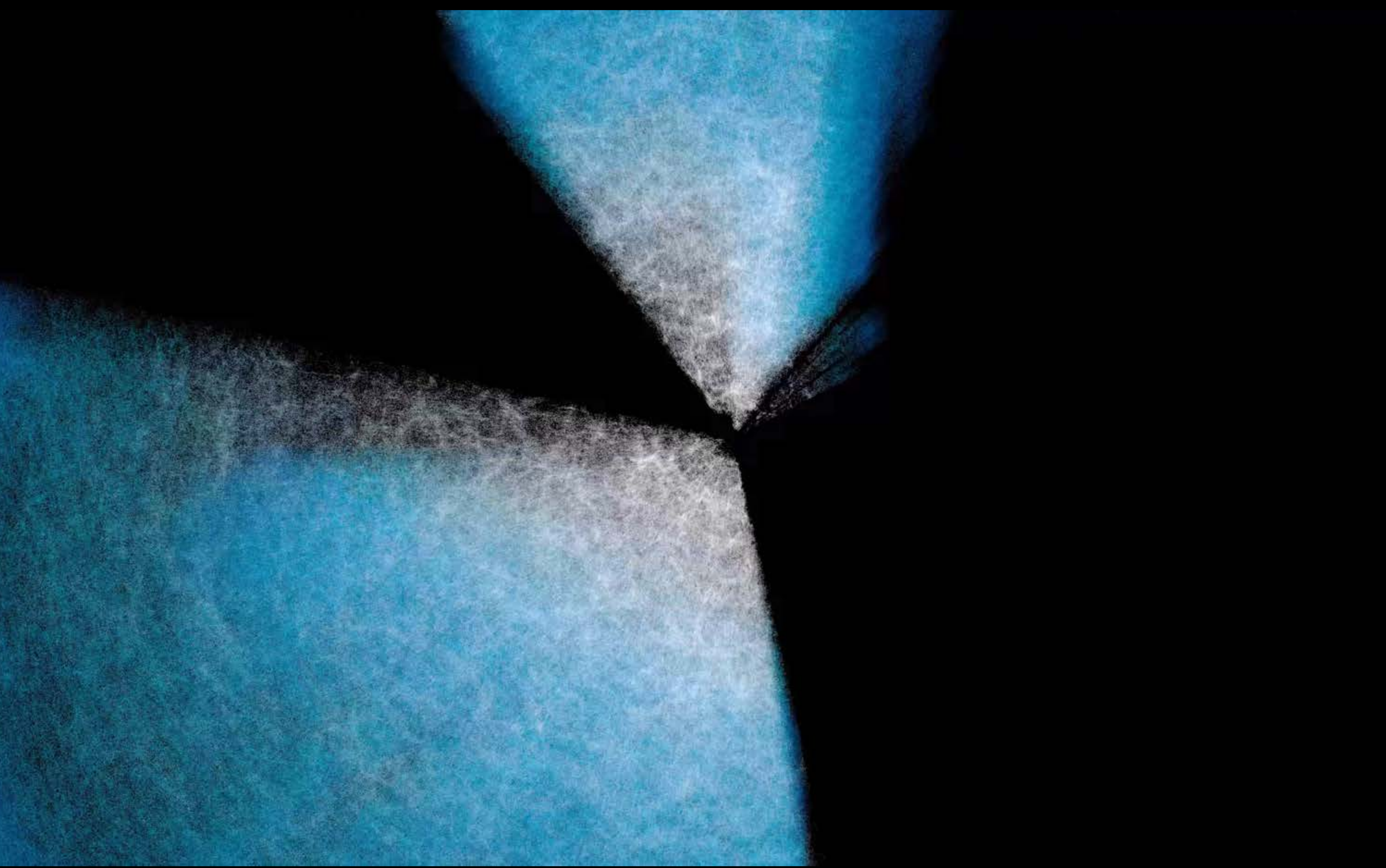
the Cosmic Web:

Lecture 1: setting the scene

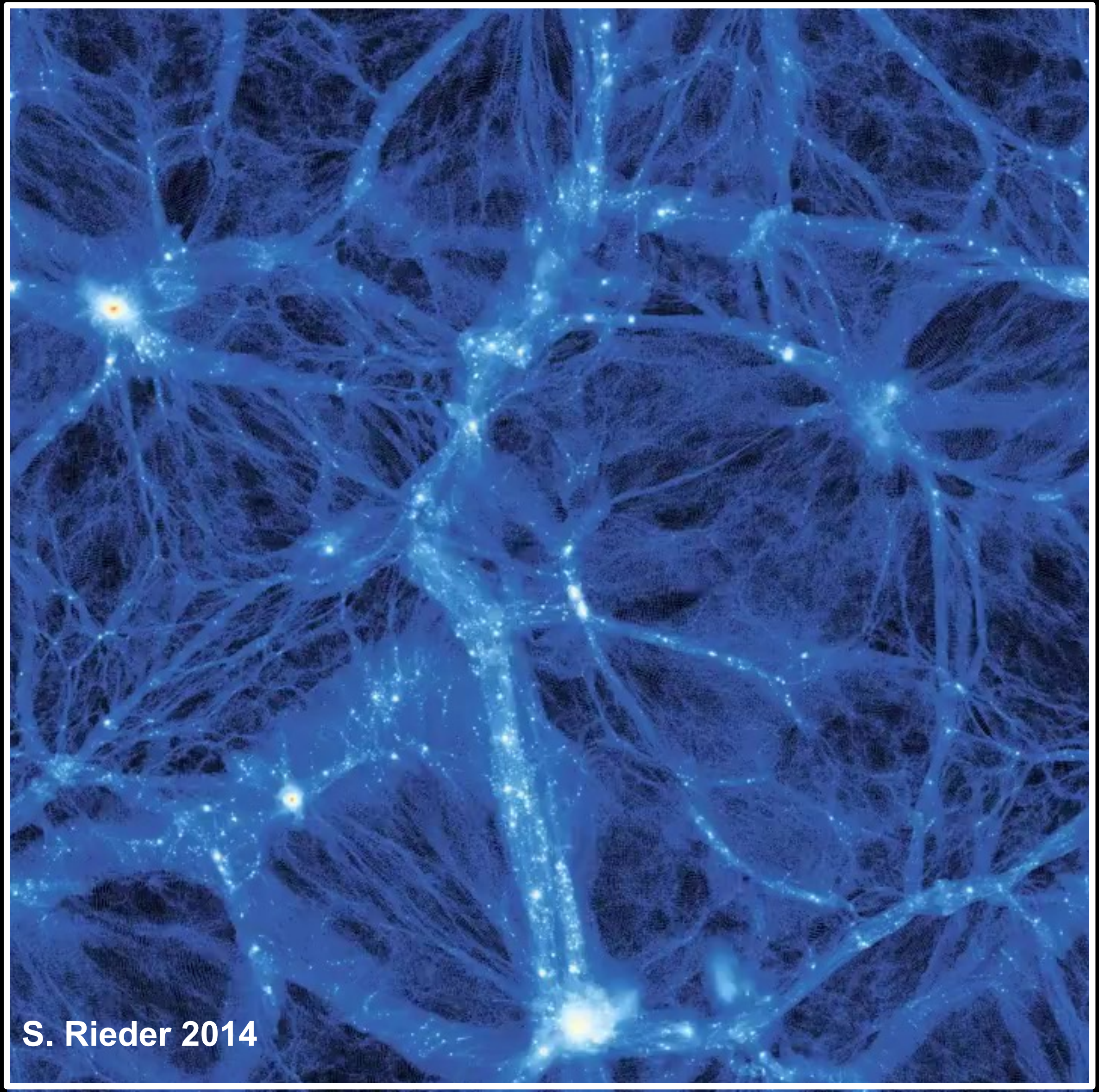
Rien van de Weijgaert
Excosm Cosmology Summerschool, Haapsalu, July 2025

Cosmic Web:
today's (DESI) view



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



on scales of ~5-100s Mpc

complex weblike pattern

in which
matter, gas & galaxies
aggregate in

- compact clusters,
- elongated filaments
- flattened sheets

around

- cosmic voids

Cosmic Web

Cosmic Web:

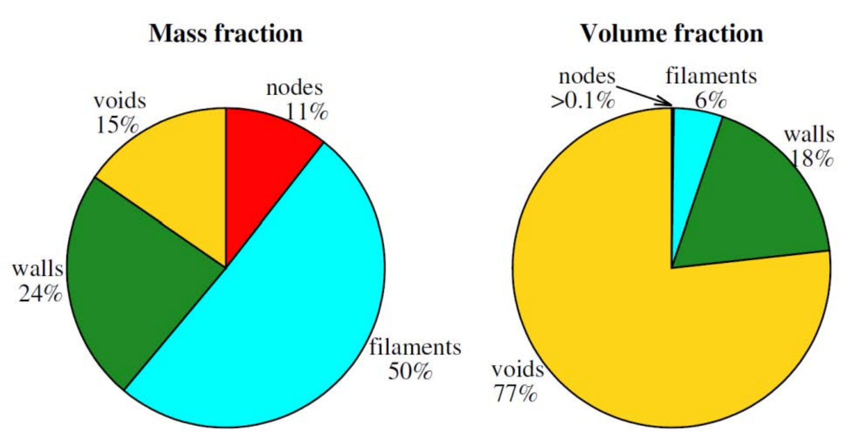
Density-Morphology Connection

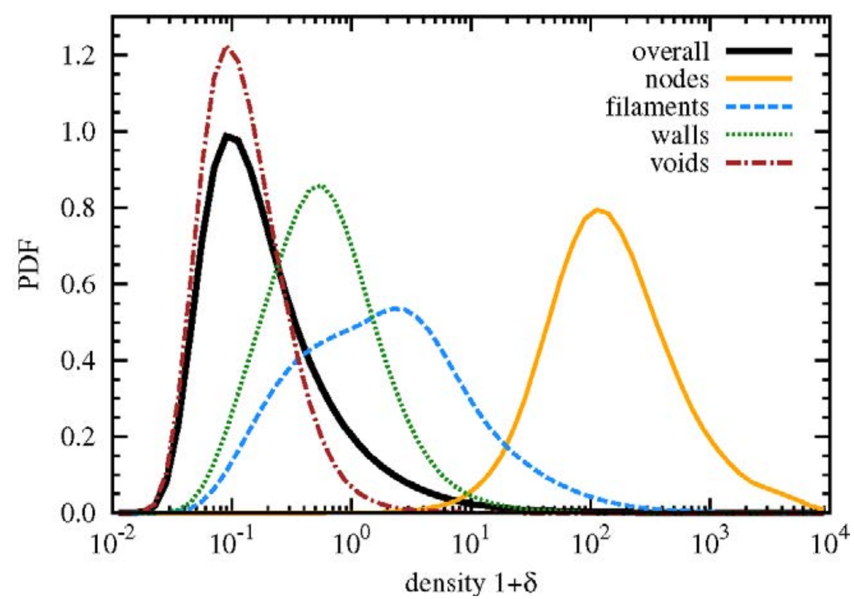
Mass & Volume content

Web morphologies

Density distribution

Individual morphologies





Cautun et al. 2014

Cosmic Web:

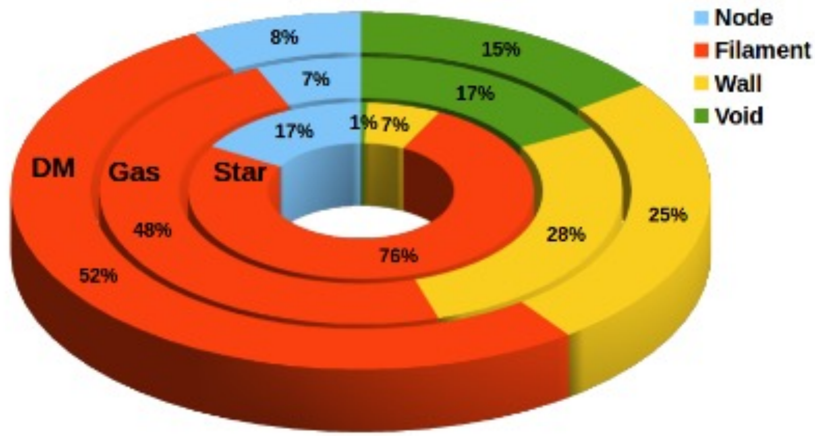
Density-Morphology Connection

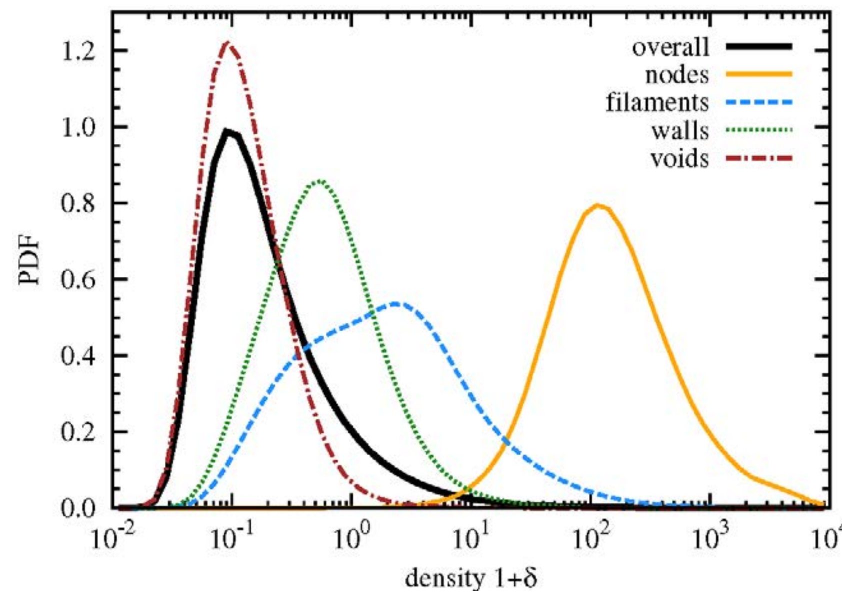
Mass & Volume fraction

Web structures

Mass density distribution

Web structures



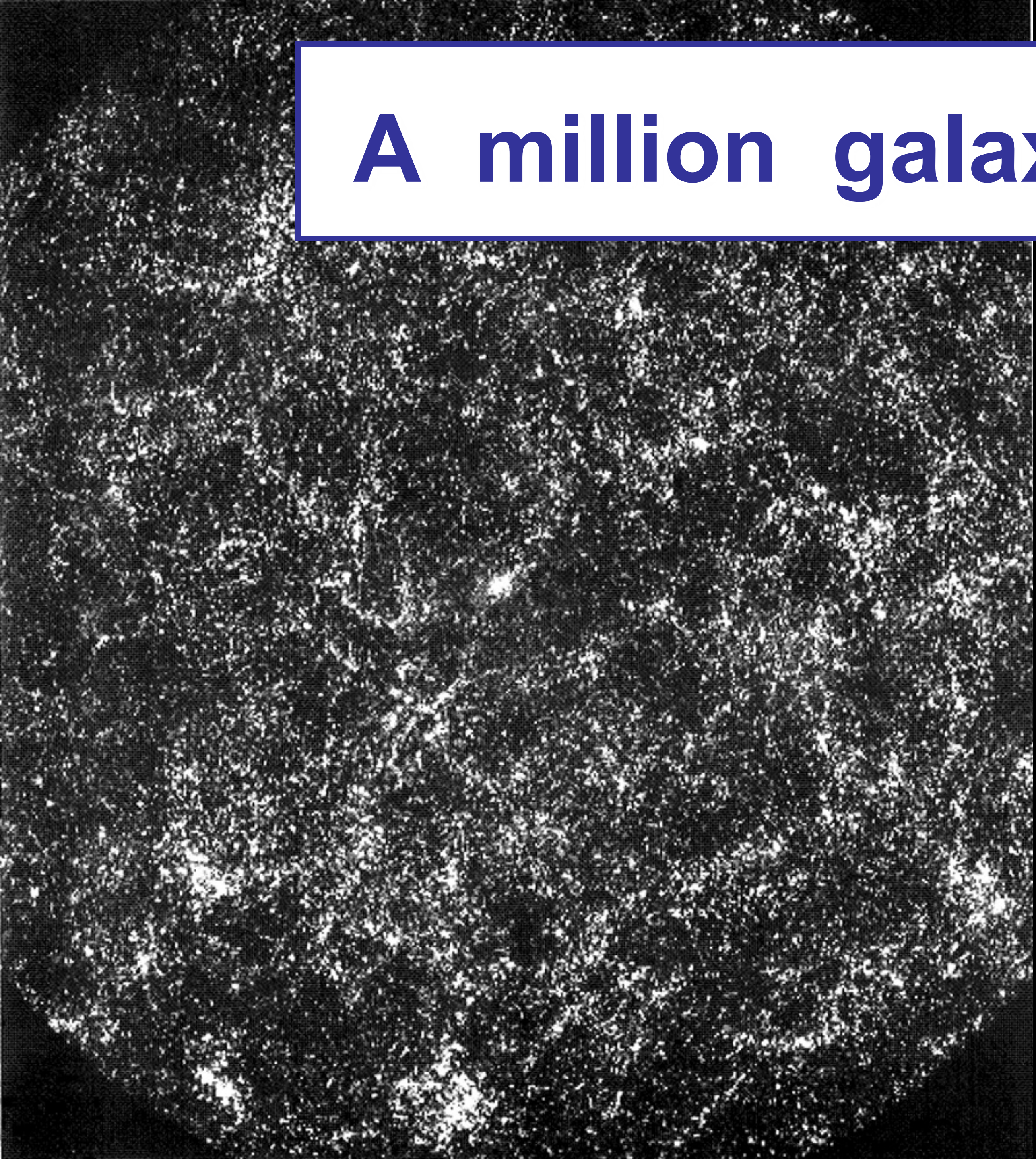


Cautun et al. 2014

Cosmic Web

Setting the Scene

A million galaxies



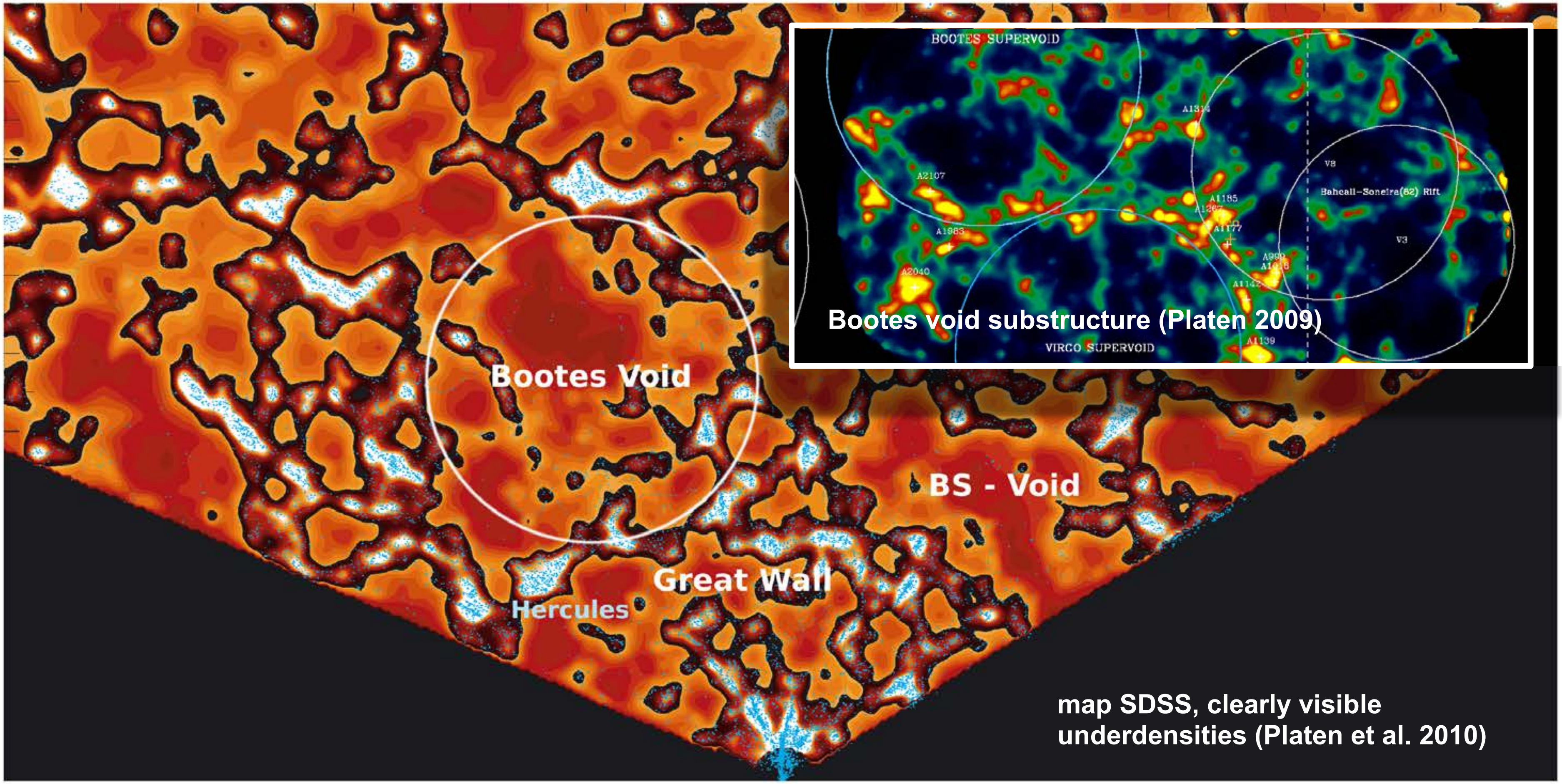
Shane-Wirtanen map:

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:

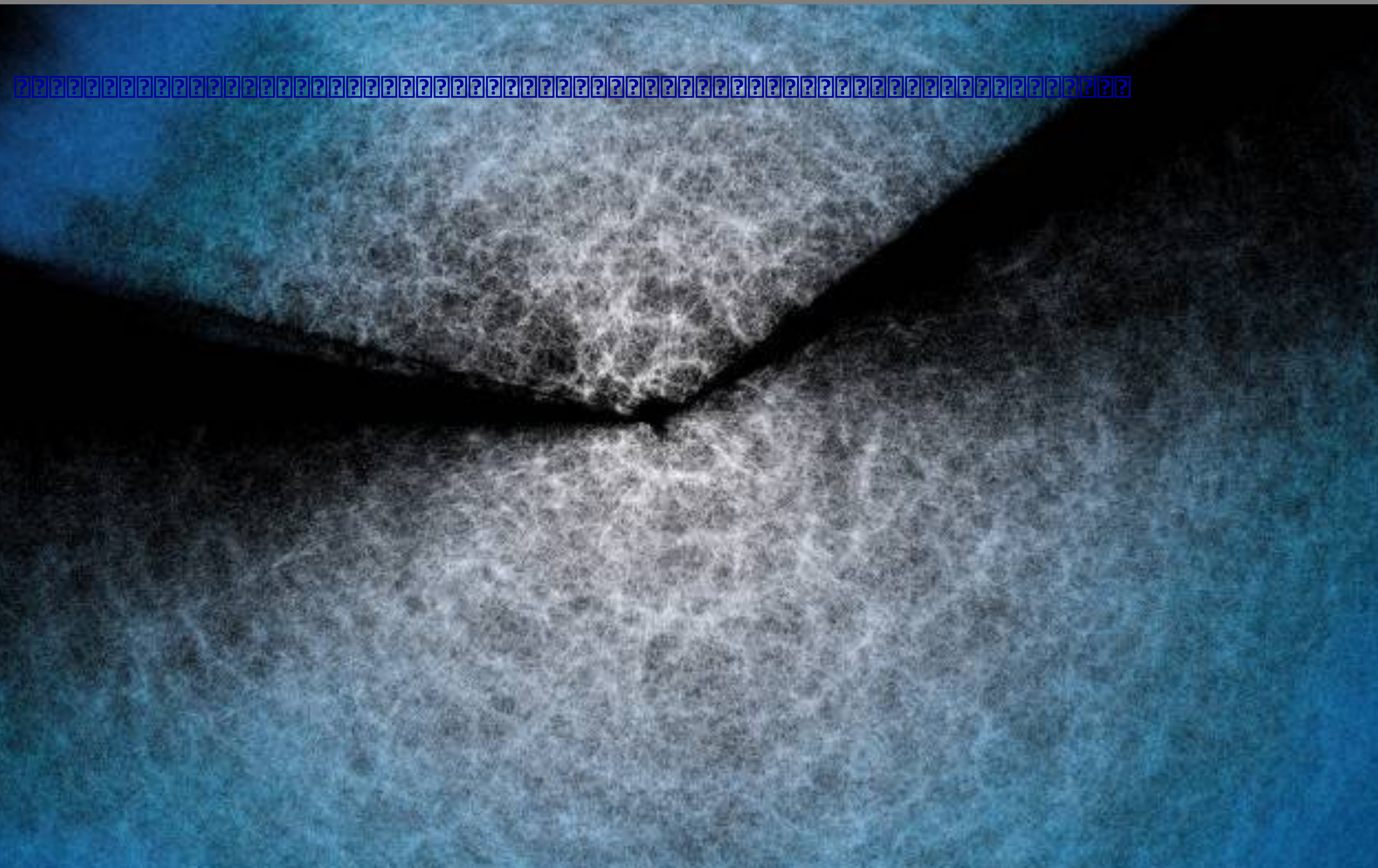
- Clearly visible are clusters
- hint of filamentary LSS features, embedding clusters

SDSS Galaxy Survey



with the advent of large galaxy redshift surveys
– LCRS, 2dFGRS, SDSS, 2MRS –
voids have been recognized as one of the quintessential components of the Cosmic Web

