

# Void Infrastructure: on Void Hierarchy and the Local Void

Rien van de Weygaert,

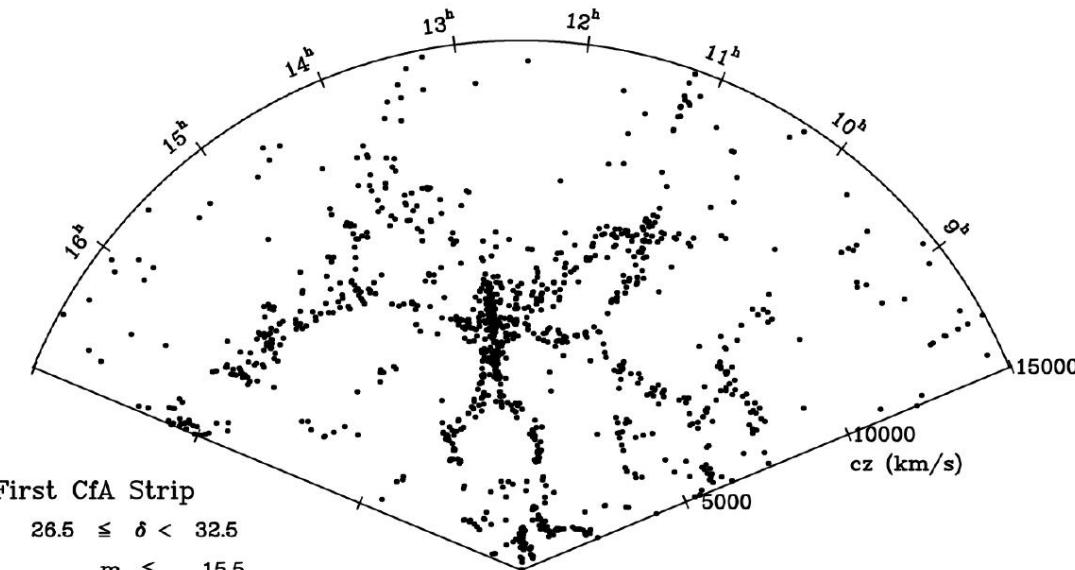
2<sup>nd</sup> Anisotropic Universe workshop, Amsterdam, April 2016

# Voids in the Local Universe

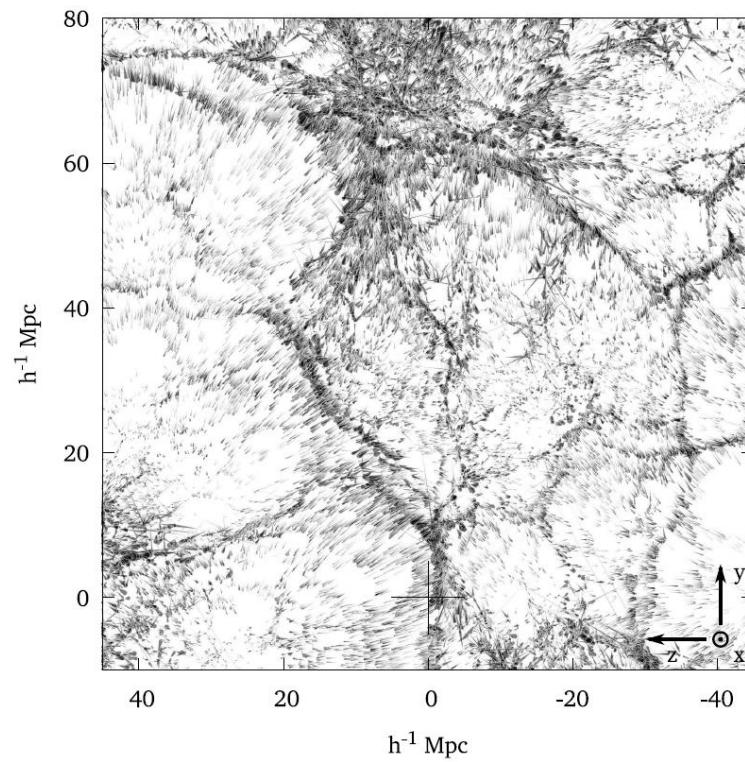
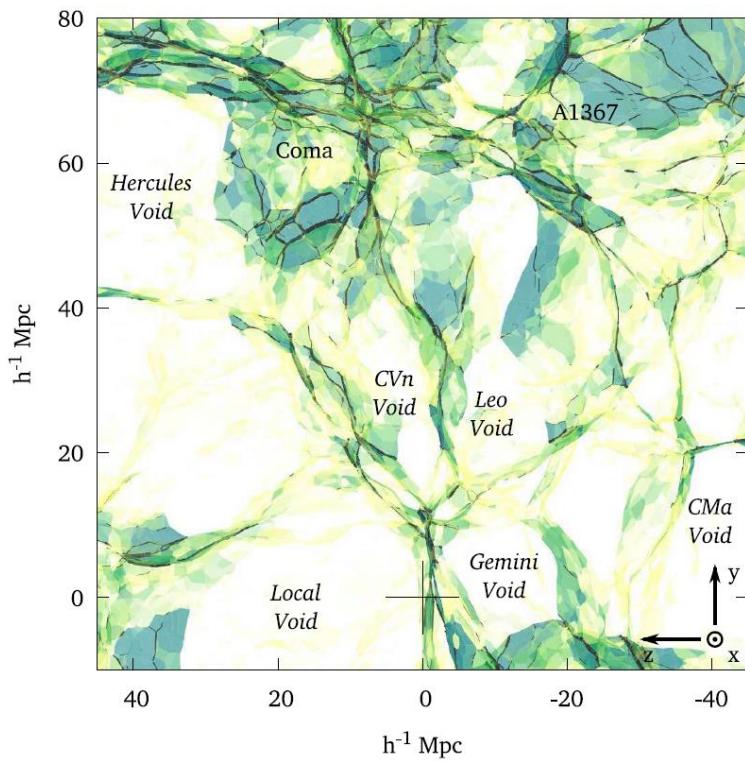


KIGEN-adhesion  
Local Void Reconstruction:

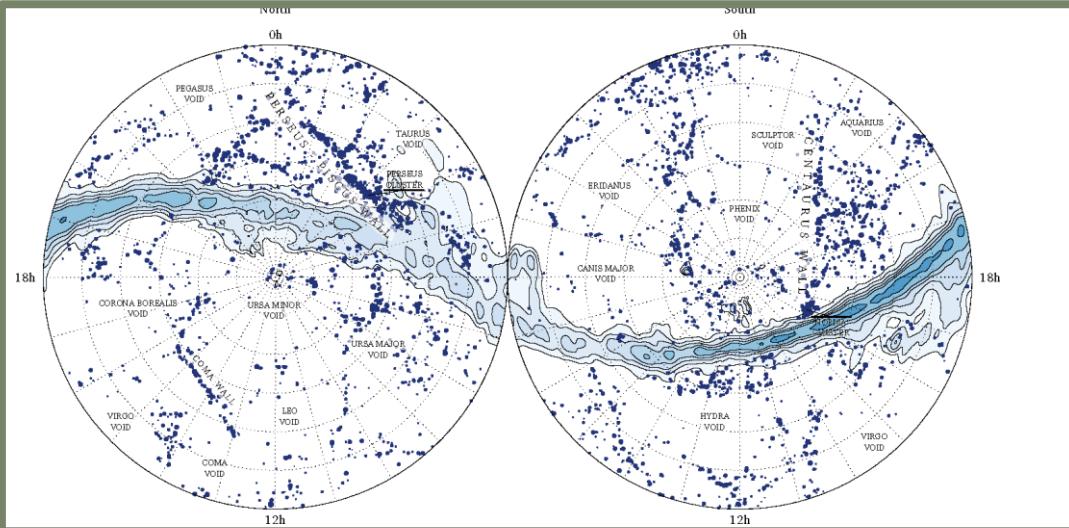
Hidding, vdW, Kitaura & Hess 2016



# Hidding 2015

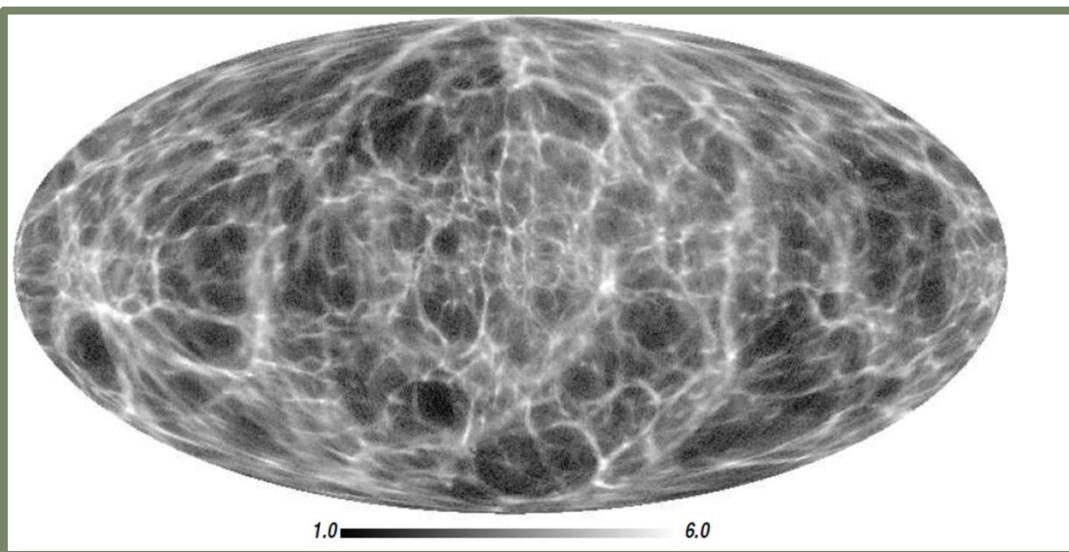


# KIGEN Reconstruction Local Universe ...



2MRS survey sky map  
Hidding 2015

Depth: ~50 Mpc



KIGEN reconstruction  
Local Cosmic Web:

Kitaura

Depth: ~185 Mpc

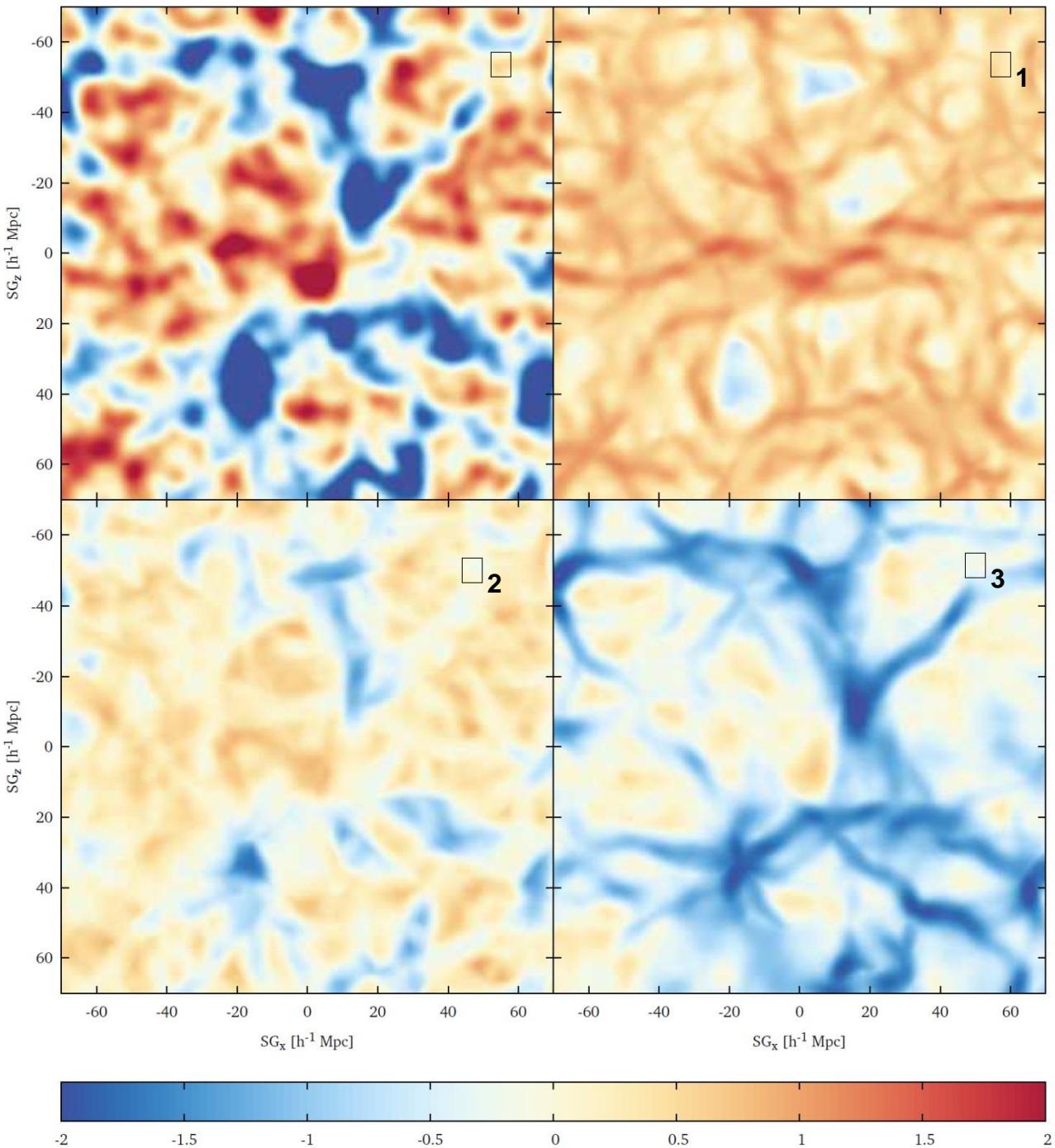
# Initial Density & Deformation Field

Local Universe  
(SG plane)

Kitaura & Hess:

Bayesian (KIGEN)  
reconstruction  
from 2MRS galaxy  
distribution

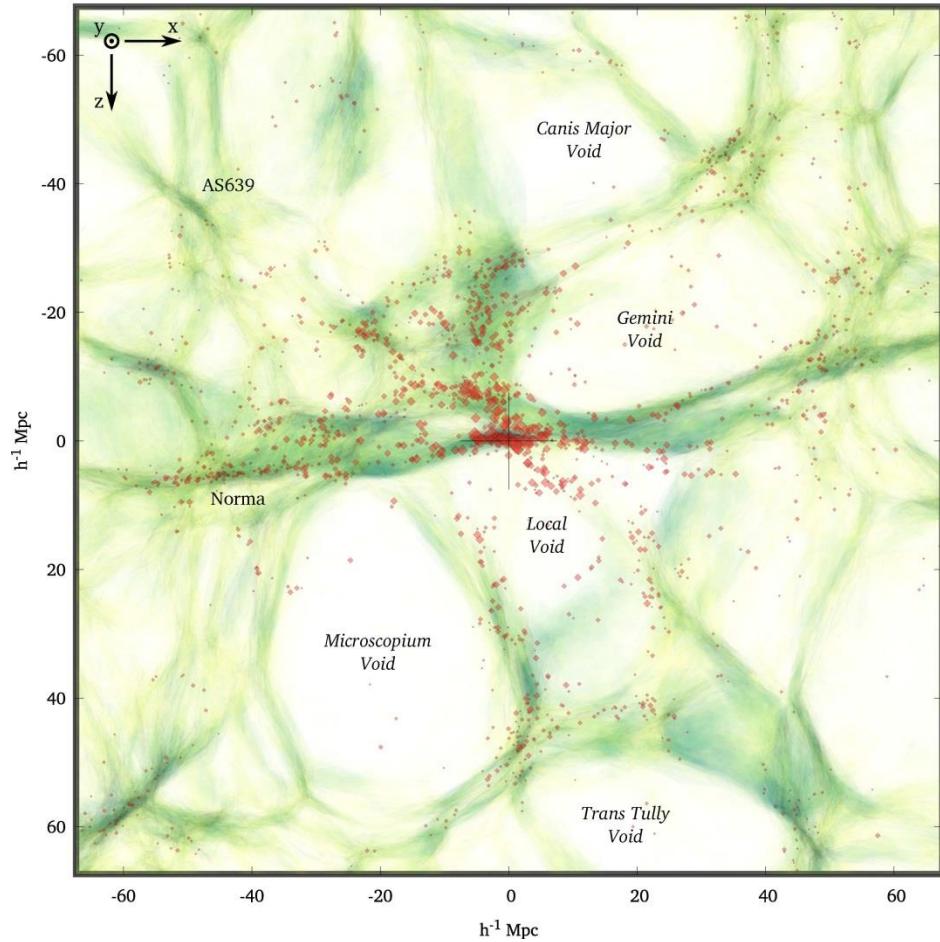
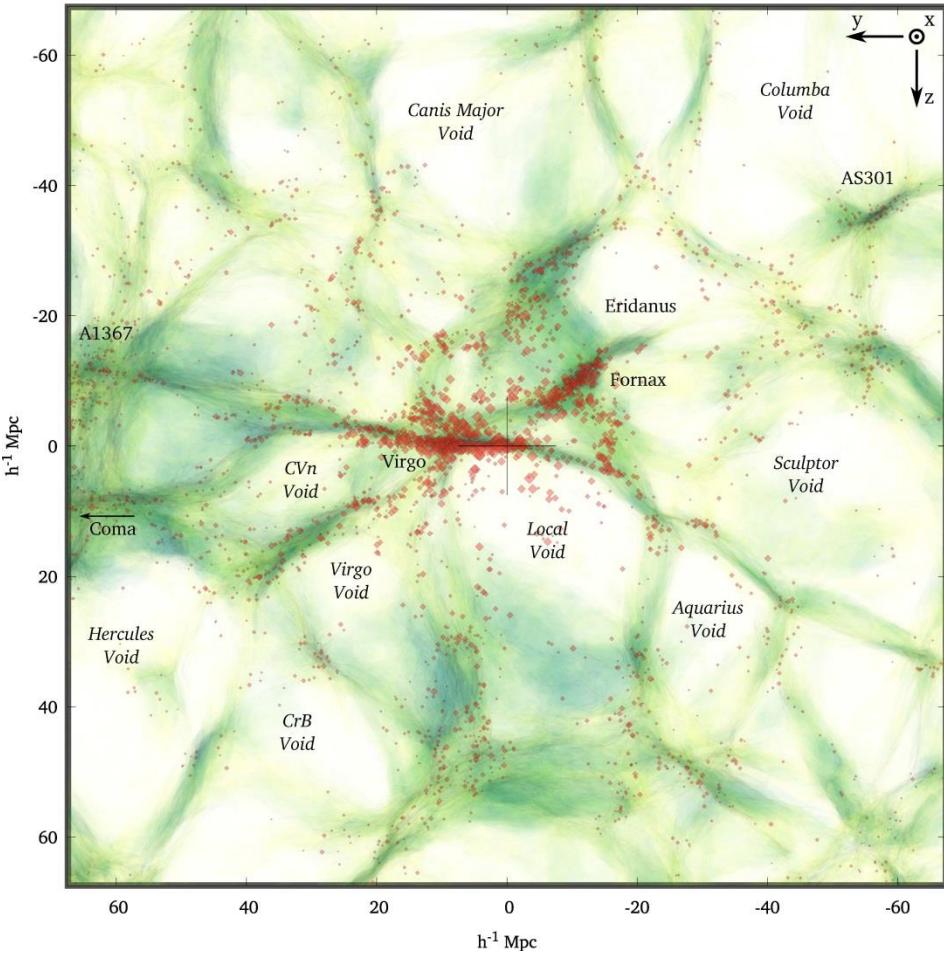
25  
constrained realizations





# Supergalactic Plane

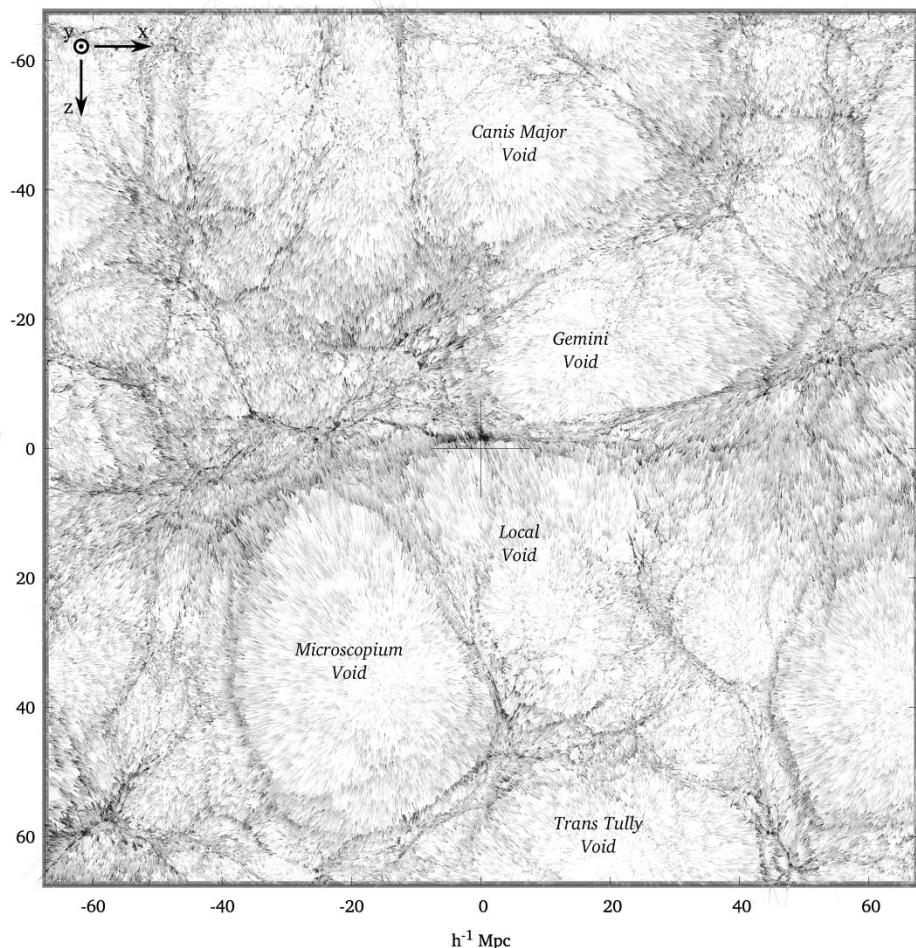
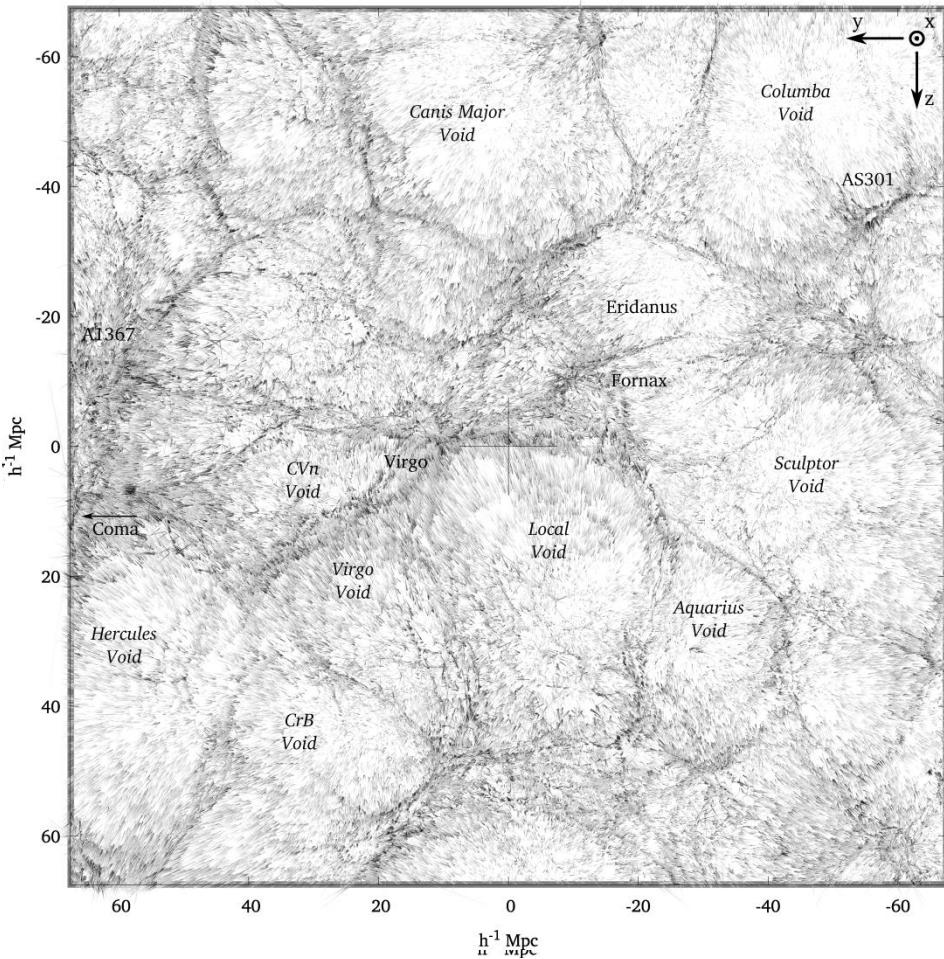
## mean adhesion reconstruction



