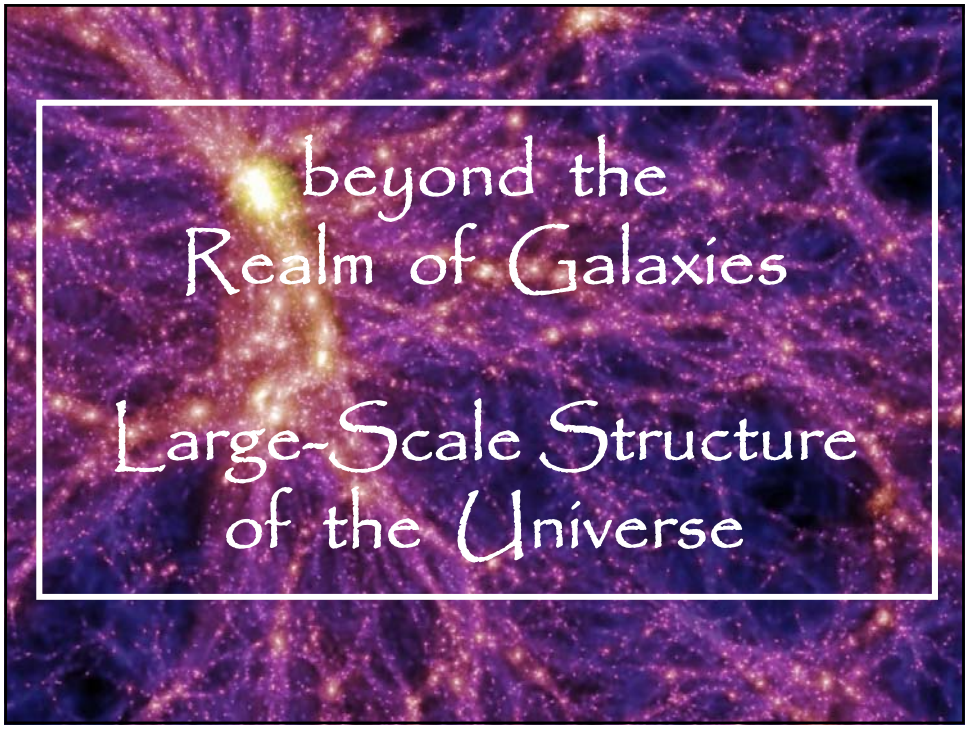

beyond the
Realm of Galaxies
Large-Scale Structure
of the Universe


beyond the
Realm of Galaxies
Large-Scale Structure
of the Universe

Megaparsec Scale Structure of the Universe

- Large Scale Structure of the Universe:

  crucial information for our understanding of structure formation in the Universe

- Dynamic Timescale ~ Hubble Time (age Universe):

  Megaparsec structures have evolved only mildly, so that one may infer their formation & evolution, and link to conditions primordial Universe

- Compare timescales:

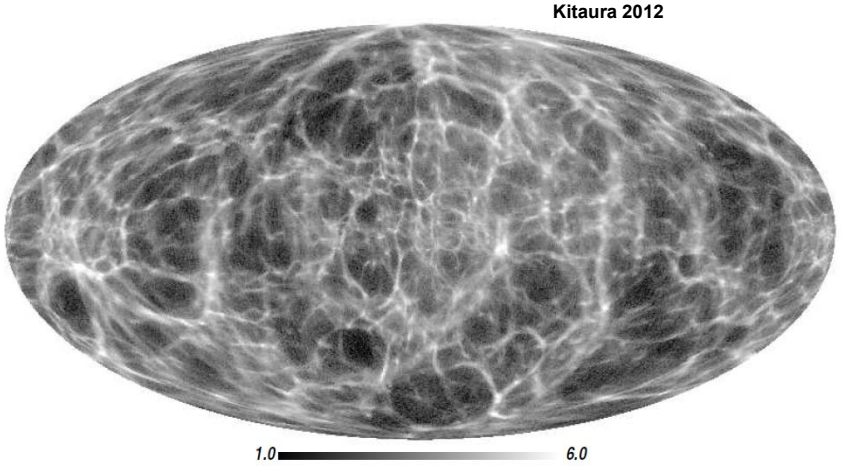
solar system	~ 1 yr
galaxy	~ 10^8 yr
clusters	~ 10^9 yr
Megaparsec structures	~ 10^{10} yr

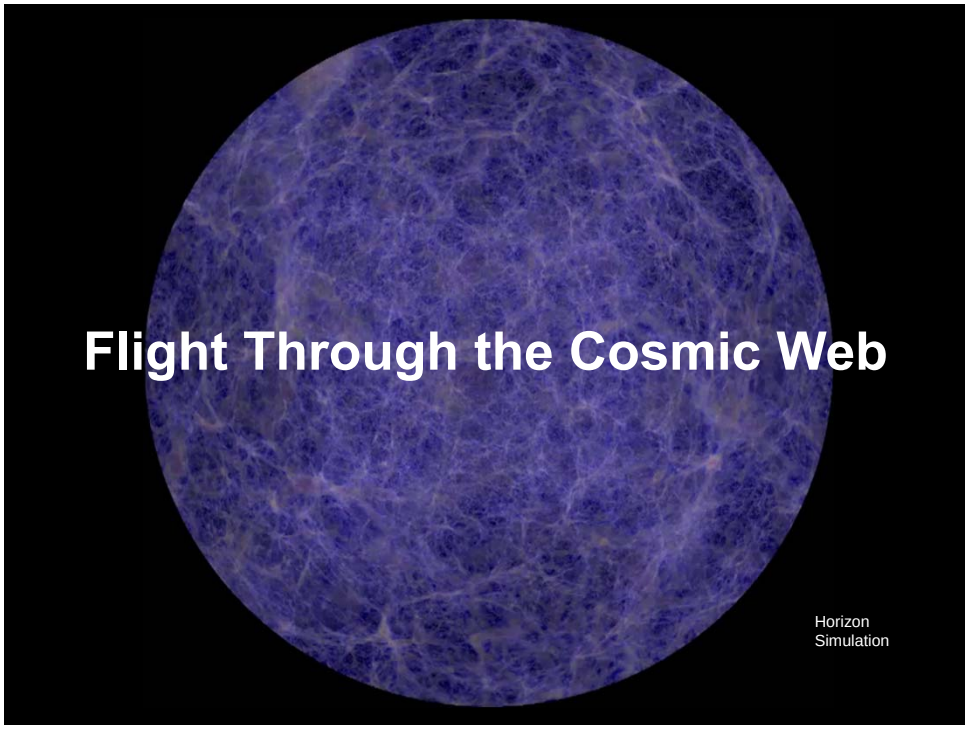
Cosmic Fossil

Cosmic Web: 2MASS

Most detailed reconstruction Local Cosmic Web (2MRS):

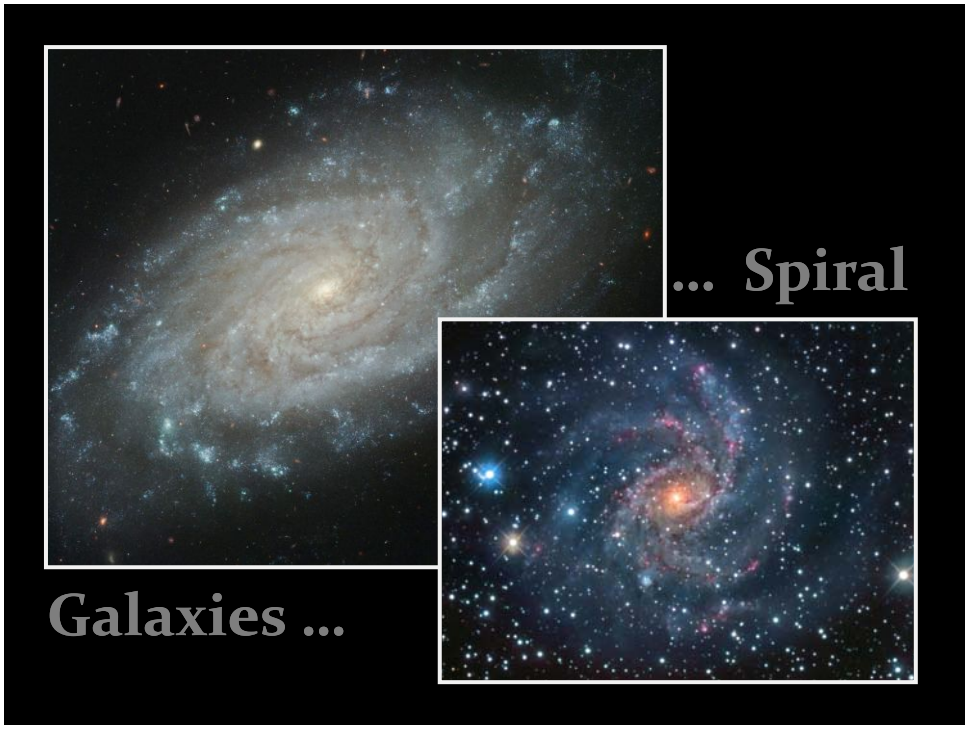
Kitaura 2012



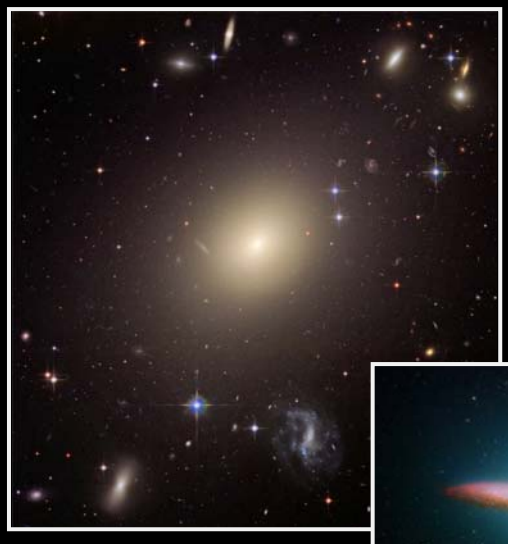

Flight Through the Cosmic Web
Horizon
Simulation


Galaxies


... Galaxies ...

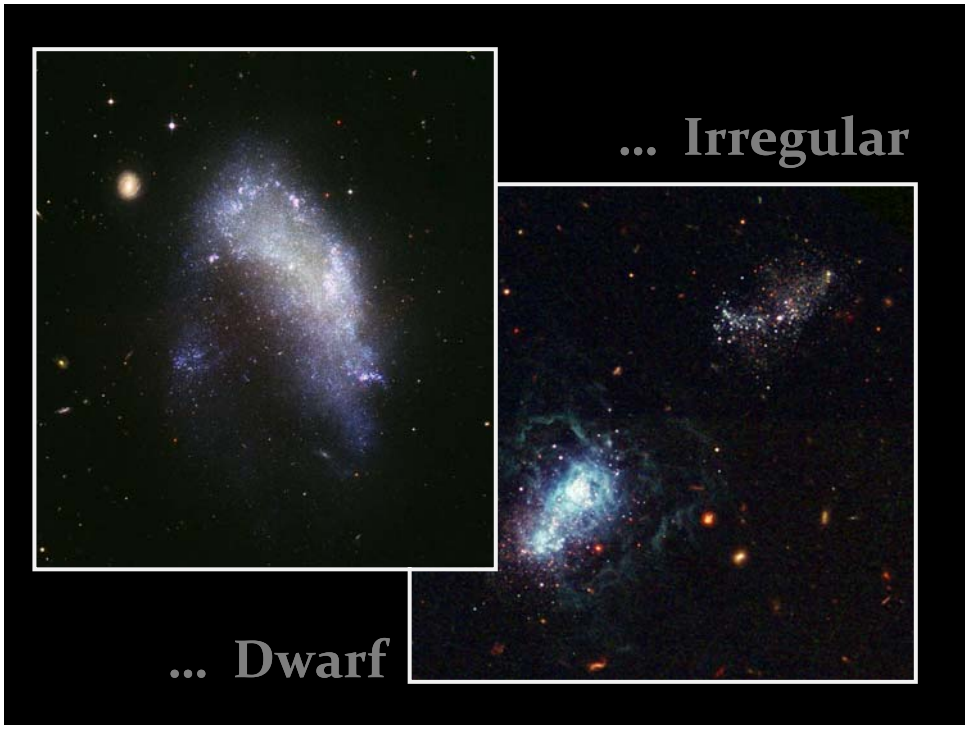

... Spiral
Galaxies ...

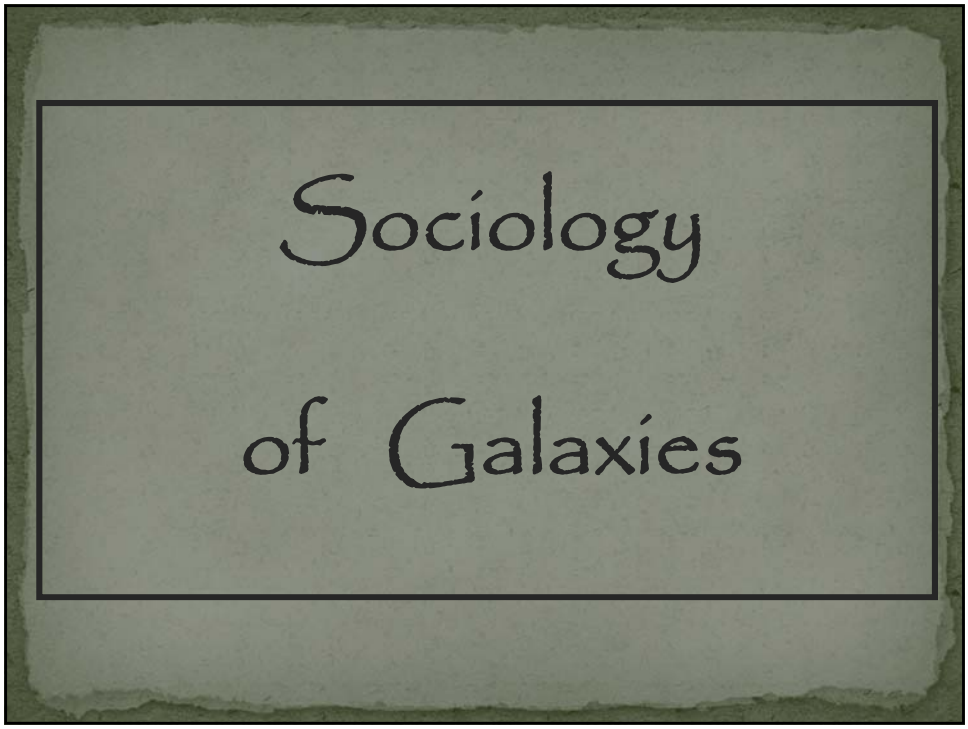
NGC 1300: a Milky Way look-alike ?



... Elliptical

... Lenticular

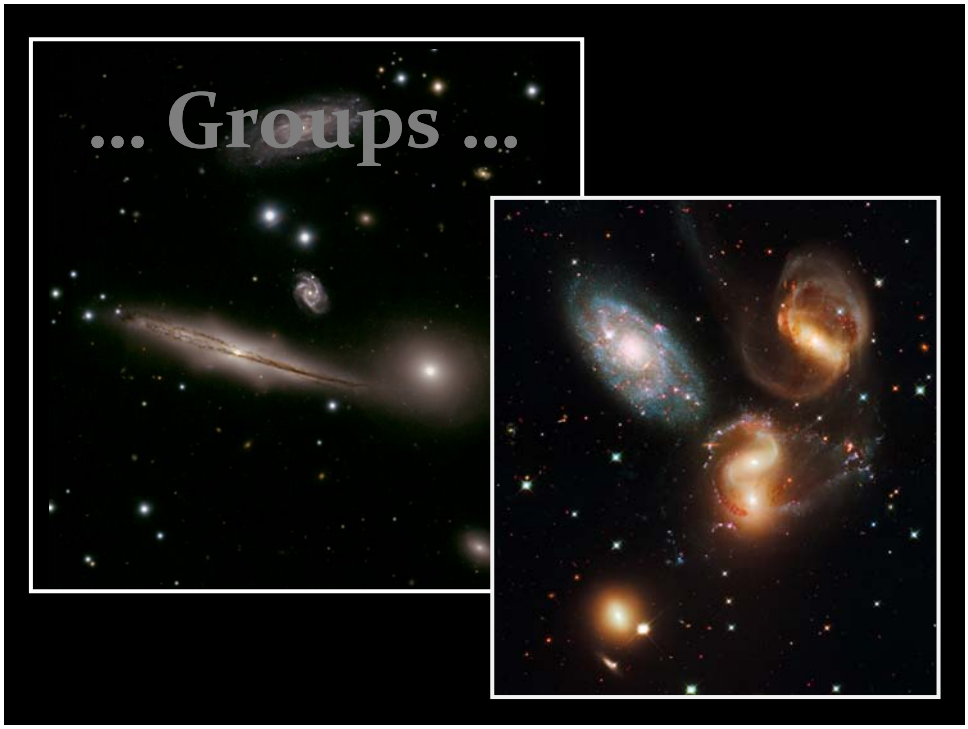

... Irregular
... Dwarf

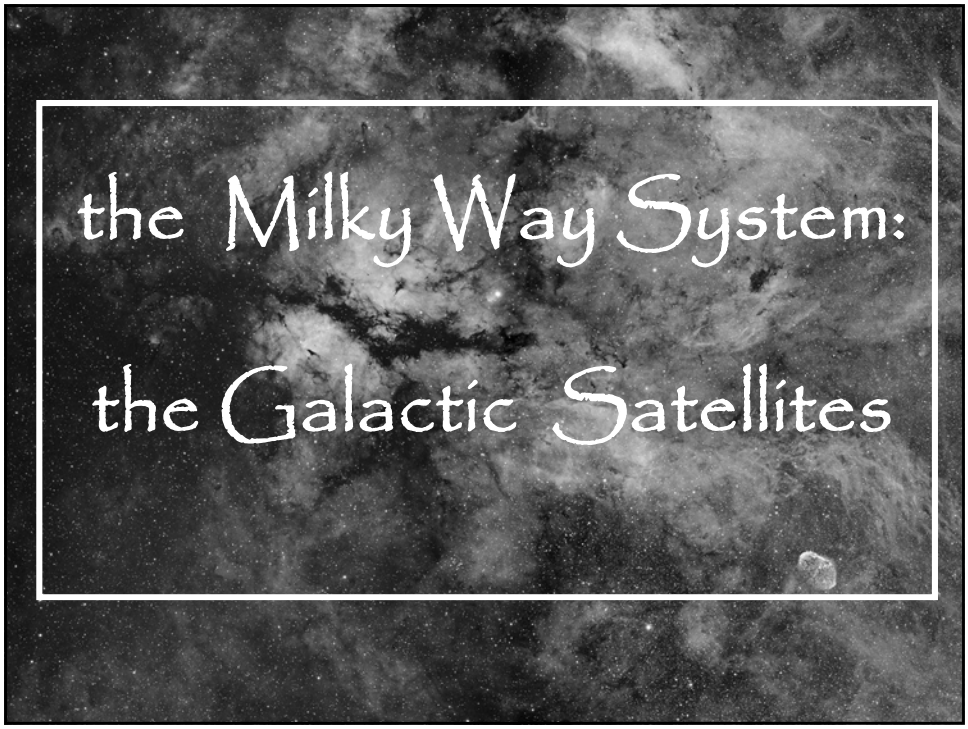

Sociology
of Galaxies

Sociology of Galaxies

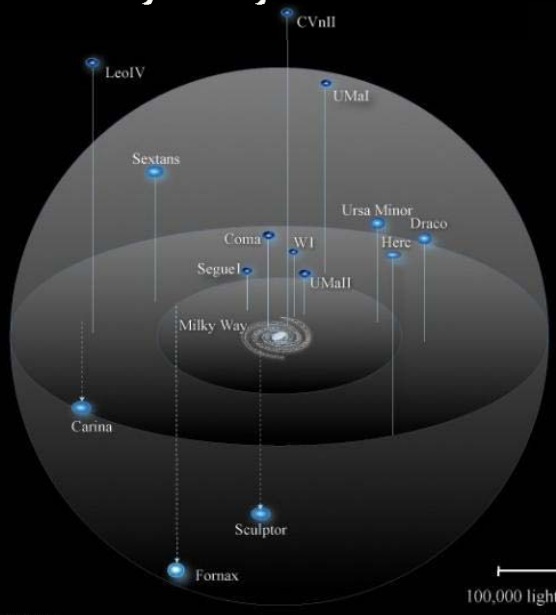
- Galaxies are not singular objects:
- they group and cluster into a hierarchy of ever larger entities.
- direct manifestation of gravitational attraction between matter: clumping of matter
- Their sociology, ie. the characteristics and patterns in which they group together, is a key to unravelling the formation of structure in the Universe.

Interacting Galaxies


... Groups ...


the Milky Way System:
the Galactic Satellites

Milky Way Satellites



The Milky Way has at least ~14 satellite galaxies.

Large & Small Magellanic Clouds:
Irregular galaxies

all other satellite galaxies:
Dwarf Spheroidal

once thought of as globulars,
Dwarf spheroidals differ on 3 major aspects:
- Dwarf Galaxies contain old stars of a more expanded variety
- mass-to-light ratio much higher in Dwarf Galaxies (significant amounts of dark matter)
- higher abundance of iron than globulars

Note:
Less dwarf satellites than expected on behalf of present theories of galaxy formation

Milky Way Satellites

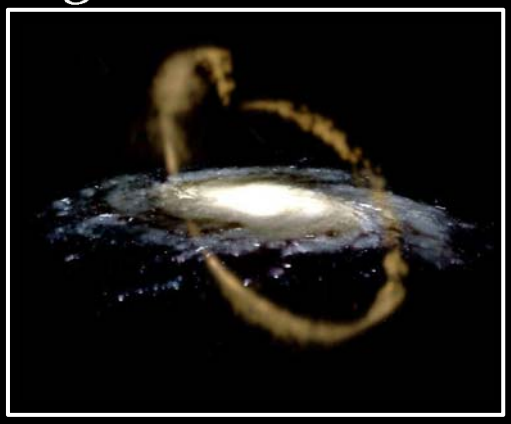
The Milky Way has at least ~14 satellite galaxies.

Large & Small Magellanic Clouds: Irregular galaxies

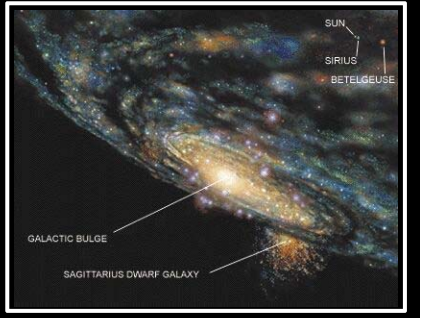
all other satellite galaxies: Dwarf Spheroidal

Sculptor Dwarf Galaxy

Sagittarius Dwarf Galaxy



Nearest known neighbour to Galaxy:
central cluster (old population II) +
loop-shaped structure wrapping around Galaxy

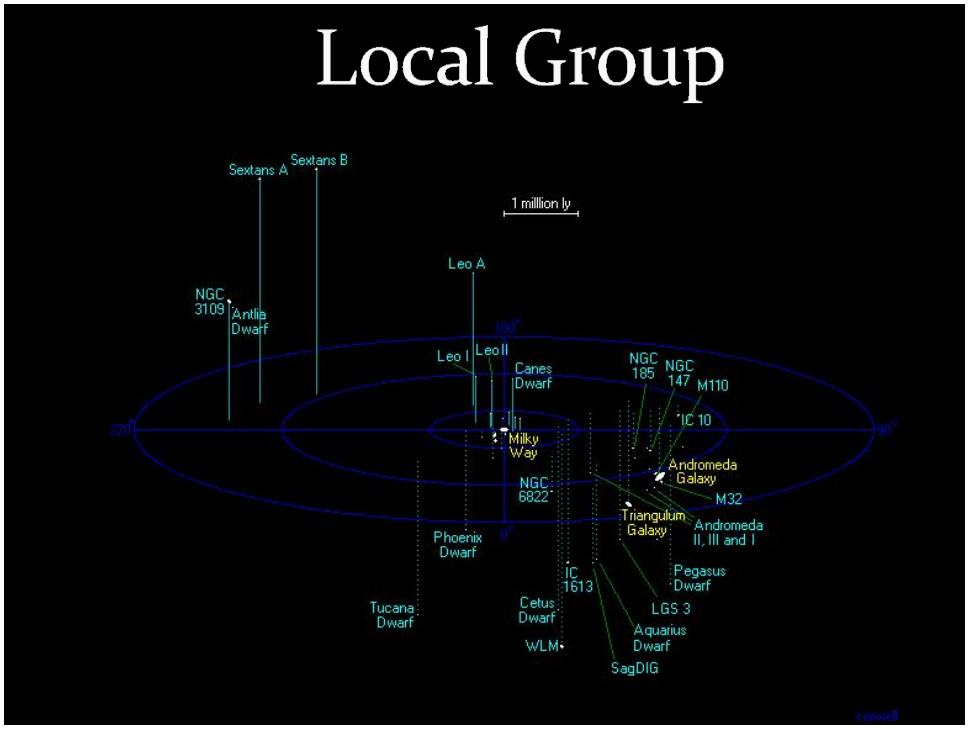


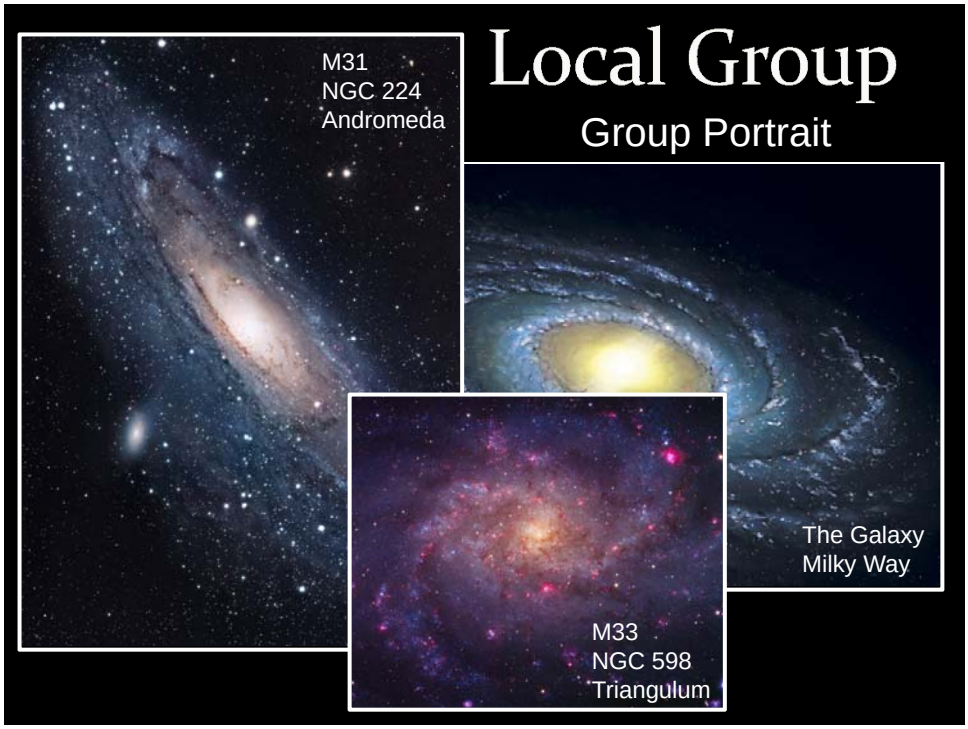
Based on current trajectory:

- Sag DEG main cluster is about to pass through the galactic disc of Milky Way within next 100 Myr
- extended loop-shaped ellipse already extended around and through our local space and on through the Milky Way galactic disc
(will be slowly absorbed into Milky Way)

Globulars:
- 4 globular clusters (incl. M54)
- dynamically linked to 3 young globulars

Multiple stellar populations:
- very oldest globular cluster populations
- stars as young as ~ 100 Myr


Local Group
Sextans A
Sextans B
1 million ly
Leo A
NGC 3109
Antlia Dwarf
Leo I
Leo II
Canes Dwarf
NGC 185
NGC 147
M110
IC 10
Milky Way
Andromeda Galaxy
NGC 6822
M32
Triangulum Galaxy
Andromeda II, III and I
Phoenix Dwarf
IC 1613
Pegasus Dwarf
Tucana Dwarf
Cetus Dwarf
LGS 3
Aquarius Dwarf
WLM
SagDIG


Local Group
Group Portrait
M31
NGC 224
Andromeda
The Galaxy
Milky Way
M33
NGC 598
Triangulum

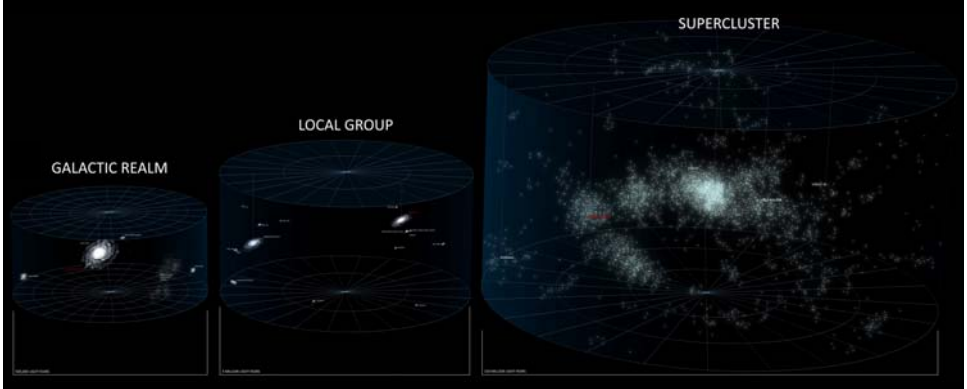
Local Group

- Milky Way satellites:
  - Sagittarius Dwarf Galaxy
  - Large Magellanic Cloud (LMC)
  - Small Magellanic Cloud (SMC)
  - Canis Major Dwarf
  - Ursa Minor Dwarf
  - Draco Dwarf , Carina Dwarf,
  - Sextans Dwarf, Sculptor Dwarf,
  - Fornax Dwarf,
  - Leo I, Leo II,
  - Ursa Major Dwarf

- M31 satellites:
  - M32,
  - M110,
  - NGC 147,
  - NGC 185,
  - And I, And II, And III,
  - And IV, And V,
  - Pegasus dSph,
  - Cassiopeia Dwarf,
  - And VIII, And IX, And X.

- Diameter Local Group: $D_{LG} \sim 3$ Mpc
- Binary (dumbbell) shape
- Mass Local Group: $M_{LG} \sim 1.29 \pm 0.14 \times 10^{12} M_{\odot}$.
- The group itself is one of many density clumps within the Local Supercluster

Local Universe: step by step



Clusters of Galaxies

- Assemblies of up to 1000's of galaxies within a radius of only
  $R \sim 1.5\text{-}2h^{-1}$ Mpc,
- Total masses:
  $M \sim 10^{14}\ M_{\odot}$
- Representing overdensities of $\Delta \sim 1000$
- Galaxy move around with velocities
  $v \sim 1000$ km/s
- They are the most massive, and most recently, fully collapsed structures in our Universe.

