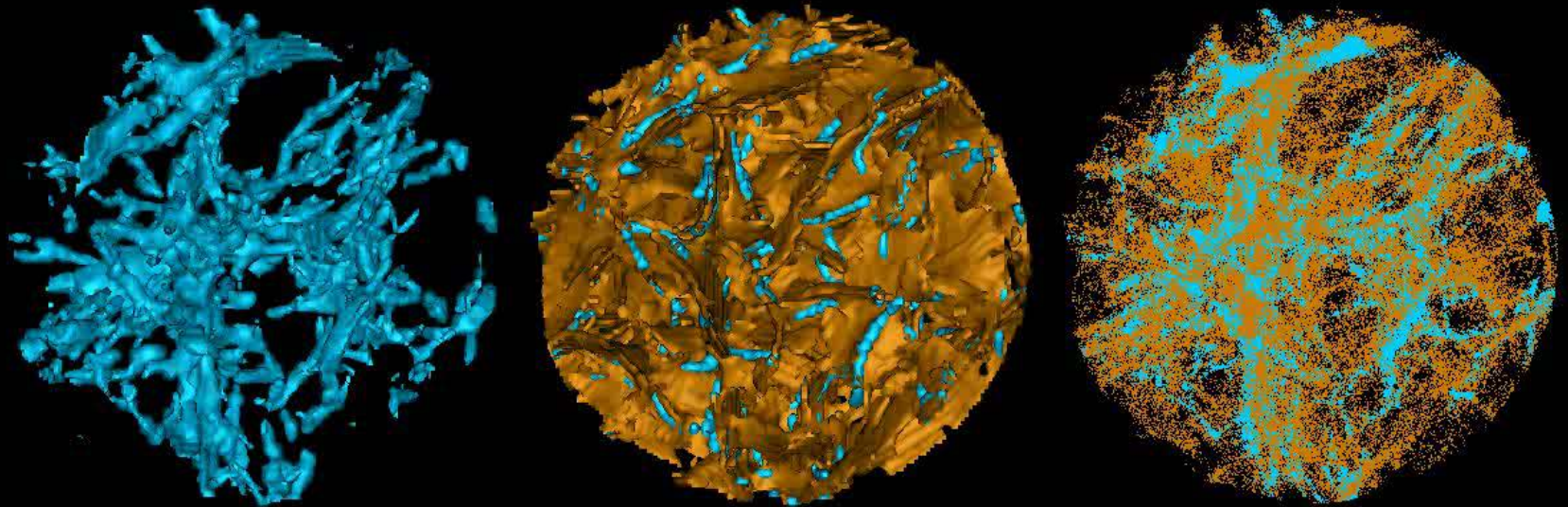


# **Much Ado: About Nothing: a Review of Voids**

Rien van de Weygaert, IAU308-Tallinn, June 2014

# The Cosmic Web



MMF/Nexus  
Cautun et al. 2013, 2014

## Stochastic Spatial Pattern

- Clusters,
  - Filaments &
  - Walls
- around
- Voids

in which matter & galaxies

have agglomerated

through gravity

# Outline

- Why voids are interesting ...
- Void (pre)history
- Void characteristics
- Void formation
- Void dynamics
- Void detection:
  - (M)WVF - Multiscale Watershed Void Finder
- Void hierarchy & Void merger trees
- Voids & Cosmology: void shapes, void outflows & supervoids
- Void galaxies & void substructure

**Voids:**

**Inventory & (Pre)history**

## REVIEW ARTICLE

## Giant voids in the Universe

Ya. B. Zeldovich\*, J. Einasto<sup>†‡</sup> & S. F. Shandarin\*

\* Institute of Applied Mathematics, Moscow A-47, 125047, USSR

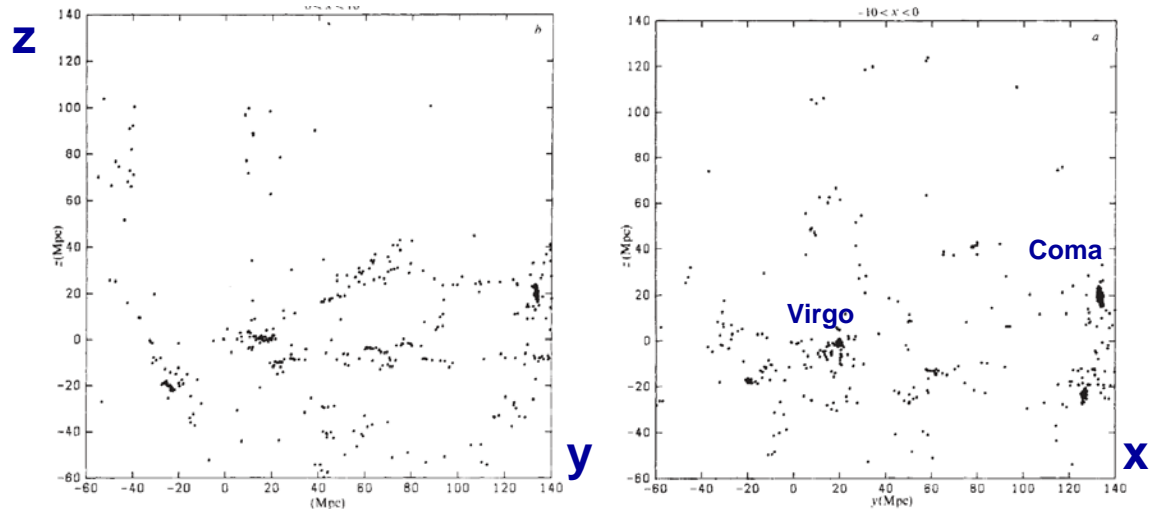
† Tartu Astrophysical Observatory, 202444 Estonia, USSR

‡ European Southern Observatory, 8046 Garching, FRG

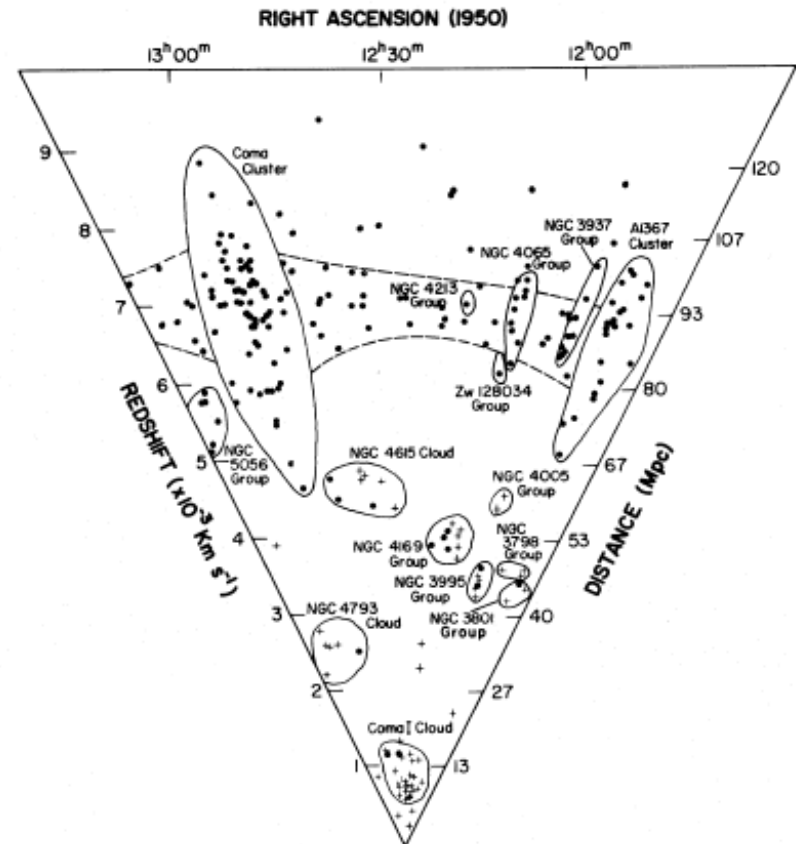
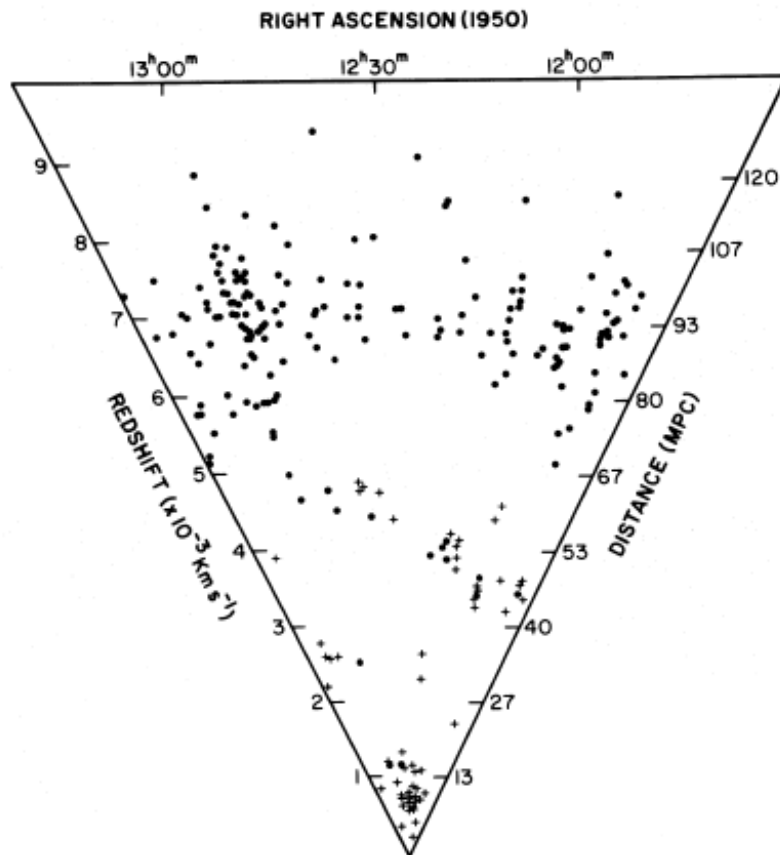
*Recent observations indicate that most galaxies are concentrated in superclusters consisting of galaxies, and clusters of galaxies, aligned along strings. Giant volumes exist between superclusters which are almost empty of visible objects. Theories of galaxy formation predict the formation of non-spherical superclusters and giant voids. Large-scale structure changes very slowly, so the currently observed structure reflects the whole history of galaxy formation and structural evolution.*

Zeldovich, Einasto &amp; Shandarin 1982:

First linking of observationally visible void regions and the theory of cosmic structure formation.



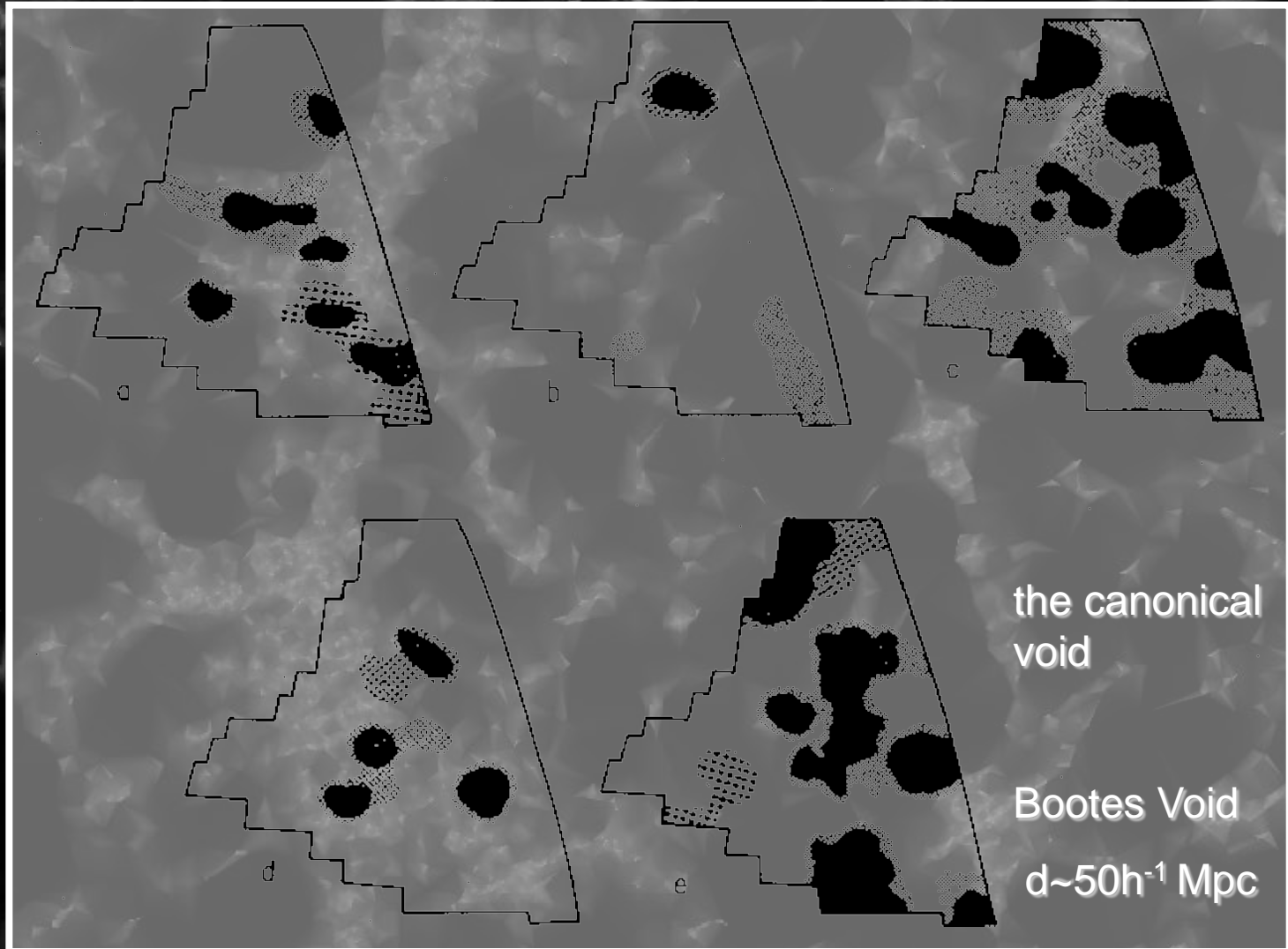
# First Voids



Gregory & Thompson 1978:  
redshift survey of Coma/A1367 supercluster region revealed existence of large  
near-empty regions of space.

# Bootes Void

Kirshner, Oemler, Schectman, Schechter (KOSS) 1981, 1987

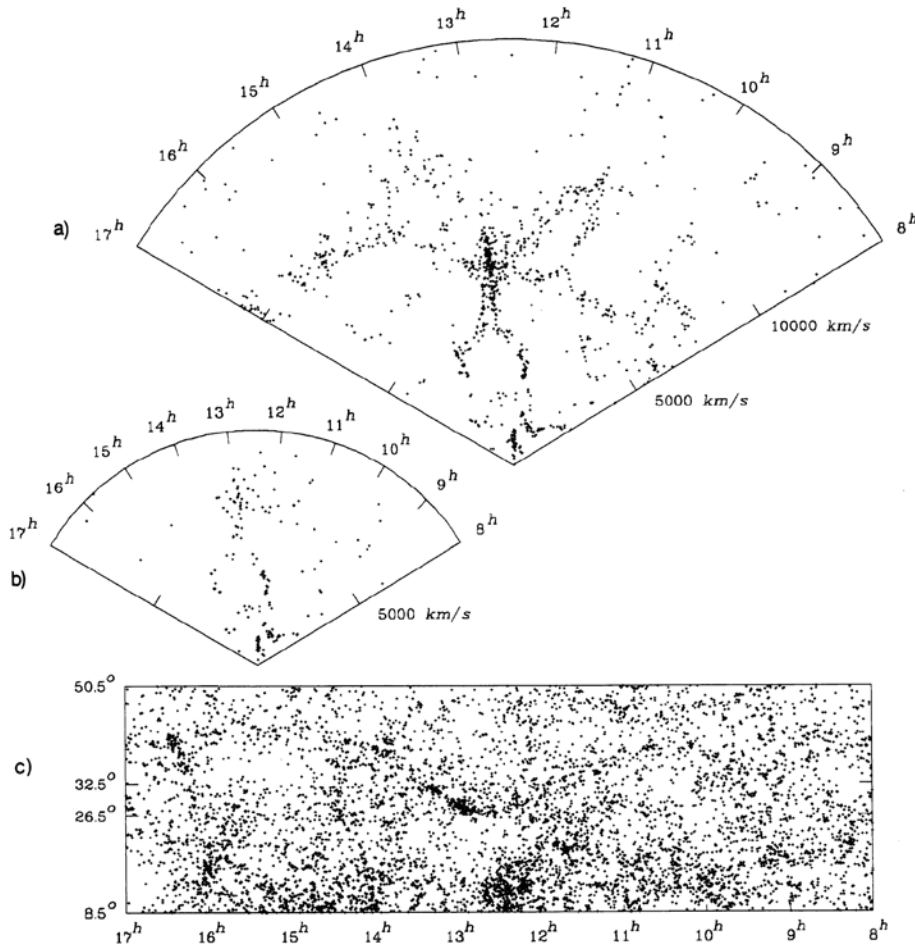


# Voids & the Cosmic Web

deLapparent, Geller & Huchra, 1986:

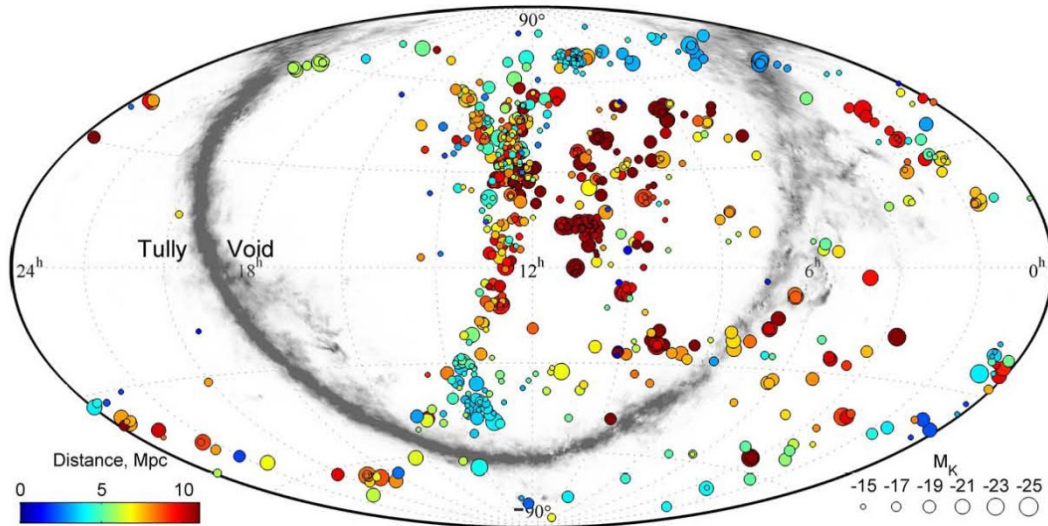
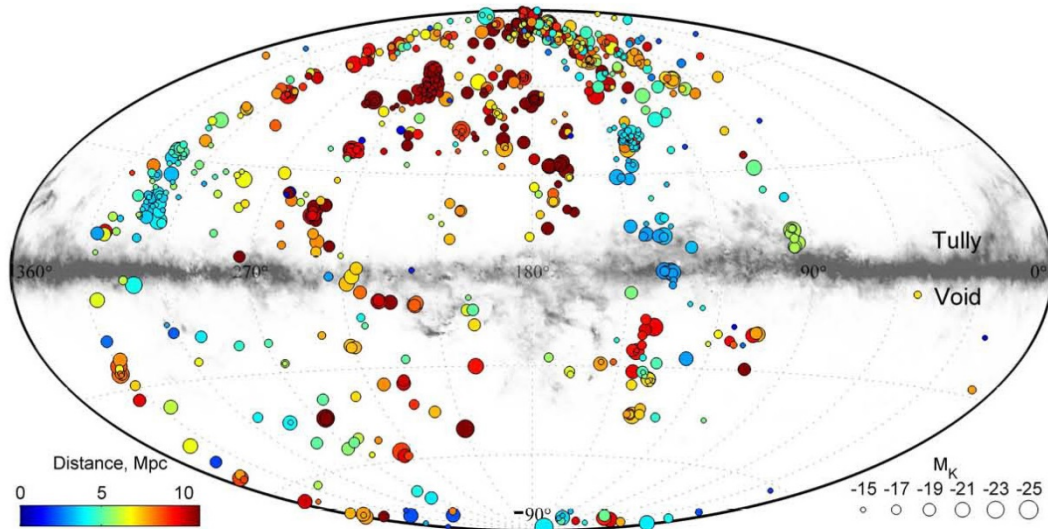
“a slice of the Universe”

Voids appear to be an integral part of a complex weblike arrangement of galaxies





# local Cosmic Web: Local Void



Karachentsev et al.

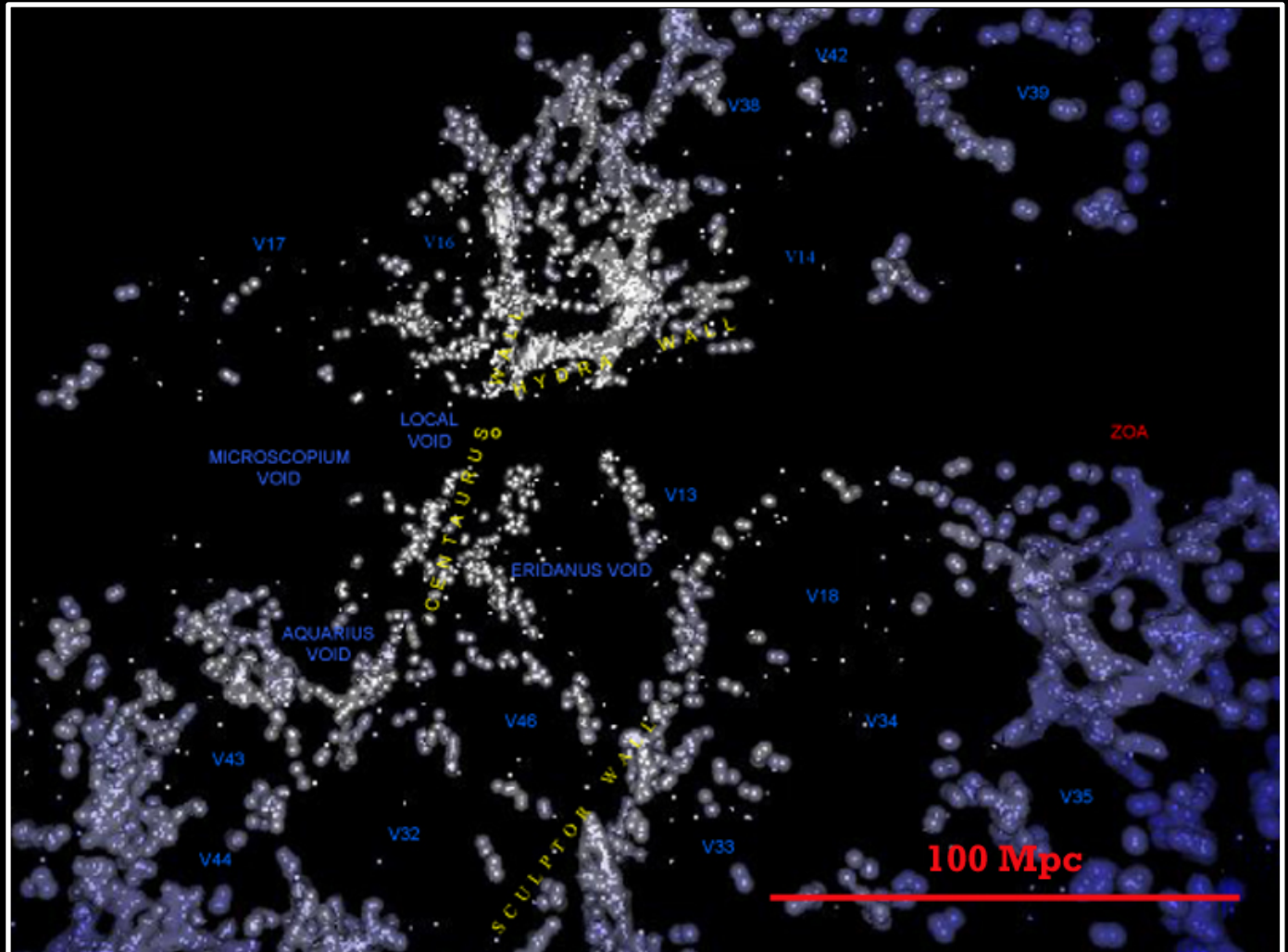
LV catalog:  
galaxies within 10 Mpc reveal  
beautifully the magnificent

Local Void – Tully Void

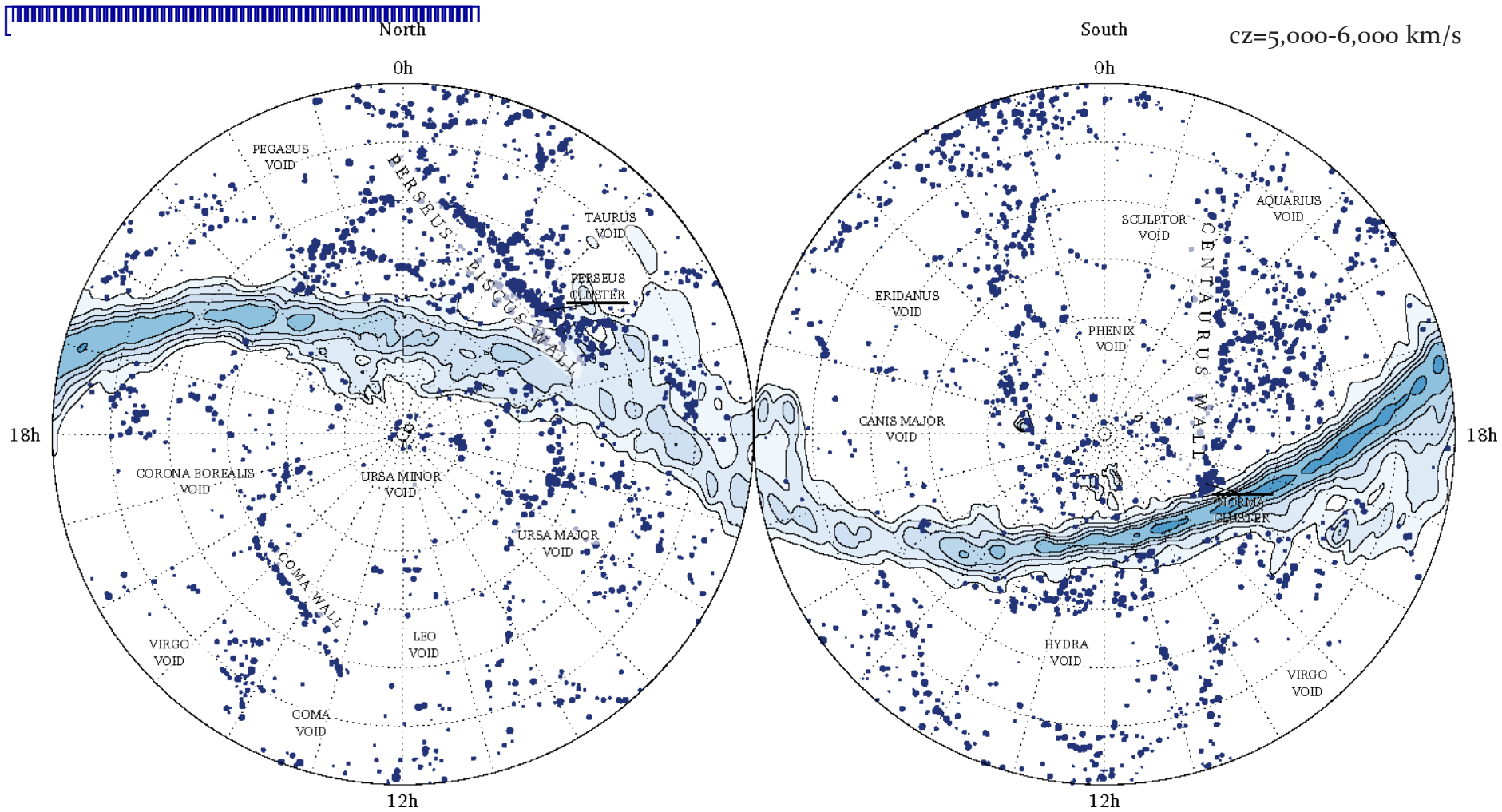
# Fairall Void Catalogue

6dF based  
catalogue

of 526  
visually identified  
voids.



# local Cosmic Web: 2MASS

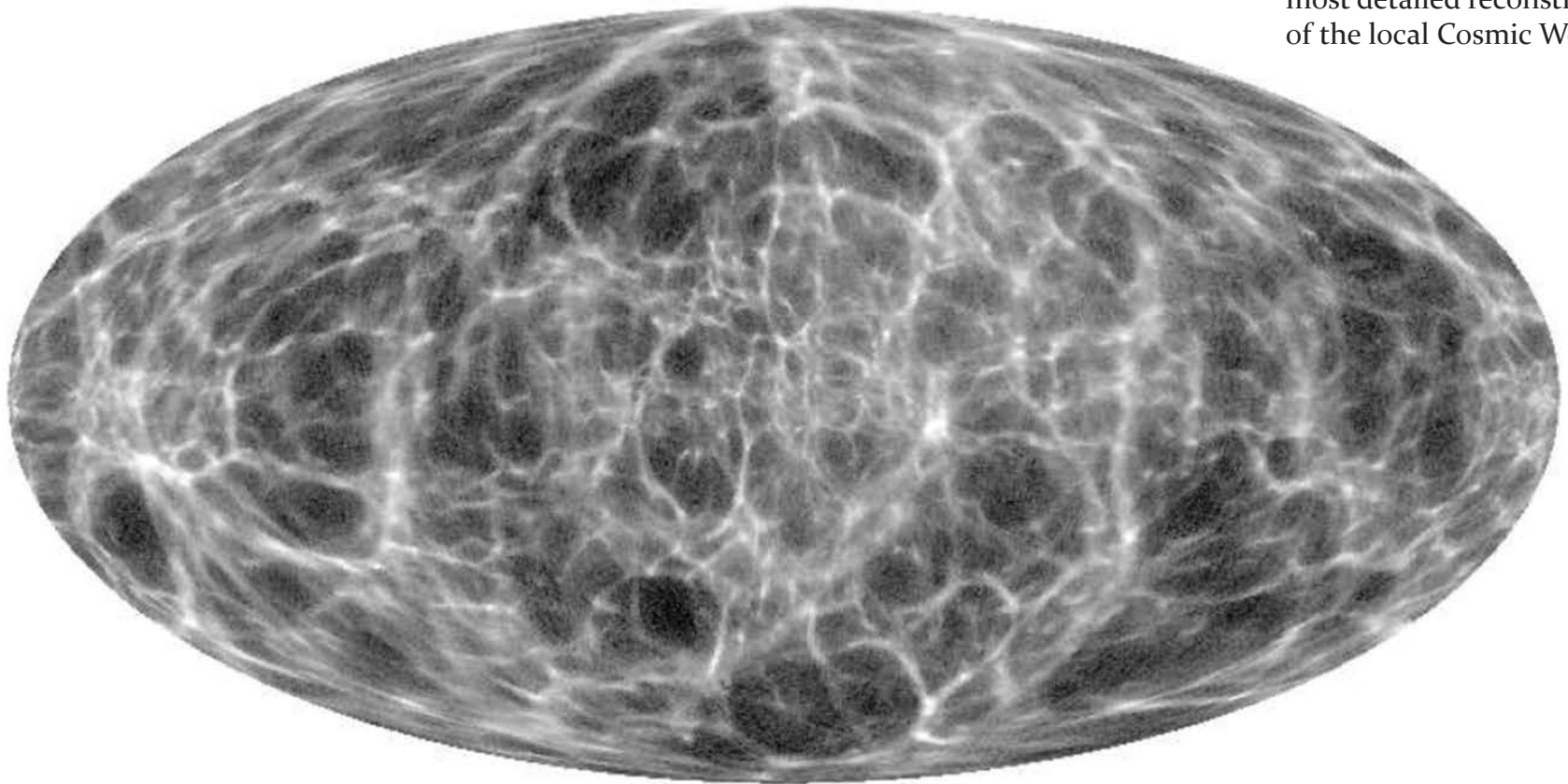


Courtesy: Johan Hidding

# local Cosmic Web: 2MASS



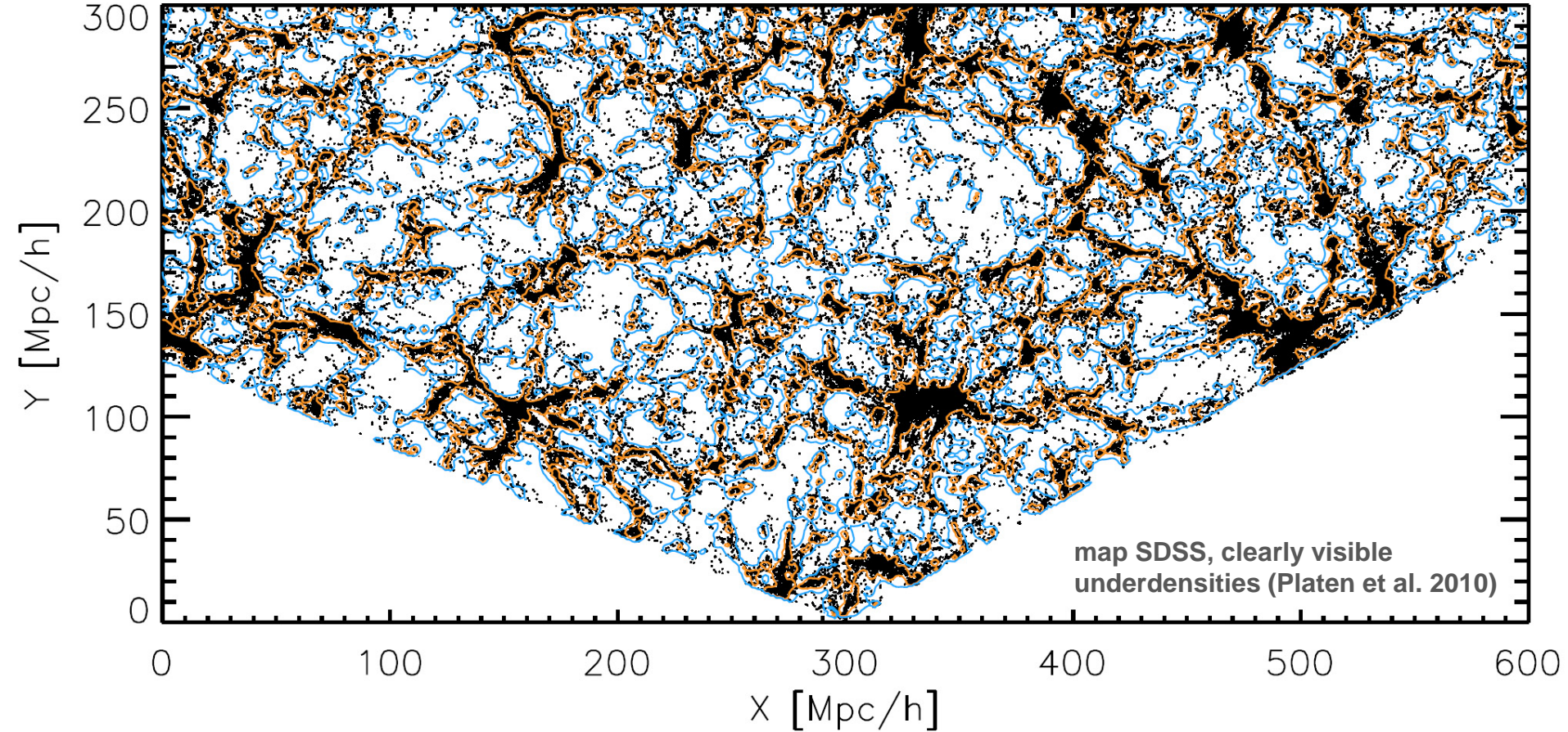
most detailed reconstruction  
of the local Cosmic Web



