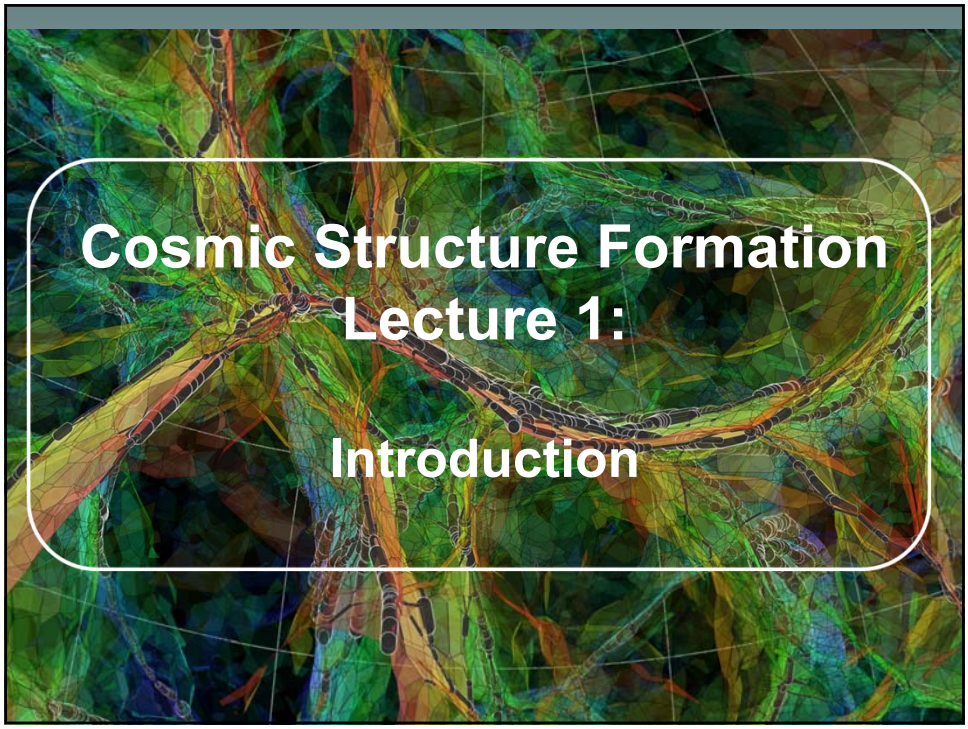
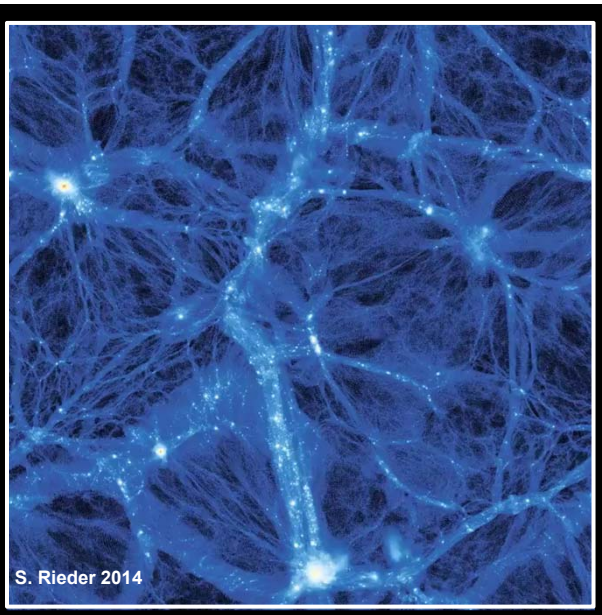


Cosmic Structure Formation
Lecture 1:
Introduction



on scales of ~0.1 -100s Mpc

complex weblike pattern

in which
matter, gas & galaxies
aggregate in

- compact clusters,
- elongated filaments
- flattened sheets

around

- cosmic voids

Cosmic Web

Cosmic Web:

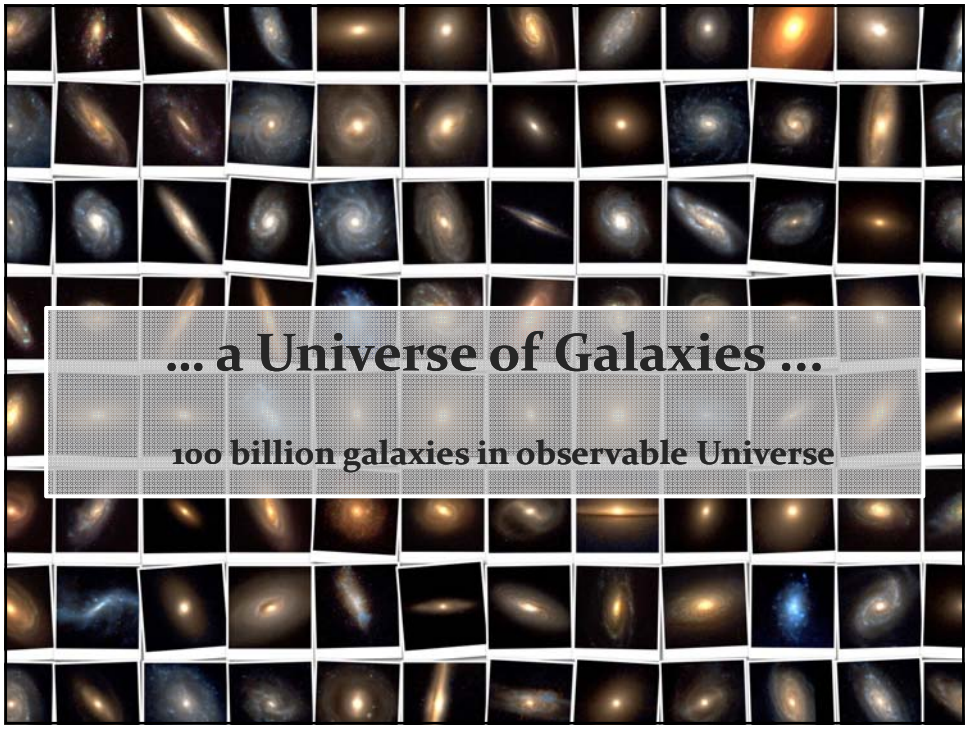
Galaxies along spatial patterns

Map of the Universe

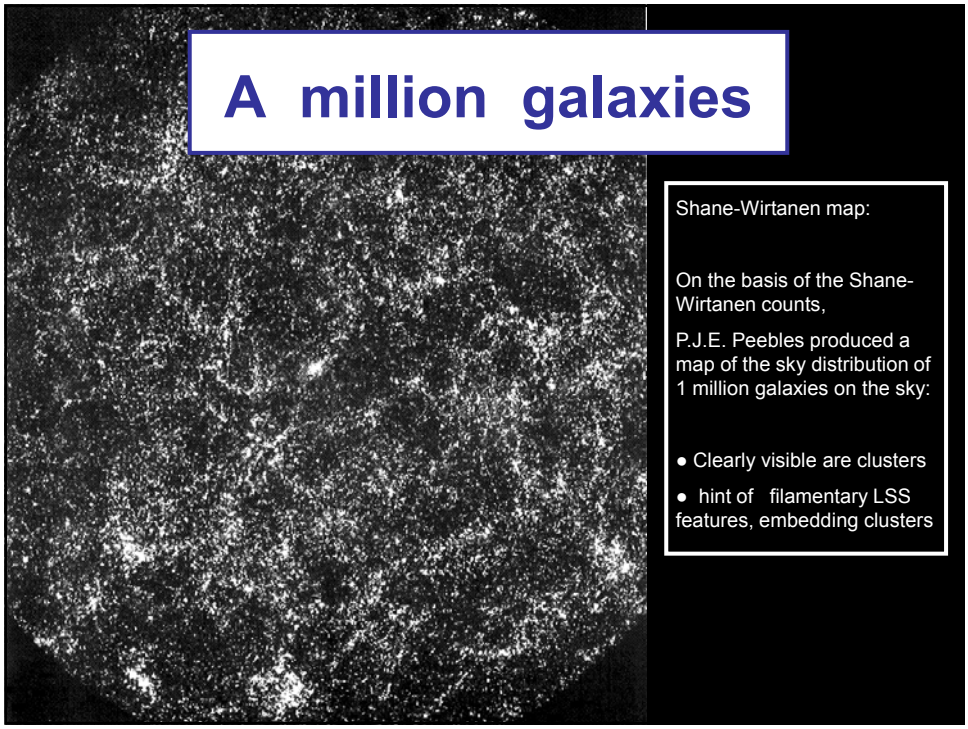
How to map the structures and patterns in the Universe ?

- Use galaxies as beacons
- Map of Galaxy positions
- Tracing of structures from distribution of galaxies

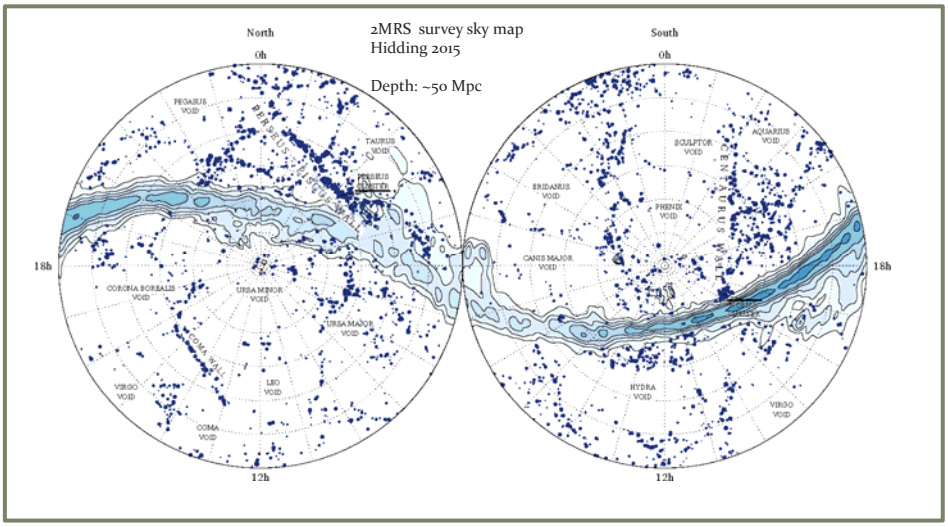

... Galaxies ...