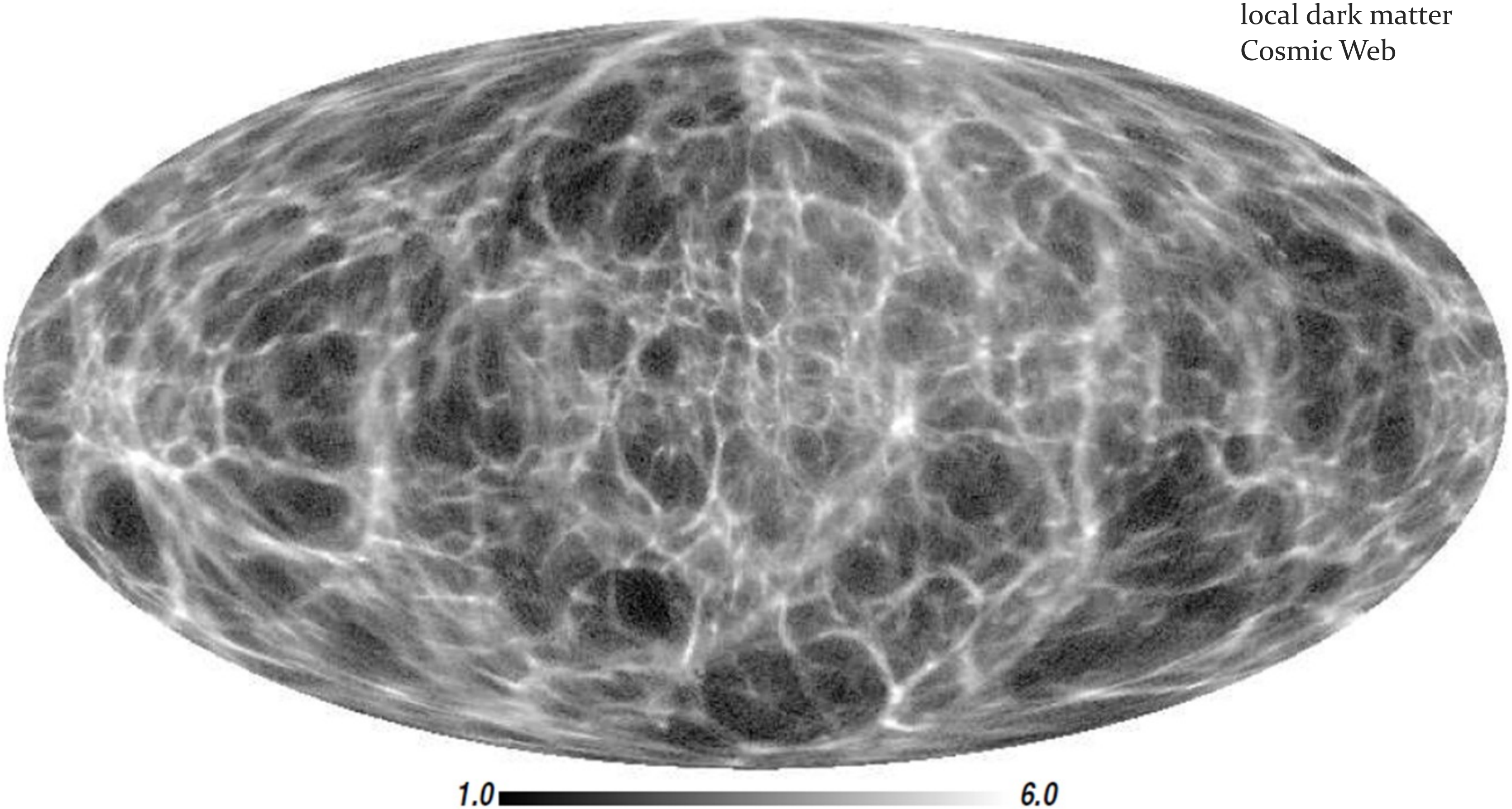
DESI Galaxy Survey



local DM Cosmic Web: 2MRS

most detailed reconstruction of the

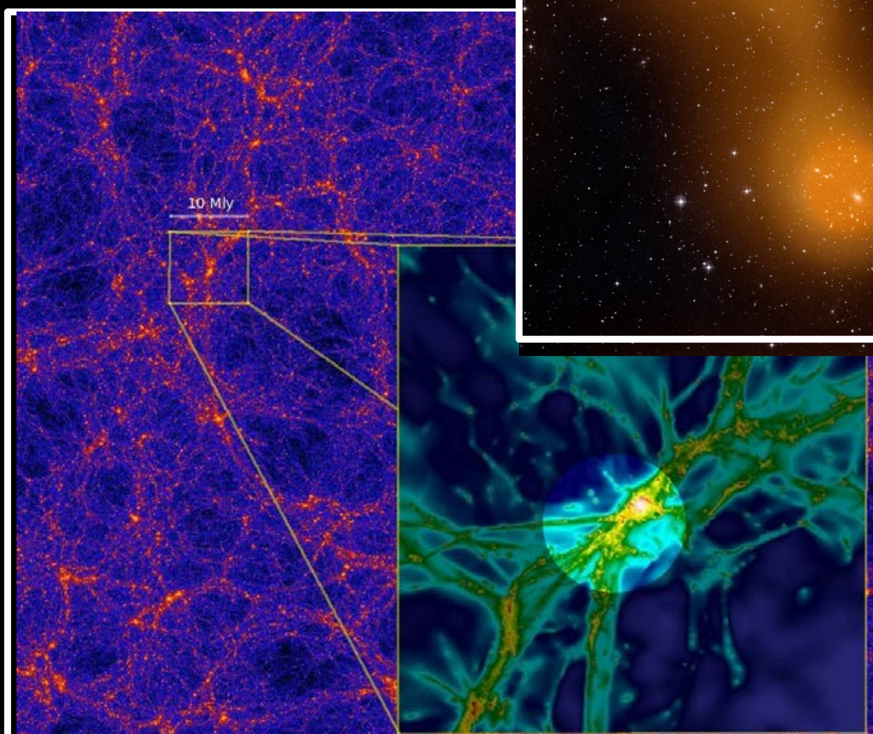
local dark matter Cosmic Web



Courtesy: Francisco Kitaura


Cosmic Web:
Dark Matter vs Gas
Illustris Simulation

the Gaseous Cosmic Web



Gaseous Cosmic Web:

Detection via:

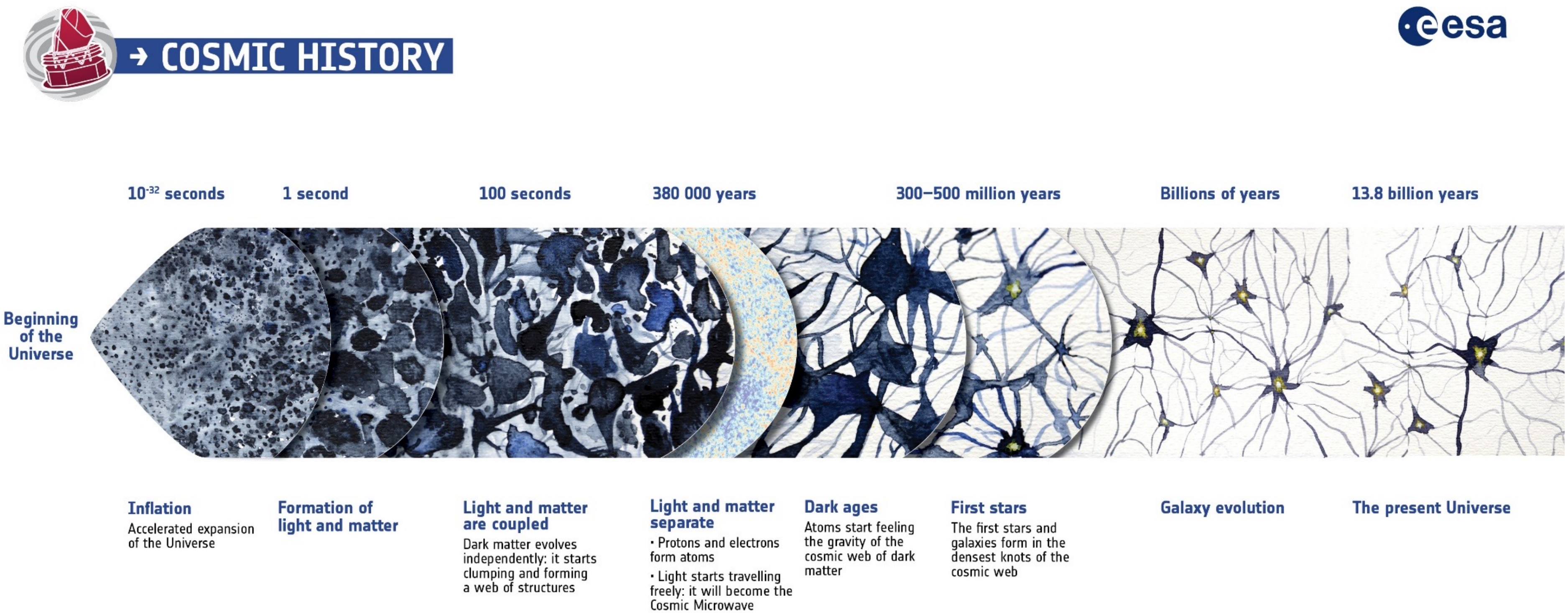
1) Lyα absorption (Lyα forest)
   - neutral hydrogen (cloud)
   - mostly at high redshift
   - absorption against quasar los.
   - possible use as tomographic tool

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)

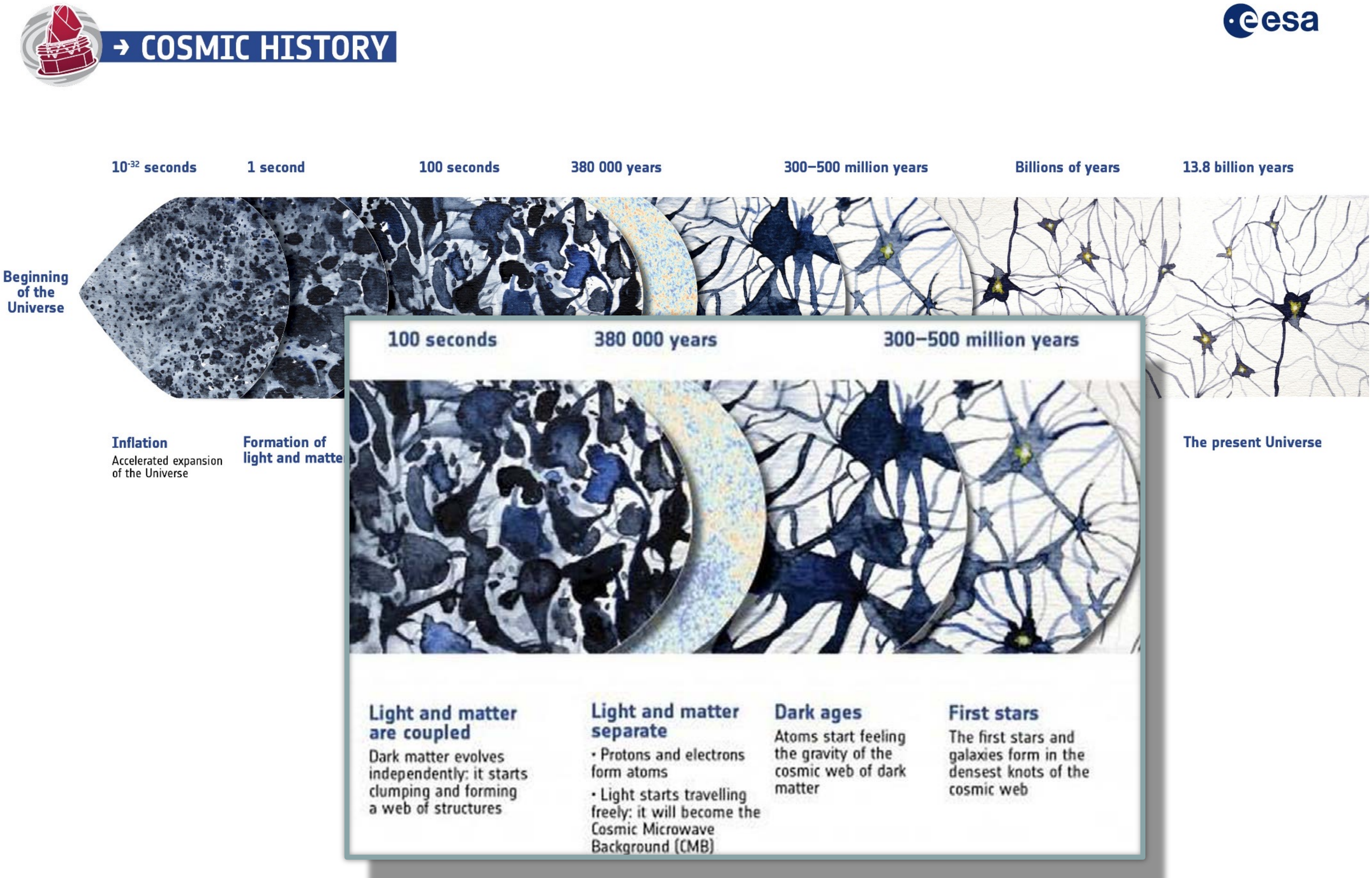
3) Sunyaev-Zeldovich scattering filaments
   - inverse Compton scattering CMB photons against hot electrons in ICM/IGM
   - has been seen in Planck (80 filam.):
   - bridges between clusters

Cosmic Web
in
Cosmic History

Cosmic Web in Cosmic History



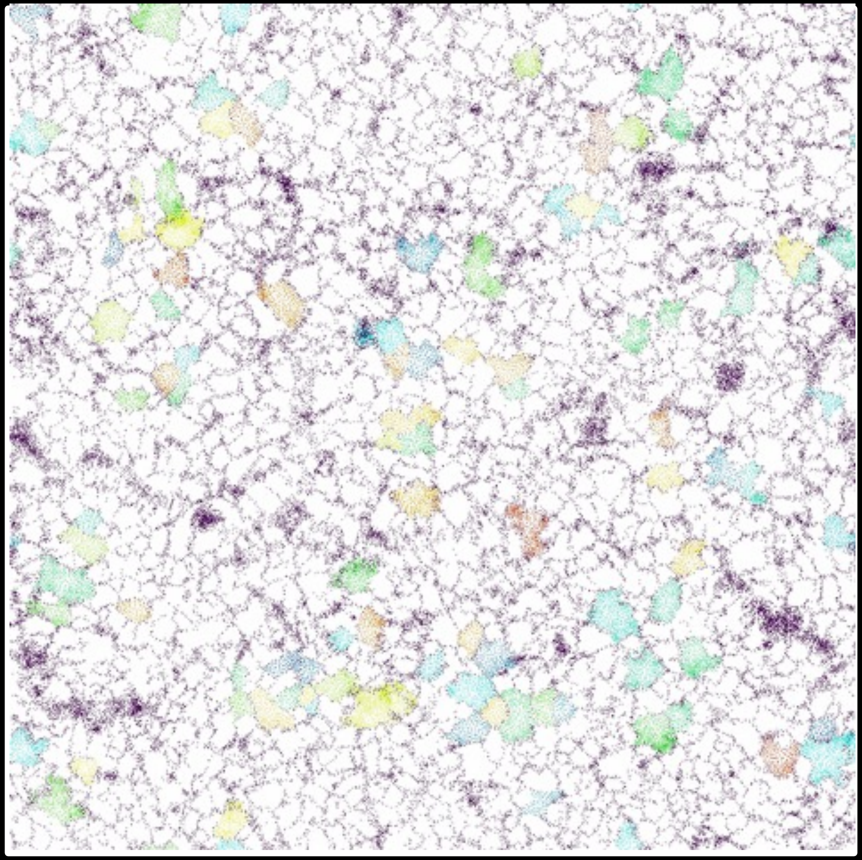
Cosmic Web at Cosmic Dawn

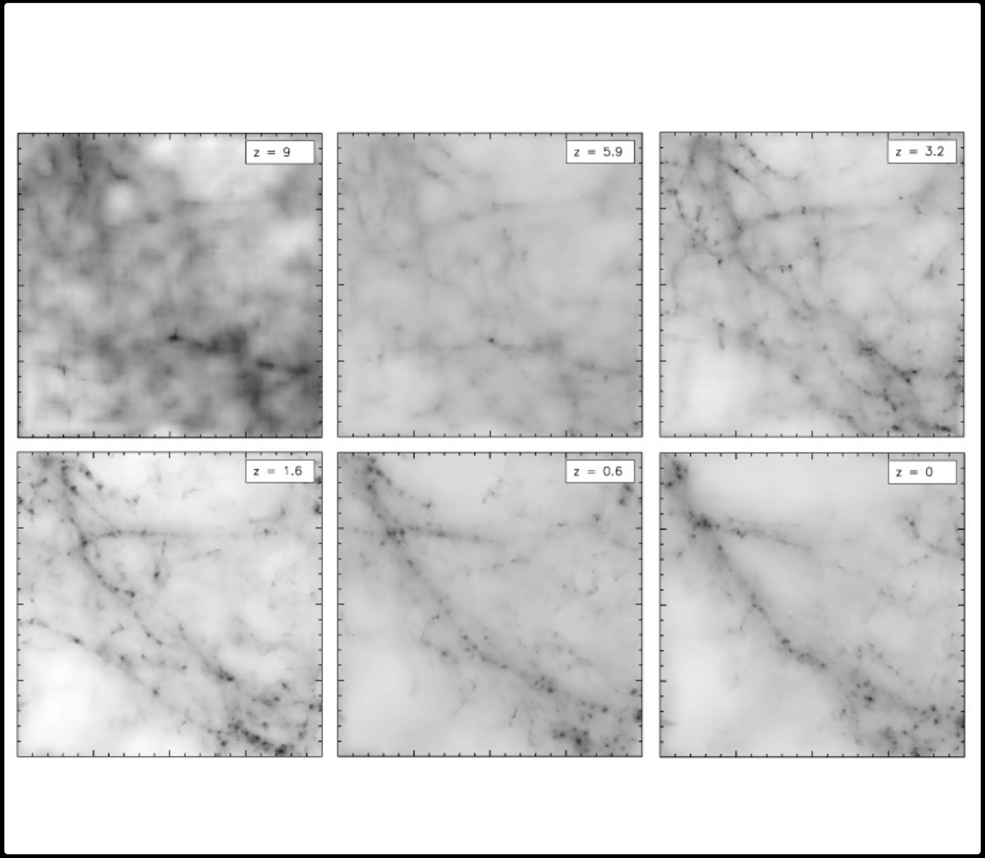


Cosmic Web in Later Universe

Hierarchical Buildup Cosmic Web

Adhesion formalism allows the geometric modelling of the hierarchical buildup of the cosmic web





