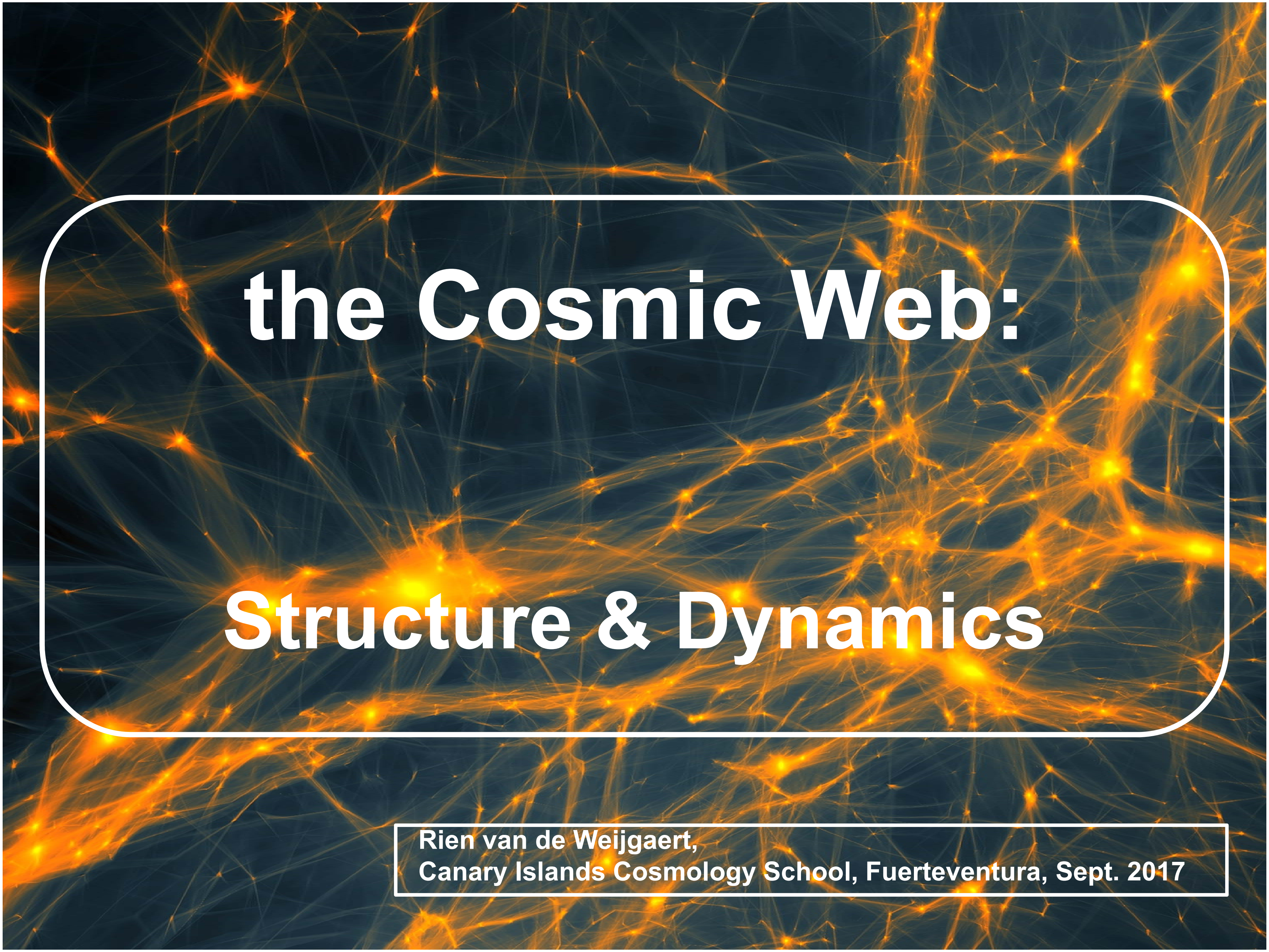
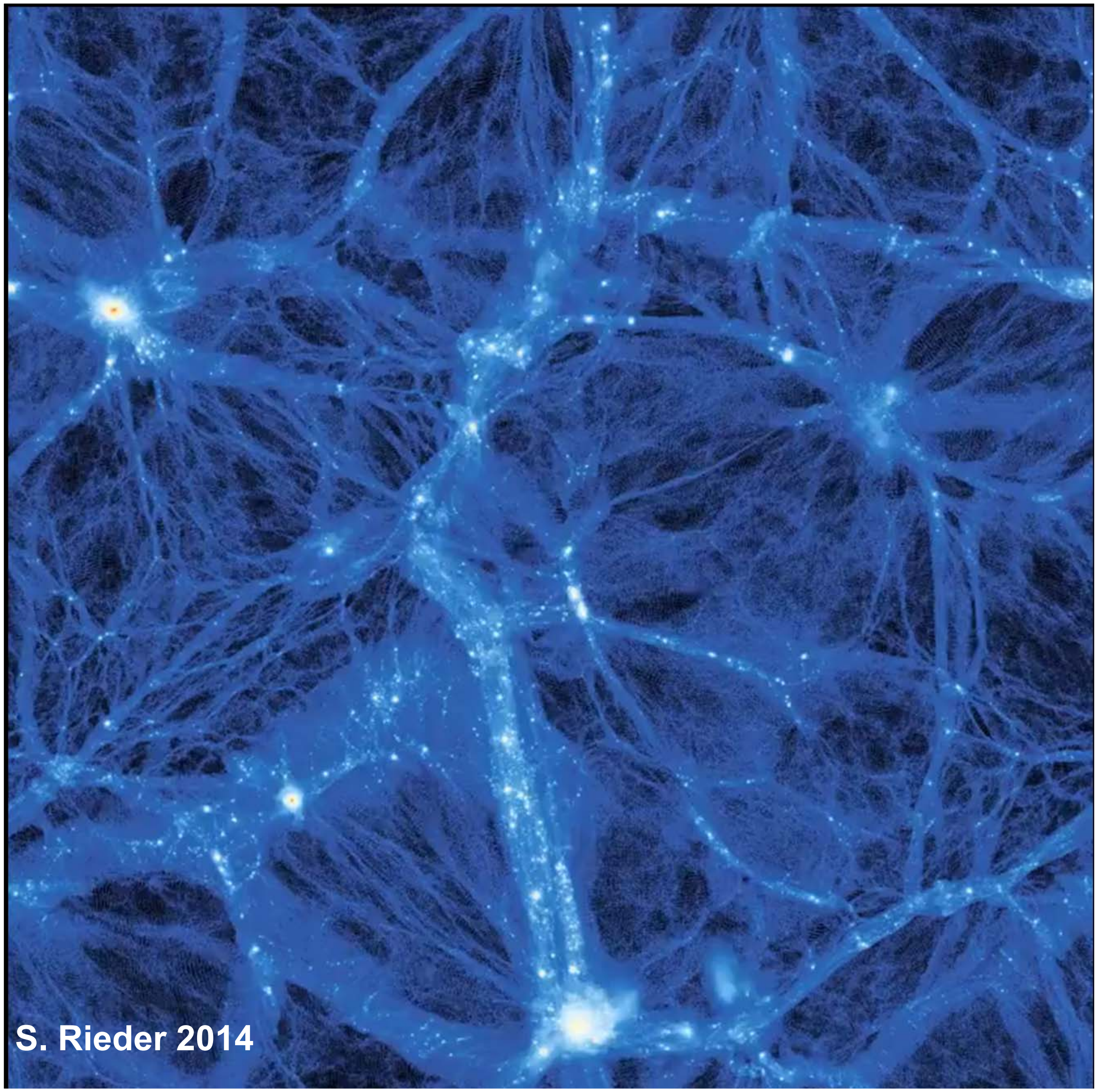

the Cosmic Web:
Structure & Dynamics
Rien van de Weijgaert,
Canary Islands Cosmology School, Fuerteventura, Sept. 2017




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

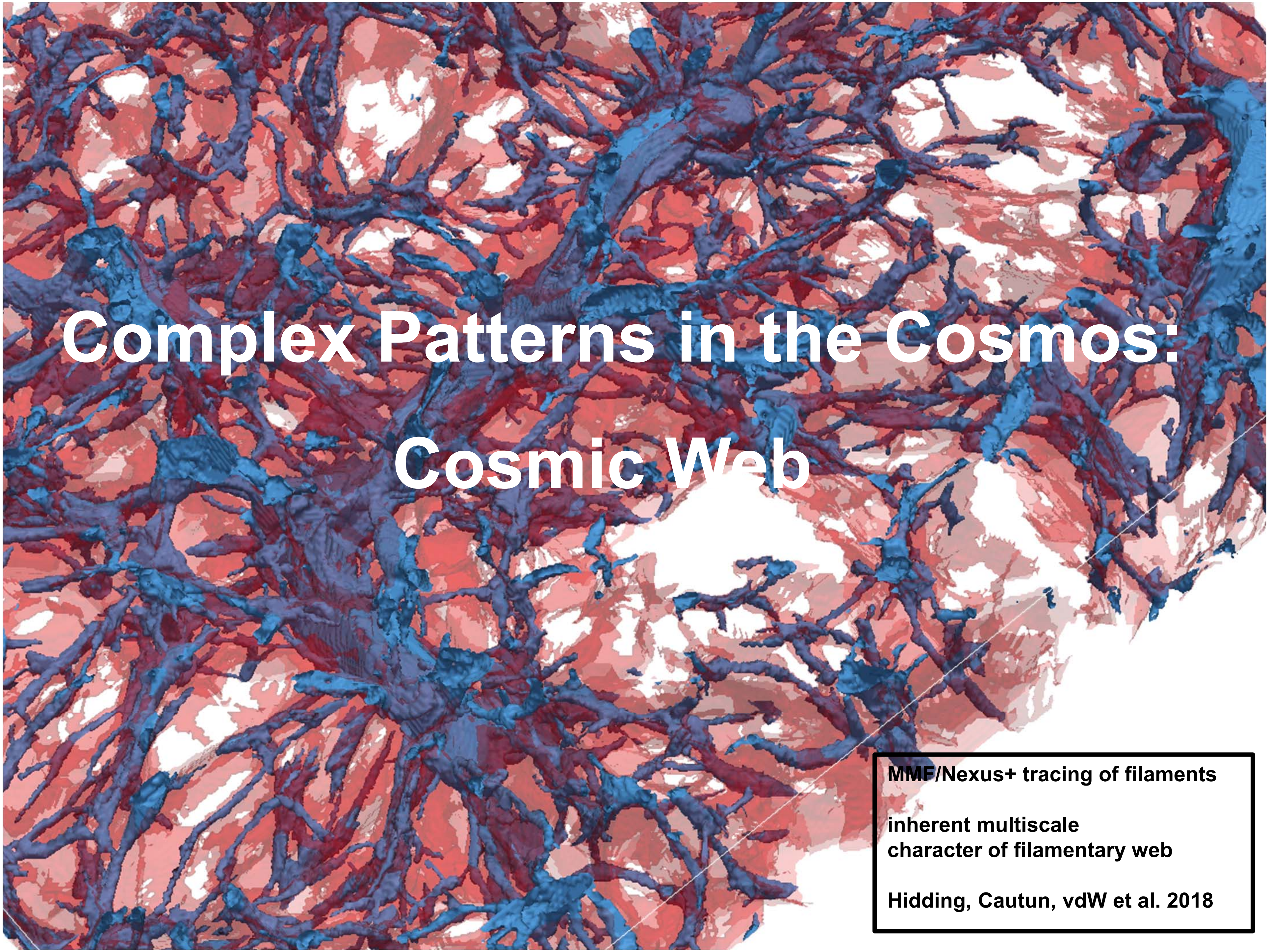
around

- cosmic voids

# Cosmic Web

# Complex Patterns in the Cosmos:

# Cosmic Web



MMF/Nexus+ tracing of filaments

inherent multiscale
character of filamentary web

Hidding, Cautun, vdW et al. 2018

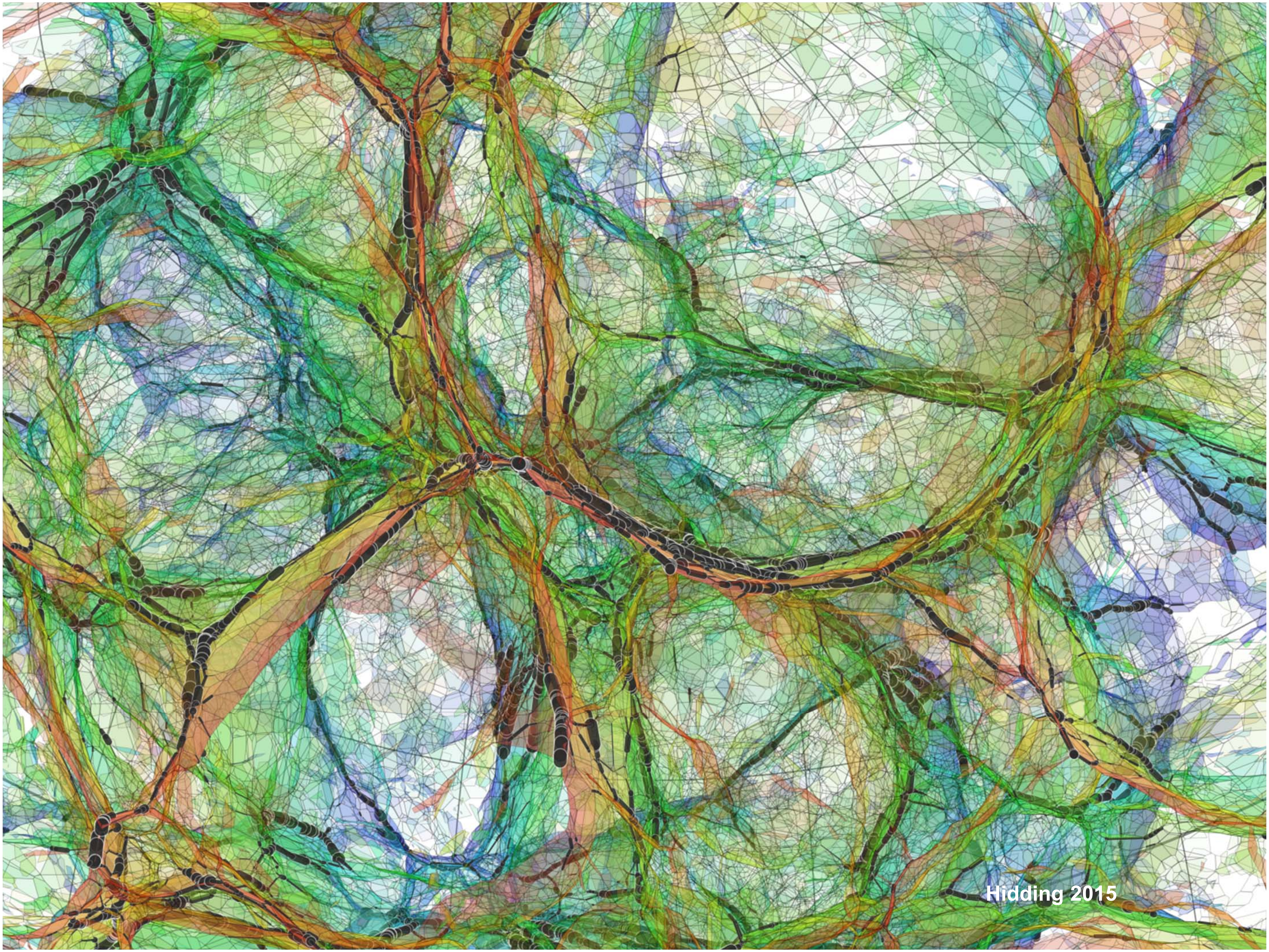
**Complex macroscopic patterns in nature arise from the action of basic, often even simple, physical forces and processes. In many physical systems, the spatial organization of matter is one of the most readily observable manifestations of the nonlinear collective actions forming and moulding them.**

**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**

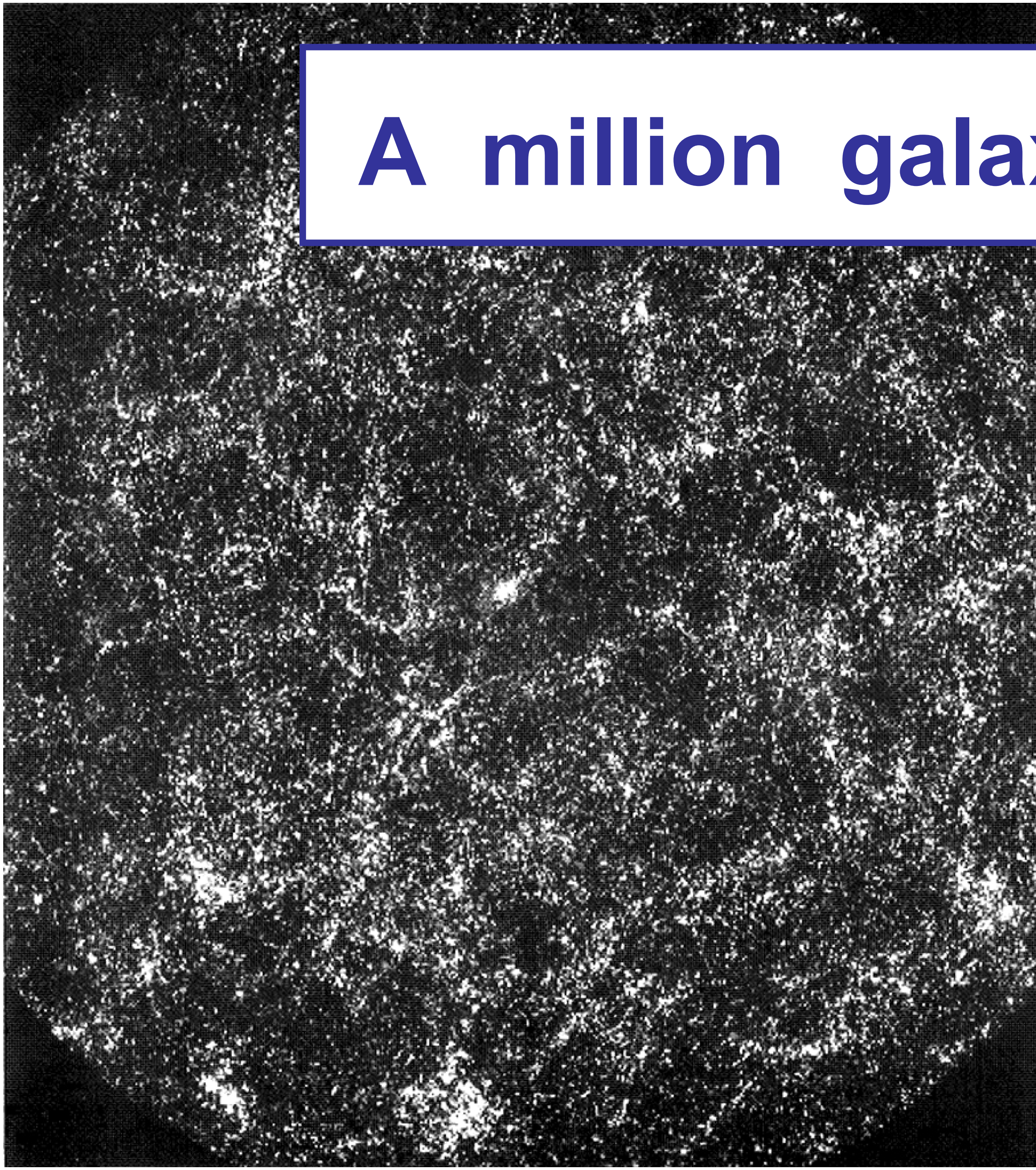
**Balbus & Hawley 1998**

# Cosmic Web

## Setting the Scene


Hidding 2015

# A million galaxies



Shane-Wirtanen map:

On the basis of the Shane-Wirtanen counts,

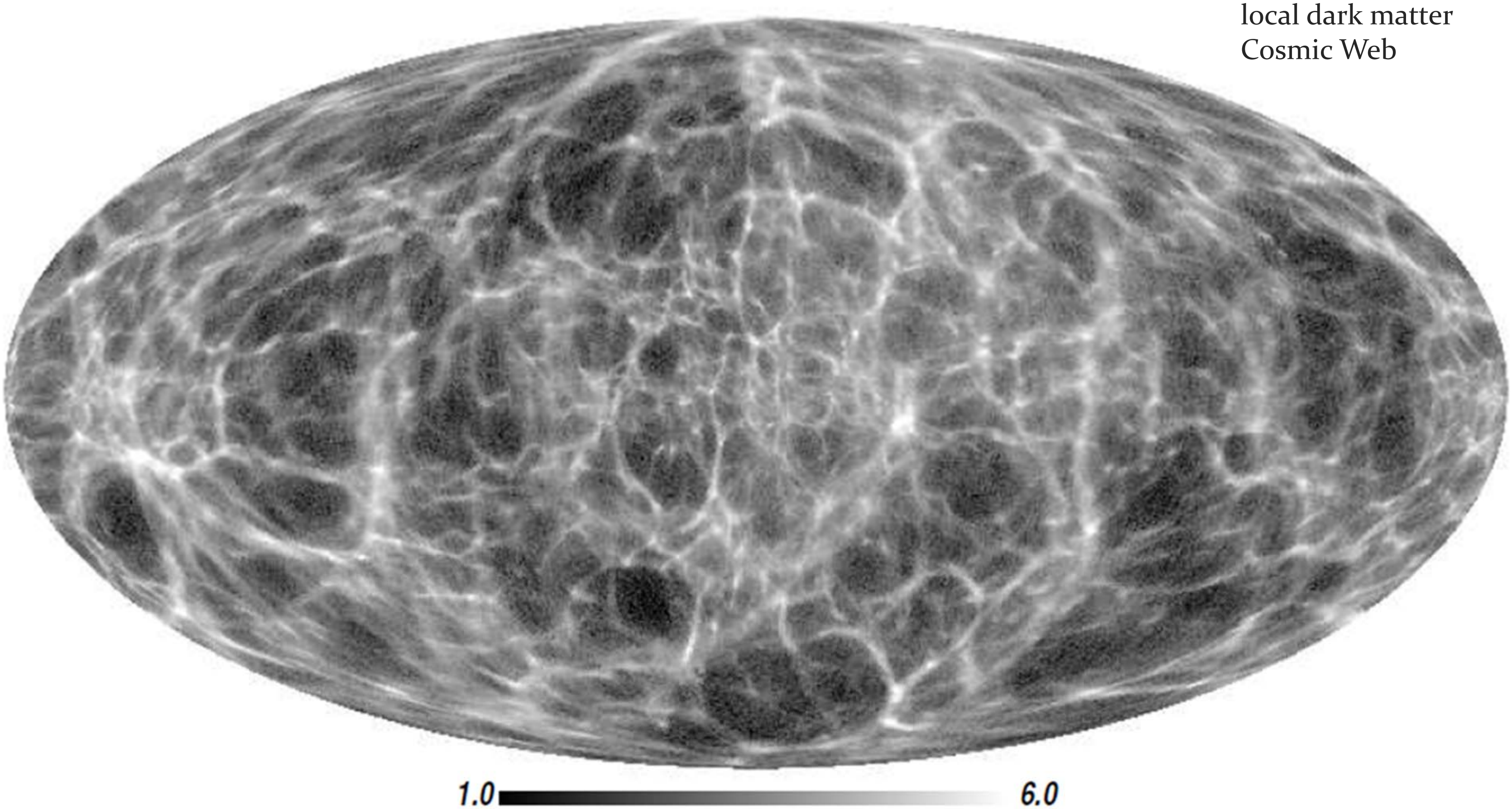
P.J.E. Peebles produced a map of the sky distribution of 1 million galaxies on the sky:

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

# local Cosmic Web: 2MRS

most detailed reconstruction
of the

local dark matter
Cosmic Web




Courtesy: Francisco Kitaura

# Cosmic Web:

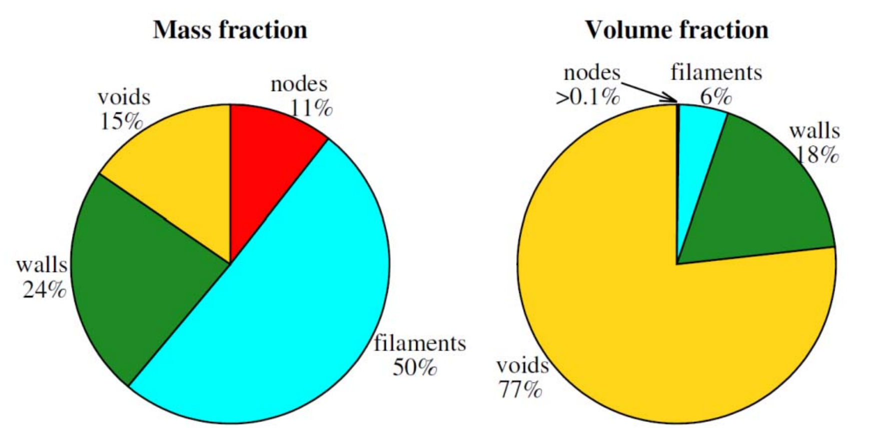
## Density-Morphology Connection

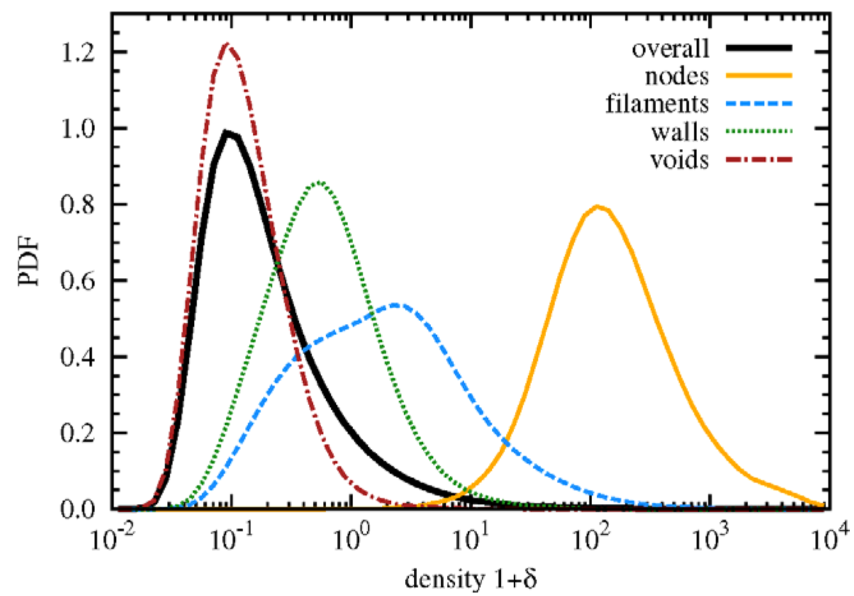
**Mass & Volume content**

**Web morphologies**

**Density distribution**

**Individual morphologies**



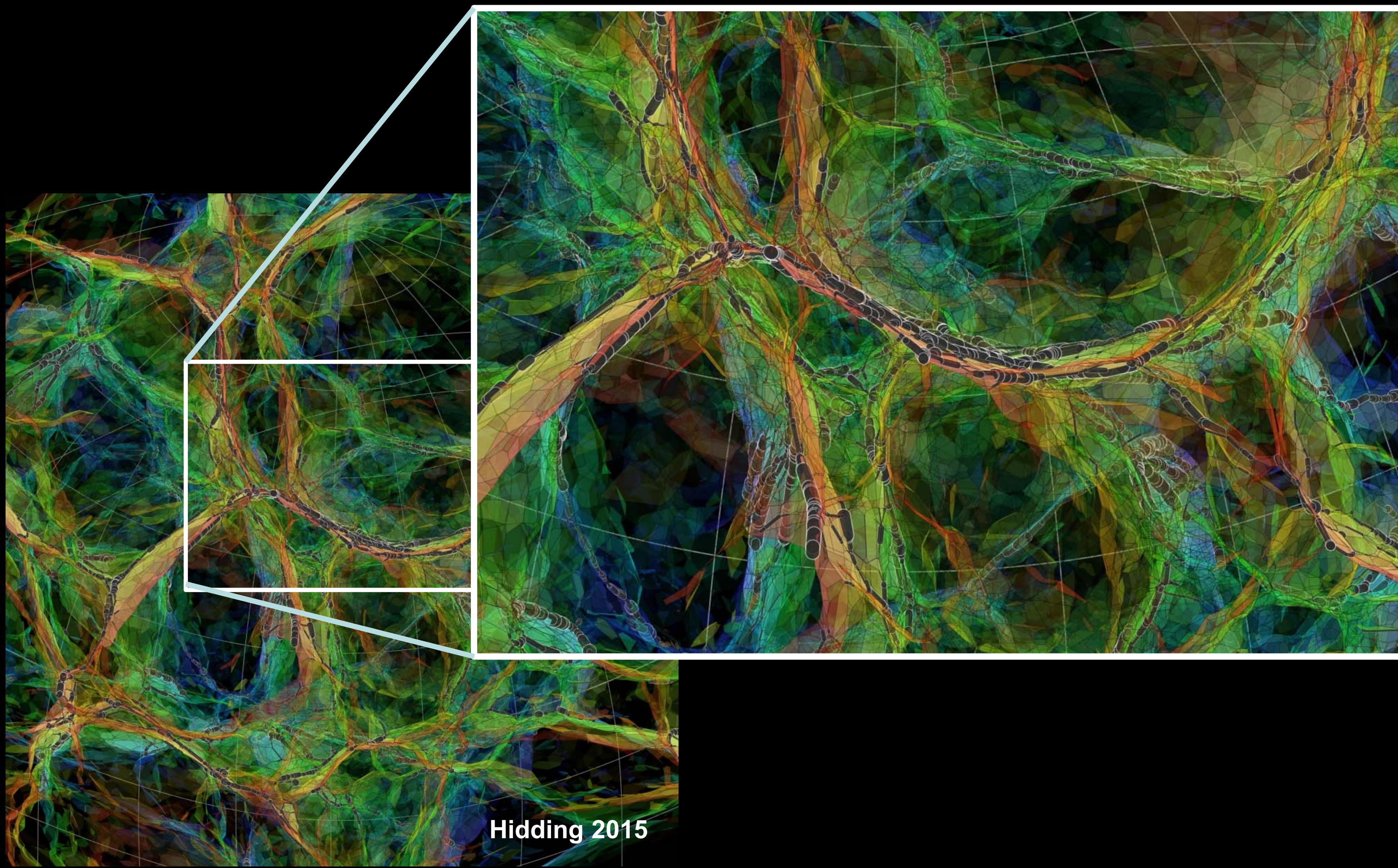



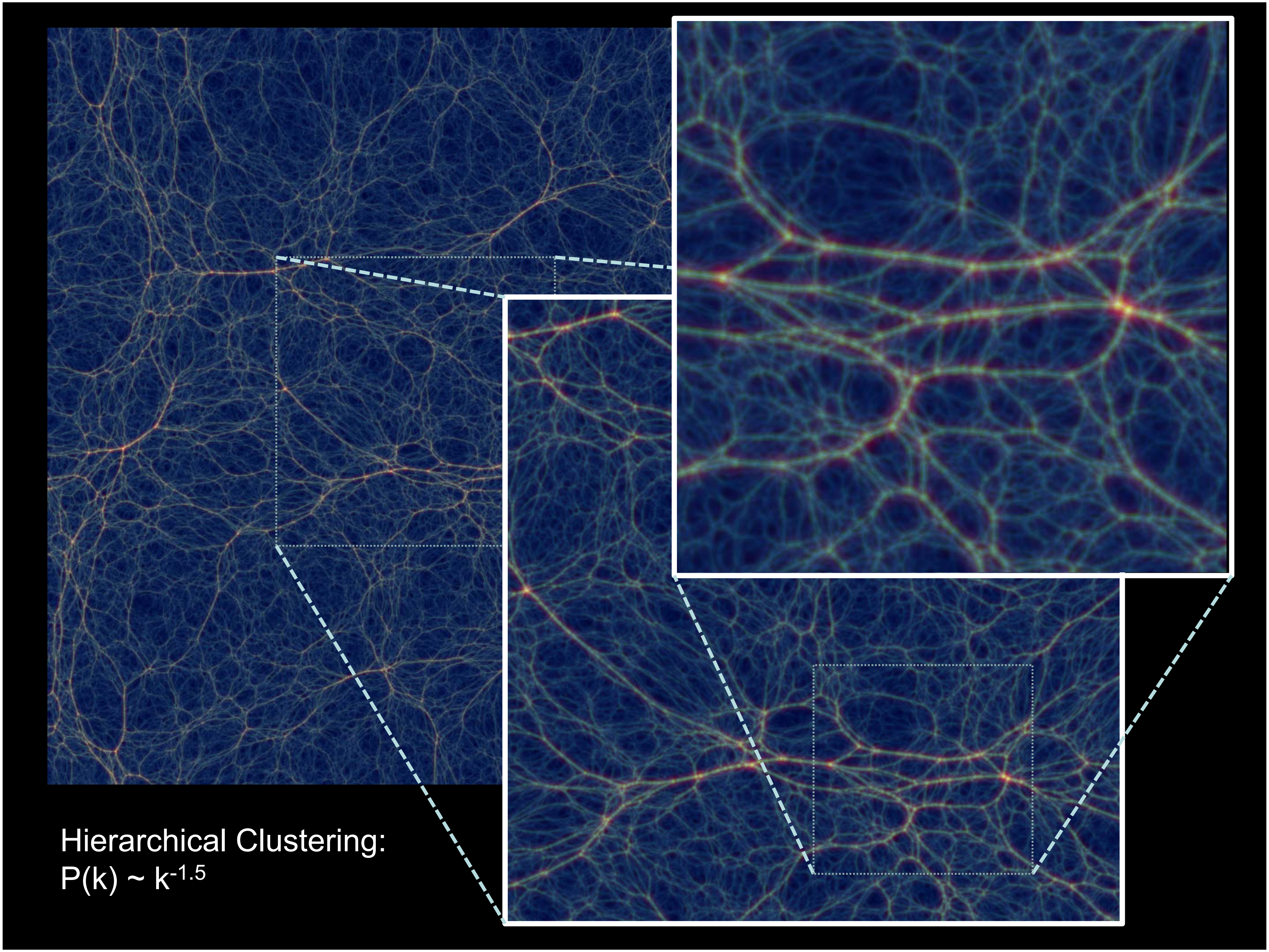

Cautun et al. 2014

# Cosmic Web Characteristics

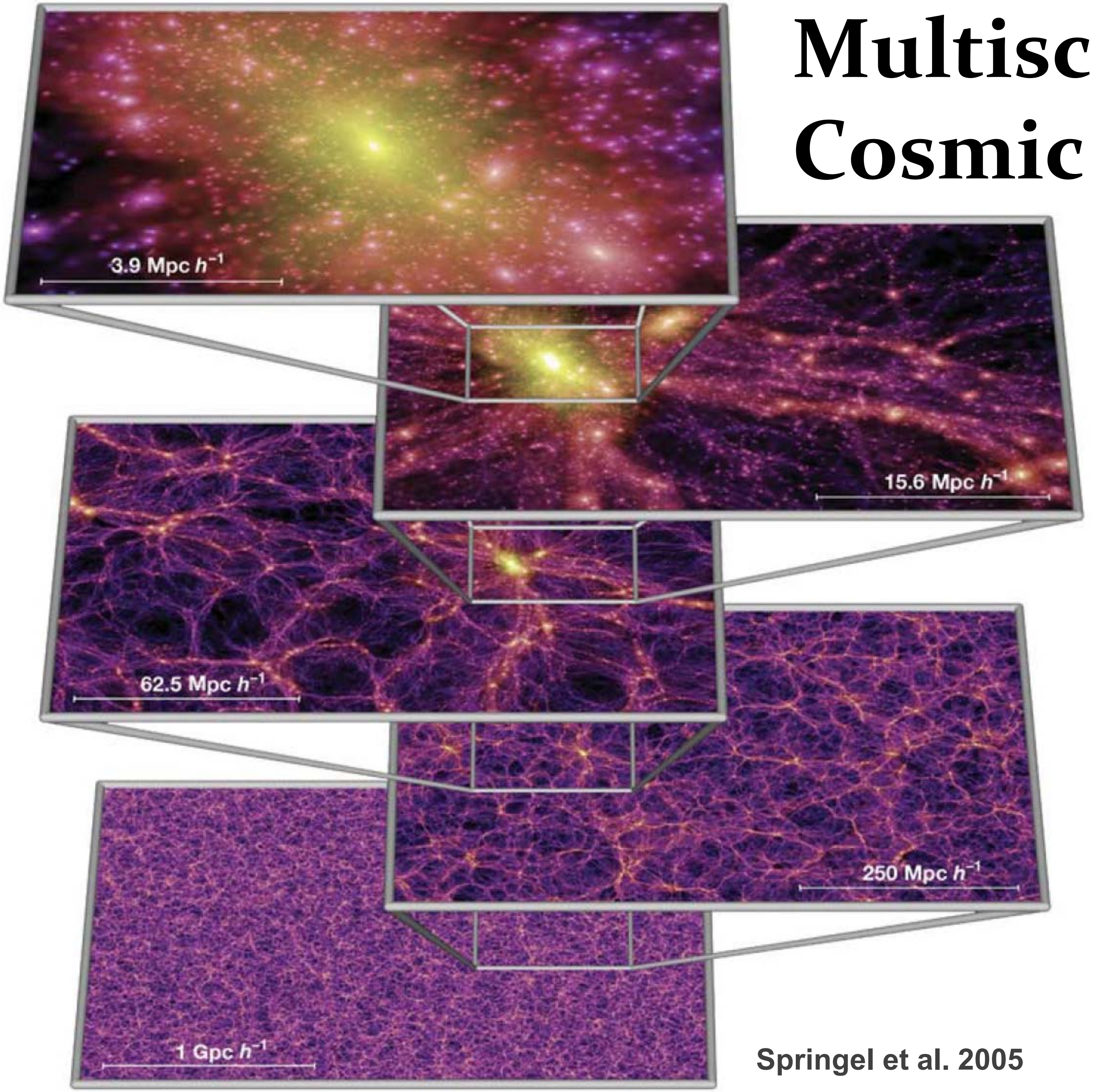
- **anisotropic structure:**
  - filaments dominant structural feature - elongated
  - sheets/walls - flattened
- **multiscale nature**
  - structure on wide range of scales
  - structures have wide range of densities
- **overdense-underdense asymmetry**
  - voids: underdense, large & roundish
  - filaments & 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




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

# Multiscale Cosmic Web

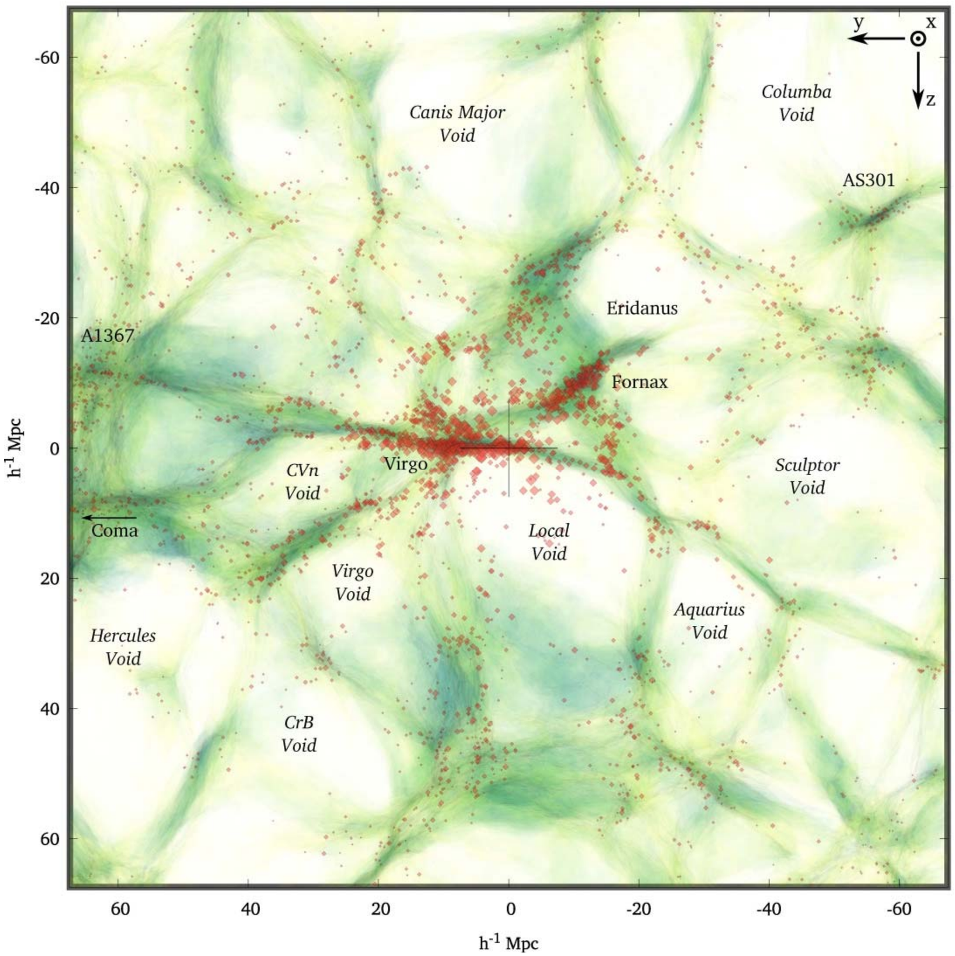


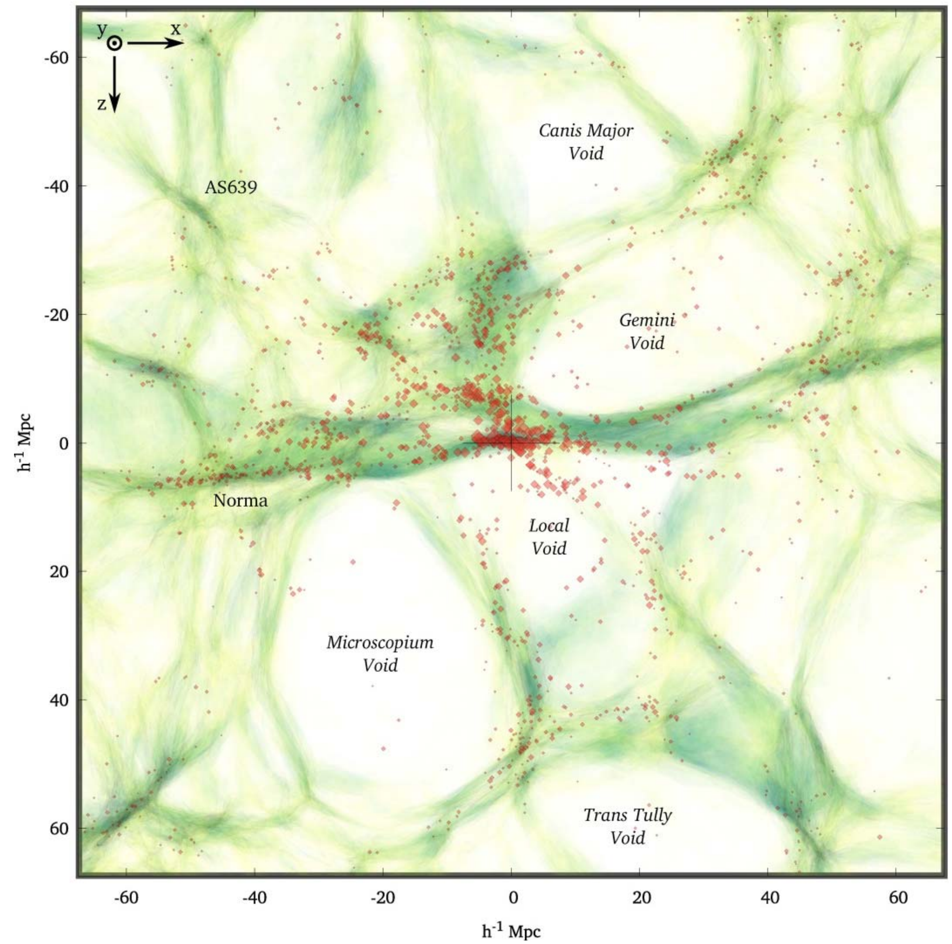

Springel et al. 2005

# Void Population Local Universe

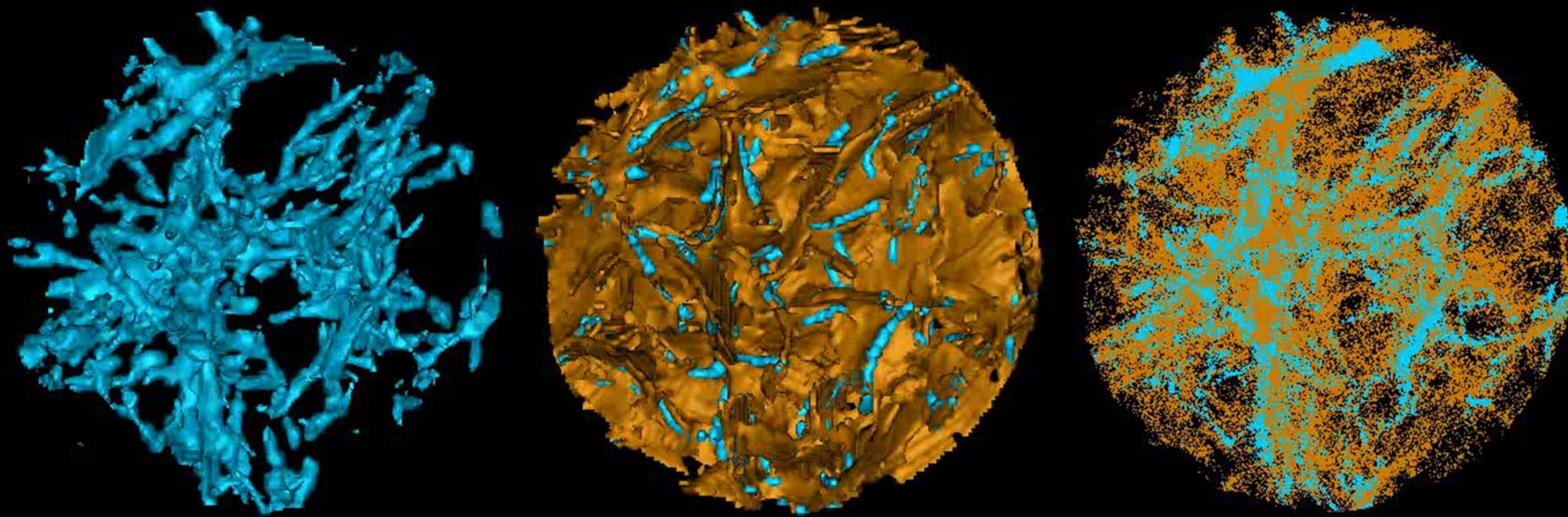
## mean KIGEN-adhesion reconstruction (2MRS)

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 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

## Dynamics & Formation:

## Program

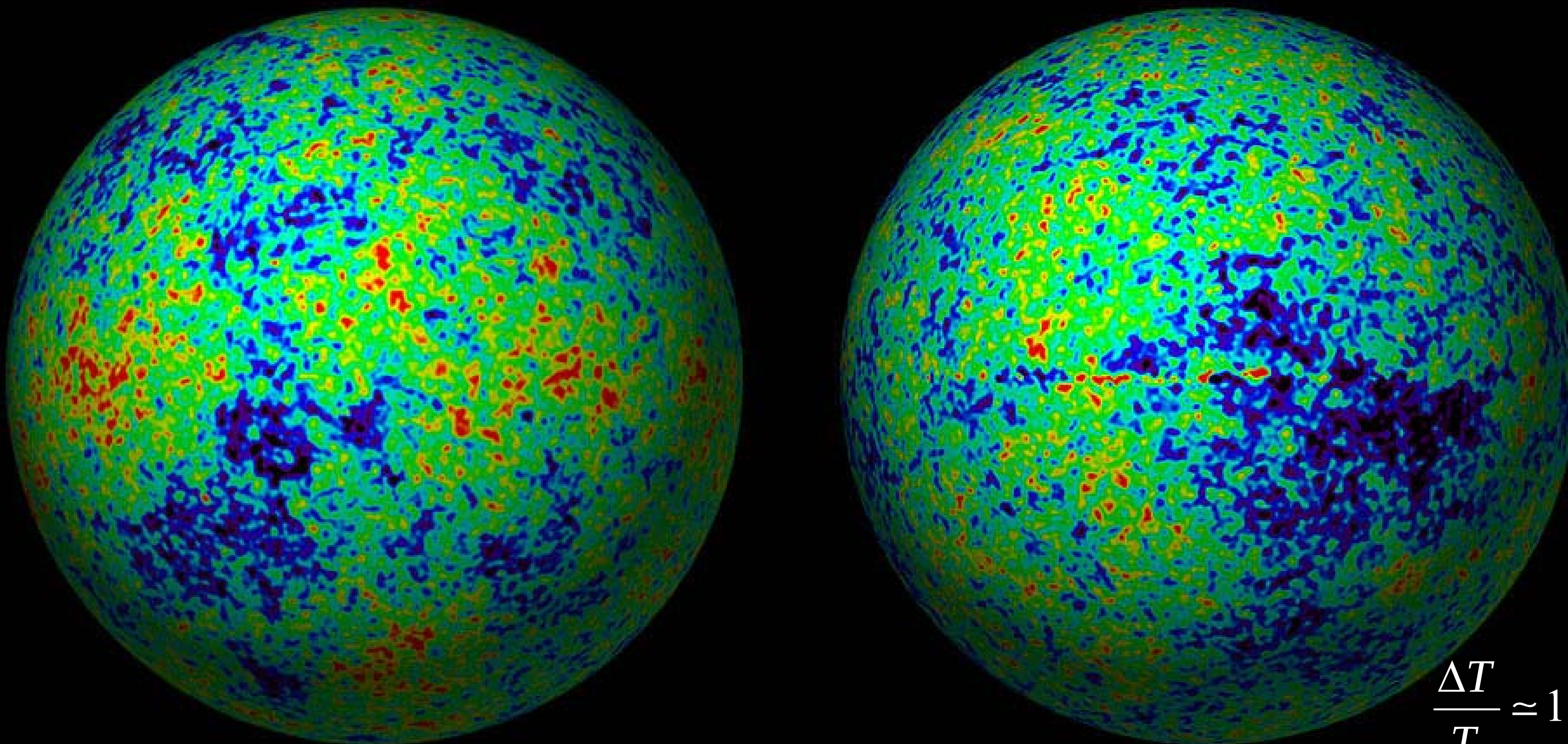
# Cosmic Web – Formation, Evolution, Dynamics

- the Mechanism - Gravitational Instability
- Anisotropic Collapse - Formation of filaments and walls
- Weaving the Web - Connection Clusters, Filaments and Walls
- Hierarchical Formation - from small to the Megaparsec Cosmic Web
- Anisotropy & Hierarchy - the Adhesion formalism
- Phase Space - Multistream structure
  - Caustics & Catastrophes
  - Skeleton of the Cosmic Web
- Voids - Void Hierarchy
  - the evolving soapsud