Clusters of Galaxies

Courtesy:
O. Lopez-Cruz

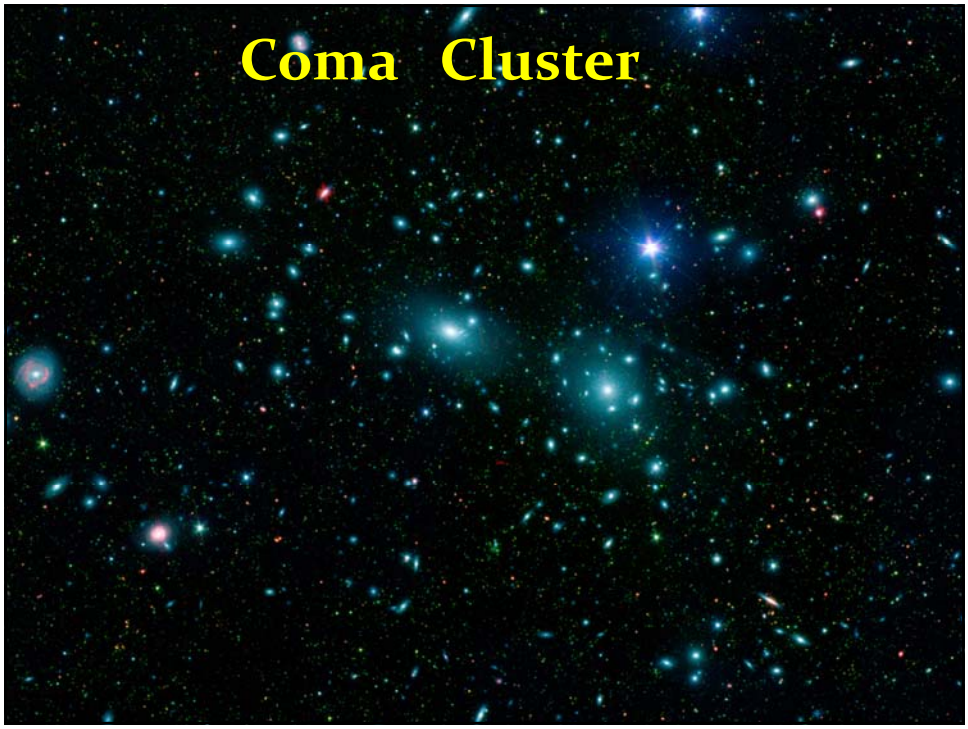
Coma Cluster

Studying Clusters

Includes many different aspects of these versatile astrophysical laboratories:

- **Optical/Infrared/Ultraviolet**
  - Galaxy Population:
    spatial distribution, kinematics, galaxy morphology
- **X-ray observations**
  - (hot, ionized) intracluster gas
  - distribution (density, temperature): cluster mass
  - abundances heavy elements (enrichment)
- **Sunyaev-Zel'dovich effect**:
  - "cluster shadows" in cosmic microwave background radiation
  - CMB microwave wavelength region
  - intracluster gas (pressure)
  - peculiar motion cluster (kinematic SZ)
- **Gravitational Lensing**
  - mainly optical, also radio, submm, ...
  - strong lensing (arcs, rings), weak lensing (sheared images)
  - dark matter mass
  - dark matter distribution
- **Radio wavelengths**
  - radio halos, radio relics
  - synchroton radiation in shocked, hot, ionized intracluster plasma


Virgo Cluster


Coma Cluster

Clusters of Galaxies

- Clusters not only contain galaxies:
- in fact, galaxies & stars are a minor component:

I. Clusters are Halos of Dark Matter:

M_{DM}/M_{total} ~ 82%

II. Clusters are Hot Balls of (highly ionized) Gas

M_{ICM}/M_{total} ~ 16-17 %

III. Galaxies are mainly raisins in a sea of dark matter & hot gas

M_{stars}/M_{total} ~ 2%

Clusters of Galaxies: X-ray intracluster gas

Baryonic matter in clusters is not only confined to galaxies:

~ 2 to 5 times more baryonic mass in the form of a diffuse hot X-ray emitting

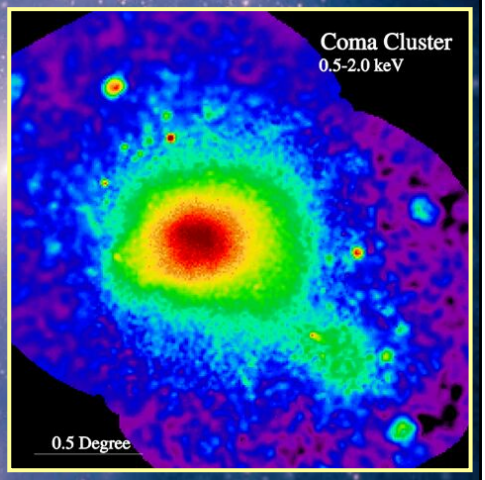
Intracluster Gas,

trapped and heated to a temperature of the order of

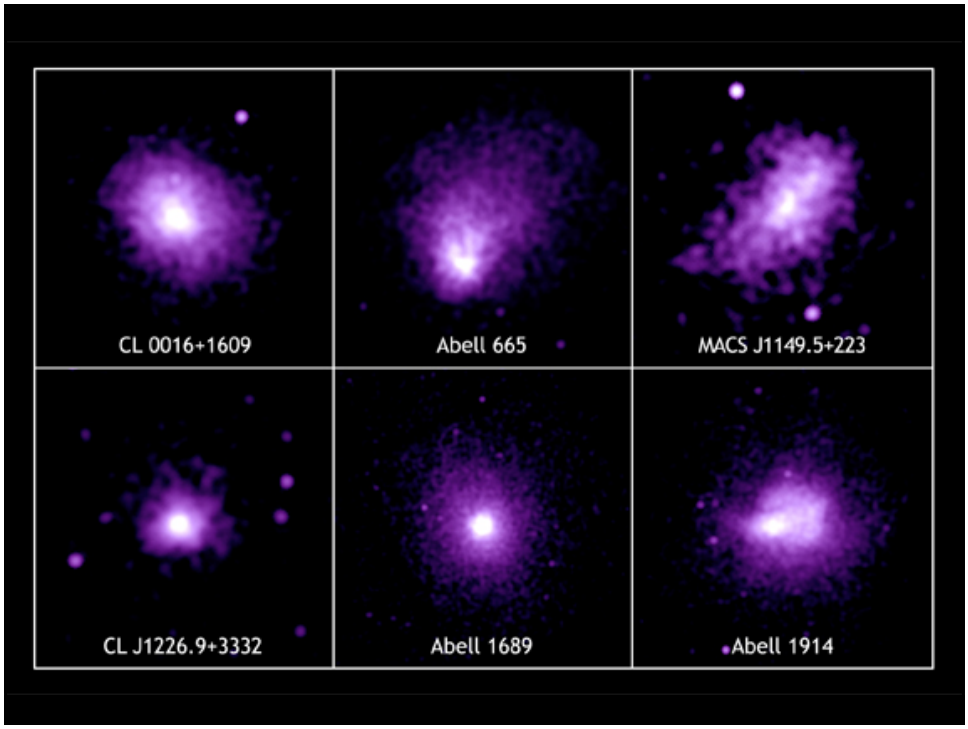
$T \sim 10^8$ K

by the gravitational potential of the cluster.

At such high temperatures, this gas is a fully ionized plasma, producing powerful X-ray emission, bremsstrahlung radiation induced by the electron-ion interactions.



ROSAT X-ray image Coma Cluster



Cluster Mass: X-ray intracluster gas

Hydrostatic Equilibrium:

$$\frac{GM(r)}{r^2} = -\frac{k_B T}{\mu m_H}\left[\frac{d\log\rho}{dr} + \frac{d\log T}{dr}\right]$$

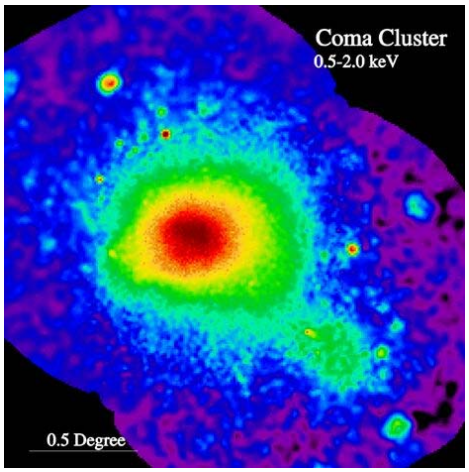
Determination Mass from X-ray observations:

-assumption:

Isothermal: $T(r)=T_o$

-density profile:

X-ray emission Bremsstrahlung: $L(r) \sim \rho(r)^2$



ROSAT X-ray image Coma Cluster

Clusters of Galaxies: Gravitational Lenses

A highly promising method to determine the amount and distribution of

matter in the Universe

looks at the way it affects

the trajectories of photons

According to

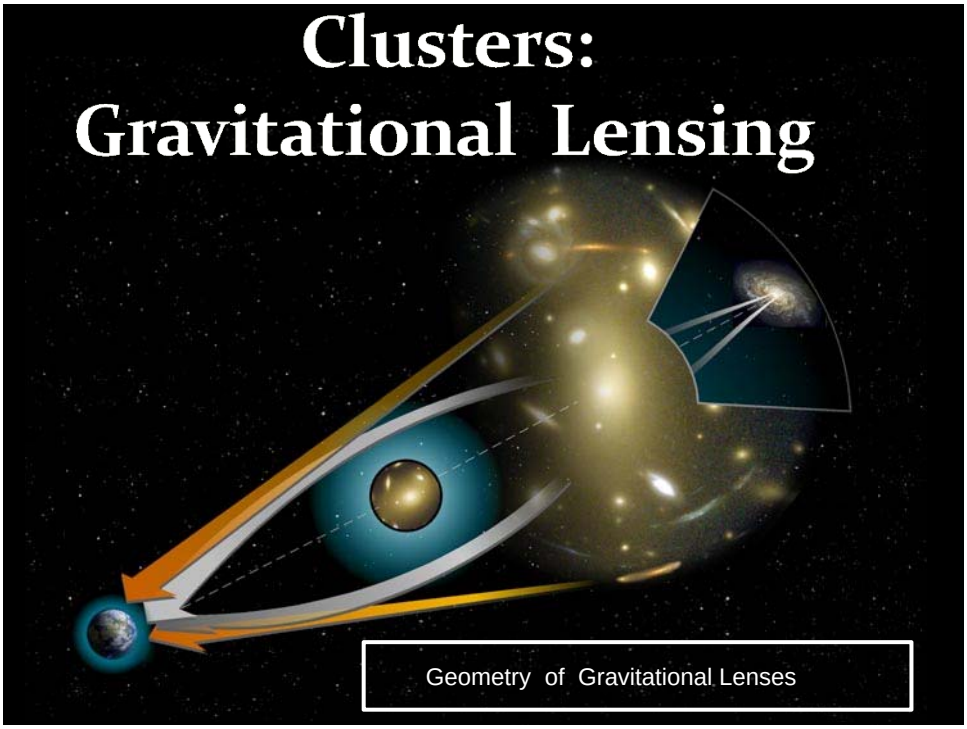
Einstein's theory of

General Relativity,

gravitational potential wells will bend and focus light. Dark matter concentrations act as a

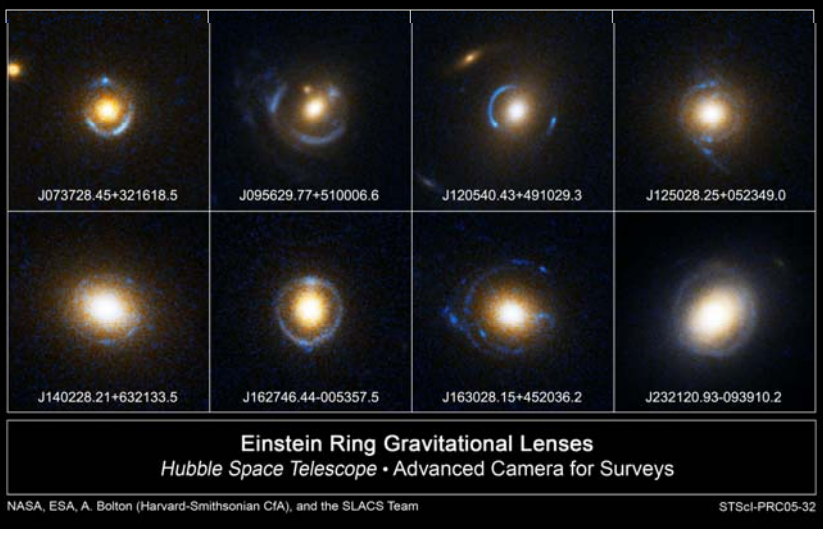
Gravitational Lens

Clusters: Gravitational Lensing



Geometry of Gravitational Lenses

Gravitational Lensing: Einstein Ring

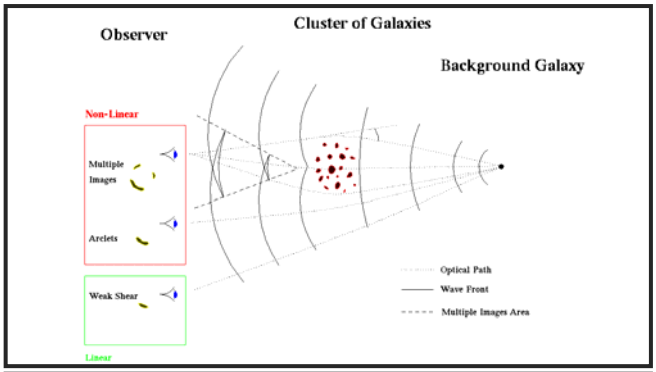


Gravitational Telescopes: Weak vs. Strong Lensing

$$\theta_E = \sqrt{\frac{4GM}{c^2}\frac{d_{LS}}{d_L d_S}}$$

Two kinds of lensing:

- **Strong Lensing:**
  $\theta < \theta_E$
  - nonlinear distortions
  - multiple image
- **Weak Lensing:**
  $\theta > \theta_E$
  - linear distortions
  - sheared images

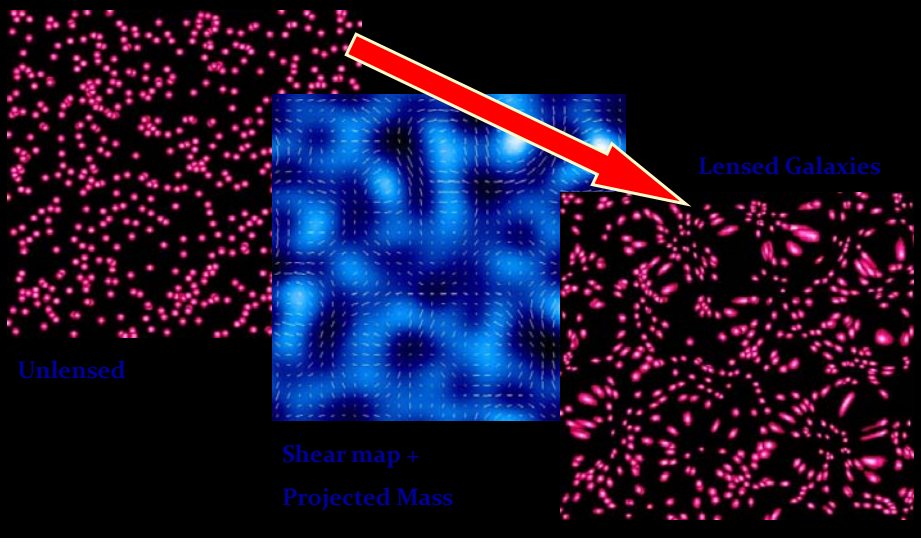


Cluster Mass determination:

Weak Lensing: Linear Inversion Distortion Field

Strong Lensing: Complex Modeling density distribution. non-trivial

Weak Gravitational Lensing



Weak Gravitational Lensing: MS1054

- z=0.83:
- one of the highest known z clusters
- Weak Lensing study by
  - Clowe et al. Keck
  - Hoekstra et al. HST

Clusters of Galaxies: Dark Matter Map

A highly promising method to determine the amount and distribution of

matter in the Universe

looks at the way it affects

the trajectories of photons.

According to

Einstein's theory of

General Relativity,

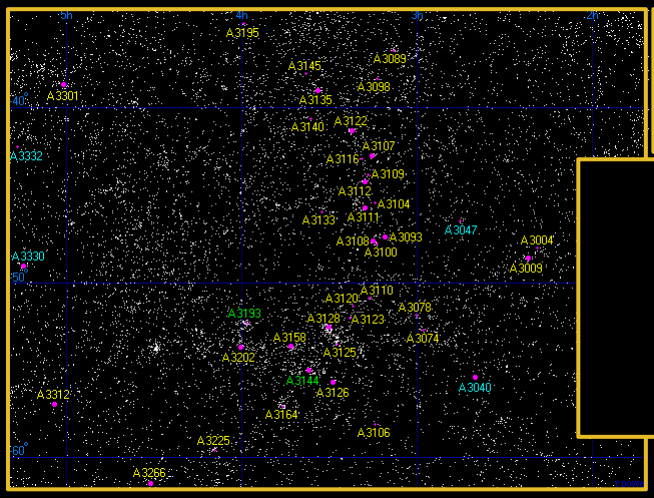
gravitational potential wells will bend and focus light. Dark matter concentrations act as a

Gravitational Lens.

Superclusters

Superclusters

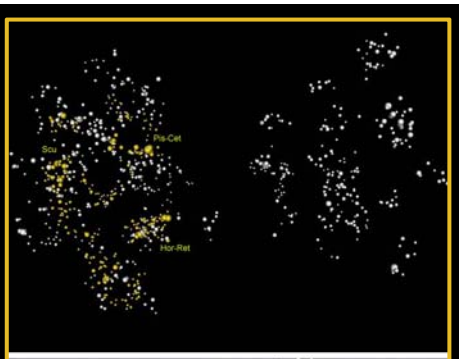
Large groups of clusters & galaxies (1-dozens)

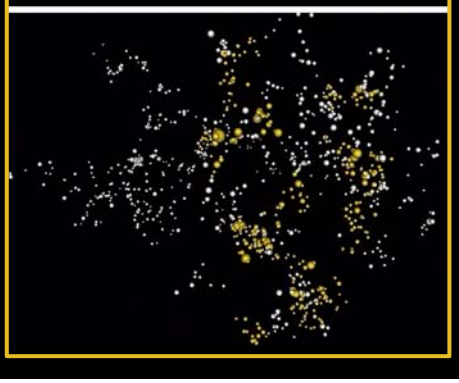


$M \sim 10^{15}$-10^{16} $M_\odot$
L ~ few-100 Mpc
irregular shaped
mild overdensity Δ~few

Superclusters:

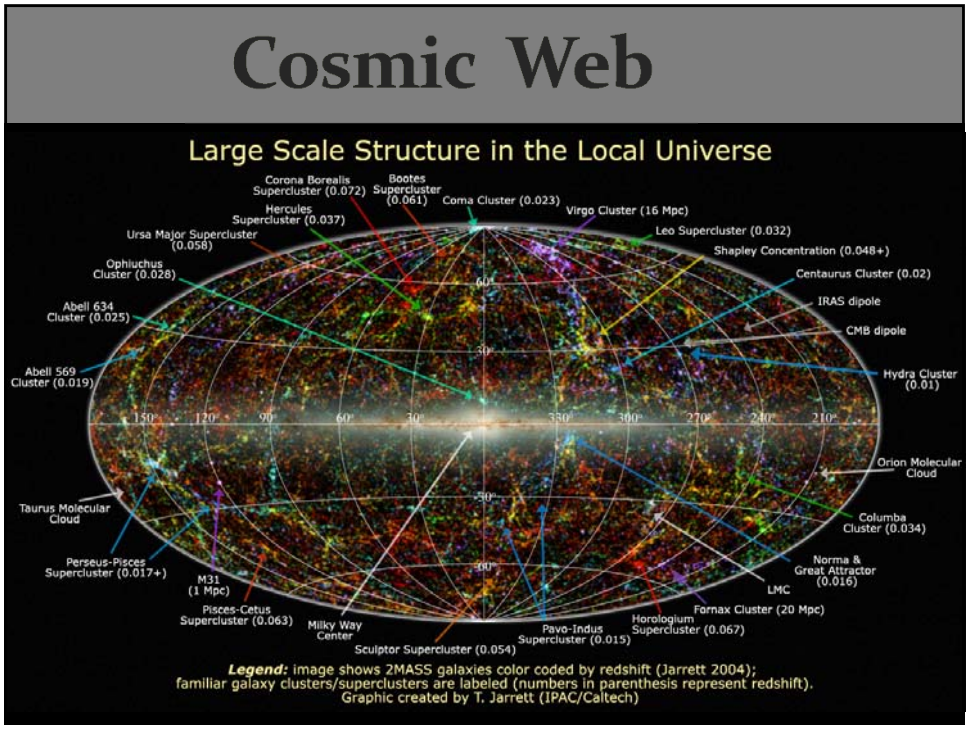
Einasto et al. sample
X-ray clusters (yellow) and
Abell clusters (white)





superclusters are not isolated single objects, but integral components in the pervasive Cosmic Web

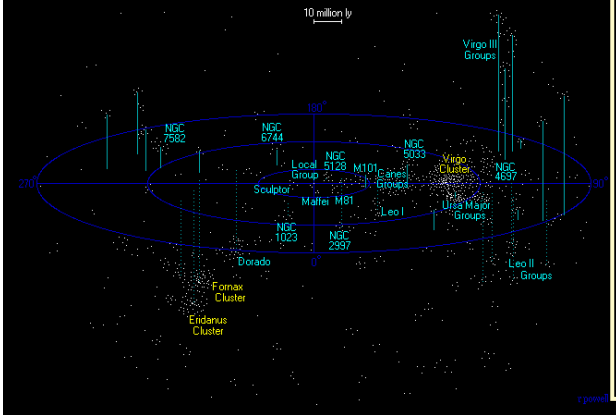

Abell 901a
Abell 901b
Abell 902
SW Group
Abell 901/902 Supercluster Dark Matter Map ▪ STAGES
Hubble Space Telescope ▪ ACS/WFC
NASA, ESA, C. Heymans (University of British Columbia), M. Gray (University of Nottingham), and the STAGES Collaboration
STScI-PRC08-03


Cosmic Web
Large Scale Structure in the Local Universe
Corona Borealis Supercluster (0.072)
Bootes Supercluster (0.061)
Coma Cluster (0.023)
Virgo Cluster (16 Mpc)
Hercules Supercluster (0.037)
Leo Supercluster (0.032)
Ursa Major Supercluster (0.058)
Shapley Concentration (0.048+)
Ophiuchus Cluster (0.028)
Centaurus Cluster (0.02)
Abell 634 Cluster (0.025)
IRAS dipole
CMB dipole
Abell 569 Cluster (0.019)
Hydra Cluster (0.01)
Orion Molecular Cloud
Taurus Molecular Cloud
Columba Cluster (0.034)
Perseus-Pisces Supercluster (0.017+)
Norma & Great Attractor (0.016)
M31 (1 Mpc)
LMC
Pisces-Cetus Supercluster (0.063)
Fornax Cluster (20 Mpc)
Milky Way Center
Horologium Supercluster (0.067)
Pavo-Indus Supercluster (0.015)
Sculptor Supercluster (0.054)
Legend: image shows 2MASS galaxies color coded by redshift (Jarrett 2004);
familiar galaxy clusters/superclusters are labeled (numbers in parenthesis represent redshift).
Graphic created by T. Jarrett (IPAC/Caltech)

Local Supercluster

our cosmic province

Local Supercluster



Courtesy: B. Tully

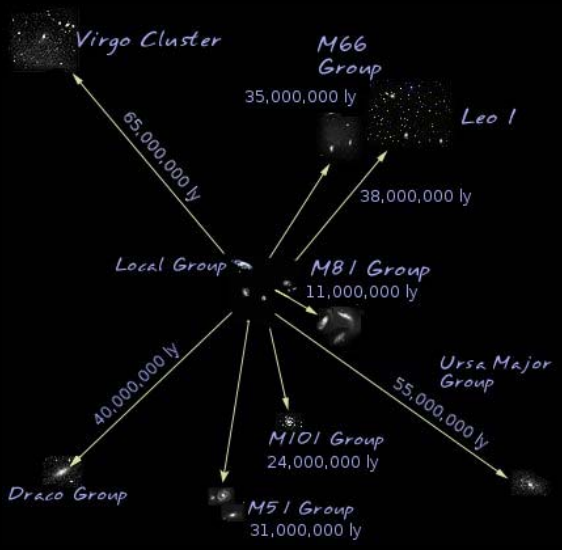
Our Local Group finds itself located at the outer region of a large supercluster region,

- **the "Local Supercluster",**
- **centered on one rich cluster, the Virgo cluster**
- **~ 33 Mpc diameter**

Wrt. other superclusters:

- **poor supercluster**
- **rather small size**

Local Supercluster



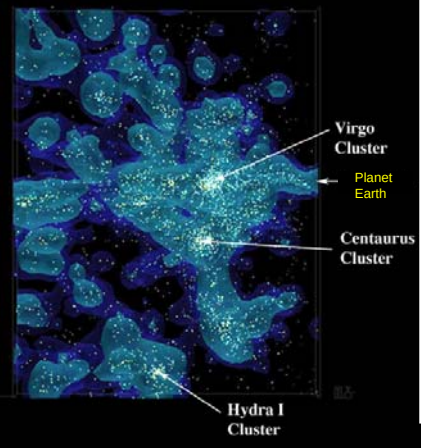
Local Supercluster:

contains:
- ~ 100 galaxy groups
- 1 rich cluster - Virgo cluster

structure:
- Central Virgo cluster
- groups & galaxies connected via filamentary extensions
- Local Group:
- outskirt Local Supercluster, on filament extending from Fornax cluster – Virgo cluster

Local Supercluster

End-on View of the Local Supercluster:



Courtesy: B. Tully

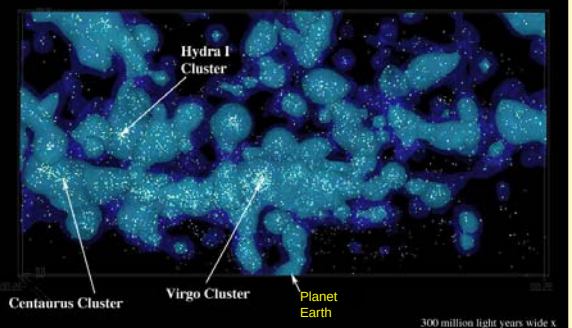
Structure Local Supercluster:

2 components:
- flattened disk 2/3rd galaxies
- spherical "halo" 1/3rd galaxies

Disk:
- thin (~ 1 Mpc) disk, 1:6 - 1:9 flattened

Local Supercluster

Polar View of Local Supercluster:



Courtesy: B. Tully

Local Supercluster:

Mass (DM): $M \sim 1 \times 10^{15}\ M_{\odot}$

Luminosity: $L \sim 3 \times 10^{12}\ L_{\odot}$

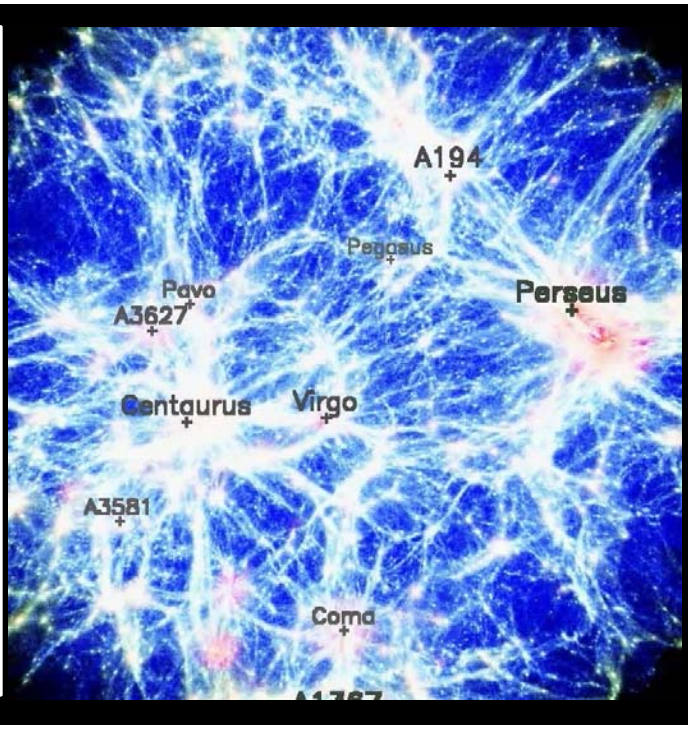
M/L ~ 300

Local Universe:

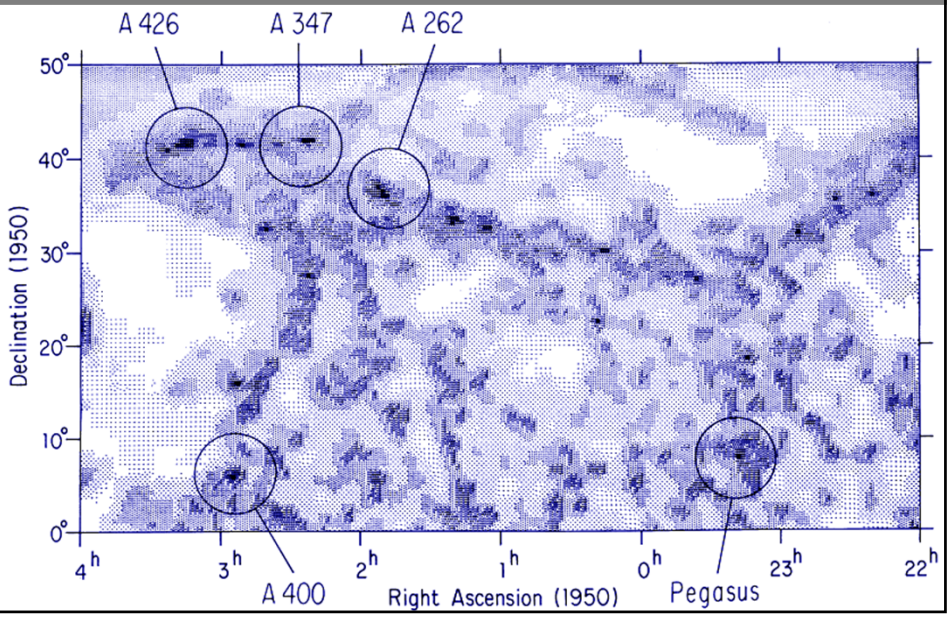
Constrained Simulation

Gas Distribution

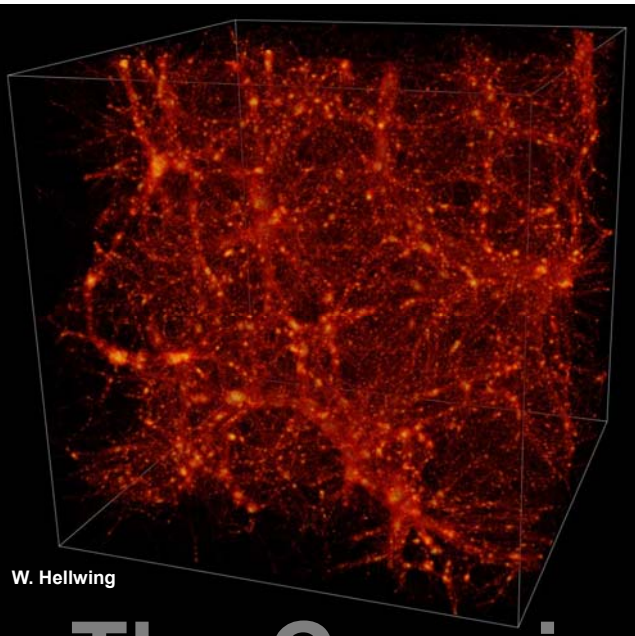
courtesy:
Klaus Dolag



Superclusters



the Cosmic Web



Stochastic
Spatial
Pattern of

- Clusters,
- Filaments &
- Walls

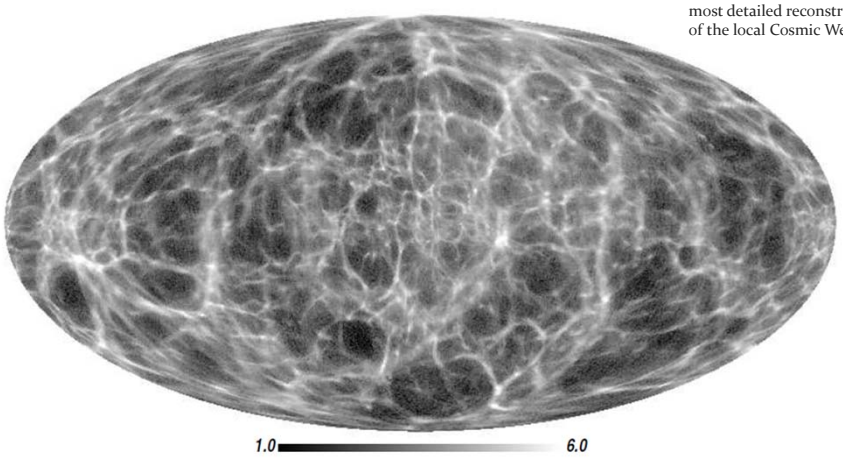
around

- Voids

in which
matter & galaxies
have agglomerated
through gravity

The Cosmic Web

local Cosmic Web: 2MRS



most detailed reconstruction of the local Cosmic Web

Courtesy: Francisco Kitaura

The Cosmic Web

Physical Significance:

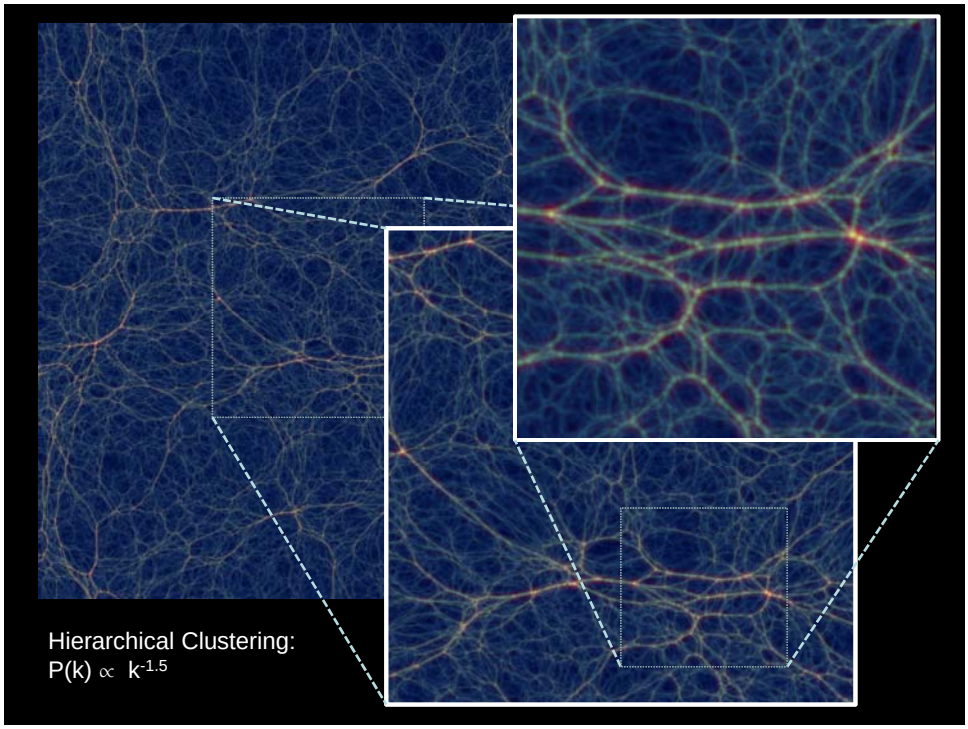
- **Manifestation mildly nonlinear clustering:**
  Transition stage between linear phase
  and fully collapsed/virialized objects

- **Weblike configurations contain**
  cosmological information:
  eg. *Void shapes & Alignments*

- **Cosmic environment within which to understand**
  the formation of galaxies.