1.0  6.0

Courtesy: Francisco Kitaura

# SDSS Galaxy Survey

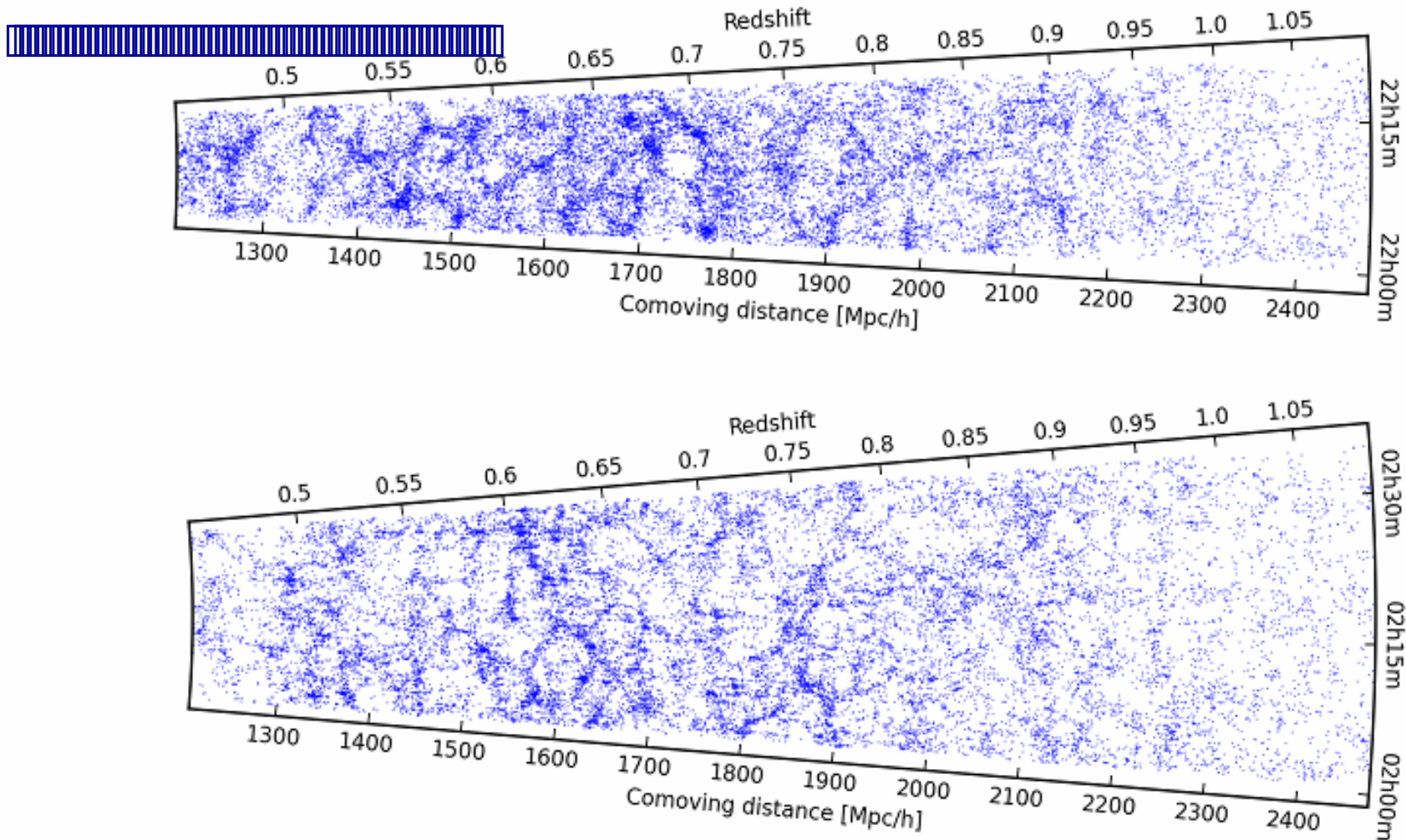


with the advent of large galaxy redshift surveys

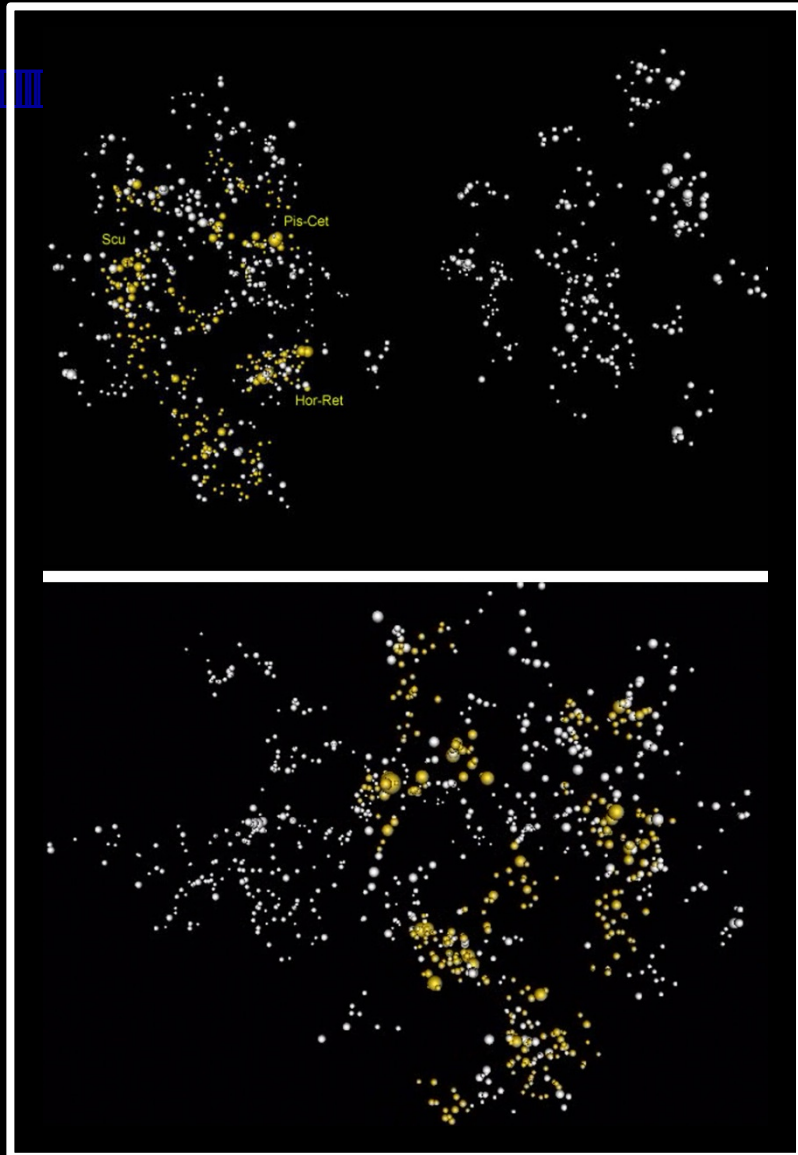
– LCRS, 2dFGRS, SDSS, 2MRS –

voids have been recognized as one of the quintessential components of the Cosmic Web

# high-z Cosmic Web: VIPERS



# Voids & Clusters



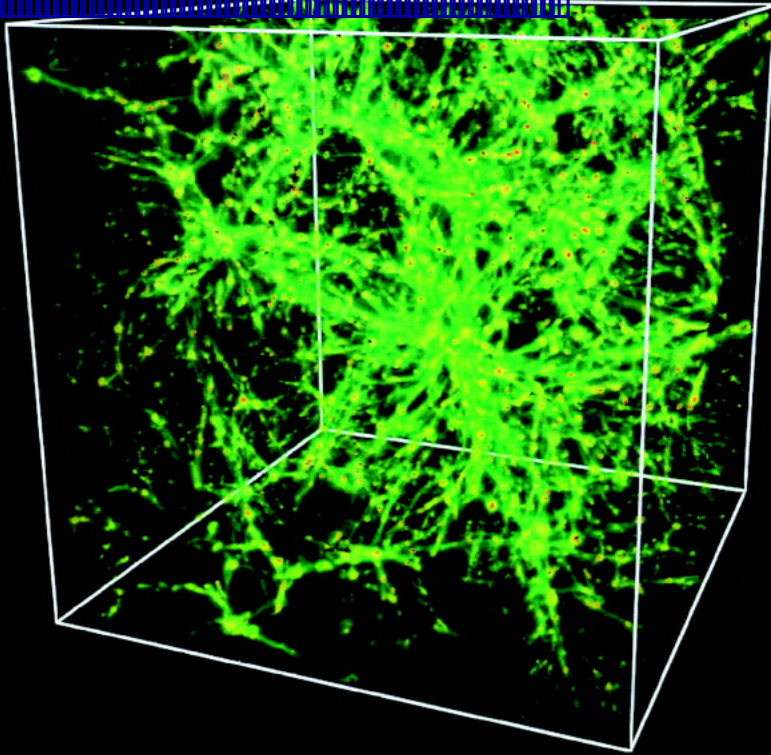
Einasto, Saar et al. (1990s)

- Superclustering in Abell/APM clusters catalog
- Finding of characteristic scale  $\sim 140$  Mpc, corresponding to large voids in the cluster distribution

Reflex II cluster catalog (Bohringer et al.) reveals same population of voids in cluster distribution

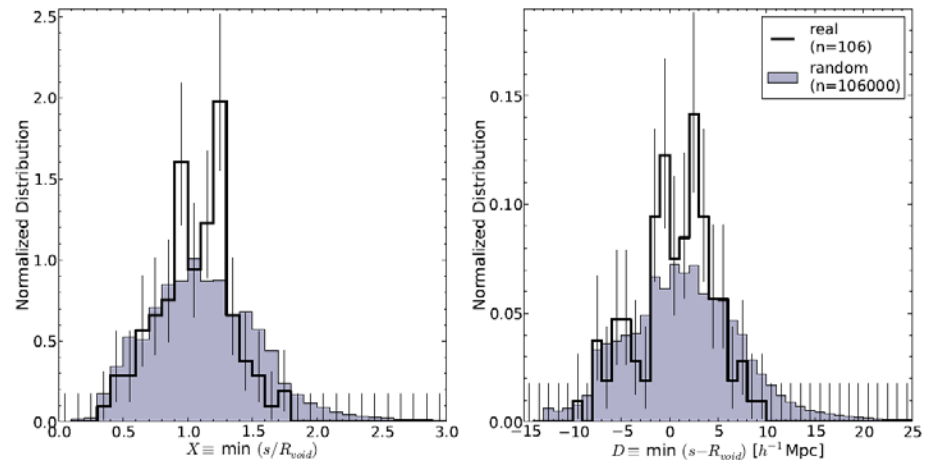
(see talk by Collins).

# Voids & the Gaseous Web



Tejos et al. 2012:

HI Ly $\alpha$  absorption systems clearly delineate voids





**Voids:**

**why interesting ?**

# Voids:

## Cosmological Significance

- **Cosmic Structure:**

prominent components of the Cosmic Web,  
structurally & dynamically of major influence,  
instrumental in spatial organization of the Megaparsec Universe.

- **Cosmological probe:**

Voids contain significant amount of information on global  
cosmological parameters:

- void substructure: test GR/modified gravity
- void outflow: dark matter
- void shapes: dark energy
- supervoids: existence; CMB - ISW

- **Galaxy Formation & Evolution:**

pristine low-density environment ideal for studying galaxy  
formation and the effects of cosmic environment on the  
evolution of galaxies.

**Voids:**

**Formation & Structure**

# Void Formation

## Void Evolution

an illustration

cosmology:

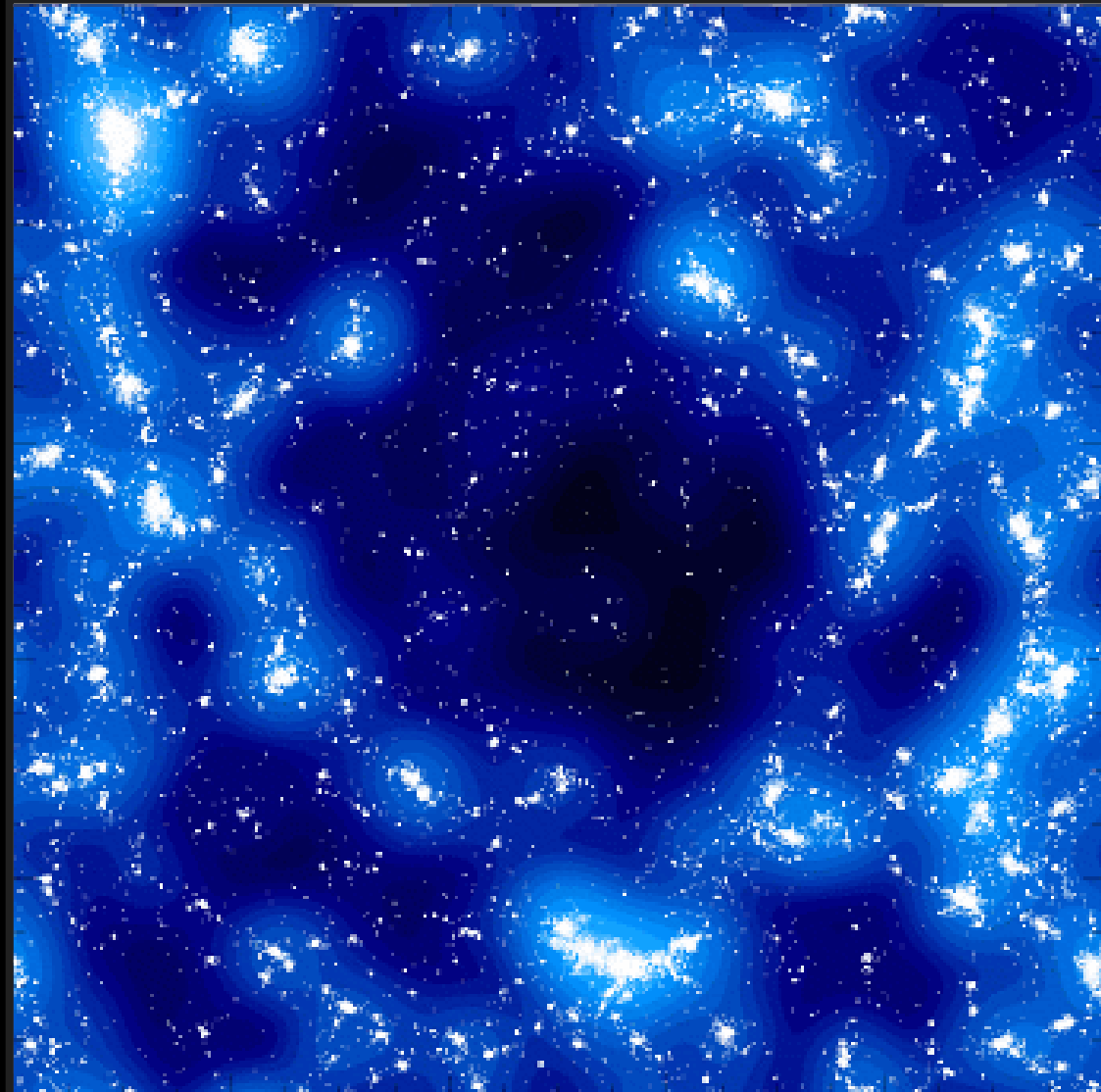
$$\Omega_m = 1.0; \quad H_0 = 70 \text{ km / s / Mpc}$$

initial conditions:

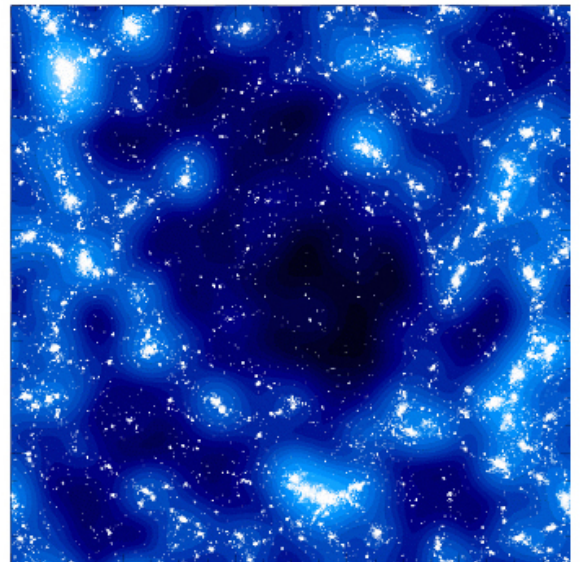
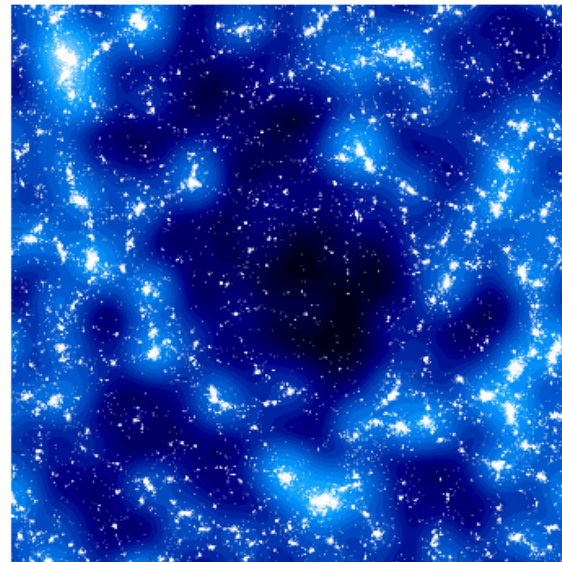
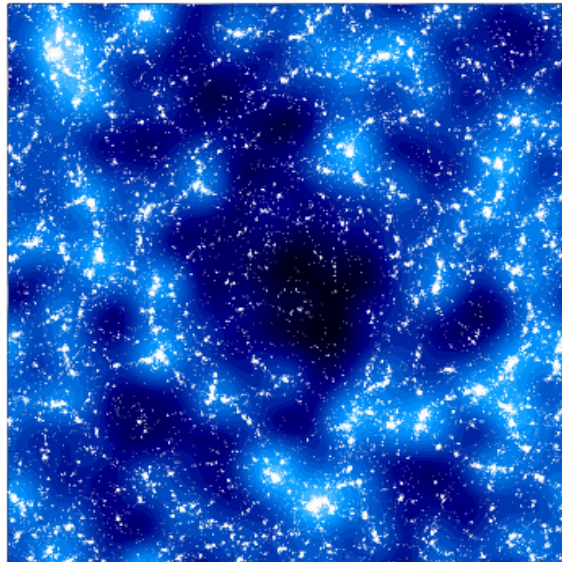
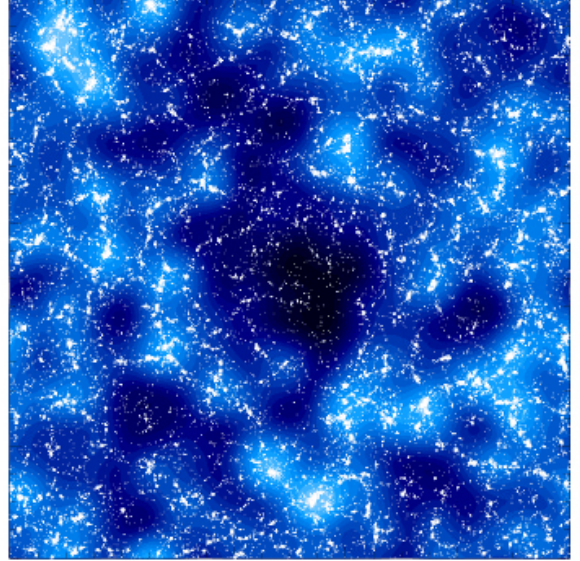
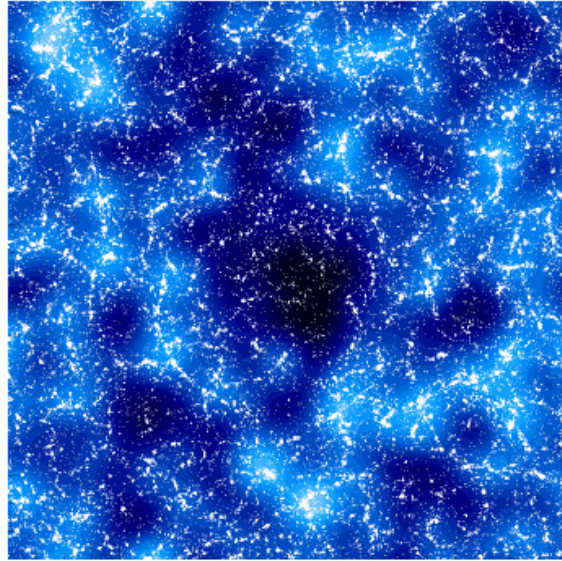
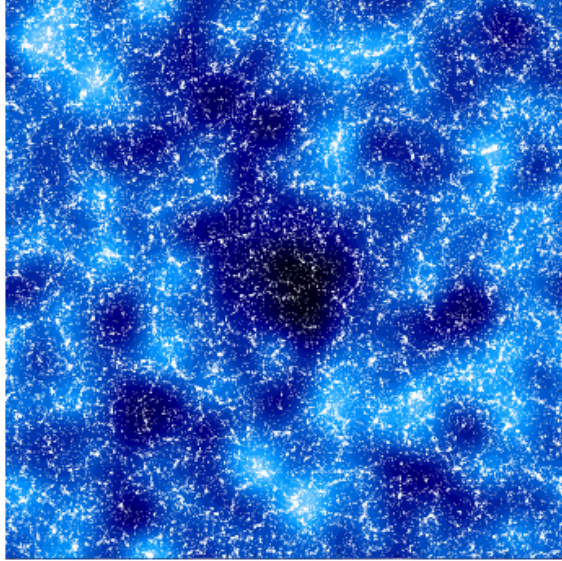
underdensity, Gaussian field

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

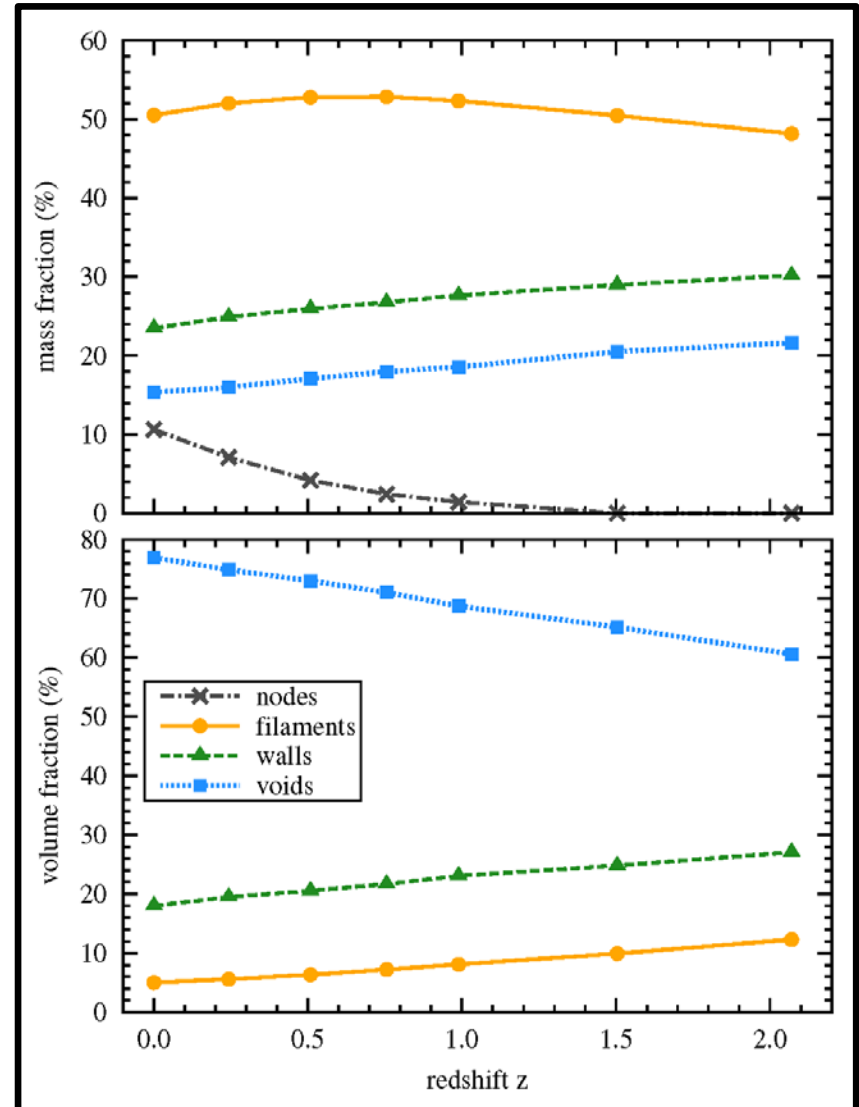
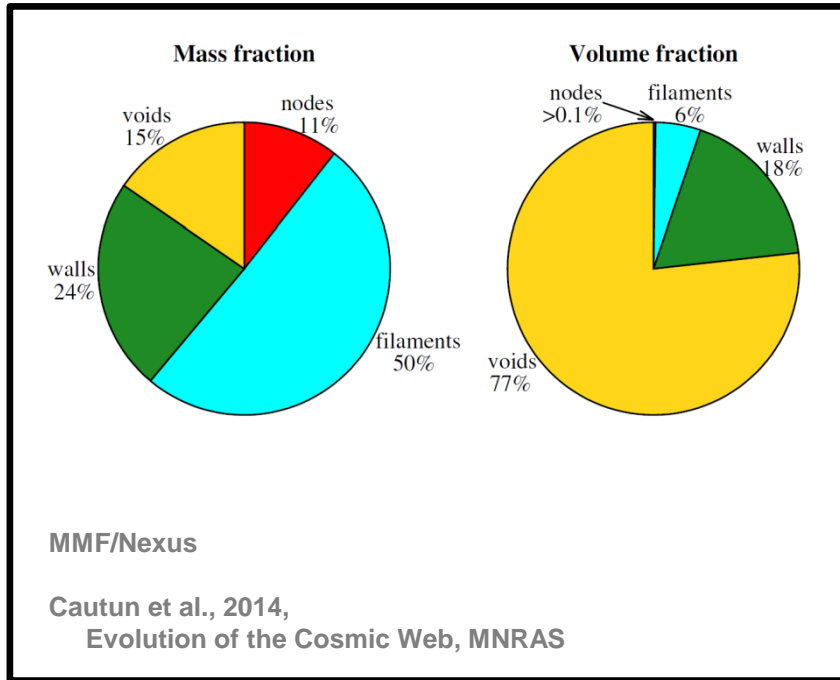
$$P(k) \propto k^{-0.5}$$



# Void Formation



# Cosmic Web & Voids

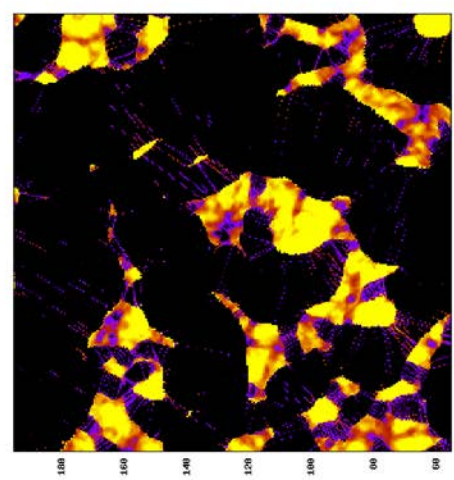
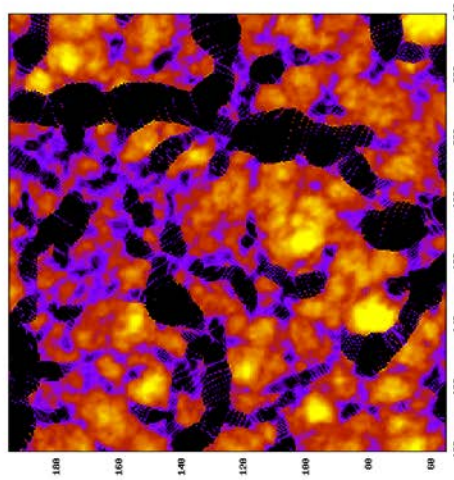
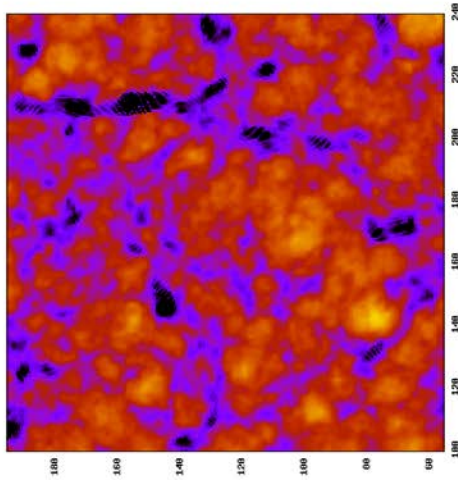


**Voids:** - occupy most of cosmic volume: **77%**  
- of mass, only: **15%**

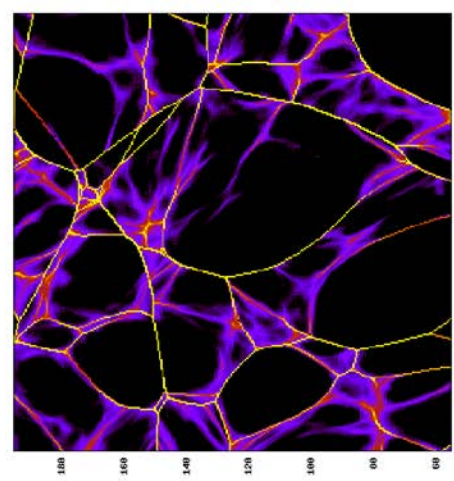
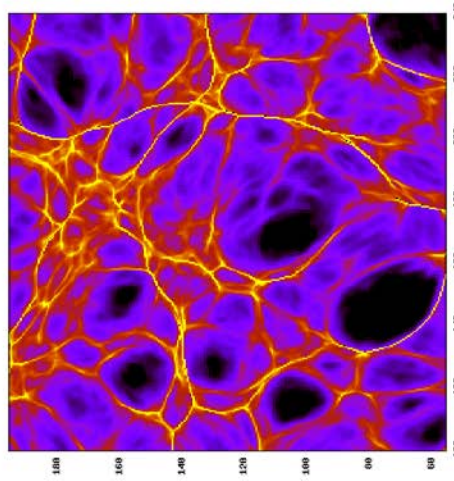
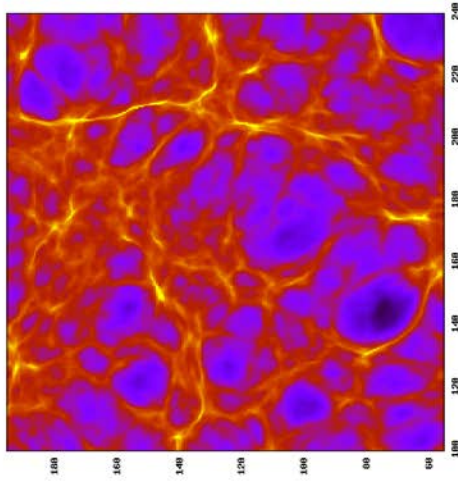
## Void evolution:

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

# Void Formation: Lagrangian View



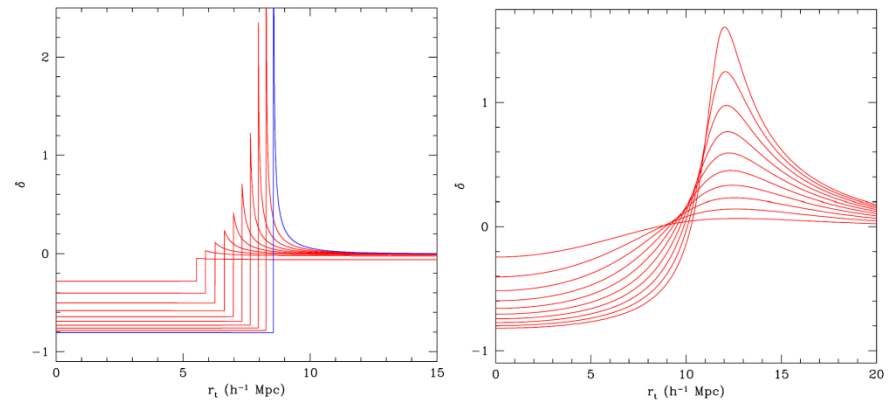
**Lagrangian  
evolution:**  
  
void regions shrink



**Eulerian  
Evolution:**  
  
void regions expand

# 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

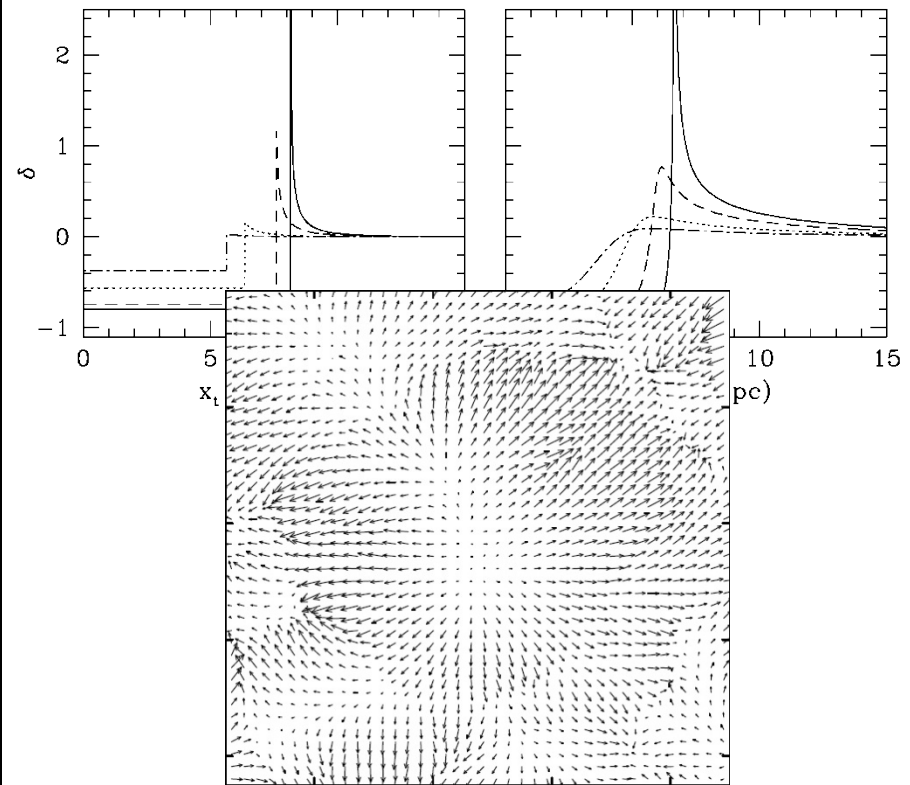




# Superhubble Expansion

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

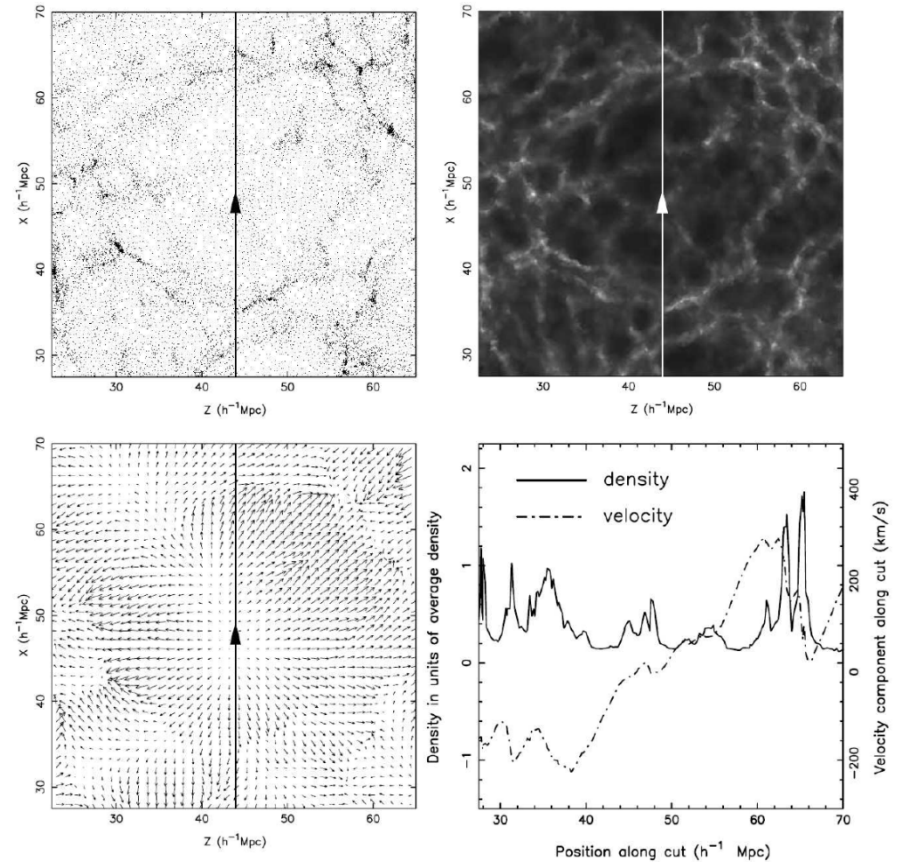
$$\theta = \frac{1}{H}(\nabla \cdot \vec{v}) \quad \Rightarrow \quad \theta_{\max} = 1.5\Omega^{0.6}$$



# Superhubble Expansion

- Superhubble Expansion  
tending towards “bucket” shape,  
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uniform velocity divergence

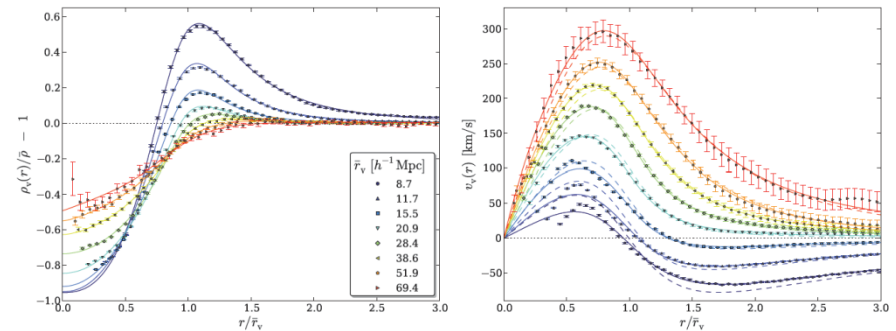
$$\theta = \frac{1}{H} (\nabla \cdot \vec{v}) \quad \Rightarrow \quad \theta_{\max} = 1.5 \Omega^{0.6}$$



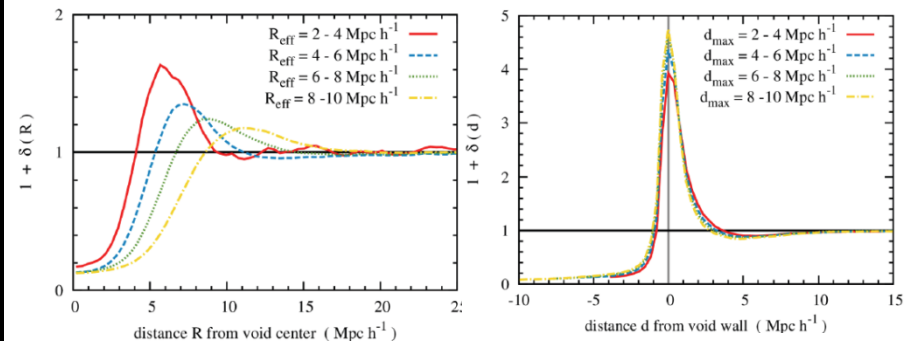
# Void Density Profile

- **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 ?



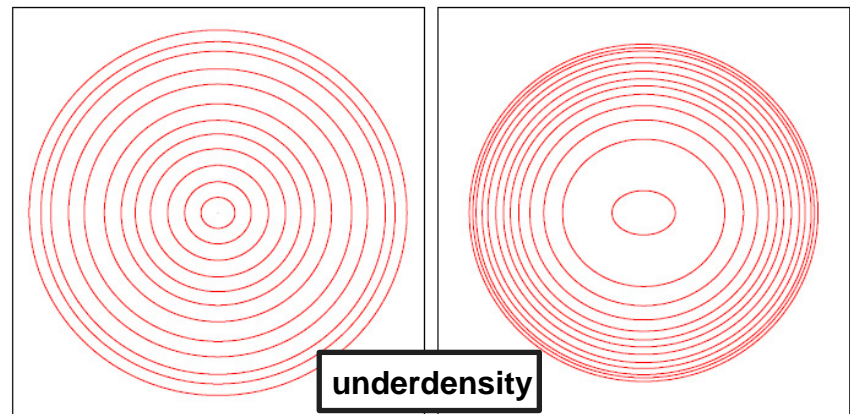
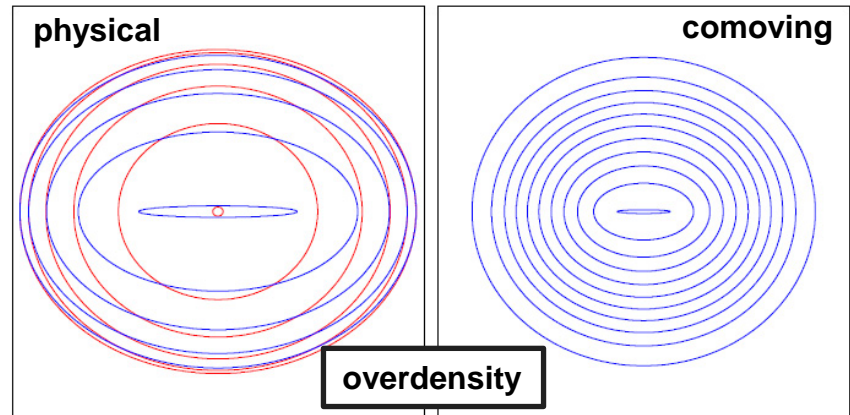
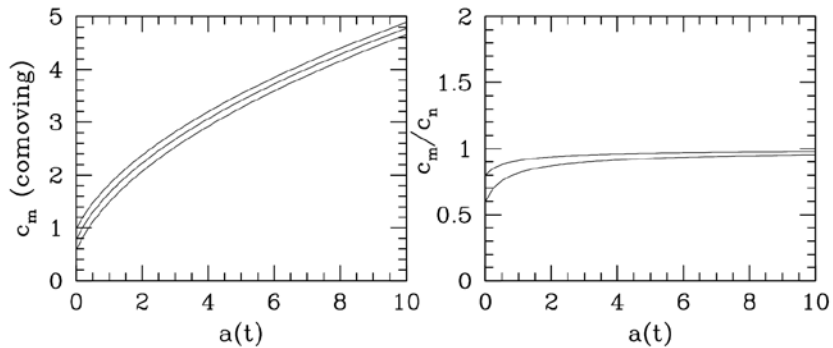
e.g. Hamaus et al. 2014



Cautun et al. 2014

# Bubble Theorem

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



# Void Shapes & Environment

- **Bubble Theorem Revisited:**

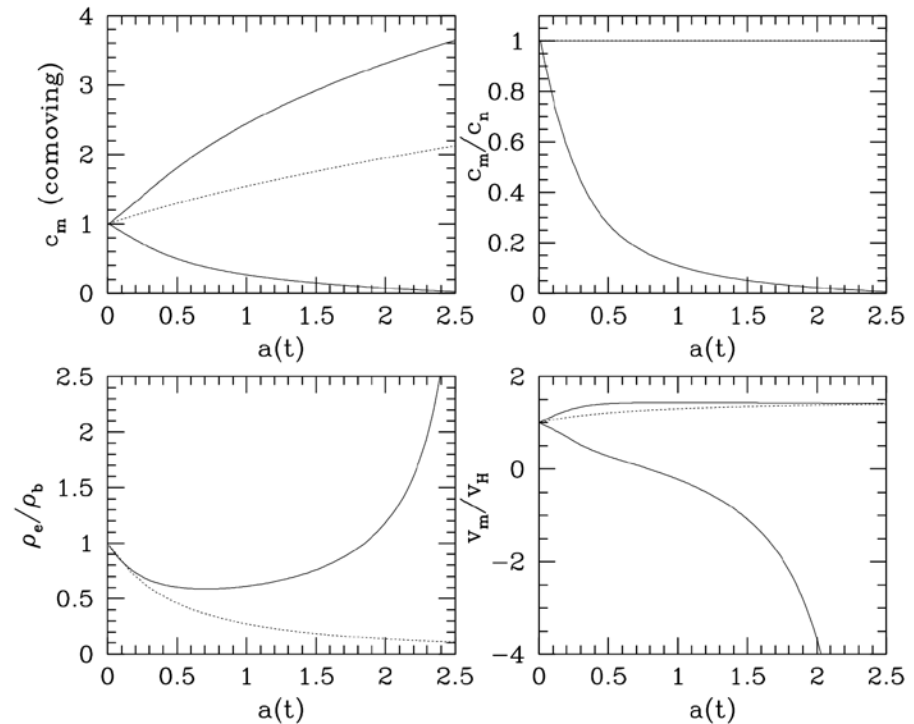
voids will not be spherical:

- Voids never isolated: run into neighbours
- Void evolution largely dominated by large scale (tidal) environment:

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

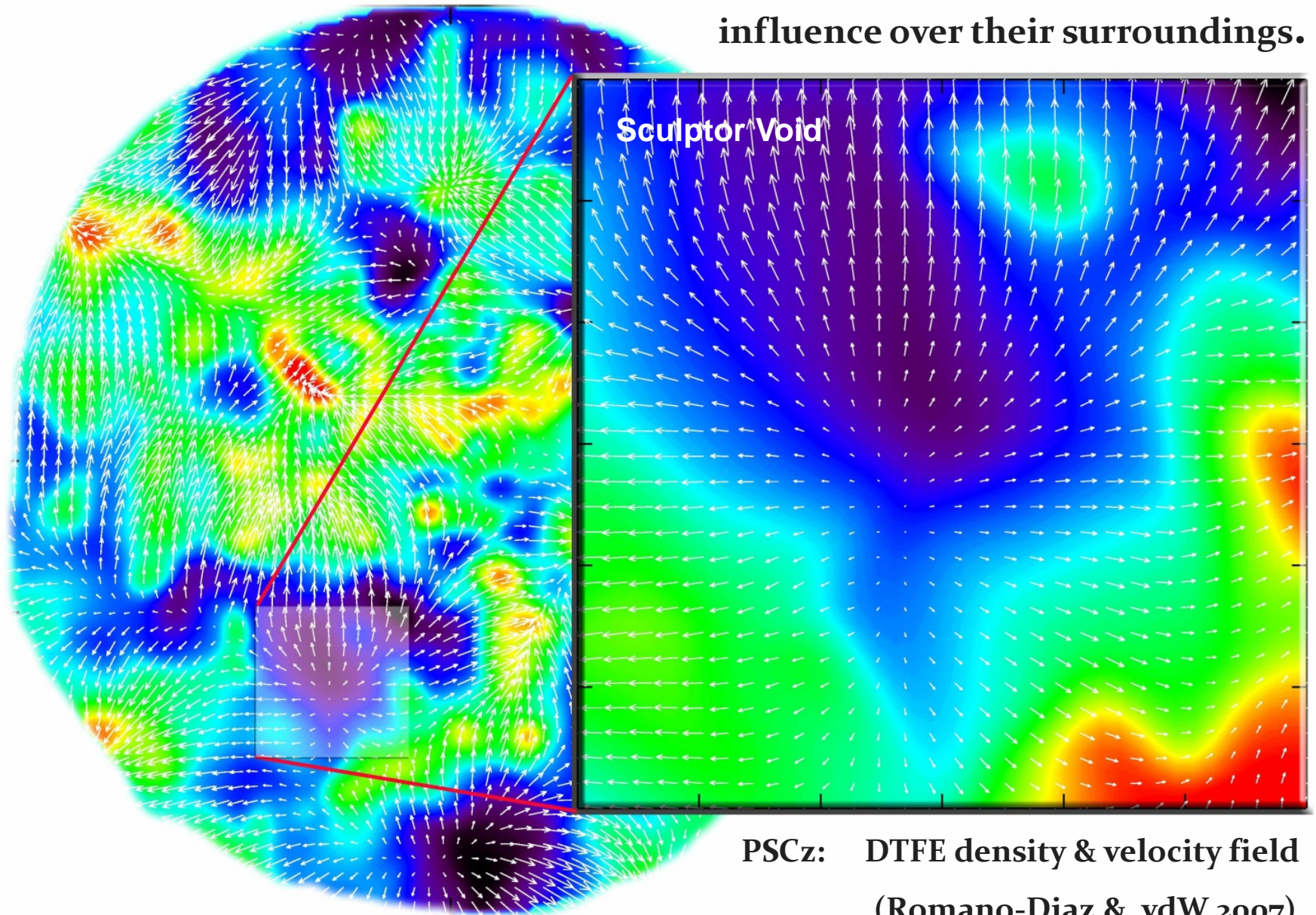
Evolution homogeneous ellipsoidal void in external tidal field  $T_{kl}$

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



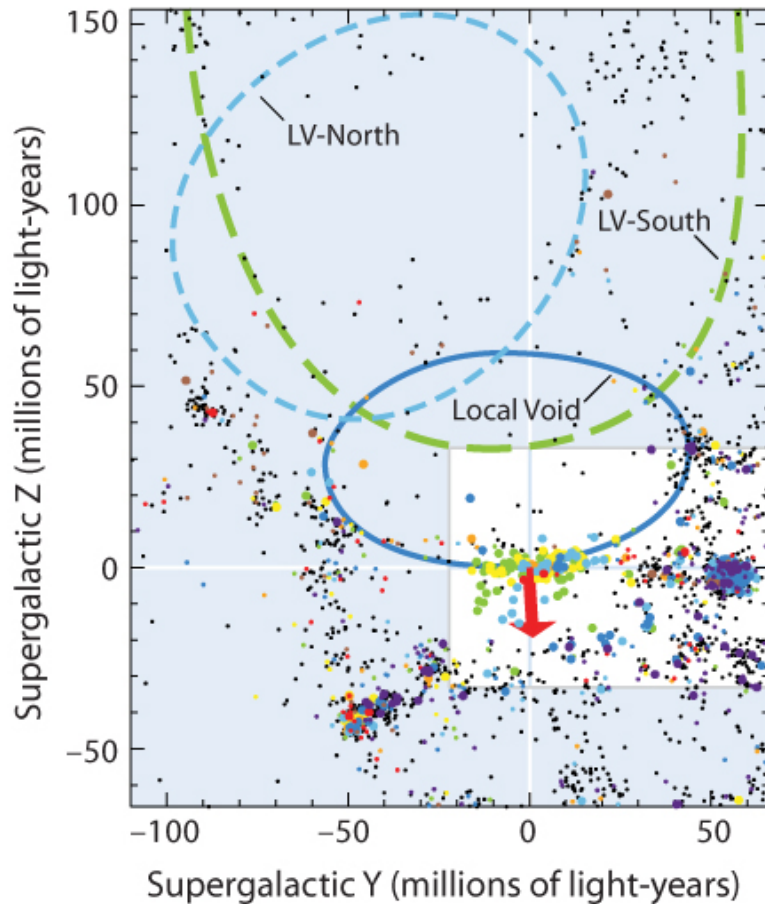
# Void Dynamics

**Voids exert a repulsing dynamical influence over their surroundings.**

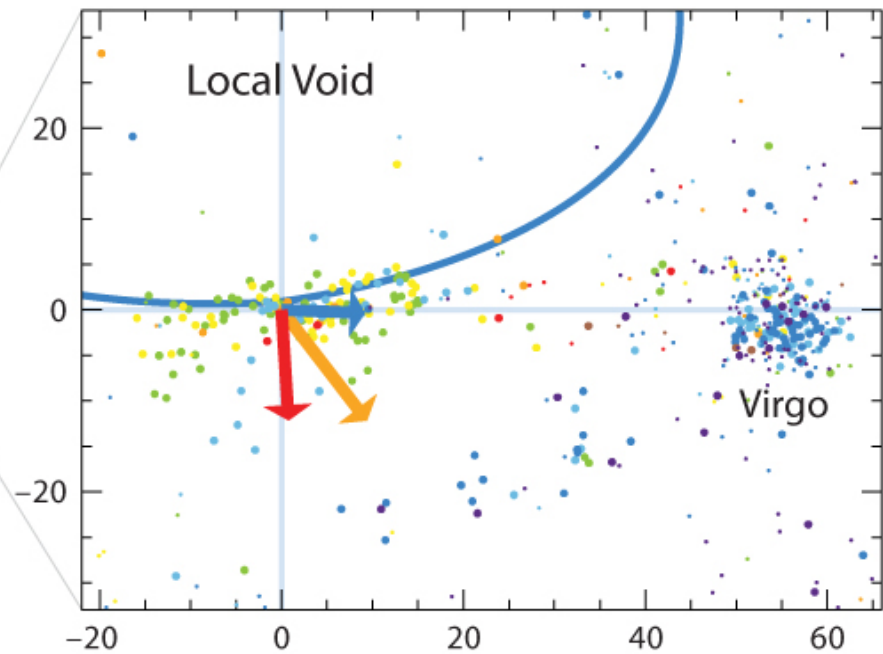


**PSCz: DTFE density & velocity field  
(Romano-Diaz & vdW 2007)**

# Push of the Local Void



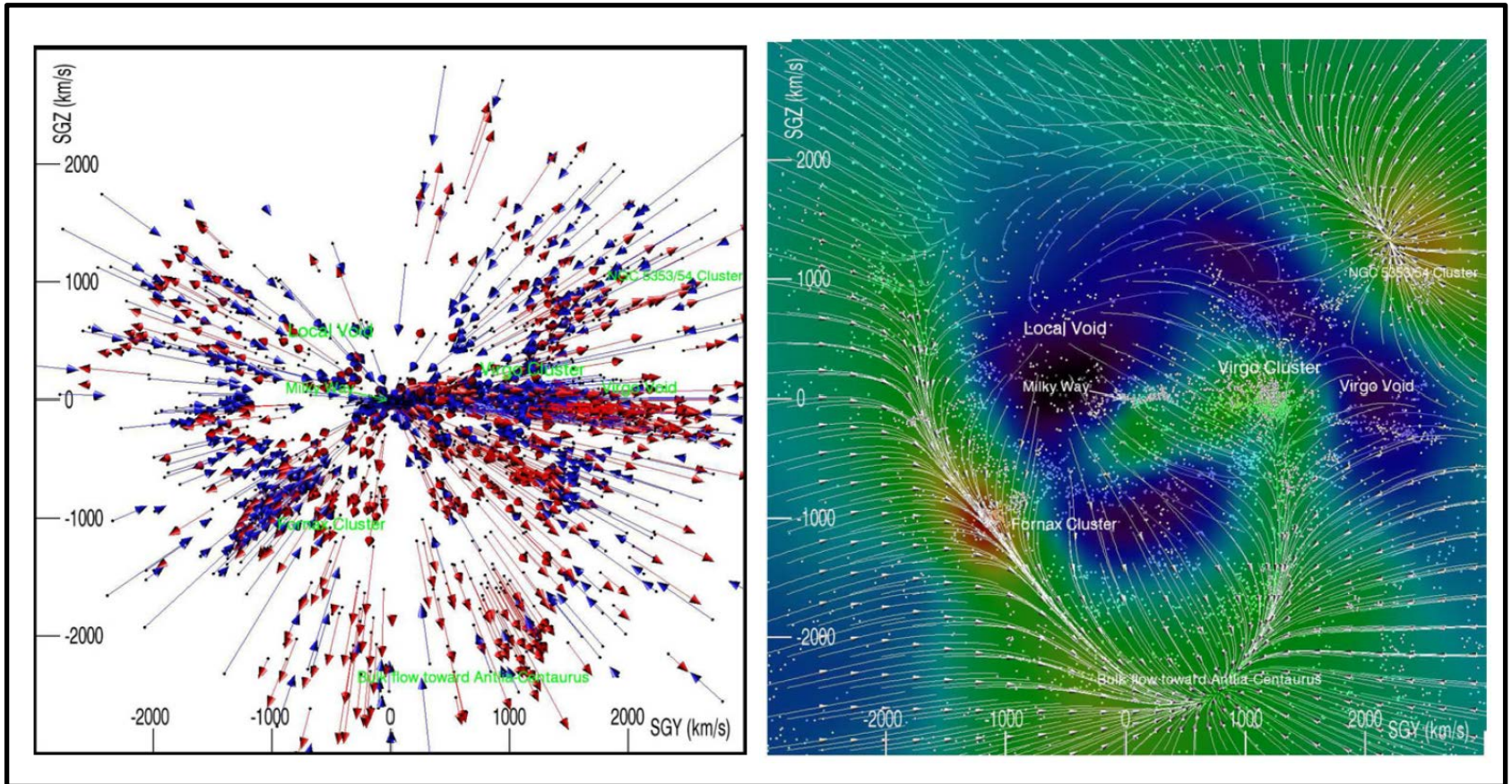
Our motion with the respect to galaxies in the Local Supercluster *Tully et al. 2008, ApJ, 676, 184*



Tully et al. 2008:  
Local Void pushes with  $\sim 260$  km/s against our local neighbourhood



# Local Void Outflow



**Courtois et al. 2013**  
**Local void expansion in Cosmoflows-2**

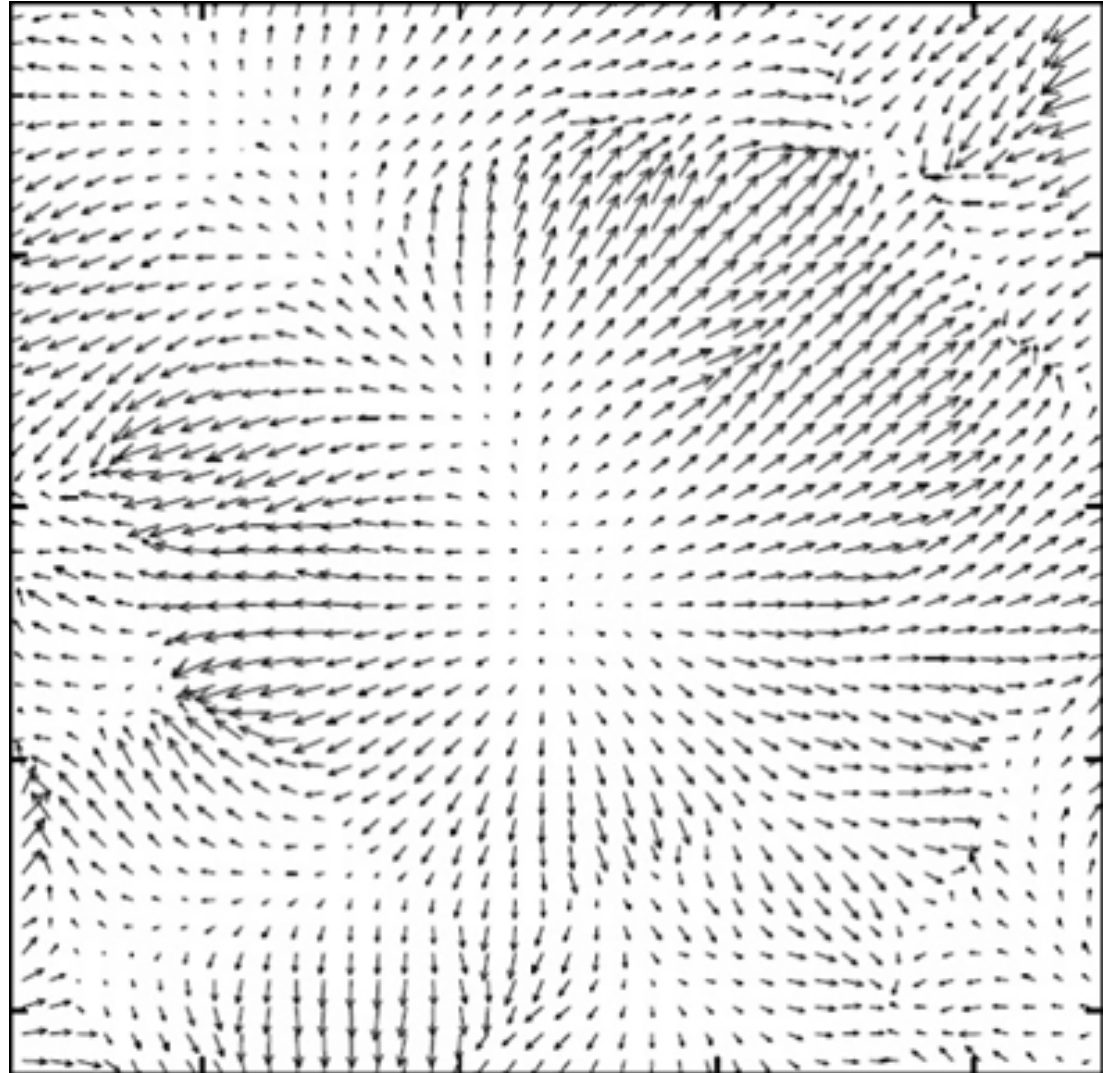
# Nonlinear Void Dynamics

Formation of Cosmic Web  
nonlinear process:

$$\nabla \cdot \vec{v} = \frac{3}{2} H a f(\Omega_m) \left\{ 1 - (1 + \delta(\vec{x}))^{2/3} \right\}$$

$$\nabla \cdot \vec{v} = -f(\Omega_m) \frac{\delta(\vec{x})}{1 + 0.18\delta(\vec{x})}$$

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



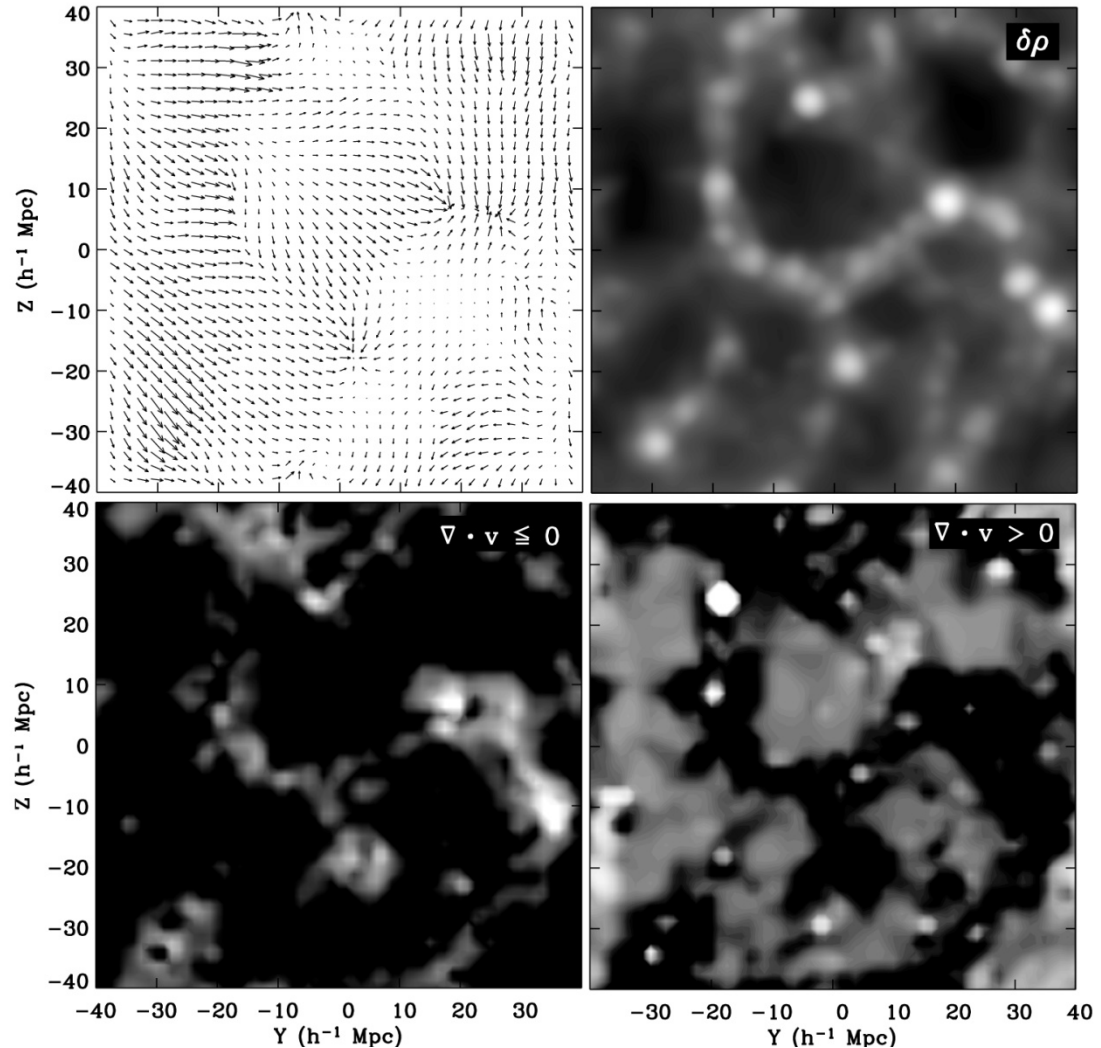
# Nonlinear Void Dynamics

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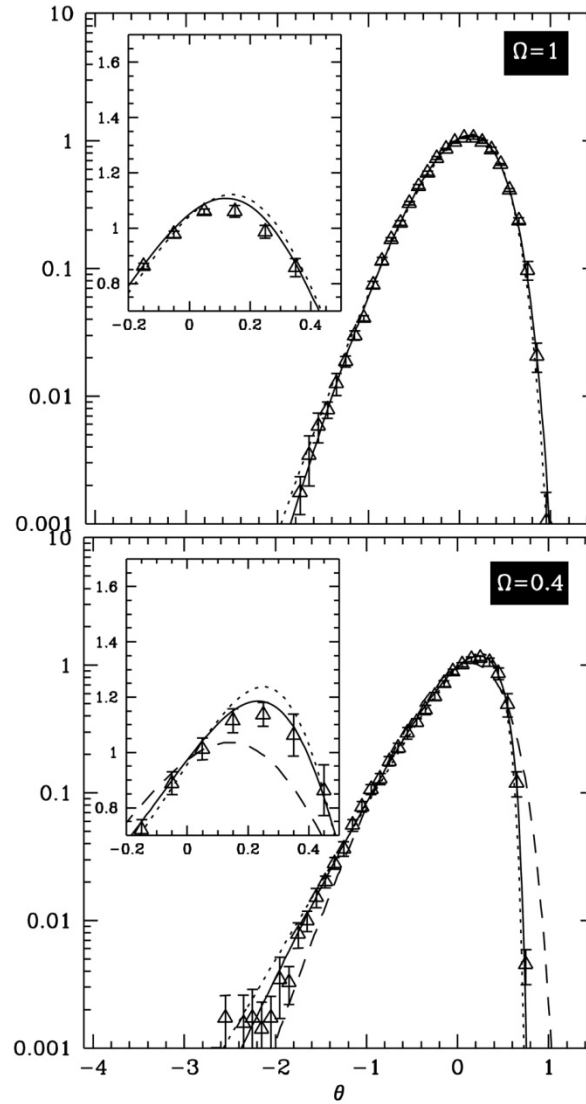
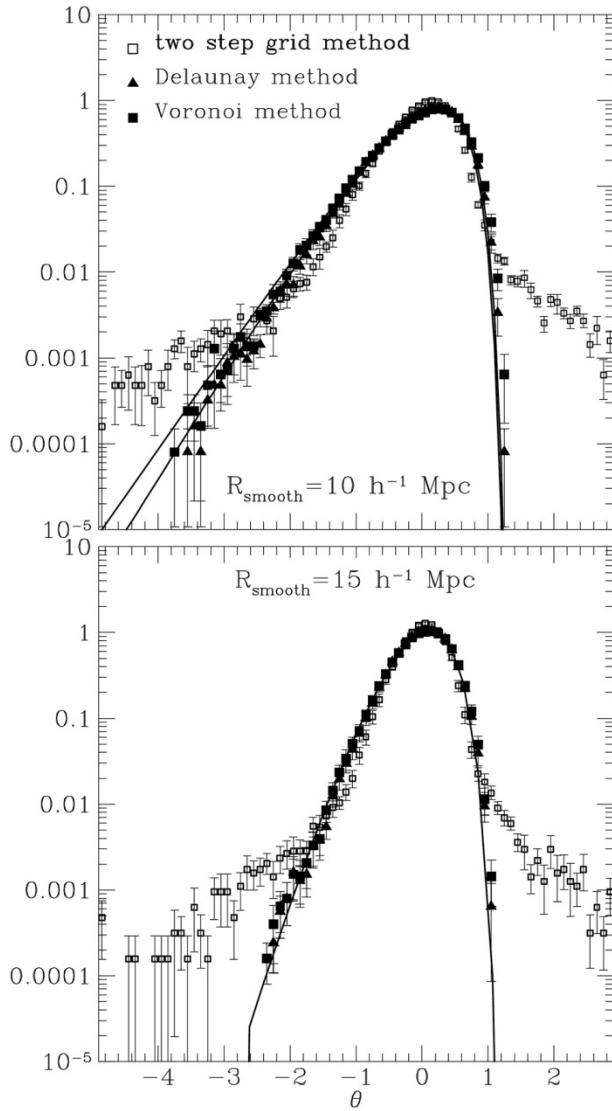
$$\nabla \cdot \vec{v} = \frac{3}{2} H a f(\Omega_m) \left\{ 1 - (1 + \delta(\vec{x}))^{2/3} \right\}$$

$$\nabla \cdot \vec{v} = -f(\Omega_m) \frac{\delta(\vec{x})}{1 + 0.18\delta(\vec{x})}$$