# Cosmic Structure Formation:

# Gravitational Instability

# Primordial Universe

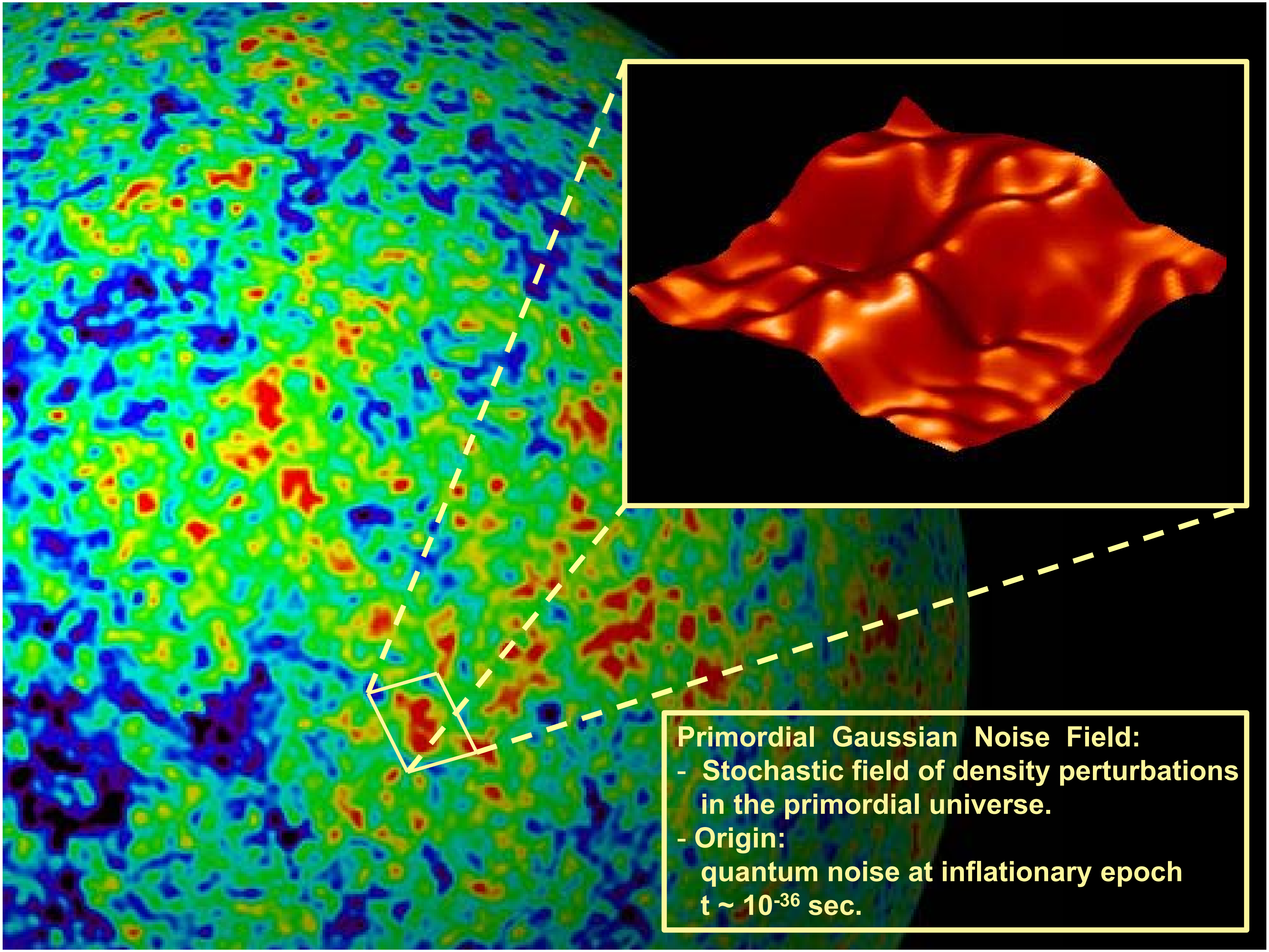


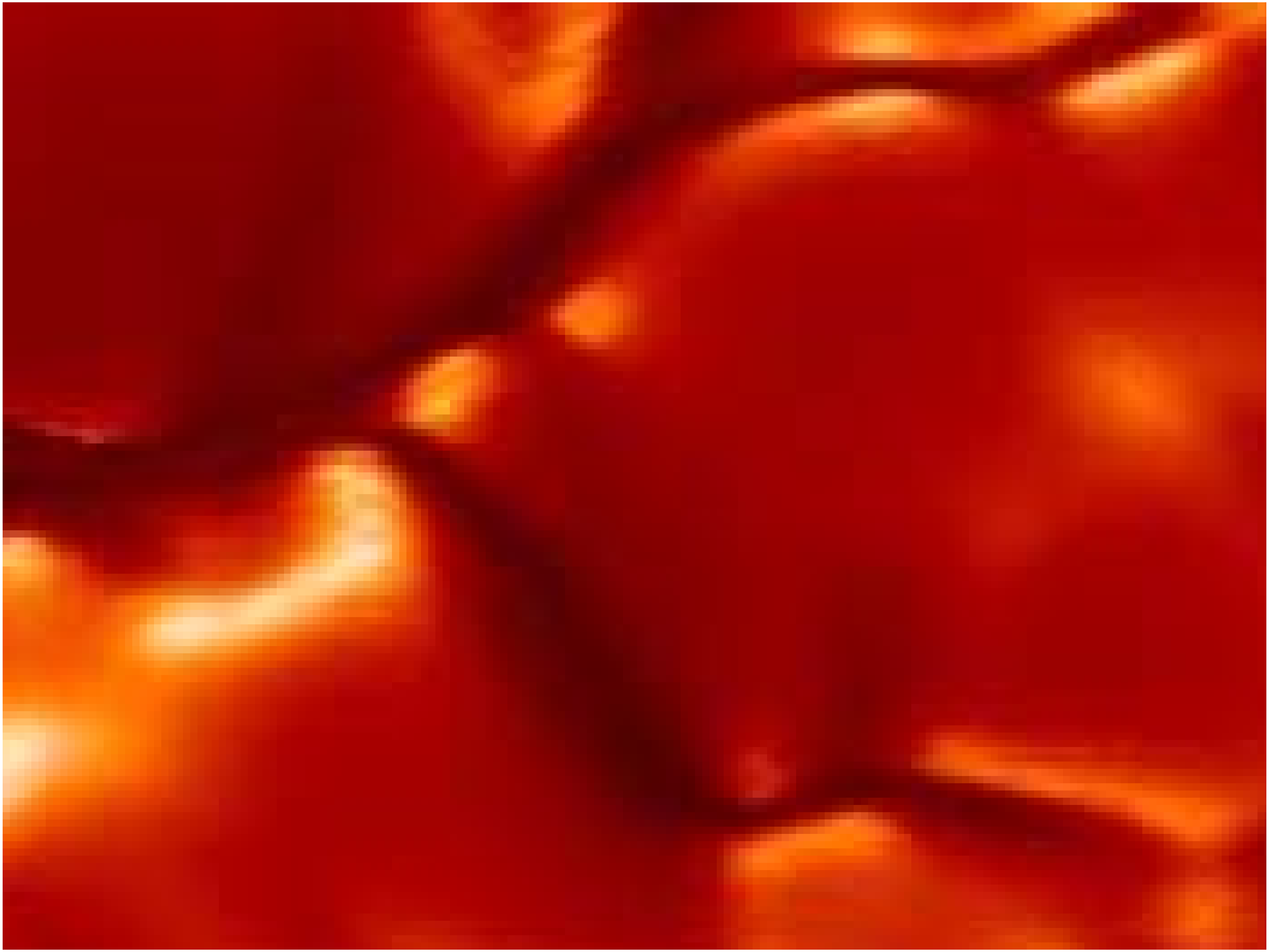
$$\frac{\Delta T}{T} \simeq 10^{-5}$$

global representation cosmic surface last scattering:  the world inside out

**Temperature Map CMB radiation:**

Tiny variations in primordial temperature, reflecting tiny inhomogeneities in
energy density of □~$10^{-5}$ K at
recombination epoch, 379,000 yrs after Big Bang

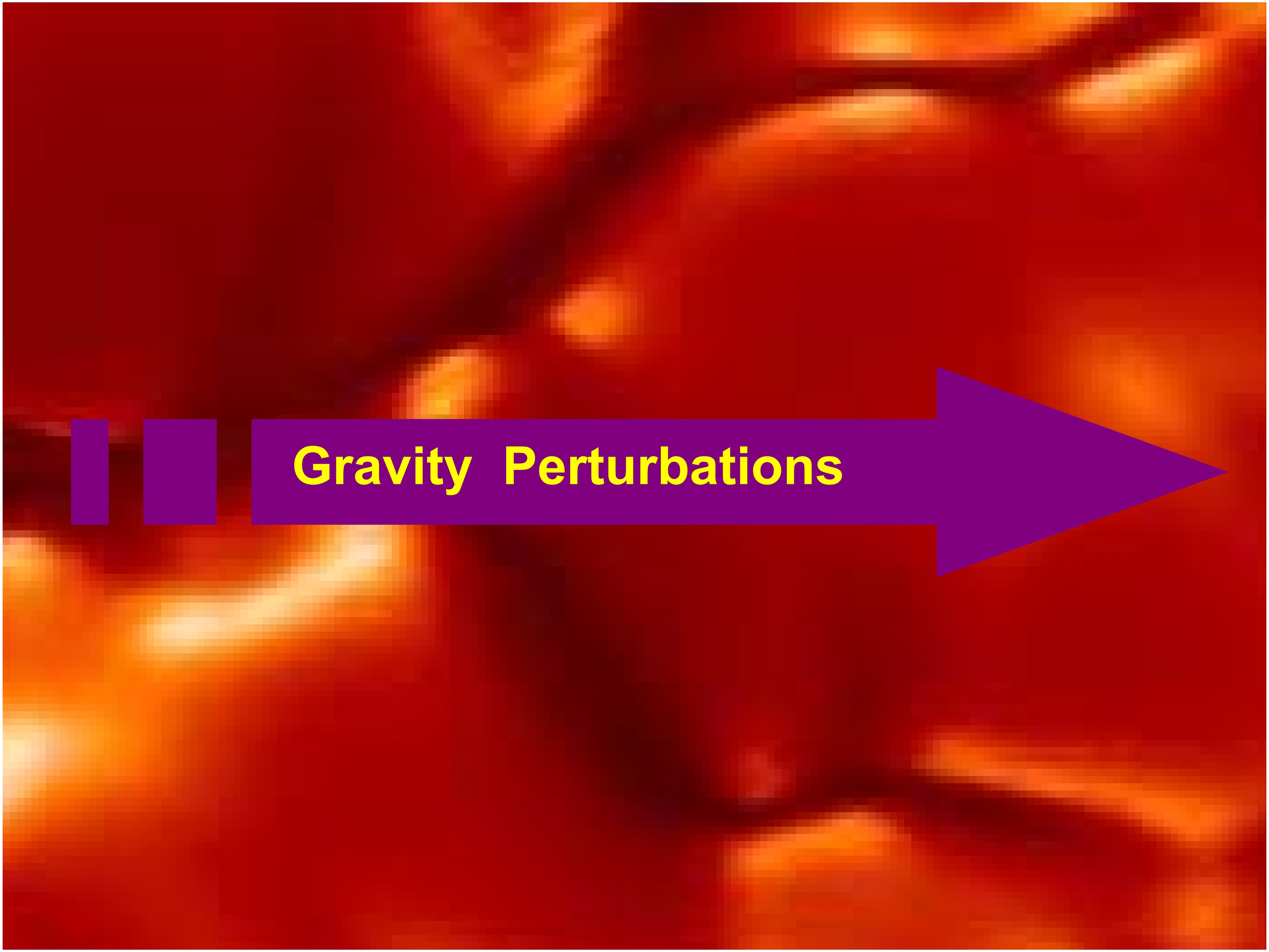

Primordial Gaussian Noise Field:
- Stochastic field of density perturbations in the primordial universe.
- Origin:
quantum noise at inflationary epoch
t ~ 10-36 sec.



**Density Perturbation Field:**

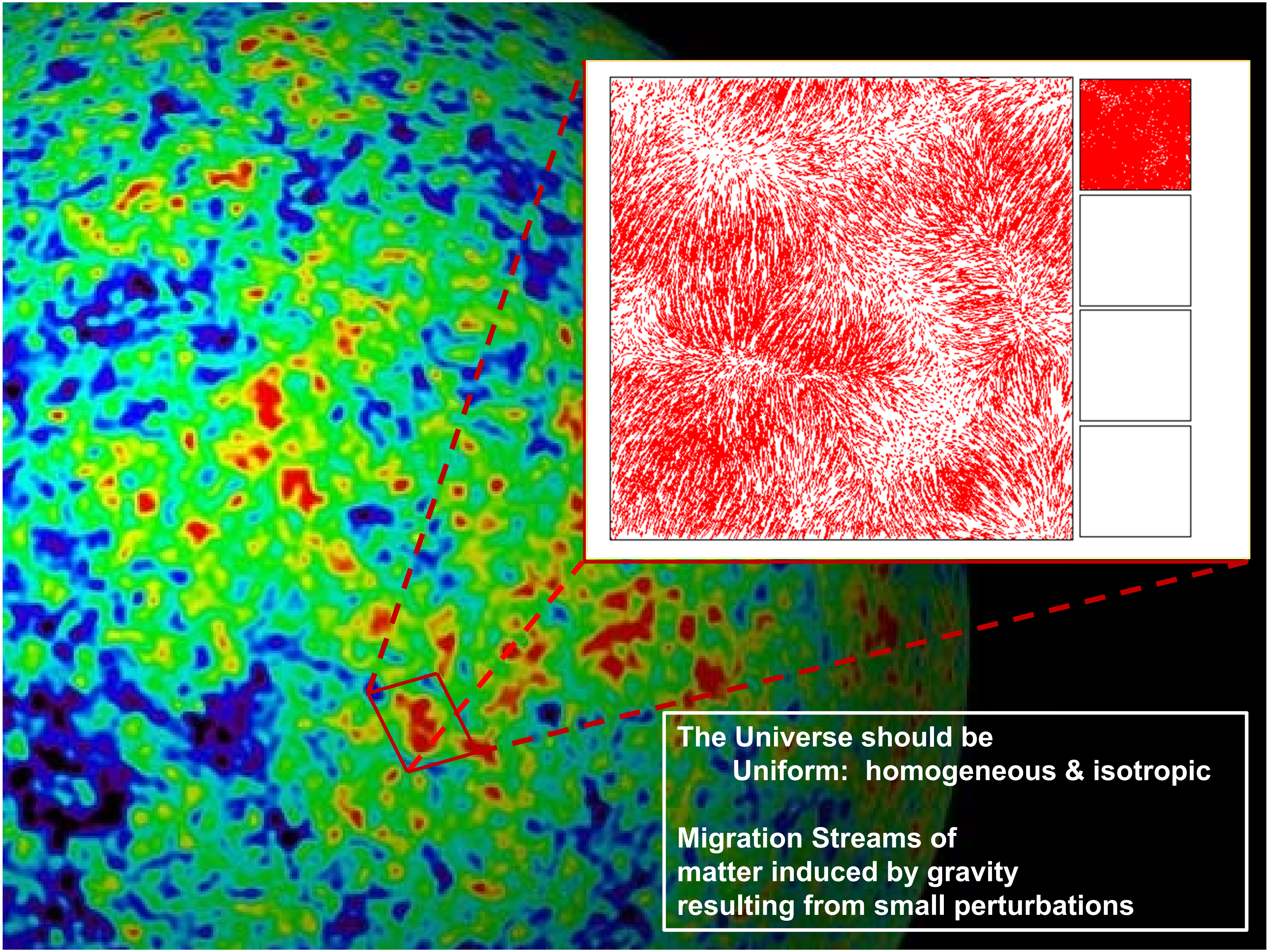
$$\delta(\vec{x},t) = \frac{\rho(x,t) - \rho_u(t)}{\rho_u(t)}$$

# Gravity Perturbations



## Gravity Perturbations

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


The Universe should be
Uniform: homogeneous & isotropic
Migration Streams of
matter induced by gravity
resulting from small perturbations

# Cosmic Structure Formation

(Energy) Density Perturbations

⬇

Gravity Perturbations

⬇

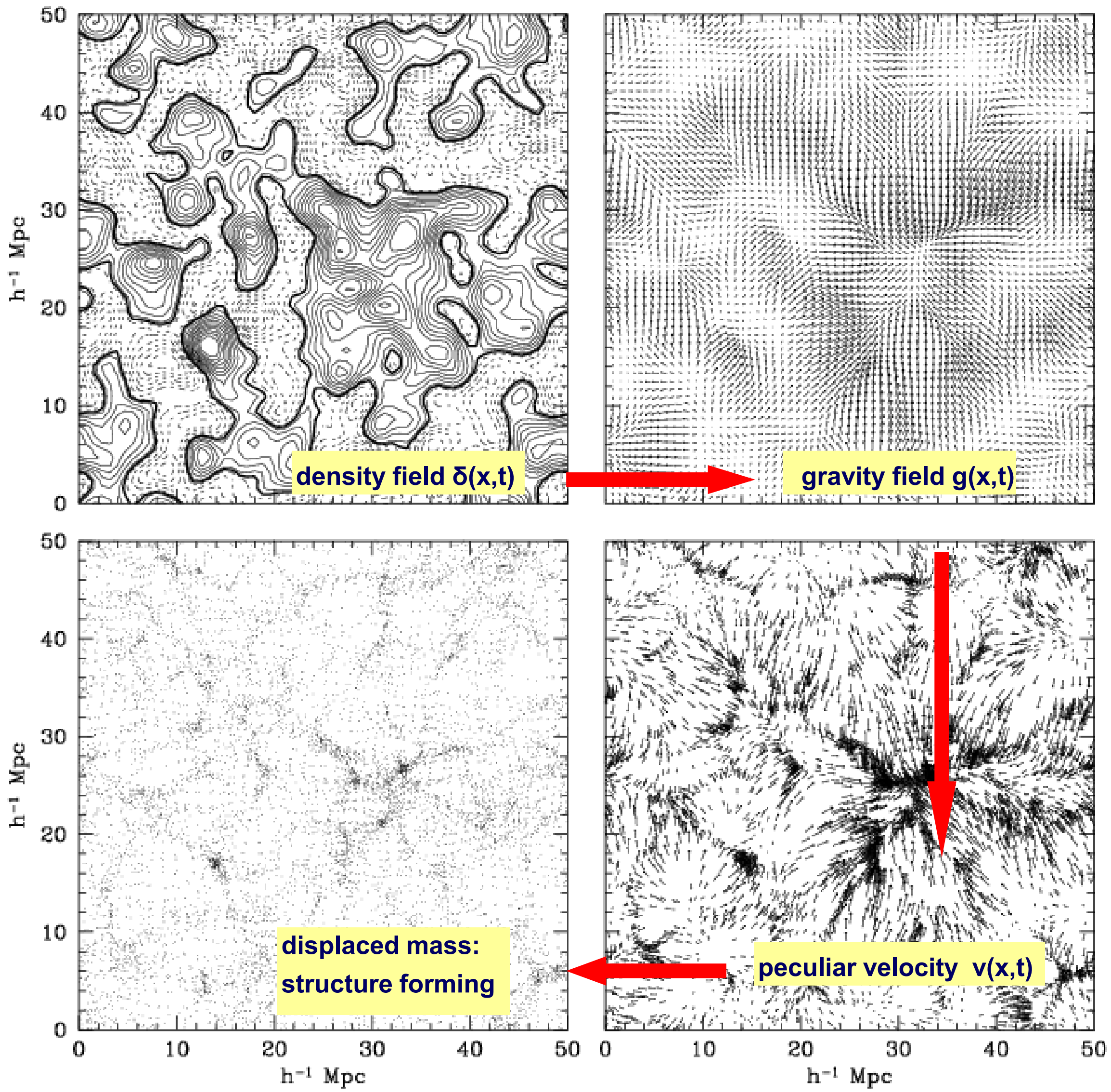
(Cosmic) Flows of (Energy) & Matter:

- 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

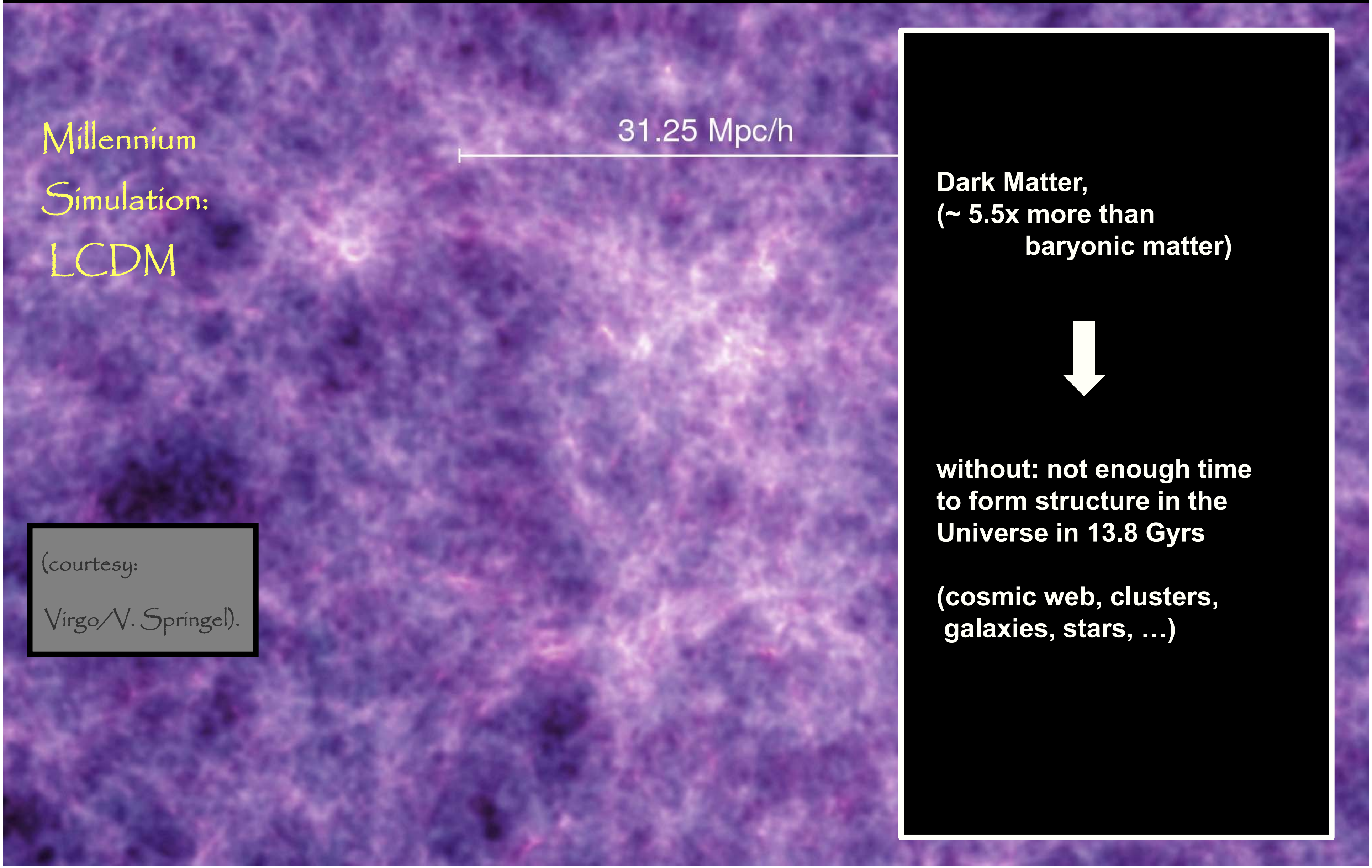
⬇

Emergence of cosmic structures

- Computer Simulations
  - succesfull confrontation with observational reality



# Cosmic Structure Formation



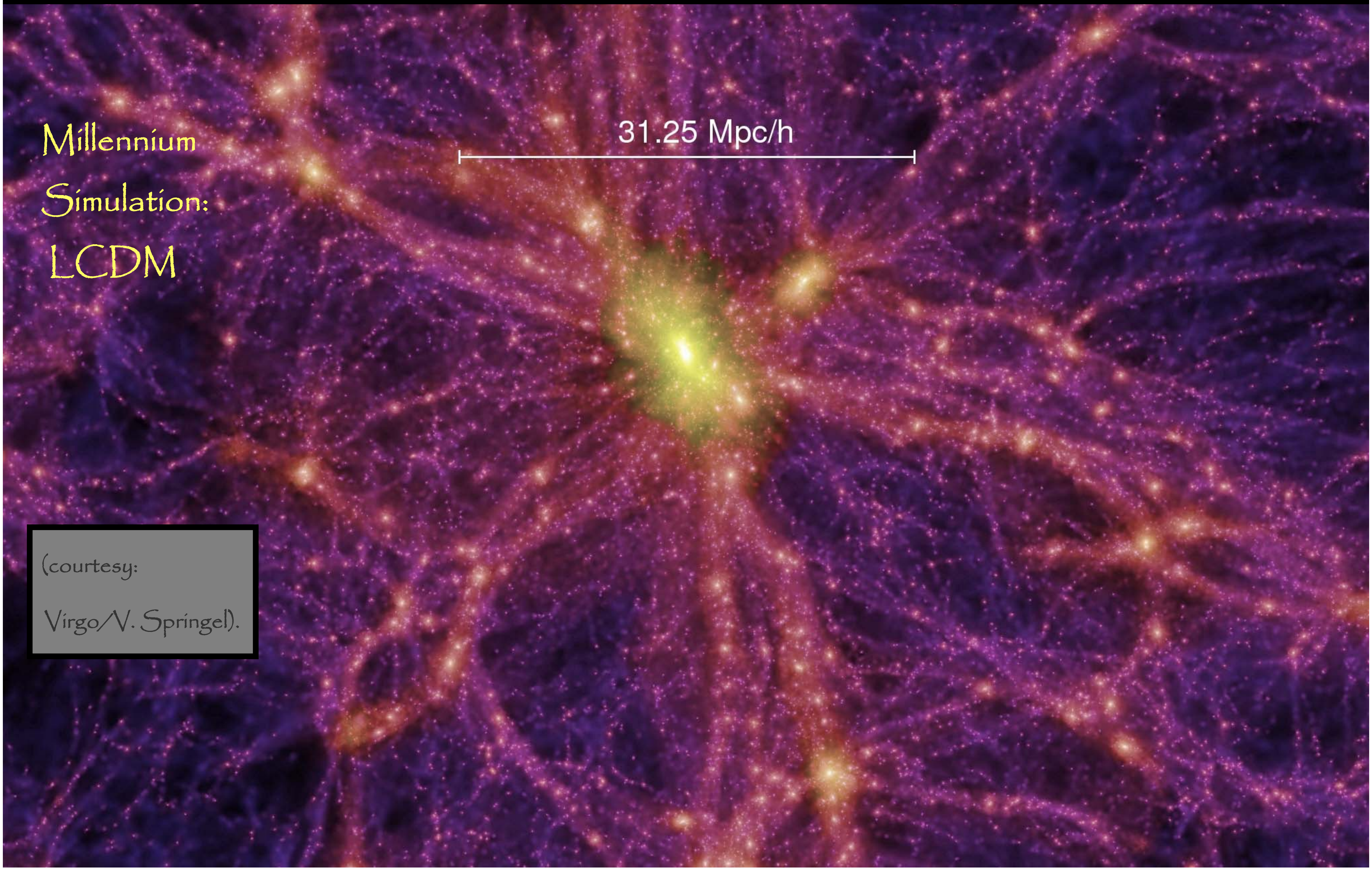

**Dark Matter,
(~ 5.5x more than
baryonic matter)**

⬇

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

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

# Cosmic Structure Formation



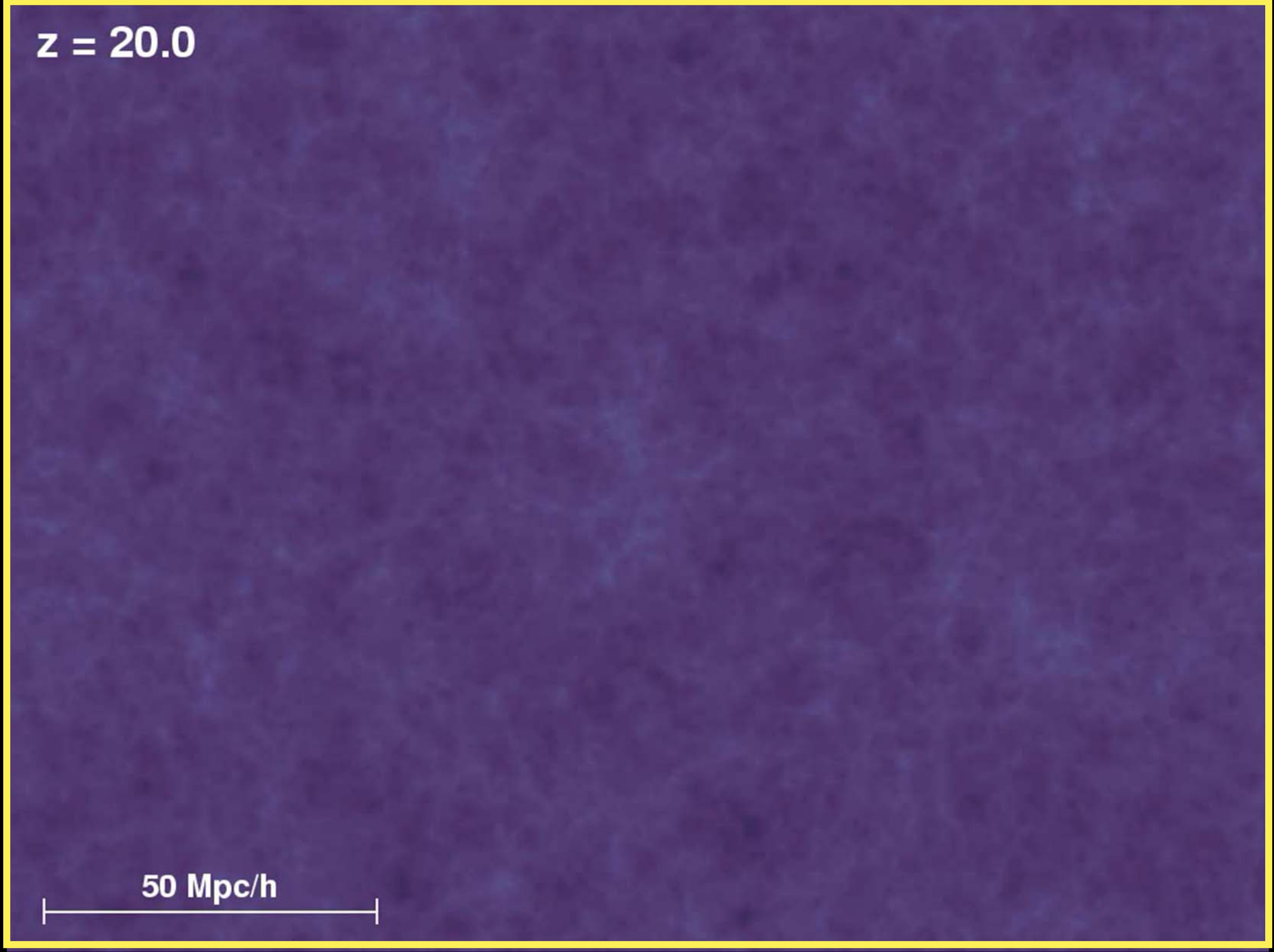
# Cosmic Structure Formation

Formation
Cosmic Web:

simulation
sequence

(cold)
dark matter

(courtesy:
Virgo/V. Springel).



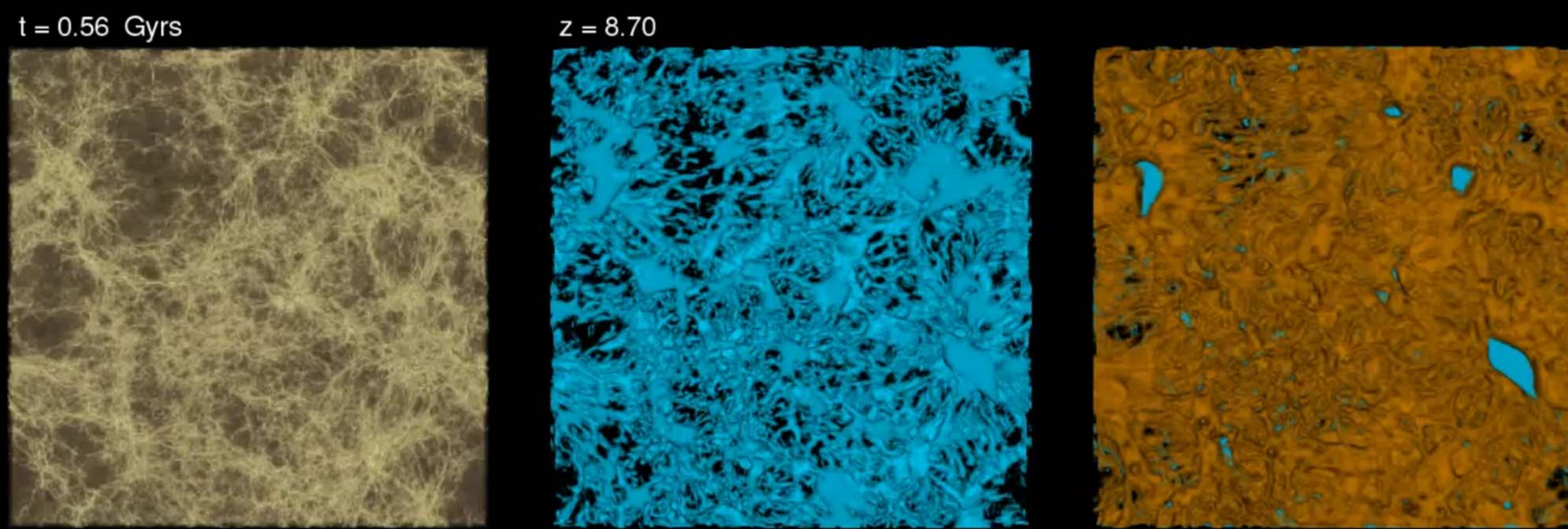
# Dynamical Evolution Cosmic Web

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

# the Cosmic Web:

# evolution of walls & filaments

# NEXUS/MMF
# Evolution Cosmic Web



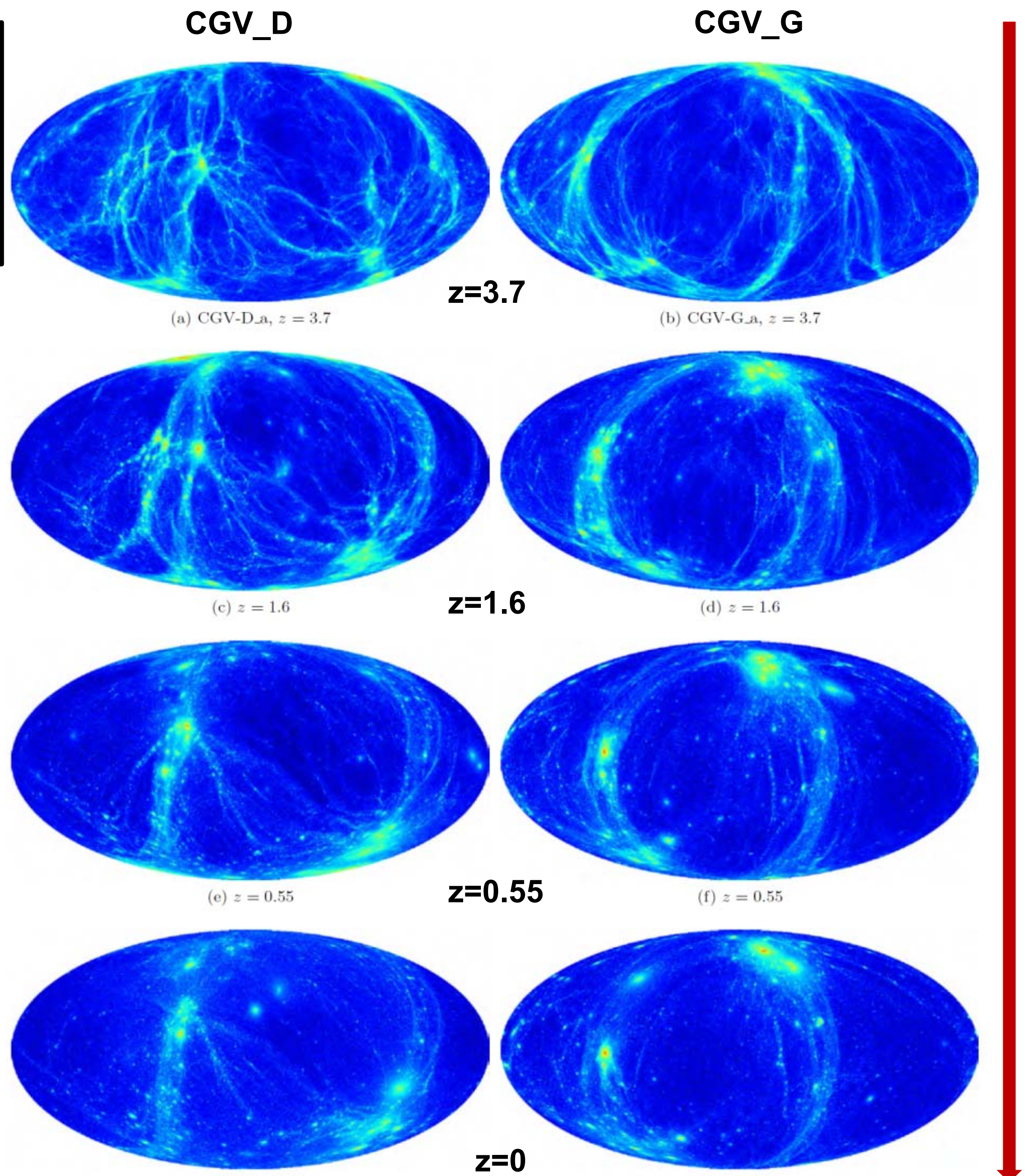

Cautun et al. 2013

# 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

Rieder et al. 2013




(a) CGV-D_a, $z = 3.7$ (b) CGV-G_a, $z = 3.7$

(c) $z = 1.6$ (d) $z = 1.6$

(e) $z = 0.55$ (f) $z = 0.55$

(g) $z = 0$ (h) $z = 0$

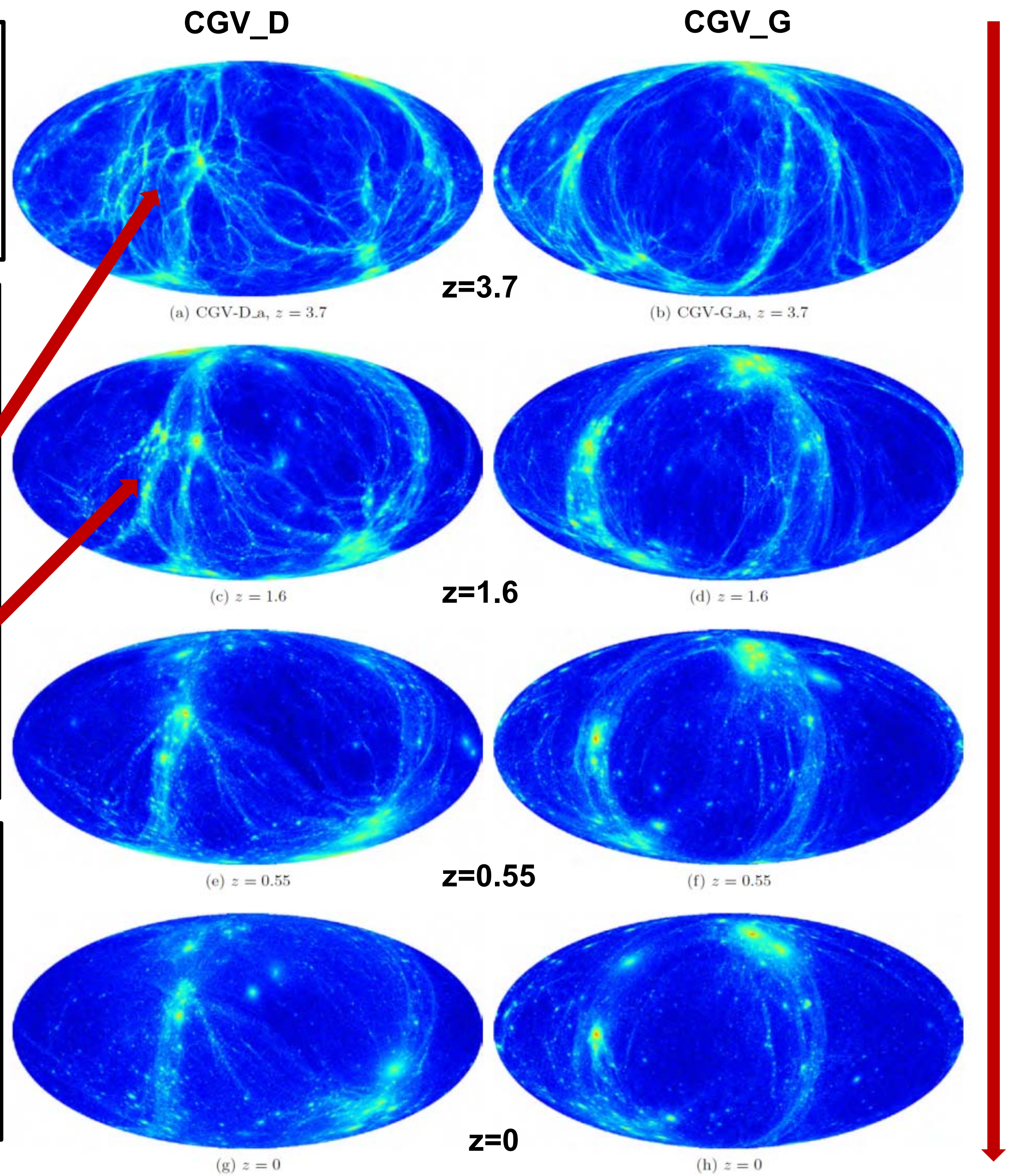
# CGV:

## on walls & filaments

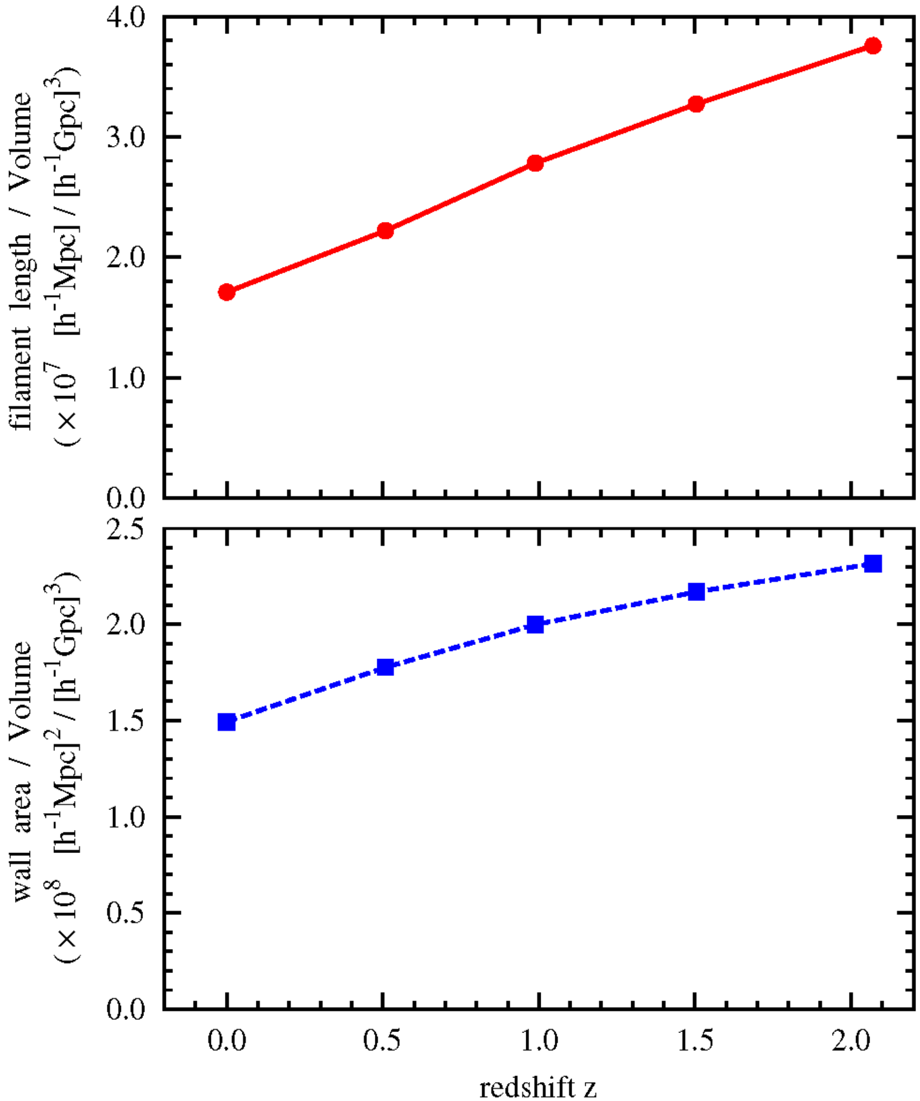
- Mollweide sky projection
  matter distribution around CGV halos
- CGV halos embedded in walls
- Walls dominate void infrastructure
- substantial fraction in filaments
  (embedded in walls)
- active dynamical evolution of
  wall-filament goes along with
  active void galaxy halo evolution

merging system of
Intravoid walls

Rieder et al. 2013



# Evolving Filament & Wall Network




Total length of filament network :

decreasing as a function of time

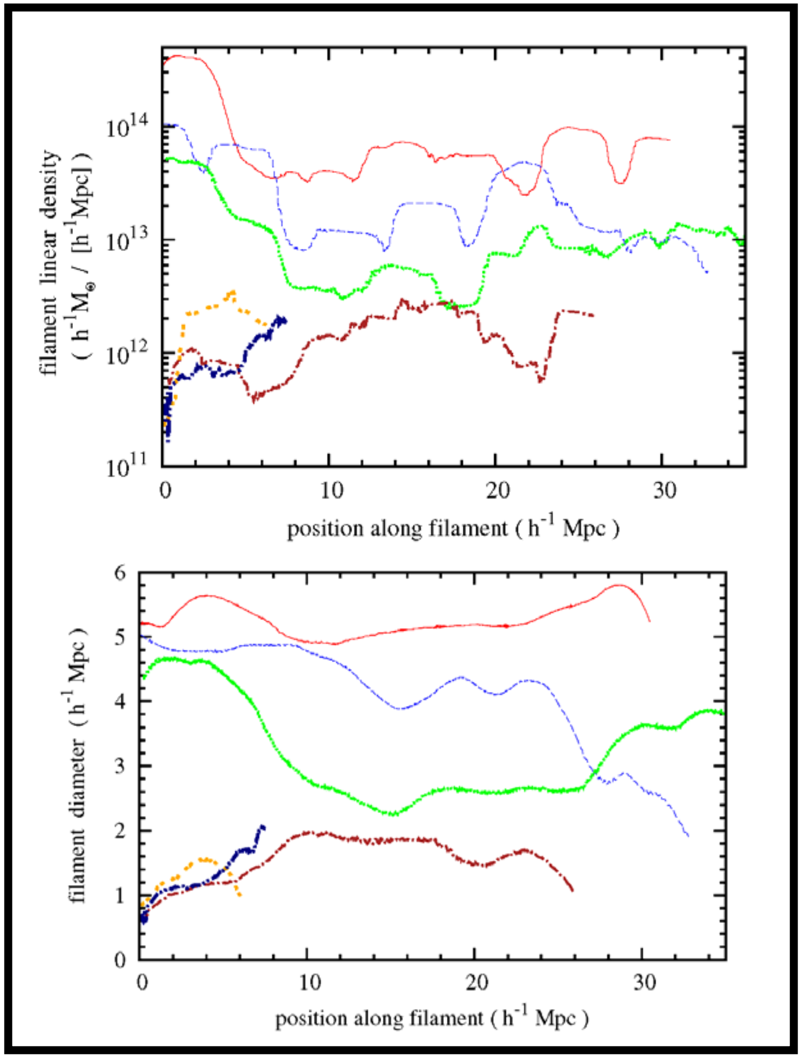
Total surface area of wall network :