Cosmic Web Characteristics

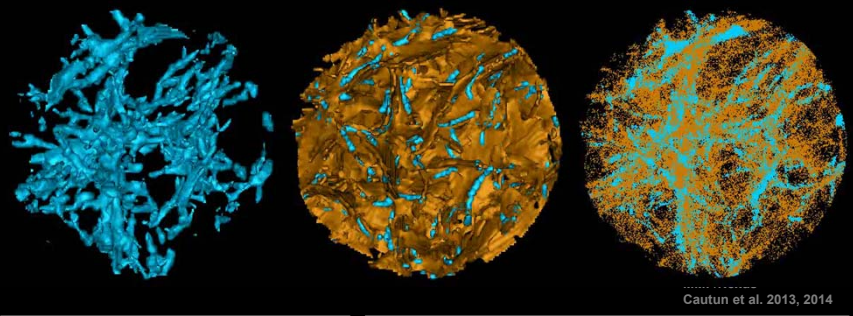
- **anisotropic structure:**
  - filaments dominant structural feature - elongated
  - sheets/walls - flattened
- **multiscale nature**
  - structure on wide range of scales
  - structures have wide range of densities
- **overdense-underdense asymmetry**
  - voids: underdense, large & roundish
  - filaments & walls: overdense, flattened/elongated
  - clusters: dense, massive & compact nodes
- **complex spatial connectivity**
  - all structural features connected in a complex, multiscale weblike network



the Cosmic Network:

weaving the cosmic tapestry

Nexus/MMF



Cautun et al. 2013, 2014

Stochastic Spatial Pattern

- Clusters,
- Filaments &
- Walls

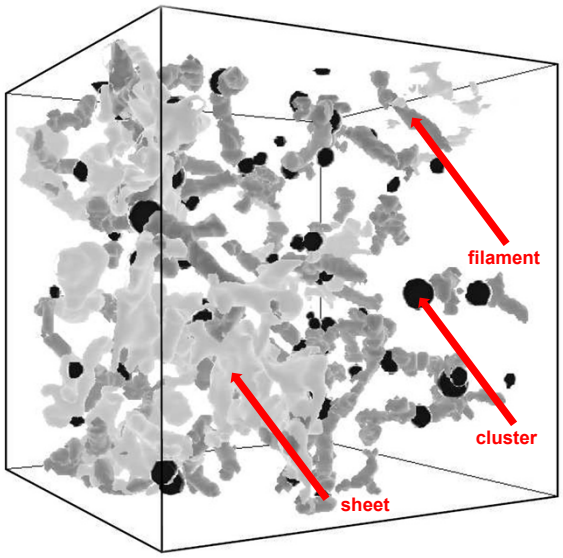
around

- Voids

in which matter & galaxies

have agglomerated

through gravity



Nexus/MMF Cosmic Web Analysis

Nexus/MMF dissection

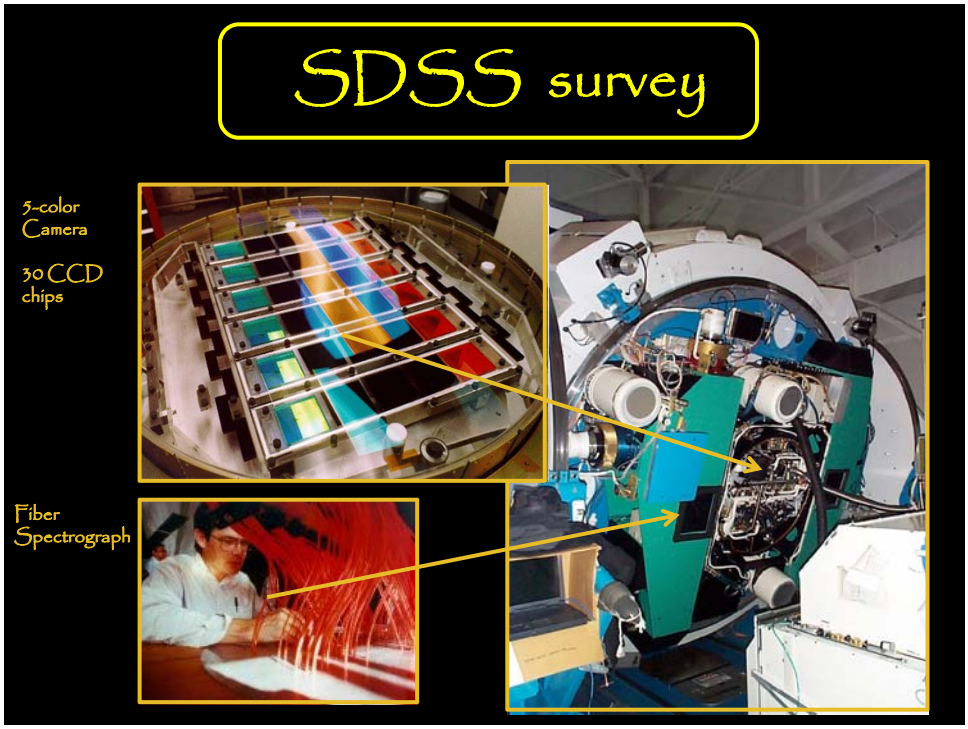
into
sheets, filaments, clusters
…

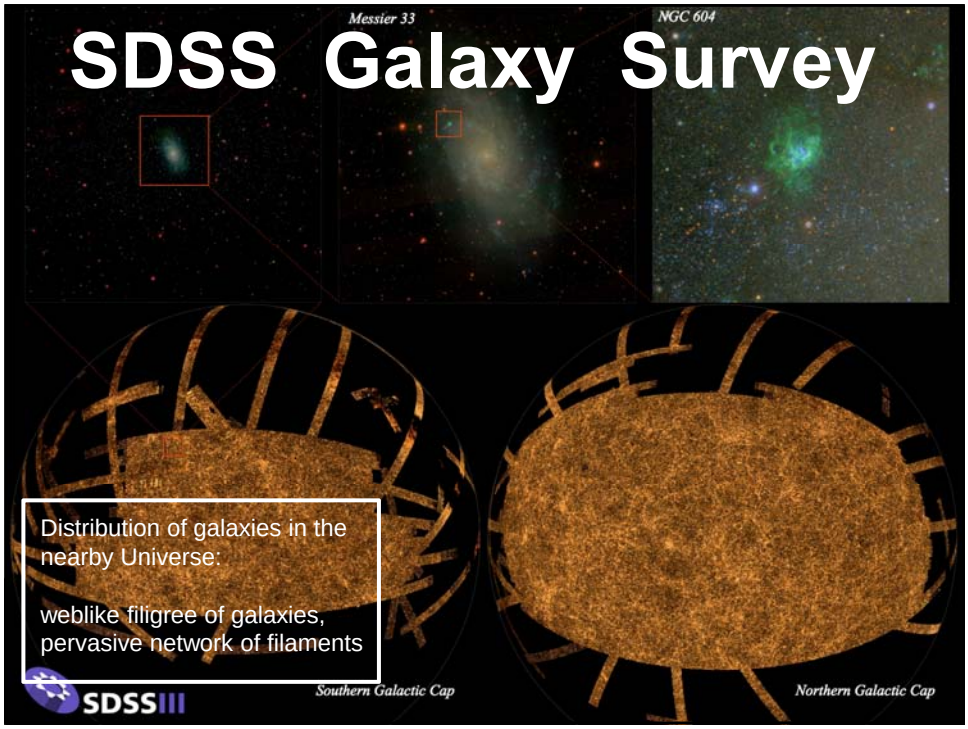
Aragon-Calvo et al. 2007

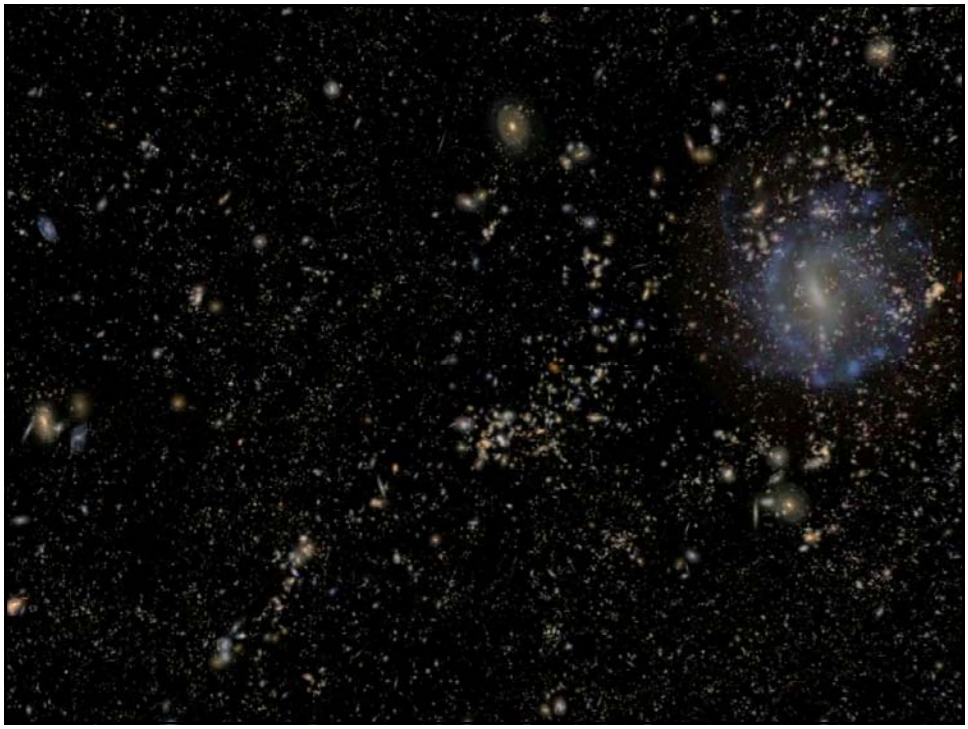
Mapping the Cosmic Web

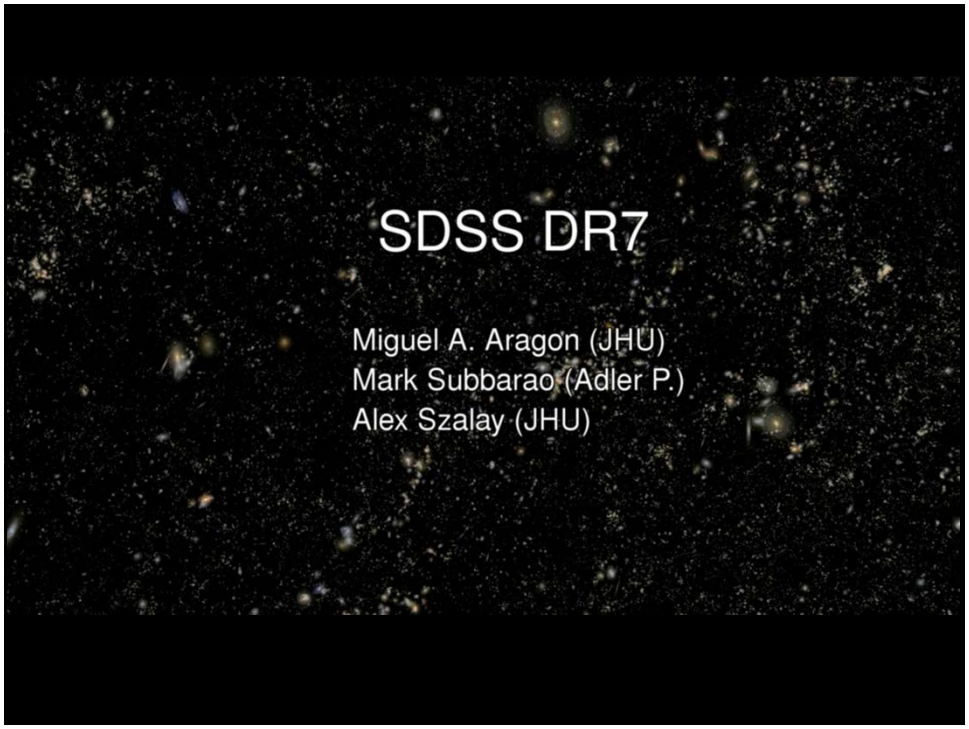
galaxy surveys

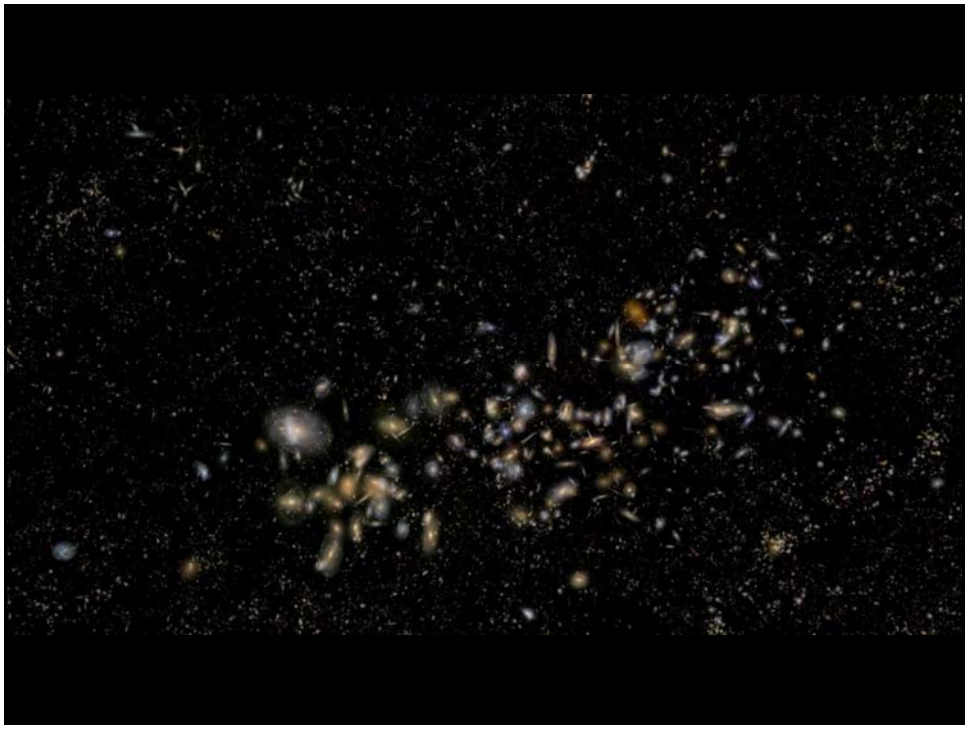
SDSS survey



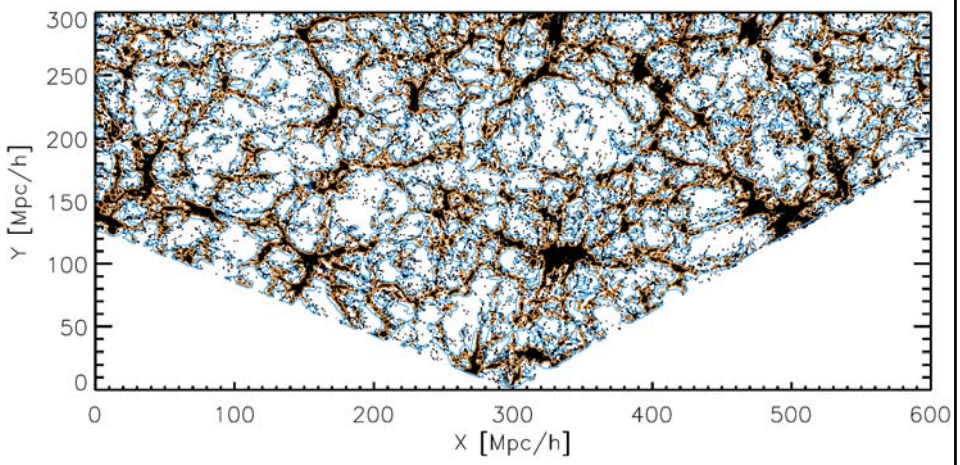

SDSS Galaxy Survey
Messier 33
NGC 604
Distribution of galaxies in the nearby Universe:
weblike filigree of galaxies, pervasive network of filaments
SDSSIII
Southern Galactic Cap
Northern Galactic Cap

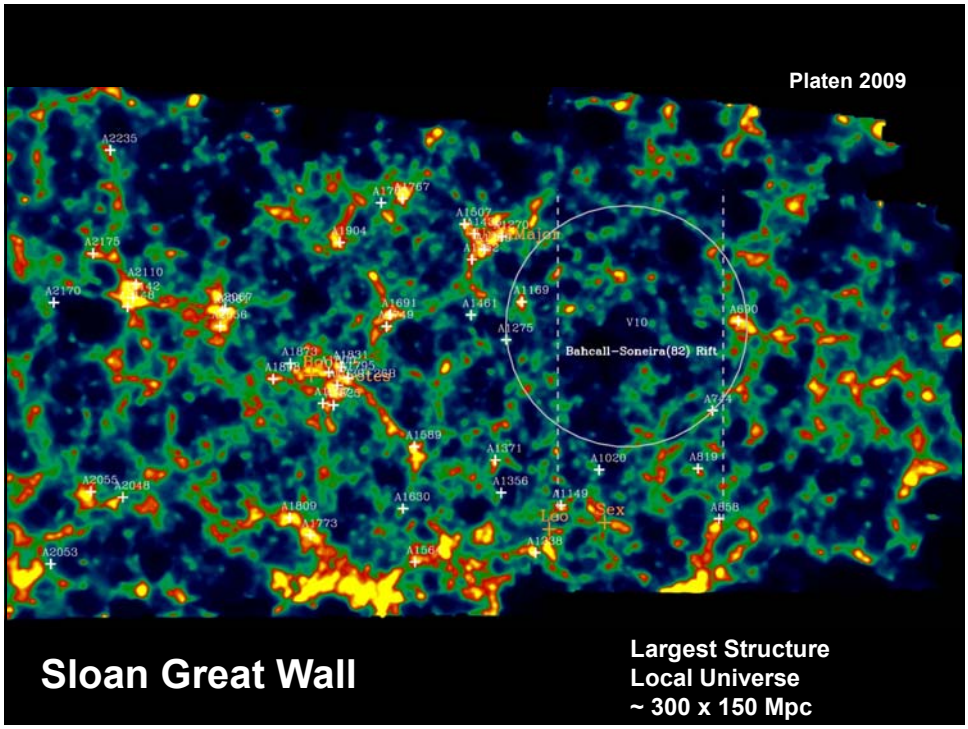



SDSS DR7
Miguel A. Aragon (JHU)
Mark Subbarao (Adler P.)
Alex Szalay (JHU)

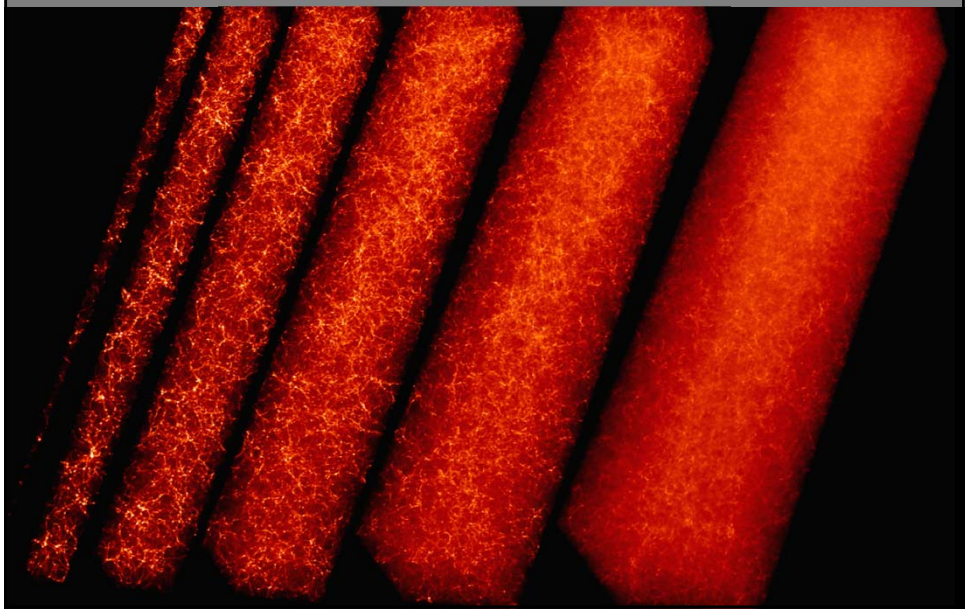


Cosmic Web

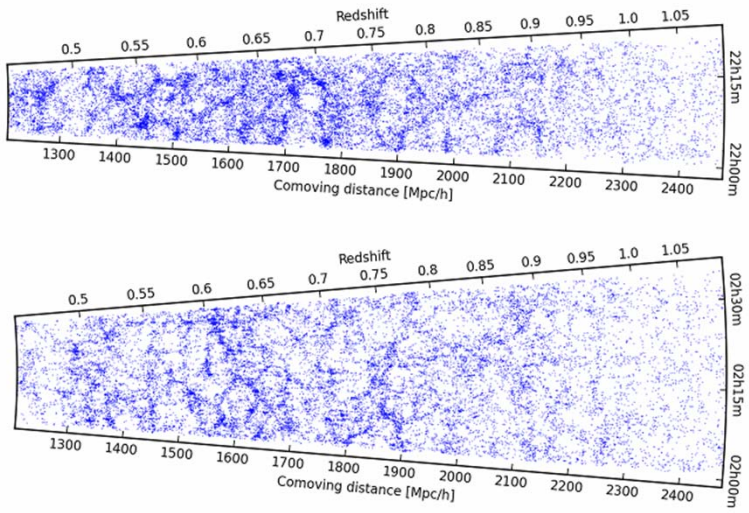

300
250
200
150
100
50
0
Y [Mpc/h]
0
100
200
300
400
500
600
X [Mpc/h]


Platen 2009
Bahcall-Soneira(82) Rift
Leo
Sex
Sloan Great Wall
Largest Structure
Local Universe
~ 300 x 150 Mpc

Cosmic Web

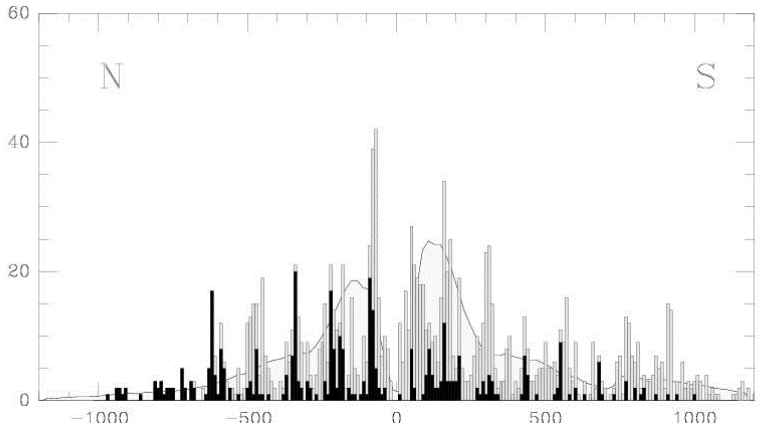


Cosmic Web at High z



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

Cosmic Web at High z



Deep pencil beam survey (Broadhurst et al):

A semi-regular pattern of redshift spikes along line of sight, indicating the passage of l.o.s. through sheets, filaments and clusters. Suggestions for a characteristic scale of ~120h^{-1} Mpc should be ascribed to the 1-D character of the redshift skewer through 3-D structure.

Cosmic Web:

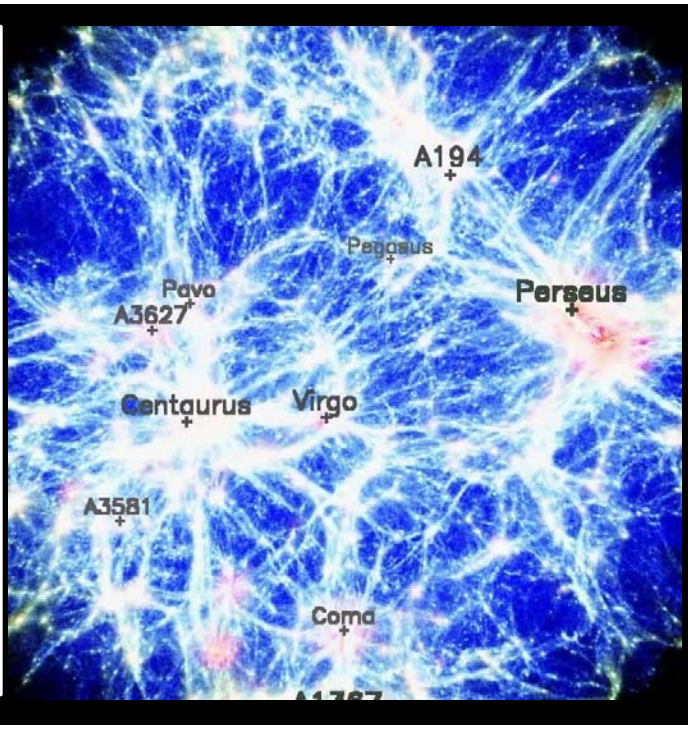
Gas & Dark Matter

Local Universe:

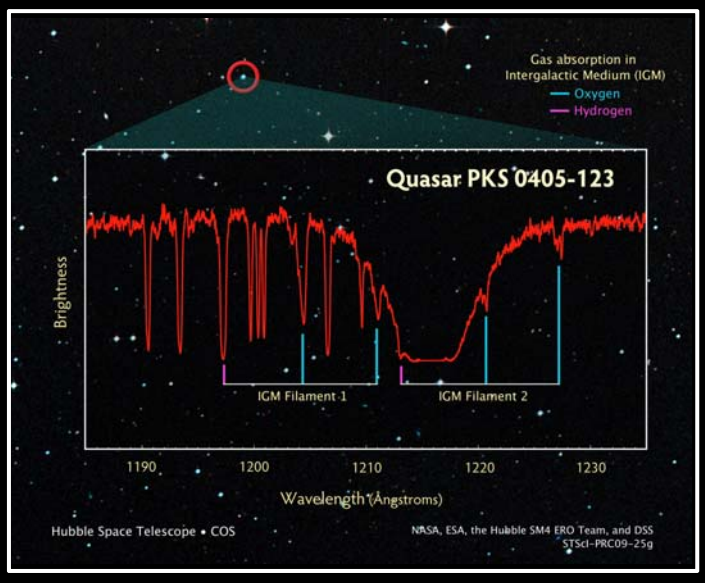
Constrained Simulation

Gas Distribution

courtesy:
Klaus Dolag



the Gaseous Cosmic Web



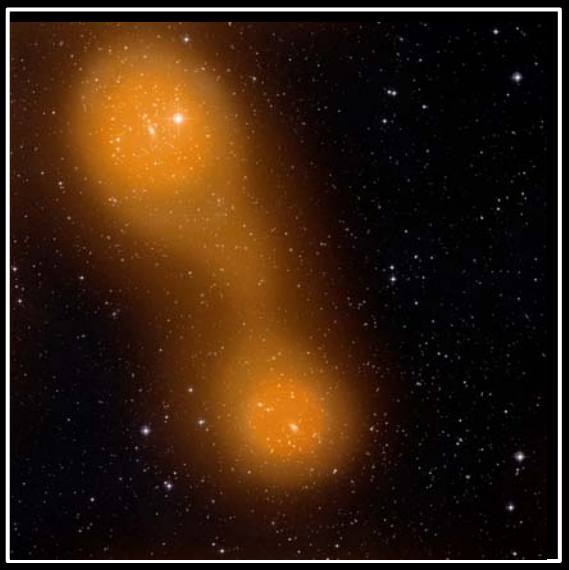
the Gaseous Cosmic Web

SZ detection of

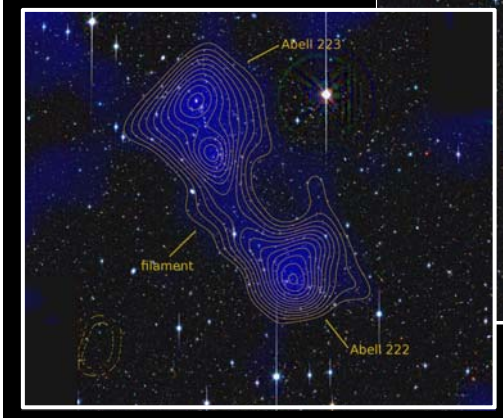
Inter-cluster bridge/filament

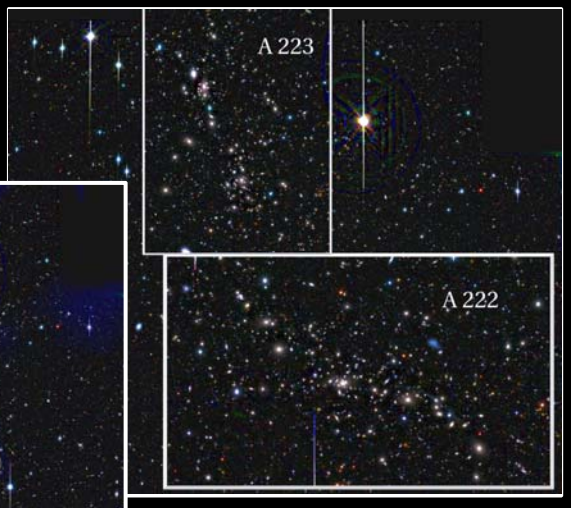
in between clusters
A401 and A399

ESA/Planck collaboration



Dark Matter Cosmic Web



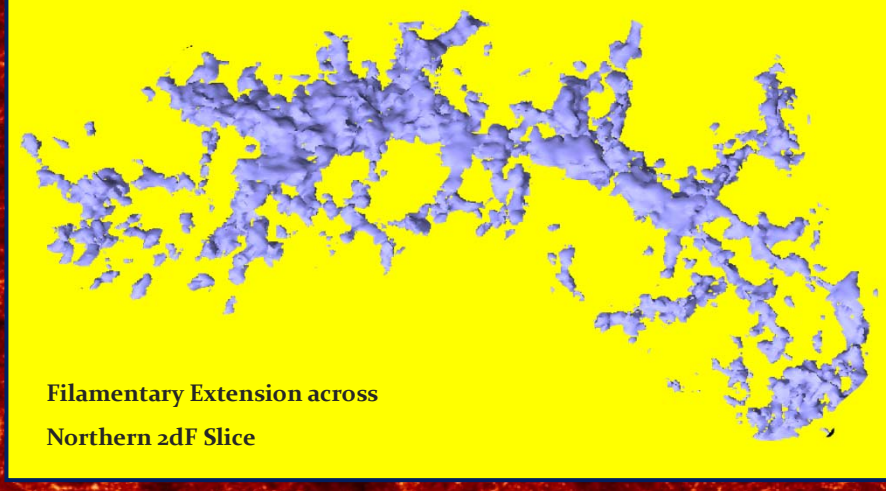


A222-A223
Dietrich et al. 2013

Cosmic Web:

The Elements

Walls, Filaments & Nodes

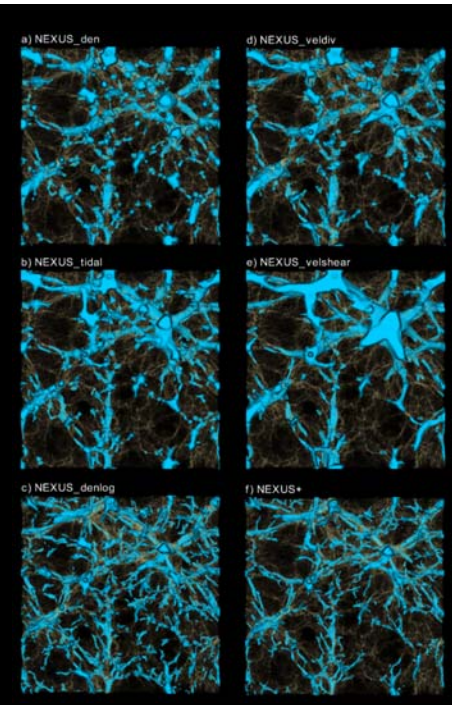


Filamentary Extension across

Northern 2dF Slice

DTFE rendering: W. Schaap

Filaments



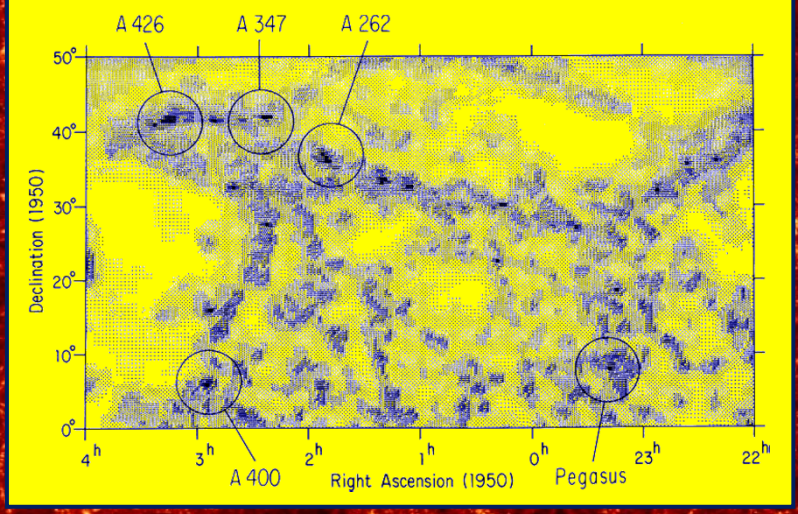
Nexus Filaments

- Nexus identification of filaments (blue)

- Identification on the basis of 6 different physical characteristics of the cosmic mass distribution:

- Density - Velocity Divergence
- Tidal field - Velocity Shear
- Log(density) - Nexus+

Pisces-Perseus Chain



21 cm line redshift survey,
Giovanelli & Haynes

Pisces-Perseus Chain

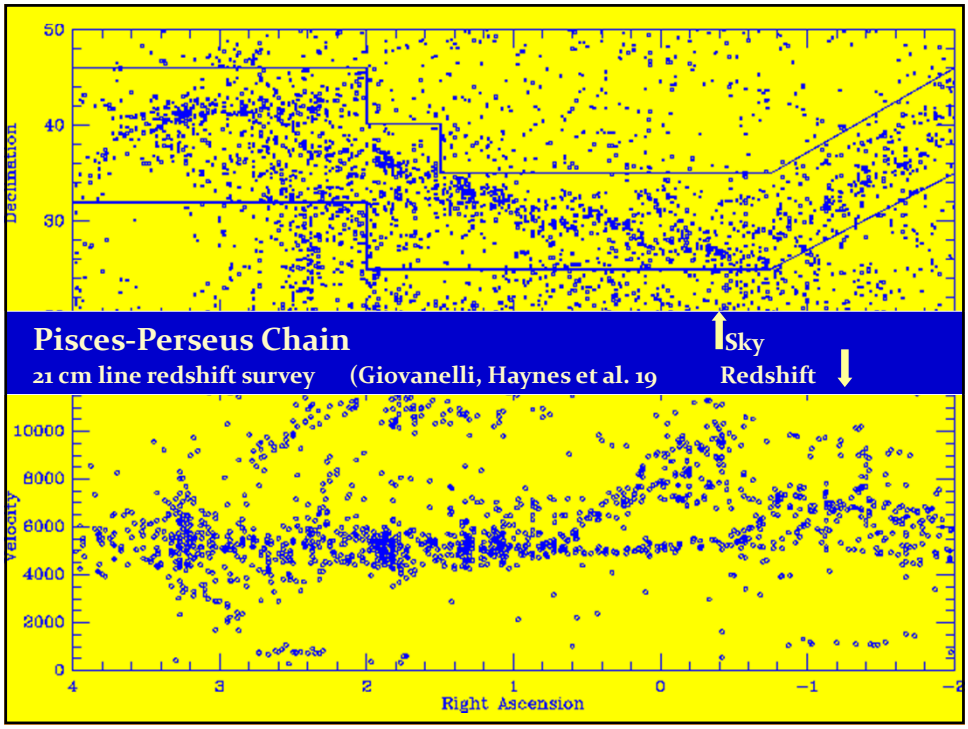
Canonic example of a strongly flattened supercluster consisting of

- sheet-like central region, dense filamentary boundary ridge
- Relative proximity (d ~ $55h^{-1}$ Mpc),
- Characteristic & salient filamentary morphology,
- Favourable orientation.

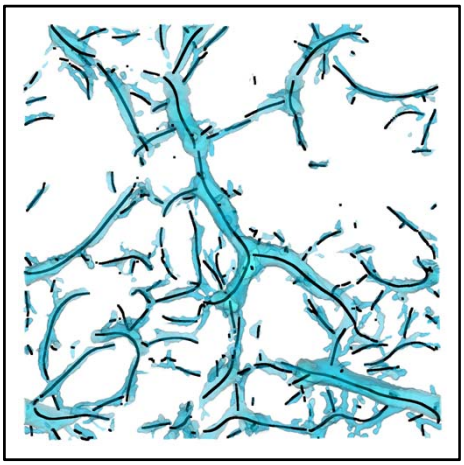
Northern boundary: ridge south-westward of Perseus cluster (A426)

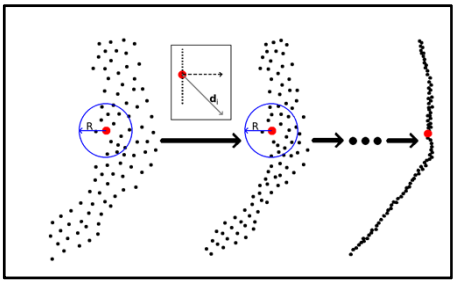
Dimensions Ridge: $5h^{-1}$ Mpc wide
$50h^{-1}$ Mpc length; possible $140h^{-1}$ Mpc extension

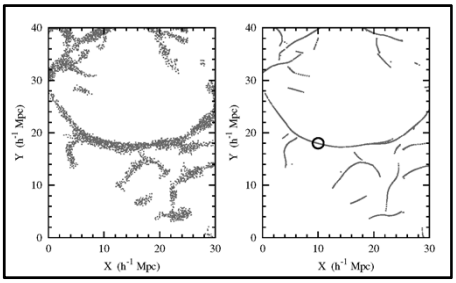
Along Ridge: high density clusters, incl. A462, A347, A262

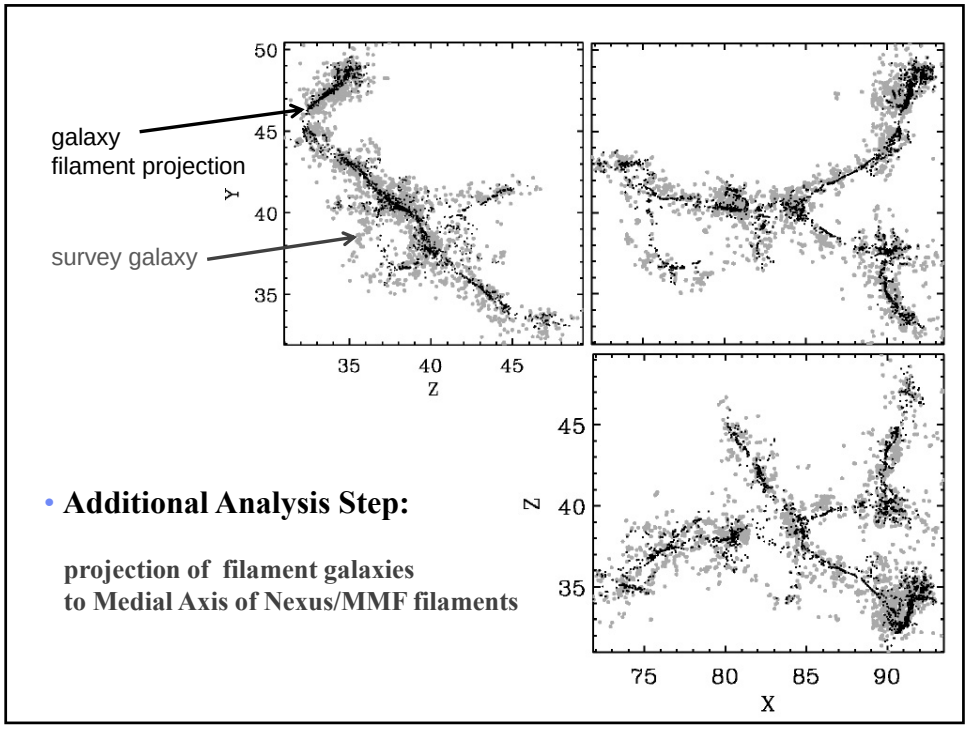


Spine of the Cosmic Web



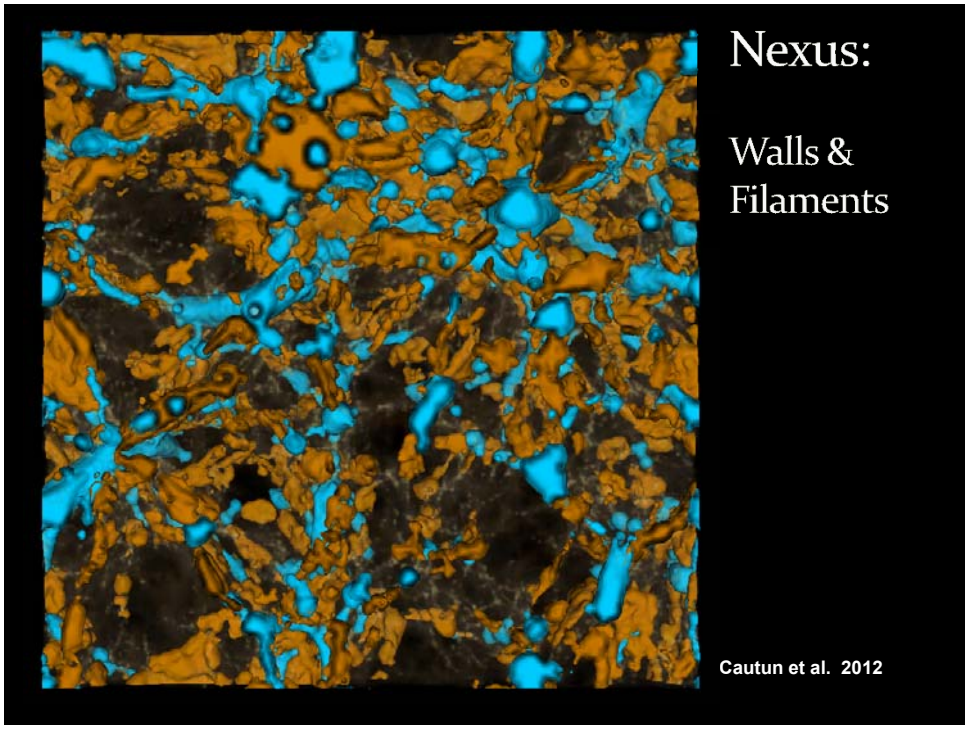


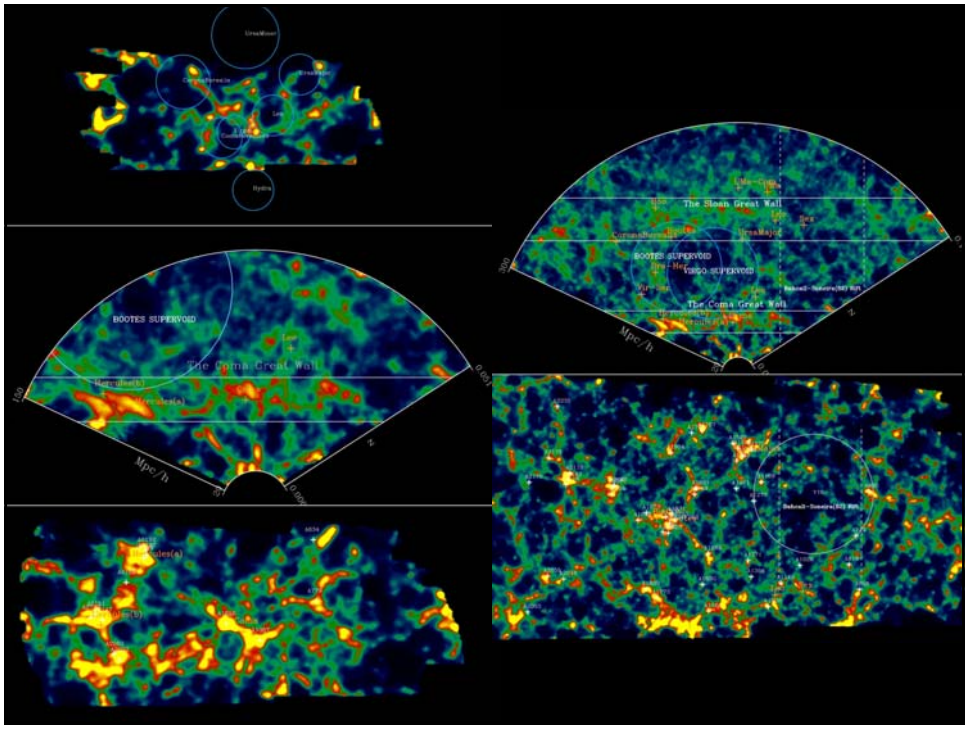


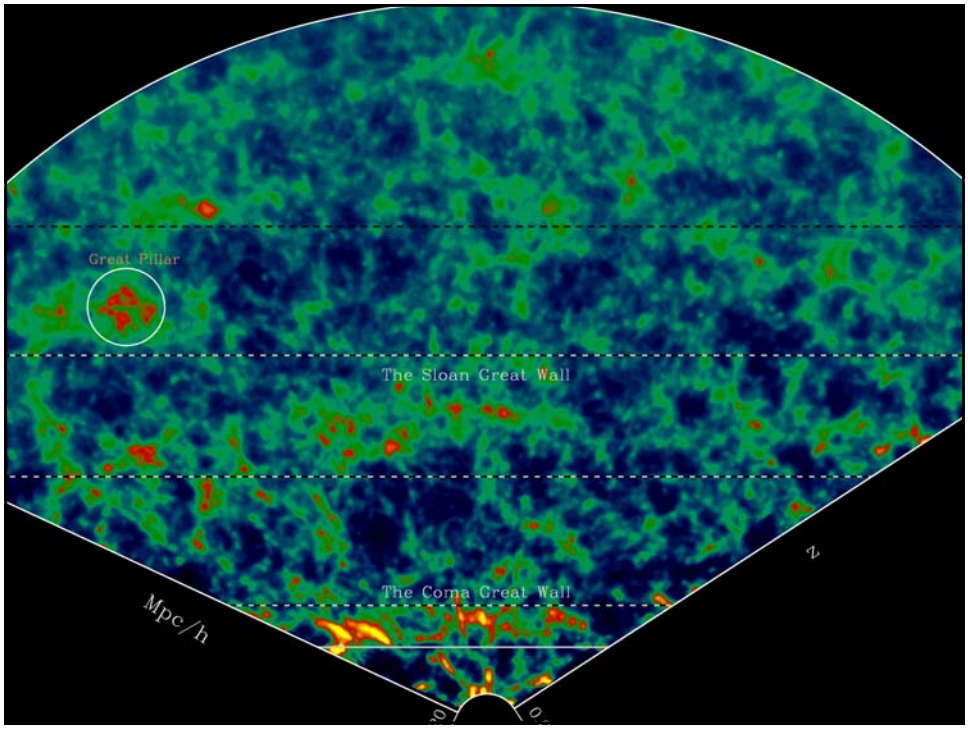


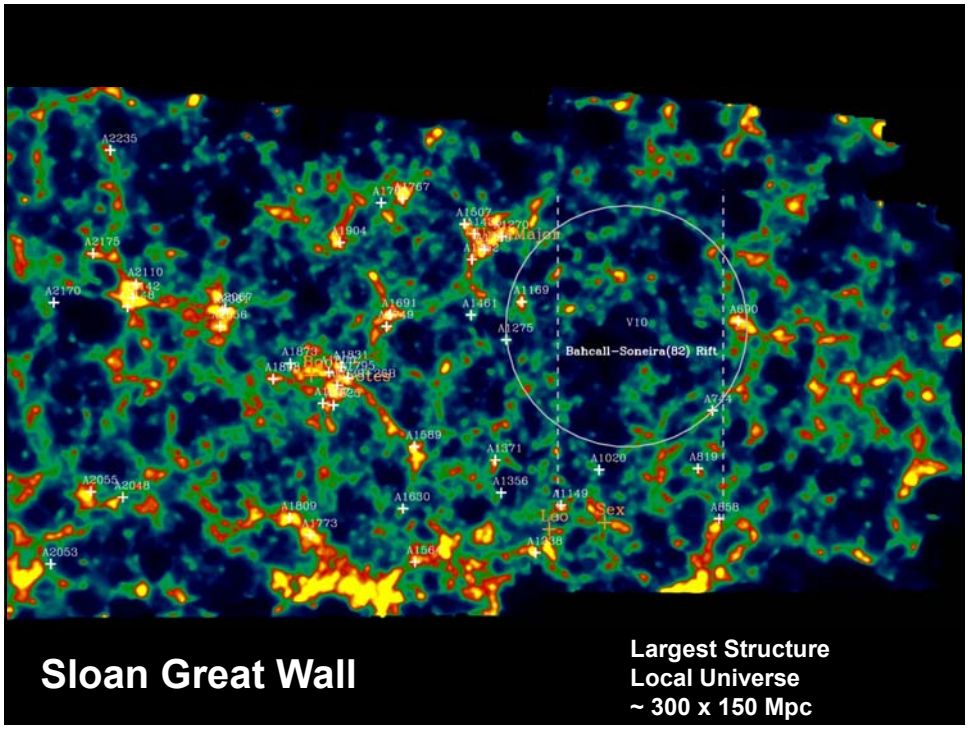
- **Additional Analysis Step:**

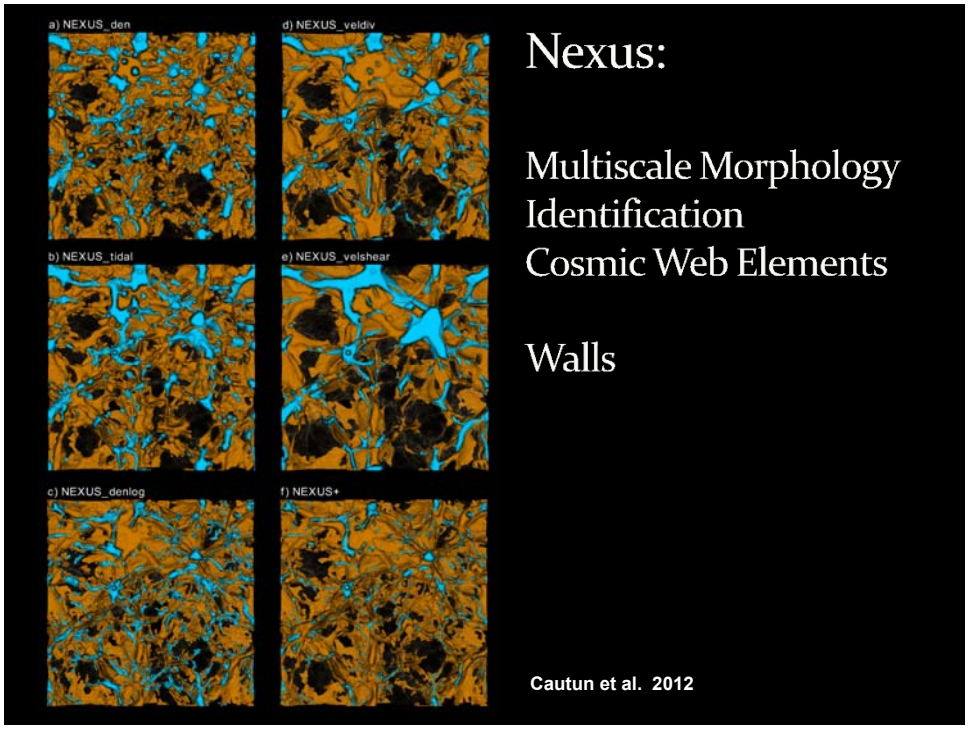
  projection of filament galaxies to Medial Axis of Nexus/MMF filaments

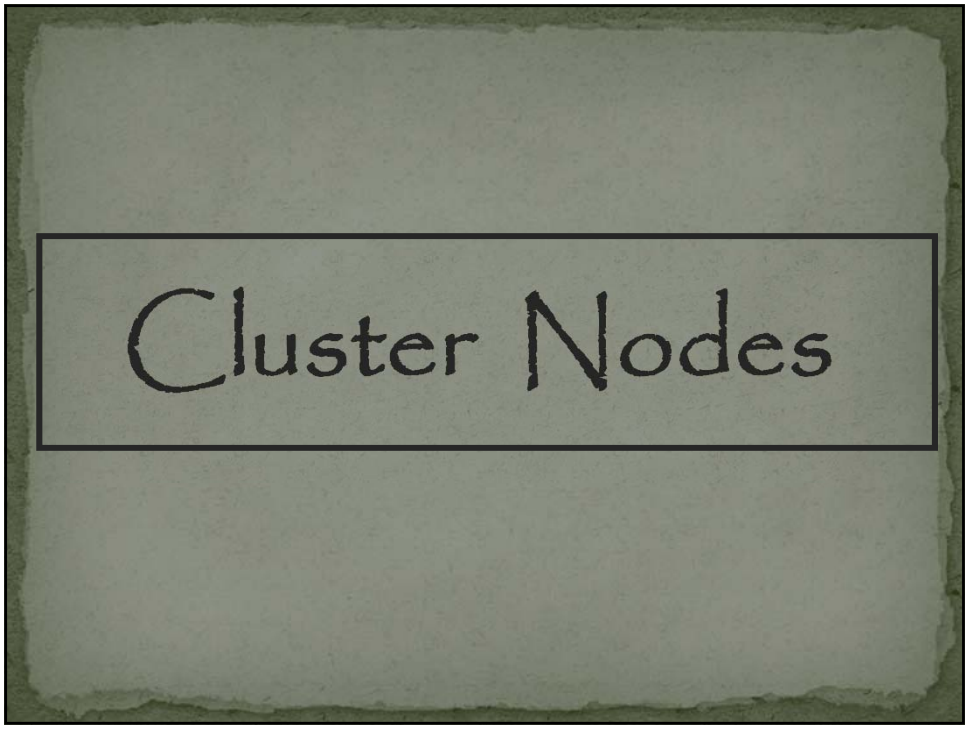

Nexus:
Walls &
Filaments
Cautun et al. 2012


BOOTES SUPERVOID
The Coma Great Wall
Mpc/h
The Sloan Great Wall
BOOTES SUPERVOID
VIRGO SUPERVOID
The Coma Great Wall
Mpc/h

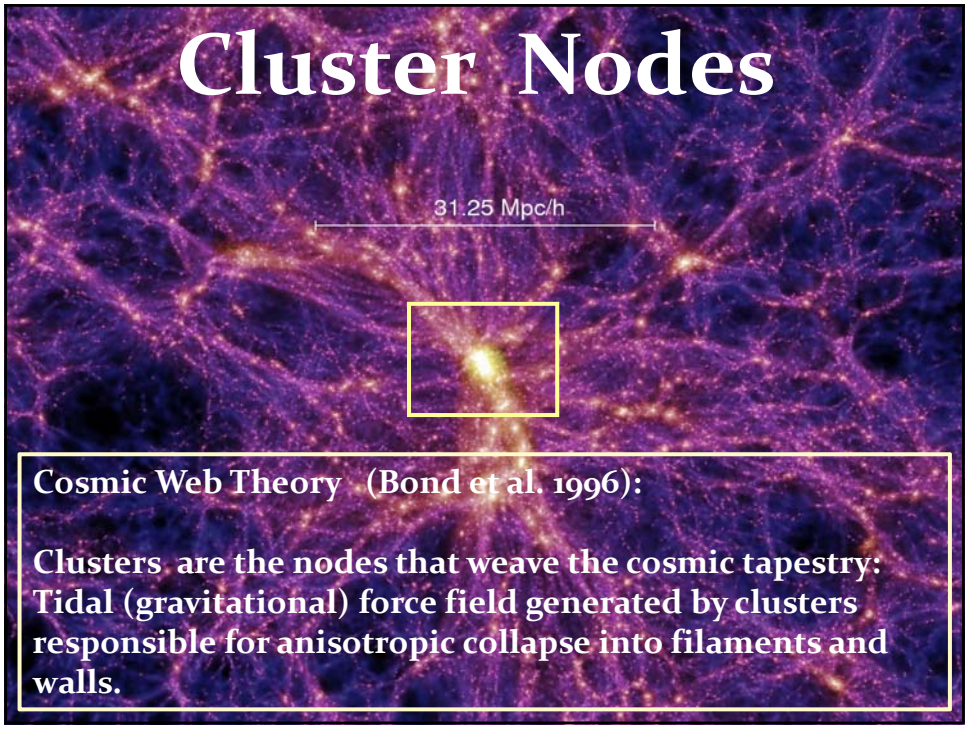

Great Pillar
The Sloan Great Wall
The Coma Great Wall
Mpc/h
z


A2235
A2175
A2110
A2170
A1904
A1691
A1461
A1169
A1276
V10
Bahcall-Soneira(82) Rift
A1589
A1371
A1020
A819
A2055
A2048
A1356
A1630
A1149
Leo
Sex
A1809
A1773
A2053
A1656
A85B
Sloan Great Wall
Largest Structure
Local Universe
~ 300 x 150 Mpc


a) NEXUS_den
d) NEXUS_veldiv
b) NEXUS_tidal
e) NEXUS_velshear
c) NEXUS_denlog
f) NEXUS+
Nexus:
Multiscale Morphology
Identification
Cosmic Web Elements
Walls
Cautun et al. 2012


