# the Cosmic Web:

## Lecture 5:
## Voids

Rien van de Weijgaert,
Cosmic Web, caput course, October 2017

# Cosmic Web

# Void Evolution

# Void Formation

## Void Evolution

**an illustration**

**cosmology:**

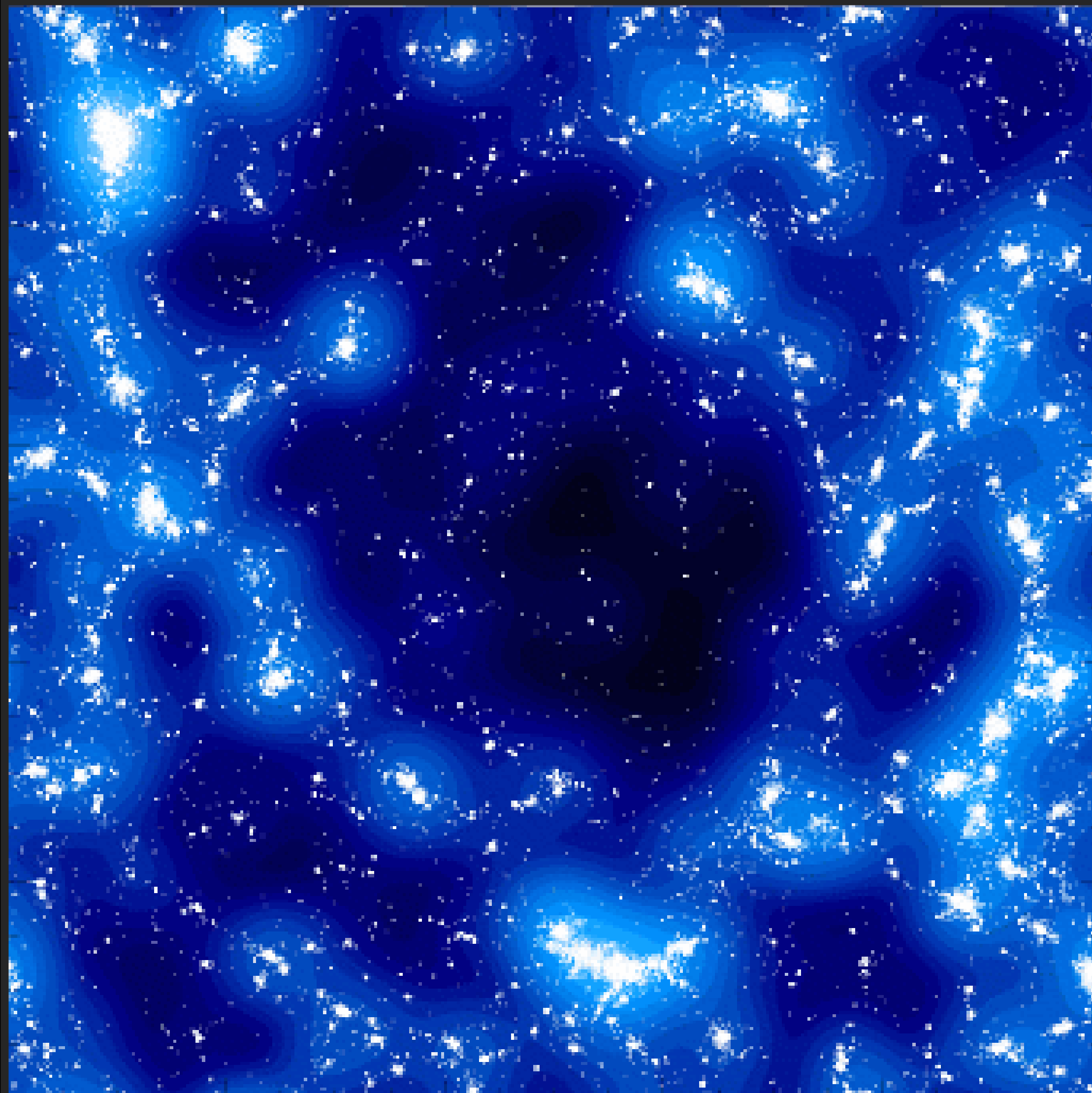
$\Omega_m = 1.0; \quad H_0 = 70 \ km/s/Mpc$