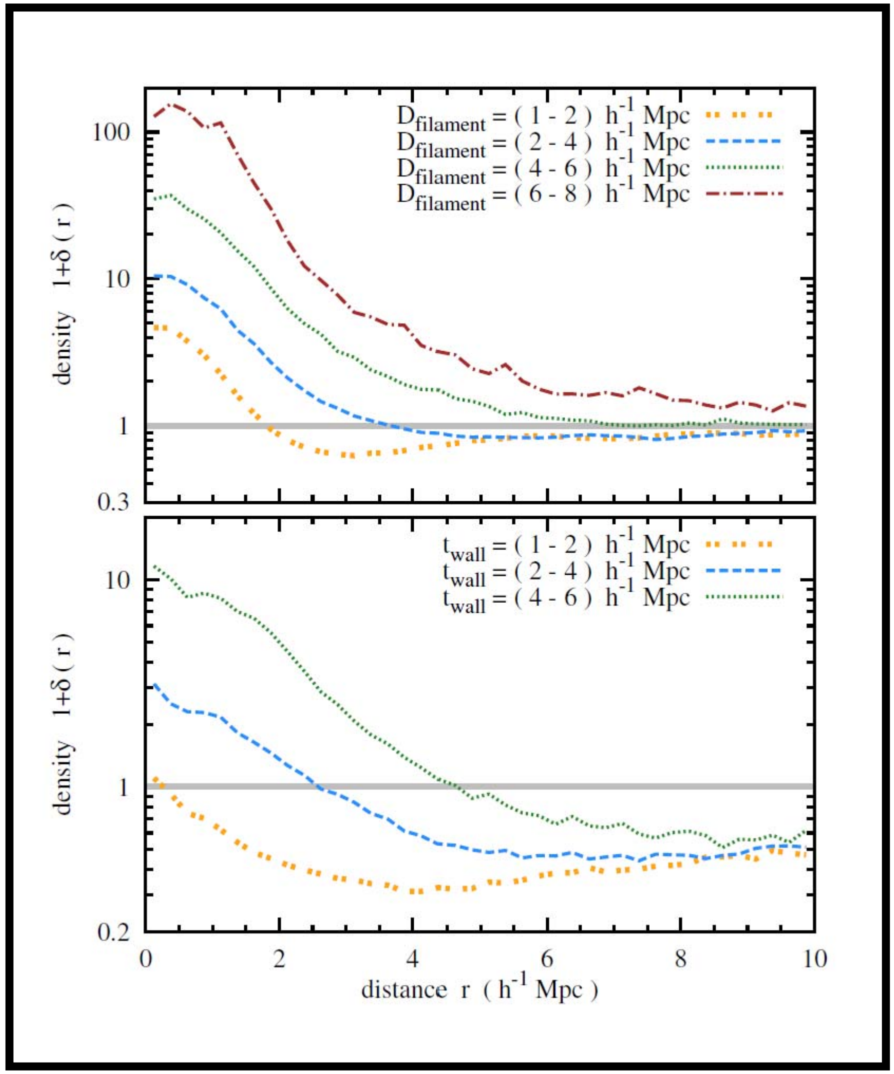
decreasing as a function of time

Cautun et al. 2014

# Walls & Filaments

## Internal Diameter & Density Profiles



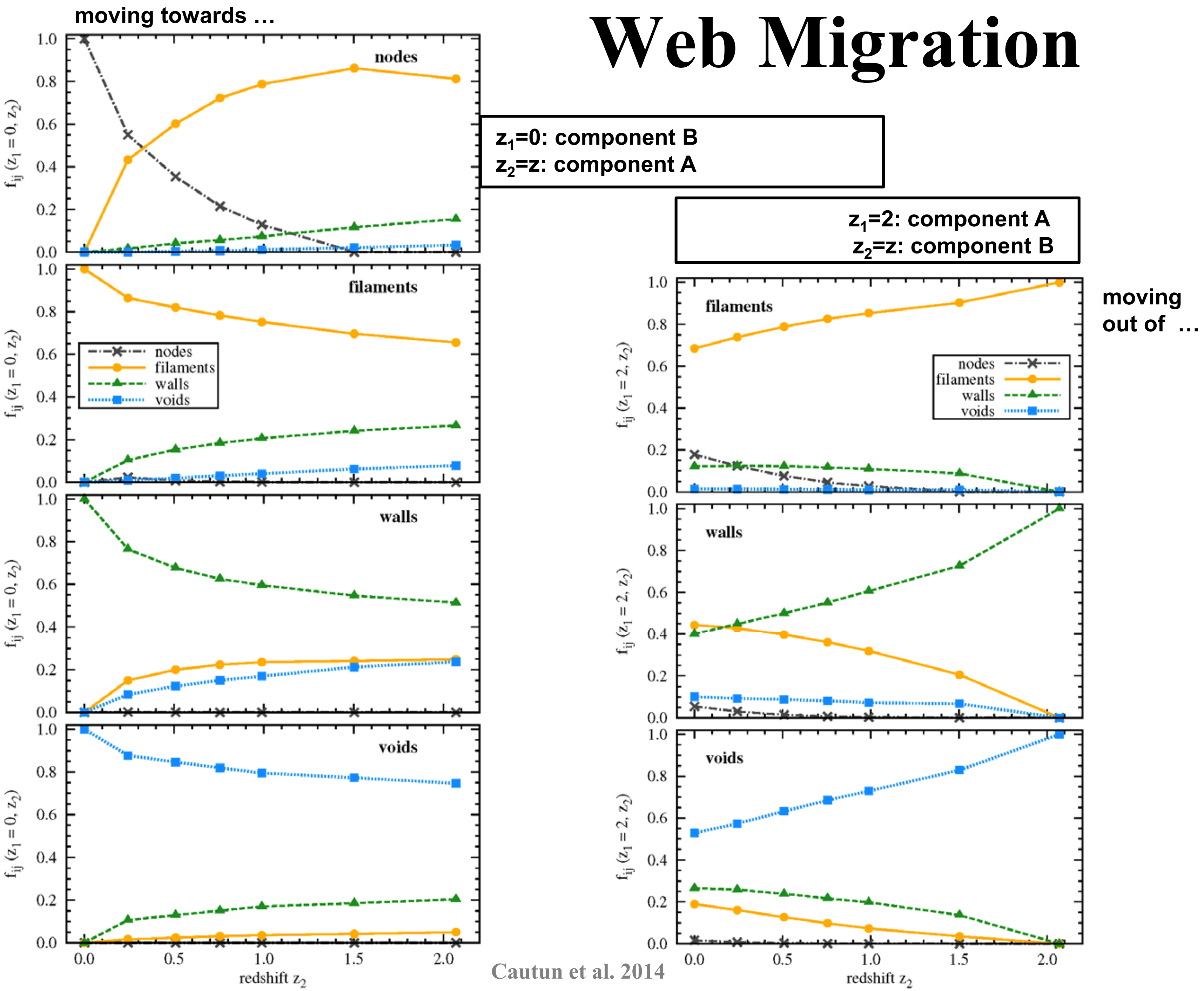




Cautun et al. 2014

# Cosmic Web:

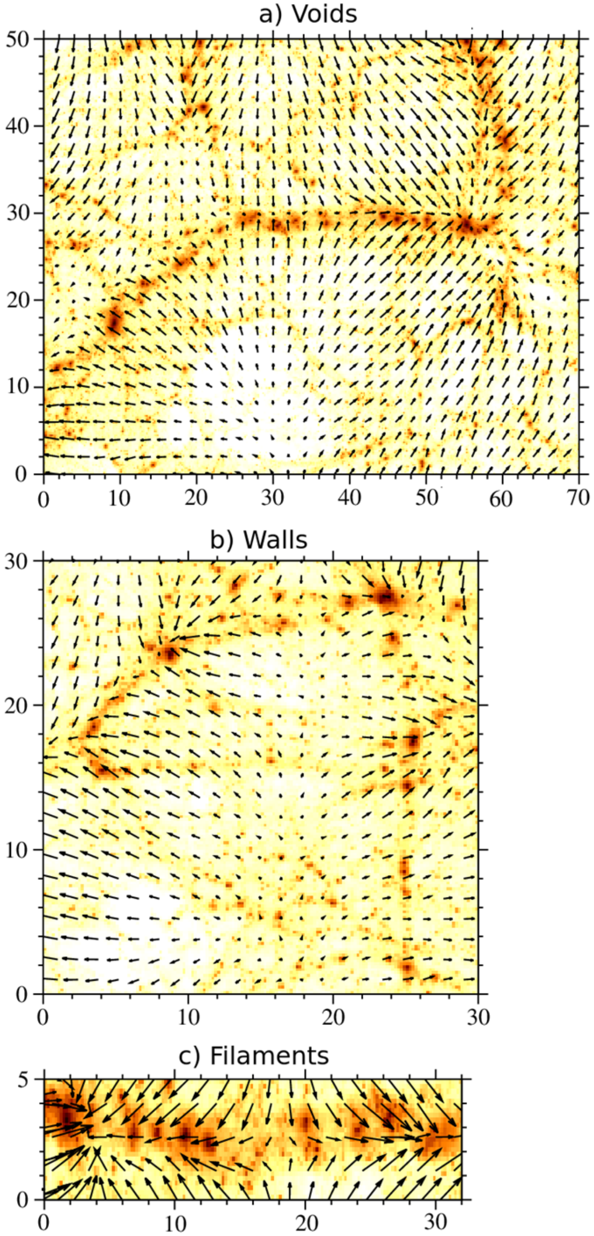
## Evolutionary Trends

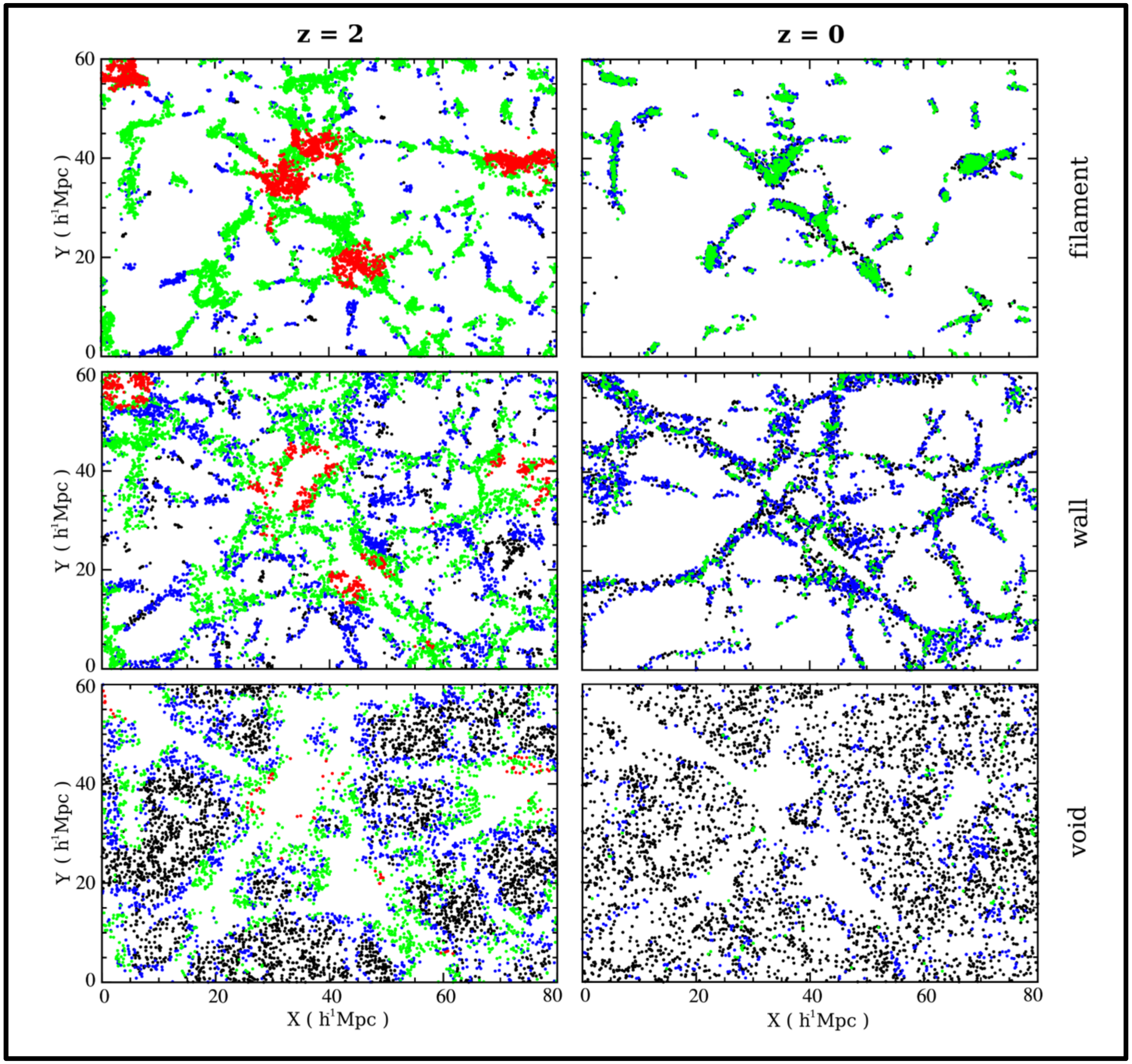
# Web Migration




Cautun et al. 2014

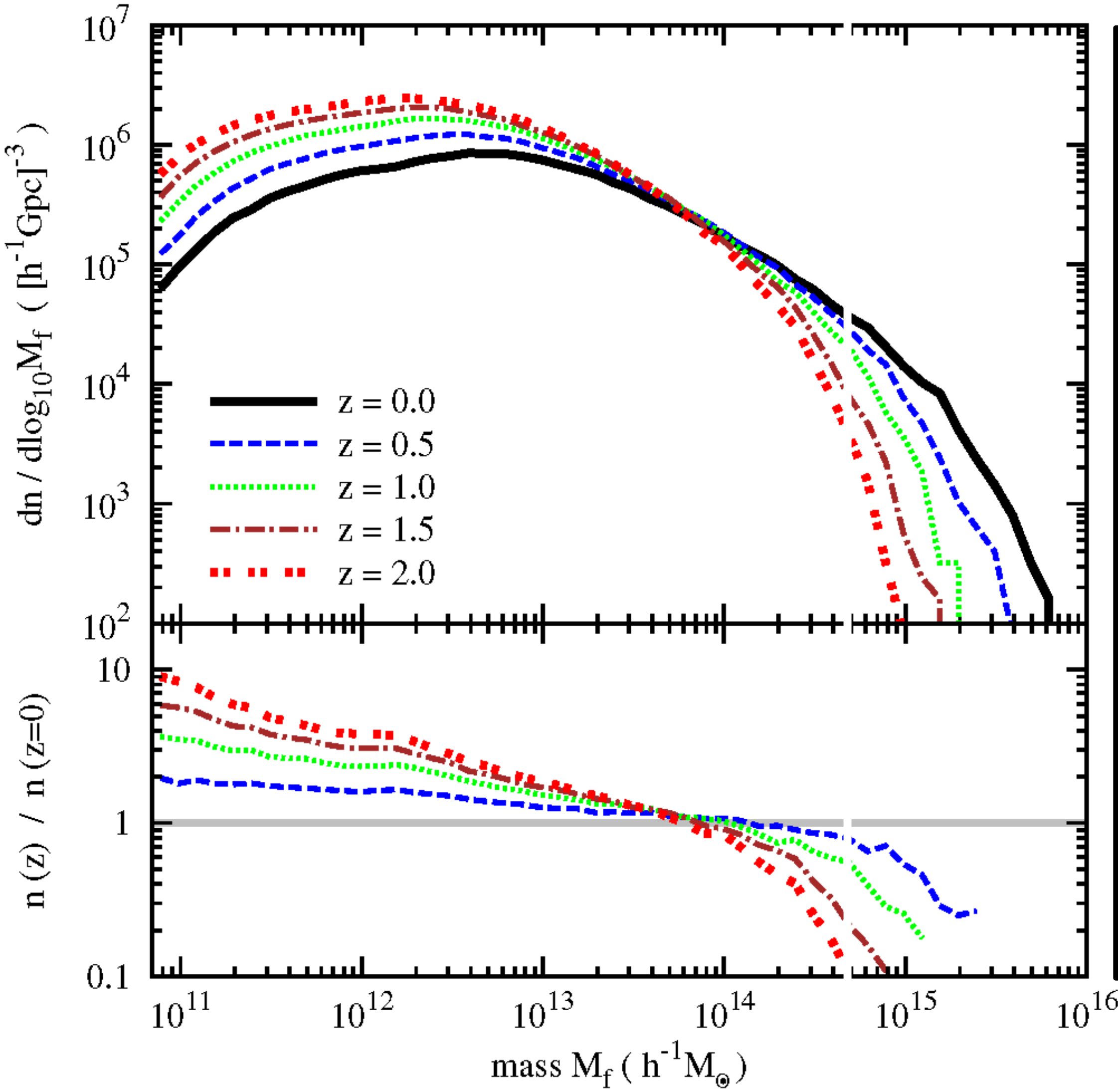
# Web Mass Emigration




Cautun et al. 2014

# Evolving Filament Population




**Filament Mass Function:**

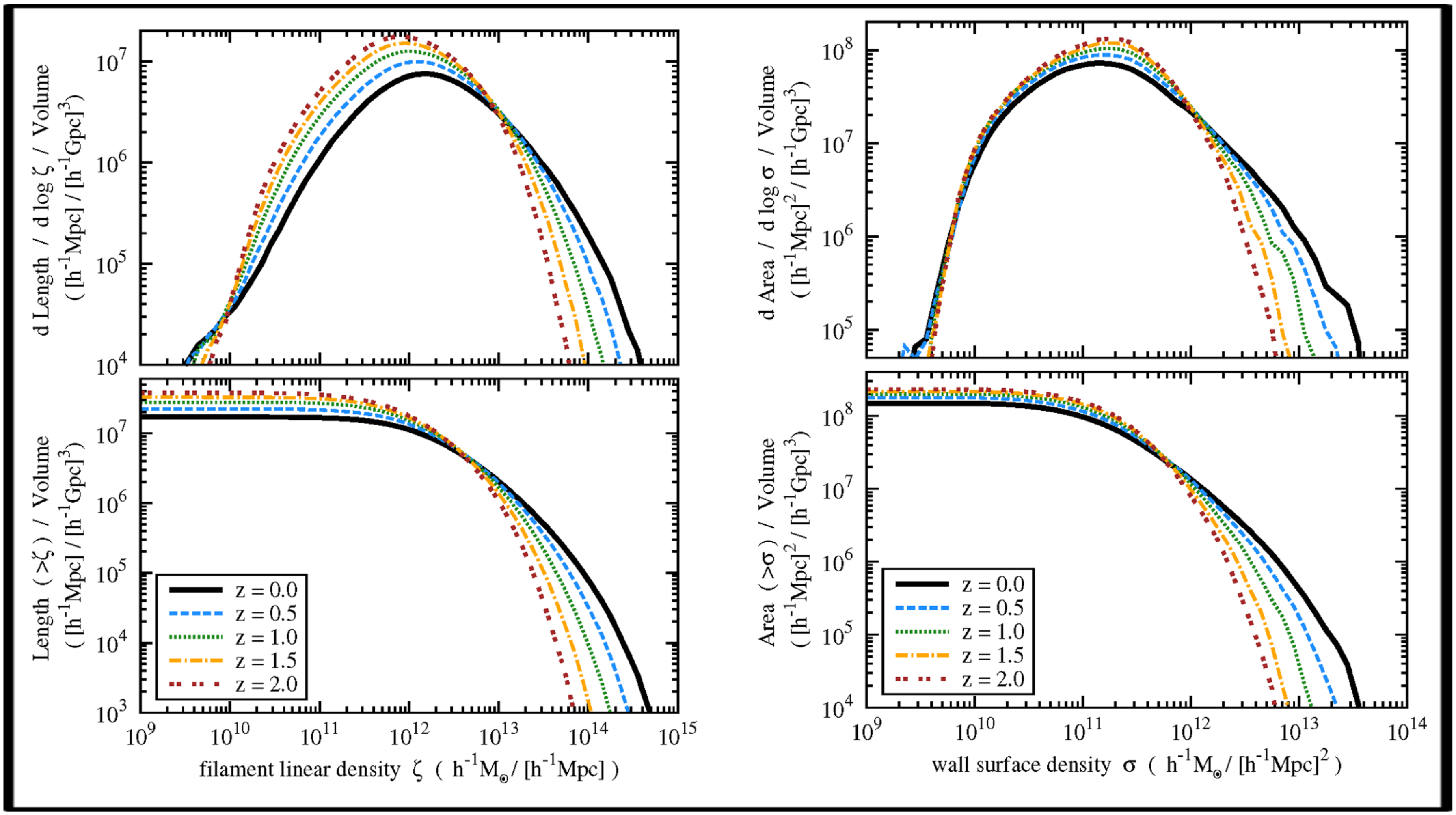
- shifting from small to large mass filaments
- reflection hierarchical evolution filament population

Cautun et al. 2014

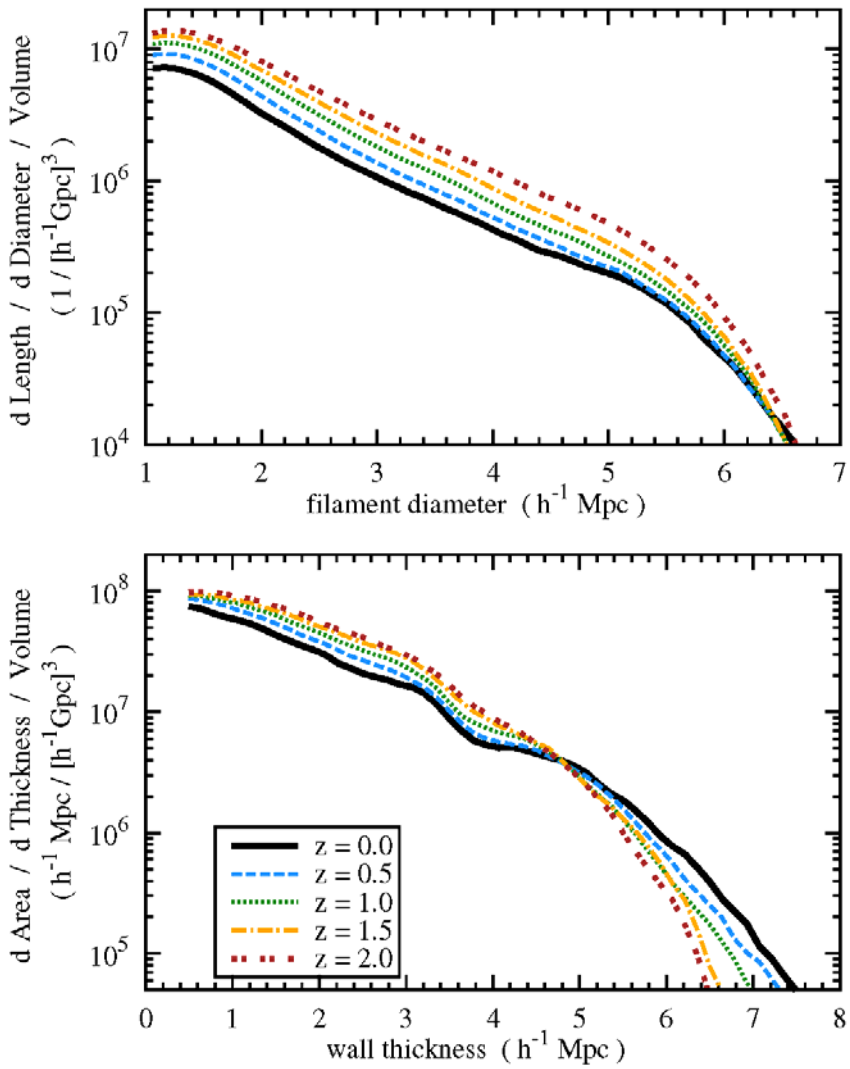
# Evolving Filament & Wall Densities

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

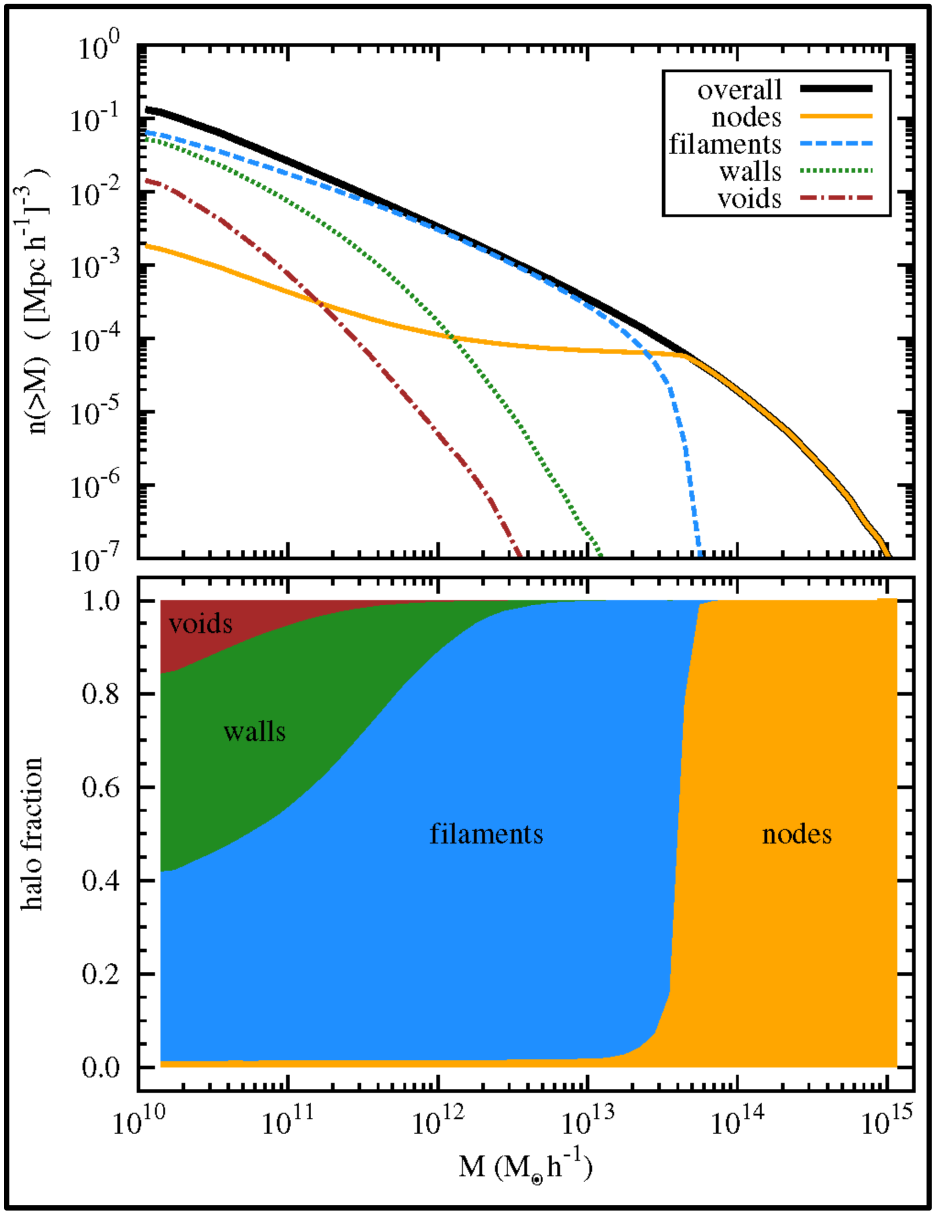
decrease of tenuous walls

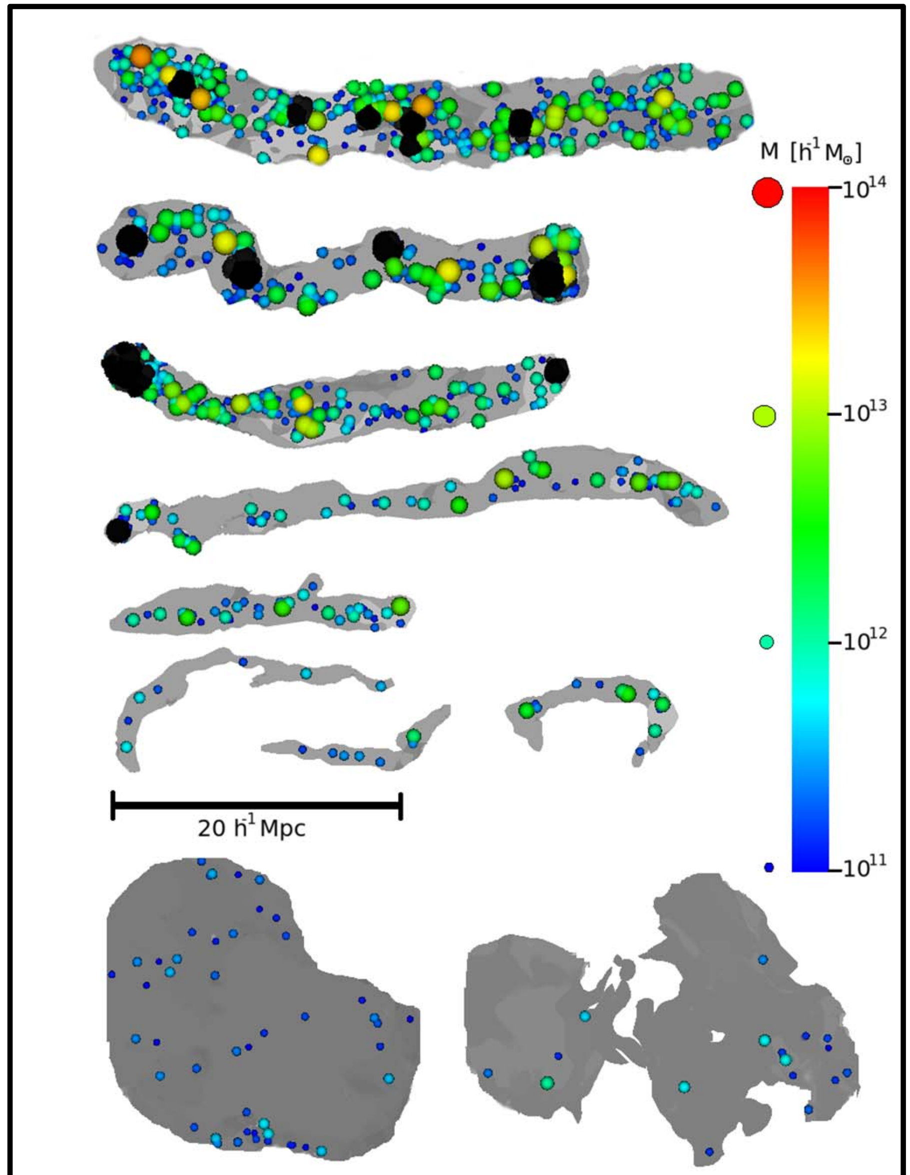
Cautun et al. 2014

# Cosmic Web:

## Halo Distribution

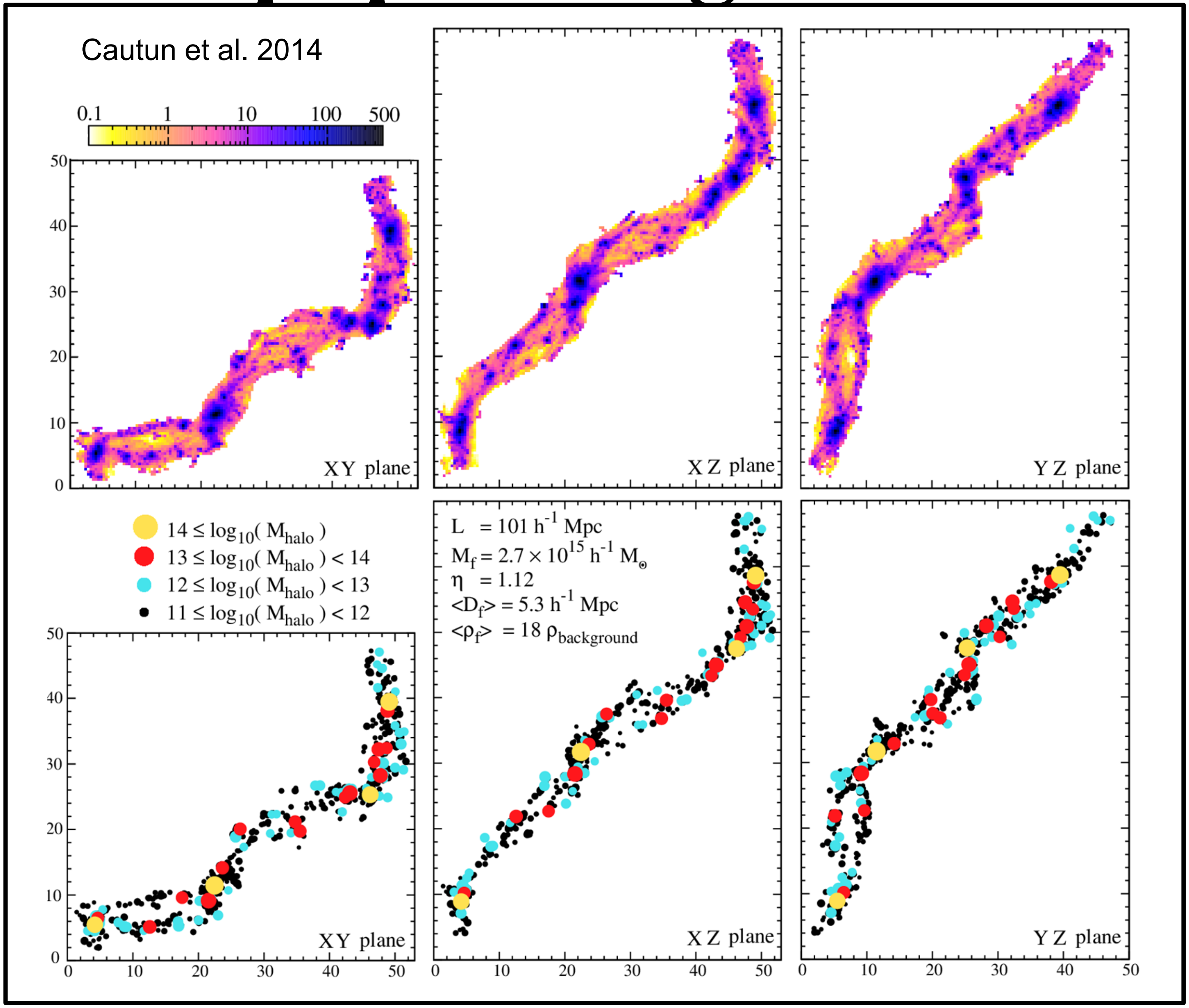
# Halos in the Cosmic Web



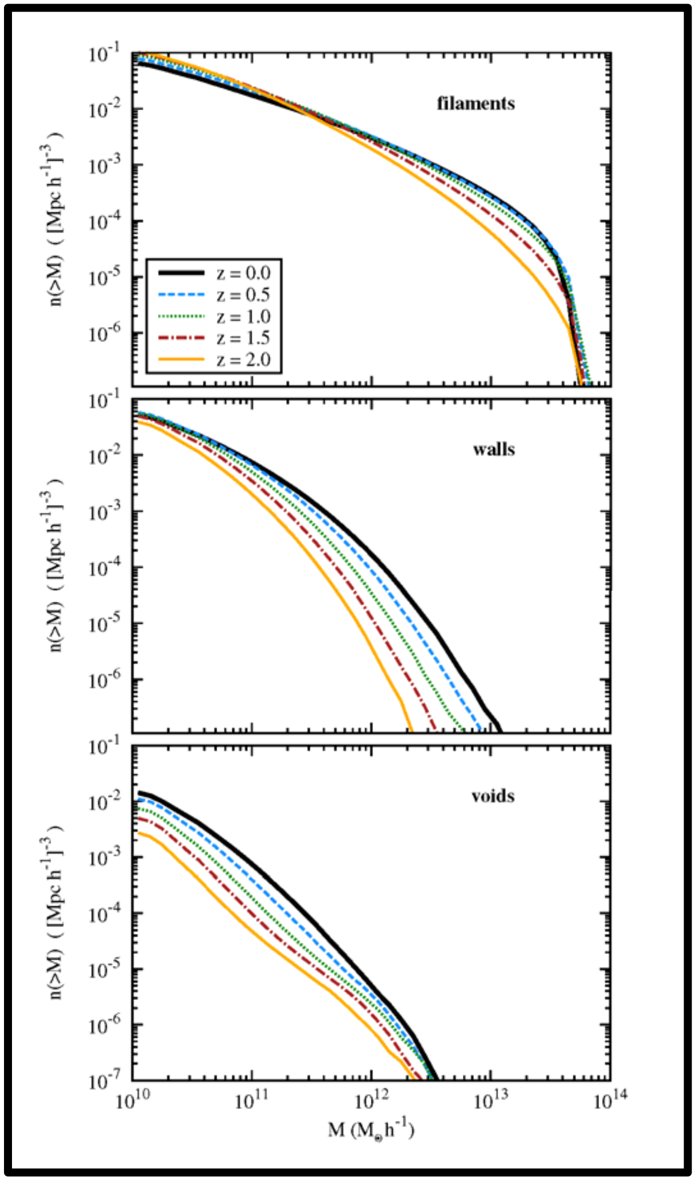



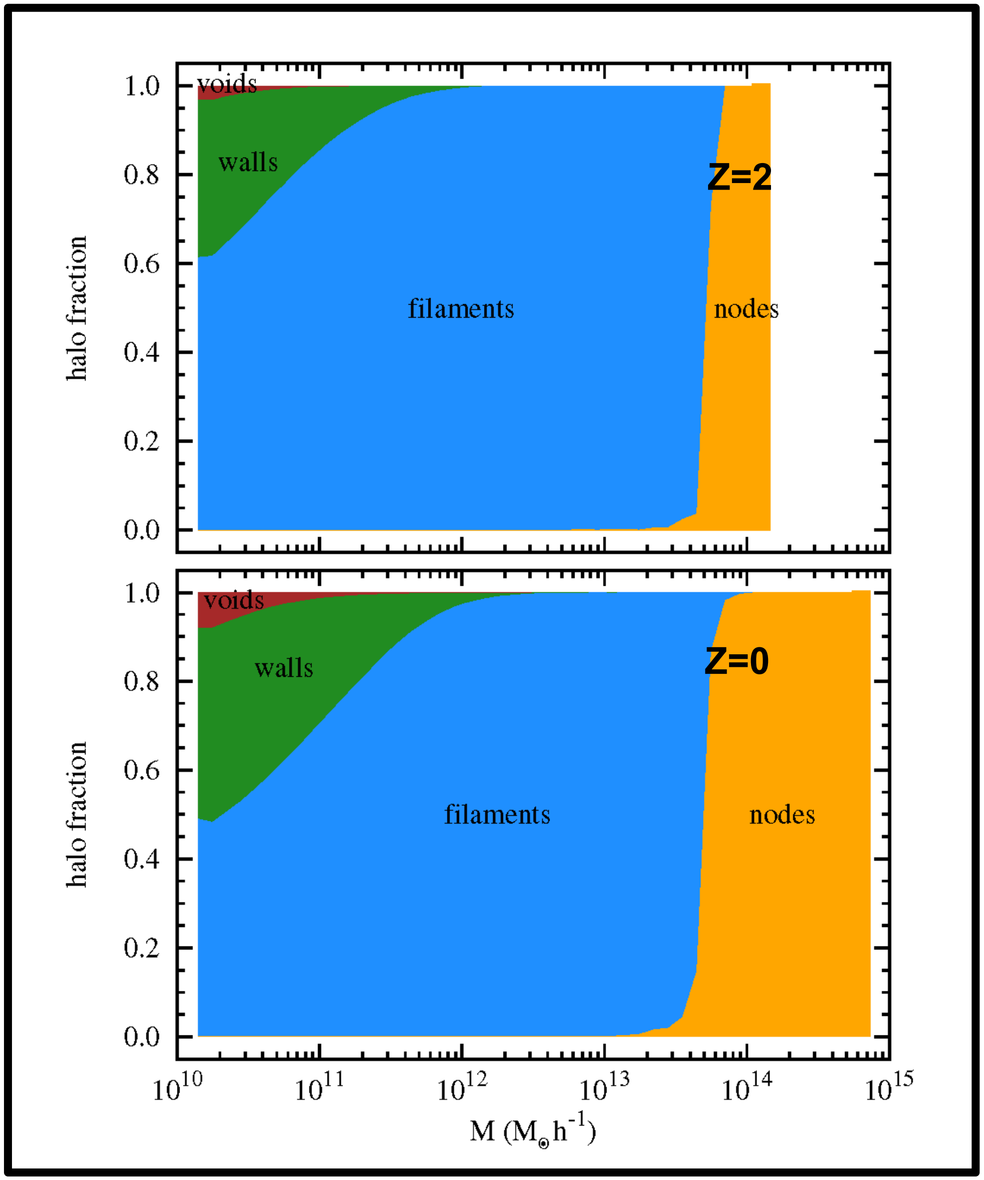

Cautun et al. 2014

# Halos populating Filaments



# Evolving Halo Population



# Dynamics of the Cosmic Web:

# Anisotropic Collapse & Zeldovich Formalism

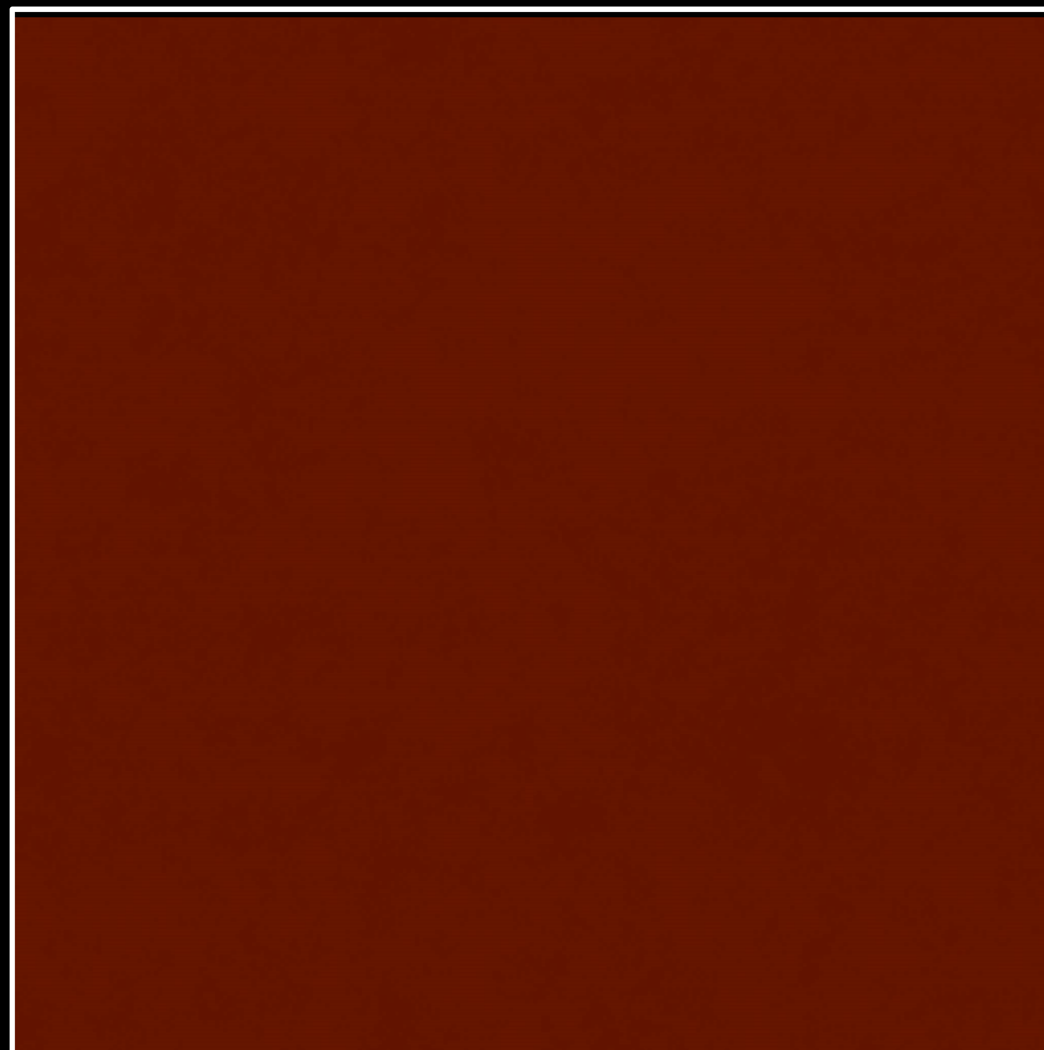

Yakov Borisovich Zel'dovich

# Zel'dovich Approximation

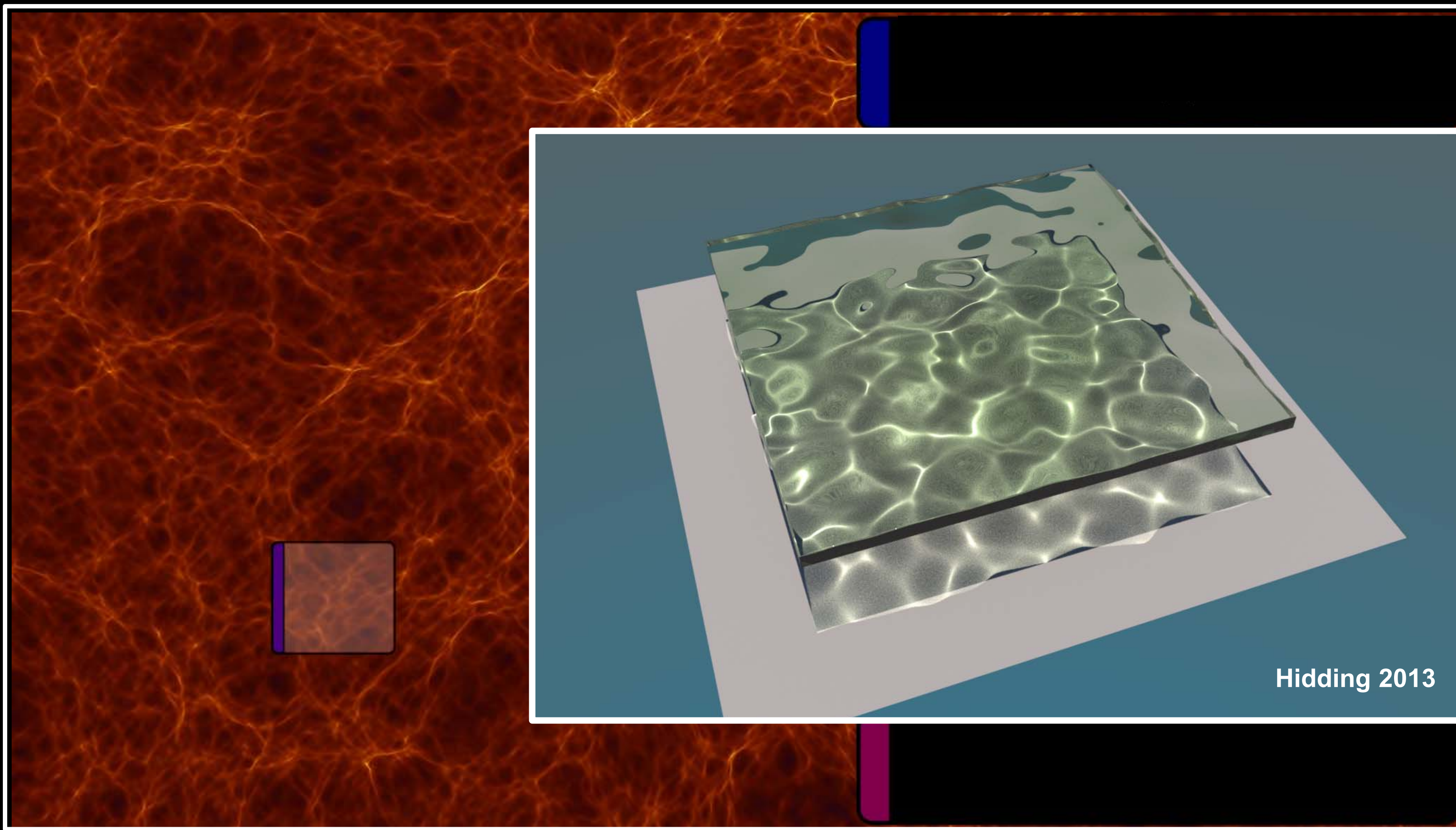
$$\vec{x} = \vec{q} + D(t)\,\vec{u}(\vec{q})$$

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

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



# Zel'dovich Approximation



# Zel'dovich Approximation

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

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

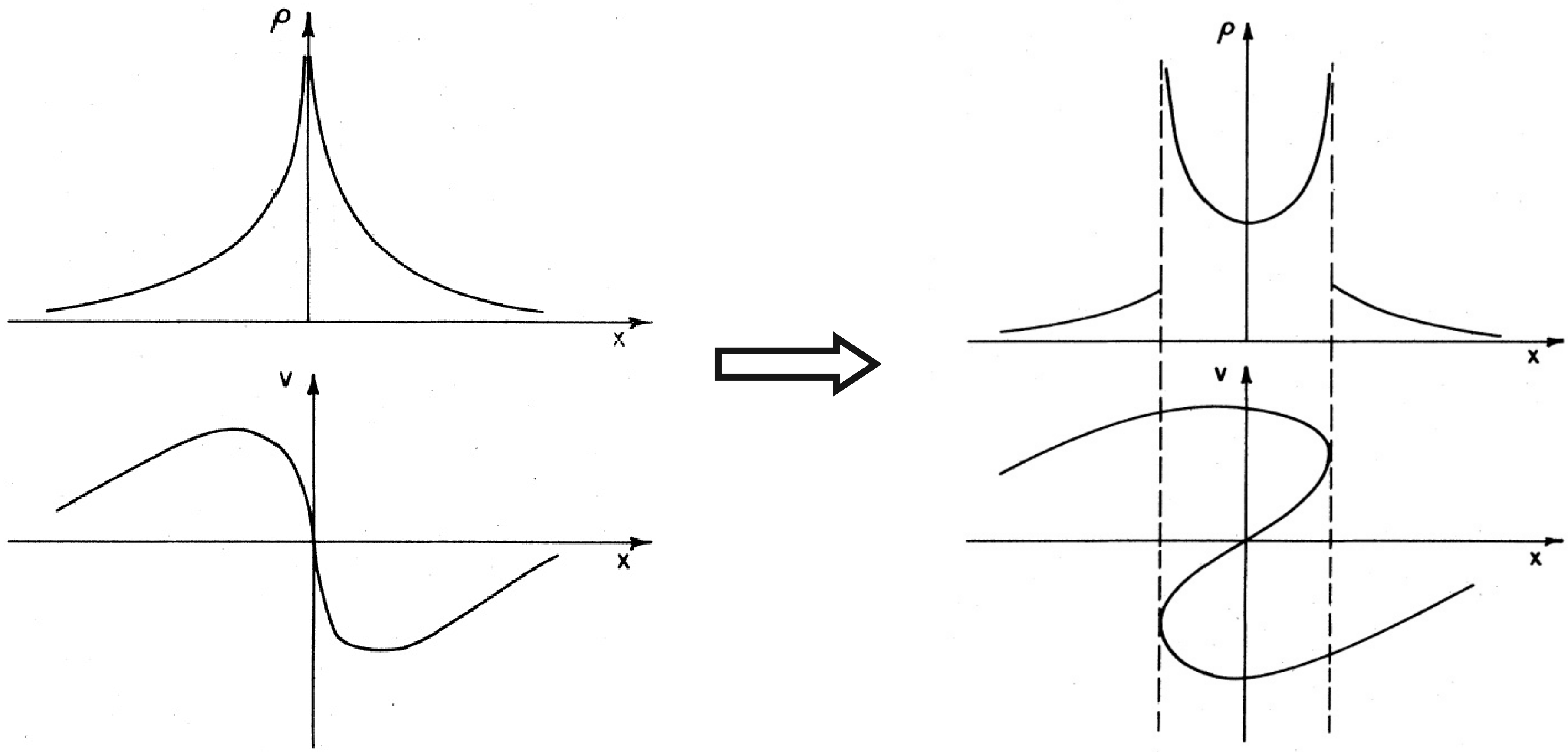
$$d_{ij} = -\frac{\partial u_i}{\partial q_j}$$

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

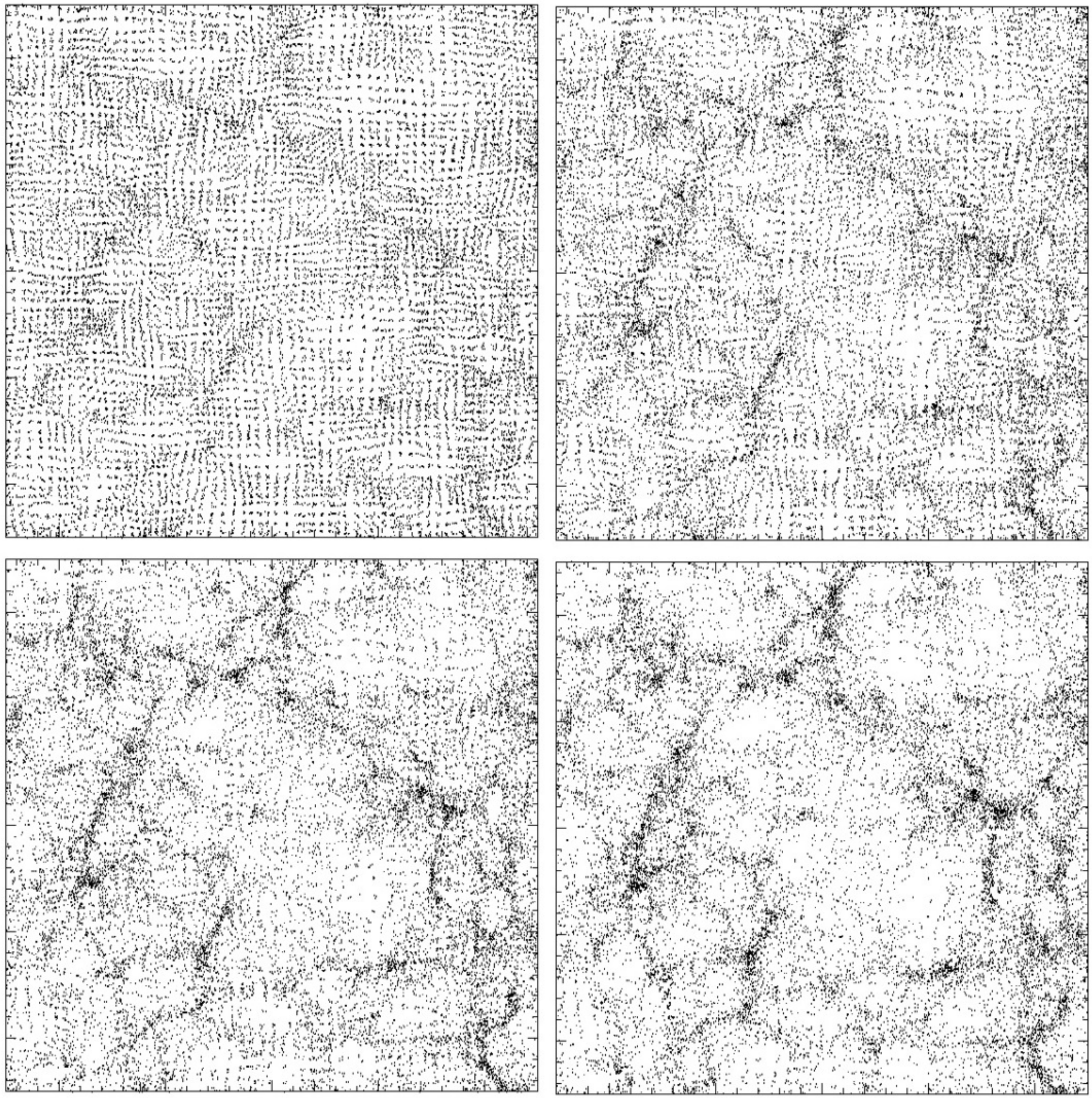
structure of the cosmic web determined by the spatial field of eigenvalues

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

# Zel'dovich Formalism: Density Evolution




Density Profile through pancake, at moment of formation and shortly thereafter (multistream)



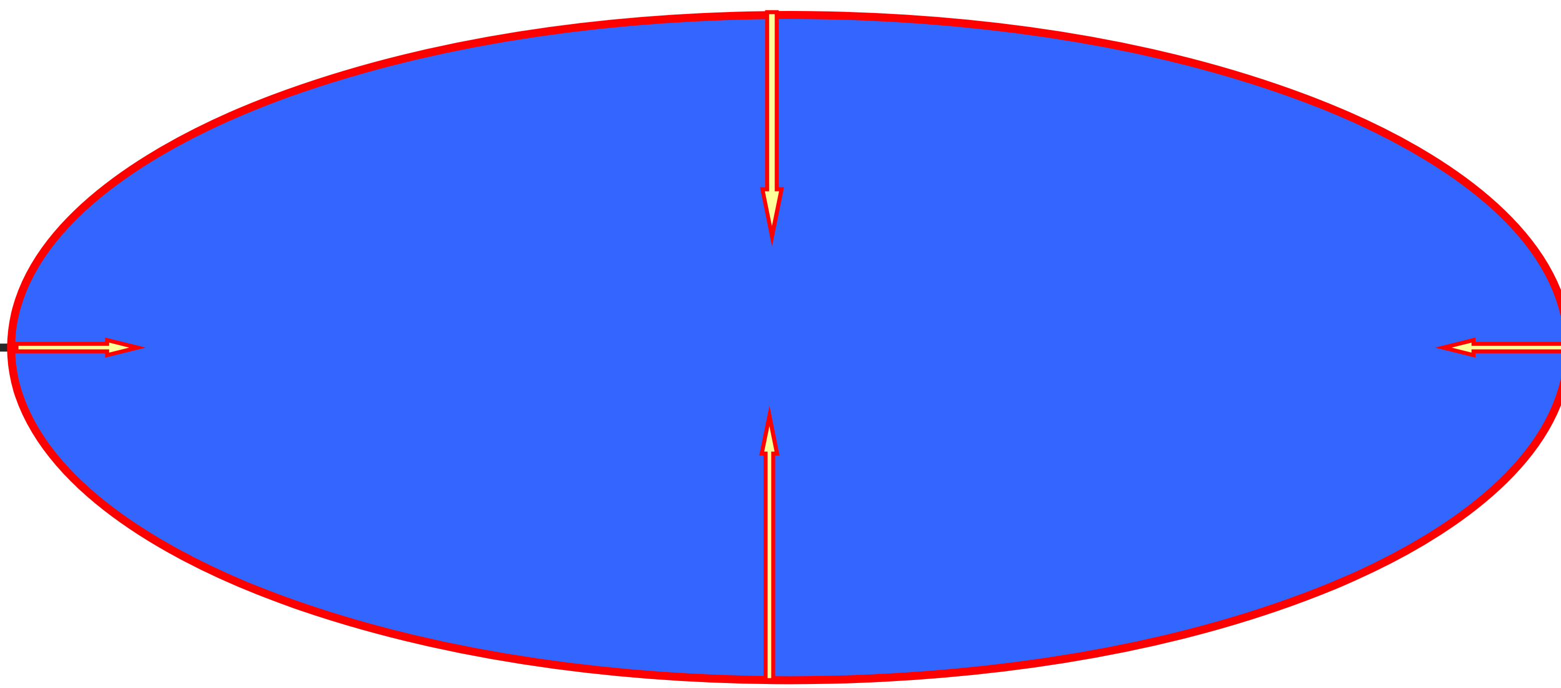
# Cosmic Web Connectivity:

# weaving the Cosmic Tapestry

# Anisotropic

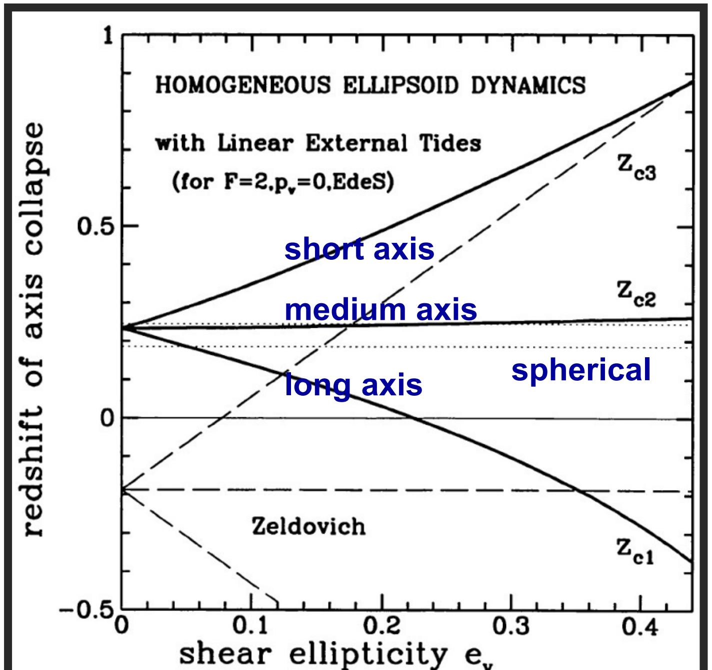
# Gravitational Collapse

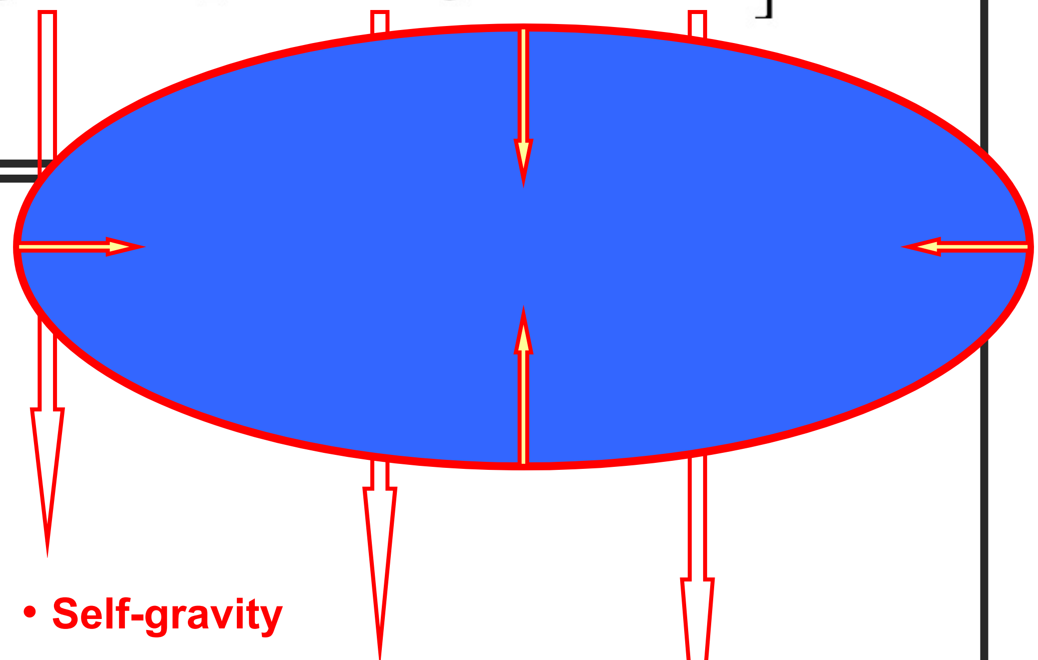
**Amplification**
**small perturbations in gravity along different directions (tidal forces)**



# Anisotropic (Ellipsoidal) Collapse

$$\frac{d^2\mathcal{R}_{\rm m}}{dt^2} = -4\pi G\rho_{\rm u}(t)\left[\frac{1+\delta}{3} + \frac{1}{2}(\alpha_m - \frac{2}{3})\,\delta + \lambda'_{\rm vm}\right]\mathcal{R}_{\rm m}$$



- Self-gravity
- Internal tidal shear (due to shape)
- External tidal shear

# Formative agent of the Cosmic Web:

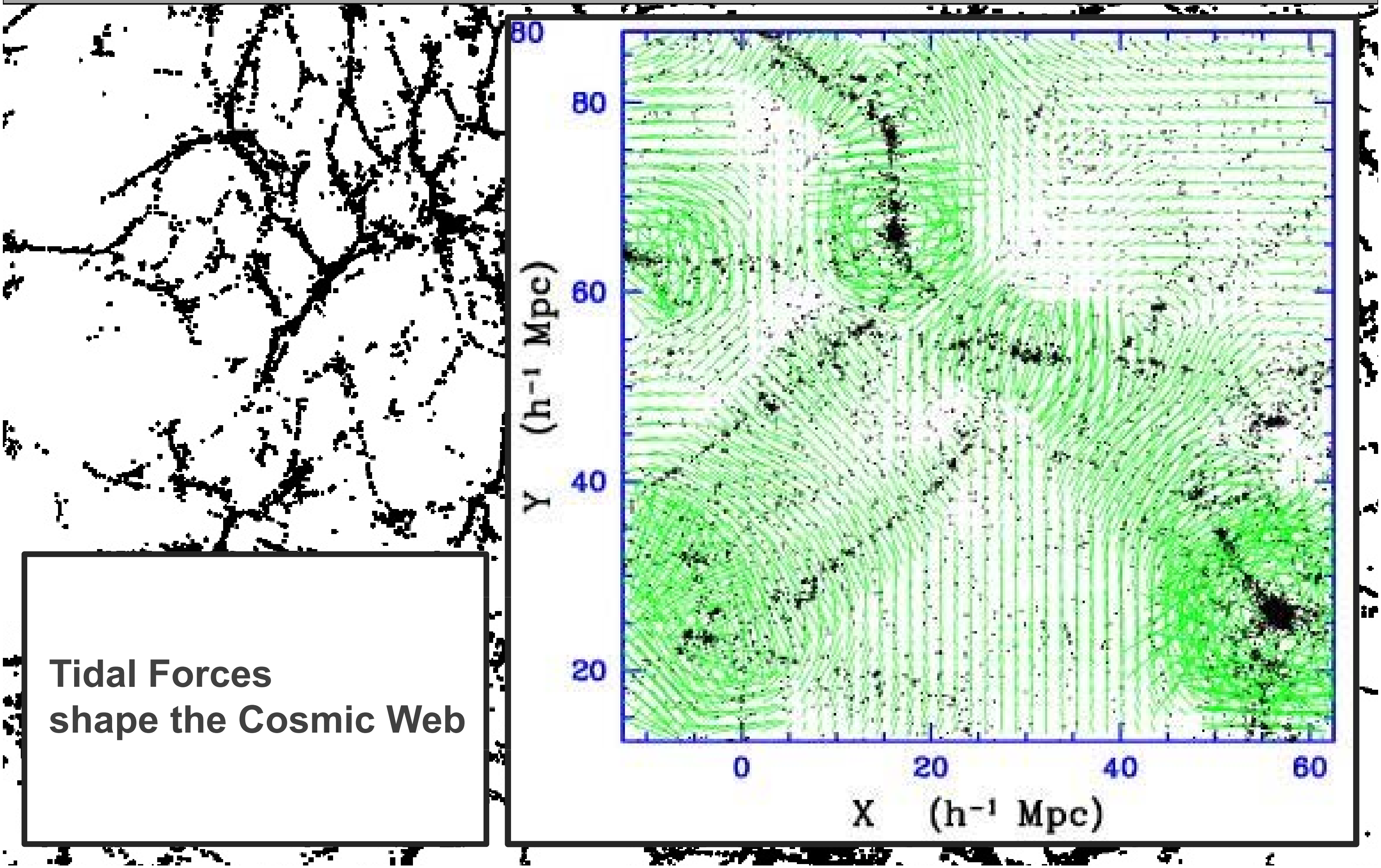
**Tidal strain induced my the Megaparsec Matter Distribution:**

- **anisotropic collapse of structures**
- **connection clusters-filaments:**

**clusters main agent for stretching filaments**

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

# Tidal Shaping of the Cosmic Web



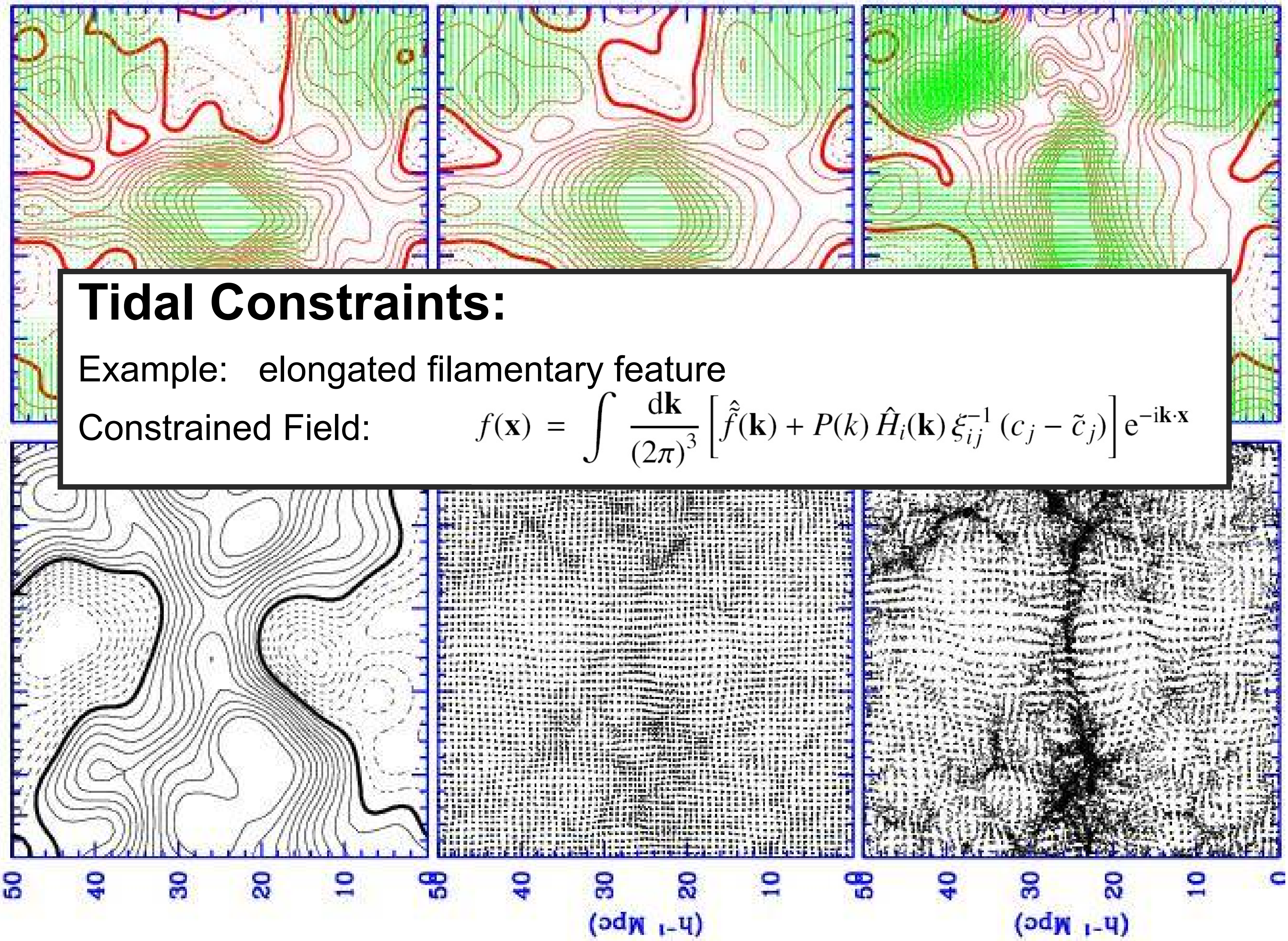

**Tidal Forces
shape the Cosmic Web**

# Tidal Constraints:

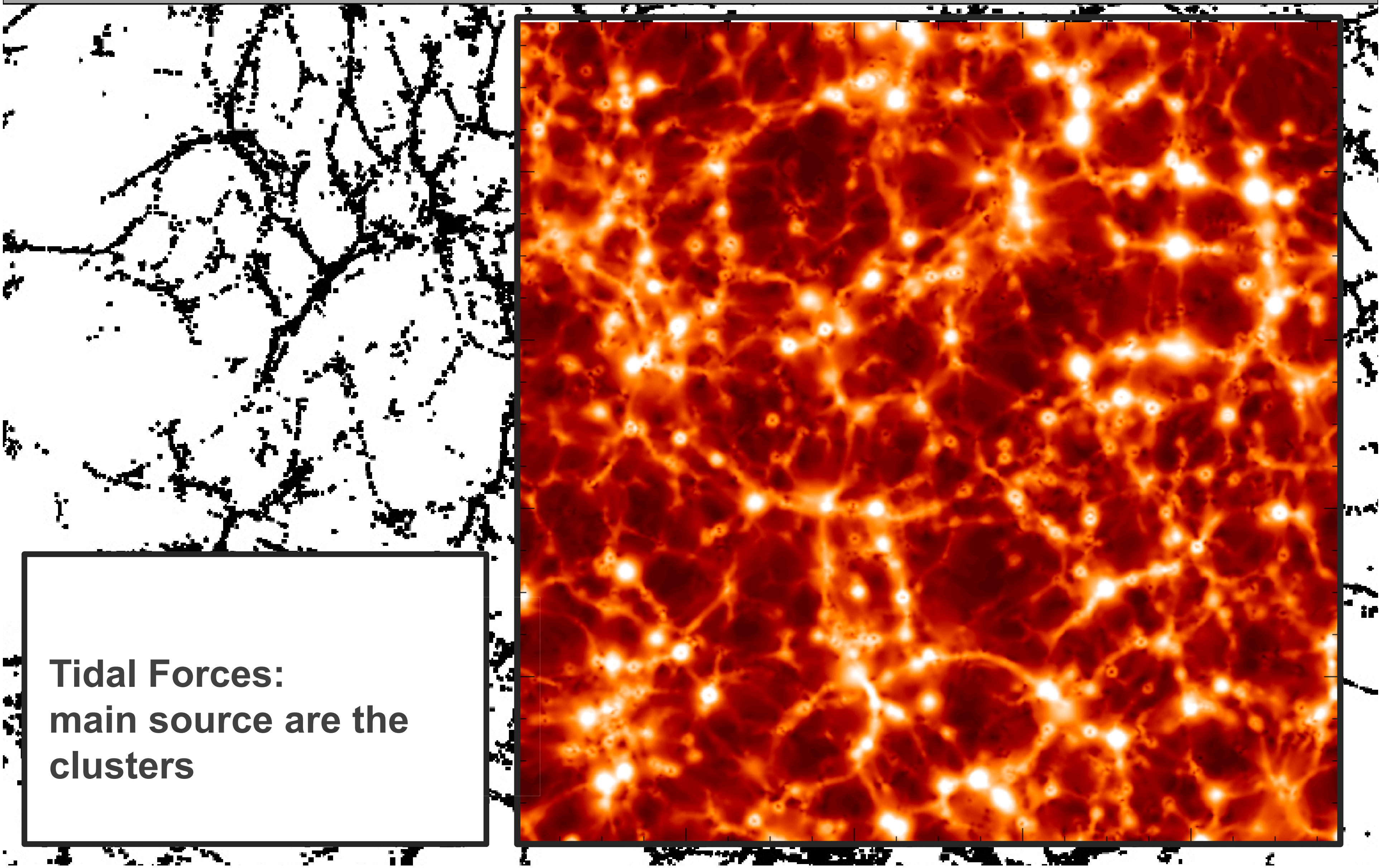
Example: elongated filamentary feature

Constrained Field:

$$f(\mathbf{x}) = \int \frac{d\mathbf{k}}{(2\pi)^3} \left[ \hat{\tilde{f}}(\mathbf{k}) + P(k)\, \hat{H}_i(\mathbf{k})\, \xi_{ij}^{-1}\, (c_j - \tilde{c}_j) \right] e^{-i\mathbf{k}\cdot\mathbf{x}}$$



# Tidal Shaping of the Cosmic Web

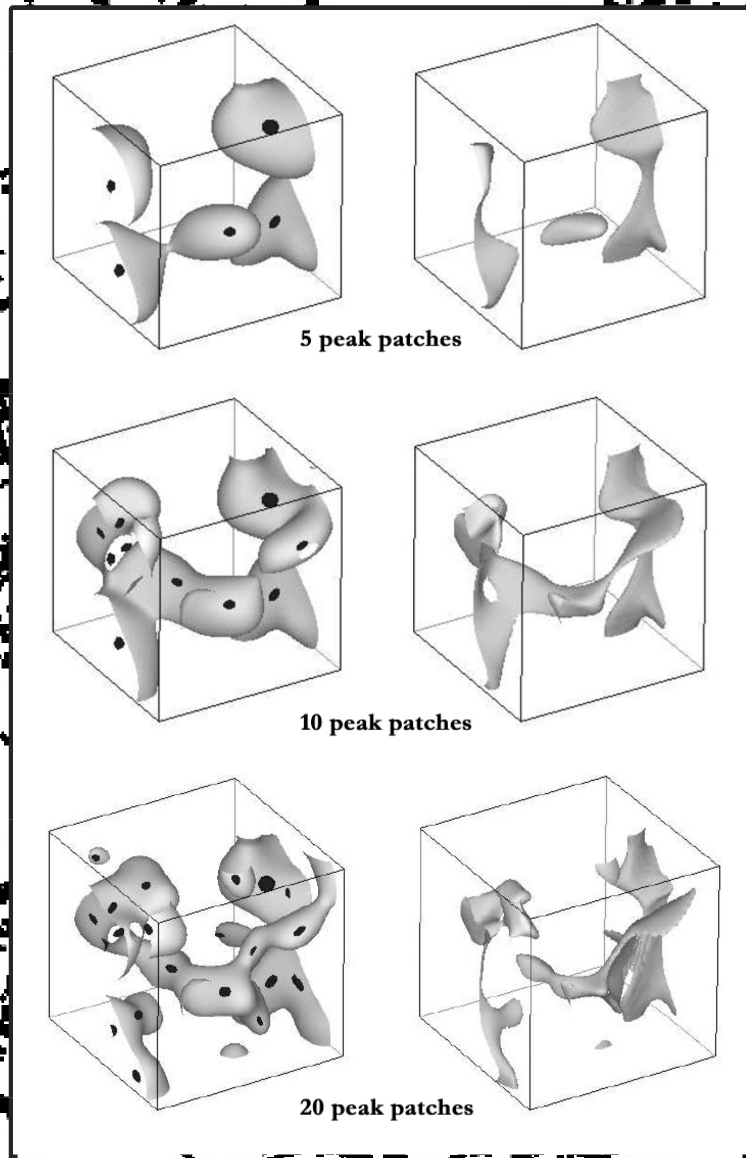


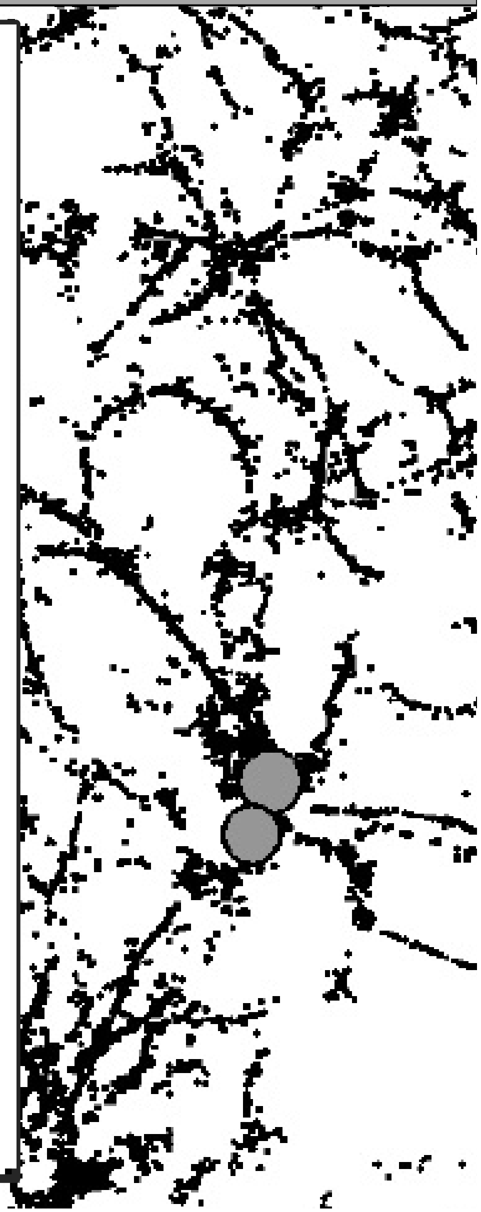
**Tidal Forces:**
**main source are the clusters**

# Tidal Shaping of the Cosmic Web

**Cosmic Web Theory**

**Bond, Kofman & Pogosyan 1996**



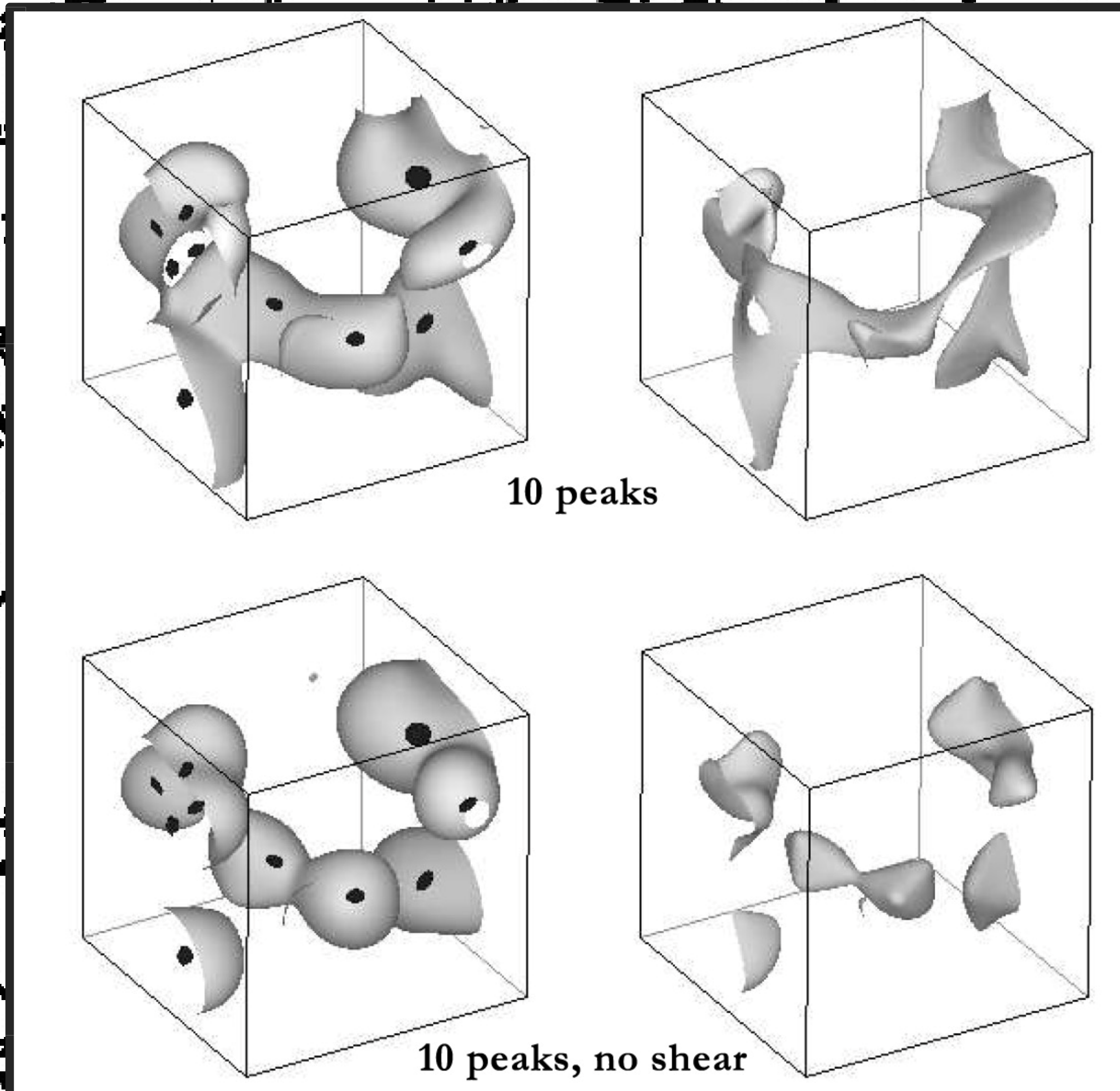
**Tidal Forces:**
**main source are the clusters**

# Tidal Shaping of the Cosmic Web

Cosmic Web Theory

Bond, Kofman & Pogosyan 1996

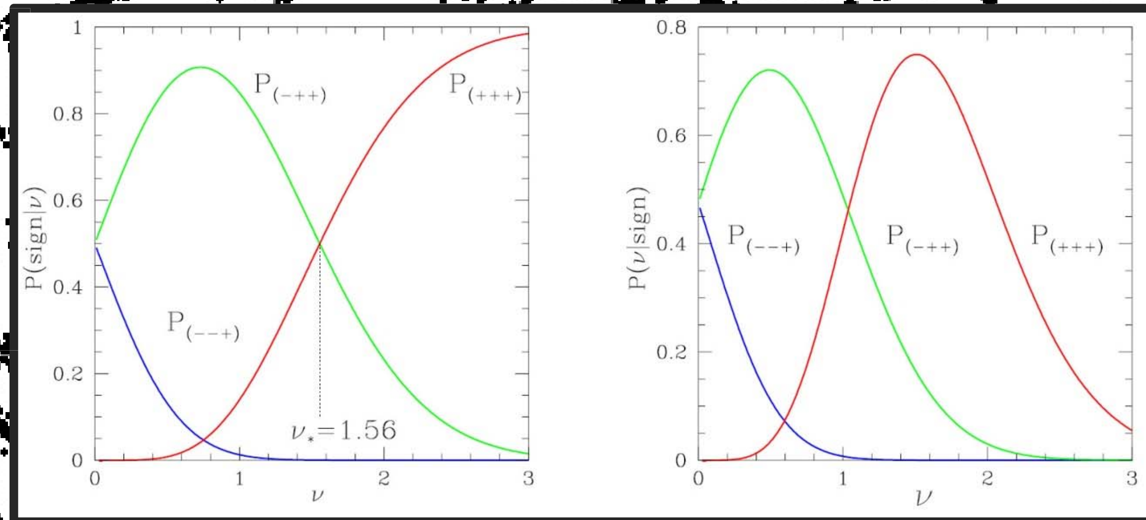
Tidal Forces:
main source are the clusters



# Tidal Shaping of the Cosmic Web

**Cosmic Web Theory**

**Bond, Kofman & Pogosyan 1996**




**Tidal Forces:**
**main source are the clusters**

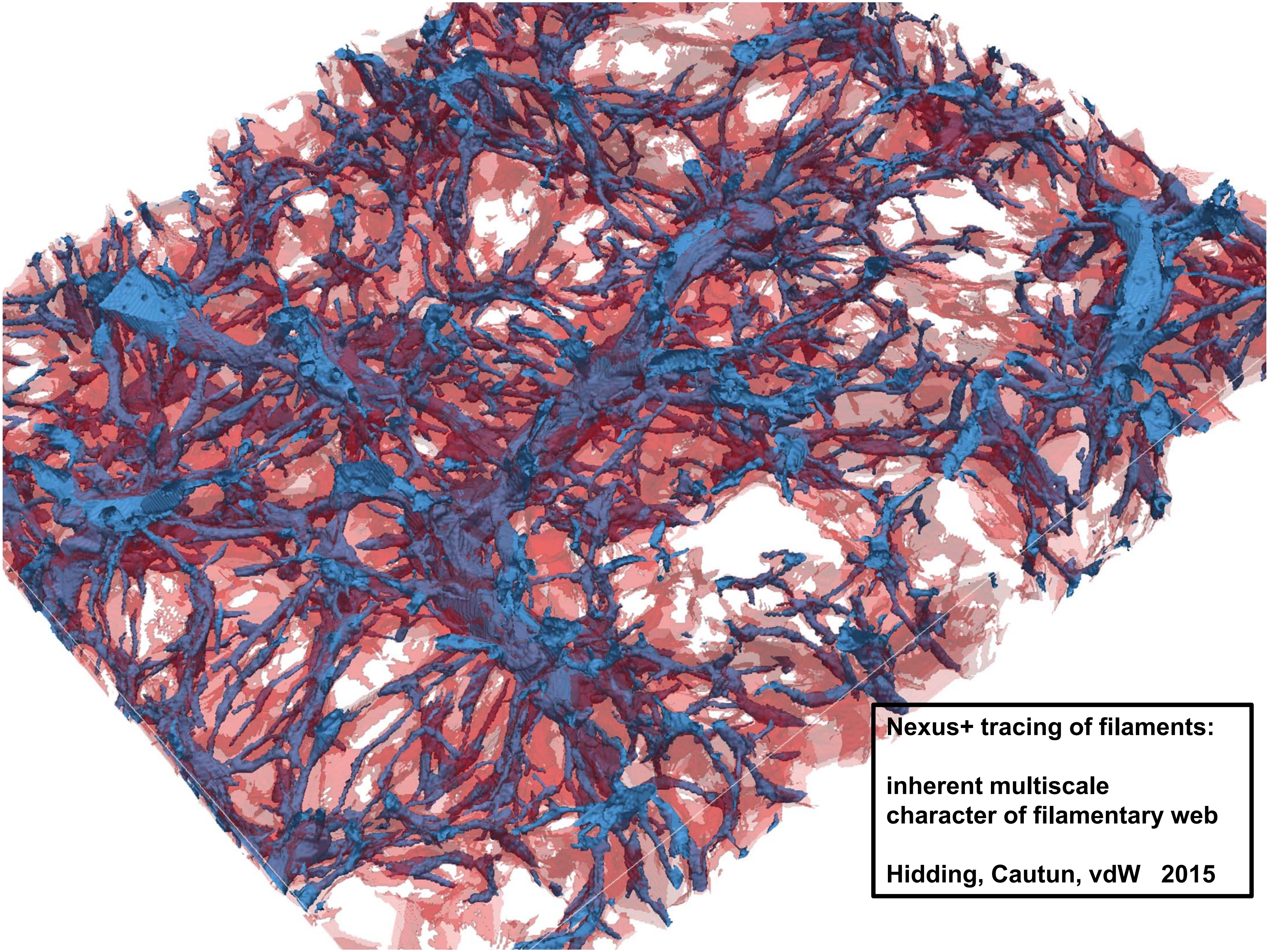
Conditional Statistics
Tidal Shear eigenvalues in Gaussian field:

in overdense regions:
most prominent structures are FILAMENTS

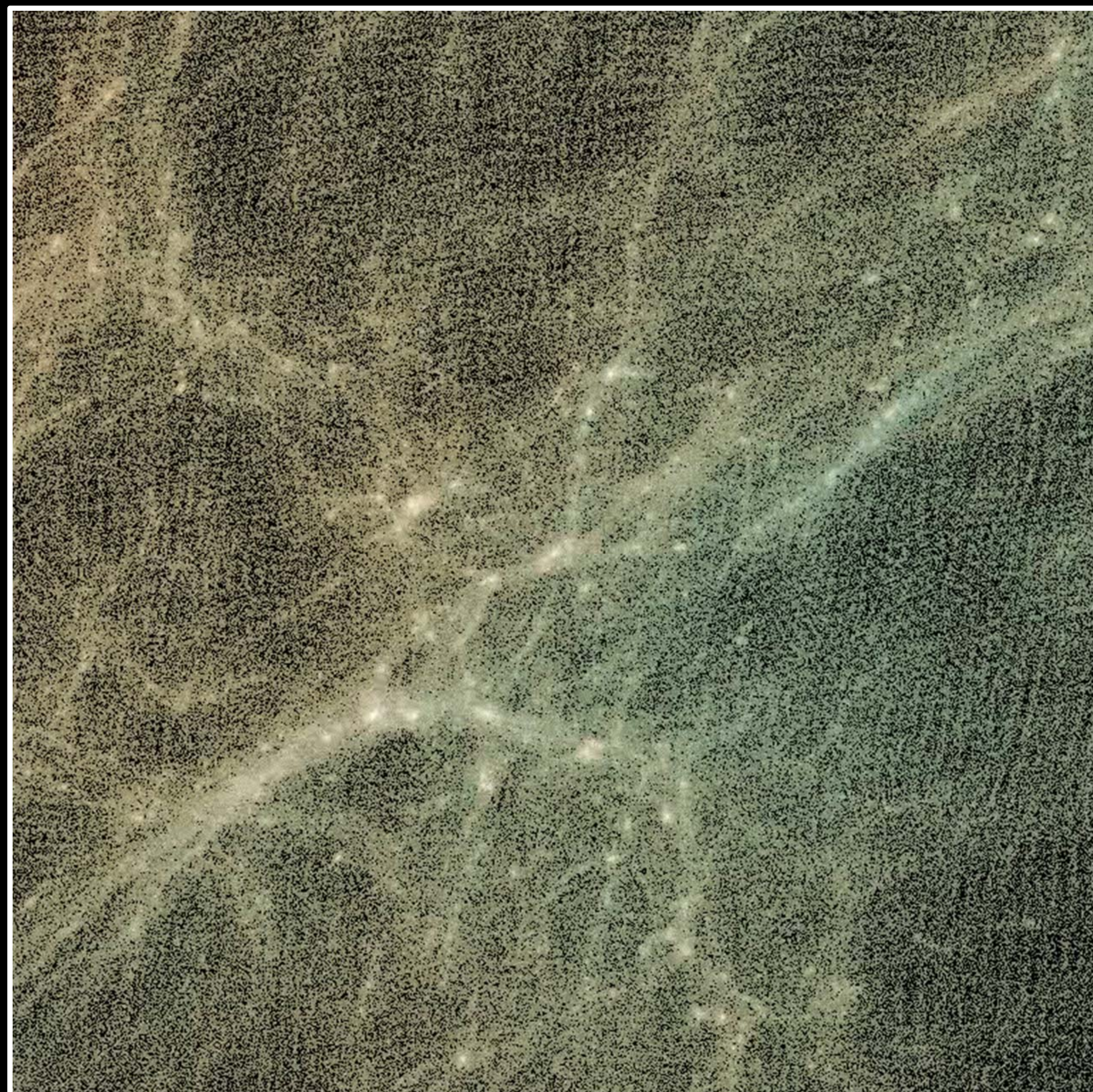
in underdense regions:
most prominent structure are WALLS

# Cosmic Web

# Hierarchical Evolution


Nexus+ tracing of filaments:
inherent multiscale
character of filamentary web
Hidding, Cautun, vdW 2015

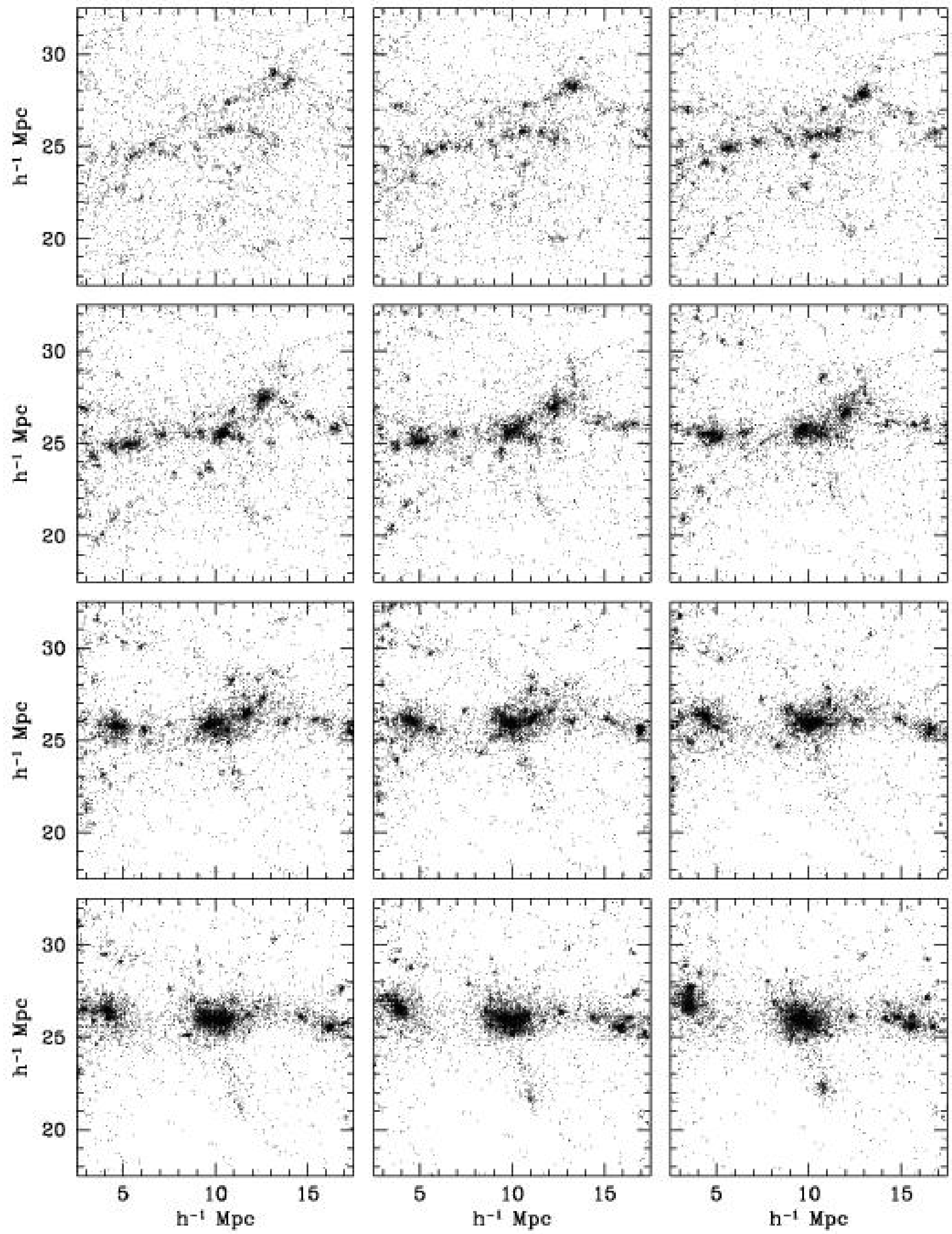
# CGV halo & web evolution



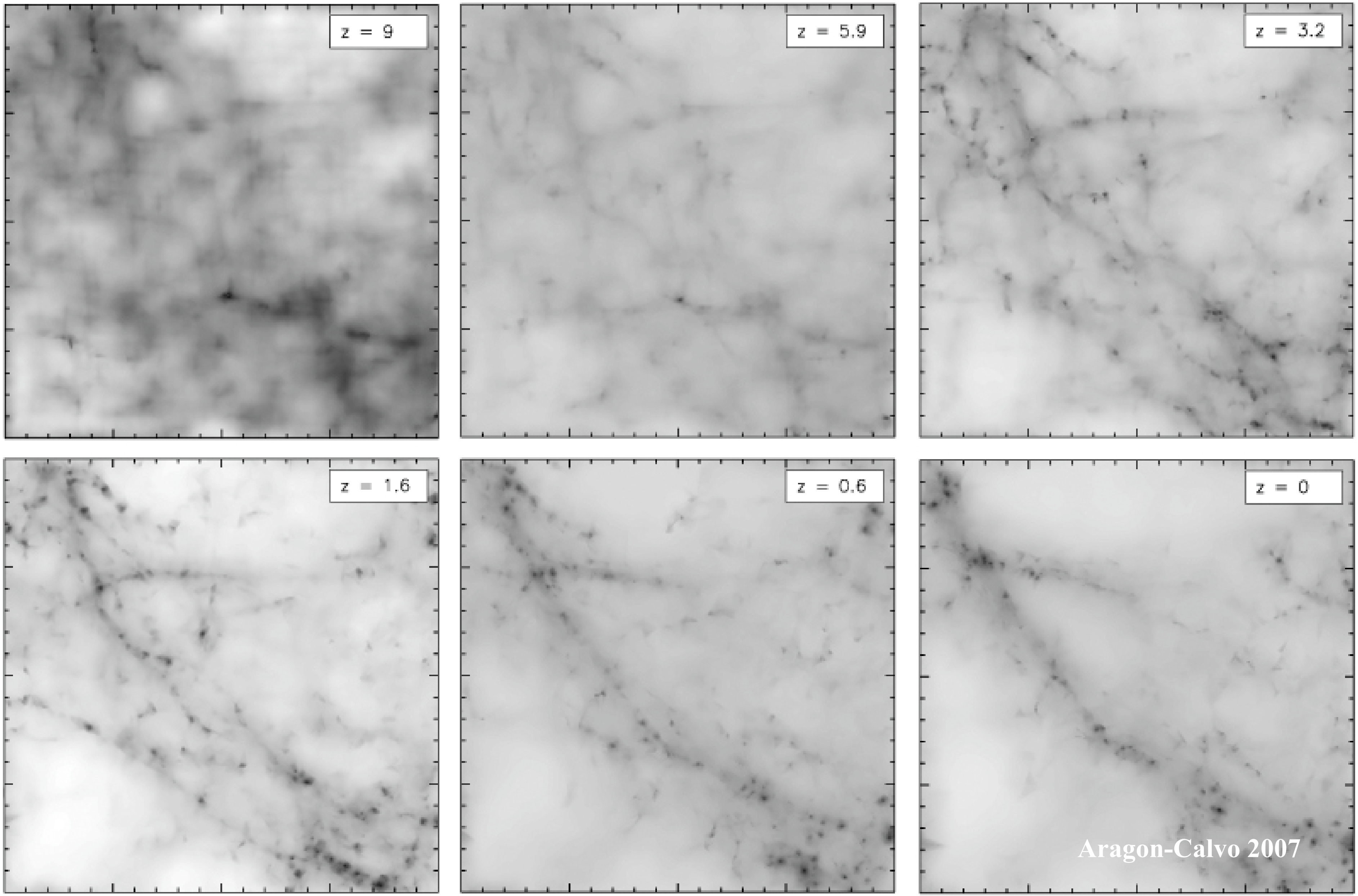
Rieder et al.
2013

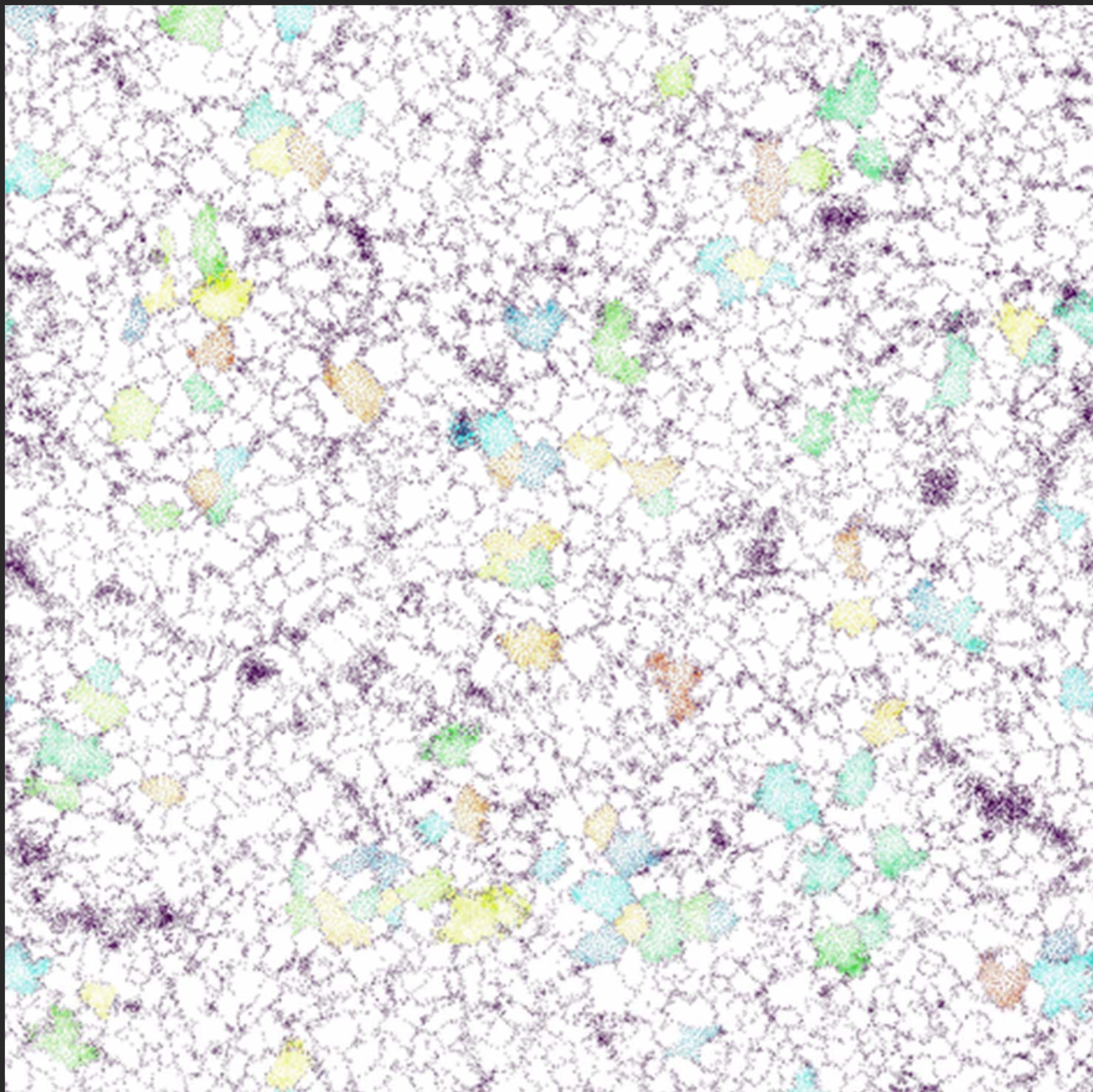
Structures in the Universe form
by
gradual hierarchical assembly:

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



# Hierarchical Filament Formation





# Void Hierarchy:

"Lagrangian" view:

void-dominated
hierarchical
development
Cosmic Web

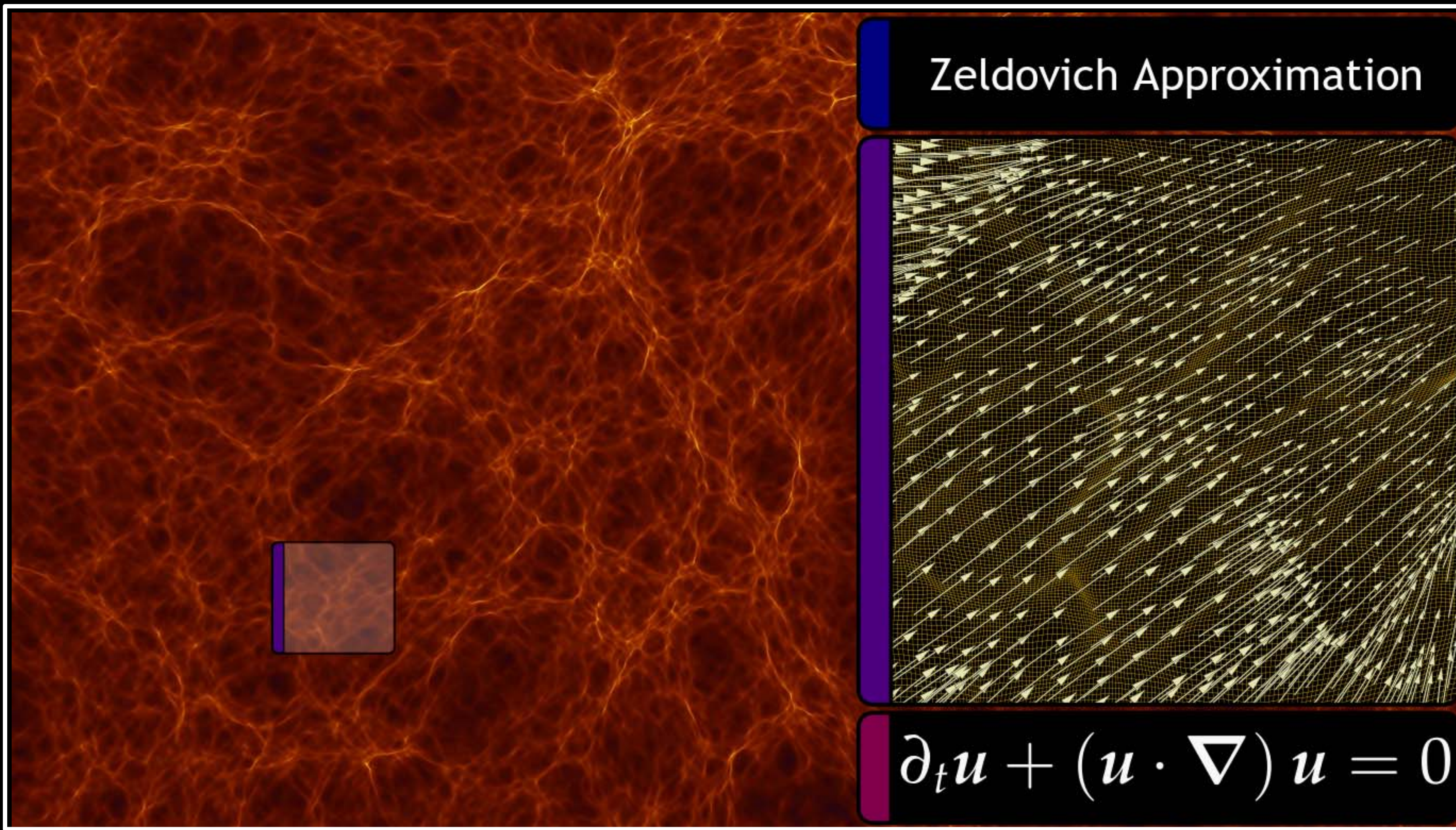
Platen & vdW 2004
Sheth & vdW 2004
Aragon-Calvo & Szalay 2012

