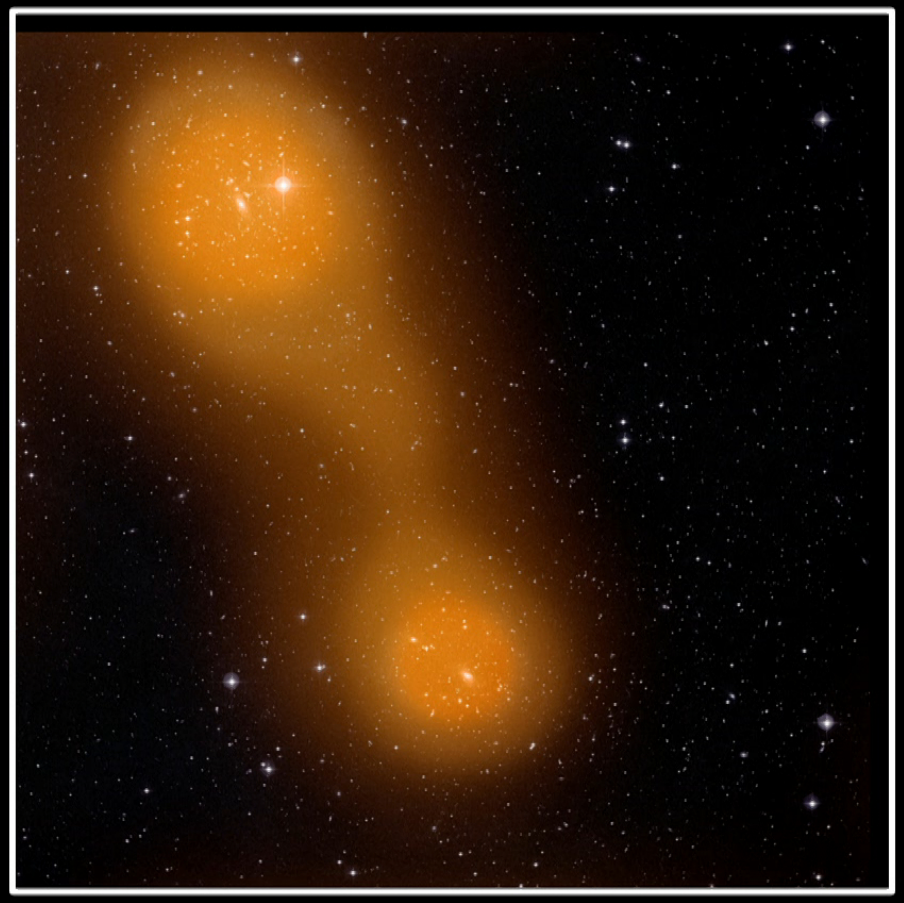
the Gaseous Cosmic Web

Sunyaev-Zeldovich
detection of

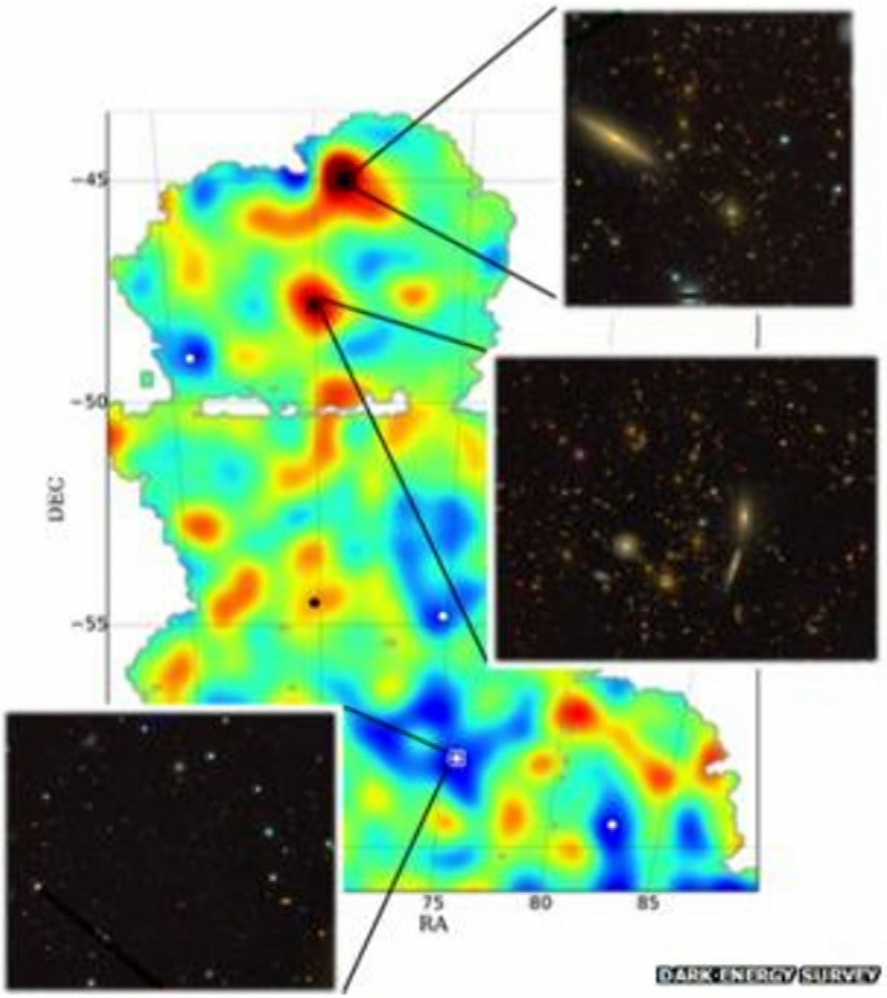
Inter-cluster bridge/filament

in between clusters
A401 and A399

ESA/Planck collaboration



Dark Energy Survey (DES)



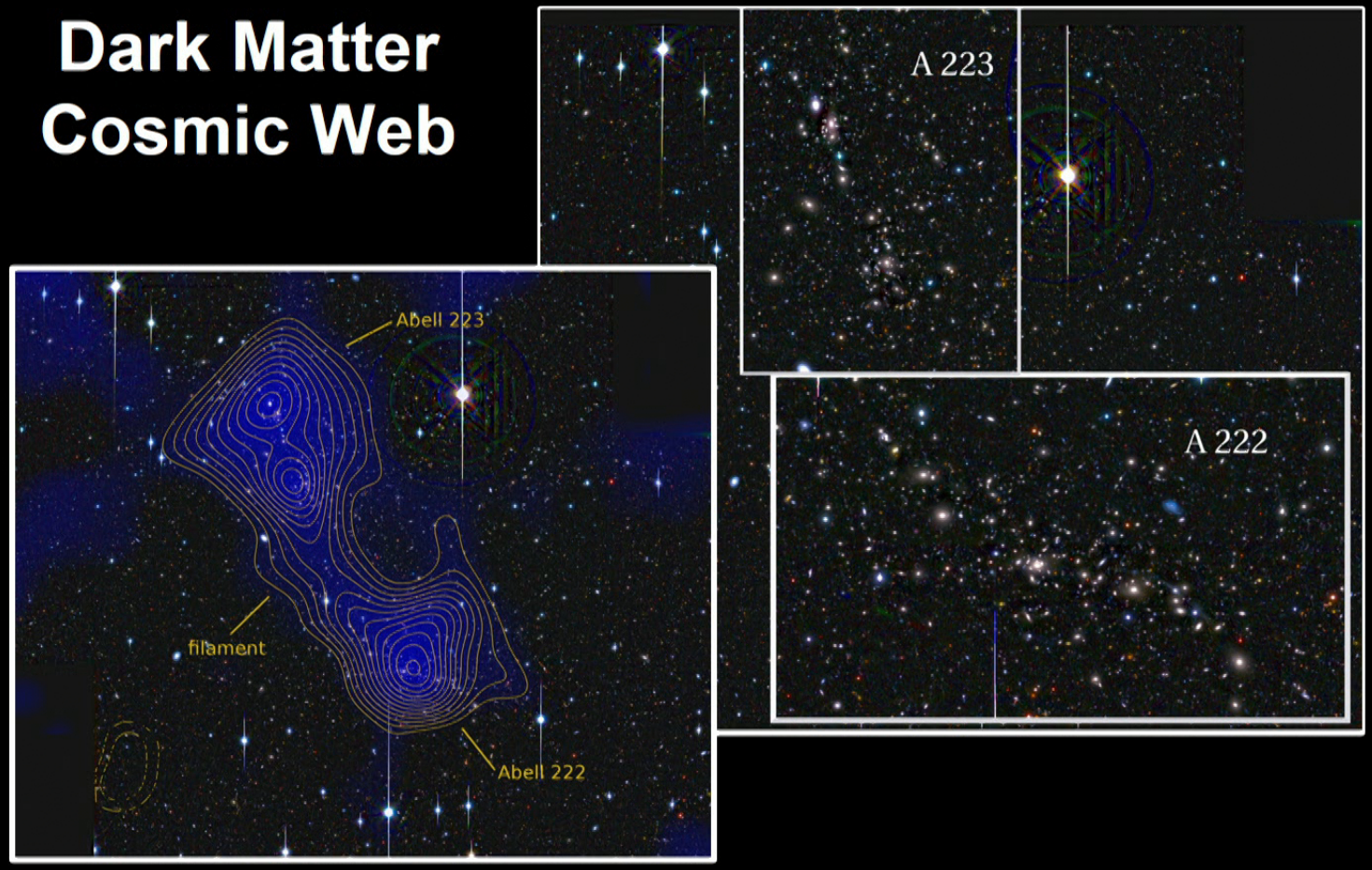
Map of
(projected) (dark) matter density:

For reference, elements of the Cosmic Web:

- Identification 2 clusters
- Reveals filamentary extensions
- Also noticeable is a void region

