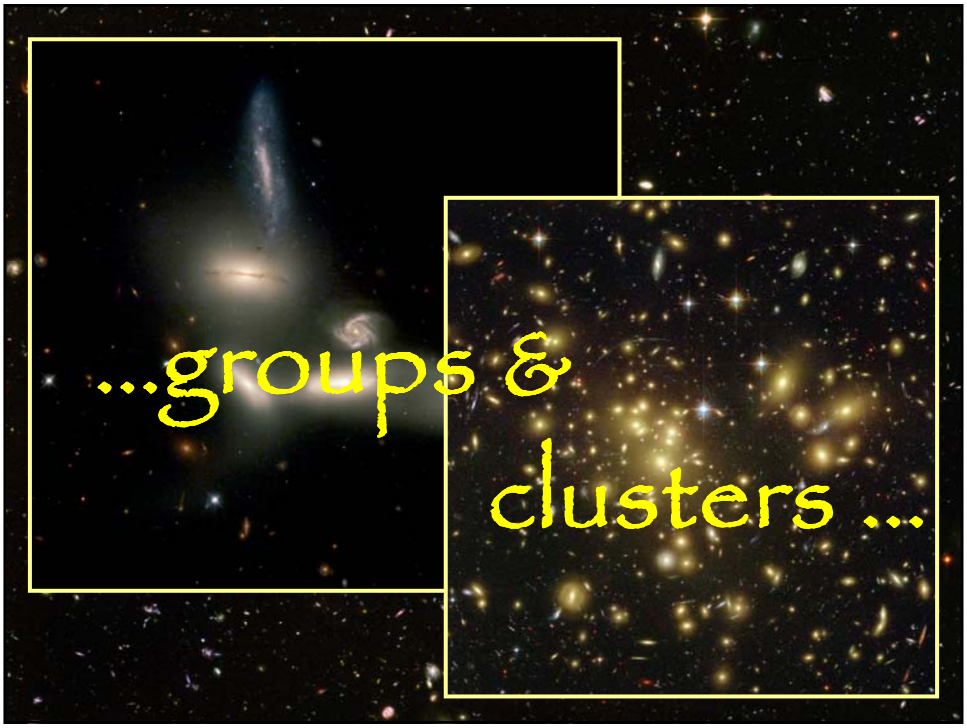
Structure in the Universe


… and their cradles …


… forming stars
in multitudes …

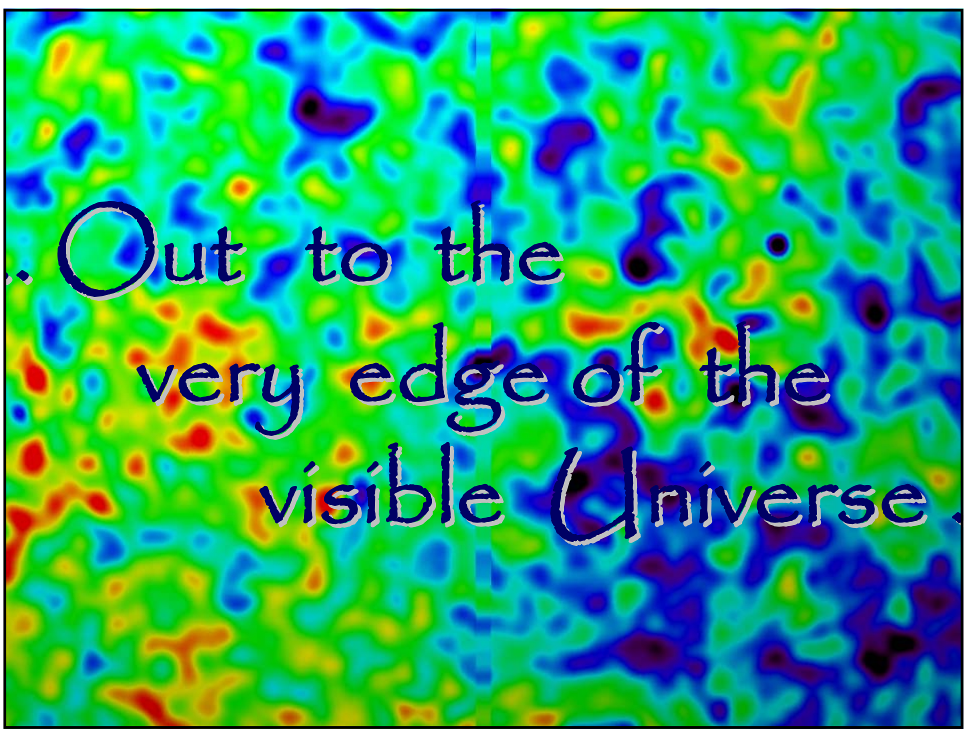

... the Galaxy ...


... galaxies ...


...groups &
clusters ...


... Out to the
furthest realms
galaxies roaming...


... into the regions
with the First Stars
setting ablaze
the skies ...


.. Out to the
very edge of the
visible Universe .

Central Theme:

Cosmic Enigma

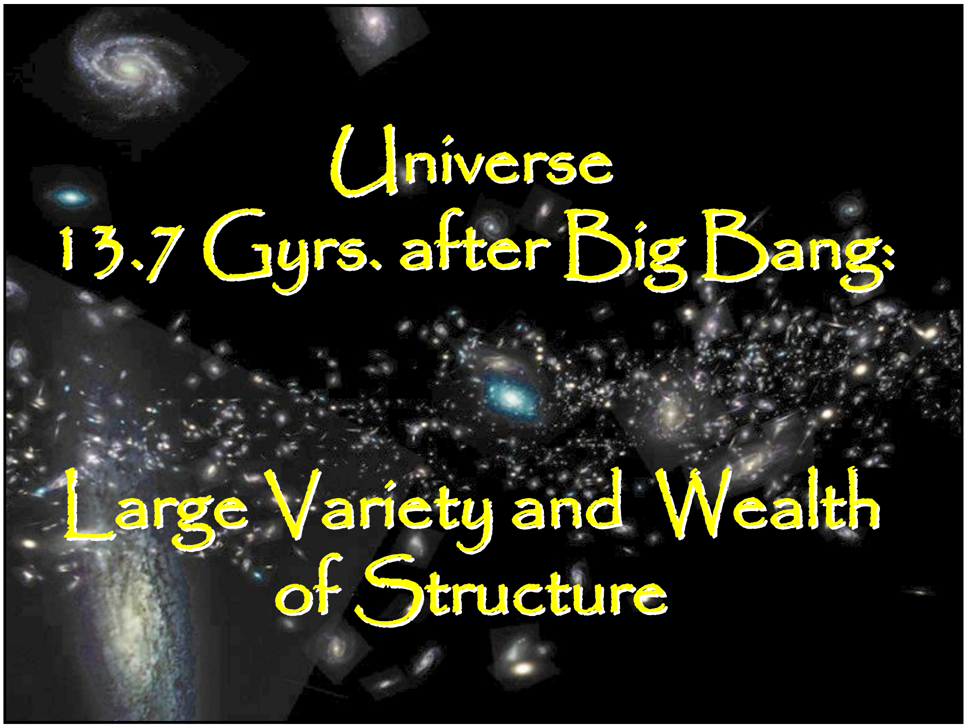
Universe

379,000 years after Big Bang

almost perfectly smooth

Microwave Background Radiation, surface of last scattering of cosmic photons is almost perfectly isotropic, all around the same temperature:

T=2.725 K



The Early Universe:

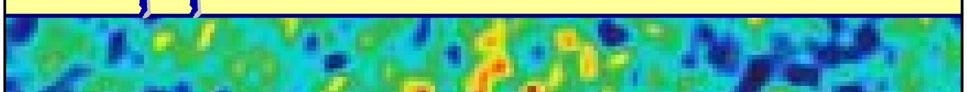
Almost perfectly homogeneous and isotropic, without any discernable structure ...

How did the present wealth and variety of structure emerge out of an almost featureless, pristine early Universe ?????

Cosmic Paradigm:

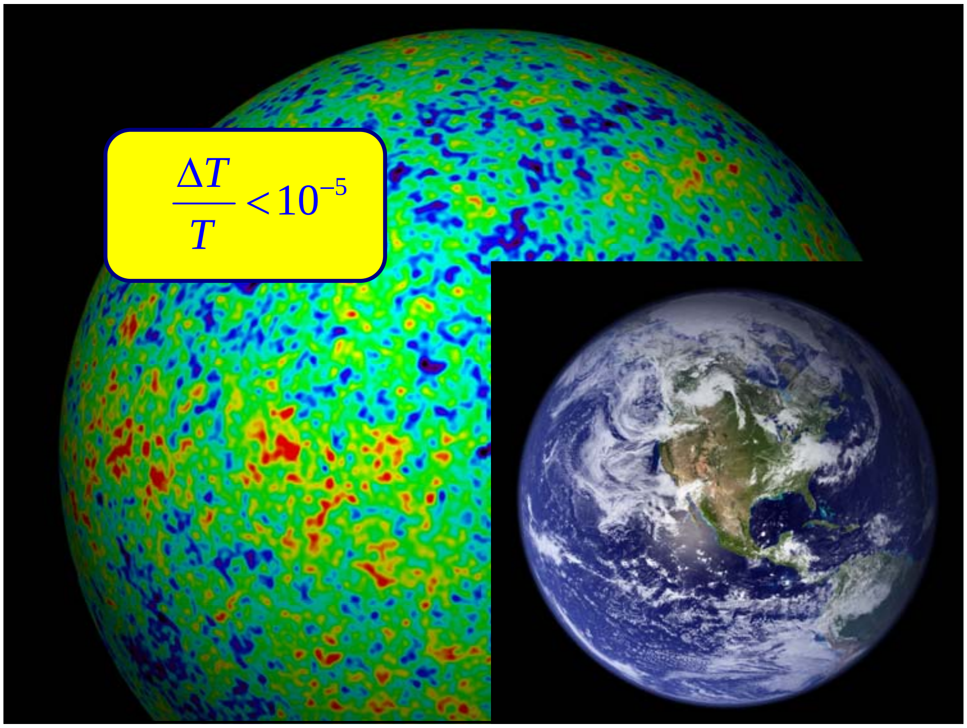
Gravitational Instability

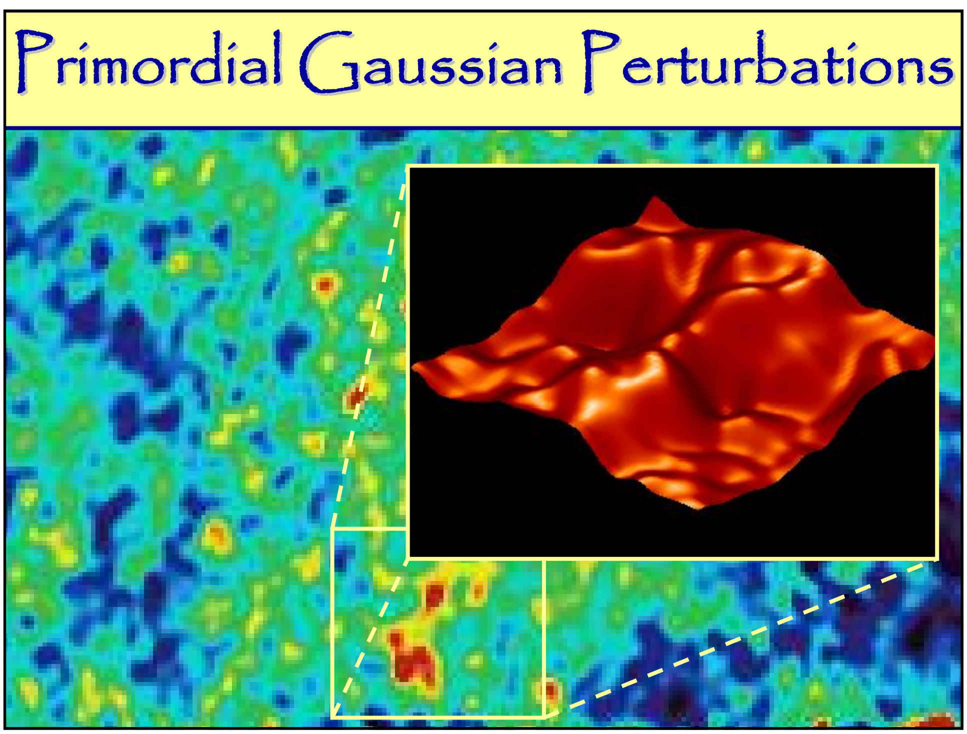
Ripples in the Universe



Tiny density perturbations in Early Universe:

- Origin: Quantum Fluctuations expanded to superhorizon scale during Inflation
- Gaussian Noise !!!
- Primordial Gaussian Density & Velocity Perturbations visible as corresponding Radiation Temperature Perturbations in Cosmic Microwave Background Radiation (CMB) Radiation


$\frac{\Delta T}{T} < 10^{-5}$


Primordial Gaussian Perturbations

Cosmic Structure Formation

After decoupling, density perturbations in the matter distribution gradually develop into forming structures by means of the "gravitational instability" mechanism. The origin of these density perturbations is still an unsettled issue. Their presence, however, has been proven beyond doubt: their imprint in the CMB beautifully confirmed by COBE and WMAP.

Hidden in the depths of the very first instances of the early universe, at present the most viable suggestion is that it concerns quantum fluctuations blown up to macroscopic proportions in an inflationary phase of cosmic expansion.

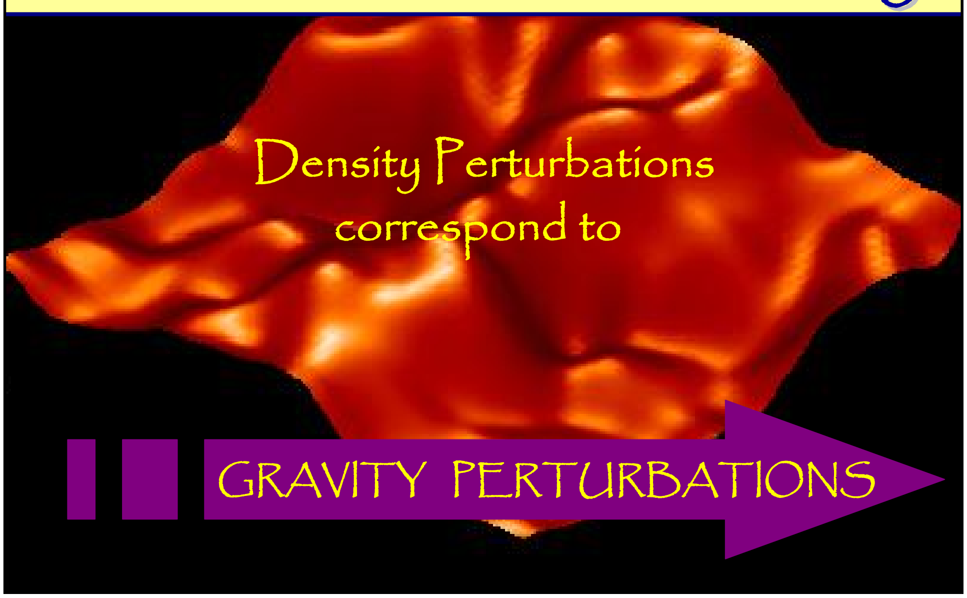
In the later phases of more "quiescent" cosmic expansion, density fluctuations, frozen while they have the superhorizon scale assumed in inflation, gradually enter the horizon (i.e they are overtaken).

From that instant on they can start growing !

$$\delta(\mathbf{x},t) \equiv \frac{\rho(\mathbf{x},t) - \bar{\rho}(t)}{\bar{\rho}(t)}$$

$$\delta(\mathbf{x}) = \int \frac{\mathbf{dk}}{(2\pi)^3} \hat{\delta}(\mathbf{k})\, \mathbf{e}^{-\mathbf{ik \cdot x}}$$

Gravitational Instability



Gravitational Instability

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

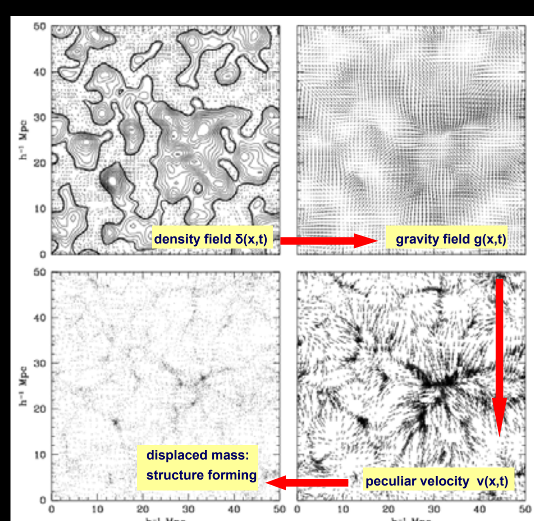
Cosmic Structure Formation

The gravity perturbations induce cosmic flows of matter. High density regions start to contract and finally collapse, assembling more and more matter from their surroundings.

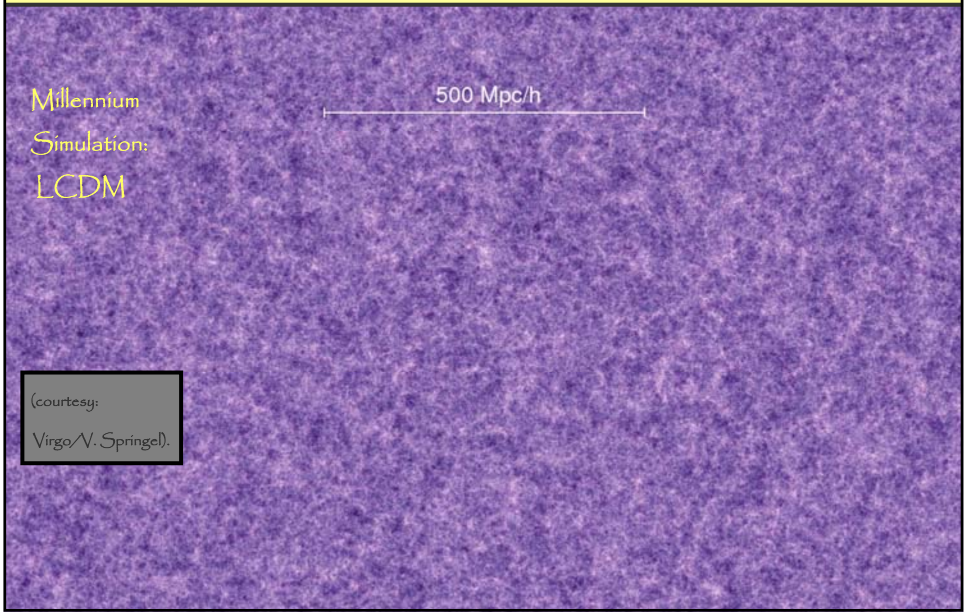
By contrast, as matter is moving out of them, low density regions turn into empty void regions.

Gradually, dependent on scale, we see the emergence of cosmic structures.

These days we can simulate the characteristics of the process through large computer simulations. Succesfull confrontation with the observational reality has given confidence in our understanding.



Millennium Simulation



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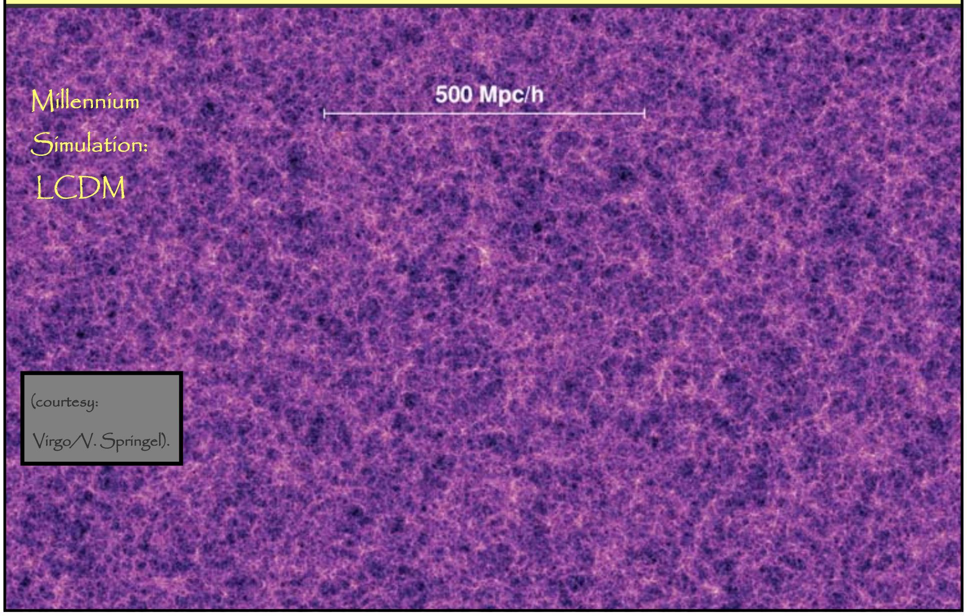

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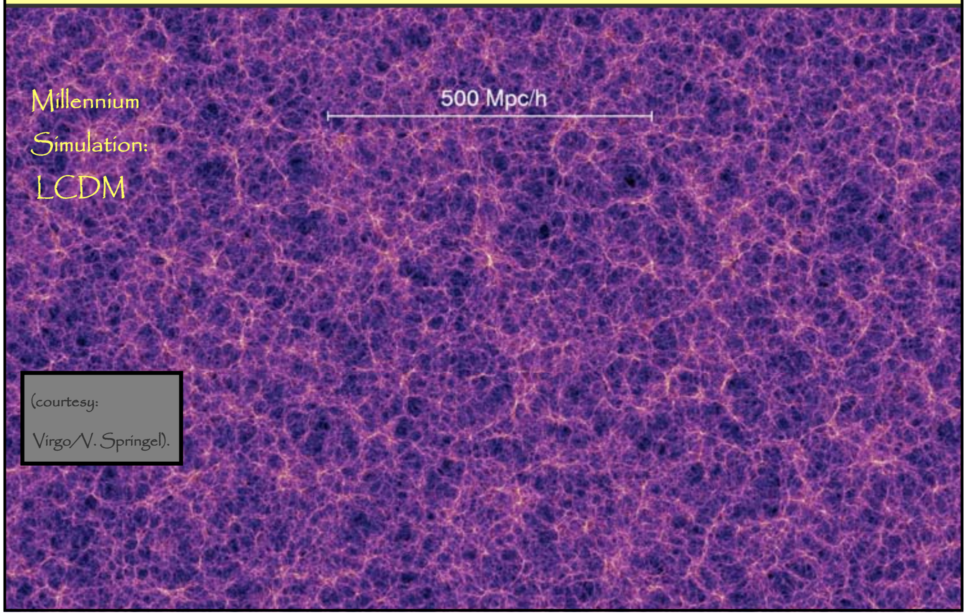

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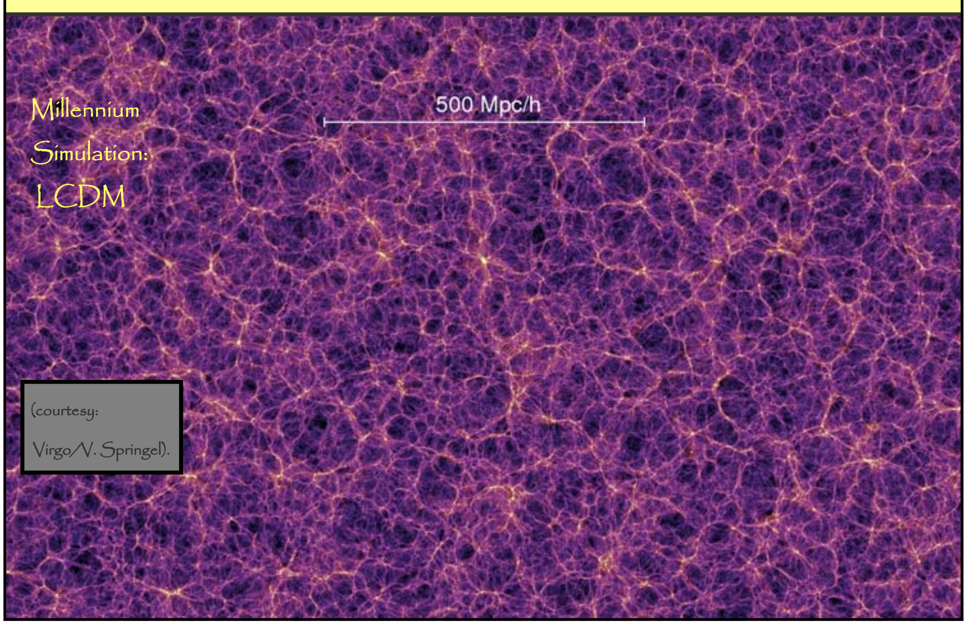

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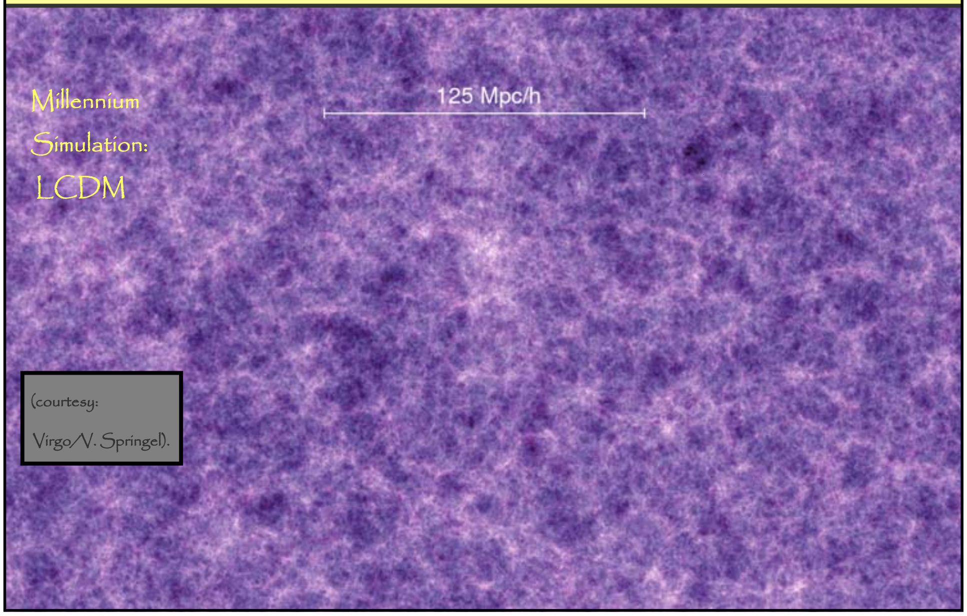
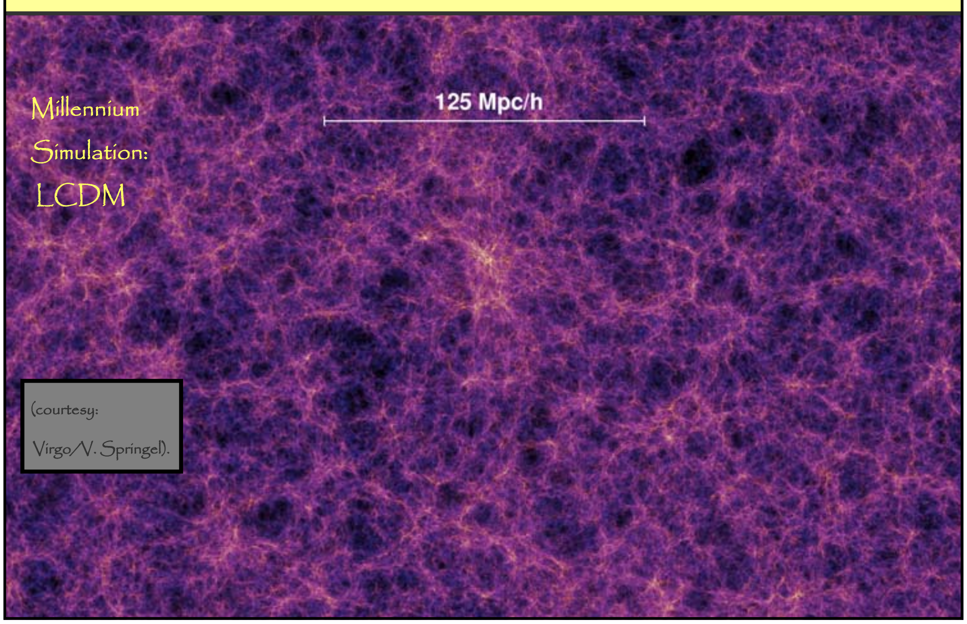


Millennium Simulation: LCDM

(courtesy: Virgo/V. Springel).