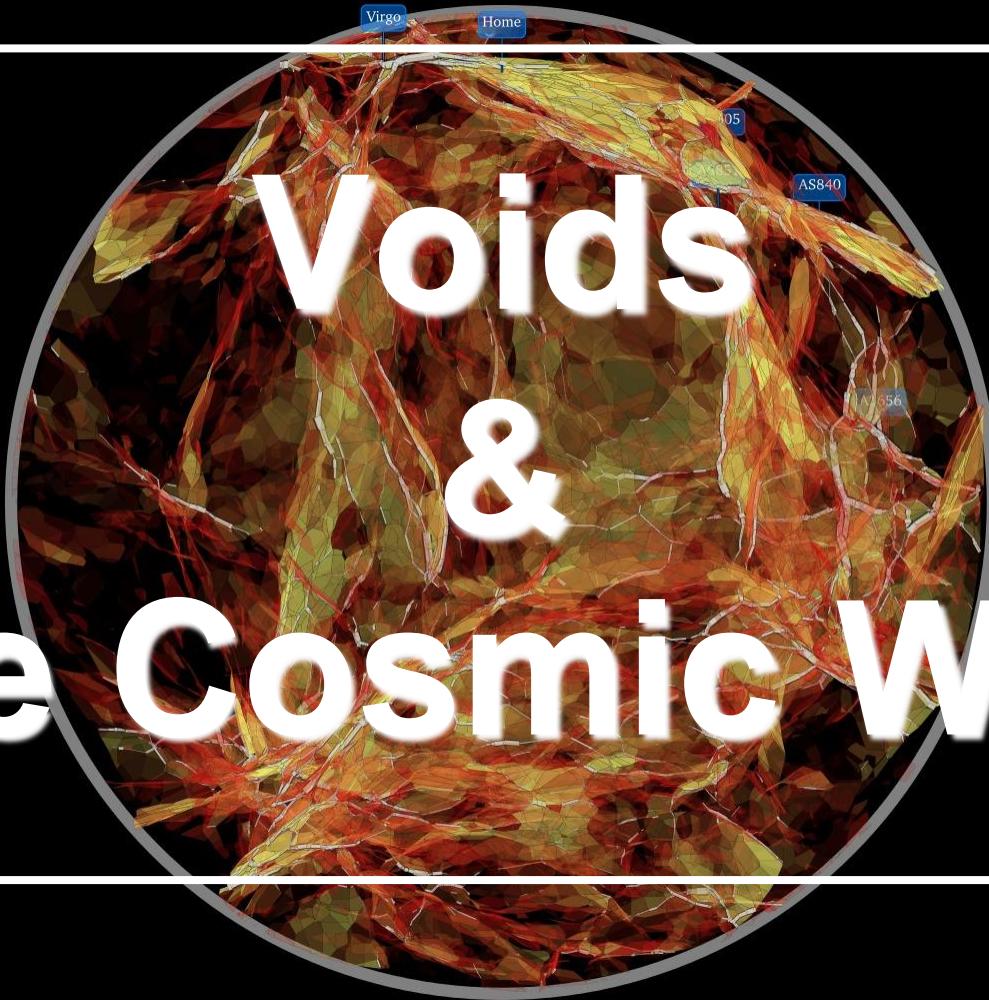


# Supergalactic Plane

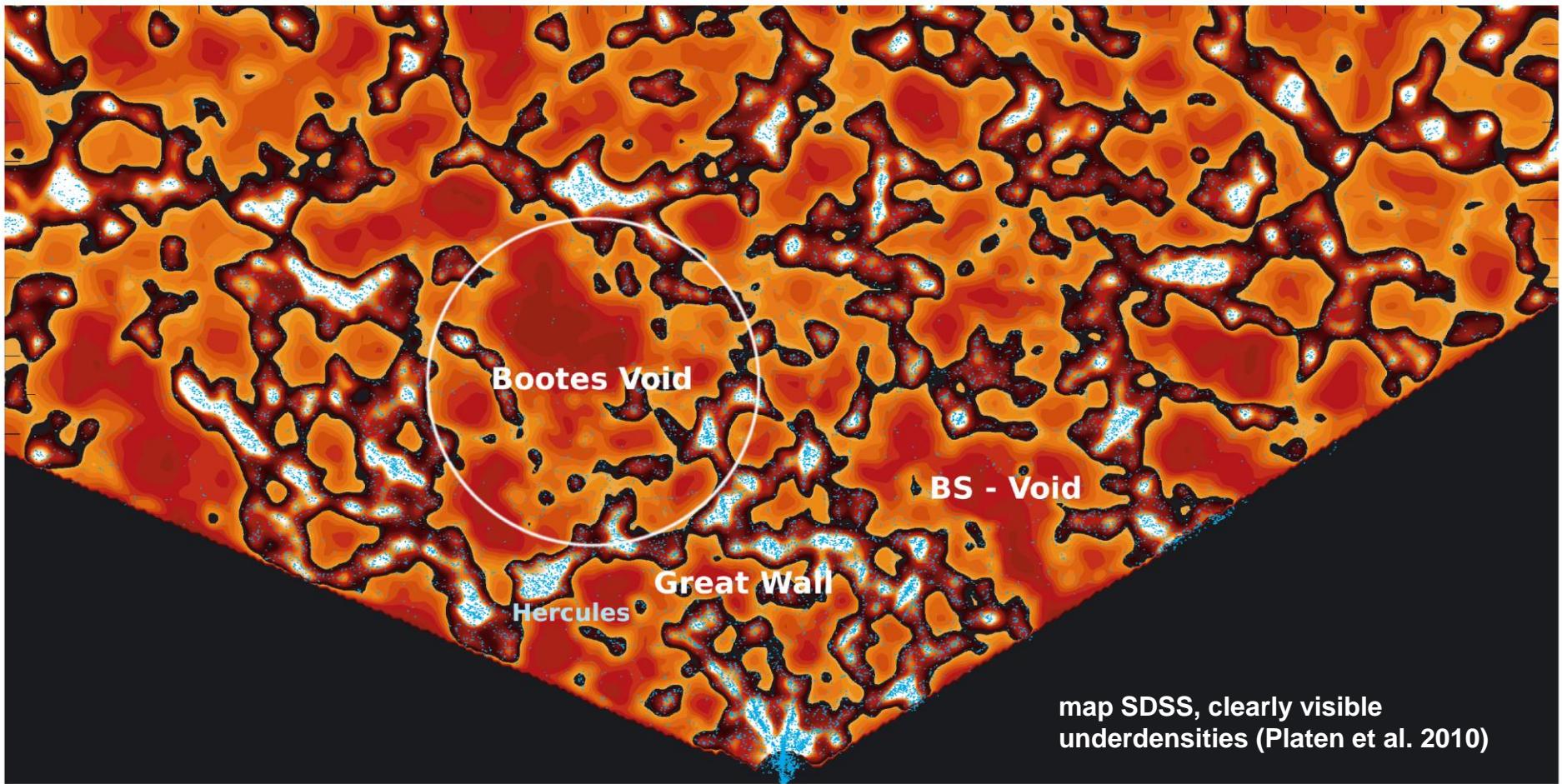
## mean adhesion reconstruction



# Voids & the Cosmic Web



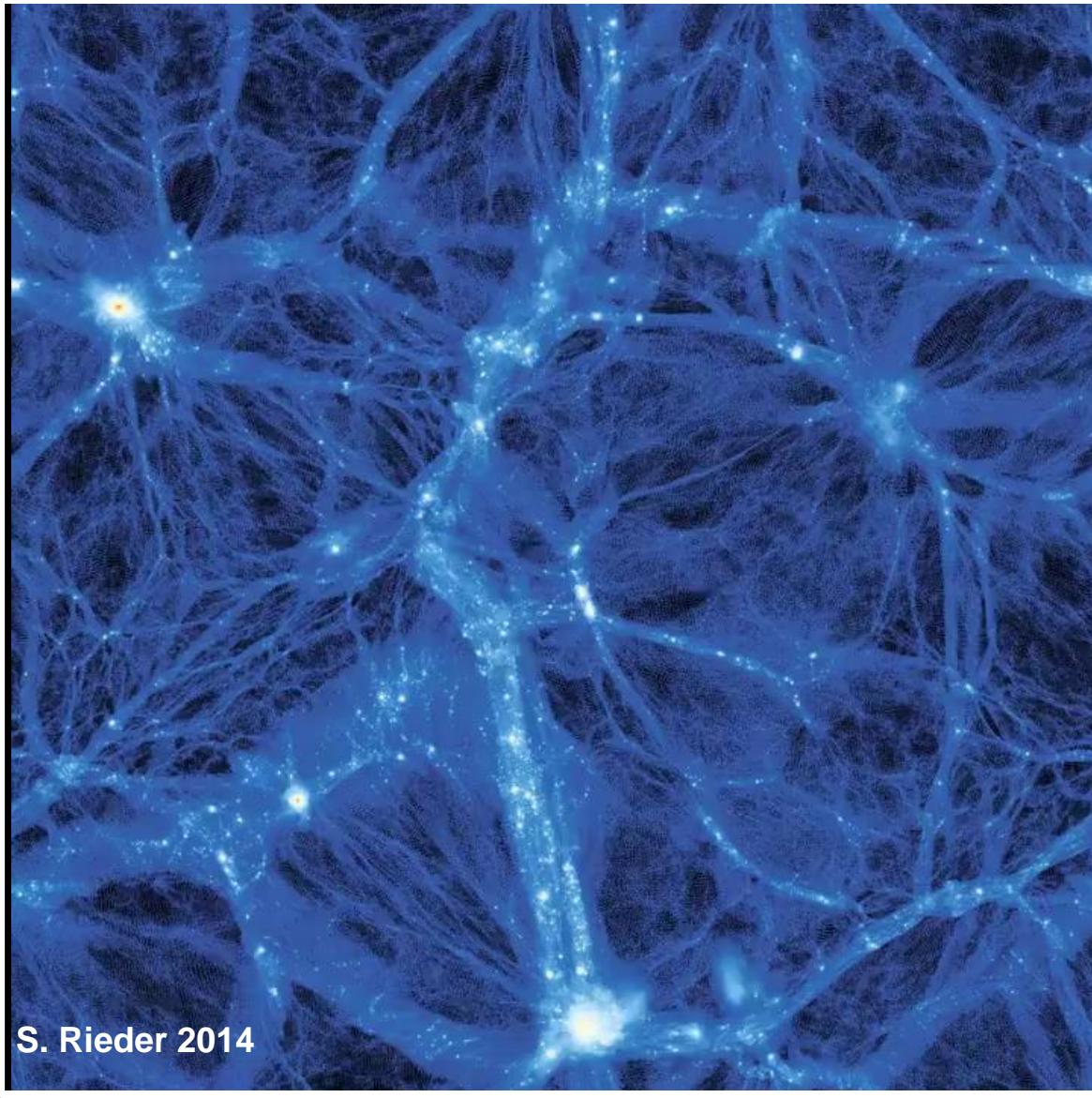
# SDSS Galaxy Survey



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



S. Rieder 2014

# Cosmic Web

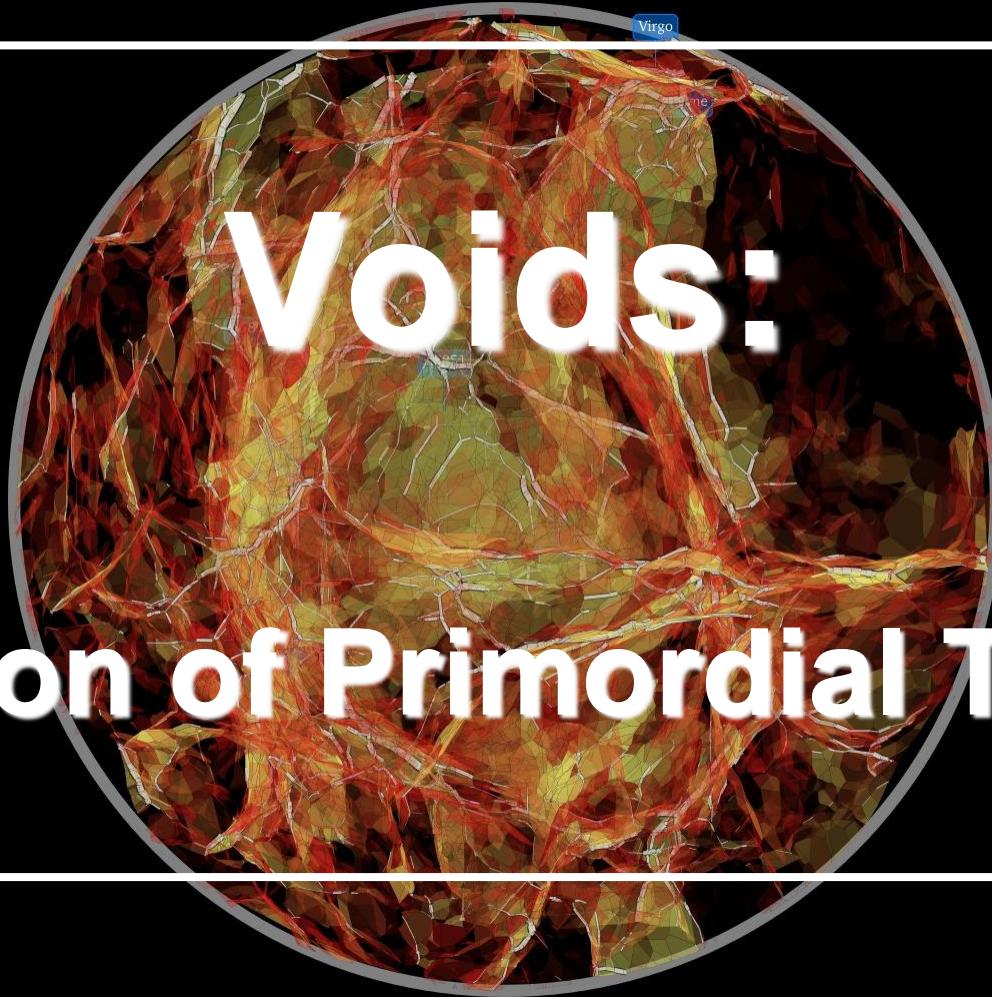
on scales of ~5-100s Mpc

complex weblike pattern

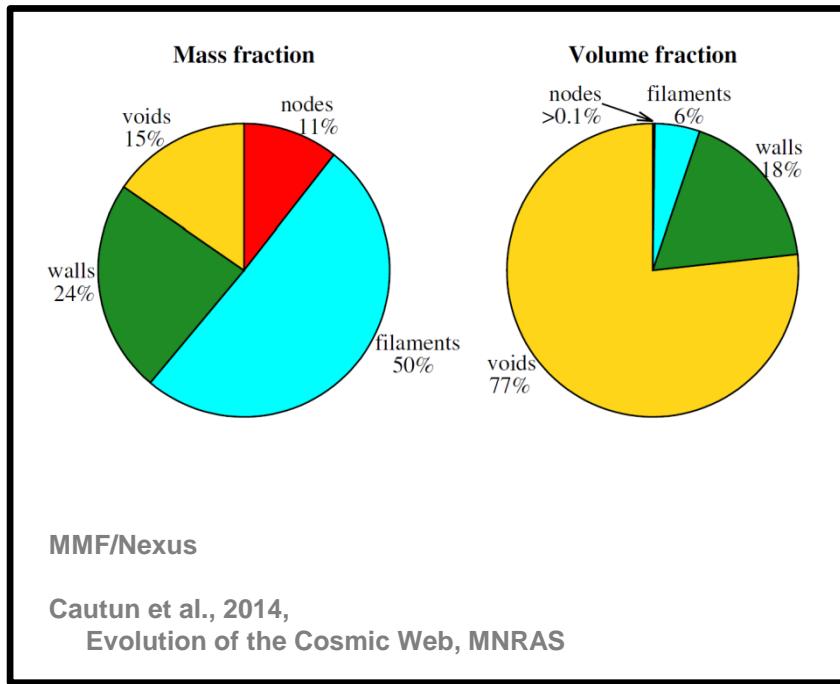
in which  
matter, gas & galaxies  
aggregate in

- ⌚ compact clusters,
- ⌚ elongated filaments
- ⌚ flattened sheets
- ⌚ around
- ⌚ cosmic voids

# Voids: Evolution of Primordial Troughs



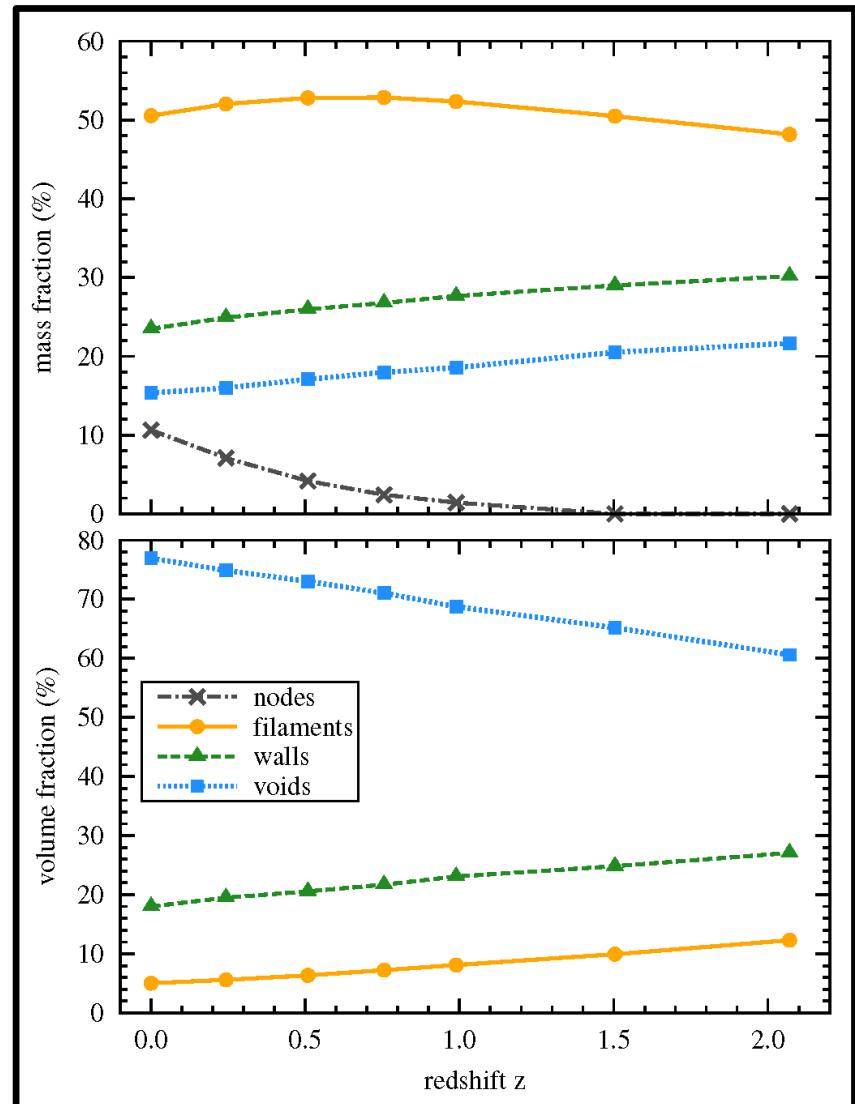
# Cosmic Web & Voids



**Voids:** - occupy most of cosmic volume: 77%  
- of mass, only: 15%

**Void evolution:**

- volume fraction increases with time  
**(void expansion)**
- mass fraction decreases with time  
**(void evacuation)**



# Void Formation

## Void Evolution

an illustration

cosmology:

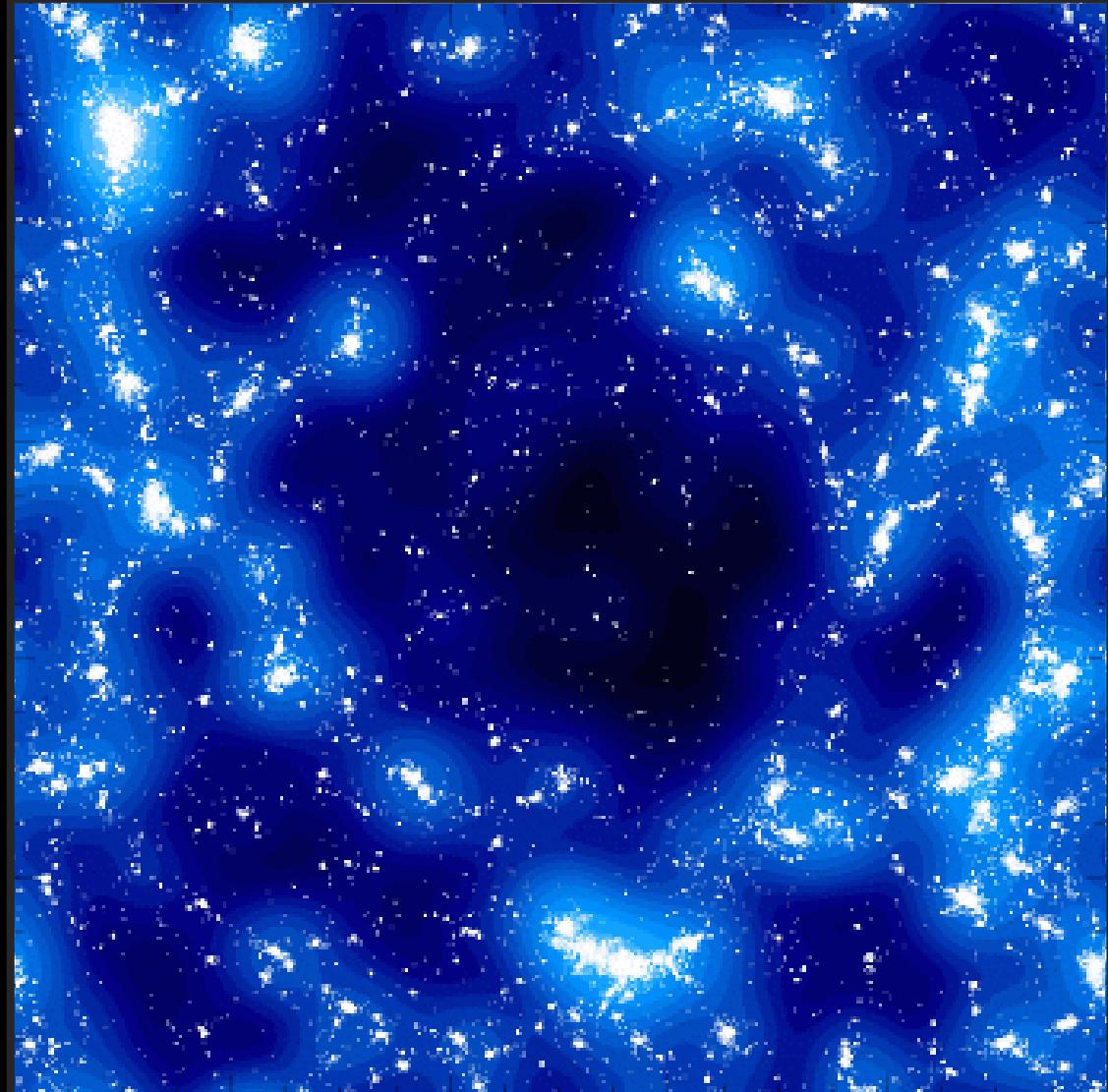
$$\Omega_m = 1.0; \quad H_0 = 70 \text{ km/s/Mpc}$$

initial conditions:

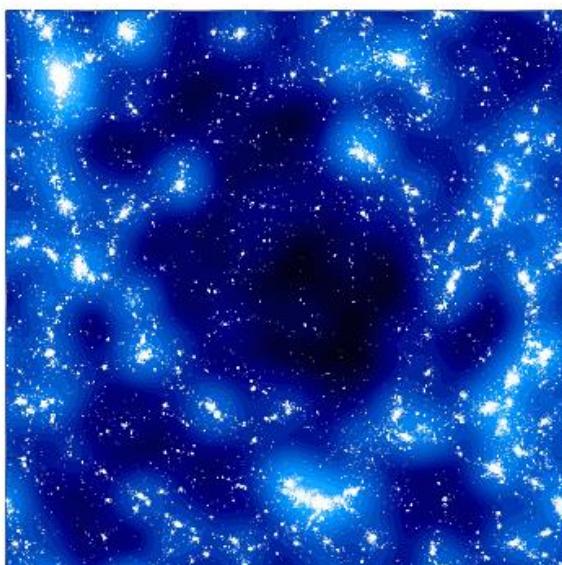
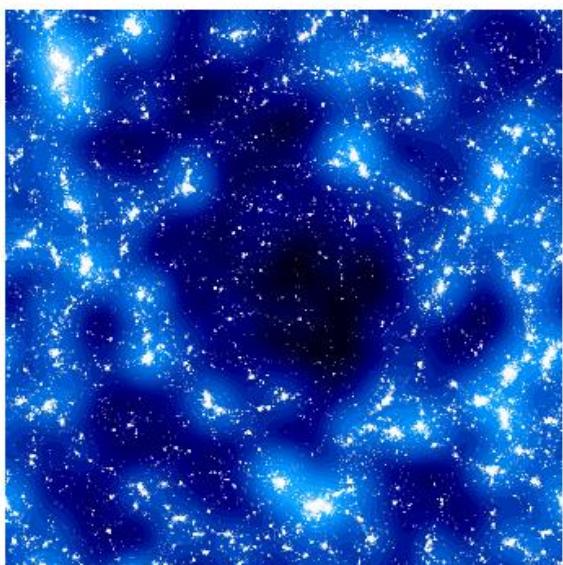
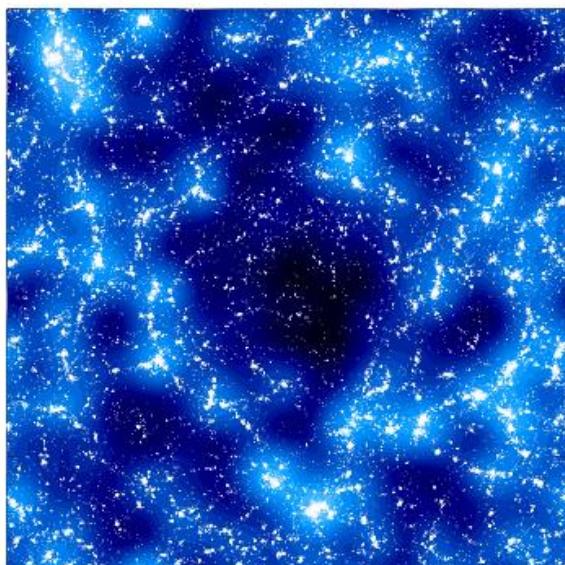
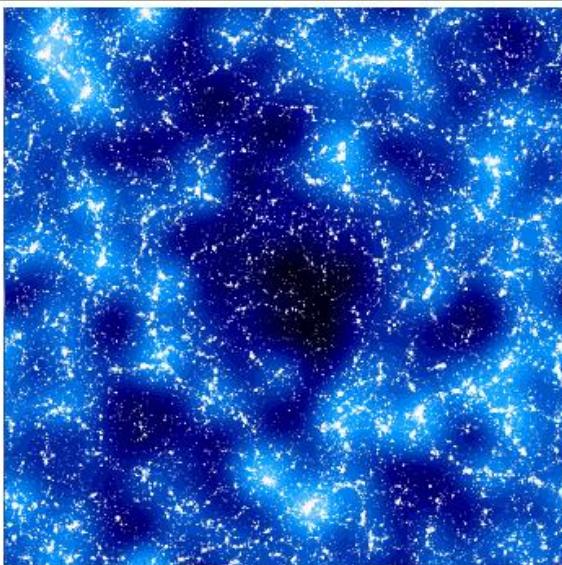
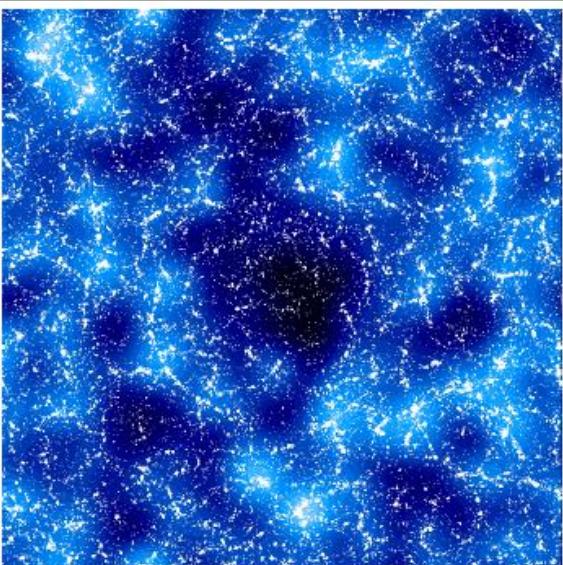
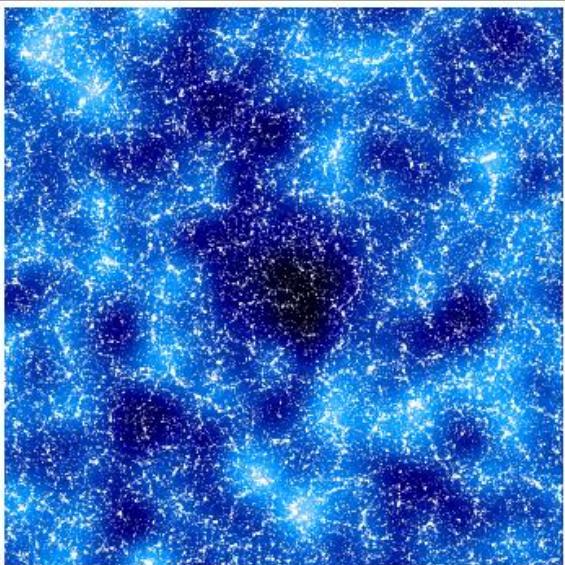
underdensity, Gaussian field

$$R_G \sim 4h^{-1}\text{Mpc}$$

$$P(k) \propto k^{-0.5}$$

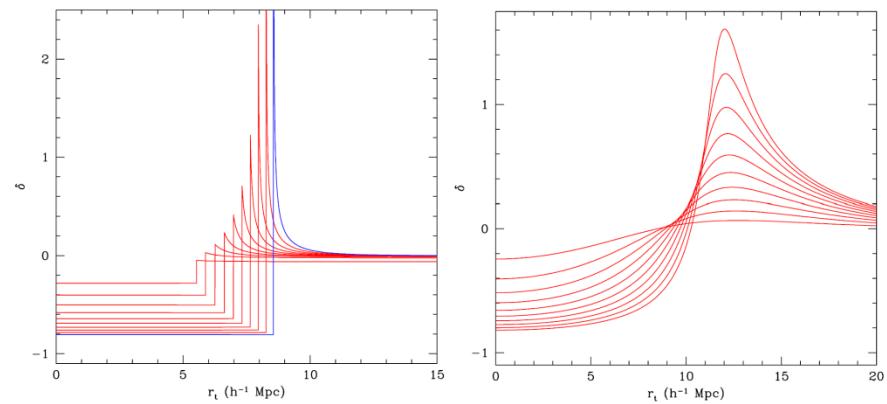


# Void Formation



# Void Evolution: The Perfect Sphere, Tophat as well

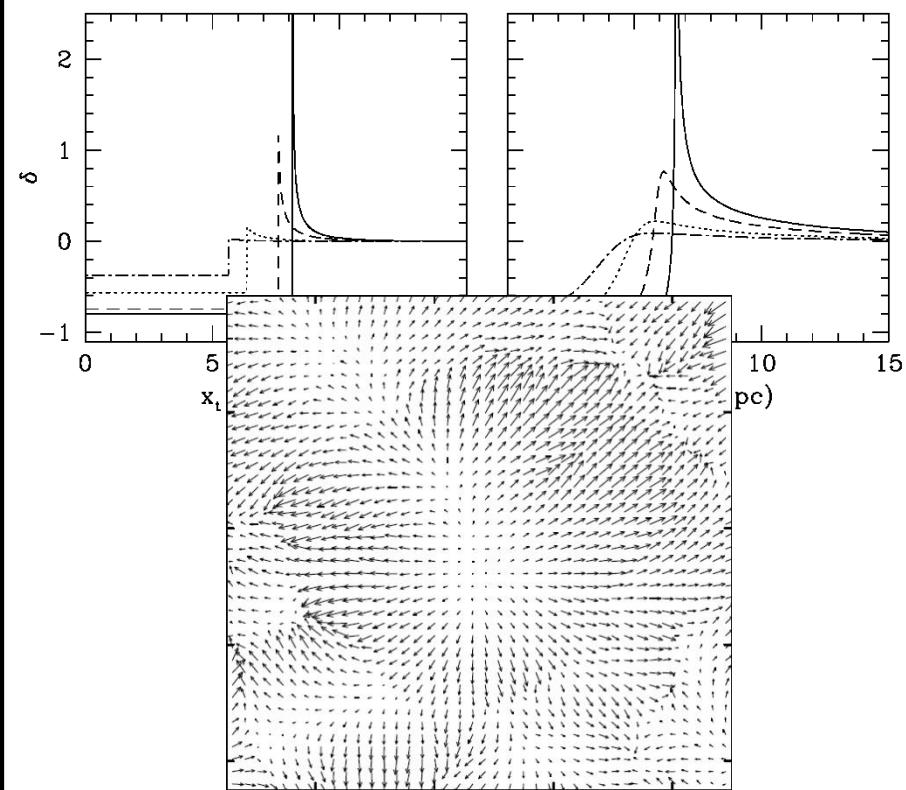
- ``Bubble Theorem''  
**Voids become increasingly spherical, due to anisotropic outward directed force**
- Tophat Configuration  
**Any initial configuration tends towards “bucket” shape**
- Density Ridge  
**Except for gentlest initial density profiles, a ridge forms**



# Superhubble Expansion

- Superhubble Expansion tending towards “bucket” shape, the void outflow is one with uniform velocity divergence

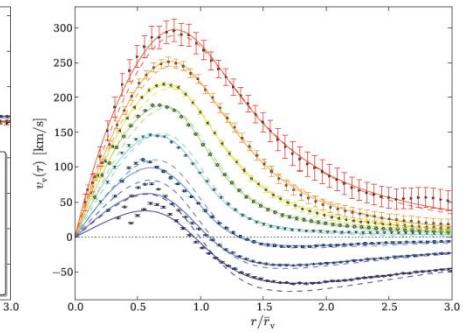
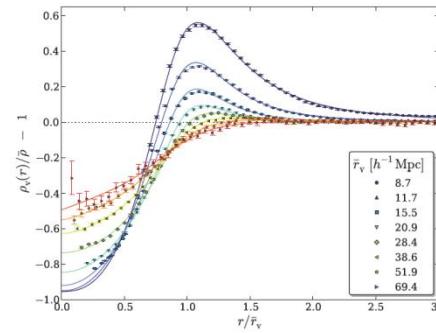
$$\theta = \frac{1}{H} (\nabla \cdot \vec{v}) \quad \Rightarrow \quad \theta_{\max} = 1.5 \Omega^{0.6}$$



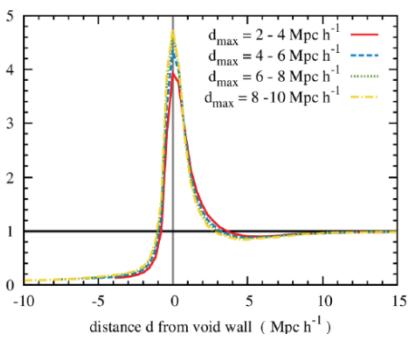
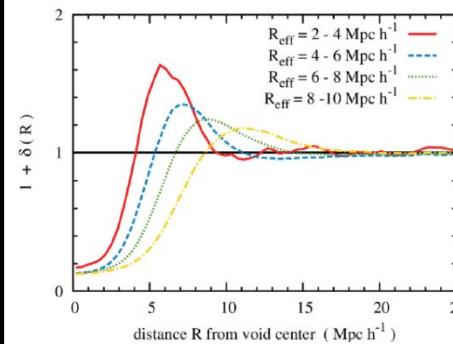
# Void Density Profile

- Tophat Configuration  
Any initial configuration tends towards “bucket” shape
- Density Ridge  
Except for gentlest initial density profiles, a ridge forms

Is there a universal void density profile ?



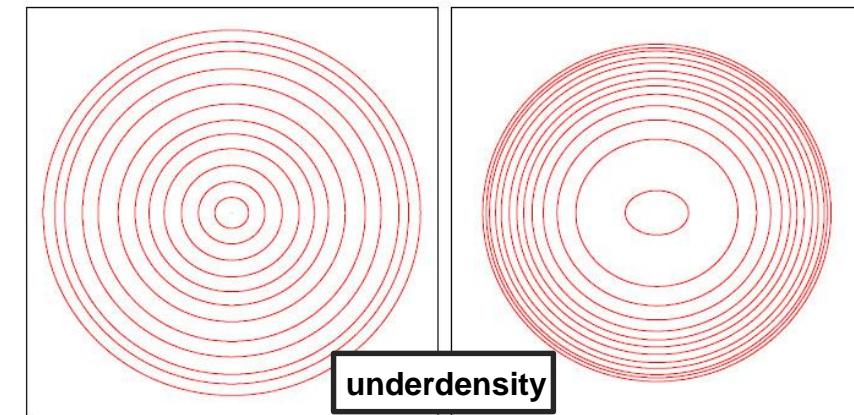
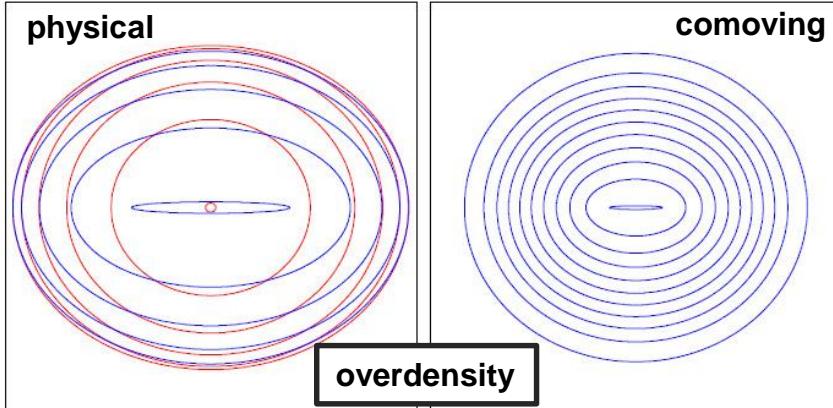
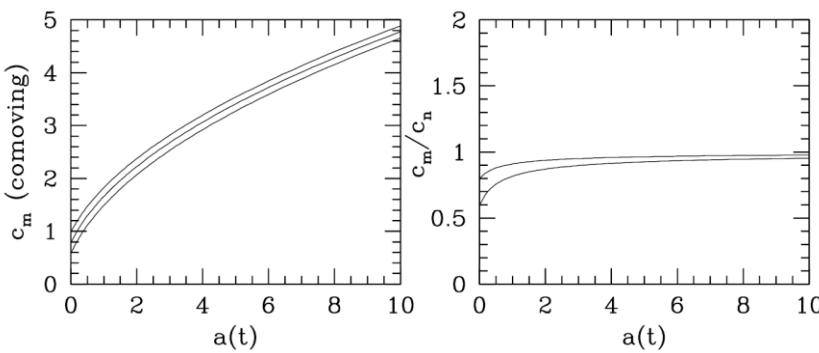
e.g. Hamaus et al. 2014



Cautun et al. 2015

# Bubble Theorem

- Bubble Theorem (Icke 1984)  
Isolated voids tend to become more spherical as they expand and evolve



# Void Shapes & Environment

- Bubble Theorem Revisited:

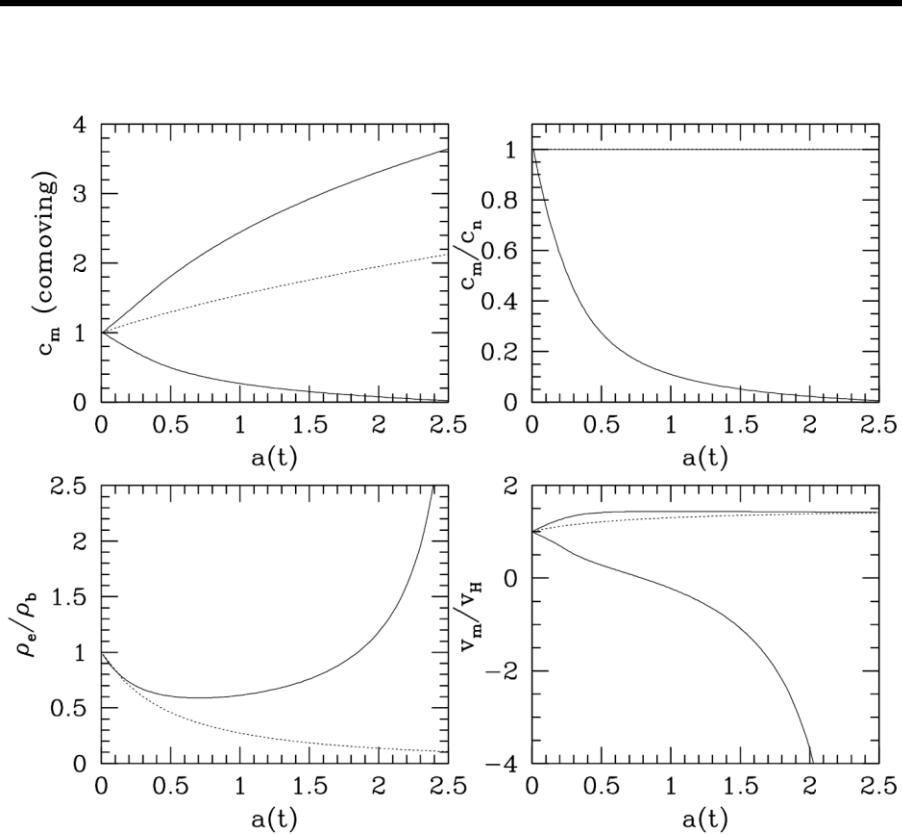
voids will not be spherical:

- Voids never isolated:
  - run into neighbours
  - boundaries overdense ridges cosmic web
- Void evolution & dynamics largely dominated by large scale (tidal) environment:

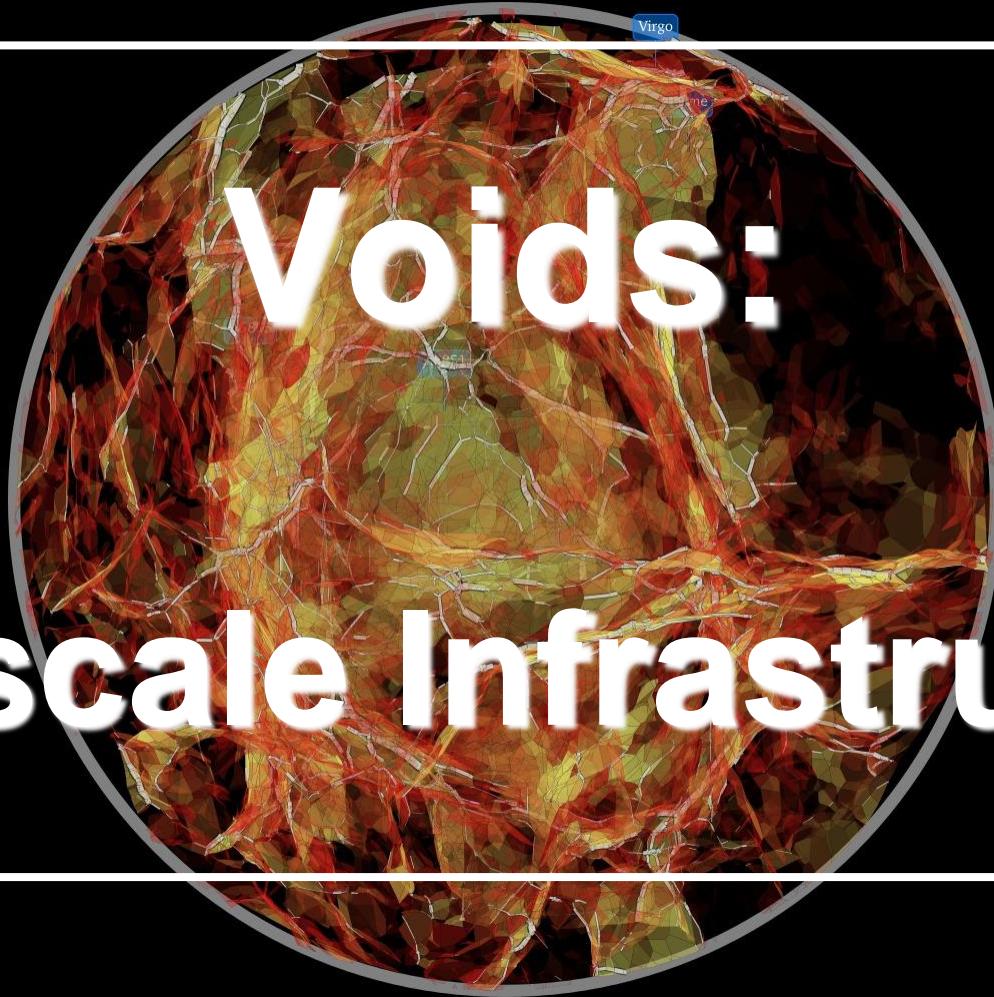
voids always represent  
restricted density fluctuation:  $|\square| < 1$

Evolution homogeneous ellipsoidal void in  
external tidal field  $T_{kl}$

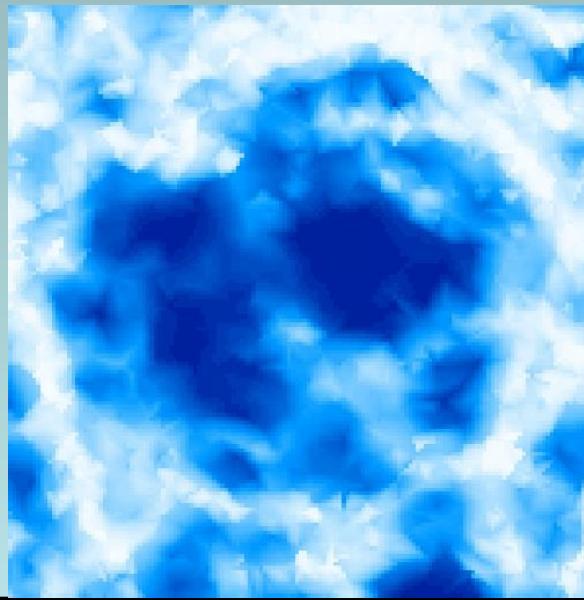
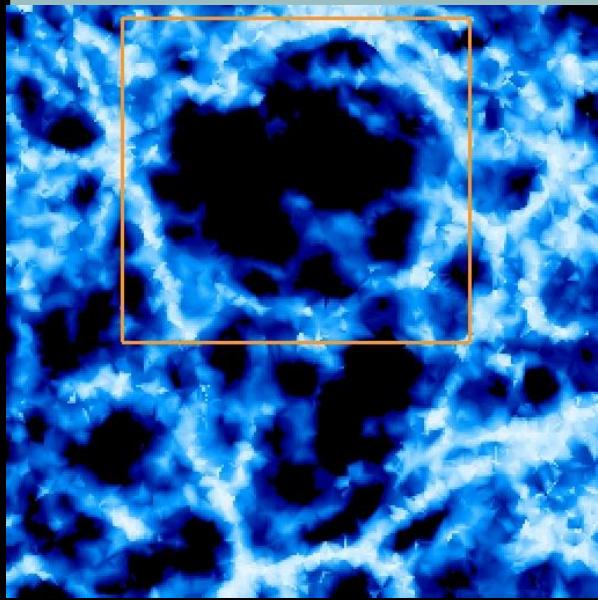
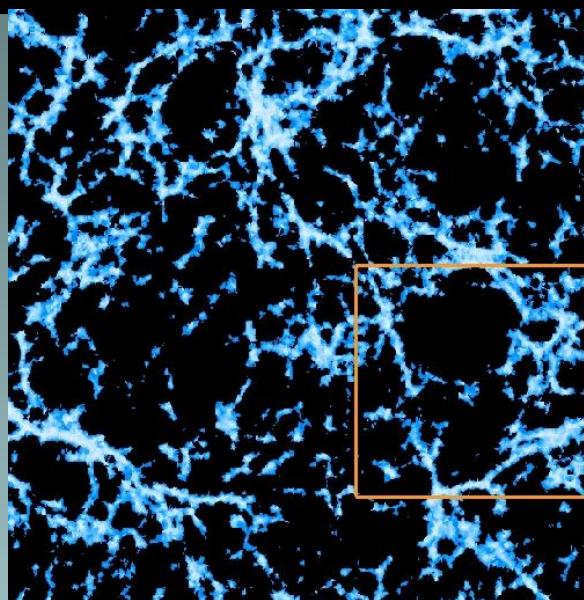
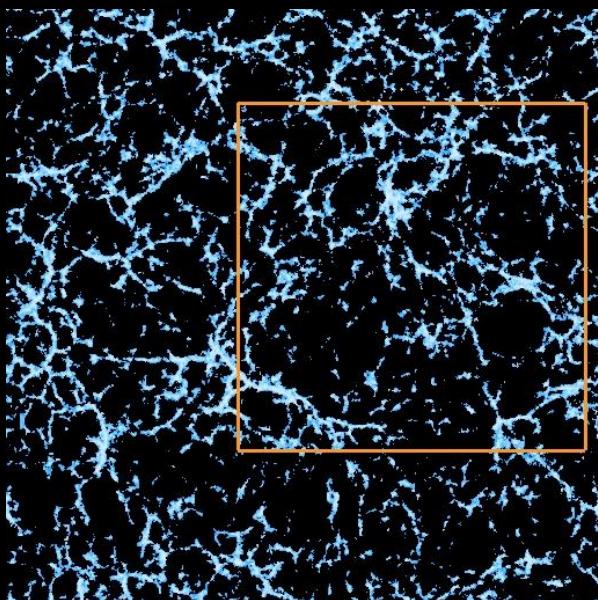
$$\frac{d^2 R_m}{dt^2} = -2\pi G \left[ \alpha_m \rho_e + \left( \frac{2}{3} - \alpha_m \right) \rho_u \right] R_m - T_{mm} R_m$$