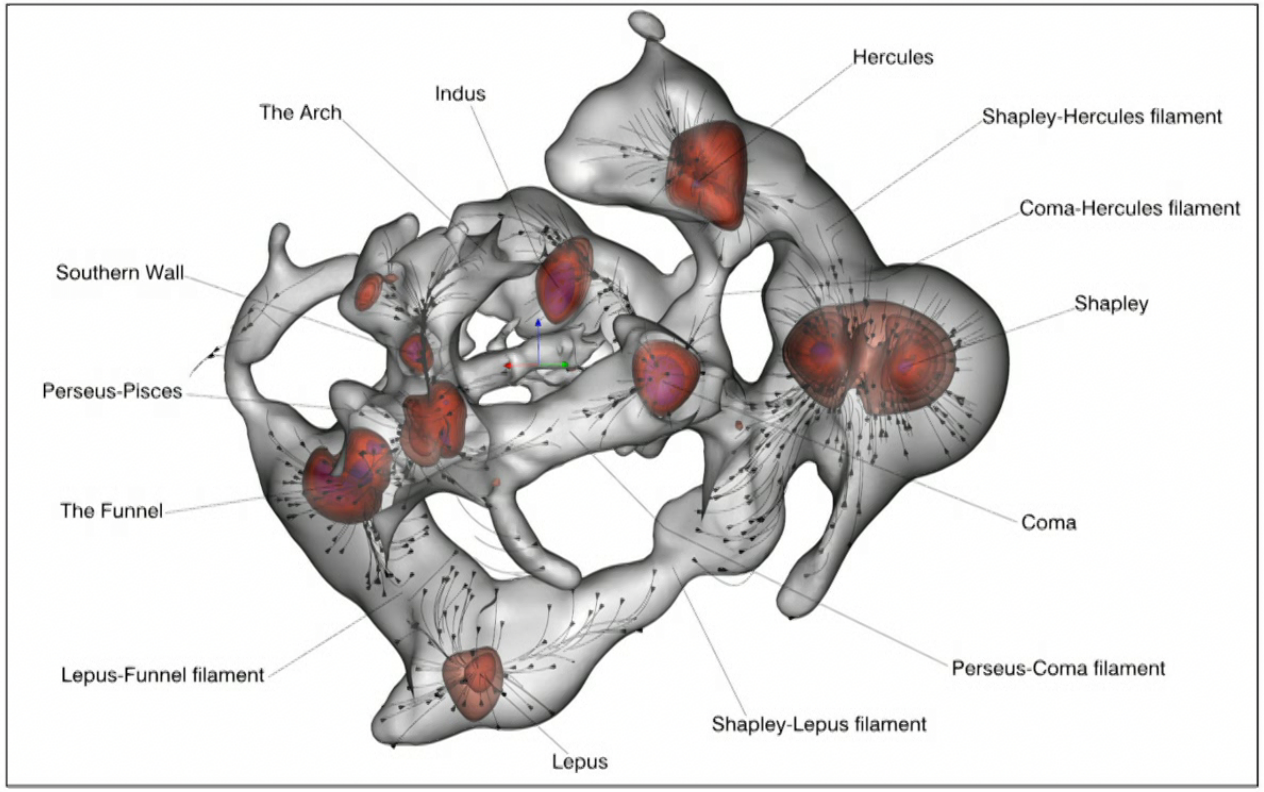
Dark Matter Cosmic Web

Dark Matter Cosmic Web



A222-A223
Dietrich et al. 2013

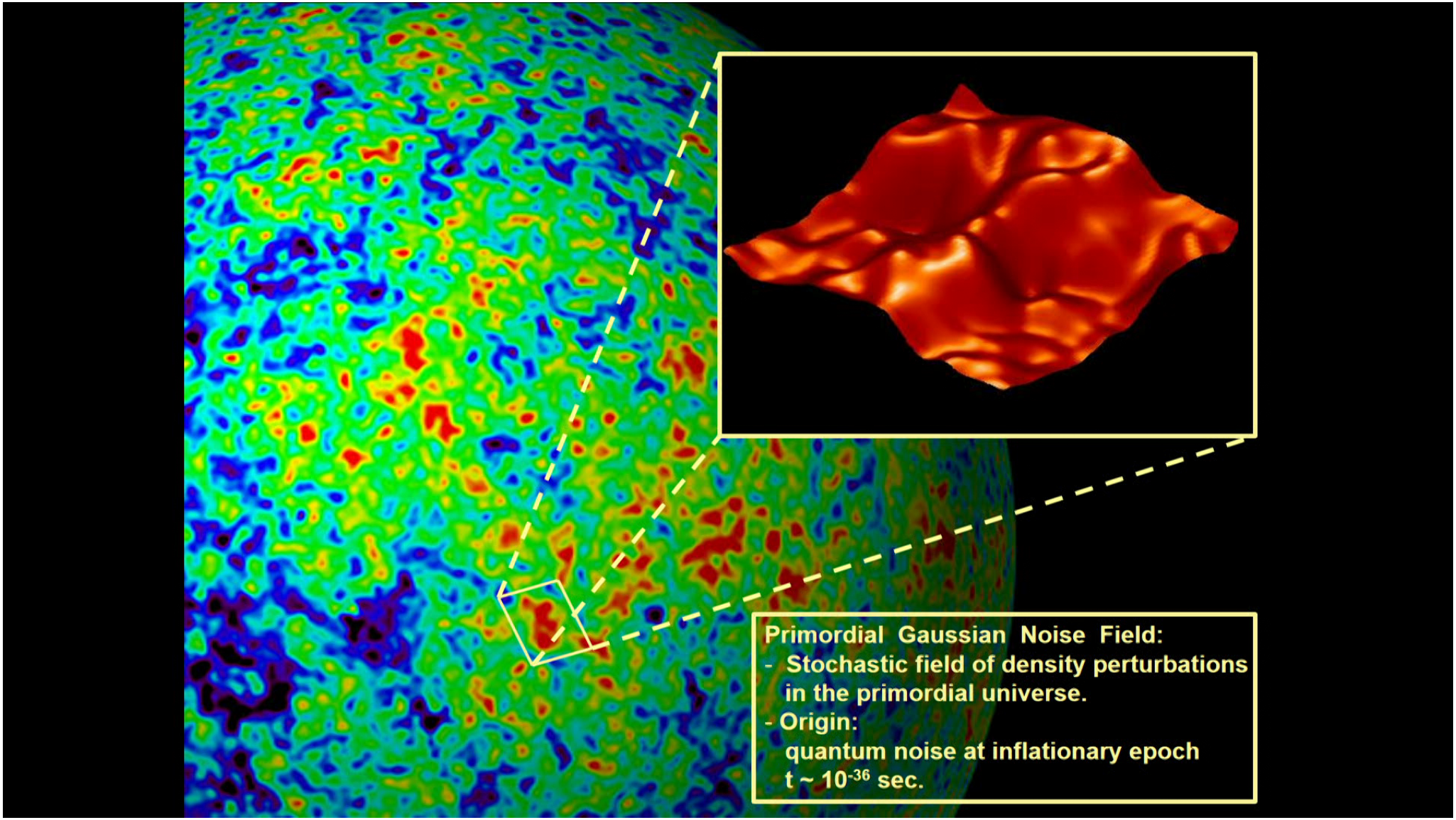
CosmicFlows-3



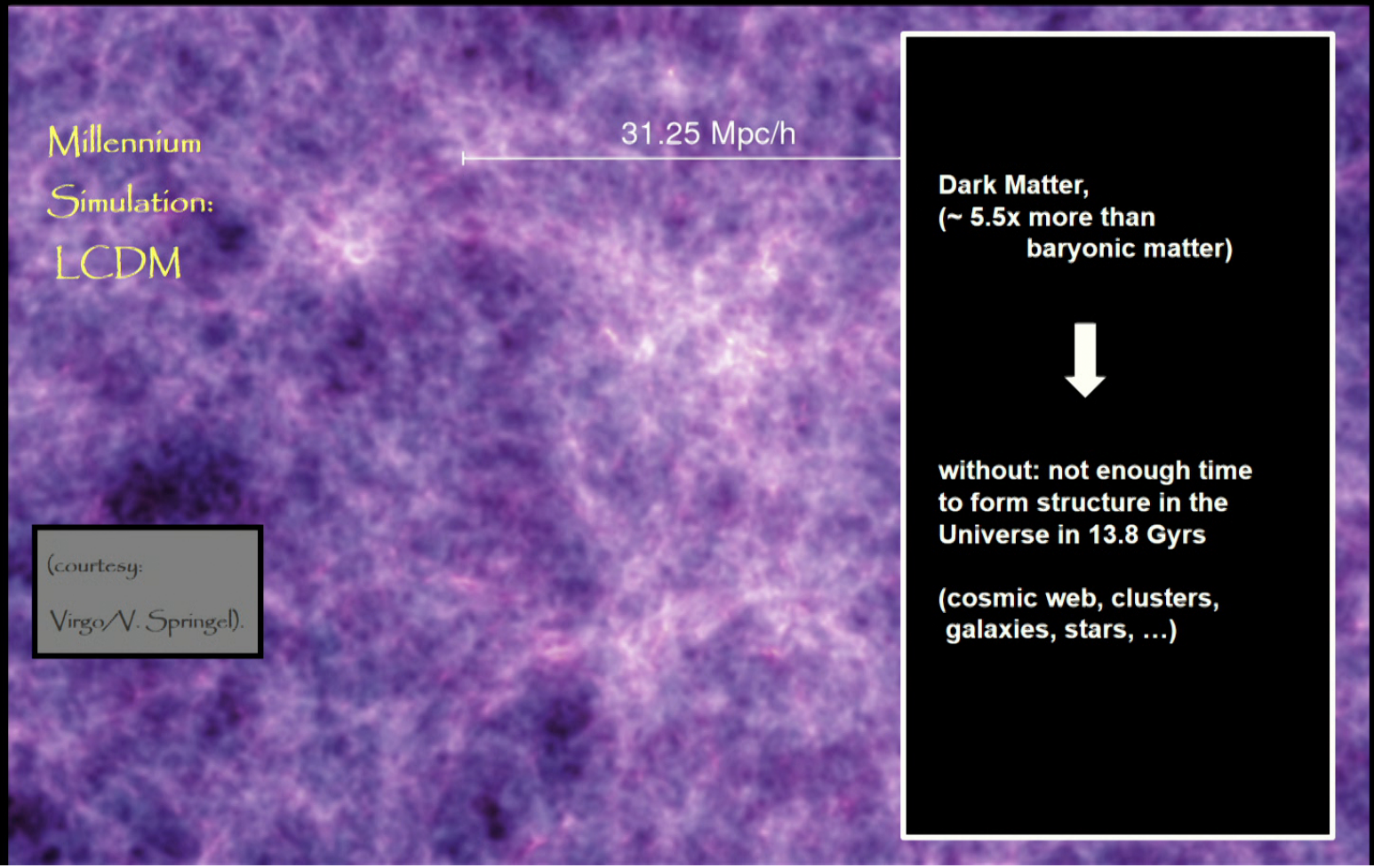
Cosmic Web morphology:
velocity shear based V-web identification flow pattern in cosmic web
(Pomarede et al. 2017)

Cosmic Structure Formation:

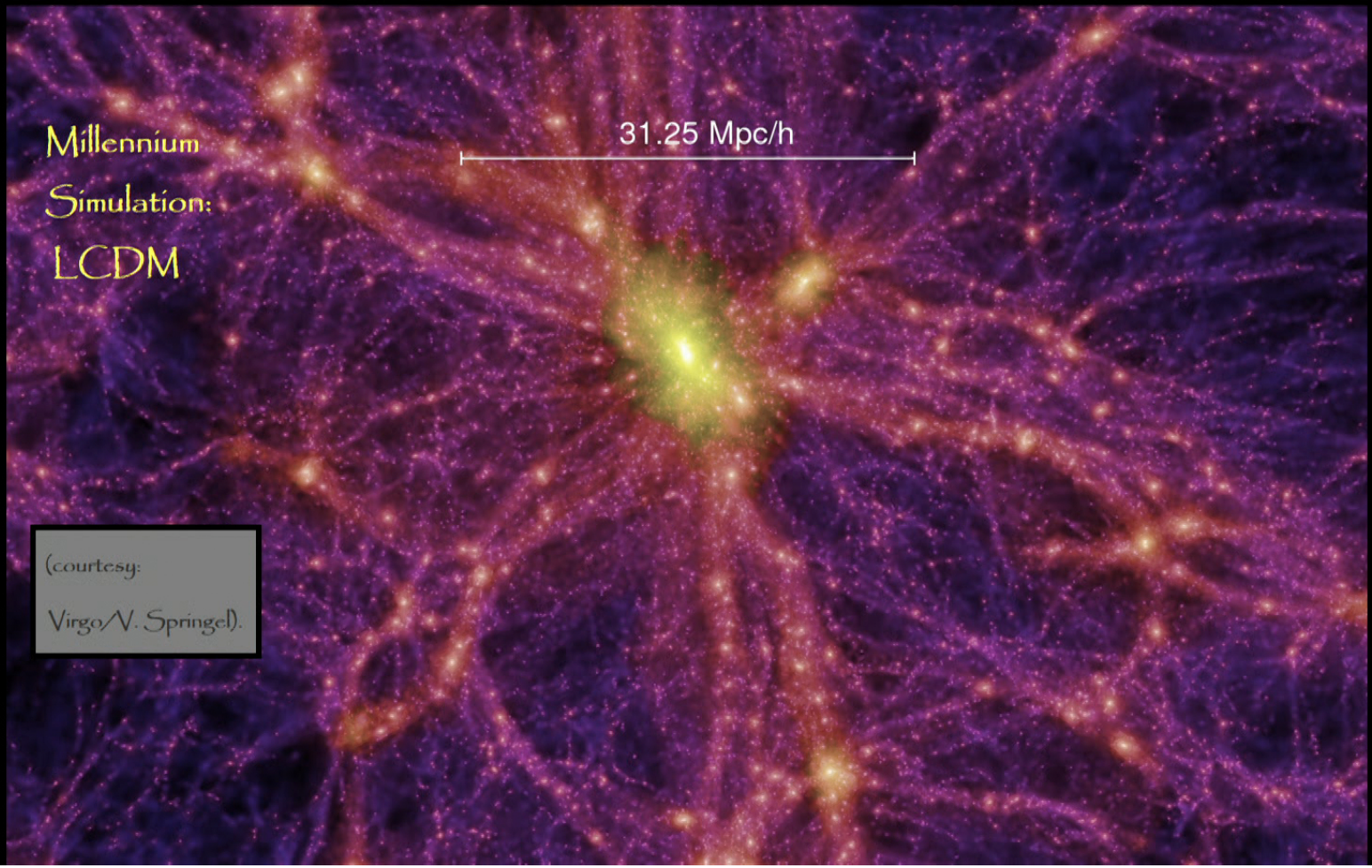
Gravitational Instability


Primordial Gaussian Noise Field:
- Stochastic field of density perturbations in the primordial universe.
- Origin:
quantum noise at inflationary epoch
t ~ 10-36 sec.