Millennium Simulation



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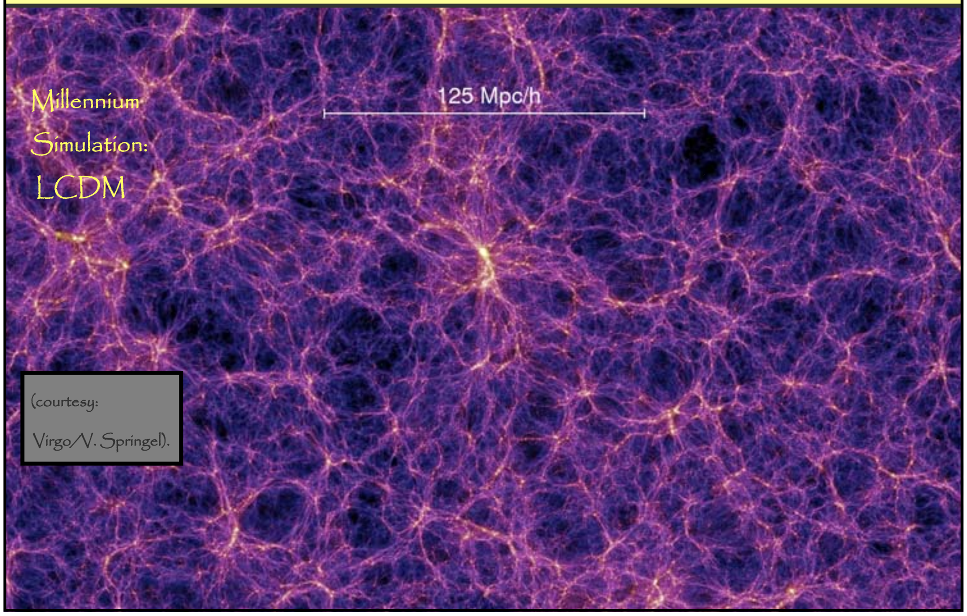

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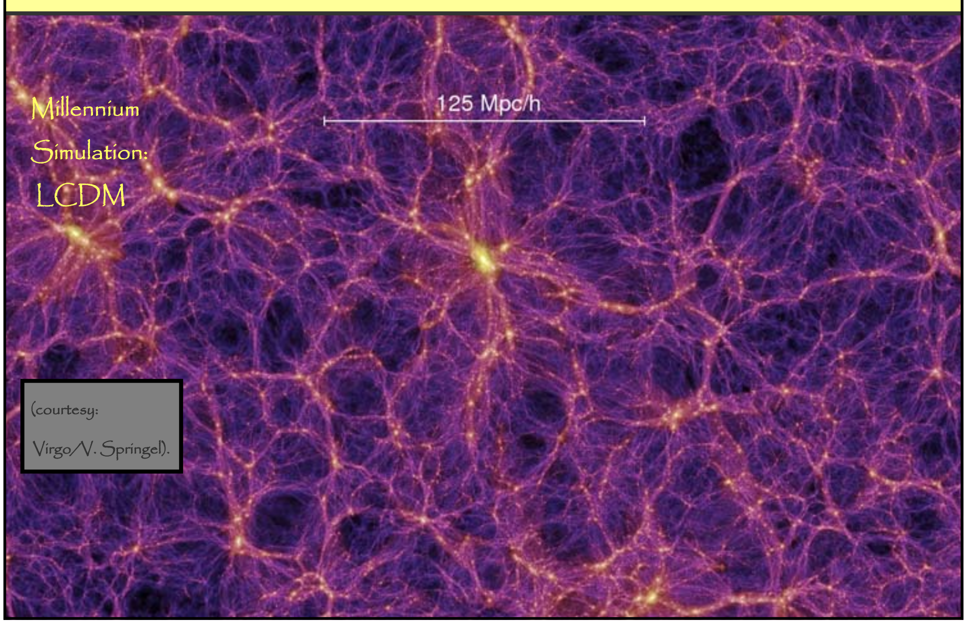

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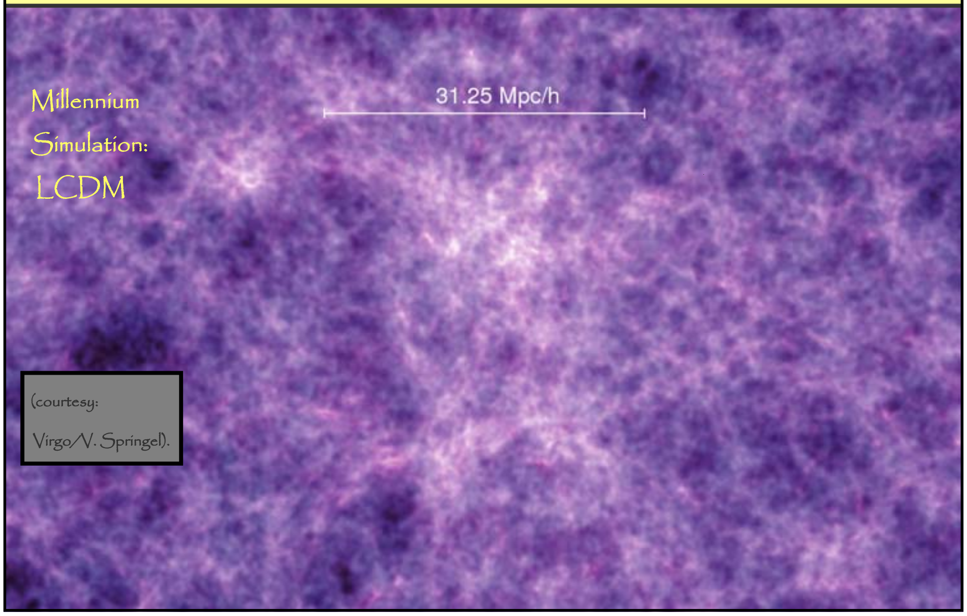

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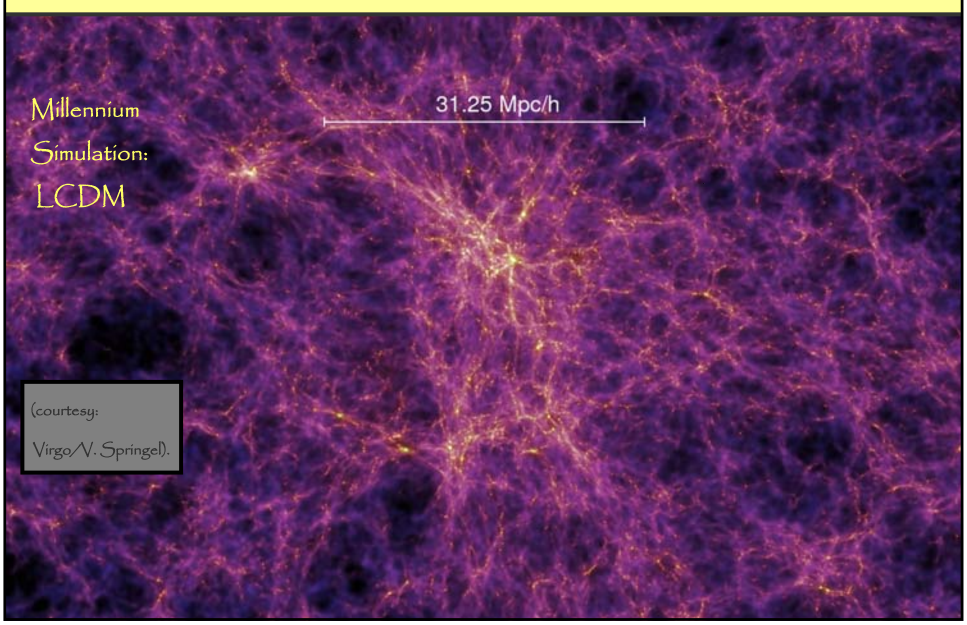

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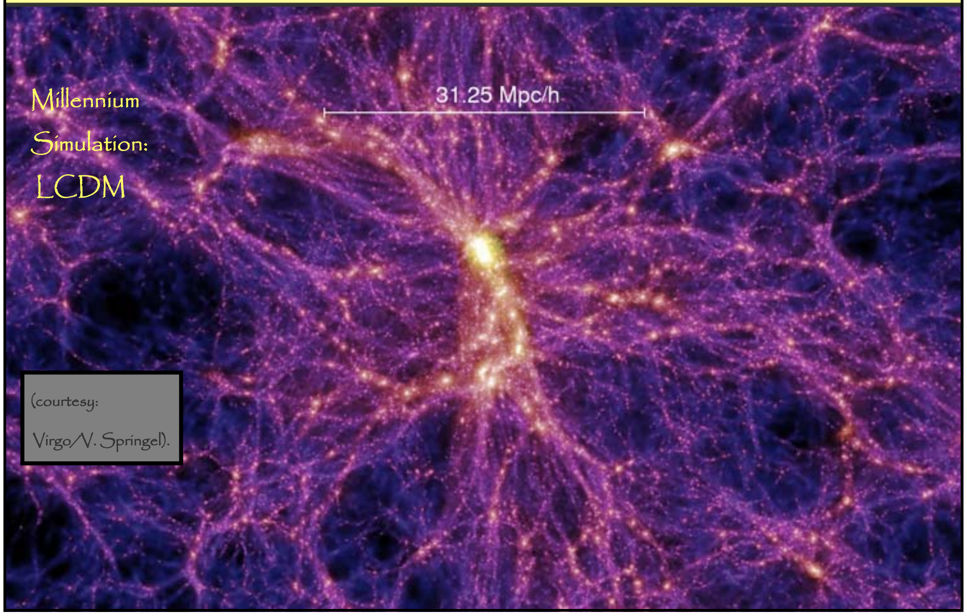

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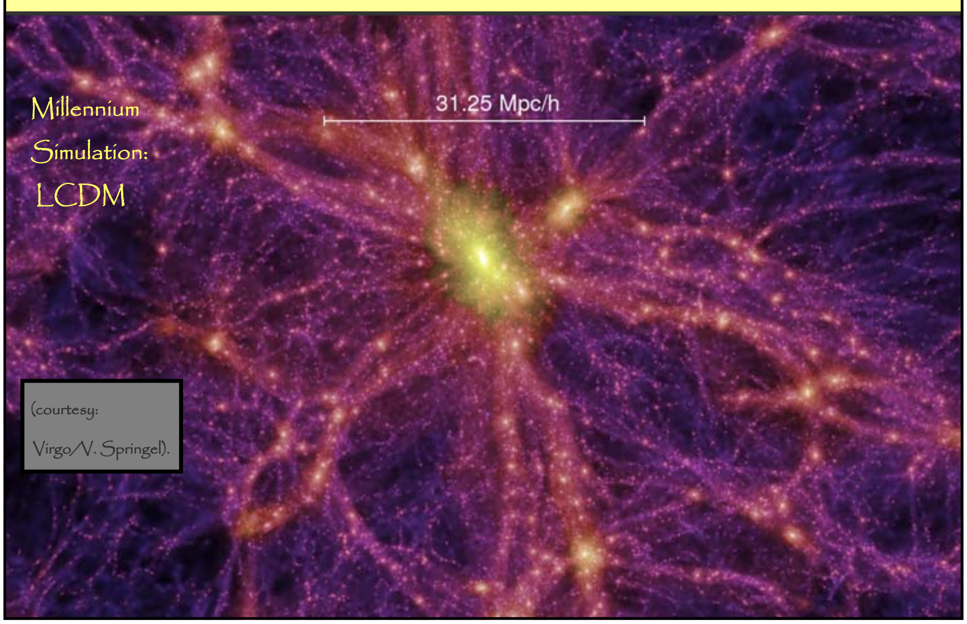


Gravitational Instability

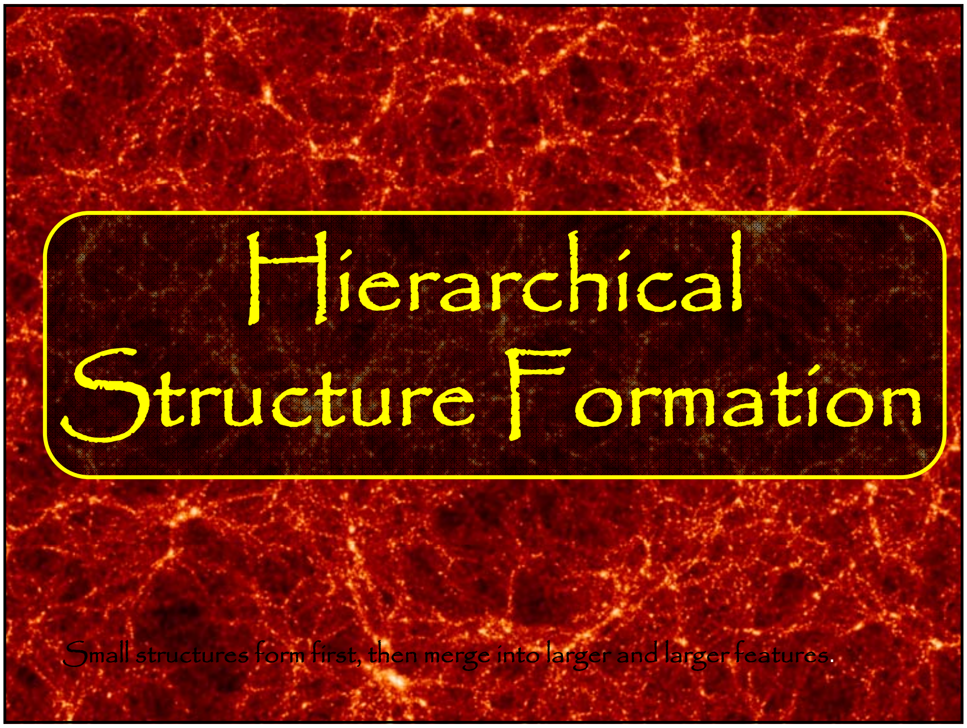
Perturbation Development:

- Generation: – .... Inflationary Phase ?
  – Gaussian Quantum Noise inflated to Cosmic Scale
- Superhorizon: – As long as perturbations superhorizon, no evolution
- Linear Growth: – Density & Velocity perturbations tiny
  Can be described analytically !
- Nonlinear Growth: – Interaction between fluctuations over range of scales
  – Emergence complex patterns & formation objects
  – Only analytical approximations,
  Computer (N-body) simulations necessary

Cosmic Structure Formation

Once the first linear phase of structure formation has passed, we start to recognize the emergence of genuine cosmic structures.
Three generic properties nonlinear structure formation:

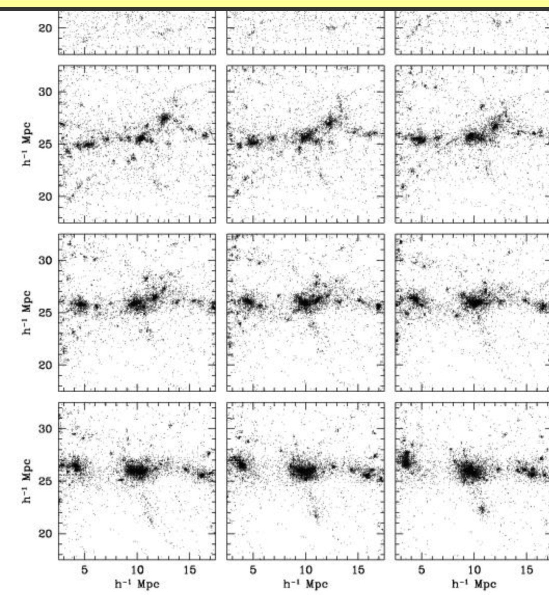
- hierarchical structure formation
- anisotropic collapse
- void formation:
  asymmetry
  overdense vs. underdense

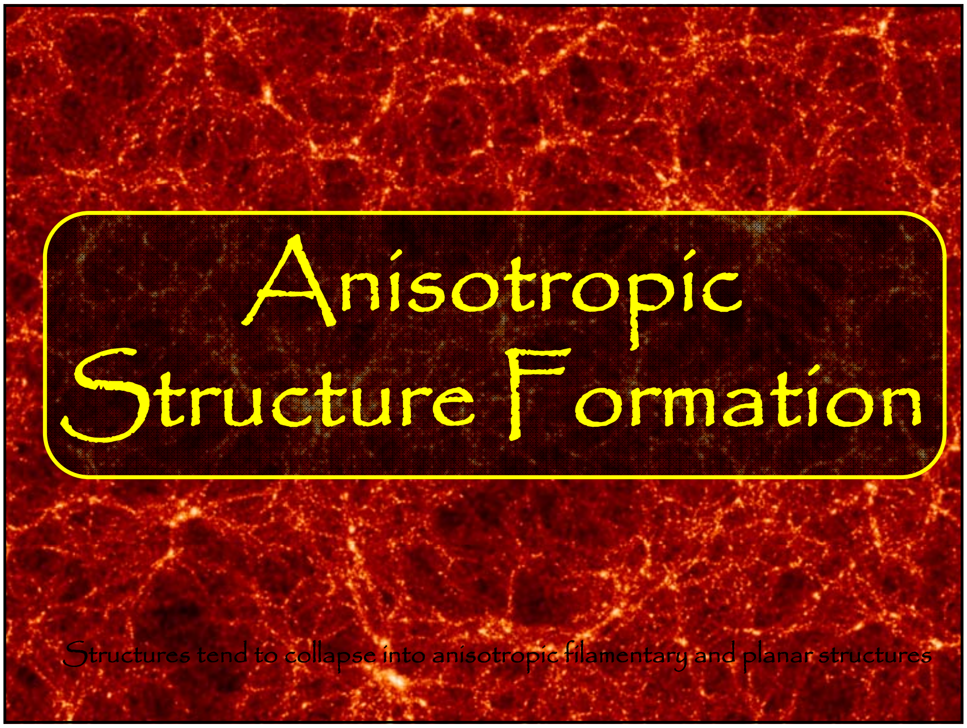


I. Hierarchical Structure Formation

Structures in the Universe form
by
gradual hierarchical assembly:

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



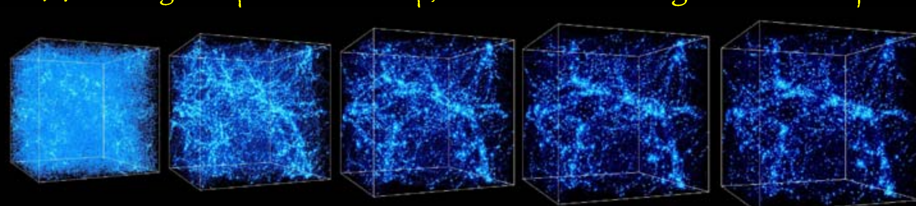


II. Anisotropic Collapse

- Gravitational Instability:
  - any small initial deviation from sphericity of a collapsing cloud gets magnified
  - gravitational collapse proceeds along sequence:

• collapse along smallest axis →	planar geometry ↔	wall
• collapse medium axis →	elongated ↔	filament
• full 3-D collapse →	clump ↔	clump/halo

- After having collapsed into a clump, virialization and emergence cosmic object



Asymmetric Structure Formation:

Void Dominance

While matter aggregates into ever denser and compacter structures, underdense void regions assume dominance in terms of occupied space.

III. Void Formation

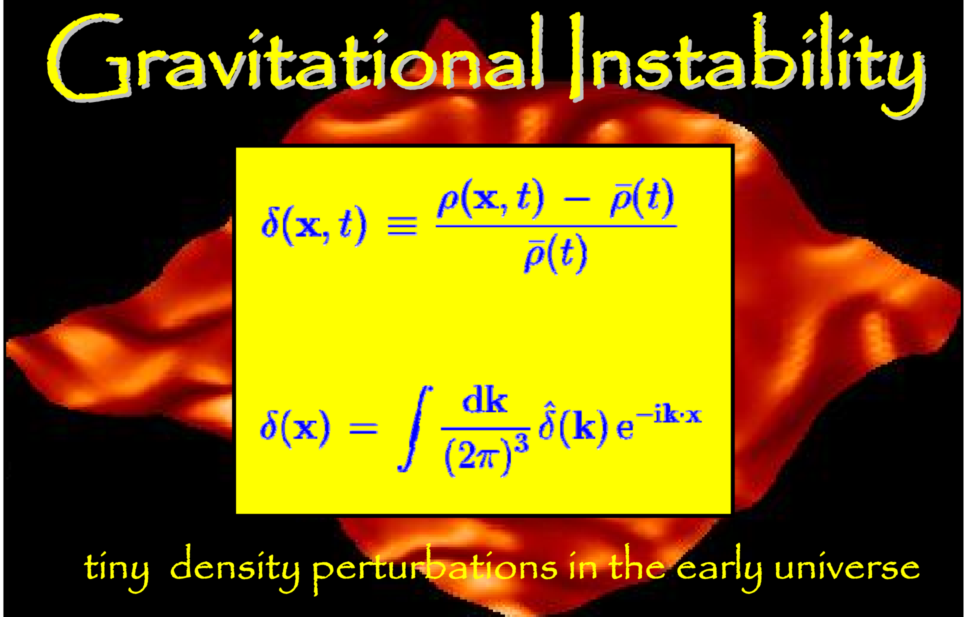
Origin of Voids:

- Voids natural product gravitational instability
- Voids evolve out of primordial underdensities:
  - Underdensity ⇒
  - Gravity Deficit ⇒
  - Matter Emigration
- Primordial Density Troughs ⇒ Present-Day voids

Structure Formation:

Power Spectrum

Gravitational Instability



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$$\delta(\mathbf{x}) = \int \frac{\mathbf{dk}}{(2\pi)^3}\,\hat{\delta}(\mathbf{k})\,\mathrm{e}^{-\mathbf{ik\cdot x}}$$

tiny density perturbations in the early universe

Gravitational Instability

Gaussian Perturbations

$$\mathcal{P}_N = \frac{\exp\left[-\frac{1}{2}\sum_{i=1}^{N}\sum_{j=1}^{N} f_i\,(\mathrm{M}^{-1})_{ij}\,f_j\right]}{\left[(2\pi)^N\,(\det \mathrm{M})\right]^{1/2}} \prod_{i=1}^{N} \mathrm{d}f_i$$

$$\Uparrow$$

$$M_{ij} \equiv \langle f(\mathbf{x}_i)\,f(\mathbf{x}_j)\rangle = \xi(\mathbf{x}_i - \mathbf{x}_j) = \xi(|\mathbf{x}_i - \mathbf{x}_j|)$$

Gaussian perturbations represent the simplest stochastic field of fluctuations imaginable. It is fully and completely characterized by its second-order moment, the autocorrelation function $\xi(r)$.

In fact, by concentrating on the contributions of the various scales and describing the field in terms of its Fourier components, we directly see that the FUNDAMENTAL function fully characterizing the Gaussian field

Power Spectrum P(k)

$$(2\pi)^3 P(k_1)\, \delta_D(\mathbf{k}_1 - \mathbf{k}_2) = \langle \hat{f}(\mathbf{k}_1) \hat{f}^*(\mathbf{k}_2) \rangle$$

Arguably, the power spectrum is the single most important function for our understanding of the cosmic structure formation process.

Power Spectrum

- Direct Characterization of contribution on different scales to inhomogeneous matter distribution
- First direct measure of inhomogeneities in spatial matter distribution
- Along with its Fourier transform, the autocorrelation function $\xi(r)$
- For Gaussian primordial field, full characterization of density field
- Directly related to potential and velocity perturbations
- Encapsulates all relevant physical processes in early Universe affecting the primordial evolution density/potential/velocity perturbations
- Highly sensitive to constituency of Universe (nature dark matter, etc.)
- This is what the early (inflationary) Universe gives us !!!

Cosmic Power Spectrum

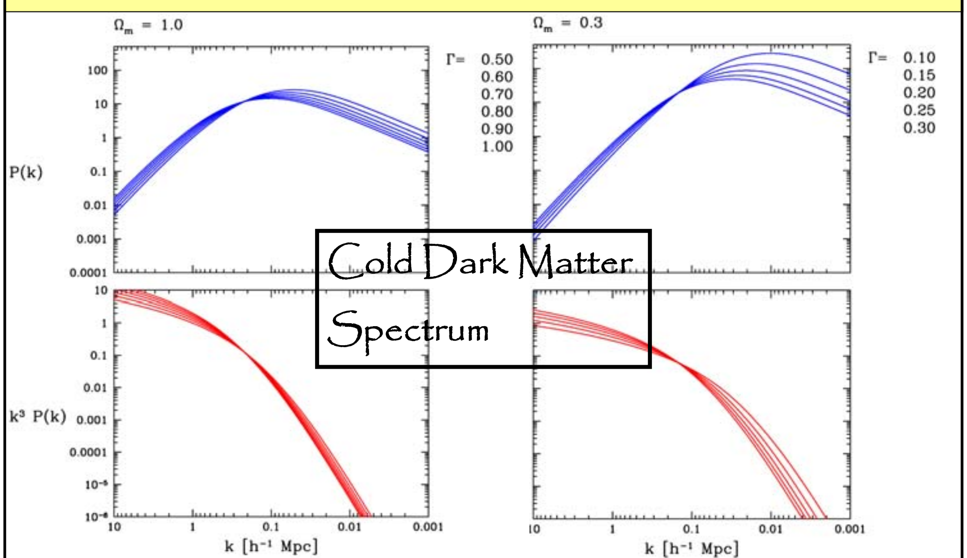
$$P(k) \propto \frac{k^n}{\left[1 + 3.89q + (16.1q)^2 + (5.46q)^3 + (6.71q)^4\right]^{1/2}} \times \frac{\left[\ln(1 + 2.34q)\right]^2}{(2.34q)^2},$$

$$q = k/\Gamma$$

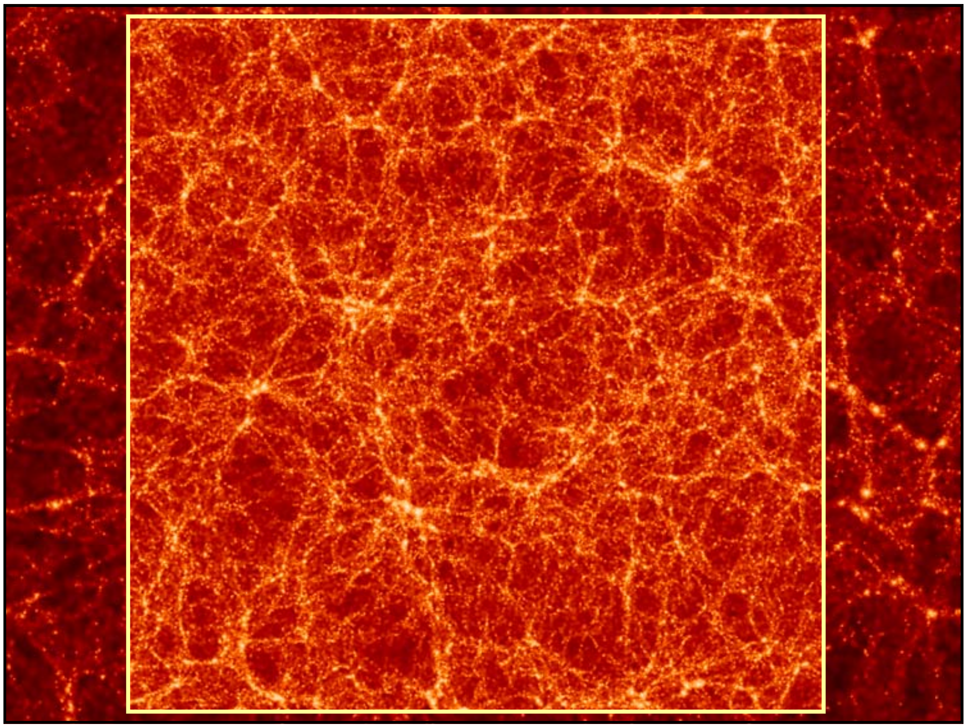
$$\Gamma = \Omega_0 h \exp(-\Omega_b - \Omega_b/\Omega_0)$$