# Voids: Multiscale Infrastructure



# Void Substructure

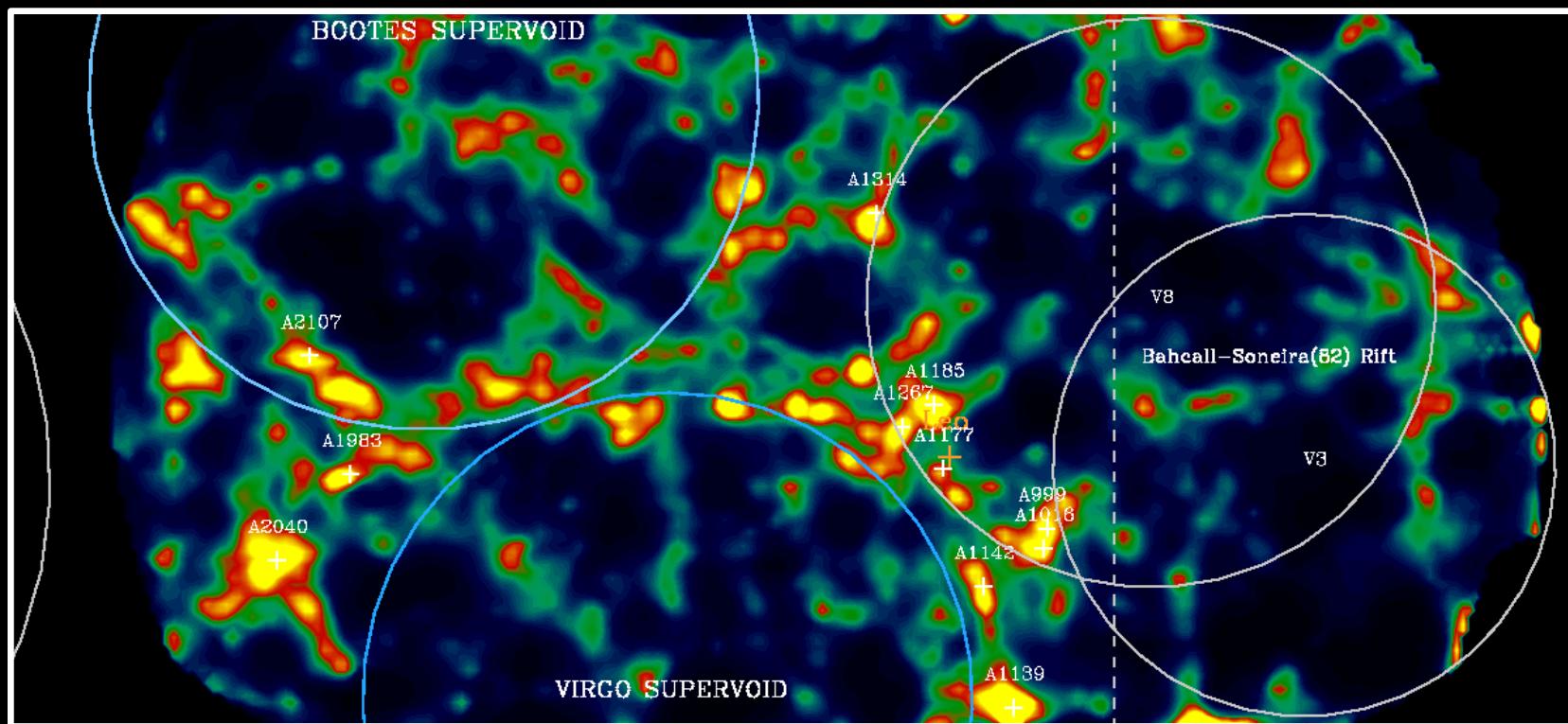


Zooming in  
over 3 levels:

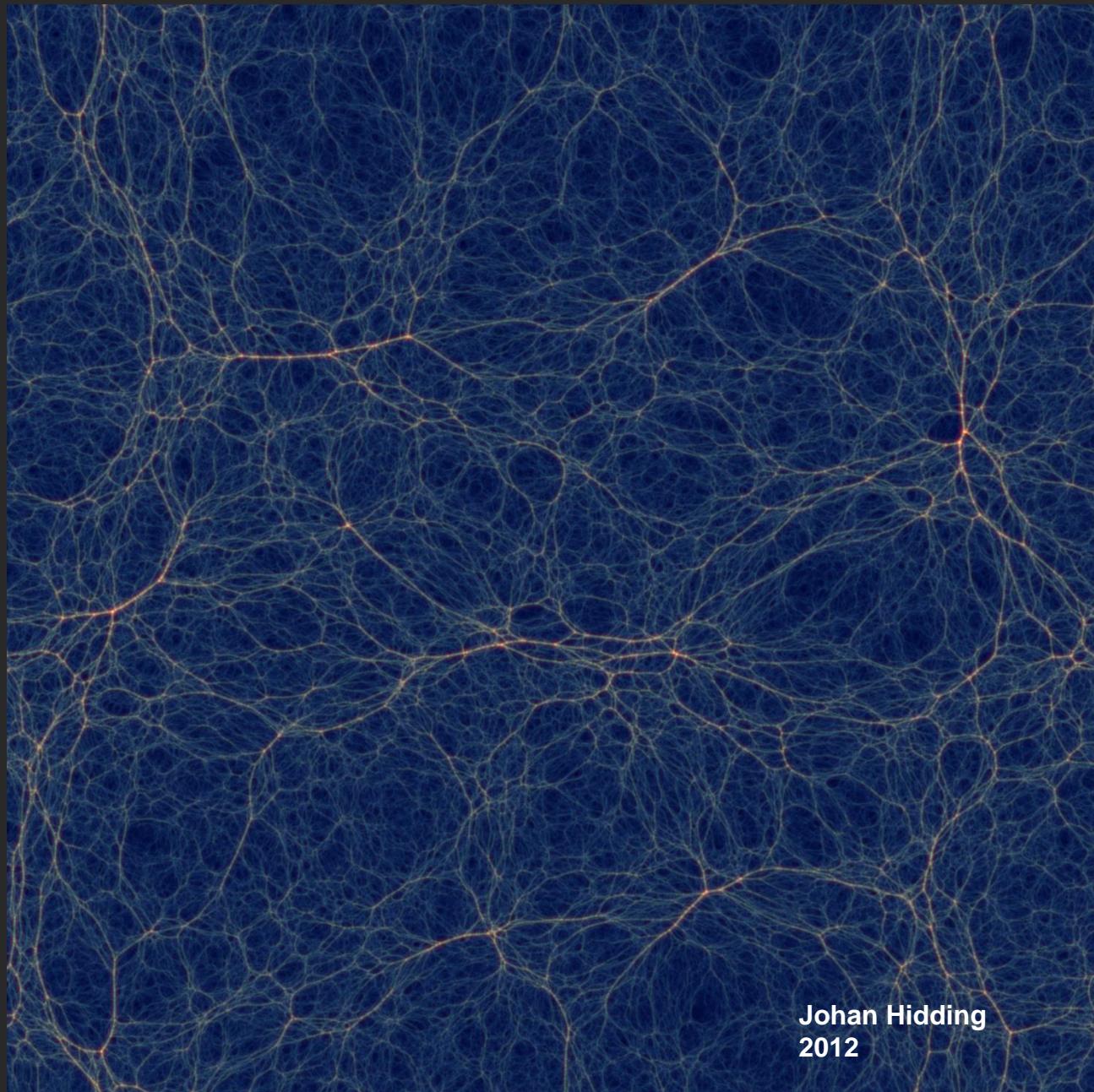
Substructure on  
every scale:

Amplitude  
diminishing at  
smaller scales

# Bootes Void: Substructure



Platen et al. 2009

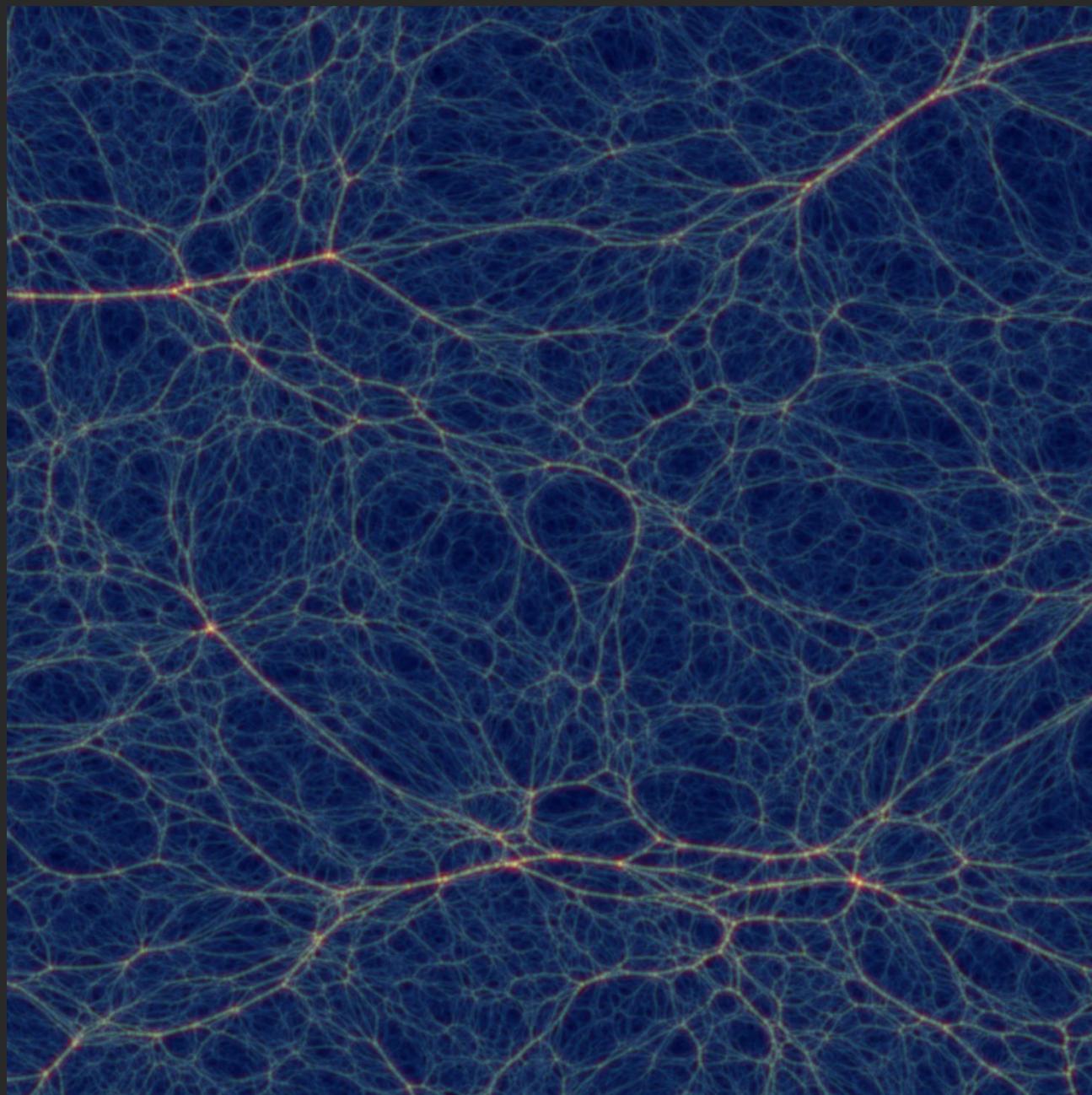


Johan Hidding  
2012

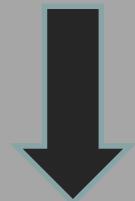
Multiscale  
Infrastructure  
Voids:



manifestation  
  
Hierarchical  
Buildup of  
Voids

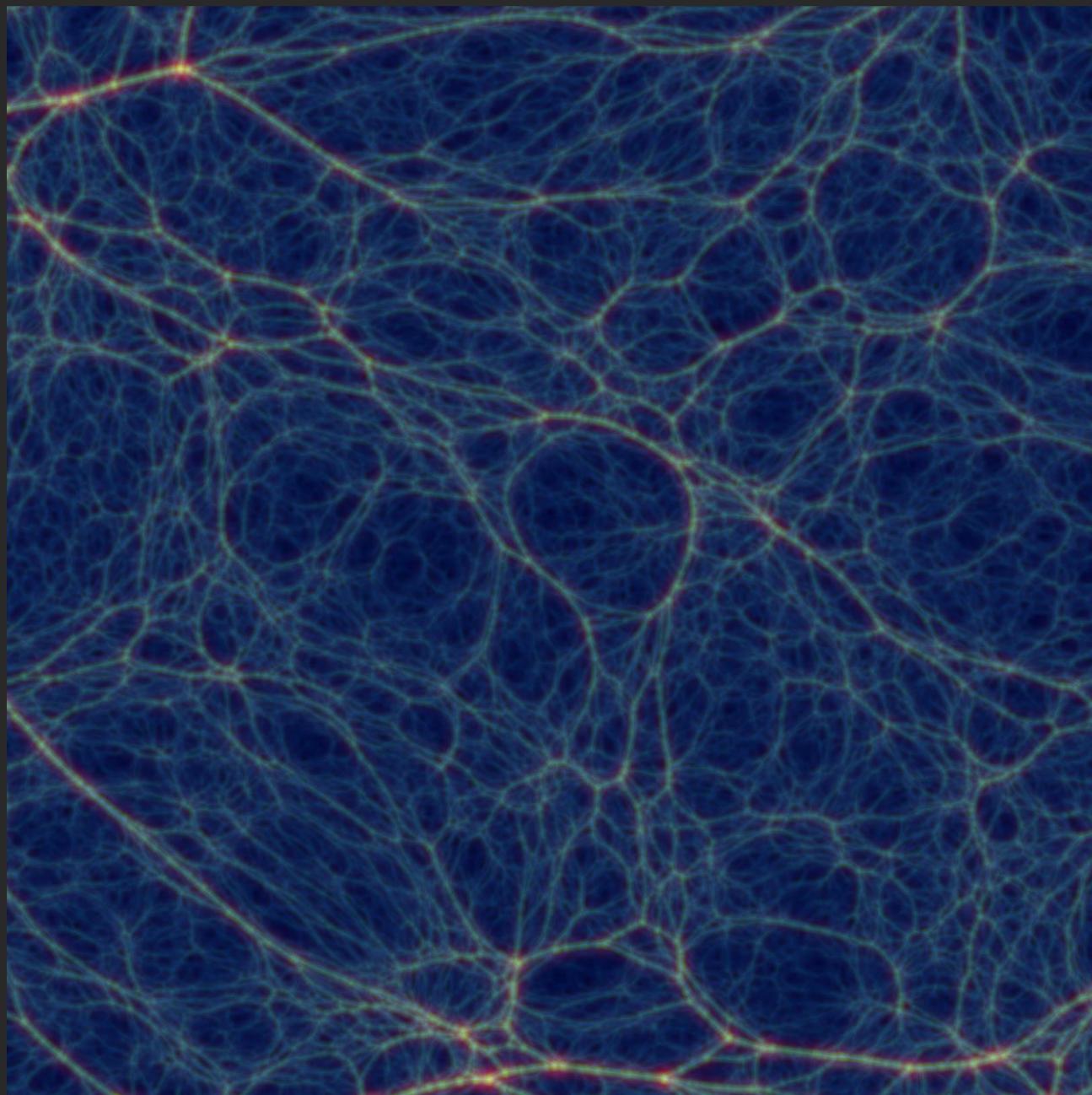


**Multiscale  
Infrastructure  
Voids:**



**manifestation**

**Hierarchical  
Buildup of  
Voids**

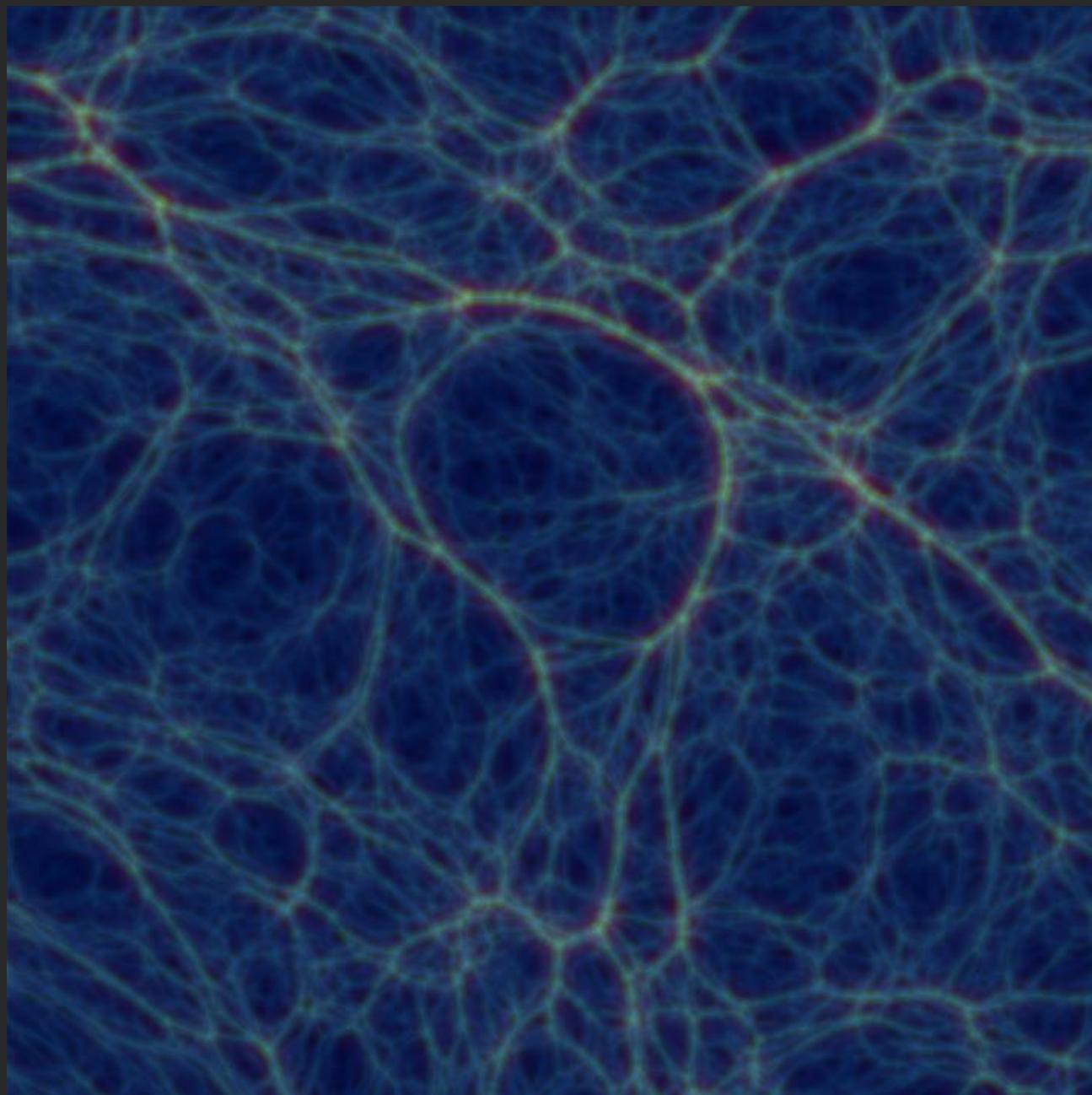


**Multiscale  
Infrastructure  
Voids:**



**manifestation**

**Hierarchical  
Buildup of  
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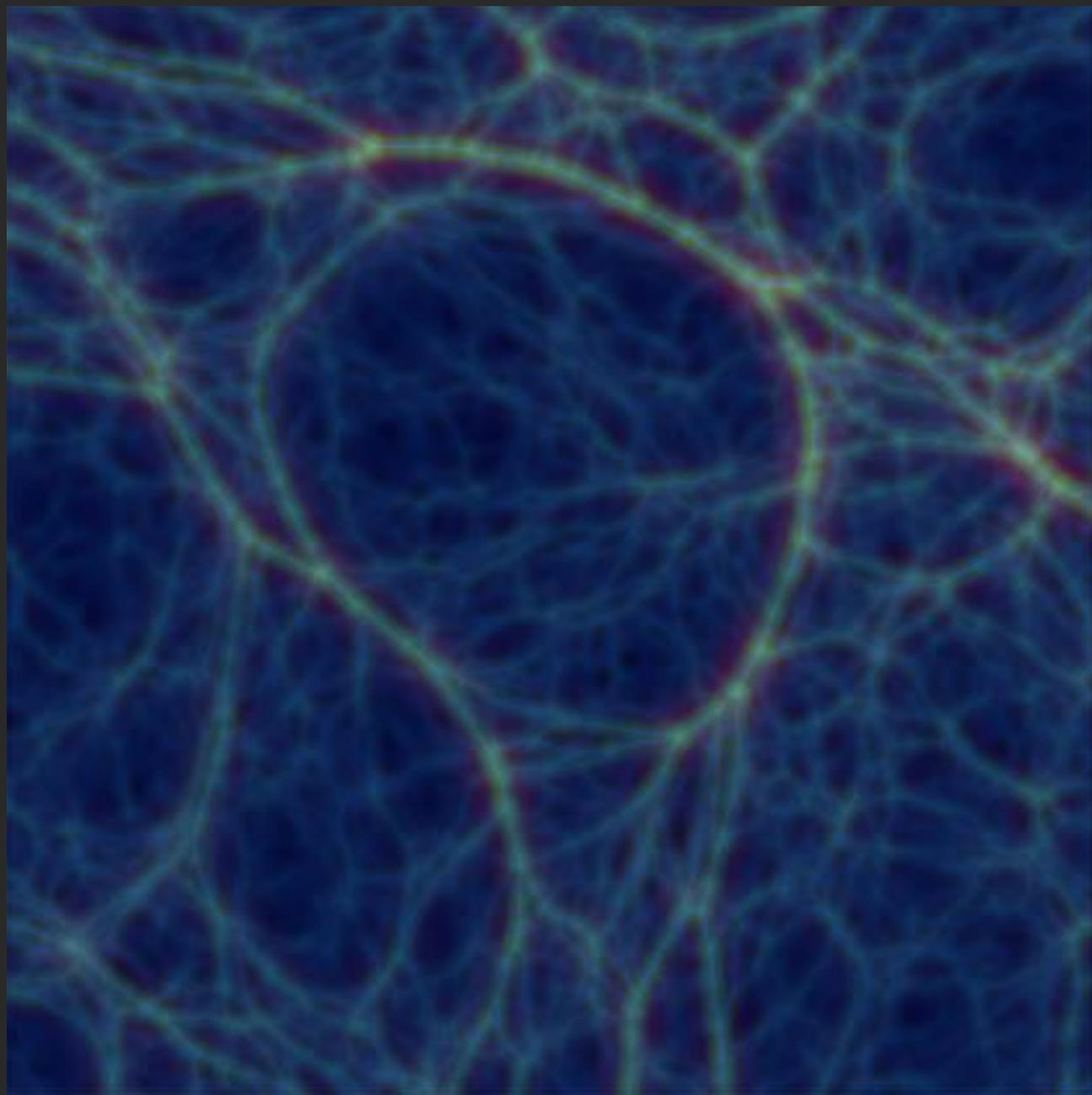


**Multiscale  
Infrastructure  
Voids:**



**manifestation**

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Buildup of  
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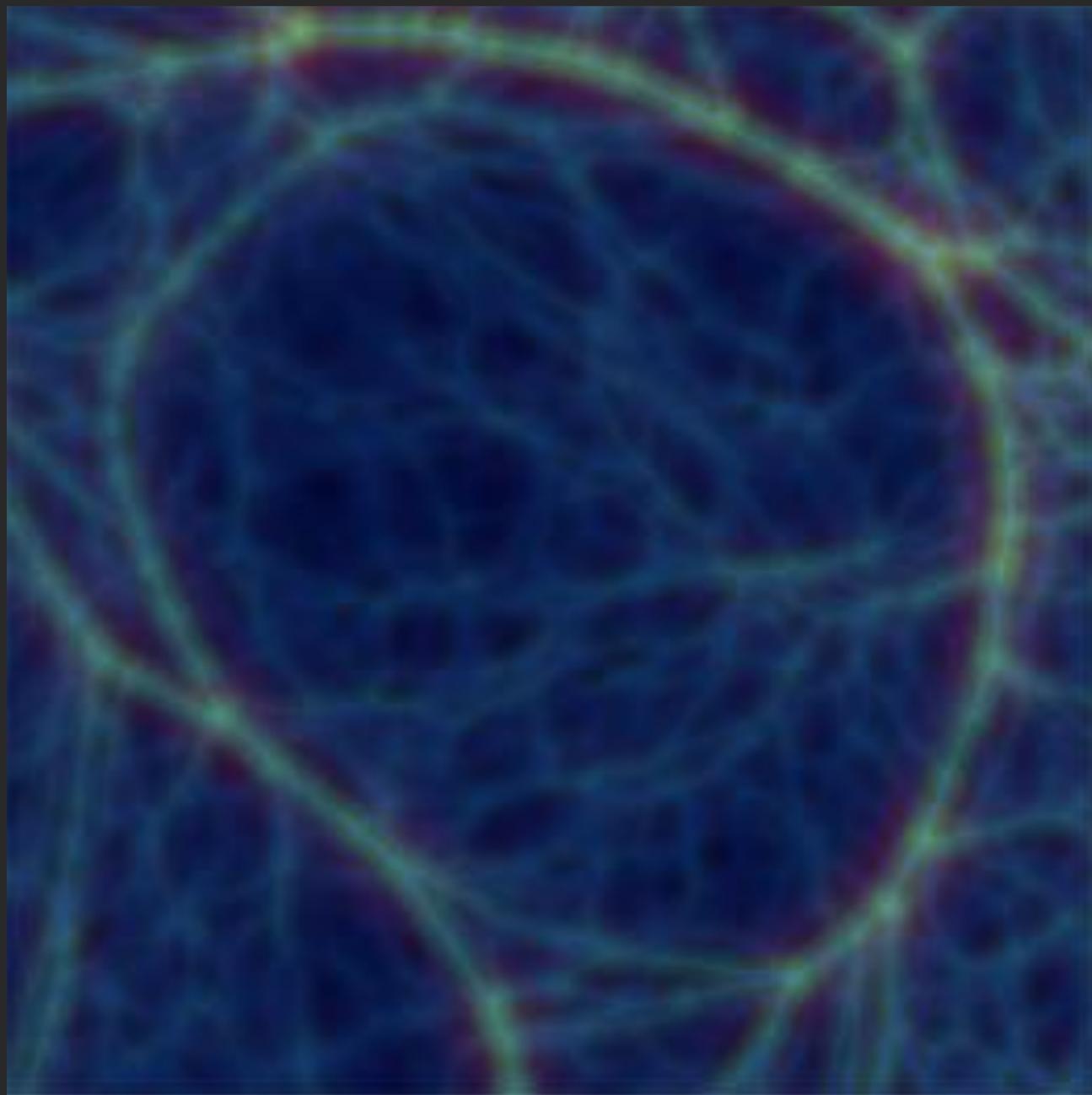