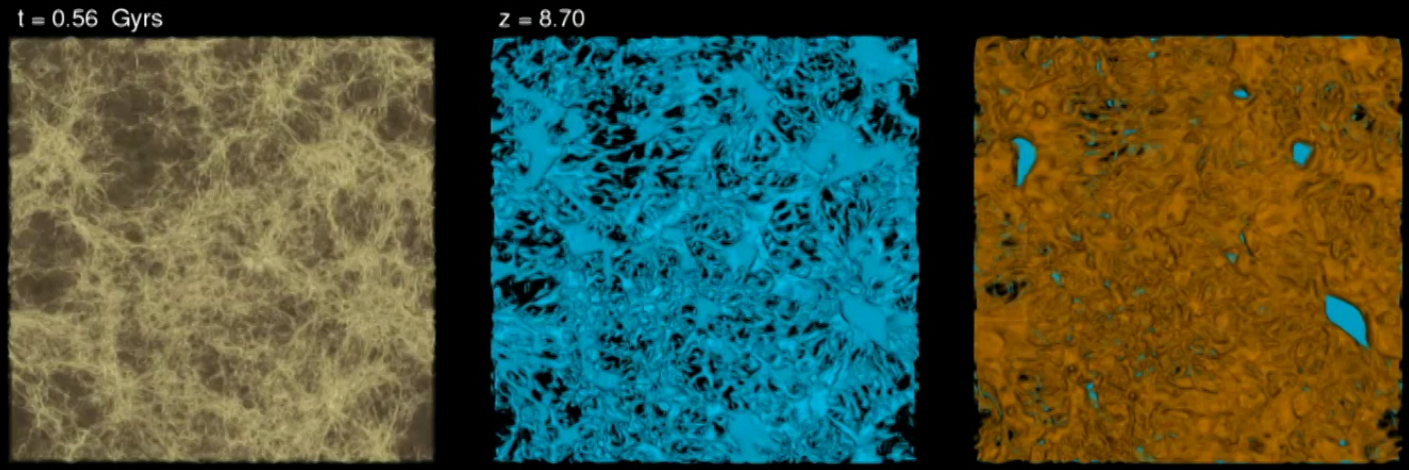
Cosmic Structure Formation



Cosmic Structure Formation



NEXUS/MMF
Evolution Cosmic Web

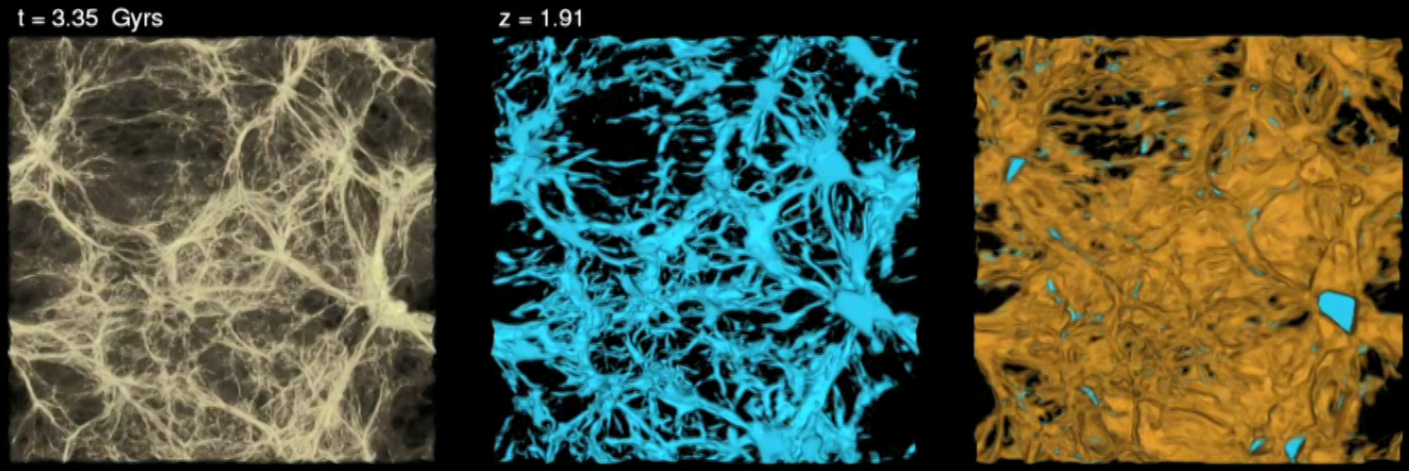


Cautun et al. 2013

Dynamical Evolution Cosmic Web

- hierarchical structure formation
- anisotropic collapse
- establishing the connectivity
- void formation:
  asymmetry
  overdense vs. underdense

NEXUS/MMF
Evolution Cosmic Web



Cautun et al. 2013

the Cosmic Web:

evolution of walls & filaments

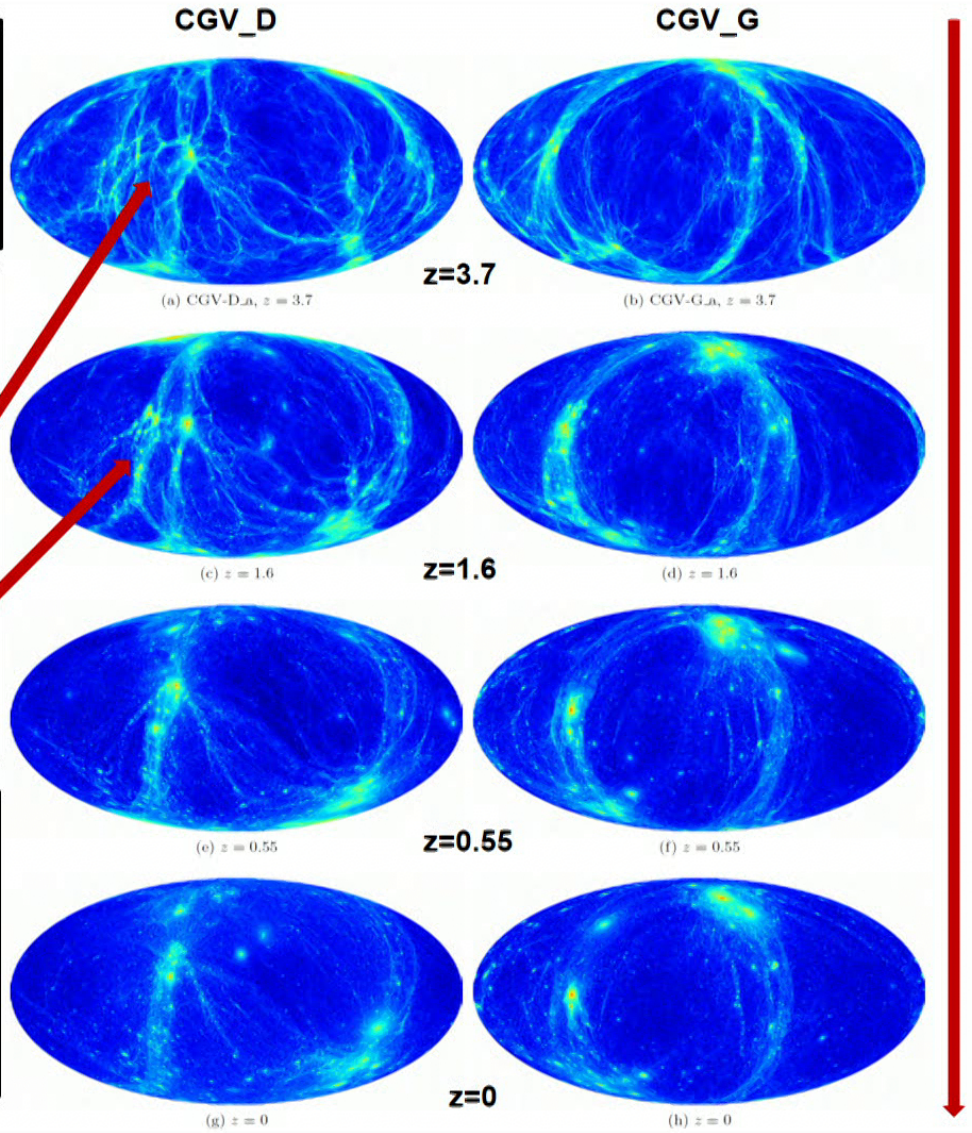
CGV:

on walls & filaments

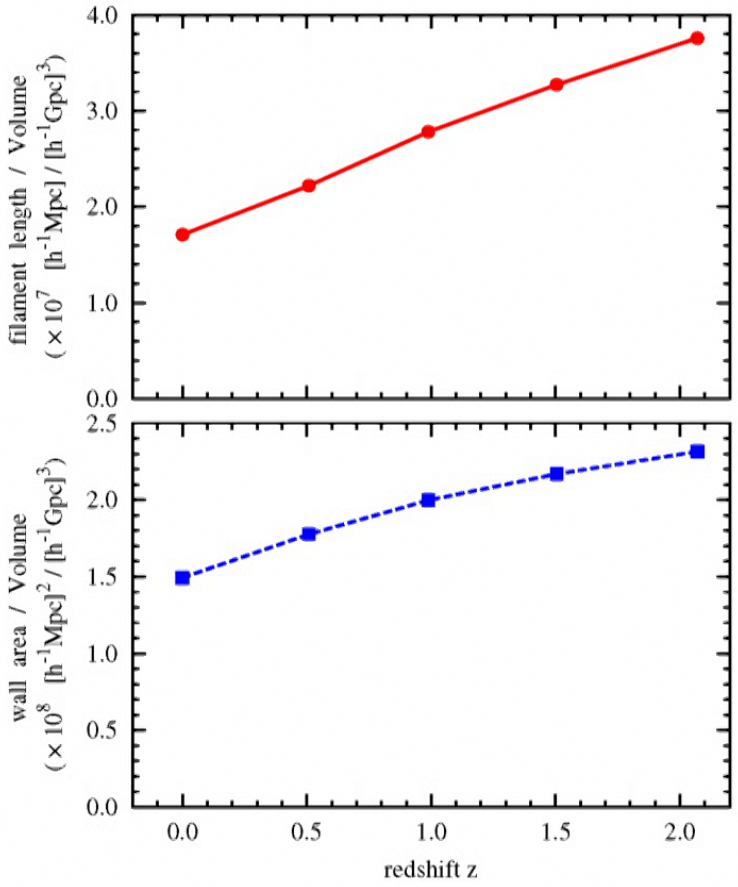
- Mollweide sky projection matter distribution around CGV halos
- CGV halos embedded in walls
- Walls dominate void infrastructure
- substantial fraction in filaments (embedded in walls)
- active dynamical evolution of wall-filament goes along with active void galaxy halo evolution

merging system of
Intravoid walls

Rieder et al. 2013



Evolving Filament & Wall Network



Total length of filament network :

decreasing as a function of time

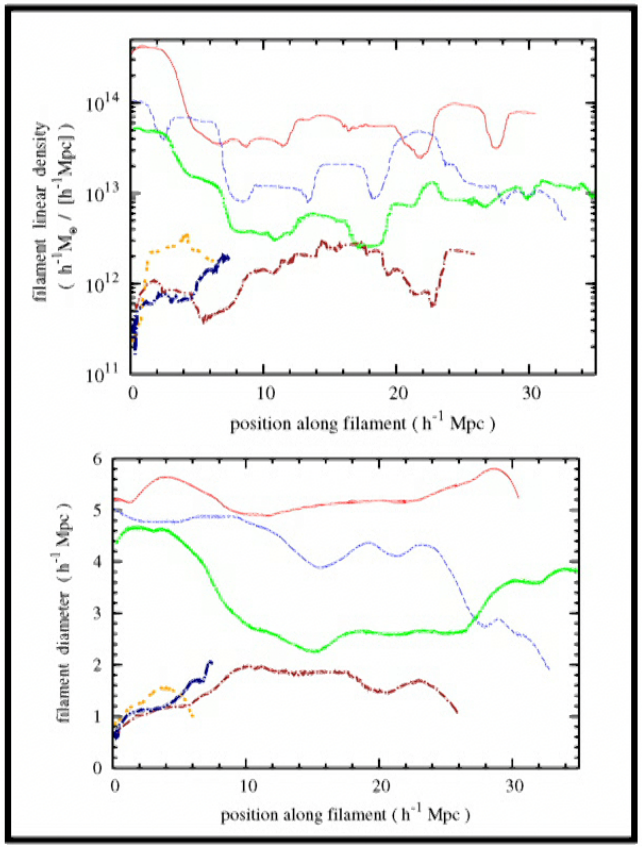
Total surface area of wall network :