Cluster Nodes

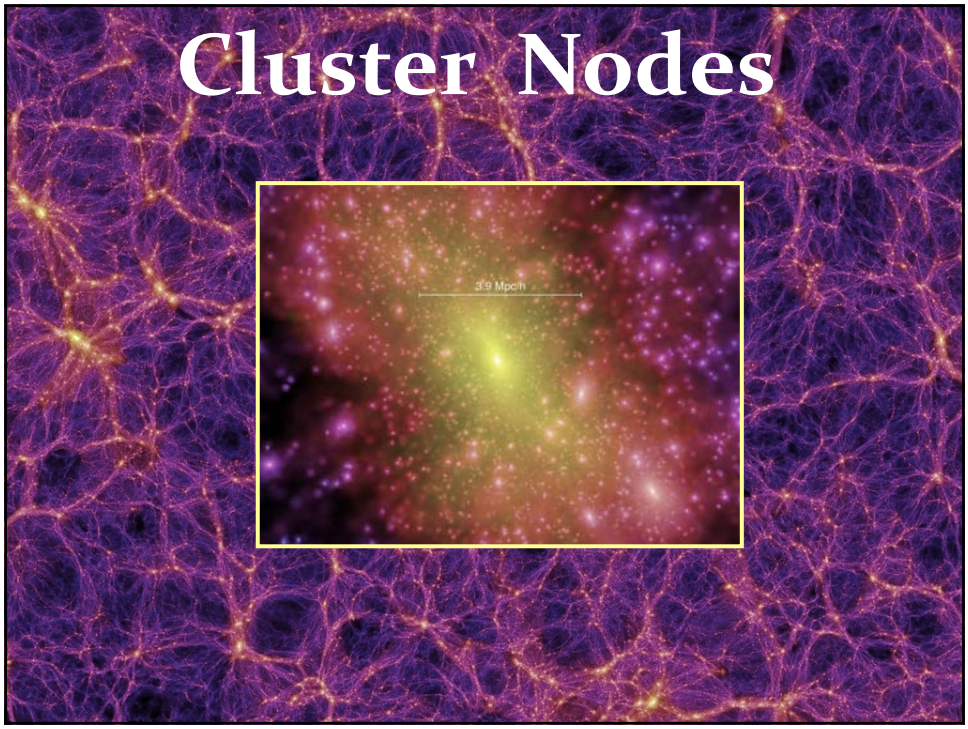
Cluster Nodes

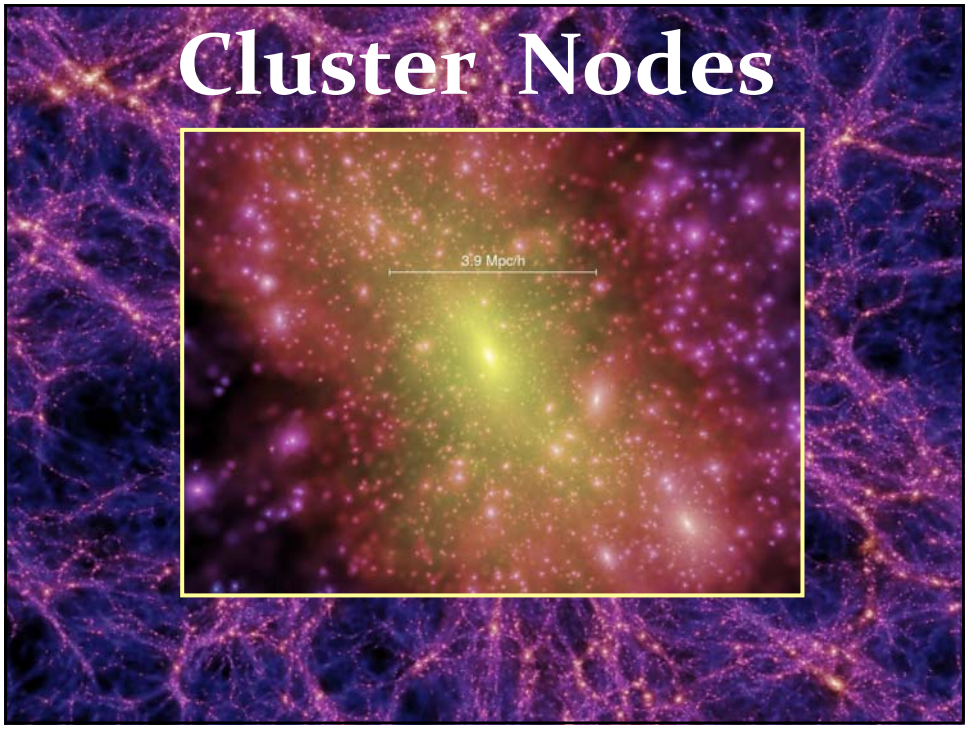


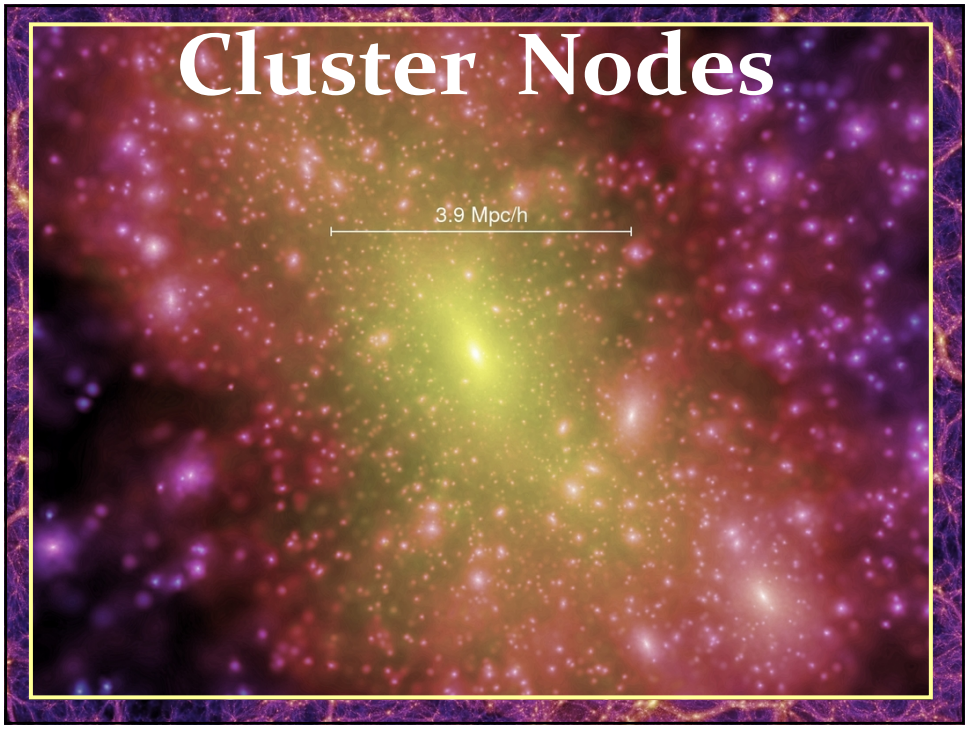
Cosmic Web Theory (Bond et al. 1996):

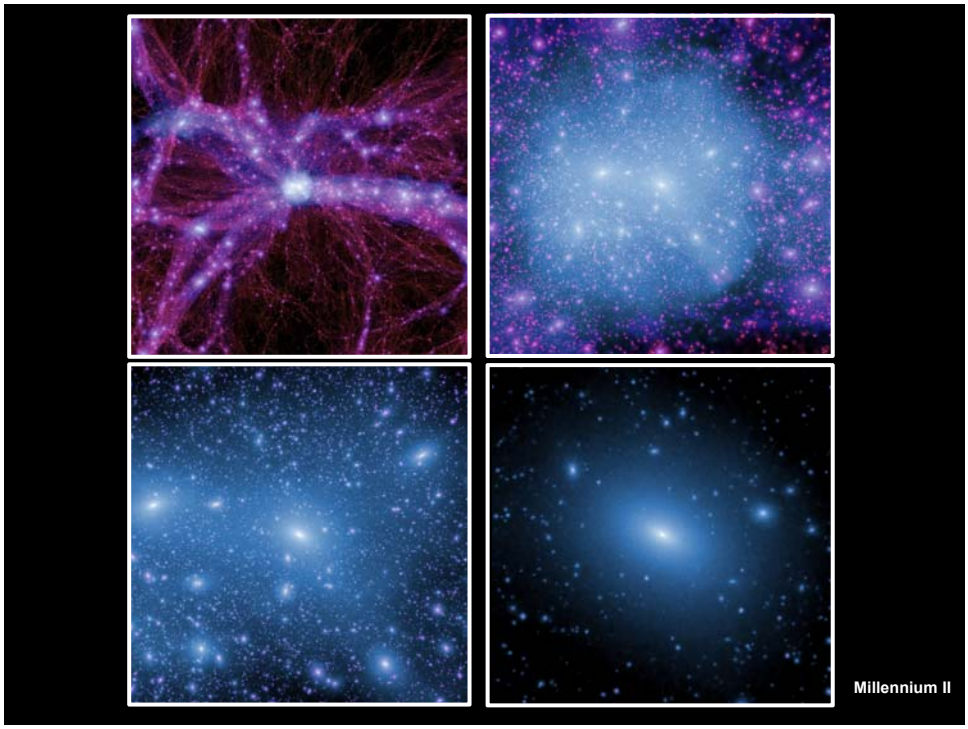
Clusters are the nodes that weave the cosmic tapestry: Tidal (gravitational) force field generated by clusters responsible for anisotropic collapse into filaments and walls.

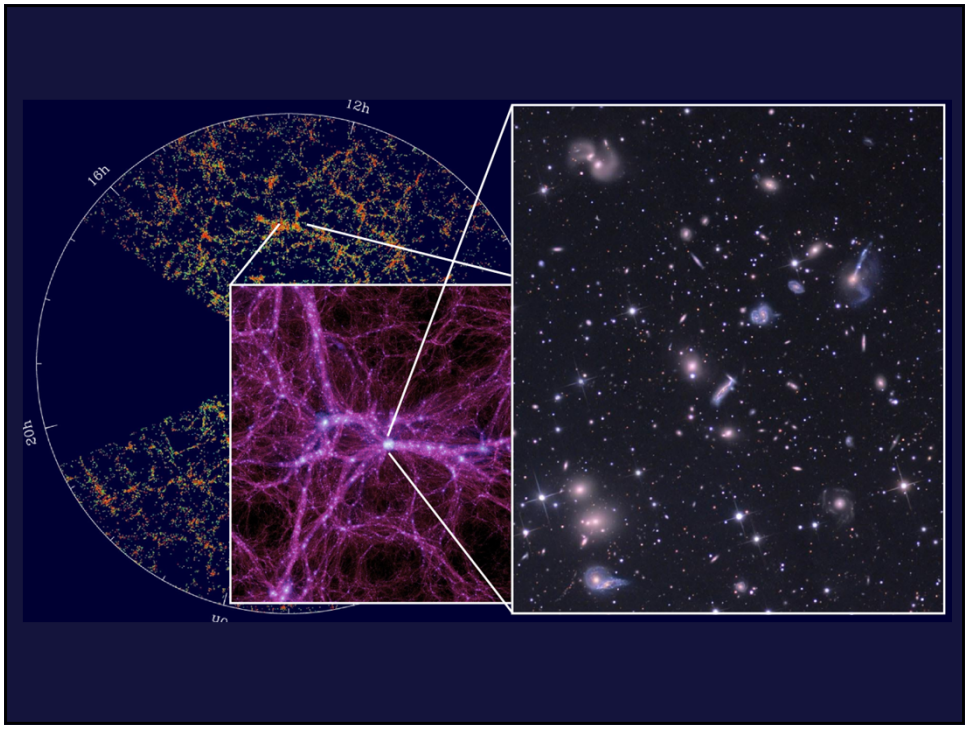
Cluster Nodes



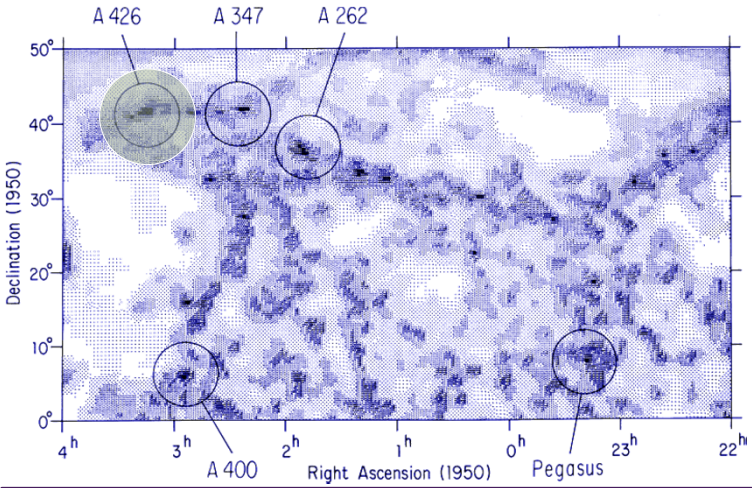

Cluster Nodes
3.9 Mpc/h


Cluster Nodes
3.9 Mpc/h


Millennium II

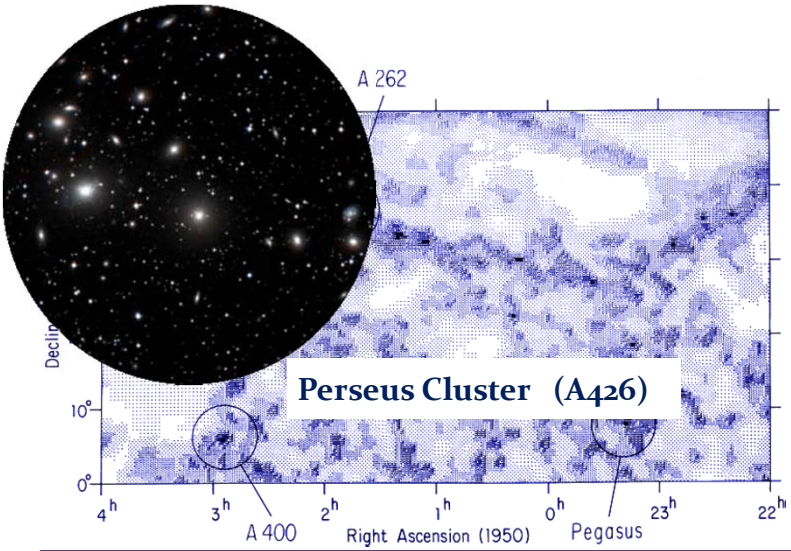

12h
16h
20h

Cluster Nodes & the Web



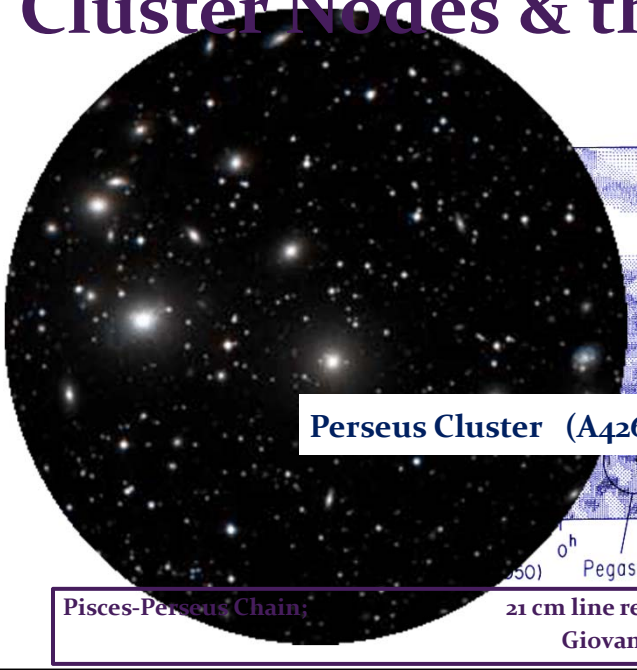
Pisces-Perseus Chain; 21 cm line redshift survey, Giovanelli & Haynes

Cluster Nodes & the Web

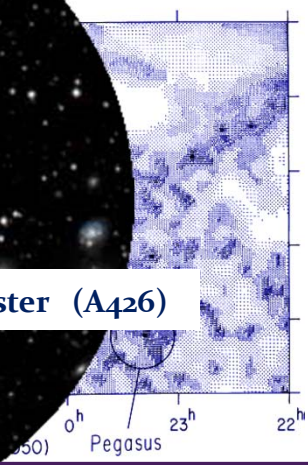


Pisces-Perseus Chain; 21 cm line redshift survey, Giovanelli & Haynes

Cluster Nodes & the Web

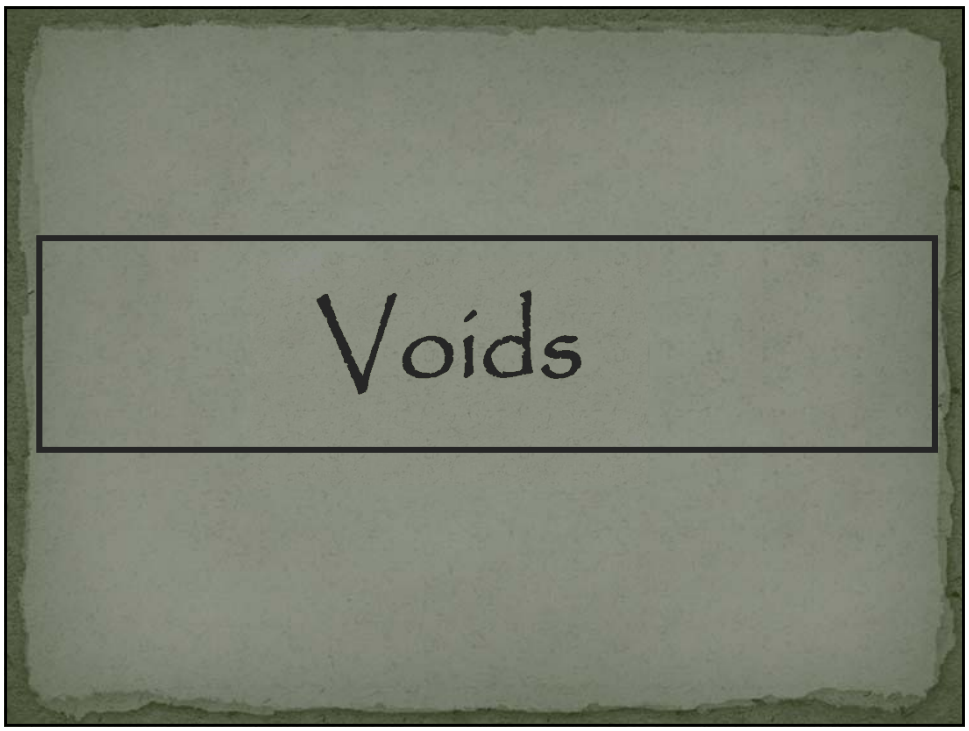


Perseus Cluster (A426)



Pisces-Perseus Chain;

21 cm line redshift survey,
Giovanelli & Haynes



Nature Vol. 300 2 December 1982 407

REVIEW ARTICLE

Giant voids in the Universe

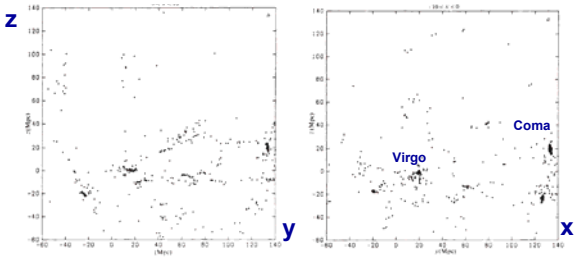
Ya. B. Zeldovich*, J. Einasto†‡ & S. F. Shandarin*

* Institute of Applied Mathematics, Moscow A-47, 125047, USSR
† Tartu Astrophysical Observatory, 202444 Estonia, USSR
‡ European Southern Observatory, 8046 Garching, FRG

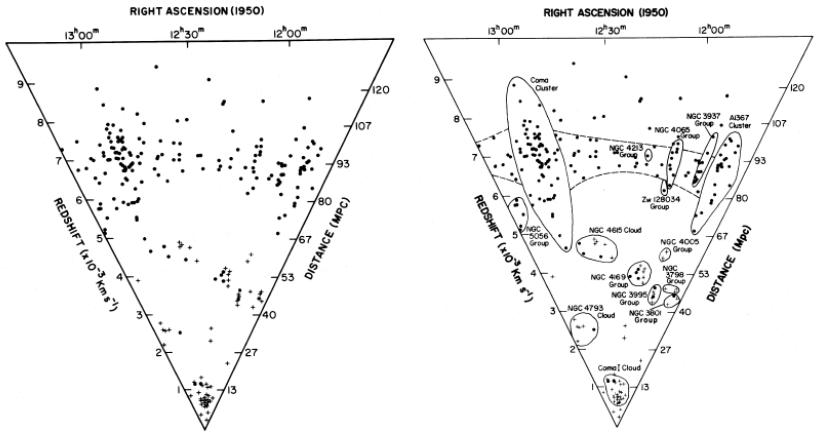
Recent observations indicate that most galaxies are concentrated in superclusters consisting of galaxies, and clusters of galaxies, aligned along strings. Giant volumes exist between superclusters which are almost empty of visible objects. Theories of galaxy formation predict the formation of non-spherical 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 & Shandarin 1982:

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



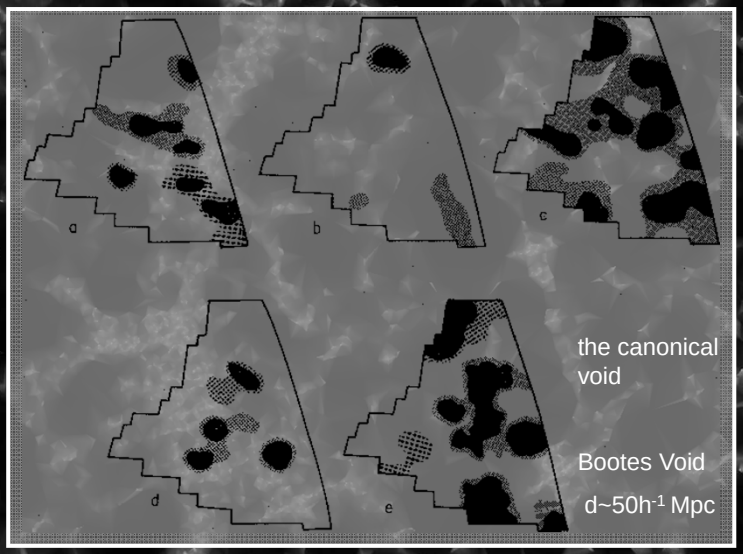
First Voids



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



Bootes Void

The Bootes Void.

Bootes void as revealed by the galaxy number space density in a sequence of five different recession velocity intervals in the direction of the Bootes constellation on the sky.

The lowest contour represents a density equal to 0.7 of the cosmic mean, each higher contour represents a factor 2 increase in density. Velocity ranges (km/s):

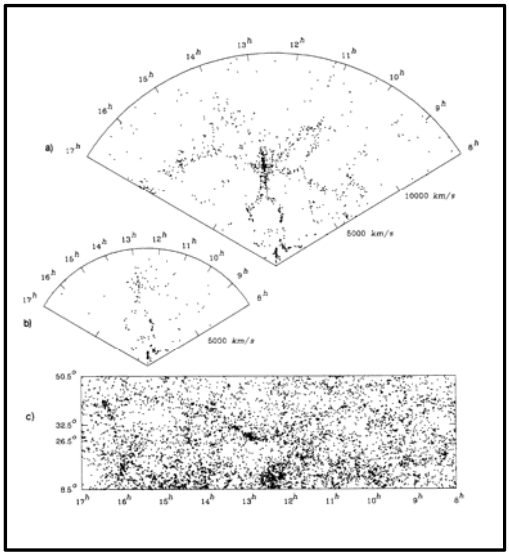
(a) 7,000-12,000 (b) 12,000-17,000 (c) 17,000-23,000

(d) 23,000-29,000 (e) 29,000-39,000

Frame (b) clearly reveals a large void in the galaxy distribution, which turns out to be roughly spherical in outline.

From: Kirshner et al. (1987)

Voids & the Cosmic Web

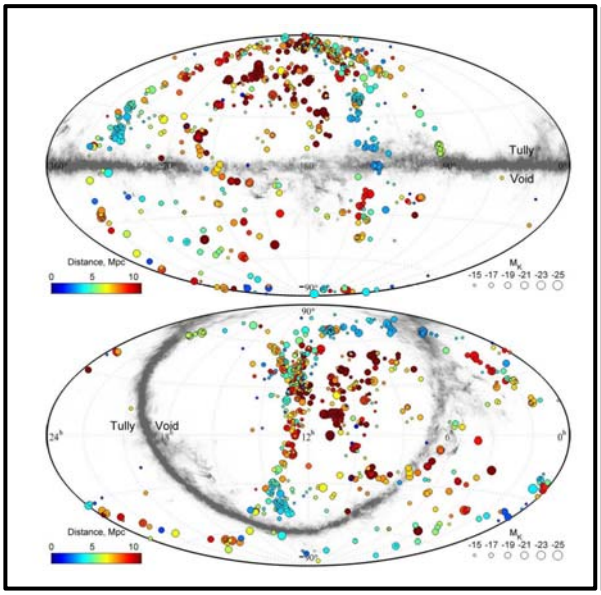


deLapparent, Geller & Huchra, 1986:

"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 etal.

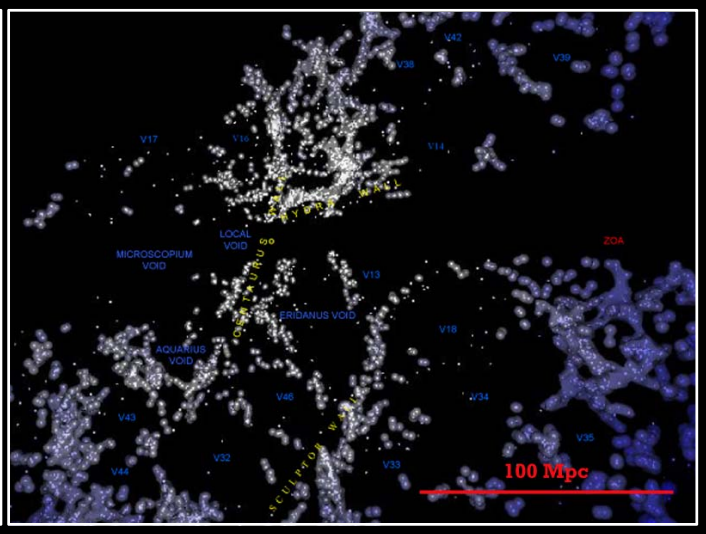
LV catalog:
galaxies within 10 Mpc reveal beautifully the magnificent

Local Void – Tully Void

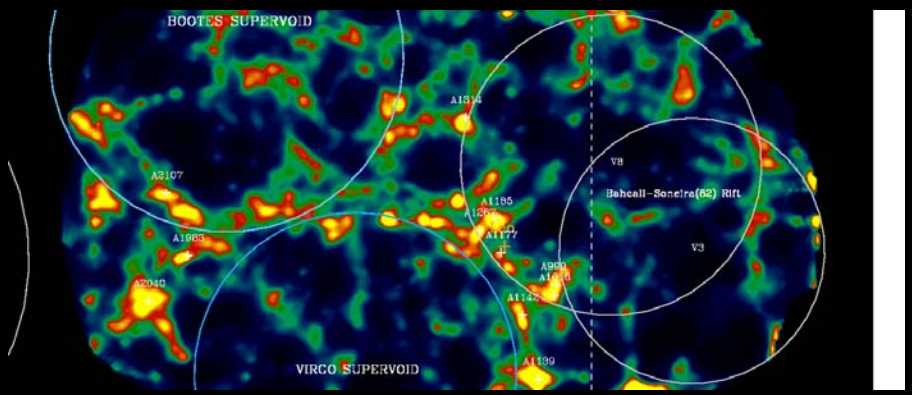
Fairall Void Catalogue

6dF based catalogue

of 526 visually identified voids.

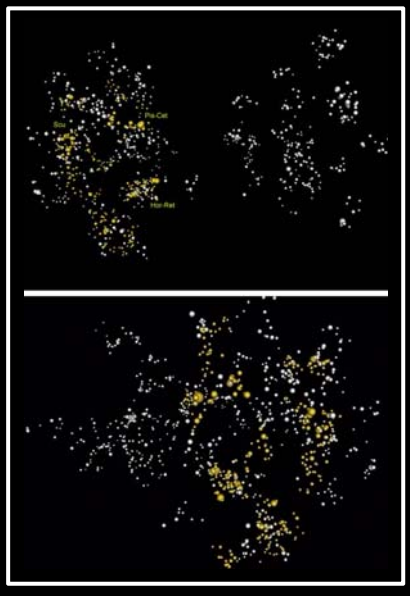


Bootes Void: Substructure



Platen et al. 2009

Voids & Clusters



Einasto, Saar et al. (1990s)

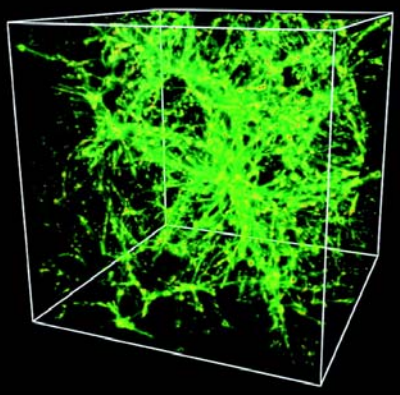
- Superclustering in Abell/APM clusters catalog

- 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

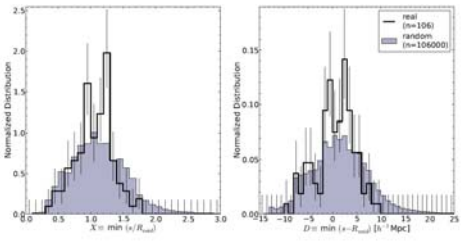
(see talk by Collins).

Voids & the Gaseous Web

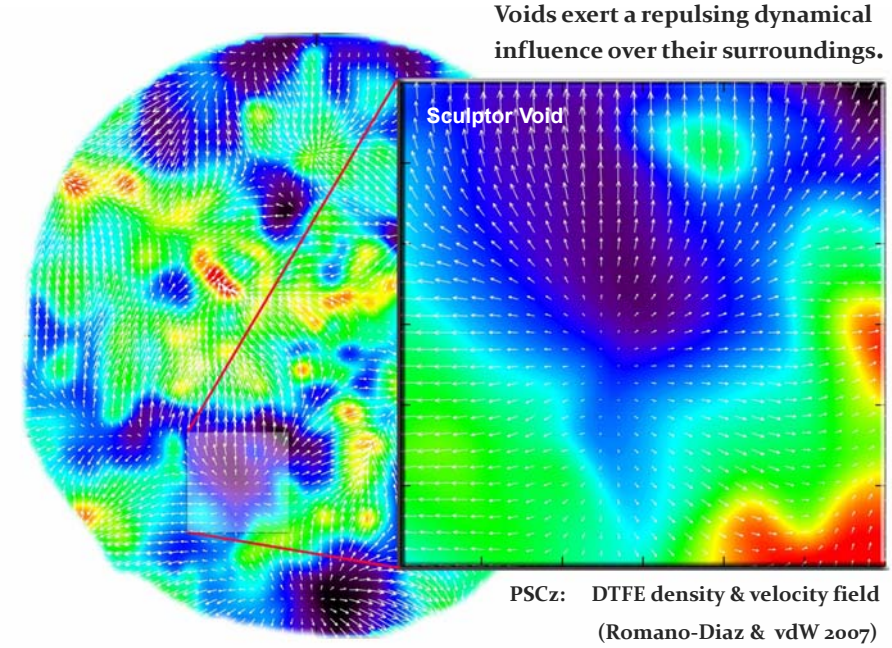


Tejos et al. 2012:

HI Lyα absorption systems clearly delineate voids

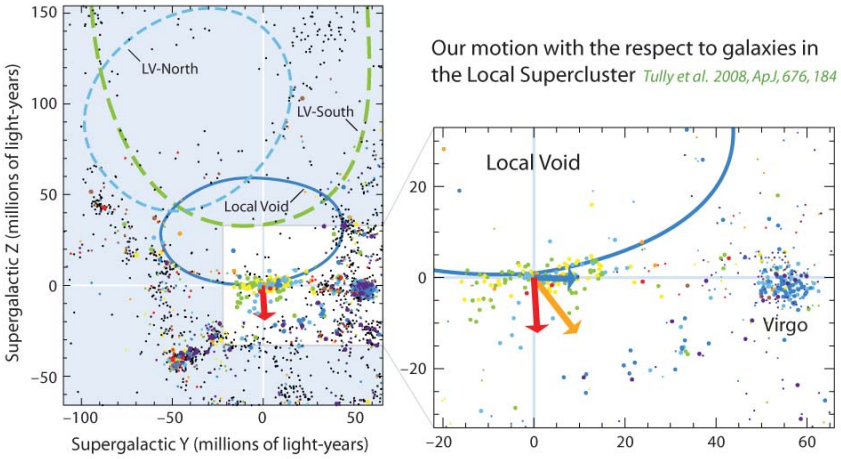


Voids exert a repulsing dynamical influence over their surroundings.