Multiscale  
Infrastructure  
Voids:

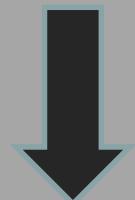


manifestation

Hierarchical  
Buildup of  
Voids

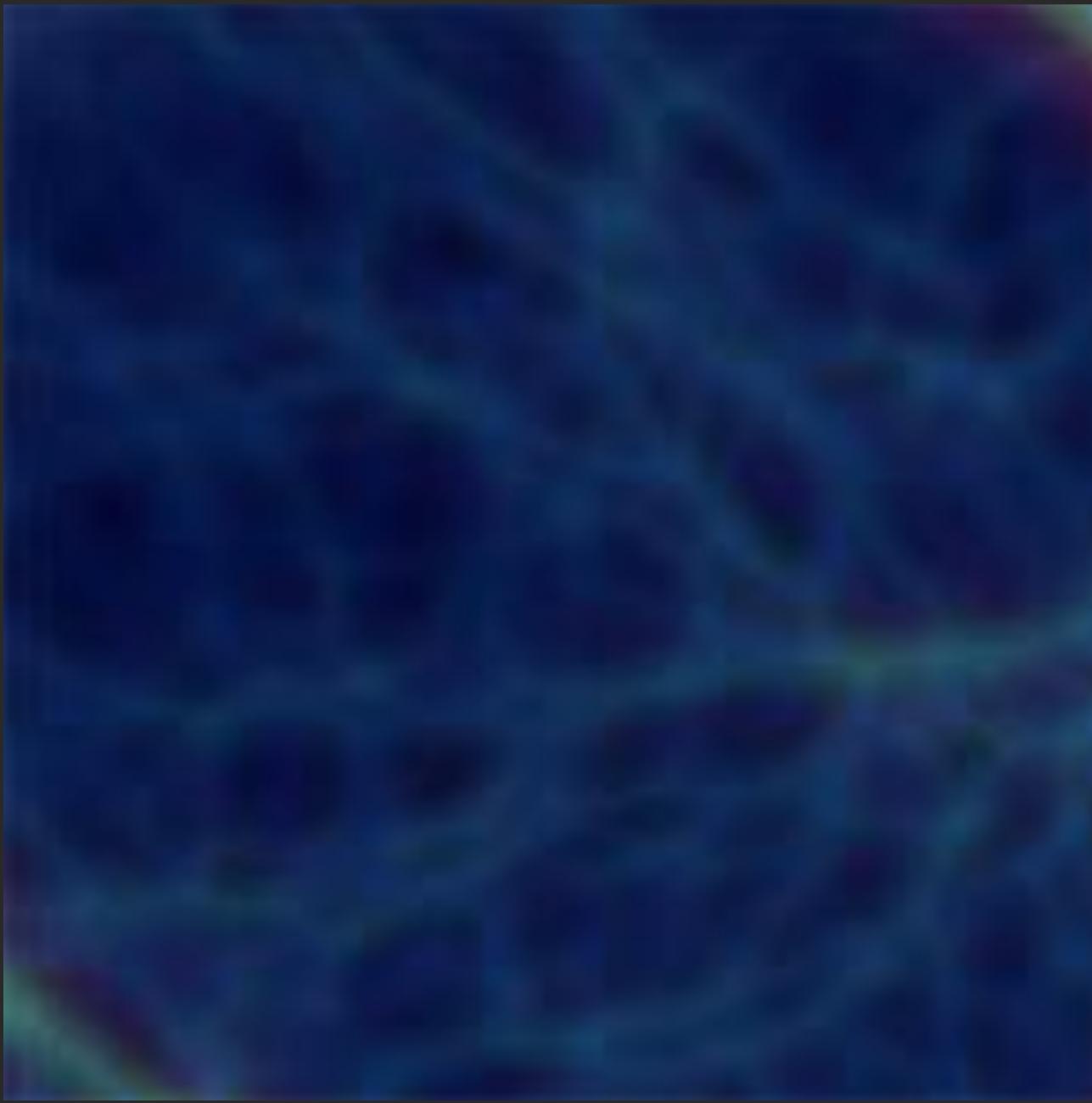


**Multiscale  
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**manifestation**

**Hierarchical  
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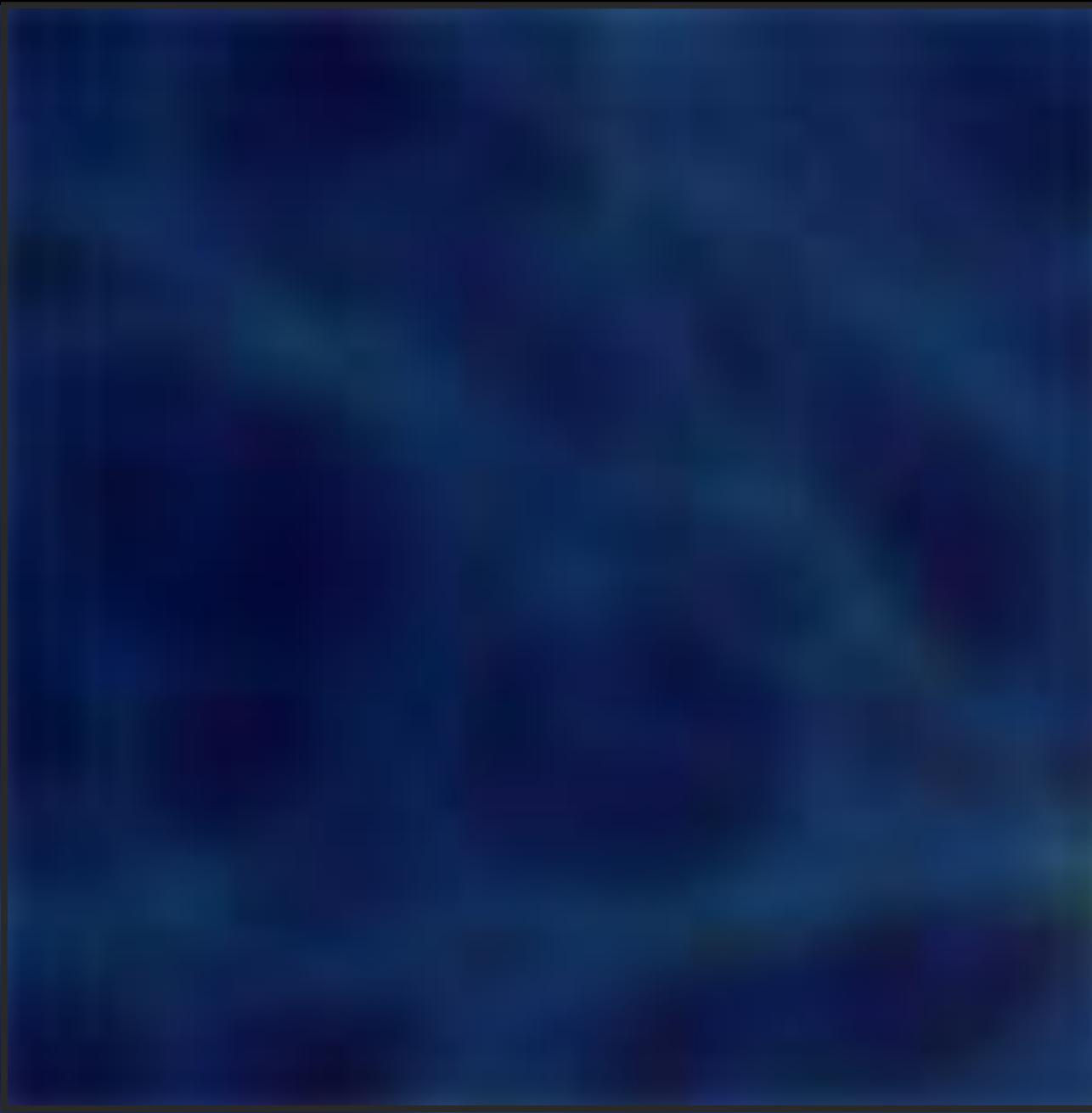


**Multiscale  
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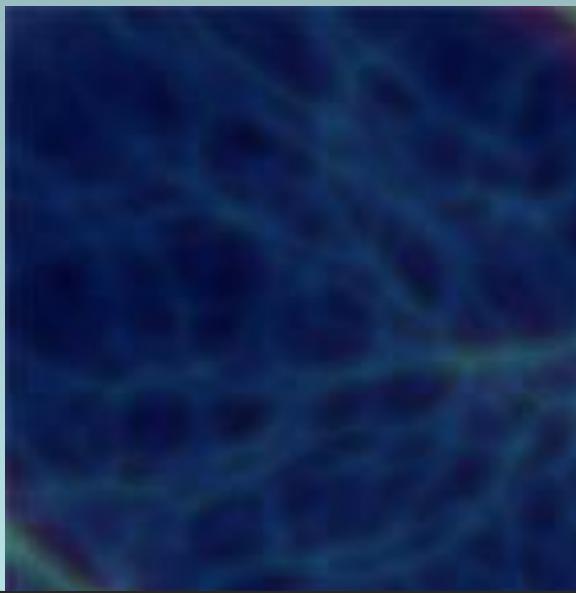
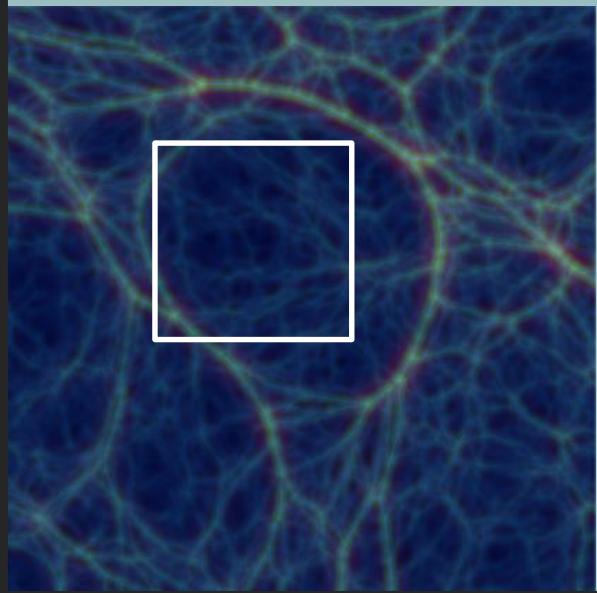
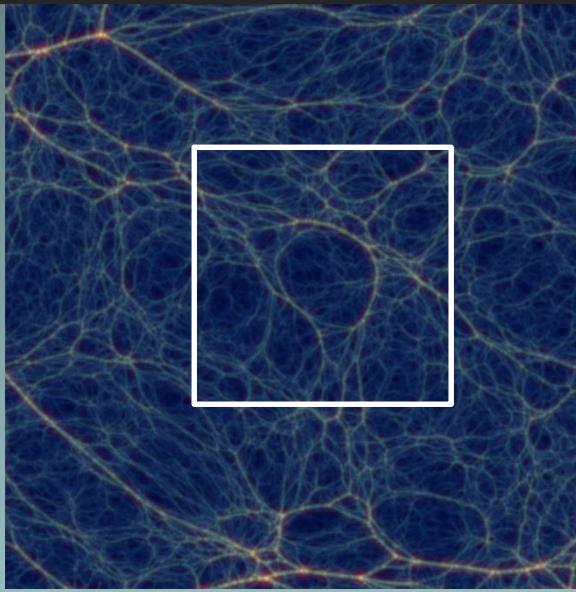
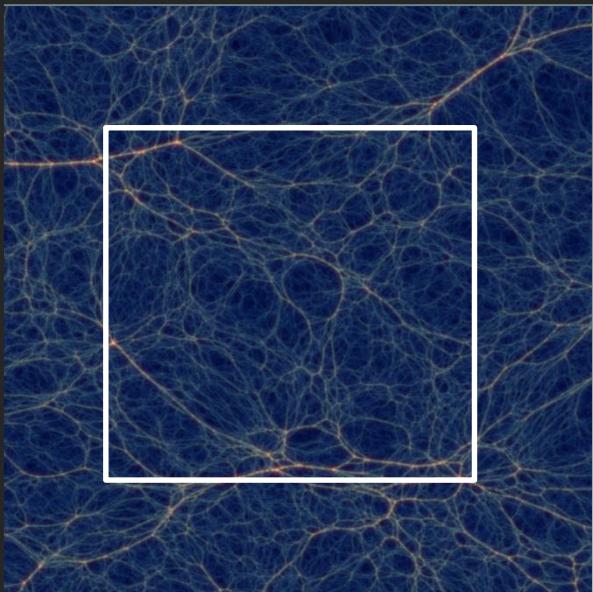
**Multiscale  
Infrastructure  
Voids:**



**manifestation**

**Hierarchical  
Buildup of  
Voids**

# Void Substructure

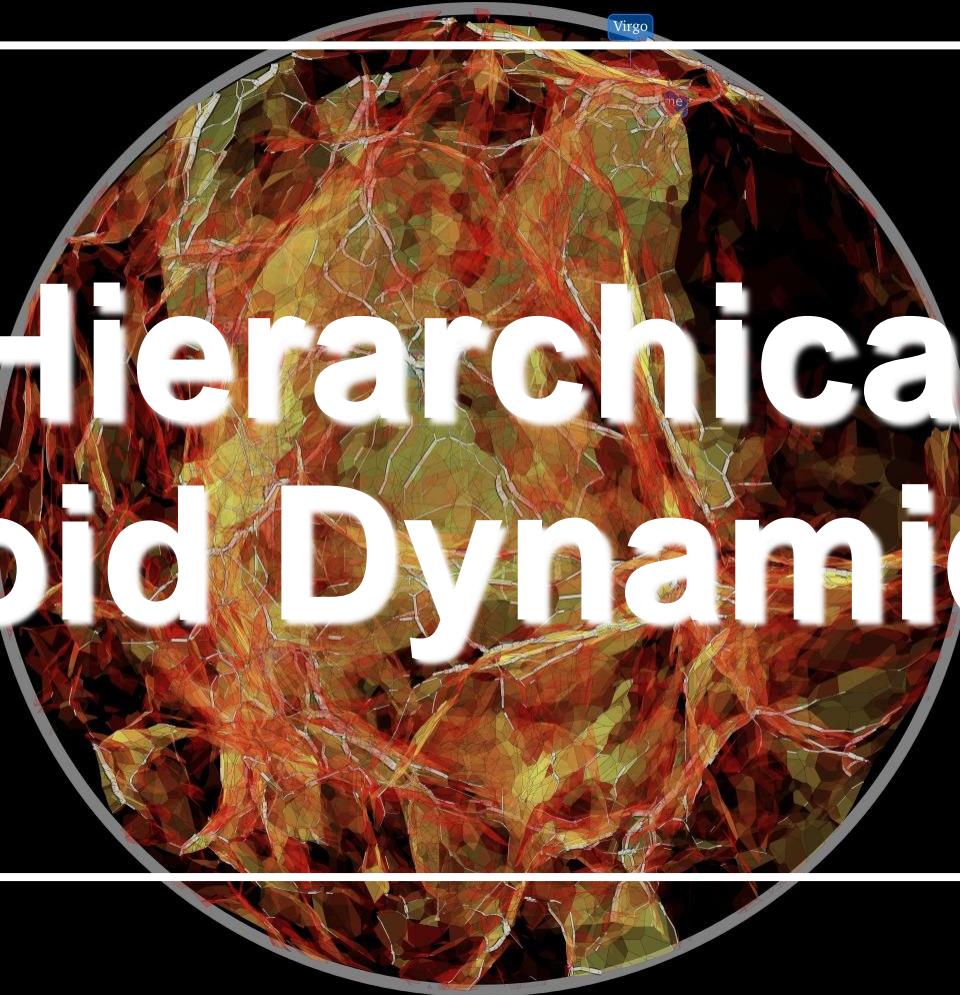


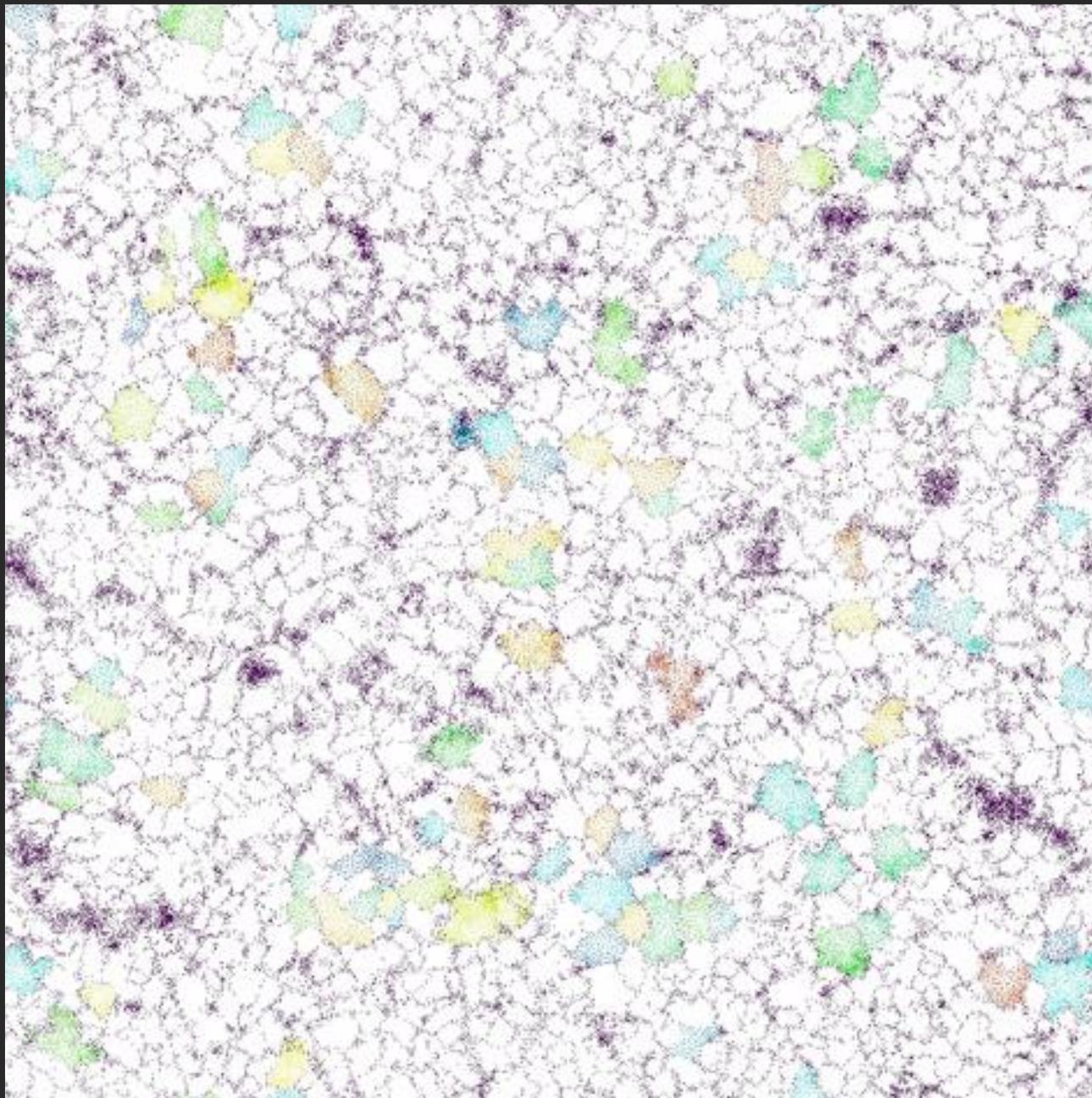
Zoom in: 3 levels

Substructure on  
all scales:

amplitude  
diminishing towards  
smaller scales

# Hierarchical Void Dynamics





## Hierarchical Web Evolution:

“Lagrangian” view:  
development and fate  
patterns LSS

Platen & vdW 2004

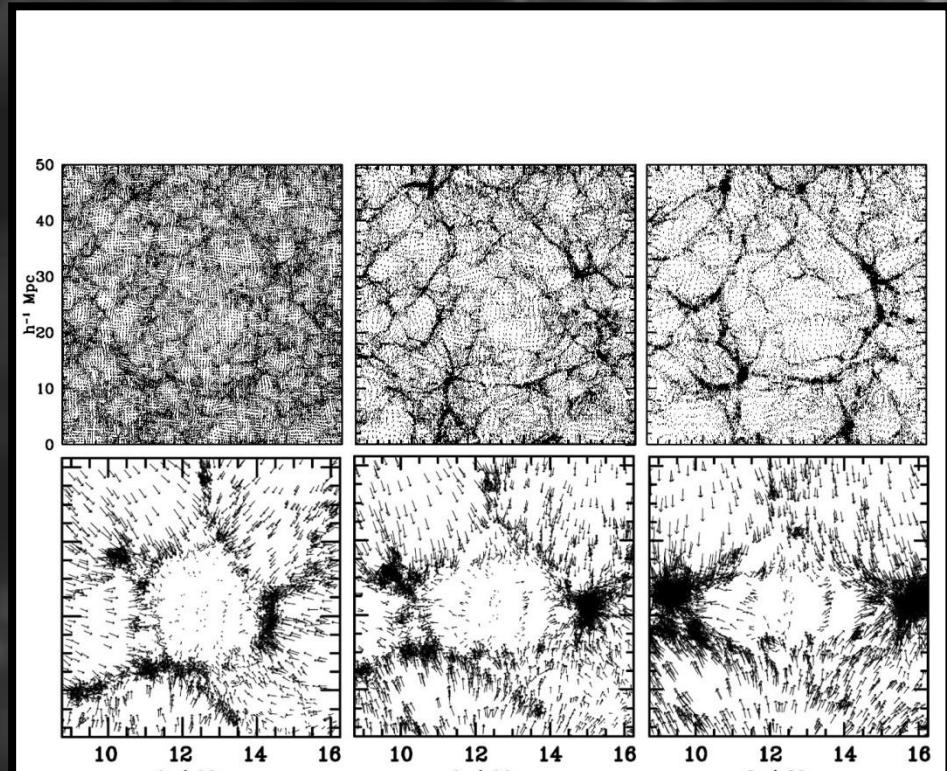
# Void Evolution Processes

- **Void Merging**

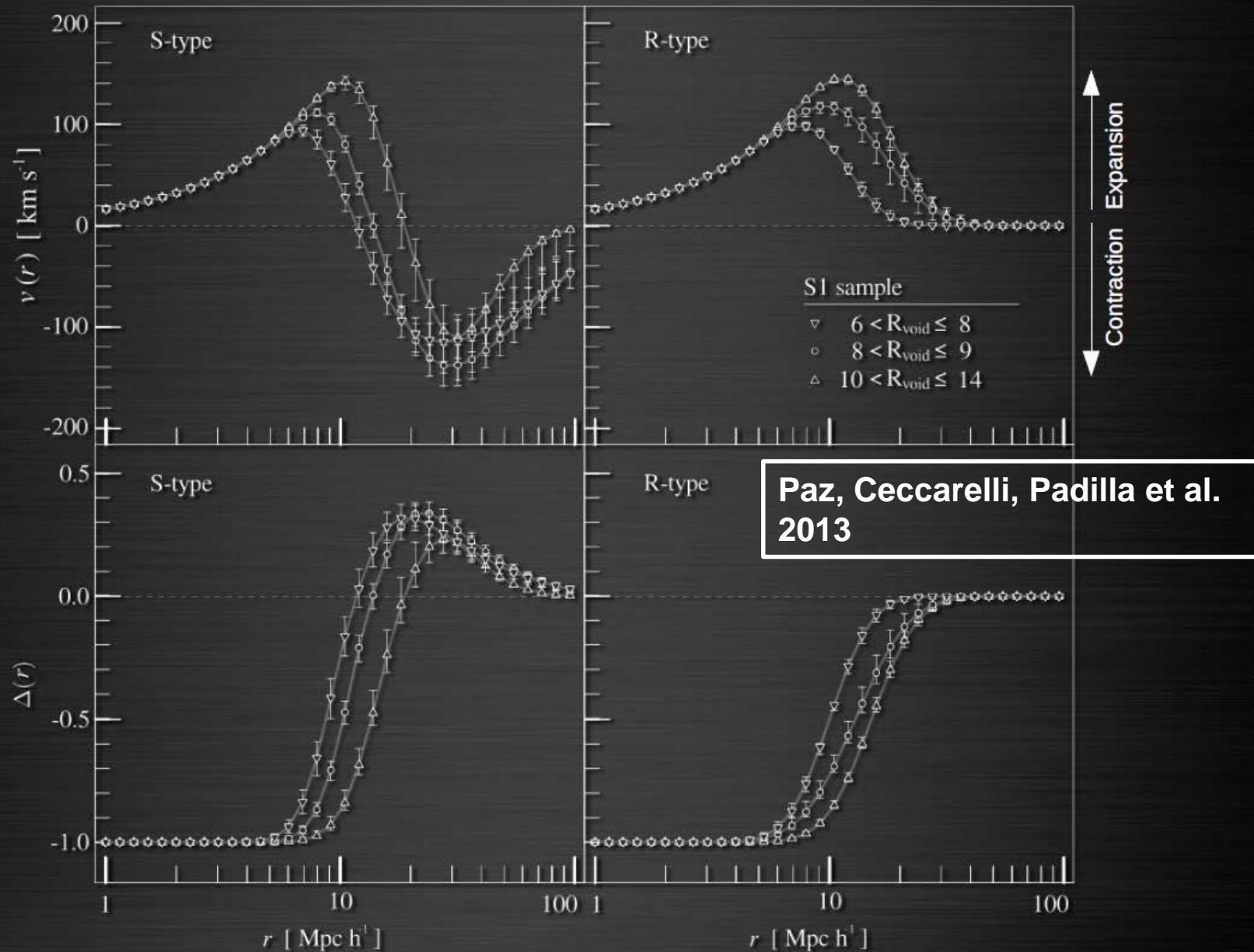
as voids expand and meet their peers, they merge into ever larger voids ...