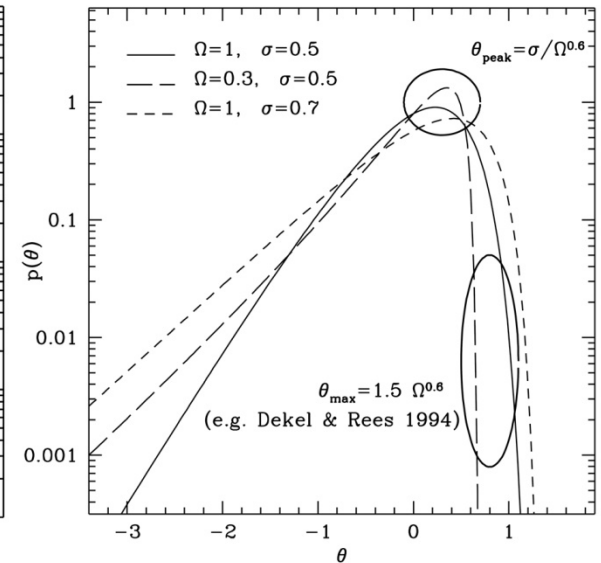
$$\theta = \frac{1}{H} (\nabla \cdot \vec{v}) \quad \Rightarrow \quad \theta_{\max} = 1.5\Omega^{0.6}$$



# DTFE Velocity Field Divergence



**Regions of positive velocity divergence:  
Outflow velocities mostly corresponding to underdense regions.**



# **Void Identification**

# the Watershed Void Finder

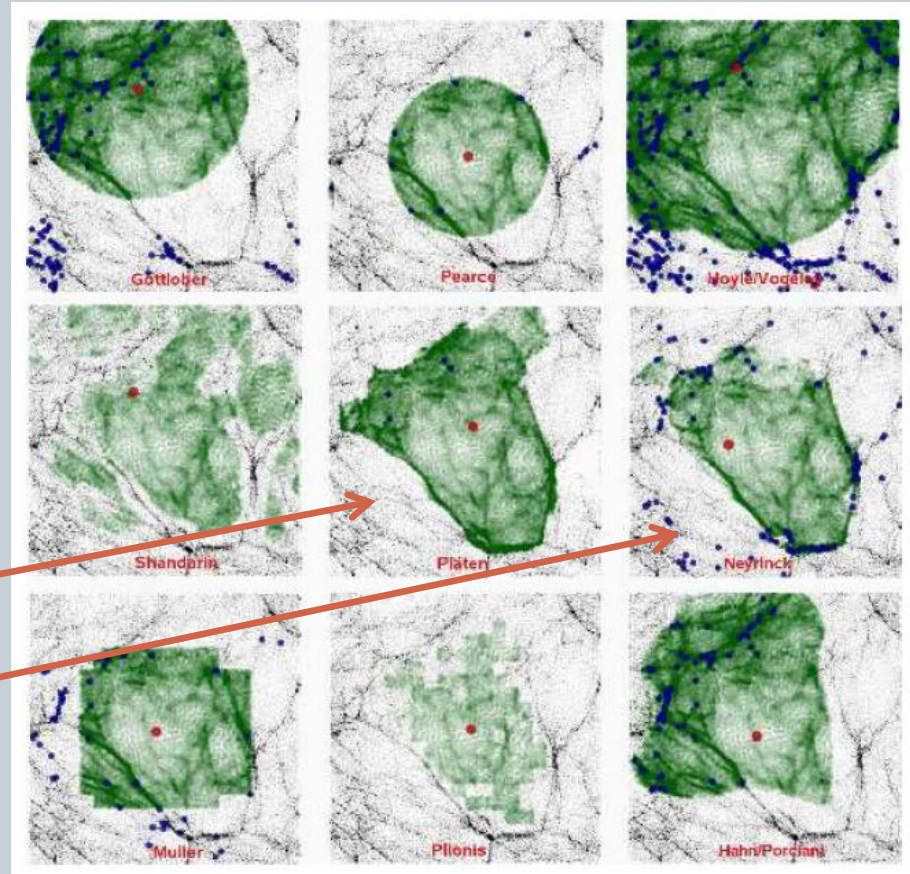
No exact definition of a void!  
→ broad range and variety of  
void detection techniques

Watershed void finders:

- closely follows real geometry  
cosmic web
- no assumptions geometry void
- no user defined parameters

→ Watershed Void Finder (WVF)  
by *Platen et al.*, 2007.

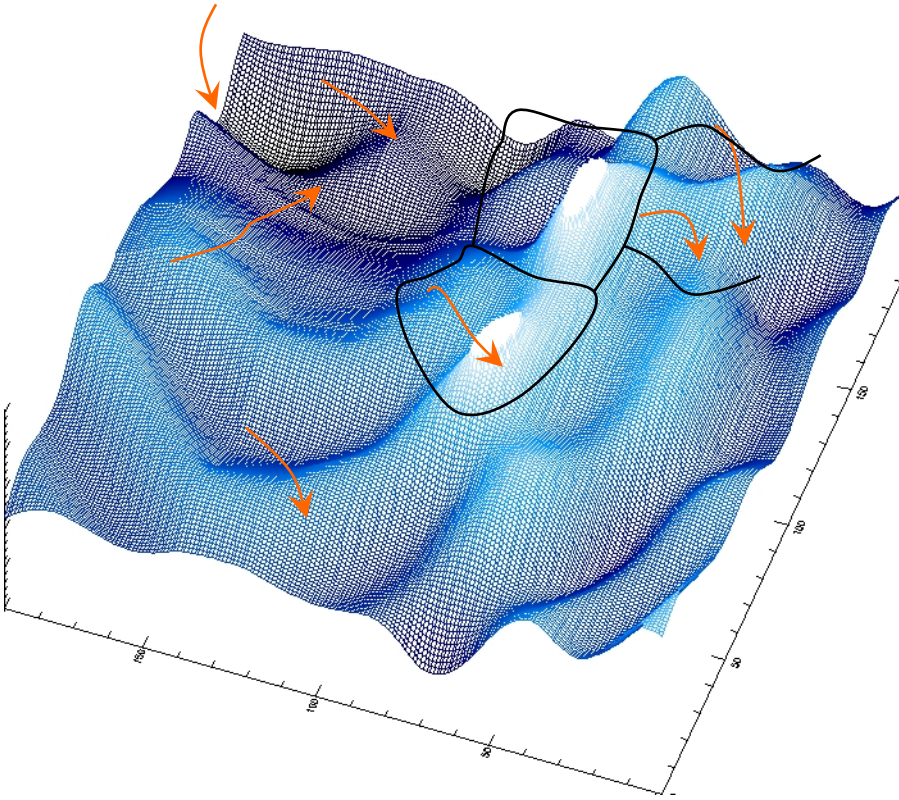
ZOBOV  
by *Neyrinck*, 2008



*Colberg et al.*, 2008  
Void Comparison Project

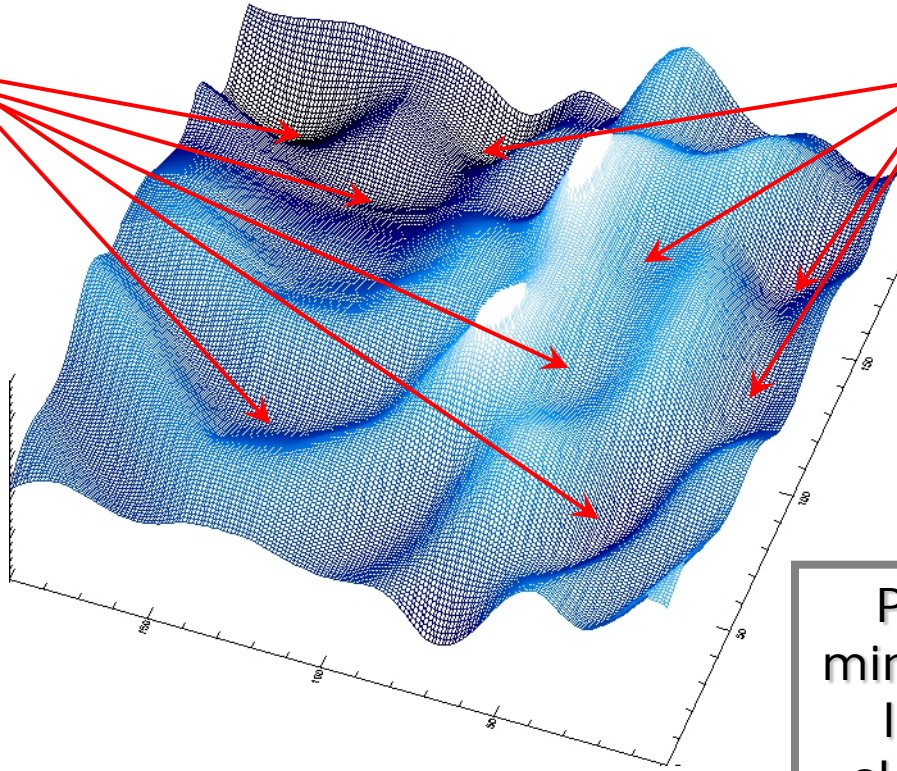
Following the water-flow into the distinct catchment basins.

Each basin belonging to one individual minima defines one region



# Surface of Density Field

Local  
Minima



Local  
Minima

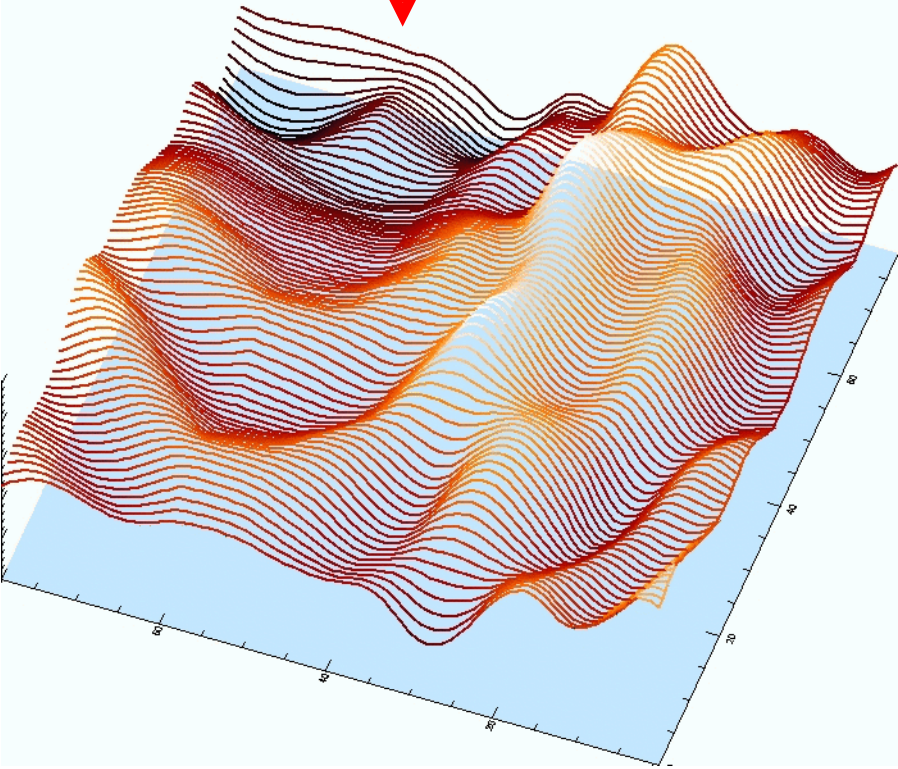
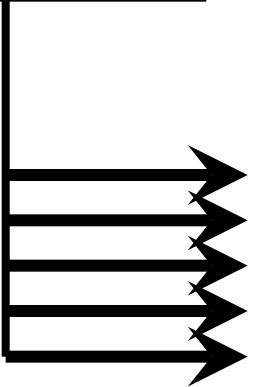
Pierce the local  
minima, and let the  
landscape sink  
slowly in a tub of  
water



Every time two different flooding basins meet we draw a dividing wall

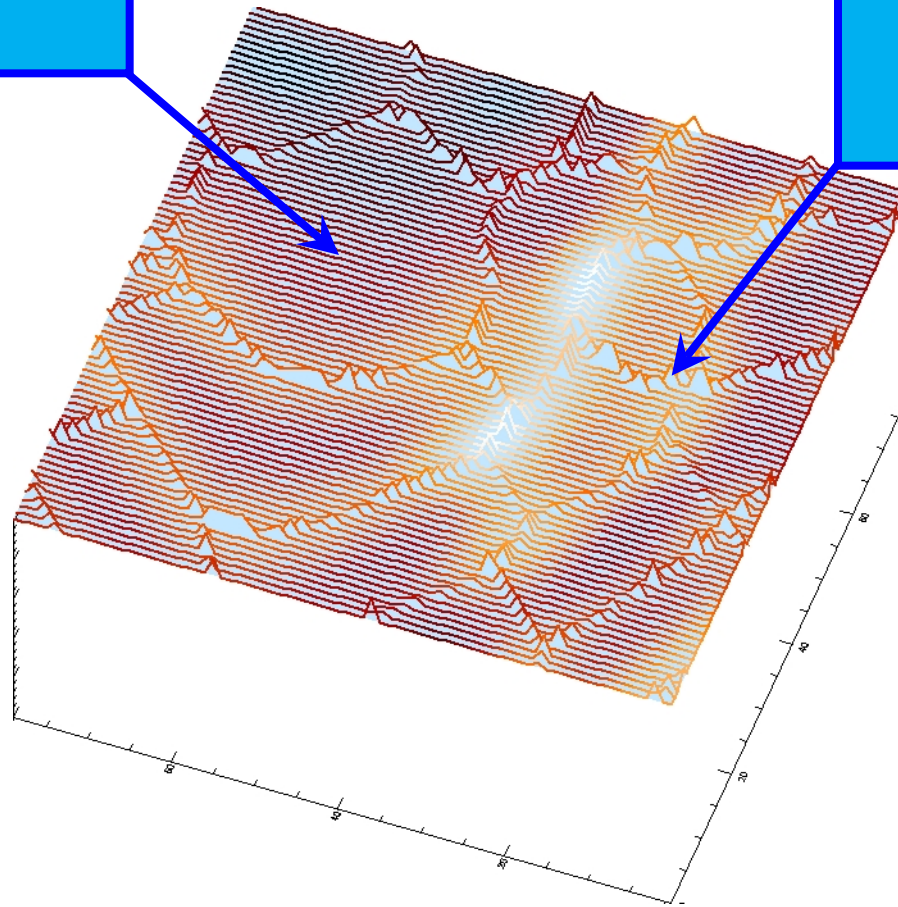


Flooding the Density Field



Void  
Patches

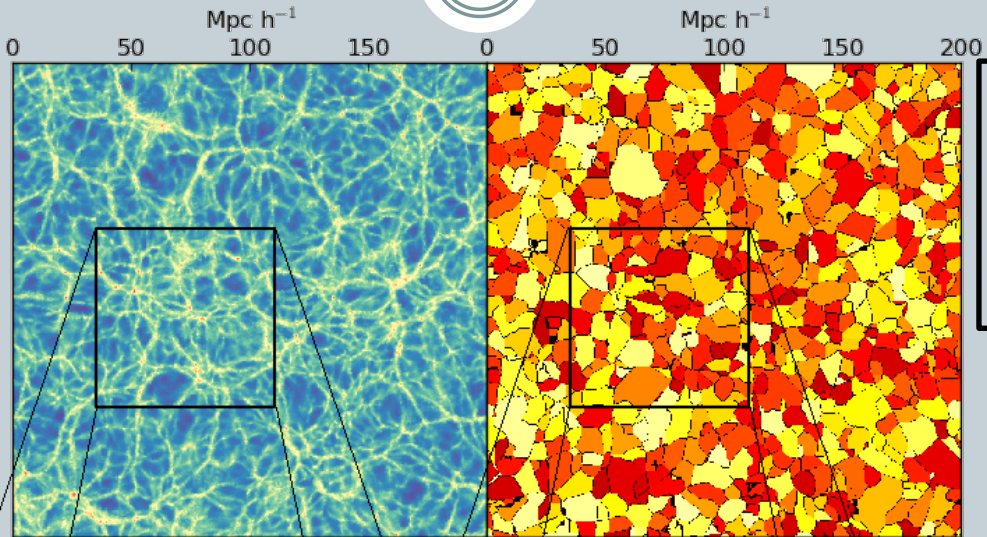
Final  
segmentation  
lines



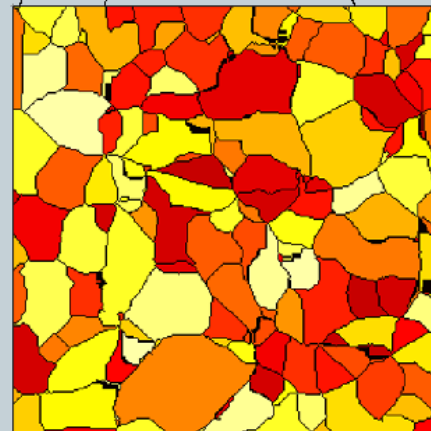
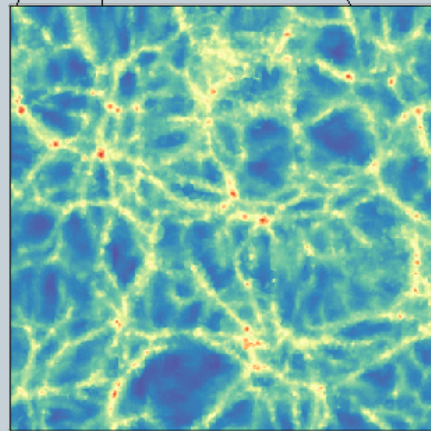
# WVF: Watershed Void Finder