... a Universe of Galaxies ...
100 billion galaxies in observable Universe

Clusters of Galaxies



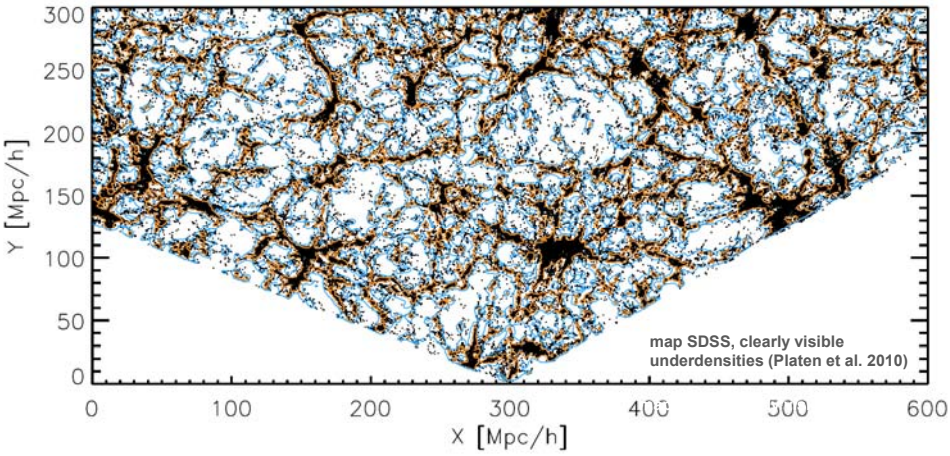
2MRS Local Universe ...



2MRS survey sky map
Hidding 2015

Depth: ~50 Mpc

SDSS Galaxy Survey

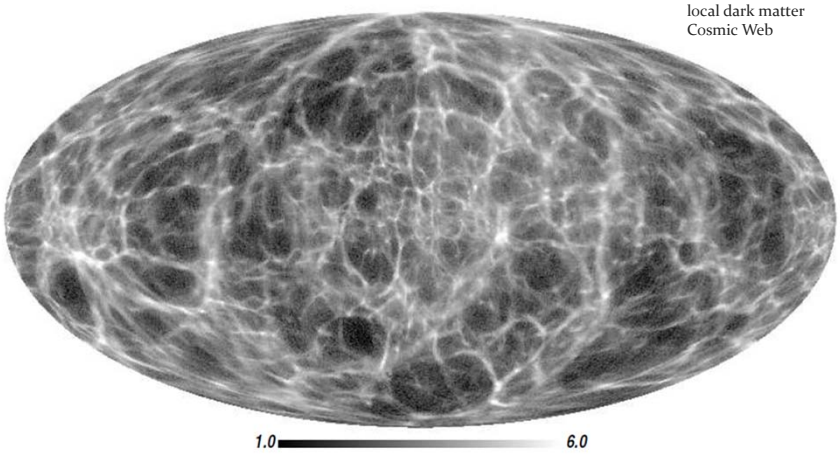


with the advent of large galaxy redshift surveys
– LCRS, 2dFGRS, SDSS, 2MRS –
the reality of the Cosmic Web as largest spatial structure and organization in nature established

local Cosmic Web: 2MRS

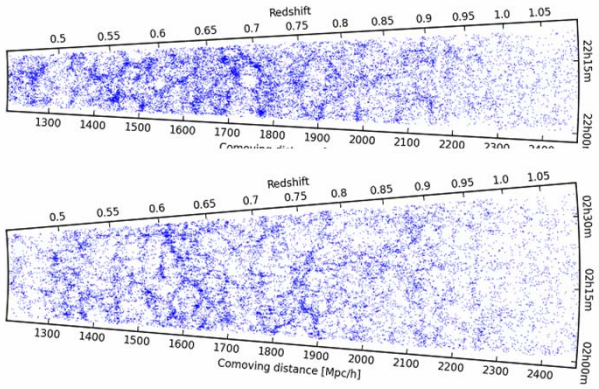
most detailed reconstruction of the

local dark matter Cosmic Web



Courtesy: Francisco Kitaura

VIPERS: Cosmic Web at High z



VIPERS
deep redshift survey,
z=0.4-1.2
(Guzzo et al. 2014-)

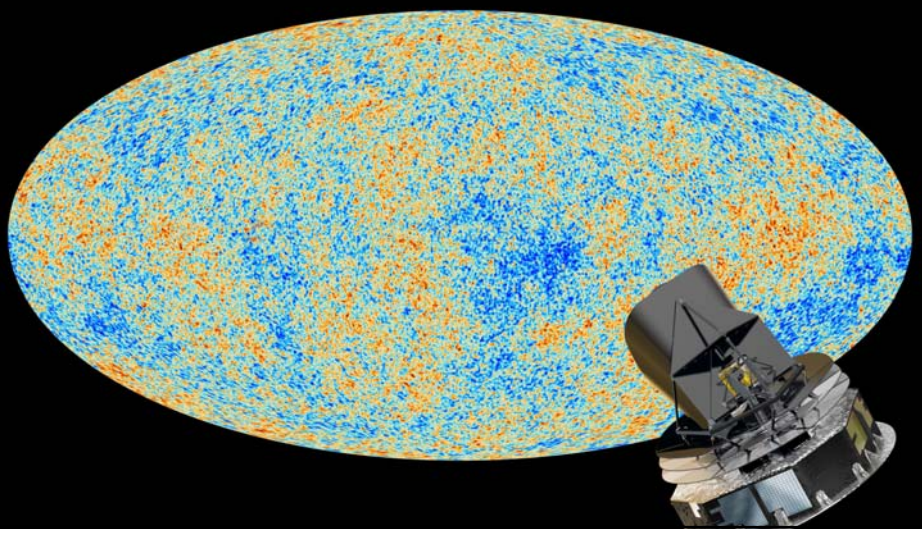
recent galaxy surveys out to high cosmic depths
- eg. DEEP, VIPERS -
establish that the Cosmic Web pervades entire Universe (up to z~5 at least)

Cosmic Structure Formation:

Gravitational Instability

Cosmic Origins

- Universe 380.000 yrs after Big Bang
- 13.8 Gyrs ago (13.798±0.037 Gyrs)
- temperature/density fluctuations ($\Delta T/T<10^{-5}$)
- perfect Gaussian random field