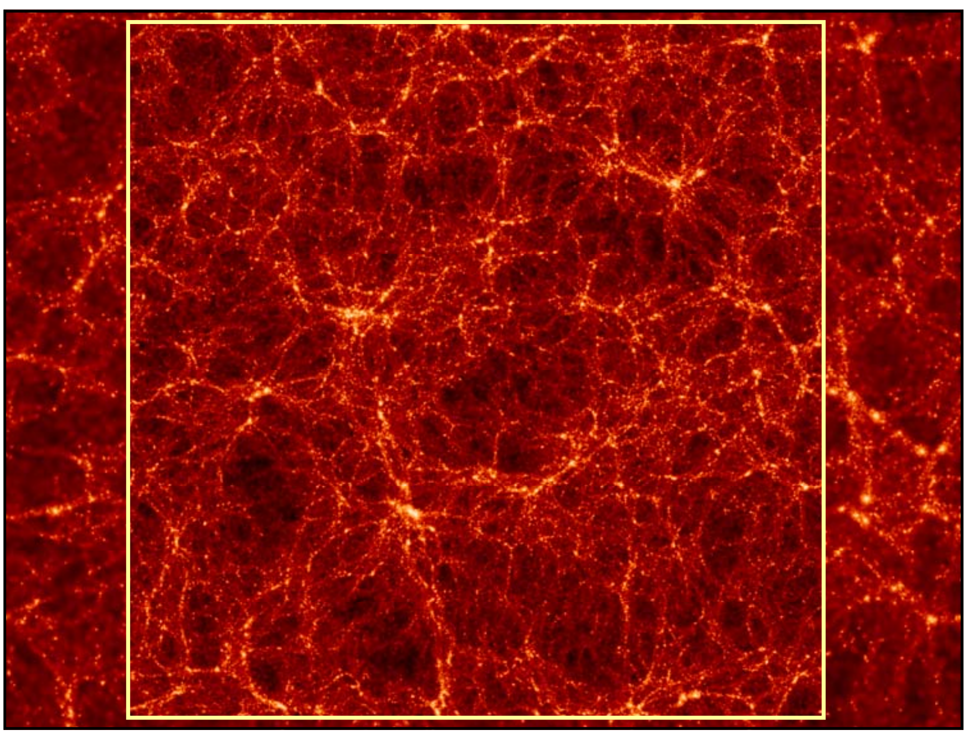
Cold Dark Matter Spectrum

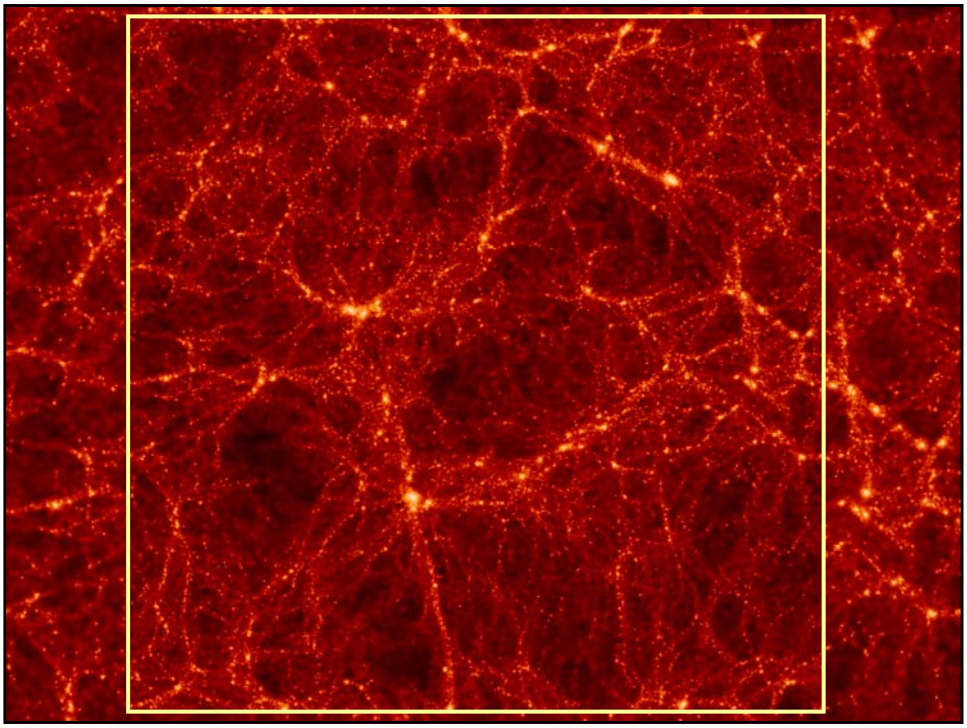
Cosmic Power Spectrum

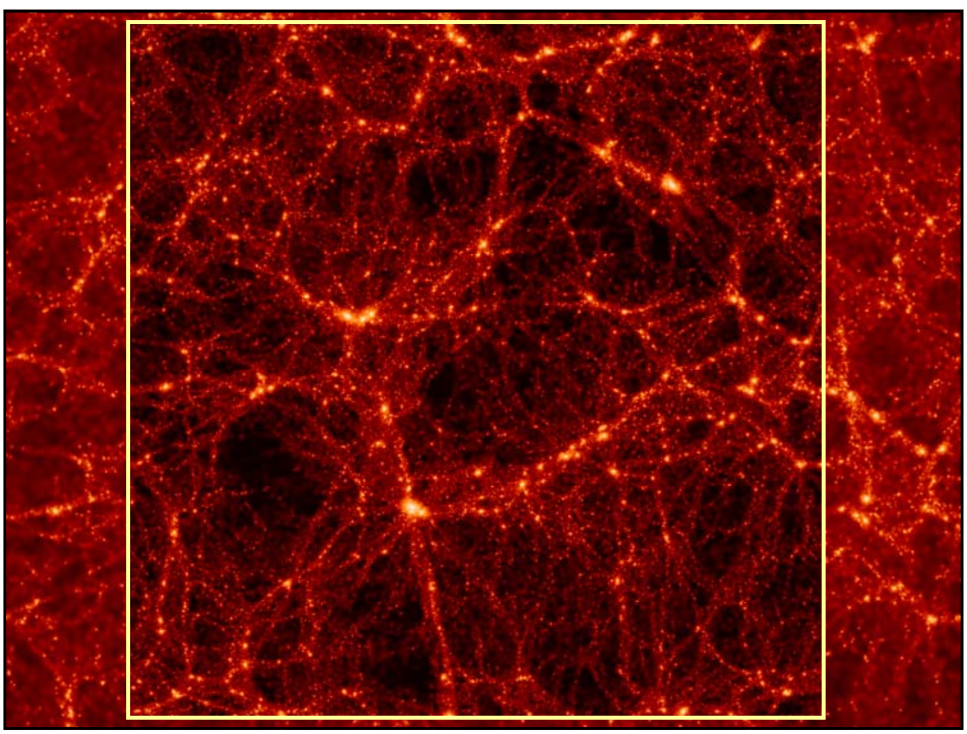


Cold Dark Matter Spectrum

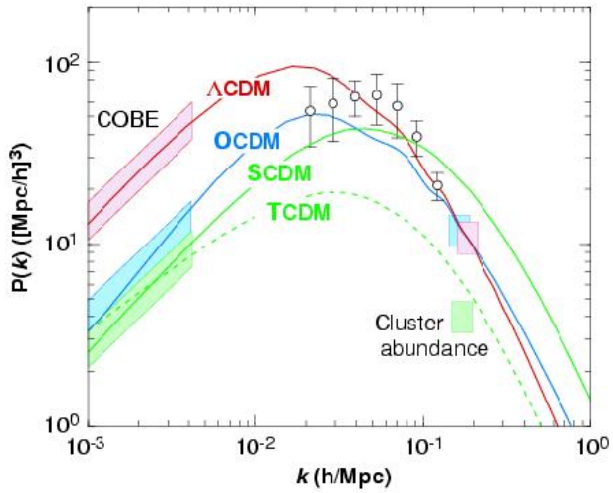




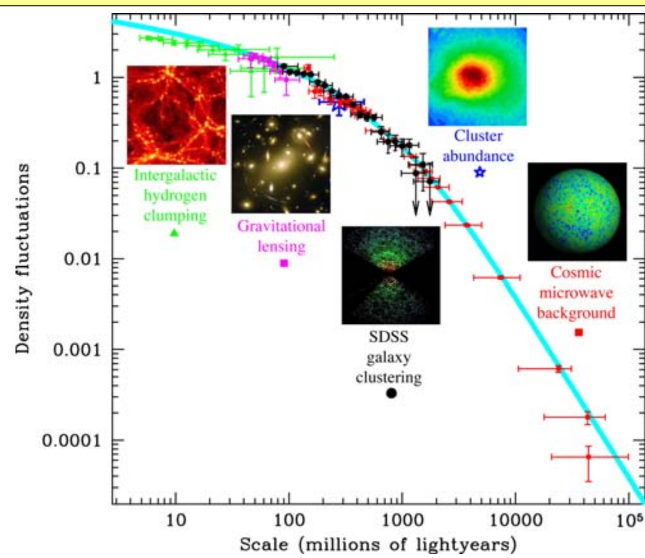




Cosmic Power Spectrum



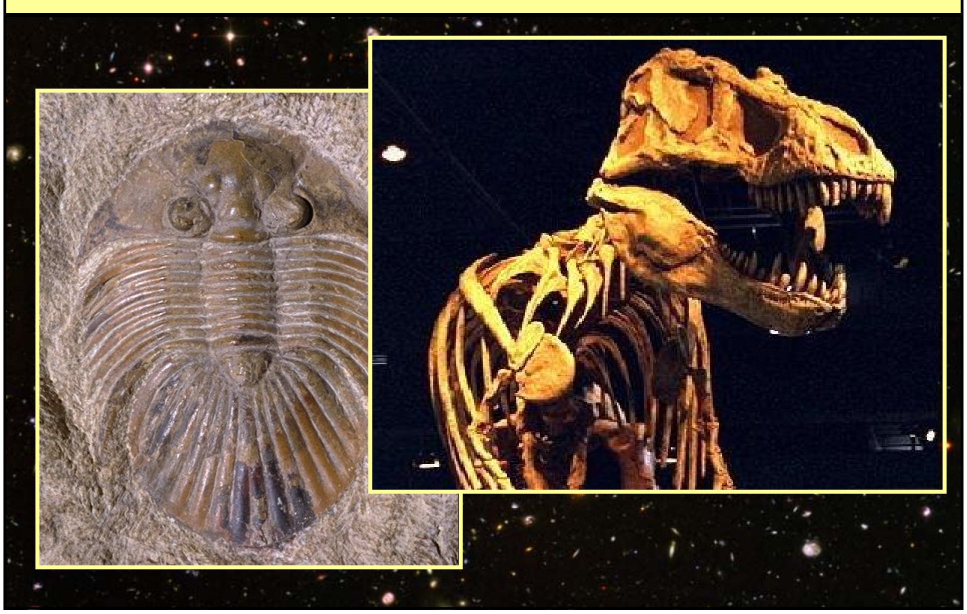
Cosmic Power Spectrum



Cosmic

Fossils

Cosmic Fossils ?



Cosmic Fossils

Which cosmic object contain direct information
on emergence and growth
of structure in the Universe ?

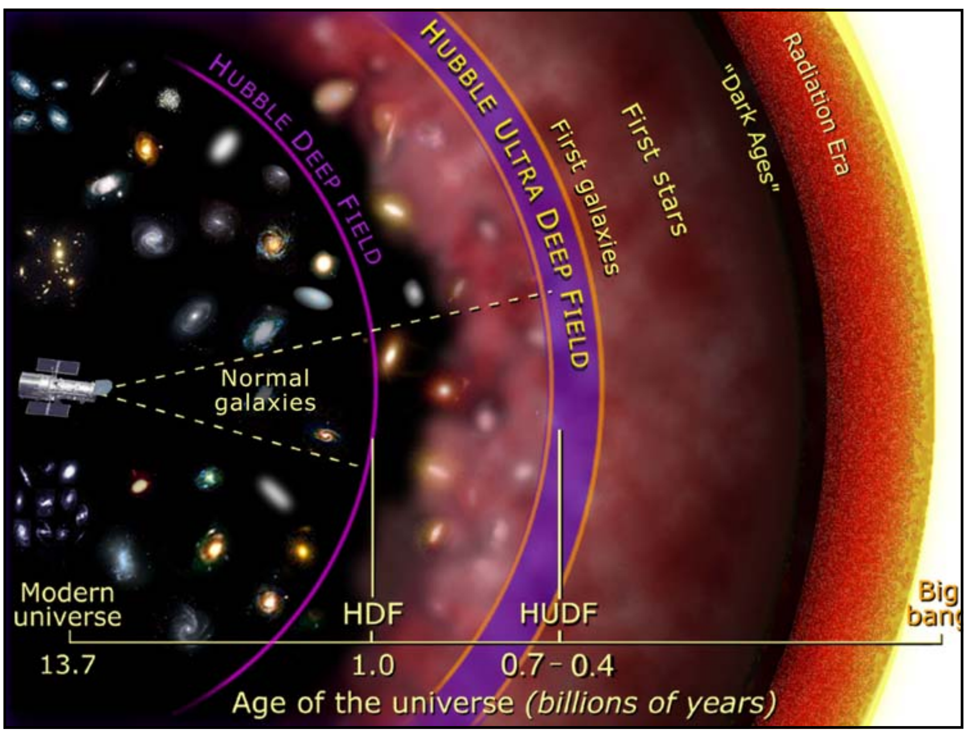
Wanted:

- Structures in youthful evolutionary phase
- Direct link with their initial conditions
- On scales of Megaparsecs, and larger, gravitational collapse only just started

Recall:

- visible (baryonic) matter but a fraction of total energy content Universe

$$\Omega_{rad} \approx 10^{-5}$$
$$\Omega_{matter} \approx 0.3$$
$$\Rightarrow \quad \Omega_{\Lambda} \approx 0.7 \quad \Leftarrow$$



- Primordial Conditions:
  - temperature fluctuations in microwave background radiation
  - polarization Cosmic Microwave Background
  - treasure trove cosmological information
- Dynamics:
  - cosmic velocity flows
  - very difficult in practice, due to large uncertainties in distance estimate/measurements of galaxies, and hence the estimated deviations from Hubble expansion.
- Mass Distribution:
  - gravitational lensing of light by cosmic matter distribution
  - very promising, just started to yield significant results …

- Galaxy Distribution:
  - galaxies supposed to be a fair reflection of underlying cosmic matter distribution
  - most detailed and investigated impression of cosmic matter distribution
    - nonlinear scales: tracing the Cosmic Web
    - Megaparsec linear scales: measuring the Power Spectrum
    - Gigaparsec linear scales: Baryonic Oscillations, Primordial Power Spectrum
    - High redshift galaxies: tracing young Universe, early stages galaxy formation

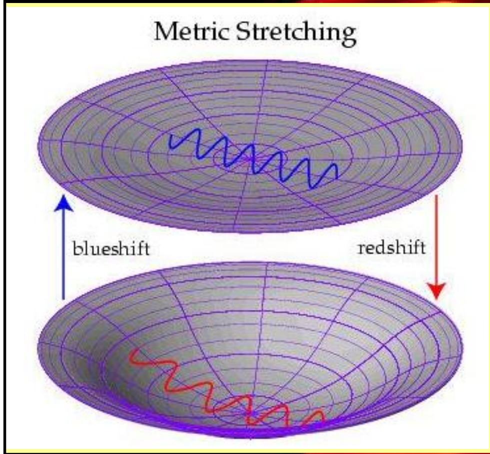
  But: formation and evolution of galaxies still a notoriously ununderstood problem, so that the relation between matter and galaxy distribution is as yet not unequivocally clear
- Quasars & AGN
  - tracing the large scale matter distribution on scales of hundreds Mpc
  - but: largely unknown how they relate to the matter/galaxy distribution

- Clusters of Galaxies
  - spatial distribution tracer Cosmic Web
  - internal structure dictated by primordial perturbations
  - Hot intracluster gas (10^{7-8} K) - accurate tracer potential cluster
    - easily observable via X-rays
- Gaseous Cosmic Web
  - Baryonic gas traces the Cosmic Web:
    Lyα forest   neutral hydrogen gas, mostly at high z
    WHIM   shock-heated gas settled in cosmic web
- Distribution & Physical State Gas @ Dark Ages
  - First Stars & Galaxies
  - Reionization of baryonic gas: very sensitive measure cosmology
- Structure of Galaxies
  - Mass distribution galaxies
  - Internal phase-space structure galaxy haloes

Embryonic Structure:

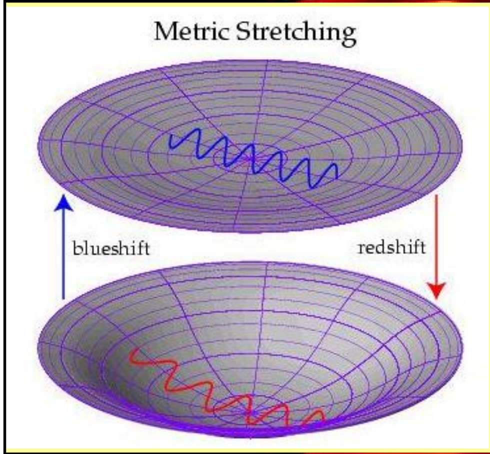
CMB:
Rippling the Photons

CMB Perturbations



- As a result of perturbations in Gravitational potential photons experience frequency shift
- While travelling through perturbation:
  - Gravitational Redshift +
  - (Relativistic) Time Dilation
- Combined effect: Sachs-Wolfe Effect

Sachs-Wolfe Effect



Sachs-Wolfe Effect

$$\frac{\Delta T}{T} \sim \frac{1}{3}\frac{\Delta\Phi}{c^2}$$

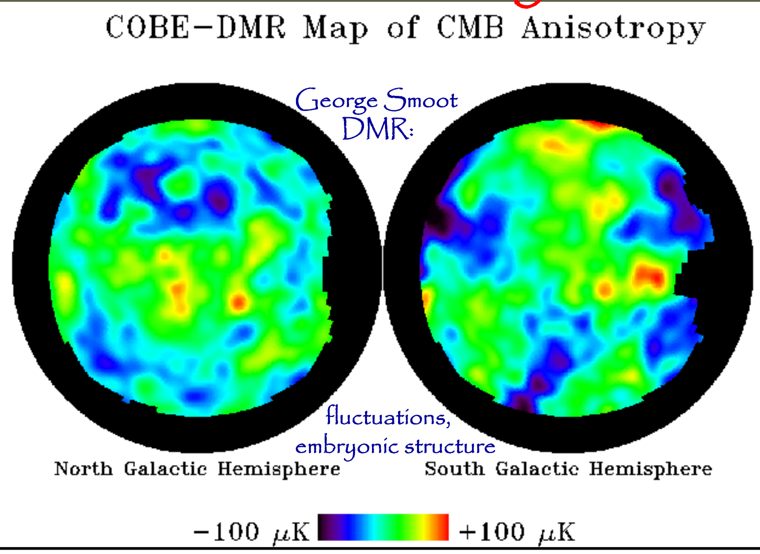
Cosmic Microwave Background

COBE (1992):

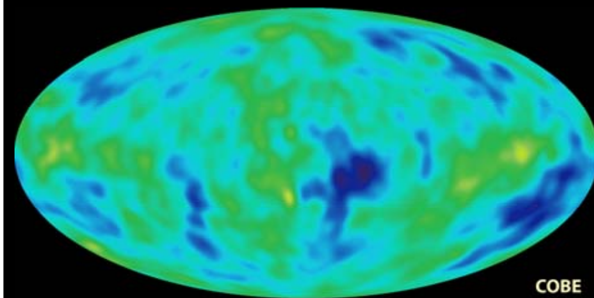
Accurate measurement Planck spectrum CMB

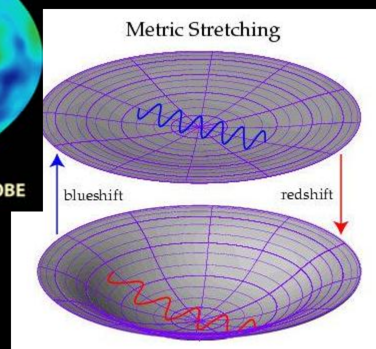
First detection angular temperature perturbations ($\theta \sim 7^o$): Sachs-Wolfe effect

Primordial Anisotropies CMB sky



Cosmic Microwave Background

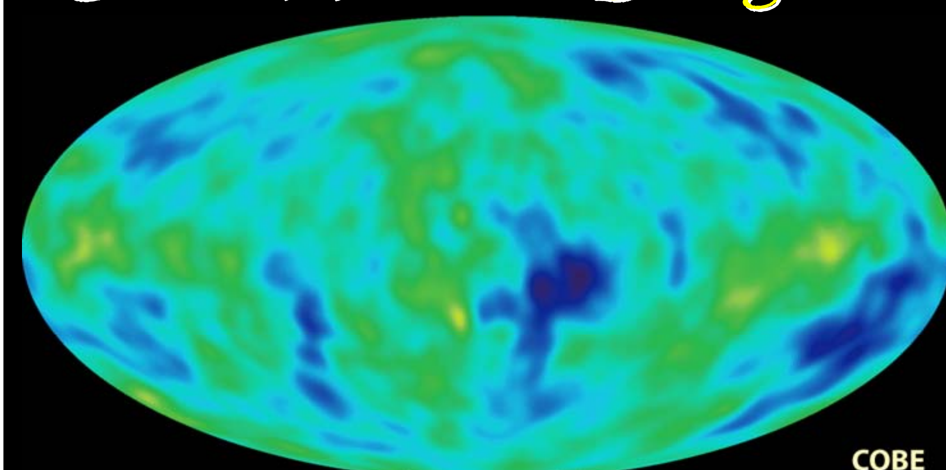




Map of the Universe at Recombination Epoch:

- 379,000 years after Big Bang
- Superhorizon perturbations in gravitational potential (Sachs-Wolfe)
- $\Delta T/T < 10^{-5}$

Cosmic Microwave Background



Map of the Universe at Recombination Epoch:

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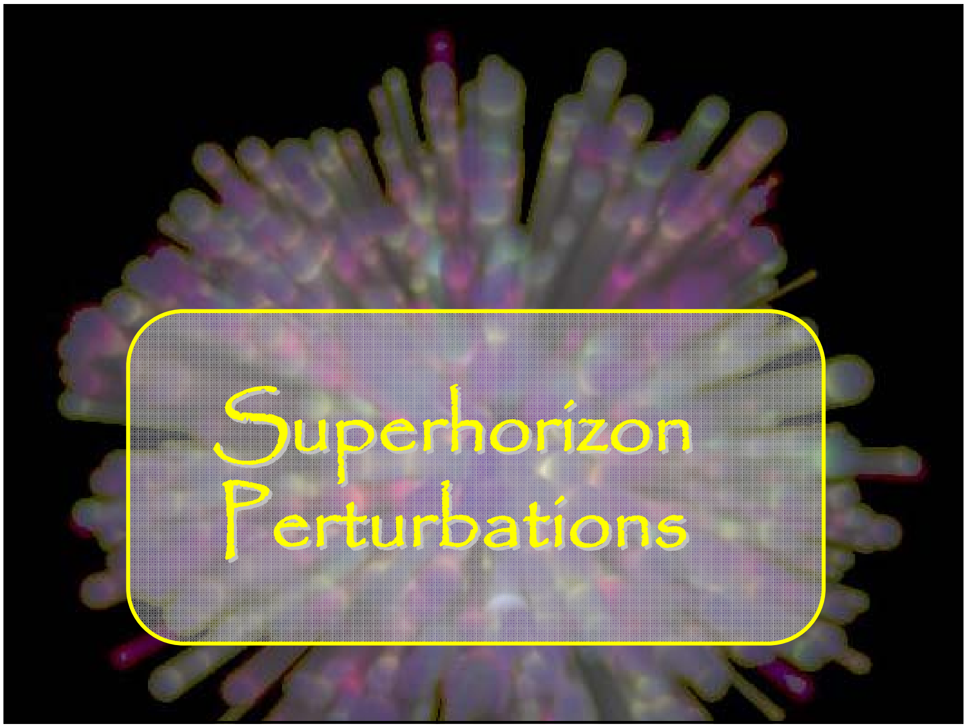
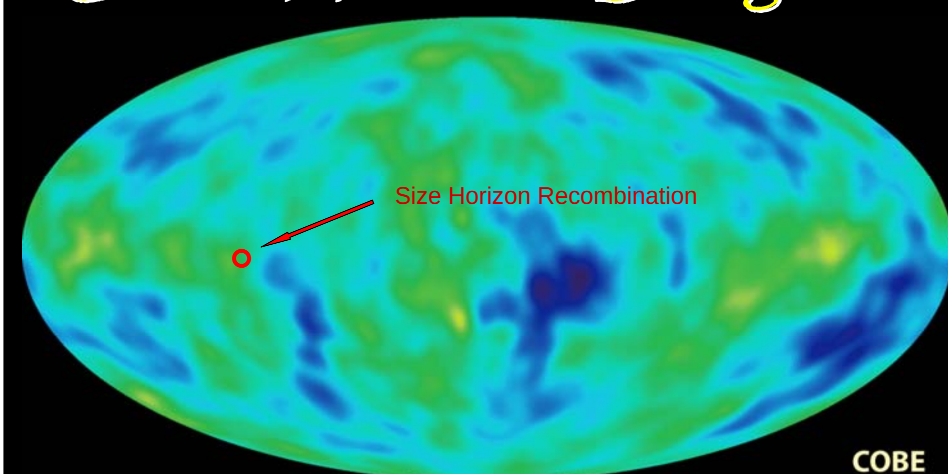
Superhorizon Perturbations

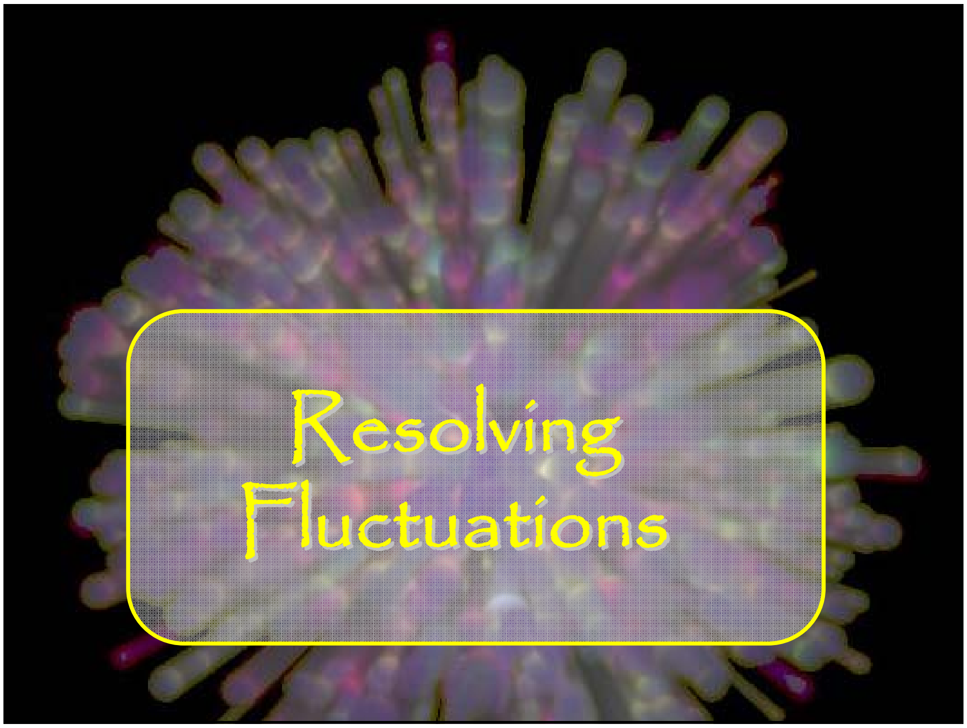


Cosmic Microwave Background



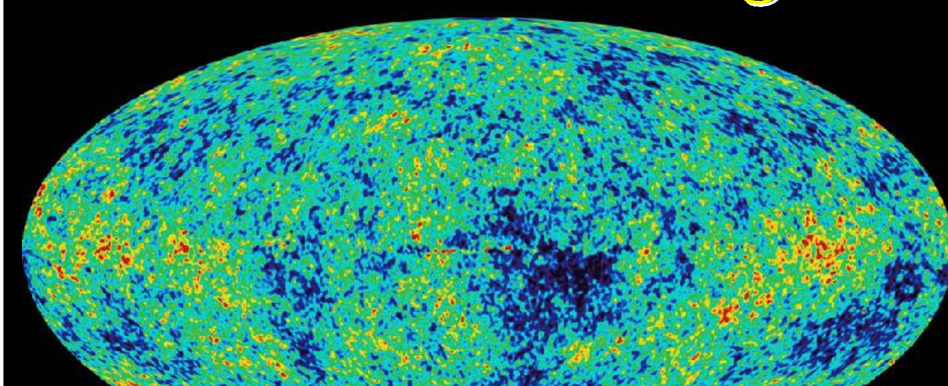
COBE measured fluctuations: > 7°
Size Horizon at Recombination spans angle ~ 1°

How can it be that regions totally out of thermal contact,
would have the same temperature ?