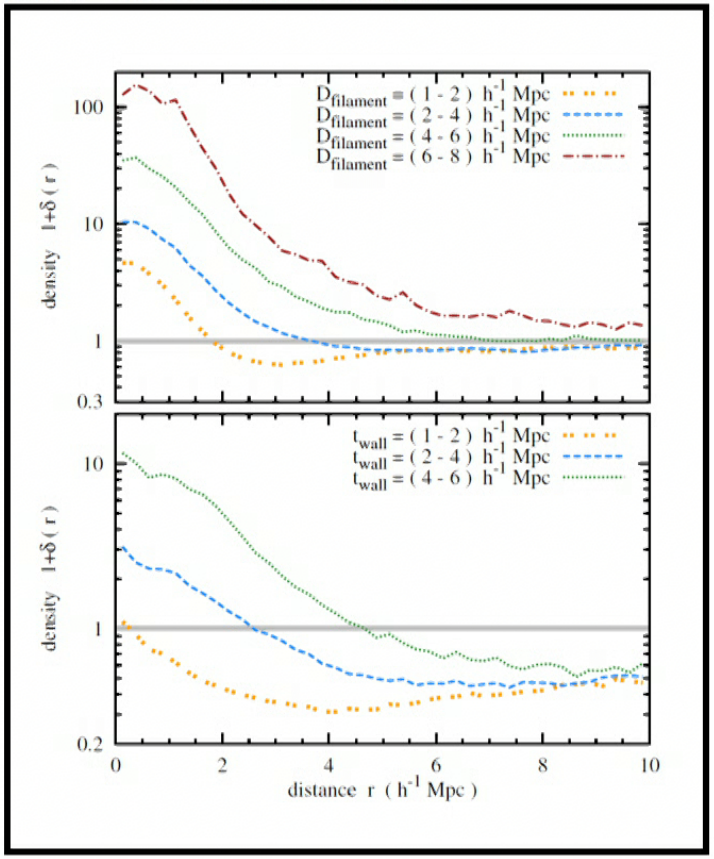
decreasing as a function of time

Cautun et al. 2014

Walls & Filaments

Internal Diameter & Density Profiles



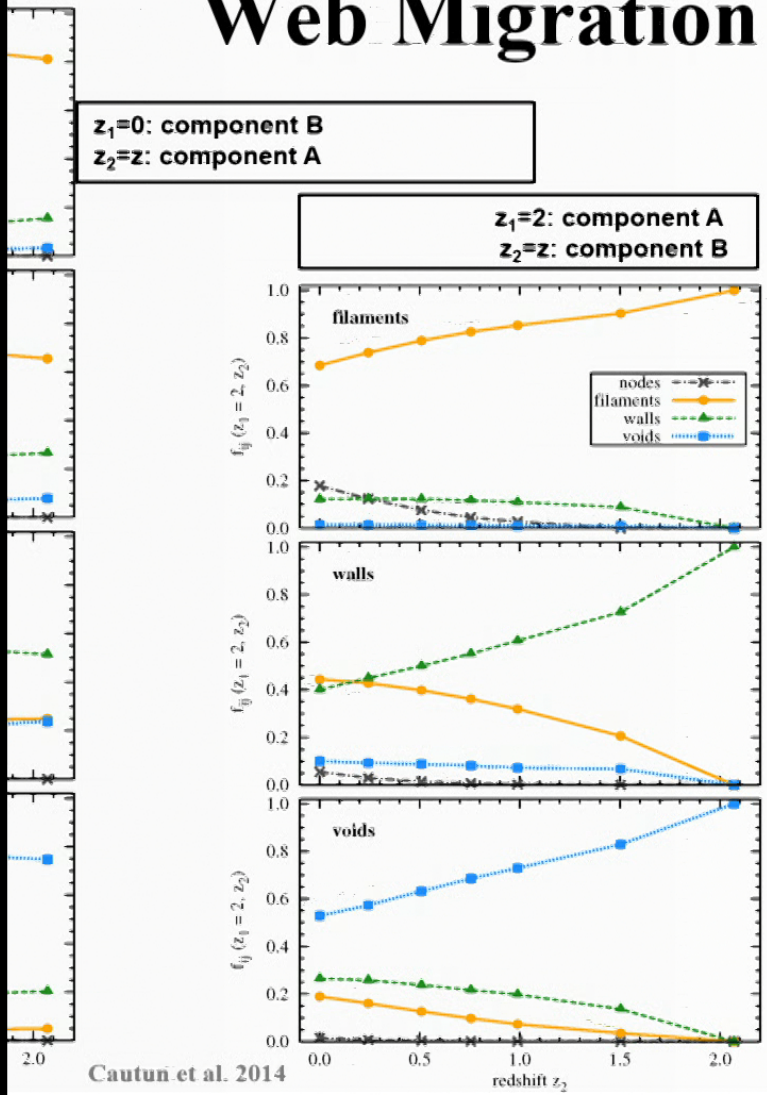


Cautun et al. 2014

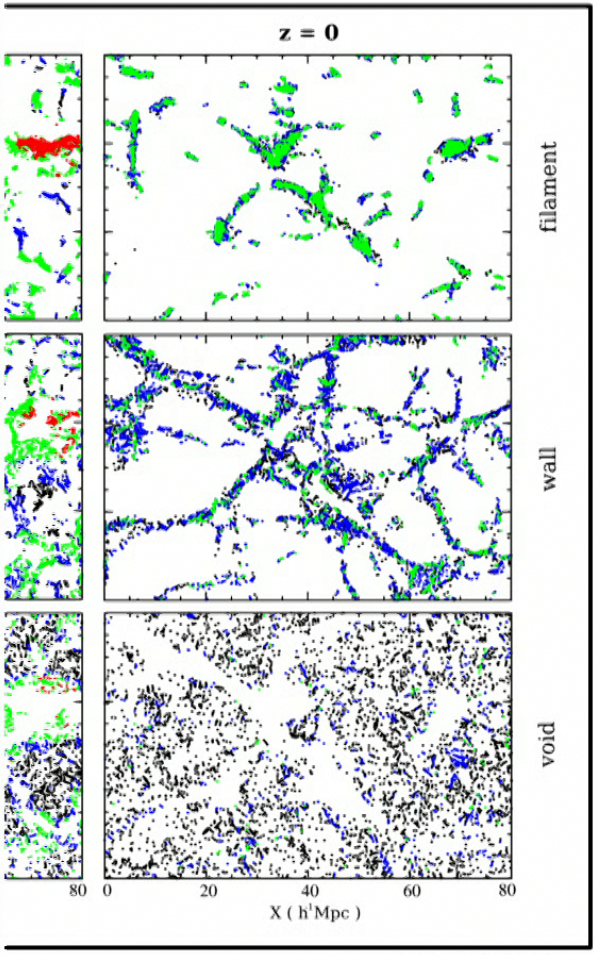
Web Migration igration

z_1=0: component B
z_2=z: component A

z_1=2: component A
z_2=z: component B



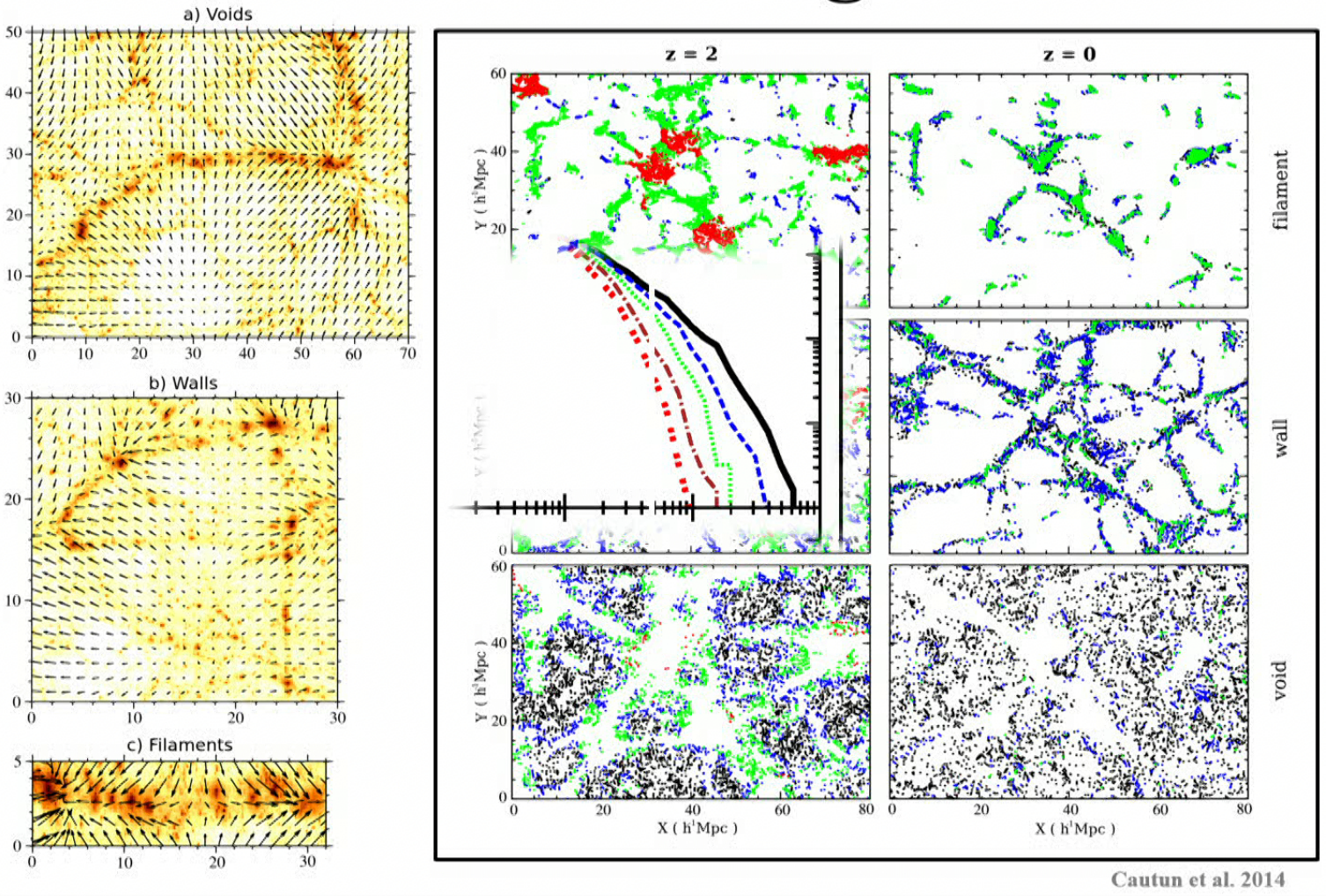
moving out of …



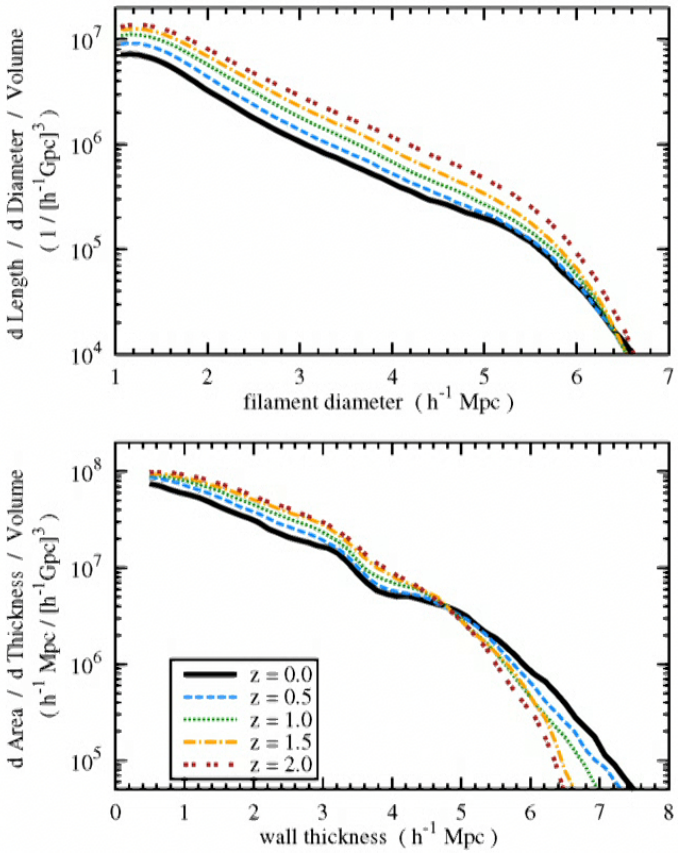
Cautun et al. 2014

Cautun et al. 2014

Web Mass Emigration



Evolving Filament & Wall Diameters



Filament population:
increasing diameter

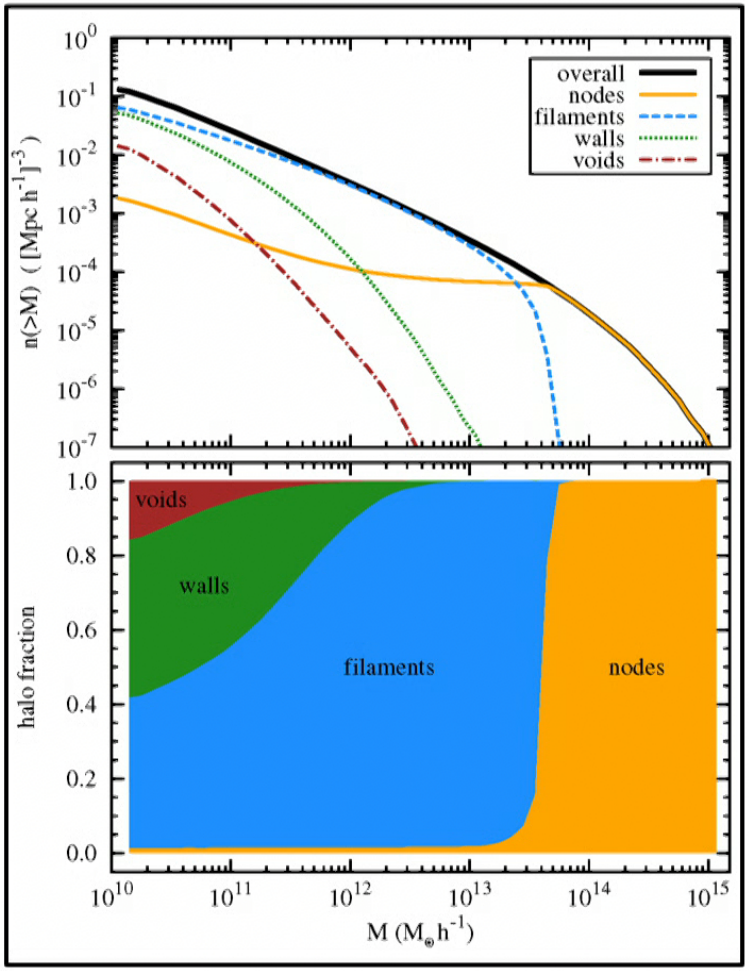
Wall population:
increasing thickness for denser walls
decrease of tenuous walls