**DTFE**  
(Delaunay Tessellation  
Field Estimator)  
density field landscape



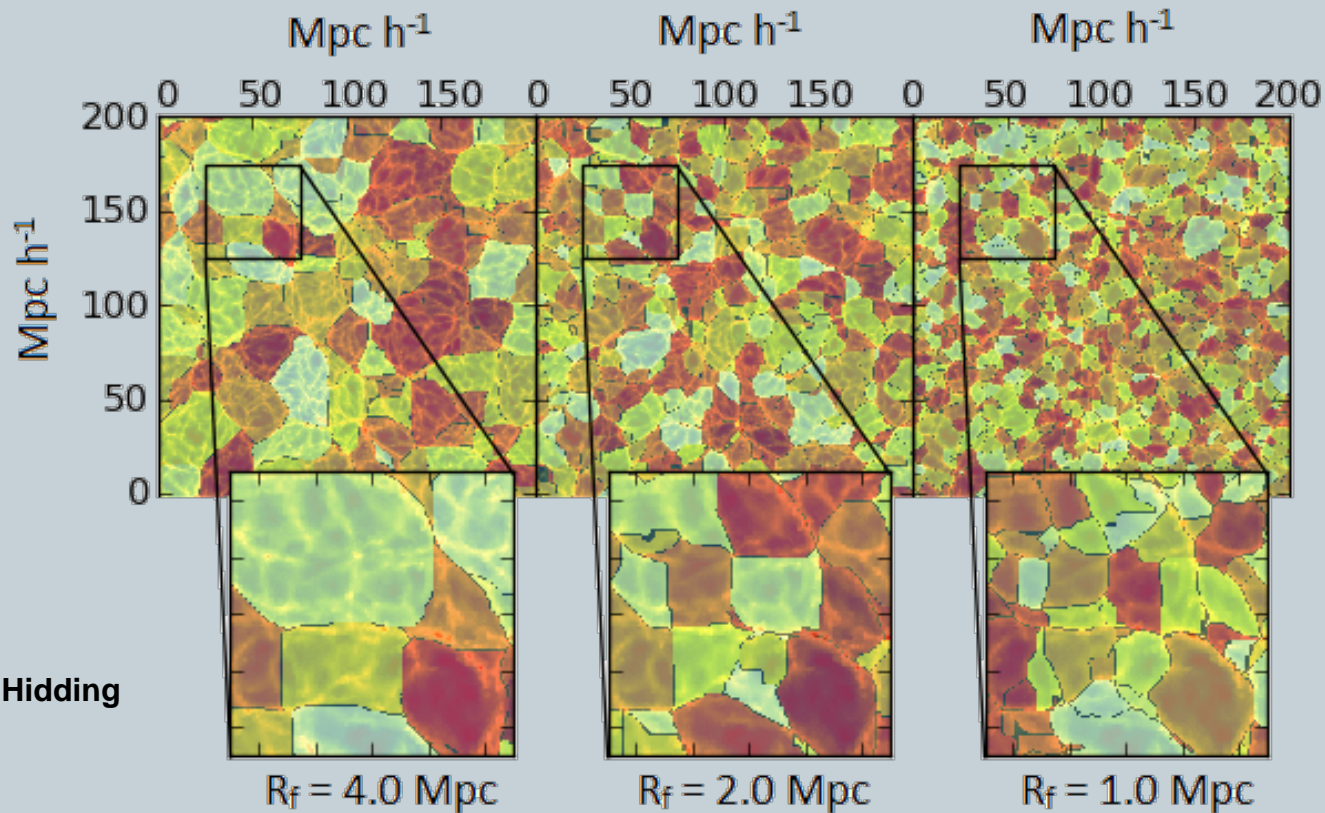
**WVF**  
watershed transform



# The Multiscale Watershed Void Finder

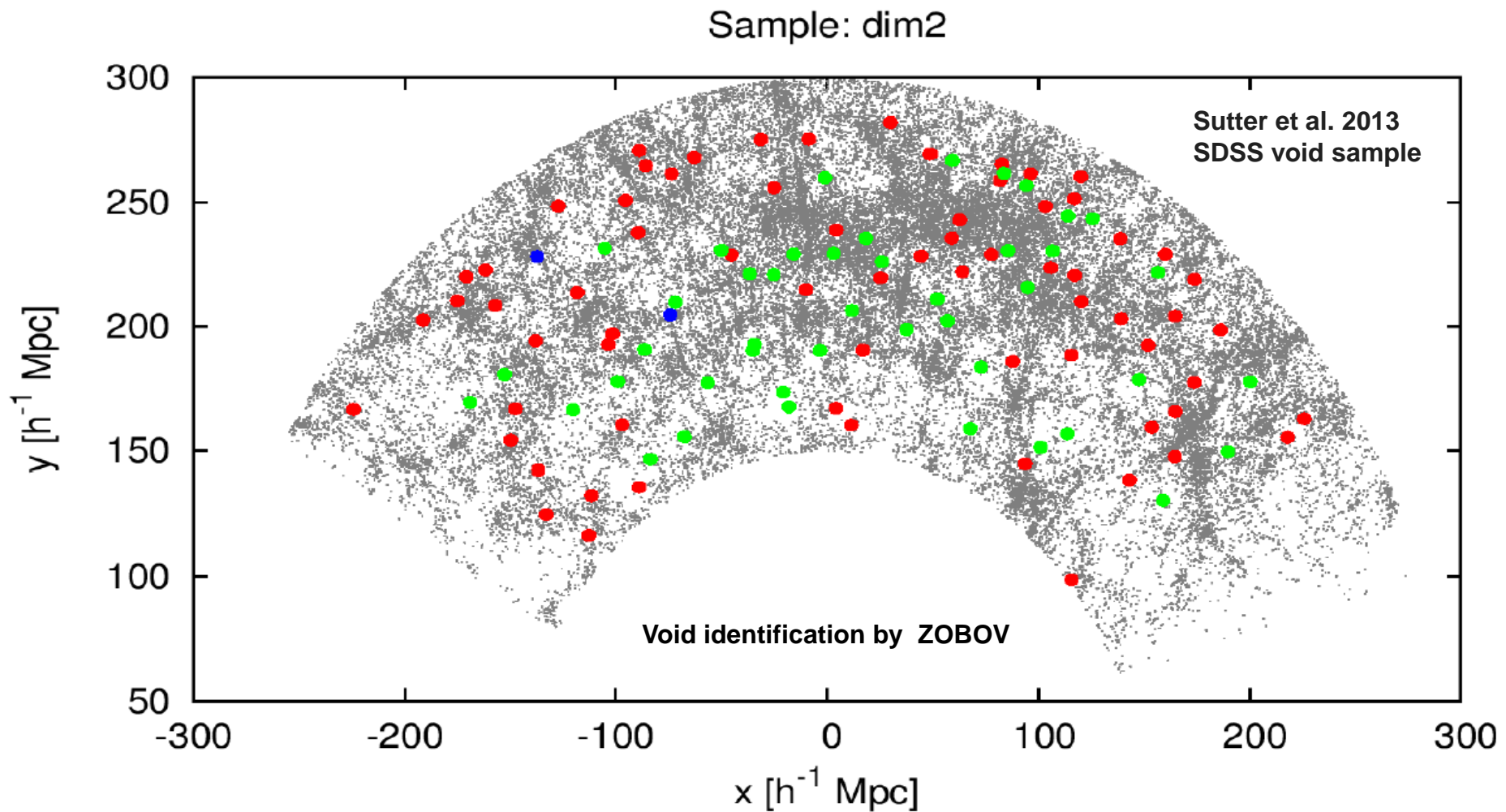


Multiscale void population:  
void population as a function of filter radius



# **Void Catalogues**

# SDSS Void Sample



$R = 5-15 h^{-1}$  Mpc  
 $R = 15-25 h^{-1}$  Mpc



$R = 25-45 h^{-1}$  Mpc



# Choosing emptiness criterion



Observational void sizes depend strongly on galaxy sample used to define voids

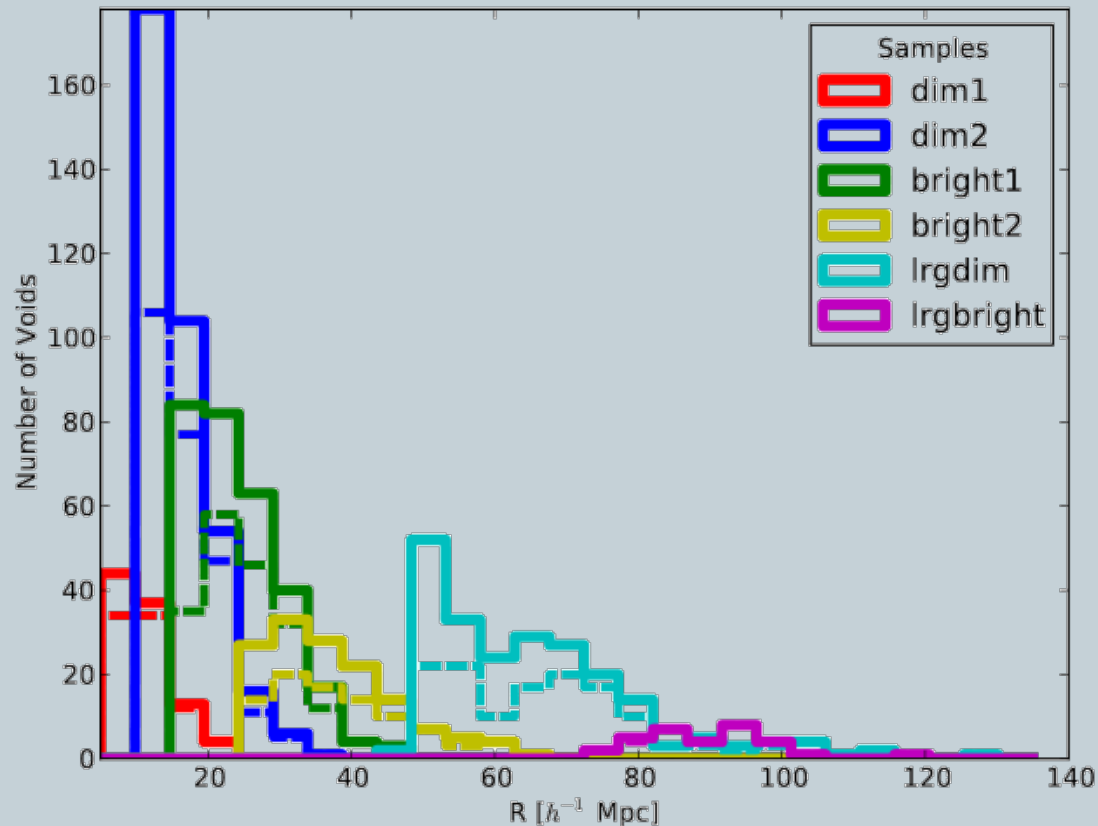


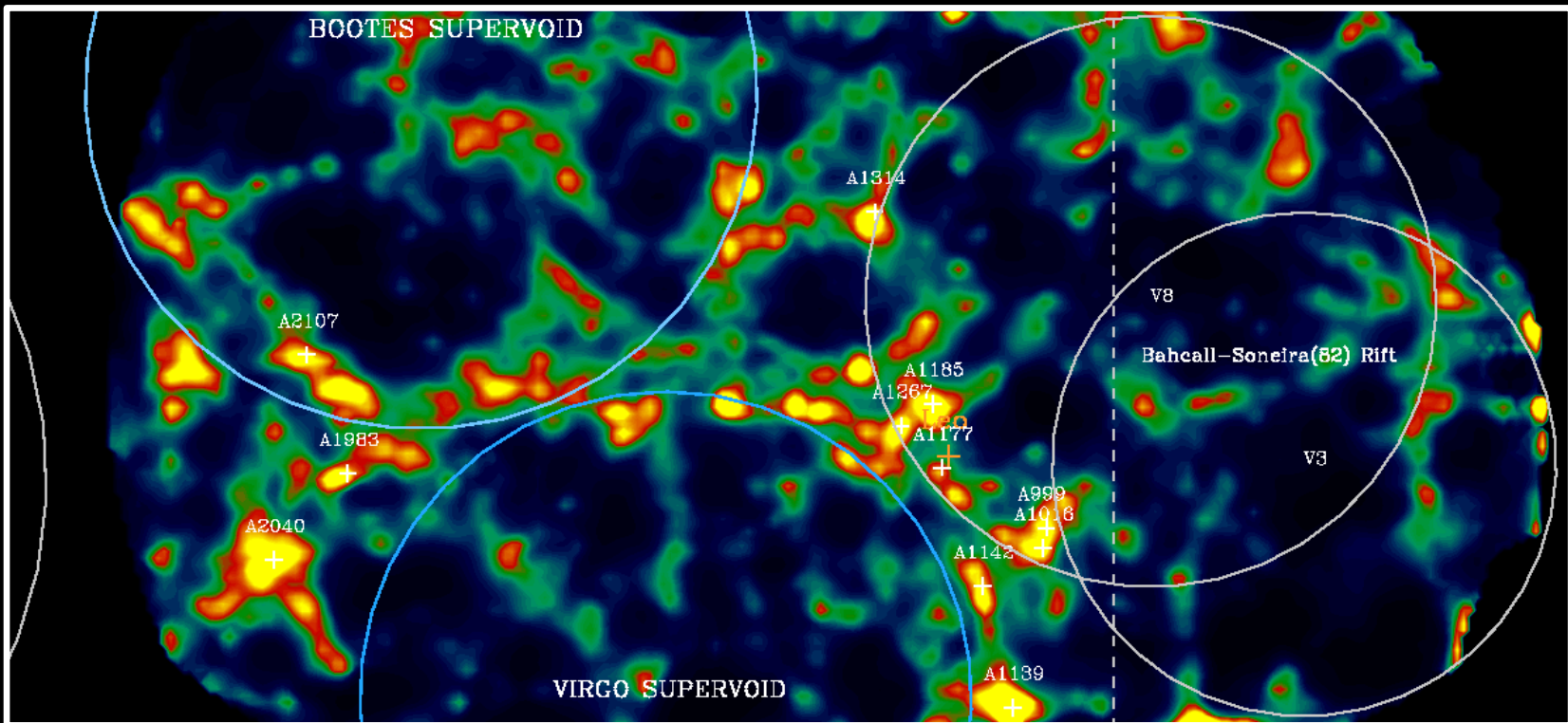
Figure from *Sutter et al., 2013*

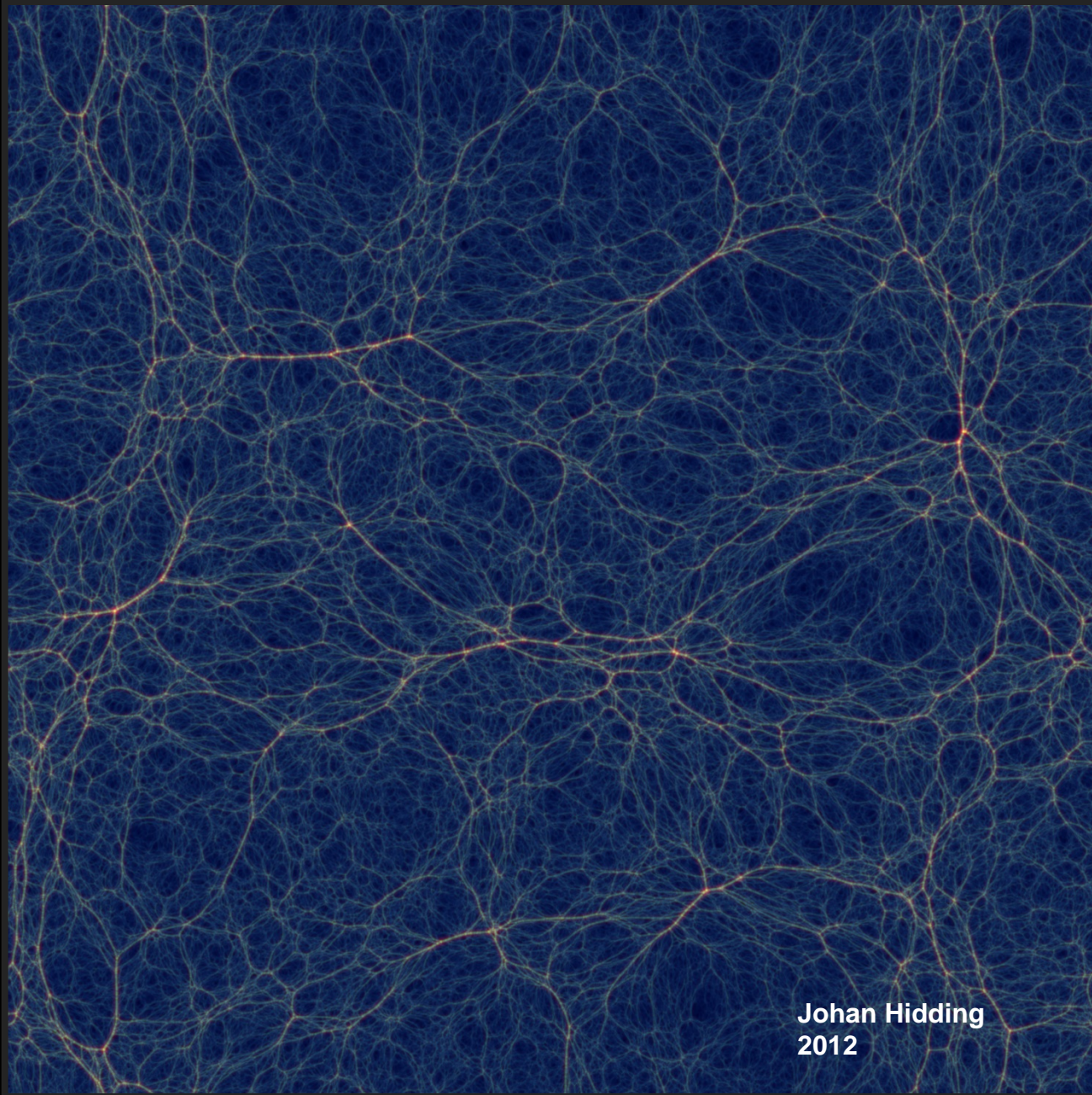
**Voids:**

**Multiscale Infrastructure**



# Bootes Void: Substructure





Johan Hidding  
2012

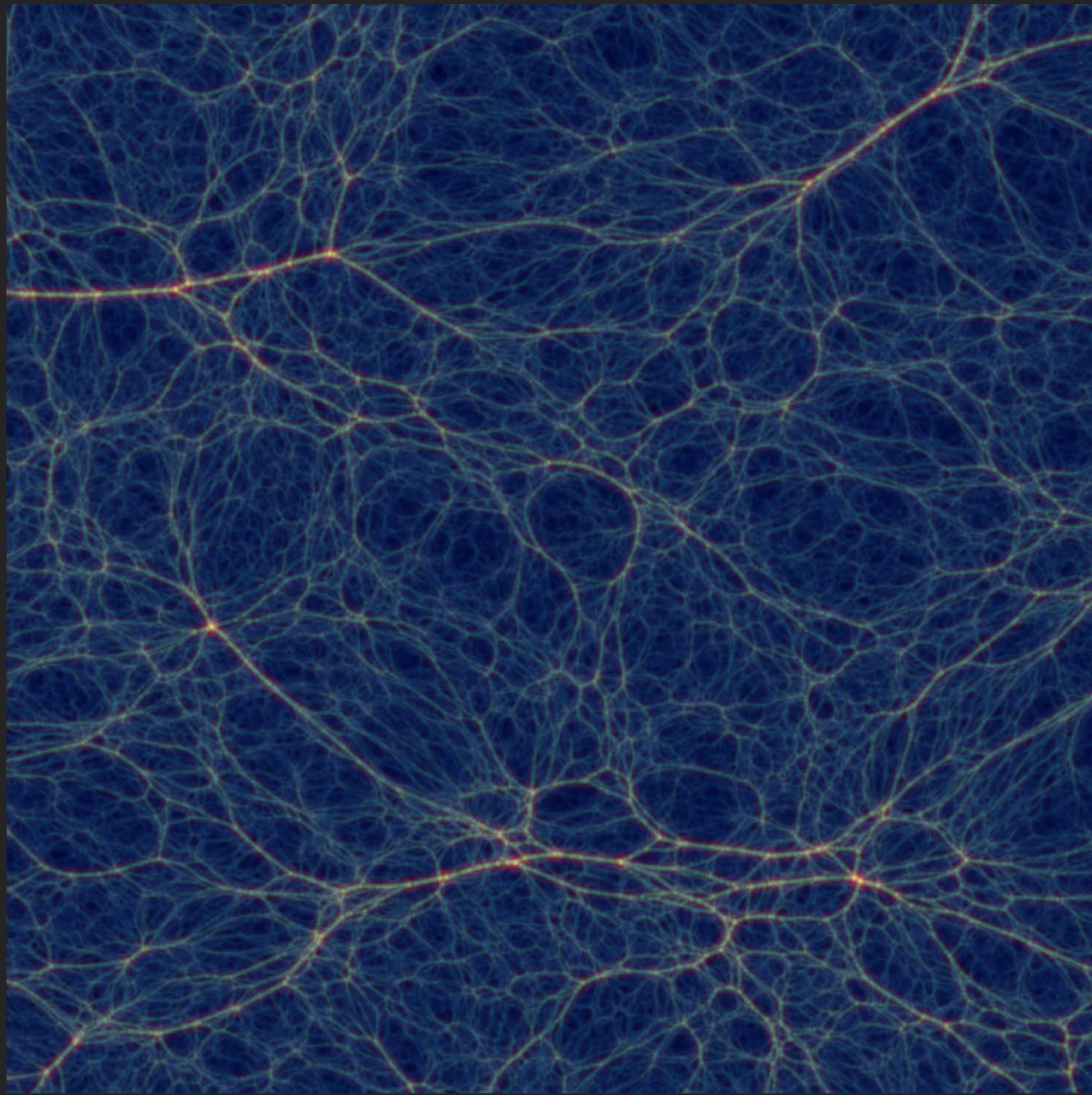
**Multiscale  
Infrastructure**

**Voids:**



**manifestation**

**Hierarchical  
Buildup of  
Voids**



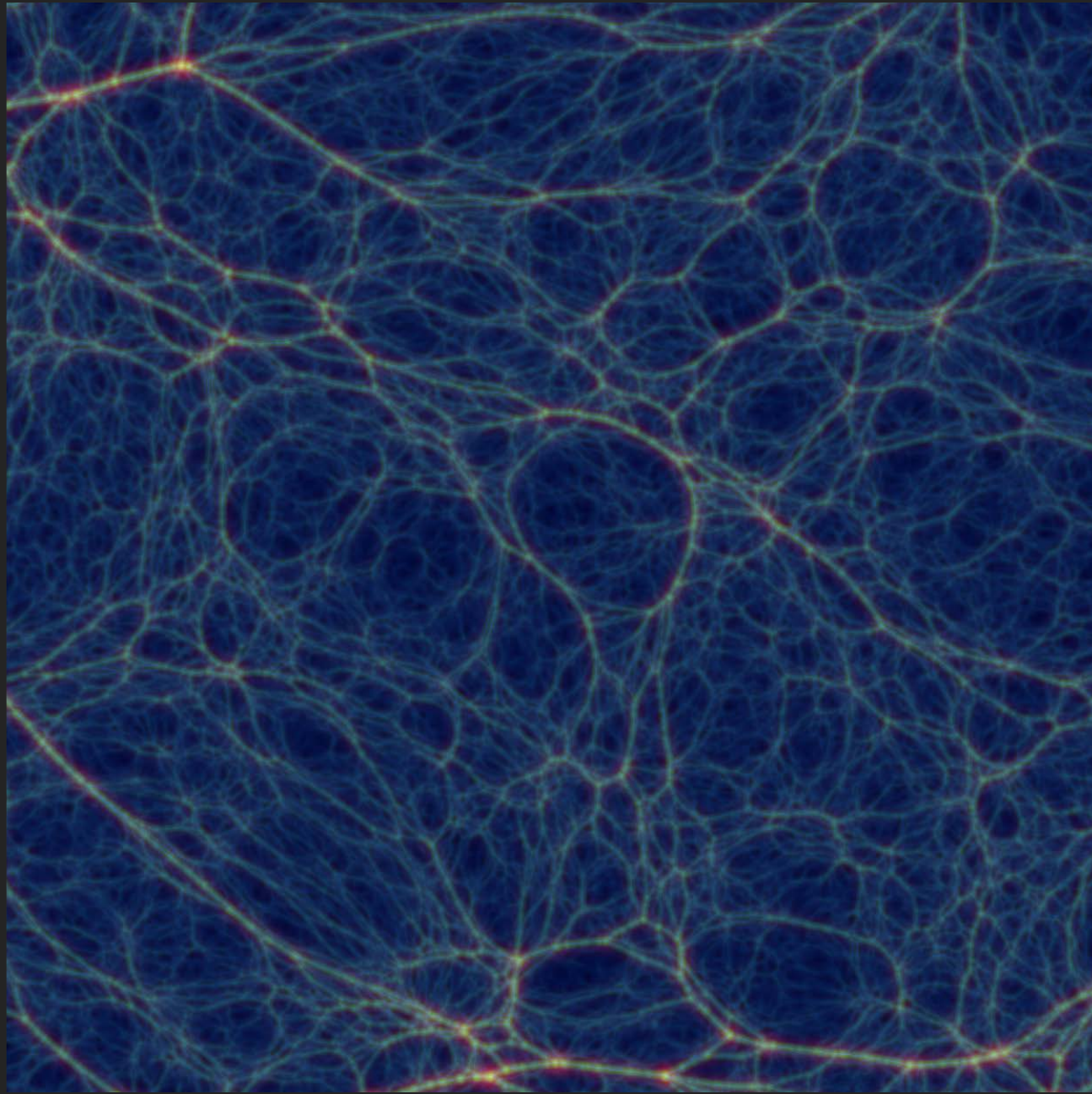
**Multiscale  
Infrastructure**

**Voids:**



**manifestation**

**Hierarchical  
Buildup of  
Voids**



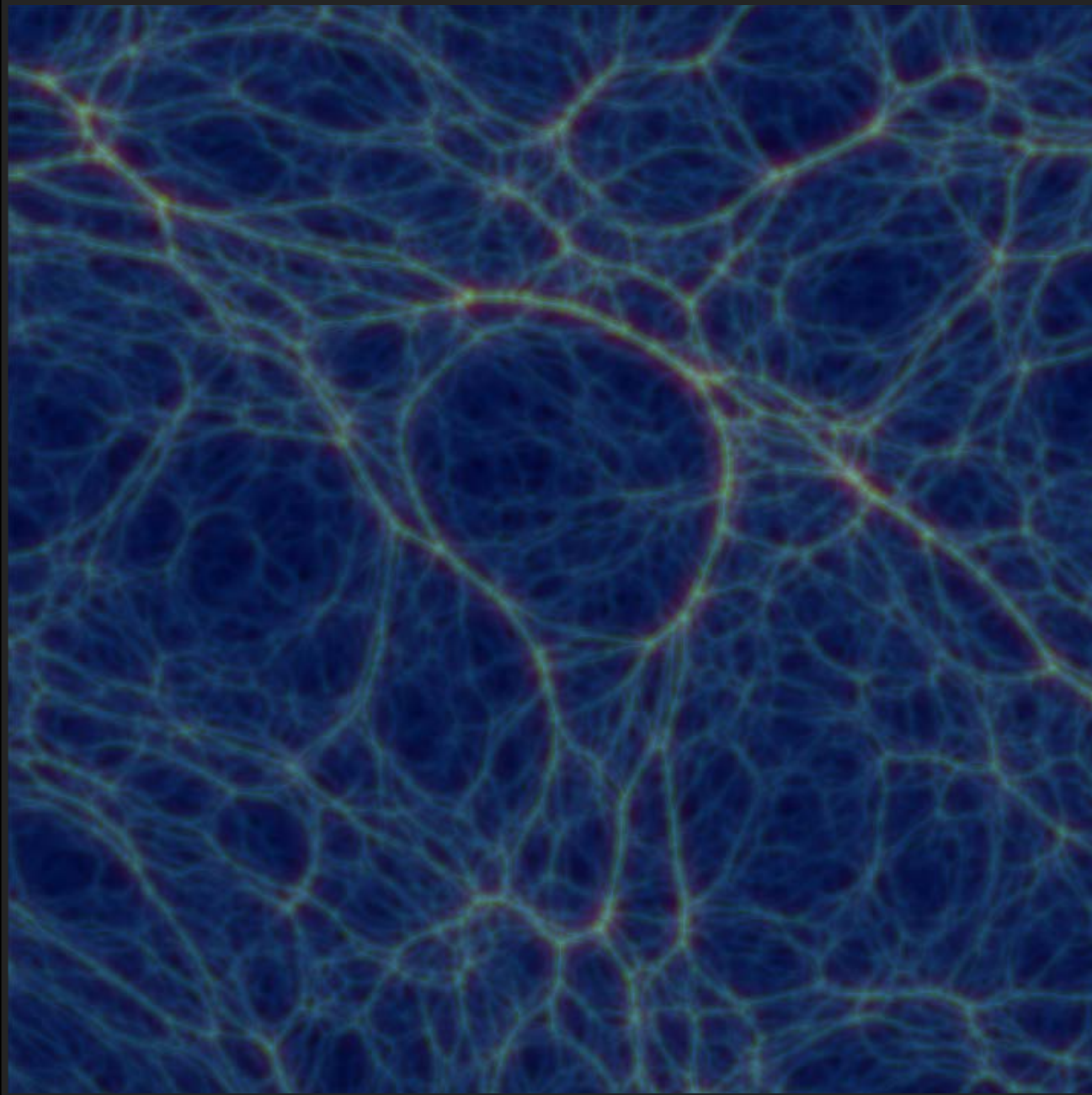
**Multiscale  
Infrastructure**

**Voids:**



**manifestation**

**Hierarchical  
Buildup of  
Voids**



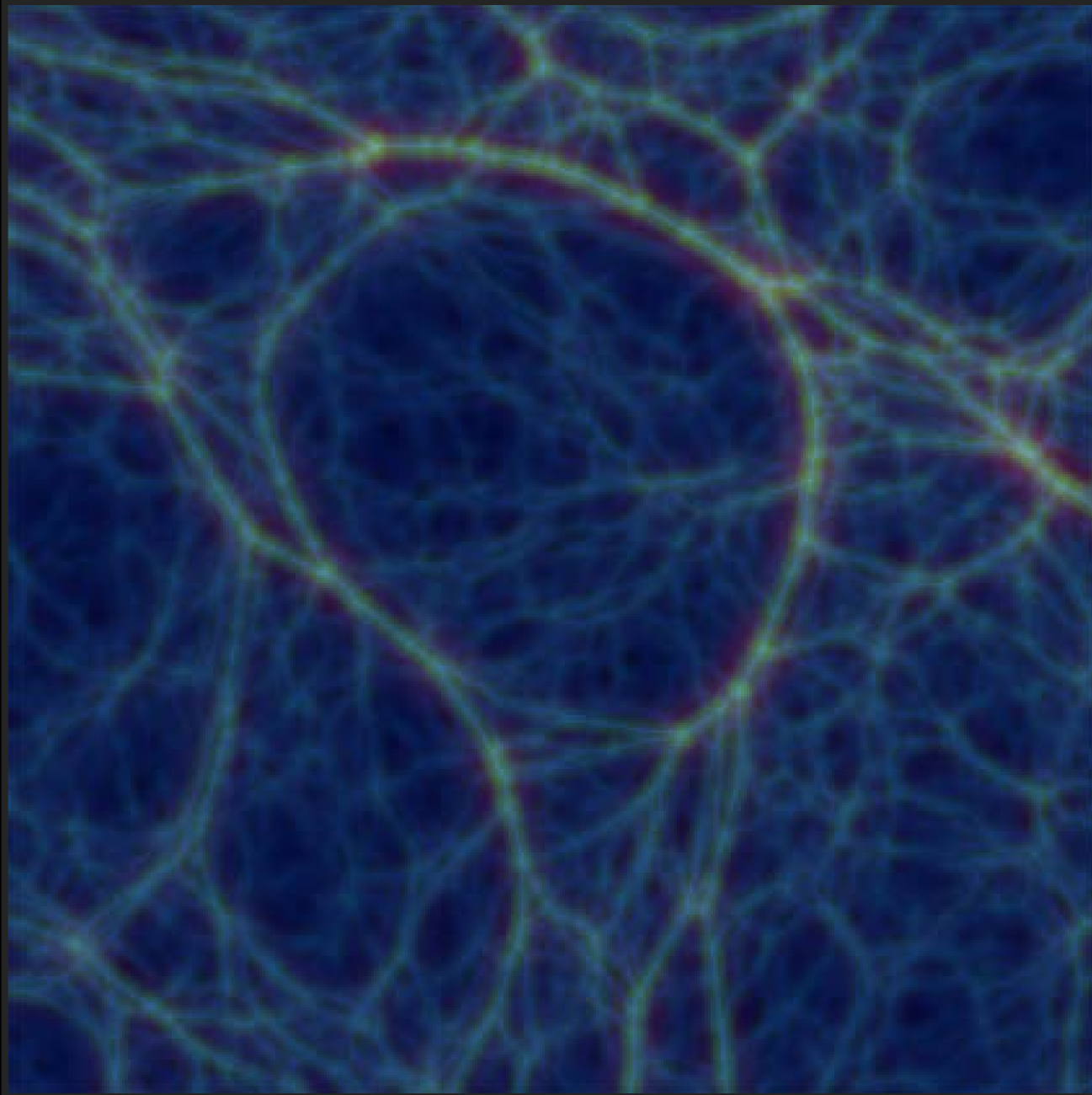
**Multiscale  
Infrastructure**

**Voids:**



**manifestation**

**Hierarchical  
Buildup of  
Voids**



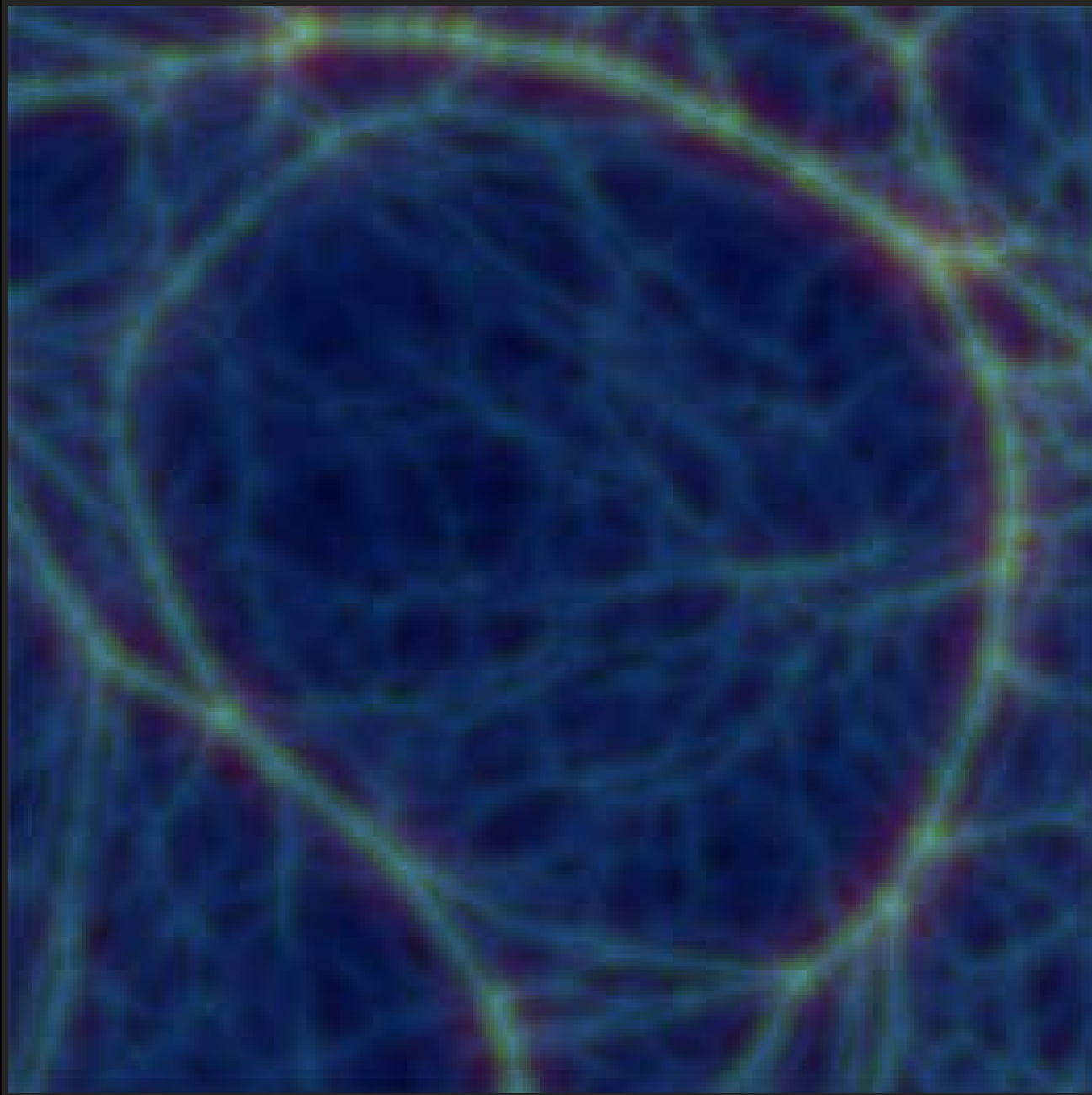
**Multiscale  
Infrastructure**

**Voids:**



**manifestation**

**Hierarchical  
Buildup of  
Voids**



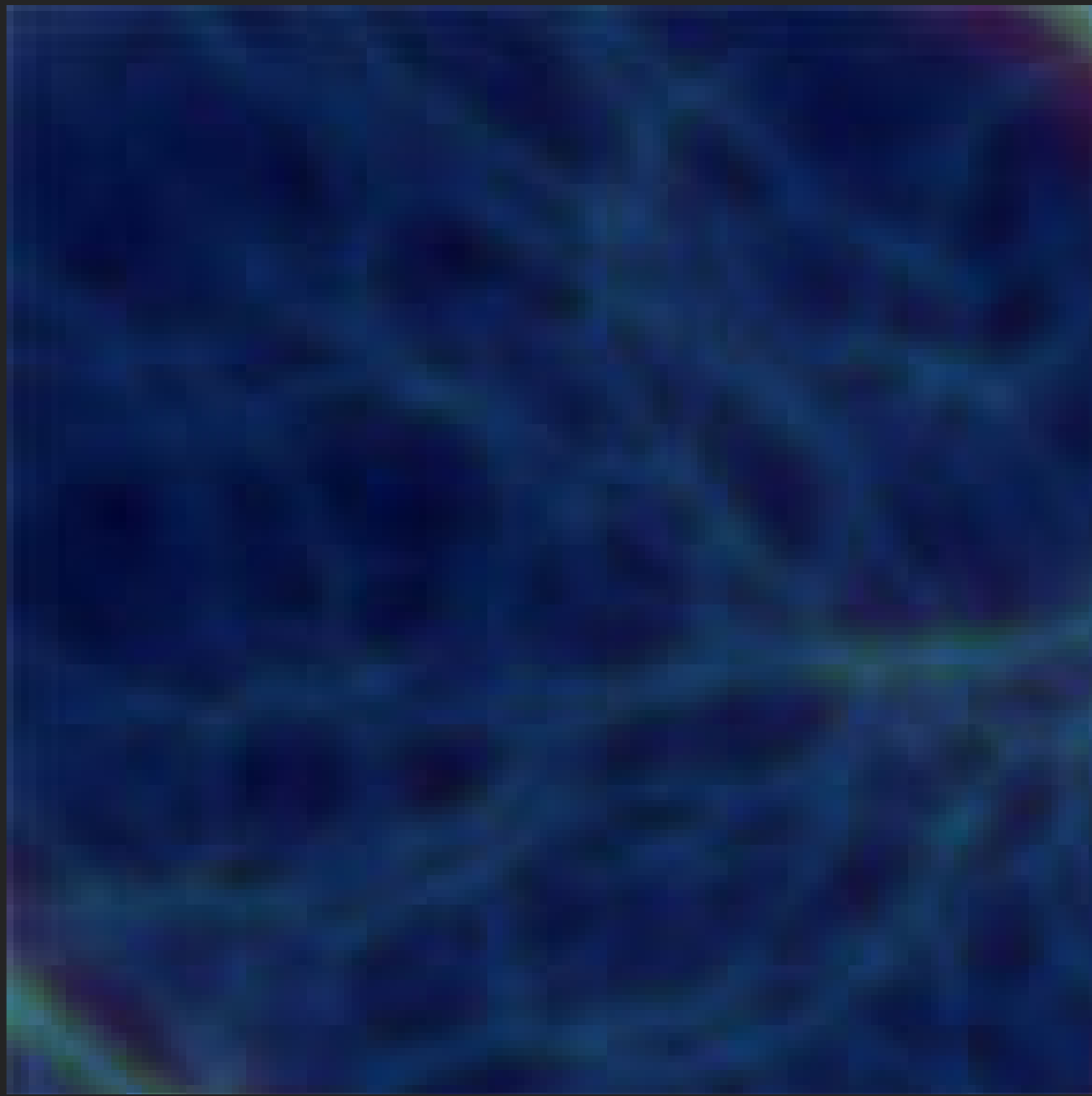
**Multiscale  
Infrastructure**

**Voids:**



**manifestation**

**Hierarchical  
Buildup of  
Voids**



**Multiscale  
Infrastructure**

**Voids:**



**manifestation**

**Hierarchical  
Buildup of  
Voids**



**Multiscale  
Infrastructure**

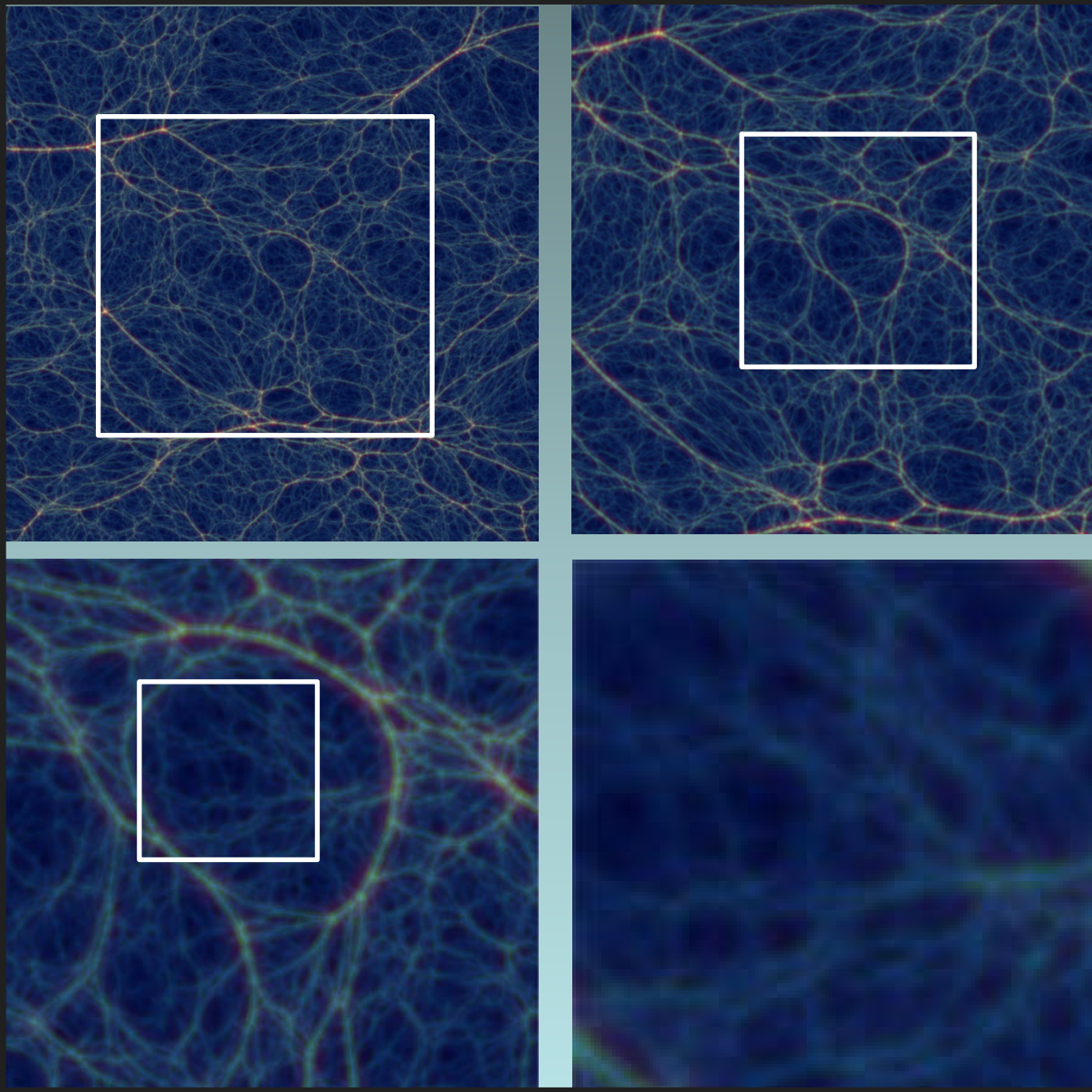
**Voids:**



**manifestation**

**Hierarchical  
Buildup of  
Voids**

# Void Substructure



Zoom in: 3 levels

Substructure on  
all scales:

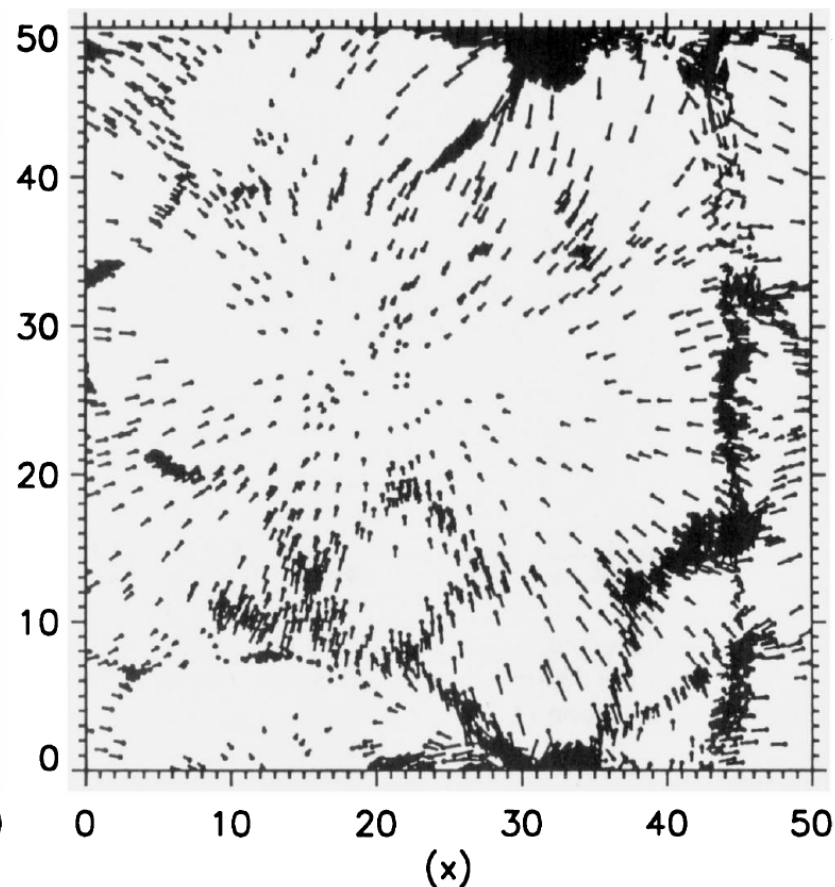
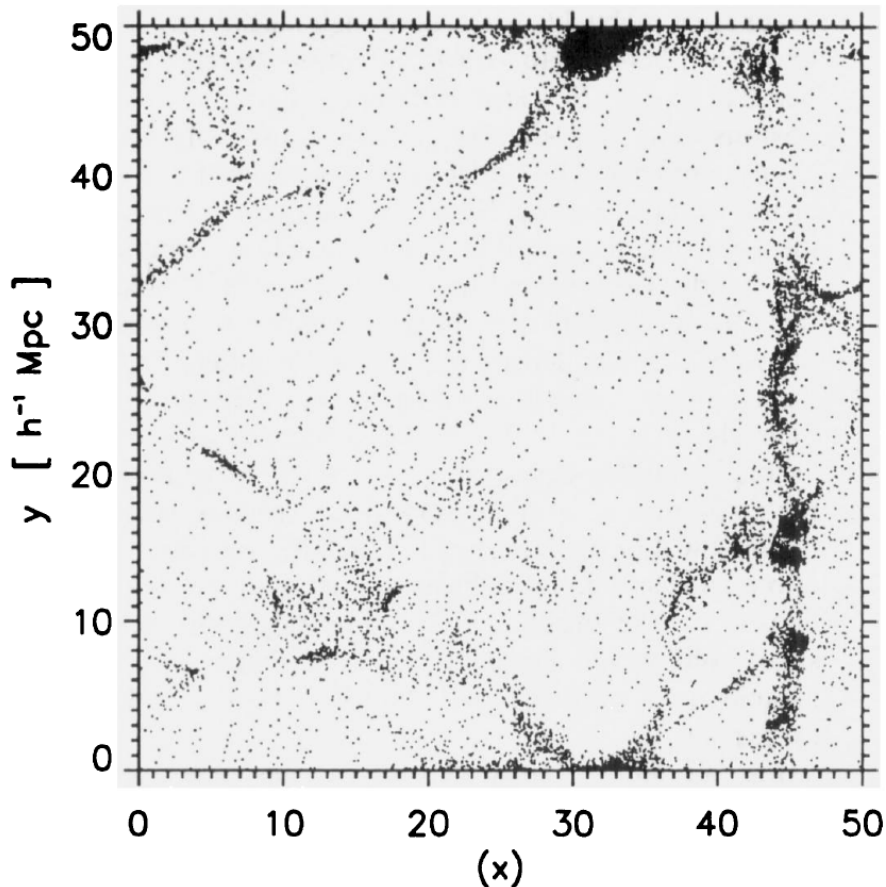
amplitude  
diminishing towards  
smaller scales