Platen & vdW 2004
Sheth & vdW 2004
Aragon-Calvo & Szalay 2012

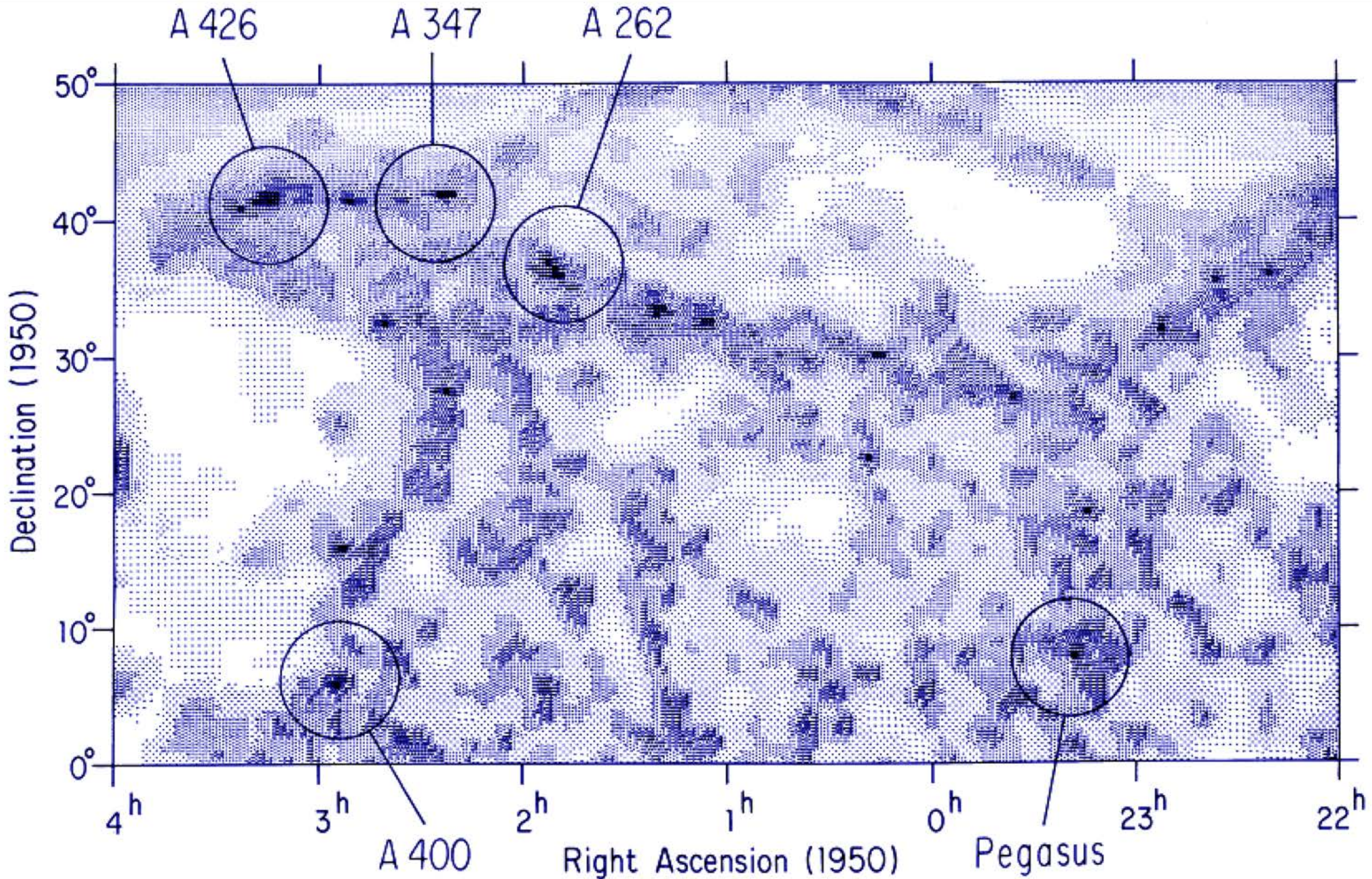
Hierarchy of Voids

Hierarchy of Filaments
Aragon-Calvo 2007

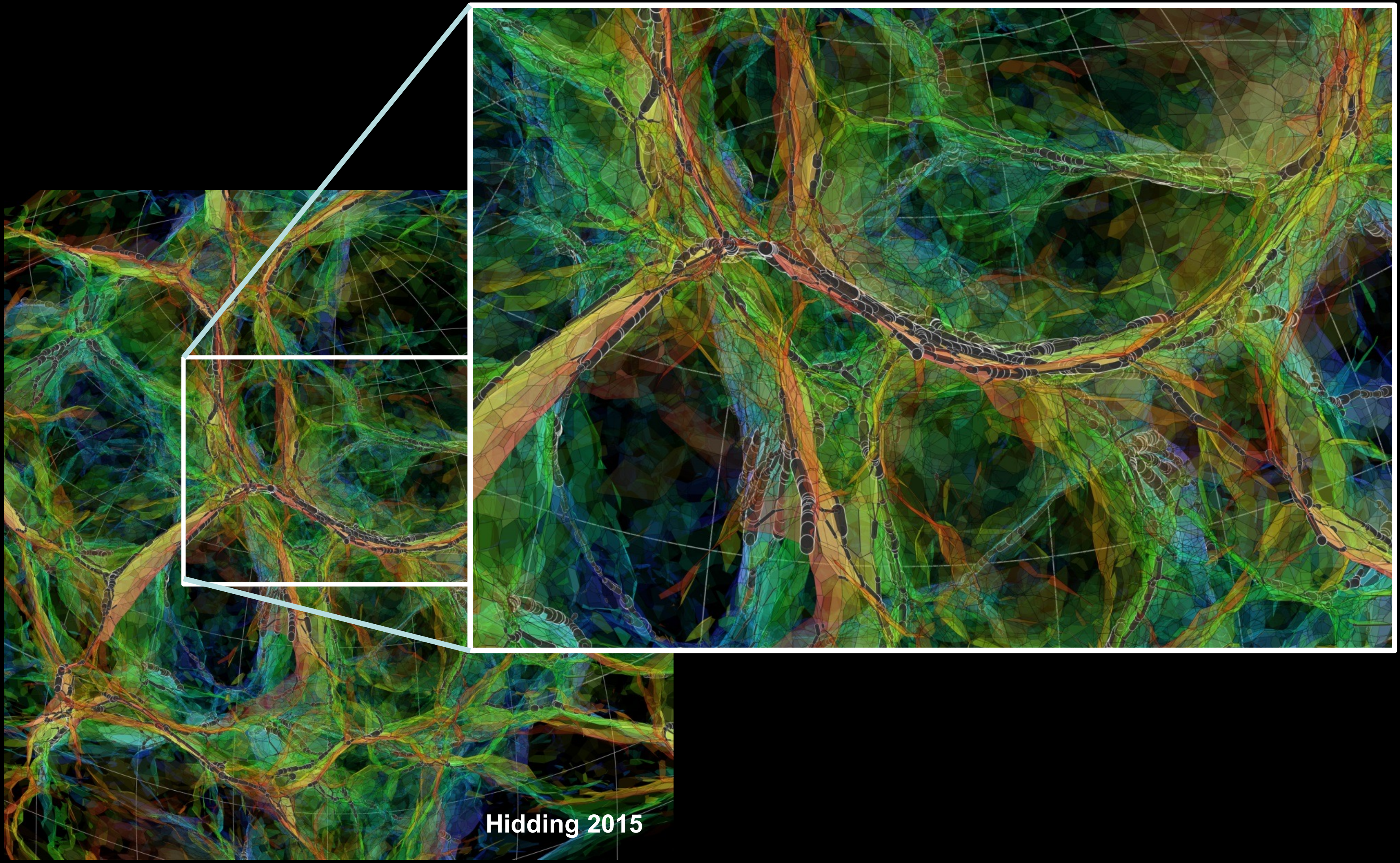
Cosmic Web

Characteristics

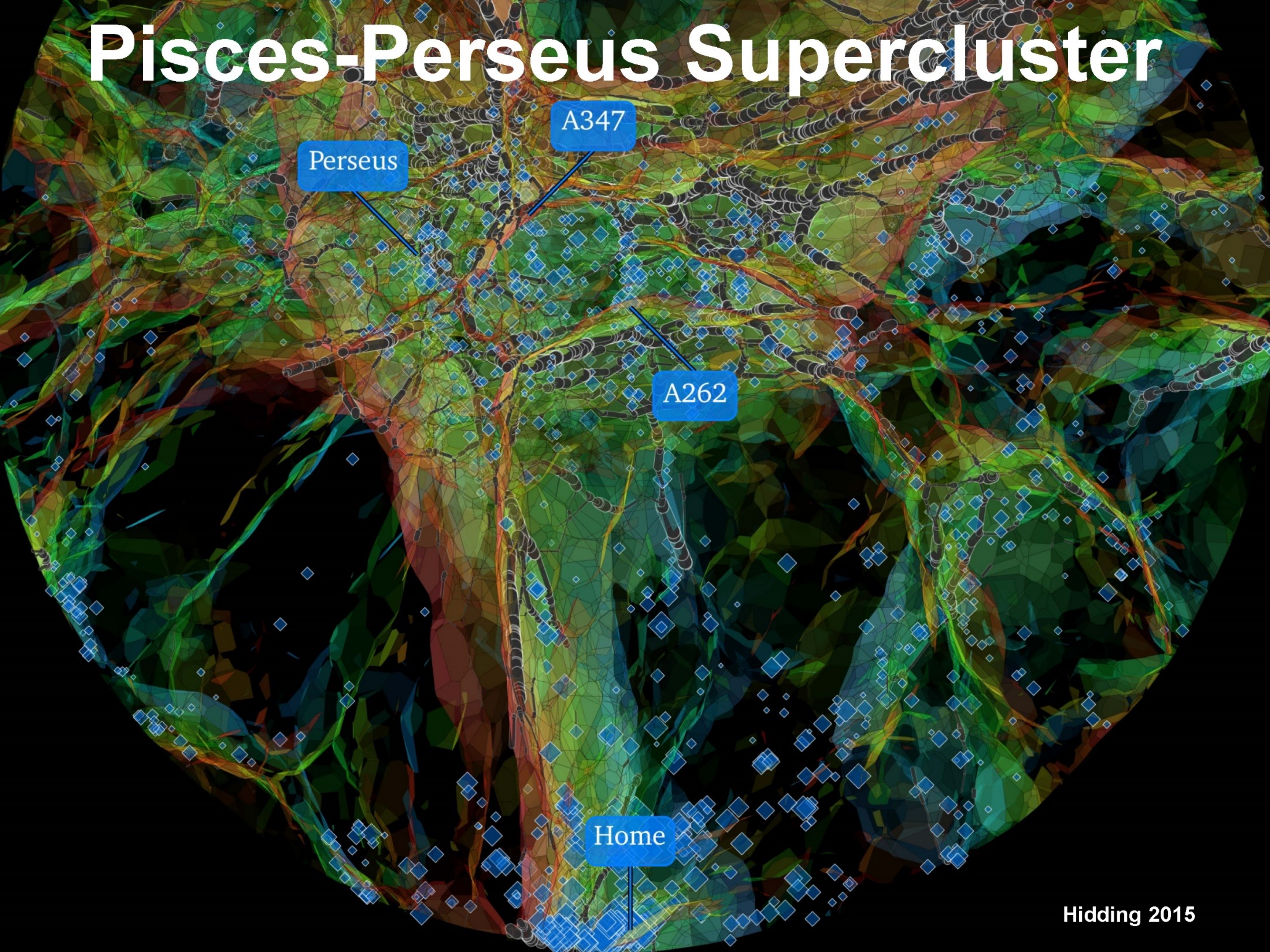
Pisces-Perseus Supercluster



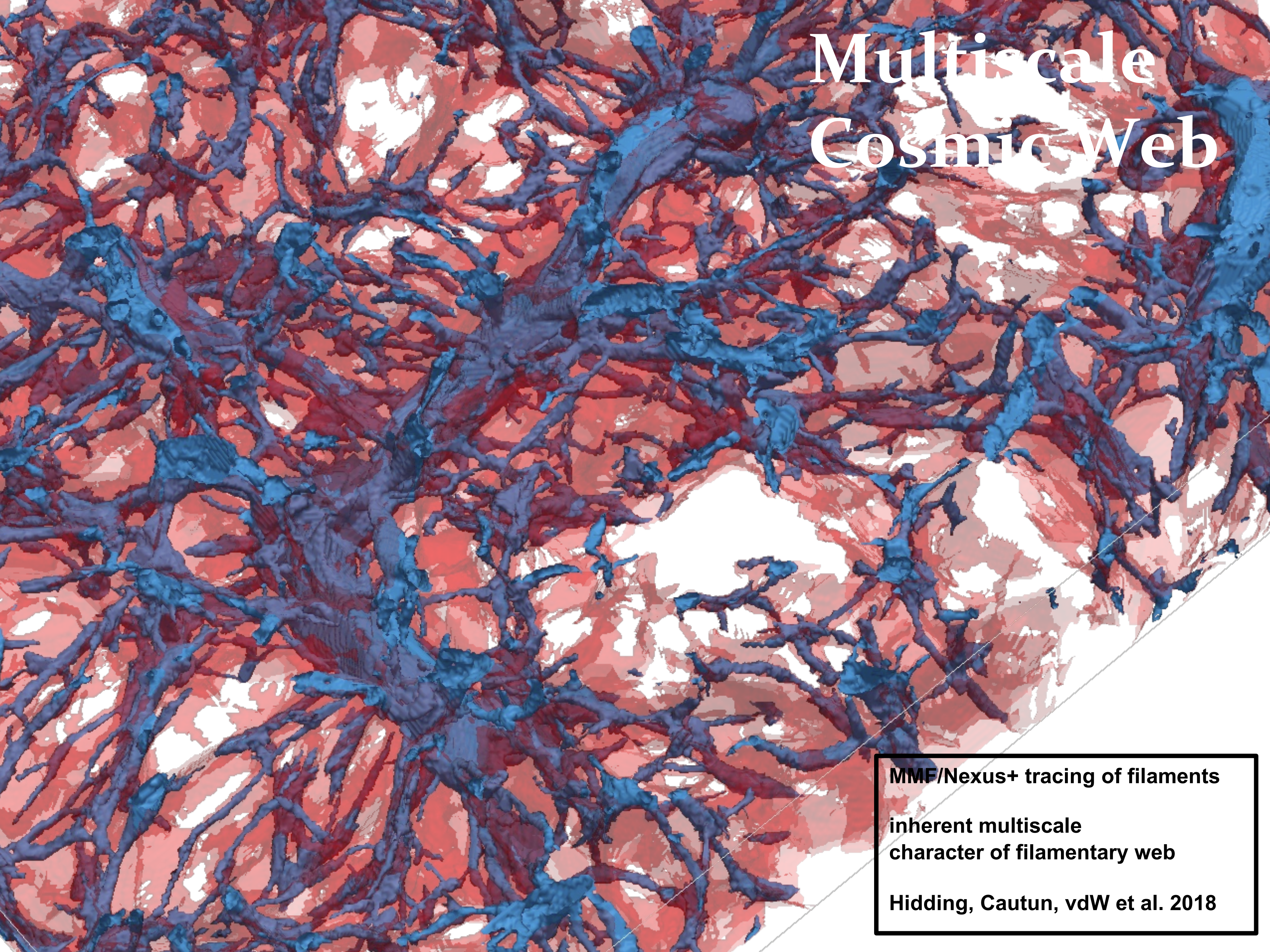
Pisces-Perseus Supercluster

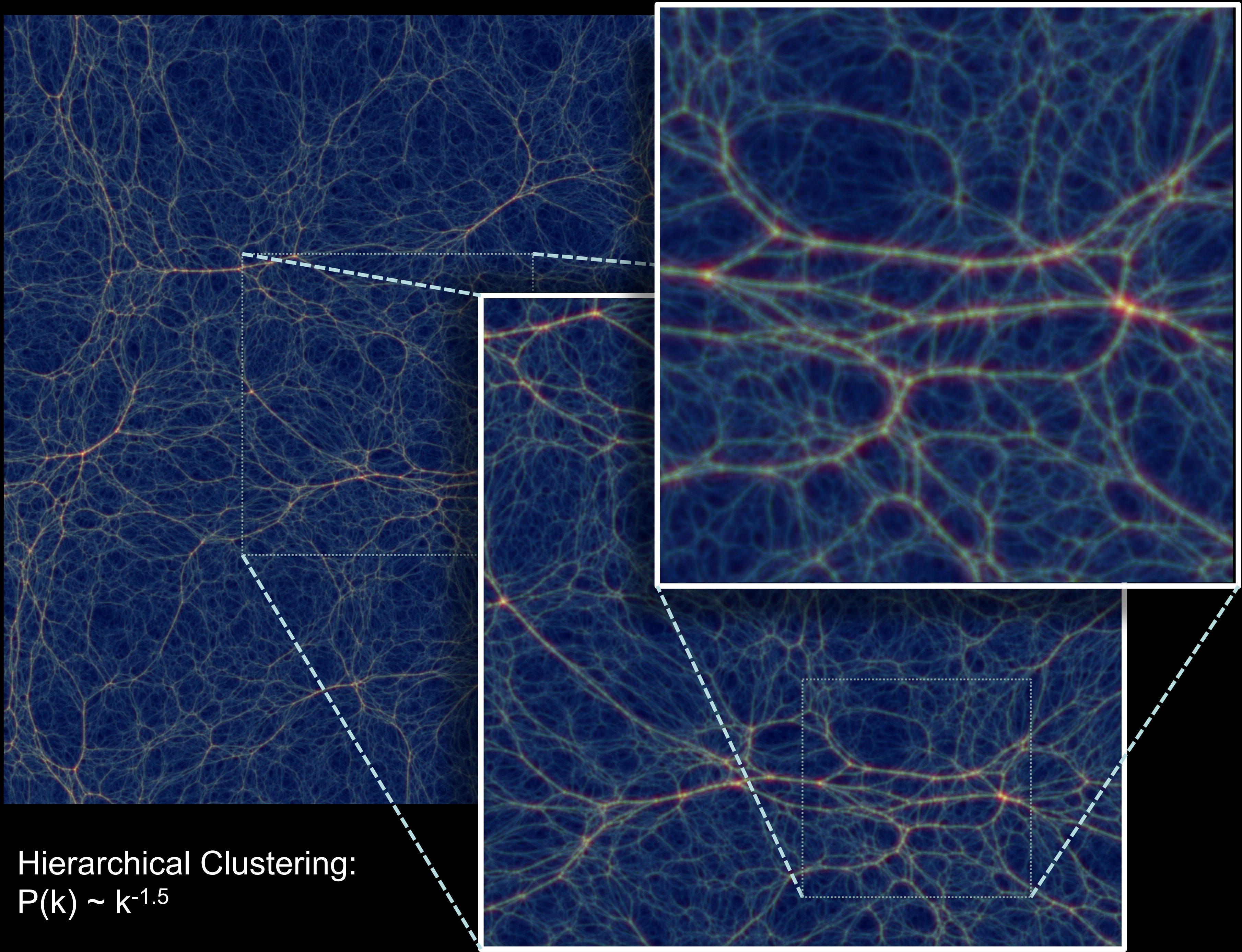


Pisces-Perseus Supercluster



Hidding 2015


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

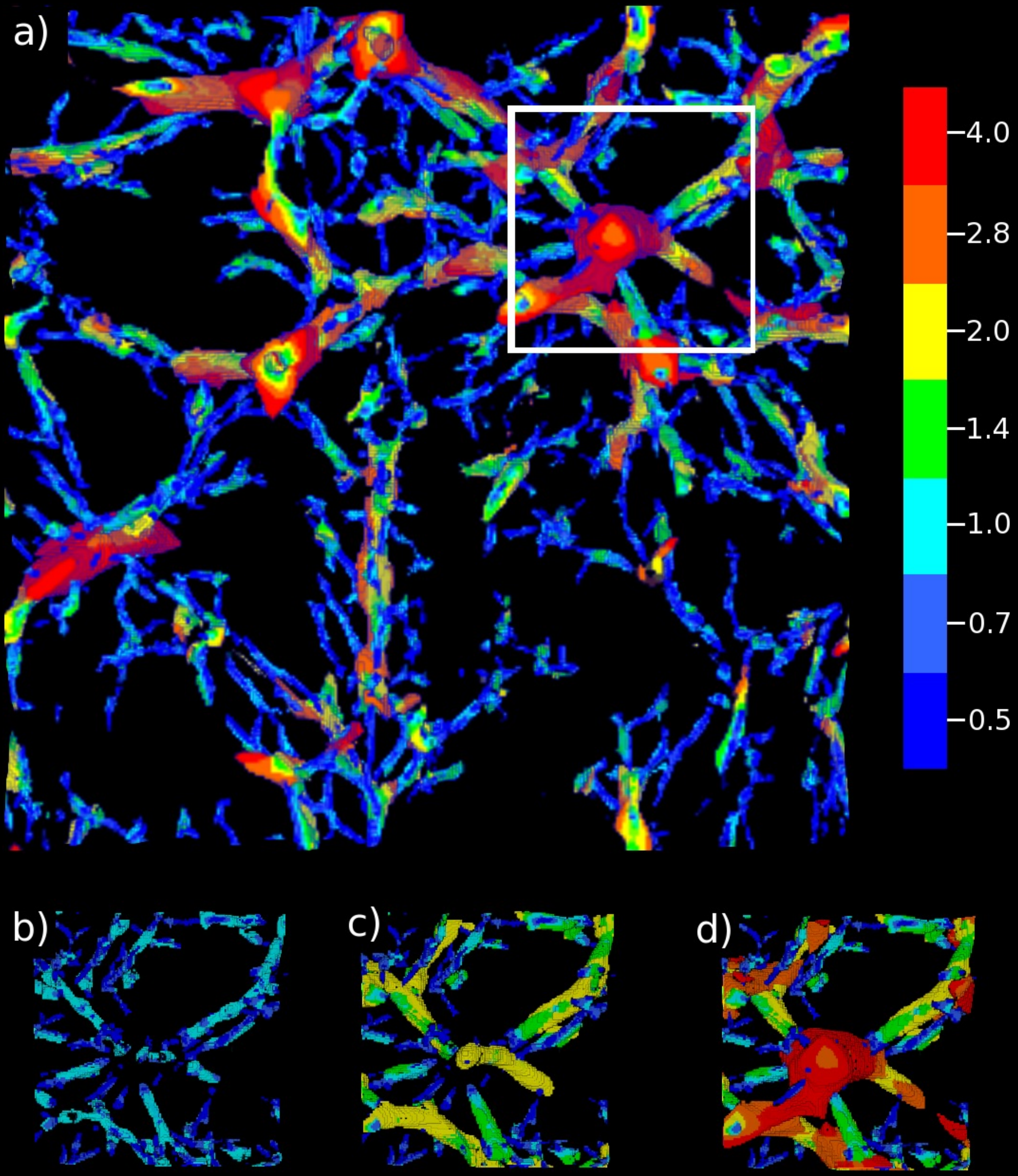


Hierarchical Clustering:
$P(k) \sim k^{-1.5}$

Nexus:

Multiscale
Morphology
Identification

Filaments



Colouring :
Local scale filament

Cosmic Voids

- Voids are prominent aspects of the Cosmic Web, instrumental in spatial organization of the Megaparsec Universe.

  Sheth & van de Weygaert 2004
  Hidding, van de Weygaert, Kitaura & Hess 2015

- Voids contain significant amount of information on global cosmological parameters:
  - void outflow: dark matter
  - void shapes: dark energy
  - supervoids: existence

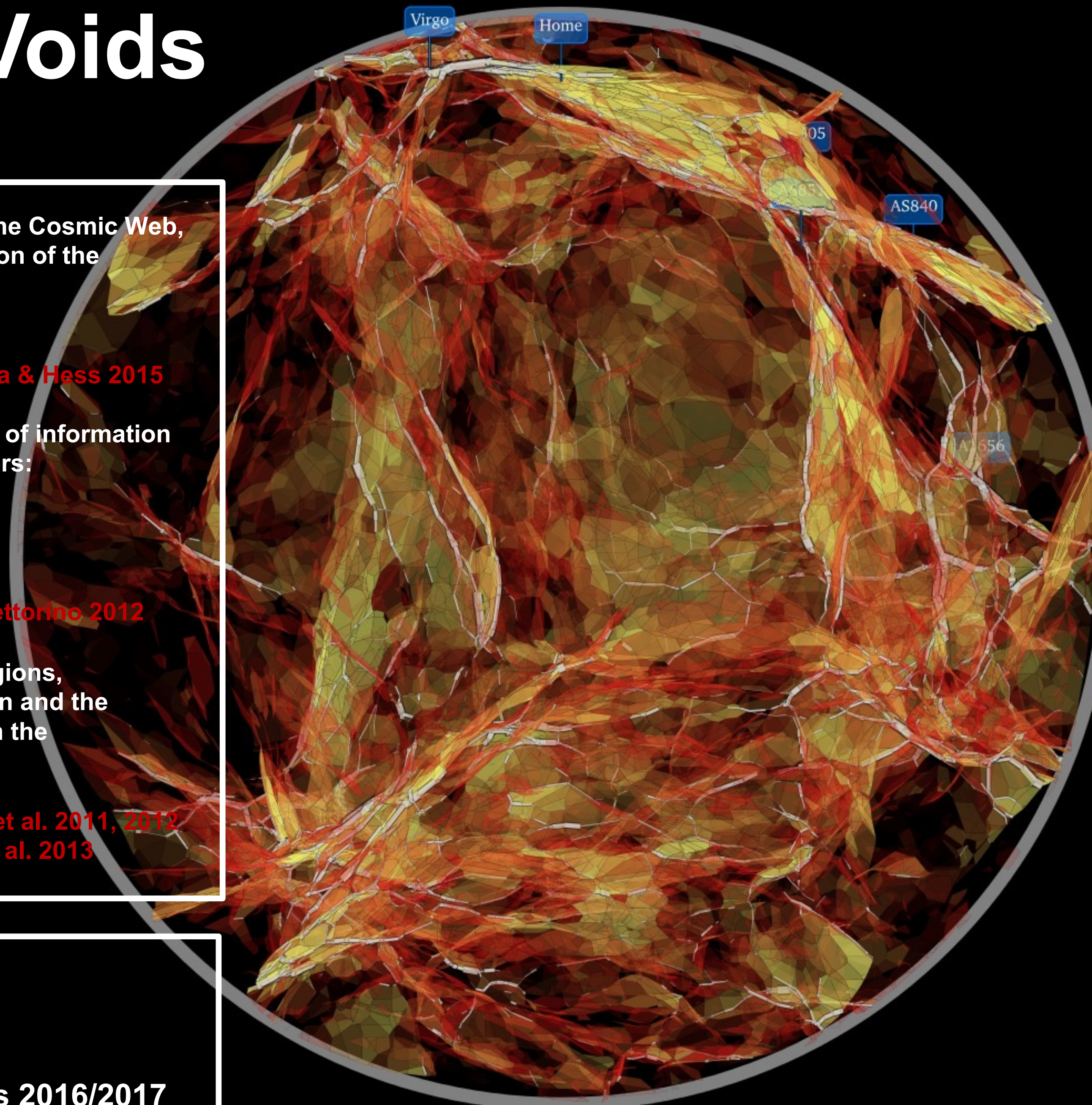
  Bos, van de Weygaert, Dolag & Pettorino 2012

- Voids are pristine low-density regions, ideal for studying galaxy formation and the effects of cosmic environment on the formation of galaxies.

  Void Galaxy Survey: Kreckel et al. 2011, 2012
  Beygu et al. 2013

Local Void

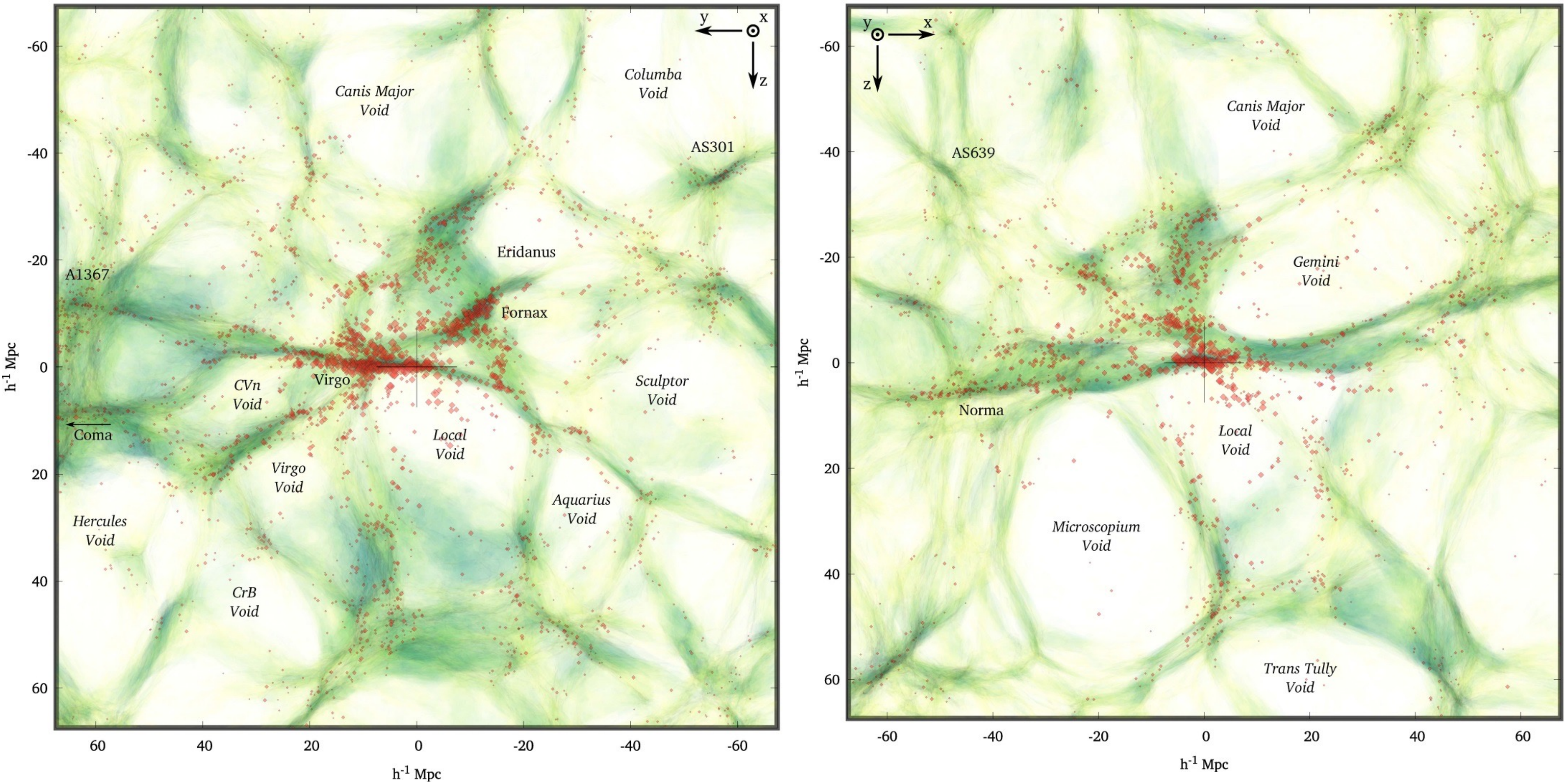
Reconstruction:
Hidding, vdW, Kitaura & Hess 2016/2017