# Hierarchical Dynamics of the Cosmic Web:

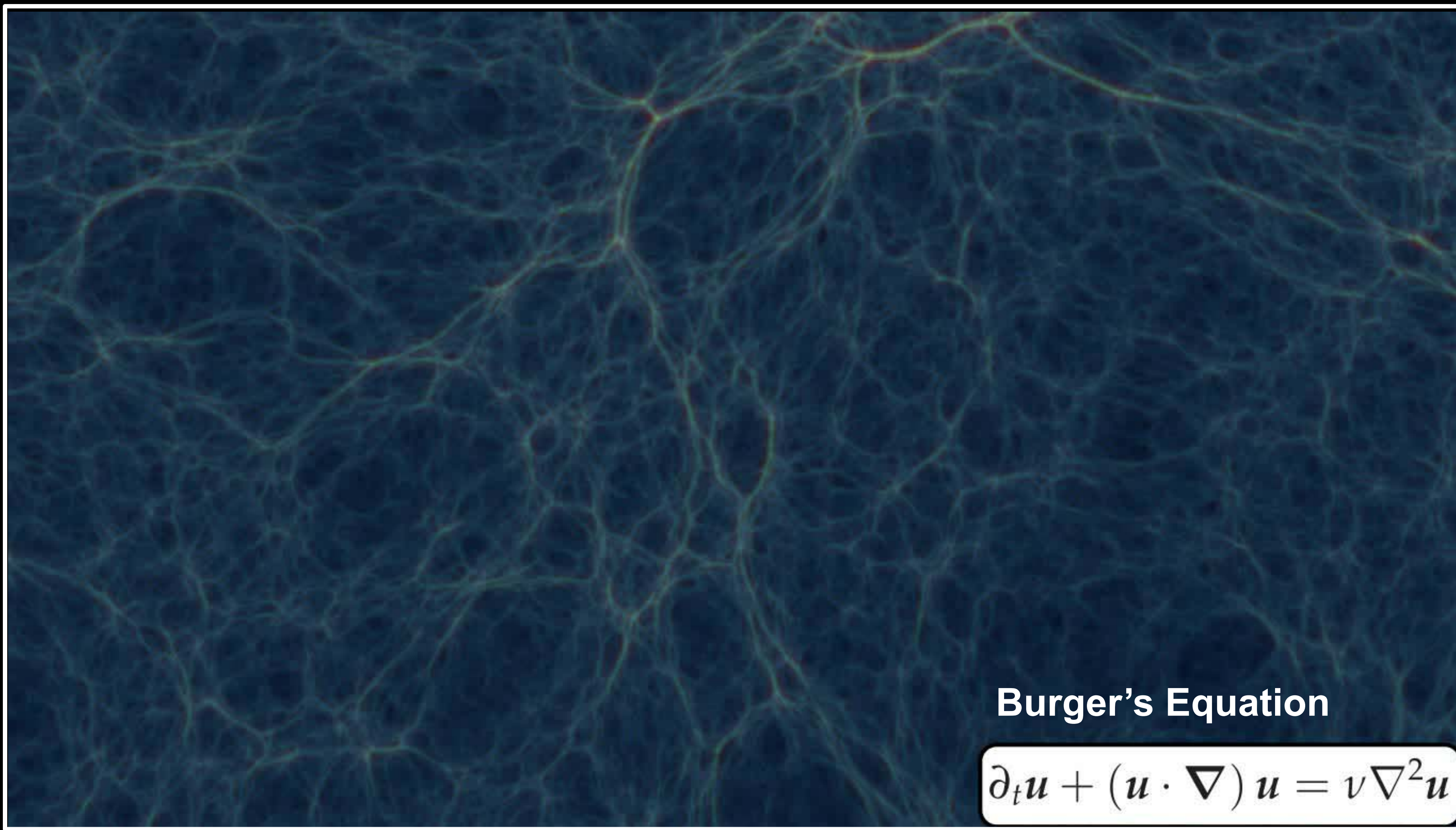
# Adhesion

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

# Zel’dovich Approximation



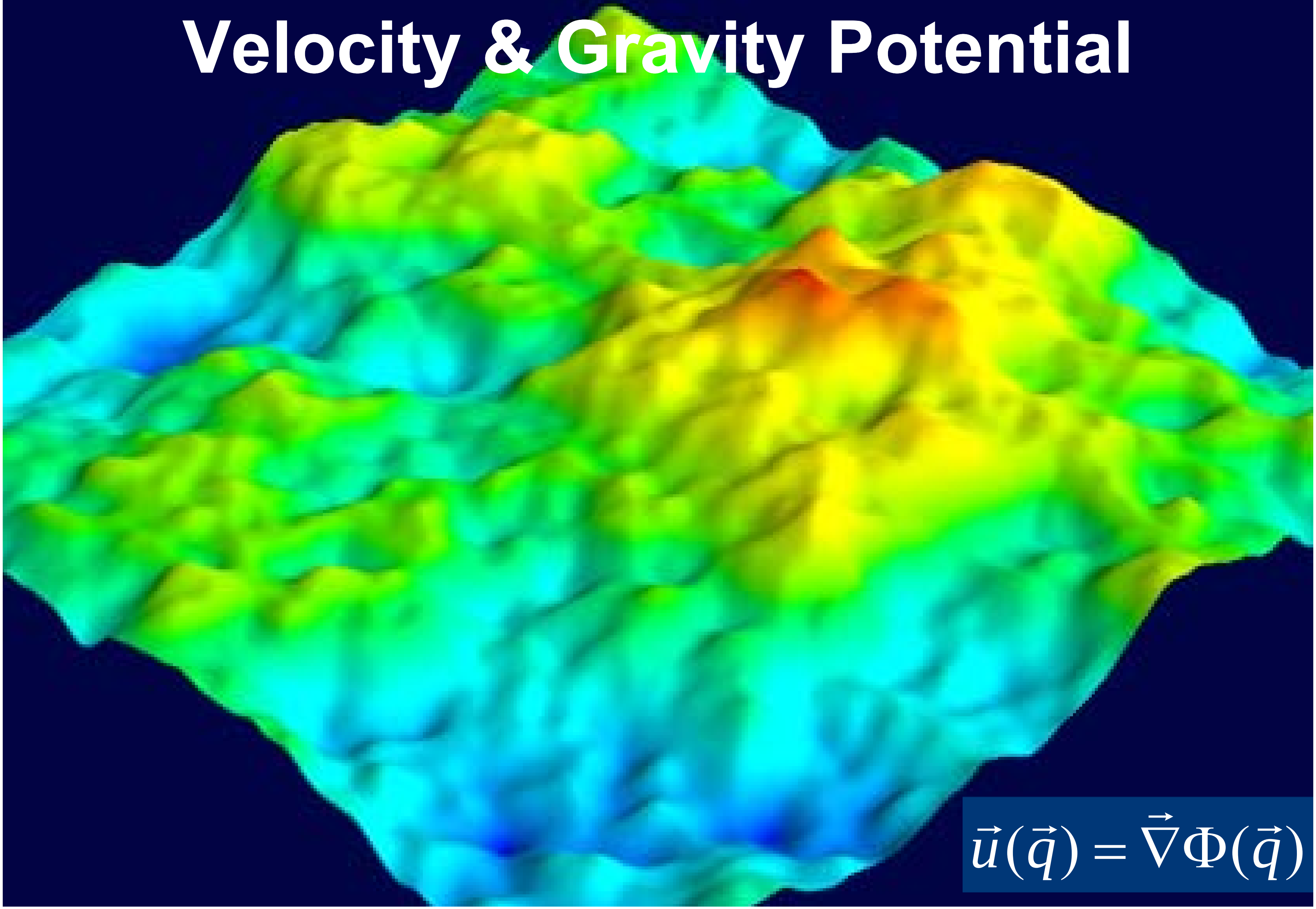
# Adhesion Approximation



Burger's Equation

$$\partial_t \boldsymbol{u} + (\boldsymbol{u} \cdot \boldsymbol{\nabla})\, \boldsymbol{u} = \nu \nabla^2 \boldsymbol{u}$$

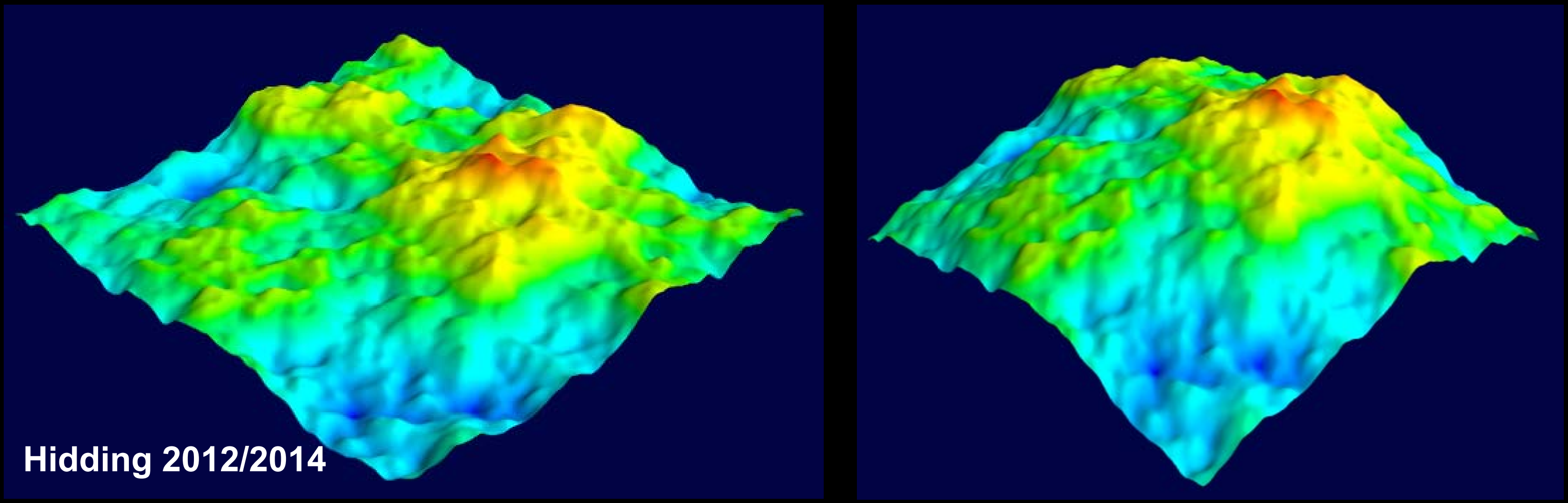
# Velocity & Gravity Potential



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

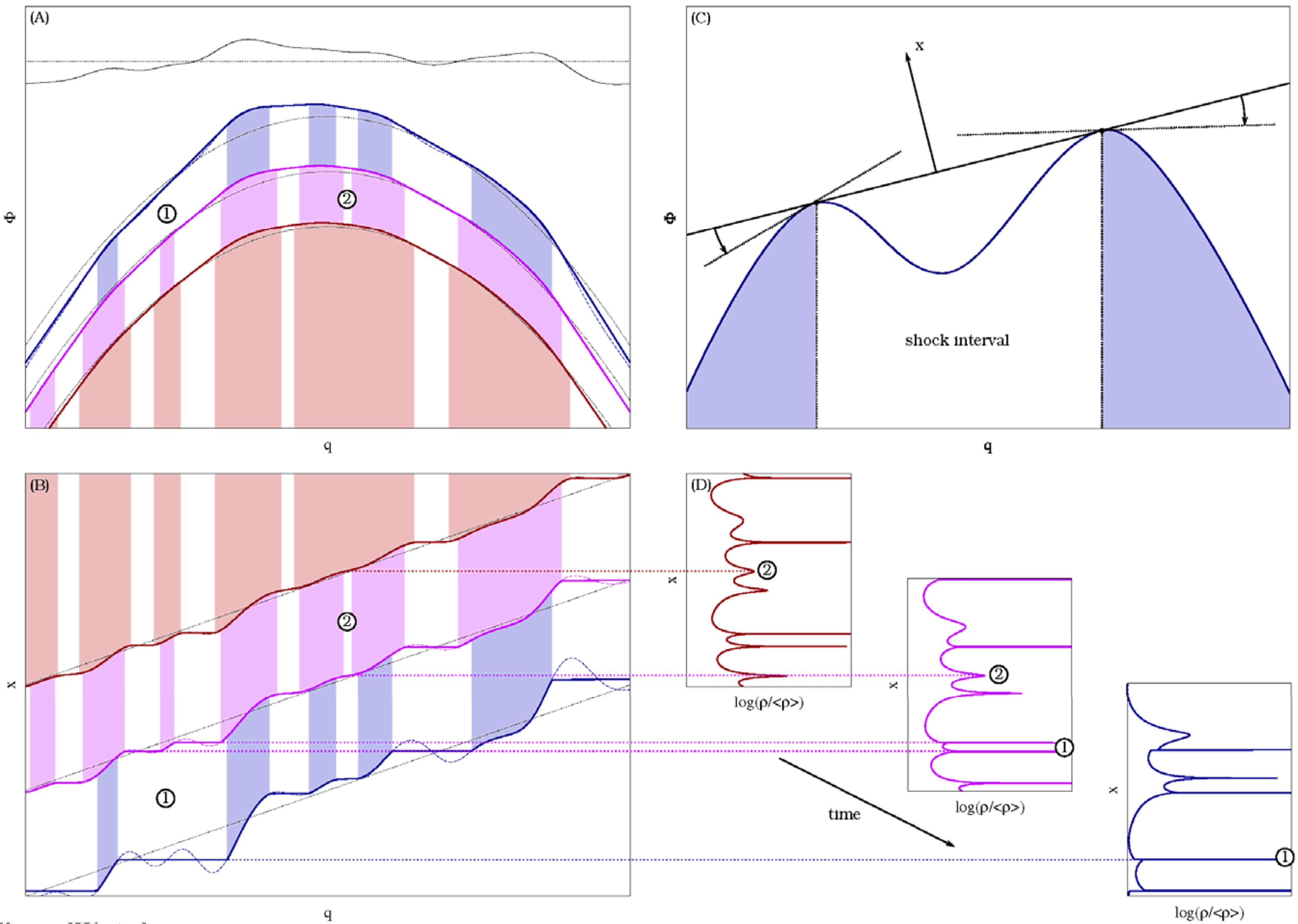
# Burger's Equation: Hopf Solution

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

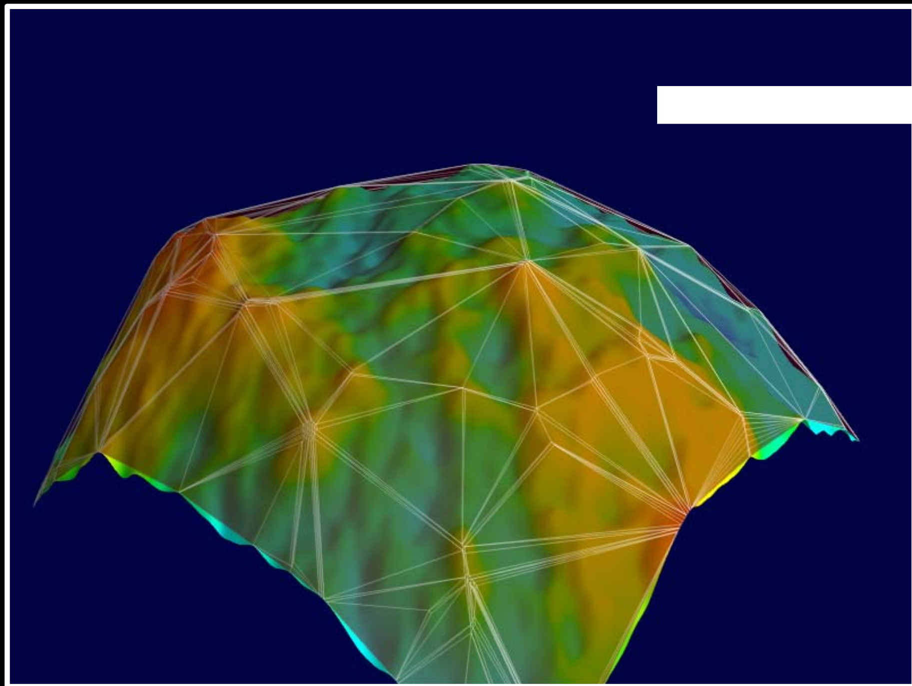


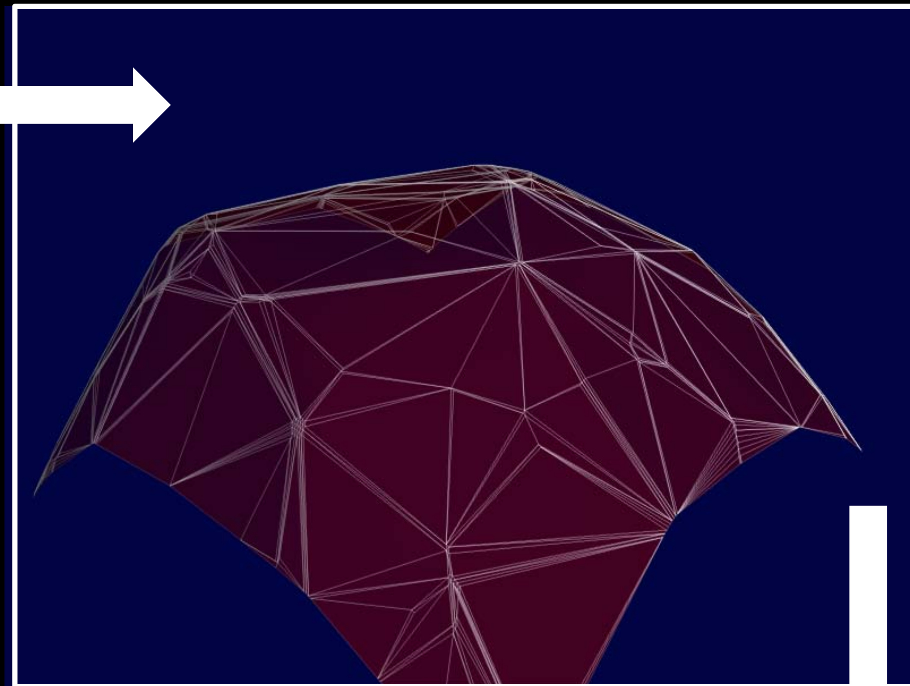

$$\Phi(\vec{x},t) + \frac{x^2}{2} = \max_q \left[ \left( t\Phi_0(q) - \frac{q^2}{2} \right) + \vec{x} \cdot \vec{q} \right]$$

# Burger's Equation: Hopf Solution




Hidding, vdW et al.

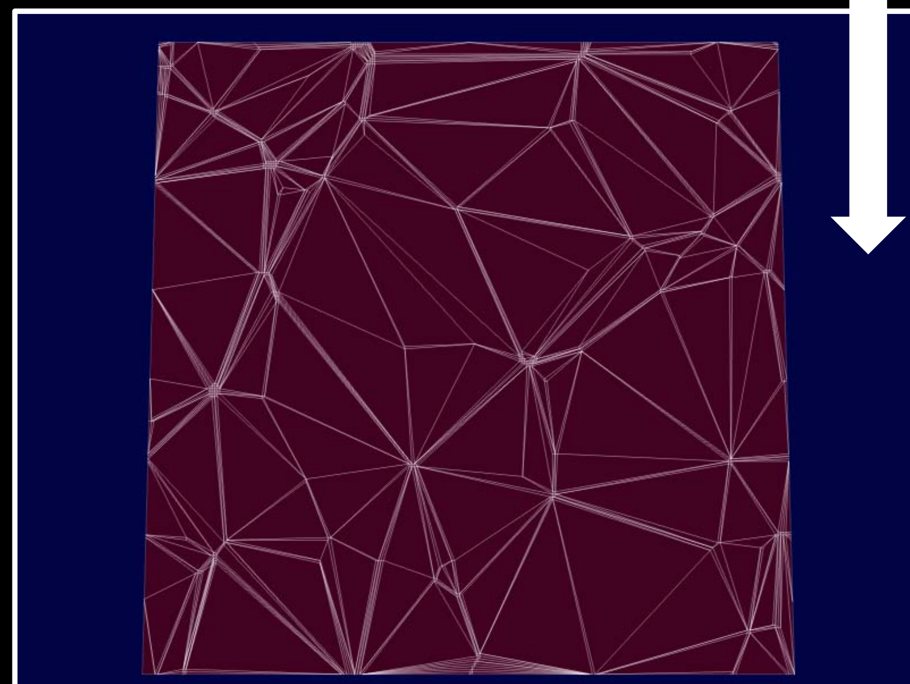




**Hidding 2012/2014**

Convex Hull
quadratically lifted potential field

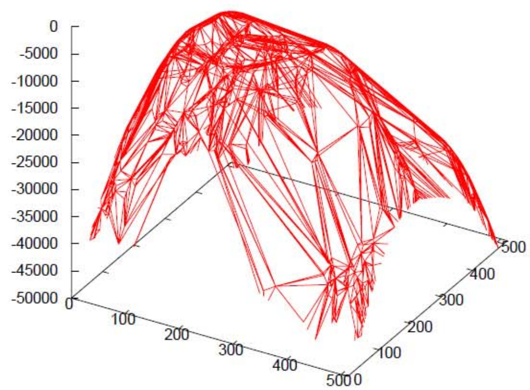
Delaunay tessellation
generated by maxima potential field

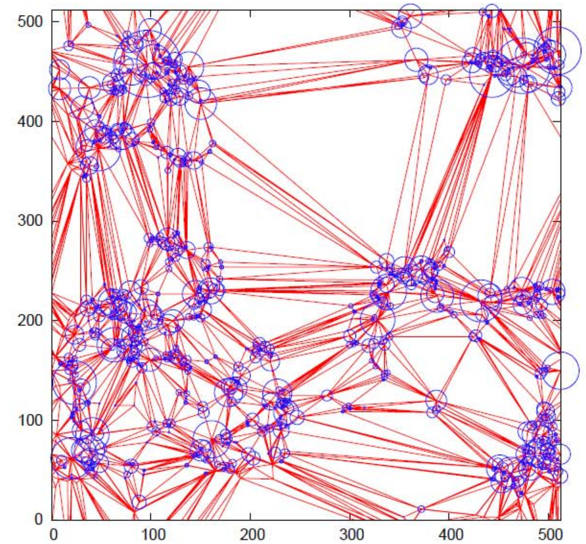


# Convex Hull – Legendre transform

Lagrangian
Space

(a)



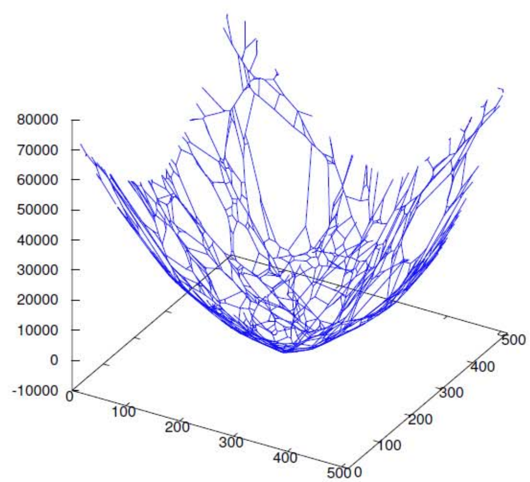



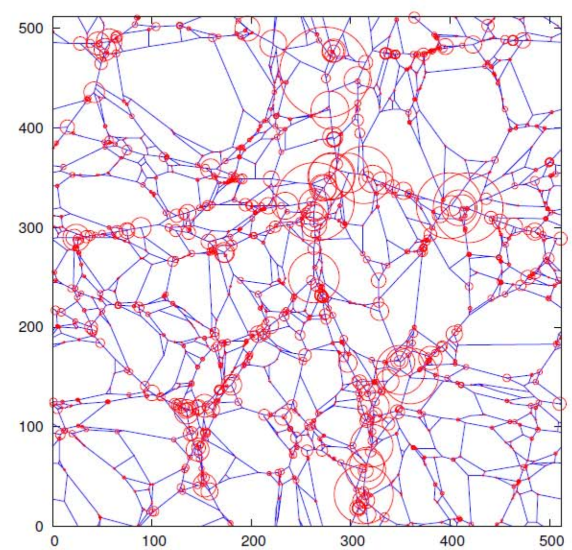

Delaunay

(weighted)

Eulerian
Space

(b)




Voronoi

(weighted)

Hidding, vdW et al.

# Hierarchical Web Evolution:

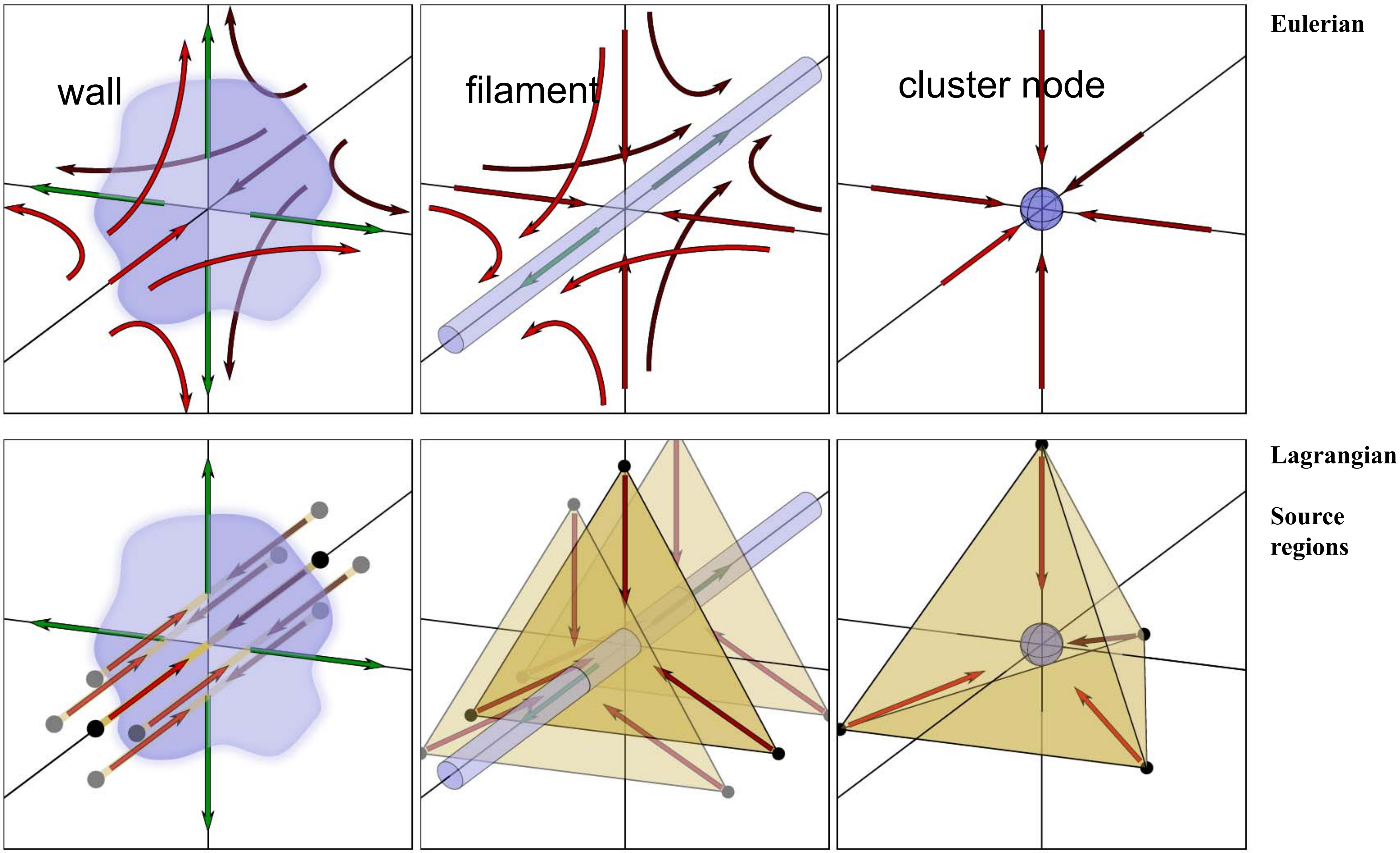
## Adhesion simulation buildup Cosmic Web

Johan Hidding

2012

# Euleriaan vs. Lagrangian

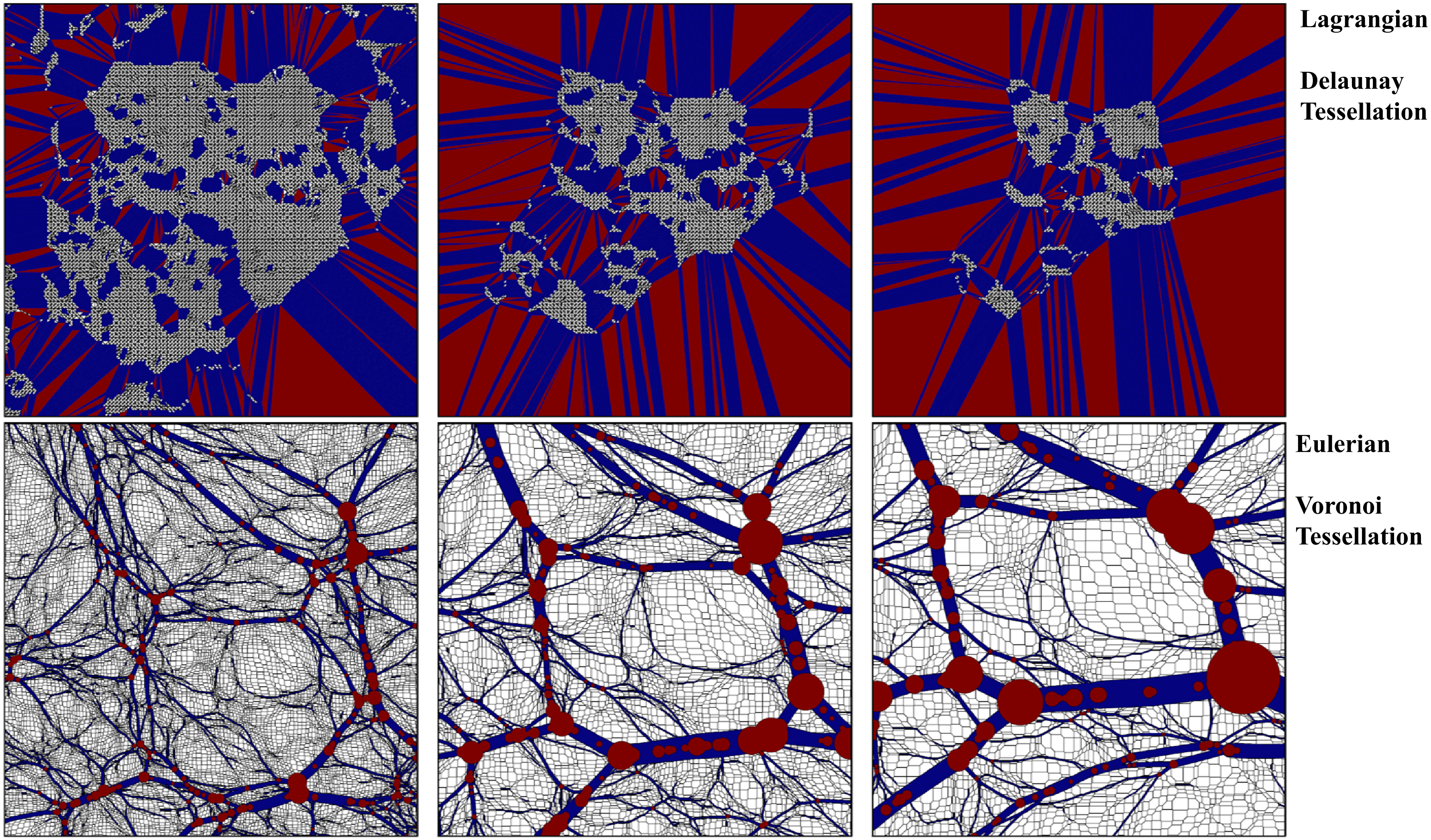
## weblike geometry



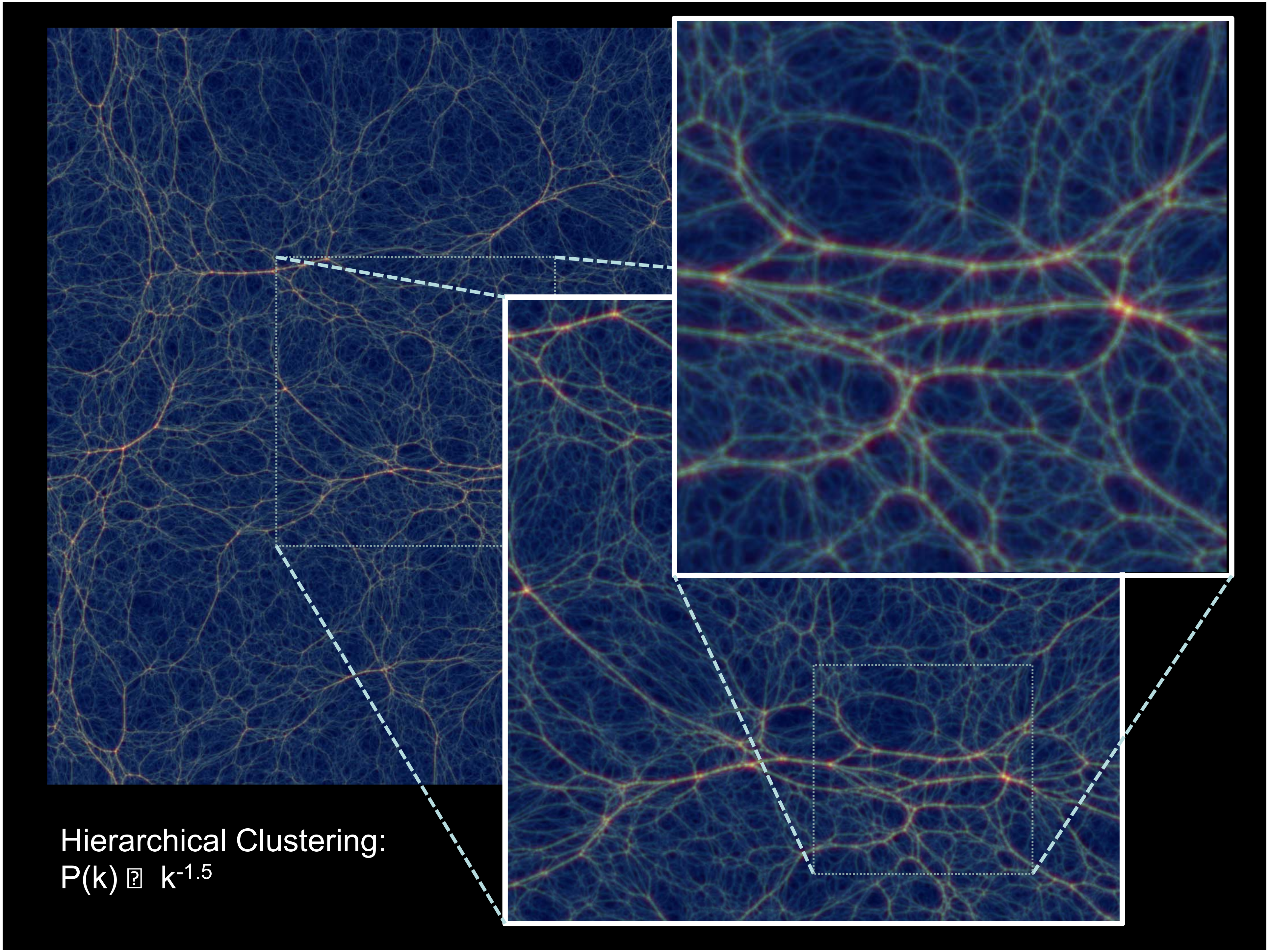

Hidding, vdW et al.

# Lagrangian – Eulerian Cosmic Web

# Delaunay- Voronoi Tessellations




Hidding, vdW et al.


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

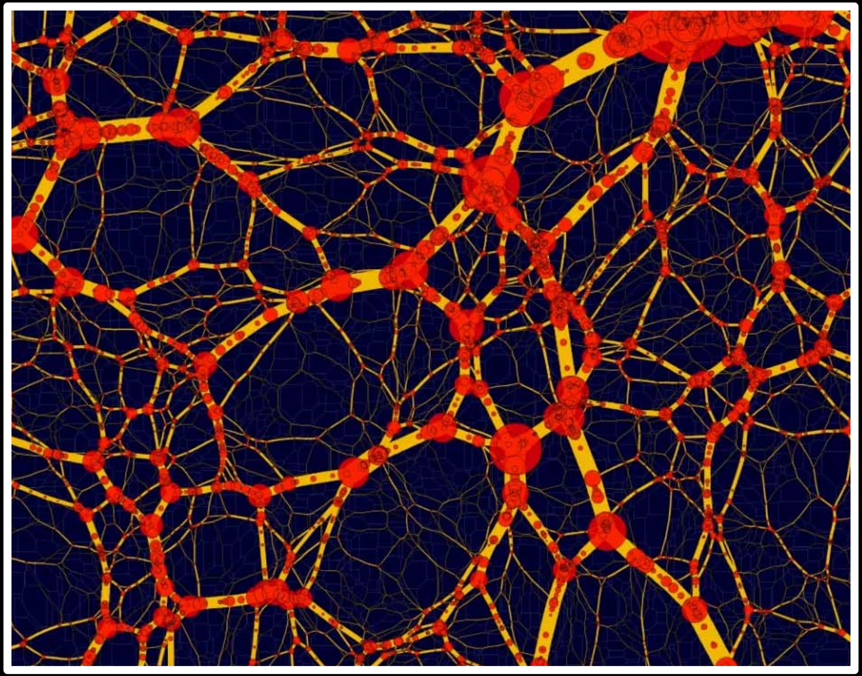
# Cosmological Sensitivity Cosmic Web

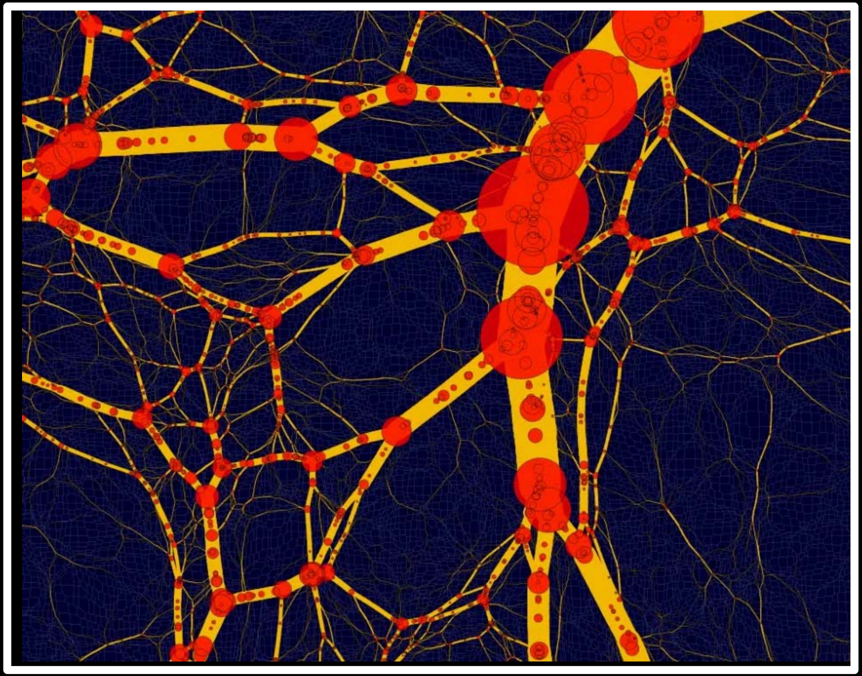
the morphology of the weblike network is
highly sensitive to the underlying cosmology

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

**Hidding 2012/2014**

$P(k) \sim k^{-2.0}$





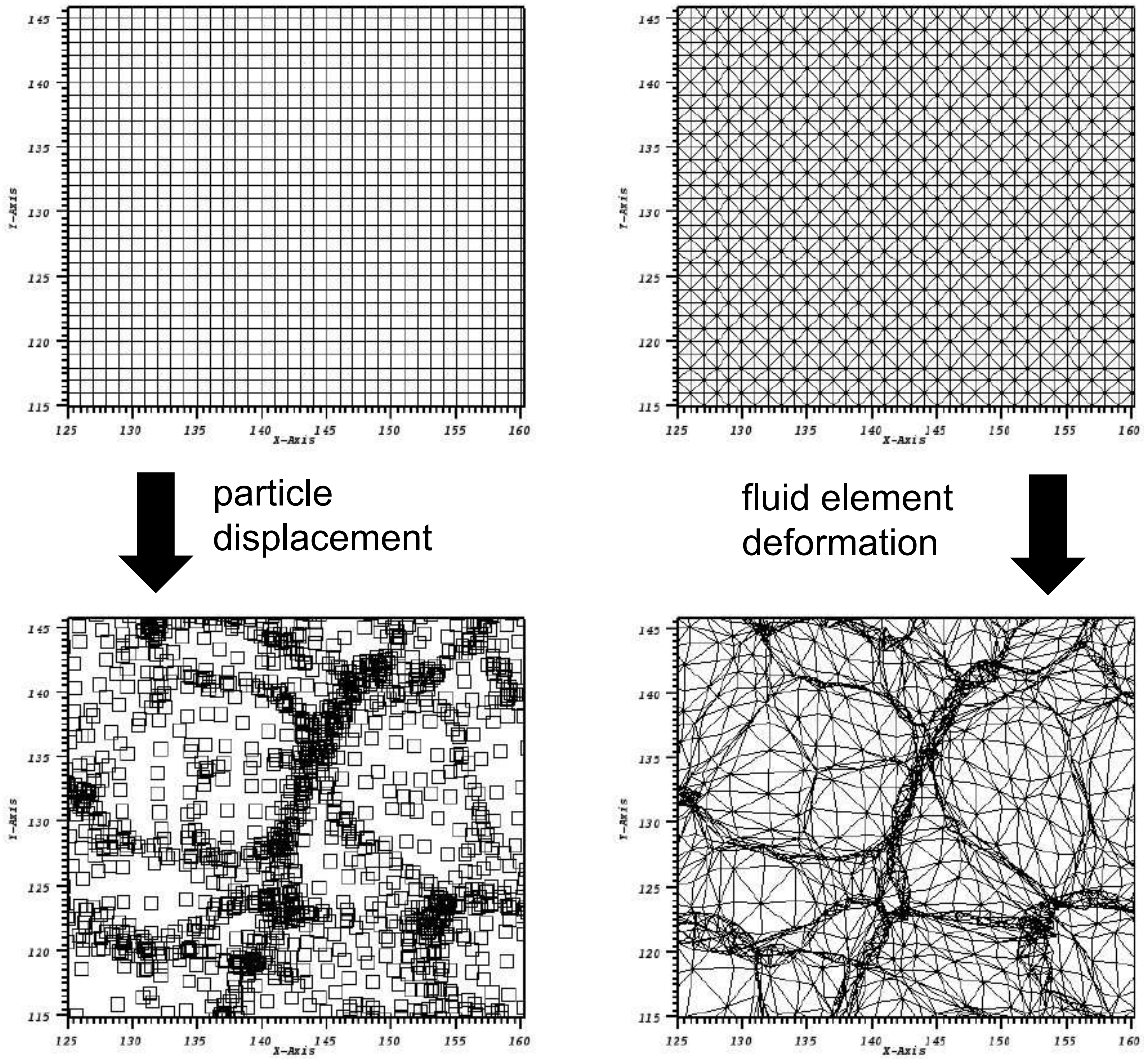
# Cosmic Web

# Phase-Space Evolution

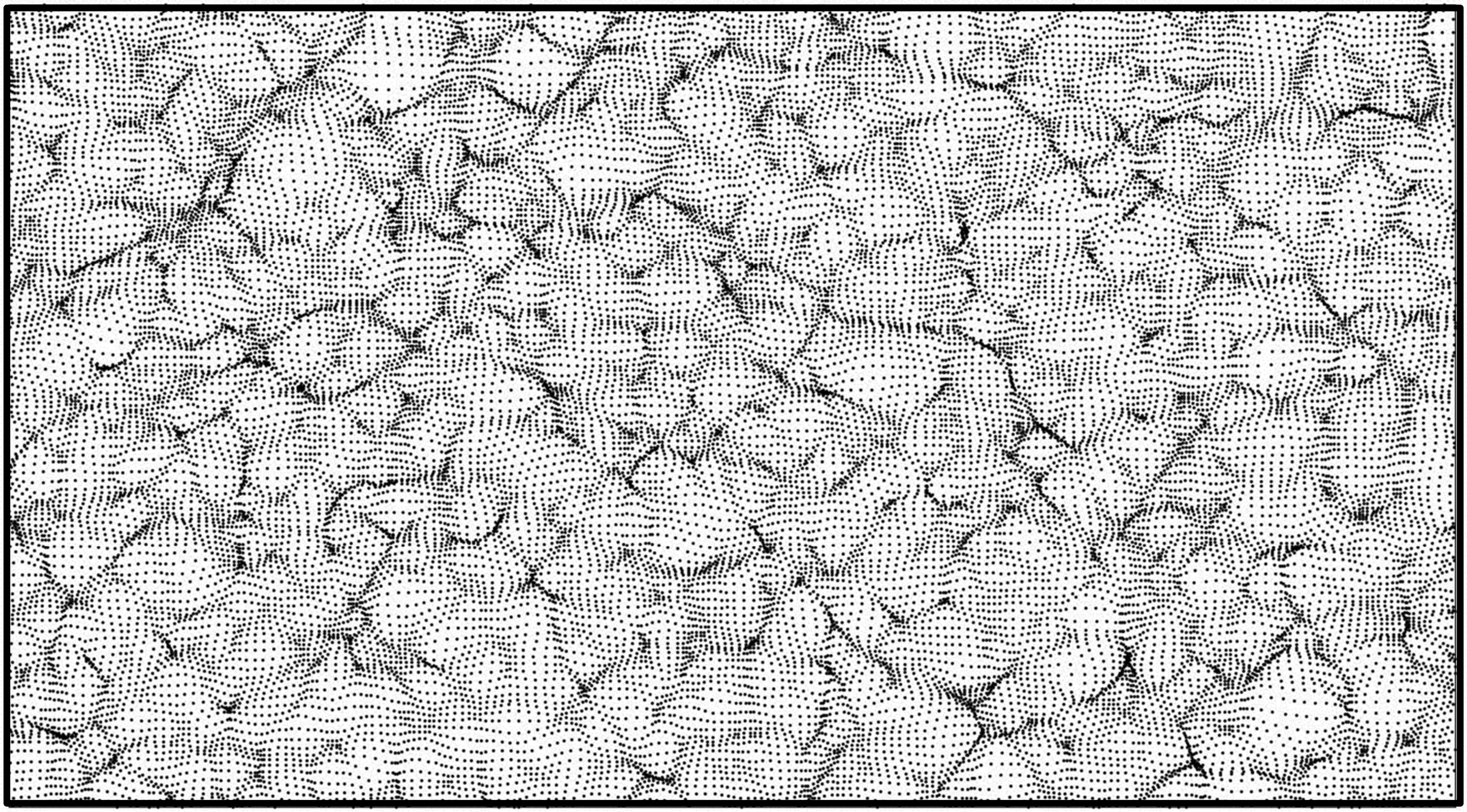
# Tessellation Deformation & Phase Space Projection

**Translation towards Multi-D space:**

- **Look at deformation of initial tessellation**
- **each tessellation cell represents matter cell**
- **evolution deforms cell**
- **once cells start to overlap, manifestation of different phase-space matter streams**



# Simulation – Discrete Particles



# Simulation – Mass Elements

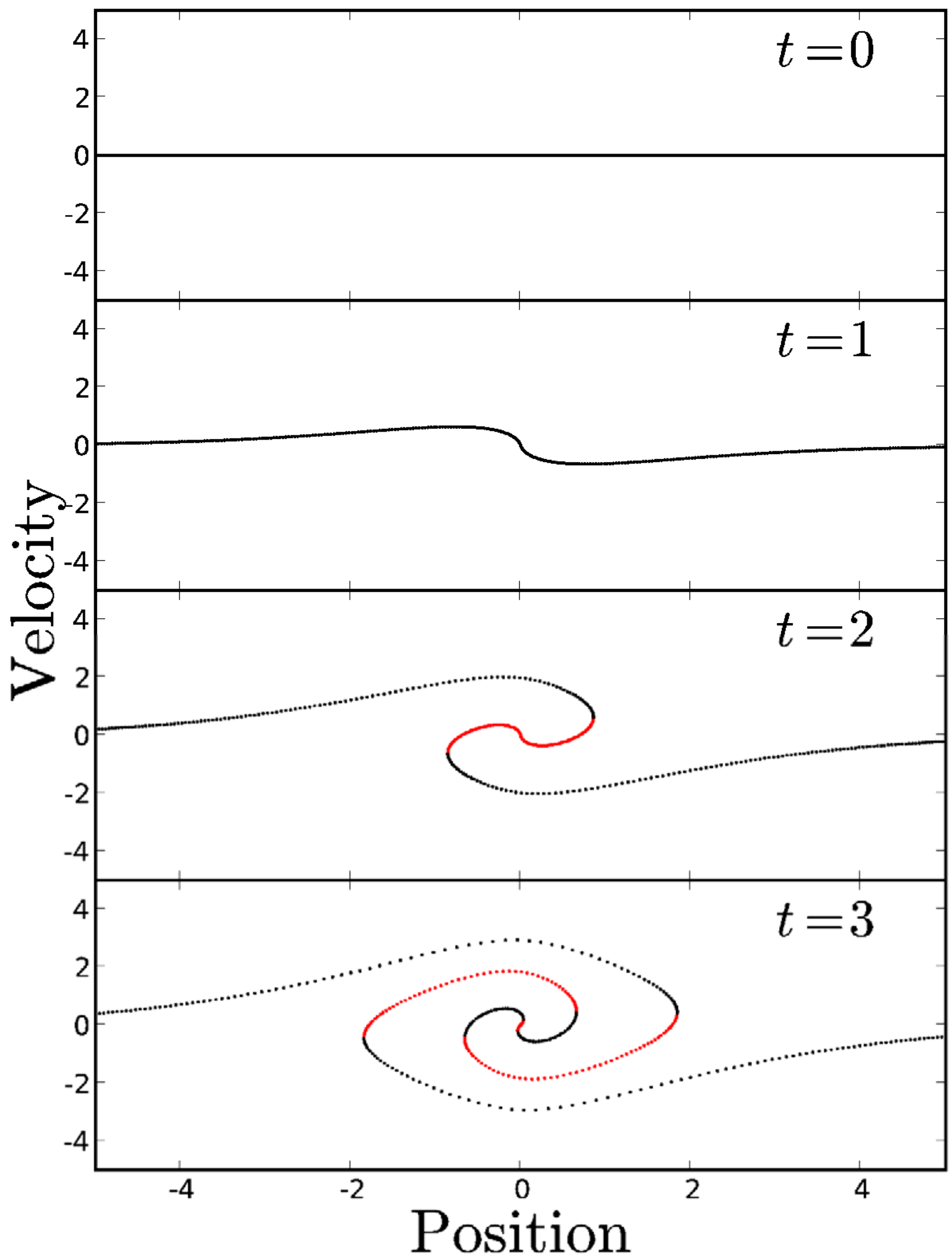
# Phase Space Evolution

Dark Matter Phase Space sheet:

3-D structure projection of a folding DM phase space sheet In 6-D phase space

- Shandarin 2010, 2011
- Neyrinck et al. 2011, 2012 Origami
- Abel et al. 2011

Evolving matter distribution in position-velocity space – 1D



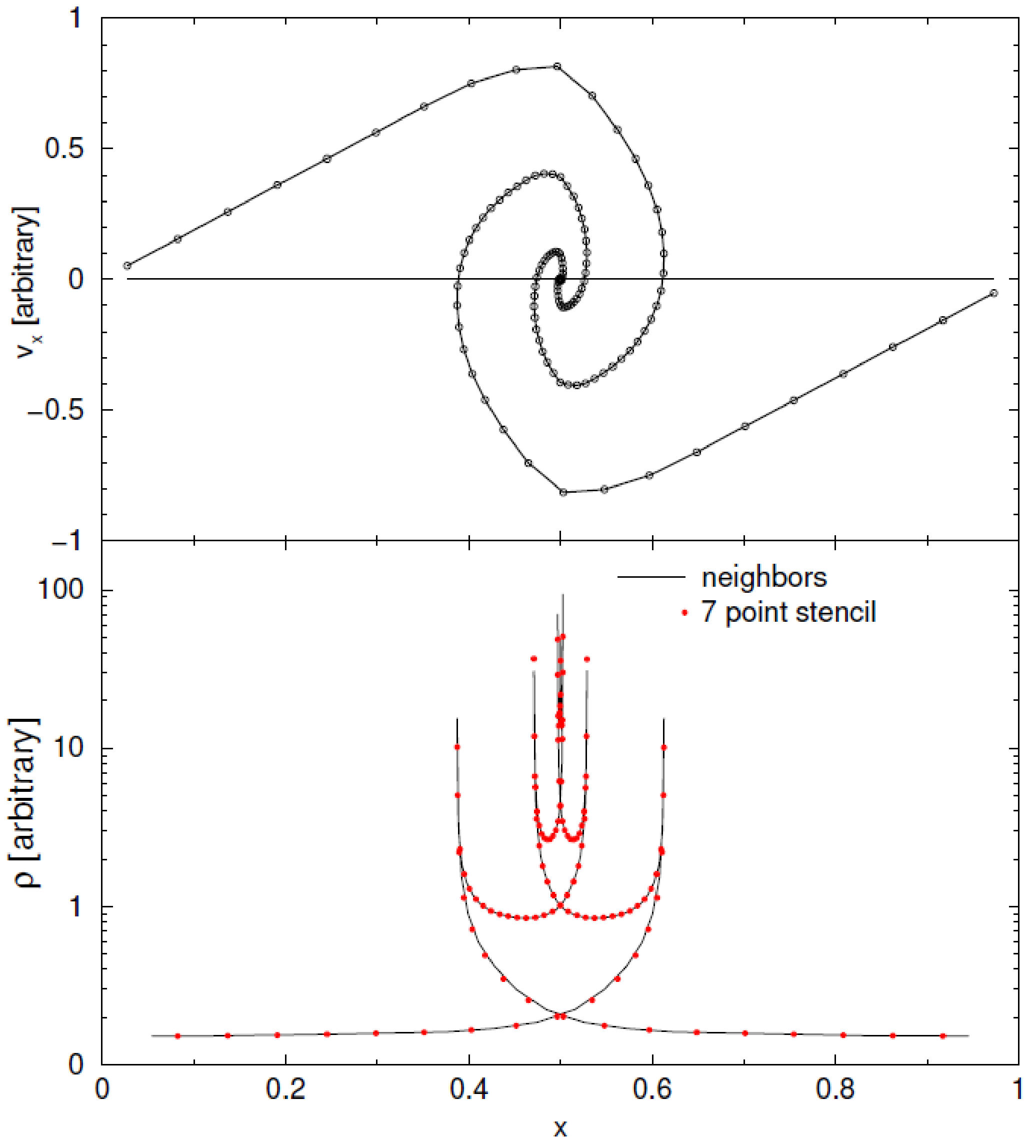
# Phase Space Evolution

**Phase space:**

**Velocity vs. Position**

**Density:**

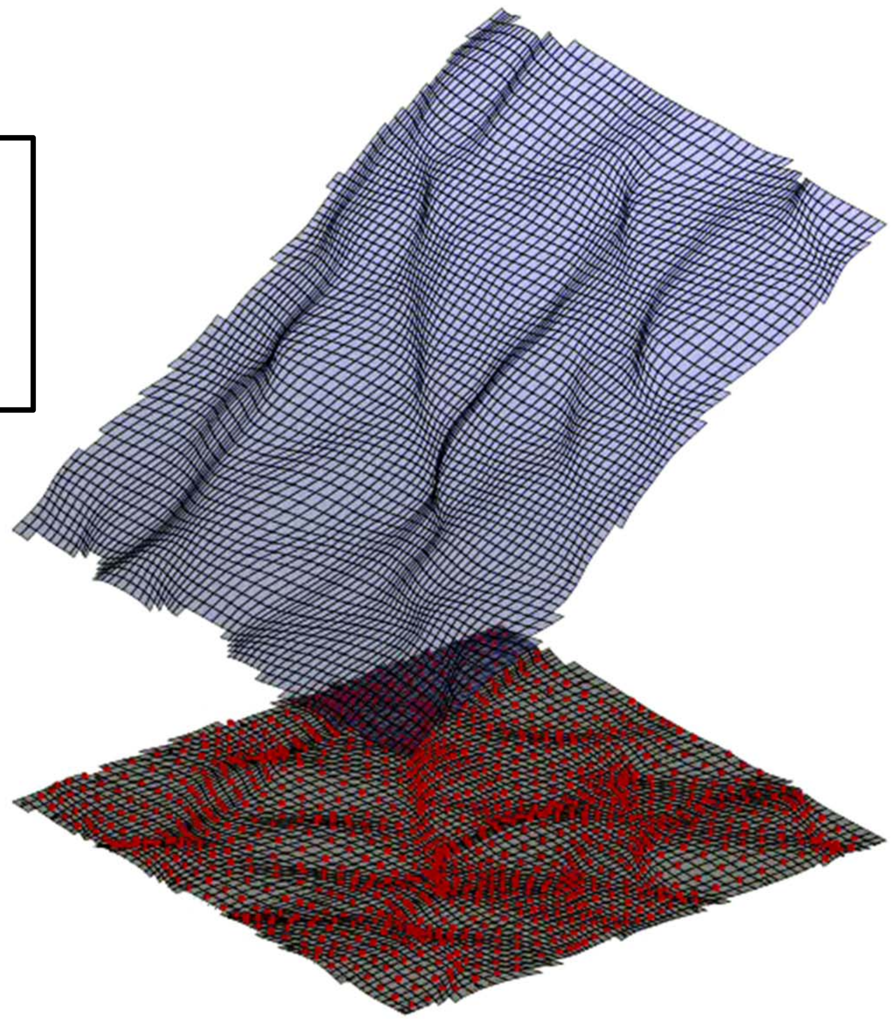
$$\rho(\vec{x},t) = \int f\left(\vec{x},\vec{v},t\right) d\vec{v}$$



# Phase-Space Evolution

**Dynamical Evolution:**

**folding the phase-space sheet {q,x}**



**Lagrangian coordinate**

**Eulerian plane**

Hidding 2014

# Tessellation Deformation & Phase Space Projection

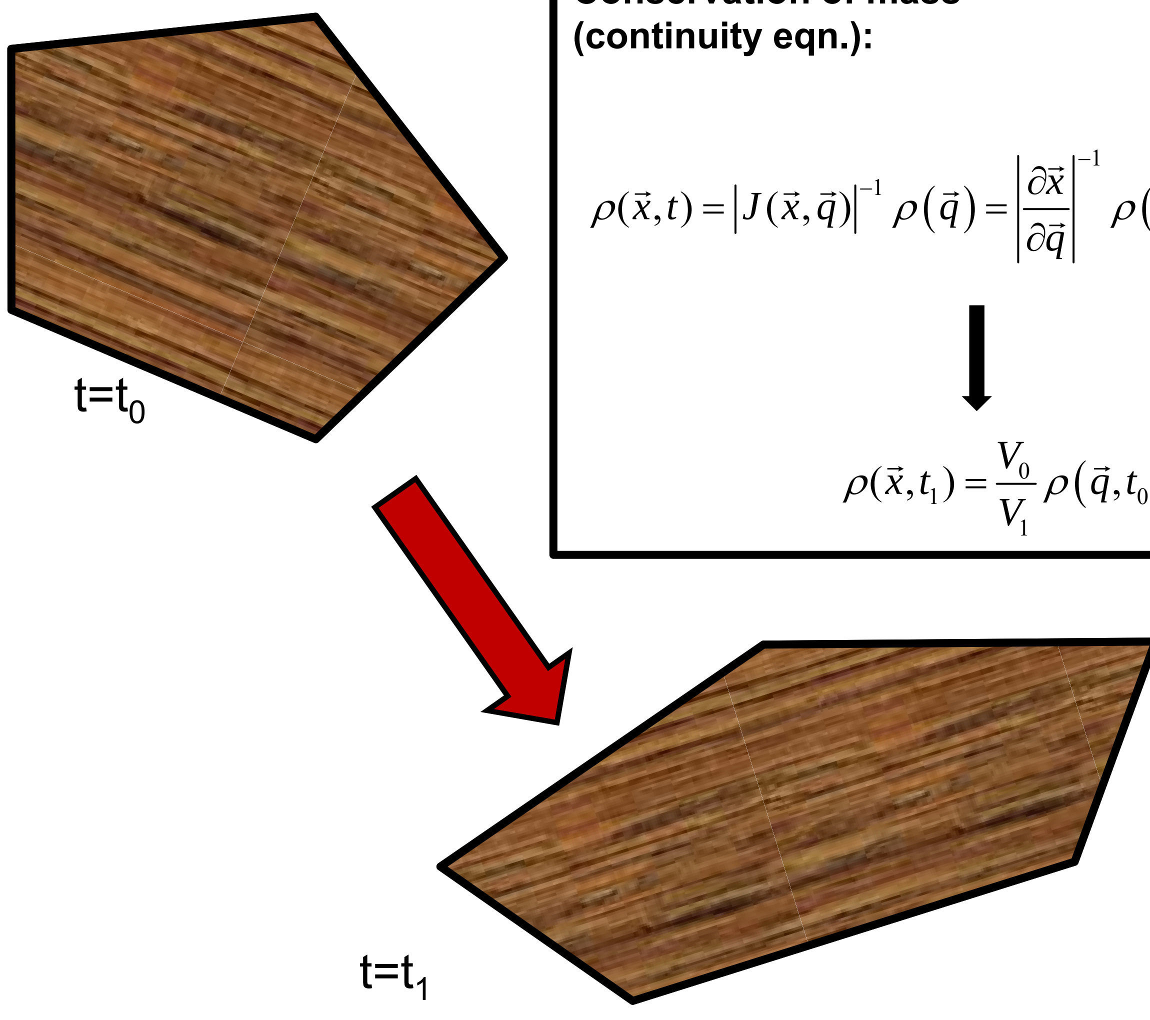
**Translation towards Multi-D space:**

- Look at deformation of initial tessellation

- each tessellation cell represents matter cell

- evolution deforms cell

**Monostream Density Evolution**



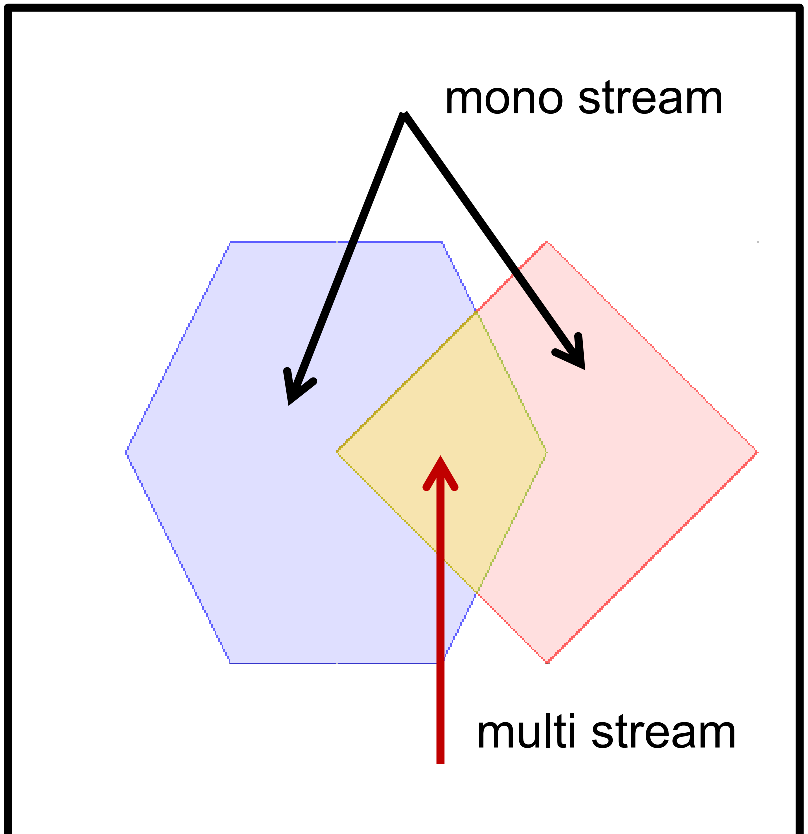

**Conservation of mass (continuity eqn.):**

$$\rho(\vec{x},t) = \left|J(\vec{x},\vec{q})\right|^{-1} \rho(\vec{q}) = \left|\frac{\partial \vec{x}}{\partial \vec{q}}\right|^{-1} \rho(\vec{q})$$

$$\Downarrow$$

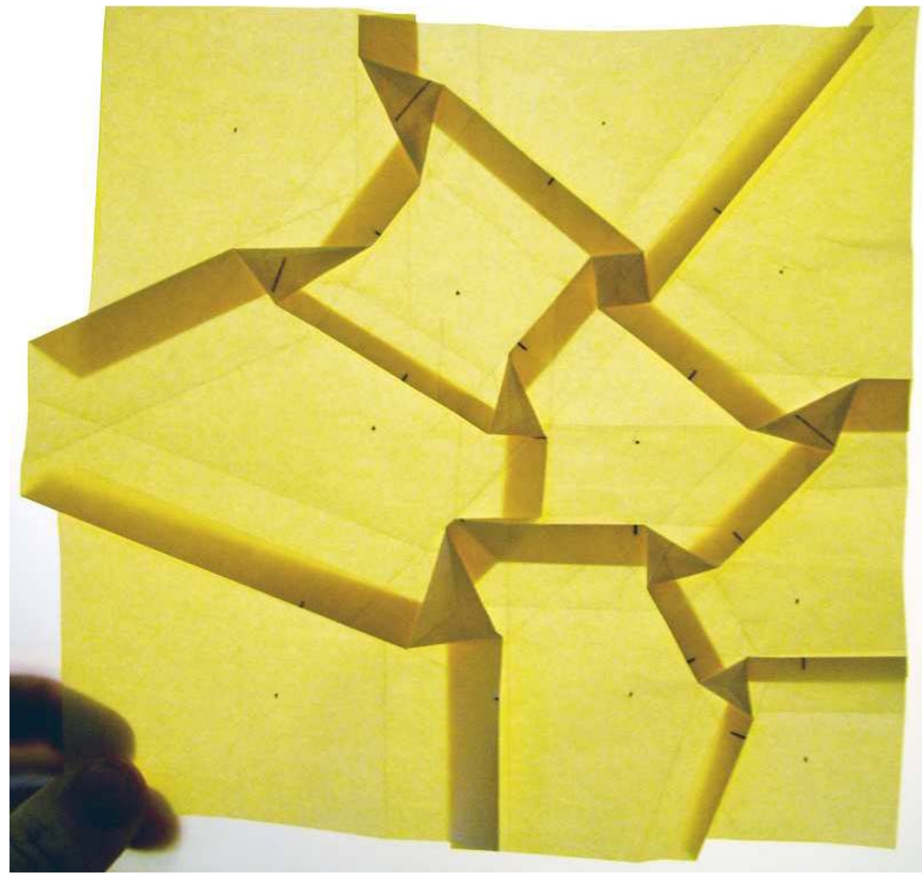
$$\rho(\vec{x},t_1) = \frac{V_0}{V_1}\,\rho(\vec{q},t_0)$$

# (Cosmic) ORIGAMI



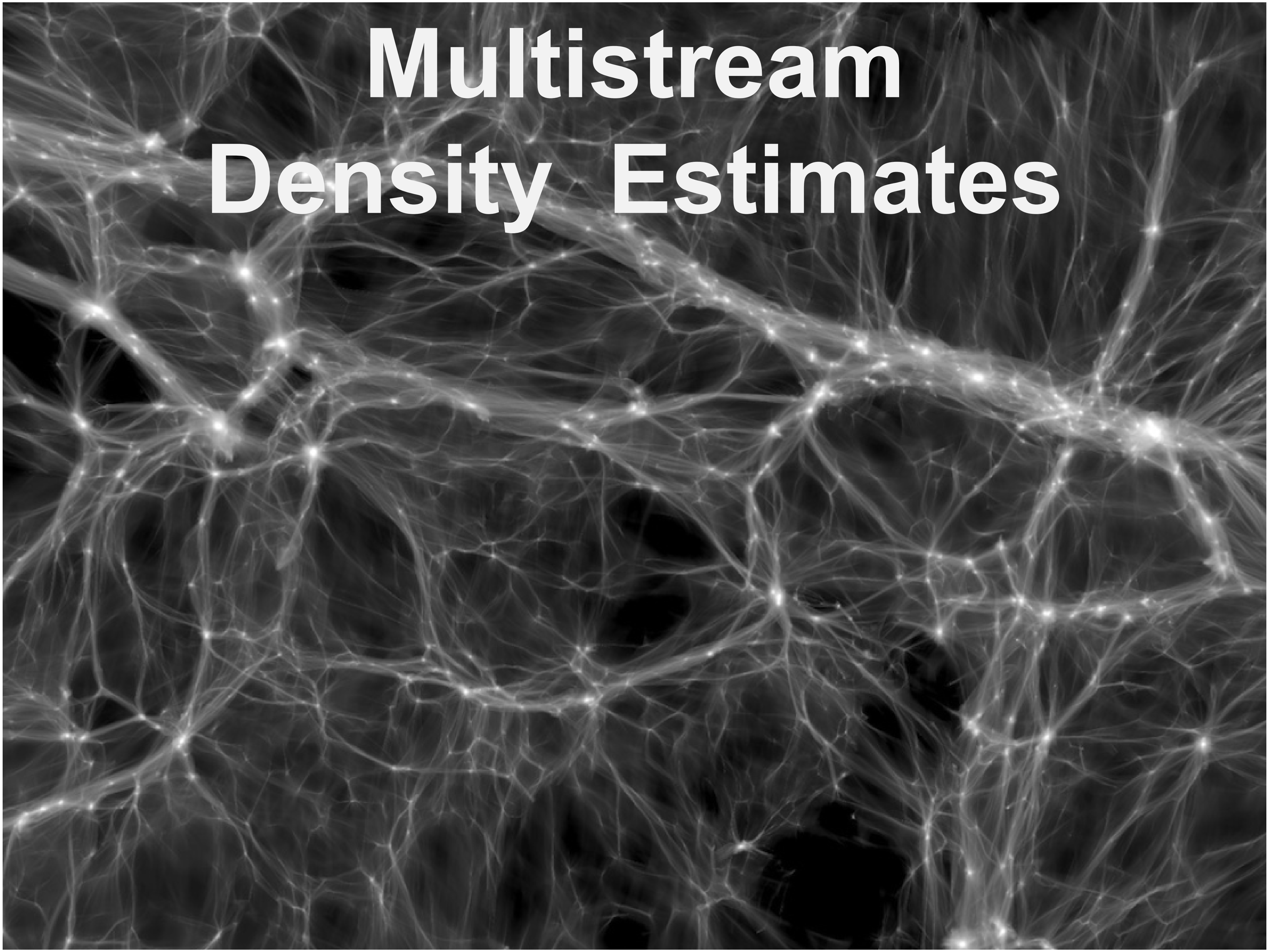

$$\rho_{total}(\vec{x}, t_1) = \sum_i \frac{V_{0i}}{V_{1i}} \rho(\vec{q}_i, t_0)$$

**Evolution of dynamical system:**
**Phase-space folding – Cosmic Origami**



Mark Neyrinck, Bridget Falck

# Multistream Density Estimates



# Cosmic Web Stream Density

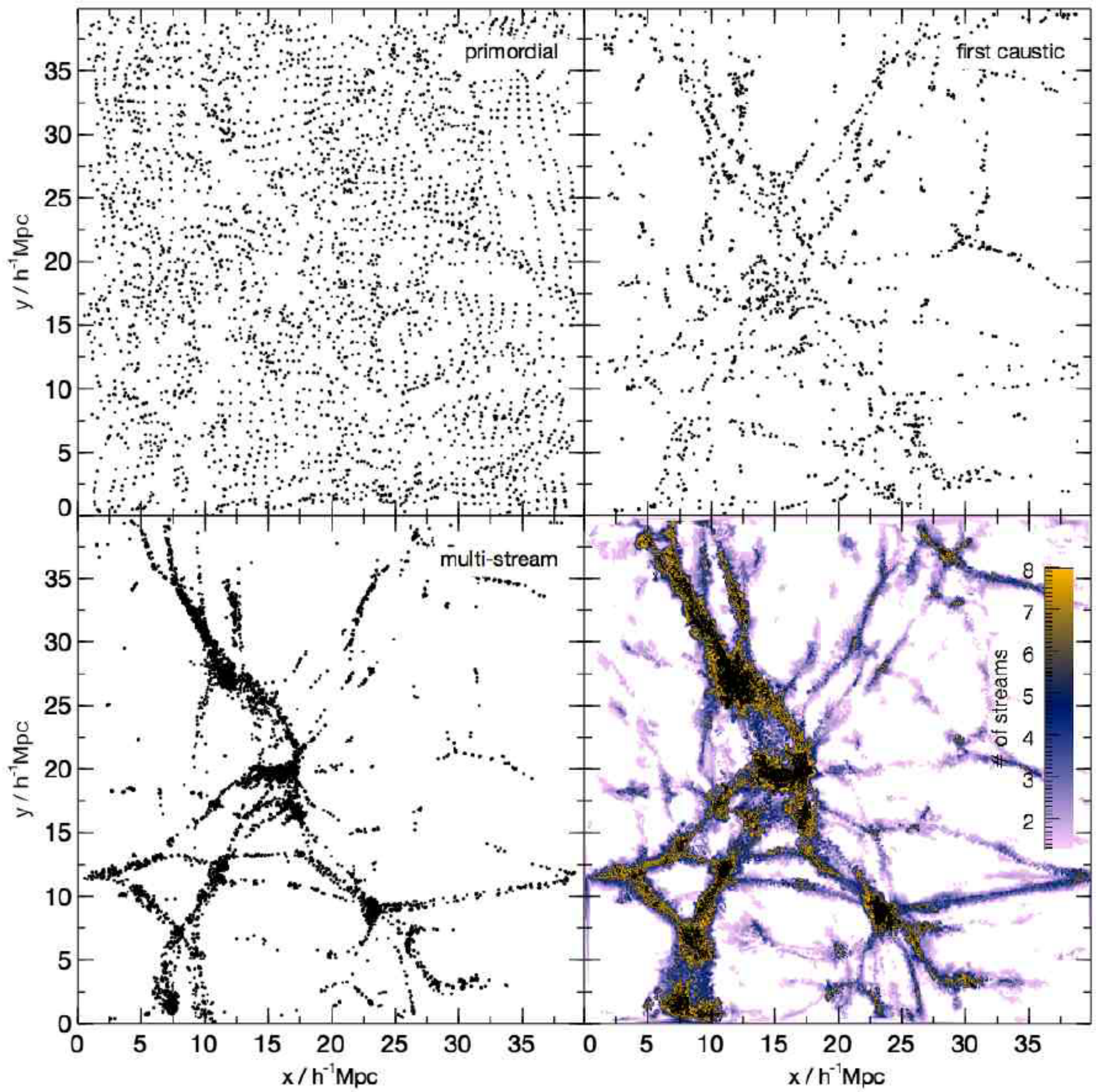
**Translation towards Multi-D space:**

**Density of dark matter streams:**

**- # phase space folds**

**=**

**# locally overlapping tessellation cells**




Shandarin 2012
Abel, Hahn & Kaehler 2012
Falck, Neyrinck et al. 2012

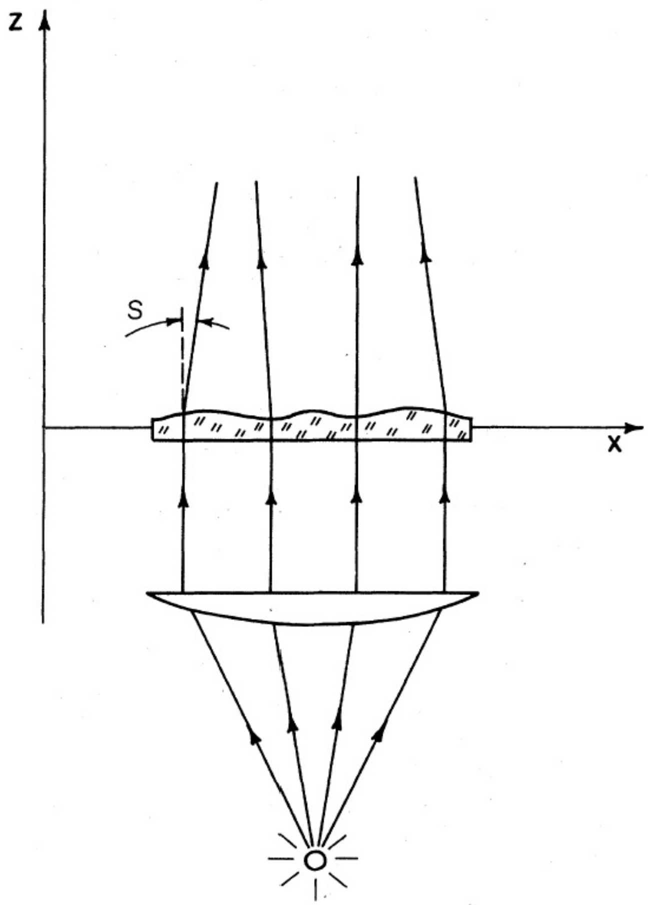
# Cosmic Web Skeleton:

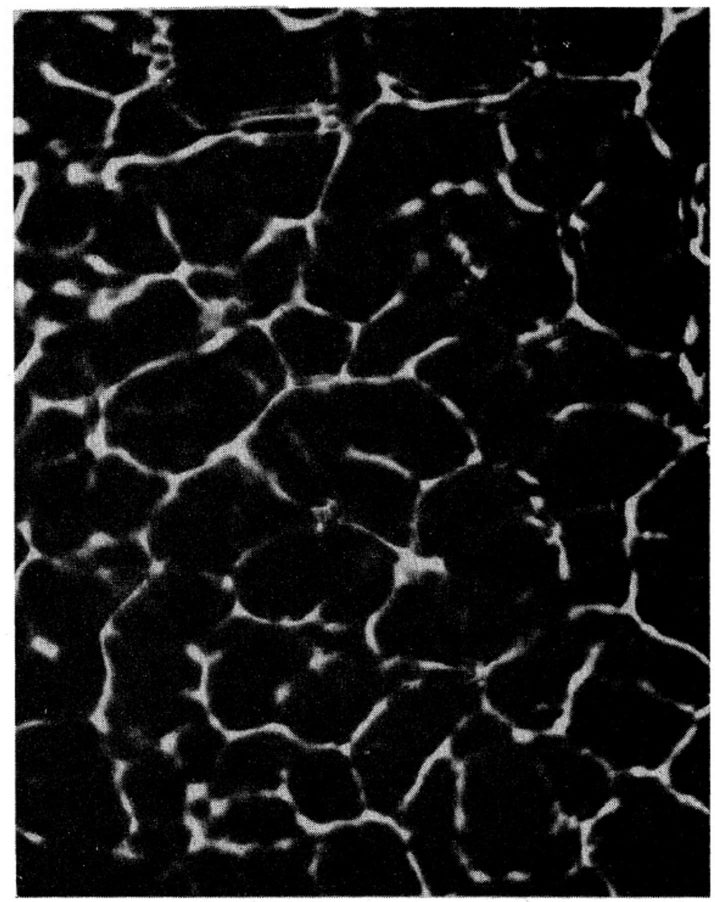
## Phase-Space Caustics
## Caustic Conditions

Hidding, Shandarin, vdW. 2014
Feldbrugge, vdW et al. 2017a
Feldbrugge, vdW et al. 2017b

# Zel'dovich Formalism:

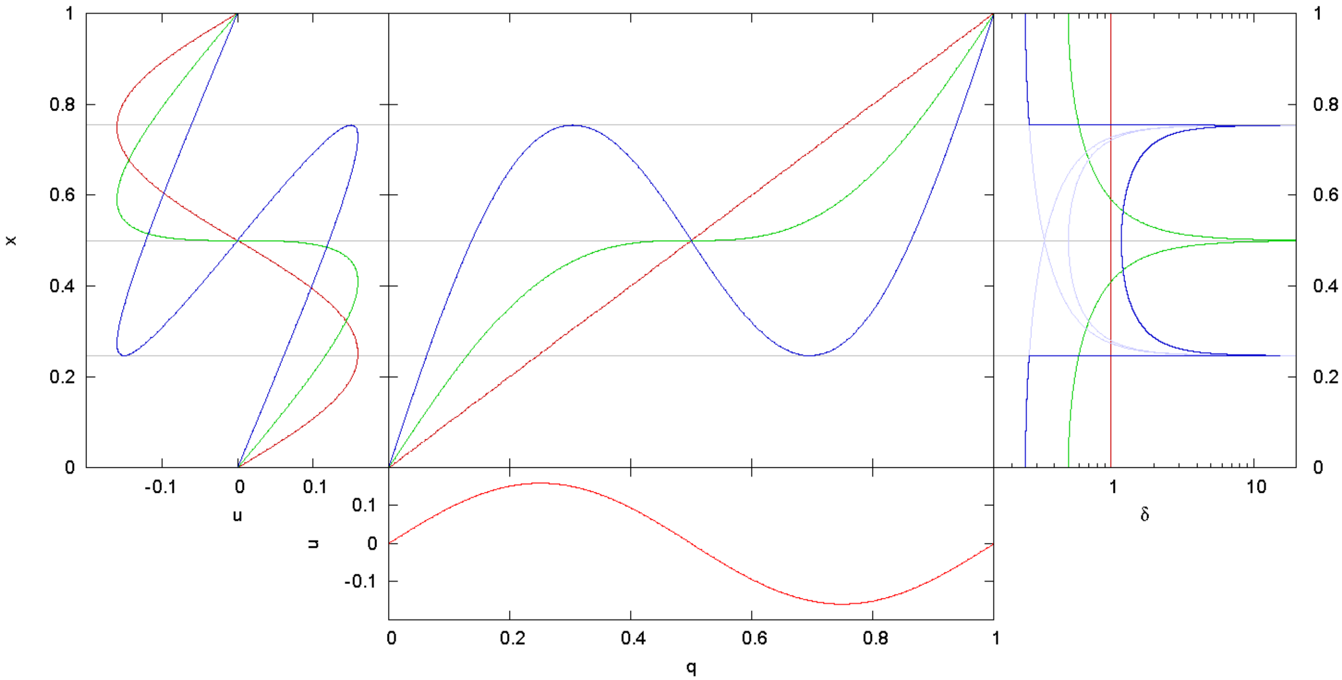
## Streaming & Caustics



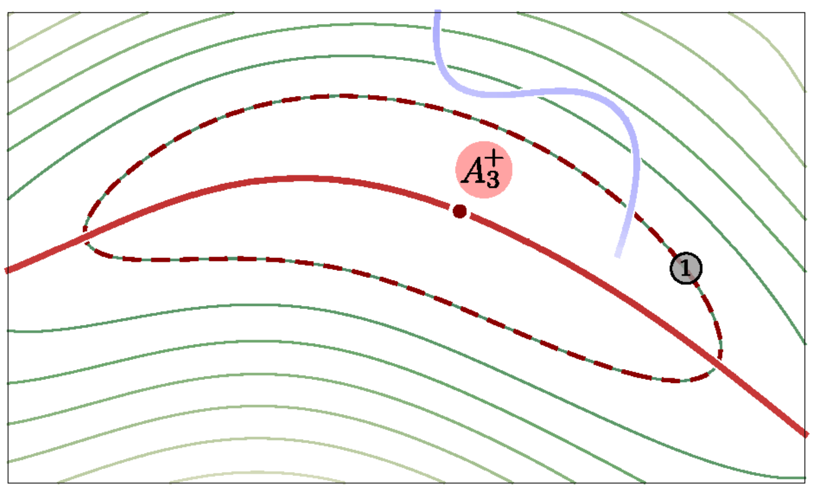
Shandarin & Zeldovich 1989

**Illustration of the formation of caustics due to streaming paths of light through deforming medium**

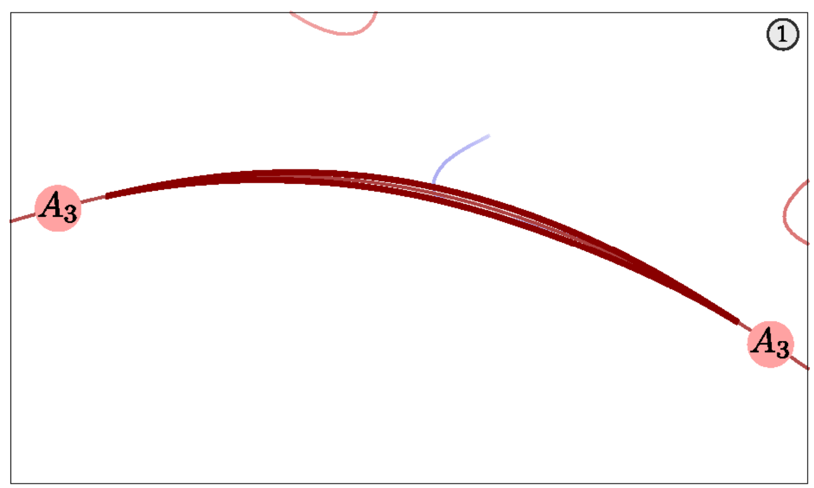



**Caustic Formation:**

# Folds & Cusps




Lagrangian space: $A_2$ contours




Eulerian space: folds & cusps

# Zel'dovich Approximation

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

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

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

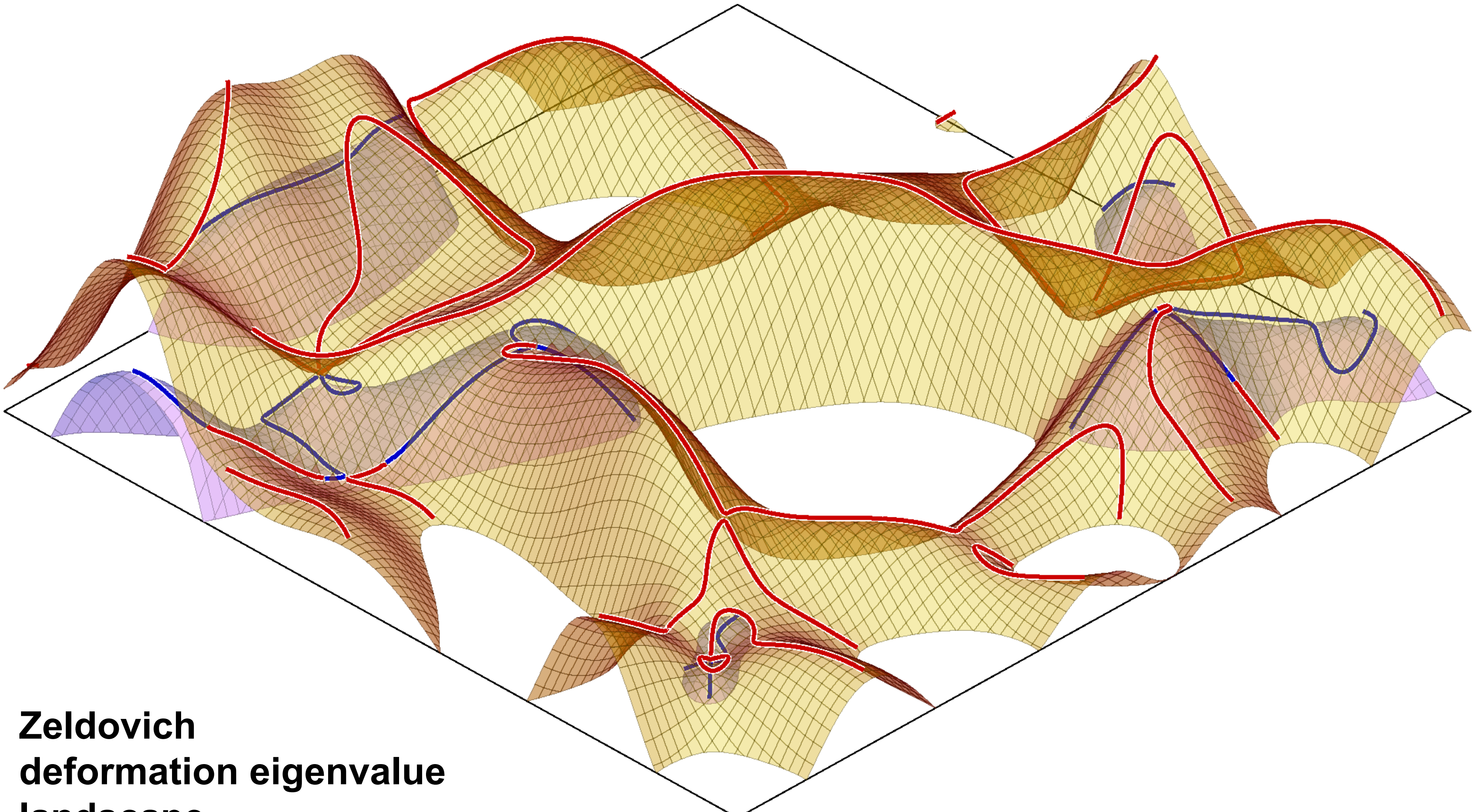
$$\rho(\vec{q},t) = \frac{\rho_u(t)}{\left(1 - D(t)\lambda_1(\vec{q})\right)\left(1 - D(t)\lambda_2(\vec{q})\right)\left(1 - D(t)\lambda_3(\vec{q})\right)}$$

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

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

# Singularities & Catastrophe:

# Deformation Field



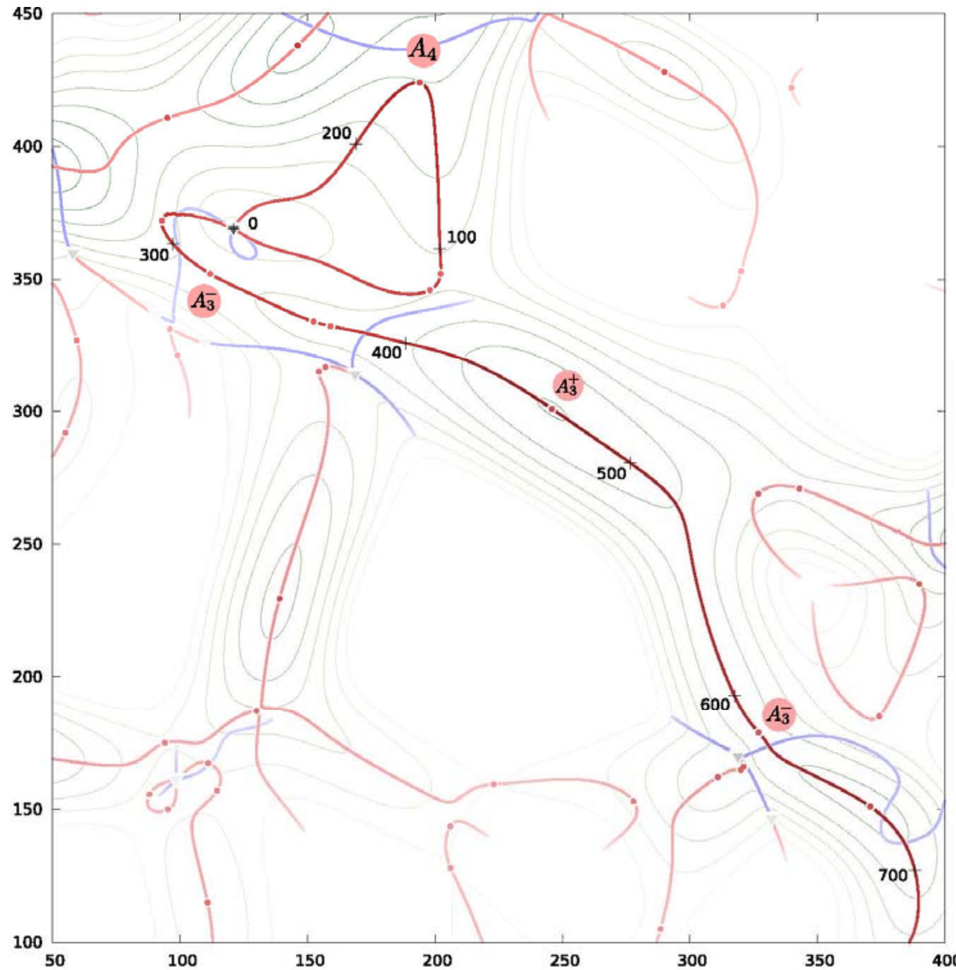
**Zeldovich deformation eigenvalue landscape**

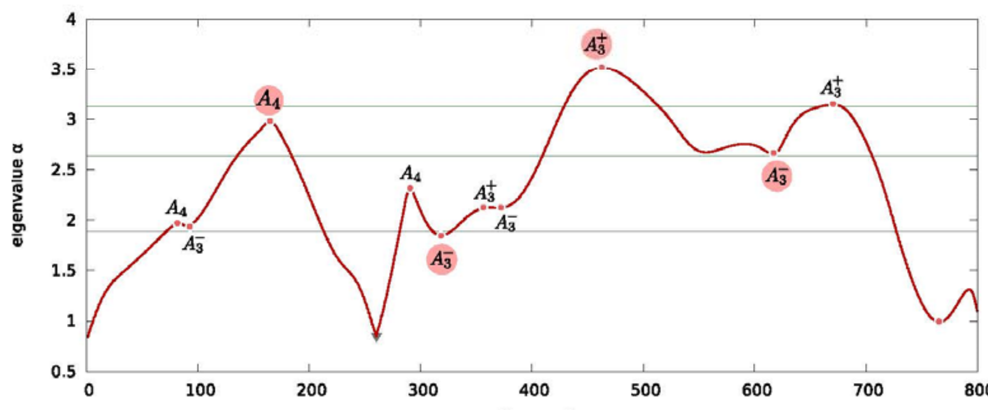
Hidding, Shandarin & vdW 2014

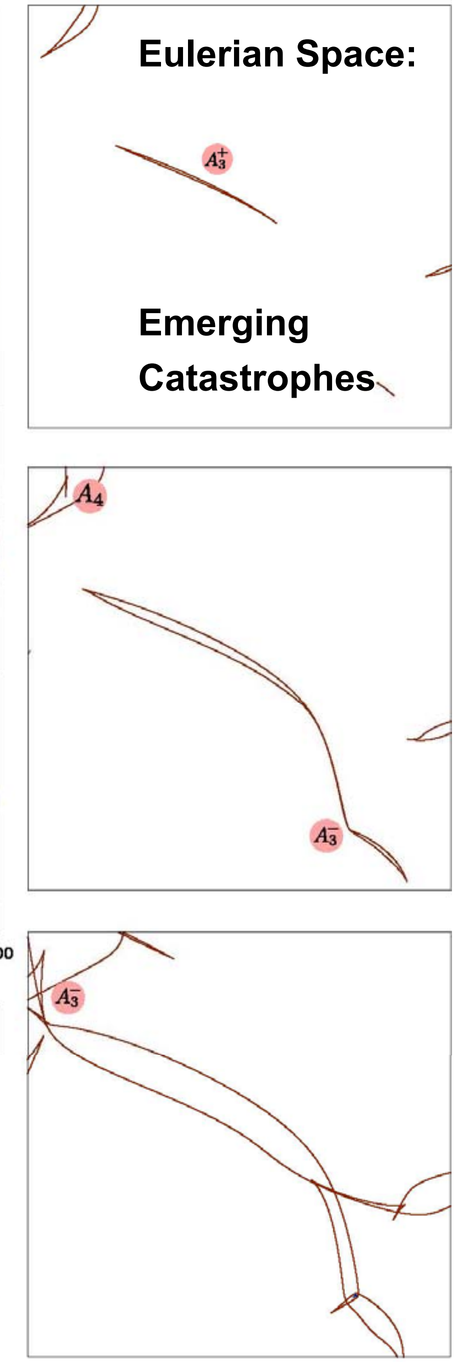
**Lagrangian Space:**

**Map**

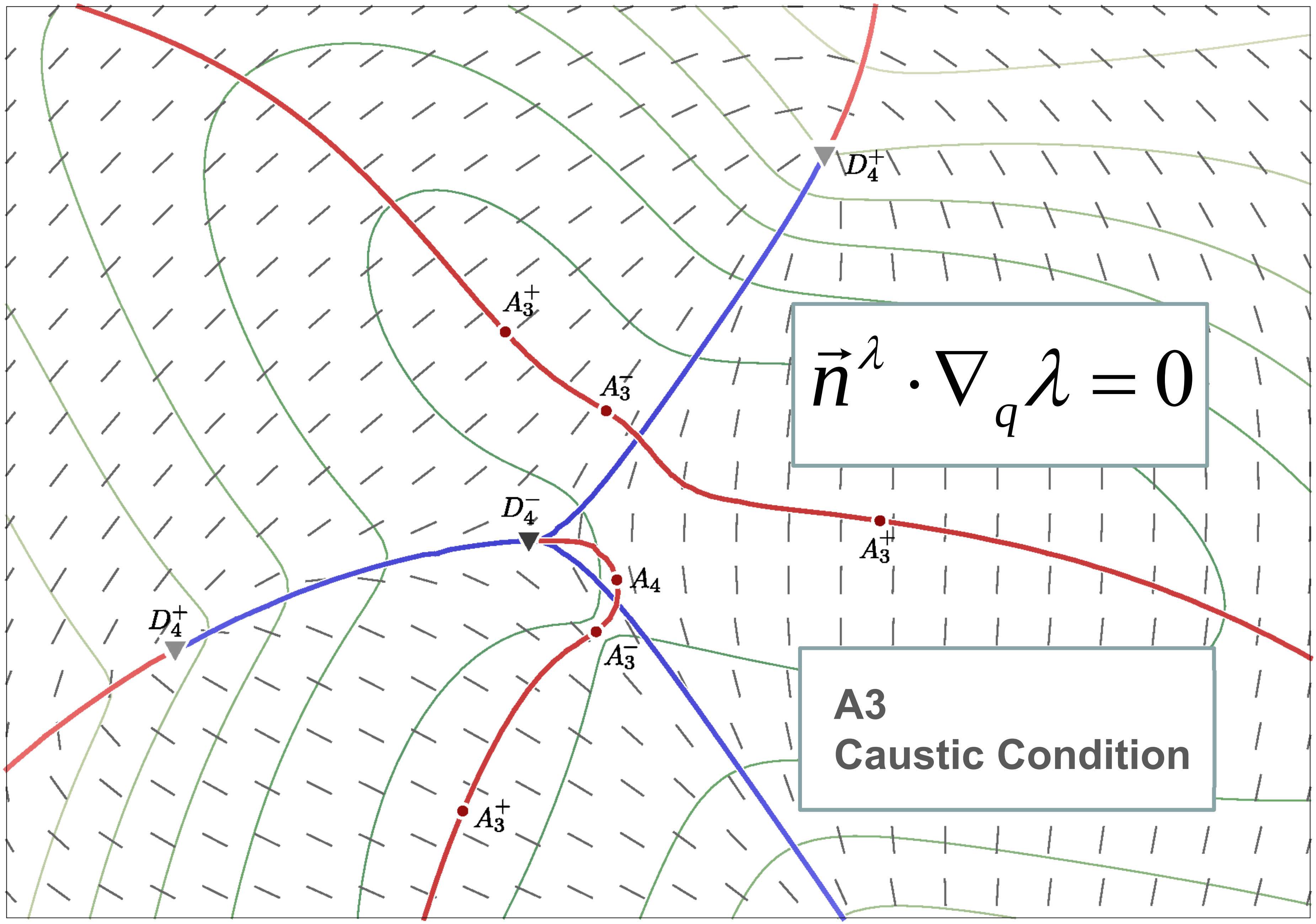
**Deformation Tensor Eigenvalue $\lambda_1$**




Feldbrugge, vdW et al. 2017a



$A_3^+$
$A_3^-$
$D_4^+$
$D_4^-$
$A_3^+$
$A_4$
$D_4^+$
$A_3^-$
$A_3^+$
$\vec{n}^{\lambda} \cdot \nabla_q \lambda = 0$
A3
Caustic Condition

# Caustic Conditions

In Lagrangian space $L$ (coordinates q),

a singularity forms in a manifold $\mathrm{M} \subset L$ at location $q_s$ when at $q_s$,

- the deformation tensor eigenvalue $\lambda_i(q_s)$
- the corresponding eigenvector $\vec{v}_i\,(q_s)$

when at least one nonzero tangent vector $\vec{T}$ such that

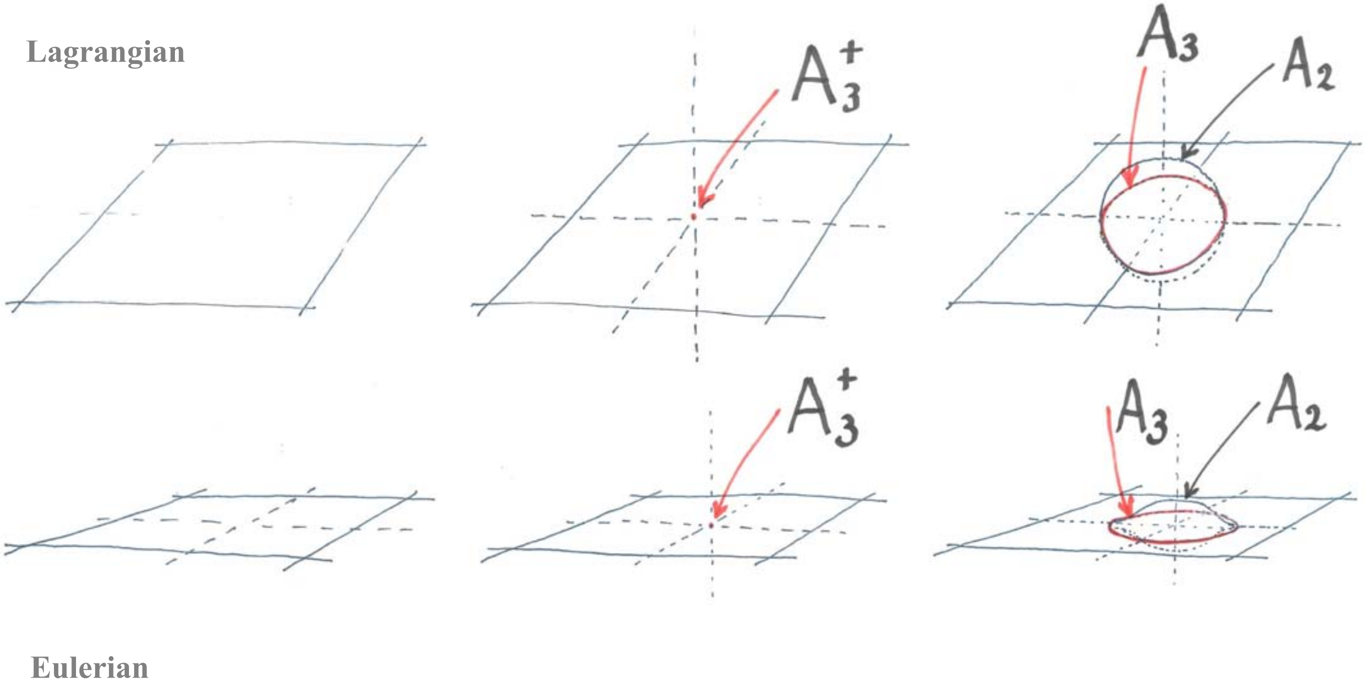
$$\{1 - D(t)\,\lambda_i(q_s)\}\;\; \vec{v}_i^{\,*}(q_s) \cdot \vec{T} = 0$$

*eg., $A_3$ caustic – cusp singularity – emerges where:*

$$\vec{n}^{\lambda} \cdot \nabla_q \lambda = 0$$

**Feldbrugge, vdW et al. 2017a**

Feldbrugge, vdW et al. 2017




**Formation of an $A_3$ cusp, along with $A_2$ folds**

## Catastrophe Theory:

Lagrangian catastrophe/caustic classification V. Arnold

(also see Zeeman, Thom)