**initial conditions:**

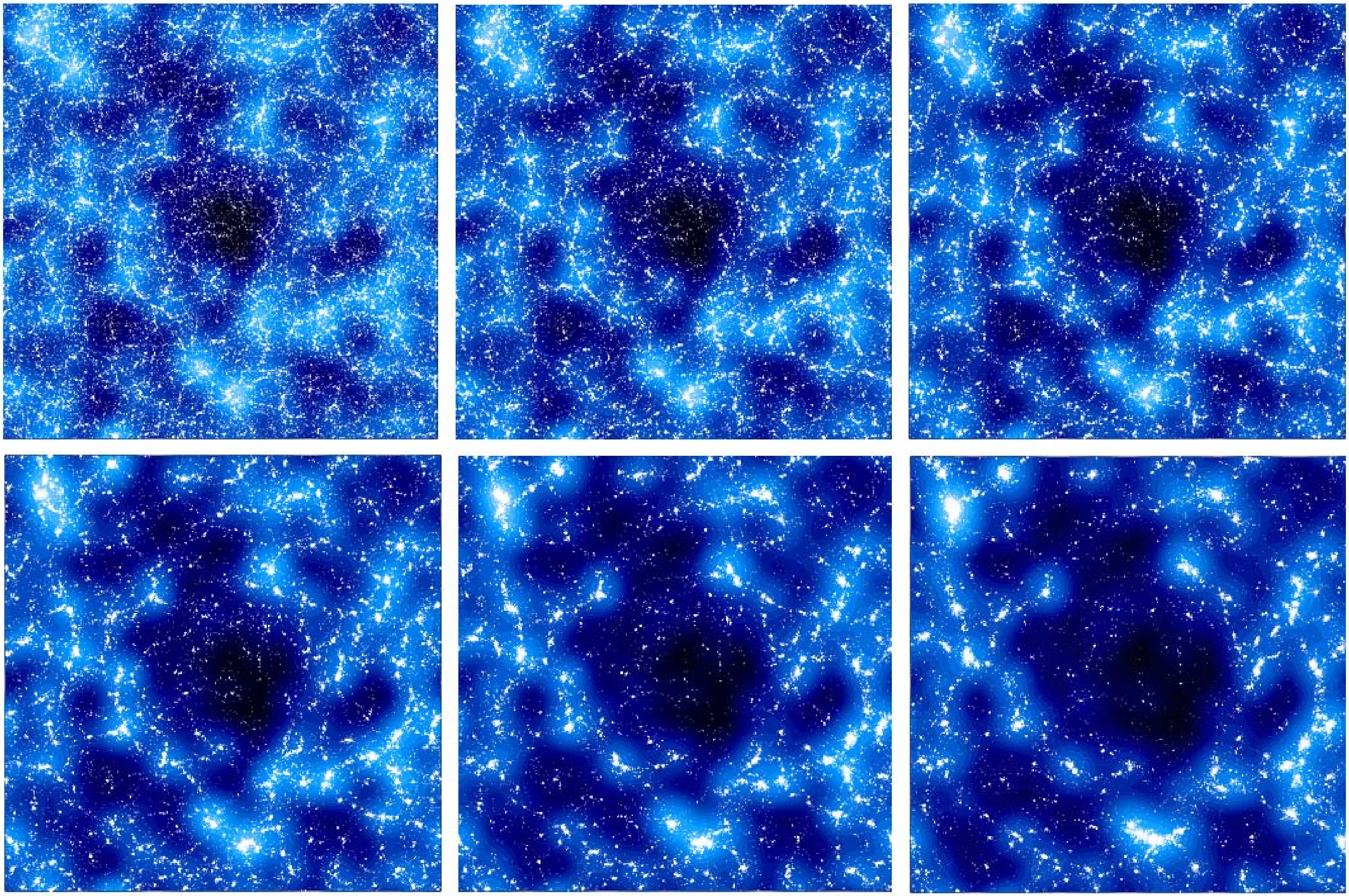
**underdensity, Gaussian field**

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

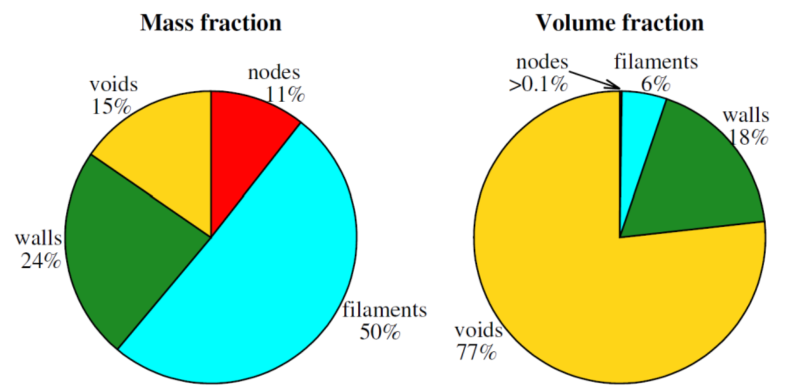
$P(k) \propto k^{-0.5}$



# Void Formation

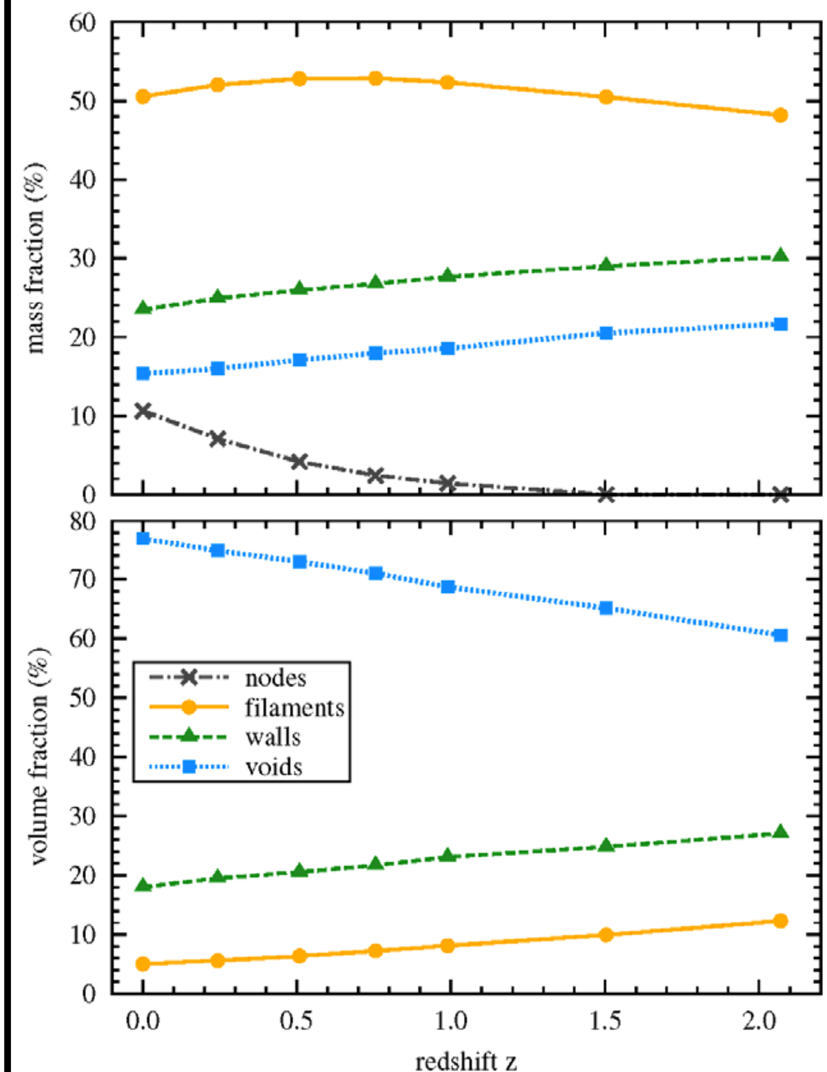


# Cosmic Web & Voids




MMF/Nexus

Cautun et al., 2014,
Evolution of the Cosmic Web, MNRAS




**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)

# Voids:

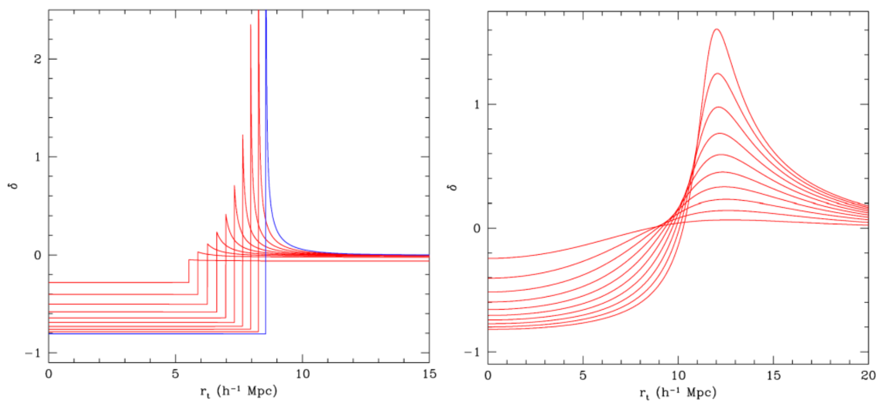
## Global Evolution

# 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

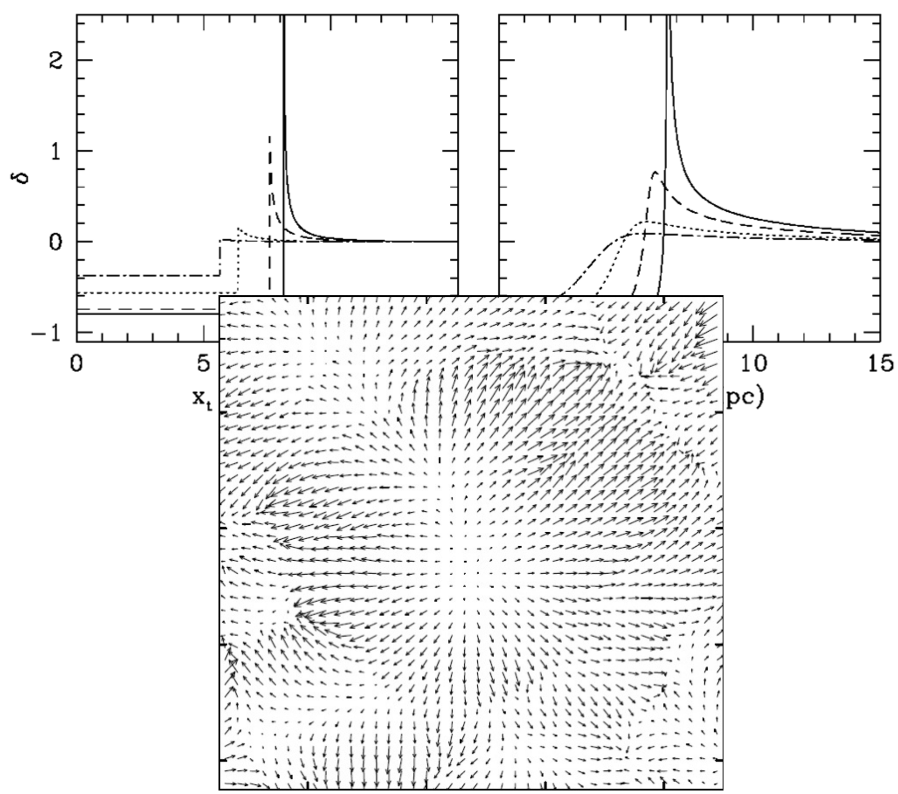
- Density Ridge
  Except for gentlest initial density profiles, a ridge forms



# Superhubble Expansion

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

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



# Void Density Profile

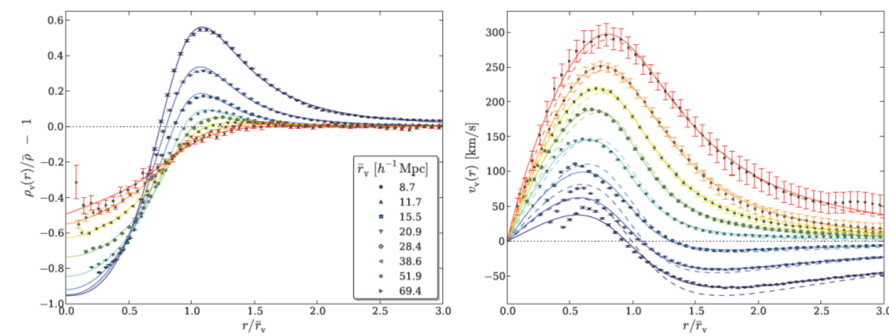
- **Tophat Configuration**

  **Any initial configuration tends towards “bucket” shape**

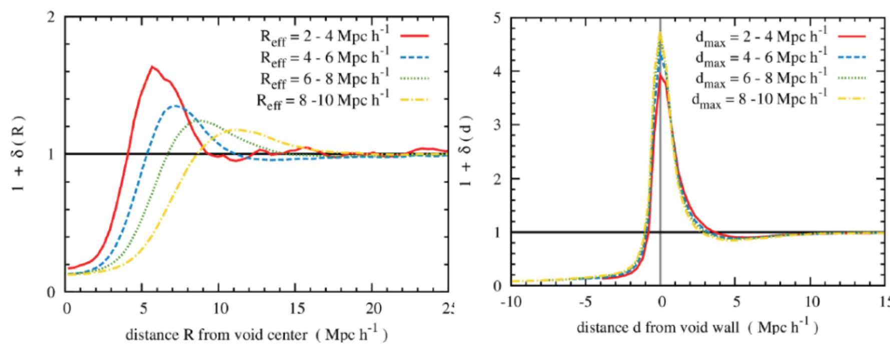
- **Density Ridge**

  **Except for gentlest initial density profiles, a ridge forms**

**Is there a universal void density profile ?**



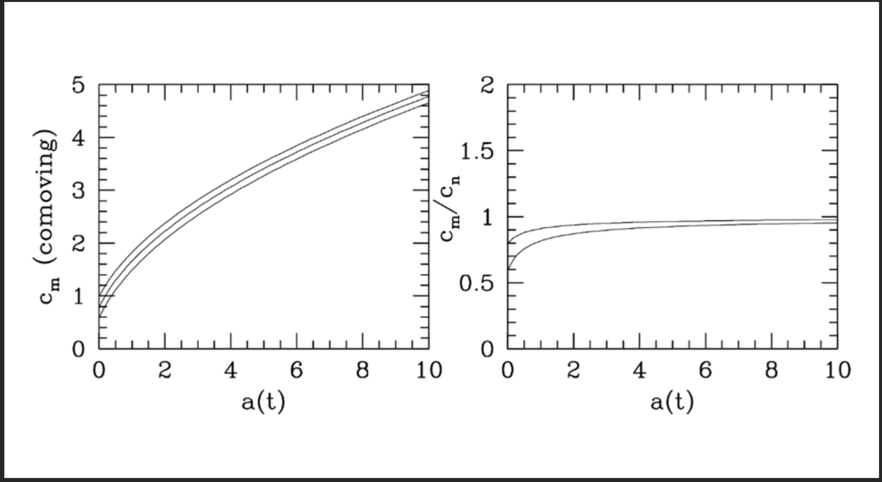

**e.g. Hamaus et al. 2014**

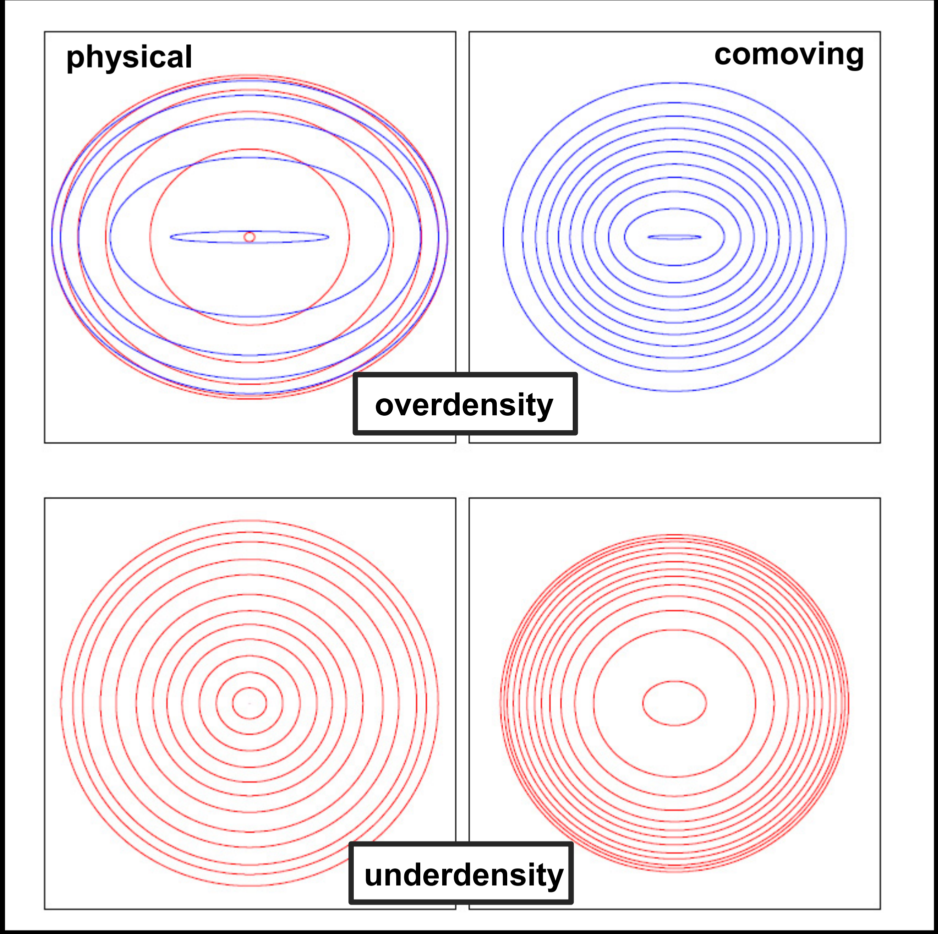



**Cautun et al. 2015**

# 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:**

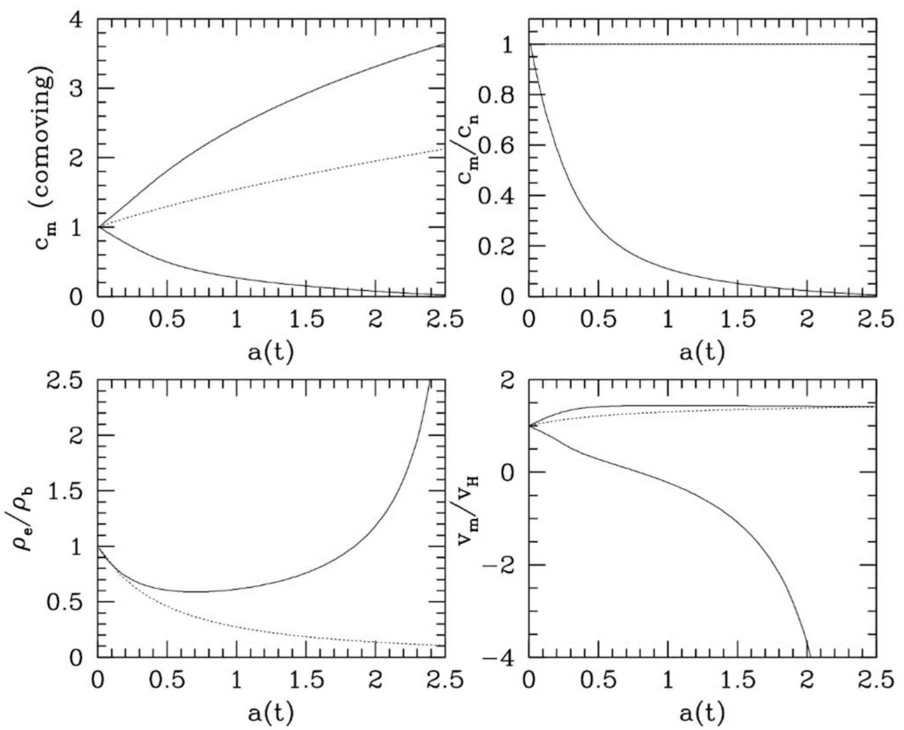
  **□ Voids never isolated: run into neighbours**