- **Void Collapse**

when embedded within an overdense or tidally sheared region (filaments ...), weak voids get squeezed out of existence...



# SDSS voids recovered velocity and density profiles

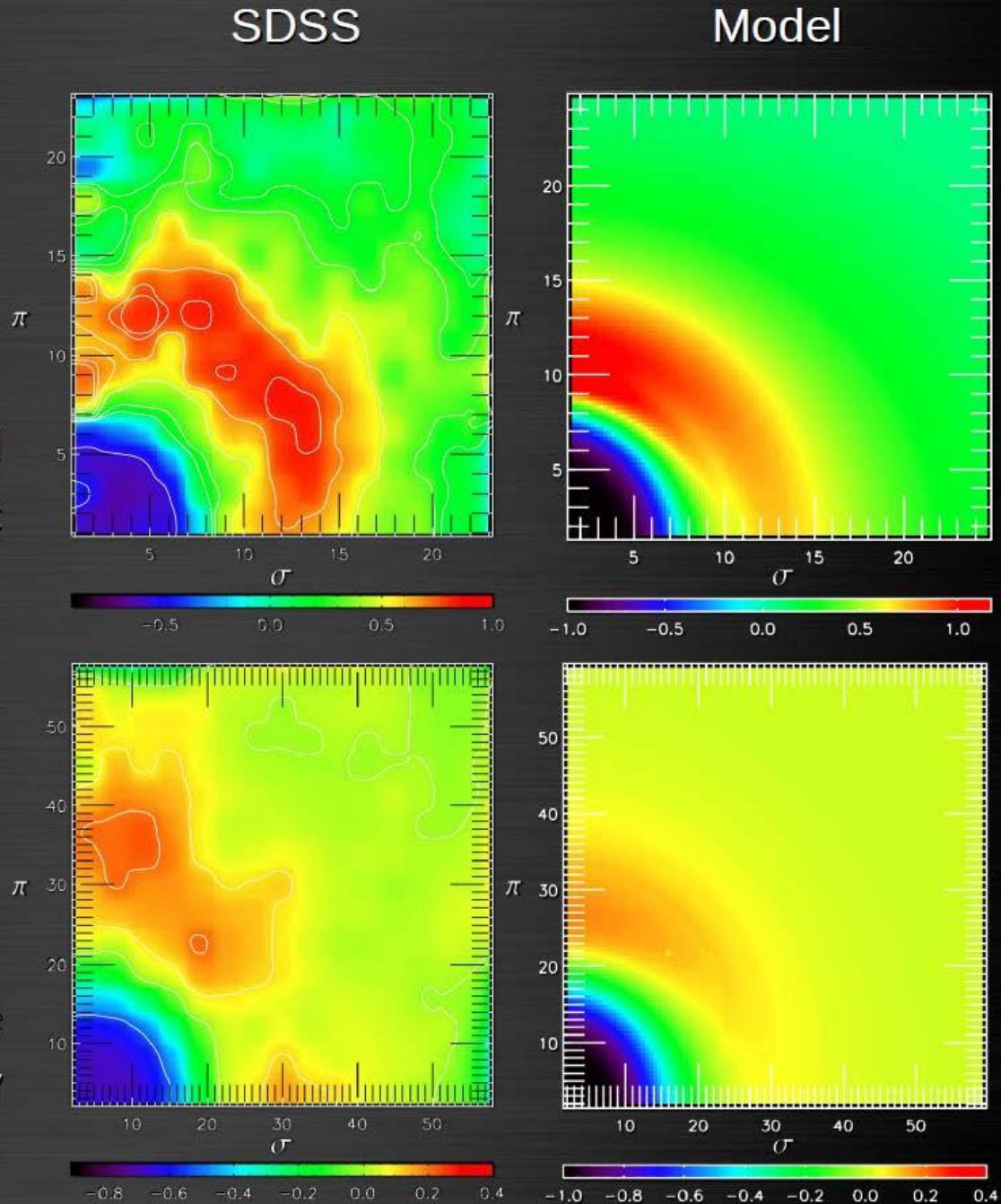


# SDSS void-galaxy correlations $\xi(\sigma, \pi)$

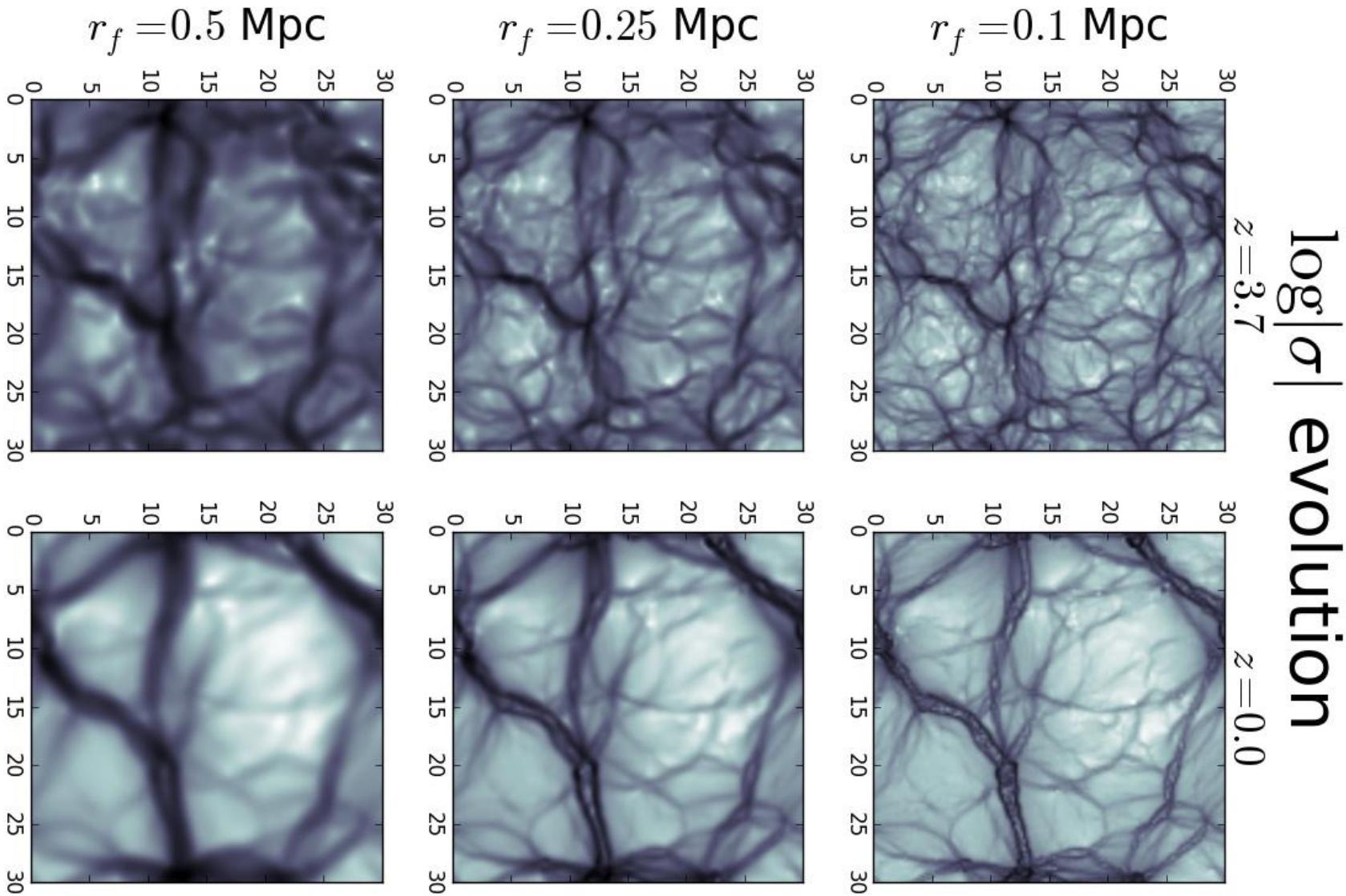
Paz, Ceccarelli, Padilla et al.  
2013

Volume Limited Sample  
 $M_r < -20.3$   
330 voids  $Z < 0.12$

Small  
V-in-C

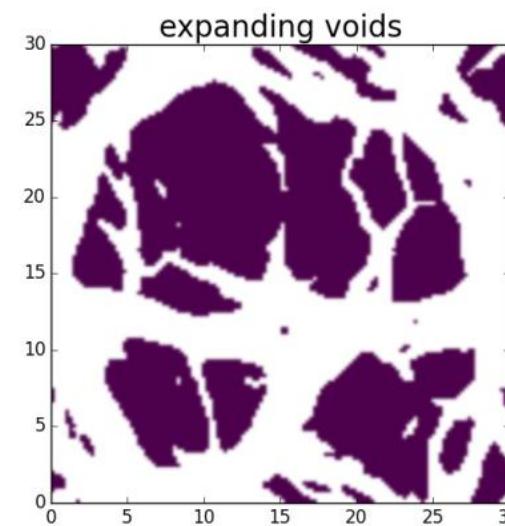
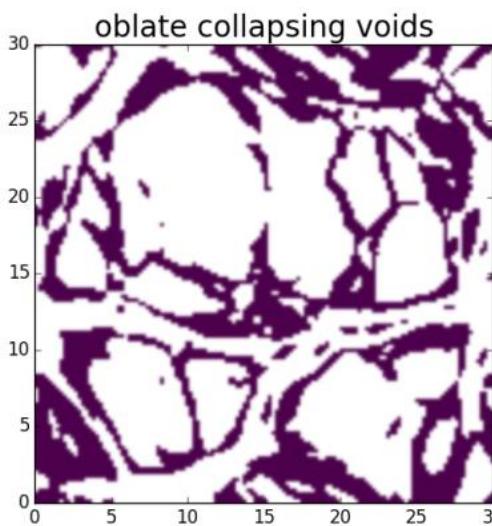
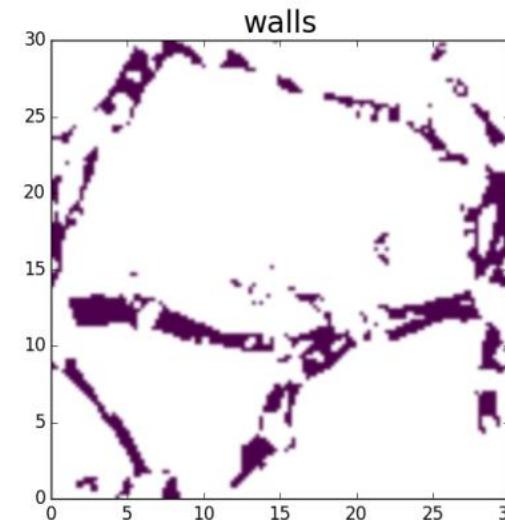
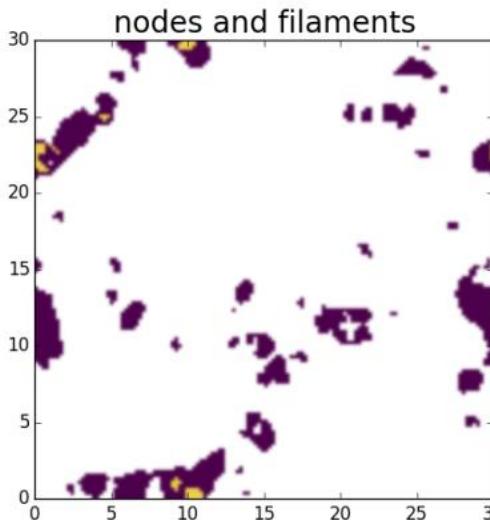


# Voids & Shearing Boundaries

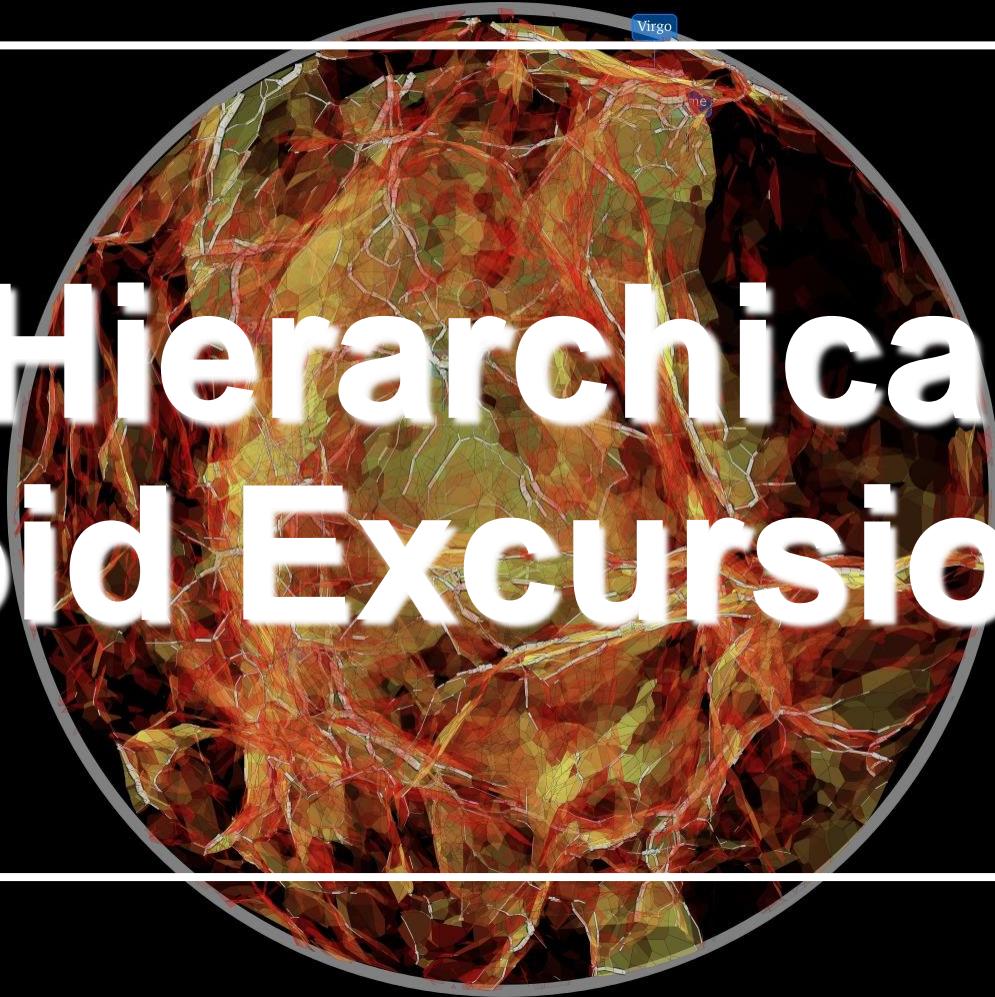


# Voids & Shearing Boundaries

web decomposition  $z=0.0$   $r_f=.25$



# Hierarchical Void Excursions



# Extended Press-Schechter

## Barrier Excursions

- Spherical linear collapse overdensity:

$$\Delta_{lin}(r, S_m, t) > \delta_c$$

- Collapse time:

$$a_{coll}(r) = \delta_c / \Delta_{lin}(r, S_m)$$

- Initial density field:

prediction object formation time:

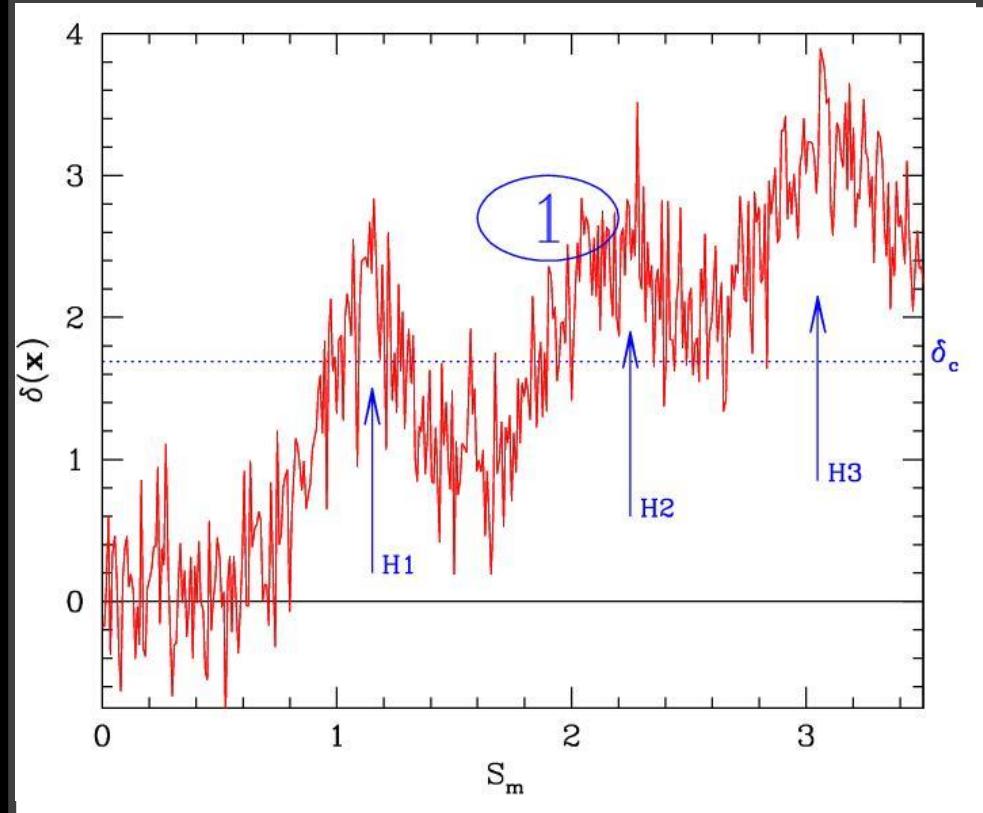
$$a_{coll}(r) \Leftrightarrow \Delta_{lin,0}(r, S_m)$$

dependent on:

Collapse Barrier  $\square_c$

- Critical density value:

$$\text{EdS , } \Omega_0=1: \quad \delta_c \sim 1.69$$



cumulative random walk:

$$\delta_s(\vec{x}; \lambda_m) = \int_{|k| < k_m} \frac{d\vec{k}}{(2\pi)^3} \hat{\delta}(\vec{k}) e^{-i\vec{k} \cdot \vec{x}}$$

# Extended Press-Schechter

## Barrier Excursions

- Spherical linear collapse overdensity:

$$\Delta_{lin}(r, S_m, t) > \delta_c$$

- Collapse time:

$$a_{coll}(r) = \delta_c / \Delta_{lin}(r, S_m)$$

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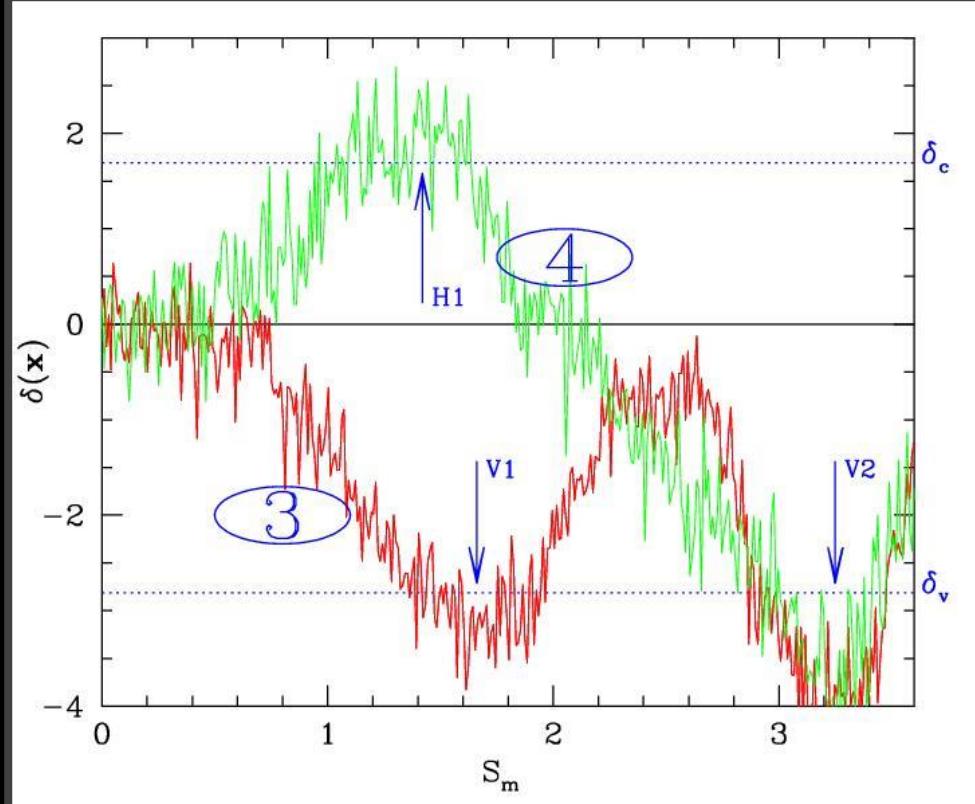
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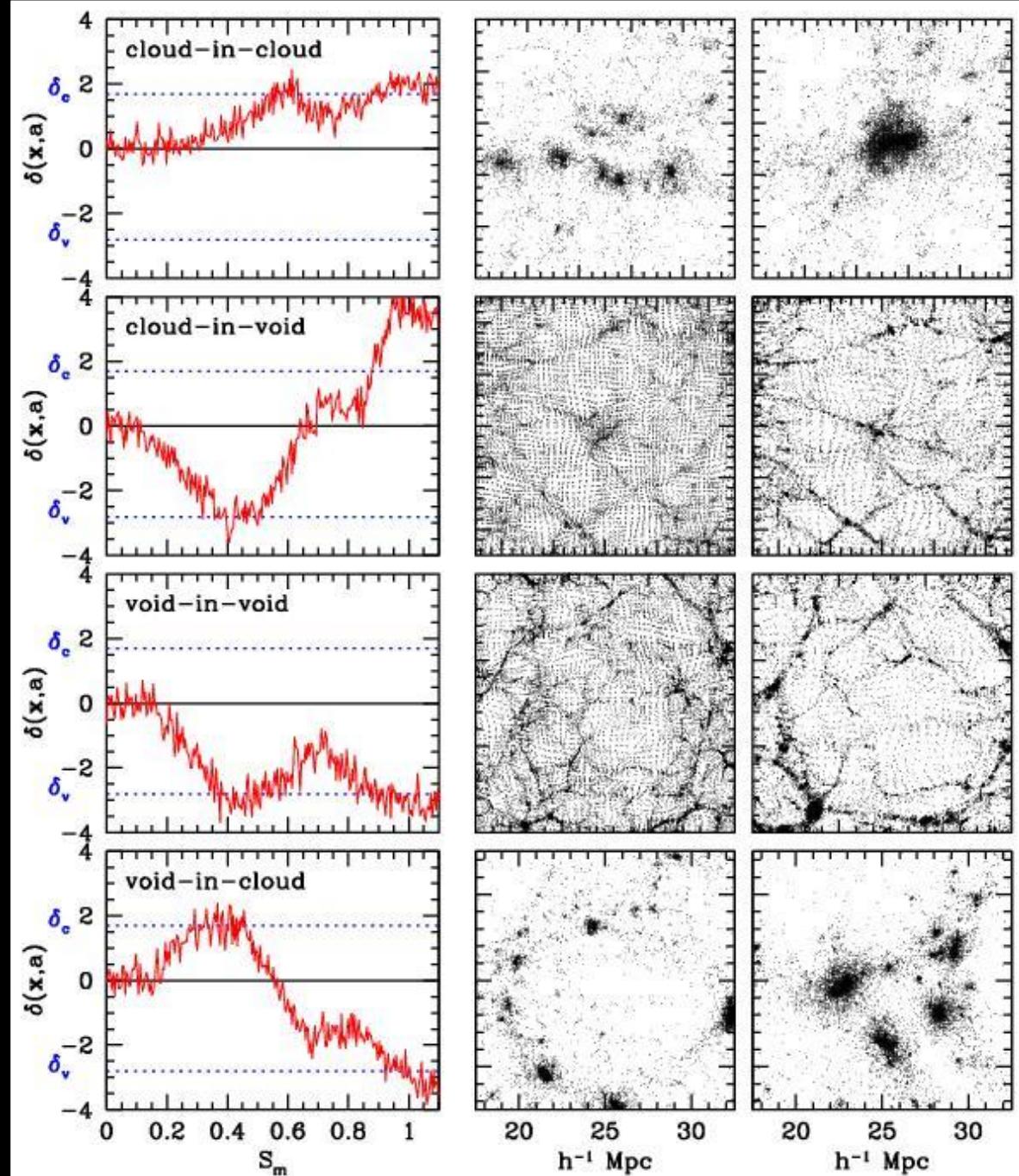
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# Hierarchical Cosmic Structure Formation