Resolving Fluctuations

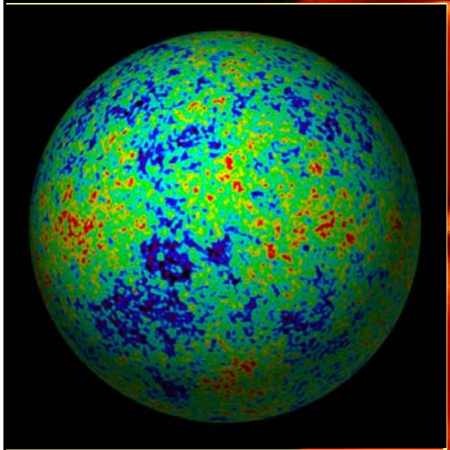
Cosmic Microwave Background



Map of the Universe at Recombination Epoch:

- 379,000 years after Big Bang
- Subhorizon perturbations: primordial sound waves
- $\Delta T/T < 10^{-5}$

Temperature Anisotropies

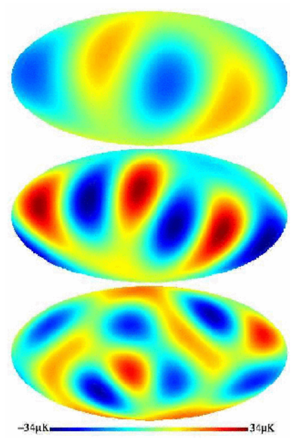


Temperature Perturbations in terms of Spherical Harmonics:

$$T(\theta,\phi) = \sum_{l,m} a_{lm} Y_l^m(\theta,\phi)$$

$$\phi \sim \frac{\pi}{l} \sim \frac{180^\circ}{l}$$

Temperature Anisotropies



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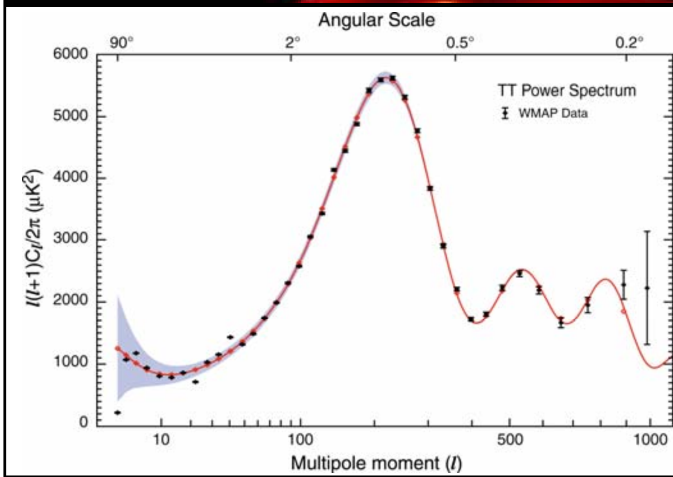
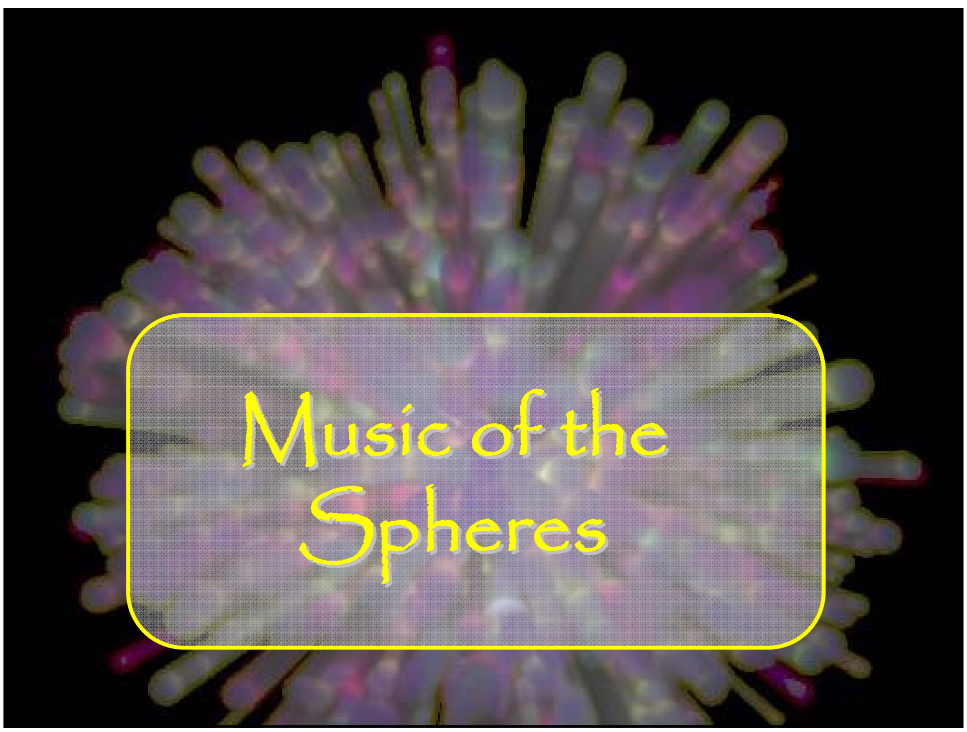
$$\phi \sim \frac{\pi}{l} \sim \frac{180^\circ}{l}$$

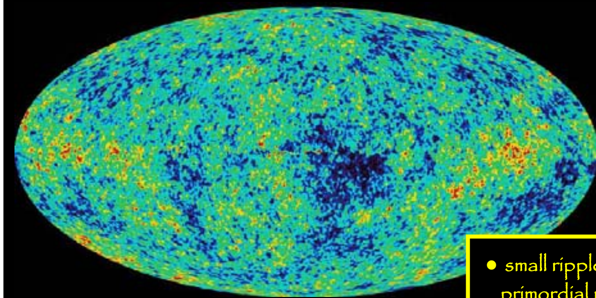
CMB Power Spectrum



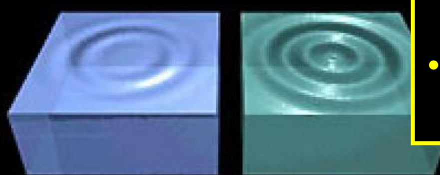
$$T(\theta,\phi) = \sum_{l,m} a_{lm} Y_l^m(\theta,\phi)$$

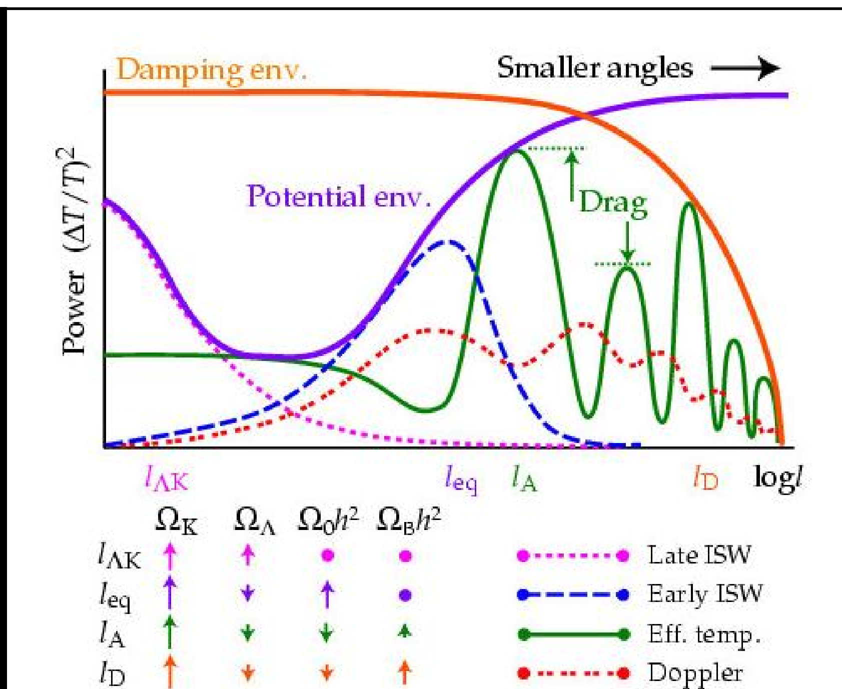


Cosmic Microwave Background

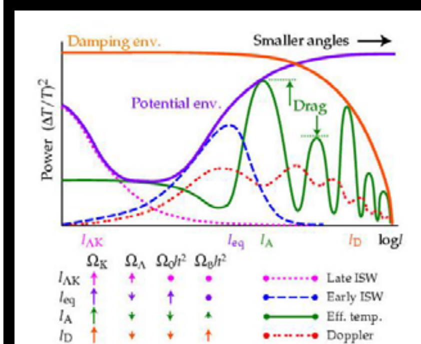


- small ripples in primordial matter & photon plasma
- gravity compresses primordial photon gas, photon pressure resists:
- compressions and rarefactions in photon gas:
  ➡ sound waves
- sound waves not heard, but seen:
  - compressions: (photon) temperature higher
  - rarefactions: lower





Music of the Spheres



Total Angular CMB Spectrum
modulated by combination of several effects,
the Primary Perturbations

1) Sachs-Wolfe potential fluctuations,
2) Acoustic perturbations
   as the corresponding potential fluct.
   enter horizon and start to collapse
3) Integrated Sachs-Wolfe
   potential perturbations:
   - Early ISW: matter/radiation at recomb.
   - Late ISW: expansion influence curvature
     & cosmological constant
4) Doppler perturbations
   velocity fluct. accompanying potential pert.
5) Silk Damping
   radiation damping of fluctuations

The Cosmic Web:

Patterns Across the Universe

A Universe of Galaxies

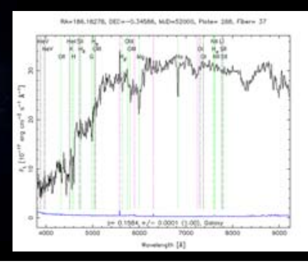
Used as point tracers of underlying cosmic density field.

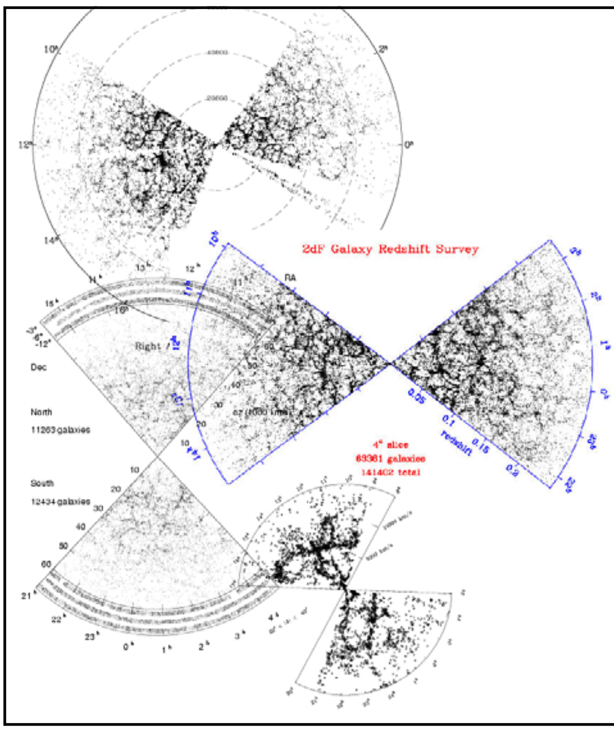
Intention is to map this cosmic matter field on Megaparsec scales.

"LSS" still reflects conditions primordial Universe:

Cosmic Fossil

galaxy spectrum: redshift-distance →





Development of our Megaparsec cosmos worldview over the past two decades. A compilation of the galaxy distribution charted in four major galaxy redshift survey campaigns:

1) The CfA/SSRS survey
2) The LCRS
   (Las Campanas redshift survey)
3) 2dFGRS
   (2dF galaxy redshift survey)
4) SDSS
   Sloan Digital Sky Survey

Over the past two decades we have witnessed a paradigm shift in our perception of the Megaparsec scale structure in the Universe. As increasing elaborate galaxy redshift surveys charted ever larger regions in the nearby Universe, an intriguingly complex and salient foamlike network came to unfold and establish itself as the quintessential characteristic of the cosmic matter and galaxy distribution.

In a great many physical systems, the spatial organization of matter is one of the most readily observable manifestations of the forces and processes forming and moulding them. Richly structured morphologies are usually the consequence of the complex and nonlinear collective action of basic physical processes.

The vast Megaparsec cosmic web is undoubtedly one of the most striking examples of complex geometric patterns found in nature. In its own right, the vast dimensions and intricate composition of the cosmic foam make it one of the most imposing and intriguing patterns existing in the Universe. Its wide-ranging Importance stems from its status as a cosmic fossil. On a scale of tens up to a few hundred Megaparsecs It is still relatively straightforward to relate the configuration at the present cosmic epoch to that of the primordial matter distribution from which it emerged. With the cosmic foam seemingly representing this phase, it assumes a fundamental role in the quest for understanding the origin of all structures in the Universe.

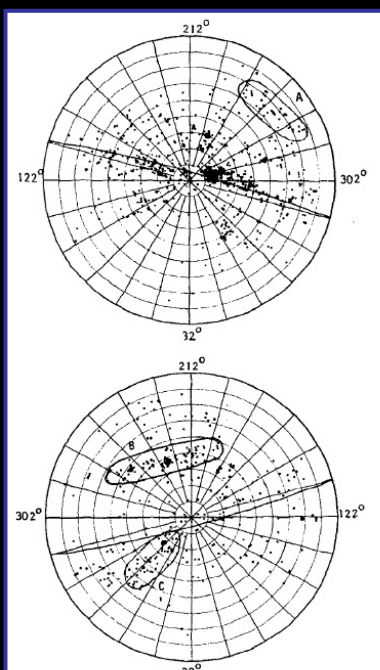
While its complex cellular morphology involves one of the most outstanding and evident aspects of the Cosmic foam, it has also remained one defying simple definitions which may be the cause of it having Remained one of the least addressed aspects. The geometry of the cosmic foam may be described as a nontrivial stochastic assembly of various anisotropic and asymmetric elements. A major deficiency in the vast majority of studies on the large scale distribution of galaxies has been the lack of suitable quantitative and statistical characterizations of the truly fundamental aspects of the comsic foam geometry.

The Cosmic Web:

A Census

Sky Maps: world all around us

Early Views



Shapley-Ames catalog (1932) of nearby galaxies:

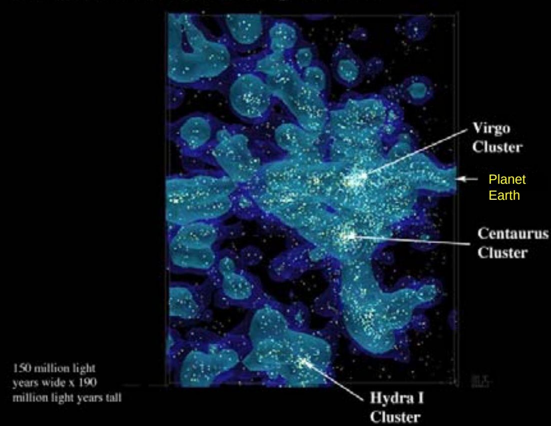
All-sky survey of galaxies to m=18.3

$\delta > -23^o$

- numerous concentrations:
  groups and clusters (incl. Virgo cluster)
- asymmetry between north and south:
  many more galaxies on northern sky
- conspicuous concentration along a line
  running through richest nearby cluster,
  the Virgo cluster:
- The Supergalactic Plane
  (first identified by de Vaucouleurs:
  the plane of our own Local Supercluster)

The Local Supercluster

End-on View of the Local Supercluster:



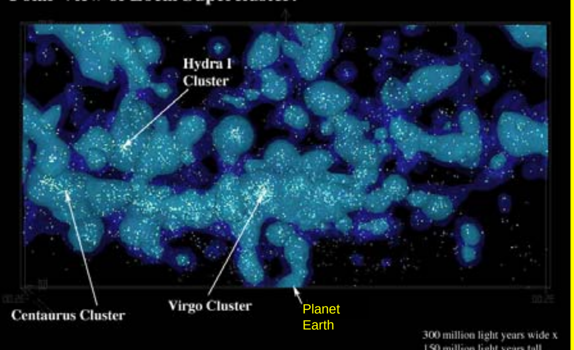
Courtesy: B. Tully

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

- the "Local Supercluster",
- a large flattened mass concentration ~ 10 h^{-1} Mpc in size,
- centered on one rich cluster, the Virgo cluster

The Local Supercluster

Polar View of Local Supercluster:

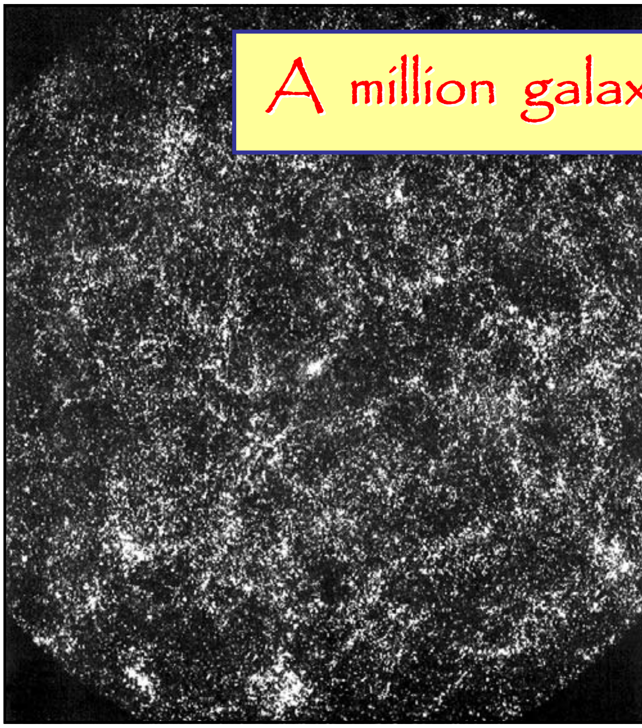


Courtesy: B. Tully

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

- the "Local Supercluster",
- a large flattened mass concentration ~ 10 h^{-1} Mpc in size,
- centered on one rich cluster, the Virgo cluster

A million galaxies



Shane-Wirtanen map:

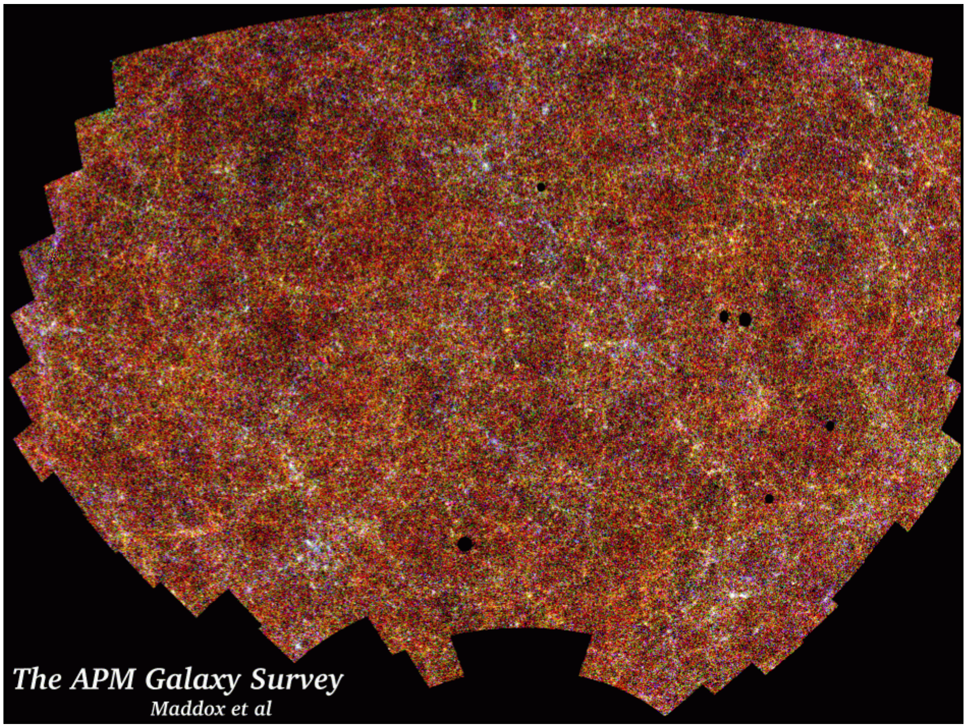
On the basis of the Shane-Wirtanen counts, P.J.E. Peebles produced a map of the sky distribution of 1 million galaxies on the sky:

- Clearly visible are clusters
- hint of filamentary LSS features, embedding clusters

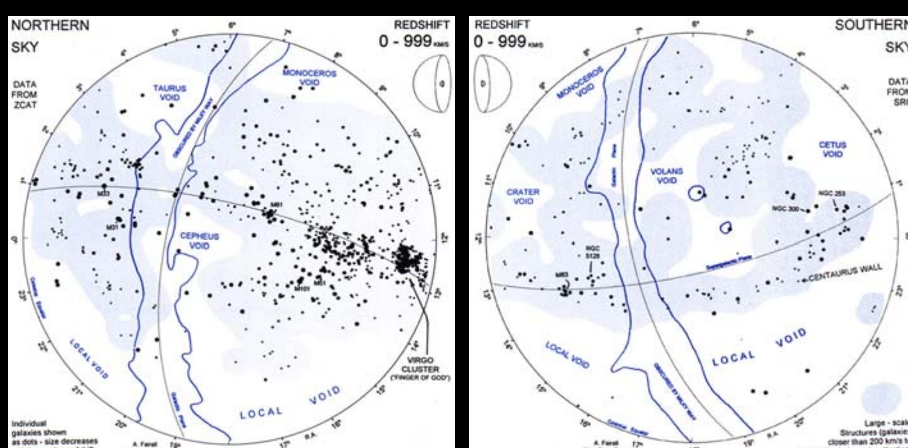
APM survey

- Sky map:
  - 2×10^6 galaxies
  - $17 < m < 20.5$
- Uniformly defined
- Sky region: 4300 sq. deg.
  - 185 UK Schmidt plates, 6° x 6°
- Large inhomogeneities, hints of weblike patterns, with clusters at densest regions.

courtesy: S. Maddox, G. Efstathiou, W. Sutherland, D. Loveday

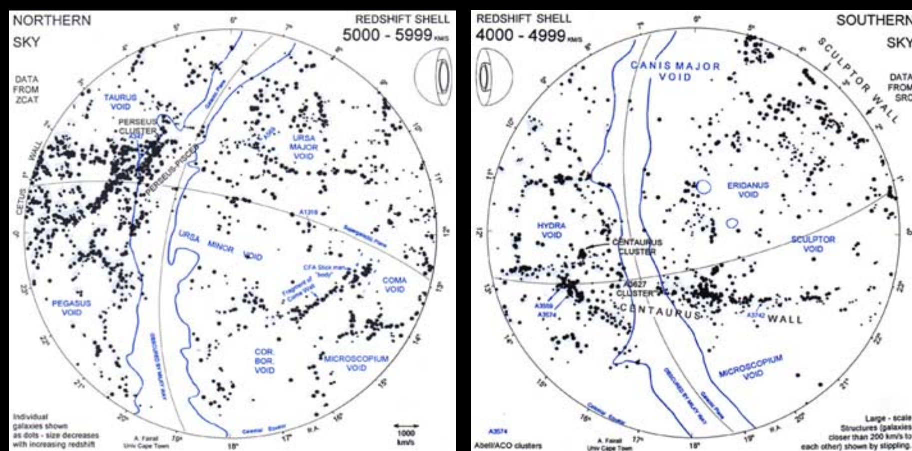


Local Views



Tony Fairall's nearby LSS map: Local Supercluster clearly visible at v < 999 km/s

Local Views: Moving into Foam

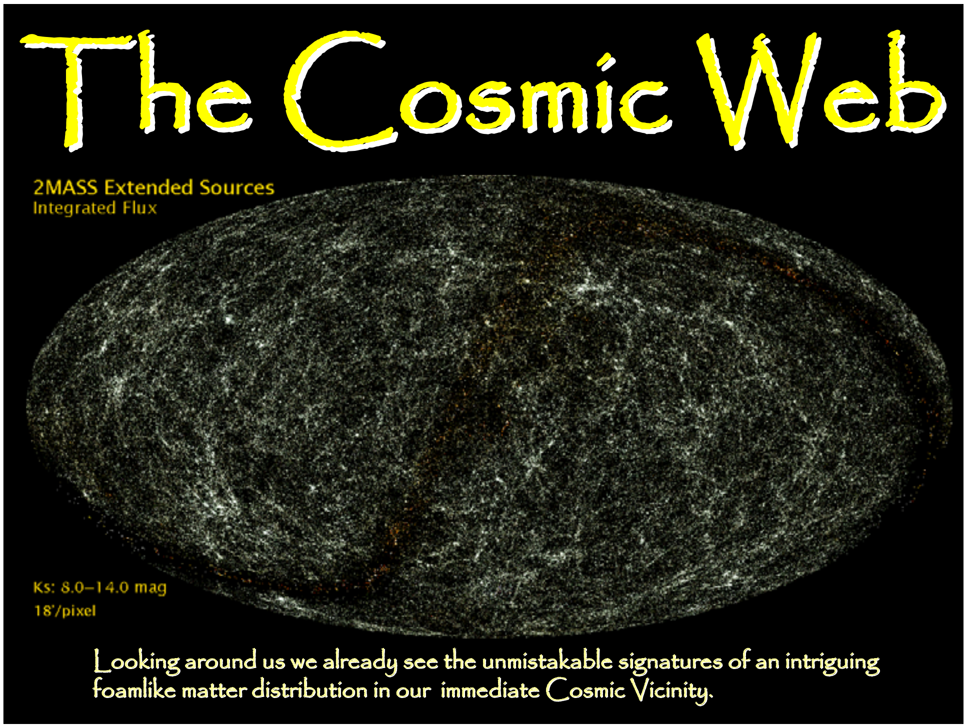


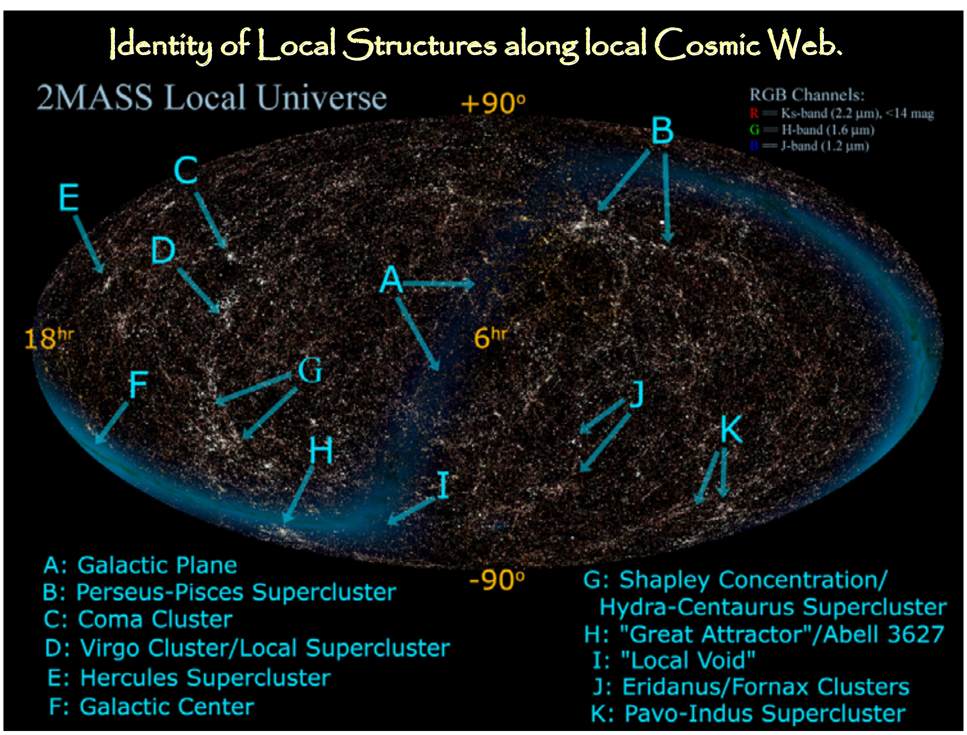
Tony Fairall's nearby LSS map: at cz=5000-5999 km/s clear views of local cosmic web

2MASS survey

- 2MASS all-sky survey: ground-based near-infrared survey whole sky, J(1.2 μm), H(1.6 μm), K(2.2 μm)
- 2MASS extended source catalog (XSC): 1.5 million galaxies
- unbiased sample nearby galaxies
- photometric redshifts: depth in 2MASS maps, "cosmic web" of (nearby) superclusters spanning the entire sky.