  **□ Void evolution largely dominated by large scale (tidal) environment:**

  **voids always represent restricted density fluctuation: |□| < 1**

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

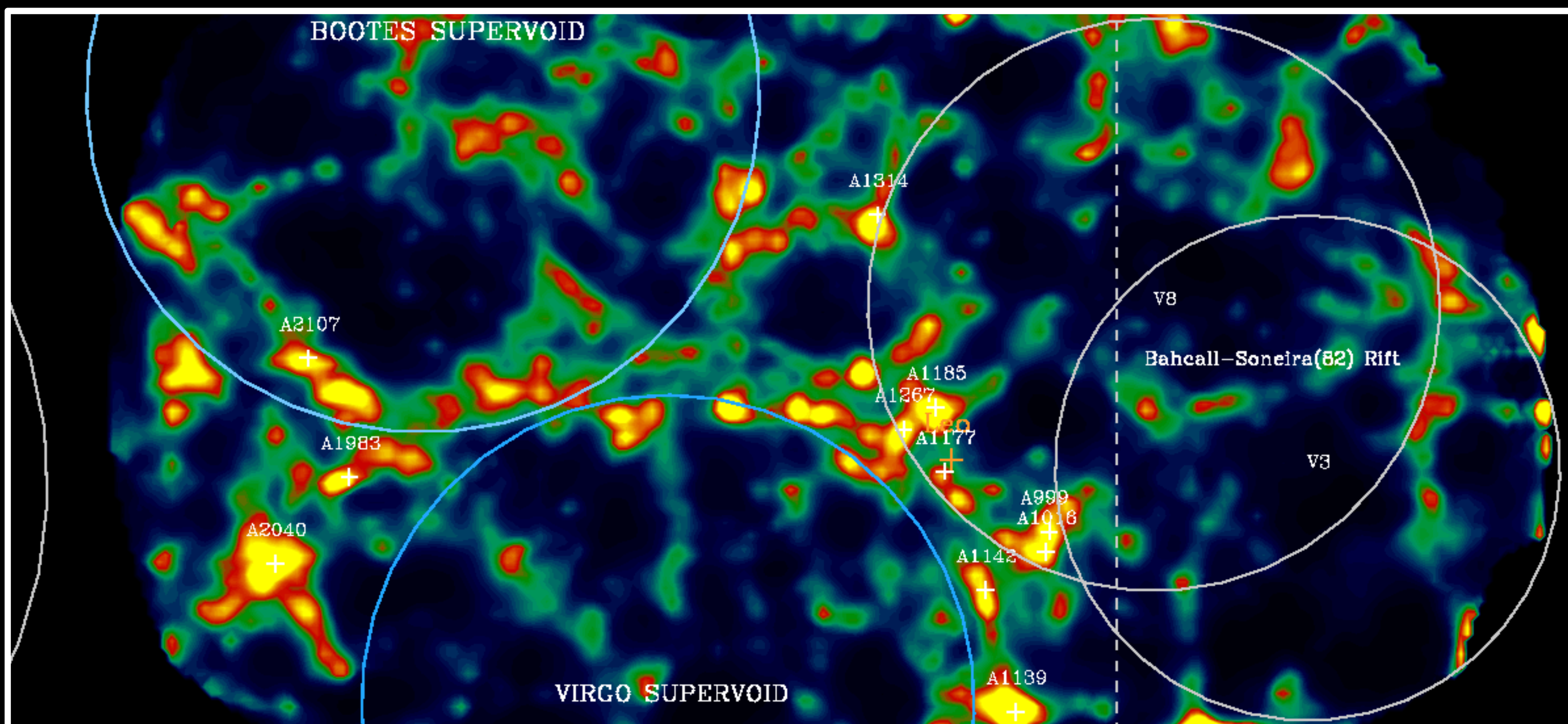
$$\frac{d^2 R_m}{dt^2} = -2\pi G \left[ \alpha_m \rho_e + \left( \frac{2}{3} - \alpha_m \right) \rho_u \right] R_m - T_{mm} R_m$$



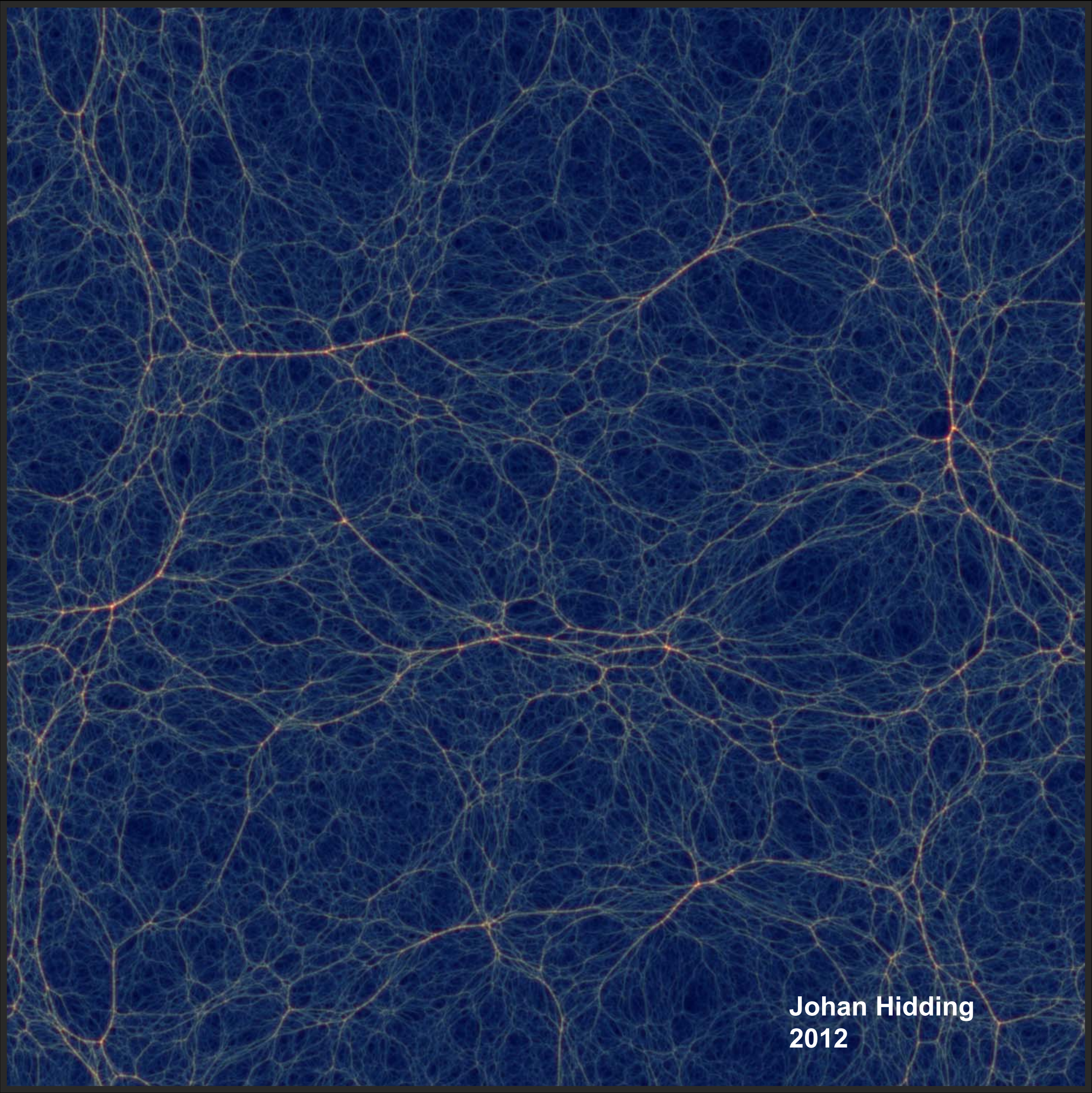
# Voids:

# Multiscale Infrastructure

# Bootes Void: Substructure




Platen et al. 2009

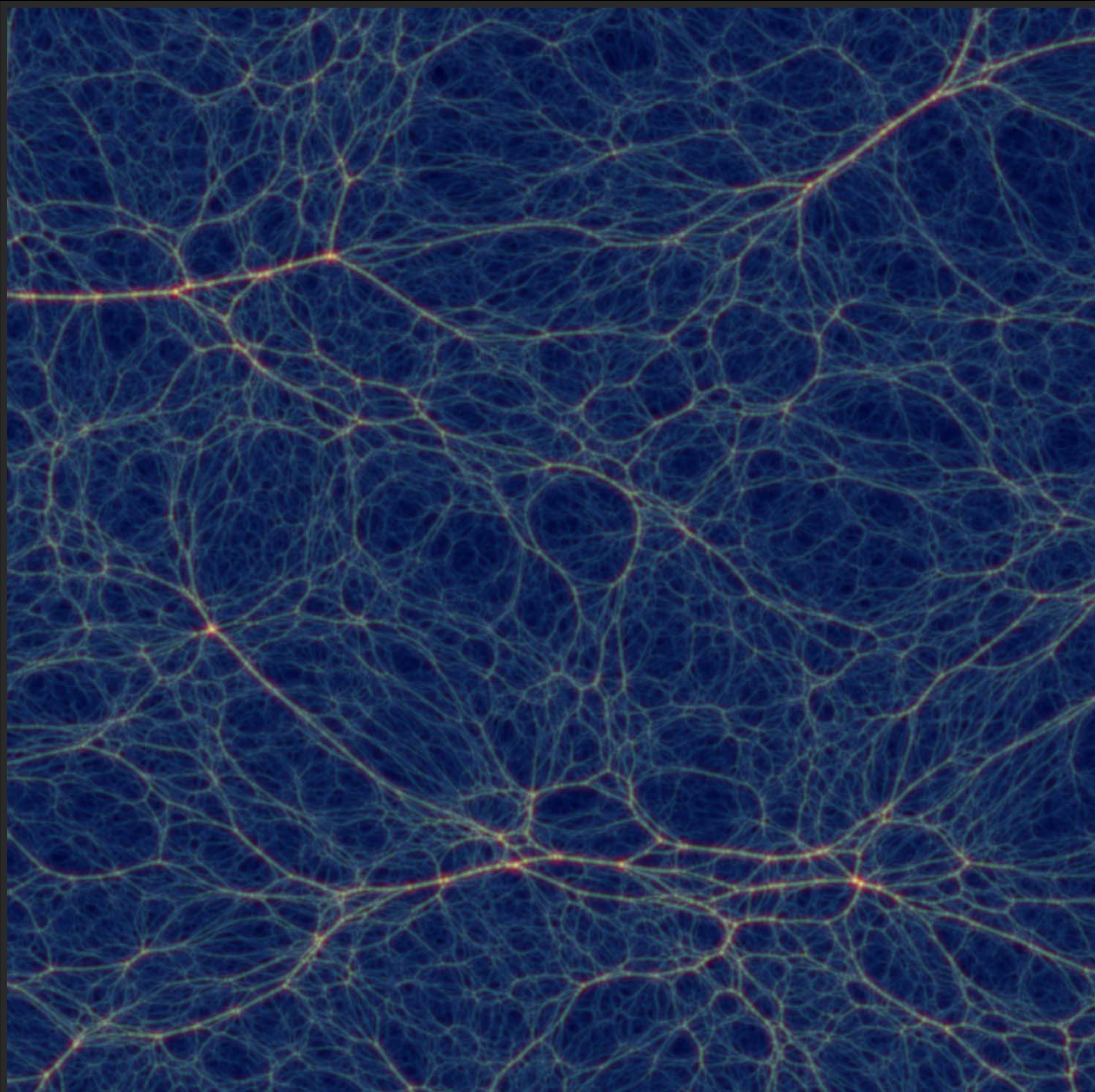



**Multiscale Infrastructure Voids:**

↓

**manifestation**

**Hierarchical Buildup of Voids**



**Multiscale Infrastructure Voids:**

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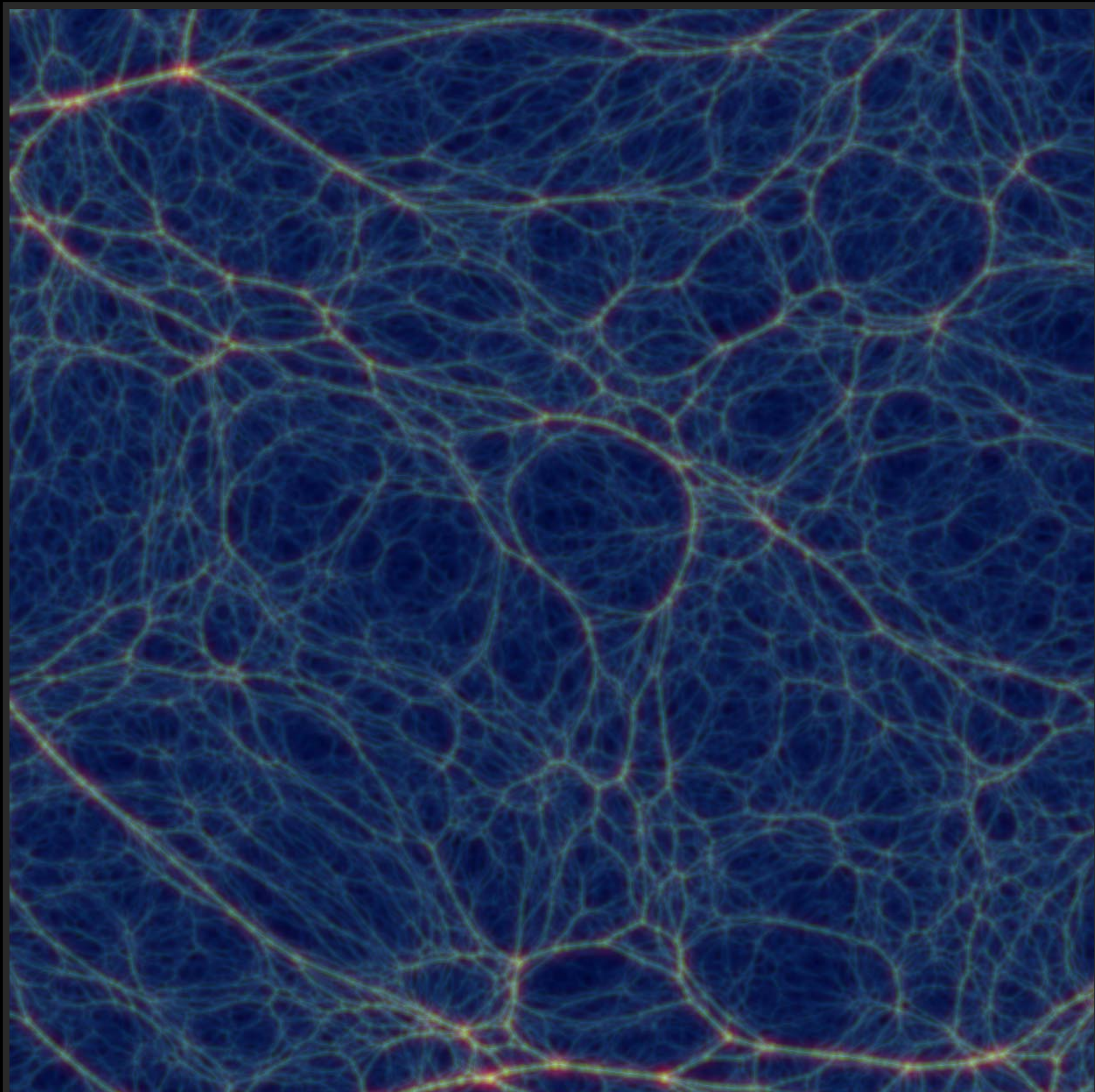