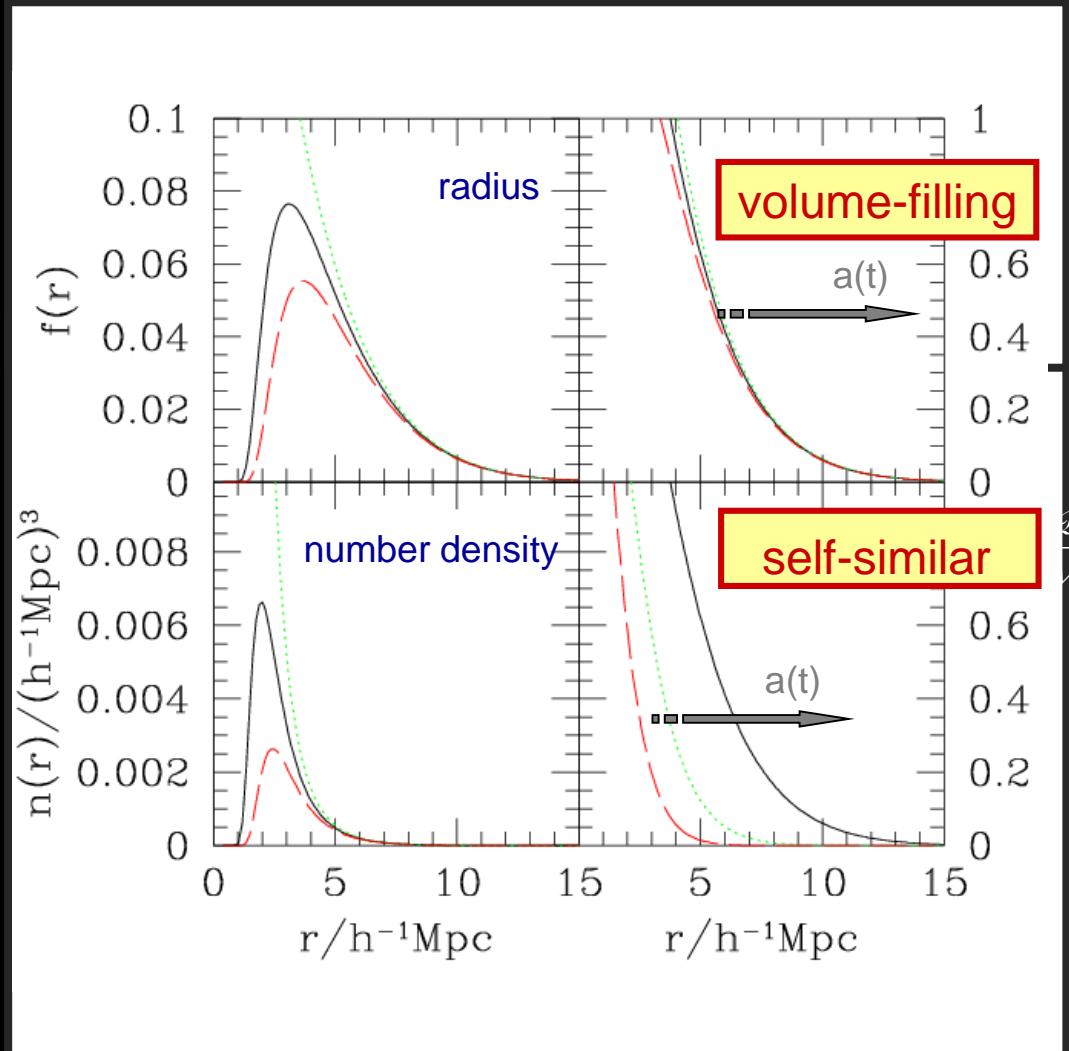
## Excursion Modes:

- Cloud-in-Cloud
- Cloud-in-Void
- Void-in-Void
- Void-in-Cloud



# Void Volume Distribution

- Small Void tail suppressed
- Peaked Void Size Distribution  
Characteristic Void Size
- Self-Similar Evolution:  
increasing  
characteristic Void Size
- Volume-filling:  
at any cosmic epoch,  
for power-law  $P(k)$ ,  
approximately void-filling
- Excess Void Expansion:  
“Super-Hubble” expansion



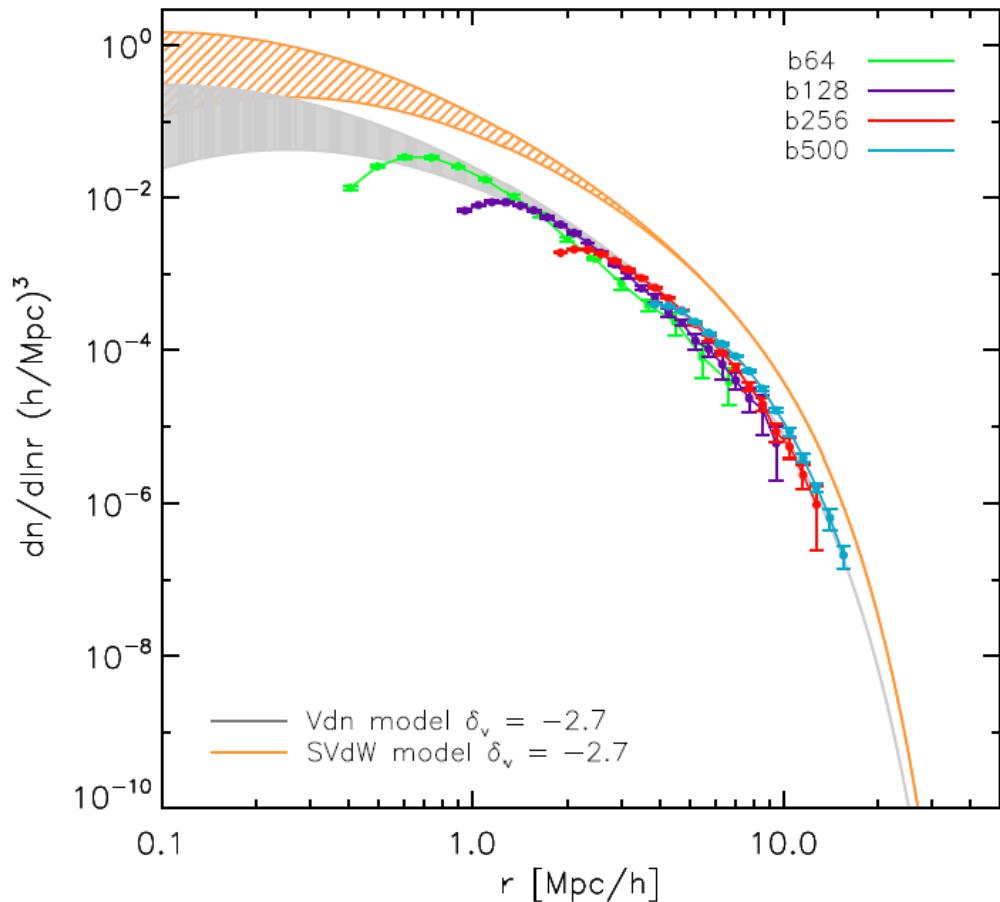
# Void Population & Excursions

Jennings et al. 2013

Two-barrier SvdW  
void excursion set formalism:

correcting simple assumption  
 $\square_v$  criterion:

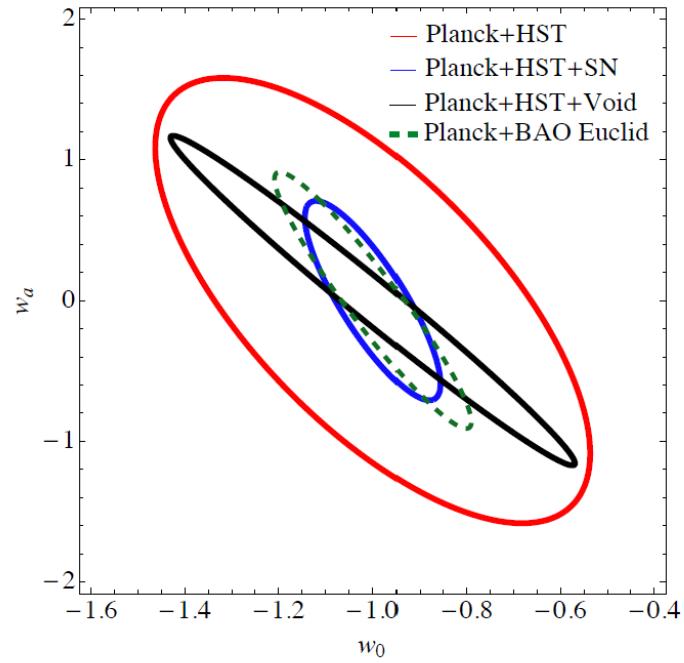
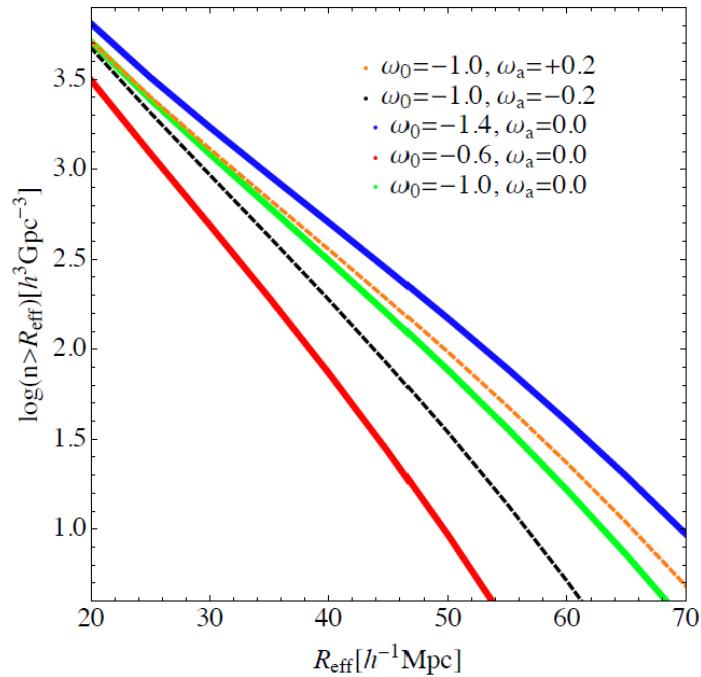
Jennings et al. 2013:  
void volume occupation constraints



# Void Abundance & Cosmology

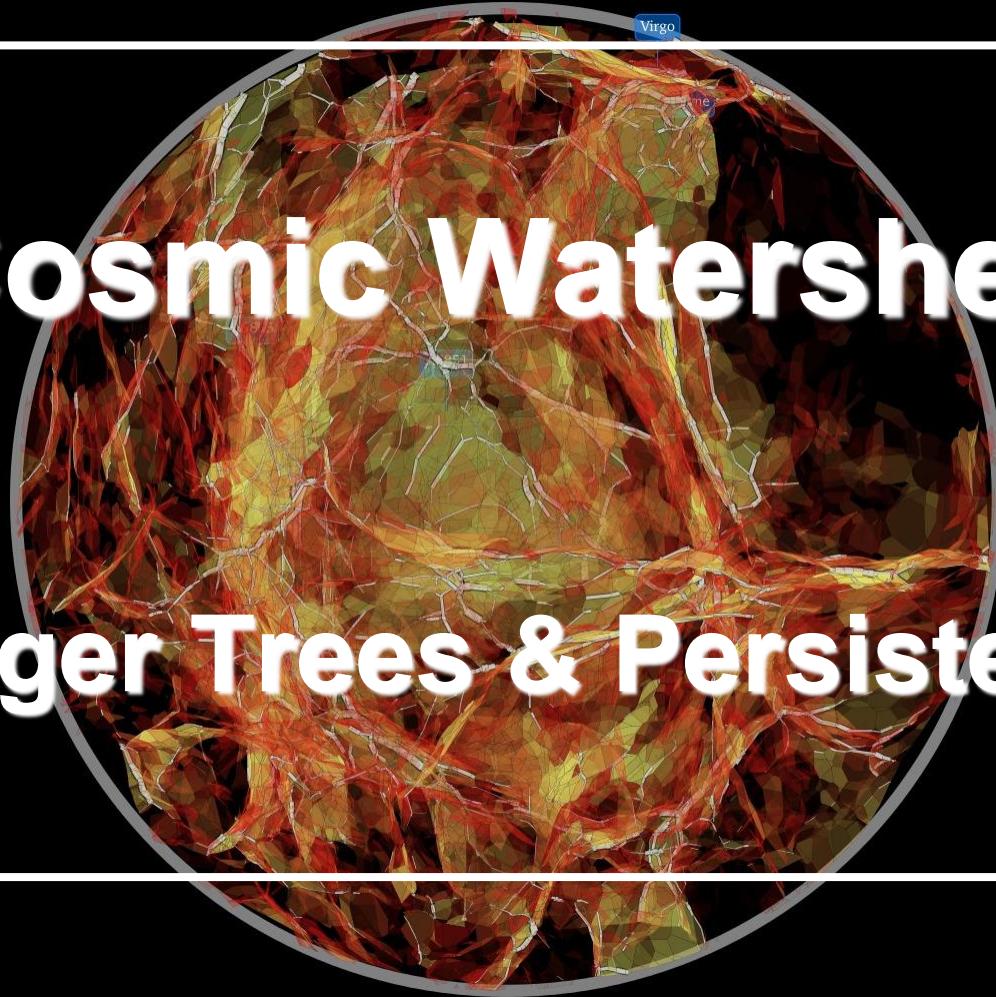
Pisani, Wandelt et al. 2015:

- Void abundances accurate measure for cosmological parameter estimation
- Estimates based on SvdW two-barrier model, calibrated by simulations

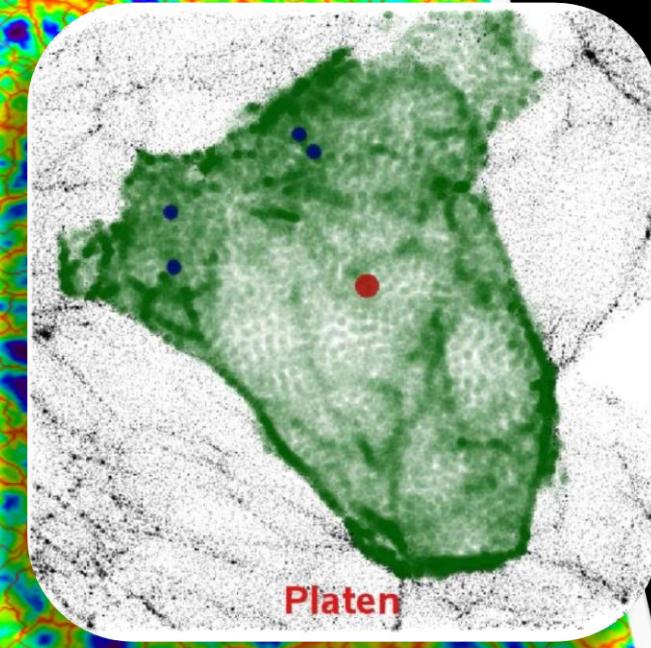
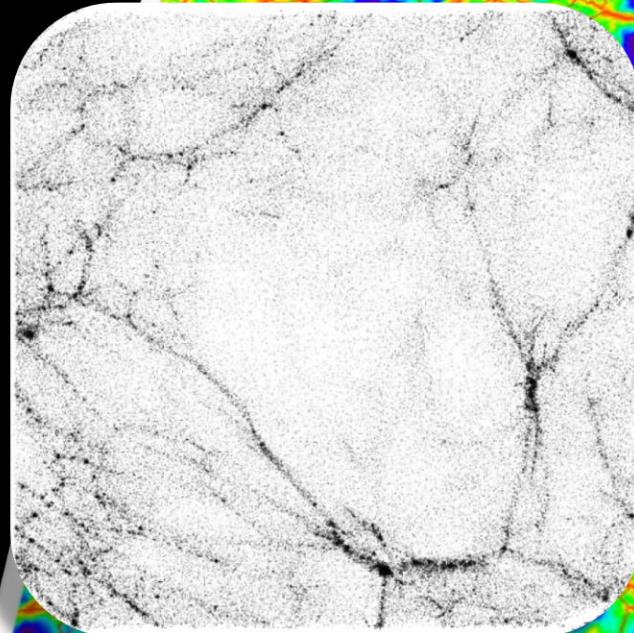
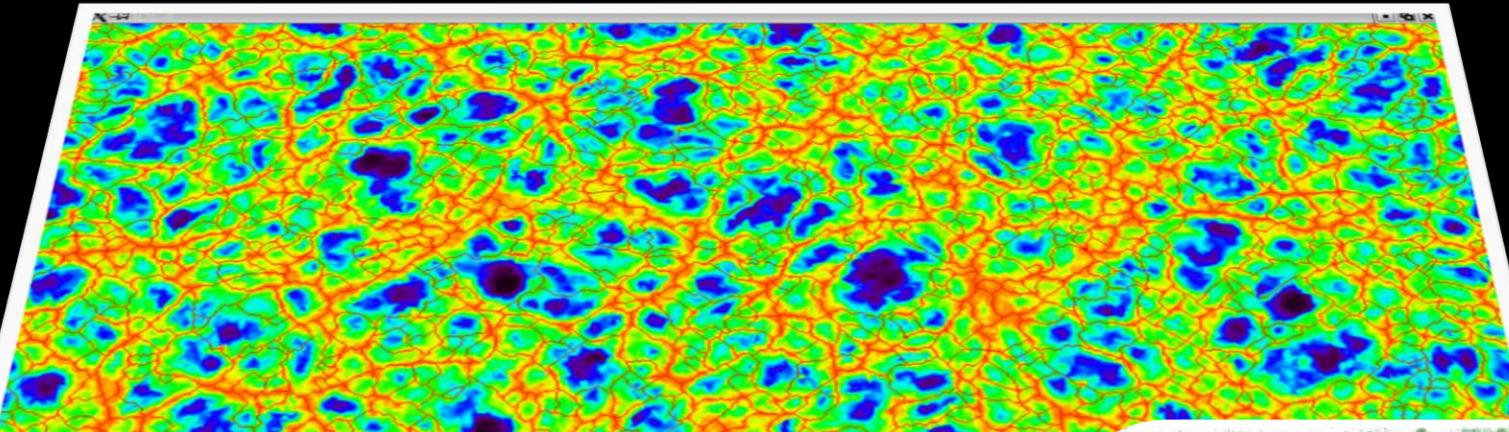


# Cosmic Watershed

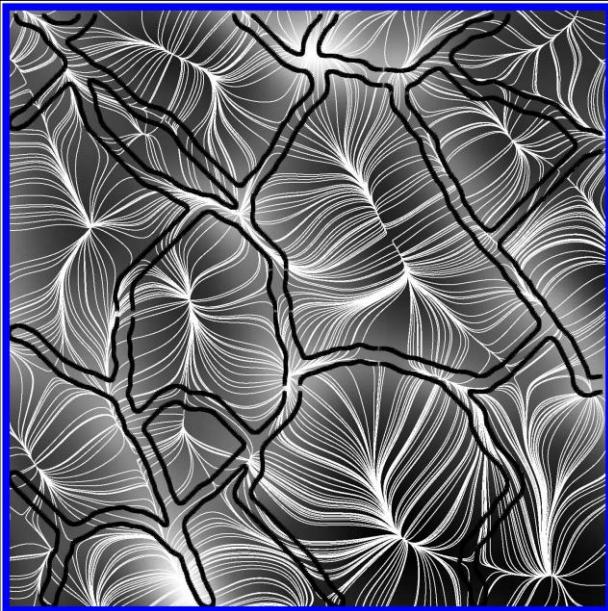
## Merger Trees & Persistence



# Watershed Void Identification



# Morse Complex

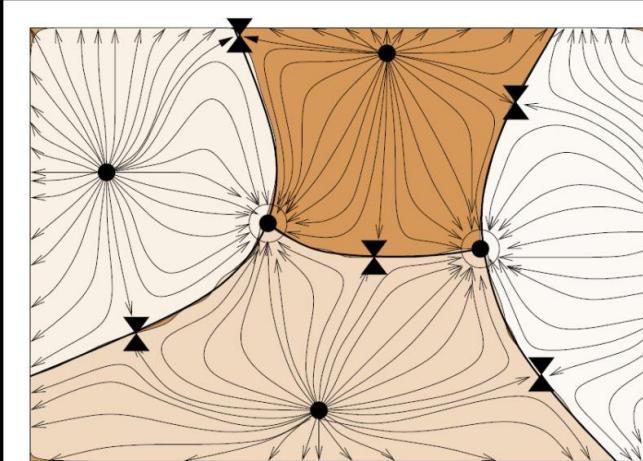


Topological structure well-behaved  $C^2$  field:

- singularities  $\vec{\nabla}f$  minima, maxima, saddles
- “flow” field
- critical integral lines: connection singularities
- saddles-maxima: spine of field
- basin minima: voids

Practical Computation:

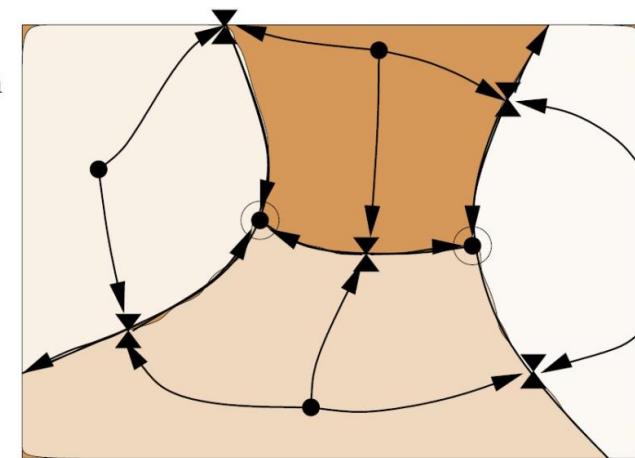
- Watershed Transform



● Maximum

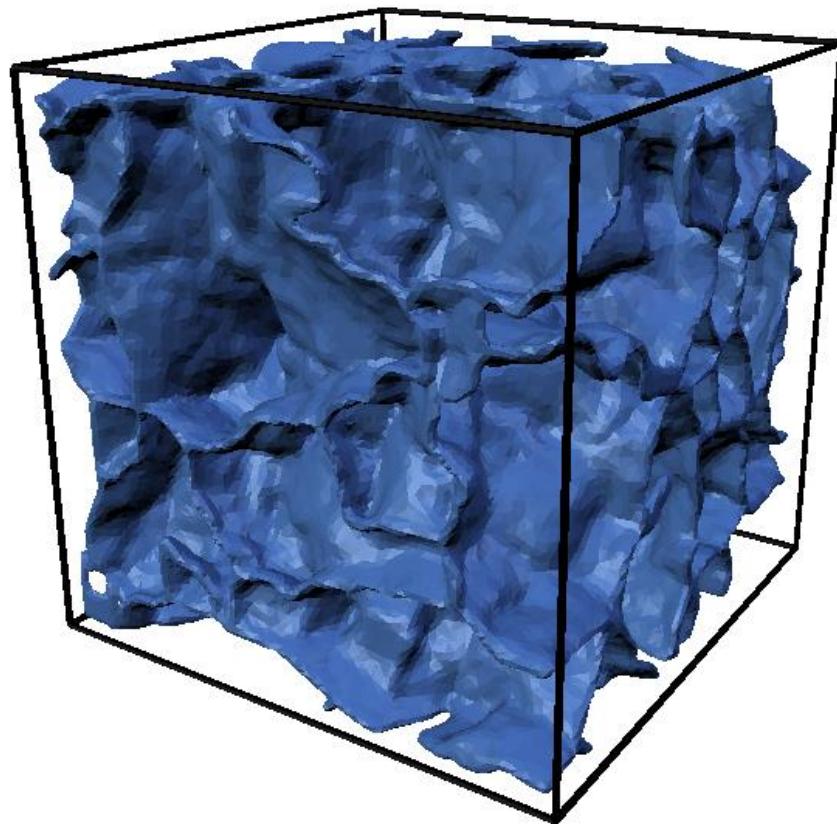
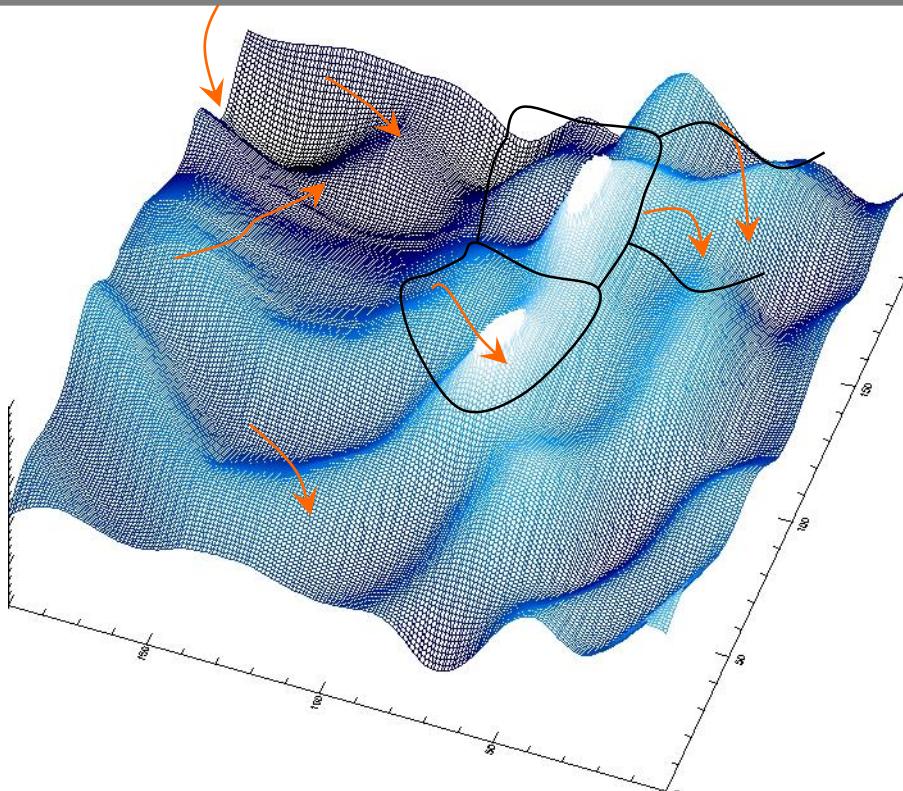
▲ Saddle