# Void Hierarchy

# Void Hierarchy

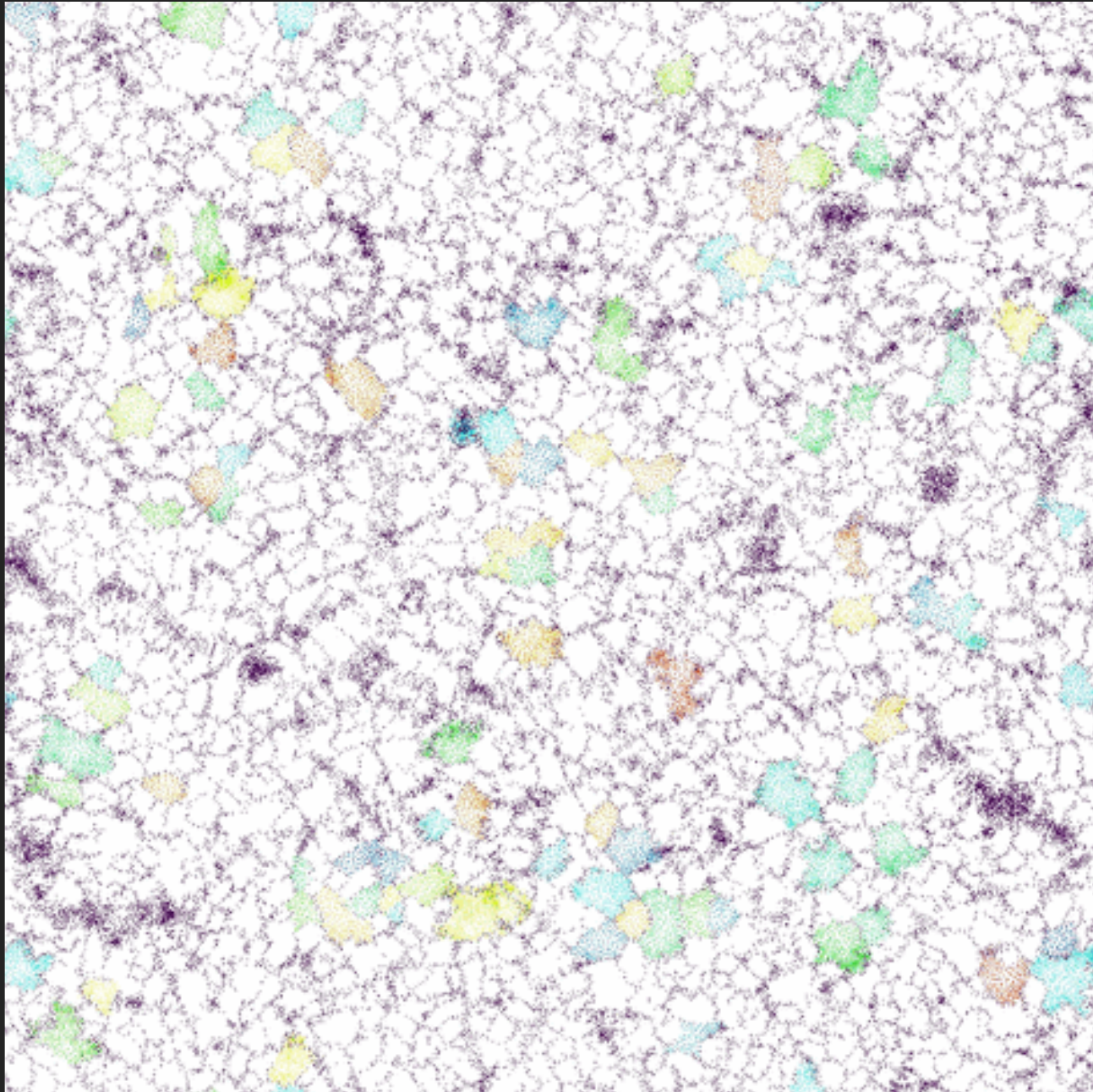
Void formation: - via gradual merging of voids  
- demolition of small voids

Dubinski et al. 1993  
Van de Weygaert & van Kampen 1993



Constrained Void Simulations:  
Van de Weygaert 1991  
vdW & van Kampen 1993

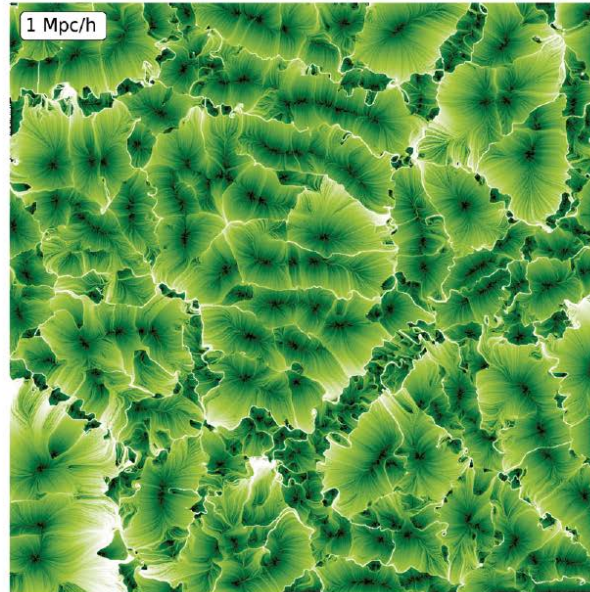
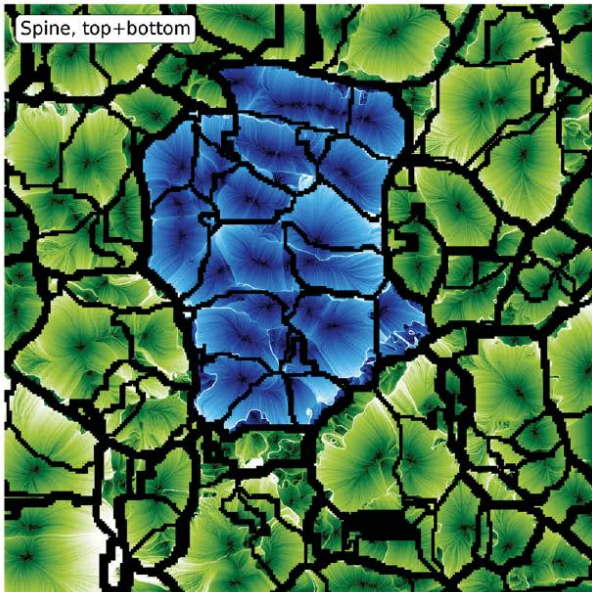
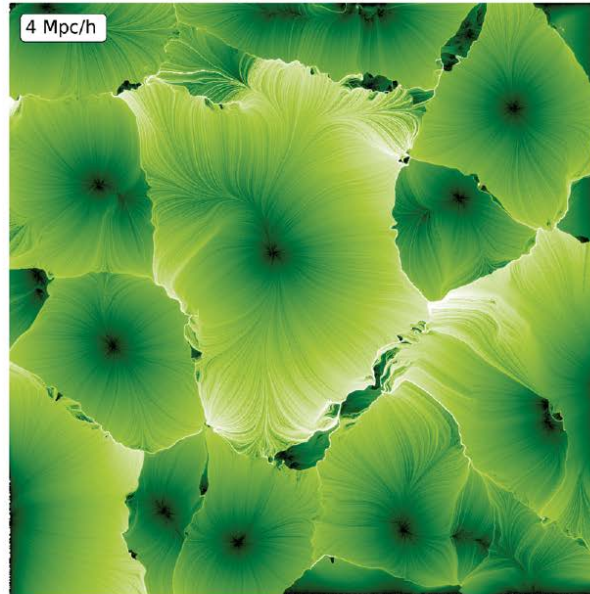
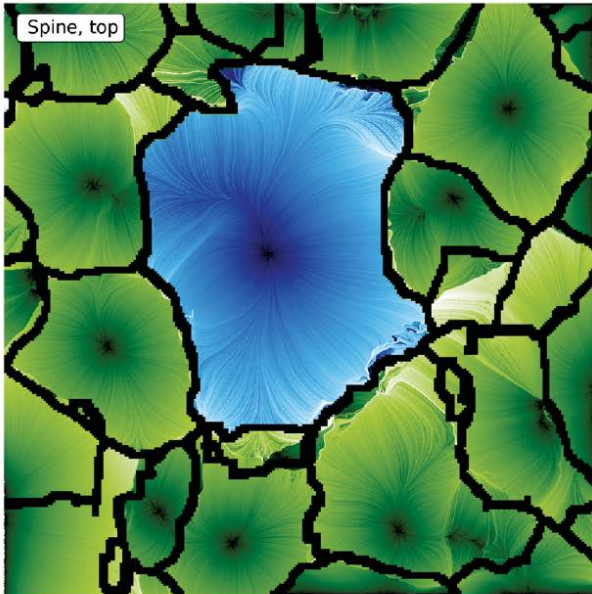
CRF formalism:  
Bertschinger 1987  
vdW & Bertschinger 1996



# Hierarchical Web Evolution:

“Lagrangian” view:  
development and fate  
patterns LSS

Platen & vdW 2004




# Hierarchical Web Evolution:

Void hierarchy  
expressed in  
multiscale structure  
velocity outflow

Aragon-Calvo & Szalay 2012

# Void Dichotomy

- Voids emerge out of primordial Gaussian density depressions
- Primordial Gaussian Density Field:  
symmetry overdense  underdense
- Why is void population:  
Not dominated by small voids ?  
What happened to (PS) hierarchy ?

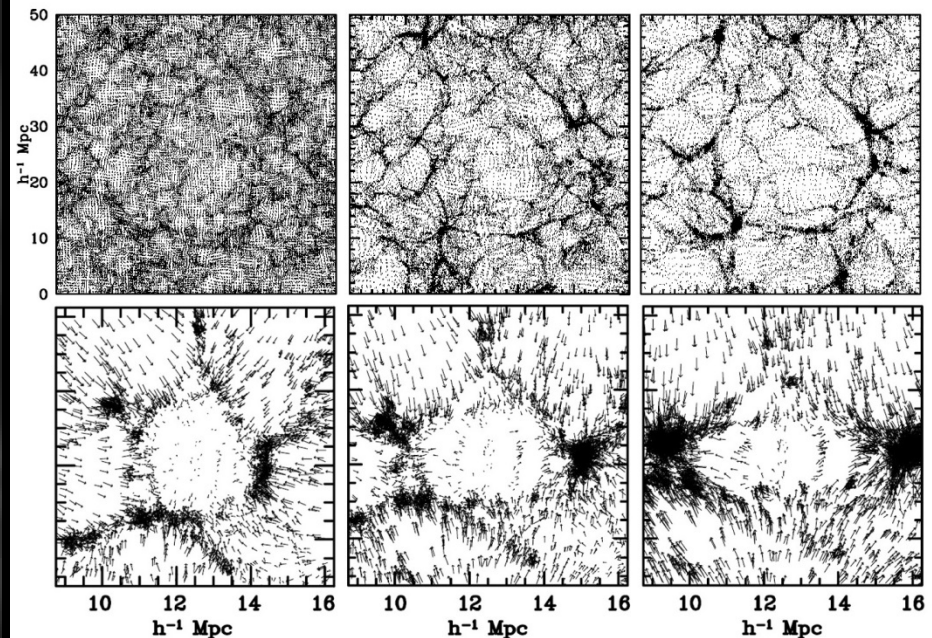
# Void Evolution Processes

- **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...



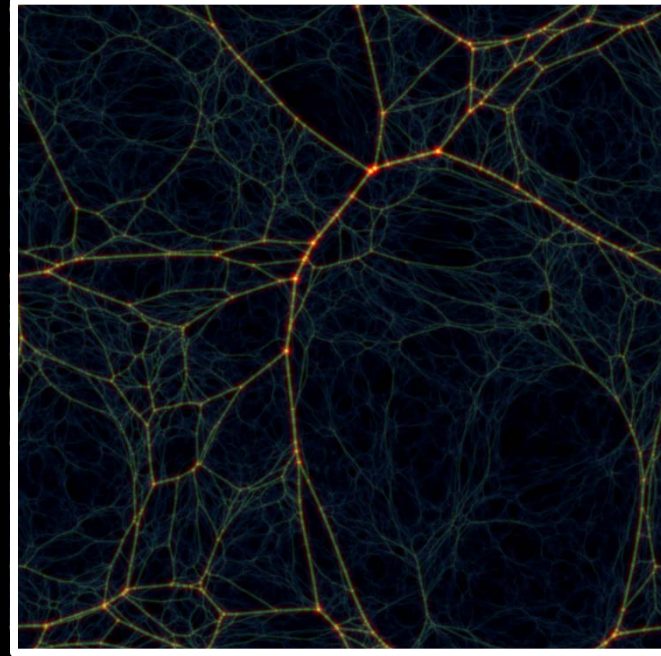
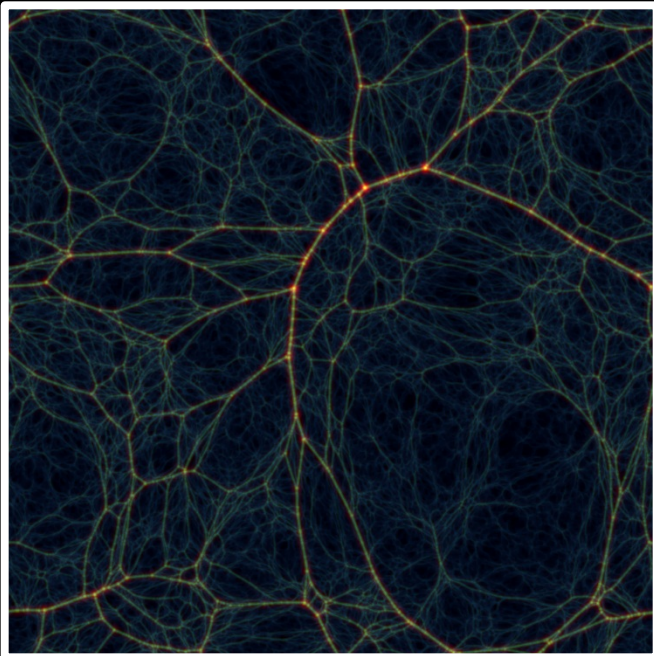
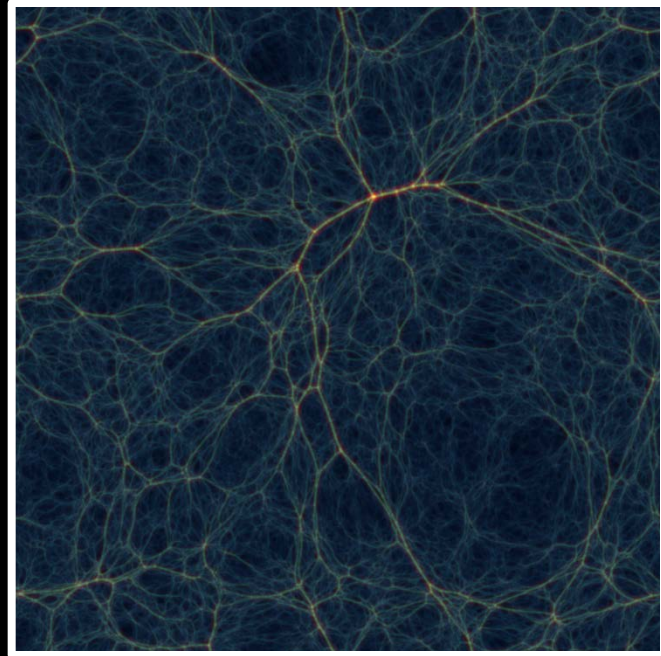
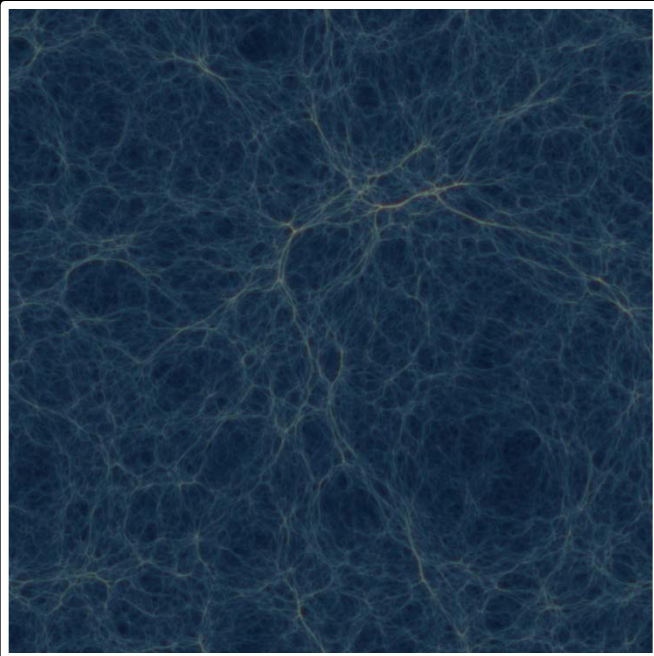


# **Hierarchical Web Evolution:**

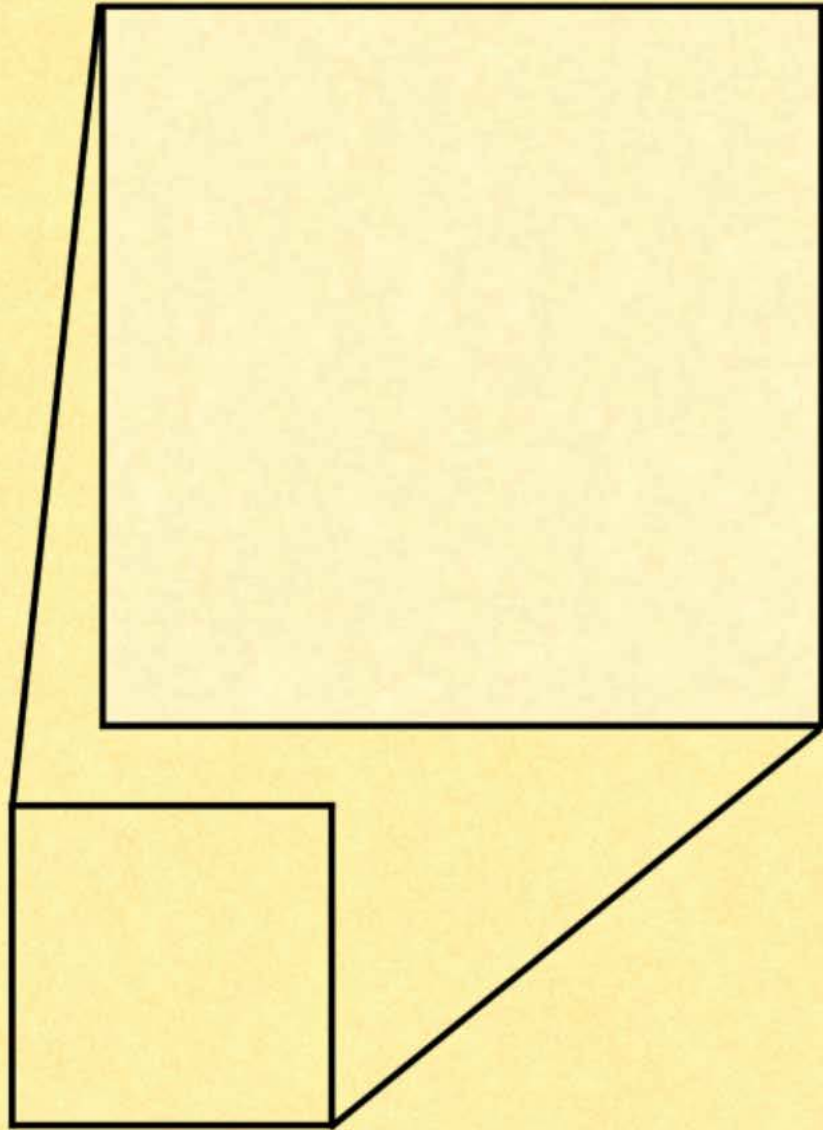
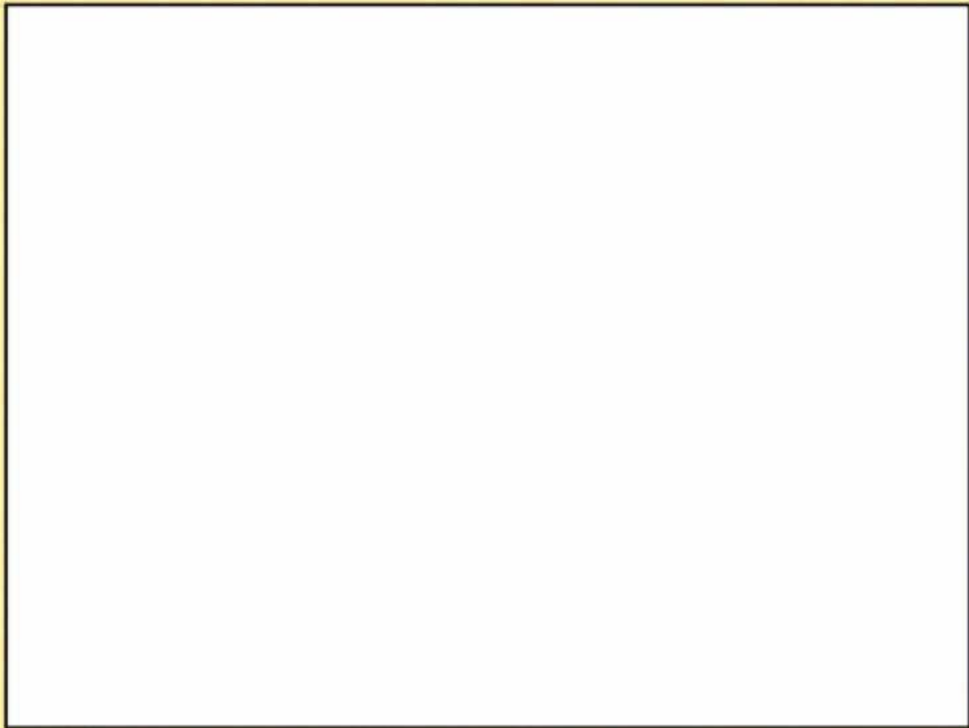
**Adhesion simulation  
buildup Cosmic Web**

**Johan Hidding  
2012**

time  
evolution



Johan Hidding  
2012



# Hierarchical Cosmic Structure Formation

## Two-Barrier Excursion Set Formalism

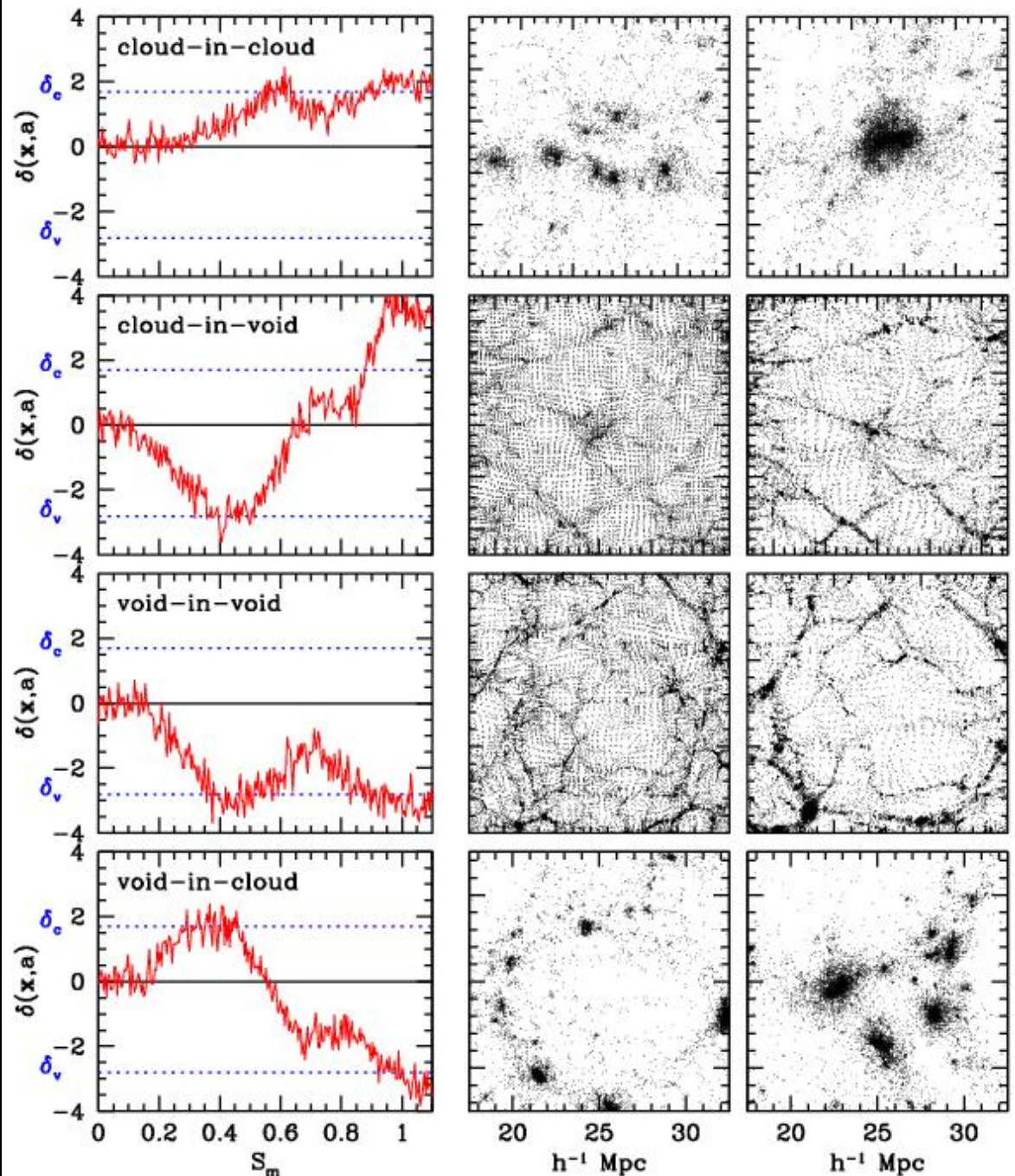
Sheth & vdW 2004

Press & Schechter 1974

Bond et al. 1991

### Excursion Modes:

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



# 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:

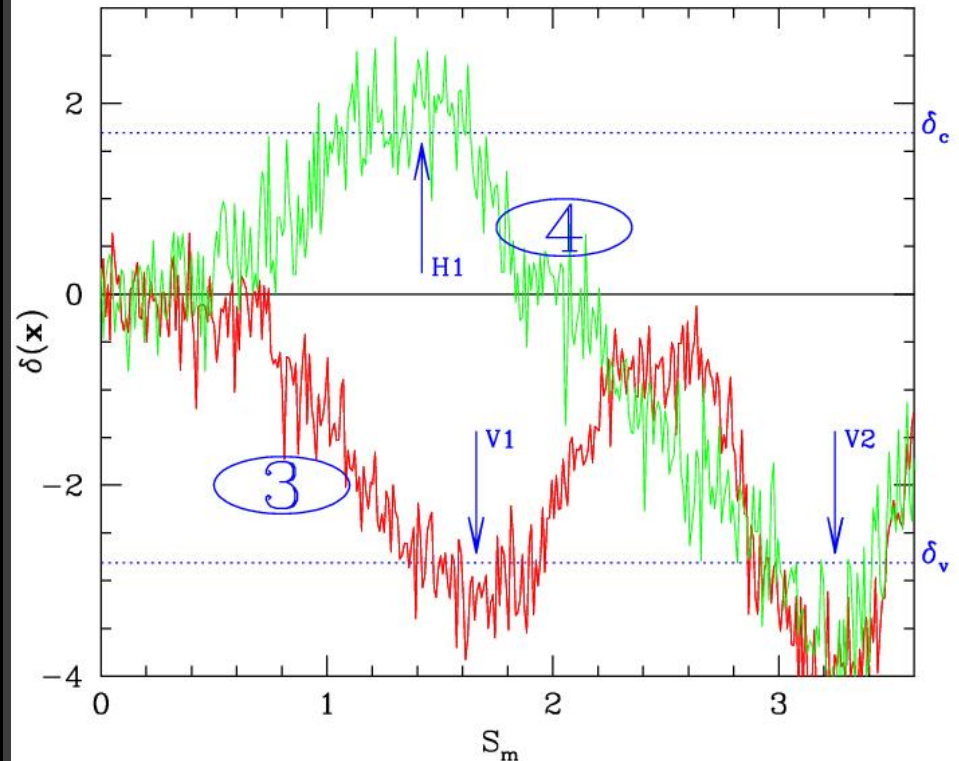
$$a_{coll}(r) \Leftrightarrow \Delta_{lin,0}(r, S_m)$$

dependent on:

Collapse Barrier  $\square_c$

- Critical density value:

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



cumulative random walk:

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

# Void Volume Distribution

(Sheth & vdW 2004)

- **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**

$$v_v(M) = \frac{|\delta_v|}{\sigma(M)} \quad \mathcal{D} \equiv \frac{|\delta_v|}{(\delta_c + |\delta_v|)}$$

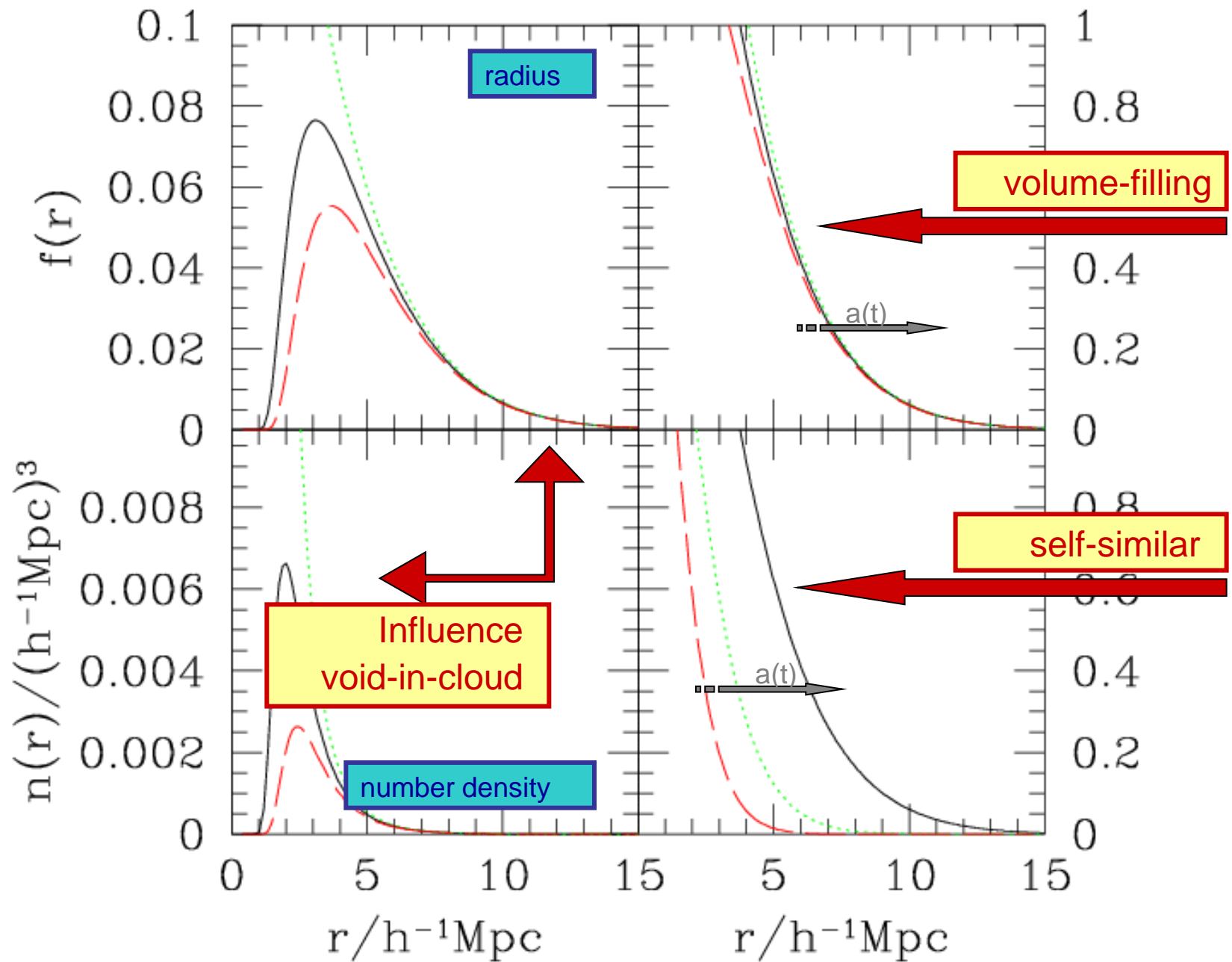
**void mass distribution function**

$$n_v(M) dM =$$

$$\sqrt{\frac{2}{\pi}} \frac{\rho_u}{M^2} v_v(M) \exp\left(-\frac{v_v(M)^2}{2}\right) \left| \frac{d \ln \sigma(M)}{d \ln M} \right| \exp\left\{-\frac{|\delta_v|}{\delta_c} \frac{\mathcal{D}^2}{4v_v^2} - 2 \frac{\mathcal{D}^4}{v_v^4}\right\}$$