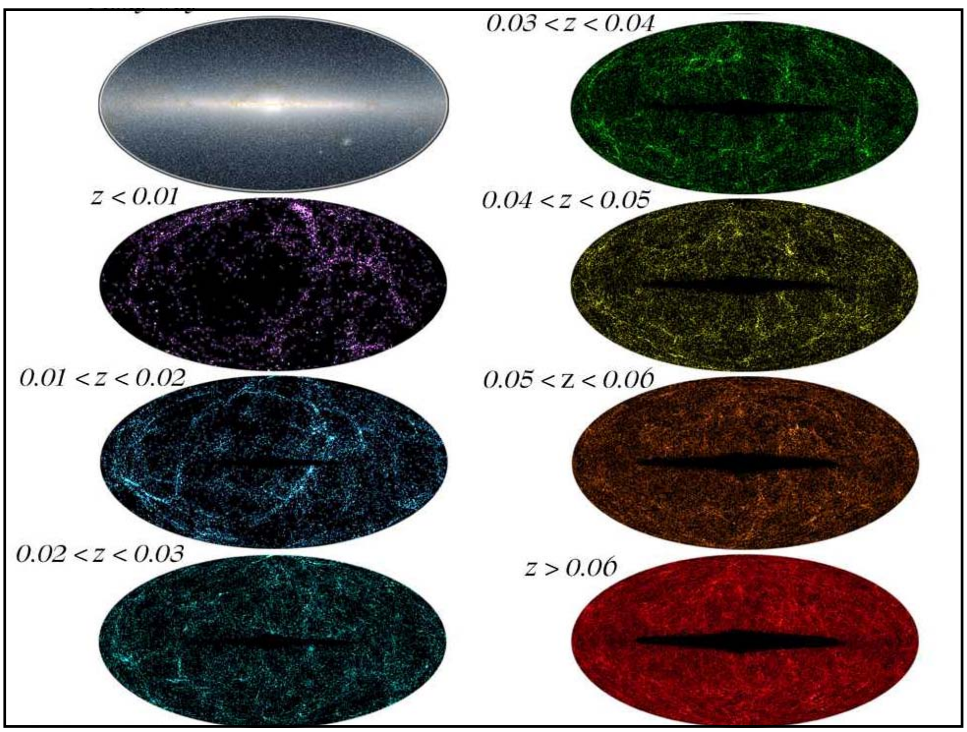
courtesy: T. Jarrett

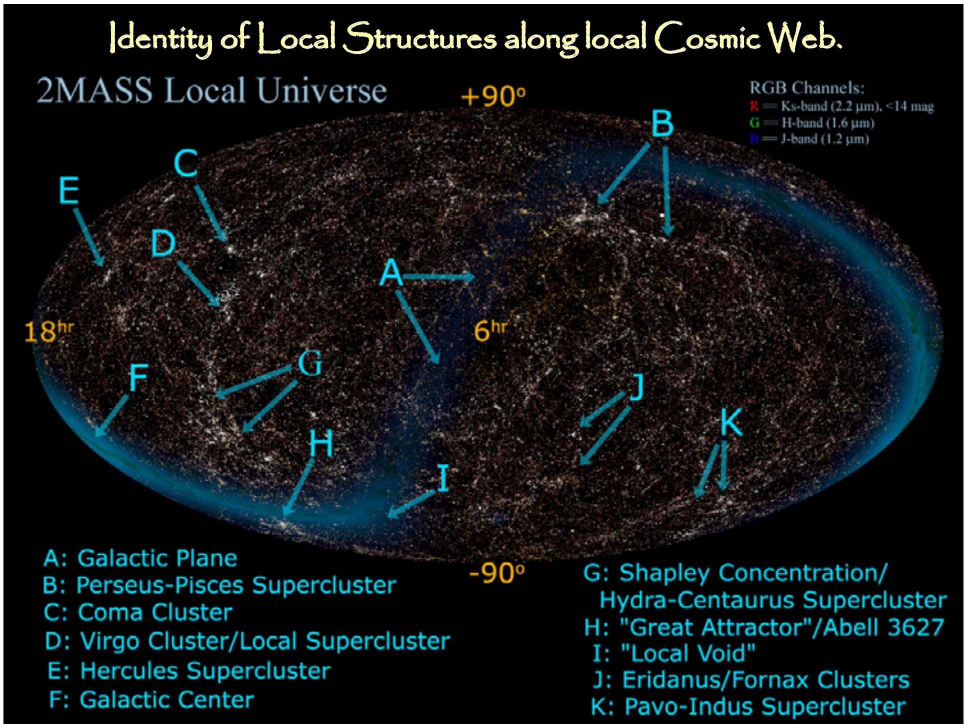

The Cosmic Web
2MASS Extended Sources
Integrated Flux
Ks: 8.0–14.0 mag
18'/pixel
Looking around us we already see the unmistakable signatures of an intriguing foamlike matter distribution in our immediate Cosmic Vicinity.


Identity of Local Structures along local Cosmic Web.
2MASS Local Universe
+90°
-90°
18hr
6hr
RGB Channels:
R — Ks-band (2.2 µm), <14 mag
G — H-band (1.6 µm)
B — J-band (1.2 µm)
A
B
C
D
E
F
G
H
I
J
K
A: Galactic Plane
B: Perseus-Pisces Supercluster
C: Coma Cluster
D: Virgo Cluster/Local Supercluster
E: Hercules Supercluster
F: Galactic Center
G: Shapley Concentration/ Hydra-Centaurus Supercluster
H: "Great Attractor"/Abell 3627
I: "Local Void"
J: Eridanus/Fornax Clusters
K: Pavo-Indus Supercluster

The Cosmic Web

2MASS: the cumulative view.
Moving outward we see the unfolding of the local cosmic foam.




Identity of Local Structures along local Cosmic Web.
2MASS Local Universe
+90°
RGB Channels:
R = Ks-band (2.2 μm), <14 mag
G = H-band (1.6 μm)
B = J-band (1.2 μm)
18hr
6hr
-90°
A B C D E F G H I J K
A: Galactic Plane
B: Perseus-Pisces Supercluster
C: Coma Cluster
D: Virgo Cluster/Local Supercluster
E: Hercules Supercluster
F: Galactic Center
G: Shapley Concentration/
Hydra-Centaurus Supercluster
H: "Great Attractor"/Abell 3627
I: "Local Void"
J: Eridanus/Fornax Clusters
K: Pavo-Indus Supercluster

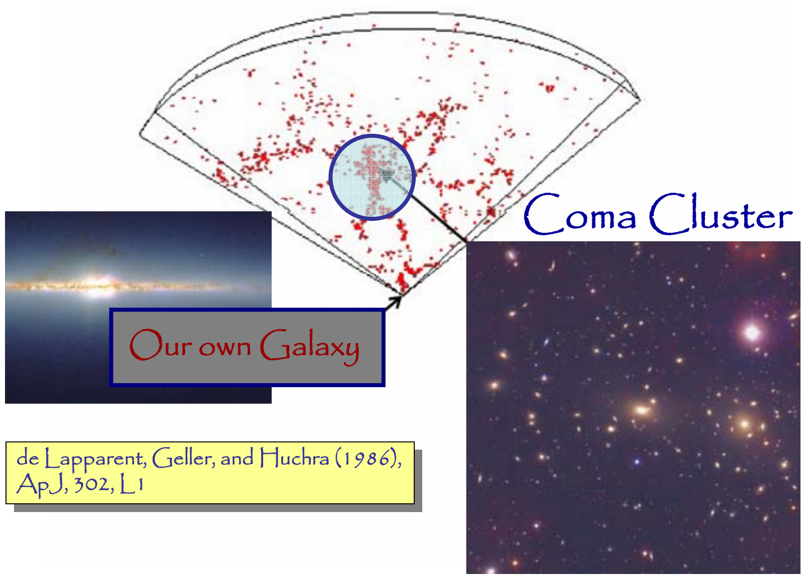
Maps of the Local Universe

The Cosmic Web Revealed:

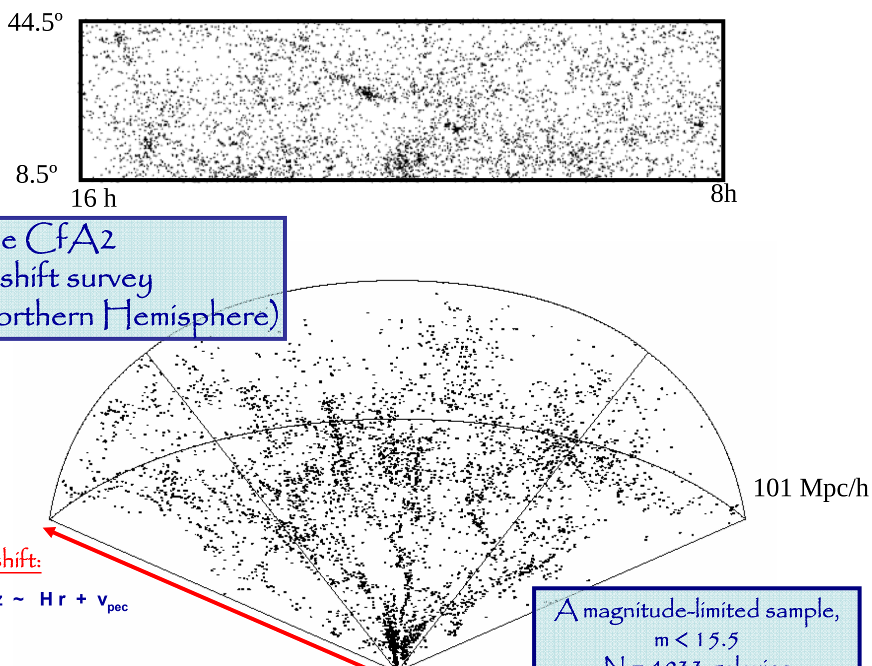
The CfA2 and SDSS survey slices

(de Lapparent, Geller, Huchra, … 1986, …)

Mapping the Universe



de Lapparent, Geller, and Huchra (1986), ApJ, 302, L1



The CfA2 redshift survey (Northern Hemisphere)

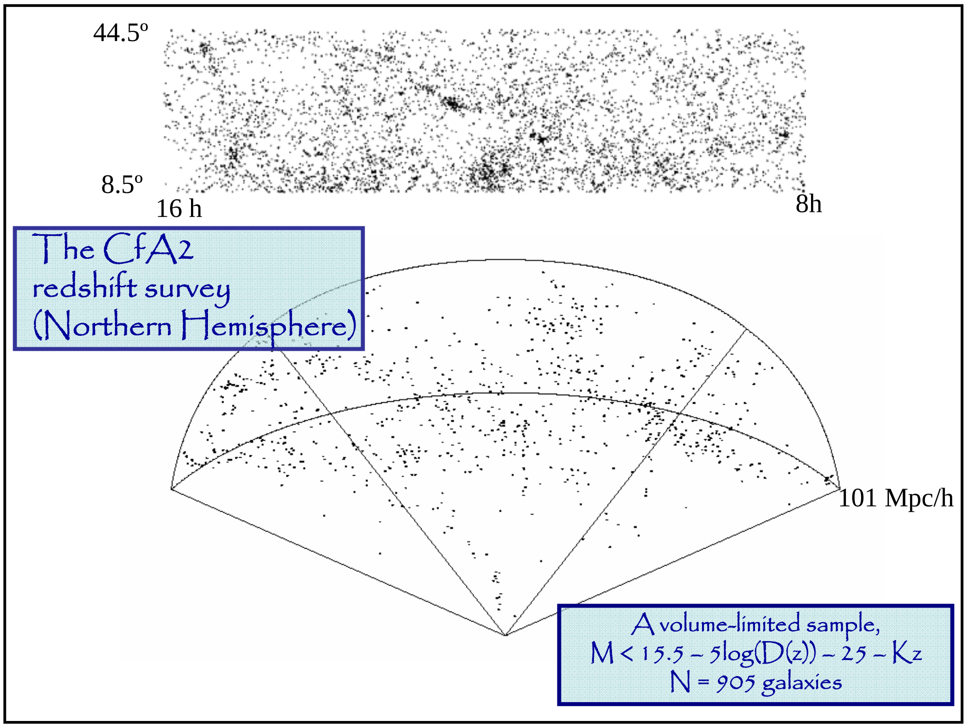
Redshift:

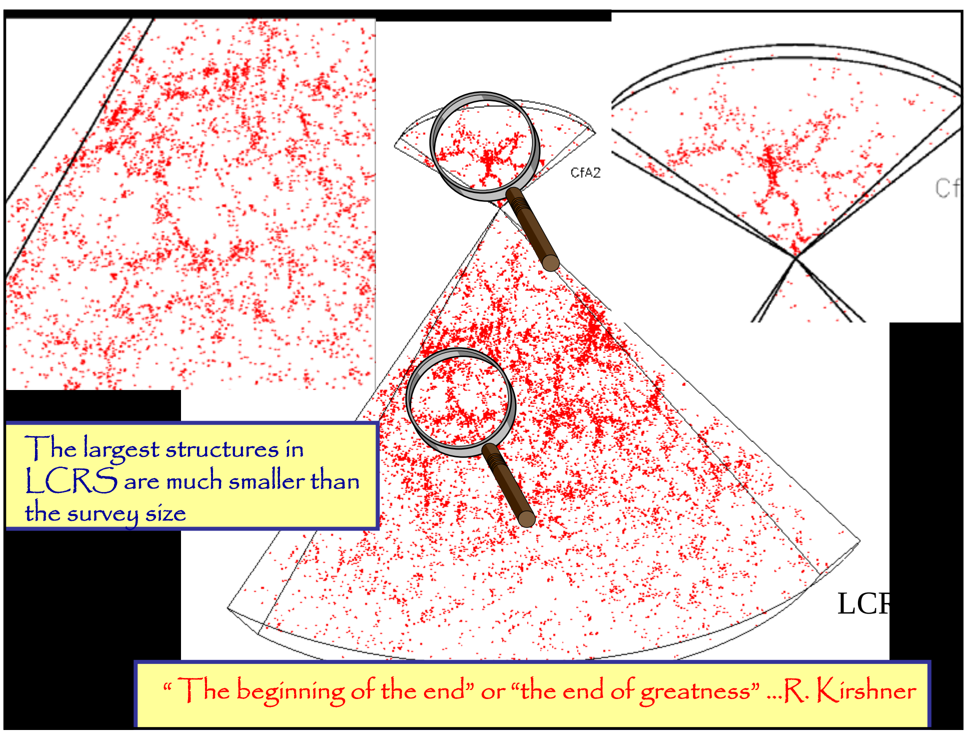
$v = cz \sim Hr + v_{pec}$

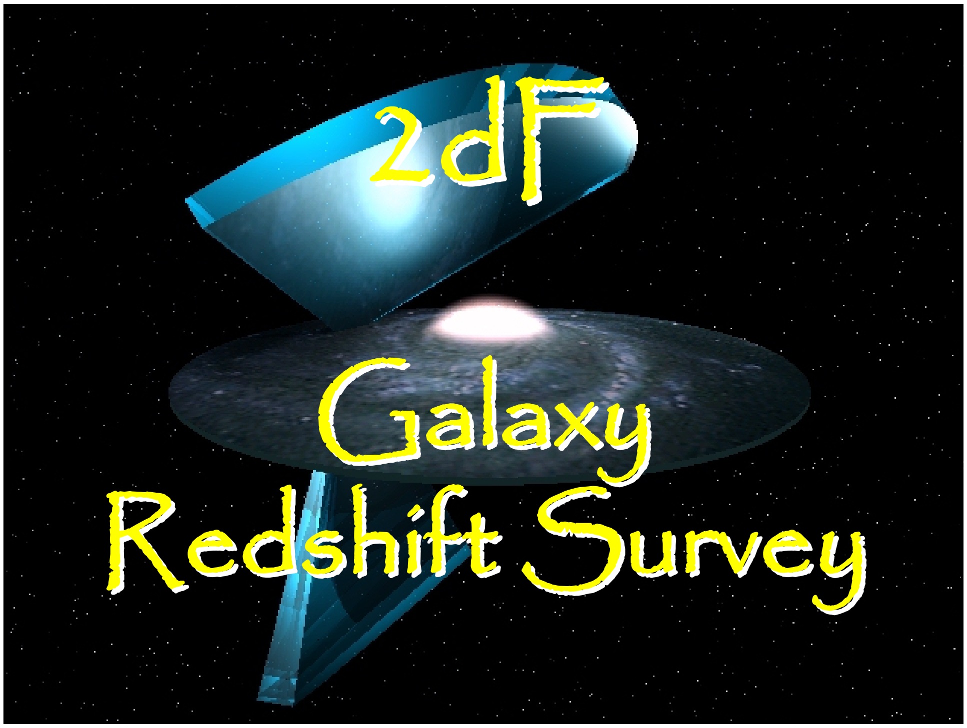
A magnitude-limited sample, $m < 15.5$

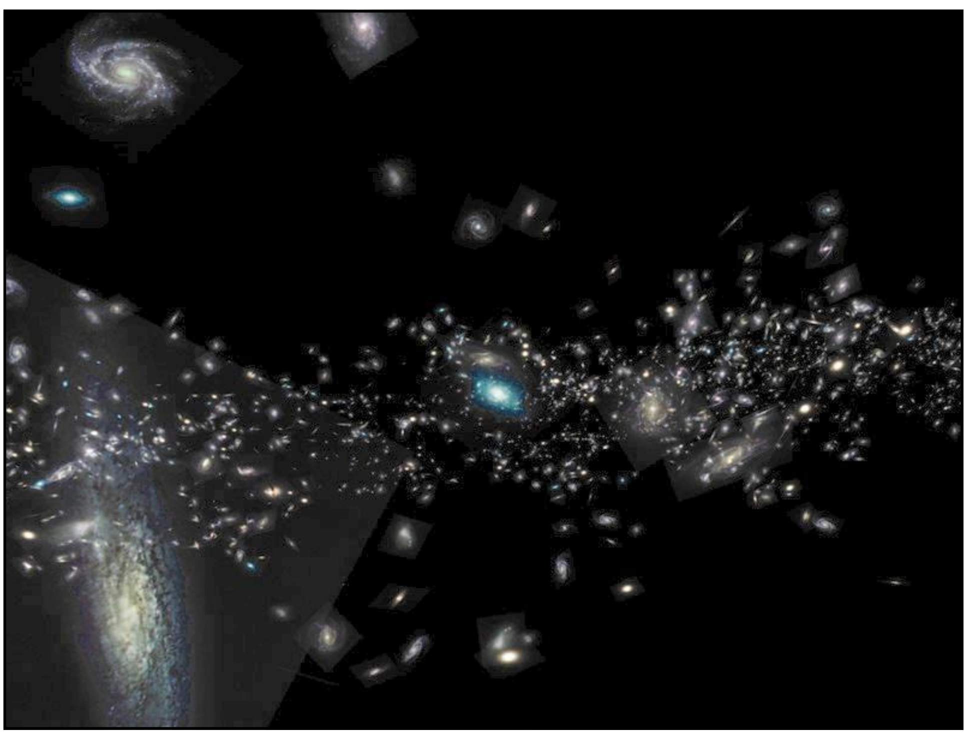
N = 4933 galaxies

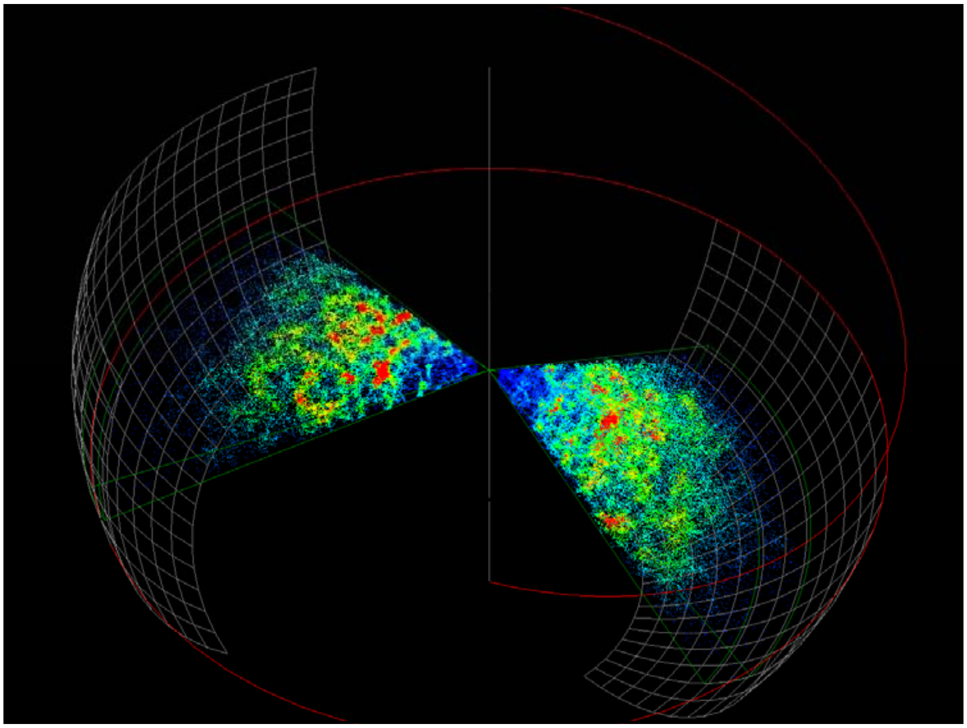
Figure courtesy: V. Martinez

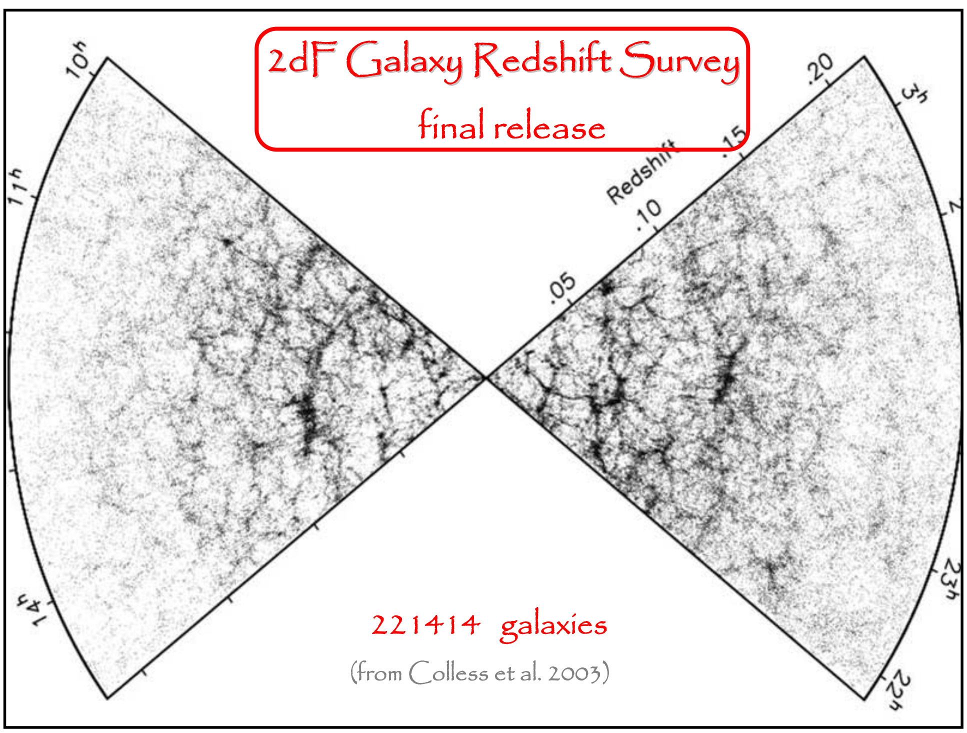

44.5º
8.5º
16 h
8h
The CfA2
redshift survey
(Northern Hemisphere)
101 Mpc/h
A volume-limited sample,
M < 15.5 – 5log(D(z)) – 25 – Kz
N = 905 galaxies


CfA2
The largest structures in
LCRS are much smaller than
the survey size
" The beginning of the end" or "the end of greatness" ...R. Kirshner


2dF
Galaxy
Redshift Survey





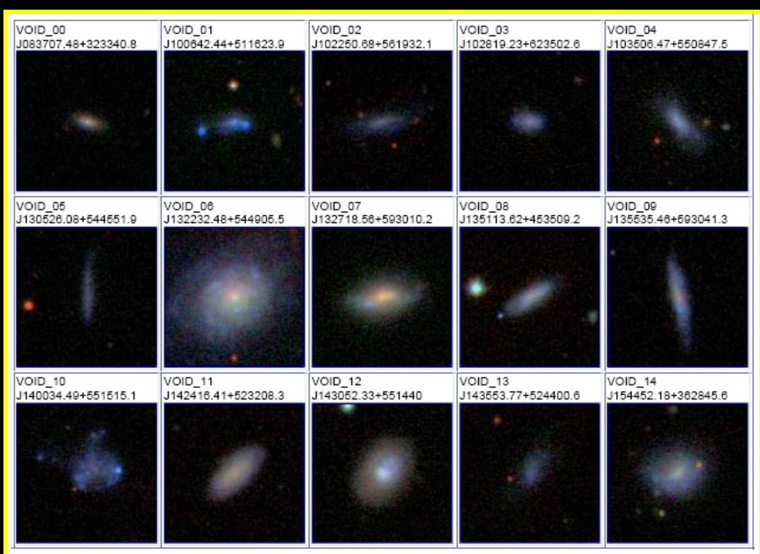

2dF Galaxy Redshift Survey
final release
Redshift
.05
.10
.15
.20
10h
11h
14h
3h
23h
22h
221414 galaxies
(from Colless et al. 2003)

SDSS survey

- Largest and most systematic (digital !) sky survey in history of astronomy.
- Images sky in 5 photometric bands !!!!
  Down to apparent magnitude r~23.1
- Covers ~ 25% of the sky: 8452 sq. deg.
- With 2dFGRS, the SDSS will produce the most extensive map of the
  spatial structure of our cosmic neighbourhood.
- Million galaxies subsequently selected for measuring redshift z:
  electromagnetic spectrum

- Total:
  sky survey: 10^8 stars, 10^8 galaxies, 10^5 quasars
  spectroscopy: 10^6 galaxies, 10^5 quasars, 10^5 stars

SDSS survey



The Cosmic Web

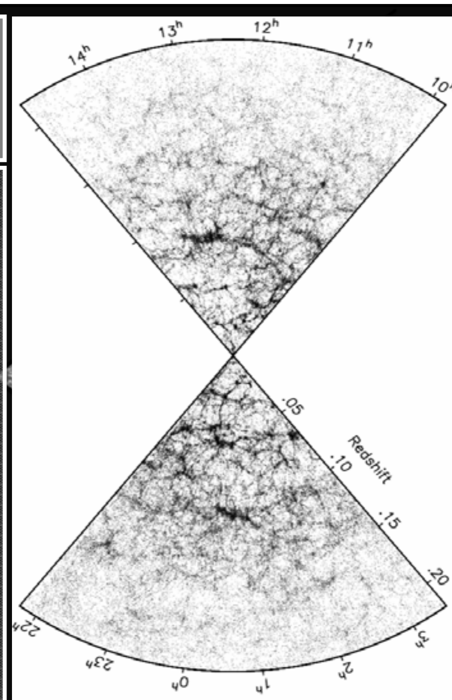
Weblike Network of Galaxies:

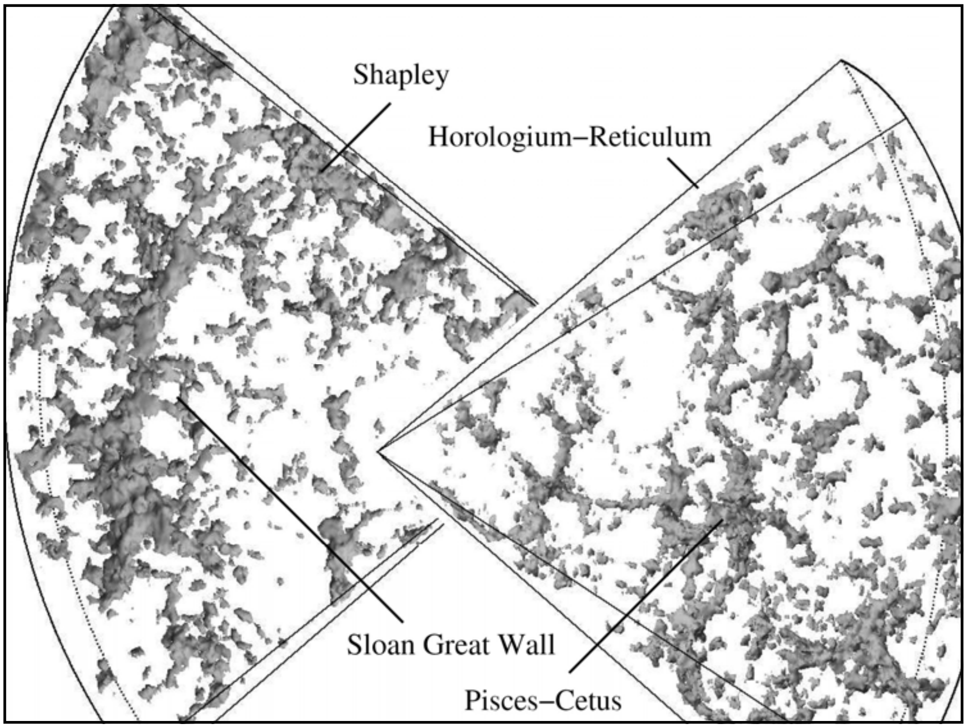
- Walls
- Filaments
- Clusters
- Voids

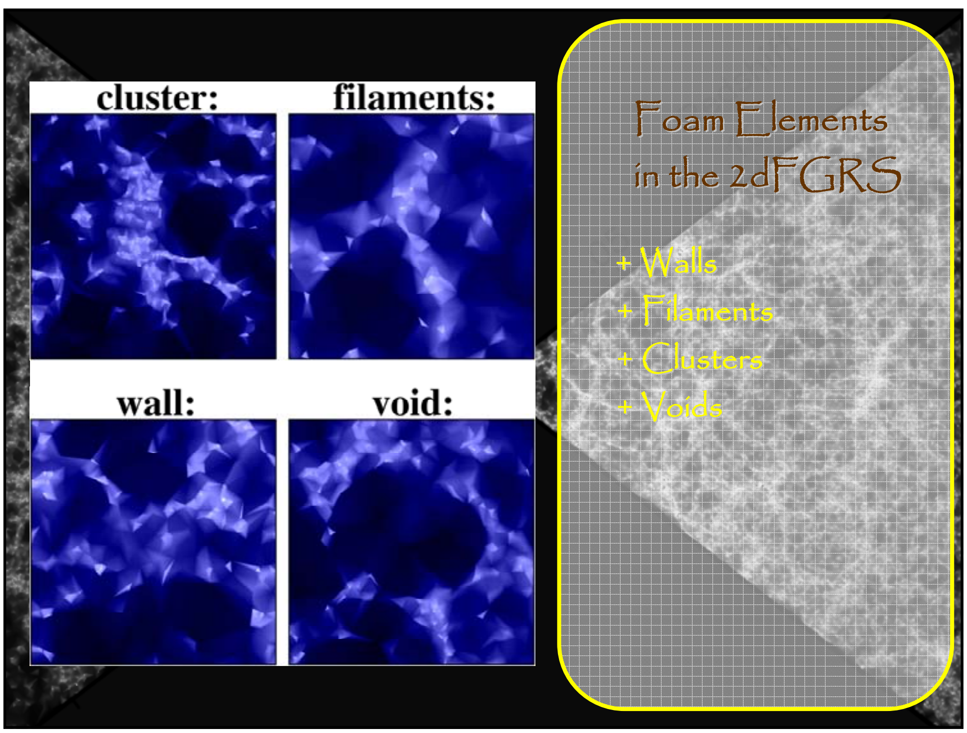
Spatial Organization:

Non-trivial stochastic pattern of filaments and walls – filaments marking the dense ridges of the walls – which join up at high-density junctions, sites of rich clusters.