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

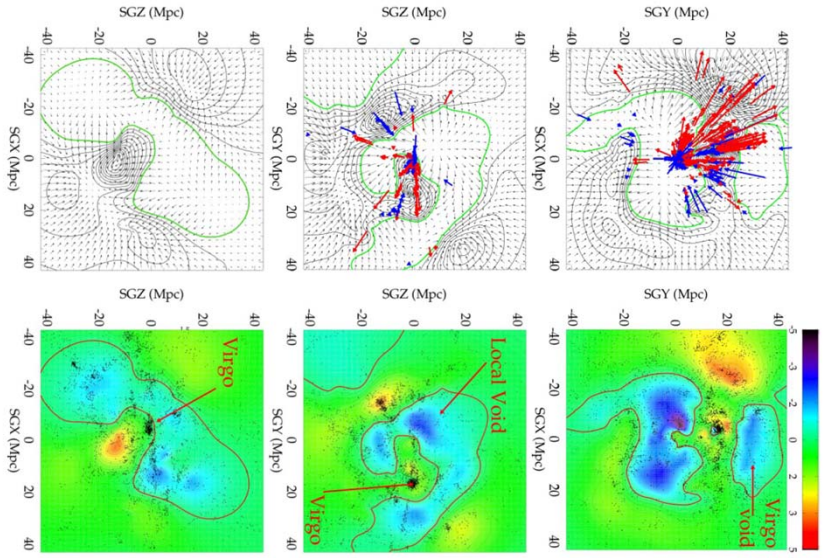
Push of the Local Void



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 ~260 km/s against our local neighbourhood

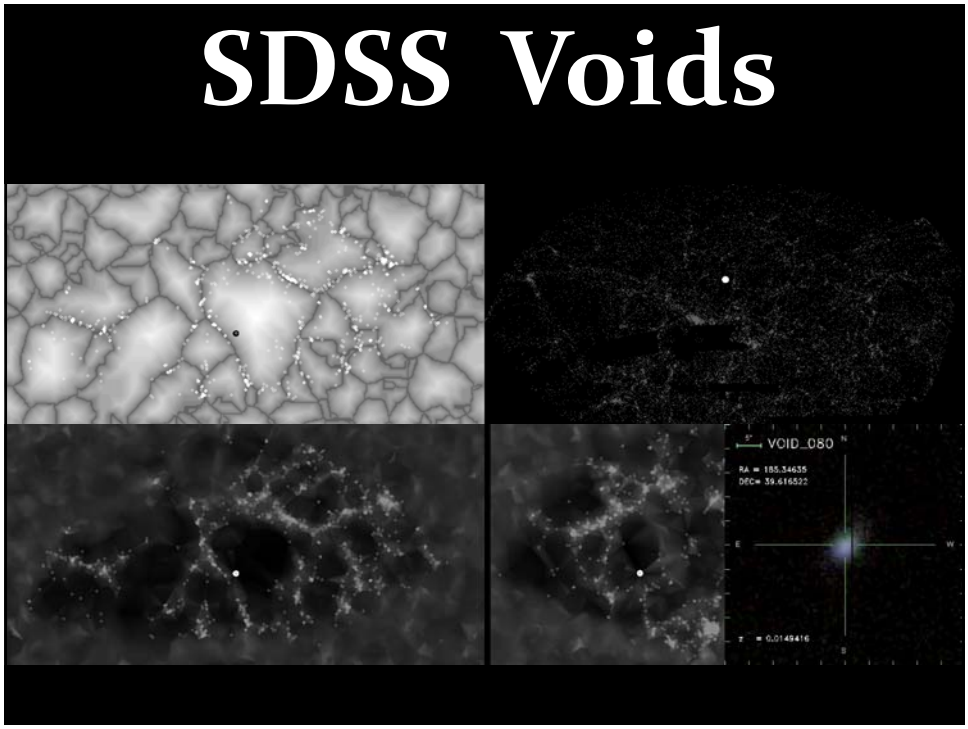
Void Dynamics: Local Void

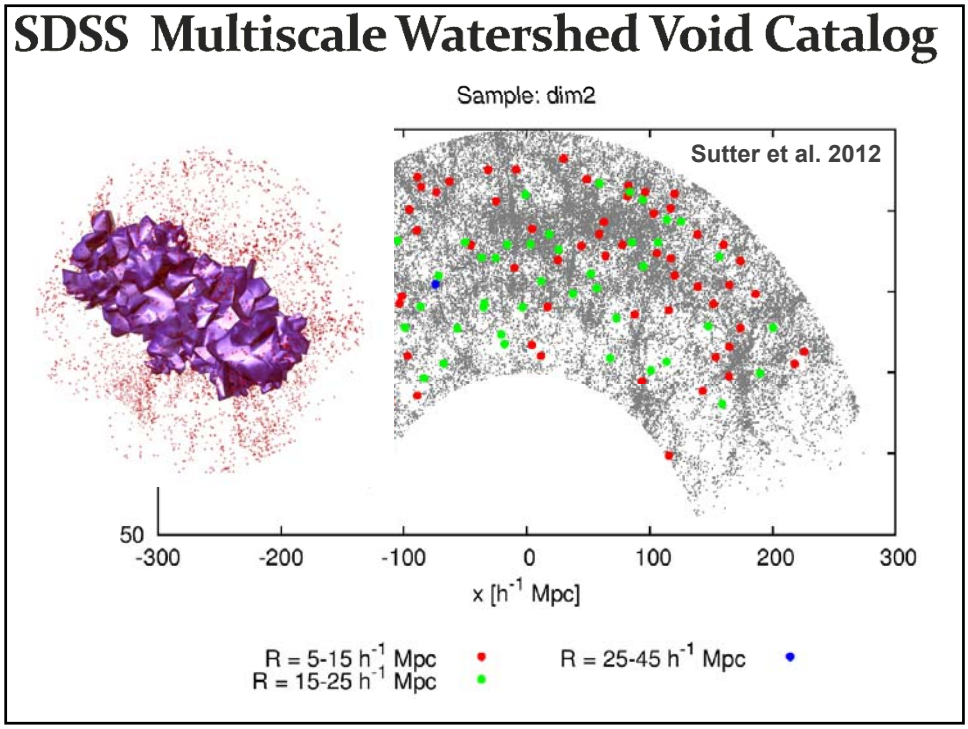


Voids: Identification & Catalogues

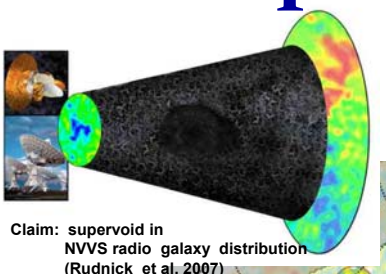
- Voids are not easily defined
  not as cleanly & objectively identifiable objects as clusters
- range of criteria & identifiers,
  often conflicting see Colberg et al. 2008
- increased interest due to cosmological/dark energy
  information contained in voids

- Catalogues:
  - Fairall 2006 by eye
  - Pan et al. 2012 Hoyle-Vogeley algorithm
  - Sutter et al. 2012 Watershed/ZOBOV multiscale


SDSS Voids
VOID_080

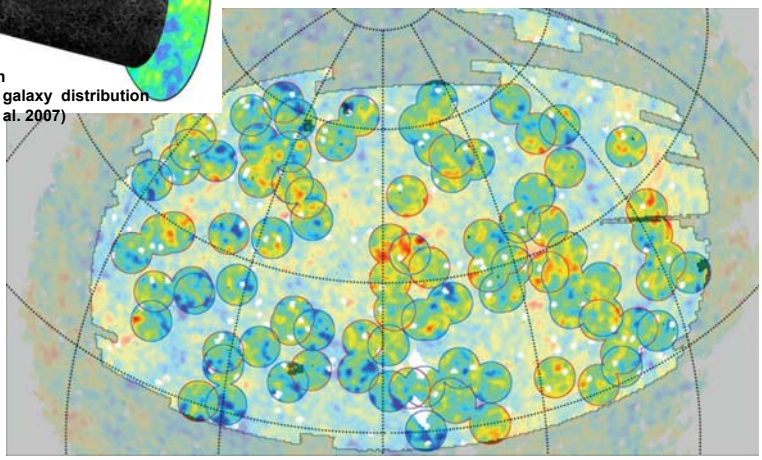

SDSS Multiscale Watershed Void Catalog
Sample: dim2
Sutter et al. 2012
50
-300
-200
-100
0
100
200
300
x [h-1 Mpc]
R = 5-15 h-1 Mpc
R = 15-25 h-1 Mpc
R = 25-45 h-1 Mpc

Supervoids ???



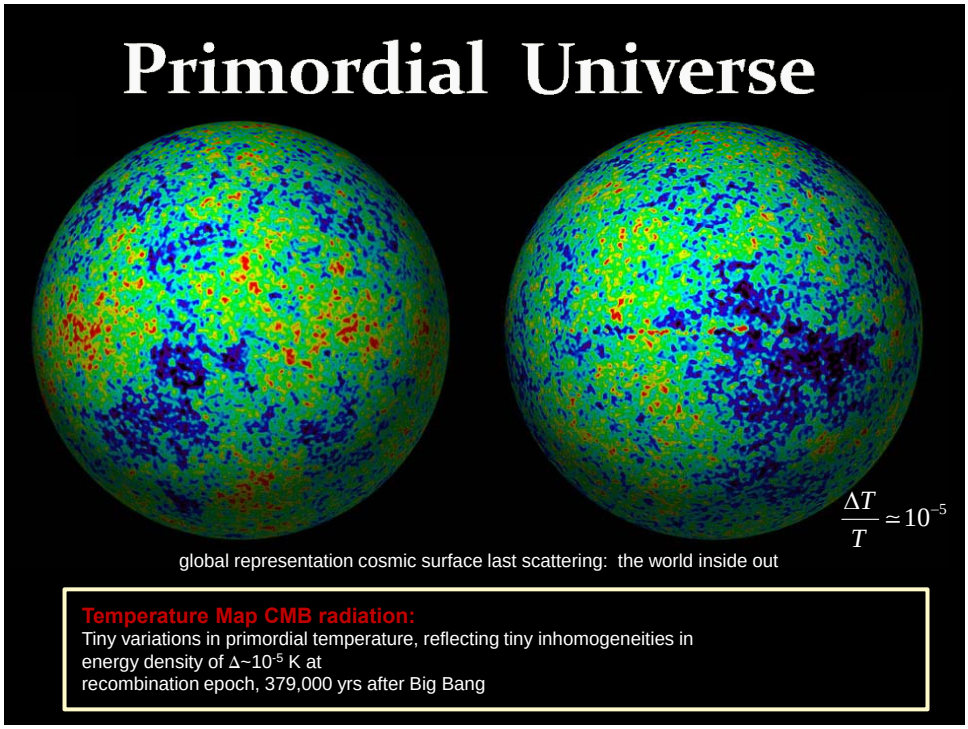
Claim: supervoid in NVVS radio galaxy distribution (Rudnick et al. 2007)

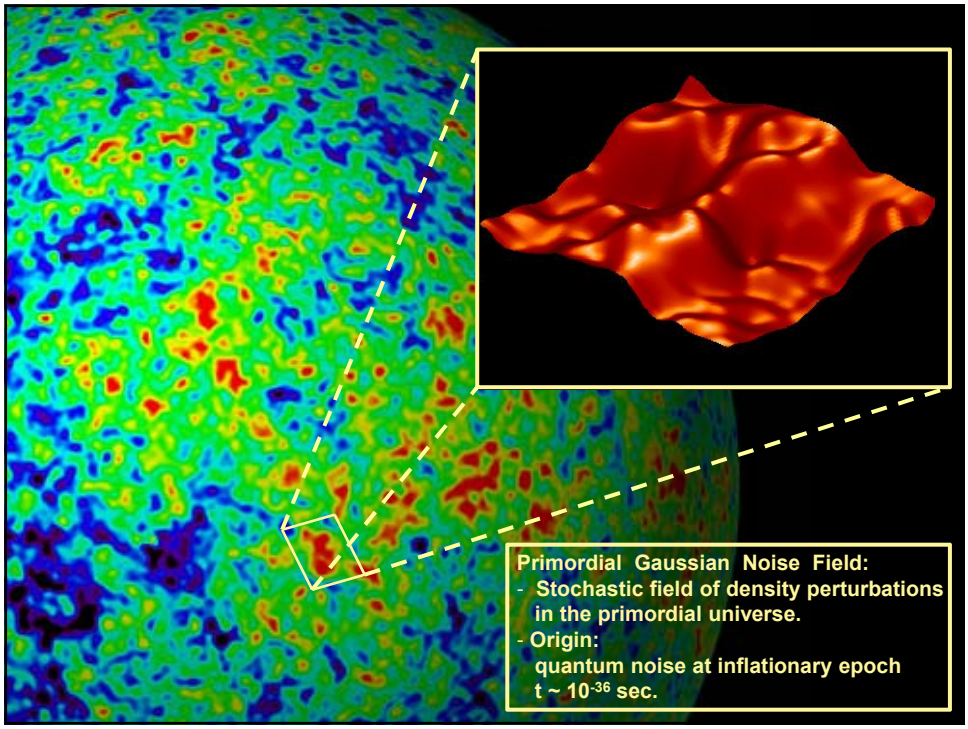
Survey possible supervoids by Granett et al.



Cosmic Structure Formation:

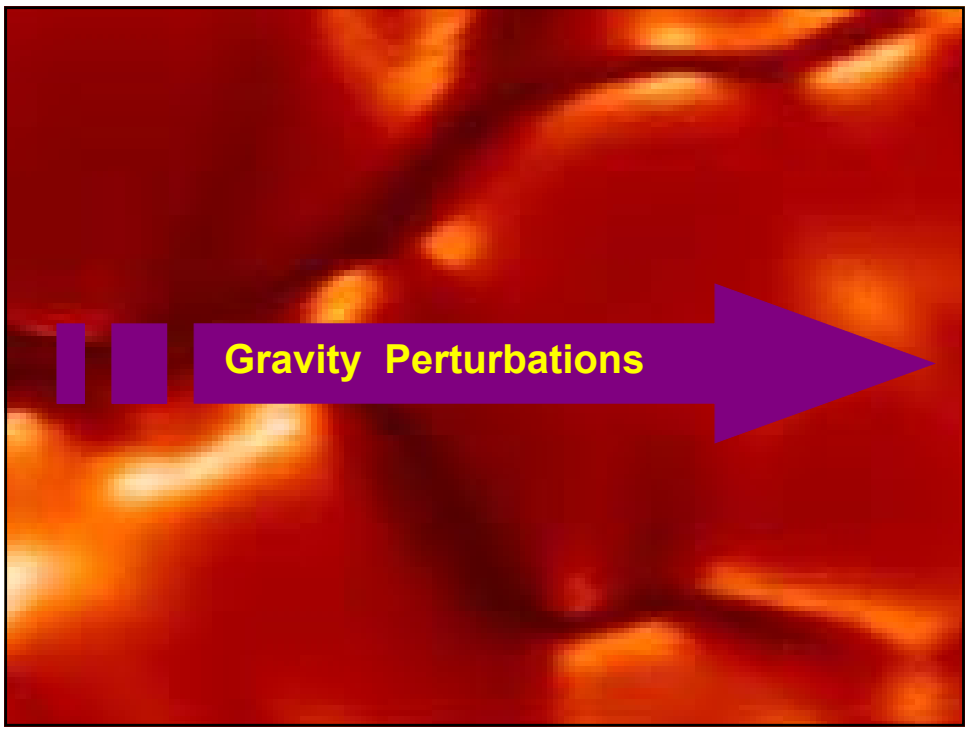
Gravitational Instability

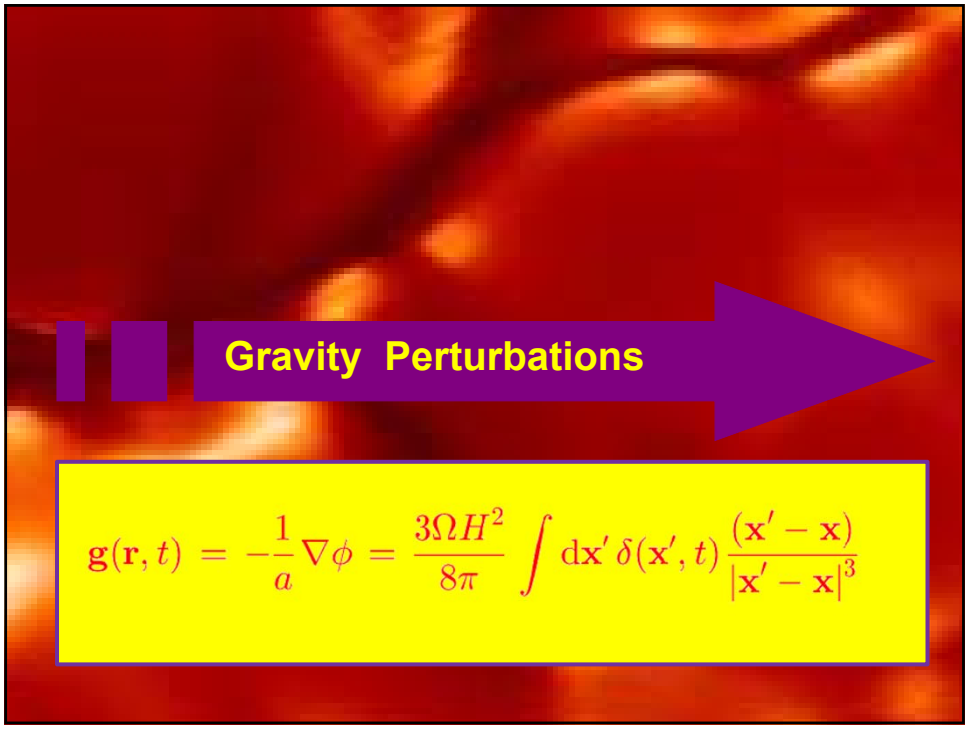

Primordial Universe
$\frac{\Delta T}{T} \simeq 10^{-5}$
global representation cosmic surface last scattering: the world inside out
Temperature Map CMB radiation:
Tiny variations in primordial temperature, reflecting tiny inhomogeneities in energy density of Δ~10-5 K at recombination epoch, 379,000 yrs after Big Bang

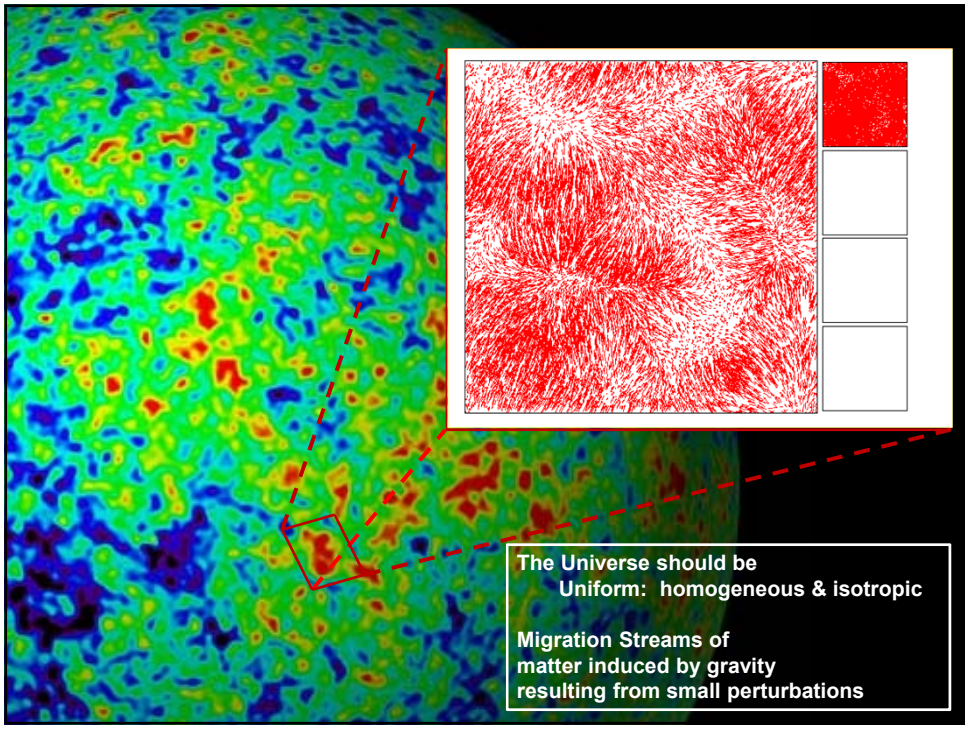

Primordial Gaussian Noise Field:
- Stochastic field of density perturbations in the primordial universe.
- Origin:
quantum noise at inflationary epoch
t ~ 10-36 sec.

Density Perturbation Field:

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




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


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

Cosmic Structure Formation

(Energy) Density Perturbations

↓

Gravity Perturbations

↓

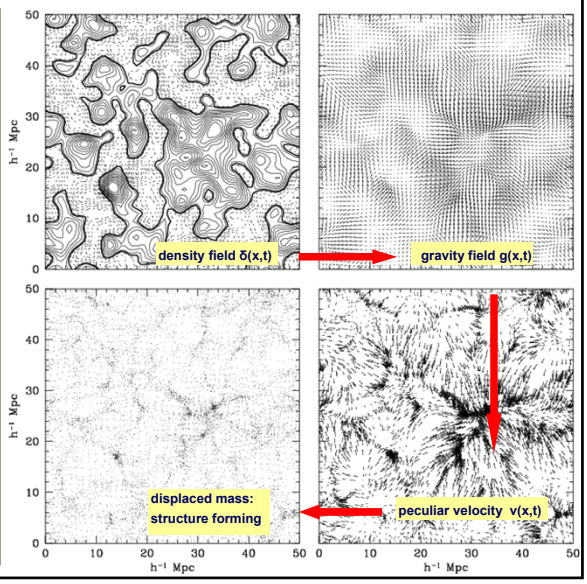
(Cosmic) Flows of (Energy) & Matter:

- towards high density regions:
  - assemble more and more matter
  - their expansion comes to a halt
  - turn around and collapse
- evacuating void regions
  - low-density regions expand
  - matter moves out of region
  - turn into prominent empty voids

↓

Emergence of cosmic structures

- Computer Simulations
  - succesfull confrontation with observational reality



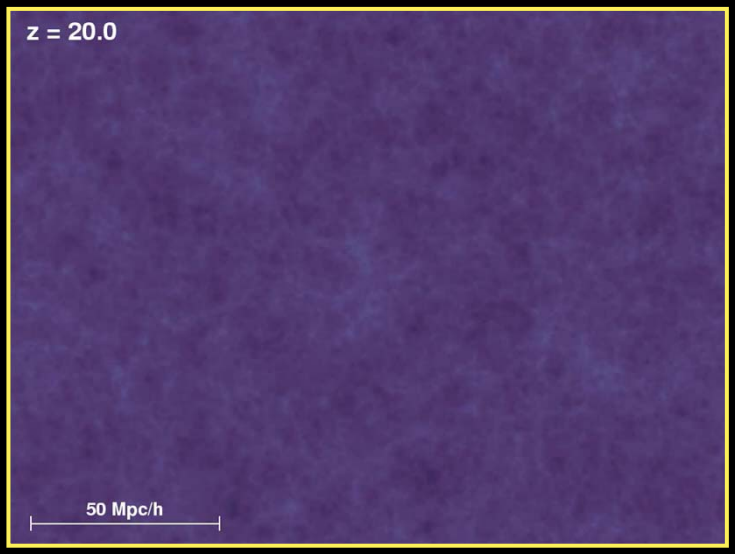
Cosmic Structure Formation

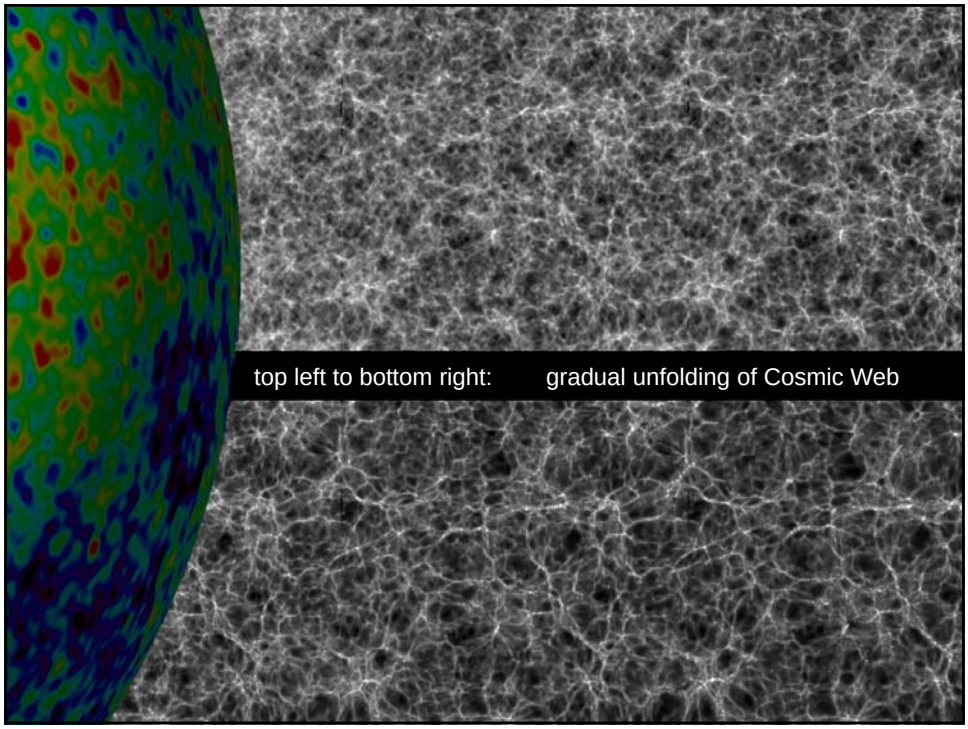
Formation Cosmic Web:

simulation sequence

(cold) dark matter

(courtesy: Virgo/V. Springel).



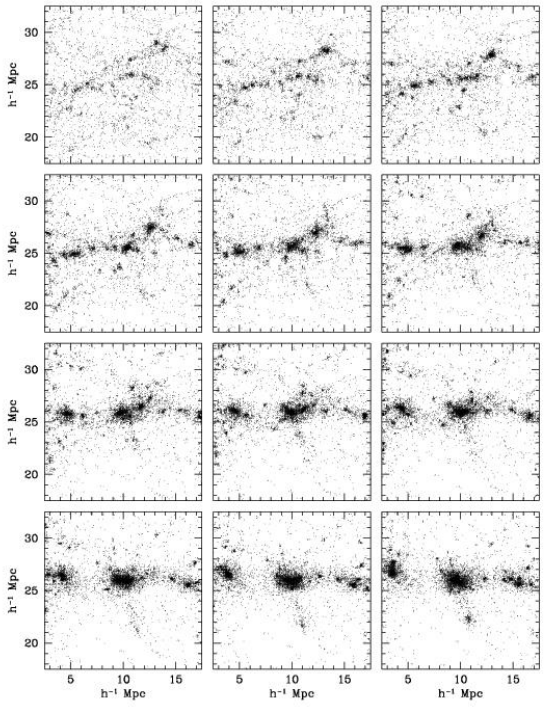


Dynamical Evolution Cosmic Web

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

Structures in the Universe form
by
gradual hierarchical assembly:

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



Voids:

Formation & Structure

Void Formation

Void Evolution

an illustration

cosmology:

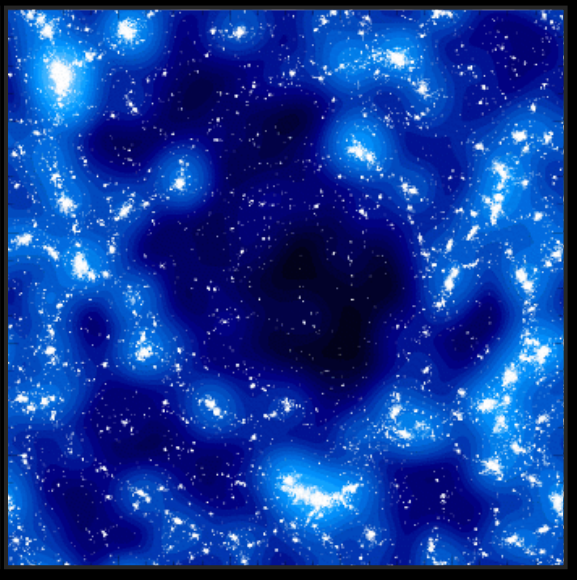
$\Omega_m = 1.0; \quad H_0 = 70 \ km/s/Mpc$

initial conditions:

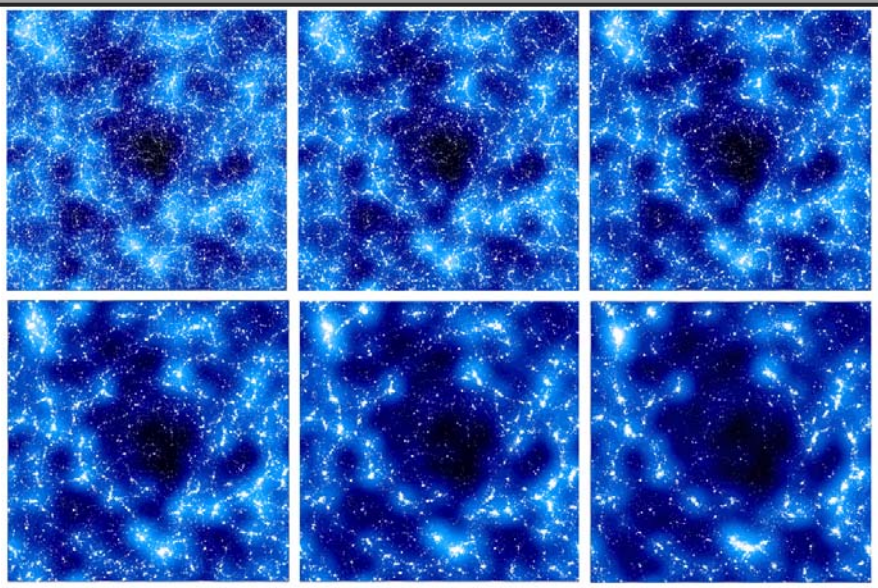
underdensity, Gaussian field

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

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



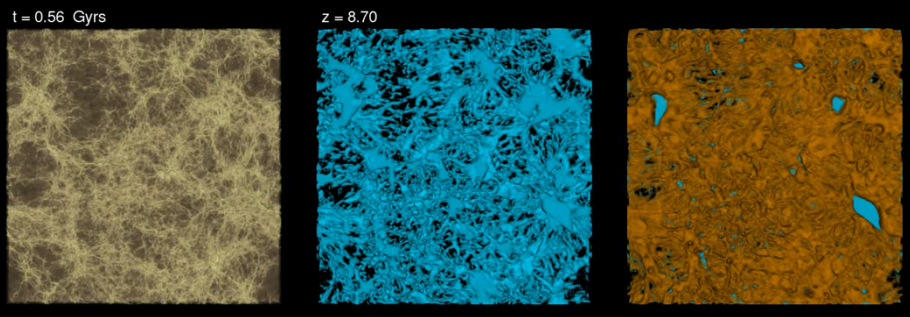
Void Formation



Multiscale Cosmic Web:

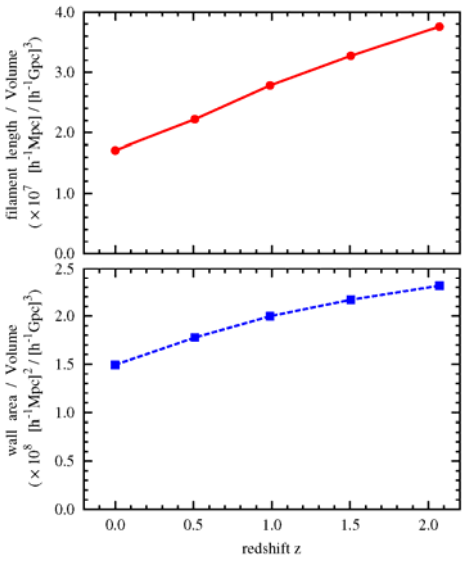
hierarchical evolution

NEXUS/MMF Evolution Cosmic Web



Cautun et al. 2013

Evolving Filament & Wall Network



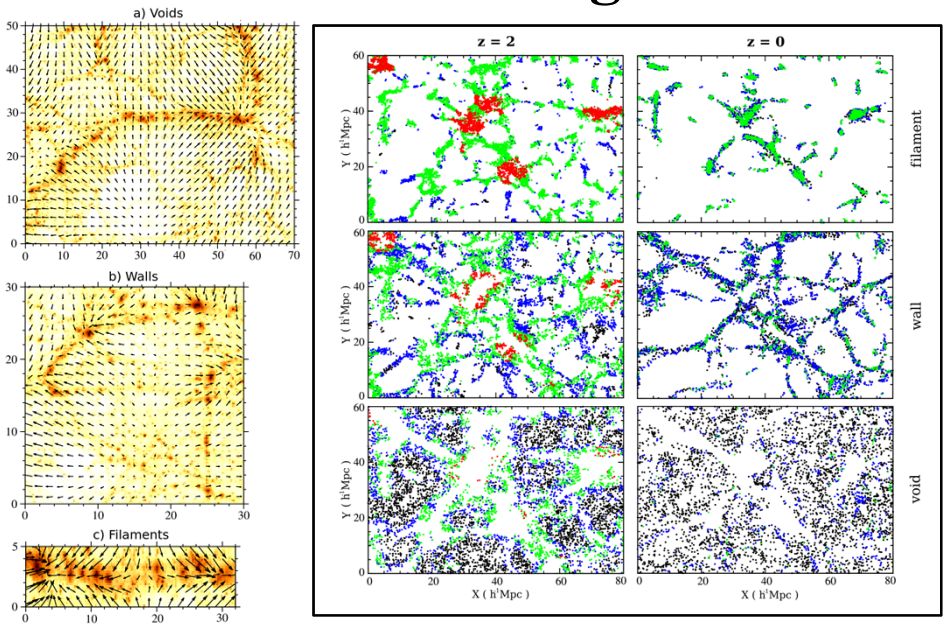
Total length of filament network :

decreasing as a function of time

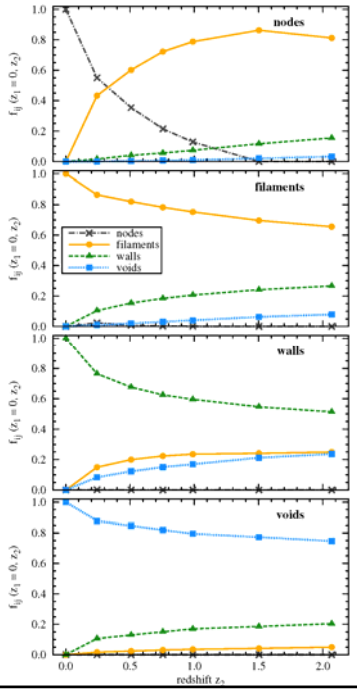
Total surface area of wall network :

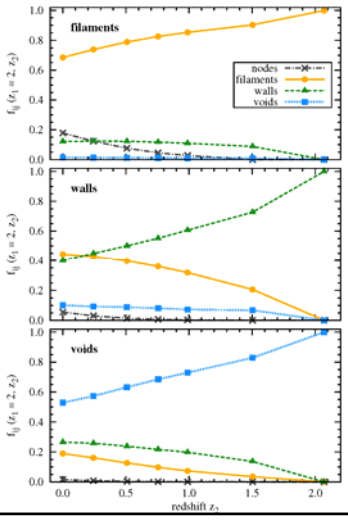
decreasing as a function of time

Web Mass Emigration



Mass Migration





CGV halo & web evolution

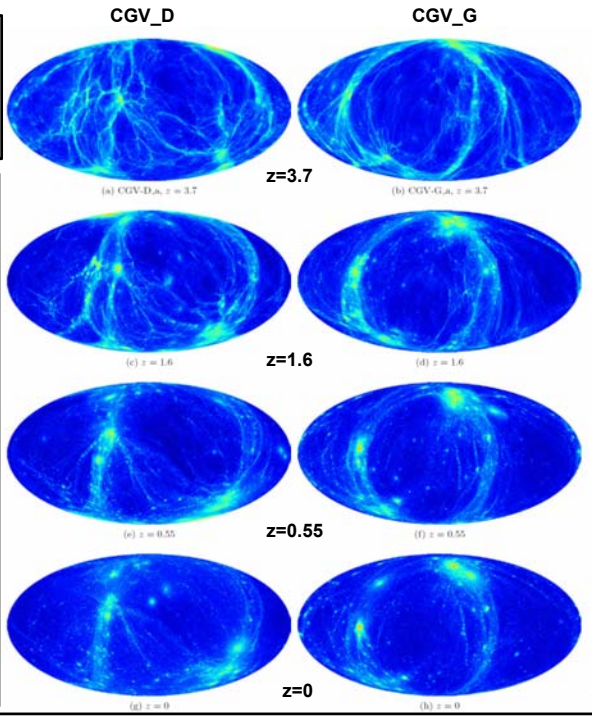
Rieder et al. 2013

CGV:

on walls & filaments

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

Rieder et al. 2013



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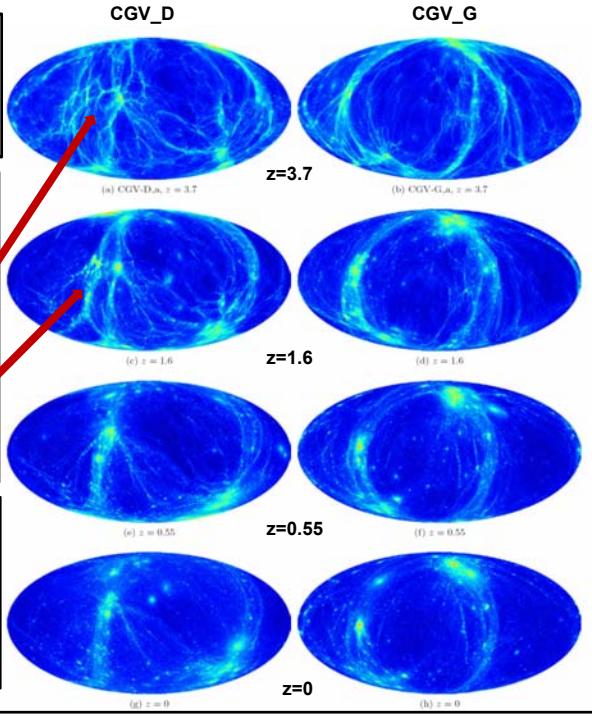
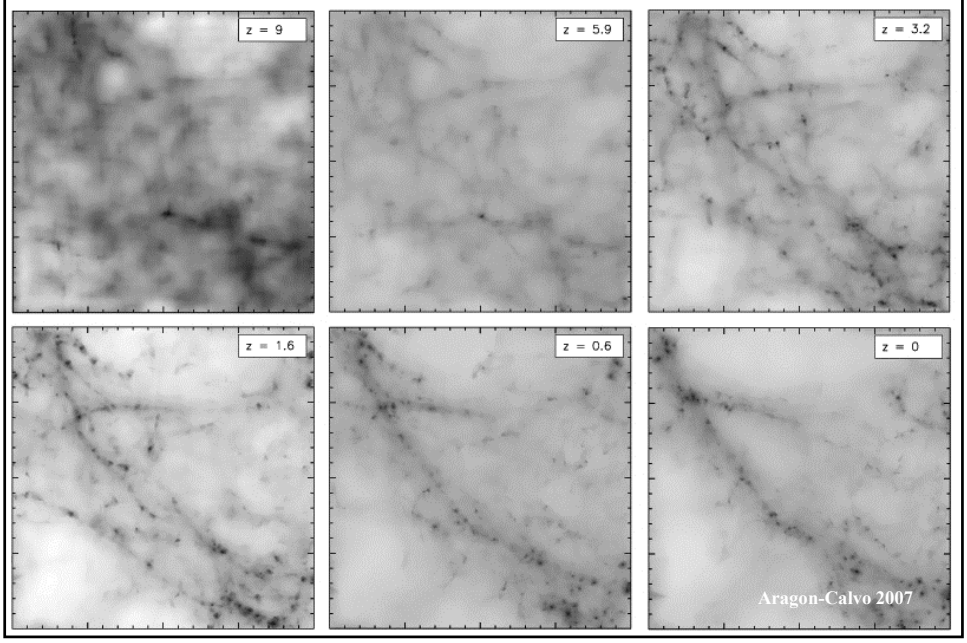
merging system of Intravoid walls



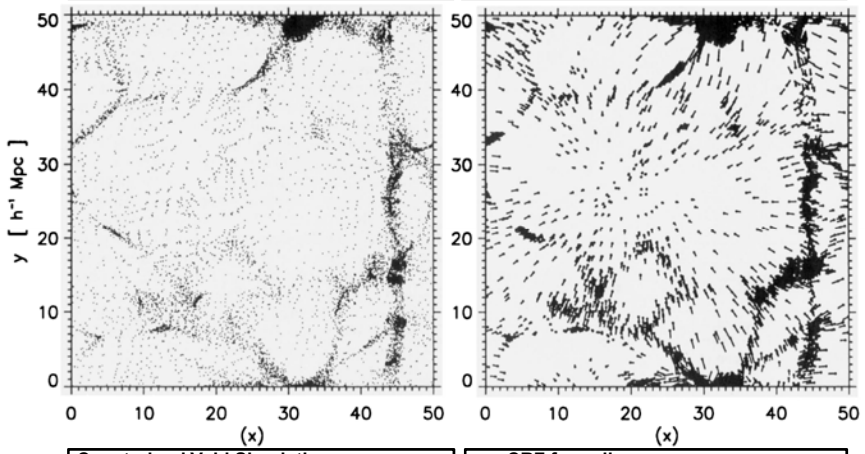
Hierarchical Filament Formation



Void Hierarchy

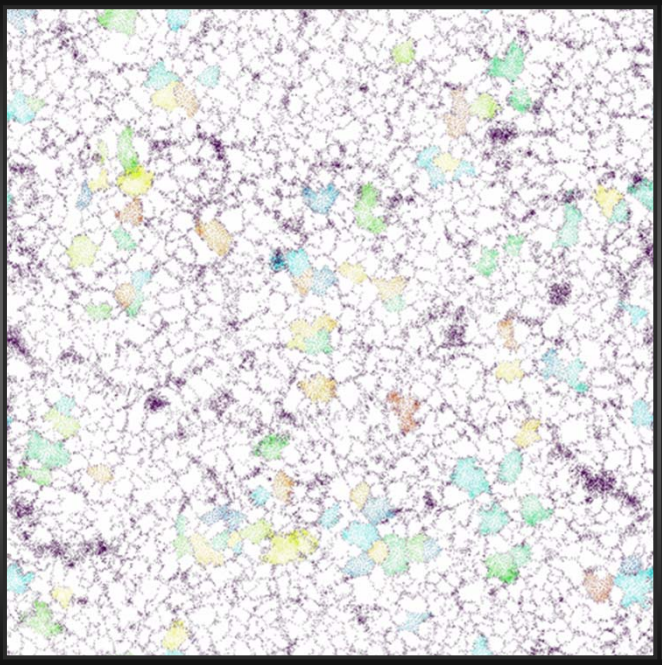
Void formation: - via gradual merging of voids
- demolition of small voids

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



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

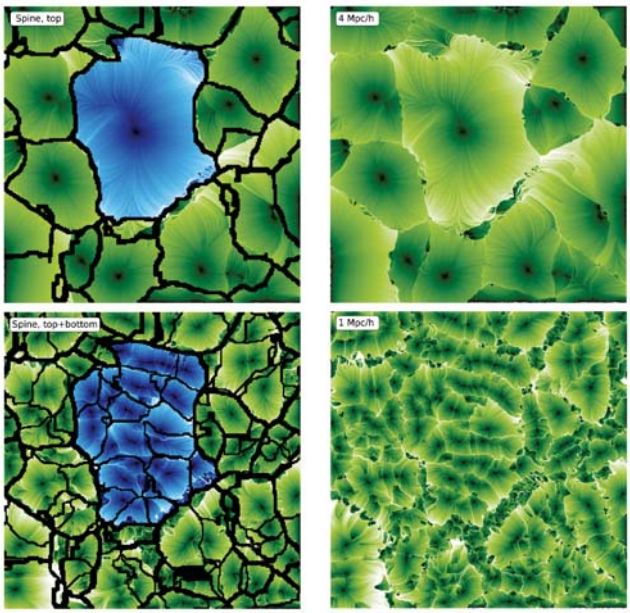
CRF formalism:
Bertschinger 1987
vdW & Bertschinger 1996



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

Weaving the Cosmic Web:

dynamics & tessellations

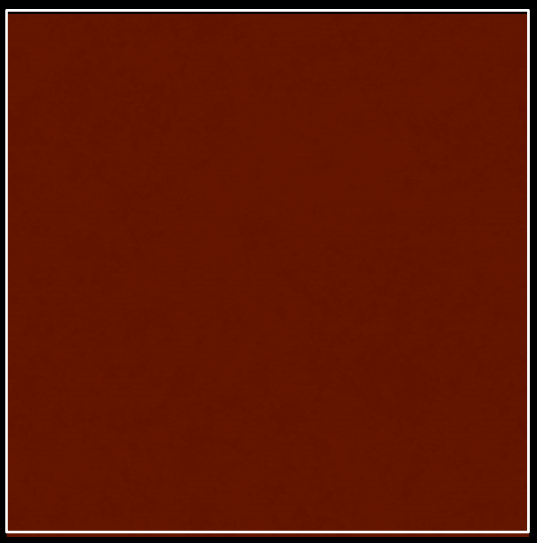
Hidding et al. 2012, Hidding et al. 2014

Zel'dovich Approximation

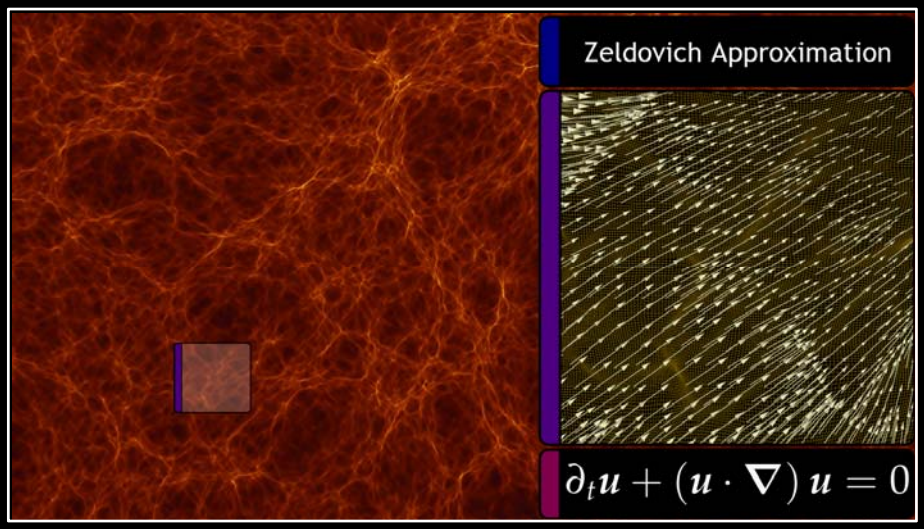
$$\vec{x} = \vec{q} + D(t)\vec{u}(\vec{q})$$

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

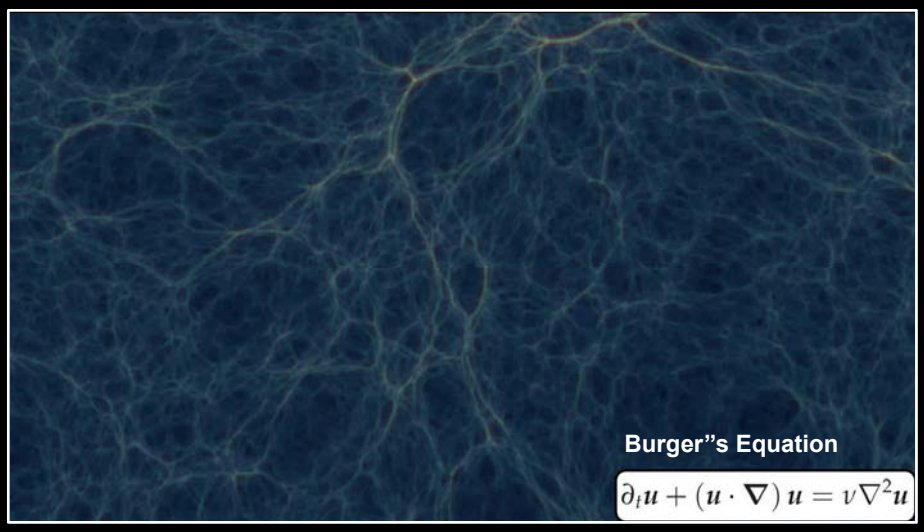
$$\Phi(\vec{q}) = \frac{2}{3Da^2H^2\Omega}\phi_{lin}(\vec{q})$$



Zel'dovich Approximation

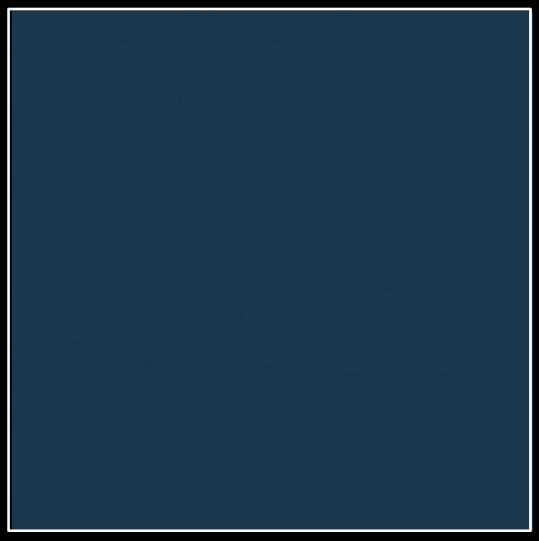


Adhesion Approximation



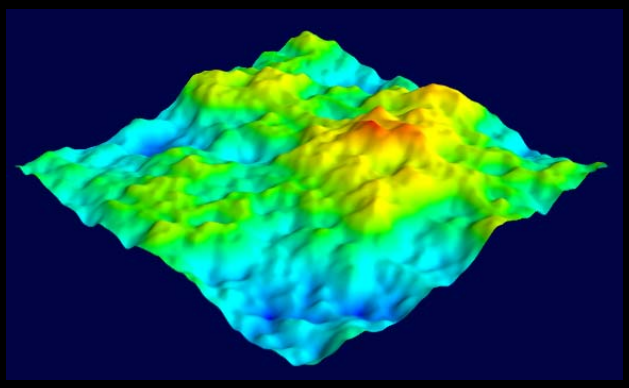
Adhesion Approximation

Gurbatov, Saichev & Shandarin 1987



Hidding 2012

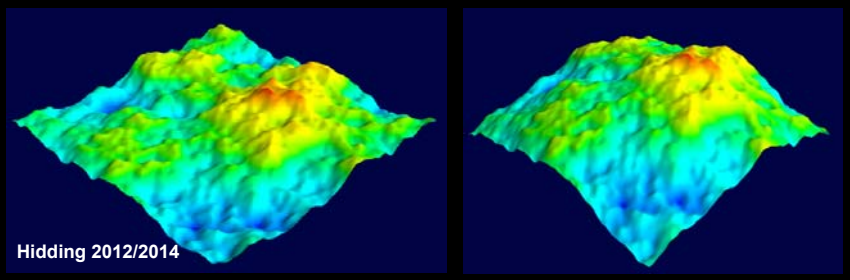
Velocity & Gravity Potential



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

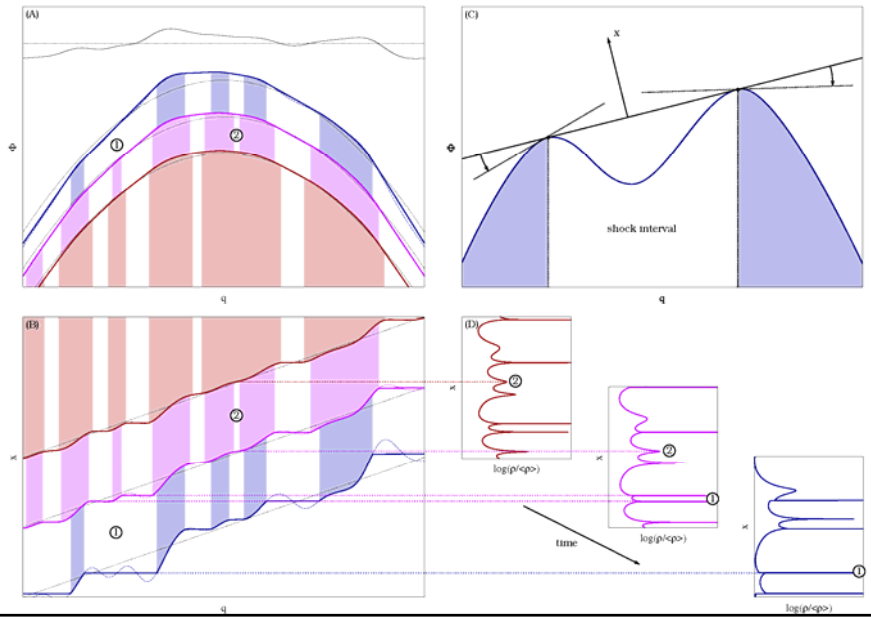
Burger's Equation: Hopf Solution

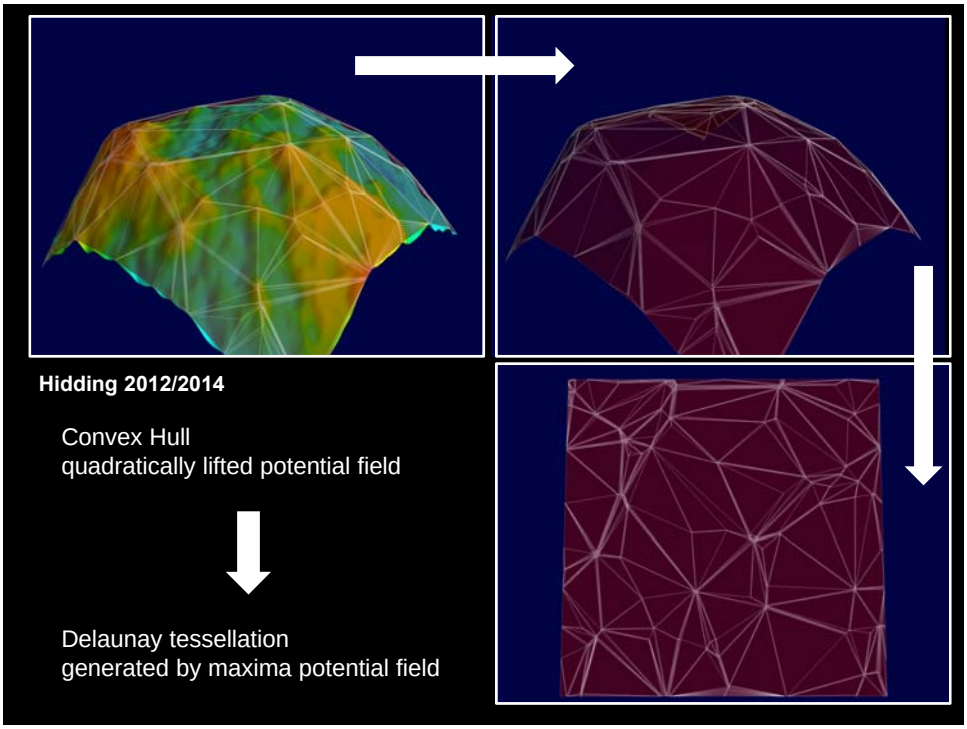
$$\frac{\partial \vec{u}}{\partial t} + \left(\vec{u} \cdot \vec{\nabla}\right)\vec{u} = \nu \nabla^2 \vec{u}$$



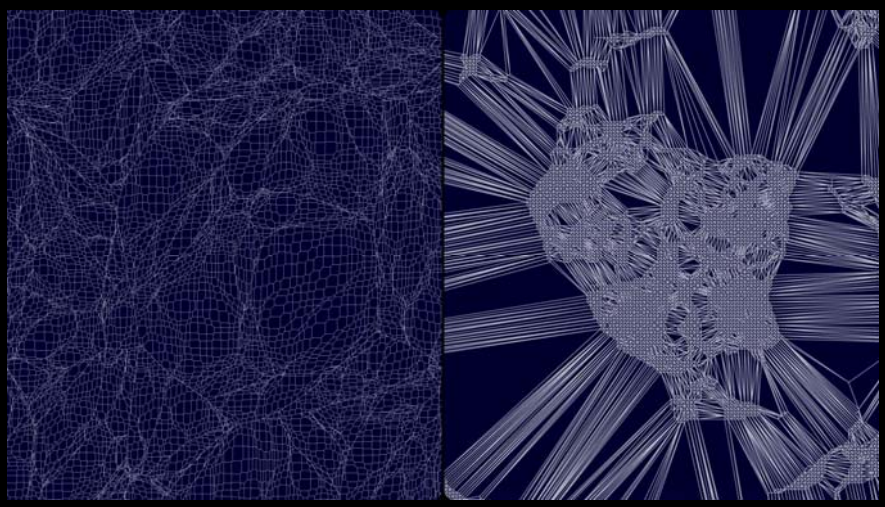
$$\Phi(\vec{x},t) + \frac{x^2}{2} = \max_q \left[\left(t\Phi_0(q) - \frac{q^2}{2} \right) + \vec{x} \cdot \vec{q} \right]$$

Burger's Equation: Hopf Solution





Eulerian – Lagrangian
Voronoi - Delaunay

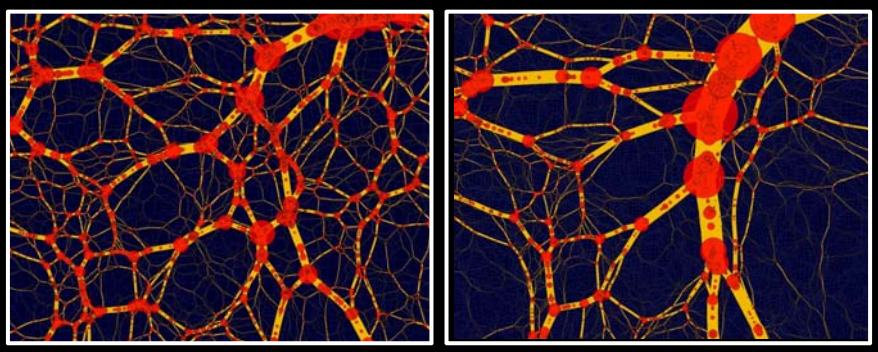


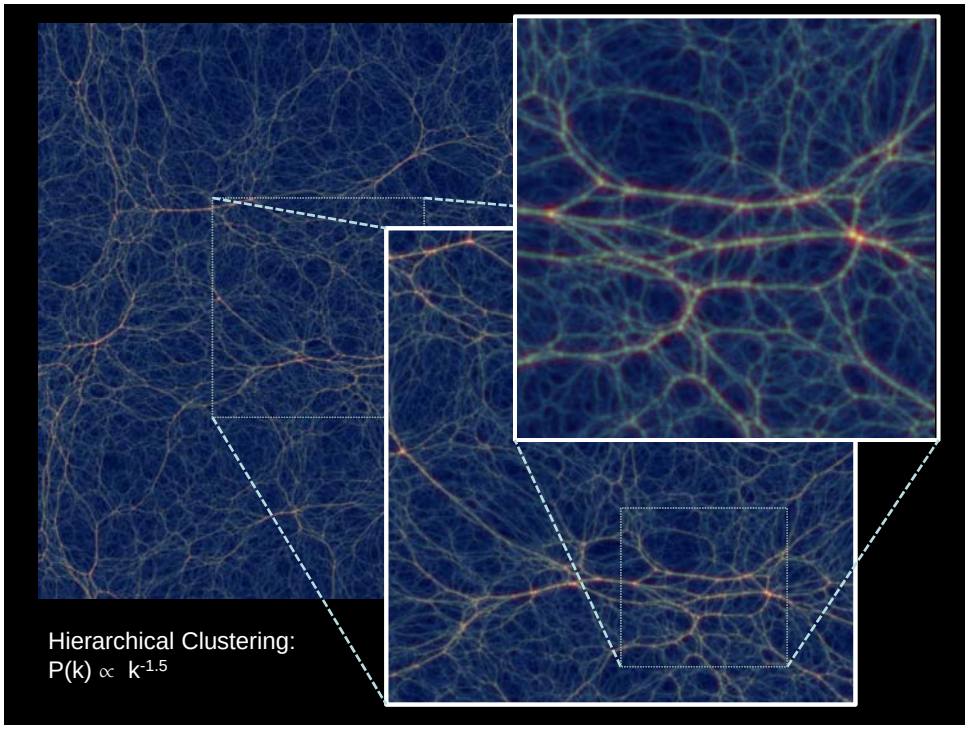
Eulerian – Lagrangian
Voronoi - Delaunay

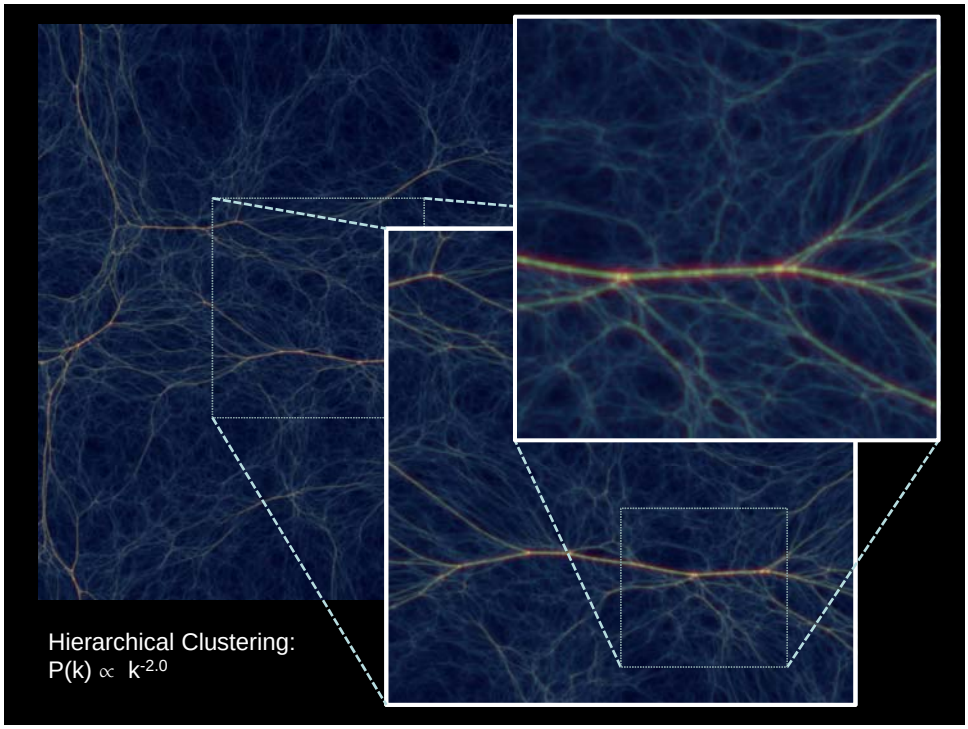
Cosmological Sensitivity

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

$P(k) \propto k^{-1.5}$ **Hidding 2012/2014** $P(k) \propto k^{-2.0}$

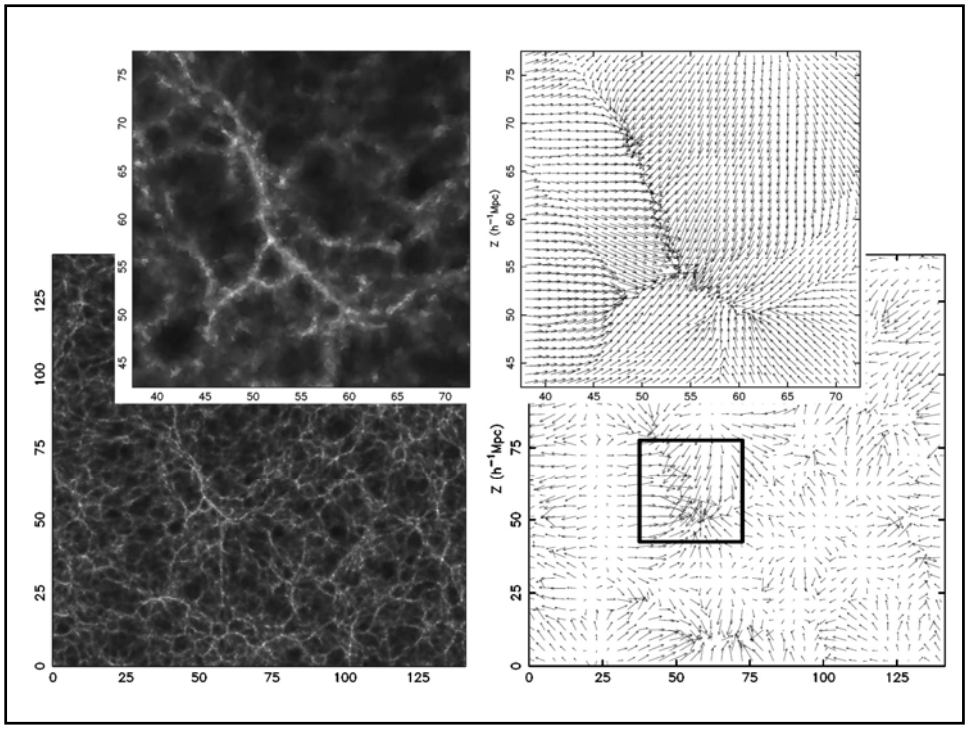



Hierarchical Clustering:
P(k) ∝ k-1.5

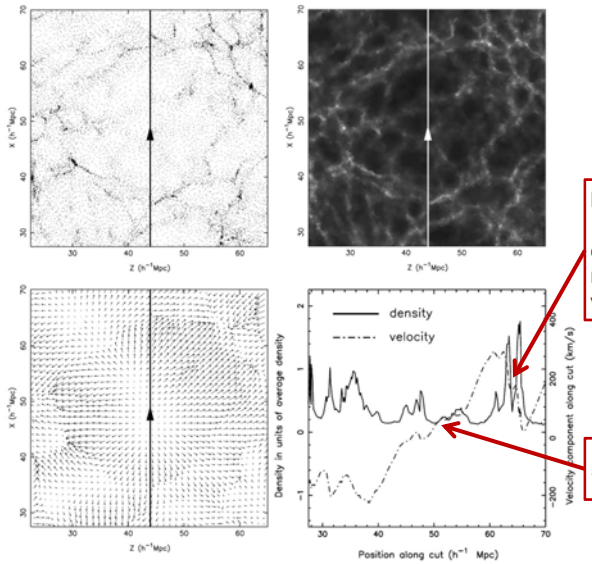

Hierarchical Clustering:
P(k) ∝ k-2.0

Cosmic Web:

Dynamics



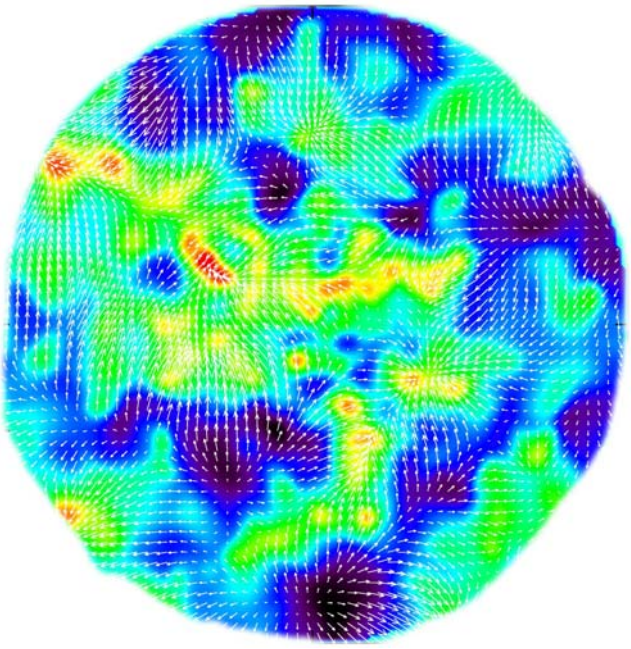
Void Velocity Flow Field



Filament/Wall:

counterflow neighbouring void

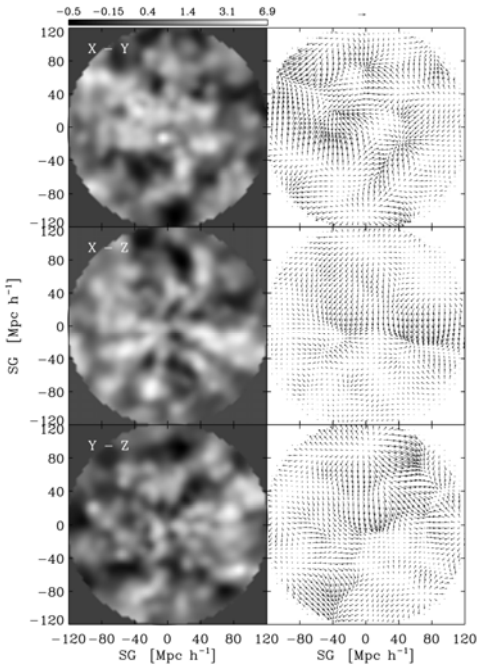
Superhubble Void Flow



Density Field
Velocity Field

superposition

- Flow throughout the volume restored
- Restored velocities volume-weighted
- Shot-noise suppressed
- assumption: no shell-crossing

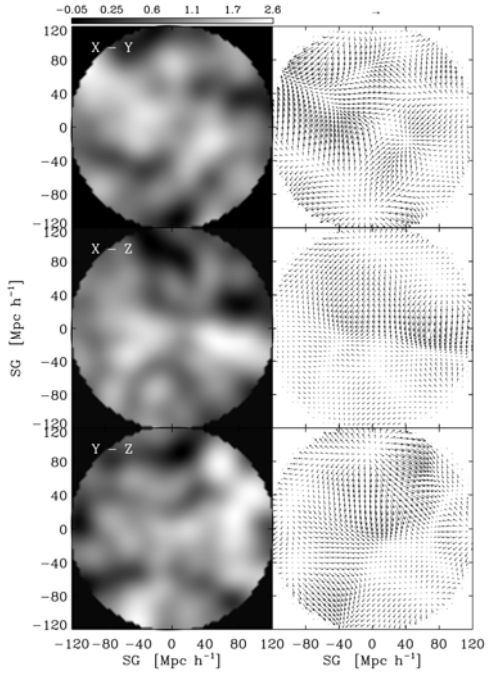


Density Field

&

Velocity Vector Field

Resolution:
R_G=3.8h^{-1} Mpc



Density Field

&

Velocity Vector Field

Resolution:
R_G=12.0h^{-1} Mpc

Phase-Space Dynamics Cosmic Web:

the Phase-Space Sheet

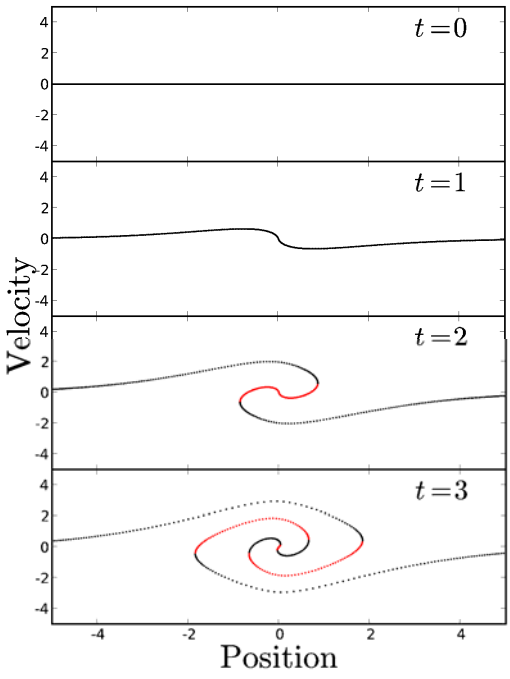
Phase Space Evolution

Dark Matter Phase Space sheet:

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

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

Evolving matter distribution in position-velocity space – 1D



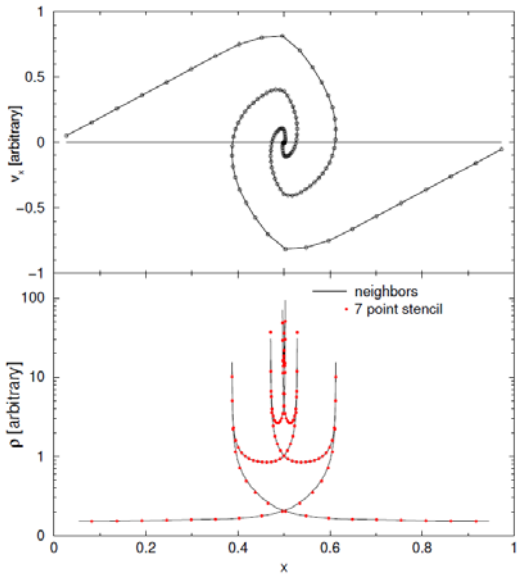
Phase Space Evolution

Phase space:

Velocity vs. Position

Density:

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



Lagrangian-Eulerian Phase Space

To follow evolving phase-space of cosmic structure, it is sometimes insightful to consider a coordinate transformation of 6D phase-space:

Eulerian coordinates $\vec{x}$ and Eulerian coordinates $\vec{q}$ of a mass element:

$$f(\vec{x},\vec{q})$$

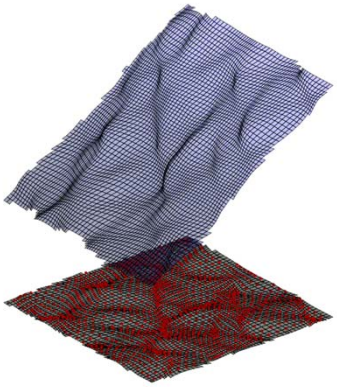
Note that in Zeldovich approximation, the velocity of a mass element is:

$$\vec{v}(\vec{q},t) = -a(t)D(t)\,f(\Omega)\;\vec{\nabla}\Phi(\vec{q})$$

Tessellation Deformation & Phase Space Projection

Translation towards Multi-D space:

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



Tessellation Deformation & Phase Space Projection

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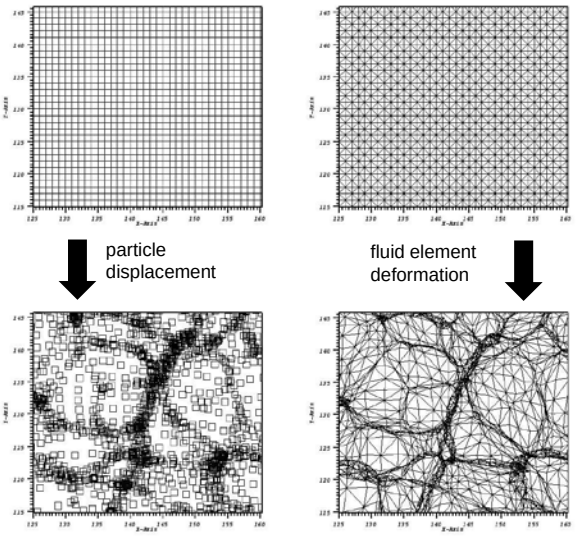
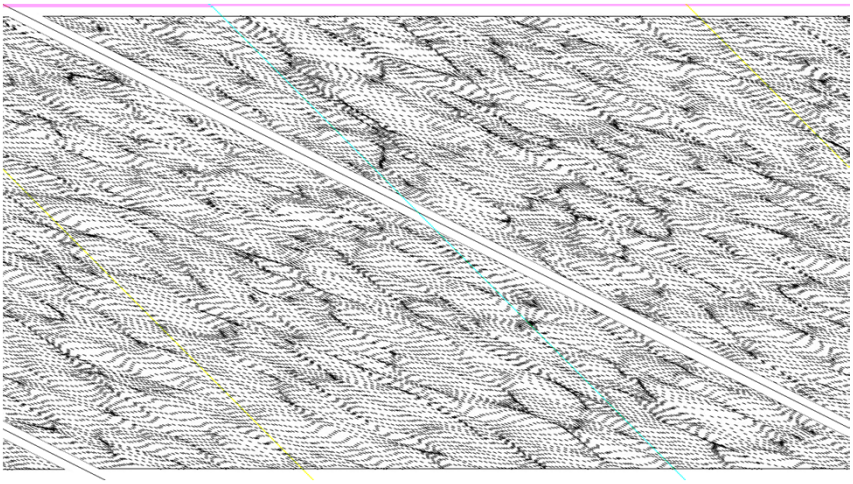


Particle Simulation



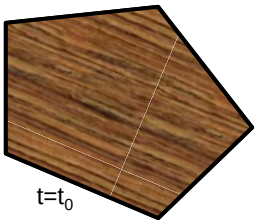
Mass Element Evolution

Tessellation Deformation & Phase Space Projection

Translation towards Multi-D space:

- Look at deformation of initial tessellation
- each tessellation cell represents matter cell
- evolution deforms cell

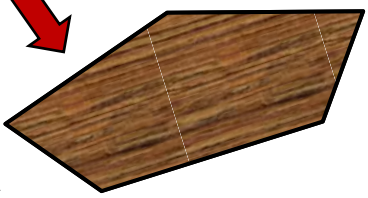
Monostream Density Evolution



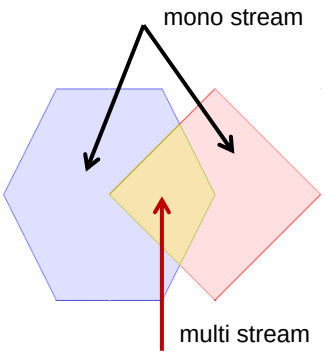
Conservation of mass (continuity eqn.):

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

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

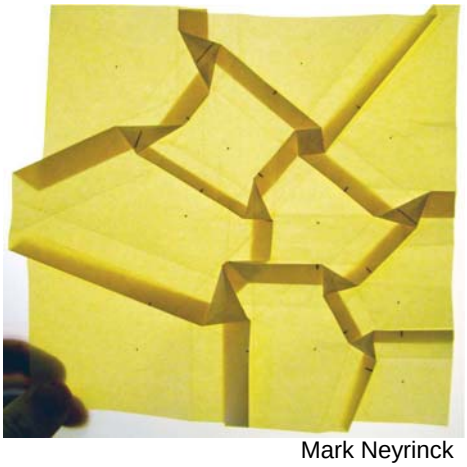


(Cosmic) ORIGAMI

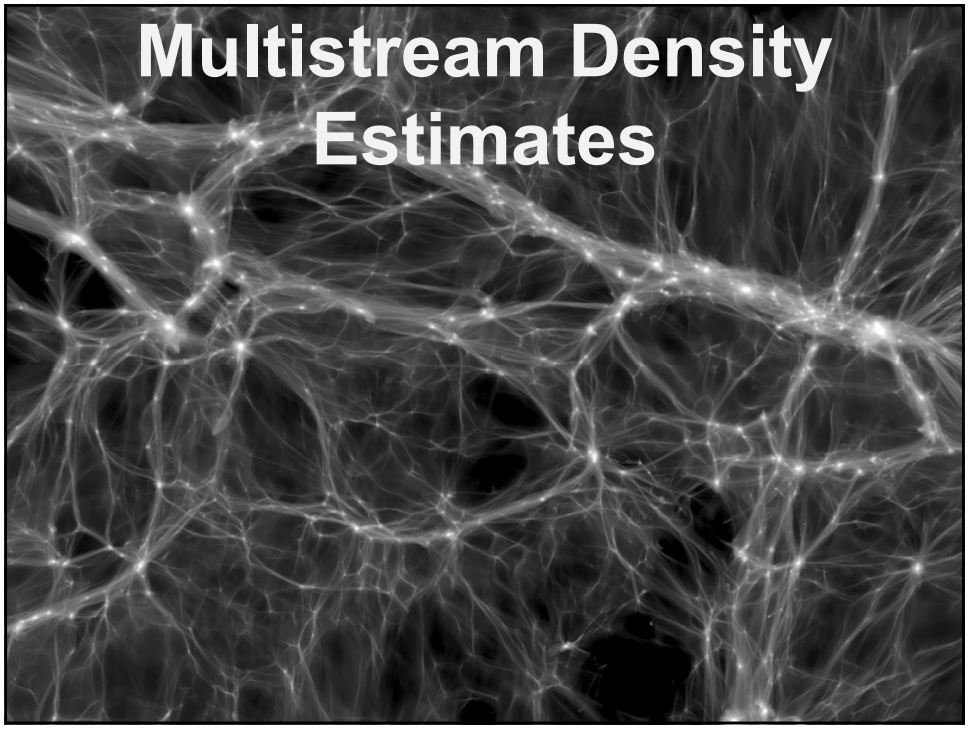


$$\rho_{total}(\vec{x},t_1) = \sum_i \frac{V_{0i}}{V_{1i}}\rho(\vec{q}_i,t_0)$$

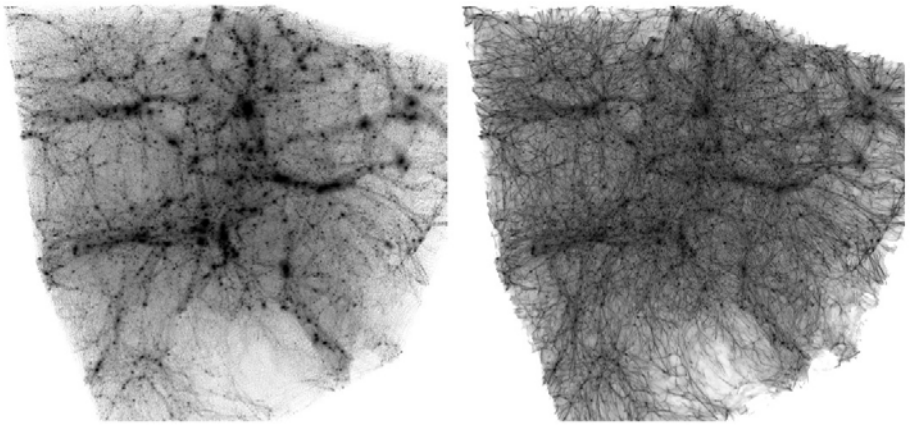
Evolution of dynamical system: Phase-space folding – Cosmic Origami



Mark Neyrinck



Multistream Density Estimates



Cosmic Web Stream Density

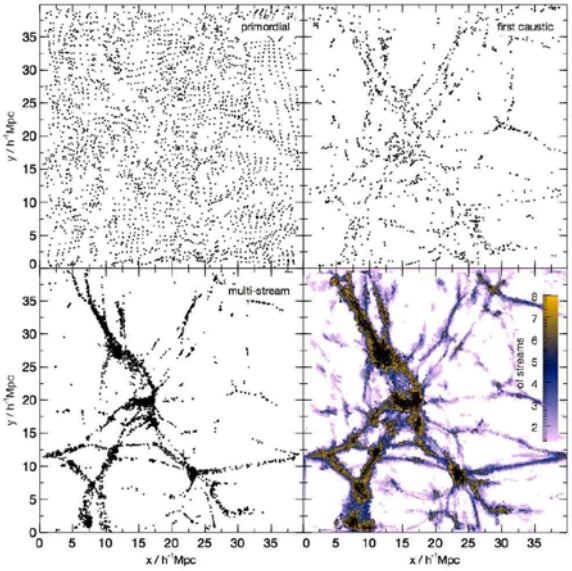
Translation towards Multi-D space:

Density of
dark matter streams:

- # phase space folds

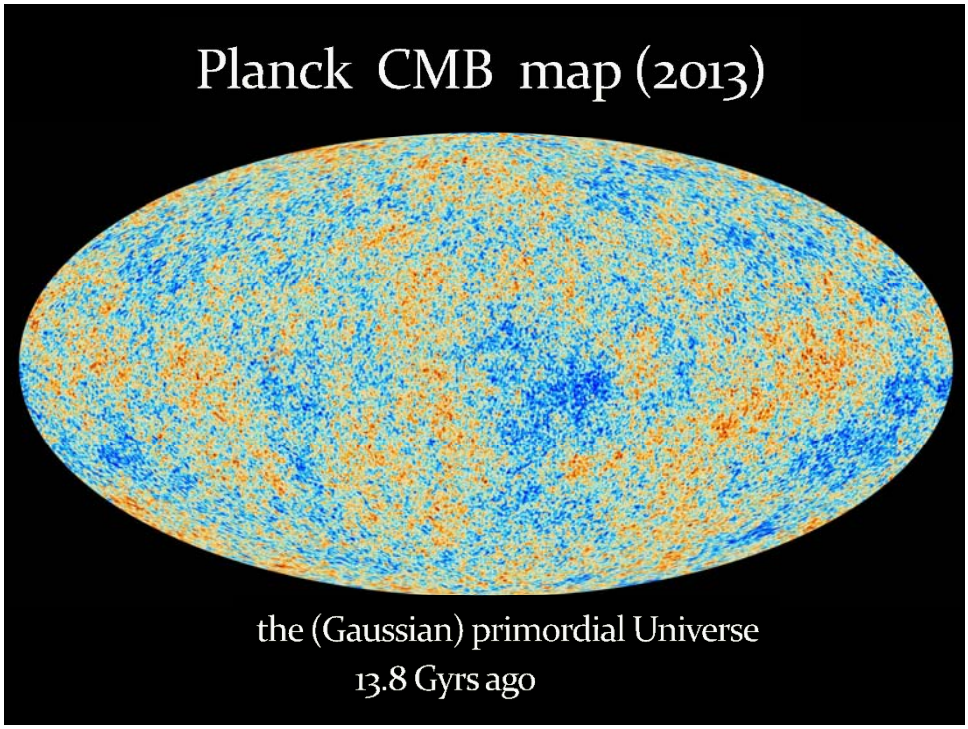
=

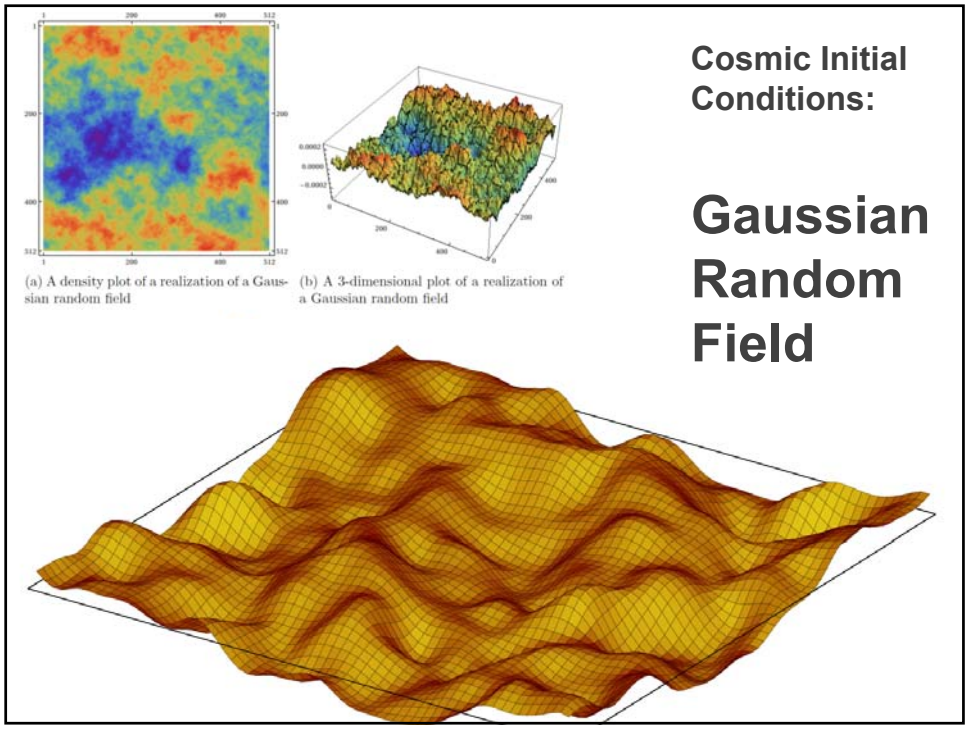
locally overlapping tessellation cells

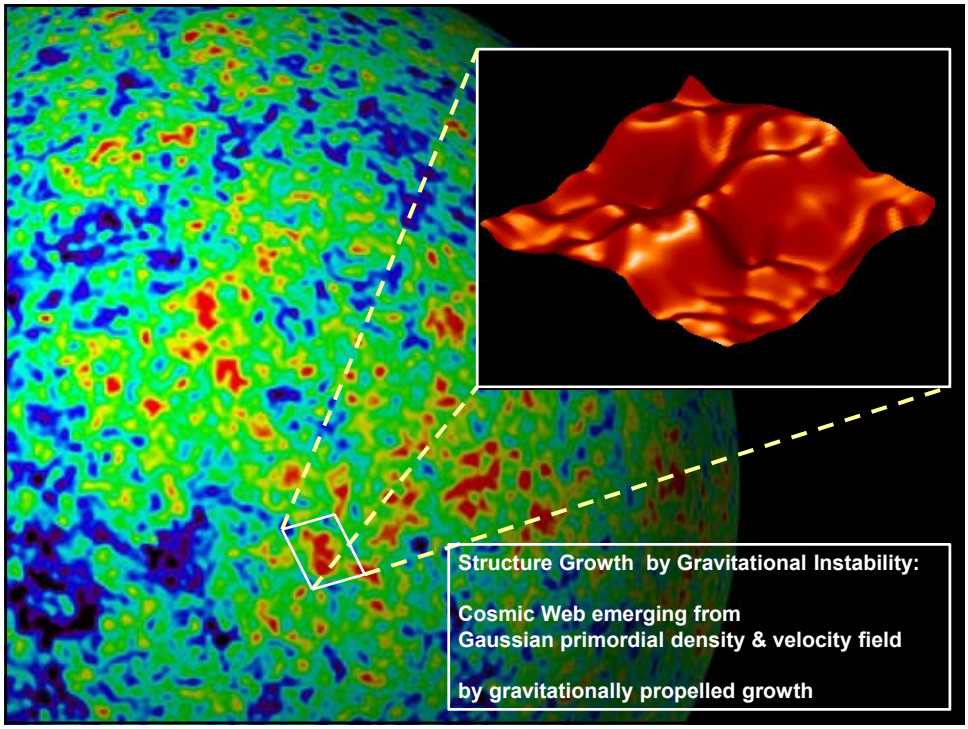


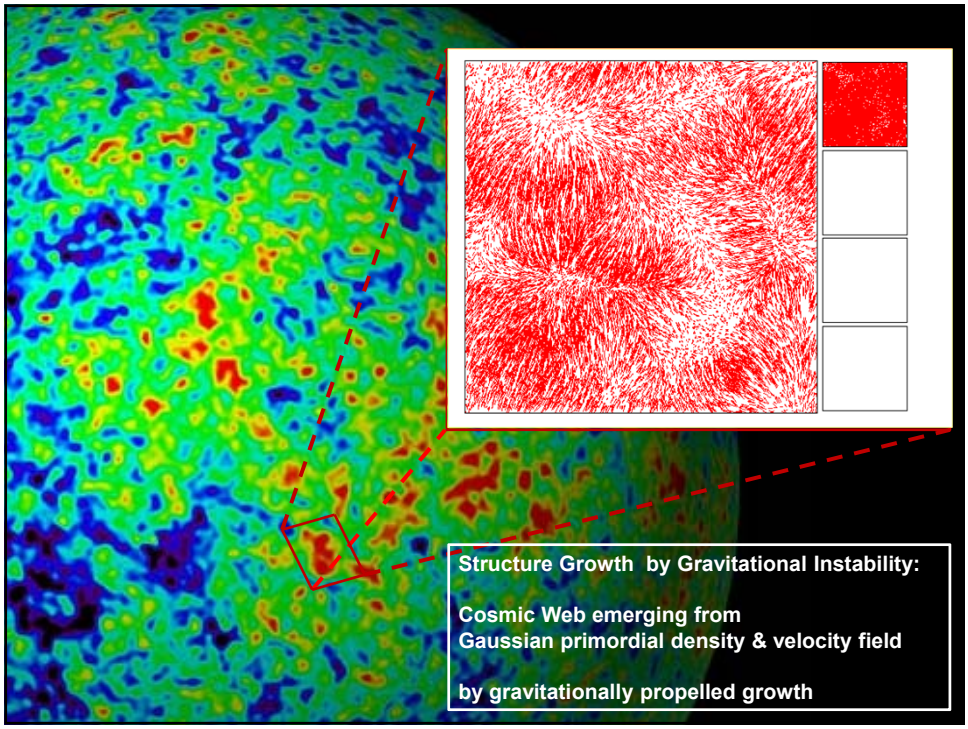
Origins:

anisotropies in CMB


Planck CMB map (2013)
the (Gaussian) primordial Universe
13.8 Gyrs ago


(a) A density plot of a realization of a Gaussian random field
(b) A 3-dimensional plot of a realization of a Gaussian random field
Cosmic Initial Conditions:
Gaussian Random Field


Structure Growth by Gravitational Instability:
Cosmic Web emerging from
Gaussian primordial density & velocity field
by gravitationally propelled growth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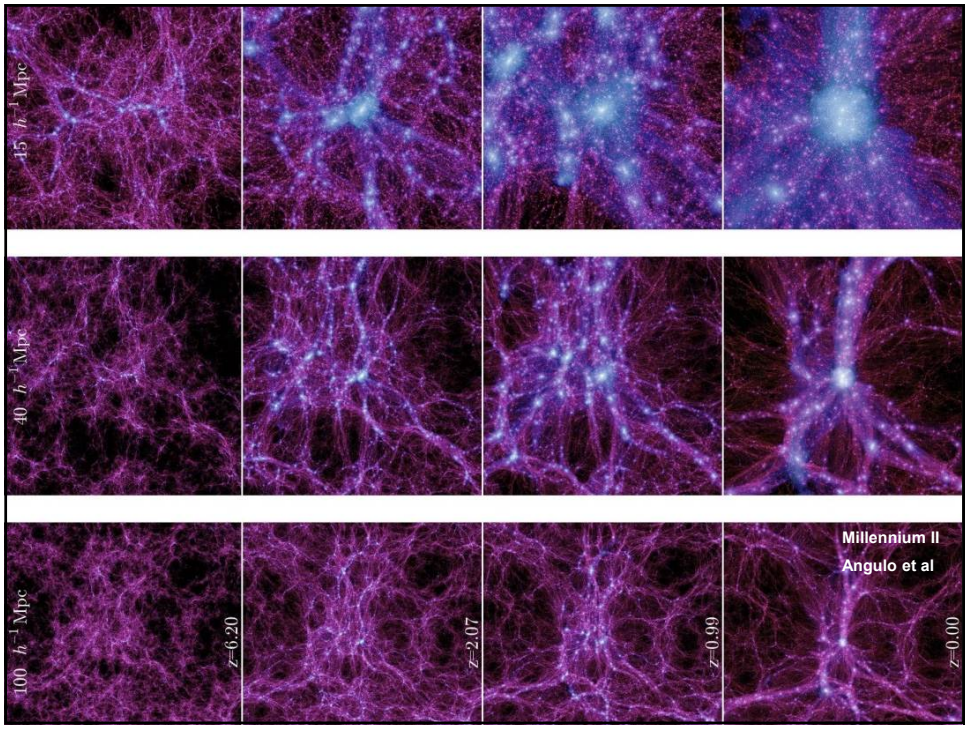
15 h^{-1}Mpc
40 h^{-1}Mpc
100 h^{-1}Mpc
z=6.20
z=2.07
z=0.99
z=0.00
Millennium II
Angulo et al