**for power-law power spectrum:**

$$n_v(M) dM \approx \sqrt{\frac{1}{2\pi}} \left(1 + \frac{n}{3}\right) \frac{\rho_u}{M^2} \left(\frac{M}{M_{v,*}}\right)^{(n+3)/6} \exp\left(-\left(\frac{M}{M_{v,*}}\right)^{(n+3)/3}\right) \exp\left\{-\frac{\mathcal{D}^2}{2} \left(\frac{|\delta_v|}{4\delta_c} + \mathcal{D}^2 \left(\frac{M}{M_{v,*}}\right)^{-(n+3)/3}\right) \left(\frac{M}{M_{v,*}}\right)^{-(n+3)/3}\right\}$$



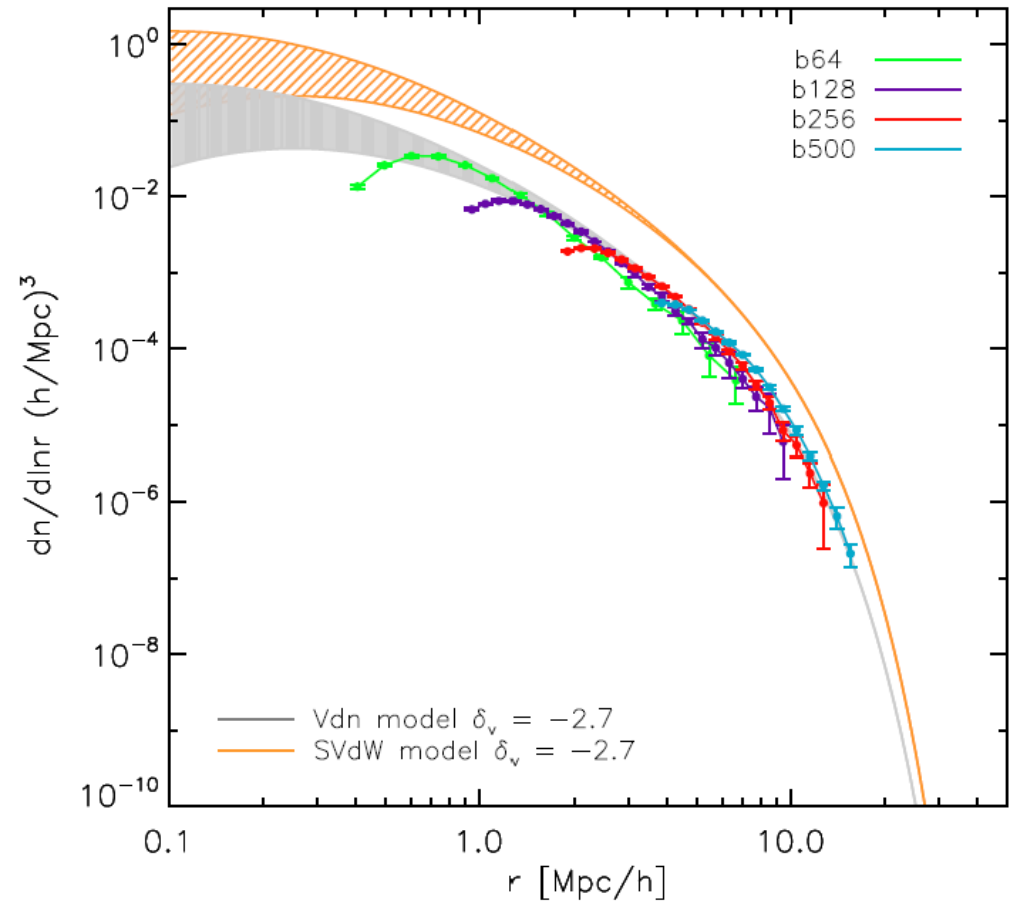
# Void Population & Excursions

Jennings et al. 2013

**Two-barrier SvDW  
void excursion set formalism:**

**correcting simple assumption  
 $\delta_v$  criterion:**

**Jennings et al. 2013:  
void volume occupation constraints**





# **Voids & Cosmology**

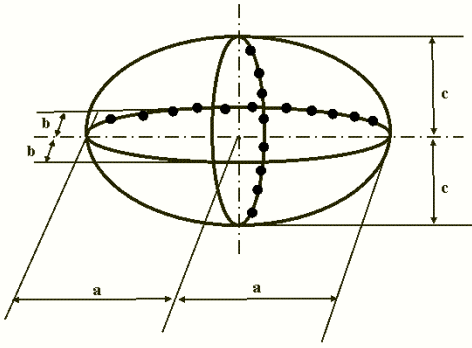
# Voids & Cosmology

- **Cosmological probe:**

Voids contain significant amount of information on global cosmological parameters:

- void substructure: test GR/modified gravity
- void outflow: dark matter
- void shapes: dark energy
- supervoids: existence; CMB - ISW

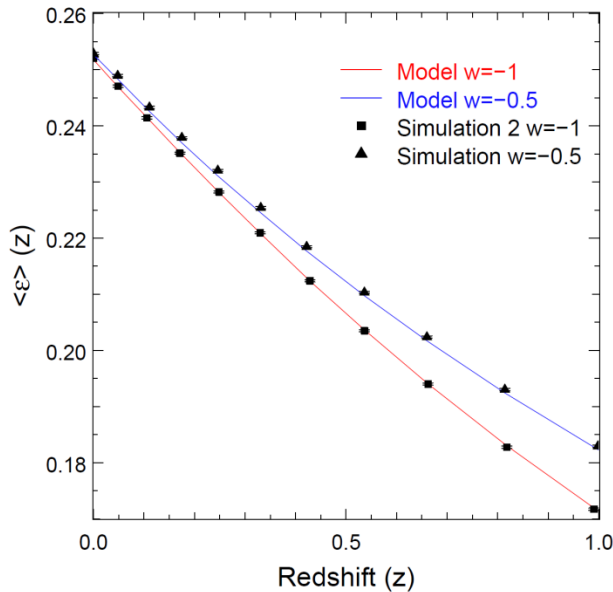
# Voids & Dark Energy



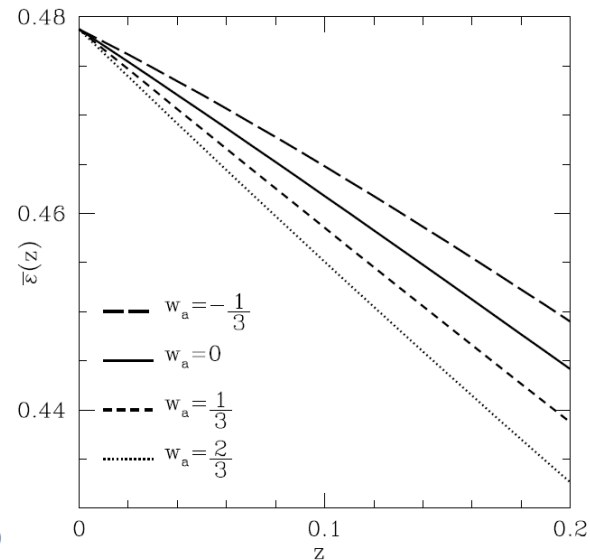
## Evolving Void Population:

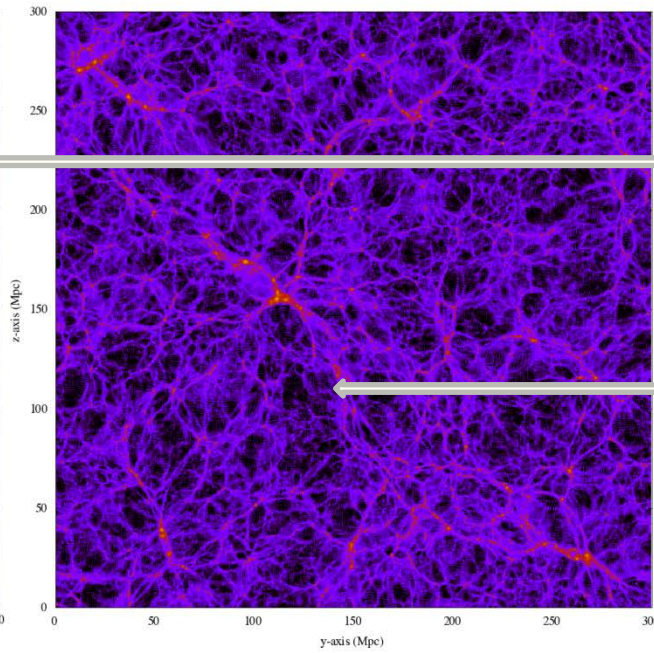
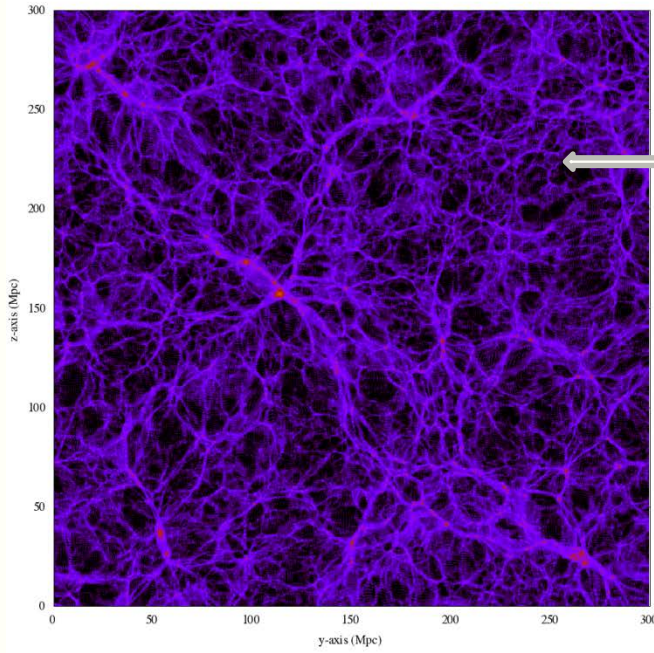
- Void shape evolution highly sensitive to:  
dark energy equation of state
- Manifestation of high sensitivity void dynamics to external tidal forces

Lavaux&Wandelt 2010



Lee & Park 2007



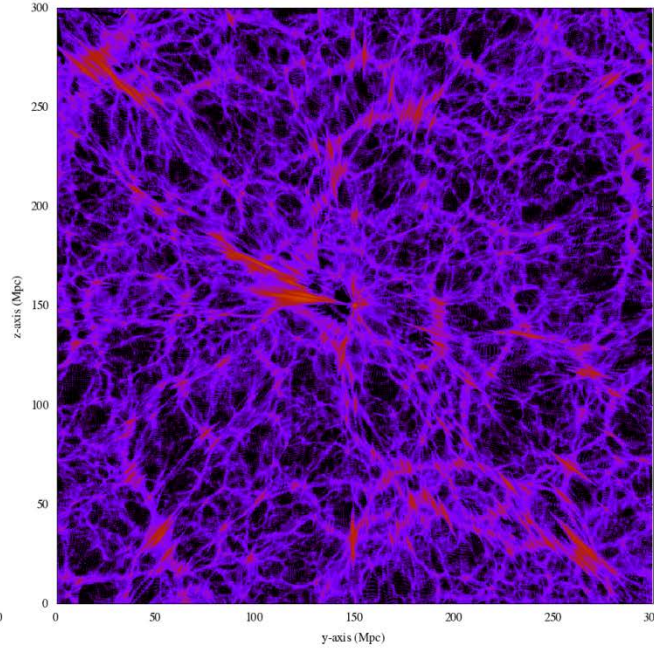
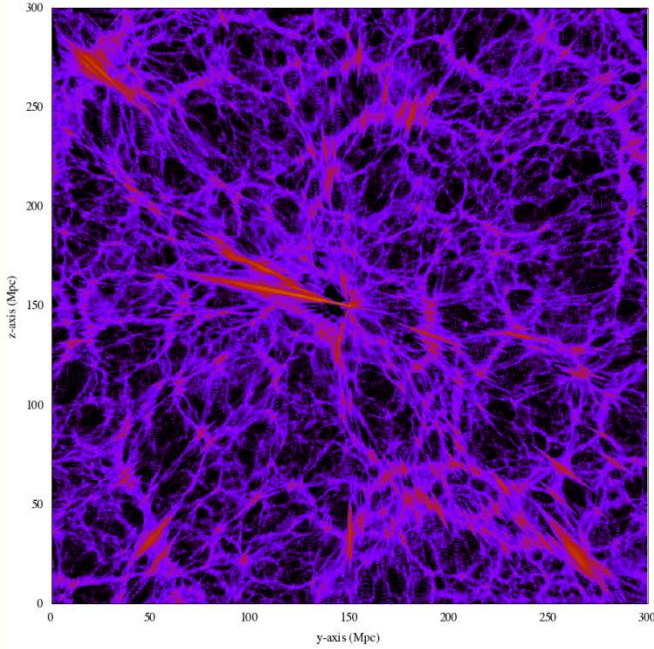


Comparison

WMAP  
concordance  
cosmology

SUGRA cosmology

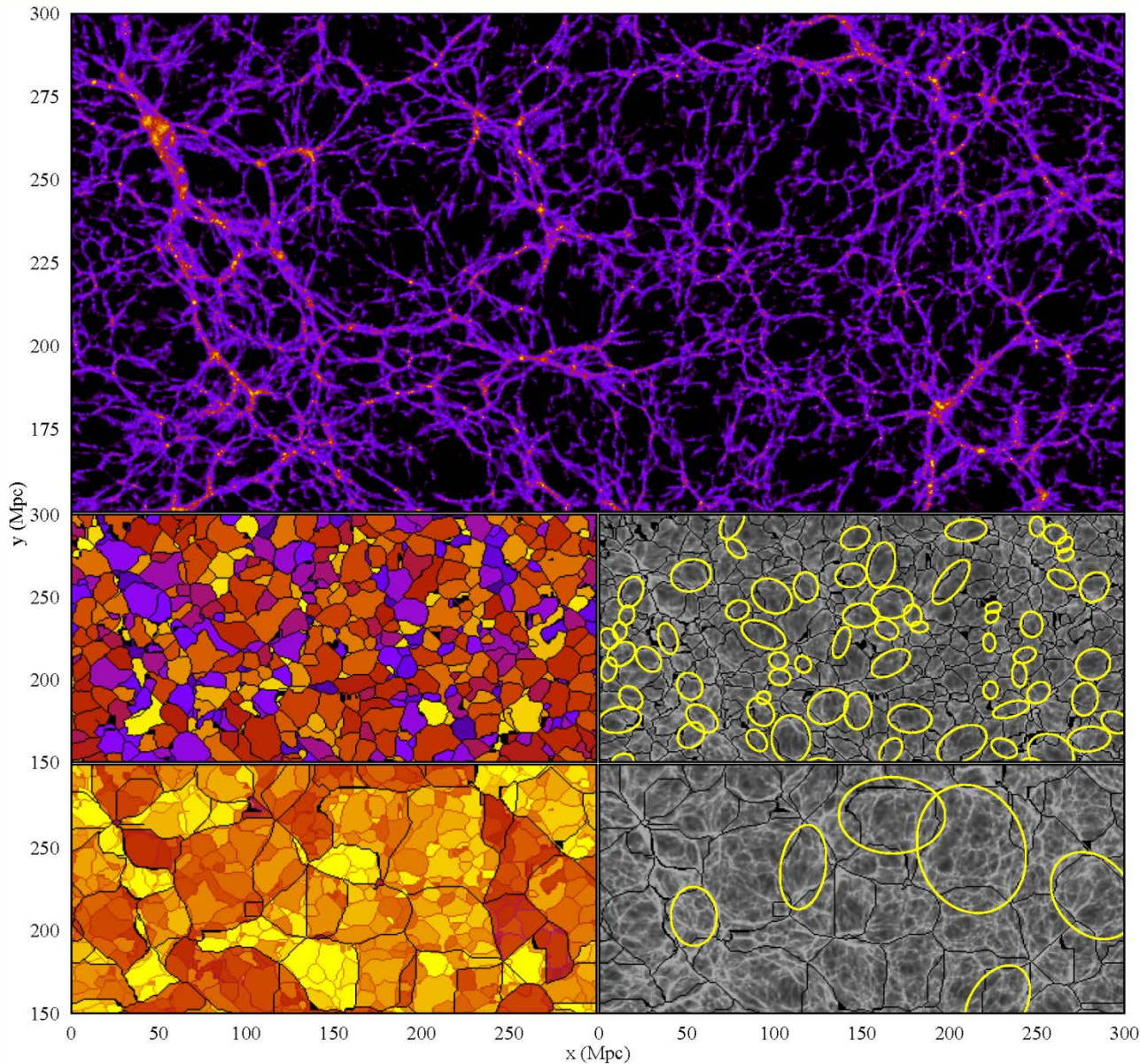
DM density  $a=1$



Redshift Space

Patrick Bos 2011

# Voids & Dark Energy



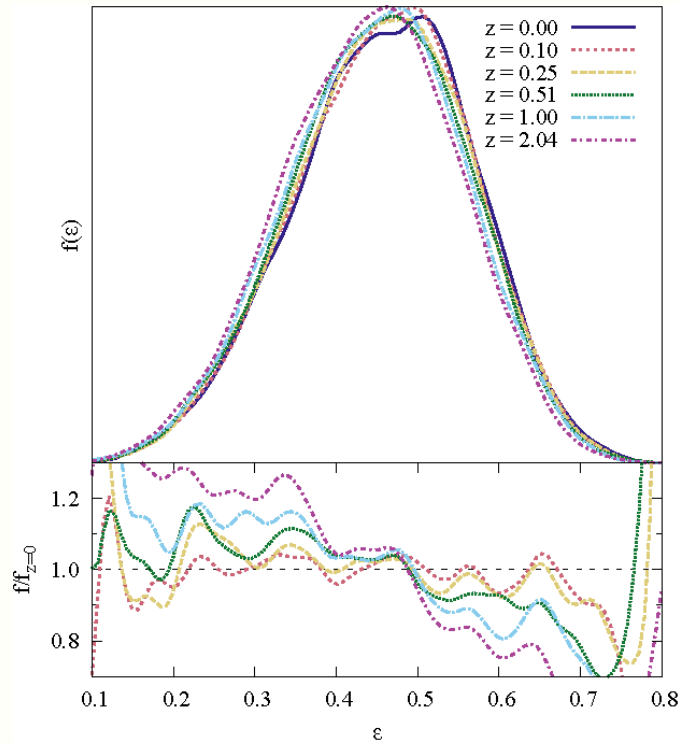
## Evolving Void Population:

Void Shape evolution:

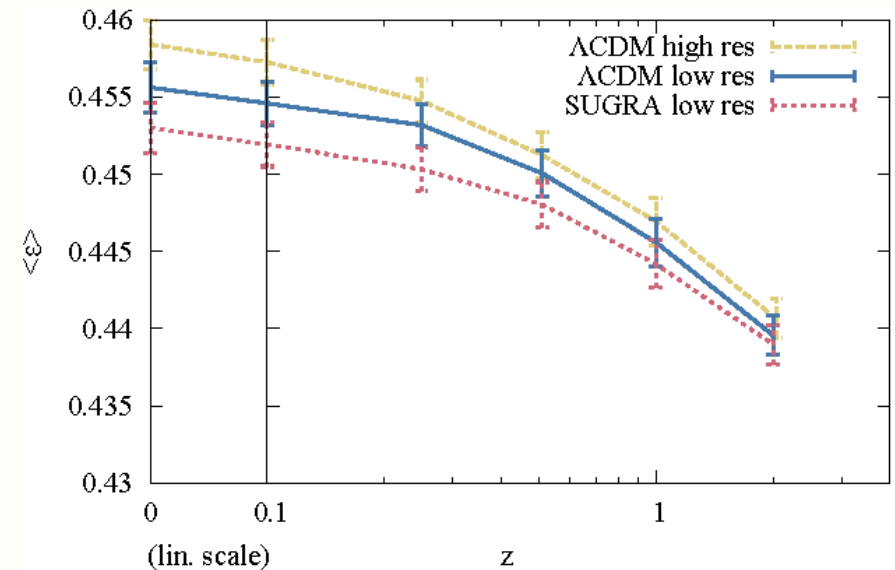
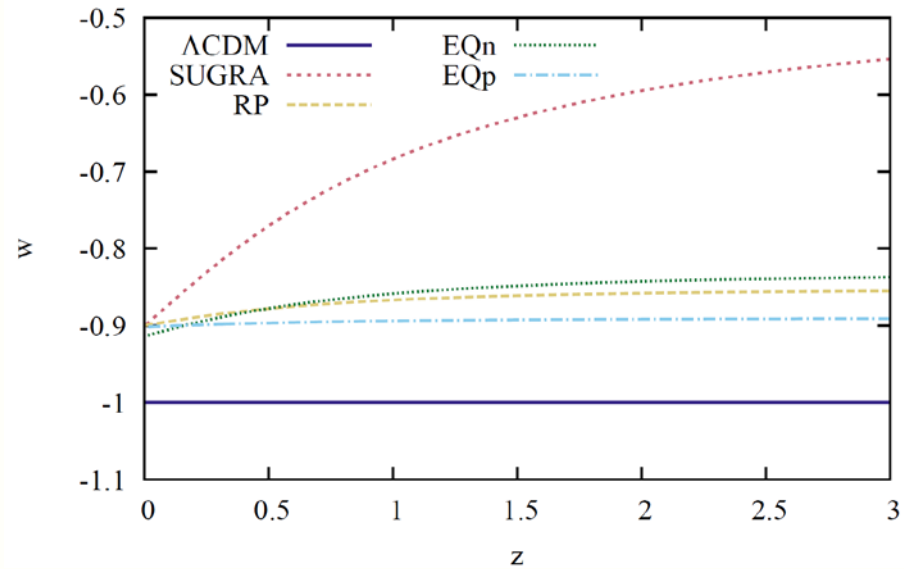
sensitive probe Dark Dnergy

Bos, vdW, Dolag & Pettorino 2012

# Voids and Dark Energy



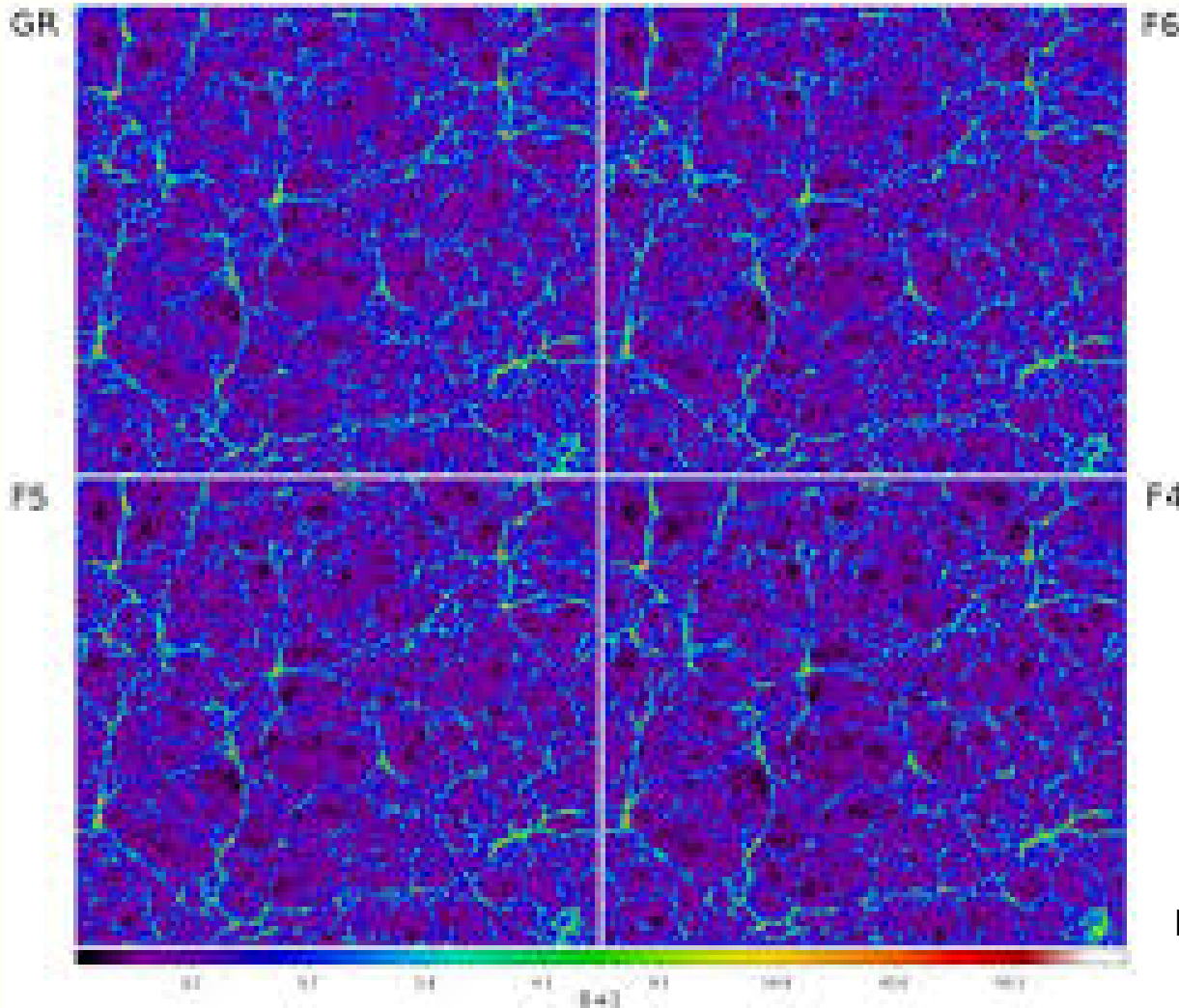
**Void shape evolution LCDM:**



## Bos, vdW, Dolag & Pettorino 2011:

- Test of void shape evolution in Nbody simulations of 5 different DE cosmologies.
- Confirms that voids get less spherical as they evolve in time ! They become more elongated !
- Distinctly different void shape evolution of DM distribution in different DE models.

# Modified Gravity & Voids



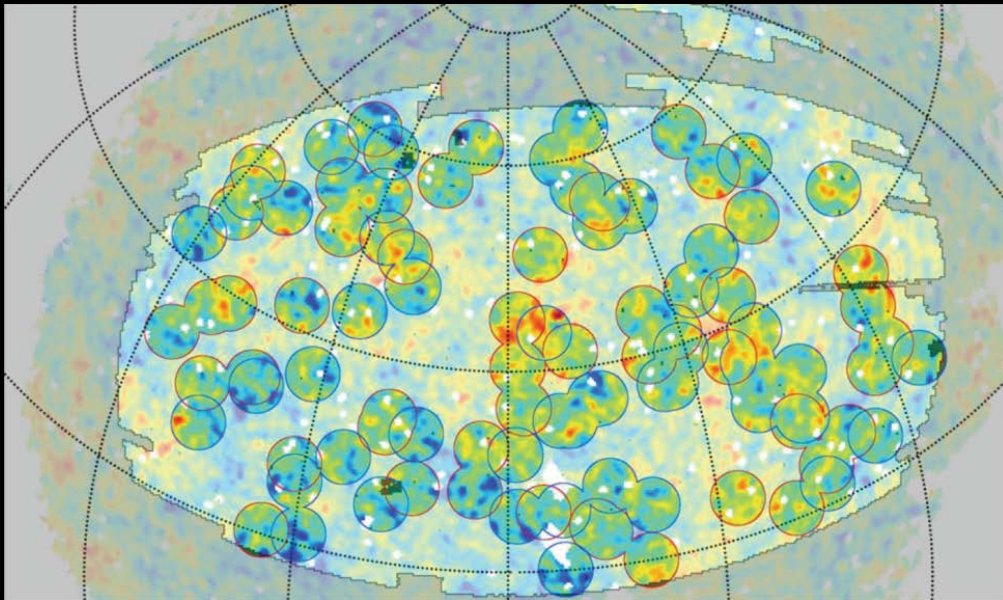
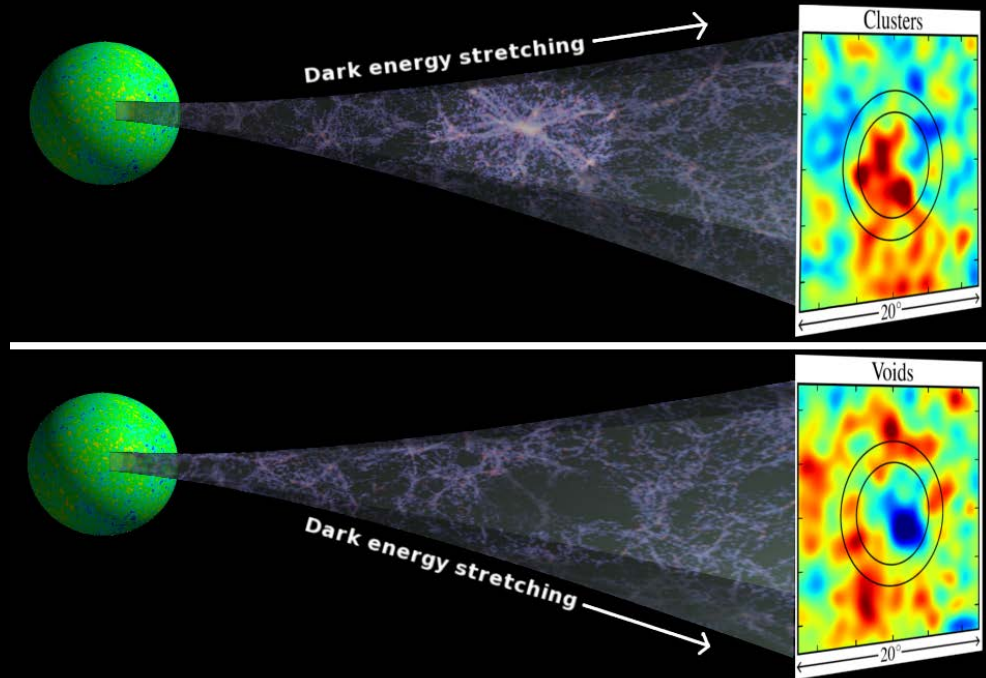
**Void Population**

**excellent probe for  
modified gravity theories:**

**e.g. Li et al. 2010, ...**

**Hellwing 2014**

# (Super)void & ISW

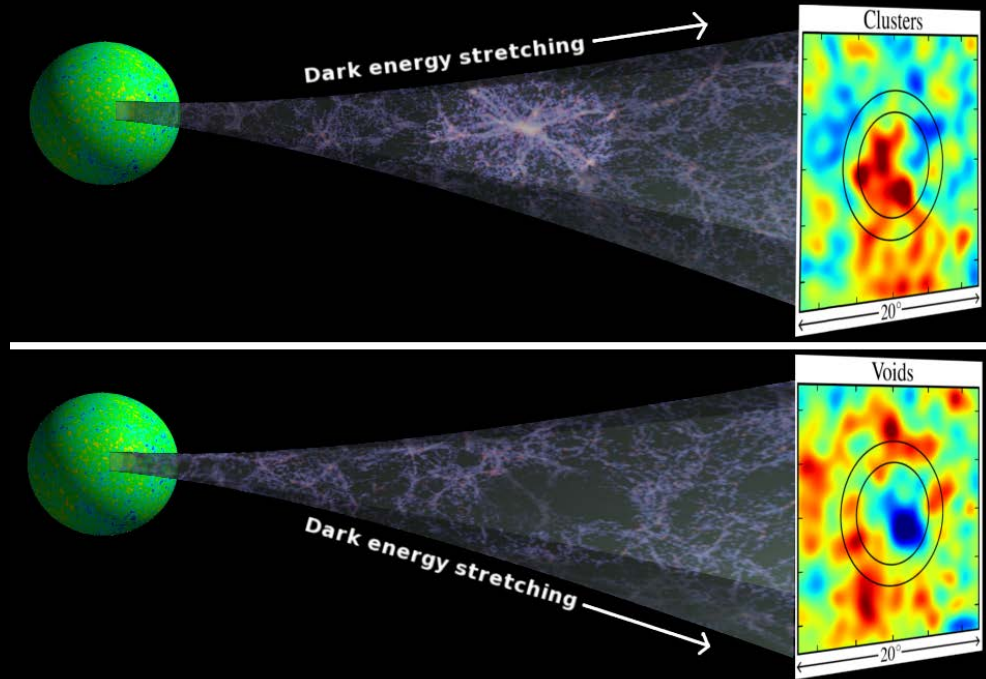


Granett et al. 2009

identification of  
(LRG) supercluster & supervoid  
Imprint on CMB

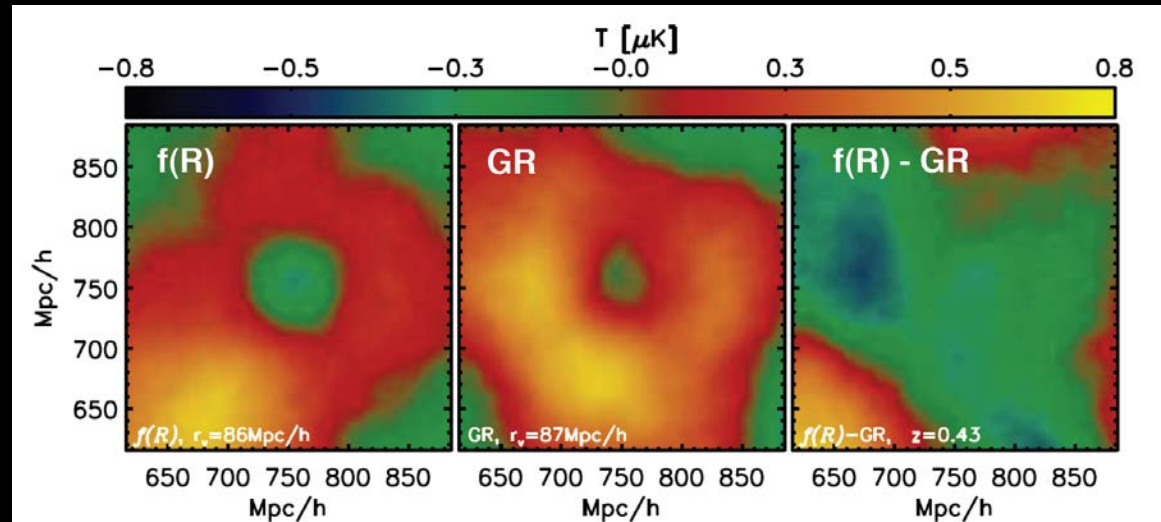


# (Super)void & ISW



Cai et al. 2013:

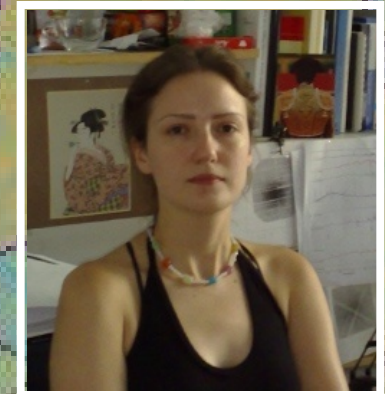
stacked ISW signal  
may be used to discriminate  
between gravity scenarios.