Multiscale Infrastructure Voids:

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manifestation

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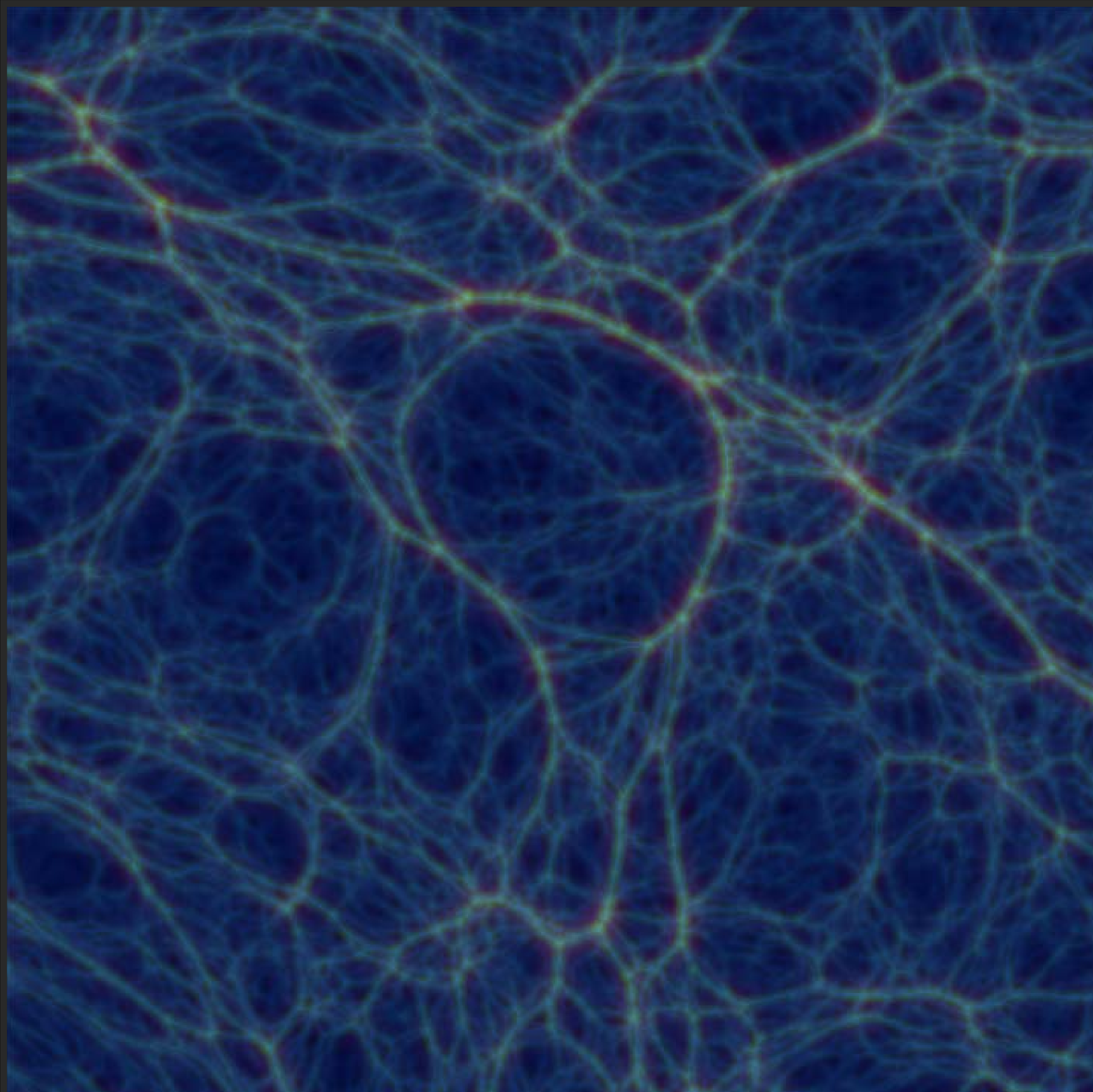
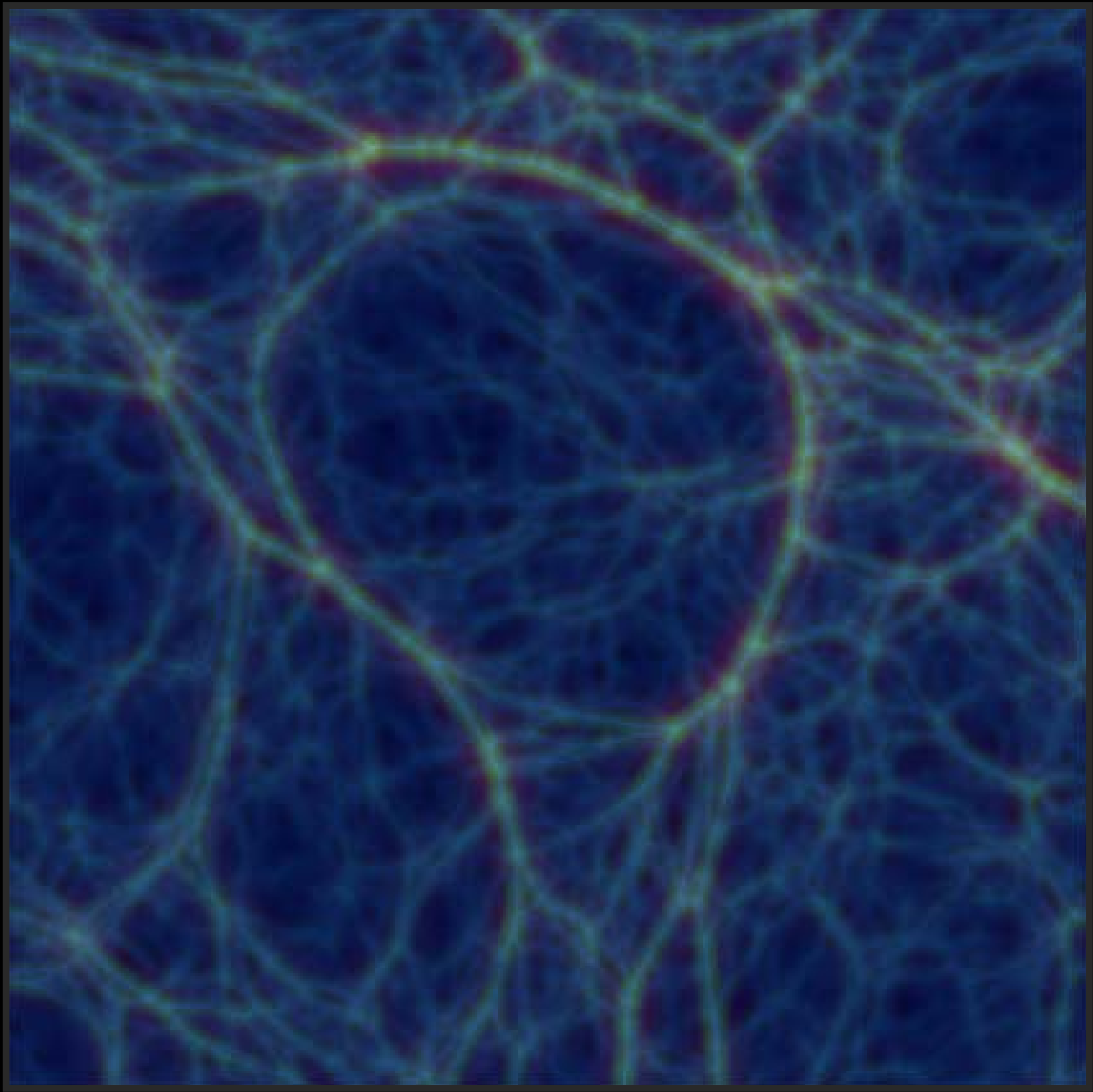


Multiscale
Infrastructure
Voids:

manifestation

Hierarchical
Buildup of
Voids



Multiscale Infrastructure Voids:

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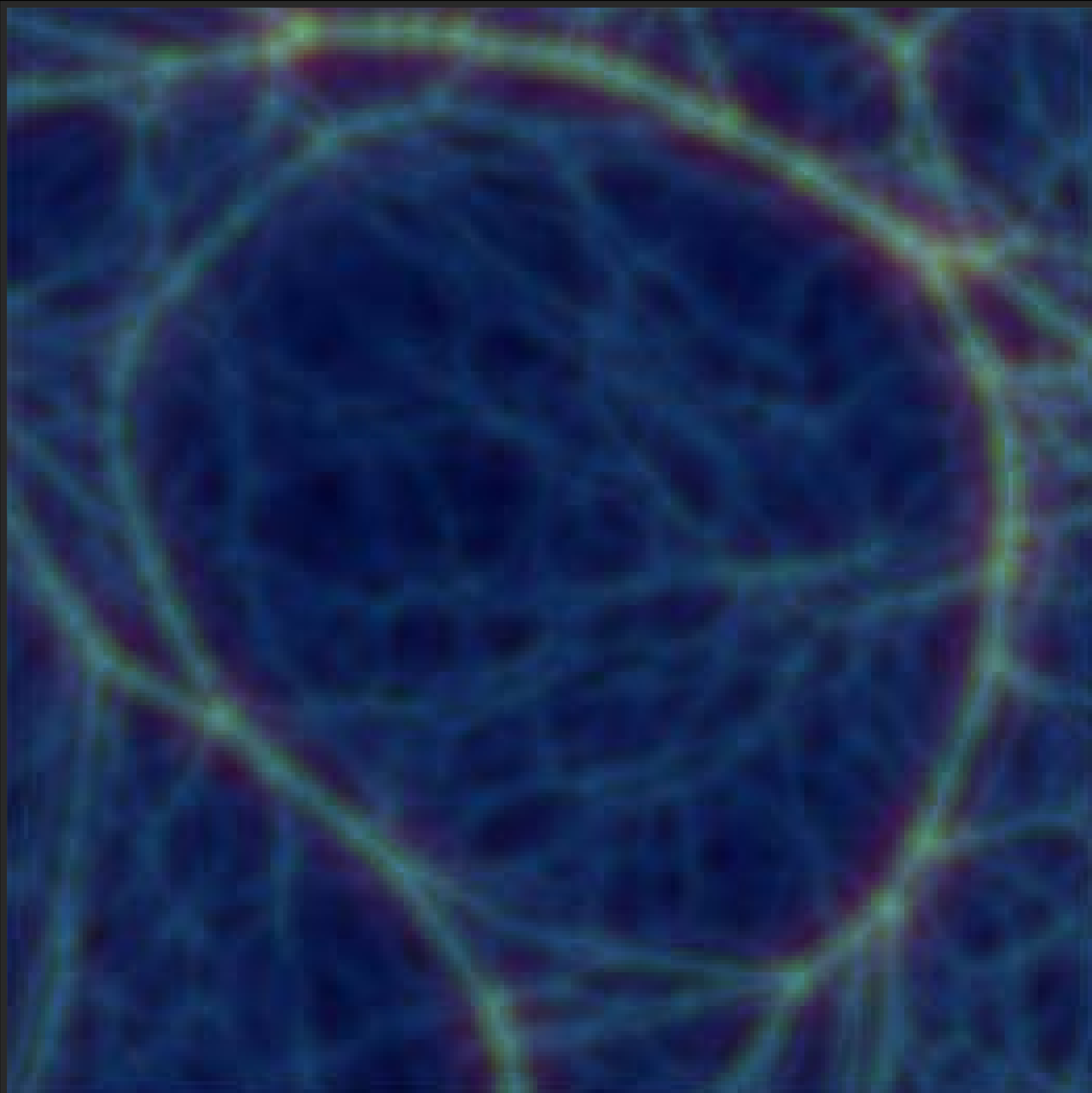
manifestation