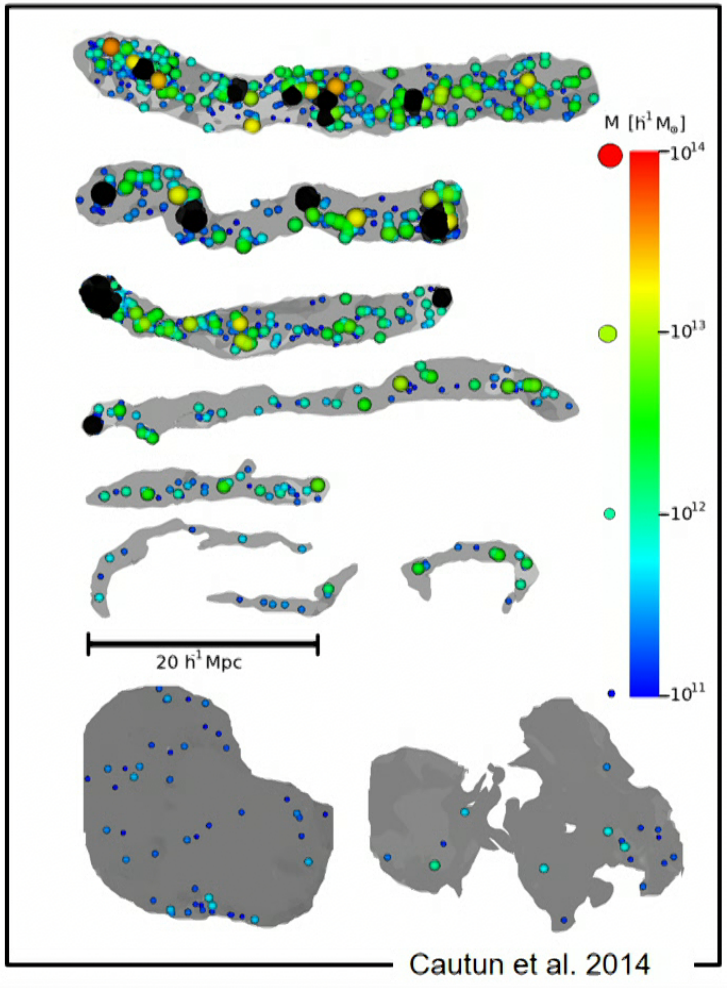
Cautun et al. 2014

Cosmic Web:

Halo Distribution

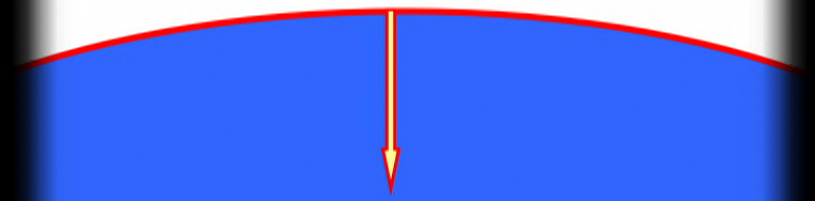
Halos in the Cosmic Web





Cosmic Web

s in gravity along different directions (tidal forces)

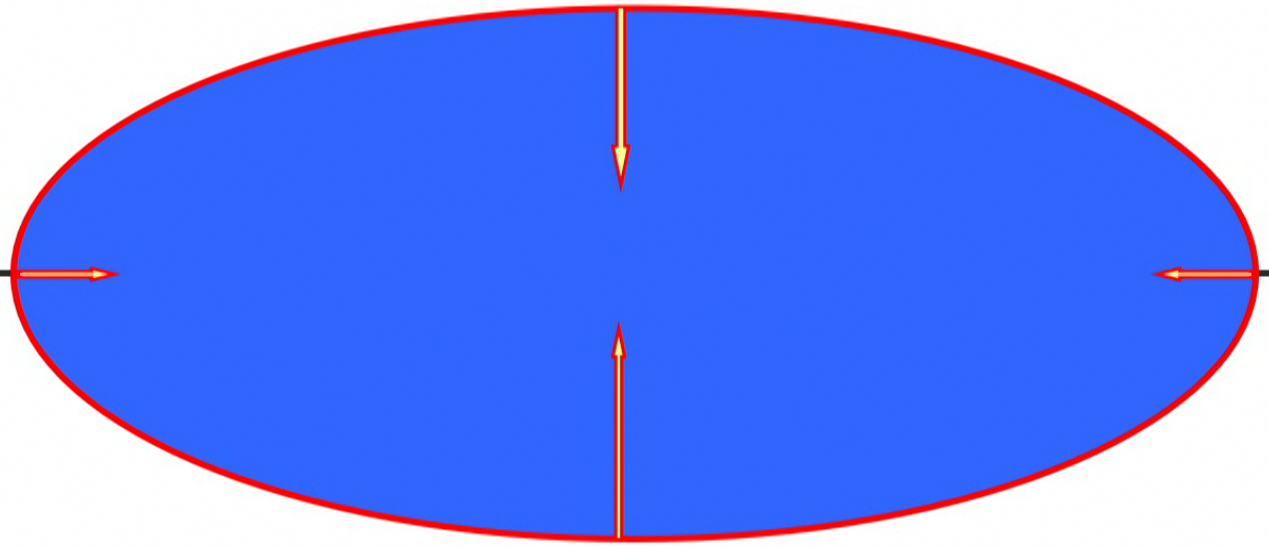


Anisotropic Collapse

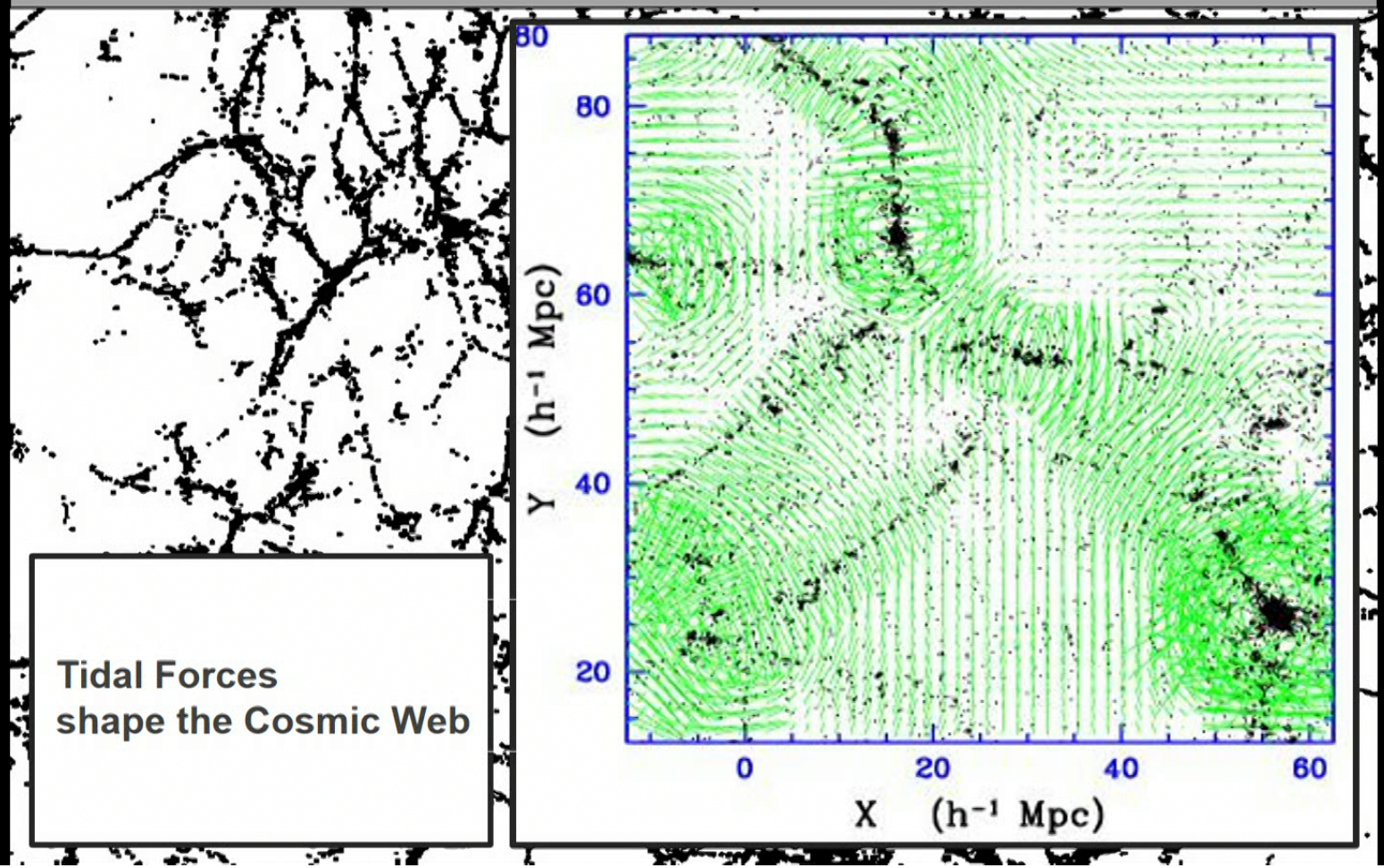
Anisotropic

Gravitational Collapse

Amplification
small perturbations in gravity along different directions (tidal forces)



Tidal Shaping of the Cosmic Web

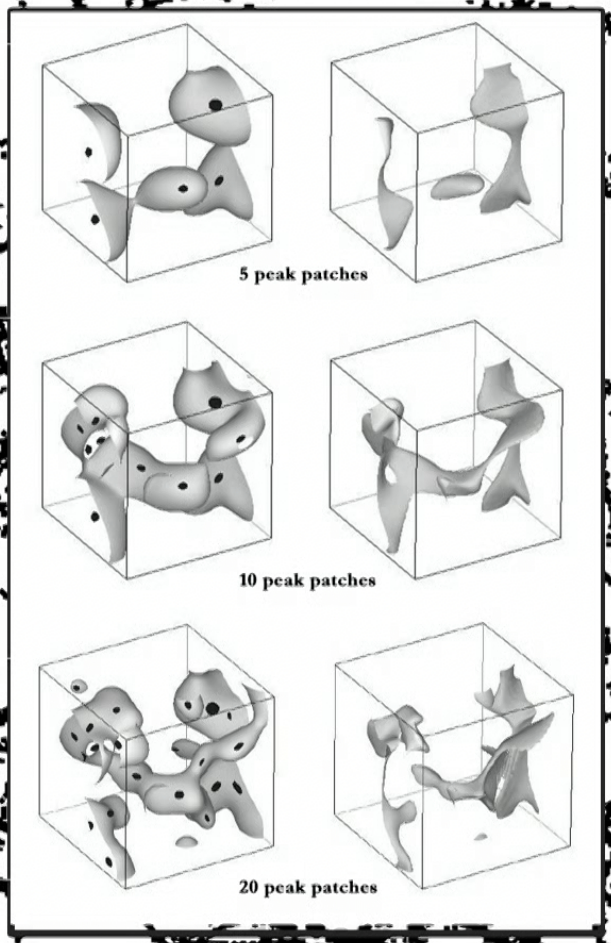


Tidal Shaping of the Cosmic Web

Cosmic Web Theory

Bond, Kofman & Pogosyan 1996

Tidal Forces: main source are the clusters



Dynamics of the Cosmic Web:

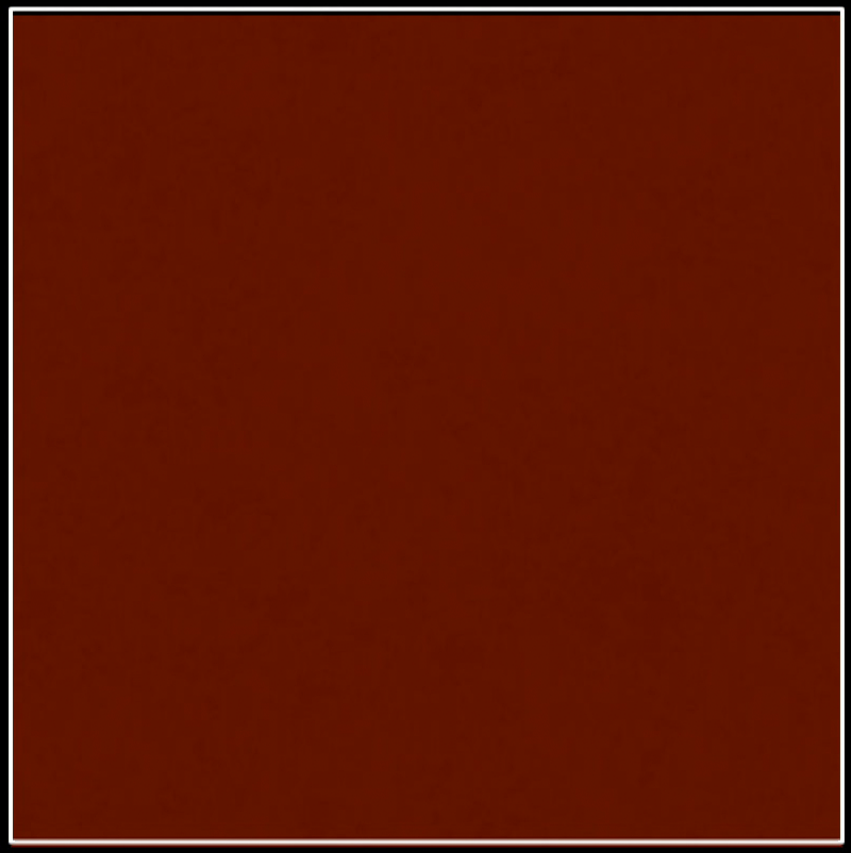
Anisotropic Collapse & Zeldovich Formalism

Zel'dovich Approximation

$$\vec{x} = \vec{q} + D(t)\vec{u}(\vec{q})$$

$$\vec{u}(\vec{q}) = -\vec{\nabla}\Phi(\vec{q})$$

$$\Phi(\vec{q}) = \frac{2}{3Da^2H^2\Omega}\phi_{lin}(\vec{q})$$



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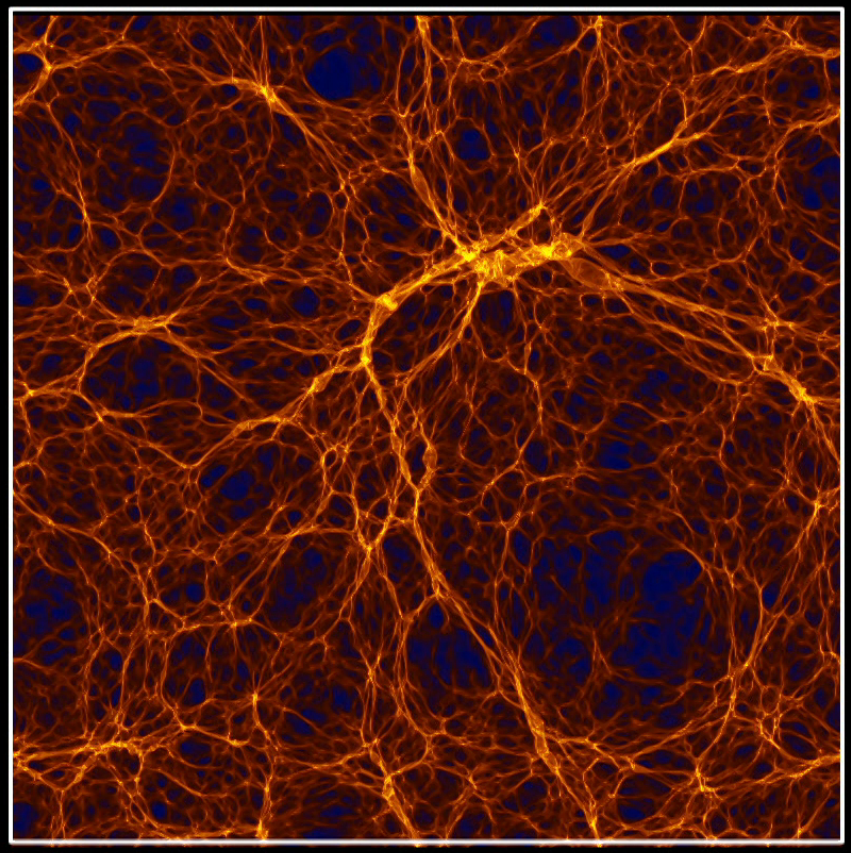


Zel'dovich Approximation

$$\vec{x} = \vec{q} + D(t)\vec{u}(\vec{q})$$

$$\vec{u}(\vec{q}) = -\vec{\nabla}\Phi(\vec{q})$$

$$d_{ij} = -\frac{\partial u_i}{\partial q_j}$$

$$\rho(\vec{q},t) = \frac{\rho_u(t)}{\left(1 - D(t)\lambda_1(\vec{q})\right)\left(1 - D(t)\lambda_2(\vec{q})\right)\left(1 - D(t)\lambda_3(\vec{q})\right)}$$

structure of the cosmic web determined by the spatial field of eigenvalues

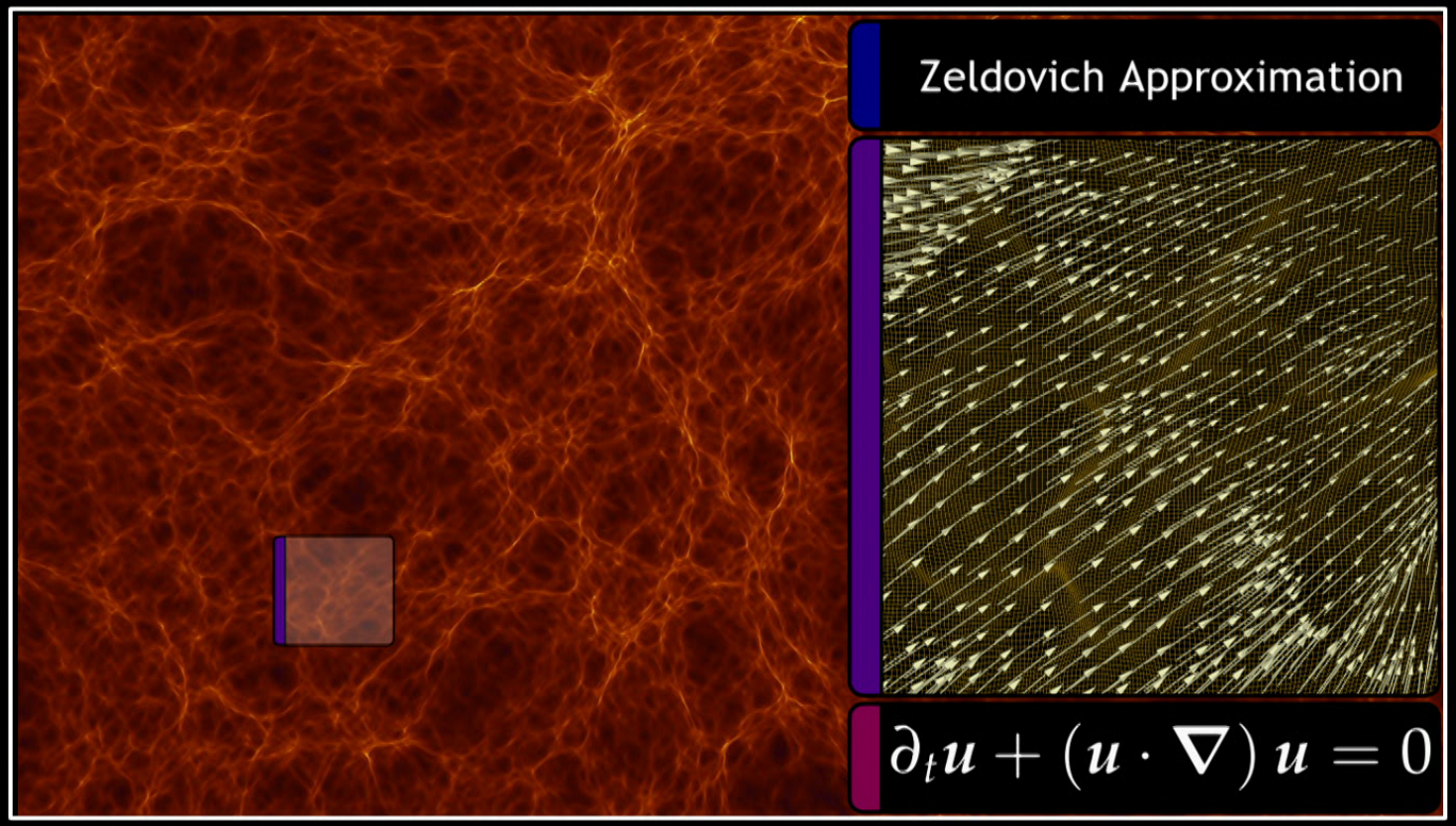
$$\lambda_1, \lambda_2, \lambda_3$$

Hierarchical Dynamics of the Cosmic Web:

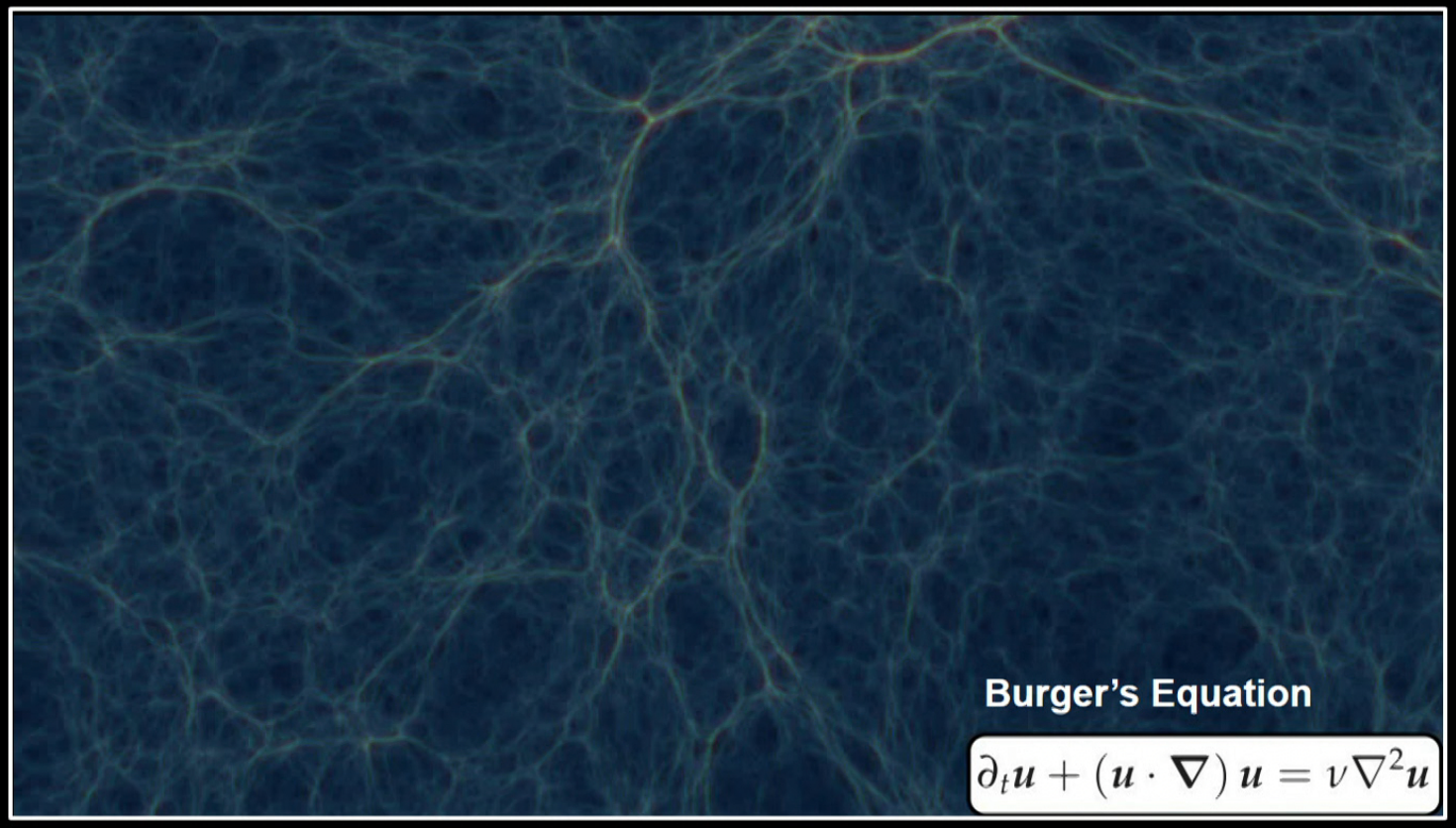
Convex Hull Adhesion

Hidding, vdW et al. 2012,
Hidding, vdW et al. 2016
Hidding, vdW et al. 2018

Zel'dovich Approximation

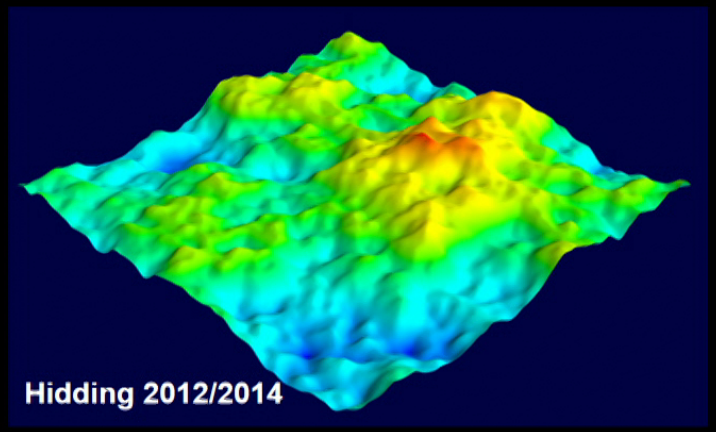


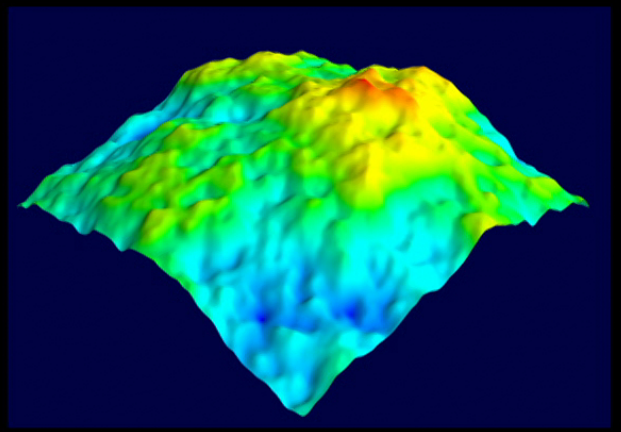
Adhesion Approximation



Burger's Equation: Hopf Solution

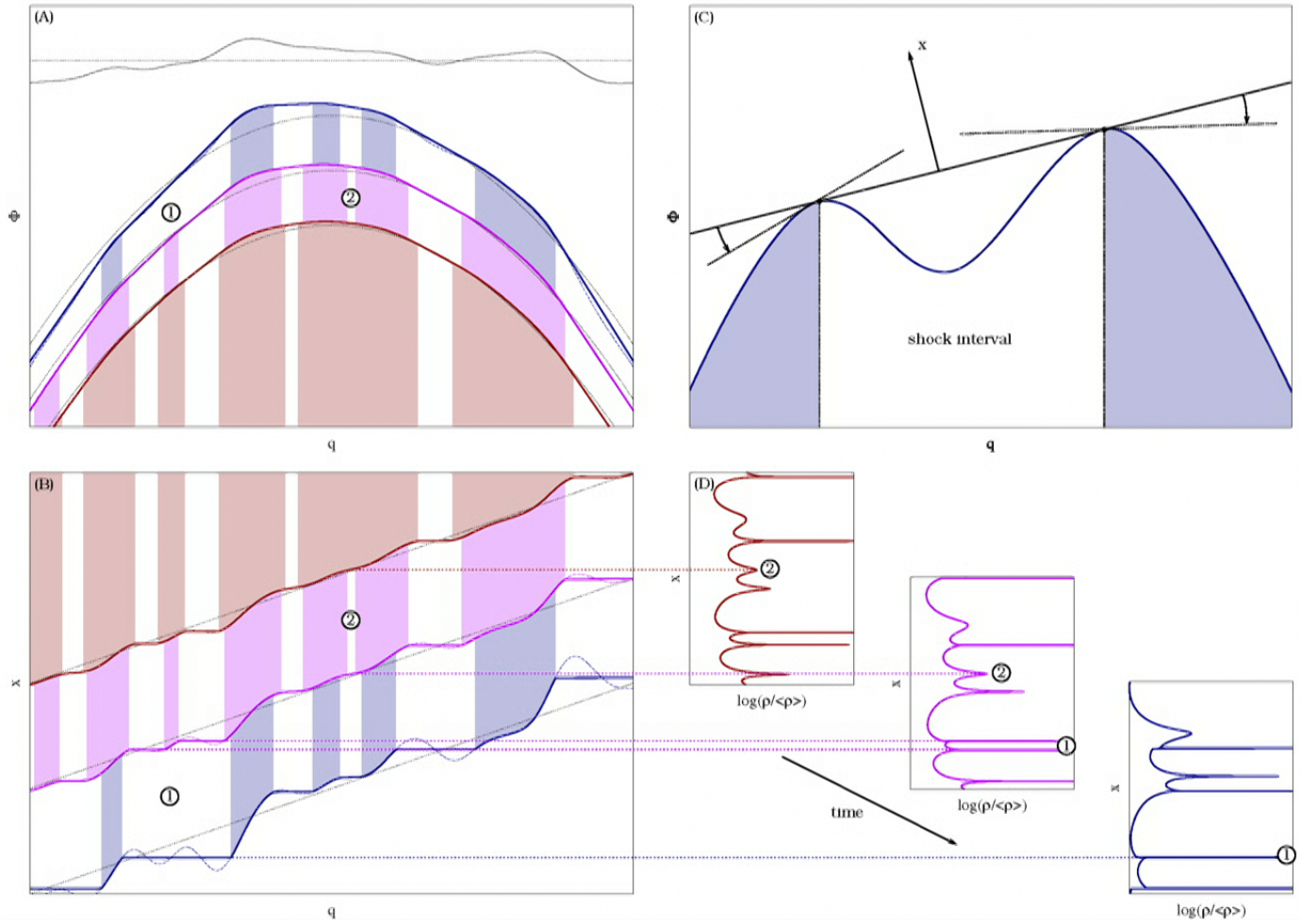
$$\frac{\partial \vec{u}}{\partial t} + \left(\vec{u} \cdot \vec{\nabla}\right)\vec{u} = \nu \nabla^2 \vec{u}$$



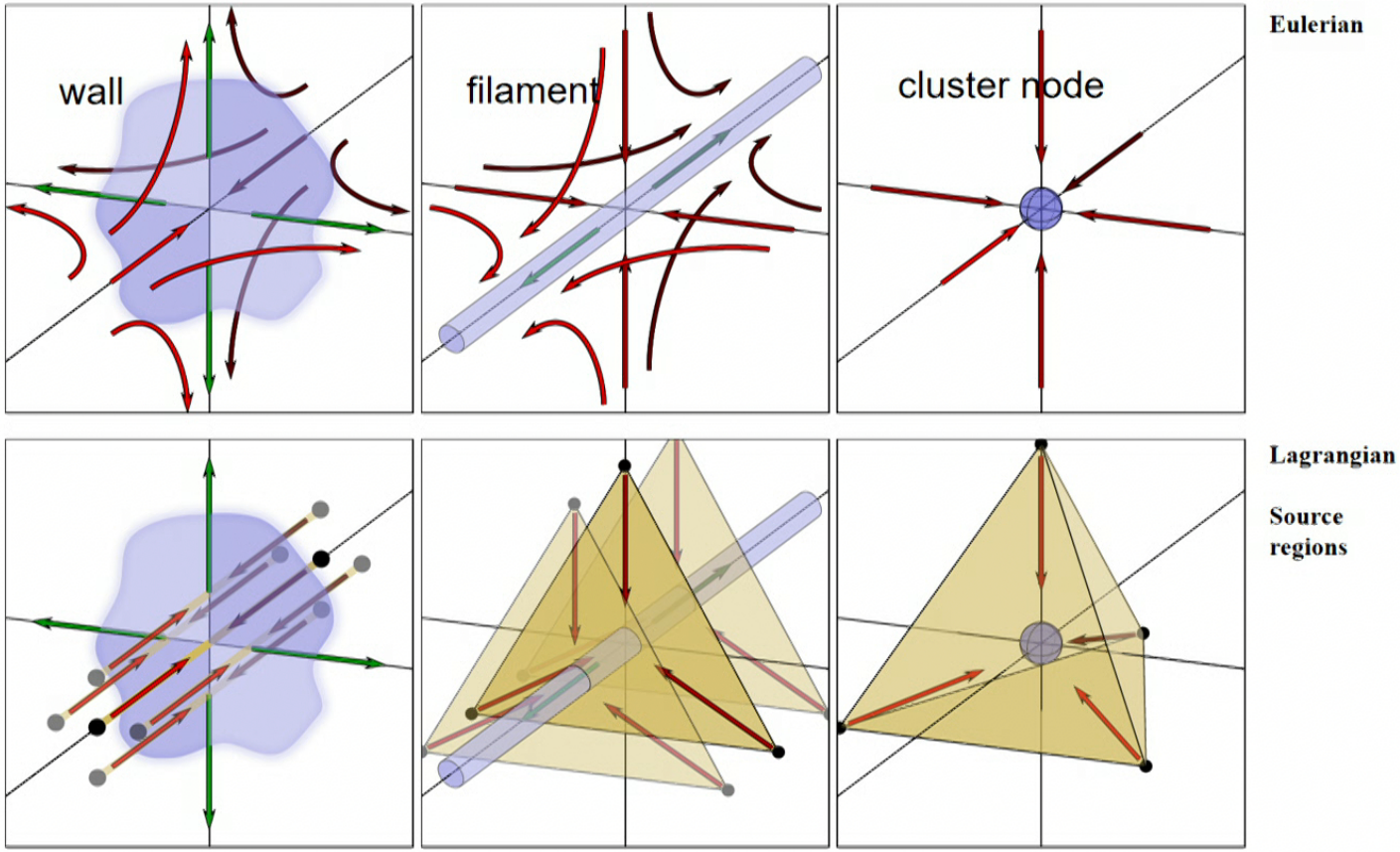


$$\Phi(\vec{x},t) + \frac{x^2}{2} = \max_q \left[\left(t\Phi_0(q) - \frac{q^2}{2} \right) + \vec{x} \cdot \vec{q} \right]$$