**D=1**

**$A_2$: folds**
**$A_3$: cusps**

**D=2**

**$A_2$: folds**
**$A_3$: cusps**
**$A_4$: swallowtail**

**$D_4$: umbilics**

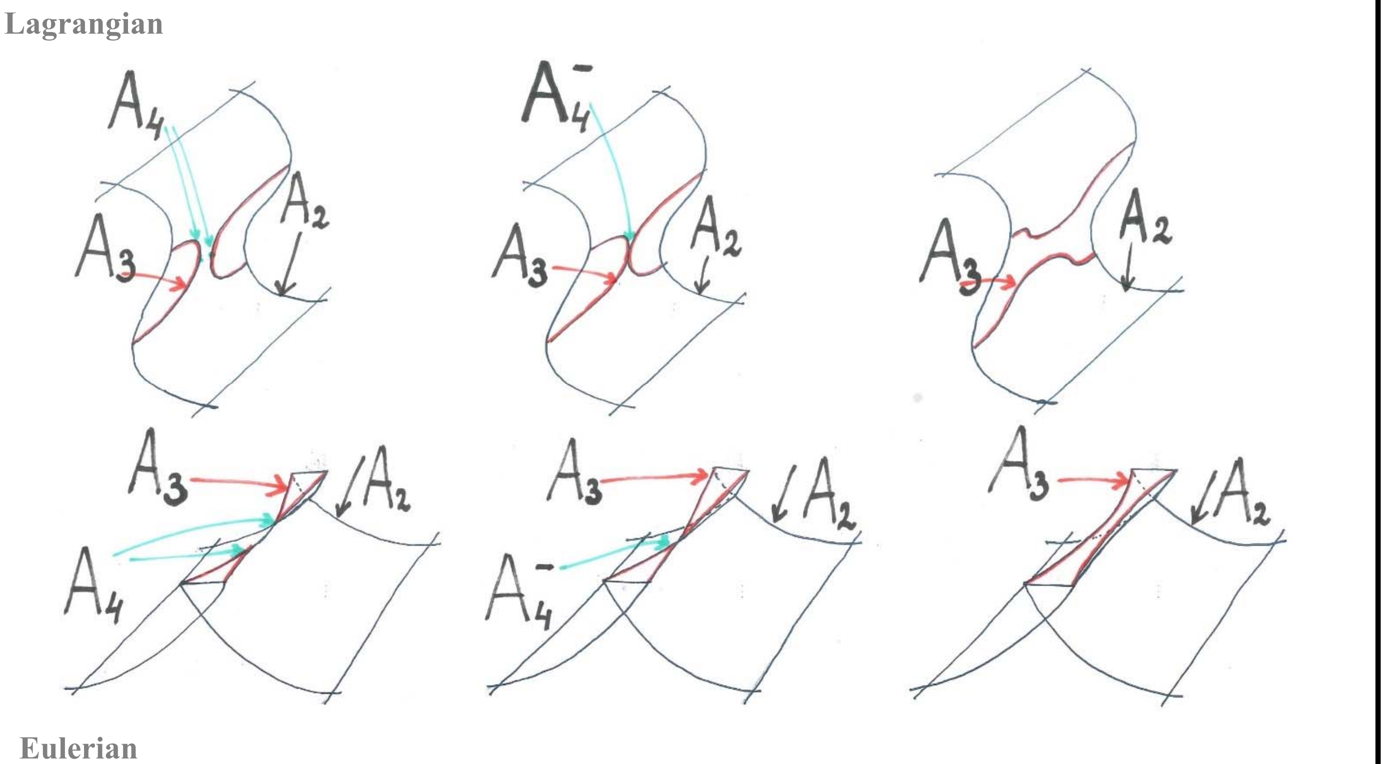
**D=3**

**$A_2$: folds**
**$A_3$: cusps**
**$A_4$: swallowtail**
**$A_5$: butterfly**

**$D_4$: umbilics**
**$D_5$**

**$E_5$**

Feldbrugge, vdW et al. 2017




**Merging of $A_3$ cusps at an $A_4$ swallowtail singularity**

**D=1**

**$A_2$: folds**
**$A_3$: cusps**

**D=2**

**$A_2$: folds**
**$A_3$: cusps**
**$A_4$: swallowtail**

**$D_4$: umbilics**

**D=3**

**$A_2$: folds**
**$A_3$: cusps**
**$A_4$: swallowtail**
**$A_5$: butterfly**

**$D_4$: umbilics**
**$D_5$**

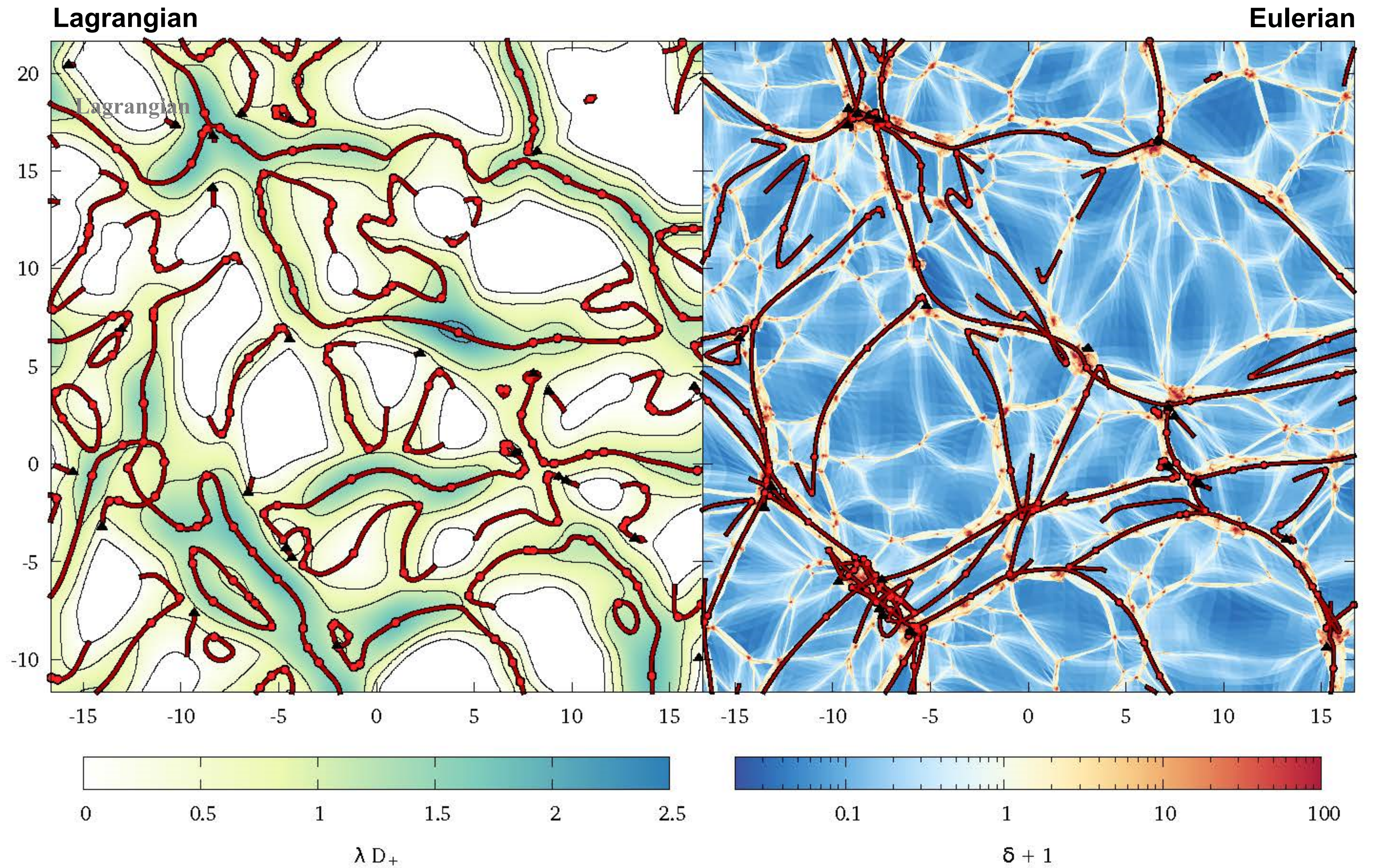
**$E_5$**

## Catastrophe Theory:

Lagrangian catastrophe/caustic classification V. Arnold

(also see Zeeman, Thom)

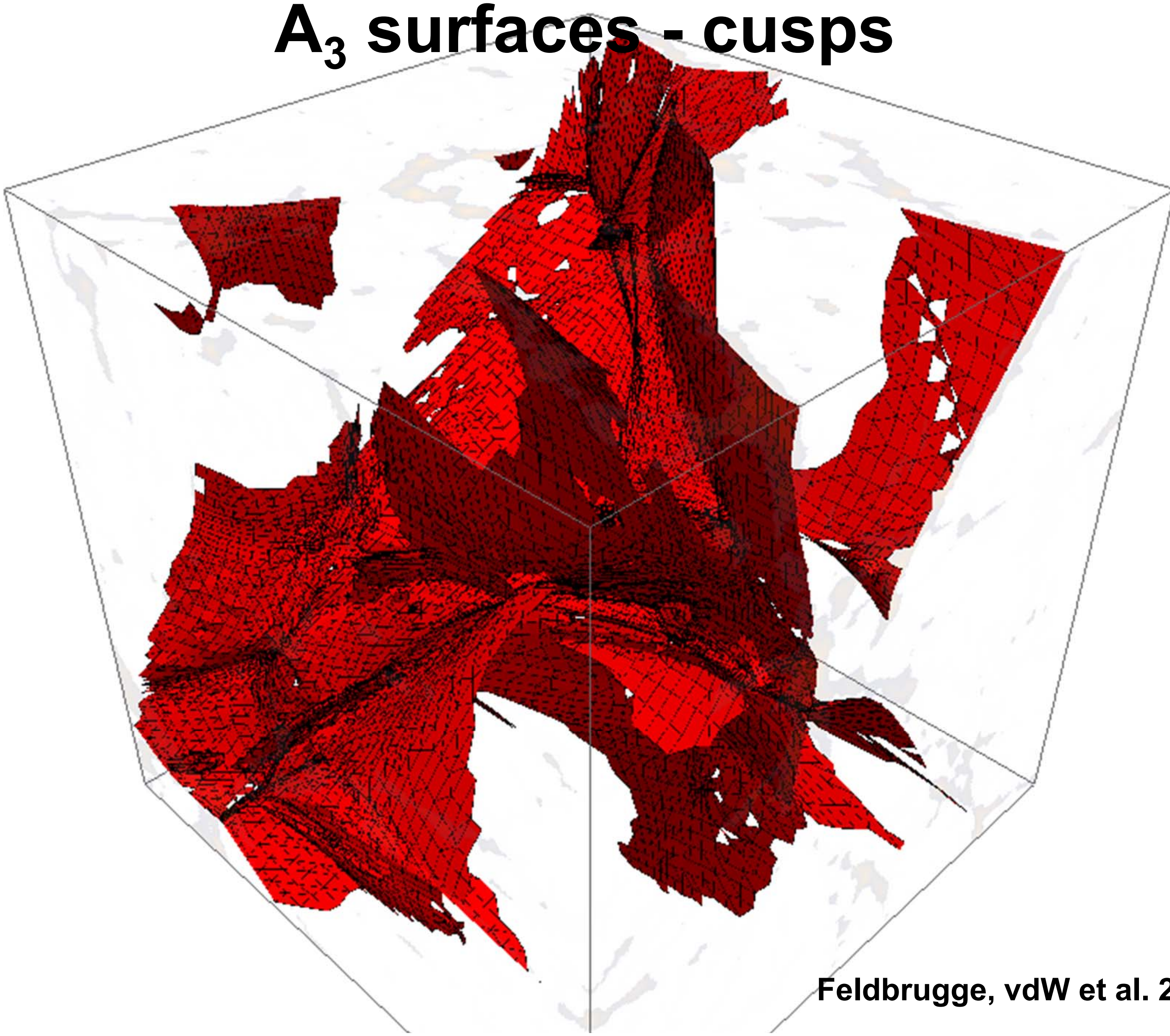
# Catastrophic Spine of (2D) Cosmic Web




Feldbrugge, Hidding, vdW 2015

# Skeleton (3D) Cosmic Web:

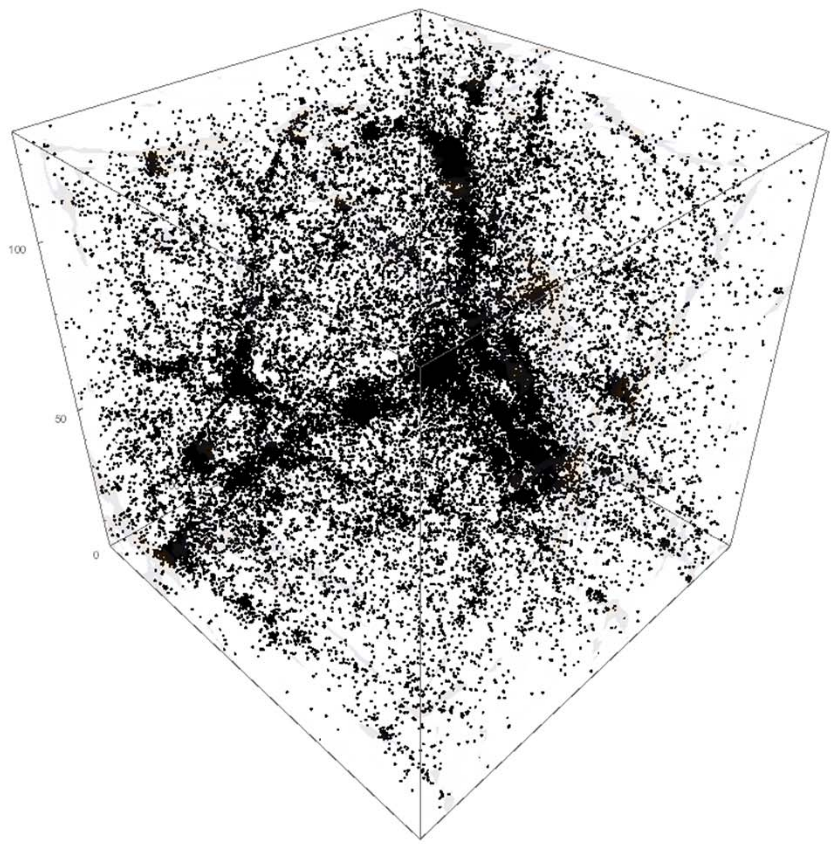
## $A_3$ surfaces - cusps

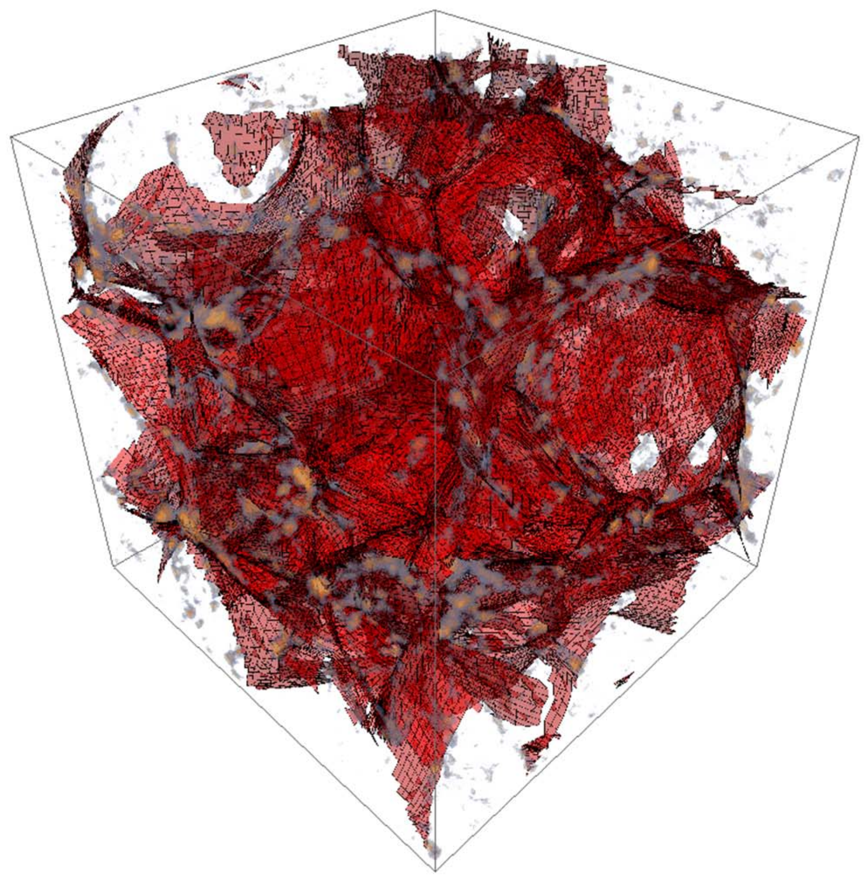


Feldbrugge, vdW et al. 2017b

# Skeleton (3D) Cosmic Web:

## $A_3$ surfaces - cusps

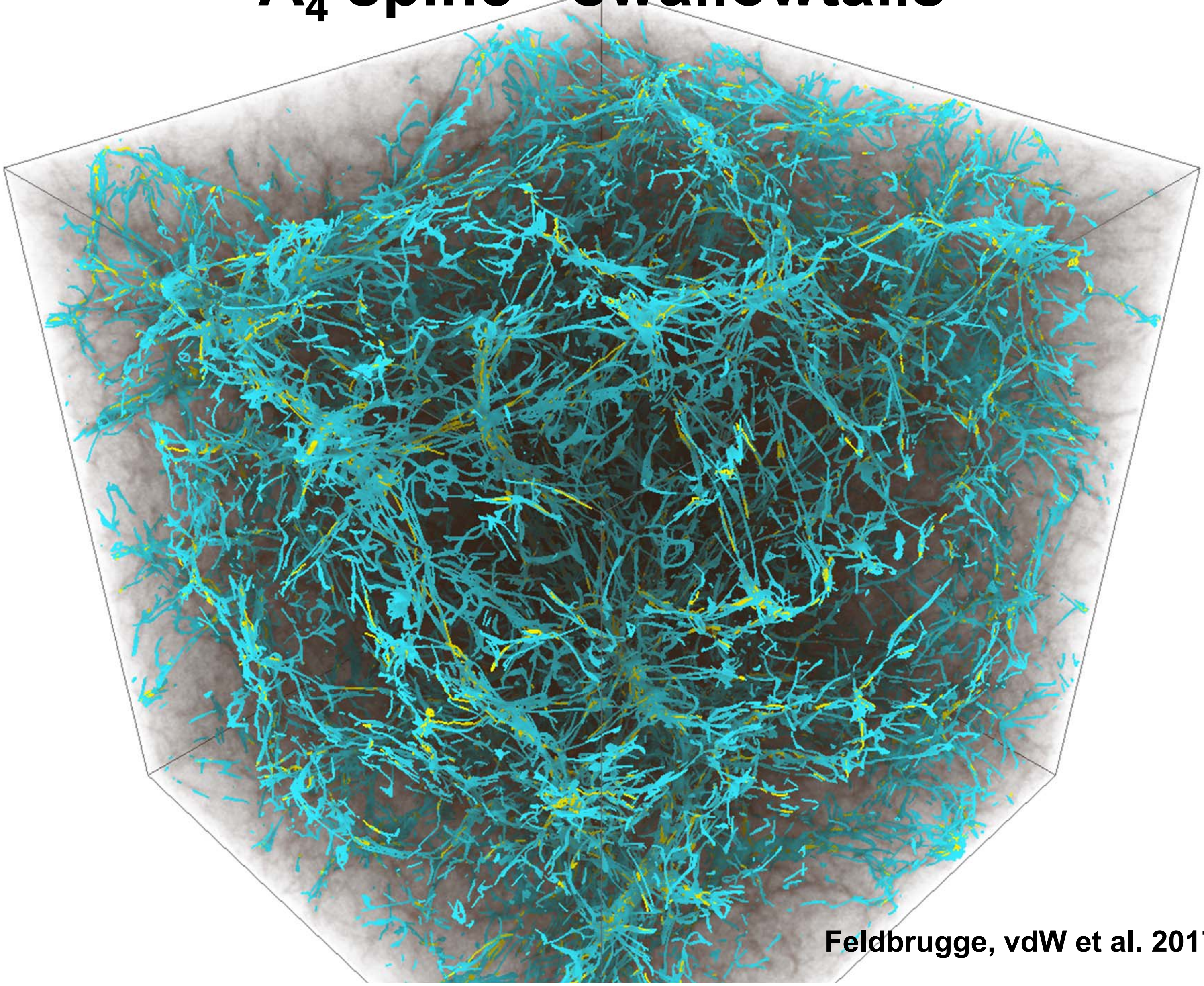


Feldbrugge, vdW et al. 2017b

# Skeleton (3D) Cosmic Web:

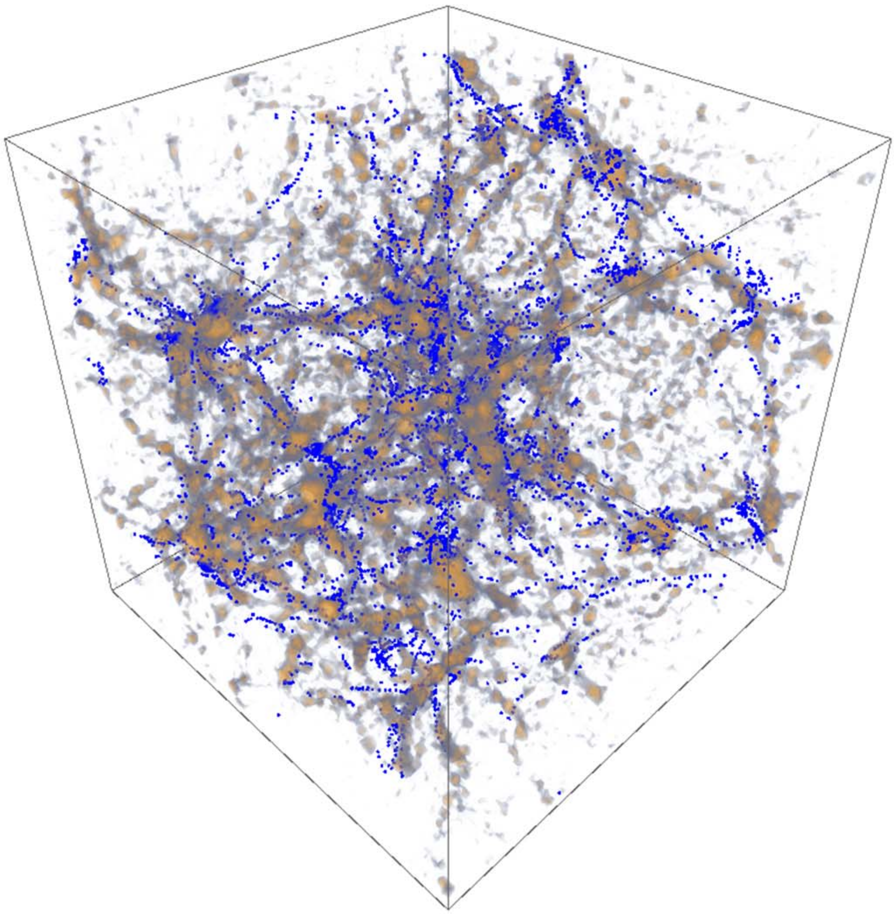
## $A_4$ spine - swallowtails

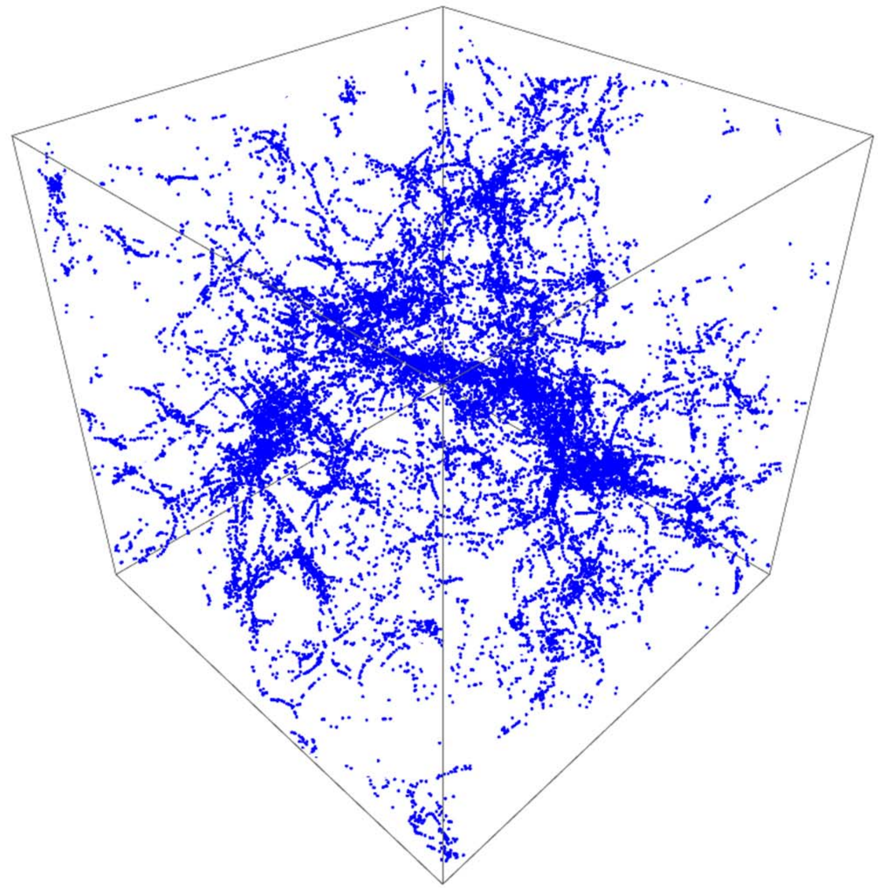


Feldbrugge, vdW et al. 2017b

# Skeleton (3D) Cosmic Web:

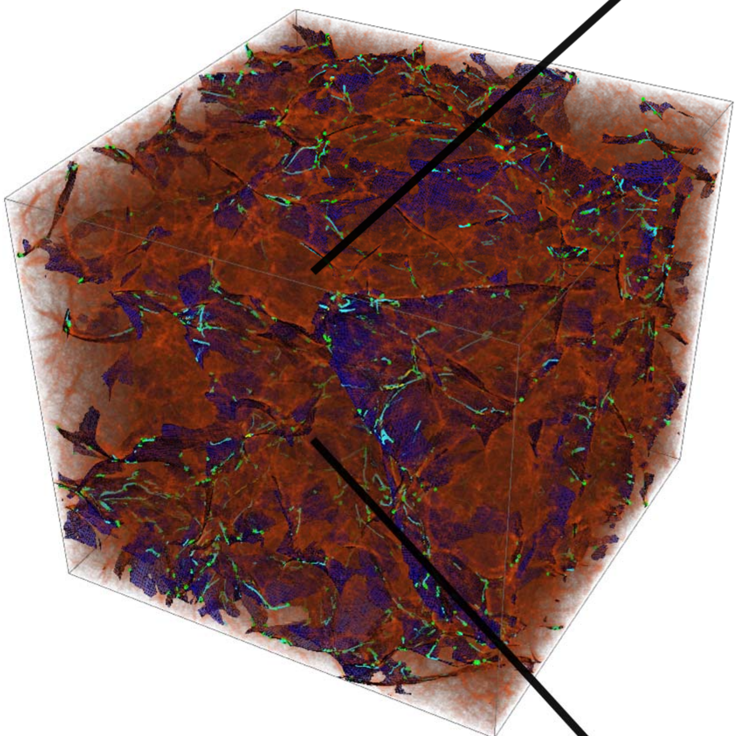
## $A_4$ spine - swallowtails

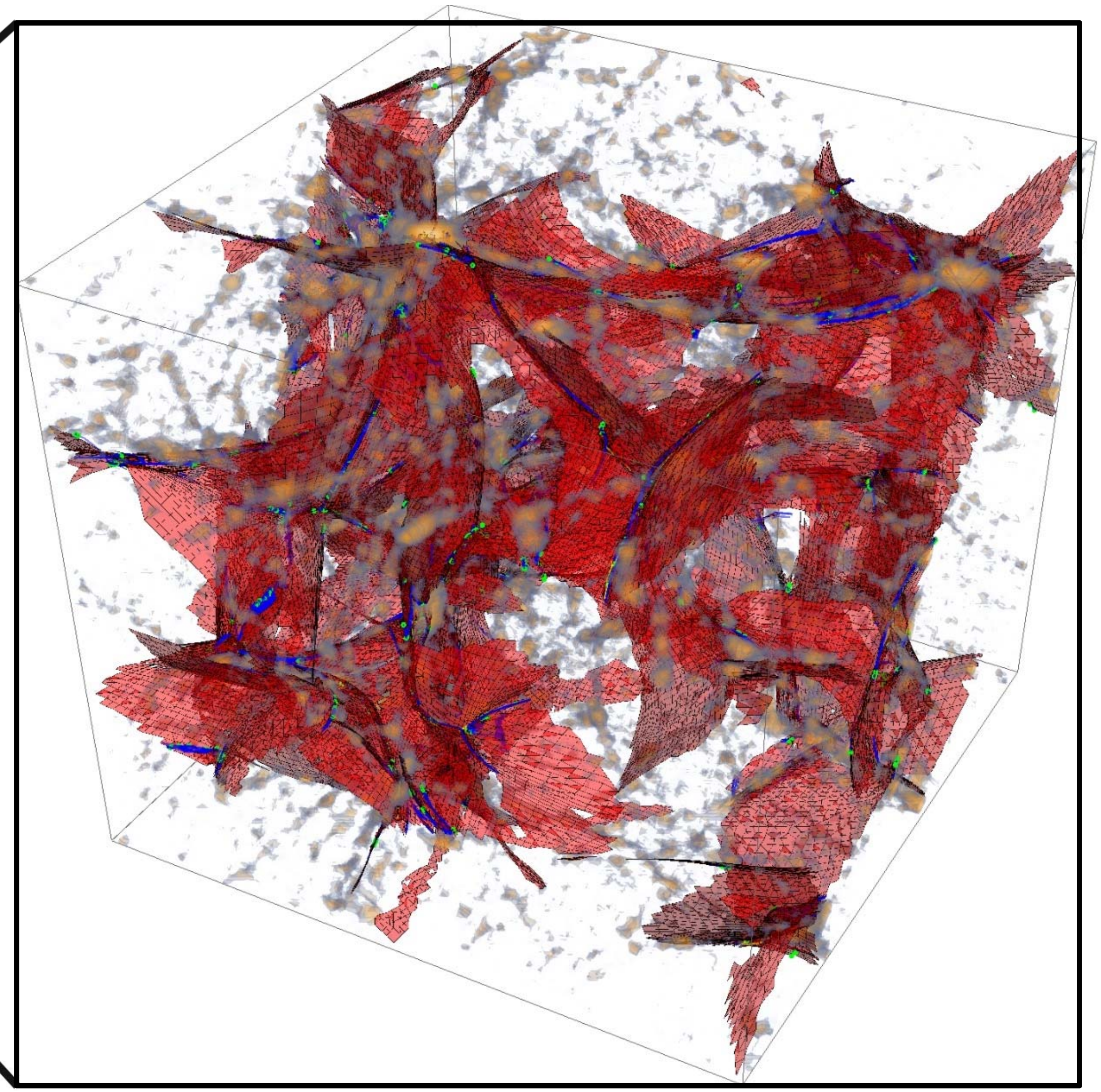




Feldbrugge, vdW et al. 2017b

# Skeleton (3D) Cosmic Web:
## catastrophic connections



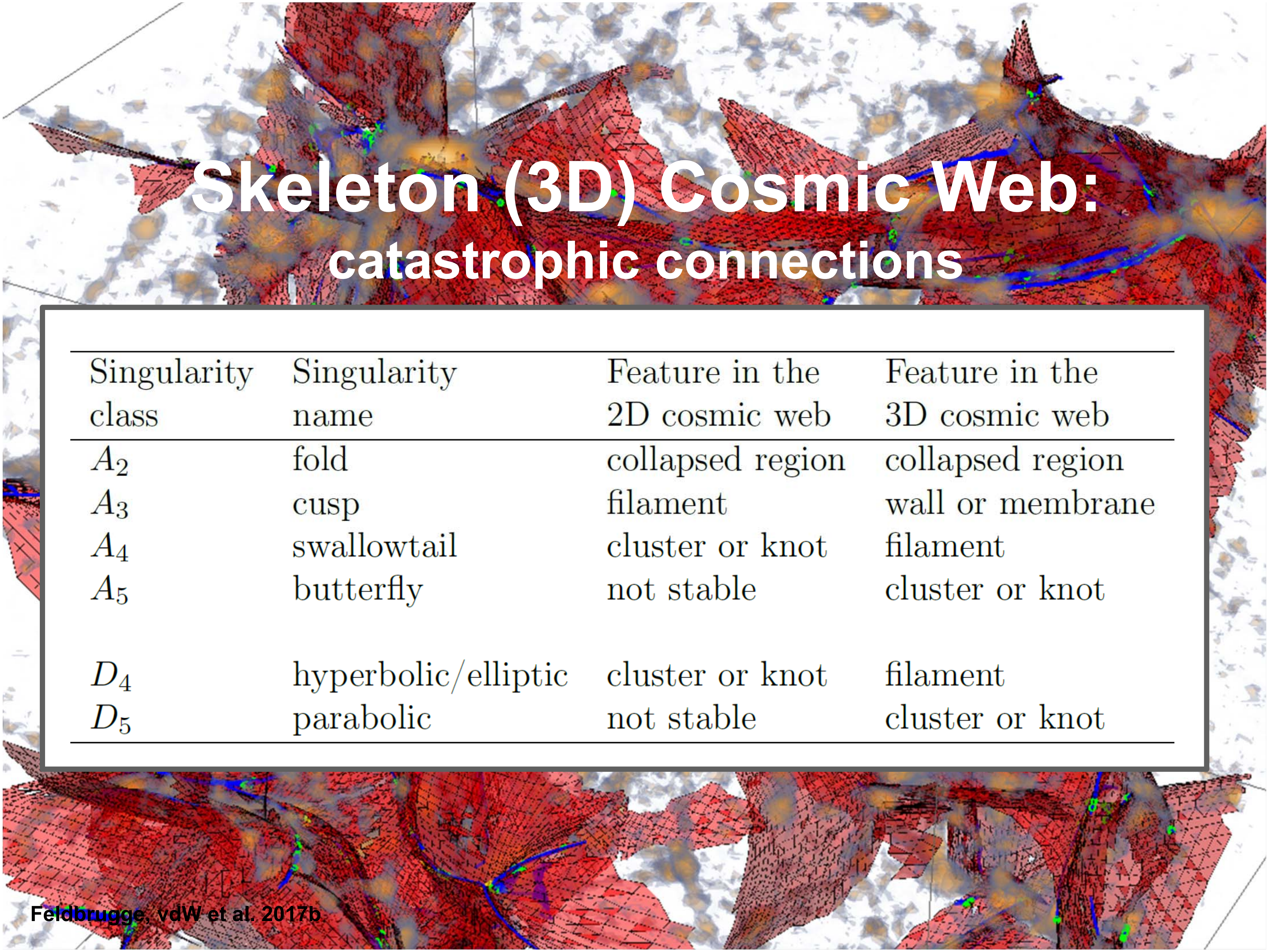


DM Nbody density field (log density)

| | | | |
|---|---|---|---|
| A3 - | cusp | - red sheets | - walls/membranes |
| A4 - | swallowtail | - blue lines | - filaments |
| A5 - | butterfly | - green points | - cluster nodes |

**Feldbrugge, vdW et al. 2017b**

# Skeleton (3D) Cosmic Web:
## catastrophic connections

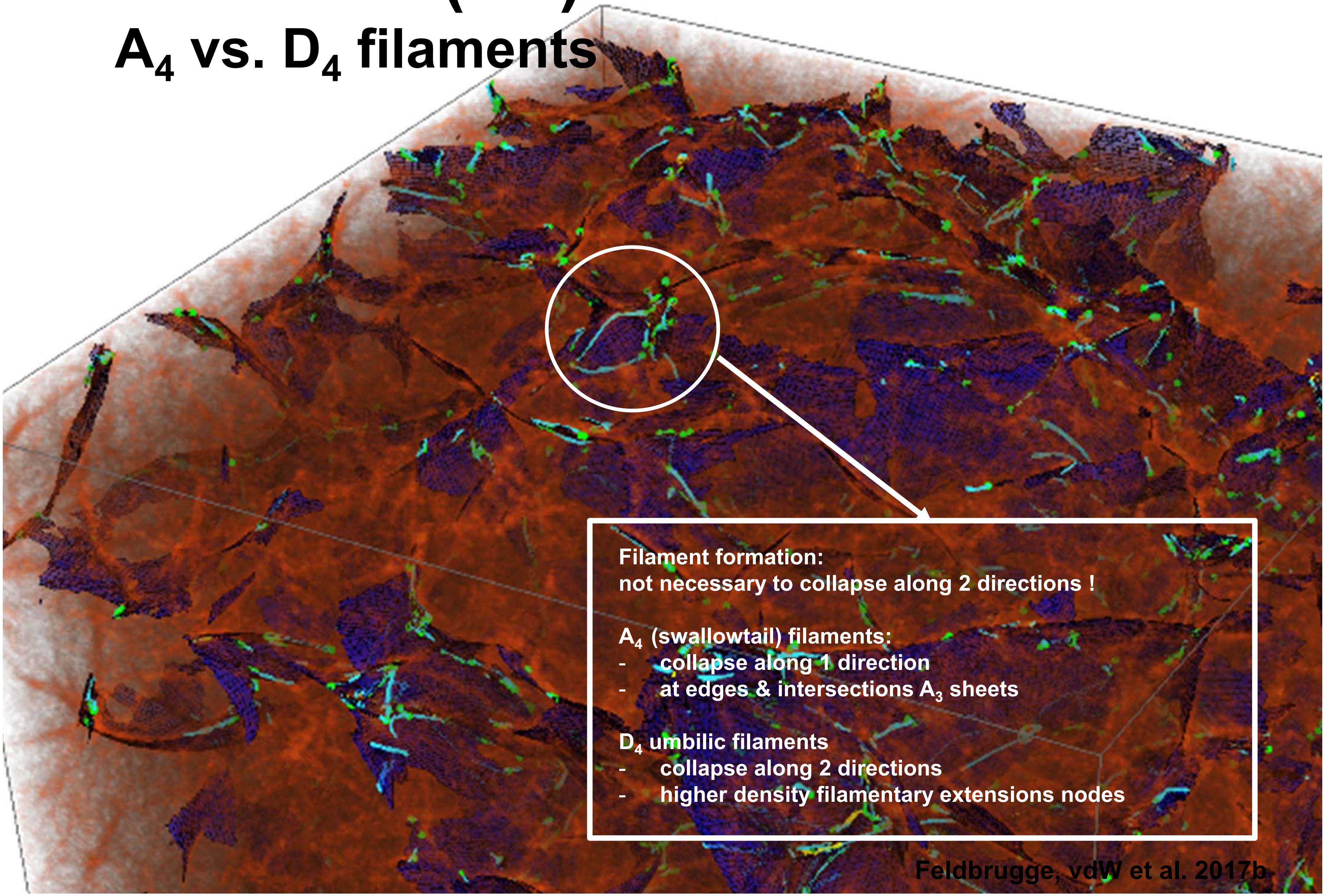


| Singularity class | Singularity name | Feature in the 2D cosmic web | Feature in the 3D cosmic web |
|---|---|---|---|
| $A_2$ | fold | collapsed region | collapsed region |
| $A_3$ | cusp | filament | wall or membrane |
| $A_4$ | swallowtail | cluster or knot | filament |
| $A_5$ | butterfly | not stable | cluster or knot |
| | | | |
| $D_4$ | hyperbolic/elliptic | cluster or knot | filament |
| $D_5$ | parabolic | not stable | cluster or knot |

Feldbrugge, vdW et al. 2017b

# Skeleton (3D) Cosmic Web:

## $A_4$ vs. $D_4$ filaments



# Cosmic Web:

# (Adhesion)
# Local Universe

**Initial**
**Density & Deformation Field**

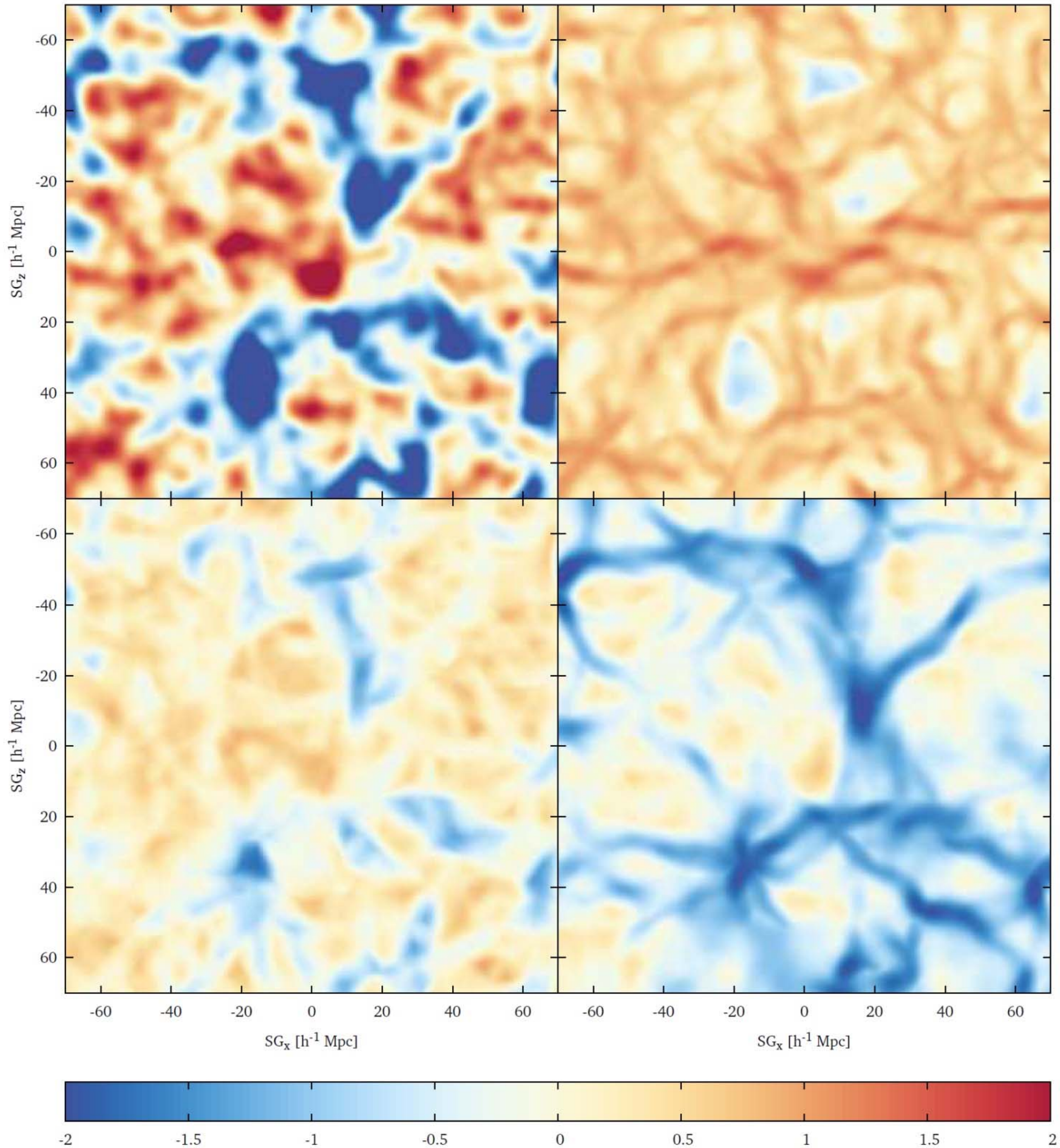
**Local Universe**
**(SG plane)**

**Kitaura & Hess:**

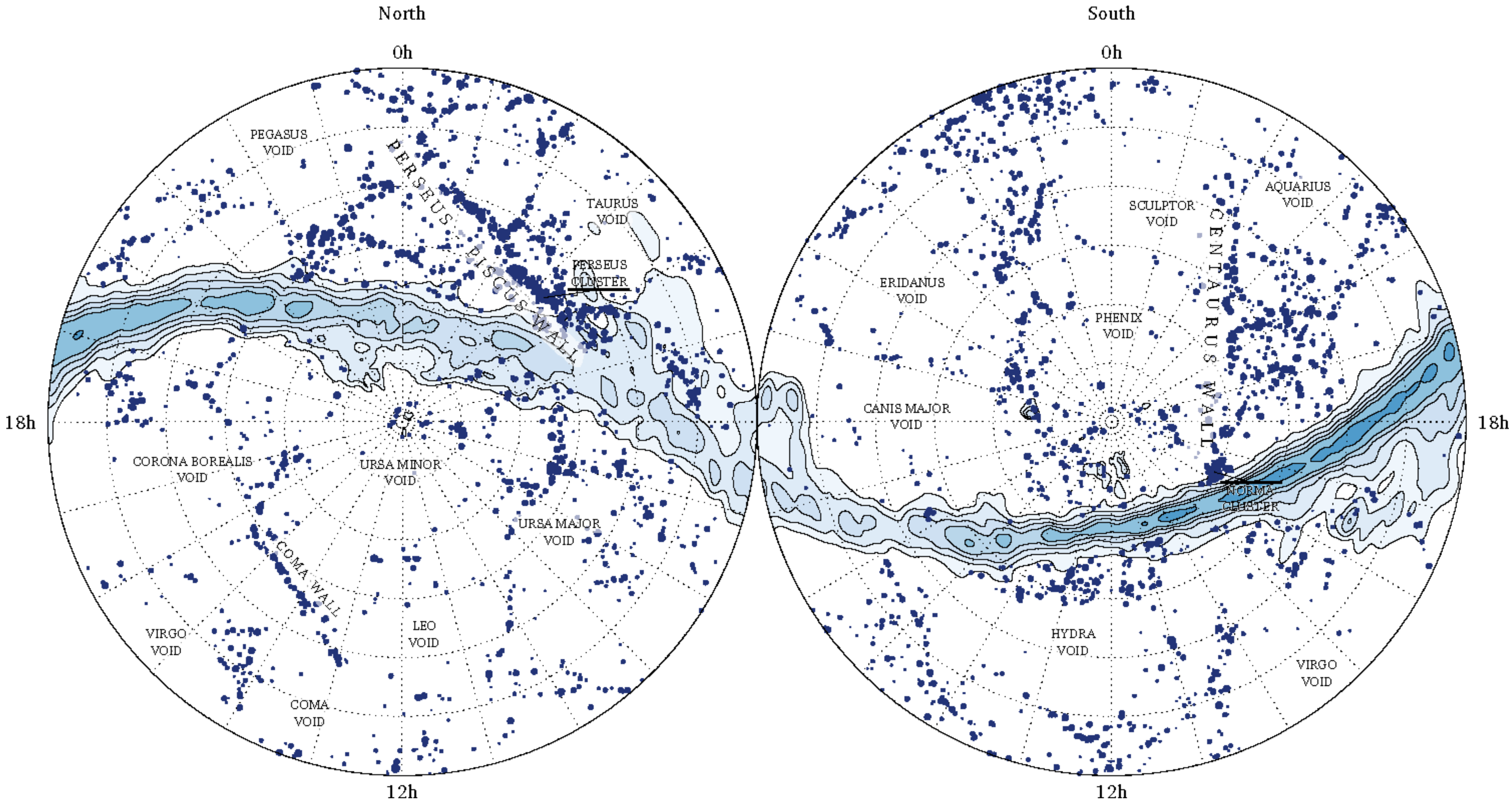
**25**

**2MRS-based**

**KIGEN Bayesian Inference**
**Constrained realizations**



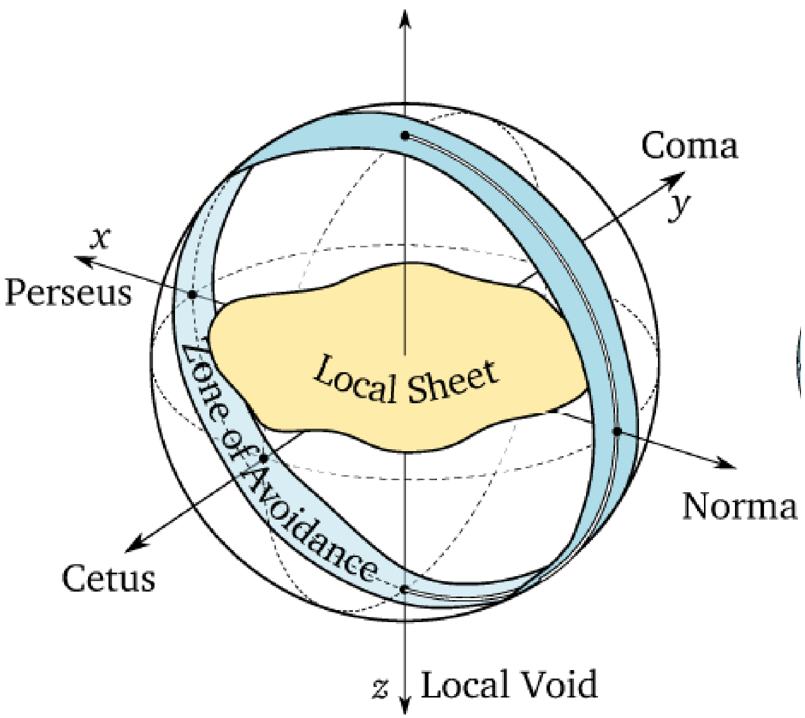
# Galaxies up to 50 Mpc ...