Hierarchical Buildup of Voids



**Multiscale Infrastructure Voids:**

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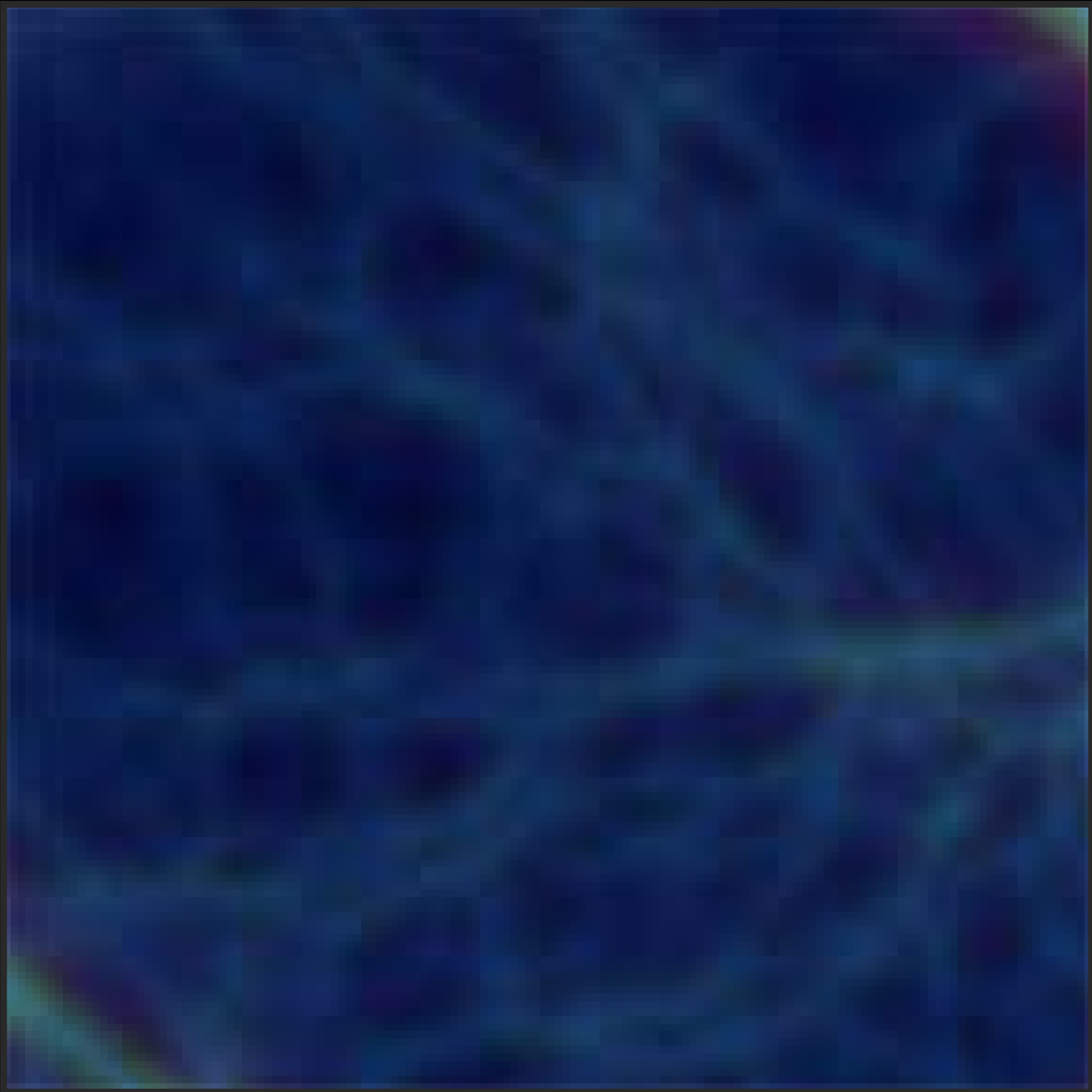
**manifestation**

**Hierarchical Buildup of Voids**



**Multiscale Infrastructure Voids:**

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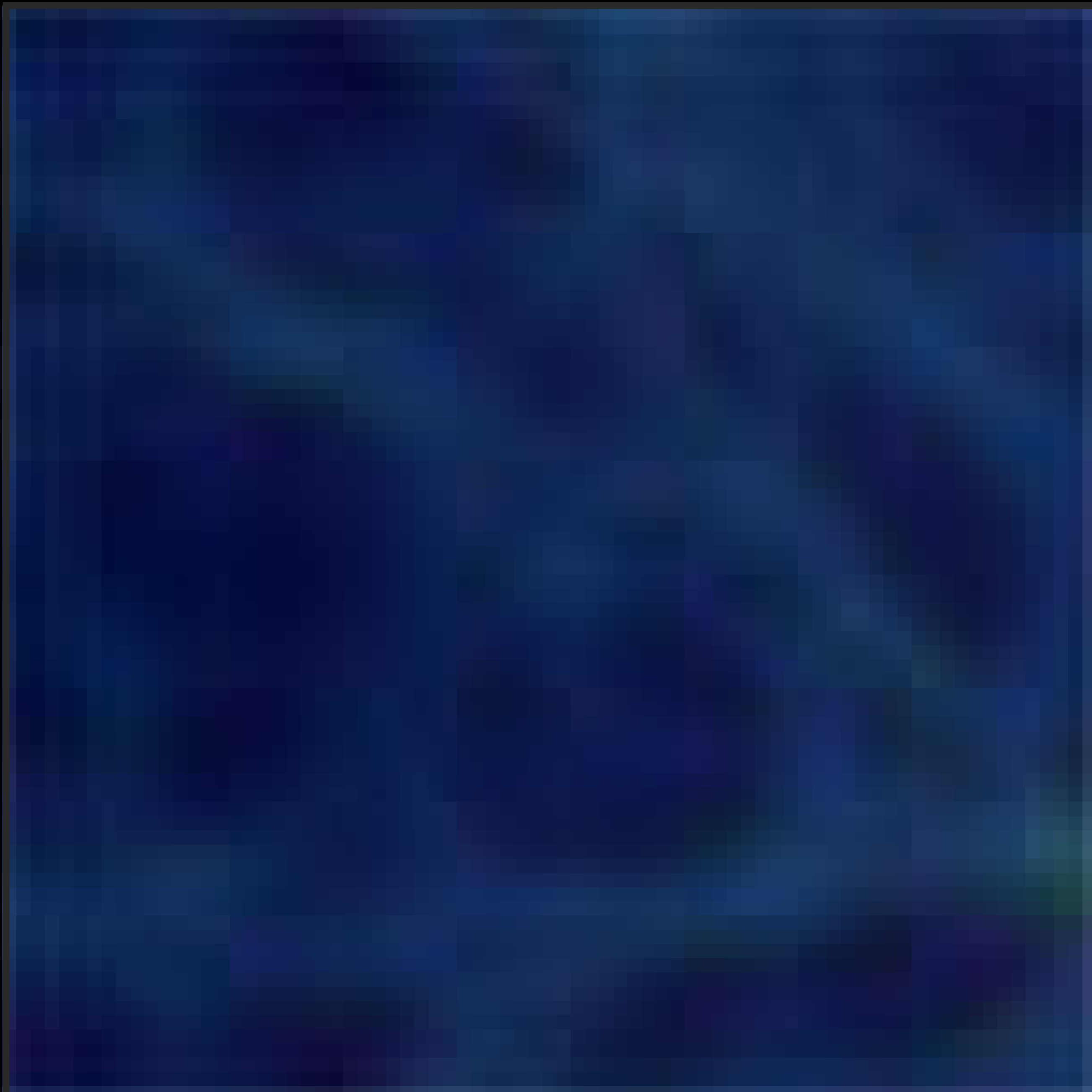
**Hierarchical Buildup of Voids**



**Multiscale Infrastructure Voids:**

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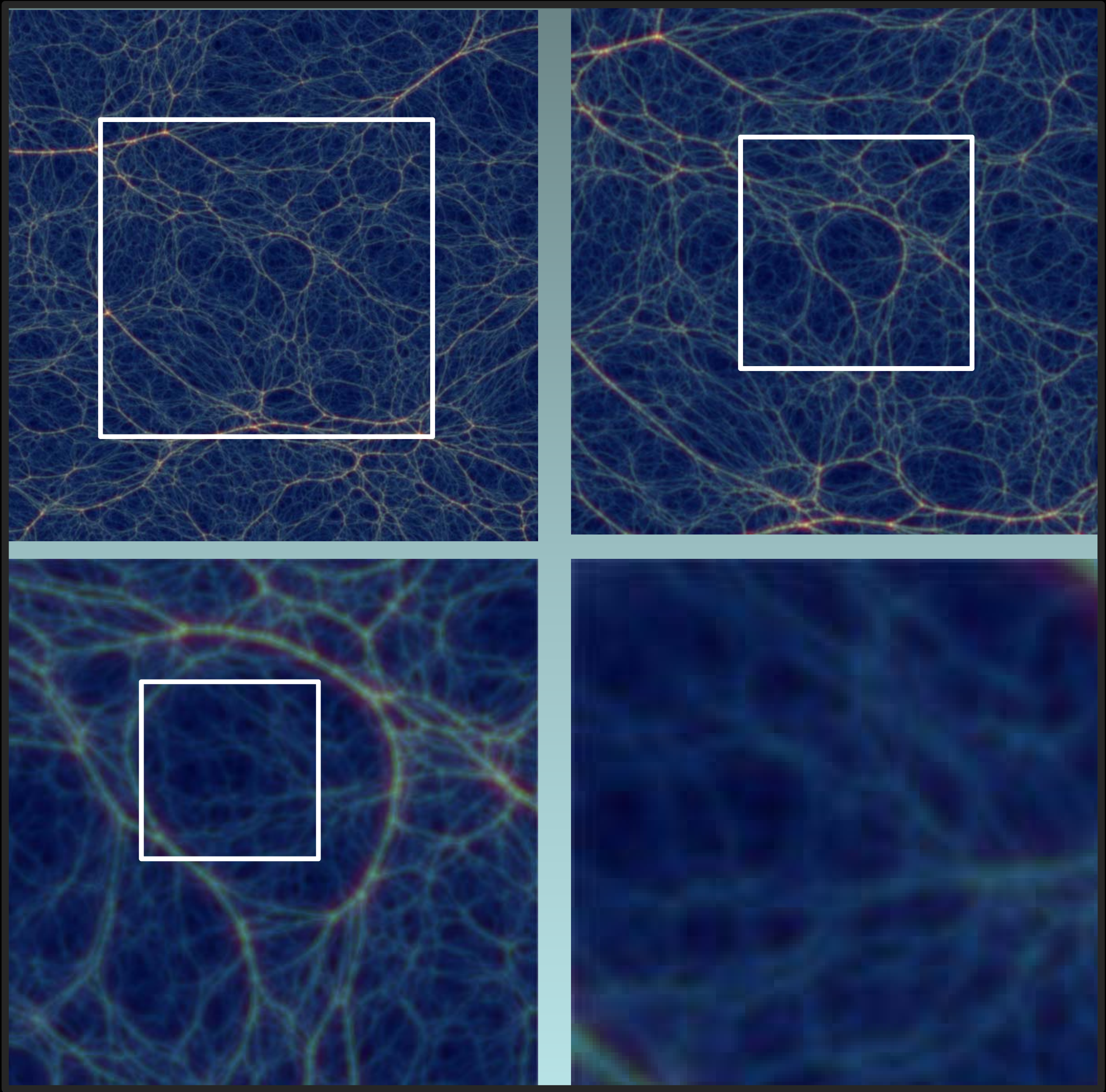
**manifestation**