# **Void Galaxies**

# Void Galaxy Survey

- Kathryn Kreckel-Stanonik MPIA Heidelberg
- Burcu Beygu Kapteyn Inst.
- Rien van de Weygaert Kapteyn Inst.
- Jacqueline van Gorkom Columbia Univ.
- Thijs van der Hulst Kapteyn Inst.
- Jim Peebles Princeton Univ.
- Erwin Platen Kapteyn Inst.
- Miguel Aragon-Calvo JHU, Baltimore
- Katarina Kovac MPA, Garching



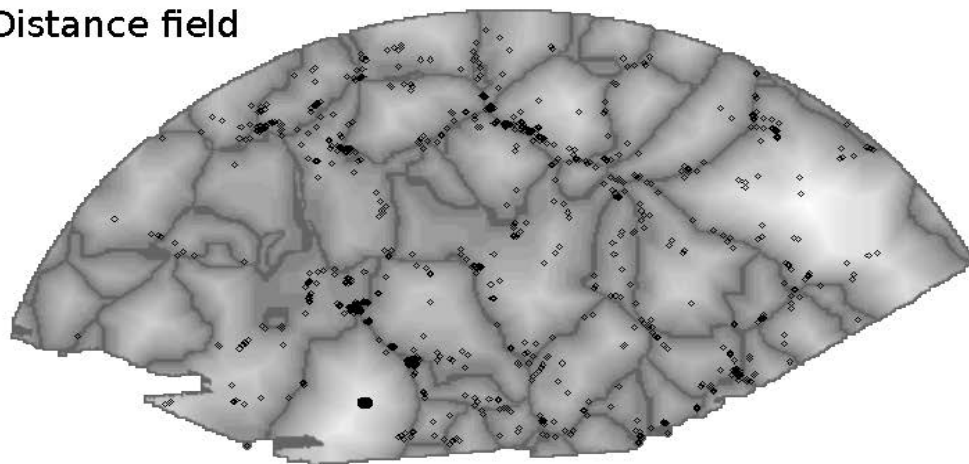
# Void Galaxy Survey (VGS)

## Multiwavelength Study

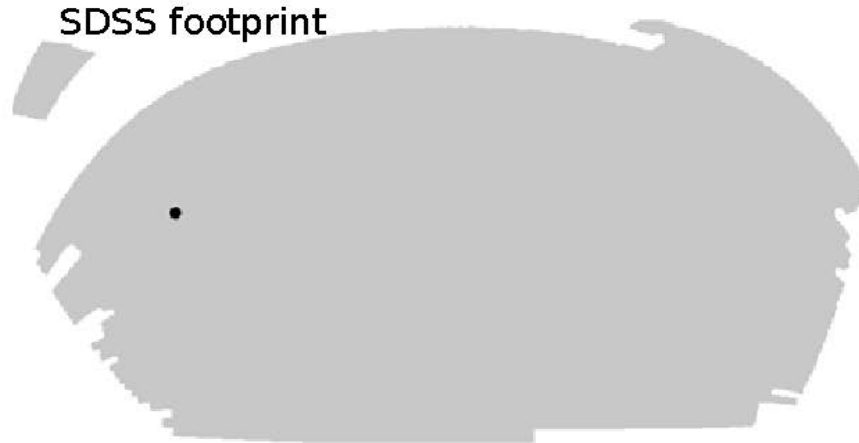
- ~ 60 galaxies located within/near the deep interior of voids in SDSS DR7
- gas content, star formation history, stellar content, kinematics & dynamics of void galaxies and their companions in a broad sample of void environments
- environmental influences on galaxy formation & evolution in isolated, supposedly pristine and undisturbed, void regions.
- Observational test theories cosmological structure formation

# Geometric Void Galaxy selection

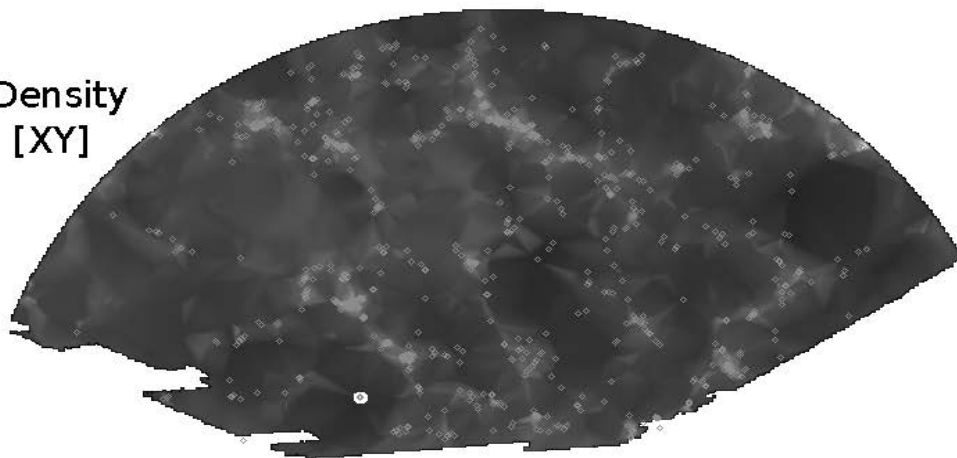
Distance field



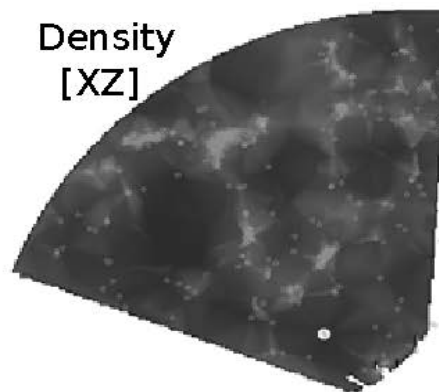
SDSS footprint



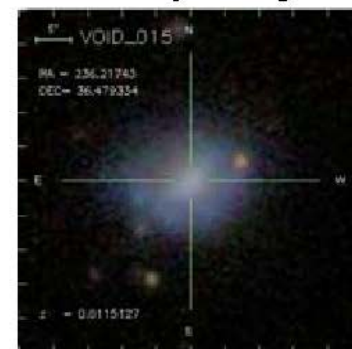
Density  
[XY]



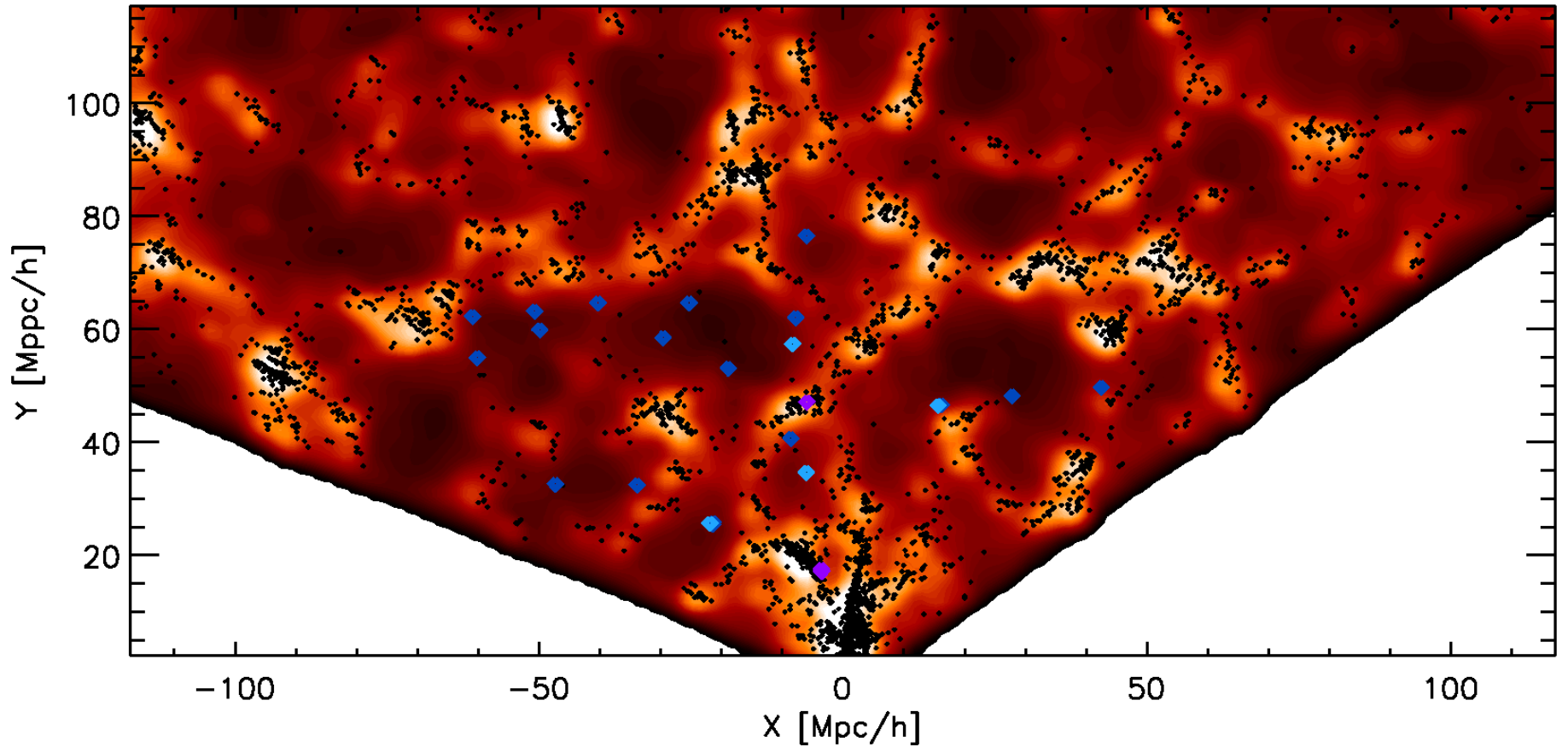
Density  
[XZ]



Galaxy image



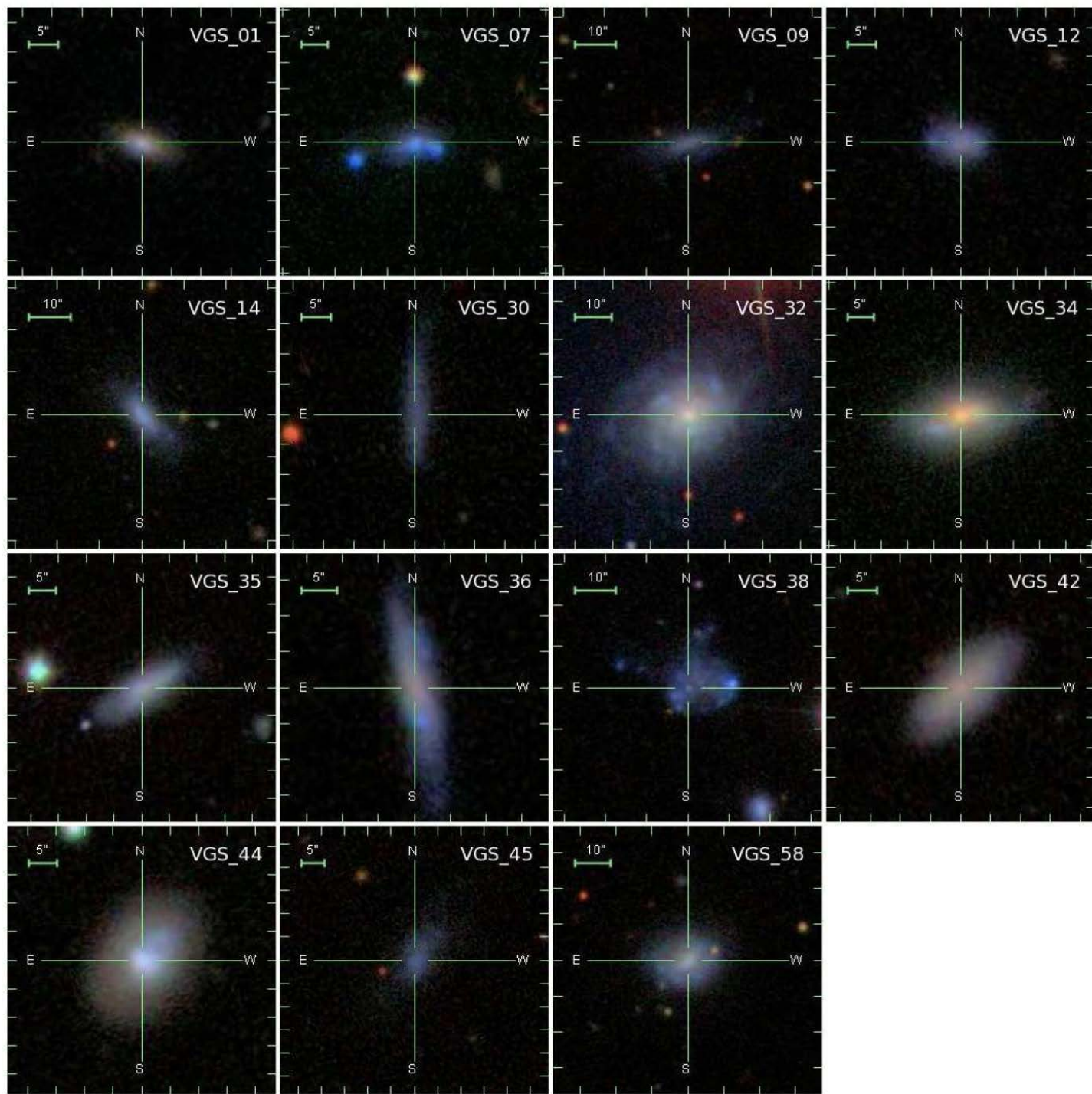
# the Void Galaxy Pilot Sample



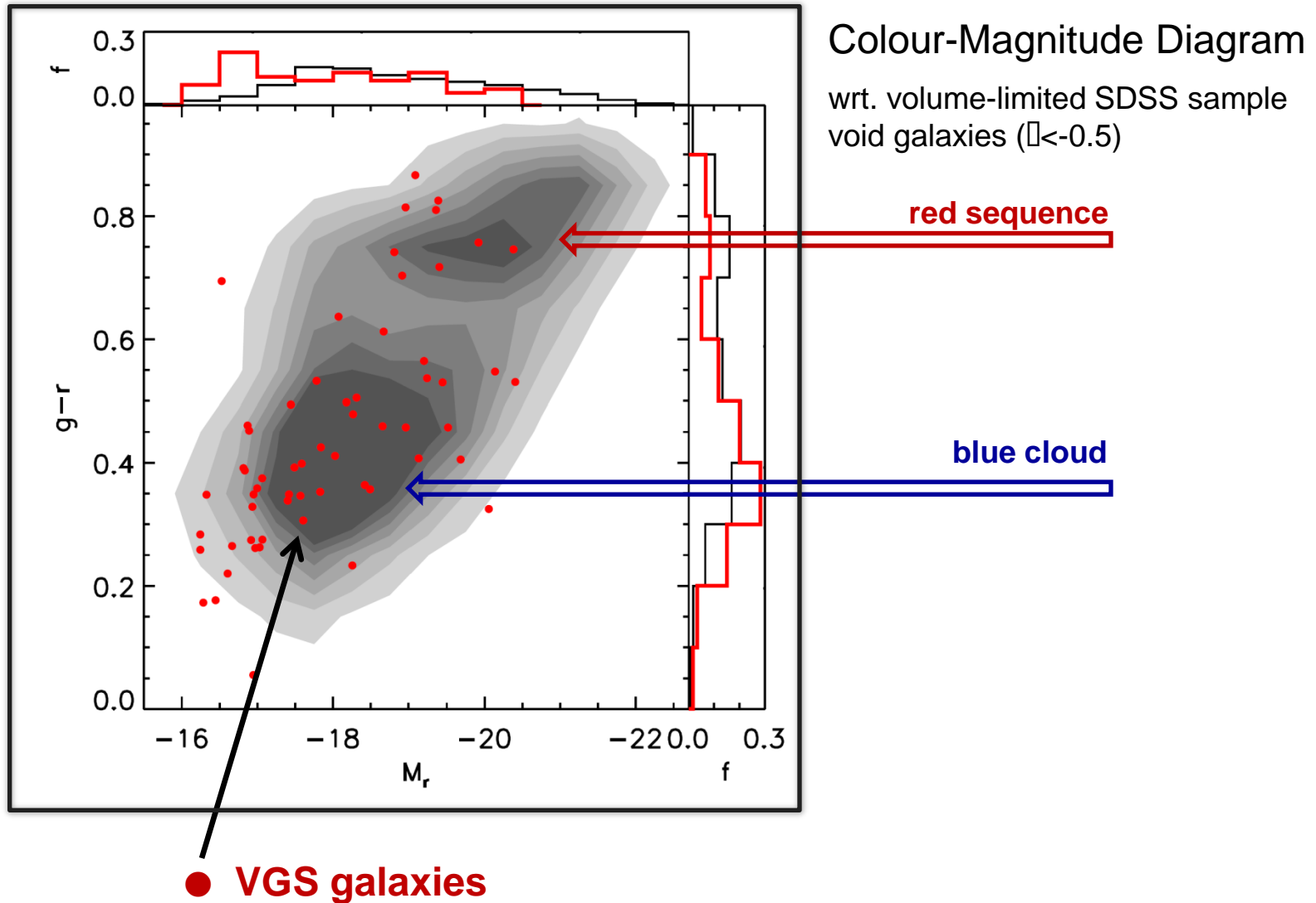
# VGS Void Galaxies

## Sample

(size scaled)



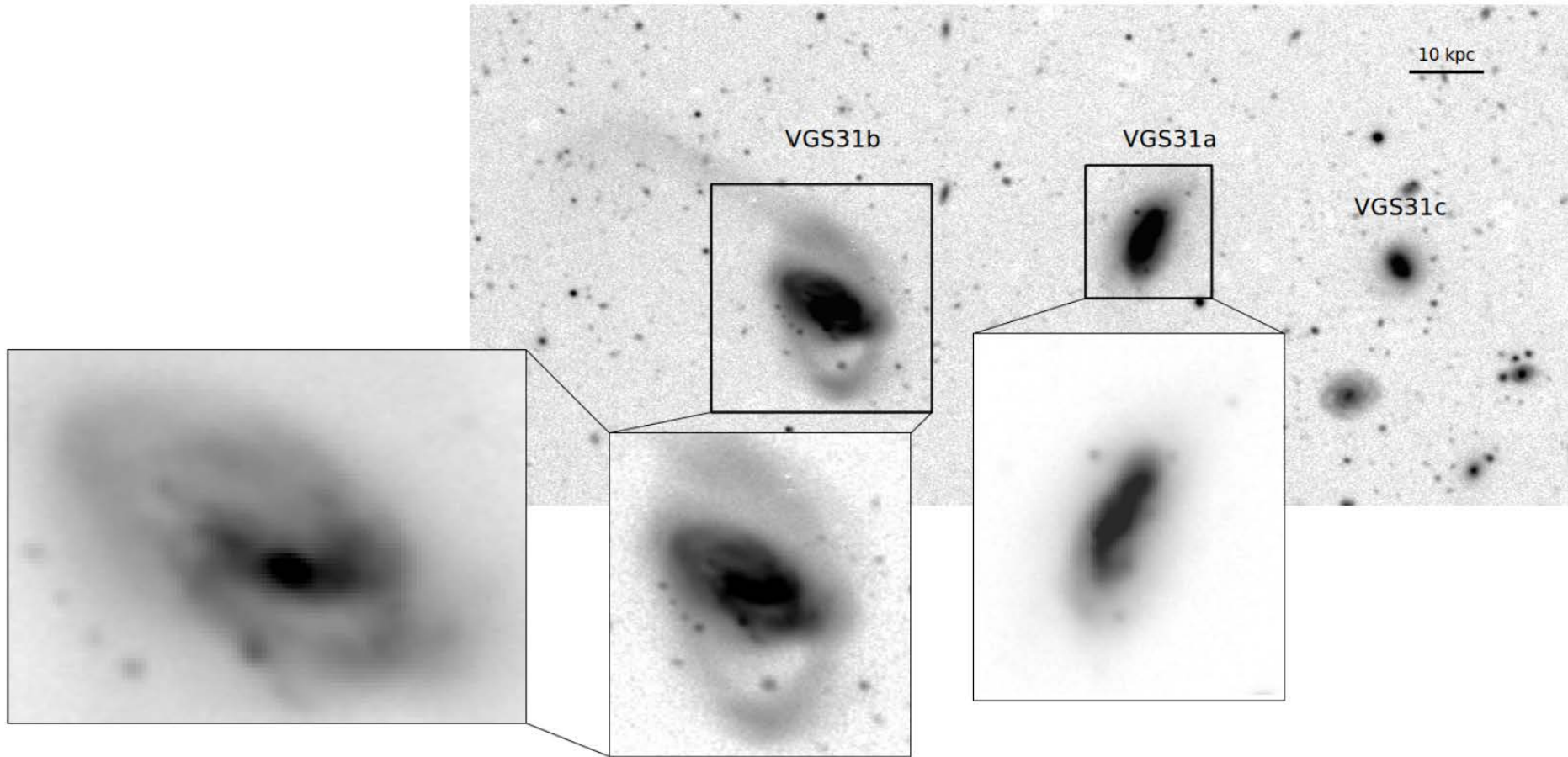
# Optical Properties Selection



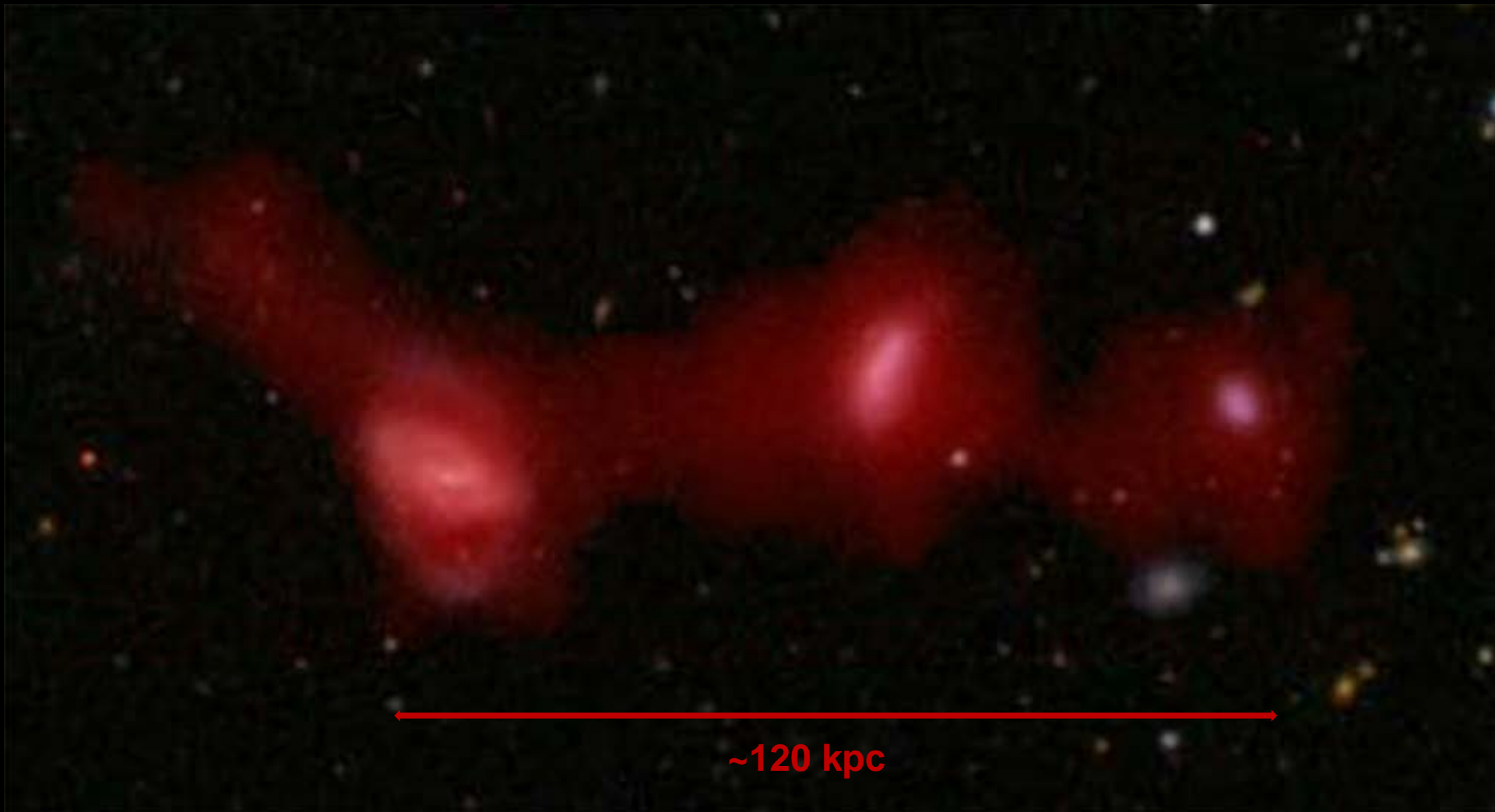


**VGS\_31**

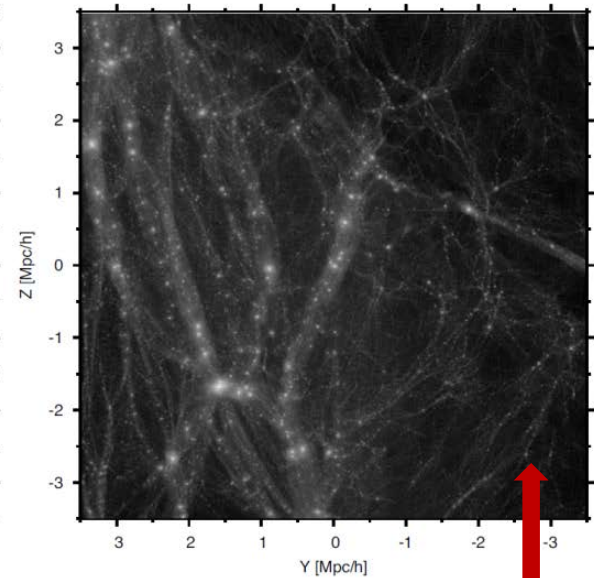
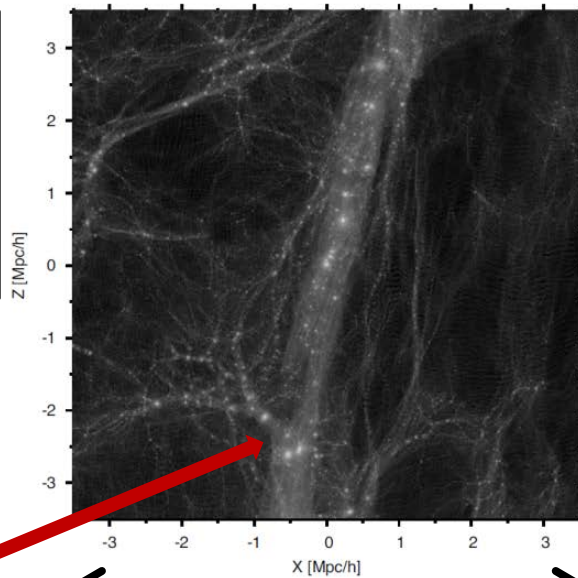
# VGS\_31: void galaxies along filament ?



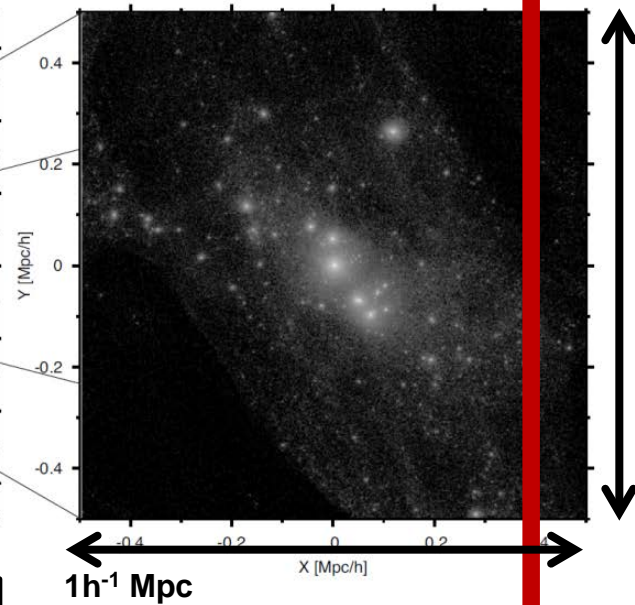
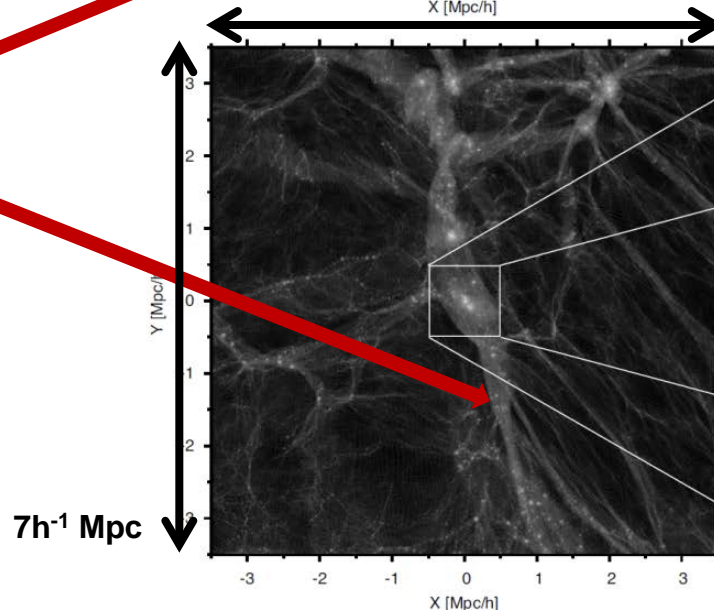
# VGS\_31: HI filament ?



# CGV\_G: on walls & filaments



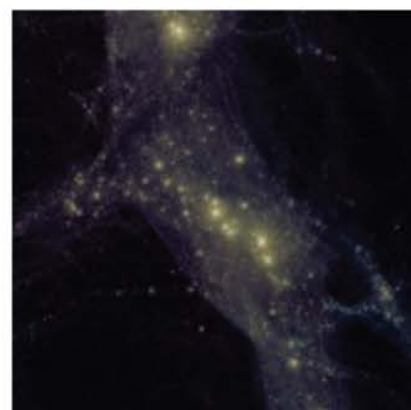
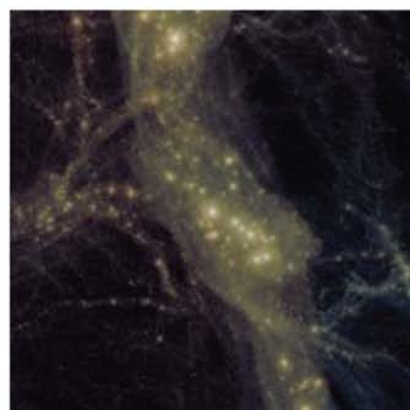
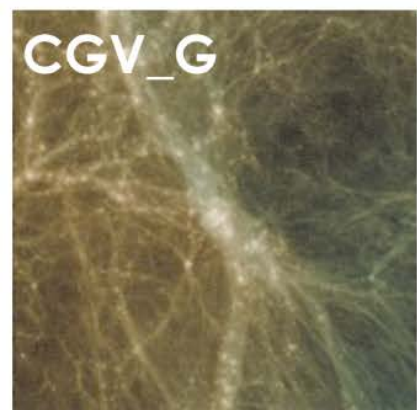
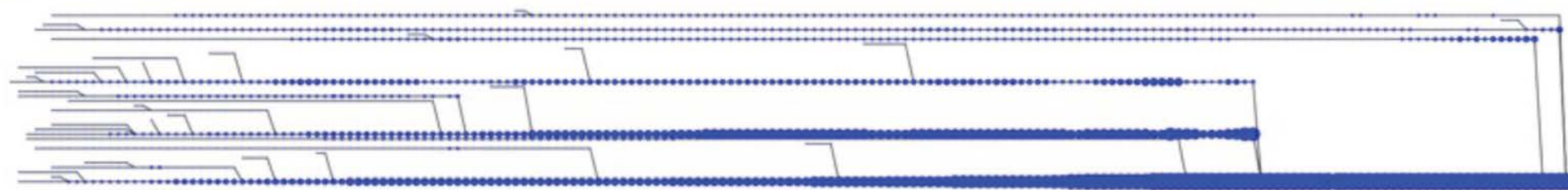
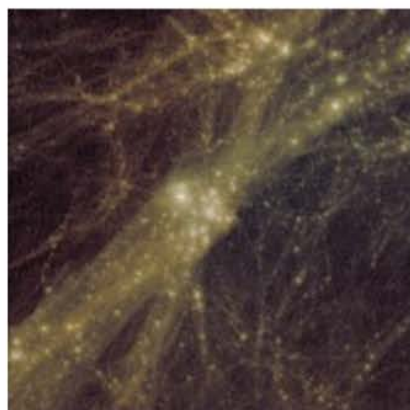
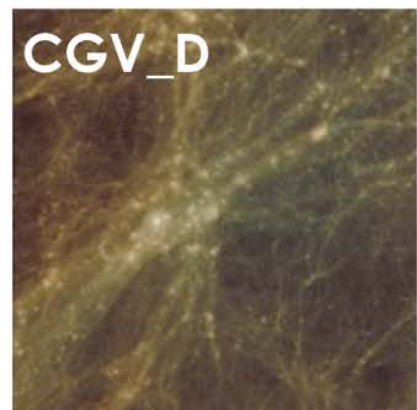
wall:  
edge-on view



wall substructure:

- intricate filigree of tenous filaments
- filaments are/get largely aligned
- dynamical action of large-scale tidal force field

wall: face-on view



0

time [Gyr]

13.5

# Conclusions

- **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**
- **Voids are very sensitive probes of dark energy**
- **Voids' isolated environment provides a very nice testing ground for the study of environmental influences on galaxy formation**
- **Voids may be sensitive probes of modified gravity**
- **Existence of supervoids (large underdense regions) may be challenging for cosmological standard scenario**