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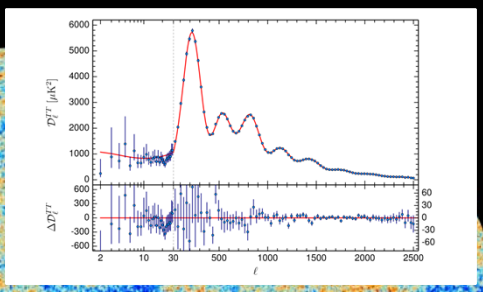
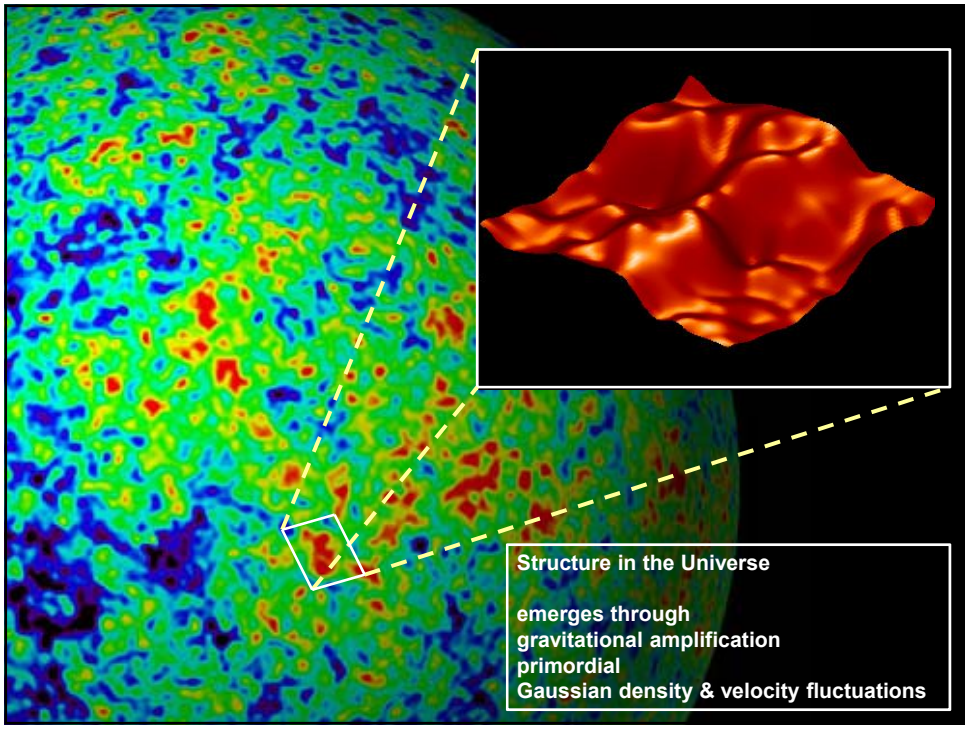
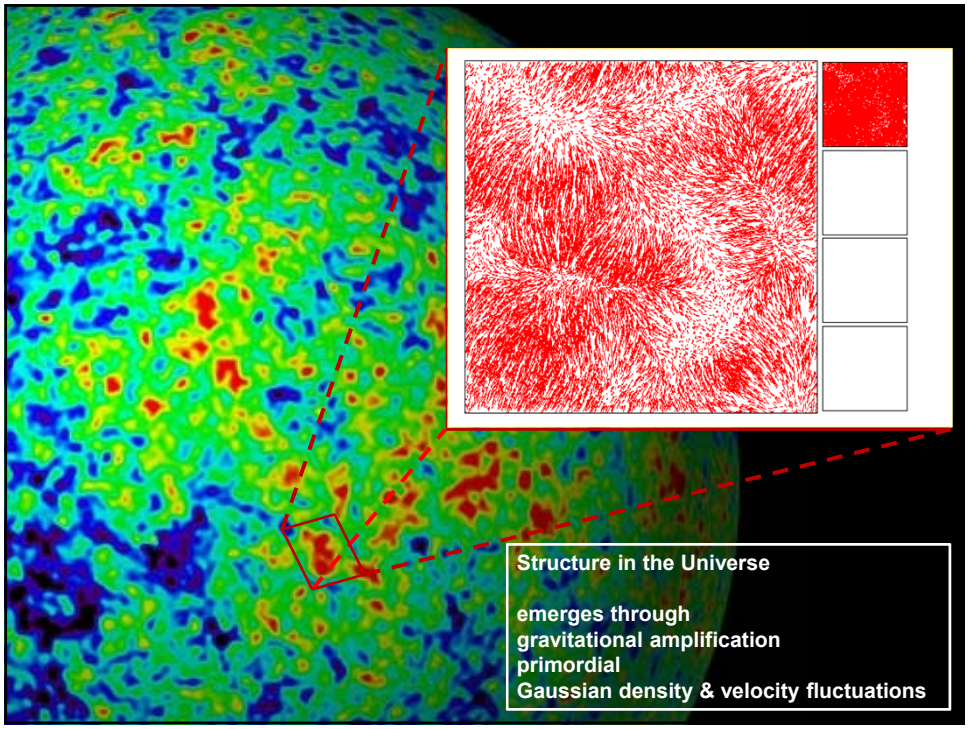
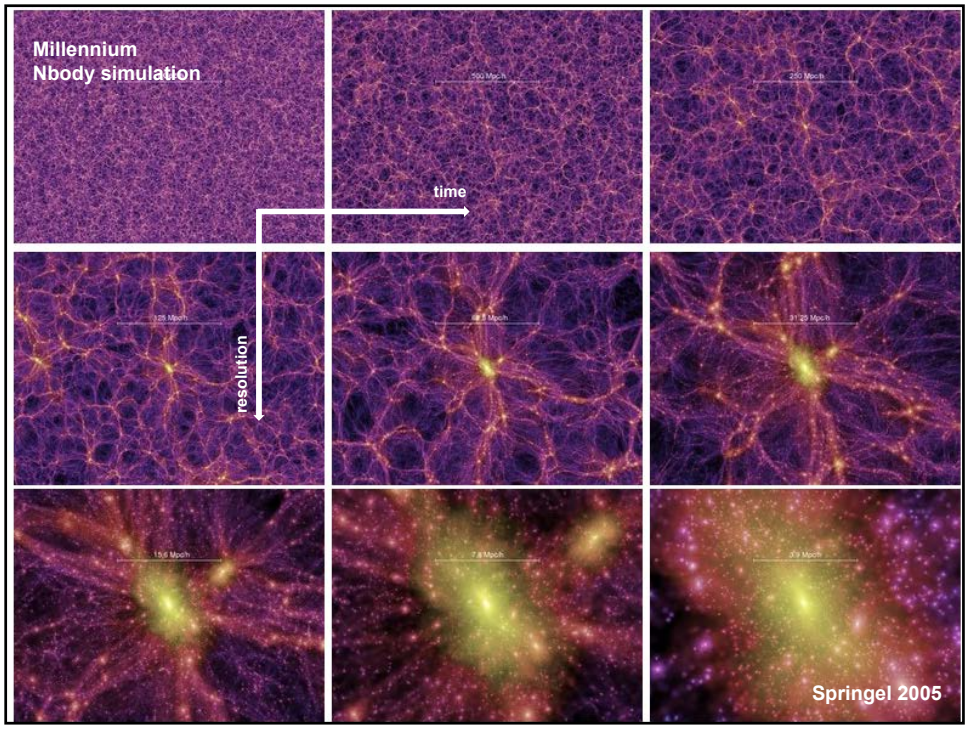
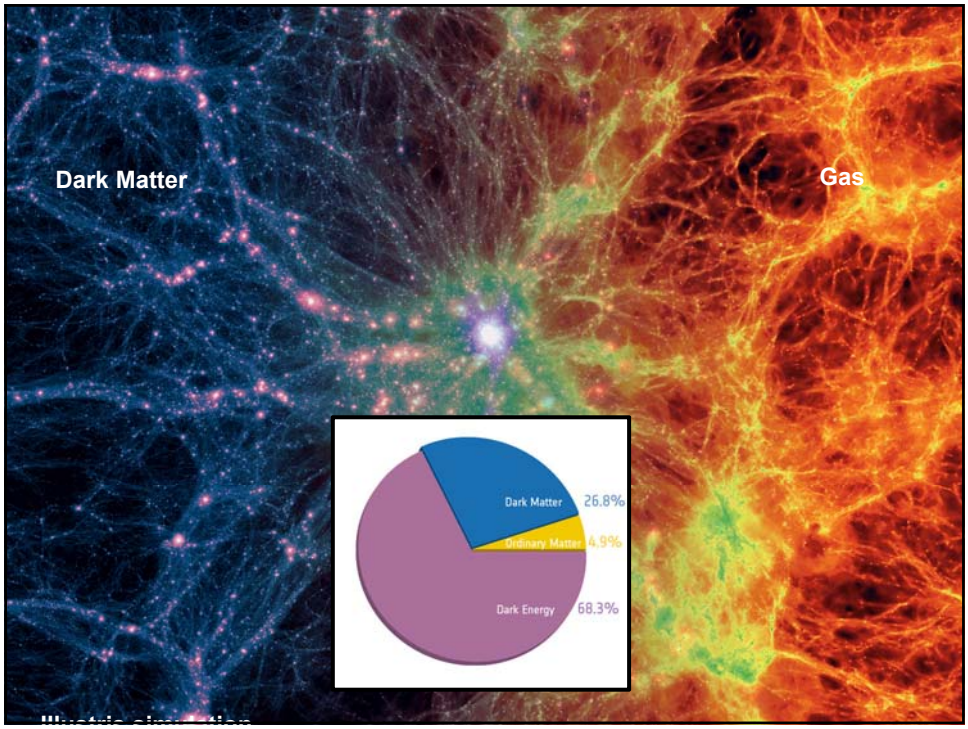




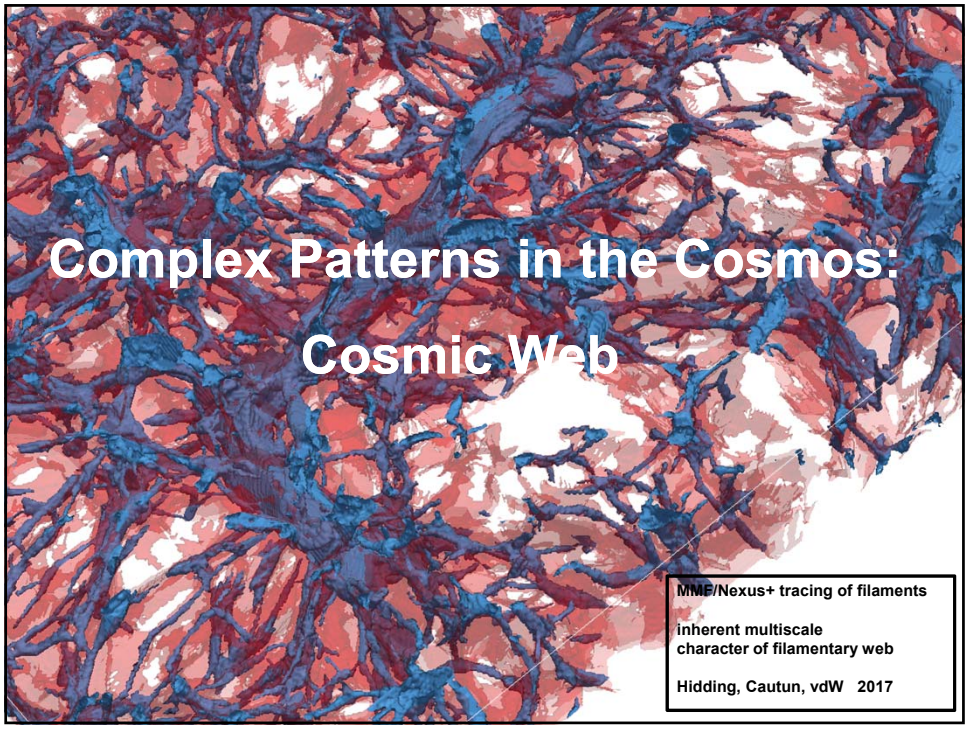

Structure in the Universe
emerges through
gravitational amplification
primordial
Gaussian density & velocity fluctuations


Millennium
Nbody simulation
time
resolution
Springel 2005

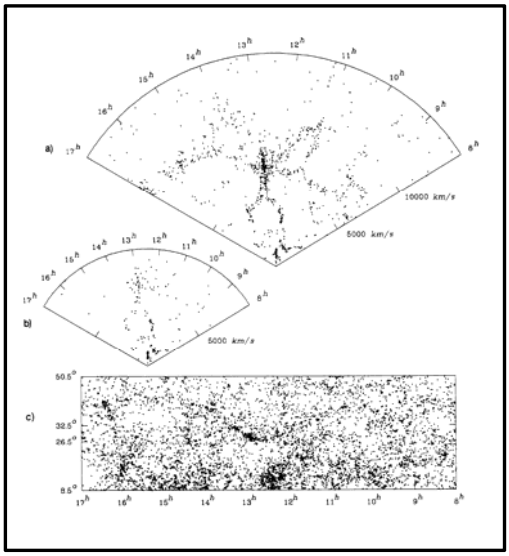


Cosmic Structure Formation:

Cosmic Web



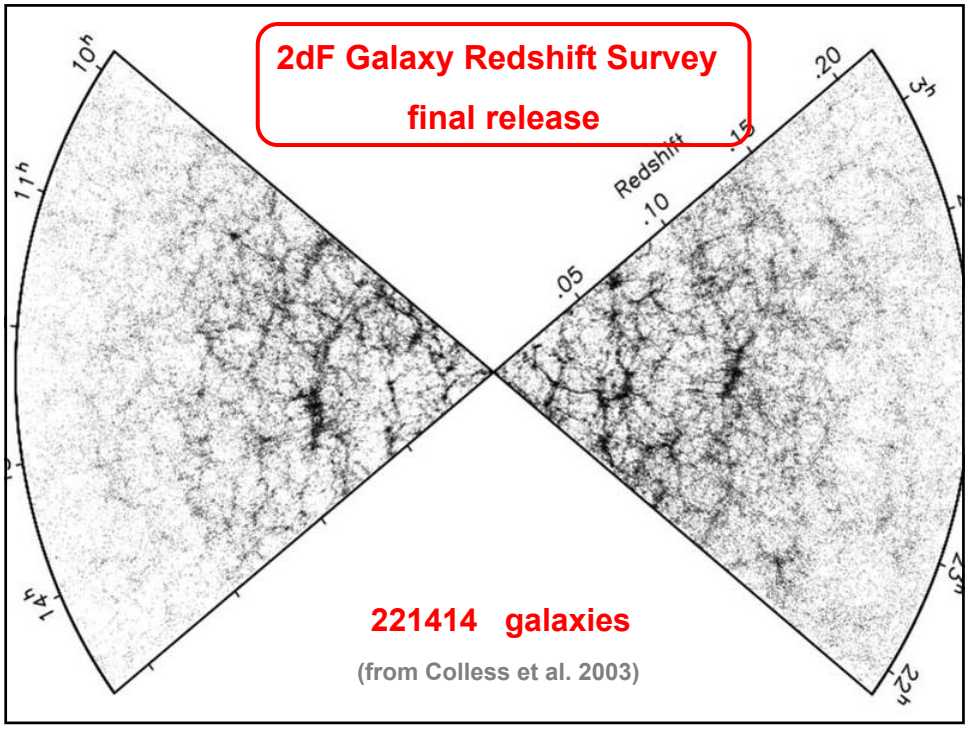
"Stickman" & Soapsud

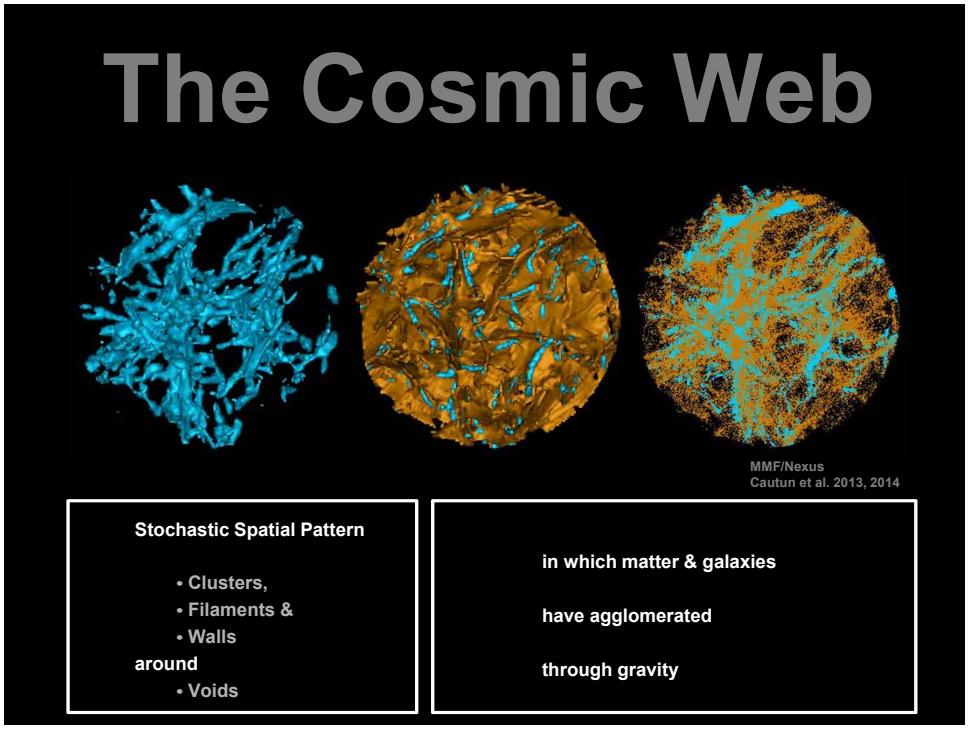


deLapparent, Geller & Huchra, 1986:

"a slice of the Universe"

Voids are an integral component of a Galaxy distribution that resembles a soapsud.

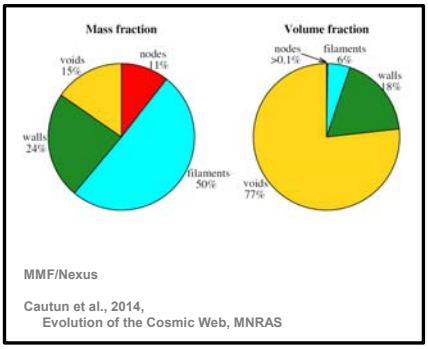

2dF Galaxy Redshift Survey
final release
Redshift
.05
.10
.15
.20
10h
11h
14h
3h
22h
221414 galaxies
(from Colless et al. 2003)


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

Cosmic Web Characteristics

- **anisotropic structure:**
  - filaments dominant structural feature - elongated
  - sheets/walls - flattened
- **multiscale nature**
  - structure on wide range of scales (~0.1-100s Mpc)
  - 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

Cosmic Web Morphology Inventory

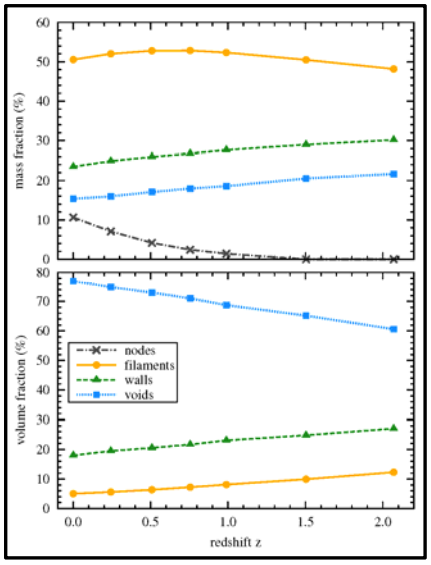


MMF/Nexus

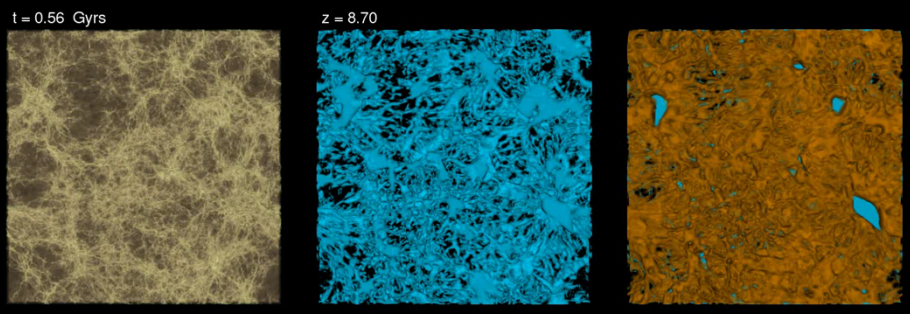
Cautun et al., 2014,
Evolution of the Cosmic Web, MNRAS

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)



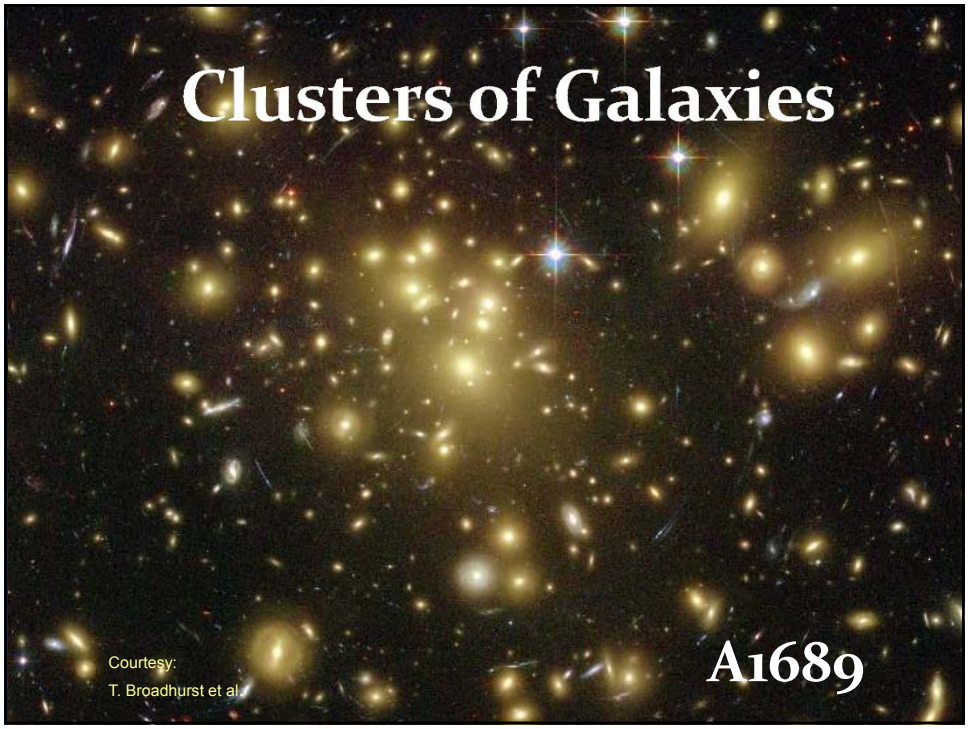
NEXUS/MMF Evolution Cosmic Web



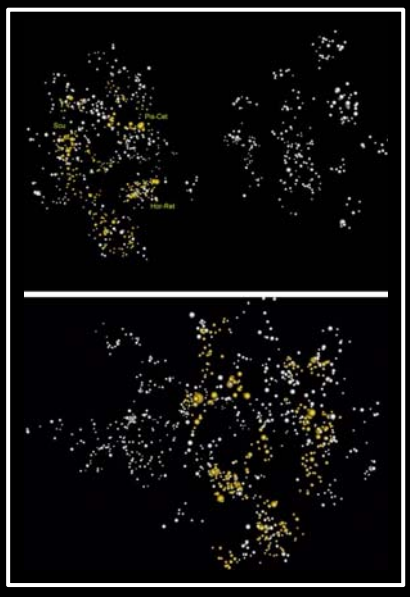
Cautun et al. 2014

Cosmic Structure Formation:

Clusters, Filaments & Voids



Voids & Clusters

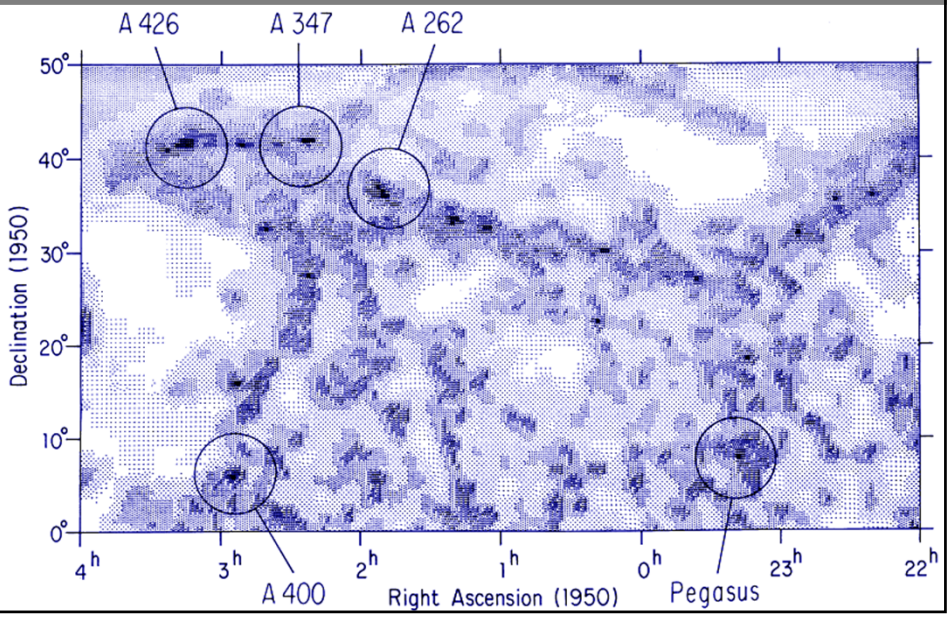


Einasto, Saar et al. (1990s)

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

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

Pisces-Perseus Supercluster

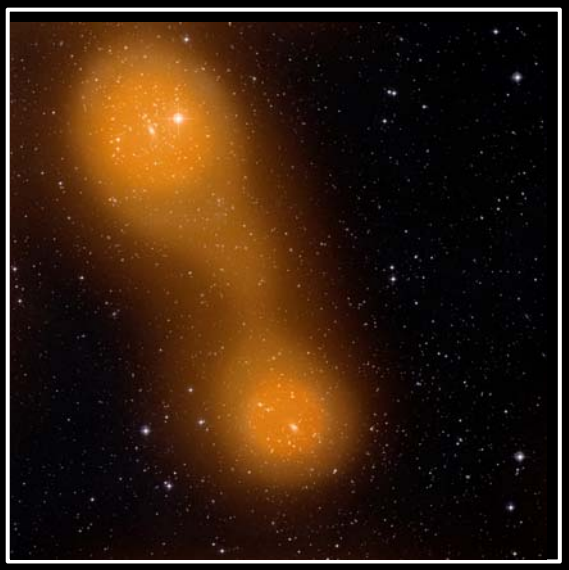


the Gaseous Cosmic Web

SZ detection of

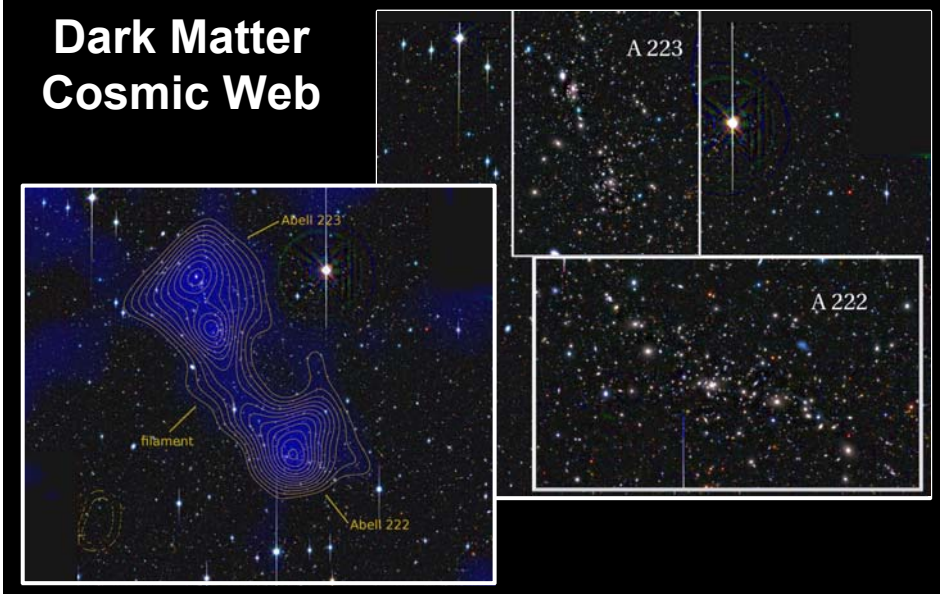
Inter-cluster bridge/filament

in between clusters A401 and A399



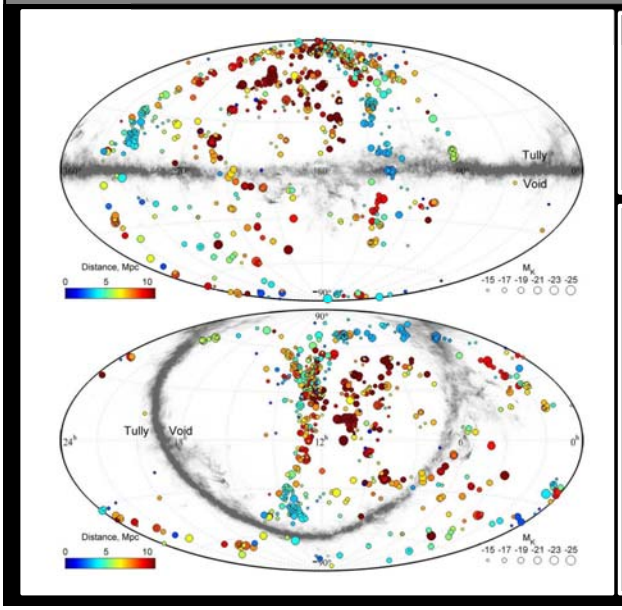
ESA/Planck collaboration

Dark Matter Cosmic Web



A222-A223
Dietrich et al. 2013

Voids in the Cosmic Web: the Local Void

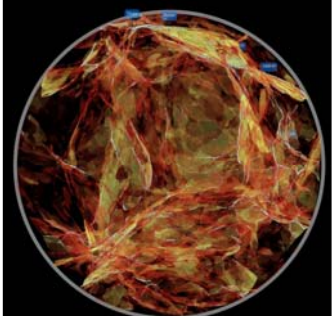


Karachentsev etal.