**Hierarchical Buildup of Voids**

# Void Substructure



Zoom in: 3 levels

Substructure on
all scales:

amplitude
diminishing towards
smaller scales

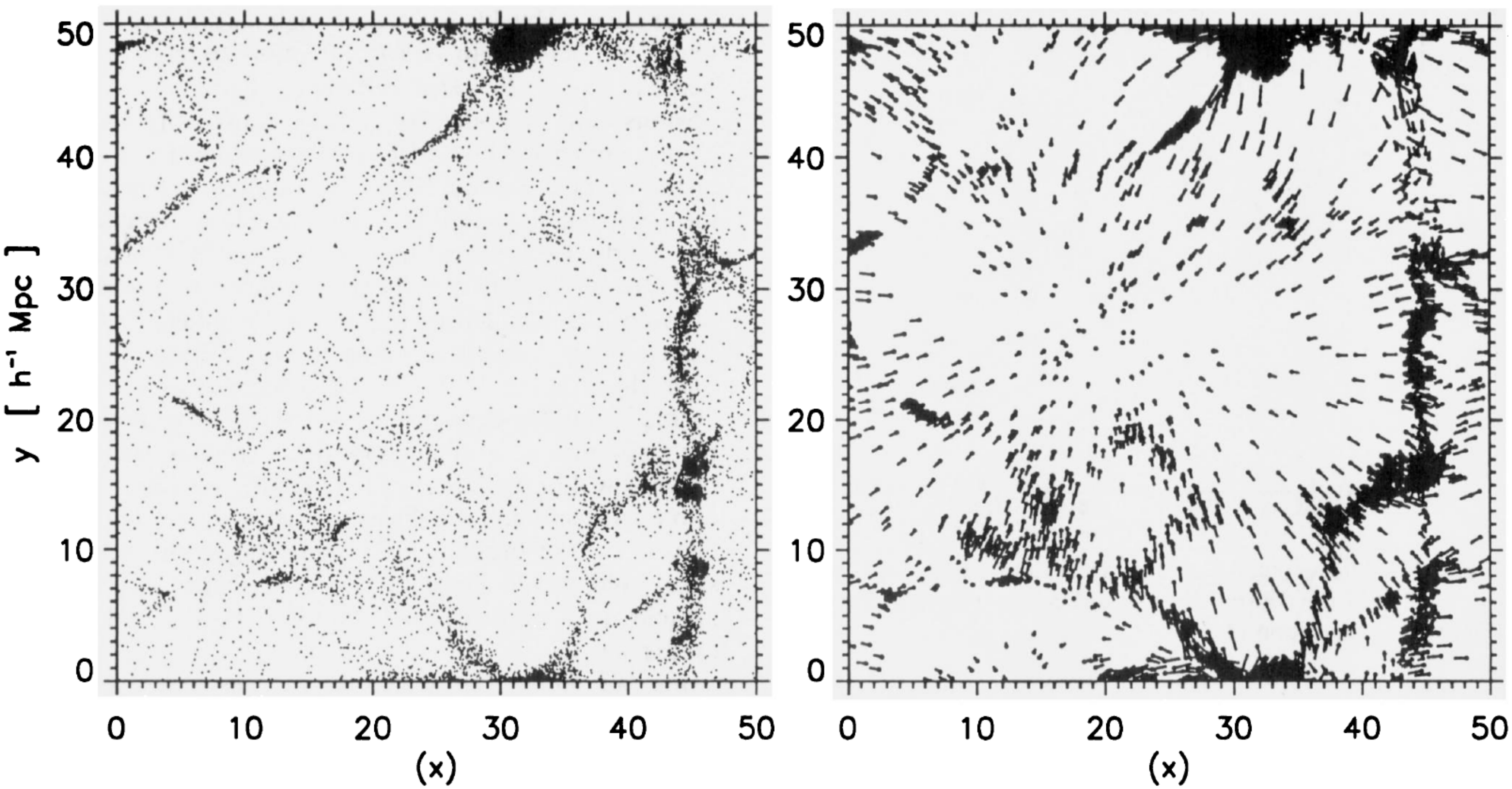
# Voids:

# Hierarchical Evolution

# Void Hierarchy

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

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



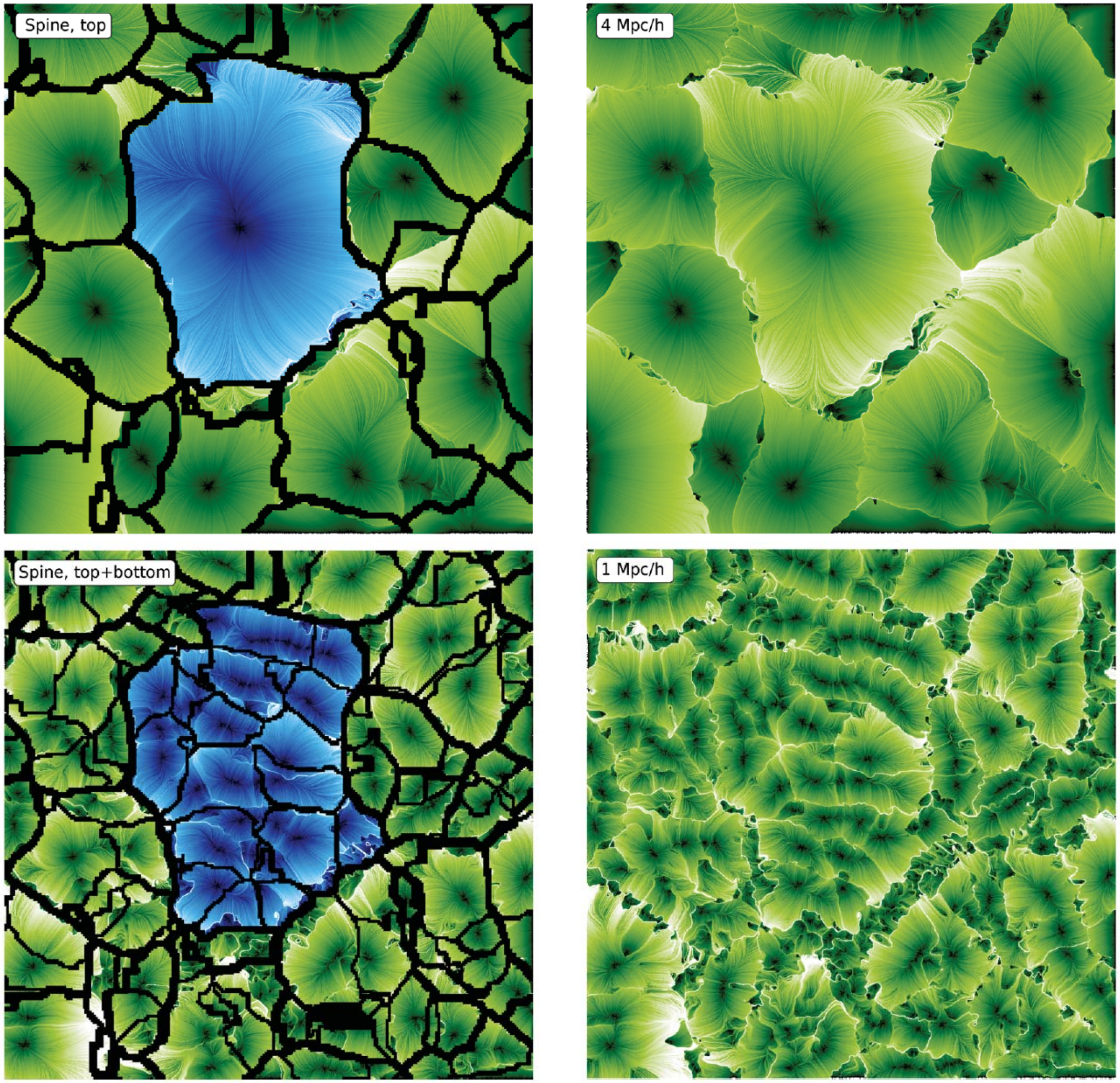

**Constrained Void Simulations:**

Van de Weygaert 1991
vdW & van Kampen 1993

**CRF formalism:**

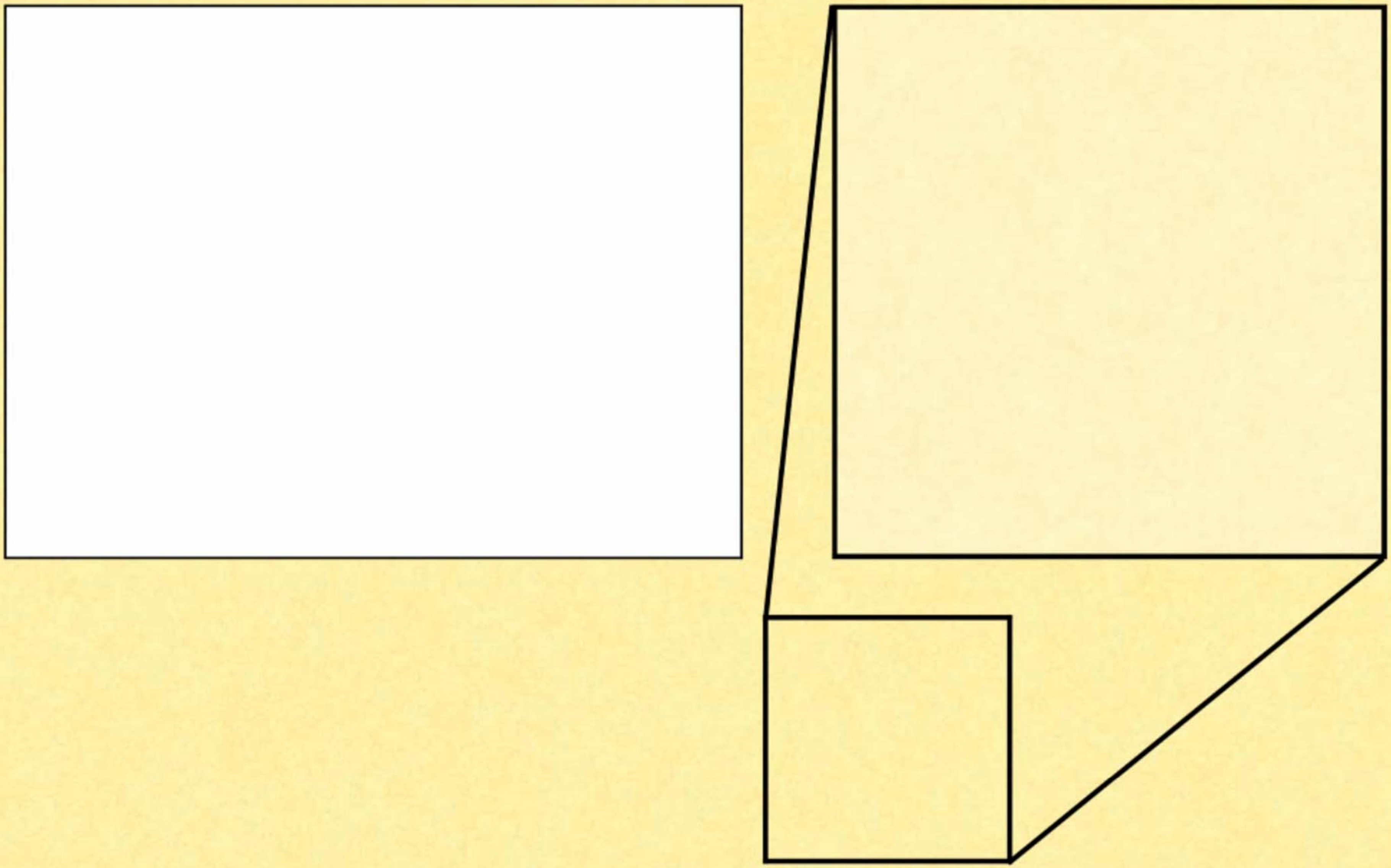
Bertschinger 1987
vdW & Bertschinger 1996

# Hierarchical Web Evolution:




**Void hierarchy expressed in multiscale structure velocity outflow**

**Aragon-Calvo & Szalay 2012**



**Dries, vdW & Hidding 2015**

# 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 ?

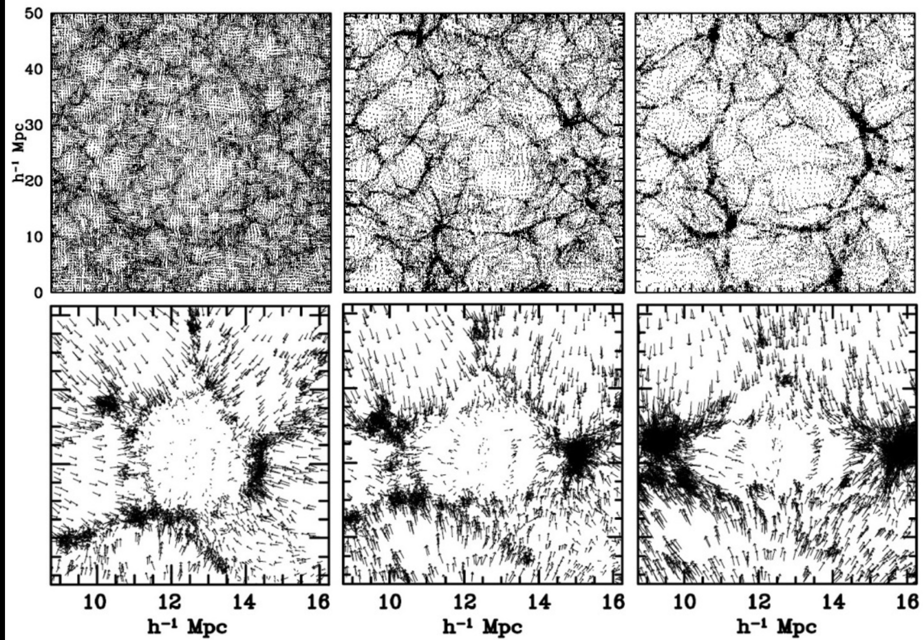
# Void Evolution Processes

- **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

# Extended Press-Schechter

## Barrier Excursions

- Spherical linear collapse overdensity:

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

- Collapse time:

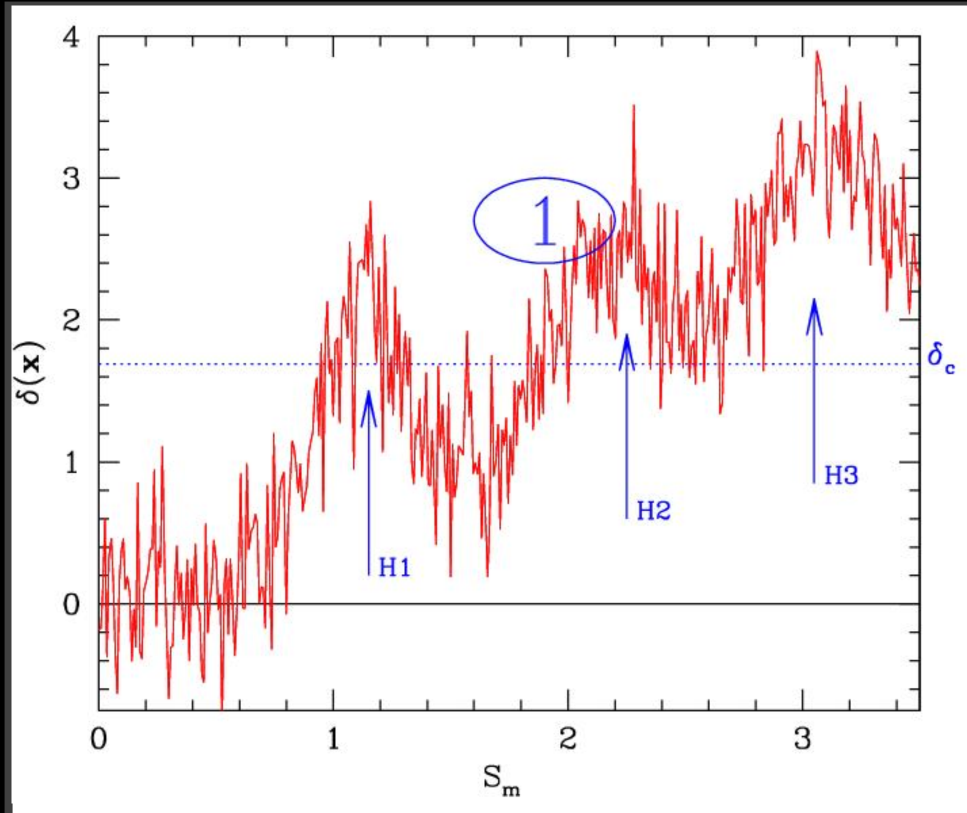
$$a_{coll}(r) = \delta_c / \Delta_{lin}\left(r, S_m\right)$$

- Initial density field:
  prediction object formation time:

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

  dependent on:
  Collapse Barrier $\delta_c$

- Critical density value:
  EdS , $\Omega_0$=1: $\delta_c$ ~ 1.69




cumulative random walk:

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

# Void Evolution: the Two-Barrier Formalism

Two critical barriers:

- embedded in underdensity
  VOID-IN-VOID
- embedded in overdensity
  VOID-IN-CLOUD
- to be counted in as voids, take only the ones who pass the void barrier, but do not pass through the cloud barrier at larger scale

Void-in-Cloud:

- key towards explaining absence small voids
- small voids get demolished in overdensities
- population of cosmic “halos” dominated by small clumps (divergent)

↔

void ranks dominated by voids ~ specific void size

# Extended Press-Schechter

## Barrier Excursions

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

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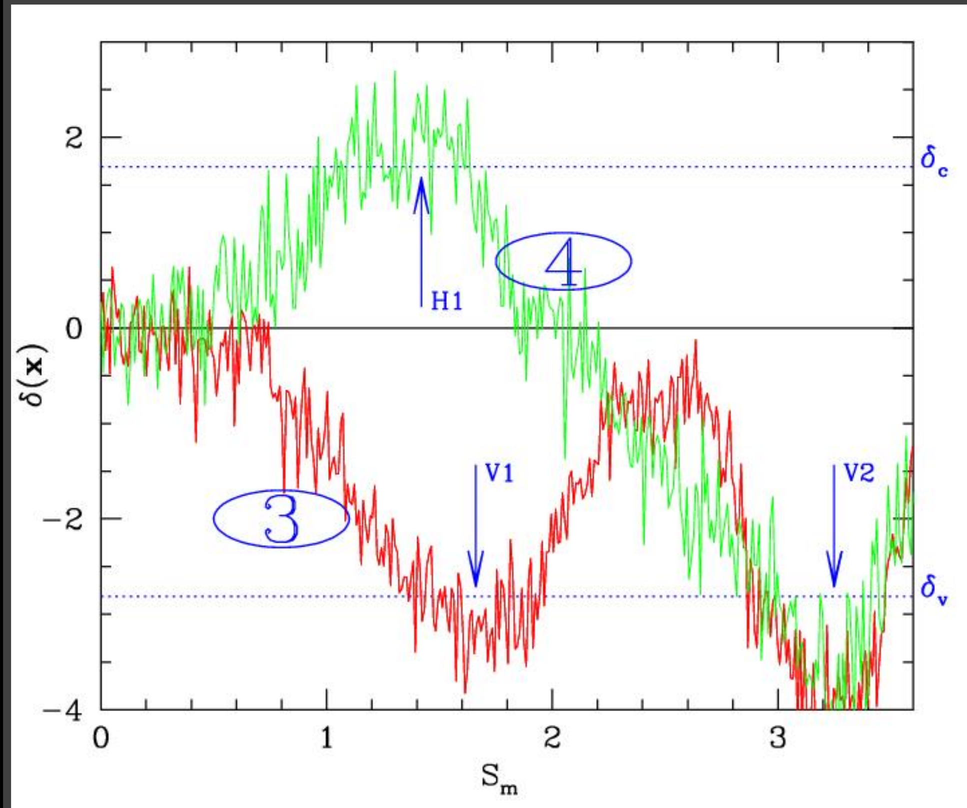


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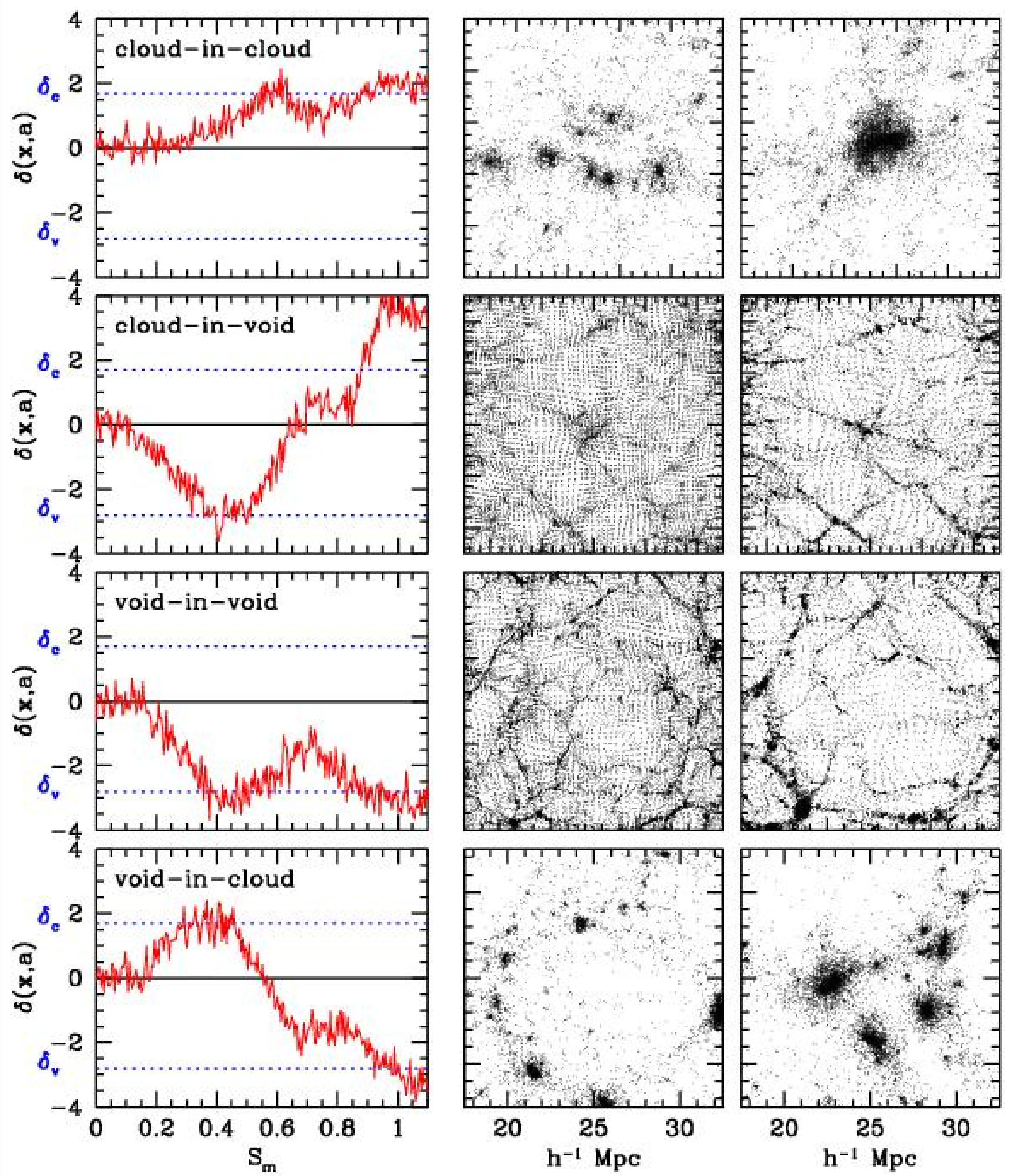
# Hierarchical

# 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**

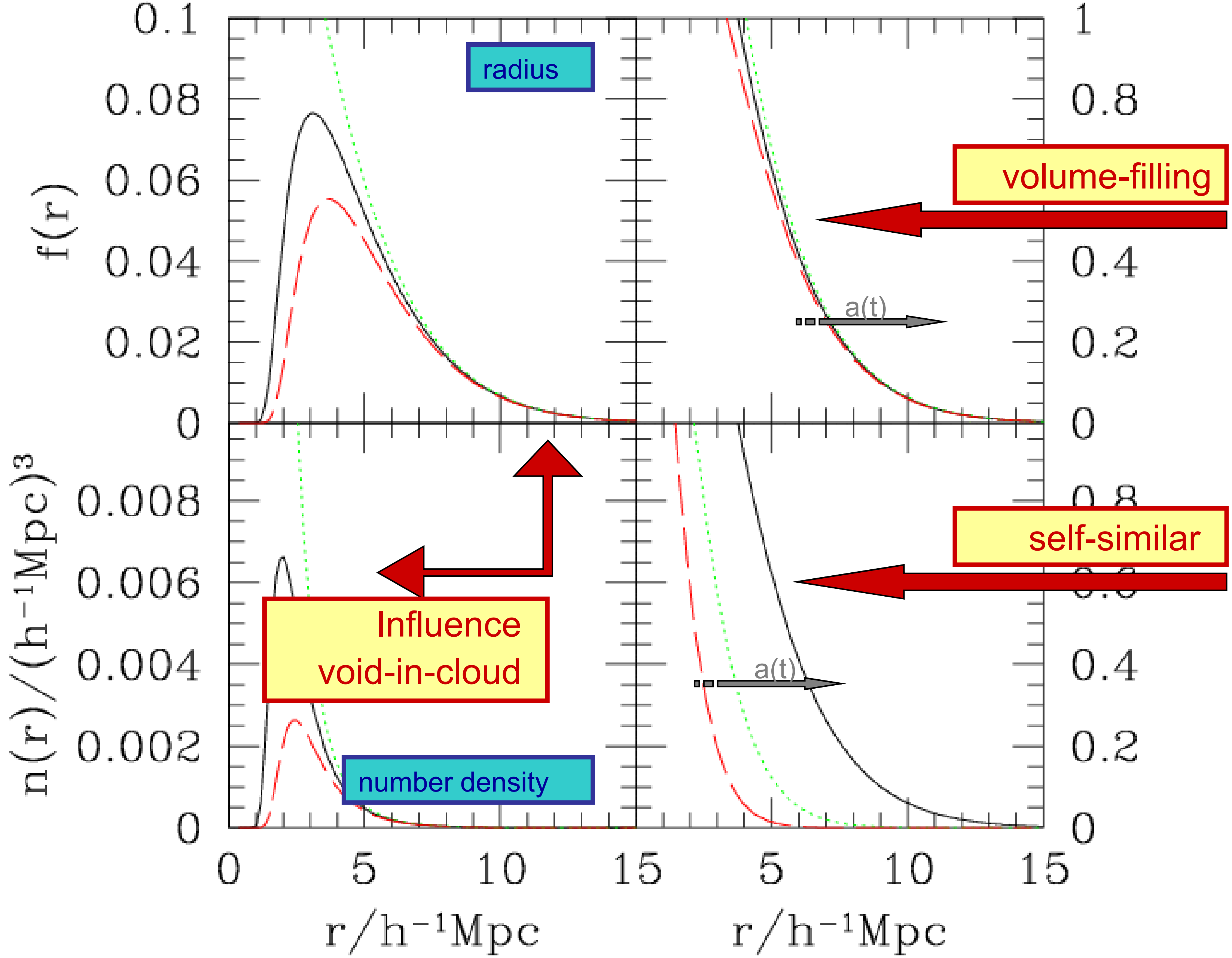
$$\nu_v(M) = \frac{|\delta_v|}{\sigma(M)} \qquad \mathcal{D} \equiv \frac{|\delta_v|}{(\delta_c + |\delta_v|)}$$