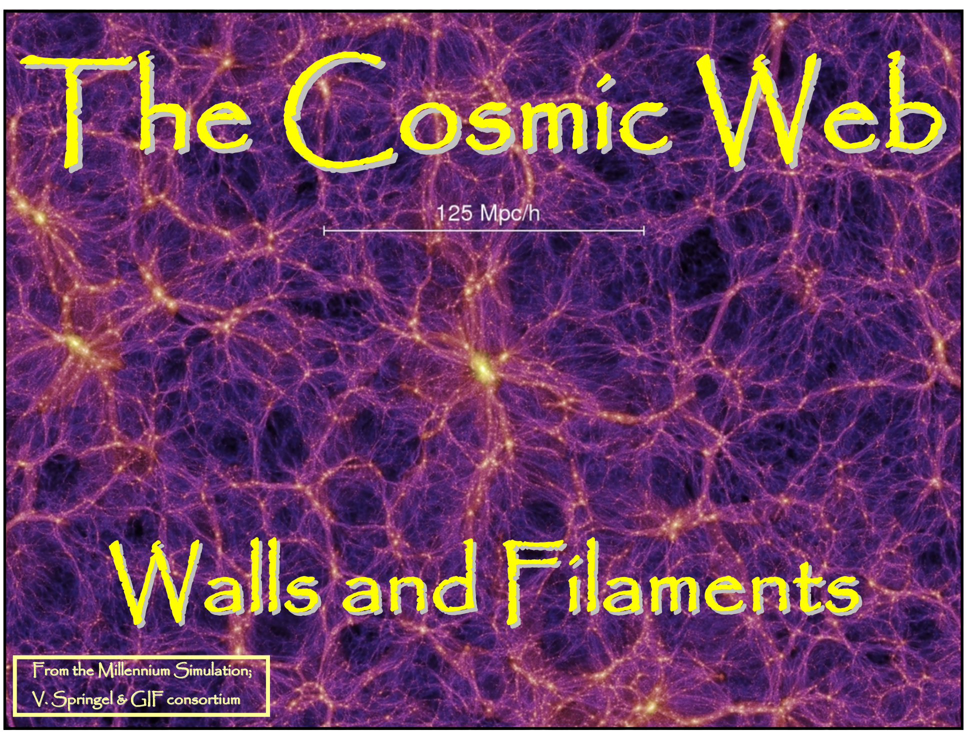
Walls, filaments and clusters framed in spatial network in which their spatial distribution is dictated by their location on the surface of roundish and near-empty voids.

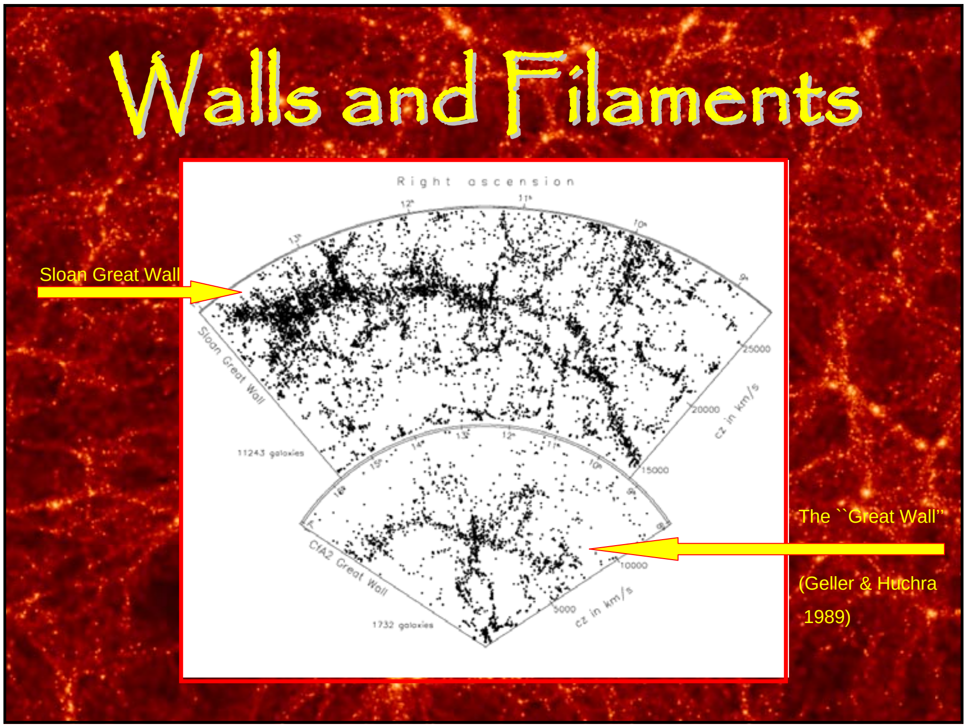


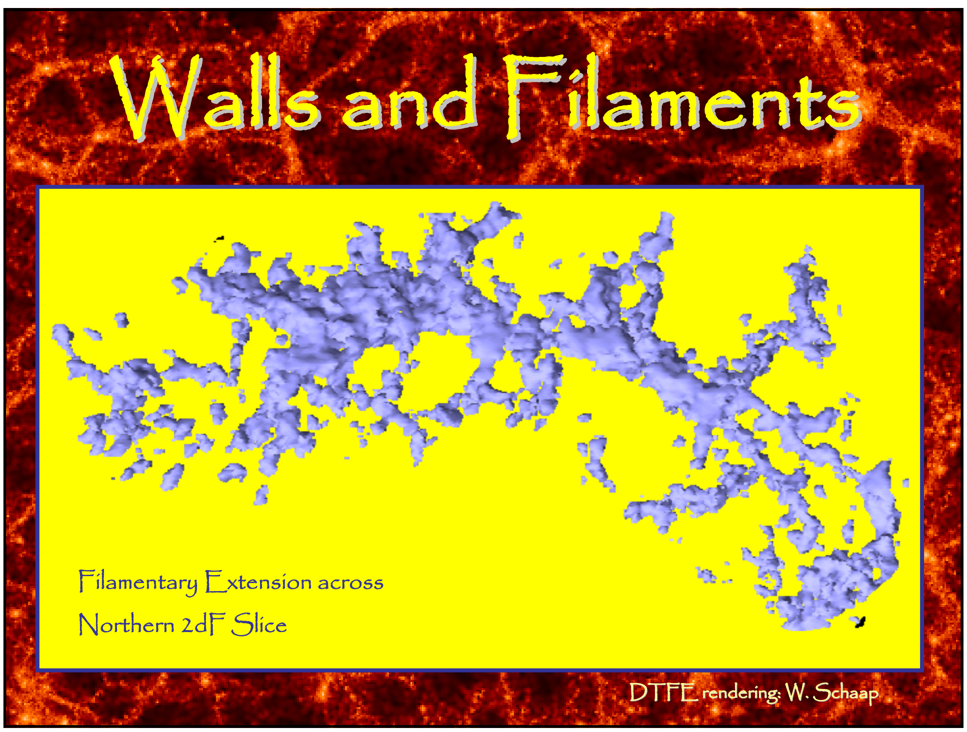

Shapley
Horologium–Reticulum
Sloan Great Wall
Pisces–Cetus


cluster:
filaments:
wall:
void:
Foam Elements in the 2dFGRS
+ Walls
+ Filaments
+ Clusters
+ Voids

The Elements




Walls and Filaments
Right ascension
Sloan Great Wall
Sloan Great Wall
11243 galaxies
CfA2 Great Wall
1732 galaxies
cz in km/s
The ``Great Wall''
(Geller & Huchra
1989)


Walls and Filaments
Filamentary Extension across
Northern 2dF Slice
DTFE rendering: W. Schaap

Walls and Filaments

Pisces-Perseus Supercluster

Canonic example of a strongly flattened supercluster consisting of

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

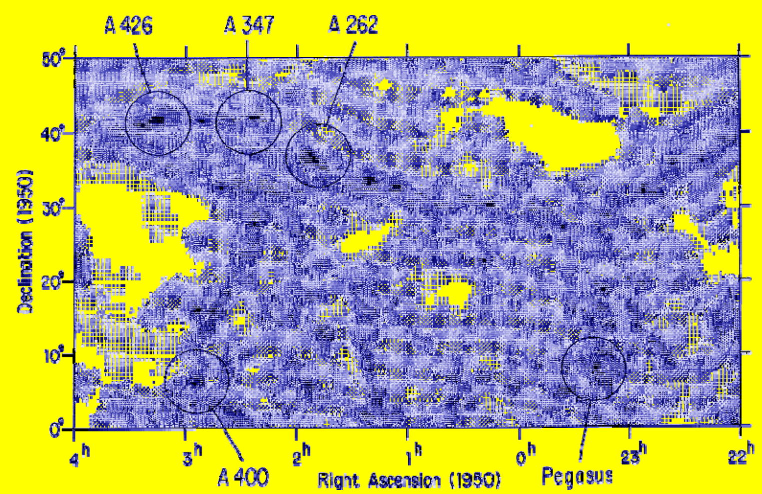
Northern boundary: ridge south-westward of Perseus cluster (A426)

Dimensions Ridge: $5h^{-1}$ Mpc wide

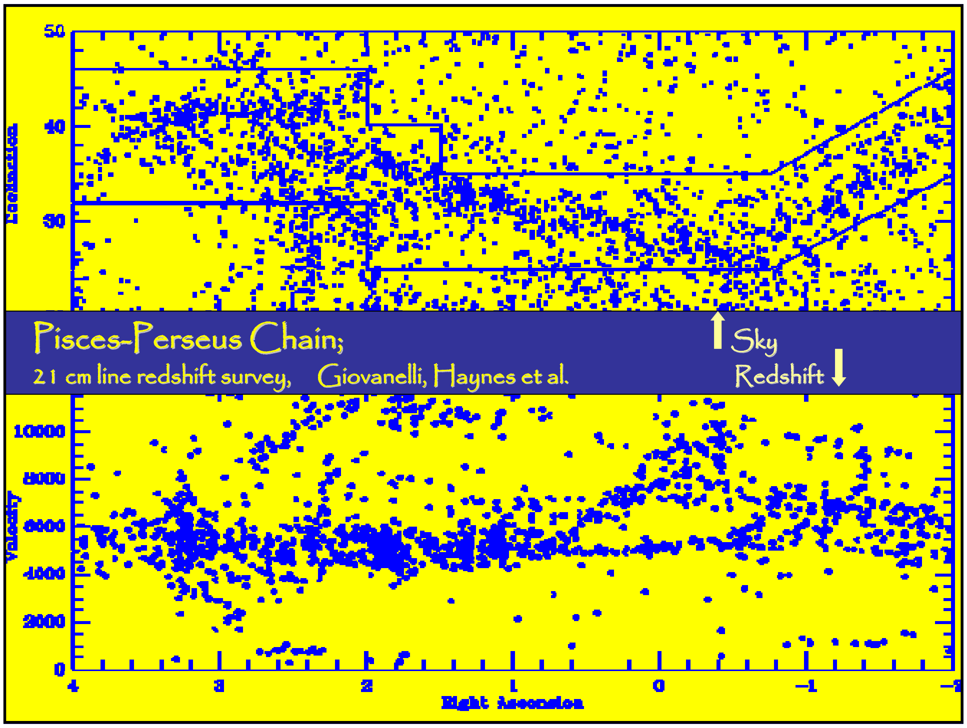
$50h^{-1}$ Mpc length; possible $140h^{-1}$ Mpc extension

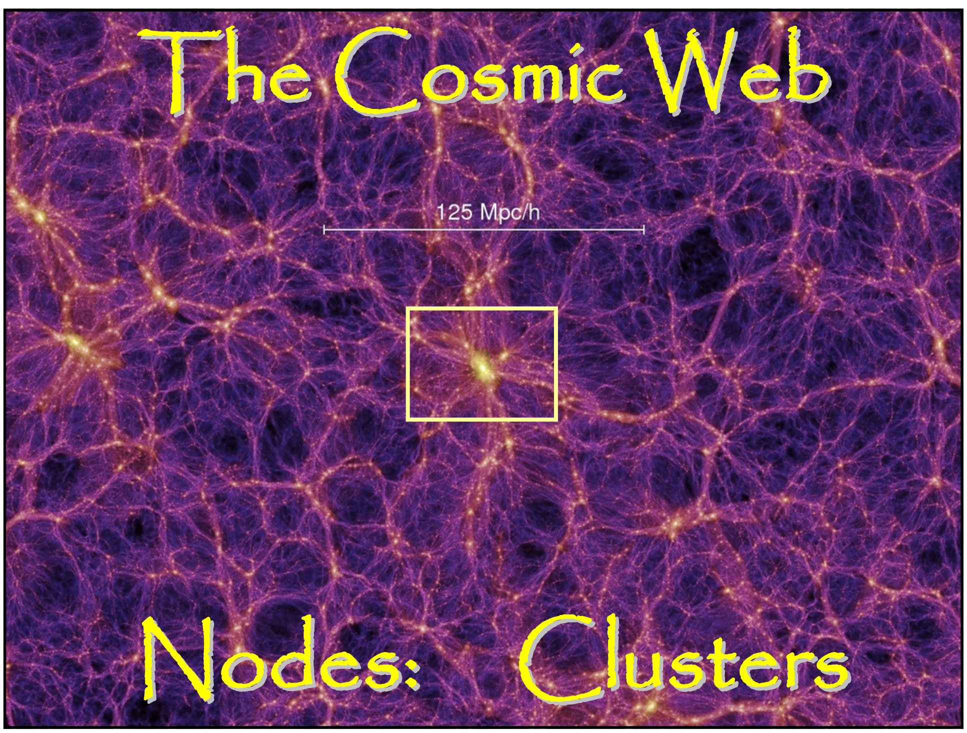
Along Ridge: high density clusters, incl. A462, A347, A262

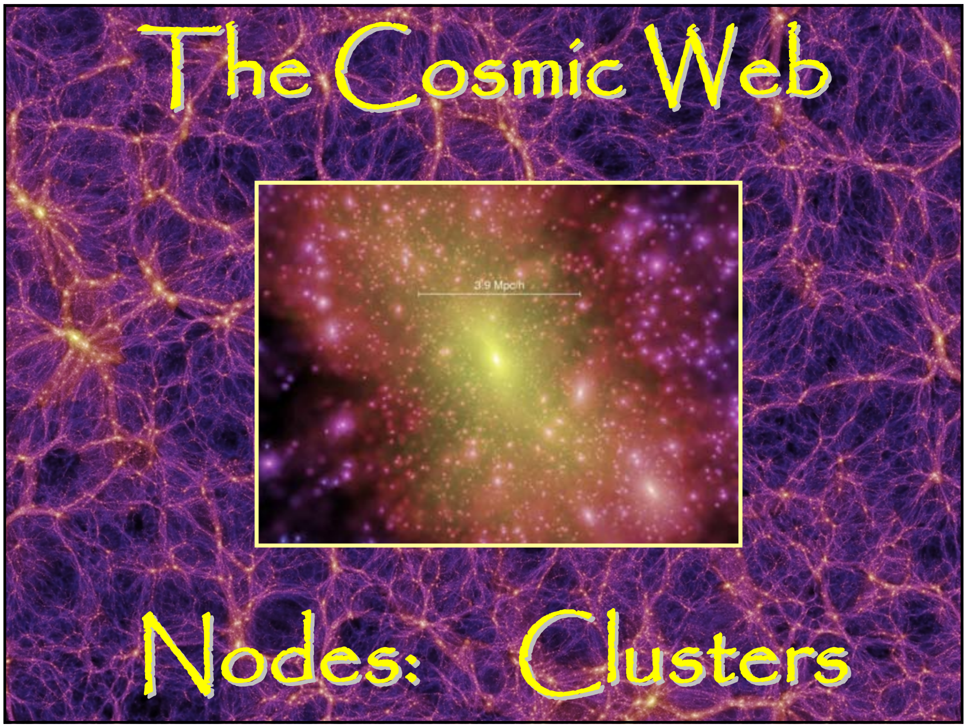
Walls and Filaments

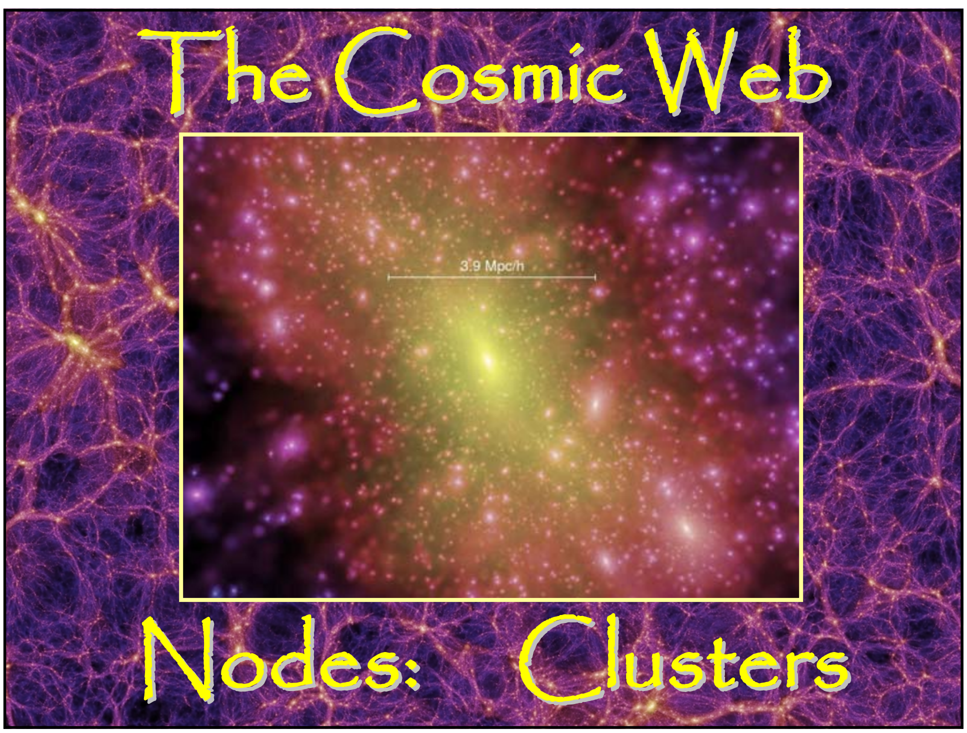


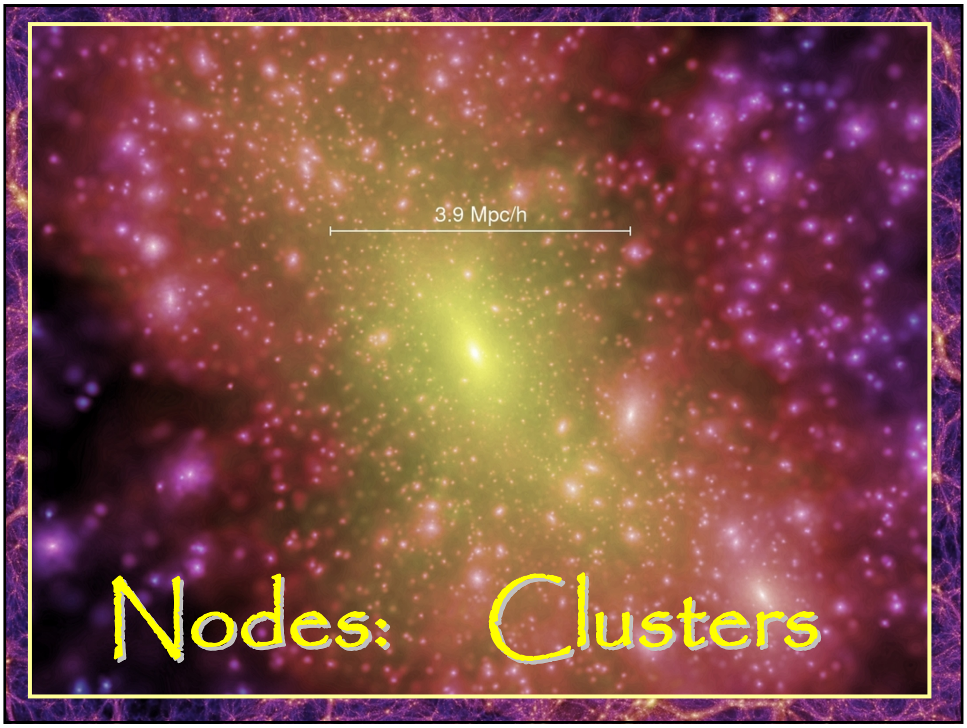
Pisces-Perseus Chain; 21 cm line redshift survey, Giovanelli & Haynes


Pisces-Perseus Chain;
21 cm line redshift survey, Giovanelli, Haynes et al.
Sky
Redshift
Declination
Velocity
Right Ascension
50
40
30
10000
8000
6000
4000
2000
0
4
3
2
1
0
−1


The Cosmic Web
125 Mpc/h
Nodes: Clusters


The Cosmic Web
3.9 Mpc/h
Nodes: Clusters

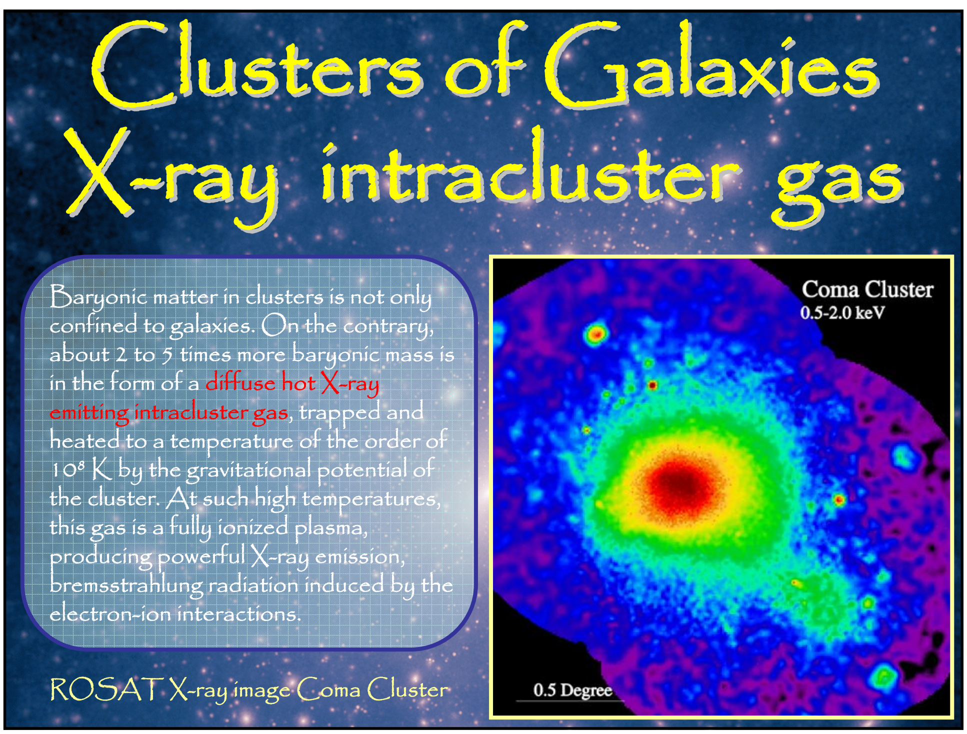

The Cosmic Web
3.9 Mpc/h
Nodes: Clusters



Clusters of Galaxies

- Assemblies of up to 1000s of galaxies within a radius of only 1.5-2h^{-1} Mpc,
- Representing overdensities of δ~1000
- Galaxy move around with velocities ~ 1000 km/s
- They are the most massive, and most recently, fully collapsed structures in our Universe.


Clusters of Galaxies
Coma Cluster
Courtesy:
O. Lopez-Cruz


Clusters of Galaxies
X-ray intracluster gas
Baryonic matter in clusters is not only confined to galaxies. On the contrary, about 2 to 5 times more baryonic mass is in the form of a diffuse hot X-ray emitting intracluster gas, trapped and heated to a temperature of the order of 10⁸ 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
Coma Cluster
0.5-2.0 keV
0.5 Degree

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.

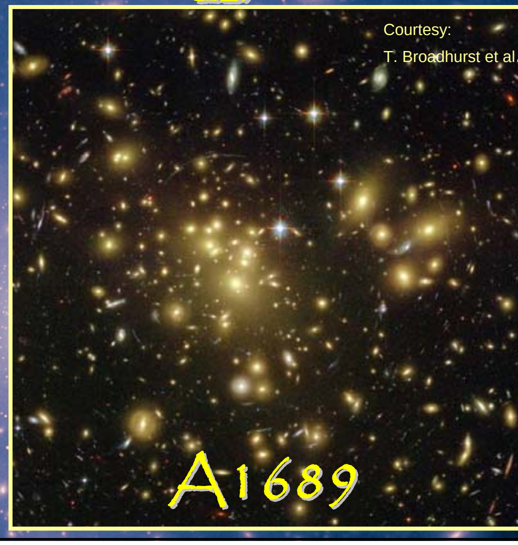
According to

Einstein's theory of

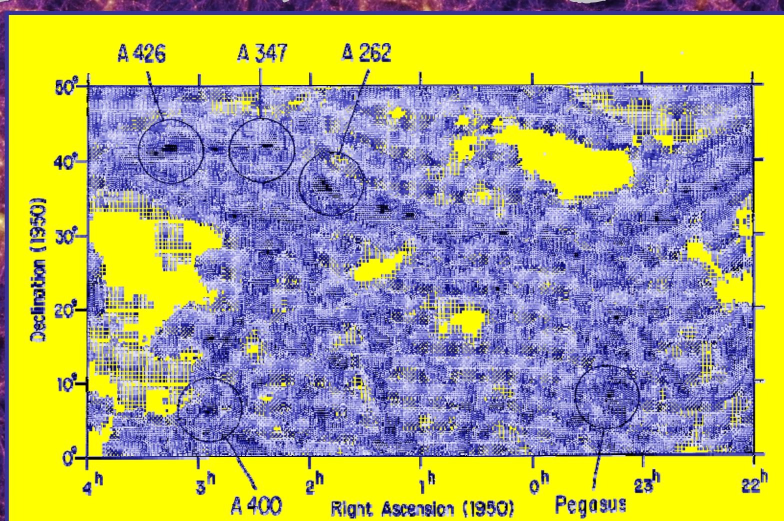
General Relativity,

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

Gravitational Lens.