LV catalog:
galaxies within 10 Mpc reveal beautifully the magnificent

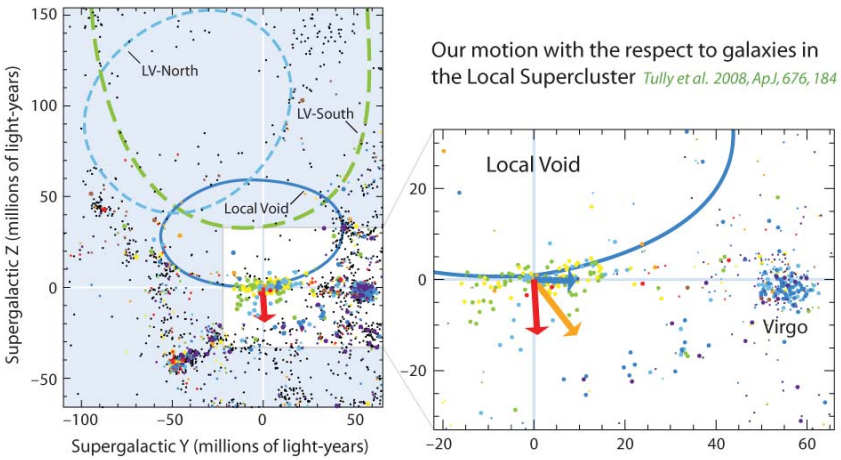
Local Void – Tully Void

Adhesion-KIGEN reconstruction



Hidding, vdW, Kitaura & Hess 2015

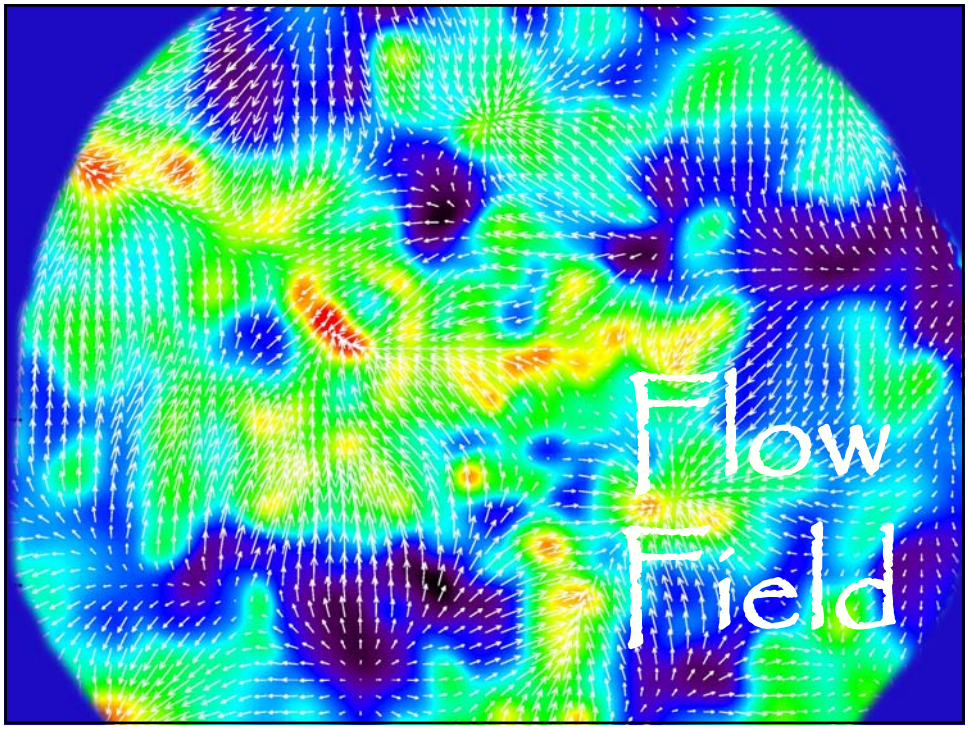
Push of the Local Void

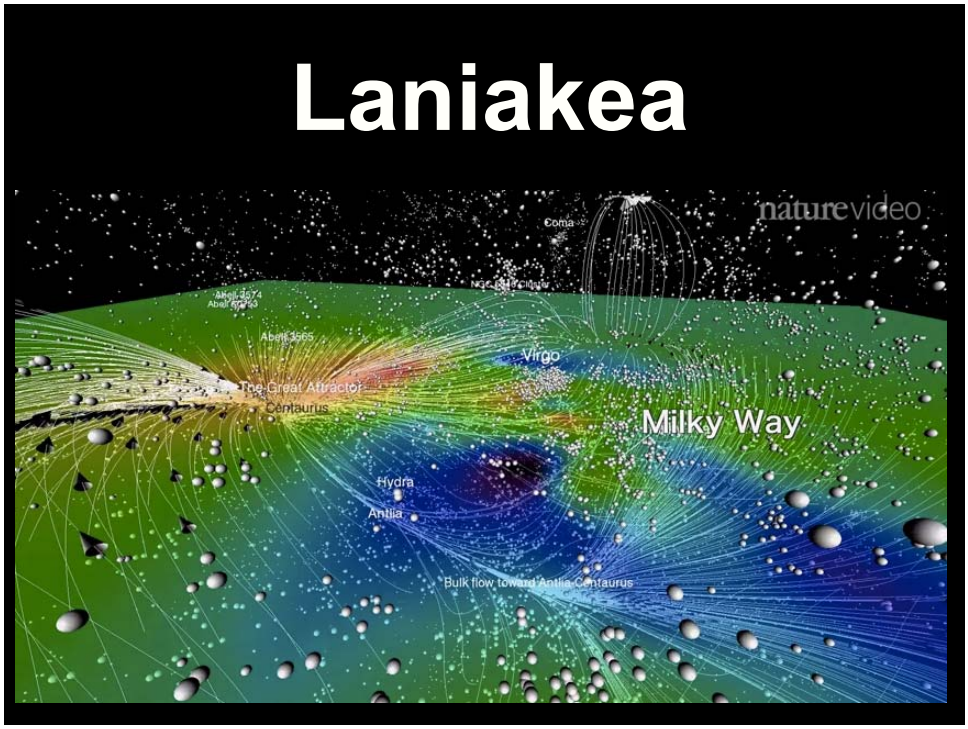


Tully et al. 2008:
Local Void pushes with ~260 km/s against our local neighbourhood

Cosmic Structure Formation:

Dynamics


Flow
Field

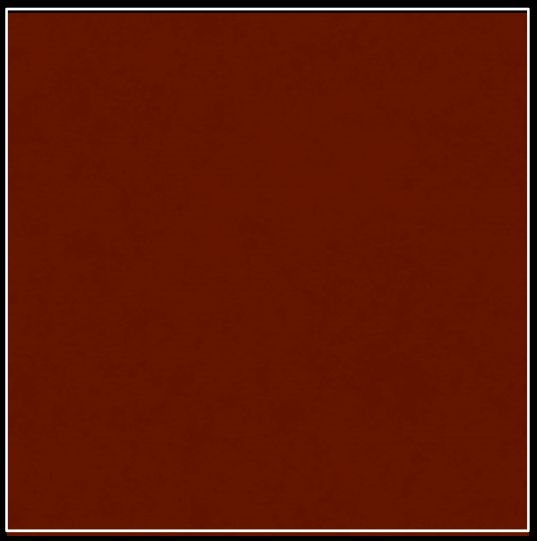

Laniakea
nature video
Coma
Abell 3565
Virgo
The Great Attractor
Centaurus
Milky Way
Hydra
Antlia
Bulk flow toward Antlia-Centaurus

Zel'dovich Approximation

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

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

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



Hierarchical Web Evolution:

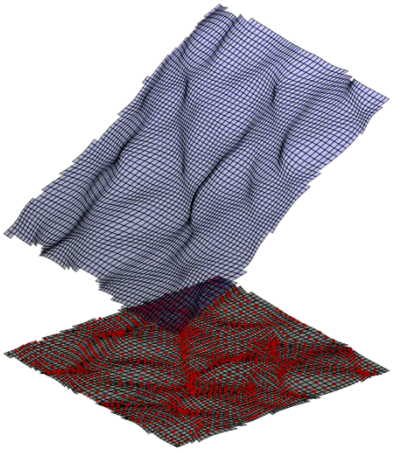
Adhesion simulation buildup Cosmic Web

Johan Hidding
2012

Phase-Space Dynamics

Dynamical Evolution:

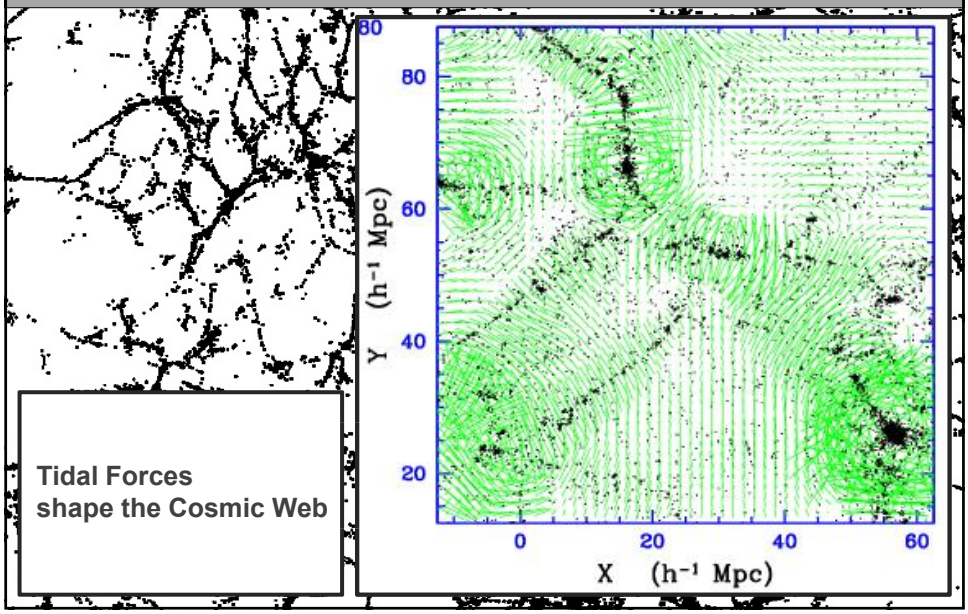
folding the phase-space sheet {q,x}



Lagrangian Coordinate q_1

Eulerian plane x

Tidal Shaping of the Cosmic Web



Tidal Forces shape the Cosmic Web

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

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

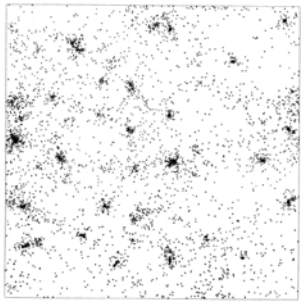
Cosmic Structure Formation:

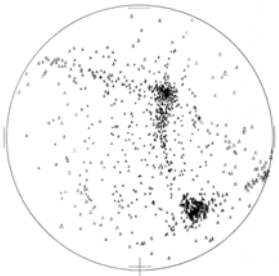
Computer Simulations

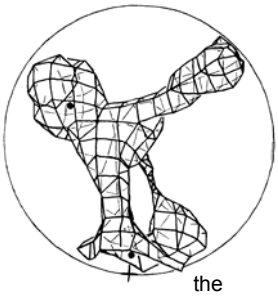
1983: Klypin & Shandarin

- 32^3 particle in cubic volume
- initial conditions: 1st time proper cosmological Gaussian conditions:

  Zeldovich approximation
- PM particle-mesh simulation



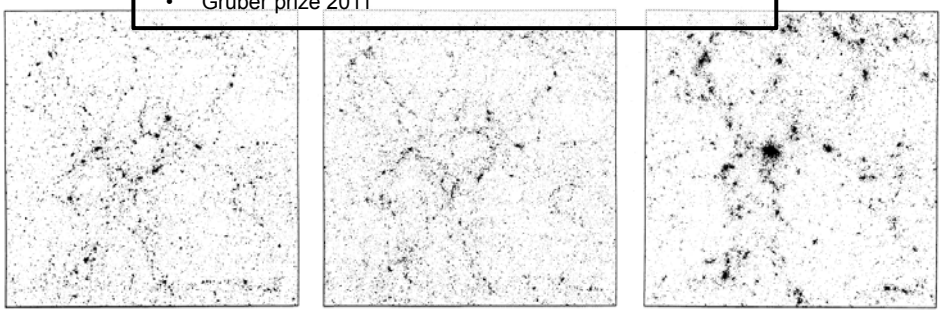


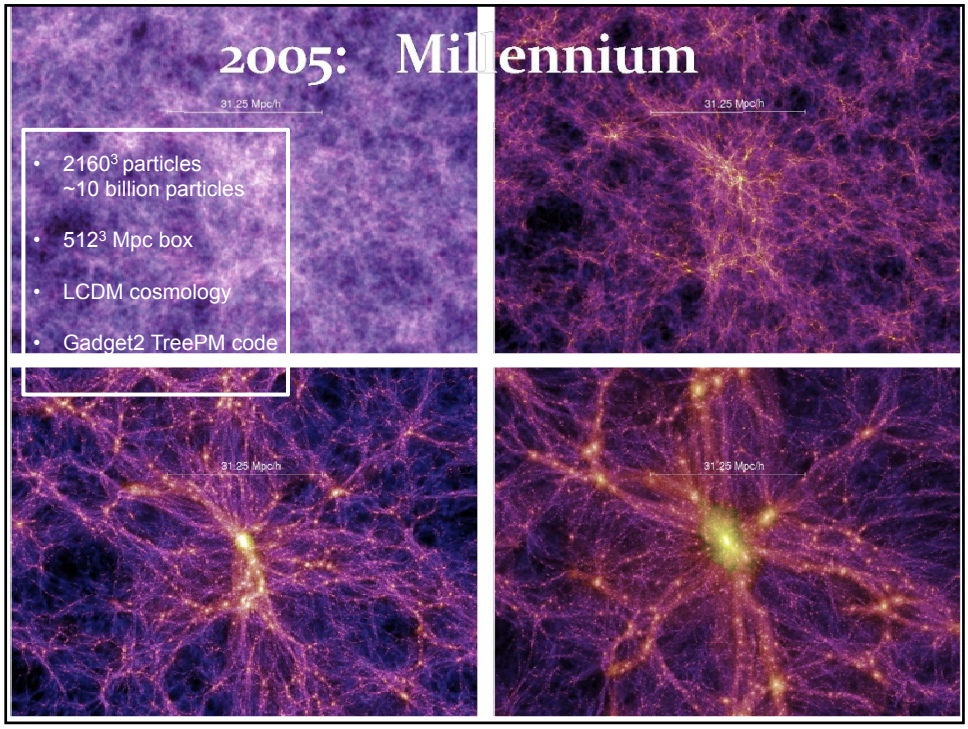


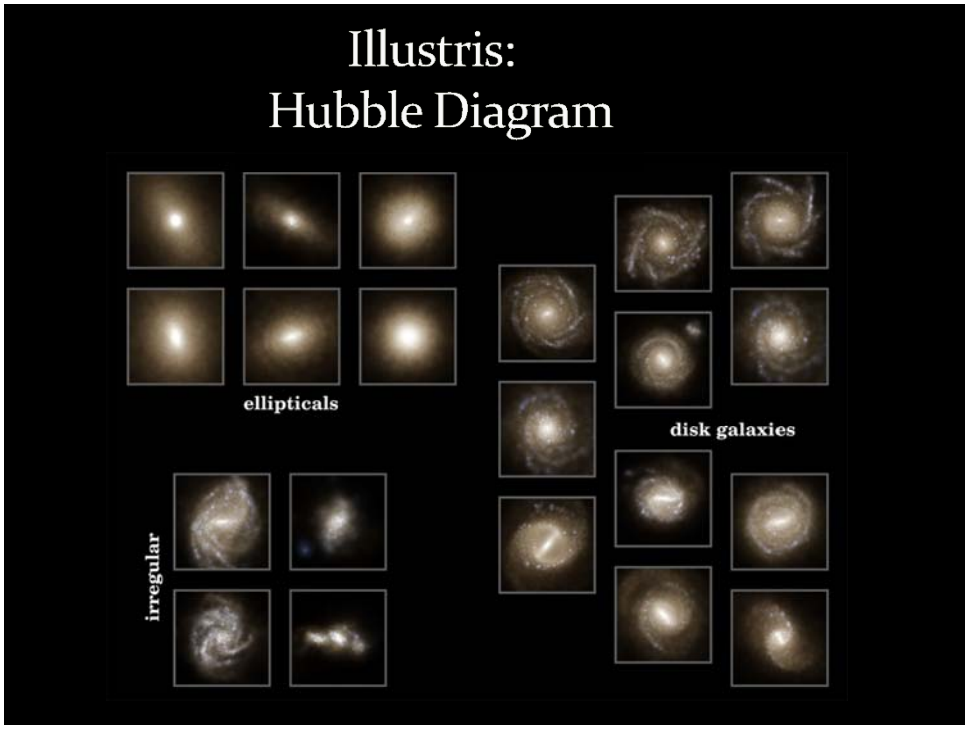
the "Cosmic Chicken"

1985-1989: DEFW, "Gang of Four"

- Davis, Efstathiou, Frenk & White
- HDM does not work: absence older small structure
- CDM simulations,
- 32^3 particles in cubic box
- P3M particle-particle particle-mesh code
- large range of publications establishes CDM as standard cosmology
- Gruber prize 2011

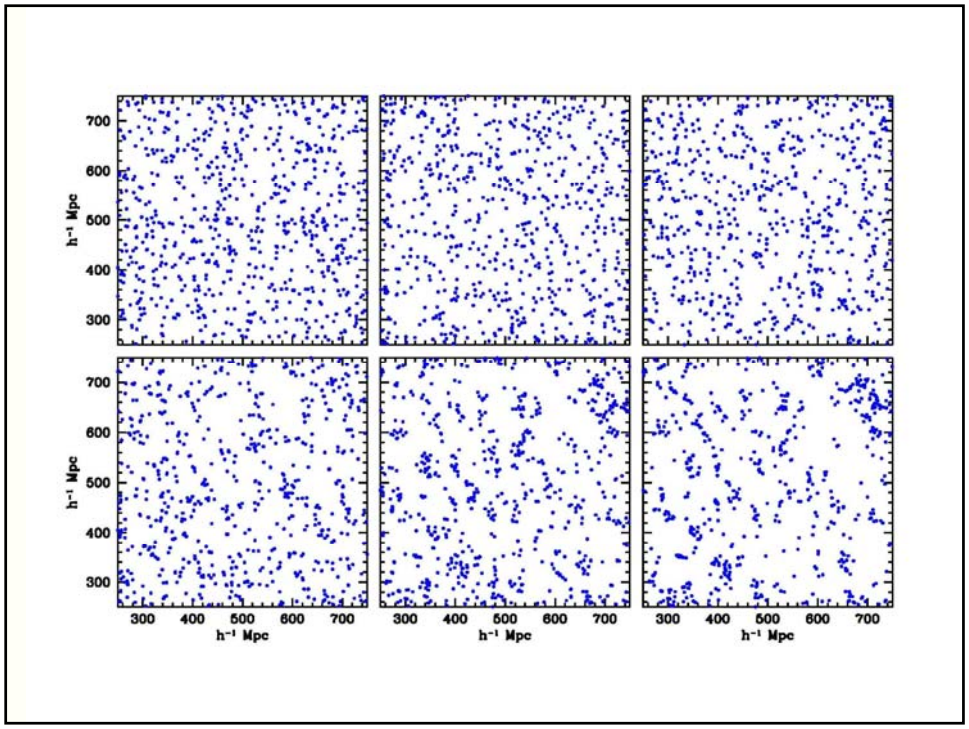



2005: Millennium
31.25 Mpc/h
• 2160^3 particles
~10 billion particles
• 512^3 Mpc box
• LCDM cosmology
• Gadget2 TreePM code
31.25 Mpc/h
31.25 Mpc/h
31.25 Mpc/h


Illustris:
Hubble Diagram
ellipticals
disk galaxies
irregular

Cosmic Structure Formation:

Structure Analysis

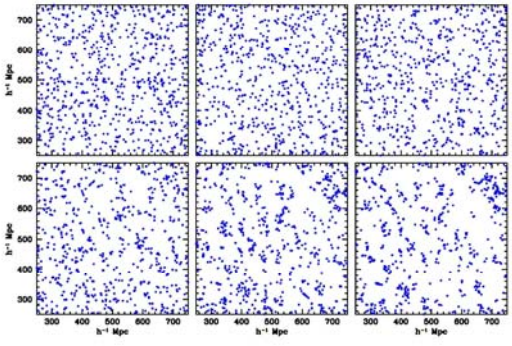


only one Universe:
Ergodic Theorem

Ensemble Averages $\Longleftrightarrow$ **Spatial Averages over one realization of random field**

- Basis for statistical analysis cosmological large scale structure
- In statistical mechanics Ergodic Hypothesis usually refers to time evolution of system, in cosmological applications to spatial distribution at one fixed time

Correlation Functions



Joint probability that in each one of

the two infinitesimal volumes dV_1 & dV_2,

at distance r,

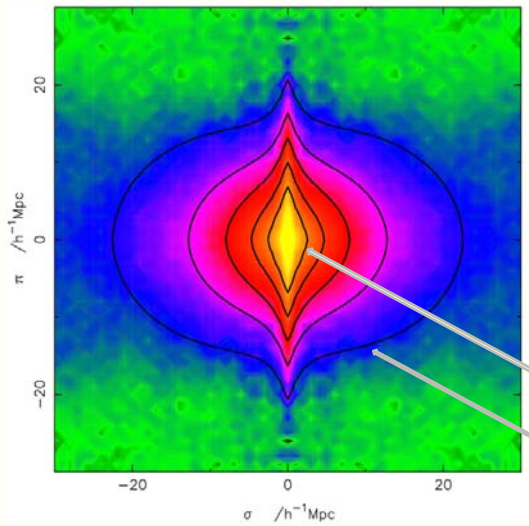
lies a galaxy

Infinitesimal Definition Two-Point Correlation Function:

$$dP(r) = \bar{n}^2 \, (1 + \xi(r)) \, dV_1 dV_2$$

mean density

sky-redshift space
2-pt correlation function $\xi(\sigma,\pi)$



Correlation function determined in sky-redshift space:

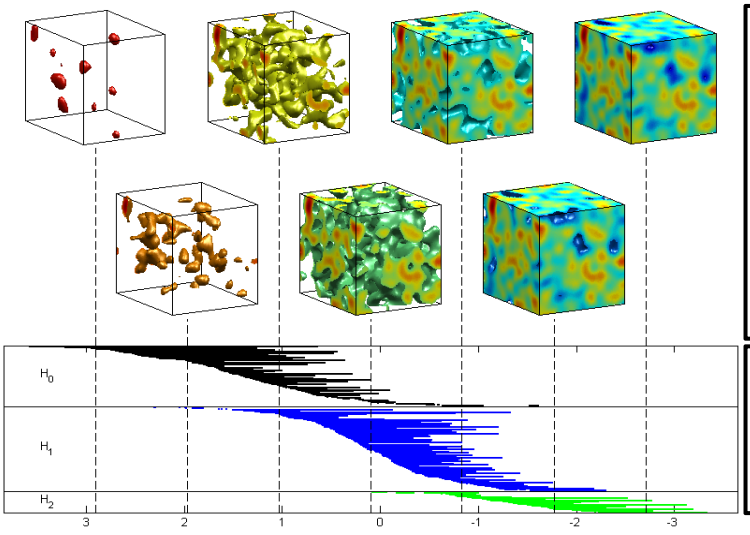
$$\xi(\sigma,\pi)$$

sky position: $\sigma = (\alpha, \delta)$
redshift coordinate: $\pi = cz$

Close distances:
distortion due to non-linear Finger of God
Large distances:
distortions due to large-scale flows

Persistent Bar Codes

Persistent Homology: "cycling" over density excursion filtration



3D Gaussian Field Filtration

Barcode Representation

(Adler & Taylor 2009)

Cosmic Reconstruction:

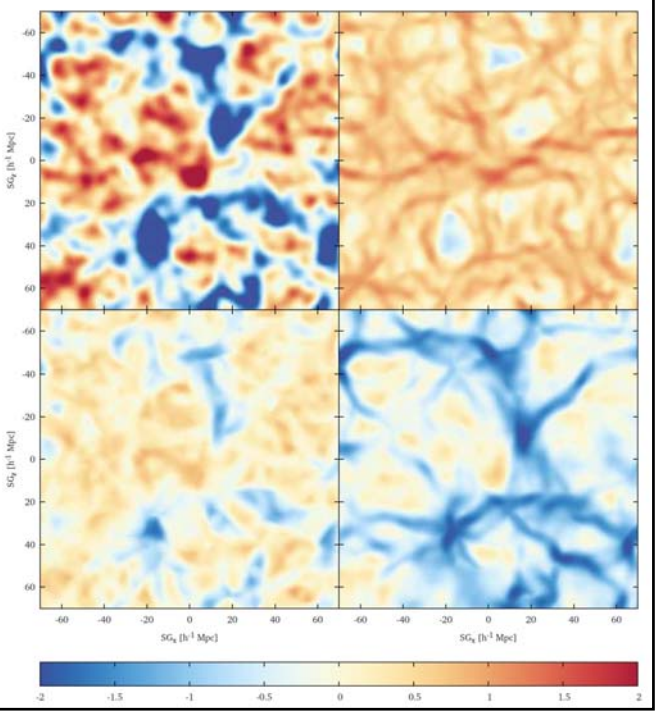
Cosmic Structure in our Local Universe

Initial Density & Deformation Field

Local Universe (SG plane)