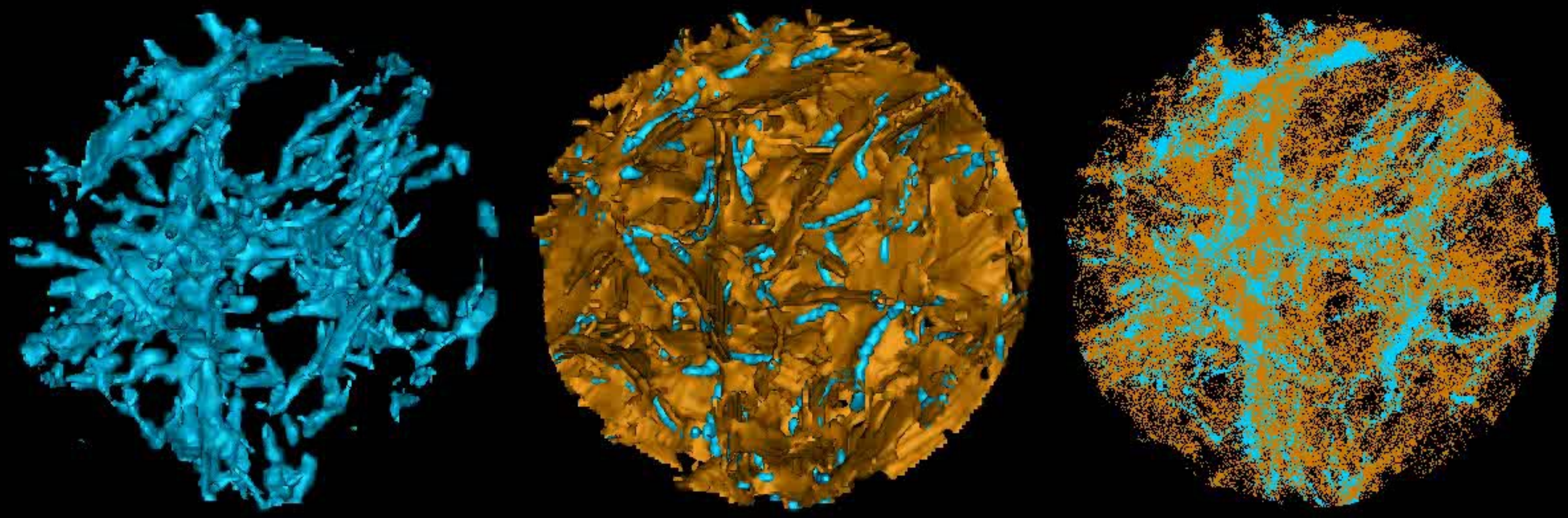
Void Population Local Universe

mean KIGEN-adhesion reconstruction (2MRS)

Hidding, Kitaura, vdW & Hess 2016/2017



Cosmic Web: Connectivity



MMF/Nexus
Cautun et al. 2013, 2014

Stochastic Spatial Pattern

- Clusters,
- Filaments &
- Walls

around

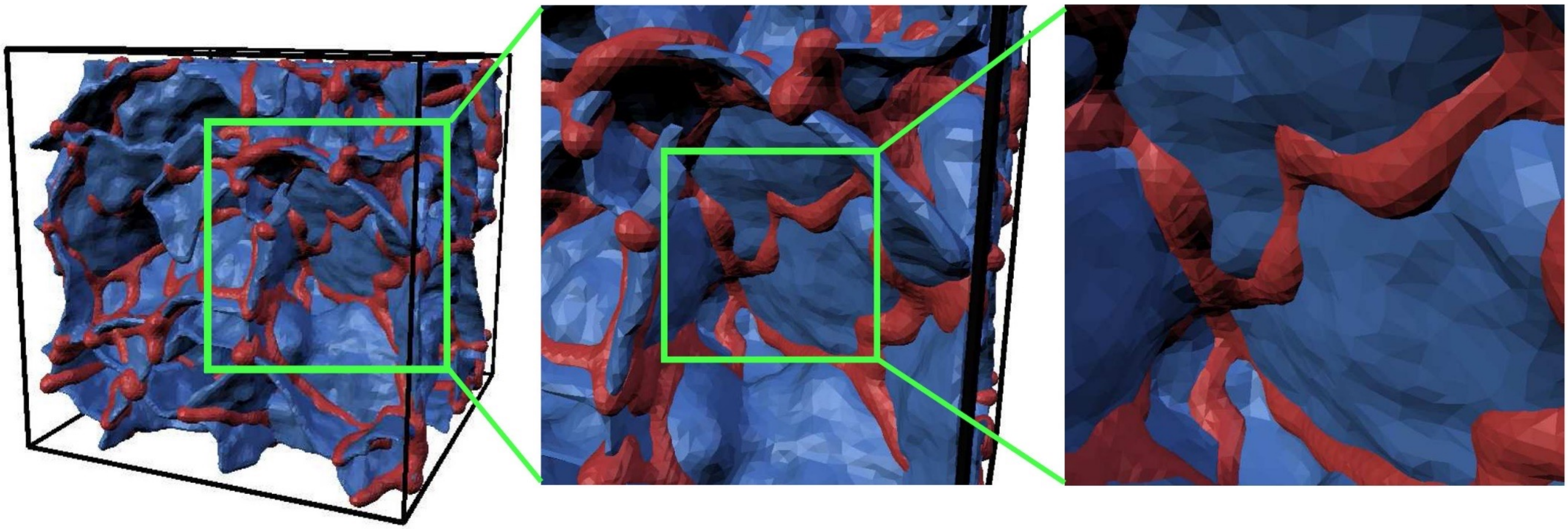
- Voids

in which matter & galaxies

have agglomerated

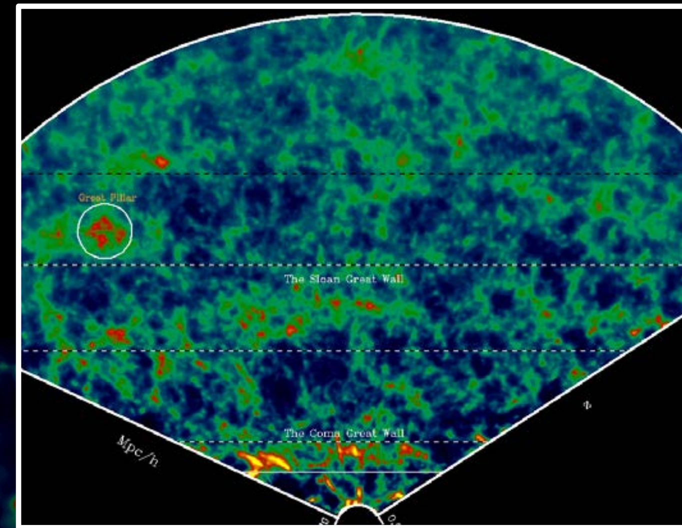
through gravity

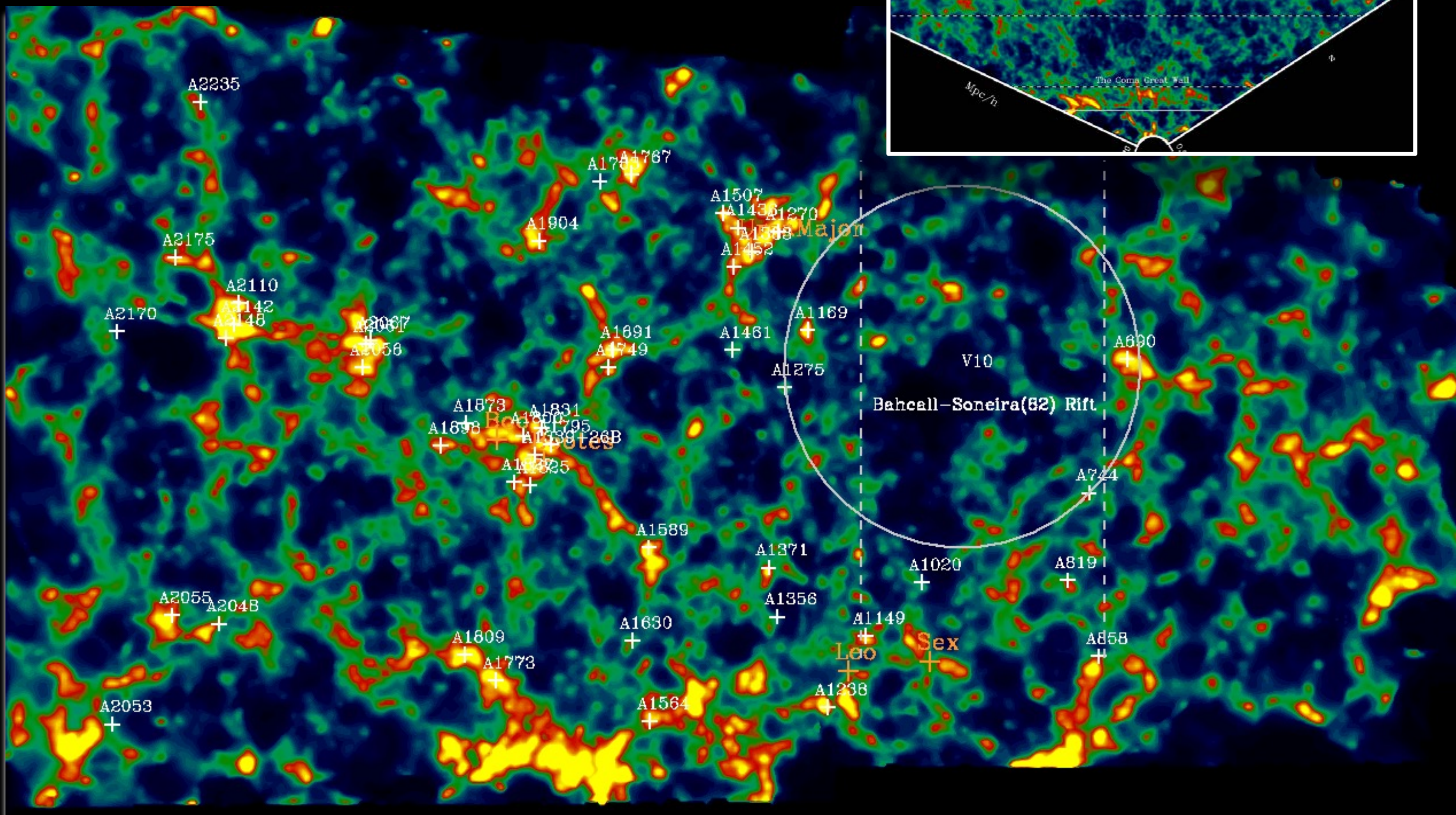
the Network:
Walls – Filaments - Nodes



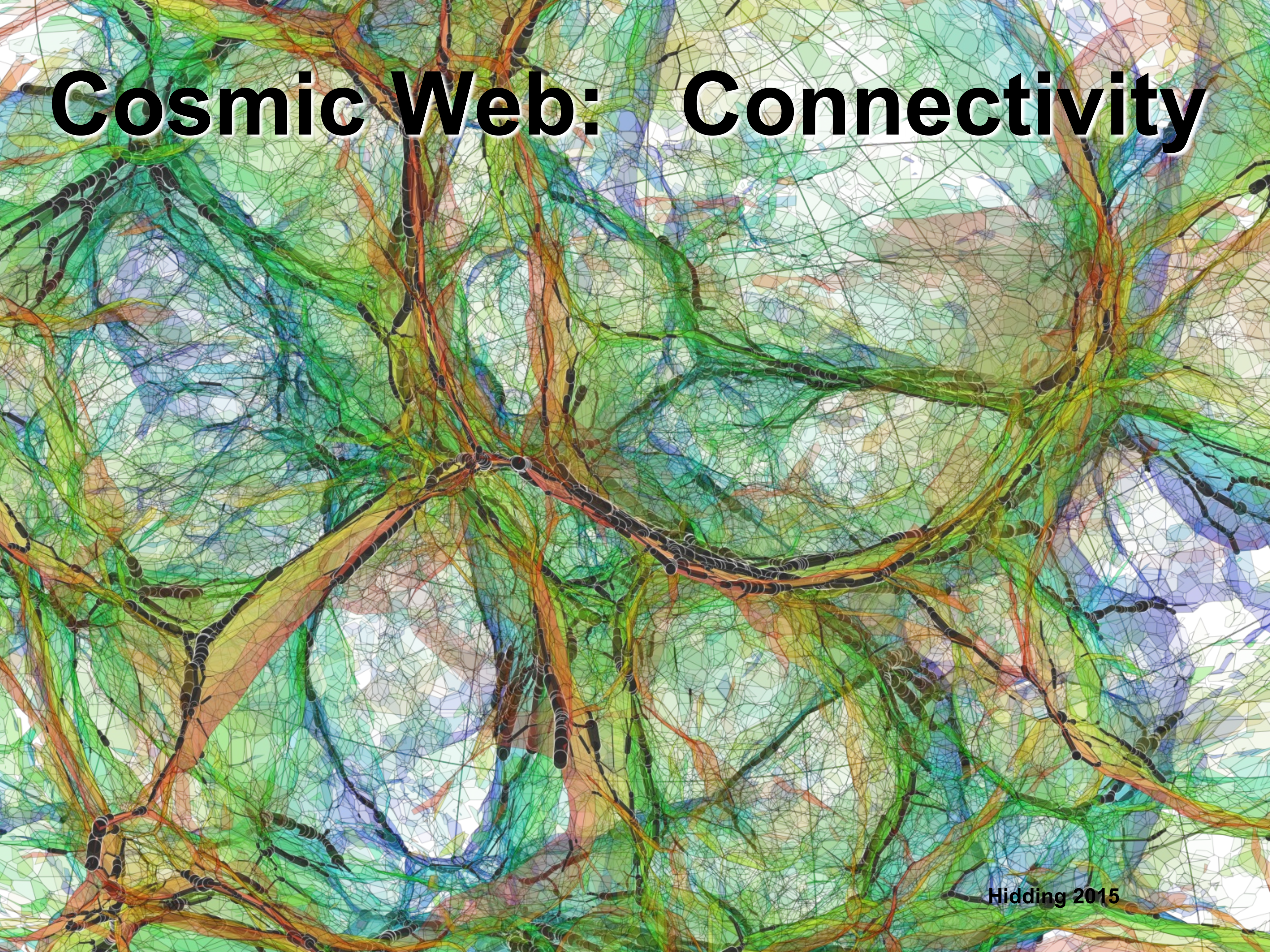
Sloan Great Wall:

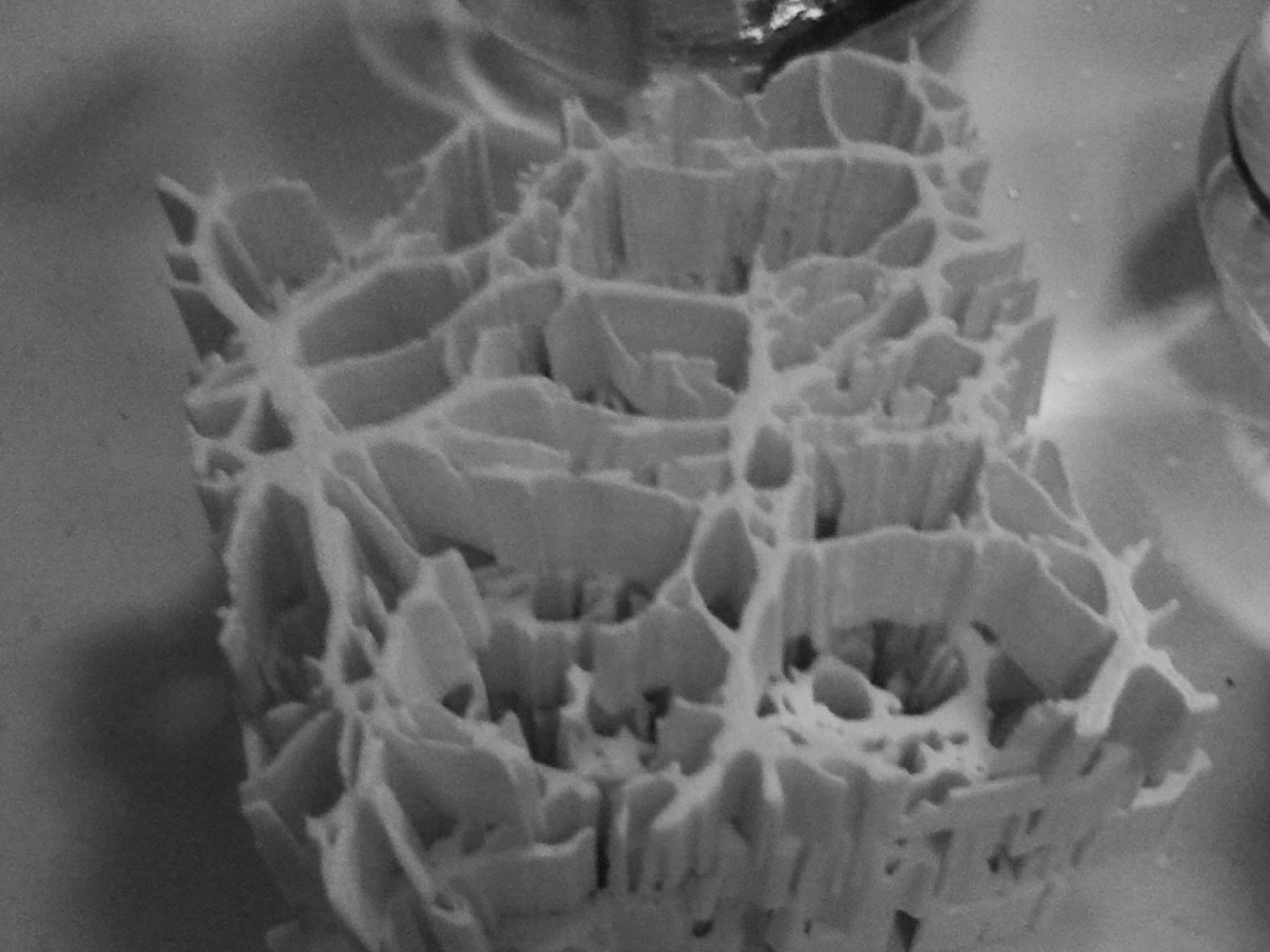
flattened assembly of cluster (nodes), filaments & voids





Cosmic Web: Connectivity





The Cosmic Web

Physical Significance:

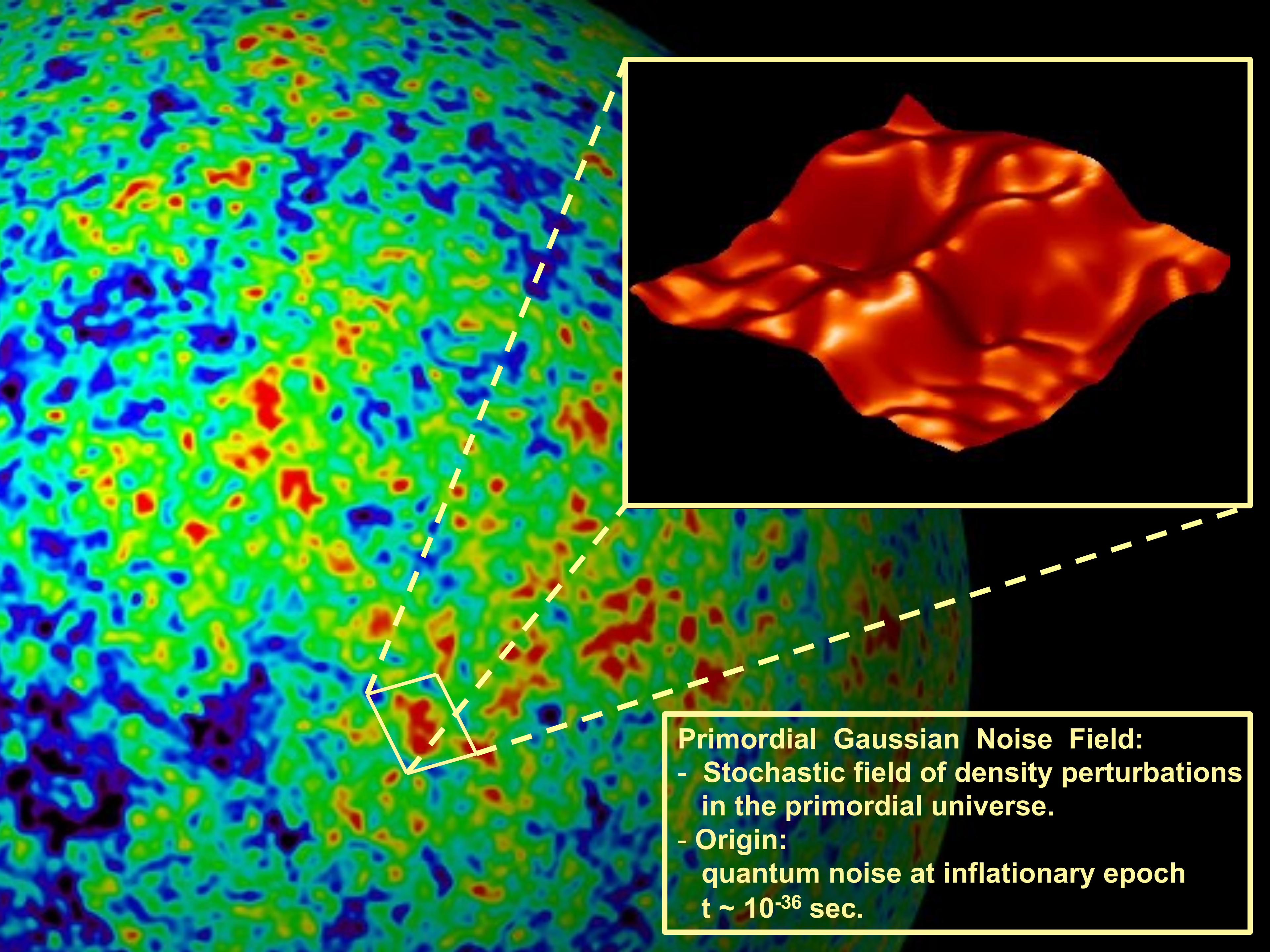
- Manifestation mildly nonlinear clustering:
  Transition stage between linear phase
  and fully collapsed/virialized objects

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

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

Cosmic 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.

Gravity Perturbations

$$\mathbf{g}(\mathbf{r},t) = -\frac{1}{a}\nabla\phi = \frac{3\Omega H^2}{8\pi}\int \mathrm{d}\mathbf{x}'\,\delta(\mathbf{x}',t)\,\frac{(\mathbf{x}'-\mathbf{x})}{|\mathbf{x}'-\mathbf{x}|^3}$$

Cosmic Structure Formation

(Energy) Density Perturbations

⬇

Gravity Perturbations

⬇

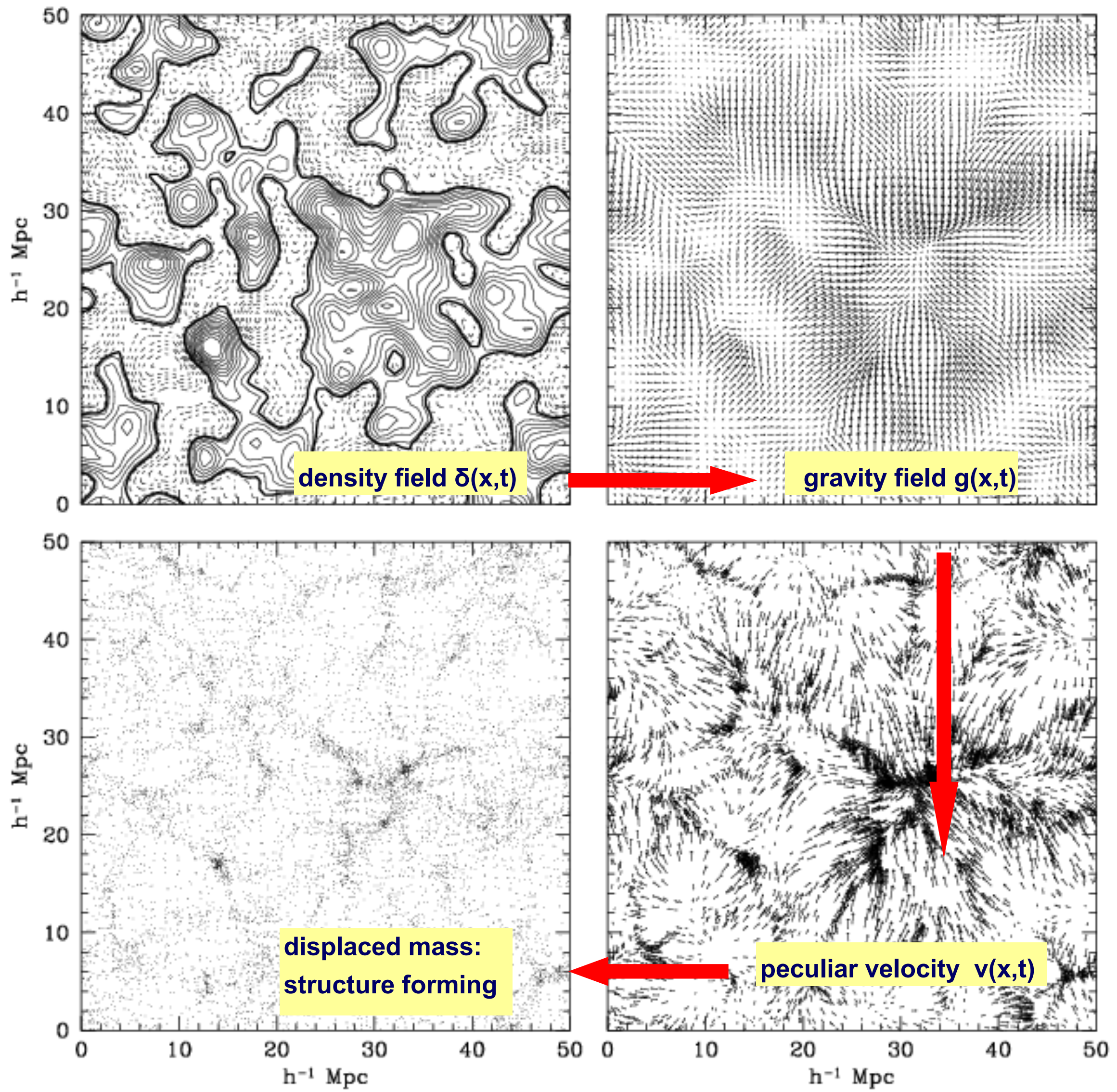
(Cosmic) Flows of (Energy) & Matter:

- towards high density regions:
  - assemble more and more matter
  - their expansion comes to a halt
  - turn around and collapse
- evacuating void regions
  - low-density regions expand
  - matter moves out of region
  - turn into prominent empty voids

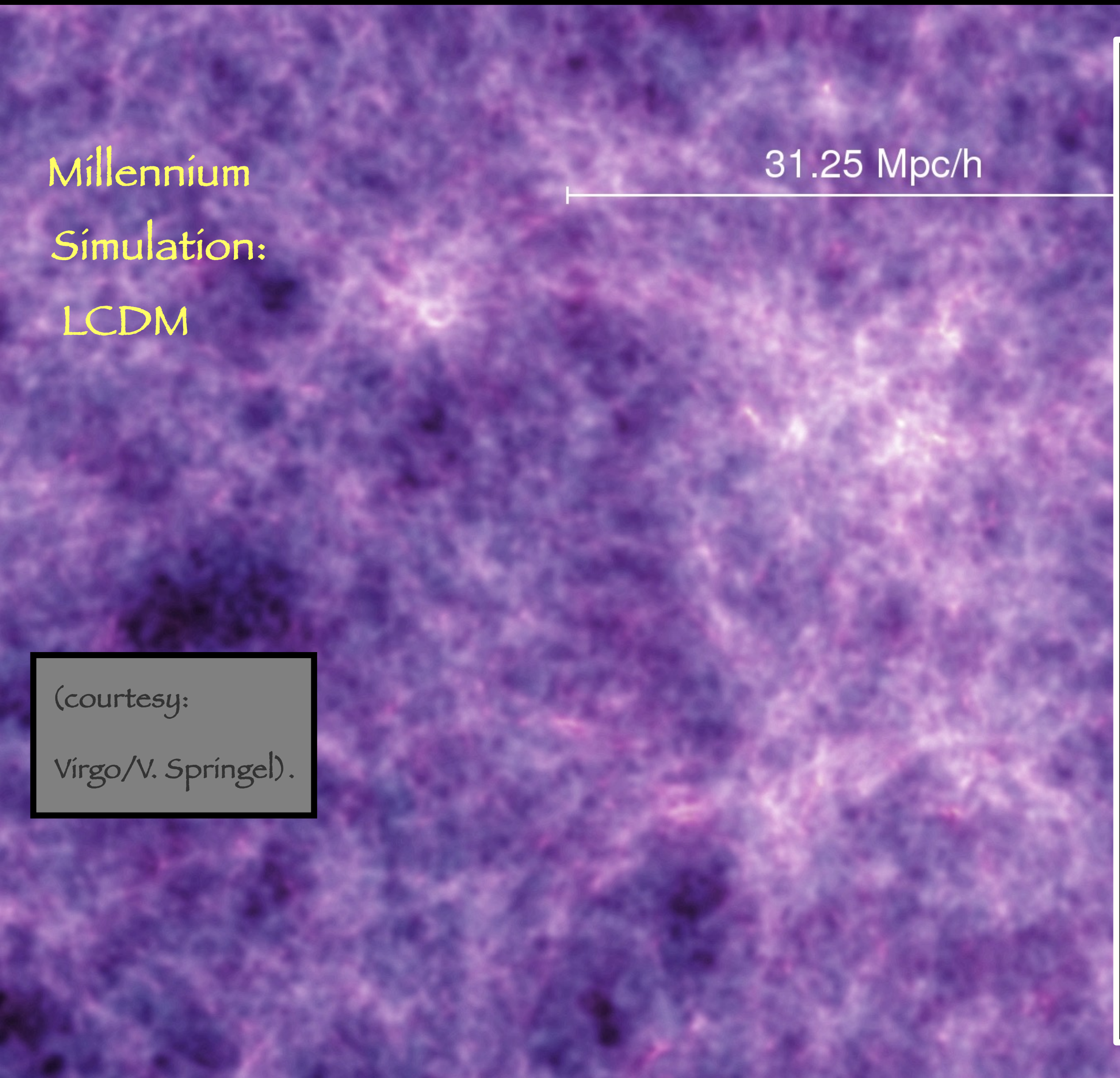
⬇

Emergence of cosmic structures

- Computer Simulations
  - succesfull confrontation with observational reality



Cosmic Structure Formation



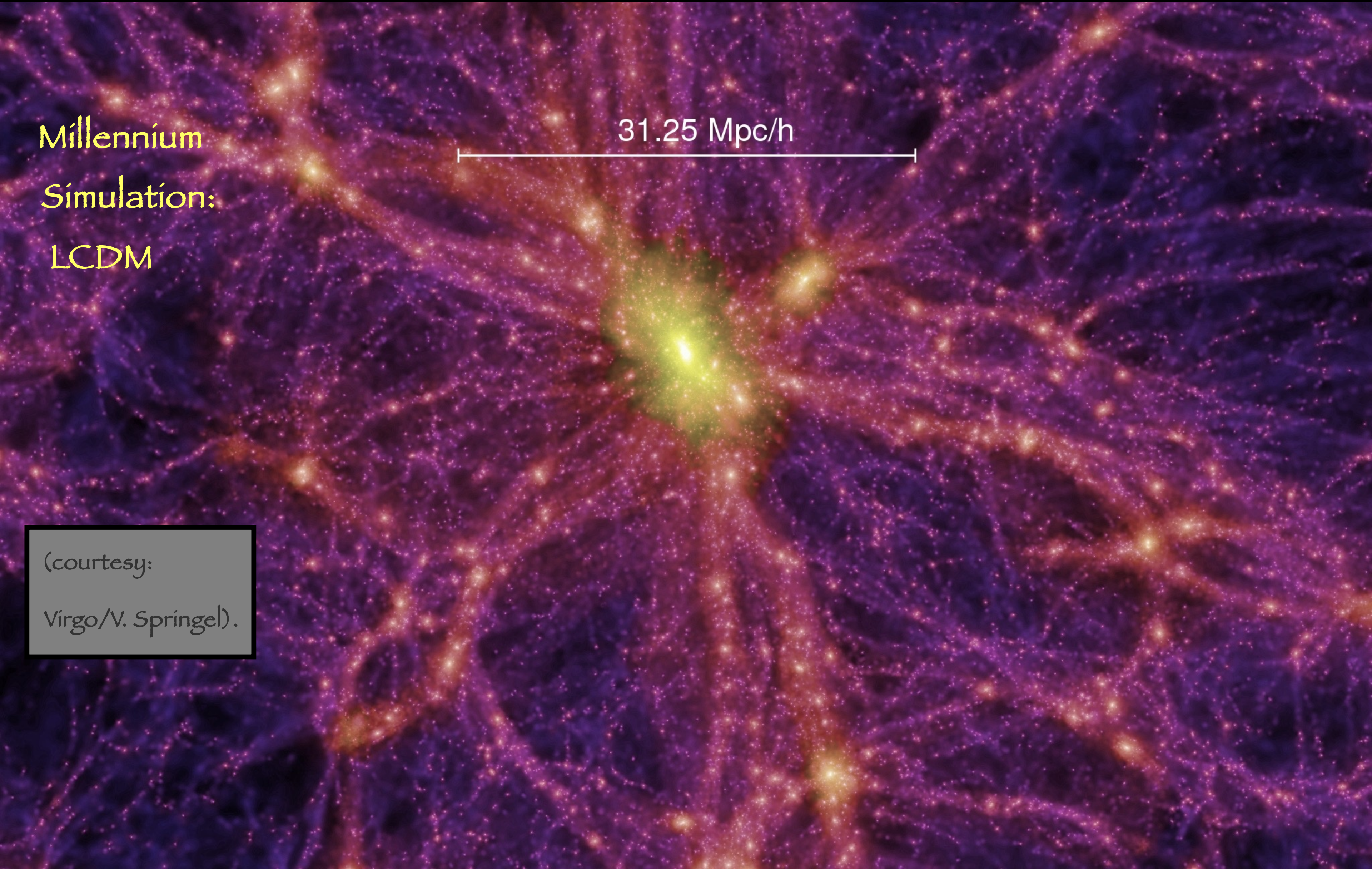
Dark Matter,
(~ 5.5x more than
baryonic matter)

⬇

without: not enough time to form structure in the Universe in 13.8 Gyrs

(cosmic web, clusters, galaxies, stars, …)

Cosmic Structure Formation



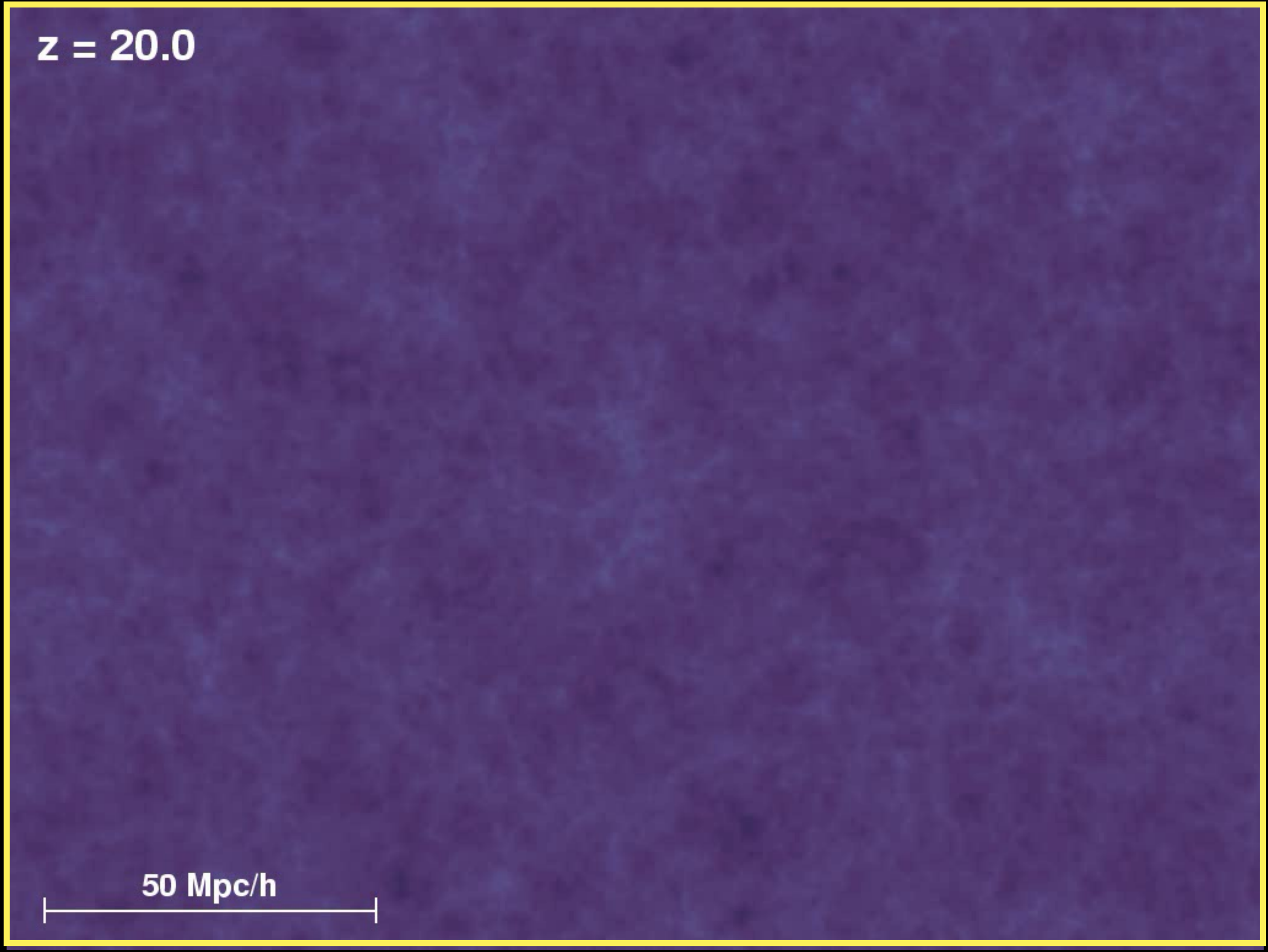
Cosmic Structure Formation

Formation
Cosmic Web:

simulation
sequence

(cold)
dark matter

(courtesy:
Virgo/V. Springel).

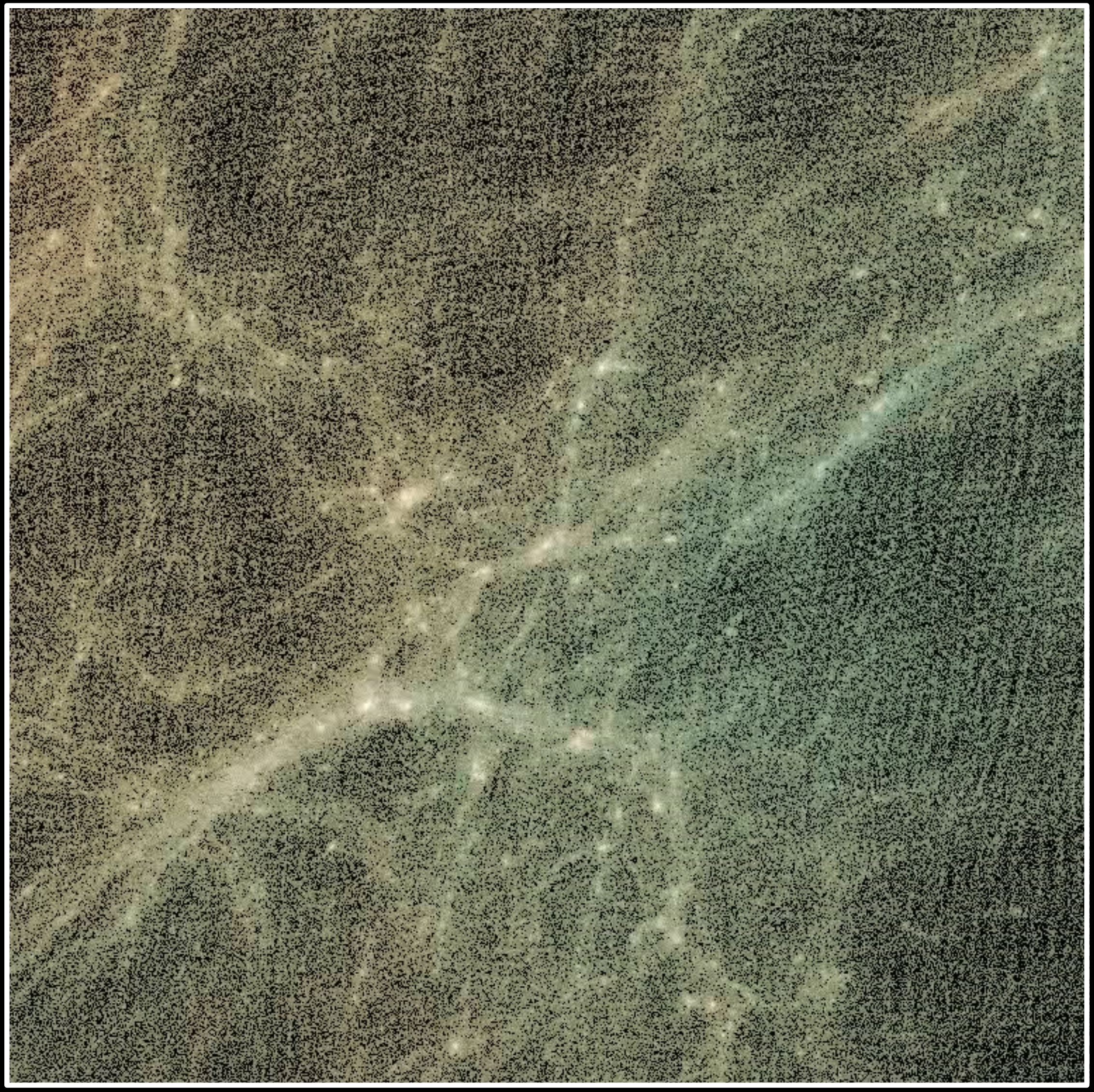


Cosmic Web Dynamical Evolution:

- Hierarchical buildup

- Tidally induced anisotropic evolution

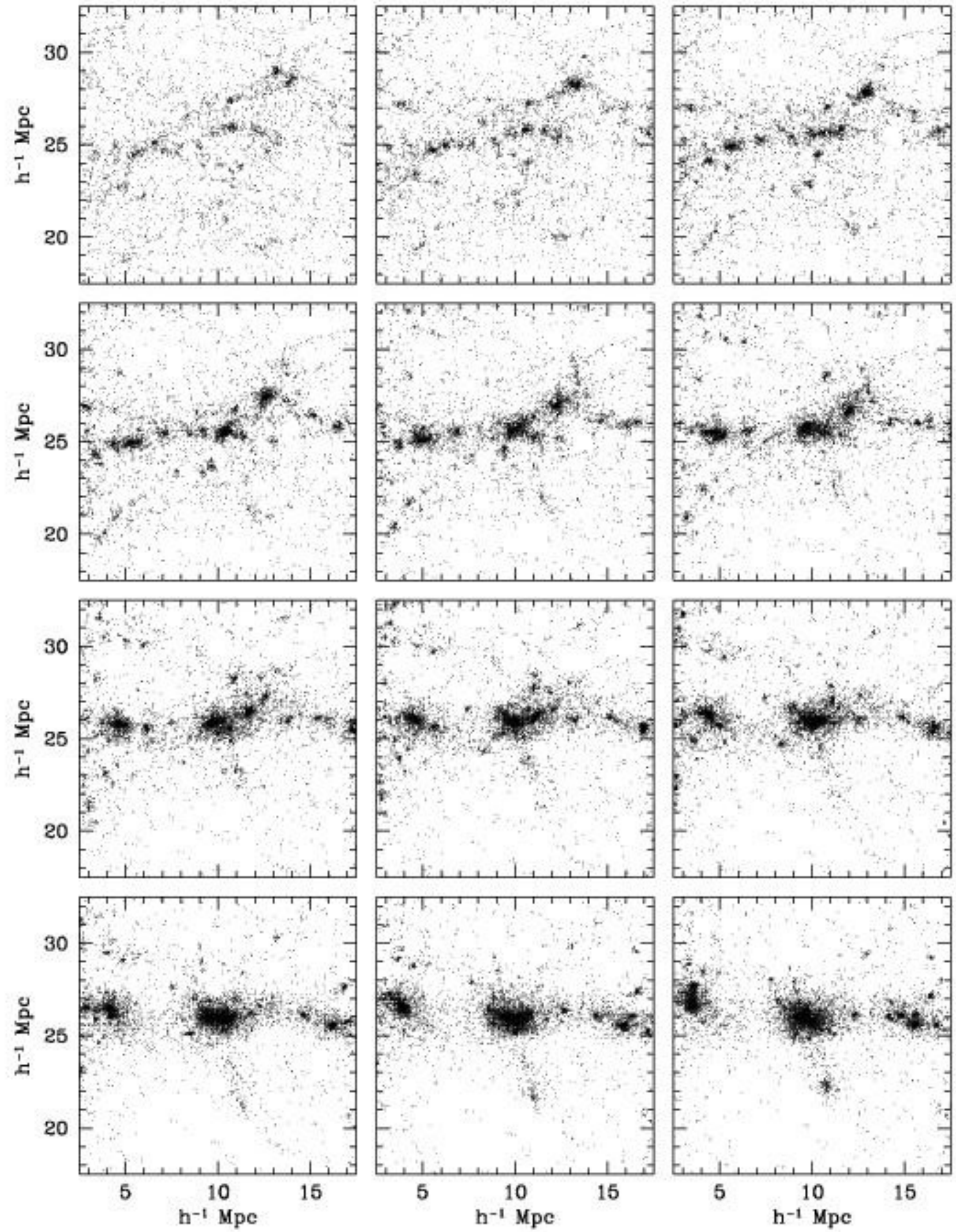
Hierarchical Evolution

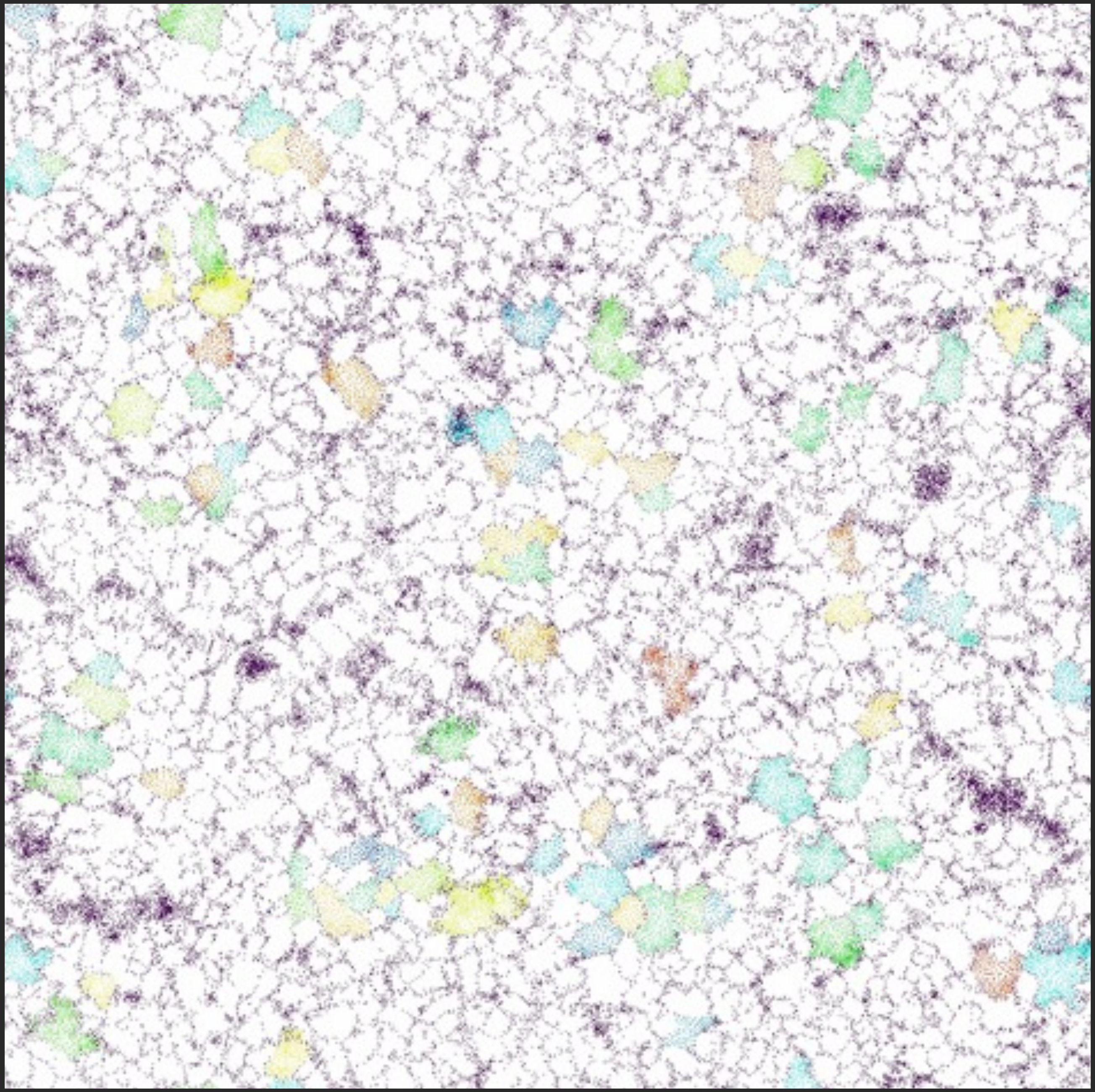


Rieder et al.
2013

Structures in the Universe form
by
gradual hierarchical assembly:

- ❖ small objects emerge & collapse first,
- ❖ then merge with other clumps
- ❖ while forming larger objects in hierarchy





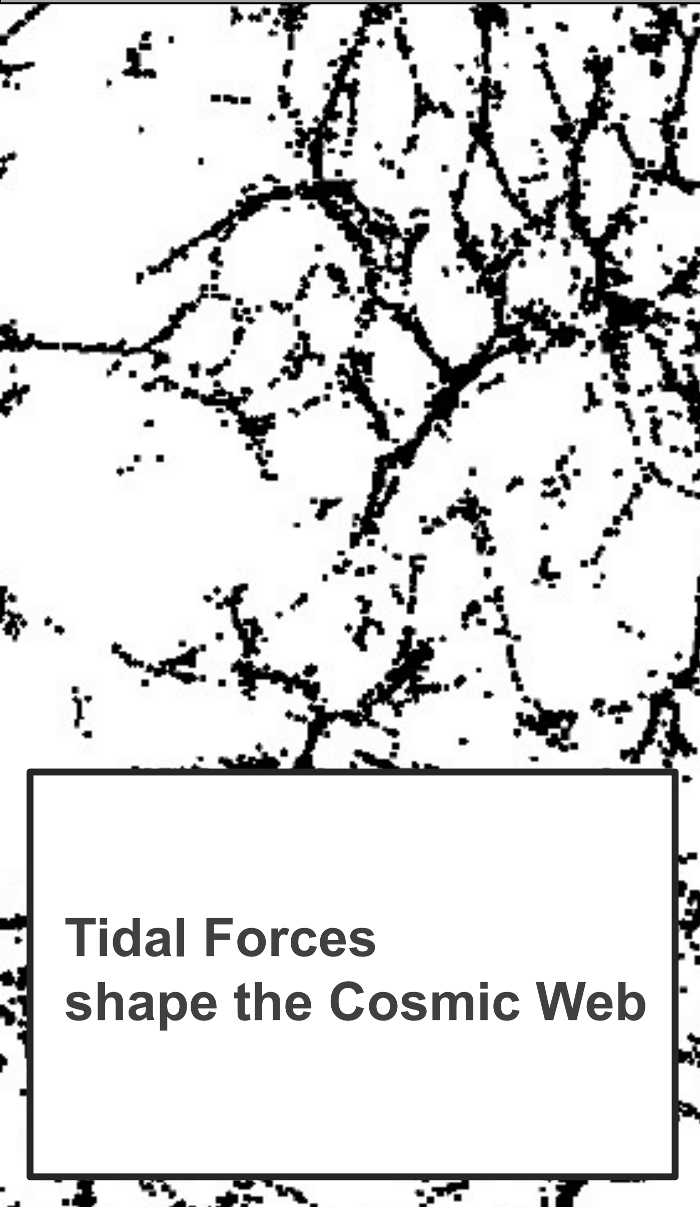
Void Hierarchy:

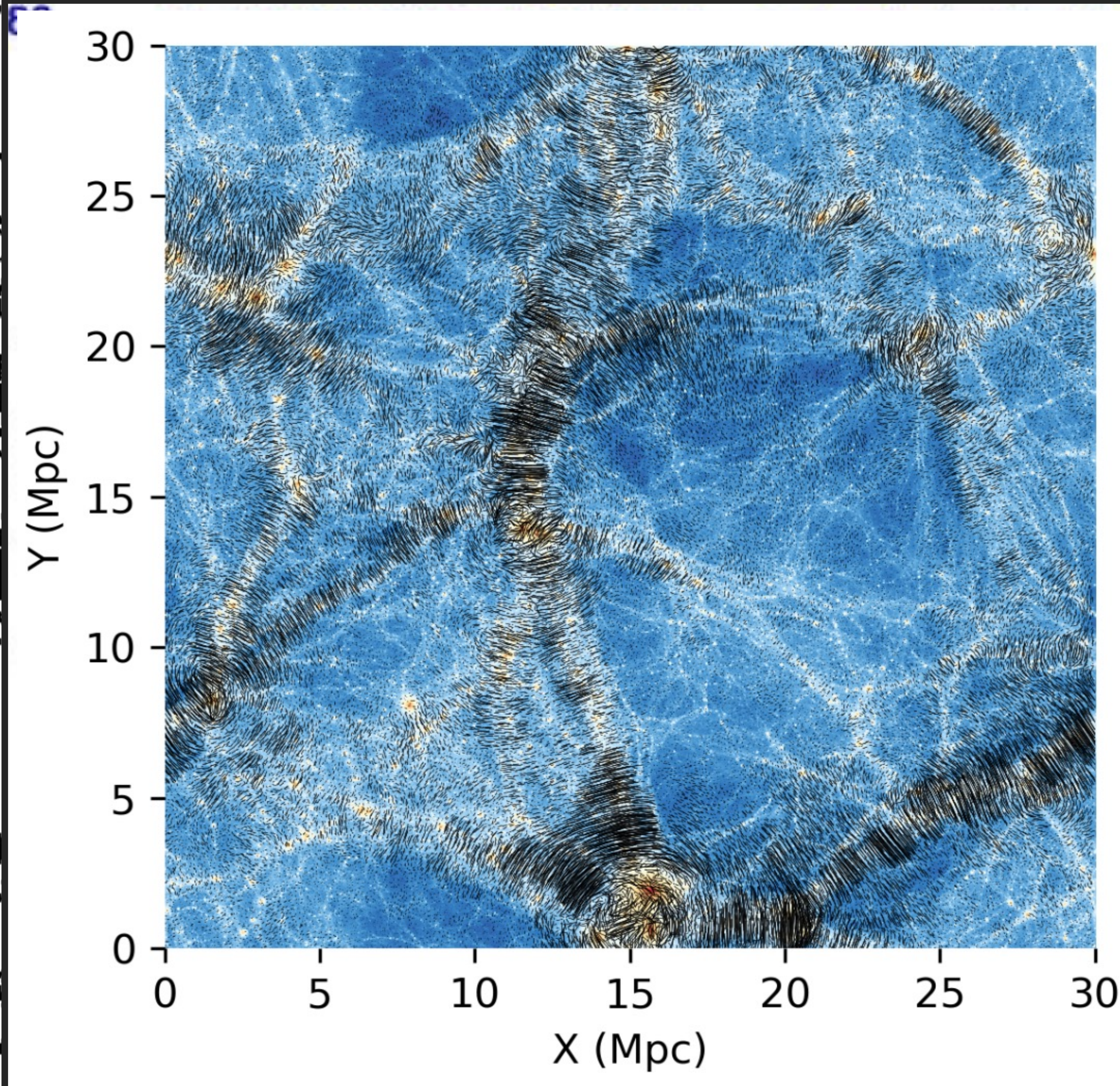
"Lagrangian" view:

void-dominated
hierarchical
development
Cosmic Web

Platen & vdW 2004
Sheth & vdW 2004
Aragon-Calvo & Szalay 2012

Tidal Shaping of the Cosmic Web





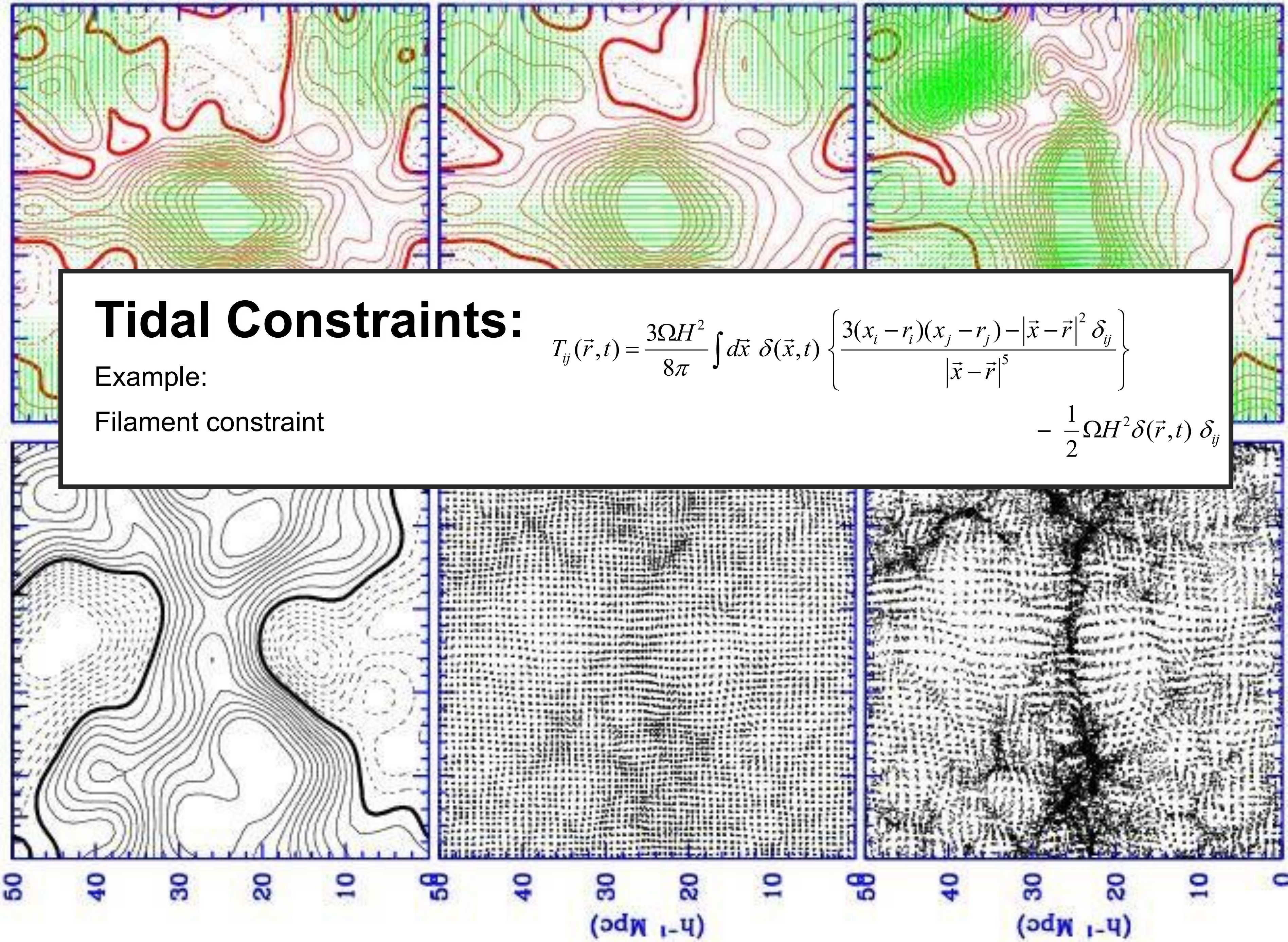
Tidal Forces shape the Cosmic Web

Tidal Constraints:

Example:

Filament constraint

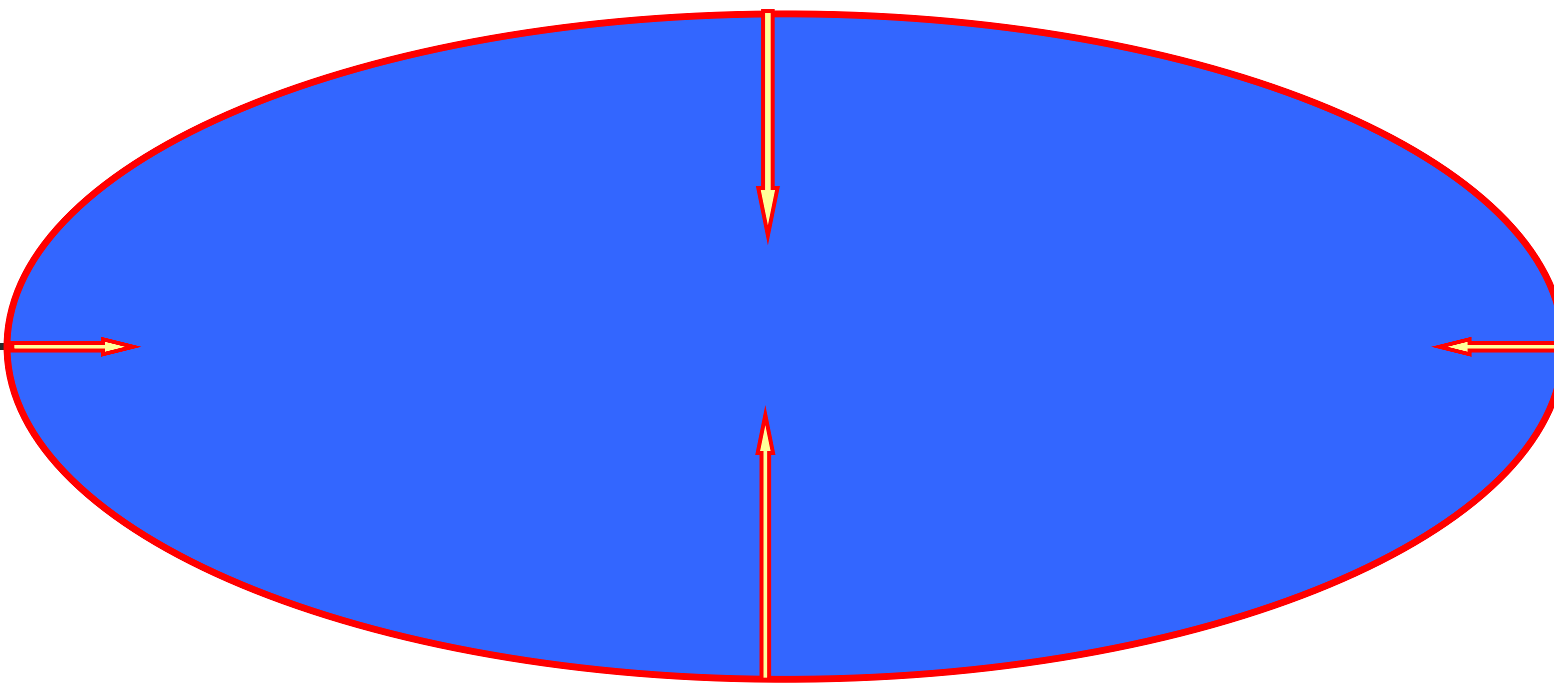
$$T_{ij}(\vec{r},t) = \frac{3\Omega H^2}{8\pi}\int d\vec{x}\;\delta(\vec{x},t)\left\{\frac{3(x_i - r_i)(x_j - r_j) - |\vec{x}-\vec{r}|^2\,\delta_{ij}}{|\vec{x}-\vec{r}|^5}\right\} - \frac{1}{2}\Omega H^2 \delta(\vec{r},t)\;\delta_{ij}$$



Anisotropic

Gravitational Collapse

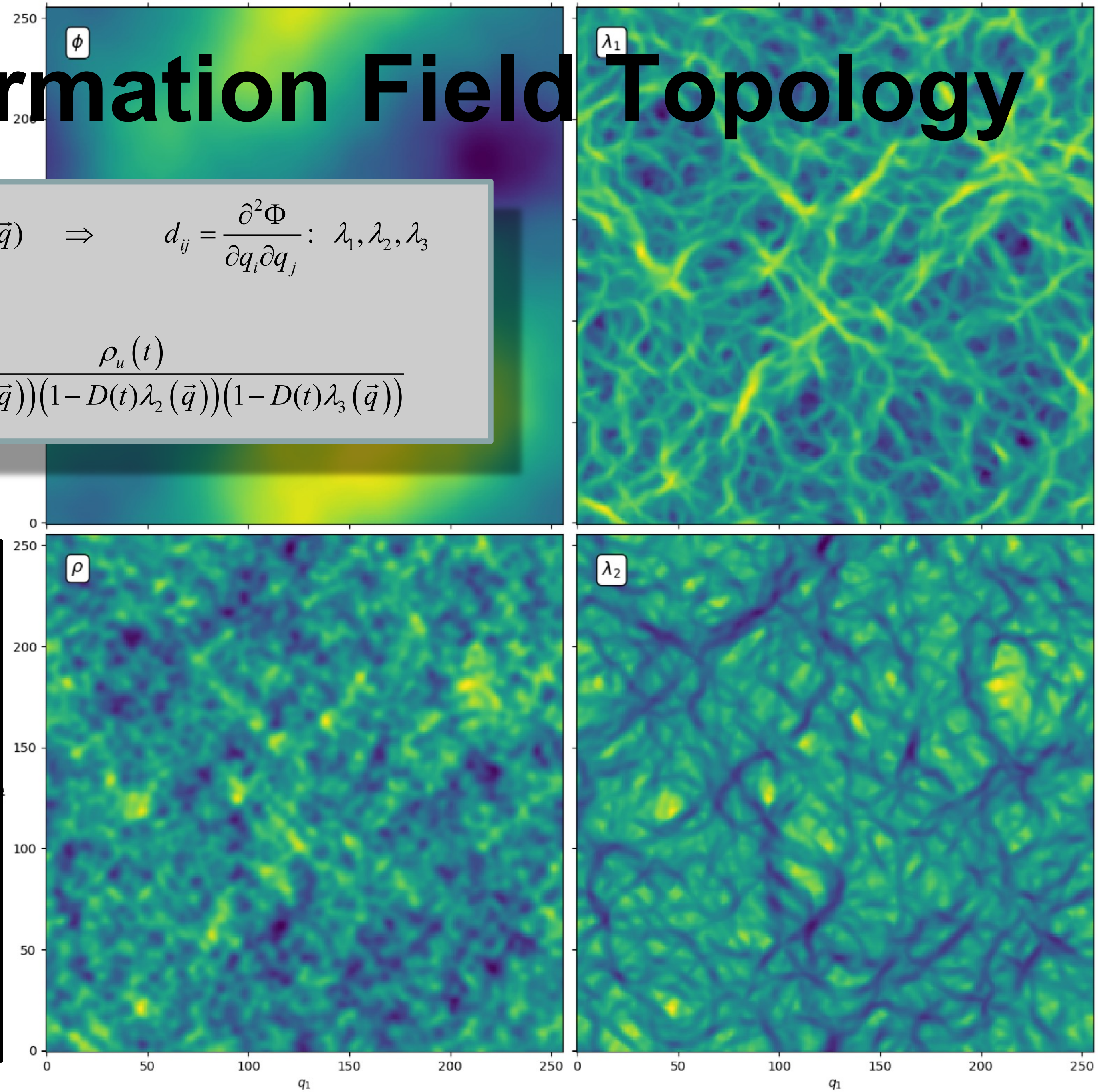
Amplification
small perturbations in gravity along different directions (tidal forces)



Deformation Field Topology

$$\vec{x}(\vec{q},t) = \vec{q} - D(t)\vec{\nabla}\Phi(\vec{q}) \quad \Rightarrow \quad d_{ij} = \frac{\partial^2 \Phi}{\partial q_i \partial q_j} : \; \lambda_1, \lambda_2, \lambda_3$$

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



Deformation eigenvalue Landscape
(initial Gaussian field)

Connectivity Cosmic Web:

Topology deformation field

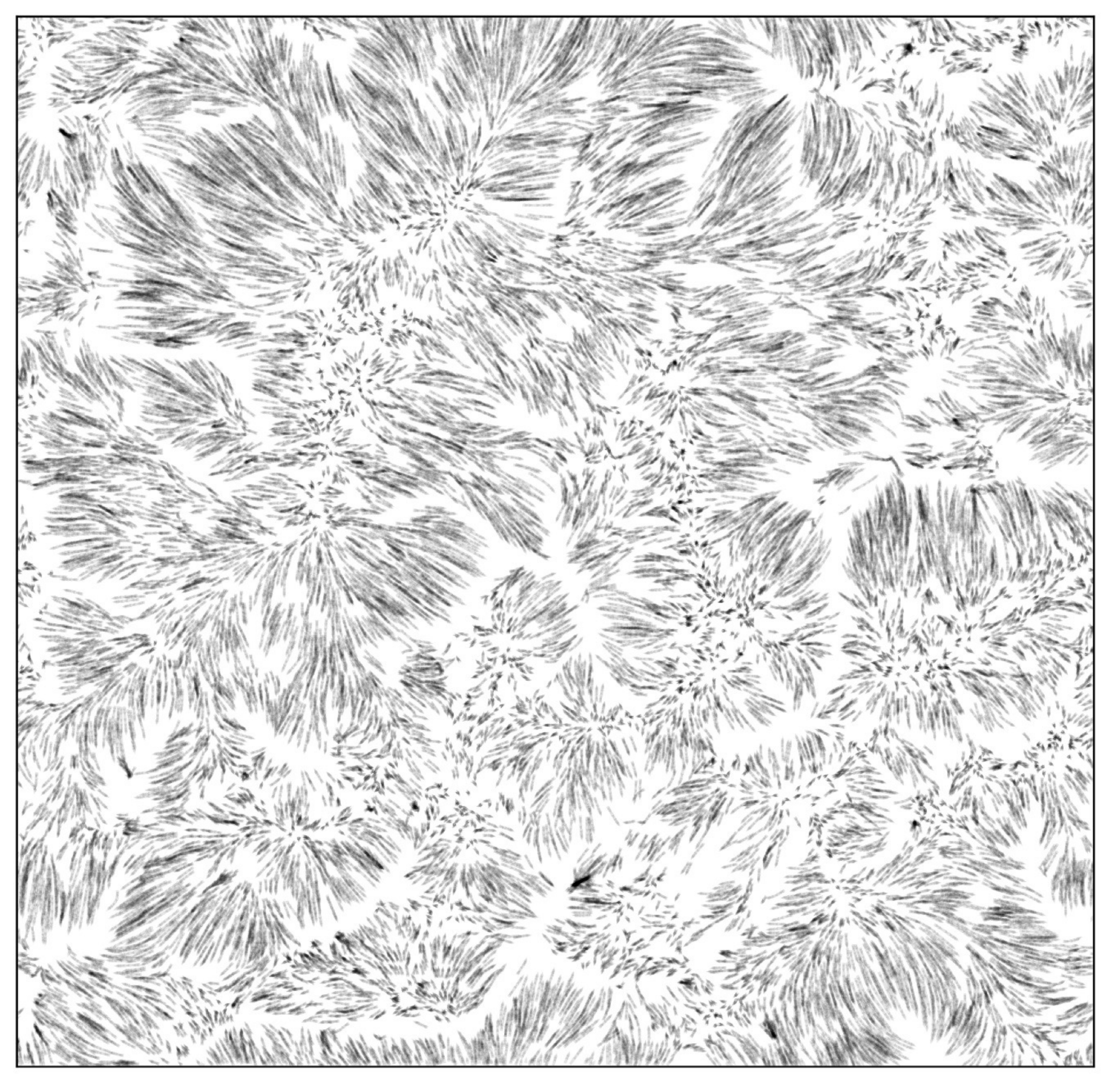
Cosmic Web Dynamics: Summary

- ***Filaments*** **rule !**

yet

- ***Voids*** **organize !**

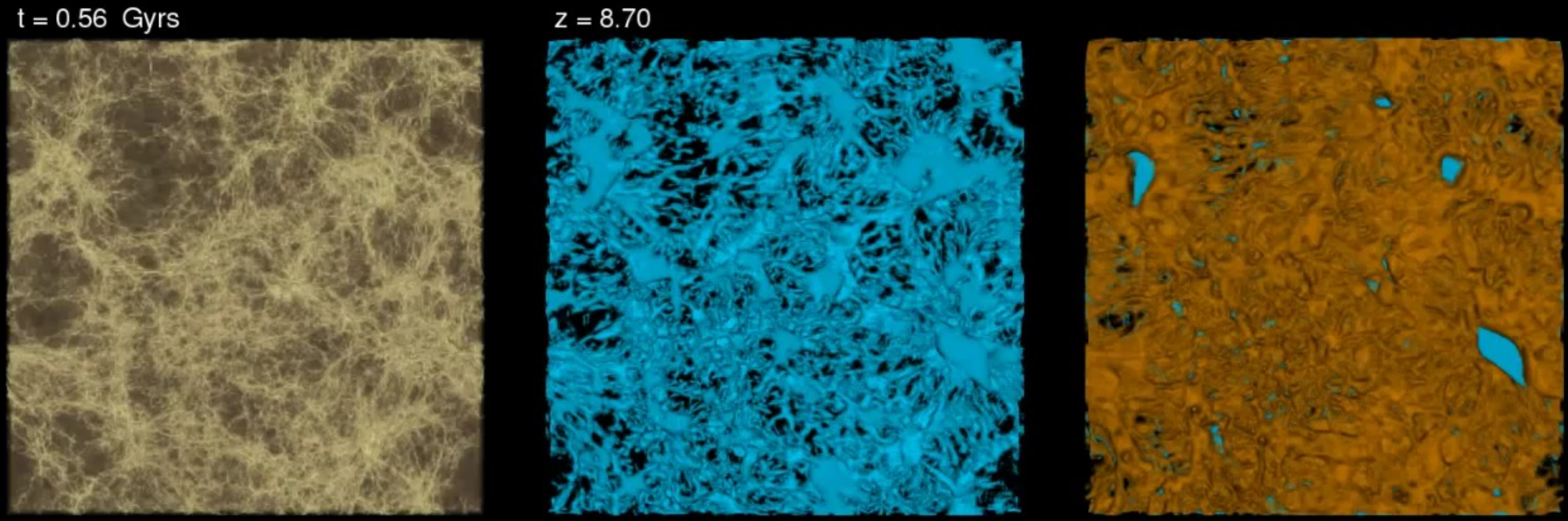
- strict hierarchy
  filaments-voids-walls-cluster nodes
- Filaments dominate force & tidal field
- Voids organize:
  - structural pattern cosmic web
  - connectivity cosmic web
- Voids very important at high z
- Cluster nodes:
  relatively recent & fast
  growing influence



the Cosmic Web:

evolution of walls & filaments

NEXUS/MMF Evolution Cosmic Web



Cautun et al. 2013

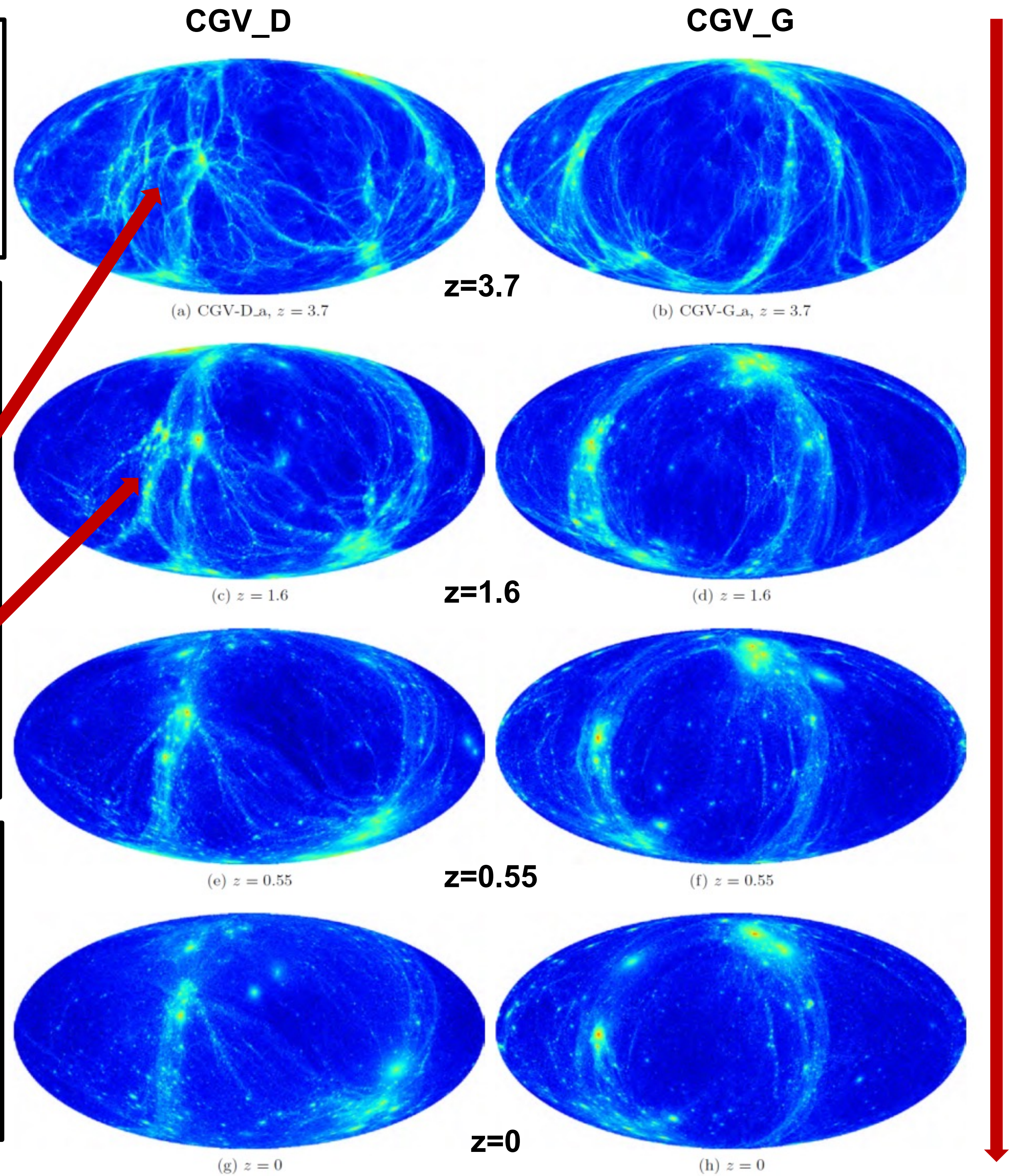
CGV:

on walls & filaments

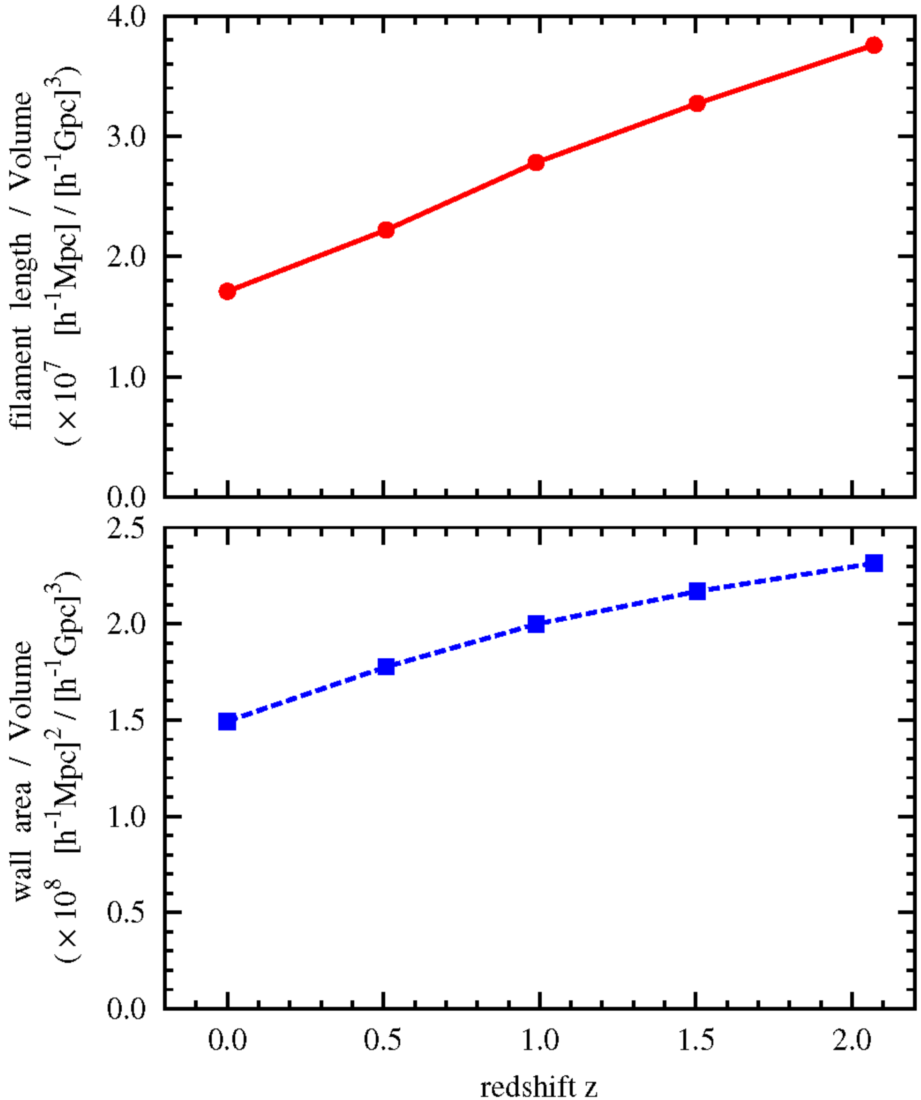
- Mollweide sky projection
  matter distribution around CGV halos
- CGV halos embedded in walls
- Walls dominate void infrastructure
- substantial fraction in filaments
  (embedded in walls)
- active dynamical evolution of
  wall-filament goes along with
  active void galaxy halo evolution

merging system of
Intravoid walls

Rieder et al. 2013



Evolving Filament & Wall Network



Total length of filament network :

decreasing as a function of time

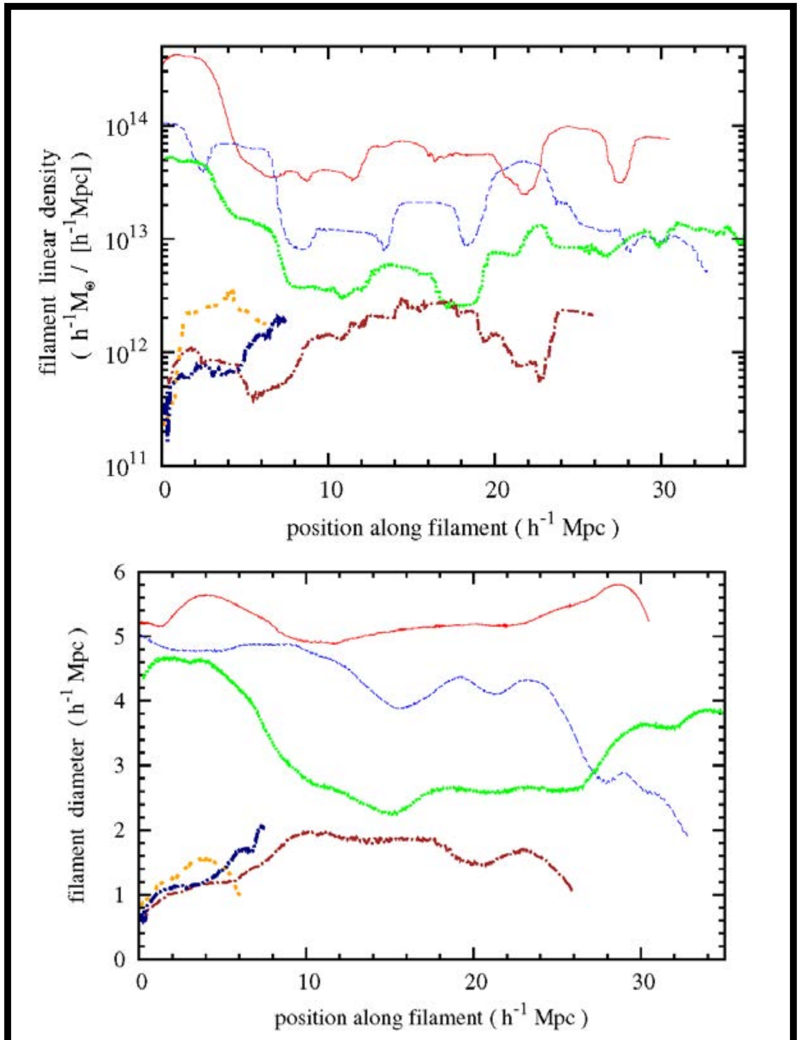
Total surface area of wall network :

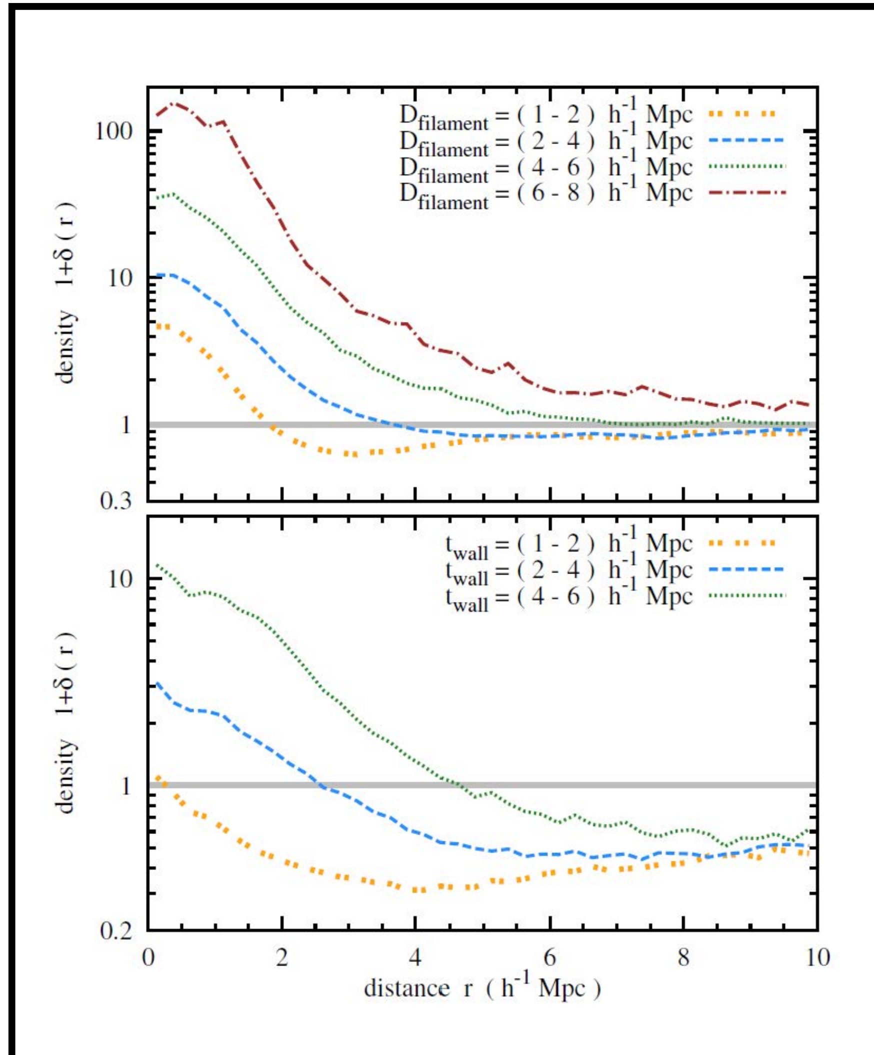
decreasing as a function of time

Cautun et al. 2014

Walls & Filaments

Internal Diameter & Density Profiles





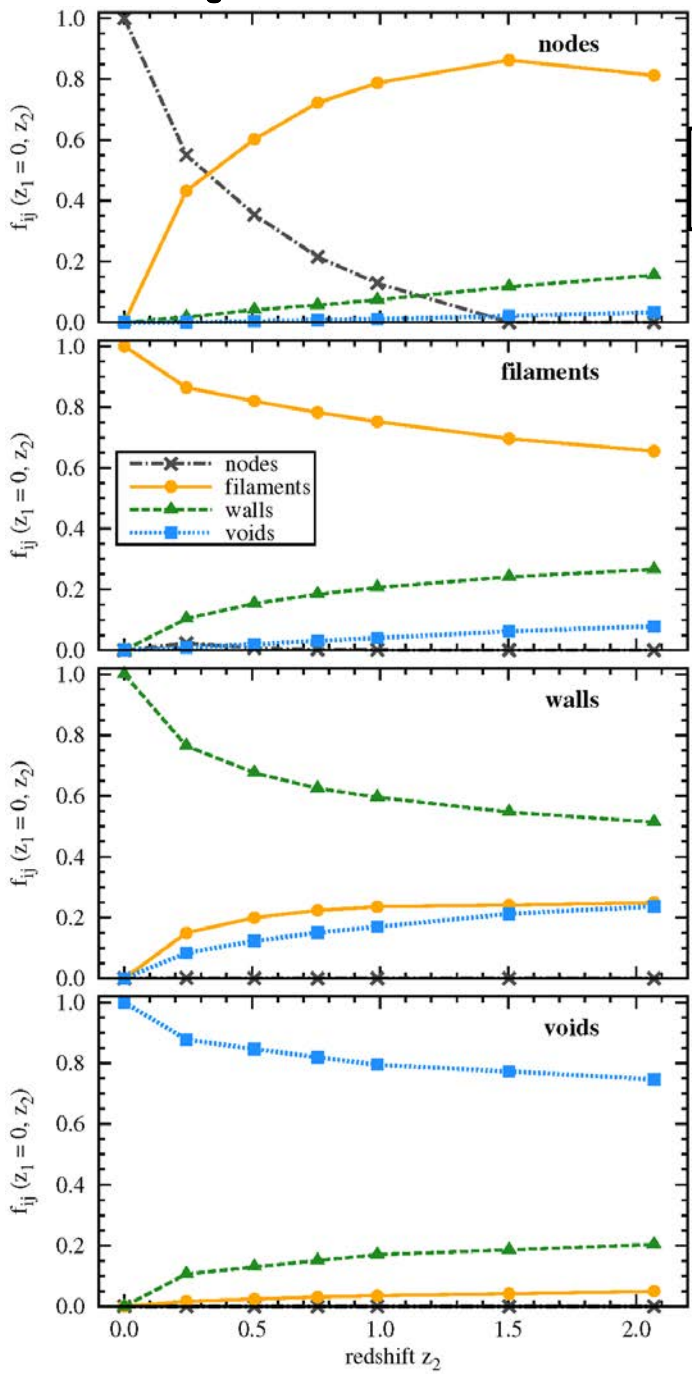
Cautun et al. 2014

Cosmic Web:

Evolutionary Trends

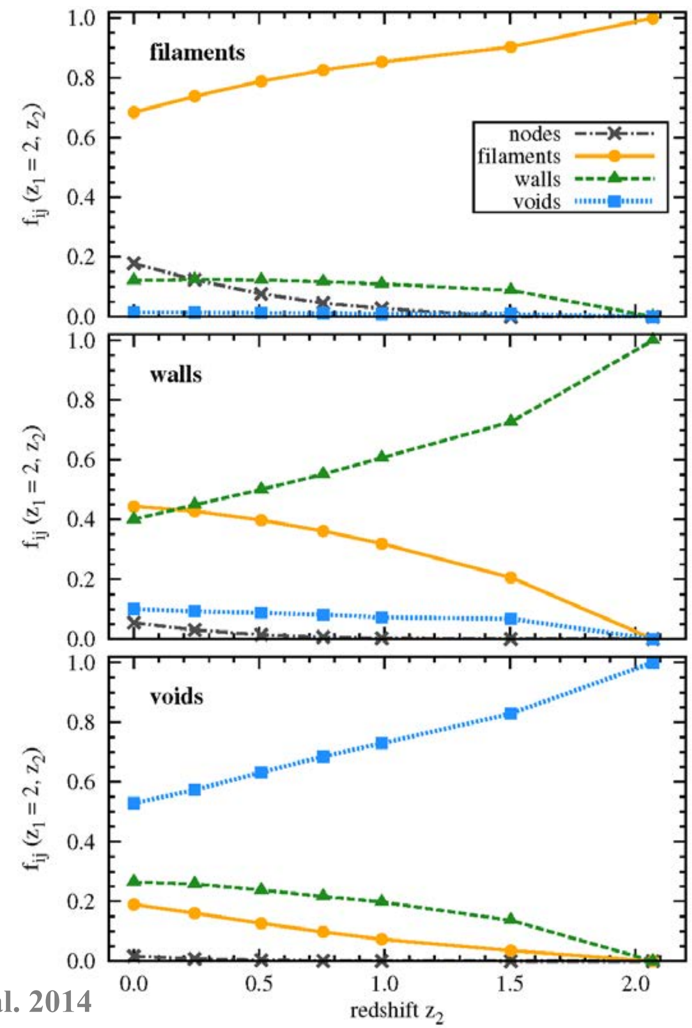
Web Migration

moving towards …



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

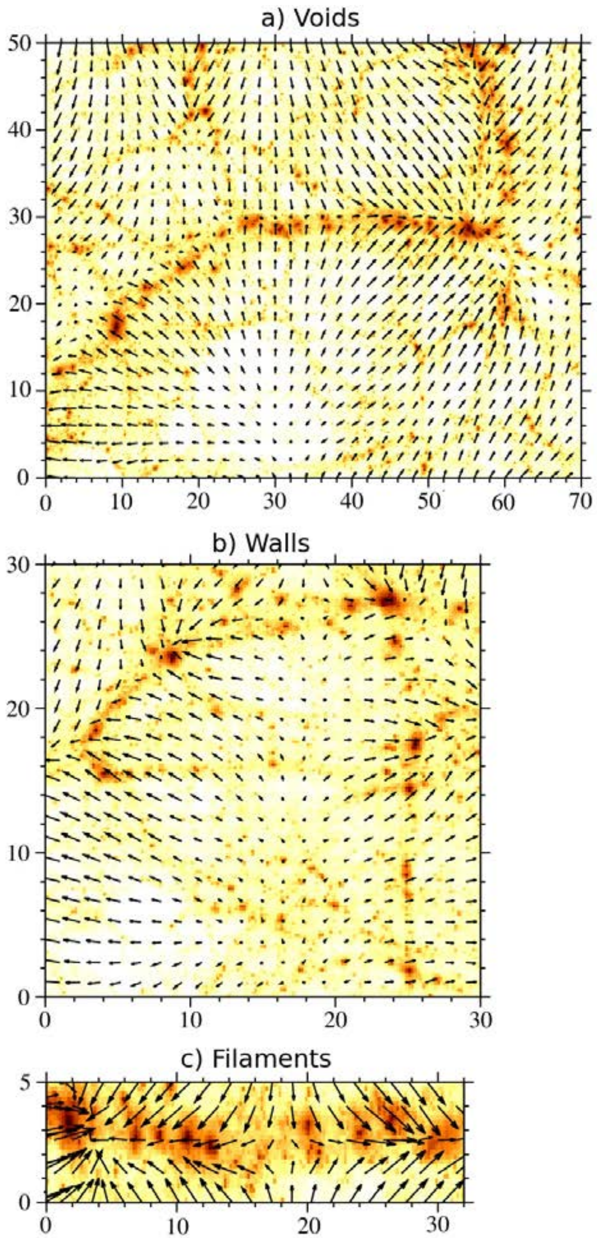
z_1=2: component A
z_2=z: component B

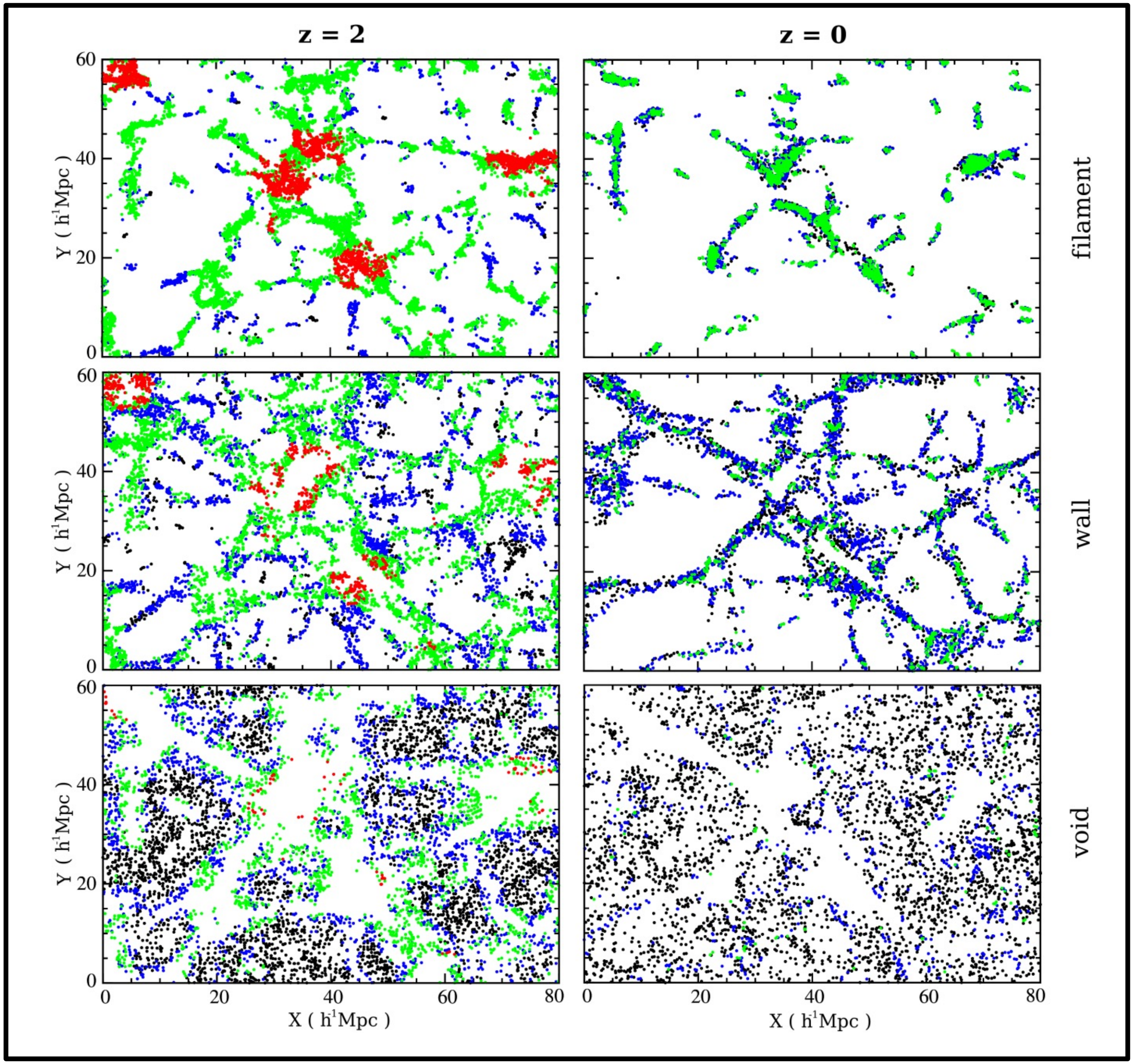


moving out of …

Cautun et al. 2014

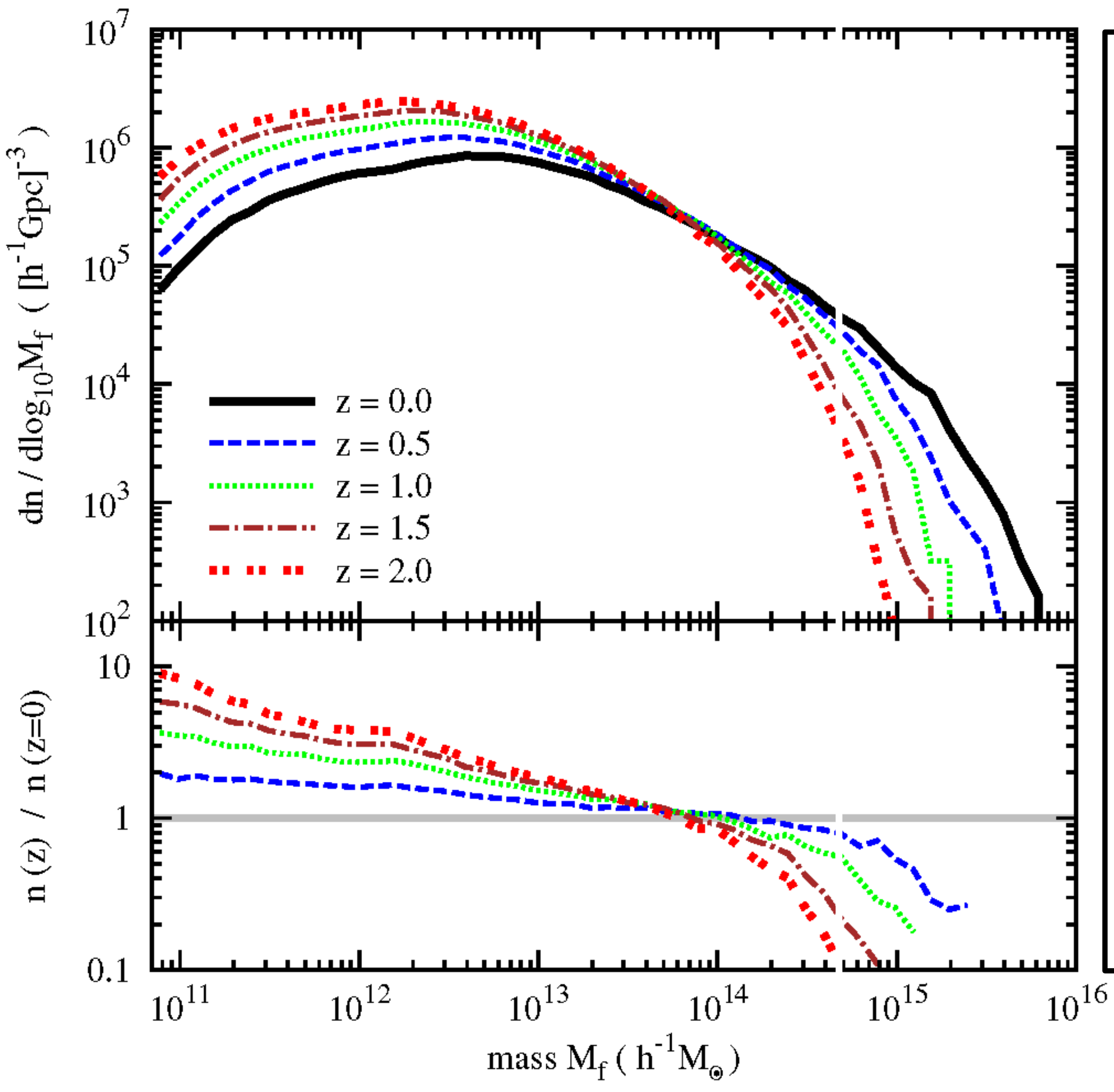
Web Mass Emigration





Cautun et al. 2014

Evolving Filament Population



Filament Mass Function:

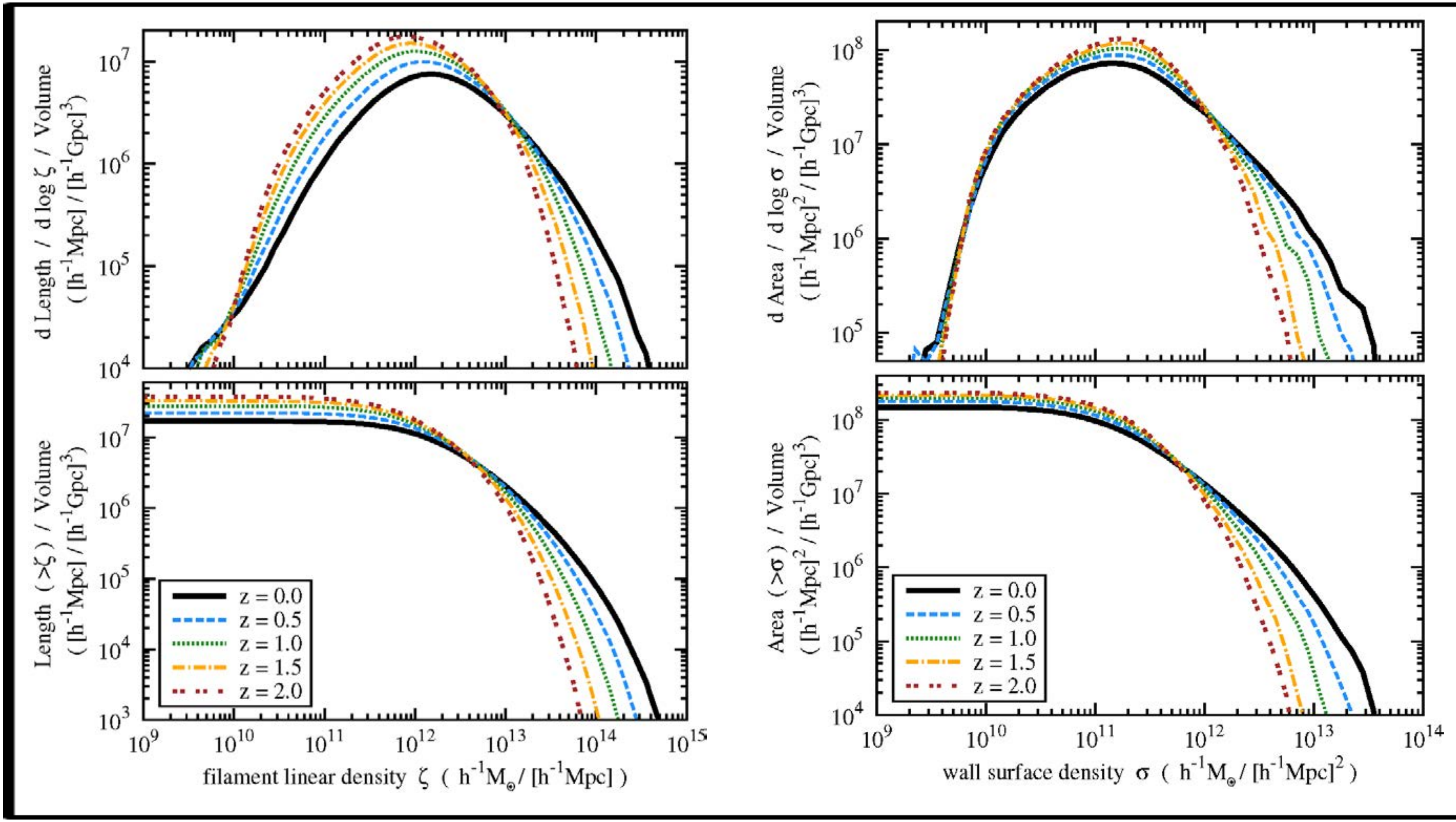
- shifting from small to large mass filaments
- reflection hierarchical evolution filament population

Cautun et al. 2014

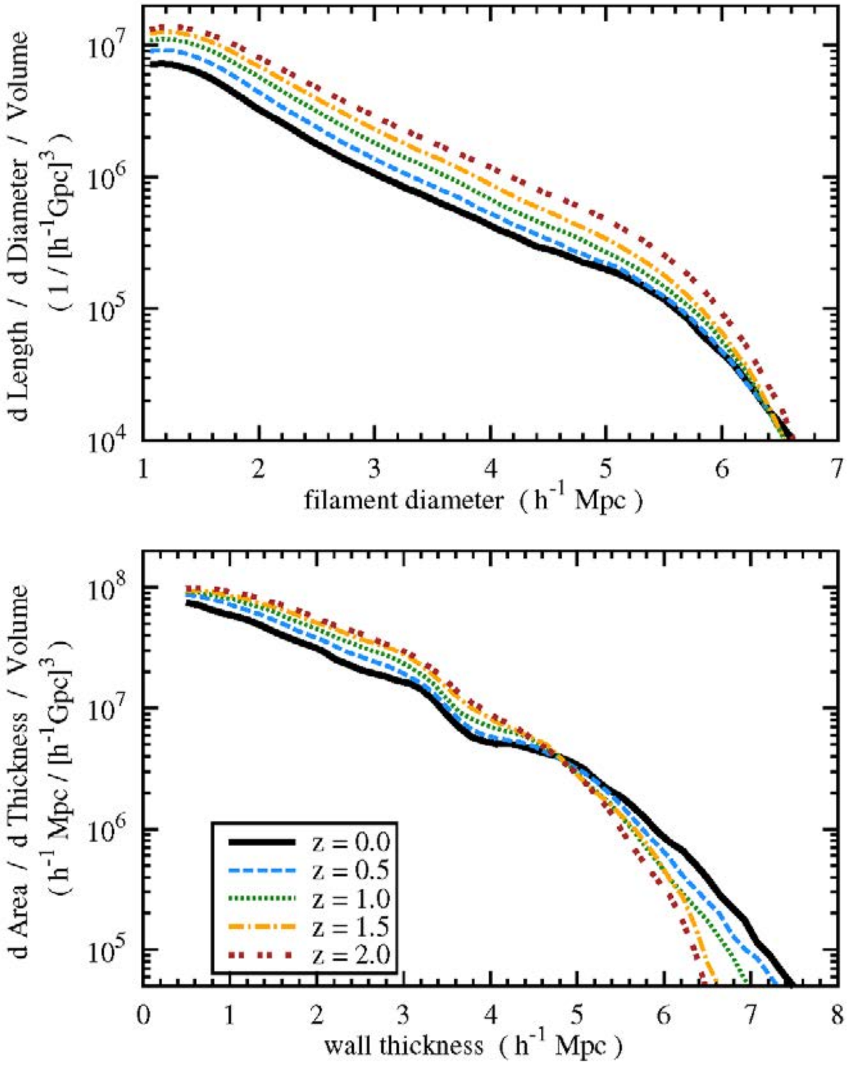
Evolving Filament & Wall Densities

Filament population: evolves continuously towards more dense filaments
Wall population: tenuous walls do not evolve into more dense walls

Cautun et al. 2014



Evolving Filament & Wall Diameters



Filament population:
increasing diameter

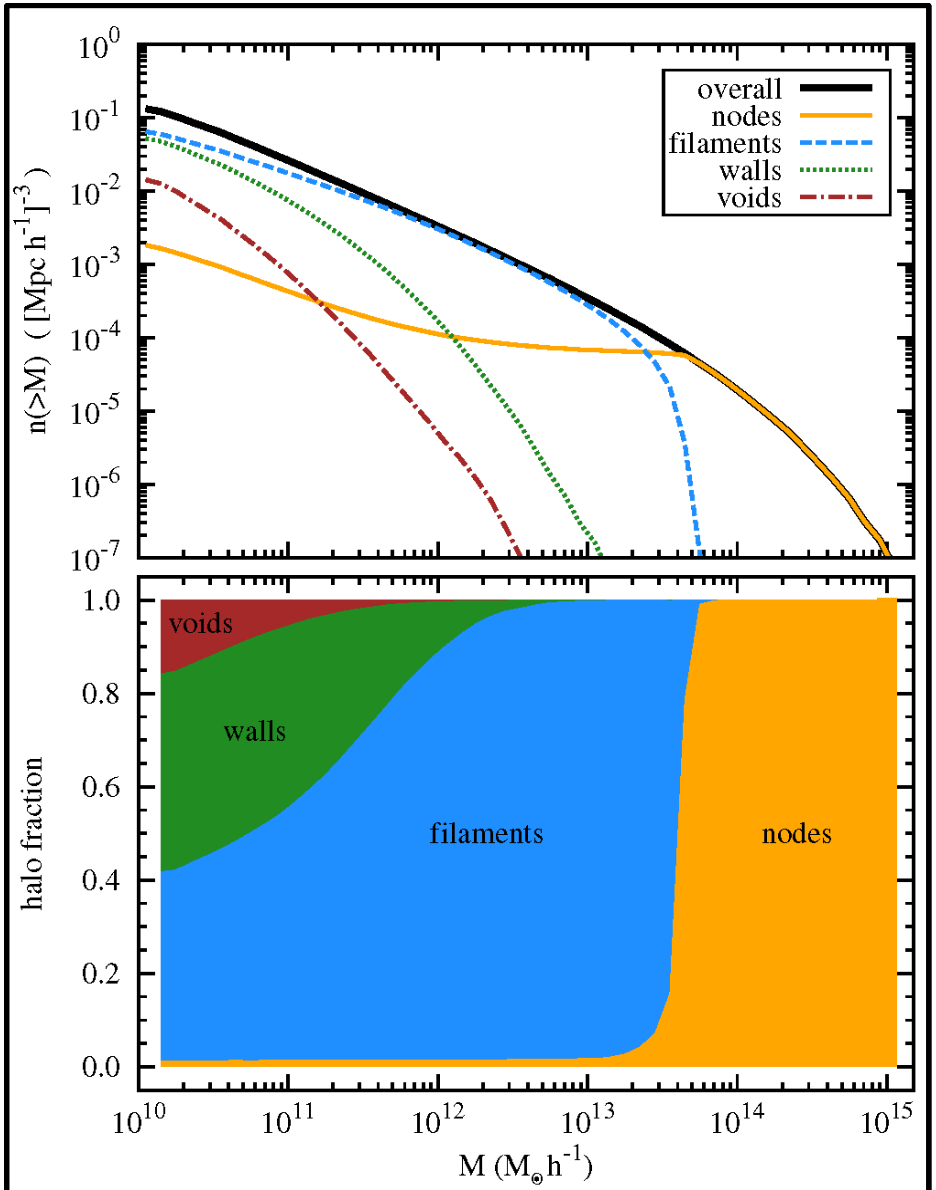
Wall population:
increasing thickness for denser walls
decrease of tenuous walls

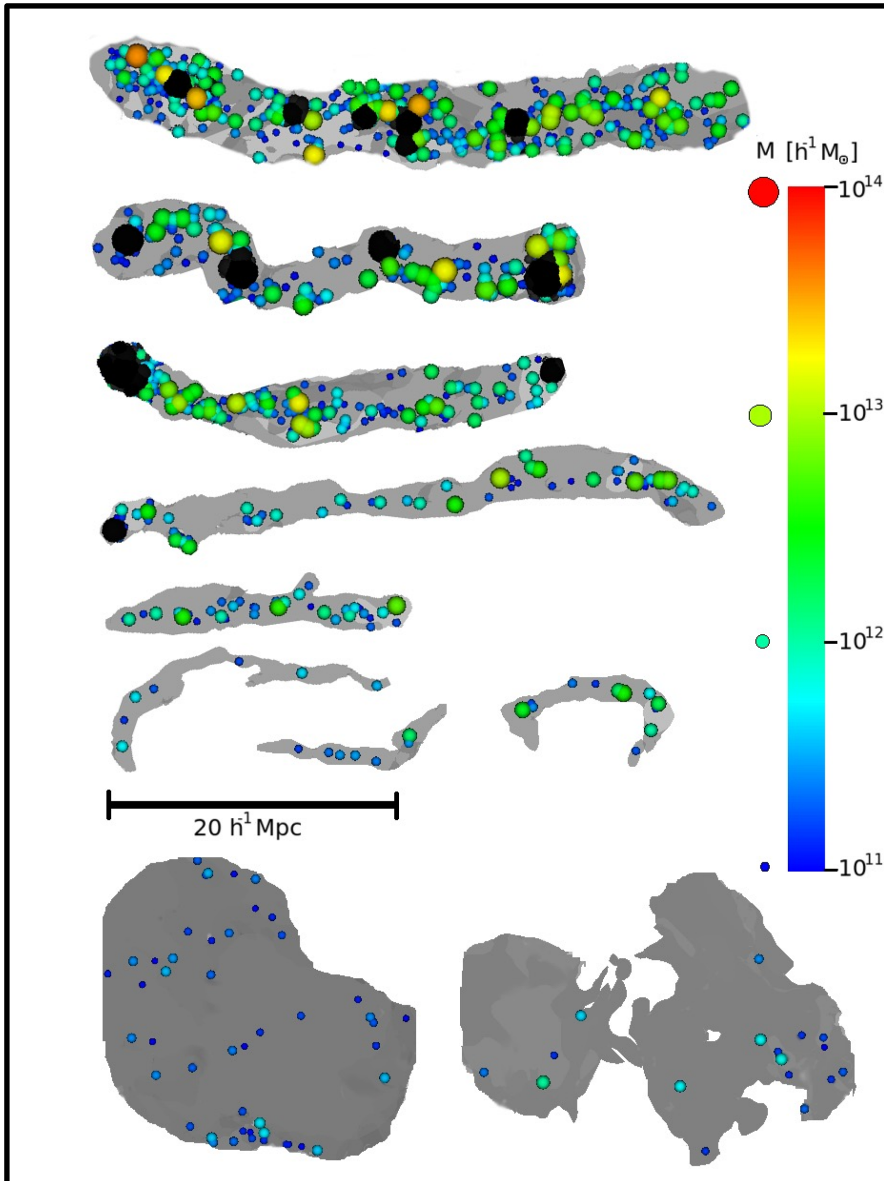
Cautun et al. 2014

Cosmic Web:

Halo Distribution

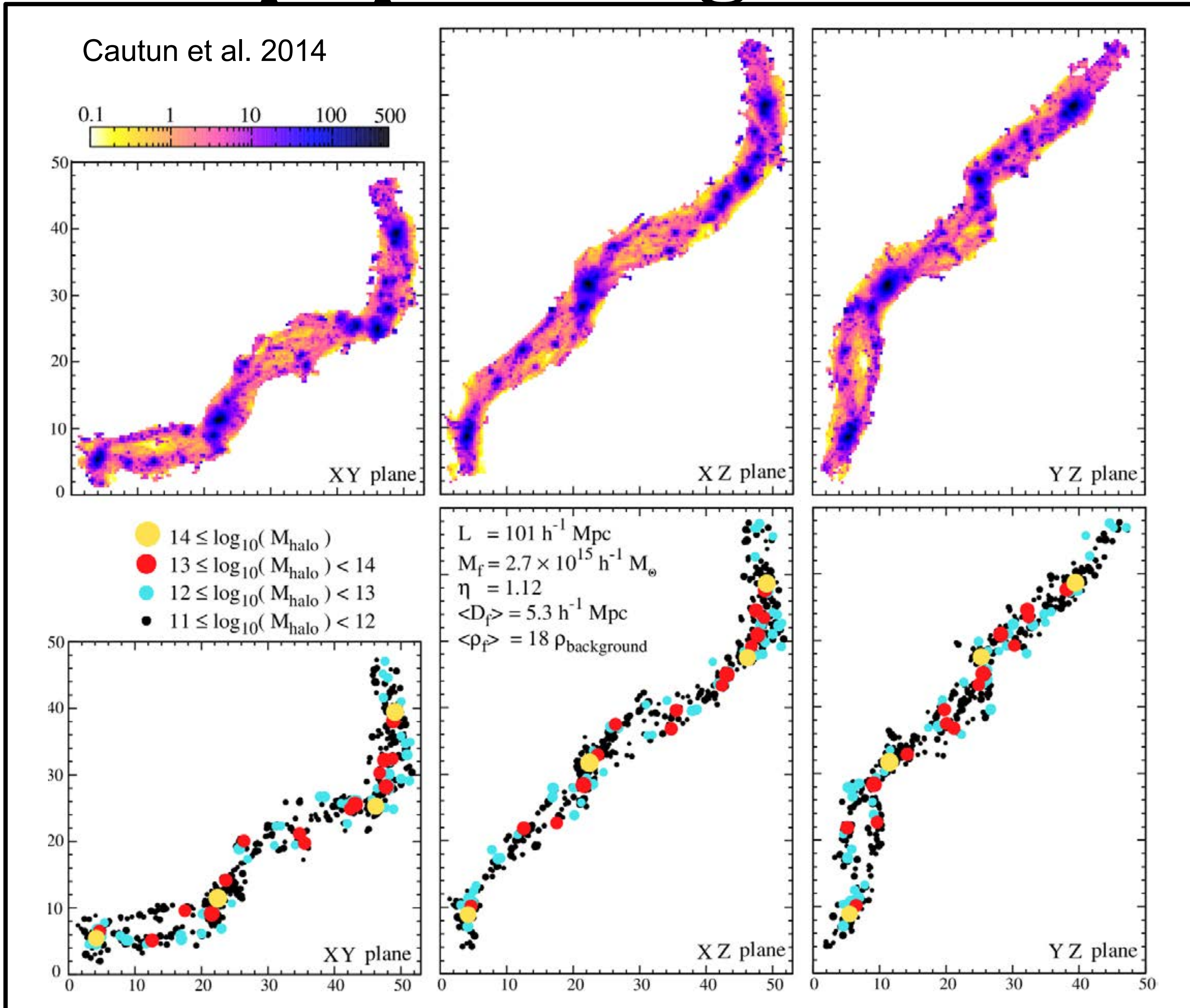
Halos in the Cosmic Web





Cautun et al. 2014

Halos populating Filaments

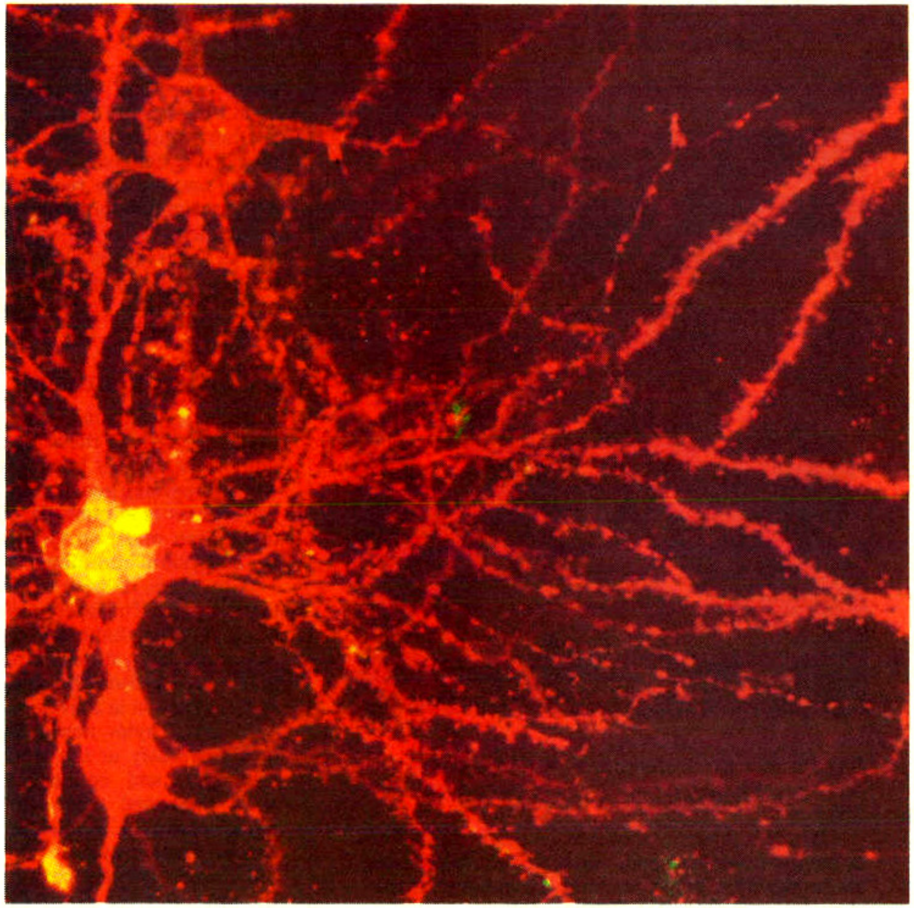


Objectives

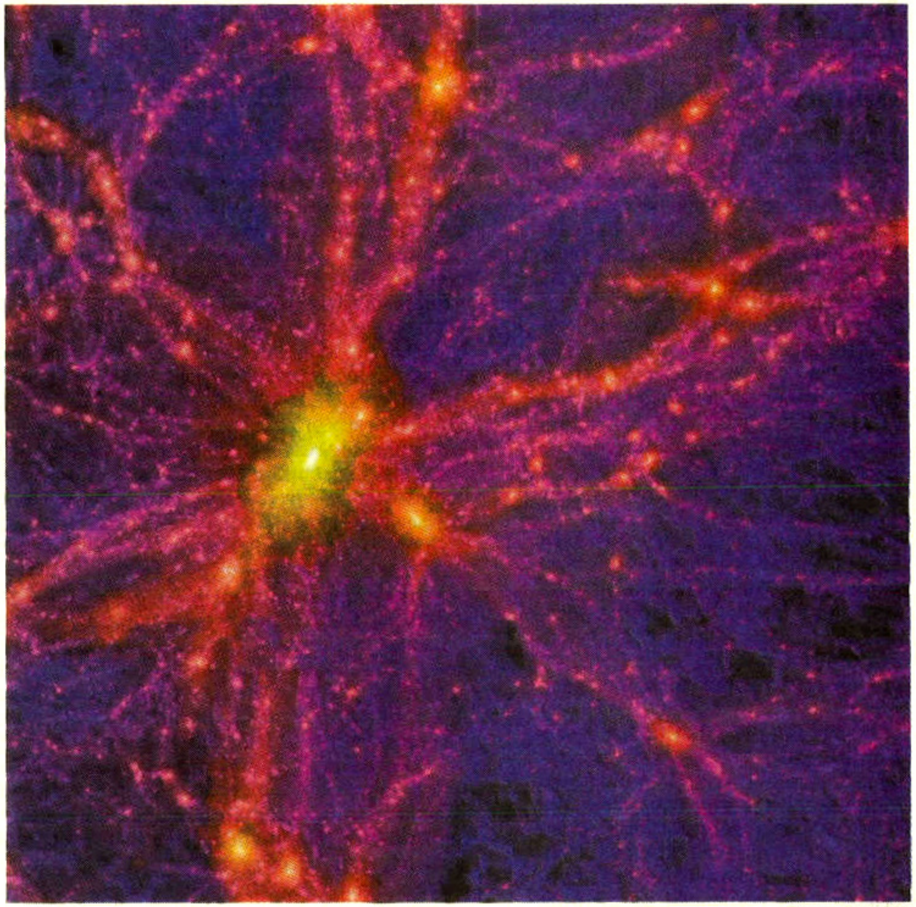
Complex macroscopic patterns in nature arise from the action of basic, often even simple, physical forces and processes. In many physical systems, the spatial organization of matter is one of the most readily observable manifestations of the nonlinear collective actions forming and moulding them.

The richly structured morphologies are a rich source of information on the physical forces at work and the conditions under which the systems evolved. In many branches of science the study of geometric patterns has therefore developed into a major industry for exploring and uncovering the underlying physics

Balbus & Hawley 1998



Mark Miller



Virgo Consortium

Scientific Themes:

- L’art pour l’art:
  - The cosmic web is an interesting astrophysical structure, of intriguing complexity & geometry
  - challenge to understand its structure & dynamics
  - “and the forces & processes that shaped it ...”
- Cosmology:
  - Is there cosmological information hidden in the structure & dynamics of the Cosmic Web ?
  - How to extract such information, given the large variety and differences between methods to dissect the Cosmic Web
- Galaxies
  - How are galaxies influenced by the weblike nature of the cosmic mass distribution in which they form & evolve ?
- Patterns:
  - What is a filament ?
  - What is a wall ?
  - What is a void ?
- Reconstruction:
  - How to map the cosmic mass distribution such that its weblike & multiscale nature is retained ?