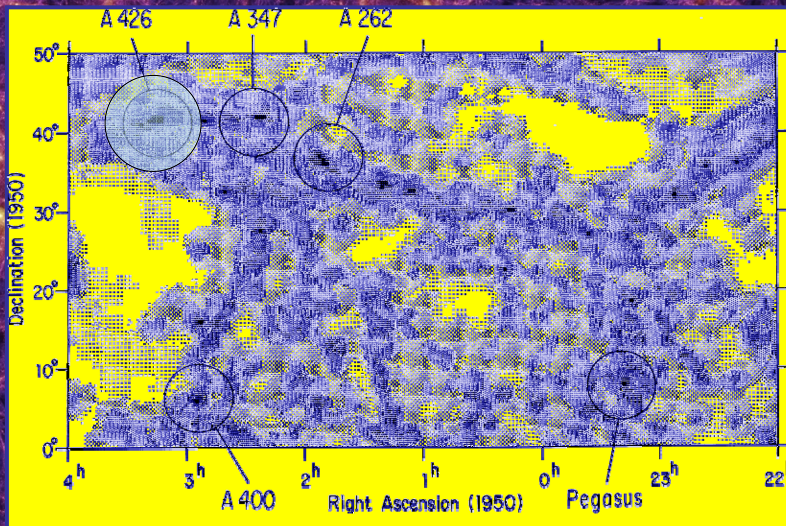


Cosmic Web & Clusters



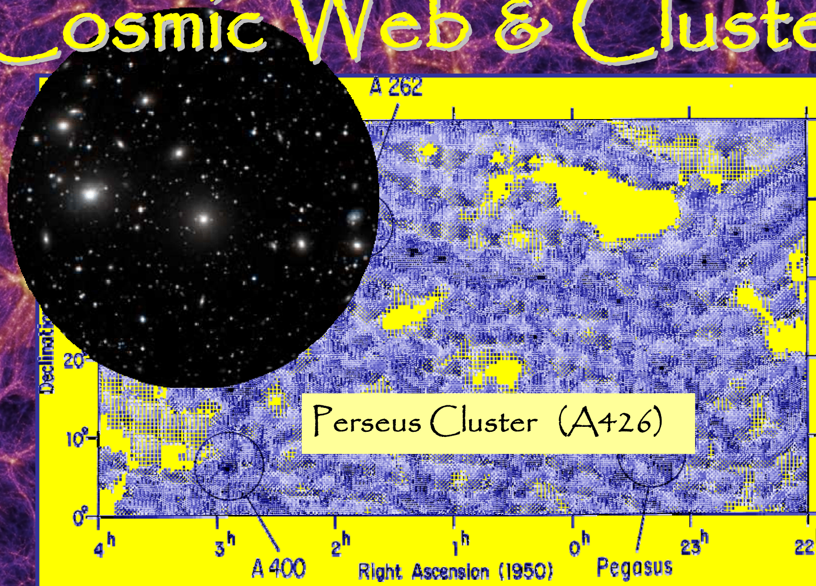
Pisces-Perseus Chain; 21 cm line redshift survey, Giovanelli & Haynes

Cosmic Web & Clusters

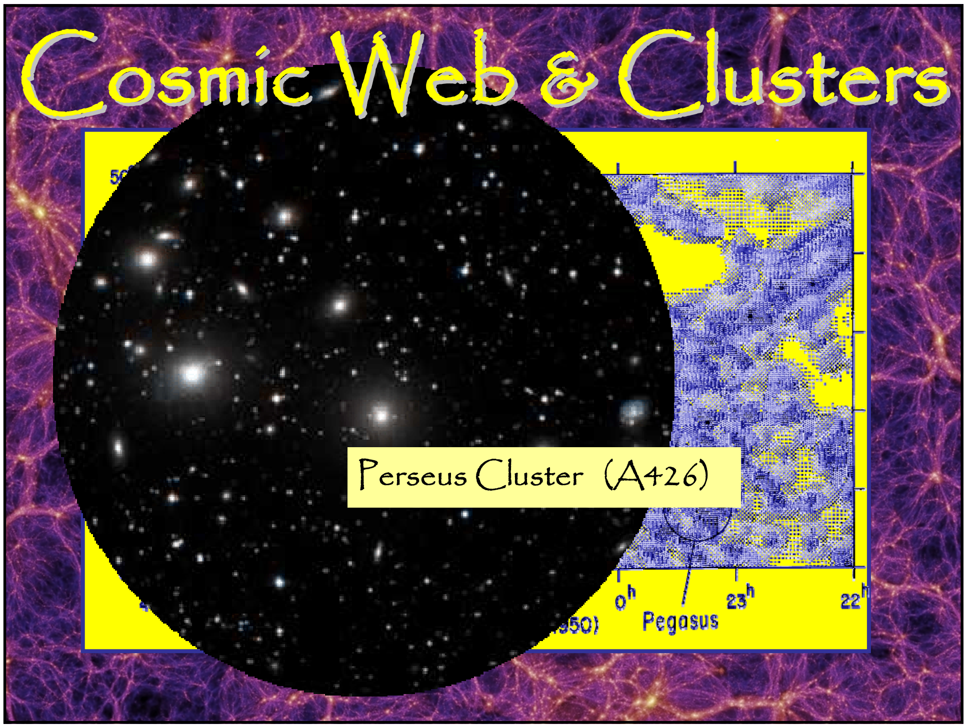


Pisces-Perseus Chain; 21 cm line redshift survey, Giovanelli & Haynes

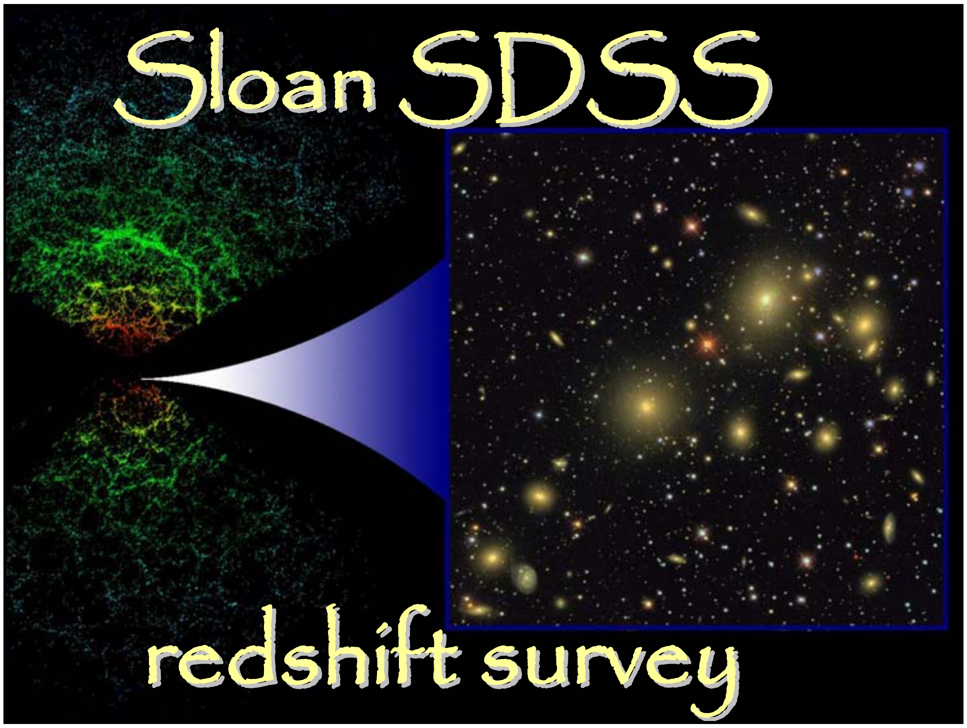
Cosmic Web & Clusters

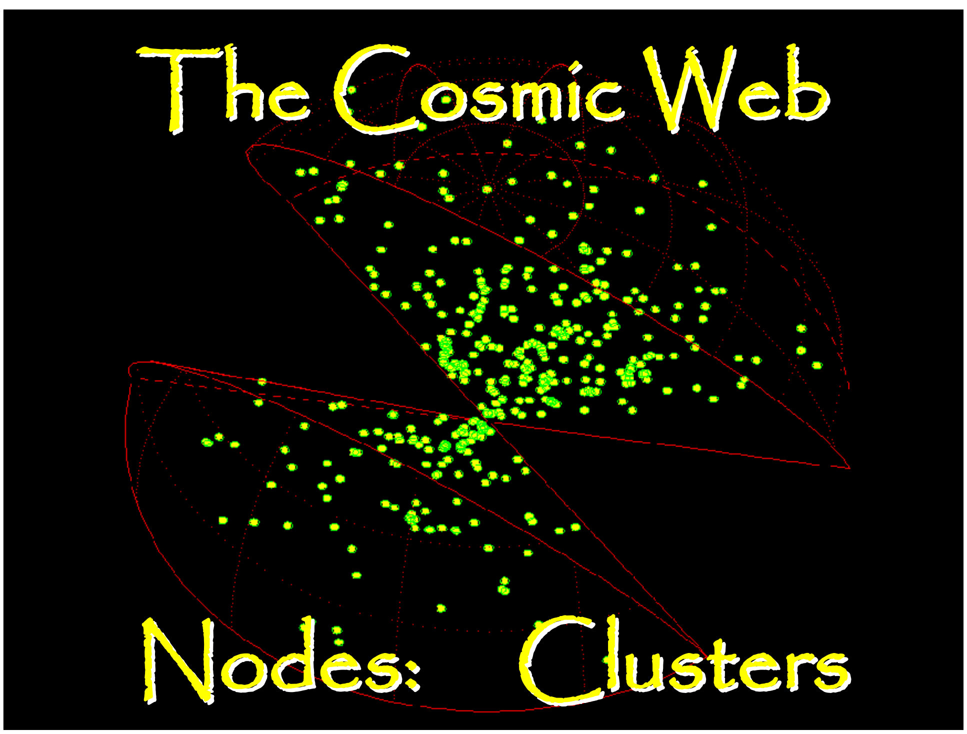


Perseus Cluster (A426)

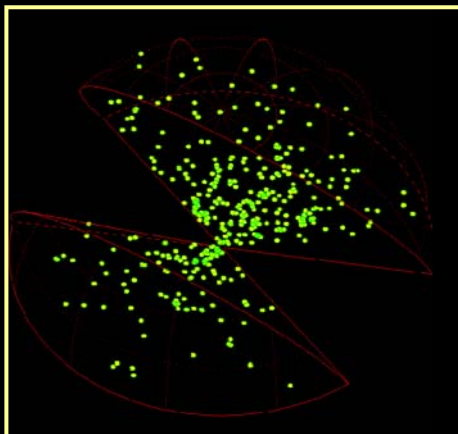

Cosmic Web & Clusters
Perseus Cluster (A426)
0h
23h
22h
Pegasus


Cosmic Web & Clusters
Perseus Cluster (A426)


Sloan SDSS
redshift survey


The Cosmic Web
Nodes: Clusters

The Cosmic Web



The spatial cluster distribution.

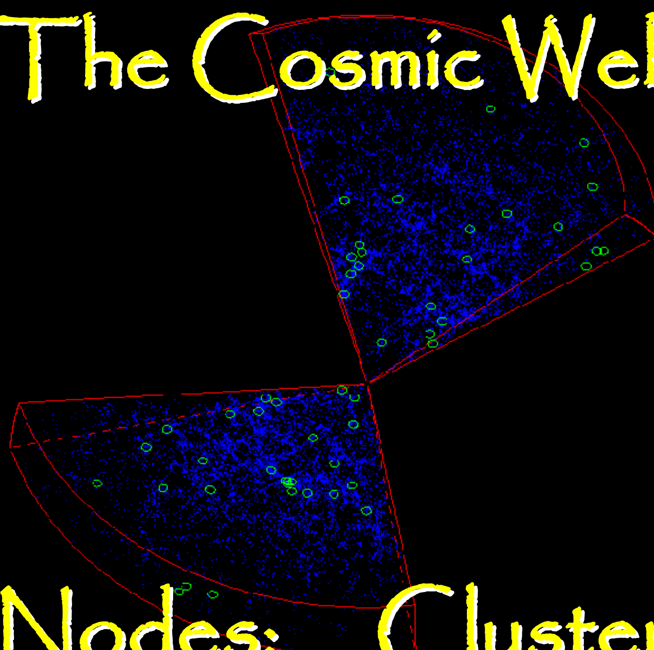
The full volume of the X-ray cluster REFLEX cluster survey within a distance of $600h^{-1}$ Mpc. The REFLEX galaxy cluster catalogue contains all clusters brighter than an X-ray flux of 3x10 ergs cm^{-2} over a large part of the in the southern sky. The missing part of hemisphere delineates the region highly obscured by the Galaxy.

REFLEX: Boehringer et al. (2001)

Courtesy: Borgani & Guzzo (2001)

Nodes: Clusters

The Cosmic Web



Nodes: Clusters

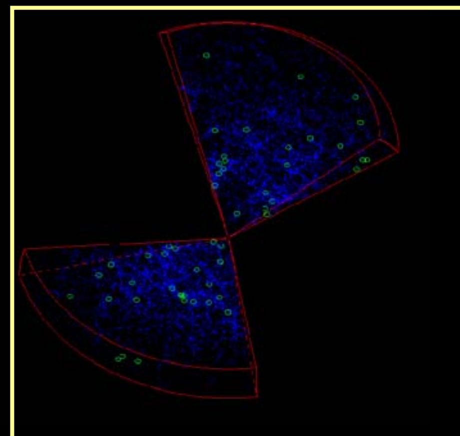
The Cosmic Web

The spatial cluster distribution and relation to Cosmic Web.

The green circles mark the positions of REFLEX X-ray clusters in the northern and southern slices of the Las Campanas redshift survey (LCRS, Shectman et al. 1996), out to a maximum distance of 600h^{-1} Mpc. Underlying, in blue, the galaxies in the LCRS delineate a foamlike distribution of filaments, walls and voids.

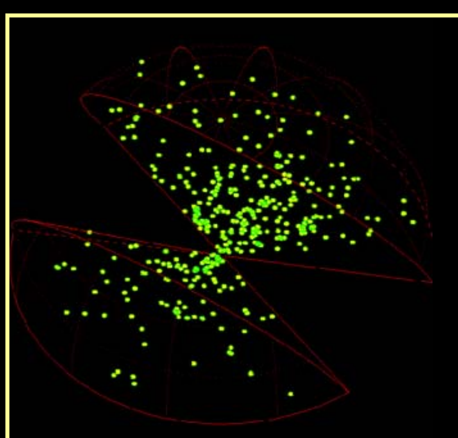
REFLEX: Boehringer et al. (2001)

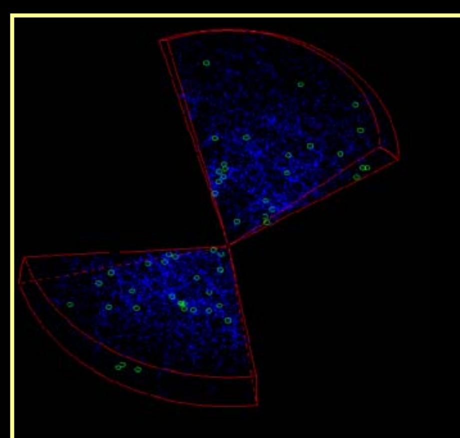
Courtesy: Borgani & Guzzo (2001)



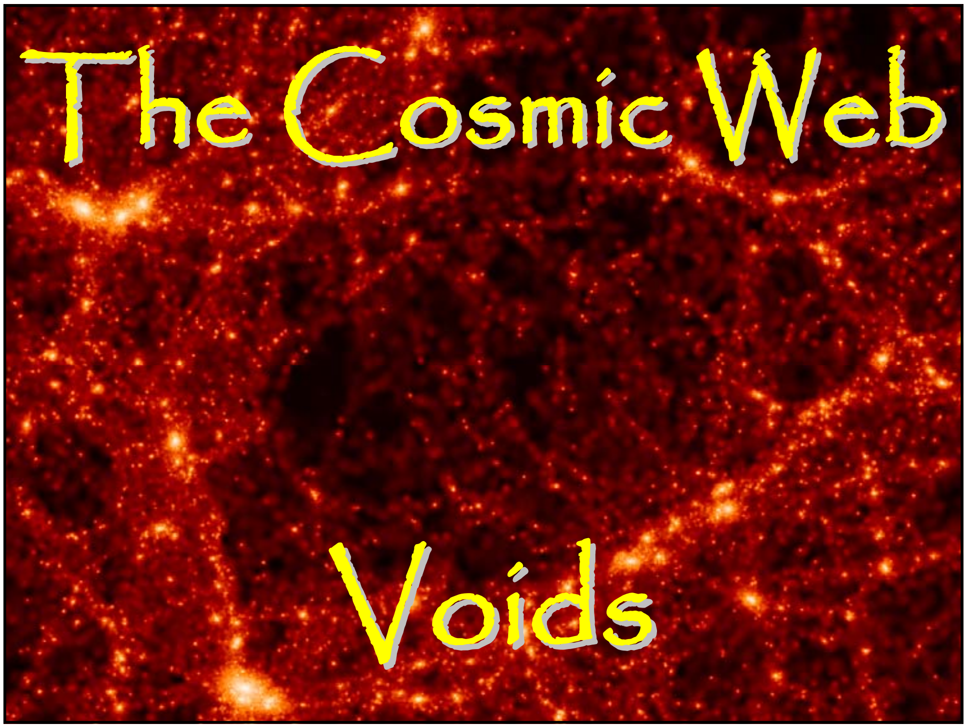
Nodes: Clusters

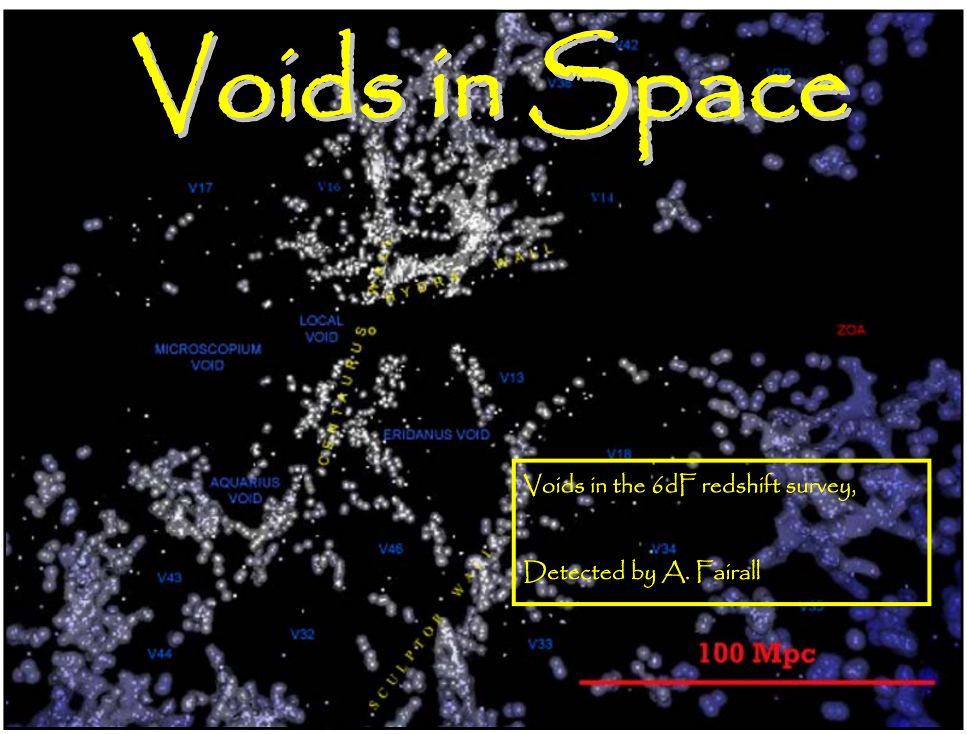
The Cosmic Web



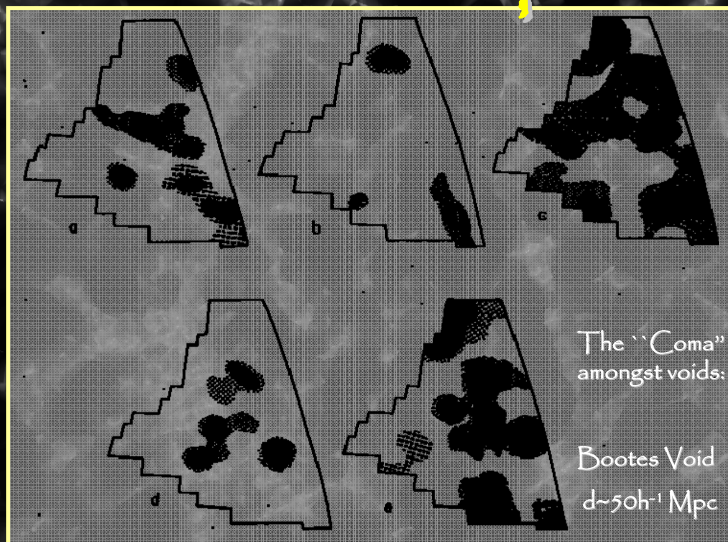


Nodes: Clusters


The Cosmic Web
Voids


Voids in Space
V17
V16
V14
HYDRA WALL
LOCAL VOID
MICROSCOPIUM VOID
ZOA
V13
ERIDANUS VOID
V18
AQUARIUS VOID
Voids in the 6dF redshift survey,
Detected by A. Fairall
V46
V34
V43
V32
V44
V33
100 Mpc

Voids in Space



Voids in Space

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.

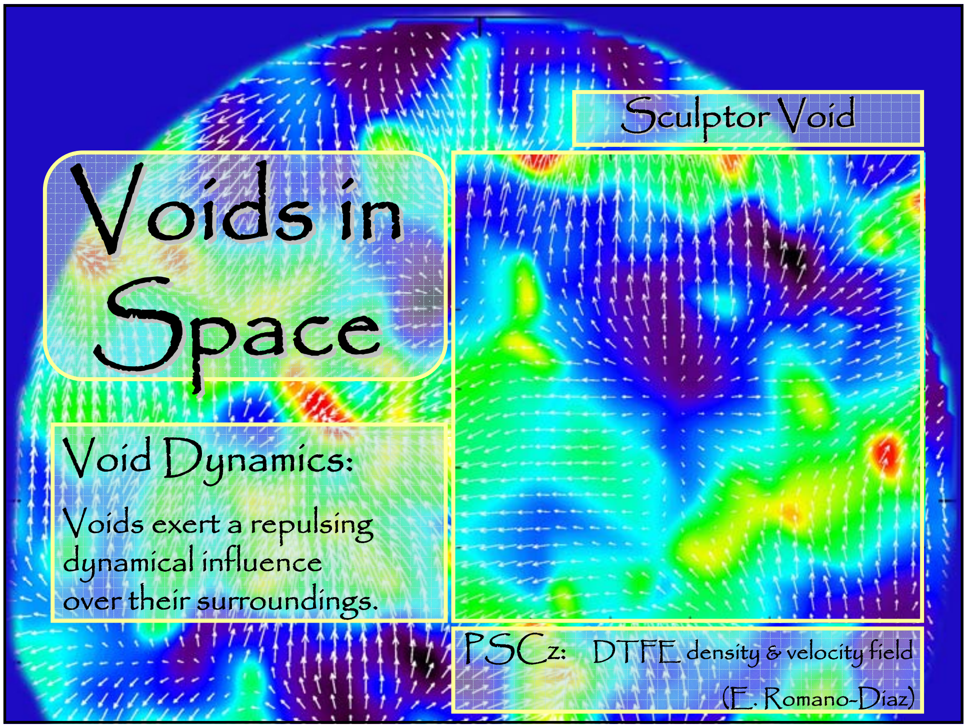
The lowest contour represents a density equal to 0.7 of the cosmic mean, each higher contour represents a factor 2 increase in density. Velocity ranges (km/s):

(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

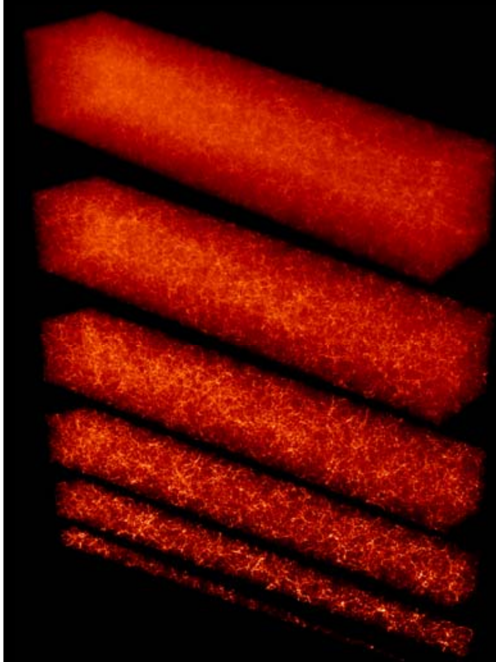
Frame (b) clearly reveals a large void in the galaxy distribution, which turns out to be roughly spherical in outline.

From: Kirshner et al. (1987)


Voids in Space
Sculptor Void
Void Dynamics:
Voids exert a repulsing dynamical influence over their surroundings.
PSCz: DTFE density & velocity field
(E. Romano-Diaz)

Web in Depth

Far Away, Long Ago

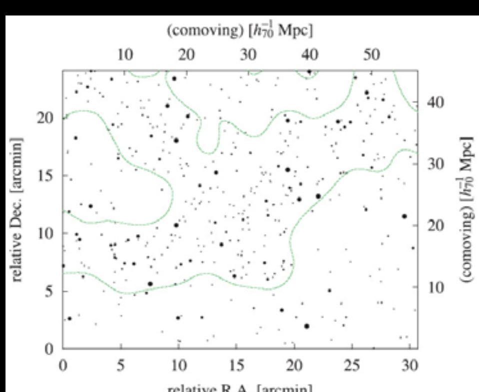


Various surveys are attempting to trace the large scale structure out to large cosmic depths/redshifts.

- Is cosmic web truly universal
- What about the scales of the web (characteristic, largest structures, ...)
- Evolution of Megaparsec scale matter distribution.

Simulation of VIRMOS redshift survey, web out to large redshift

Far Away, Long Ago

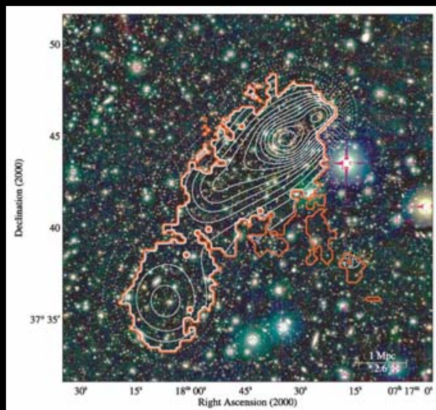


Various surveys are attempting to trace the large scale structure out to large cosmic depths/redshifts.

- Is cosmic web truly universal
- What about the scales of the web (characteristic, largest structures, ...)
- Evolution of Megaparsec scale matter distribution.

Subaru Survey: Amazing prominent large scale distribution of Lyα emitting galaxies.
A filament at redshift z~3 ?

Far Away, Long Ago

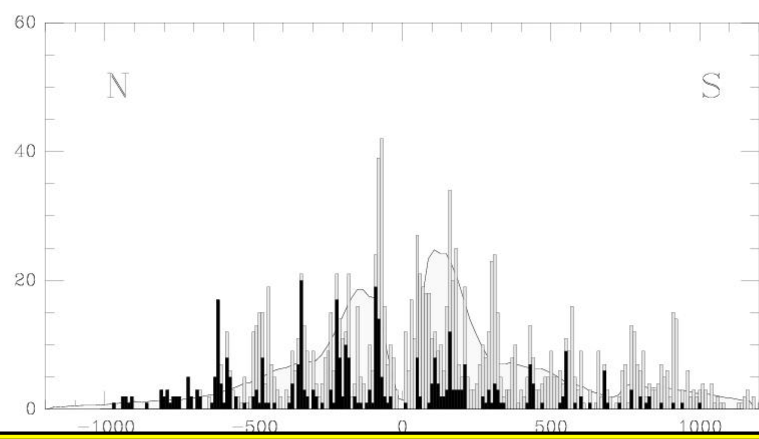


Various surveys are attempting to trace the large scale structure out to large cosmic depths/redshifts.