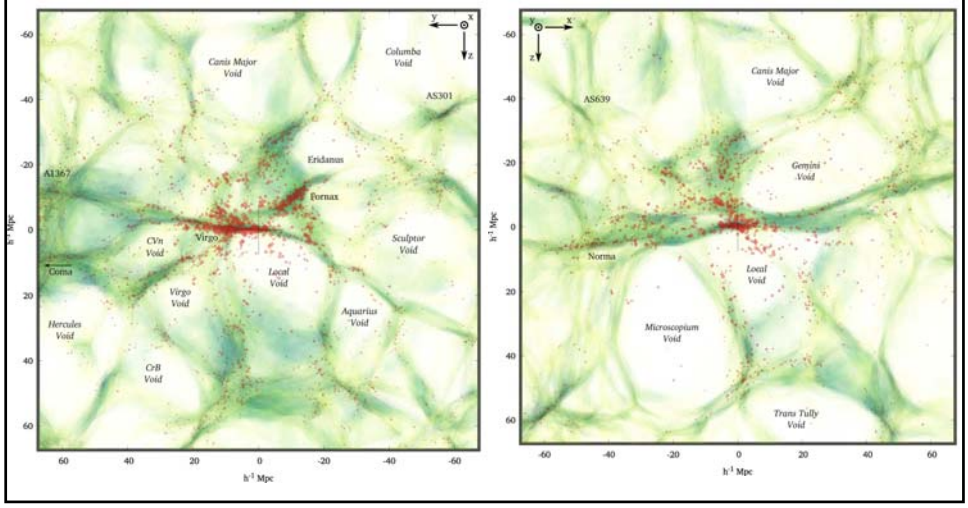
Kitaura & Hess:

25 constrained realizations



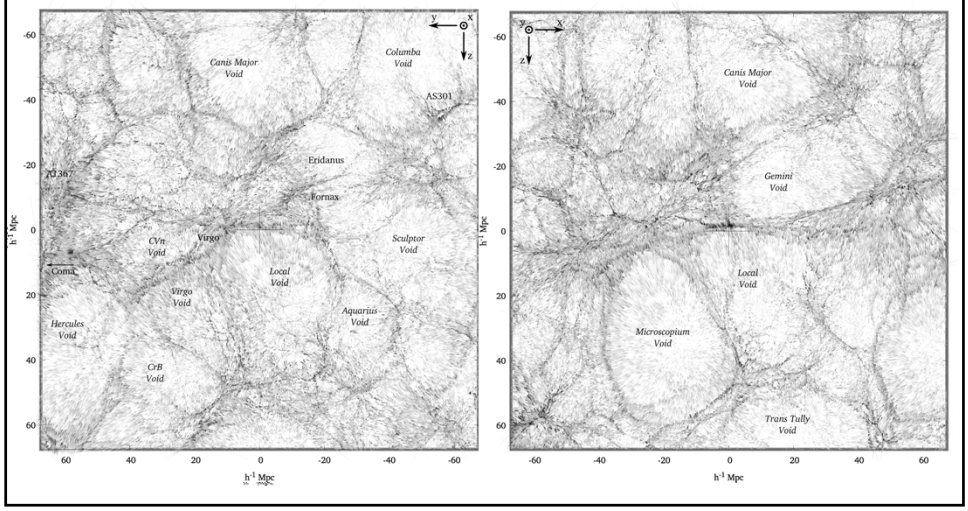
⊥ Supergalactic Plane

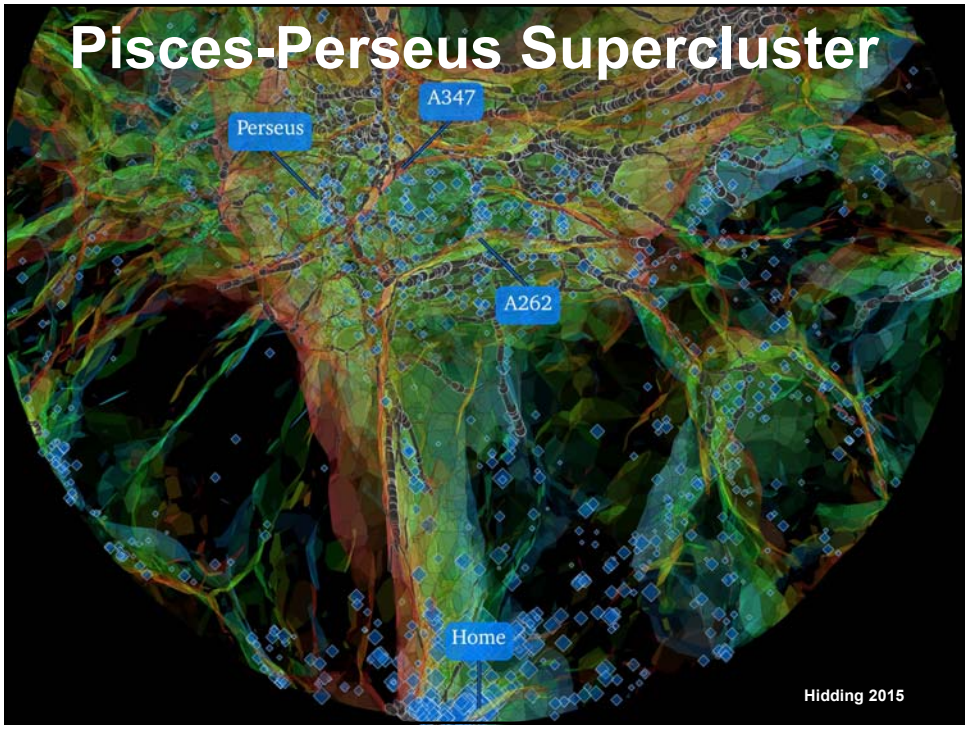
mean adhesion reconstruction

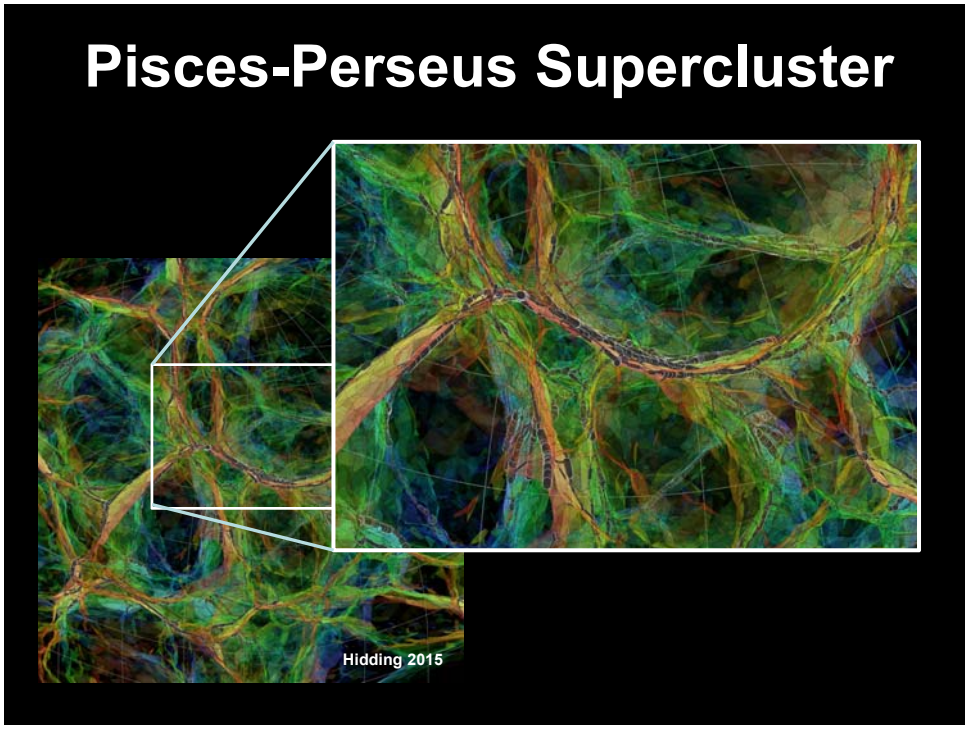


⊥ Supergalactic Plane

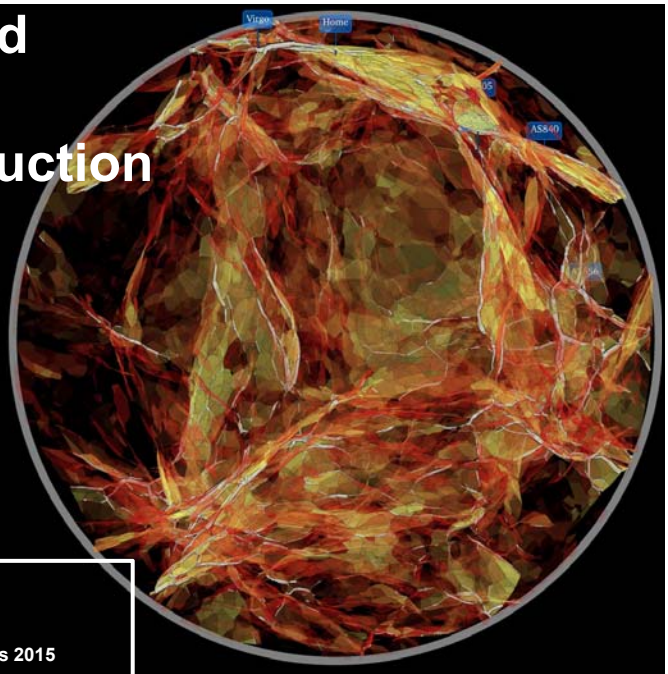
mean adhesion reconstruction




Pisces-Perseus Supercluster
A347
Perseus
A262
Home
Hidding 2015


Pisces-Perseus Supercluster
Hidding 2015

Local Void Adhesion Reconstruction



Local Void Reconstruction:

Hidding, vdW, Kitaura & Hess 2015