● Minimum



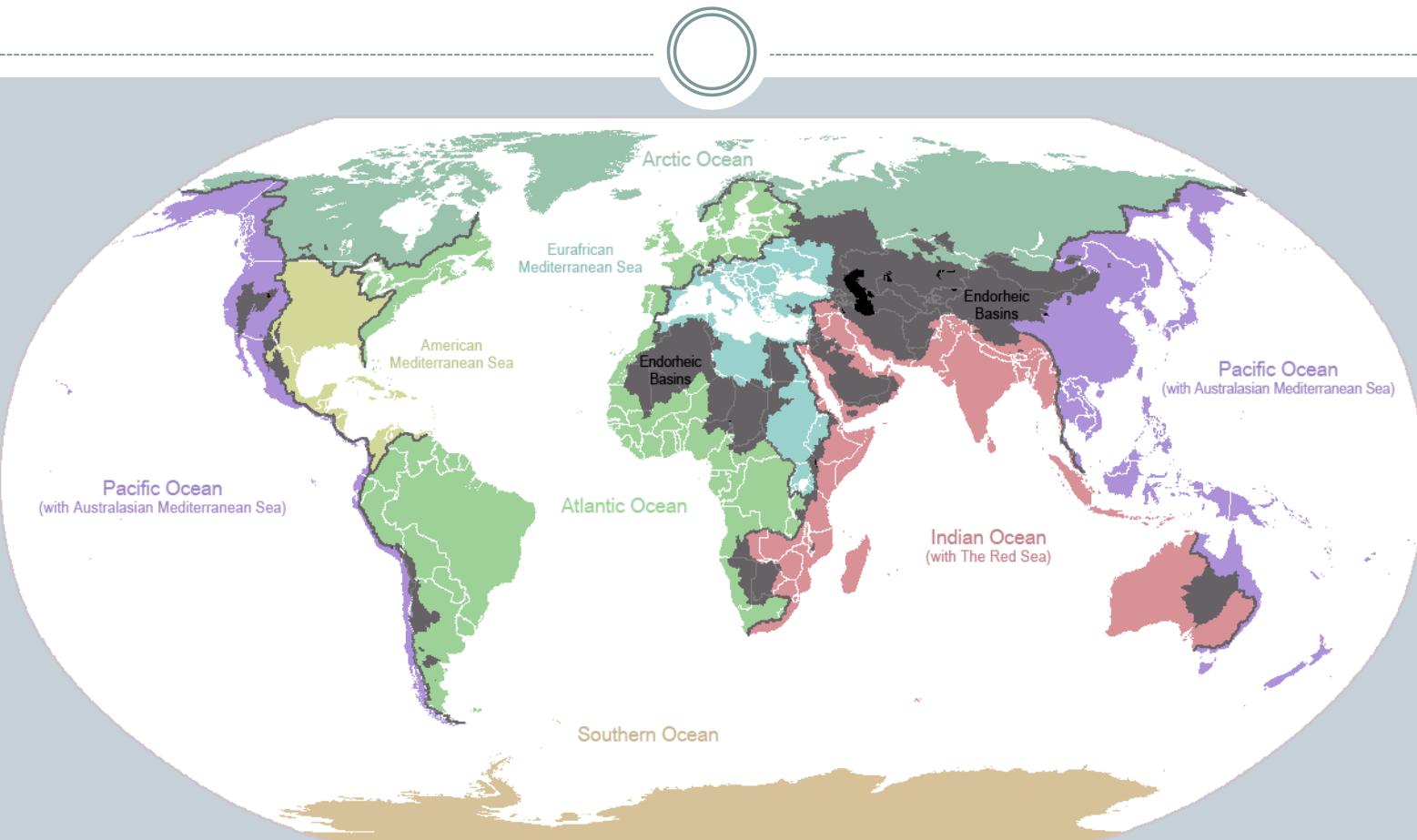
# Watershed Void Transform

Following the water flow into the distinct catchment basins.



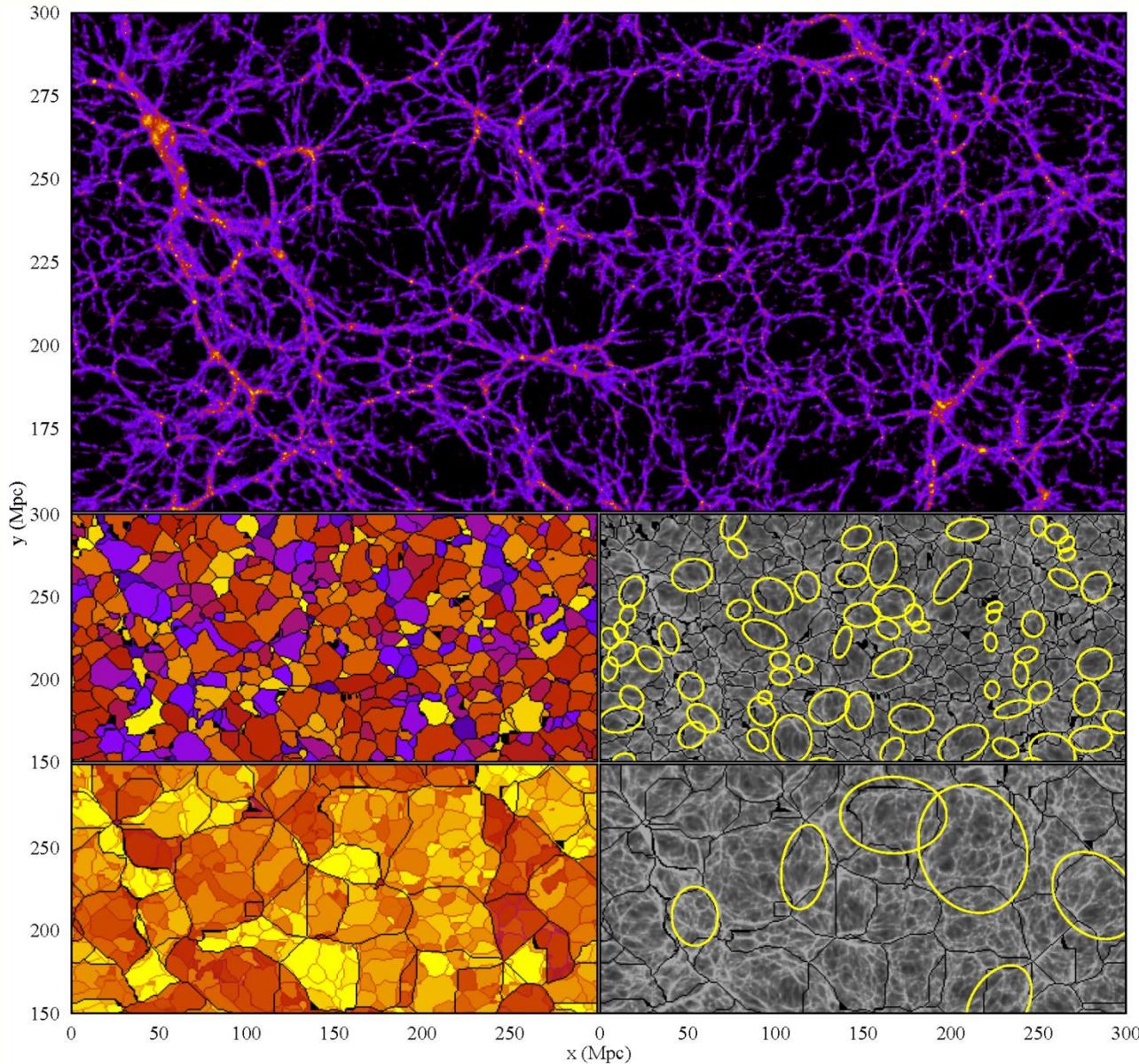
Each basin belonging to one individual minima defines one region

# Watershed Segmentation



- local height → local density
- mountain ridges → walls and filaments
  - watershed basins → voids

# WVF Void Identification



**Evolving  
Void Population:**

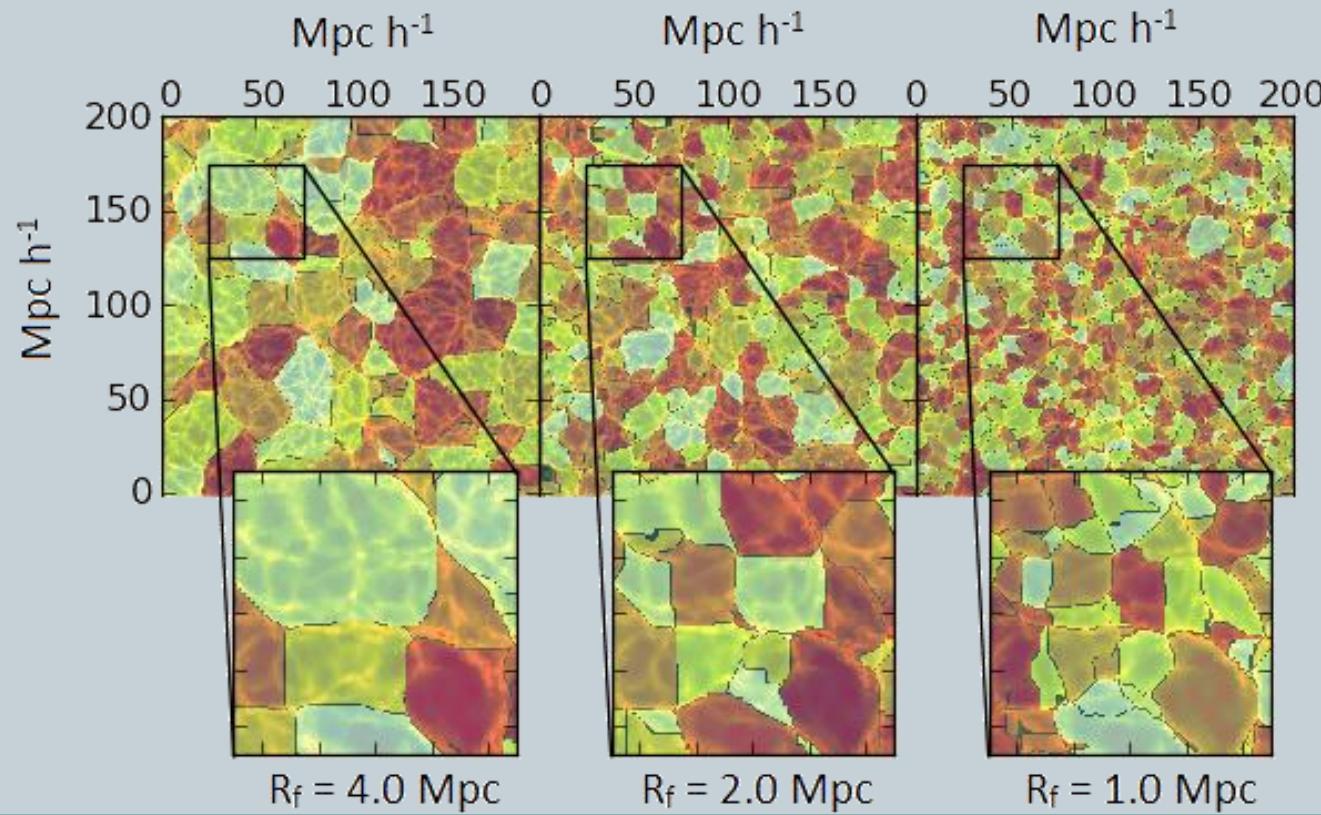
Void Shape evolution:  
sensitive probe Dark Energy

Bos, vdW, Dolag & Pettorino 2012

# The Multiscale Watershed Void Finder



Multiscale void population:  
void population as a function of filter radius

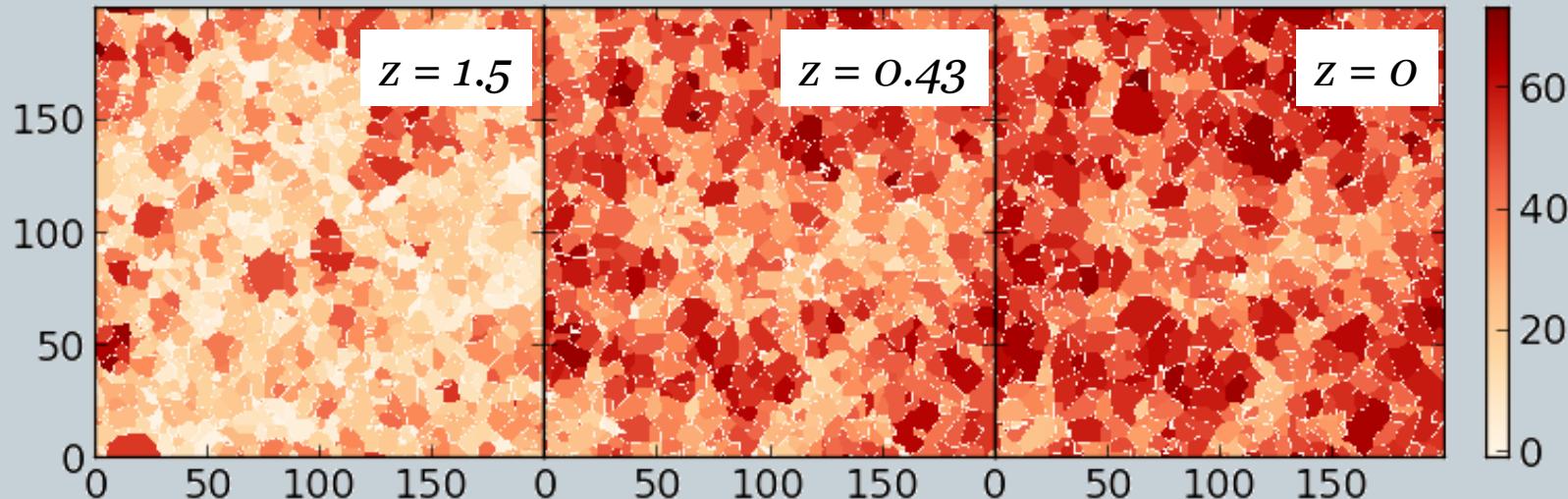


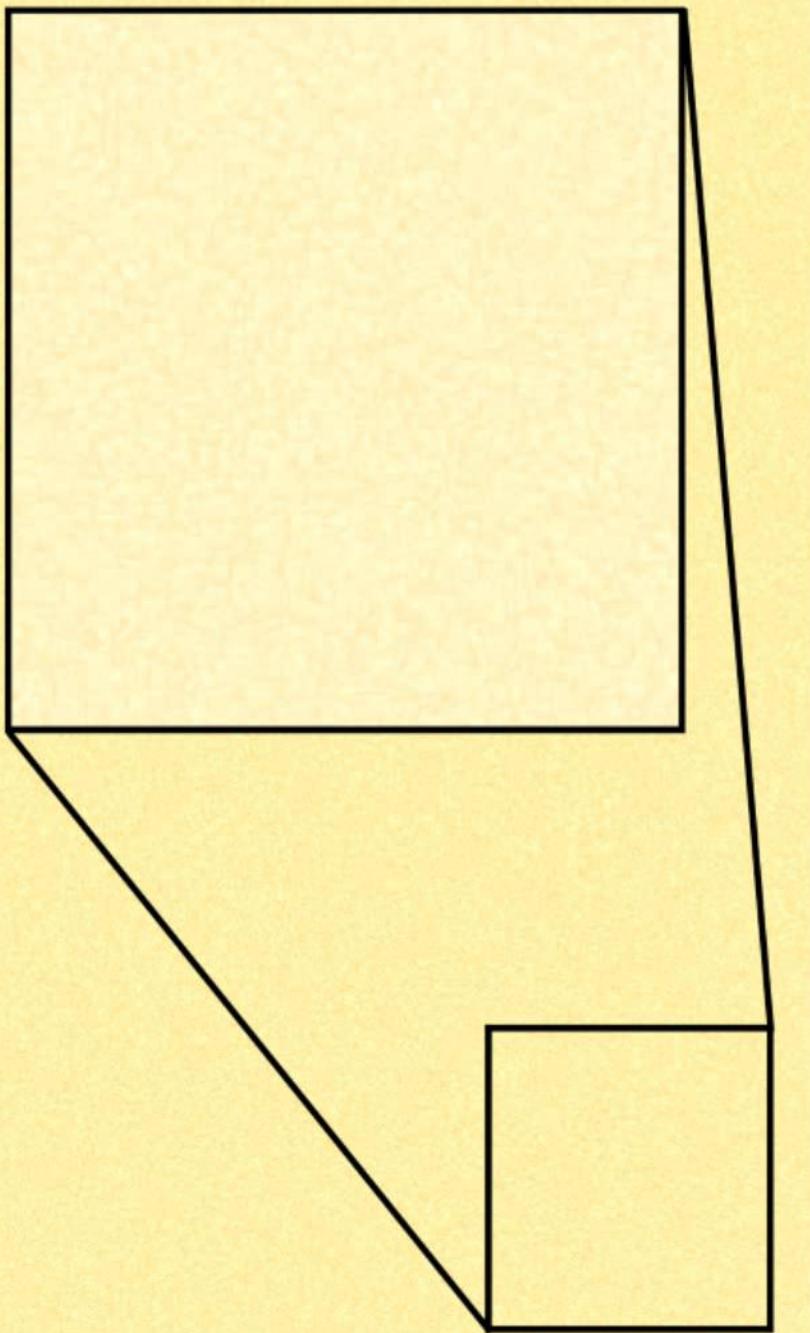
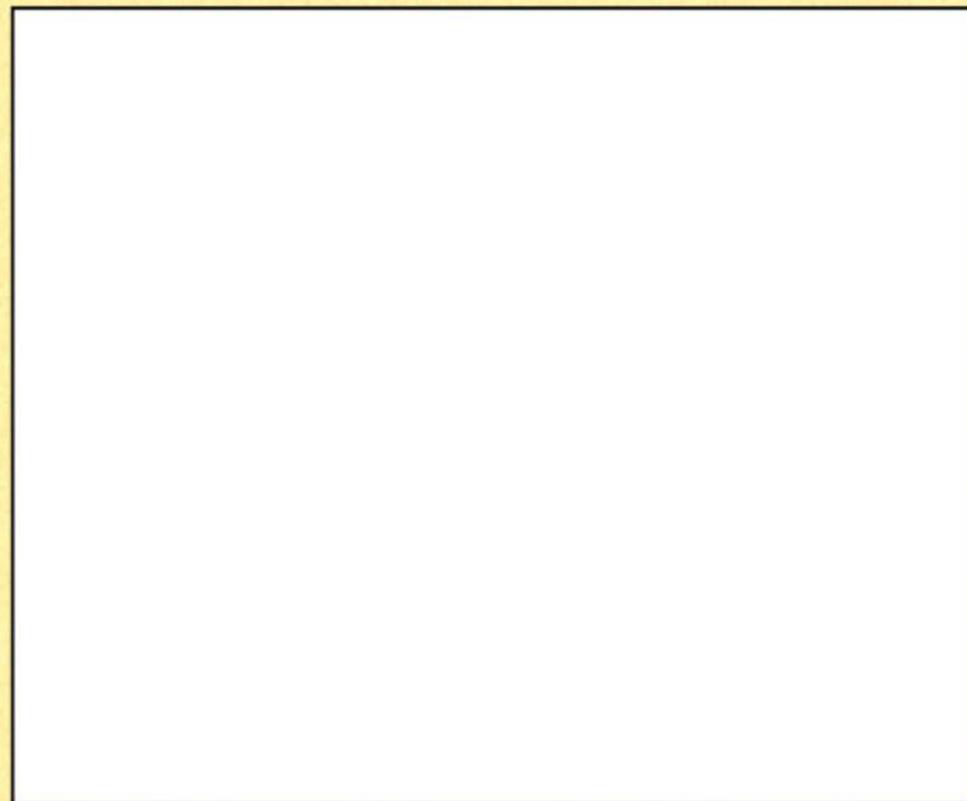
# The Multiscale Watershed Void Finder



## Multiscale Void Structure & Void Hierarchy

- Follow hierarchical buildup of (multiscale) void population
- Not all watershed basins are mature (deep) voids
- Multiscale void population: select on emptiness criterion
- At each  $z$ , establish which void child-parent connections
- Merge small voids with parents, when latter deep enough





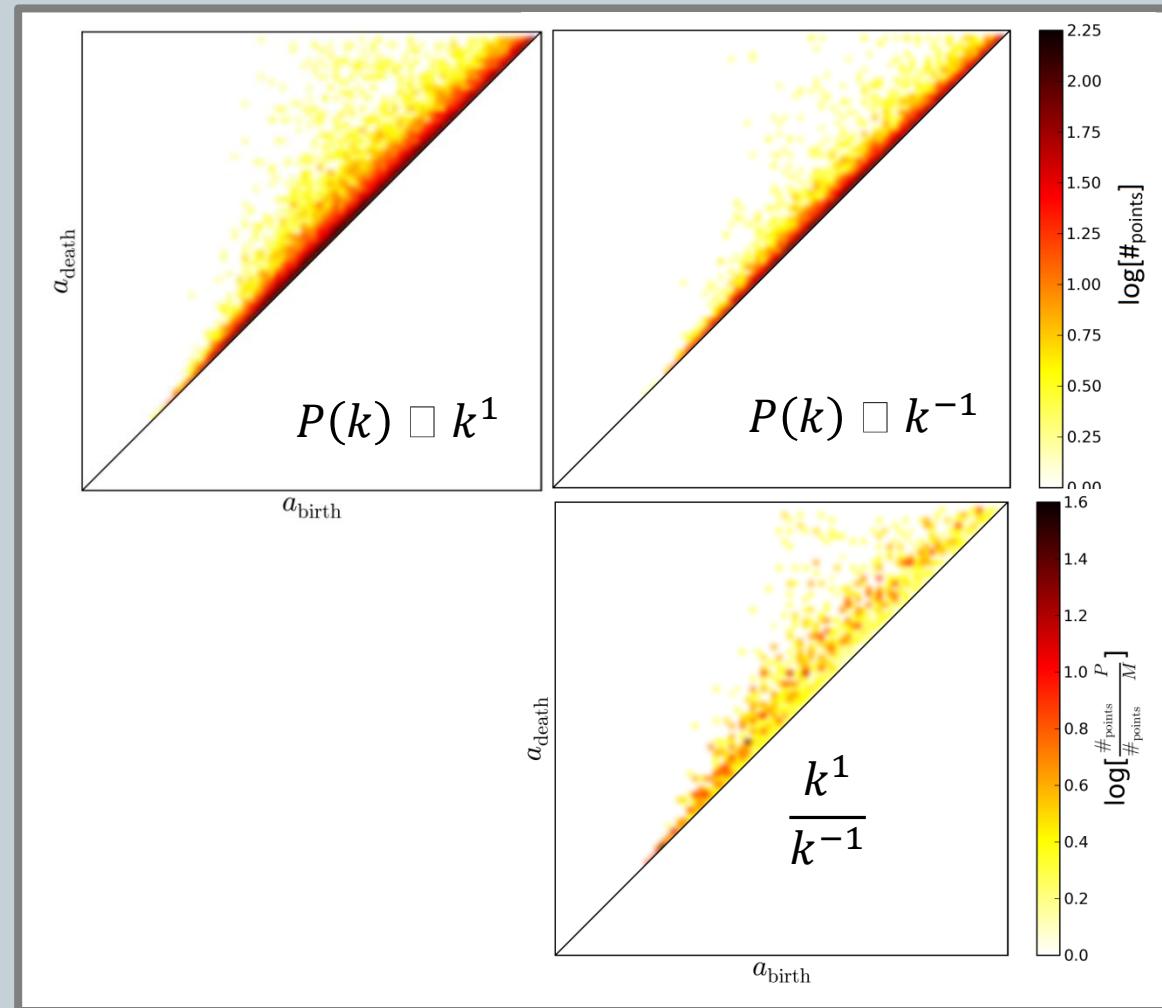
# Void persistence and merger trees

- Merger tree is only based on one parent void!
- Combine information of all merger trees into

## Persistence Diagram

(Edelsbrunner et al. 2000)

- Information w.r.t. formation and disappearance of voids due to hierarchical evolution
- Not only mathematical principle.



# Summary

- **Voids are a highly interesting component of the Megaparsec matter and galaxy distribution**
- **Voids are a dynamically dominant component of the Cosmic Web**
- **Voids evolve hierarchically, and still reflect this through their multiscale structure**
- **Two evolutionary void processes:  
void merging & void collapse**
- **Two-barrier extended PS description predicts void abundance,  
useful for testing dark energy cosmologies**
- **Void collapse seen in observations (SDSS)**
- **Local Void complex system consisting of several connected small voids**
- **Voids' isolated environment provides a very nice testing ground  
for the study of environmental influences on galaxy formation**