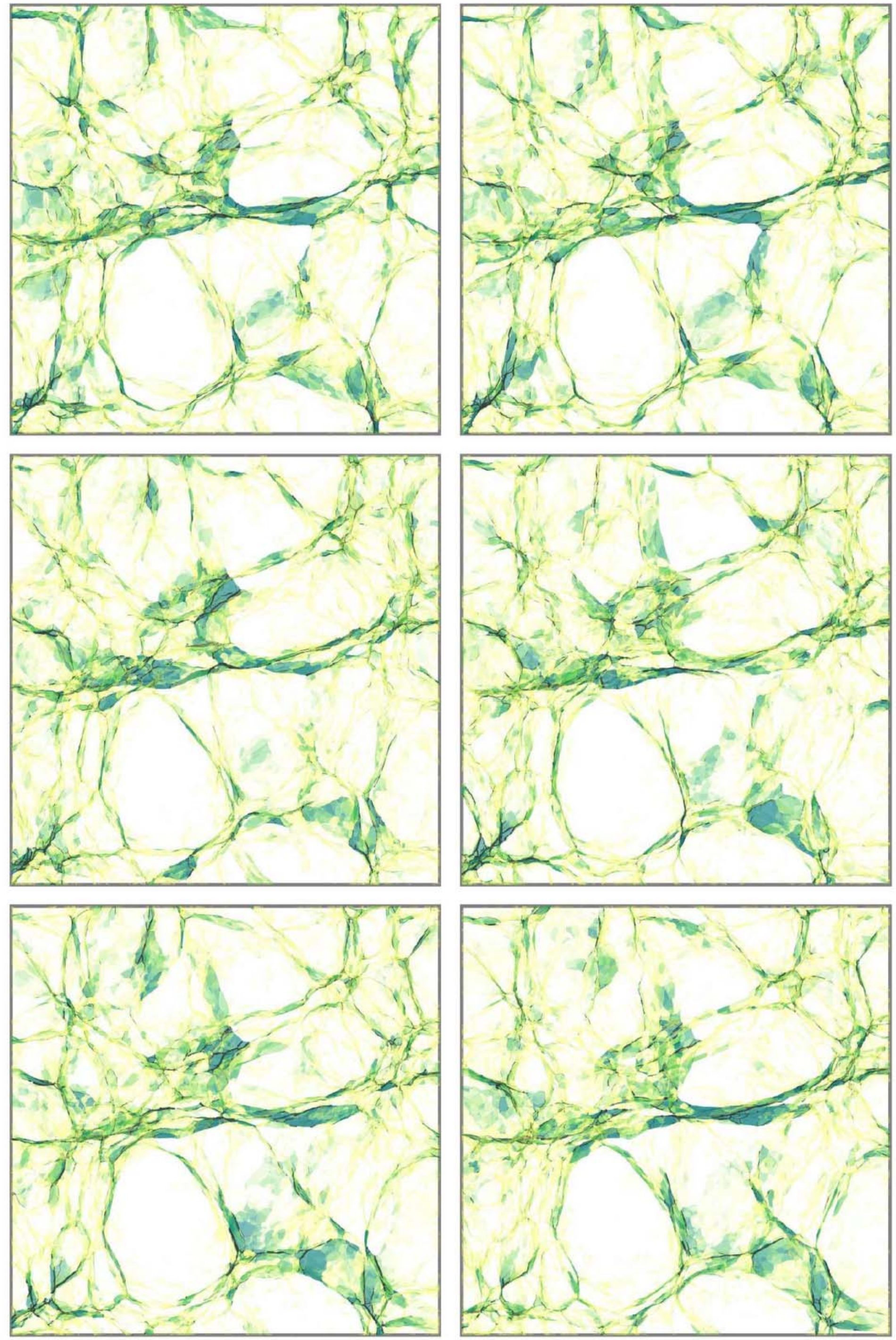



**2MRS survey sky map: Hidding 2015**

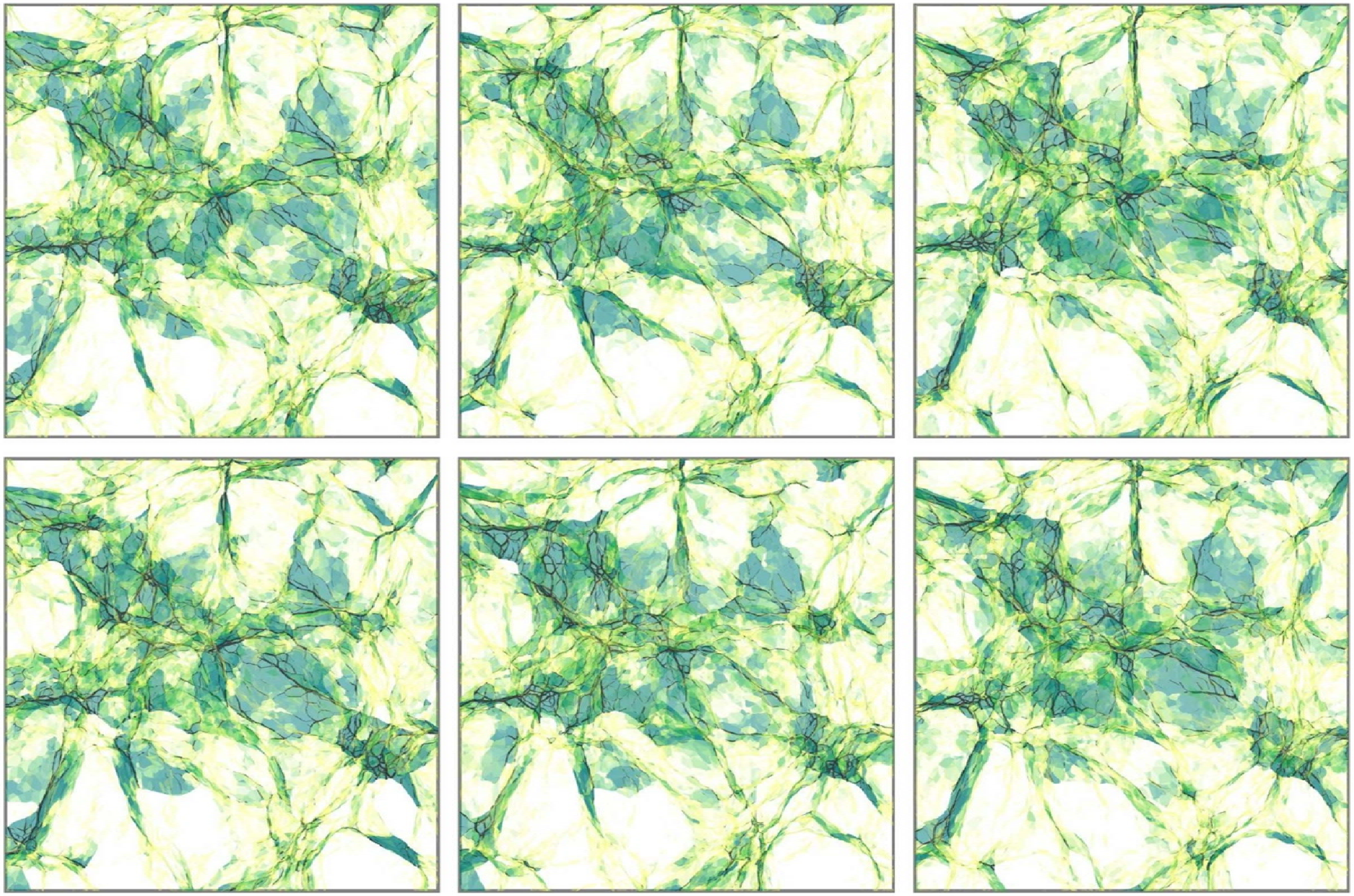
**Edge-on view Supergalactic Plane:**

**6 constrained adhesion reconstructions**

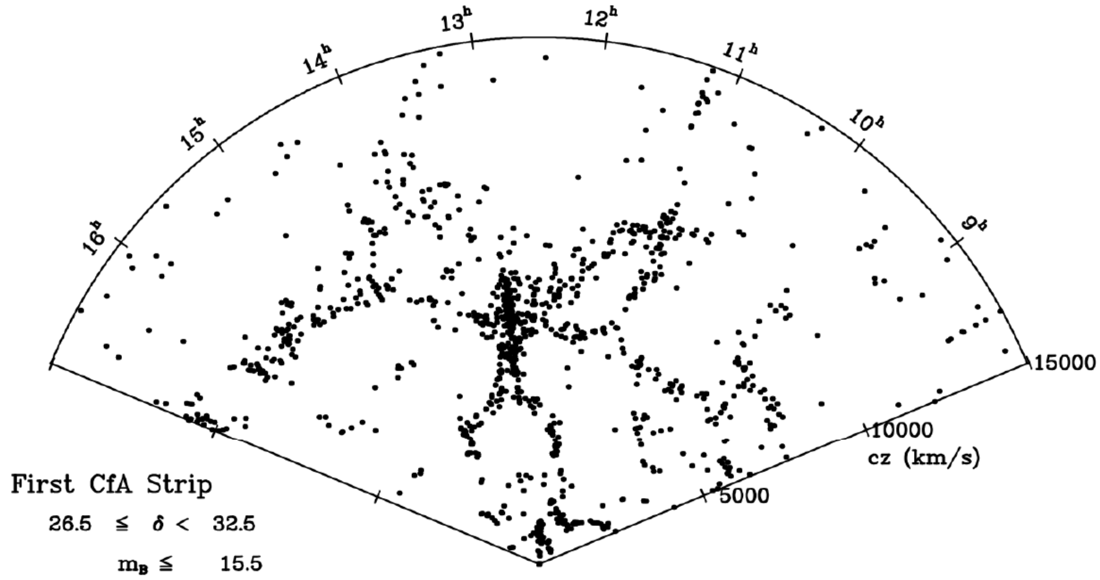


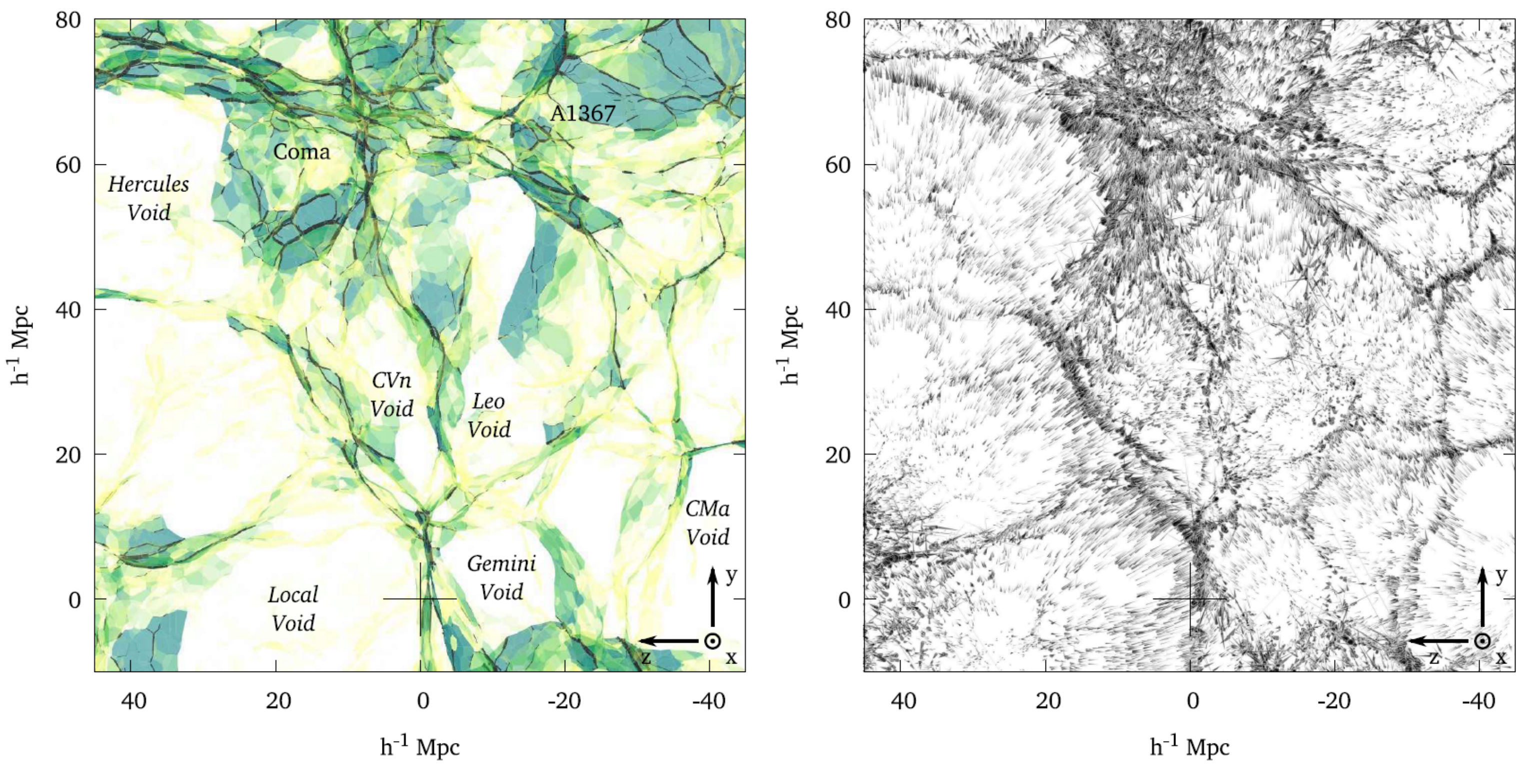
# Face-On Supergalactic Plane



**6 constrained adhesion reconstructions**



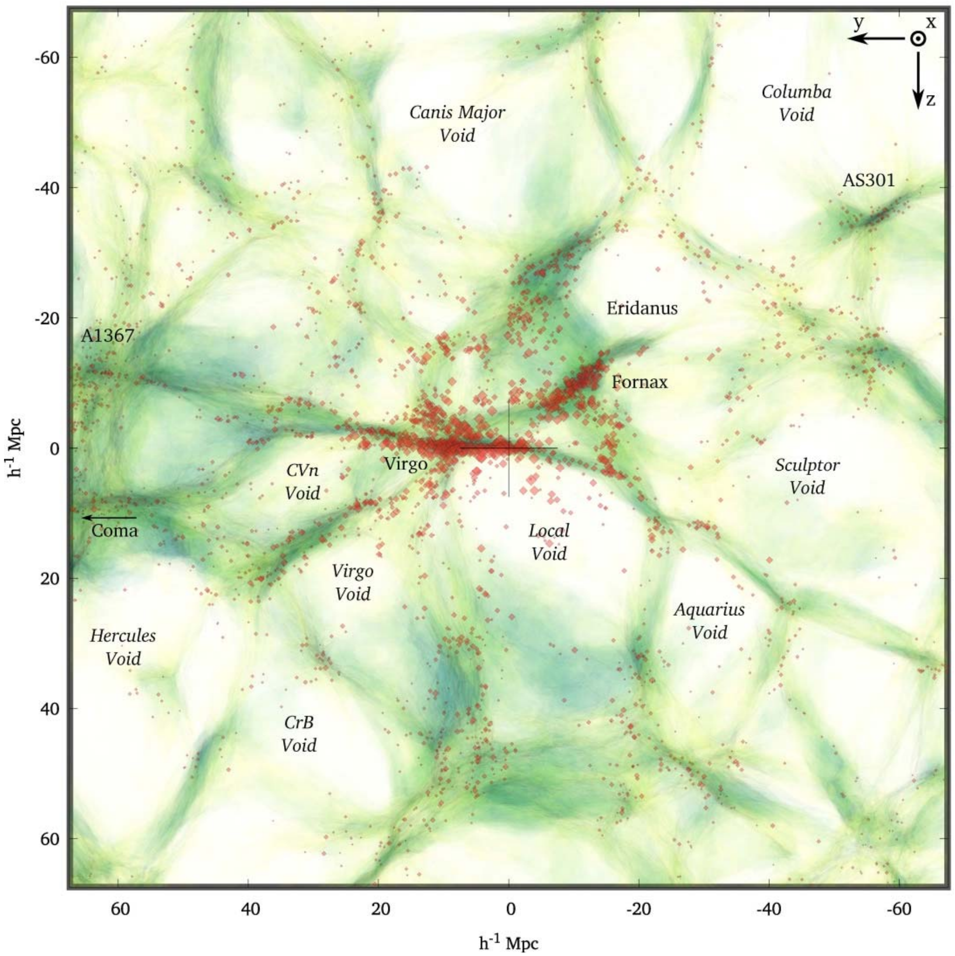
16h
15h
14h
13h
12h
11h
10h
9h
15000
10000
5000
cz (km/s)
First CfA Strip
26.5 ≤ δ < 32.5
m_B ≤ 15.5

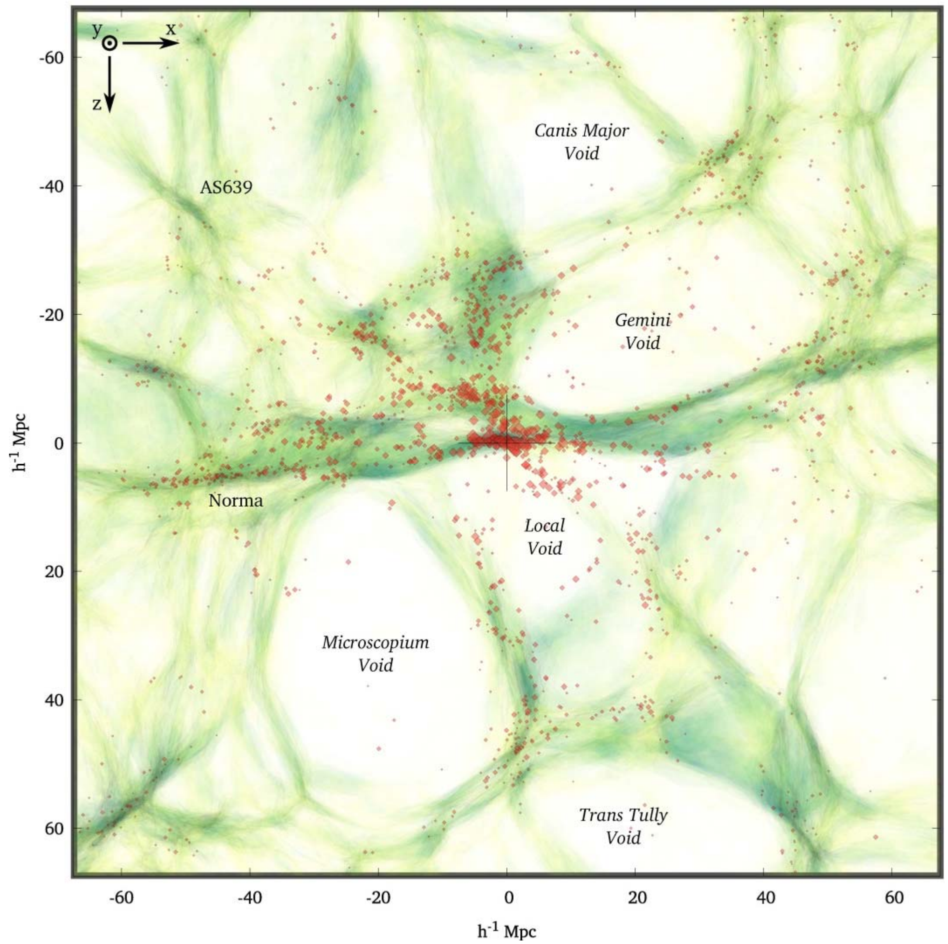



80
60
40
20
0
h^-1 Mpc
40
20
0
-20
-40
h^-1 Mpc
Coma
A1367
Hercules Void
CVn Void
Leo Void
CMa Void
Gemini Void
Local Void
y
z
x
80
60
40
20
0
h^-1 Mpc
40
20
0
-20
-40
h^-1 Mpc
y
z
x

# Supergalactic Plane

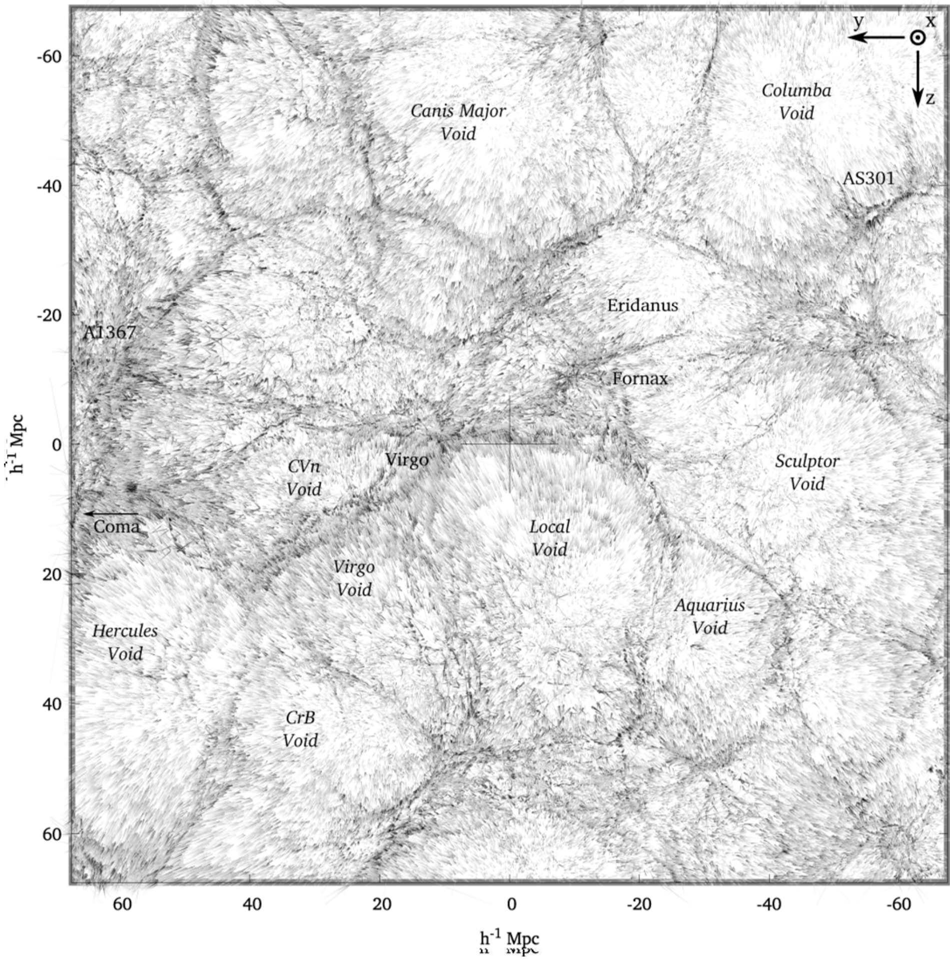
## mean field: edge-on

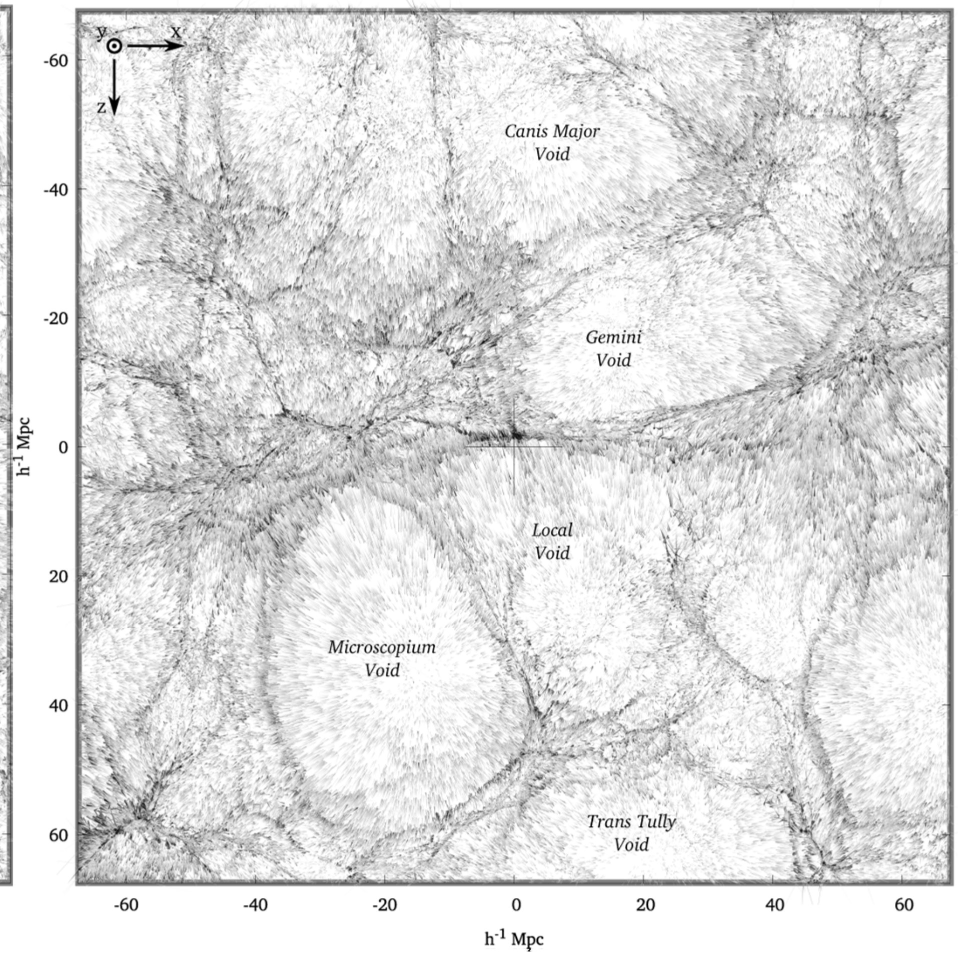


# Supergalactic Plane

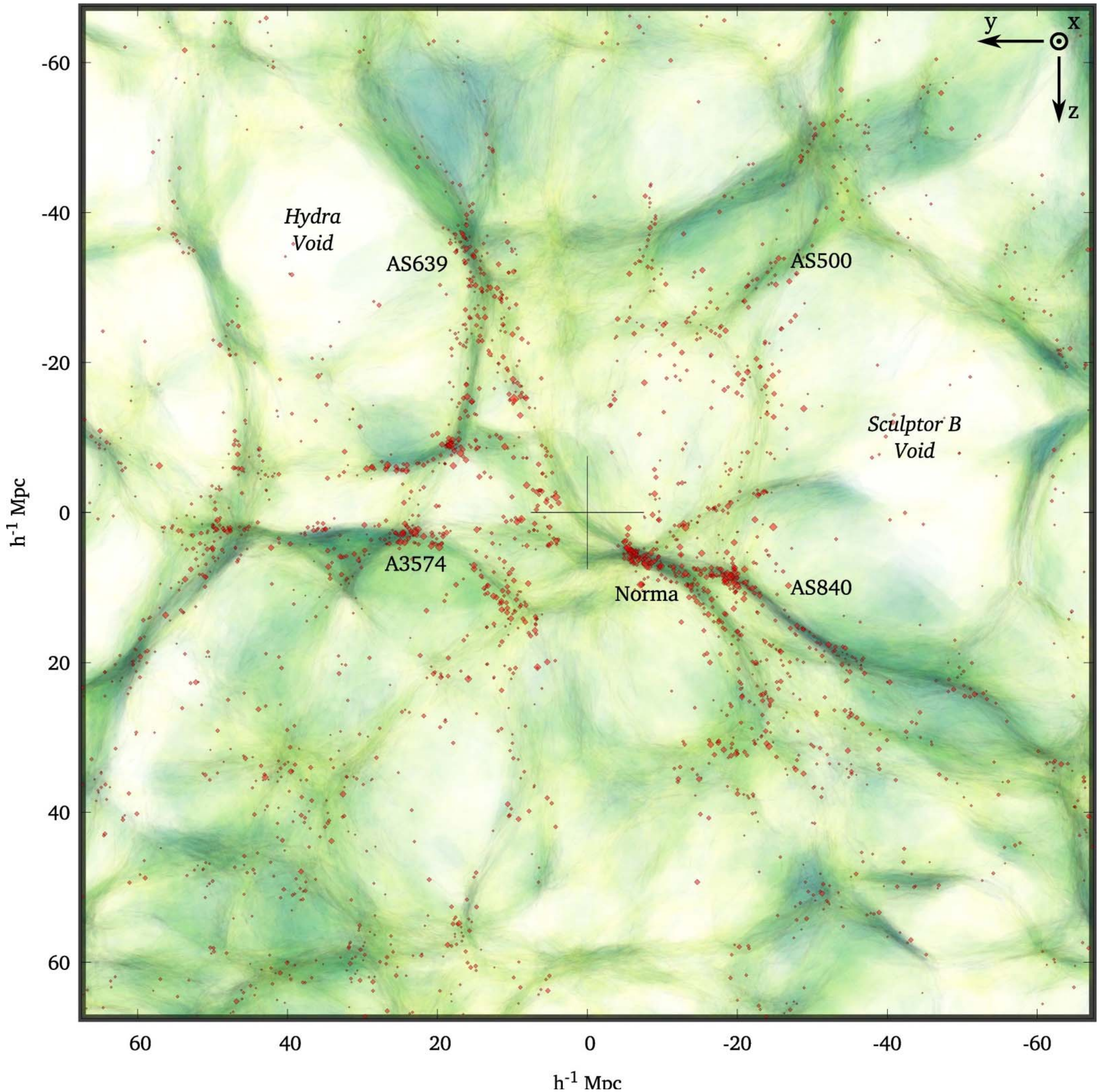
## mean field:  edge-on



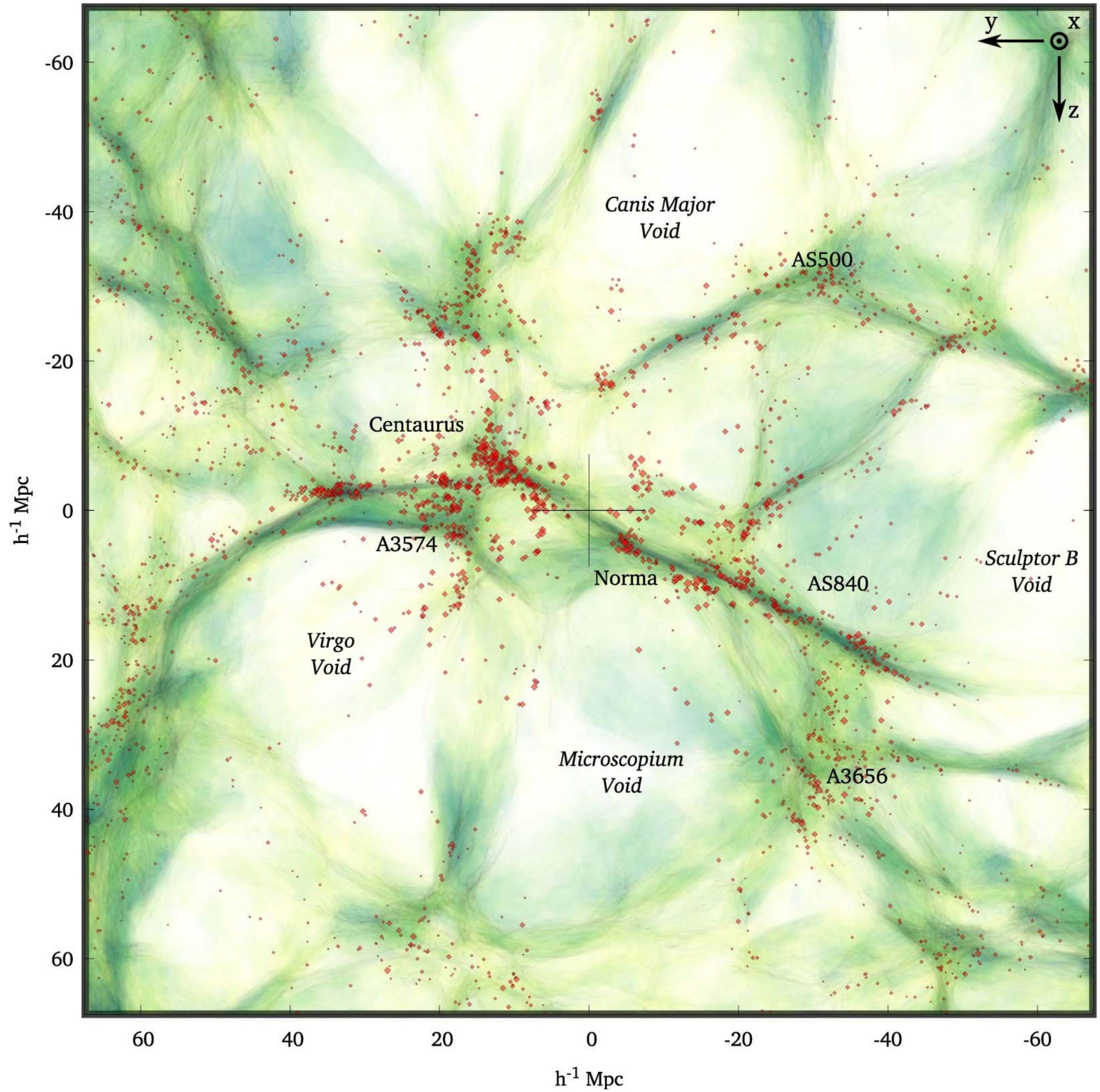



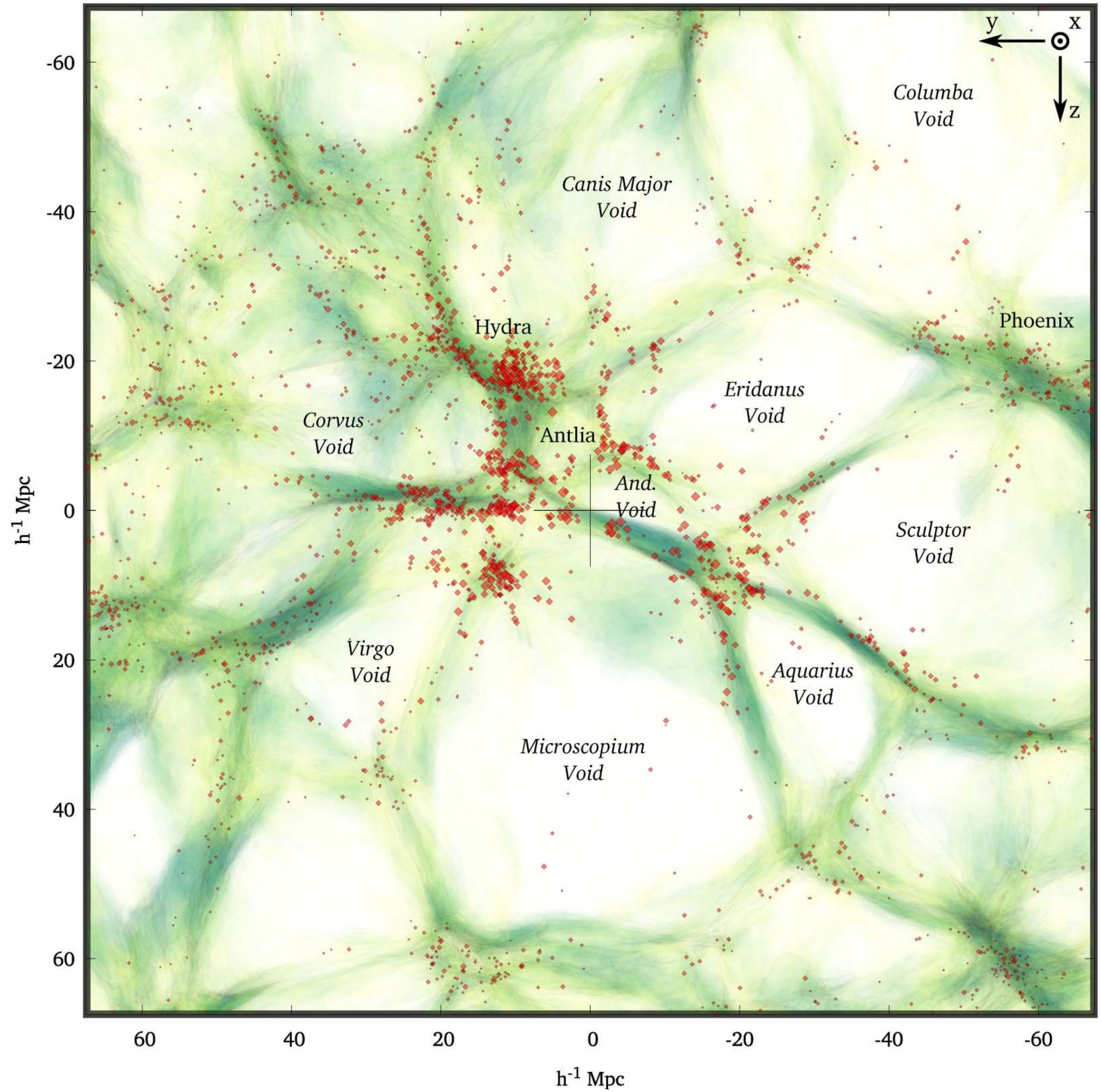
# Local Cosmic Web:

# a rough CT-scan

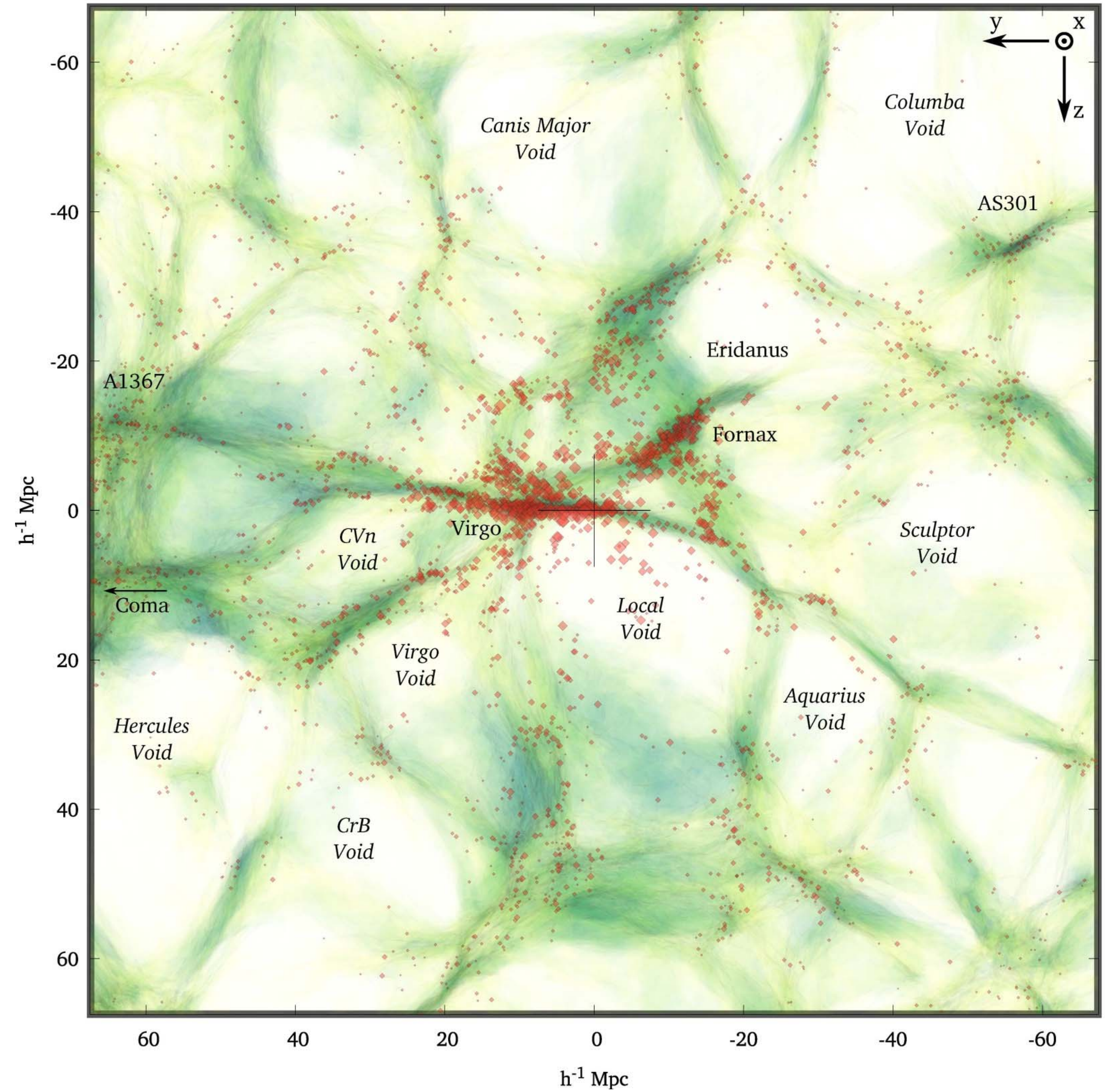


y
x
z
Hydra
Void
AS639
AS500
Sculptor B
Void
A3574
Norma
AS840
-60
-40
-20
0
20
40
60
h-1 Mpc
60
40
20
0
-20
-40
-60
h-1 Mpc

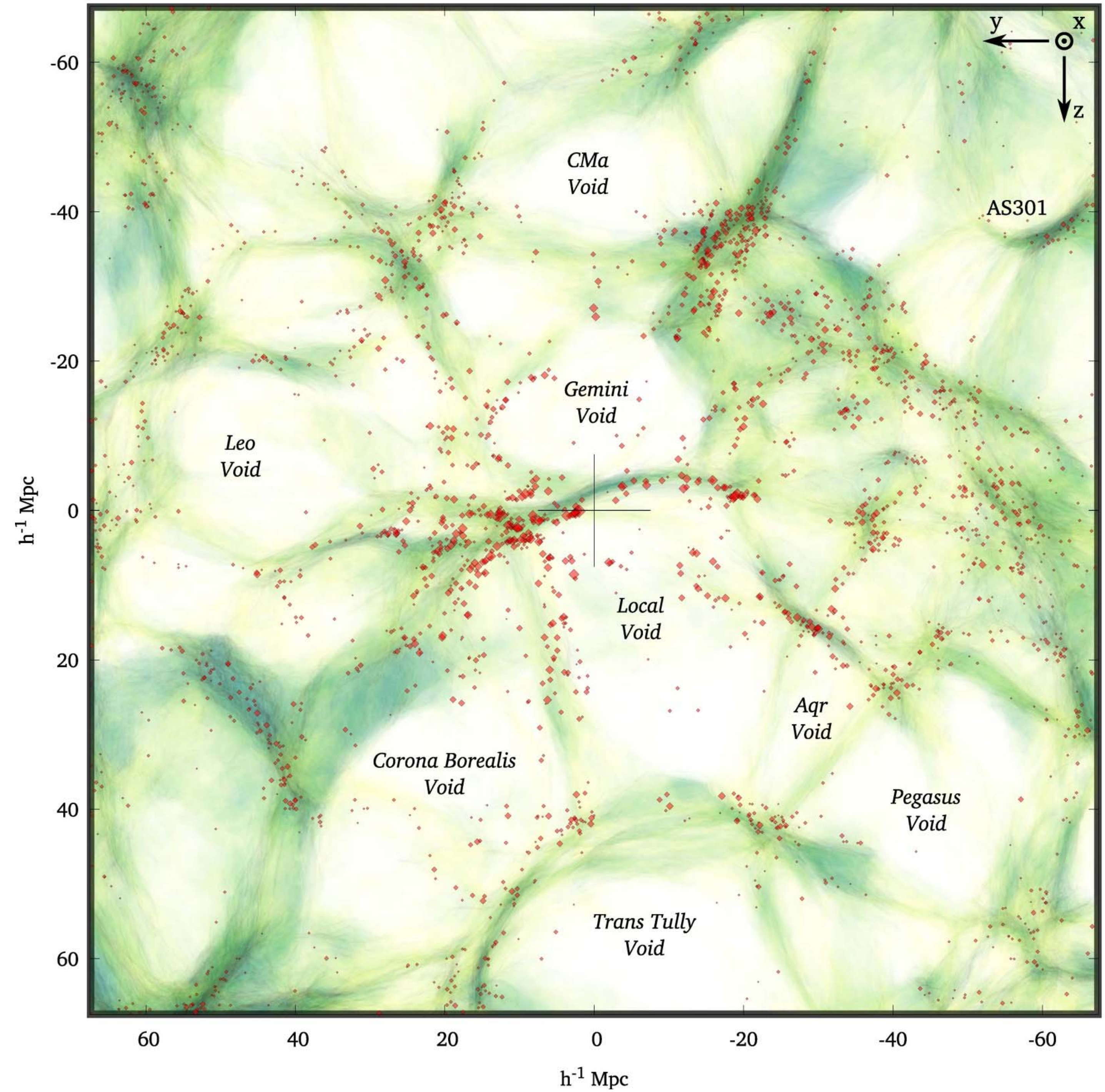

y
x
z
Canis Major
Void
AS500
Centaurus
A3574
Norma
AS840
Sculptor B
Void
Virgo
Void
Microscopium
Void
A3656
-60
-40
-20
0
20
40
60
h-1 Mpc
60
40
20
0
-20
-40
-60
h-1 Mpc



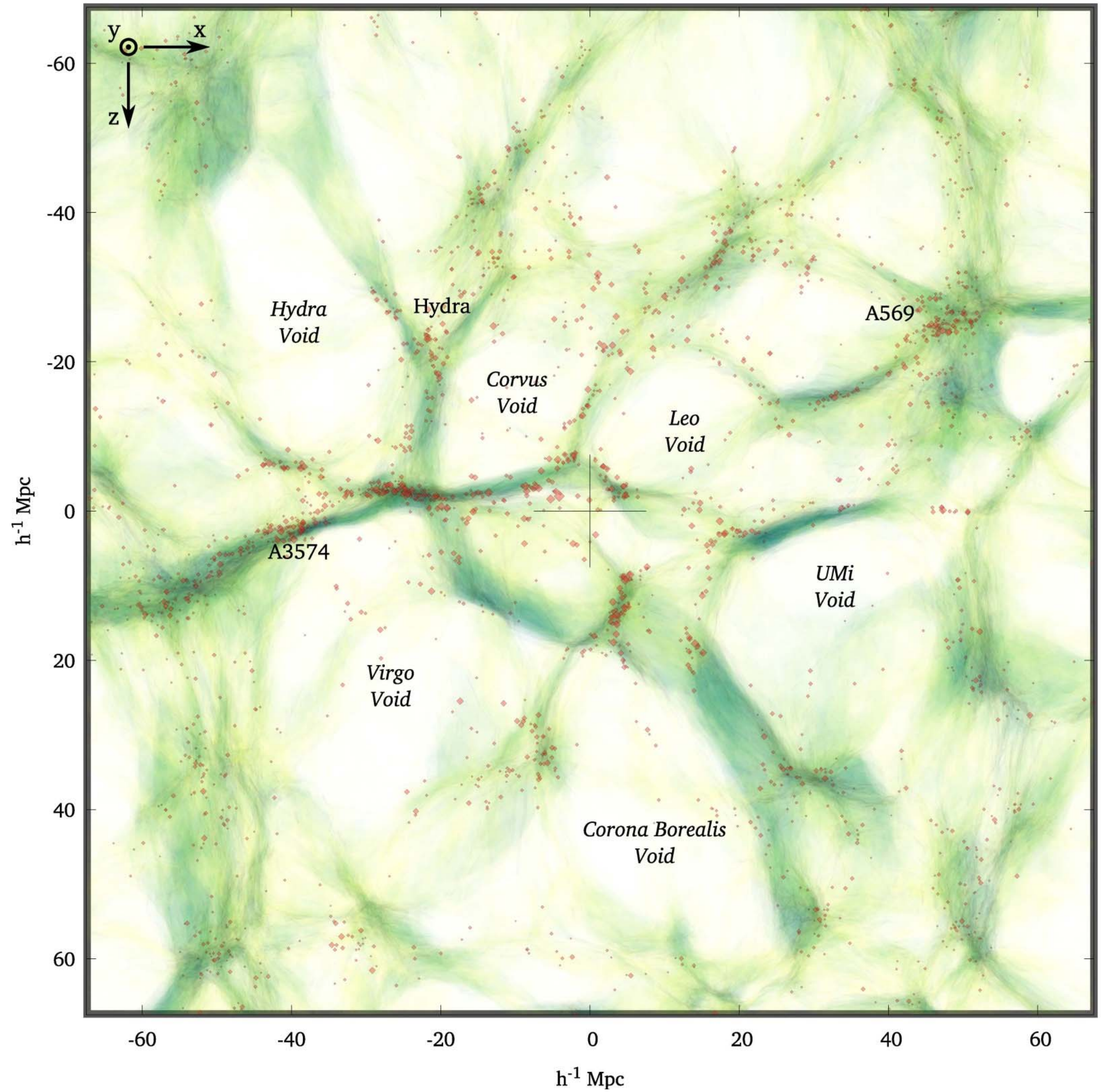
y
x
z
Columba
Void
Canis Major
Void
Hydra
Phoenix
Eridanus
Void
Corvus
Void
Antlia
And.
Void
Sculptor
Void
Virgo
Void
Aquarius
Void
Microscopium
Void
-60
-40
-20
0
20
40
60
h$^{-1}$ Mpc
60
40
20
0
-20
-40
-60
h$^{-1}$ Mpc

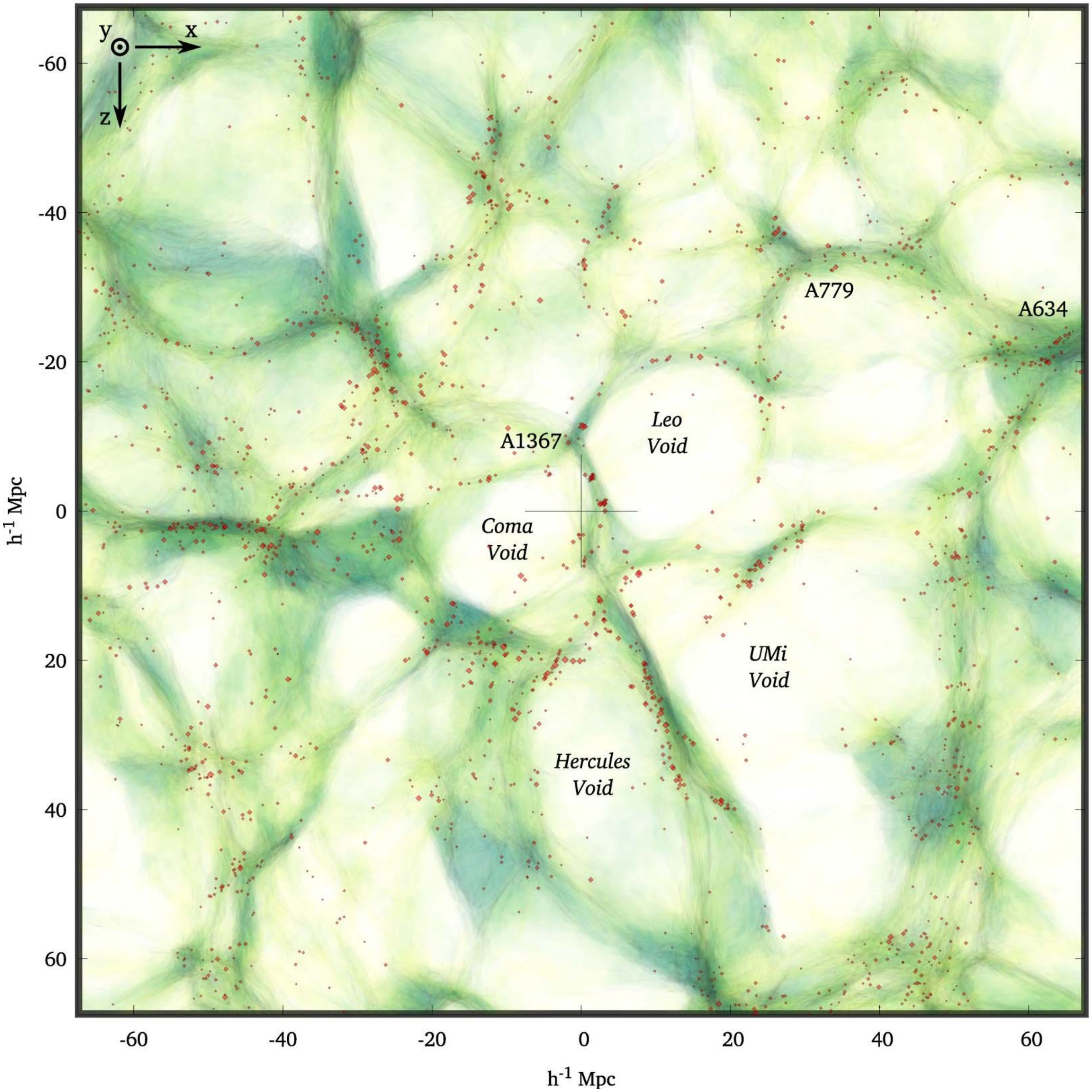


Canis Major
Void
Columba
Void
AS301
Eridanus
A1367
Fornax
Virgo
CVn
Void
Sculptor
Void
Coma
Local
Void
Virgo
Void
Aquarius
Void
Hercules
Void
CrB
Void
y
x
z
h-1 Mpc
h-1 Mpc
-60
-40
-20
0
20
40
60
60
40
20
0
-20
-40
-60



y
x
z
CMa
Void
AS301
Gemini
Void
Leo
Void
Local
Void
Aqr
Void
Corona Borealis
Void
Pegasus
Void
Trans Tully
Void
-60
-40
-20
0
20
40
60
h$^{-1}$ Mpc
60
40
20
0
-20
-40
-60
h$^{-1}$ Mpc


y
x
z
Hydra
Void
Hydra
A569
Corvus
Void
Leo
Void
A3574
UMi
Void
Virgo
Void
Corona Borealis
Void
-60
-40
-20
0
20
40
60
h-1 Mpc
h-1 Mpc

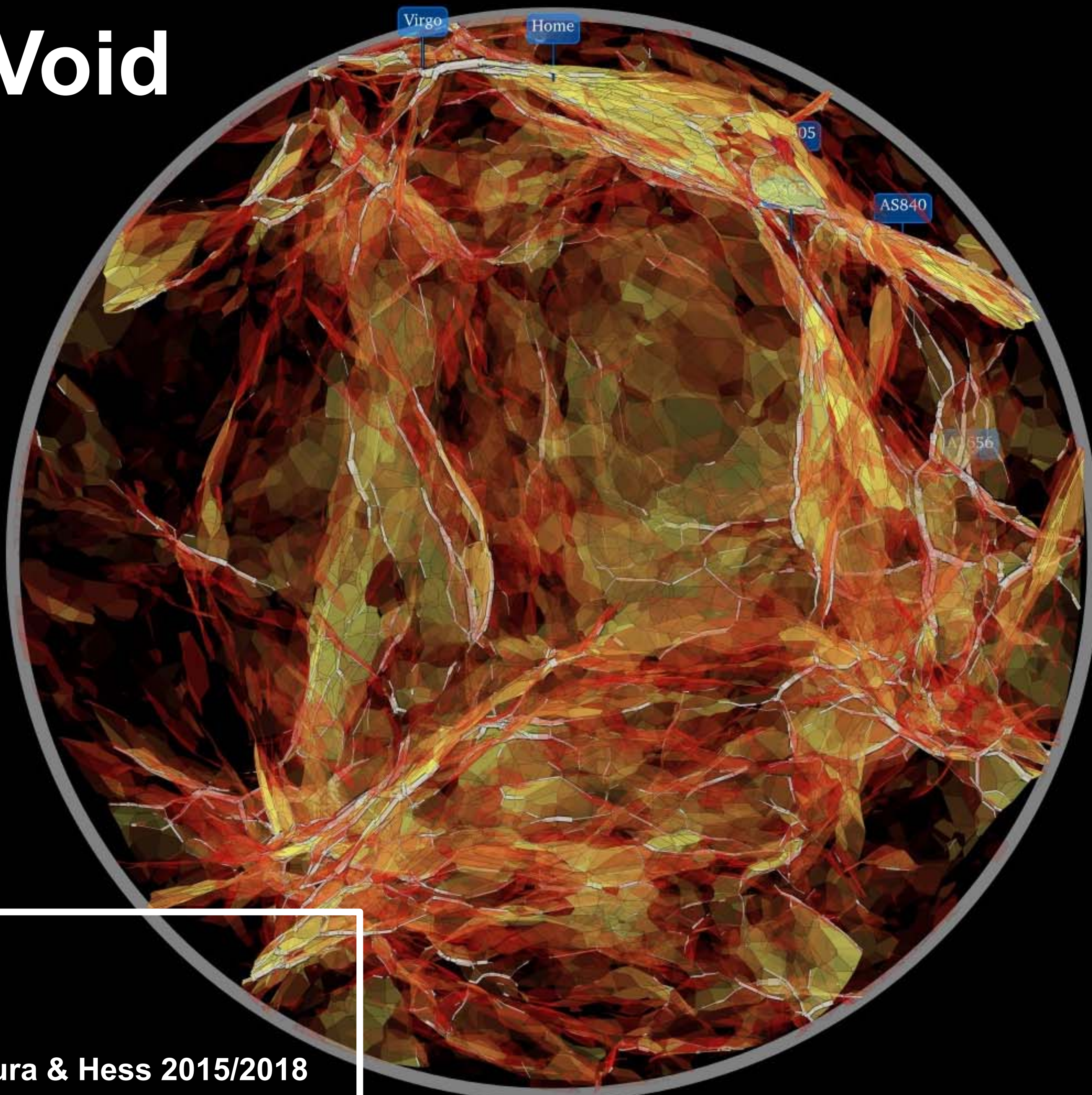


y
x
z
A779
A634
Leo
Void
A1367
Coma
Void
UMi
Void
Hercules
Void
-60
-40
-20
0
20
40
60
h-1 Mpc
h-1 Mpc

# Local Cosmic Web:

# the Local Void

# Local Void




**Local Void**

**Reconstruction:**
**Hidding, vdW, Kitaura & Hess 2015/2018**

# Cosmic Web Summary

- Cosmic Web unique probe of structure formation at transition linear to nonlinear stage.
- Structural and Dynamical analysis of the Cosmic Web poses strong challenges due to complex pattern and multiscale nature.
- Nexus/MMF formalism allows study of the evolving multiscale structure of the Cosmic Web.
- Interplay between morphological elements of filaments, walls, cluster nodes and voids.
- Dynamically cluster nodes dominant, structurally (mass, halo content) the filaments.
- Adhesion formalism highly suited for following the dynamical evolution of the weblike structure.
- Adhesion formalism & tessellation-based solution allow investigation of cosmological sensitivity of the cosmic web.

continued: part 2

# Flows & Voids