**void mass distribution function**

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

**for power-law power spectrum:**

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


radius
volume-filling
a(t)
Influence
void-in-cloud
number density
self-similar
a(t)
f(r)
n(r)/(h⁻¹Mpc)³
r/h⁻¹Mpc
r/h⁻¹Mpc
0.1
0.08
0.06
0.04
0.02
0
0.008
0.006
0.004
0.002
0
1
0.8
0.4
0.2
0
0.4
0.2
0
0
5
10
15
5
10
15

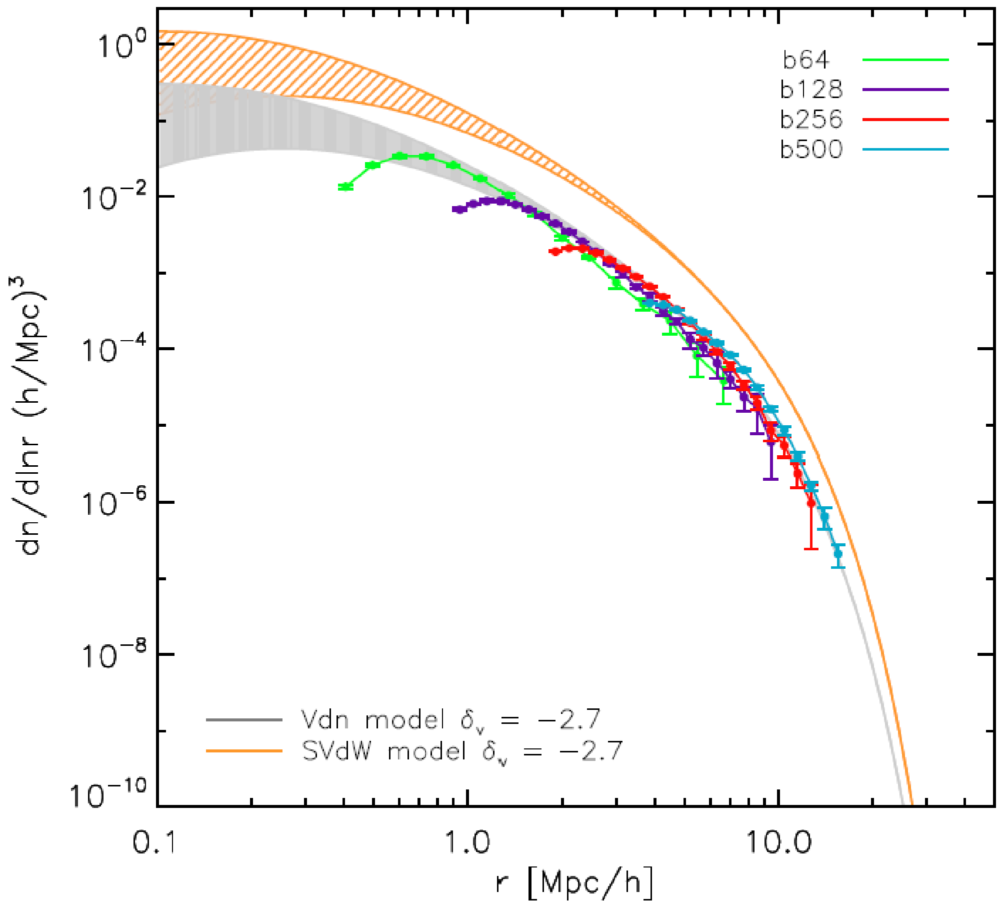
# Void Population & Excursions

Jennings et al. 2013

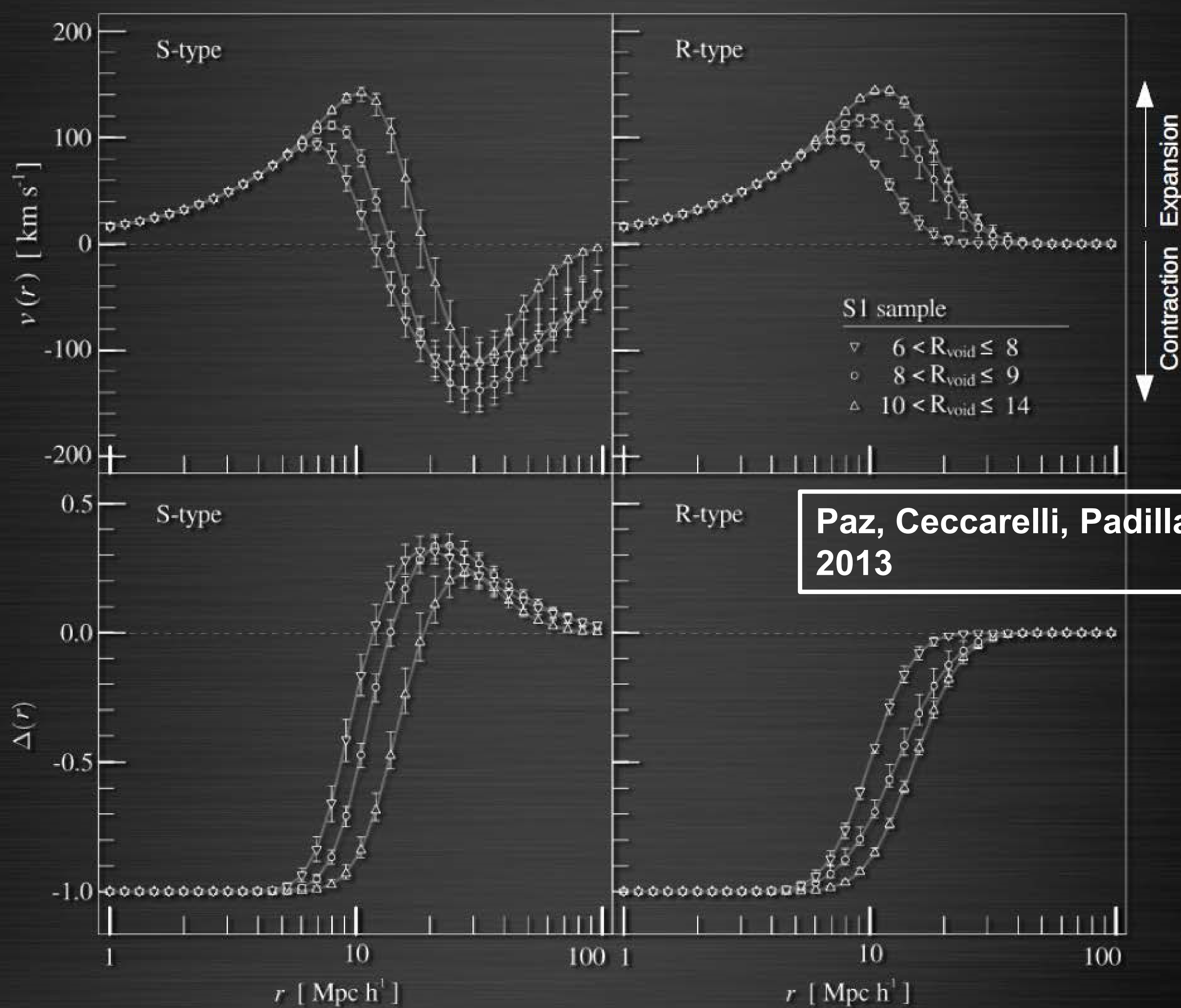
**Two-barrier SvdW**
**void excursion set formalism:**

**correcting simple assumption**
**delta_v criterion:**

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



# SDSS voids recovered velocity and density profiles



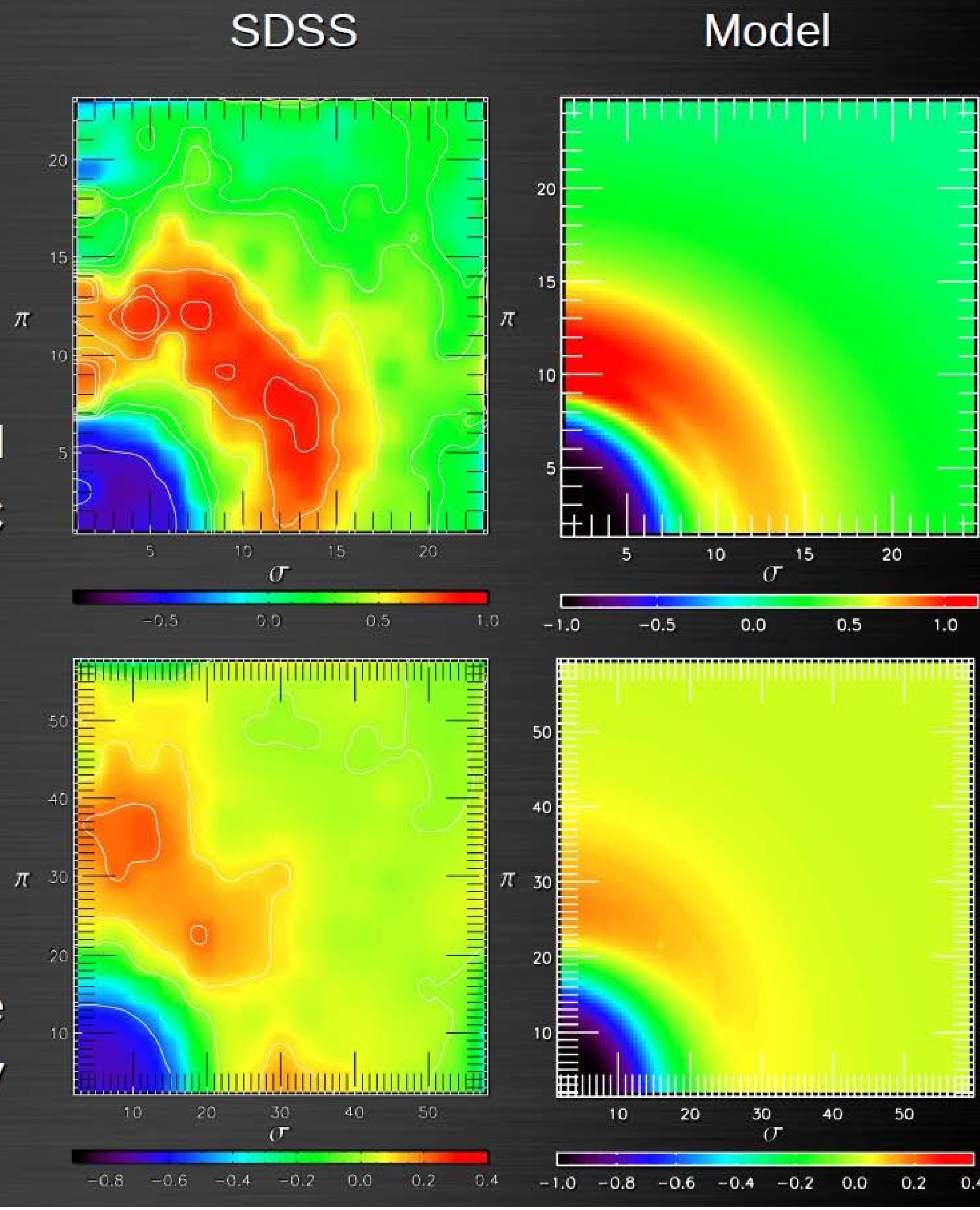

**Paz, Ceccarelli, Padilla et al. 2013**

# SDSS void-galaxy correlations ξ(σ,π)

**Paz, Ceccarelli, Padilla et al. 2013**

Small V-in-C

Large V-in-V




Volume Limited Sample

Mr < -20.3

330 voids Z < 0.12