Burger's Equation: Hopf Solution

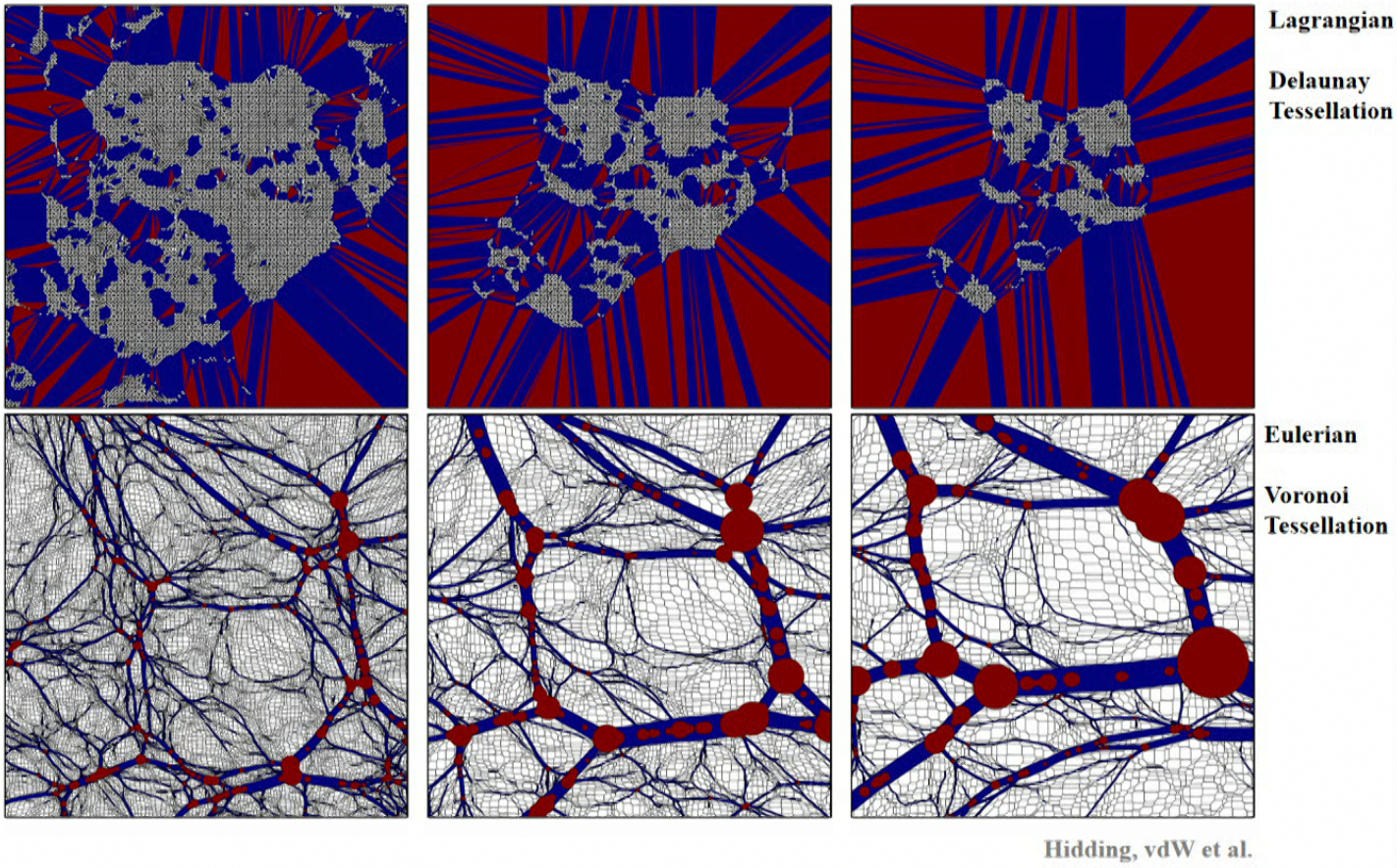


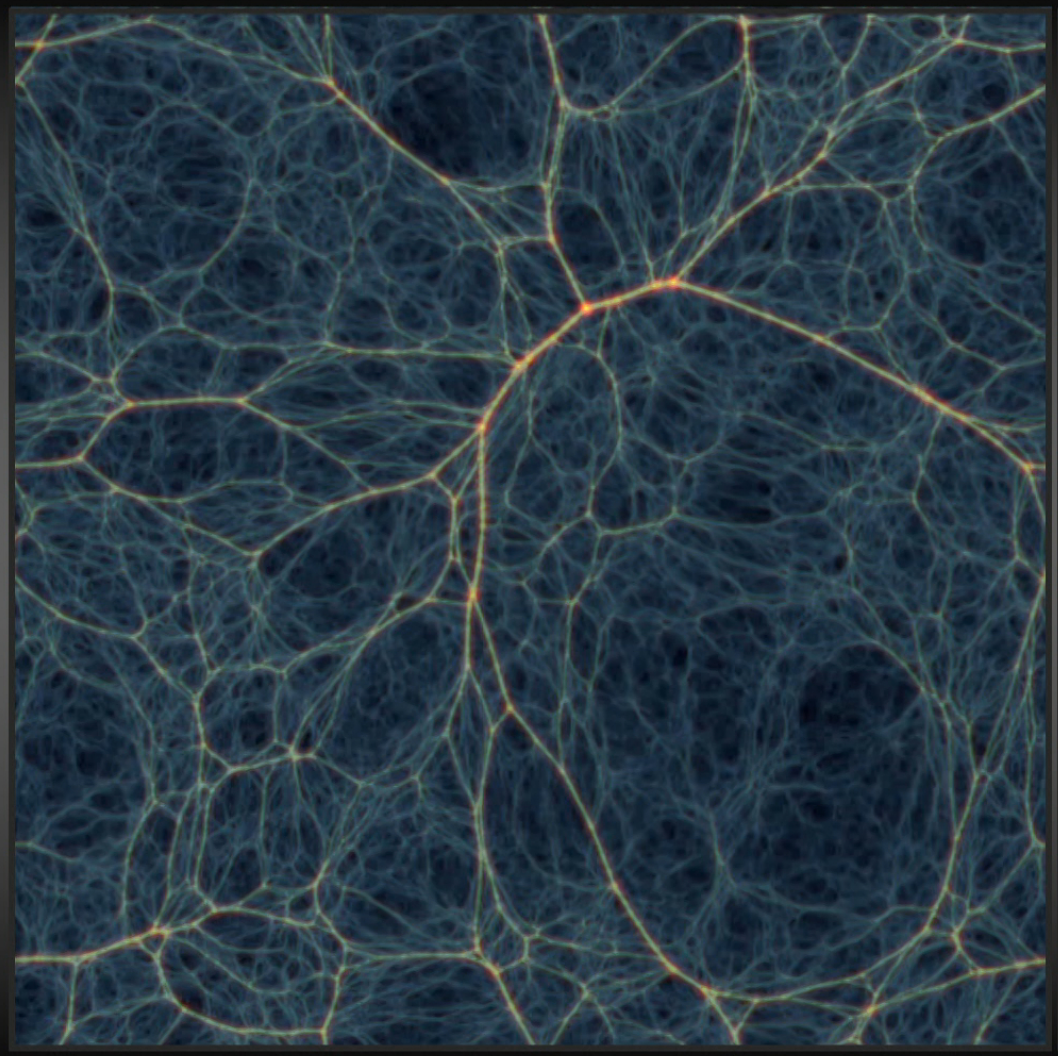
Eulerian vs. Lagrangian
weblike geometry



Lagrangian – Eulerian Cosmic Web

Delaunay- Voronoi Tessellations





Hierarchical Web Evolution:

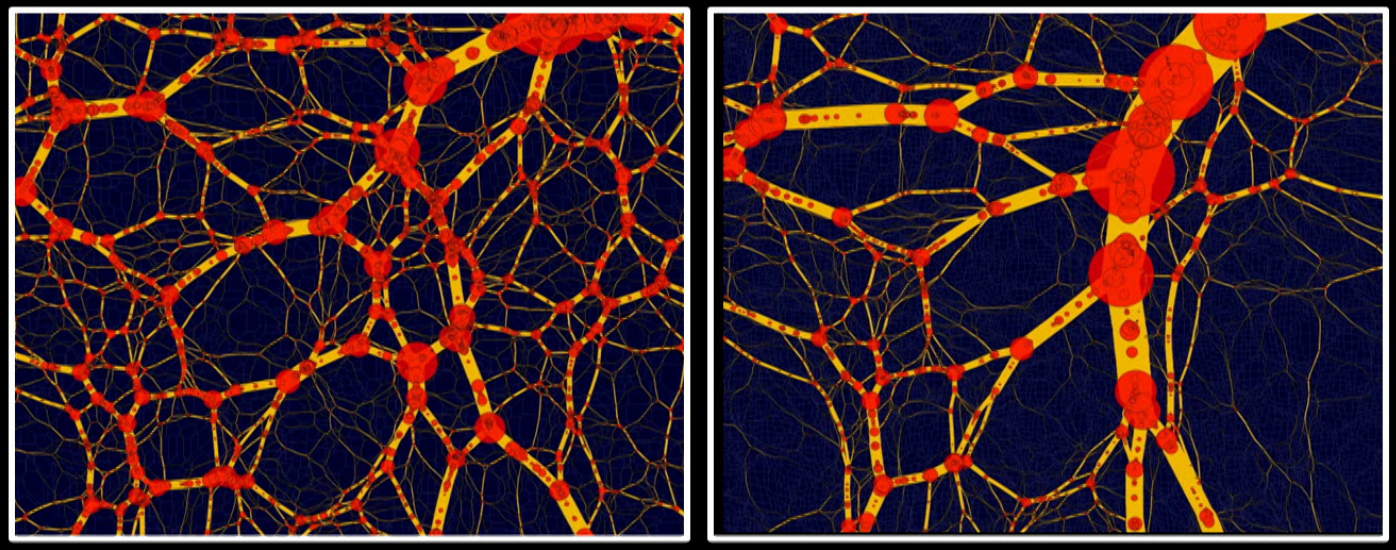
Adhesion simulation buildup Cosmic Web

Johan Hidding
2012

Cosmological Sensitivity Cosmic Web

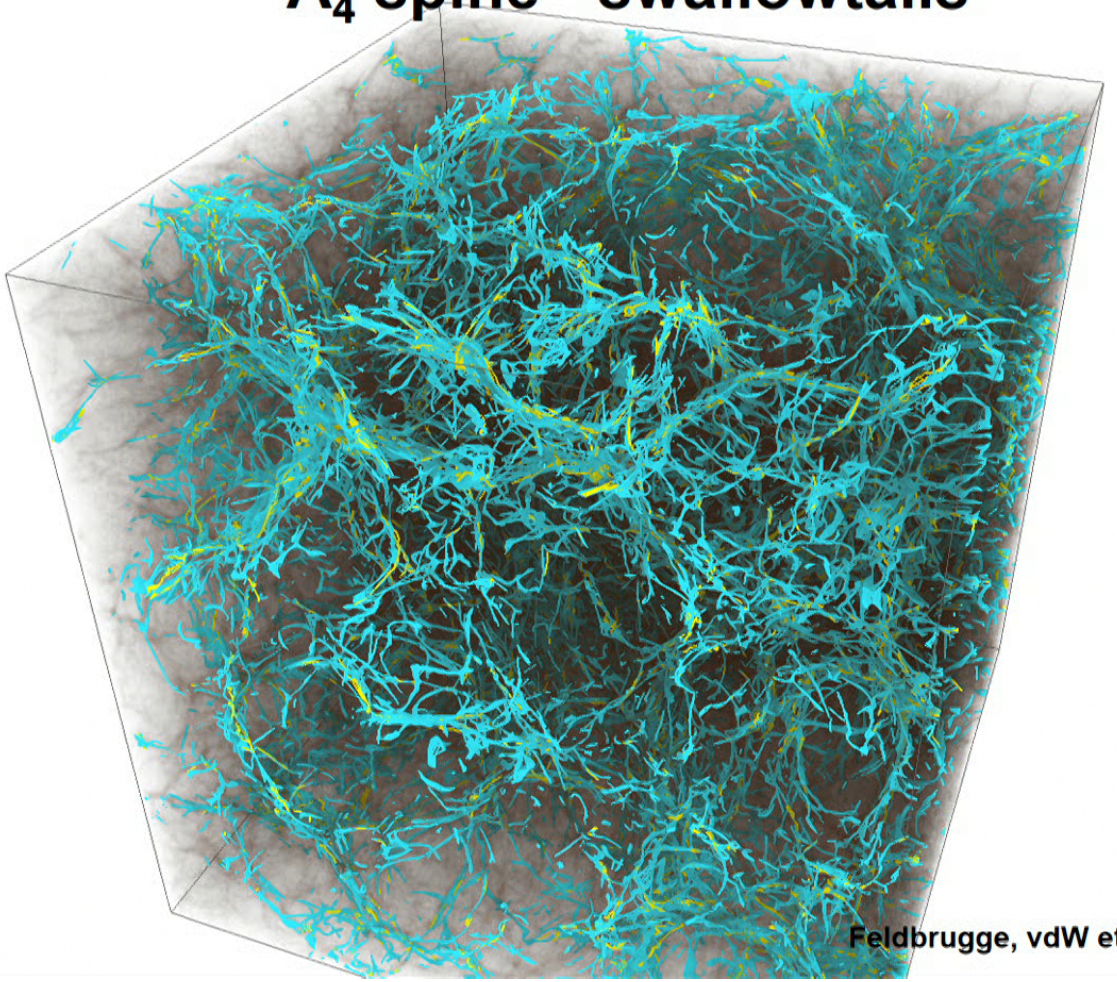
the morphology of the weblike network is
highly sensitive to the underlying cosmology

$P(k) \sim k^{-1.5}$ **Hidding 2012/2014** $P(k) \sim k^{-2.0}$



Skeleton (3D) Cosmic Web:

A_4 spine - swallowtails



Feldbrugge, vdW et al. 2017b