- Is cosmic web truly universal ?
- What about the scales of the web (characteristic, largest structures, …)
- Evolution of Megaparsec scale matter distribution.

Ebeling et al. (2004):
A filamentary structure in between two rich clusters.

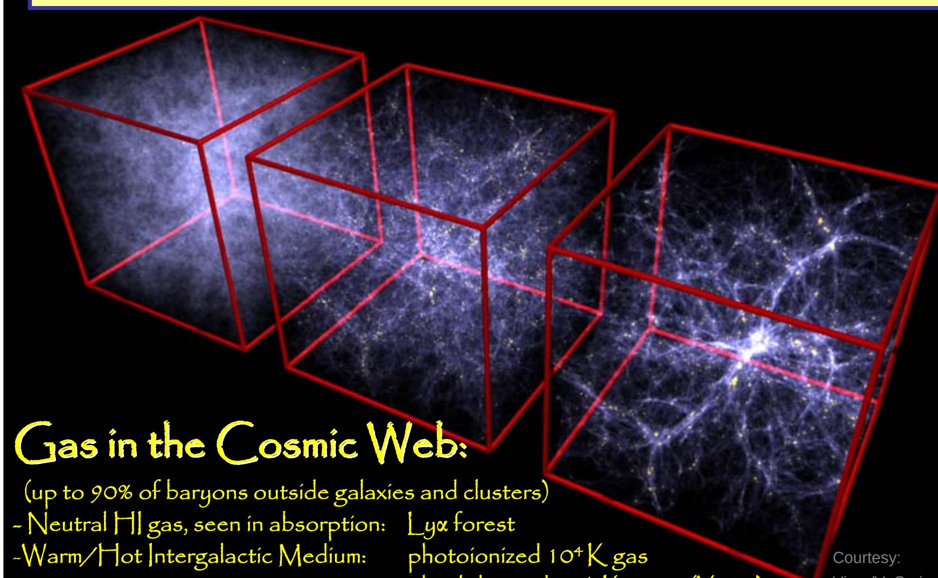
Far Away, Long Ago



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.

The Gastrophysical Web

The Gastrophysical Web



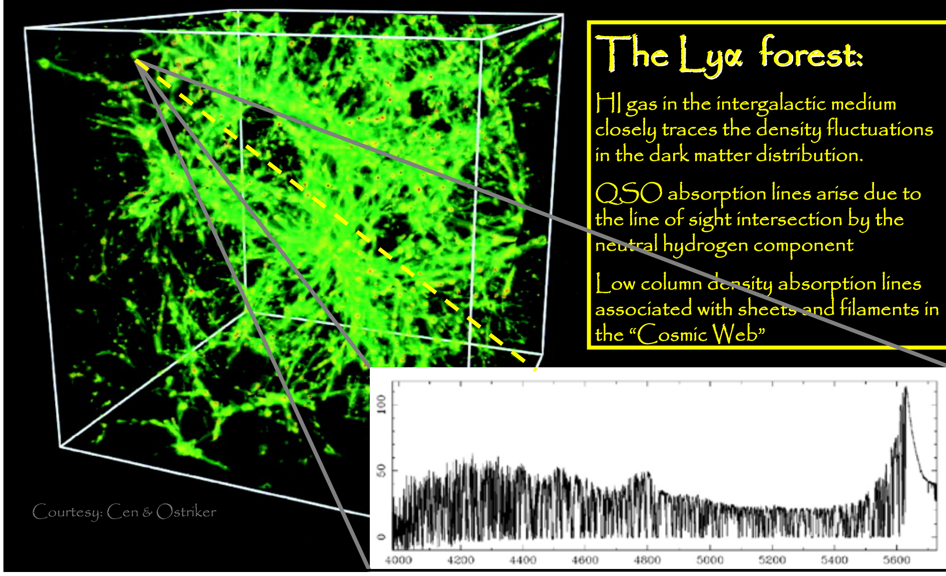
Gas in the Cosmic Web:

(up to 90% of baryons outside galaxies and clusters)

- Neutral HI gas, seen in absorption: Lyα forest
- Warm/Hot Intergalactic Medium: photoionized 10^4 K gas; shock-heated 10^6 K gas (X-ray)

Courtesy: Virgo/V. Springel

The Gastrophysical Web



The Lyα forest:

HI gas in the intergalactic medium closely traces the density fluctuations in the dark matter distribution.

QSO absorption lines arise due to the line of sight intersection by the neutral hydrogen component

Low column density absorption lines associated with sheets and filaments in the "Cosmic Web"

Web Dynamics

Cosmic Migration Flows

CMB Dipole:

We move wrt Universe: v ~ 620 km/s

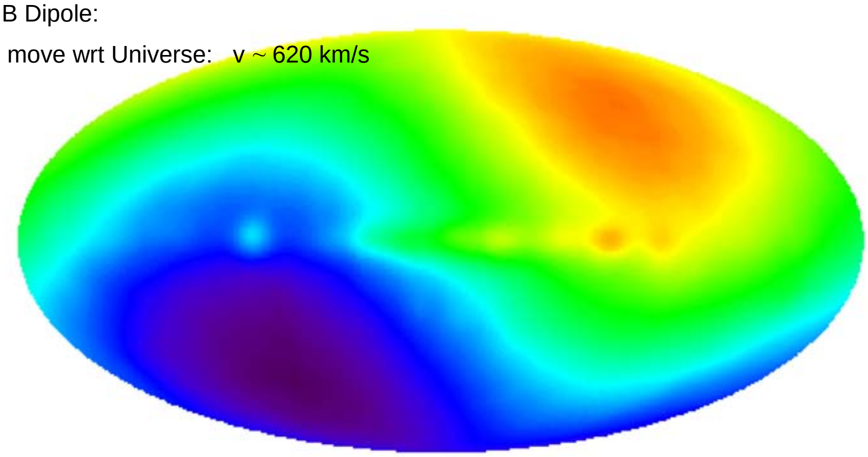
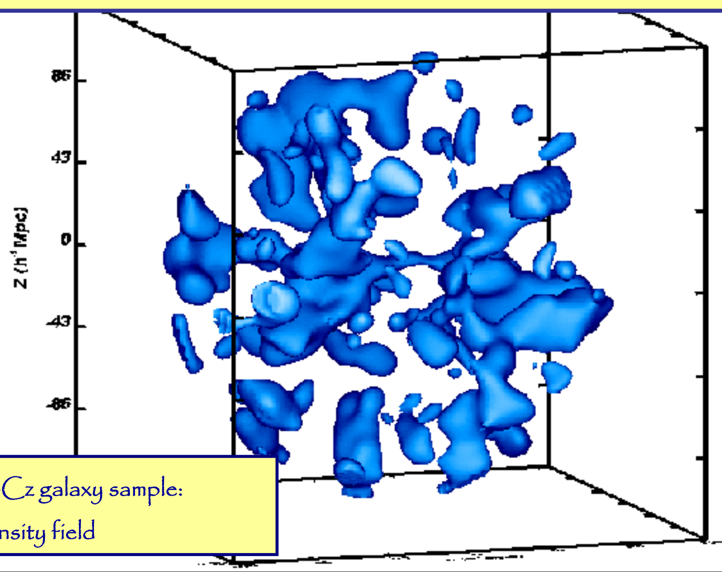


Figure 11. The Cosmic Microwave Background dipole as measured by the DMR instrument of the COBE microwave background satellite (see also Kogut et al. 1993)

Cosmic Migration Flows



PSCz galaxy sample:

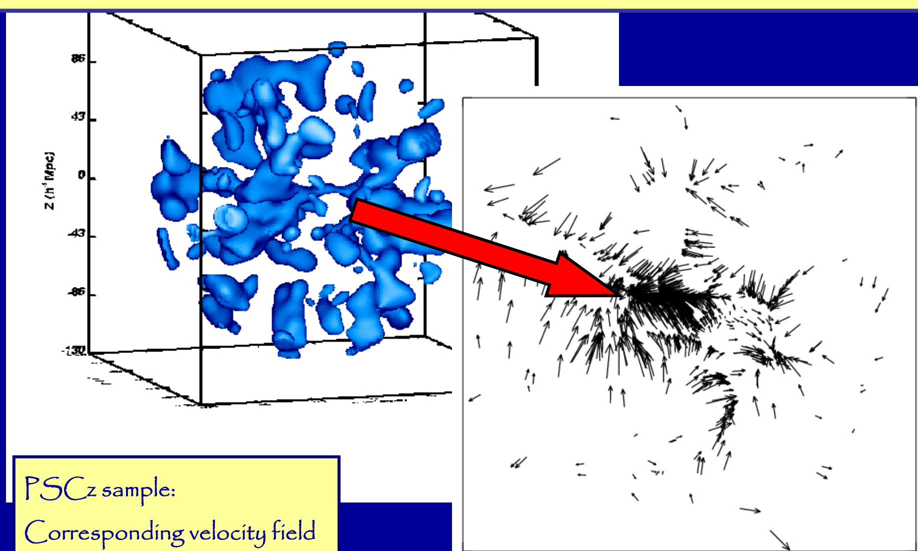
Density field

Cosmic Migration Flows

$$\mathbf{v} \;=\; \frac{H\,f}{4\pi G\,\rho_u}\,\mathbf{g} \;=\; \frac{2\,f}{3H\Omega}\,\mathbf{g}$$

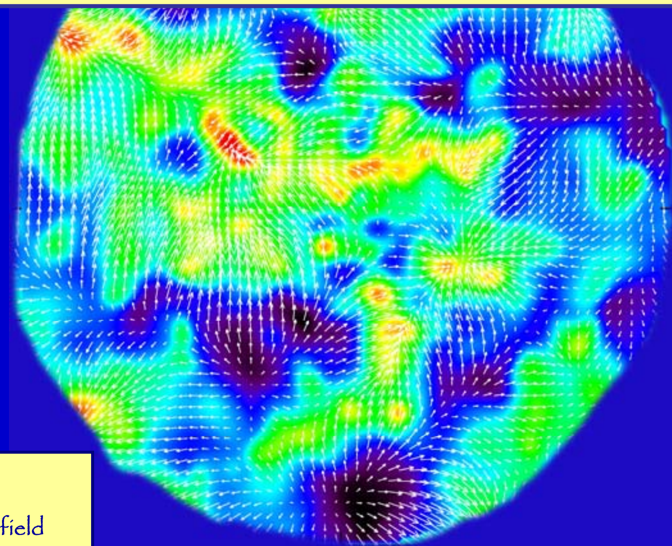
$$\mathbf{v}(\mathbf{x},t) \;=\; \frac{H}{4\pi}\,\frac{f(\Omega_m)}{b}\,a \int d\mathbf{x}'\;\delta_{gal}(\mathbf{x}',t)\;\frac{(\mathbf{x}'-\mathbf{x})}{|\mathbf{x}'-\mathbf{x}|^3} \qquad (158)$$

Cosmic Migration Flows



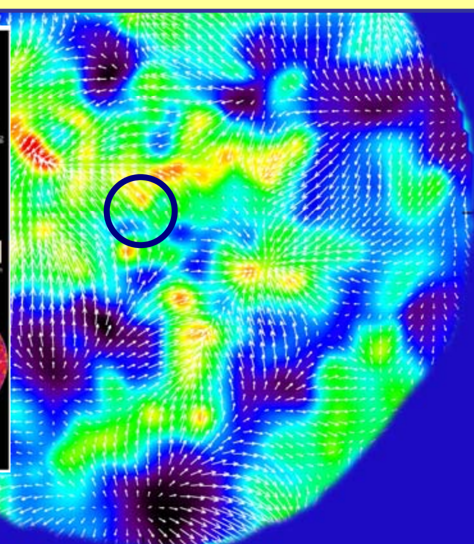
PSCz sample:
Corresponding velocity field

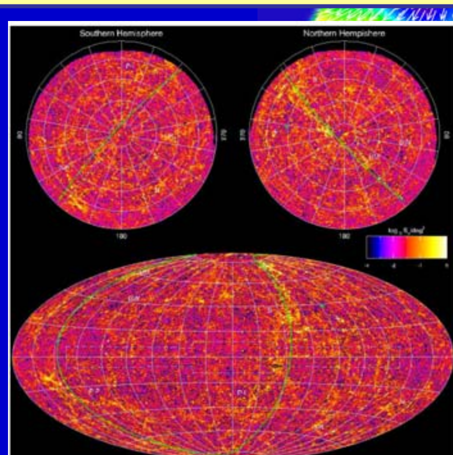
Cosmic Migration Flows



PSCz sample,
Map Density & Flow field

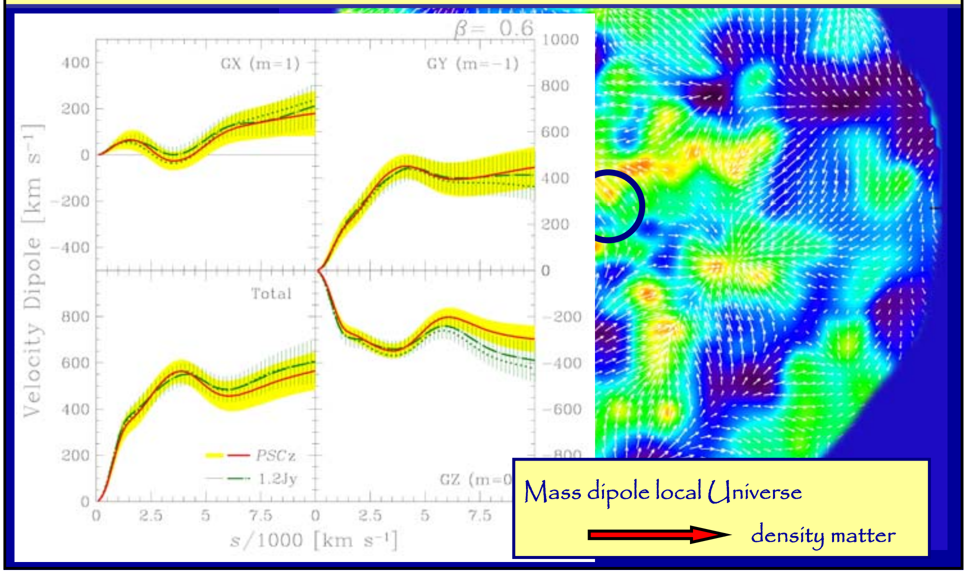
Cosmic Migration Flows





PSCz sample & 2MASS sky
Flow around Local Group

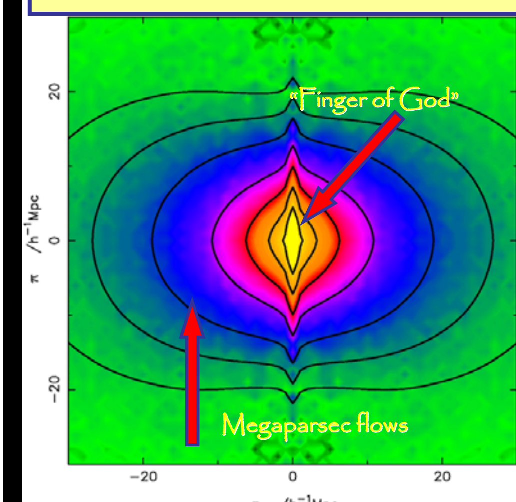
Cosmic Migration Flows



Mass dipole local Universe

density matter

the Web: Migration Flows



Large scale flows lead to redshift distortions:

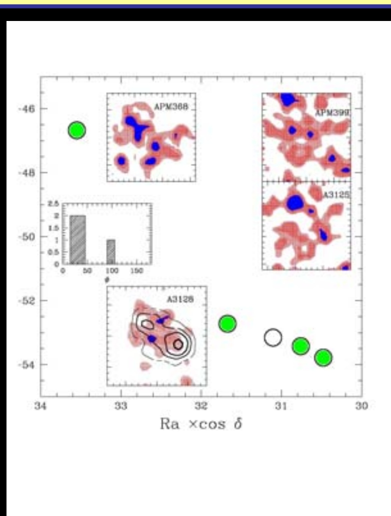
$$cz = Hr + v_{pec}$$

These flows are part of the assembly of large scale structures, and reach largest values as matter is transported along the filaments into the clusters.

When mapping the galaxy distribution in redshift space, this induces a distortion:

- Flattening along z as matter flows into Megaparsec features (v < 600 km/s).
- Extension due to thermal motions inside cluster (v ~ 1000 km/s): "Fingers of God"

Web Dynamics: Alignments



Plionis 2005

Of outmost importance for understanding the dynamical origin of the cosmic web is that of alignments between and around clusters of galaxies.

The presence of such alignments is an indication for the tidal origin of the cosmic web with the clusters as the dominant tidal agents.

This forms an essential ingredient of the "Cosmic Web" theory of Bond et al.

Work by various groups, most notably Plionis and collaborators, indicate that indeed clusters, and galaxies around them, reveal significant alignments.

Cosmic Shear & Gravitational Lensing

Gravitational Lensing

A highly promising method to determine the amount and distribution of matter in the Universe does not concentrate on the way in which Dark Matter affects

- the motions of galaxies and the intracluster gas,

but instead 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 will therefore act

Gravitational Lens

A1689, HST, Broadhurst et al.

Gravitational Lensing

Illustration:

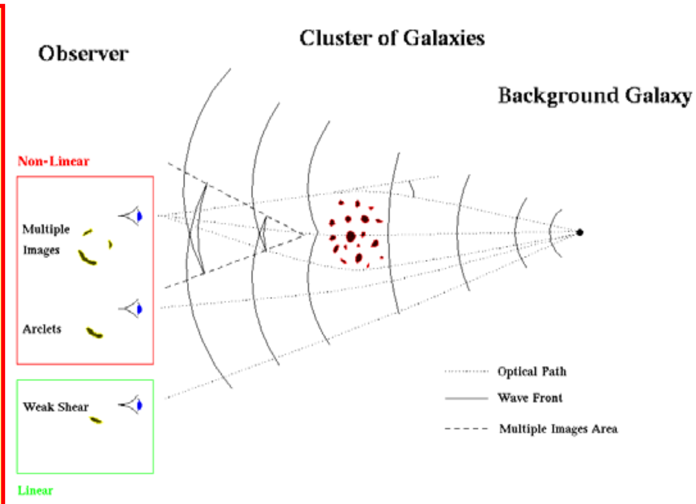
Mass passing in front of background of galaxies, distorting their received images.

Clusters: Gravitational Lensing

Illustration:

Dependent on whether the light passes within Einstein radius or outside, we deal with:

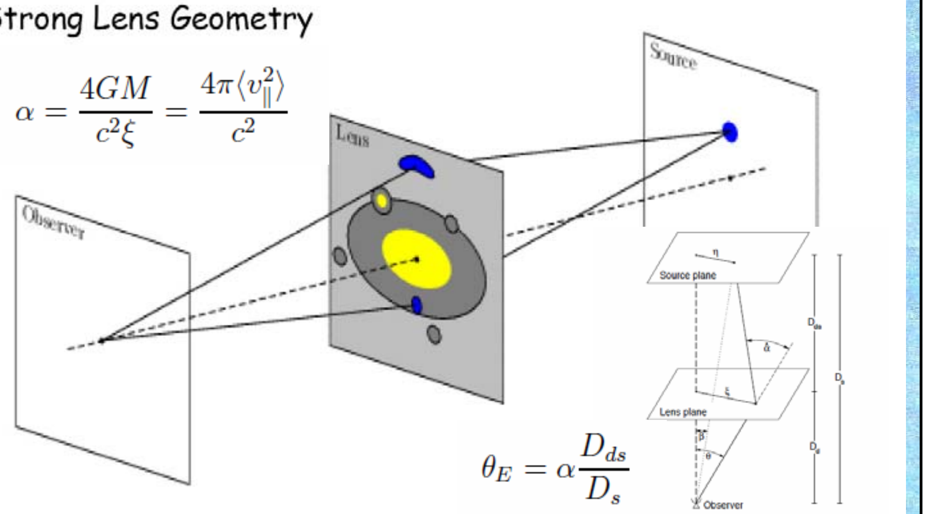
- Strong Lensing:
  nonlinear distortions
- Weak Lensing:
  linear distortions



Gravitational Strong Lensing

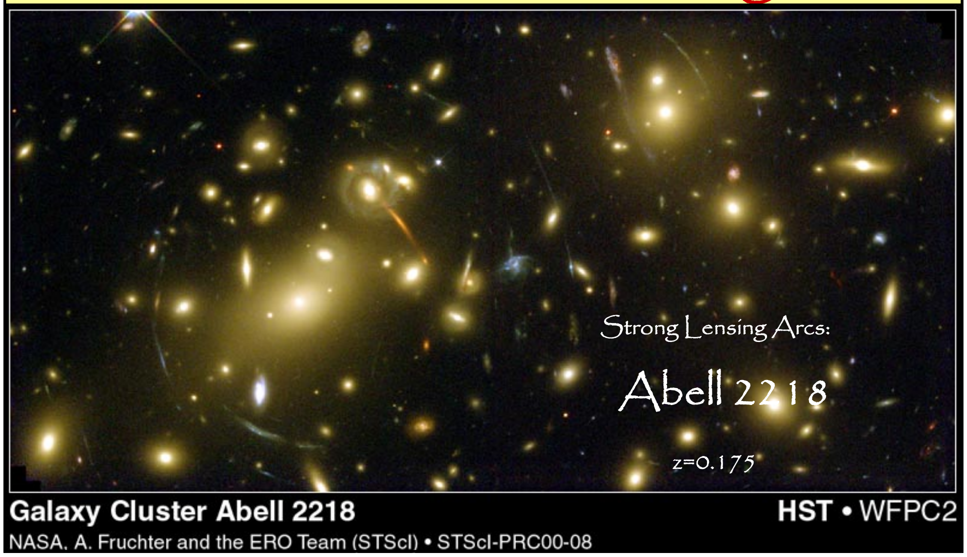
Strong Lens Geometry

$$\alpha = \frac{4GM}{c^2 \xi} = \frac{4\pi \langle v_{\parallel}^2 \rangle}{c^2}$$

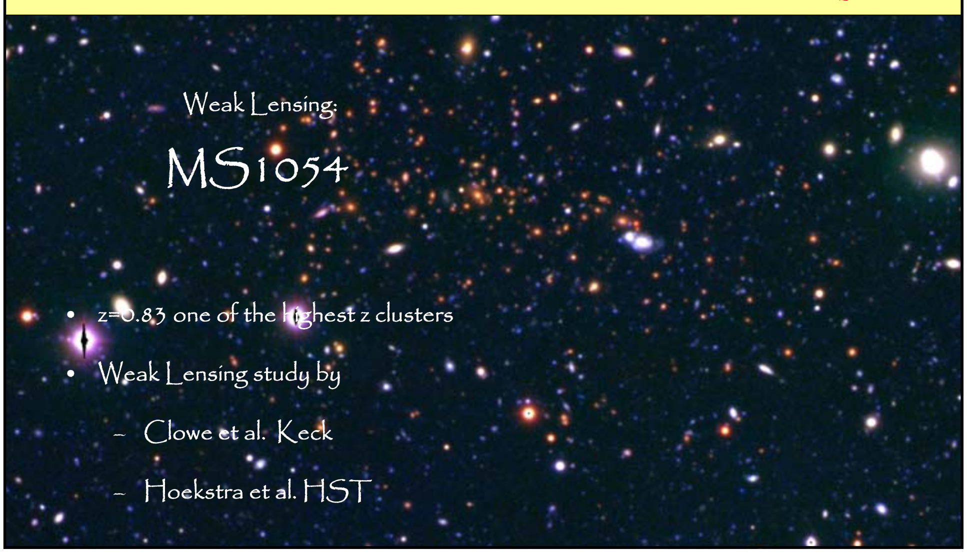


$$\theta_E = \alpha \frac{D_{ds}}{D_s}$$

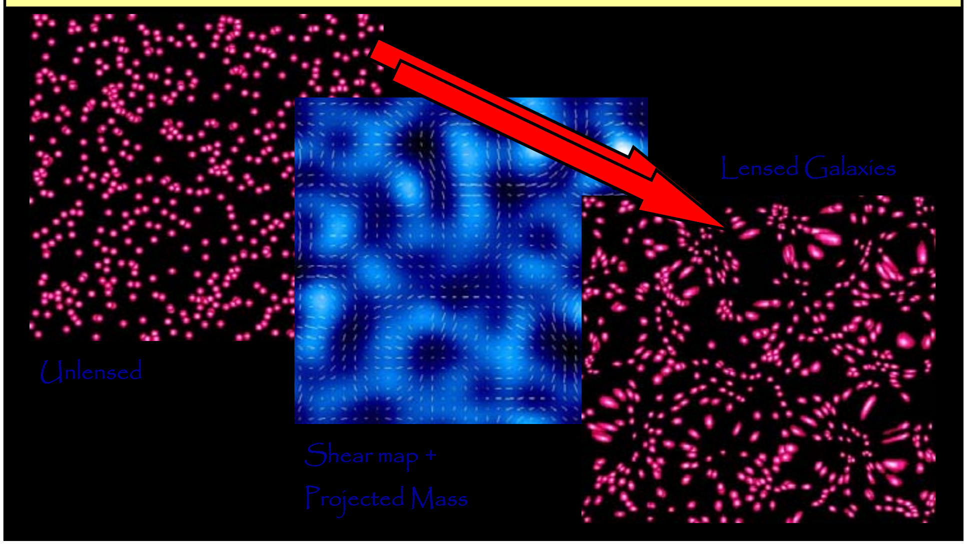
Clusters: Gravitational Lensing



Clusters: Gravitational Weak Lensing



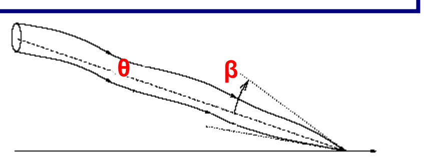
Gravitational Weak Lensing



Gravitational Lensing

$$A_{ij} \equiv \frac{\partial \beta_i}{\partial \theta_j} = \begin{pmatrix} 1-\kappa & 0 \\ 0 & 1-\kappa \end{pmatrix} + \begin{pmatrix} -\gamma_1 & \gamma_2 \\ \gamma_2 & \gamma_1 \end{pmatrix}$$

Magnification — Shear

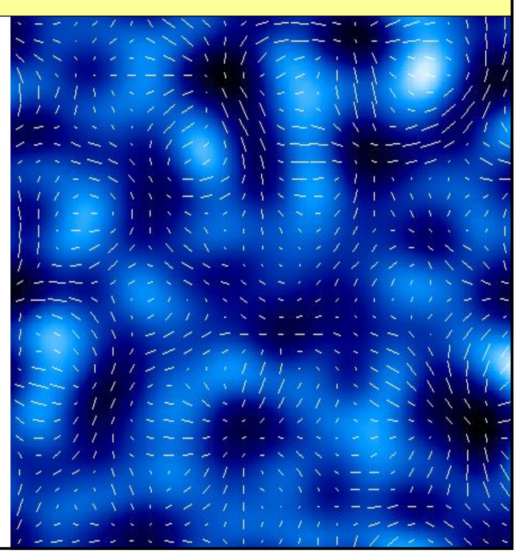


$$\kappa = \frac{1}{2}(\phi_{,11} + \phi_{,22})$$

$$\gamma_1 = \frac{1}{2}(\phi_{,11} - \phi_{,22})$$

$$\gamma_2 = \phi_{,12}$$

$$\phi_{,ij} = \frac{\partial^2 \phi}{\partial \theta_i \partial \theta_j}$$

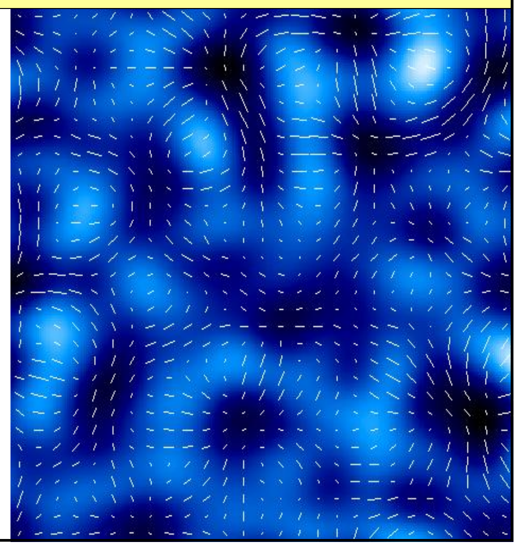


Gravitational Lensing

$$\kappa = \frac{1}{2}(\phi_{,11} + \phi_{,22})$$
$$\gamma_1 = \frac{1}{2}(\phi_{,11} - \phi_{,22})$$
$$\gamma_2 = \phi_{,12}$$
$$\phi_{,ij} = \frac{\partial^2 \phi}{\partial\theta_i \partial\theta_j}$$

Lensing Potential related to Peculiar Gravitational Potential

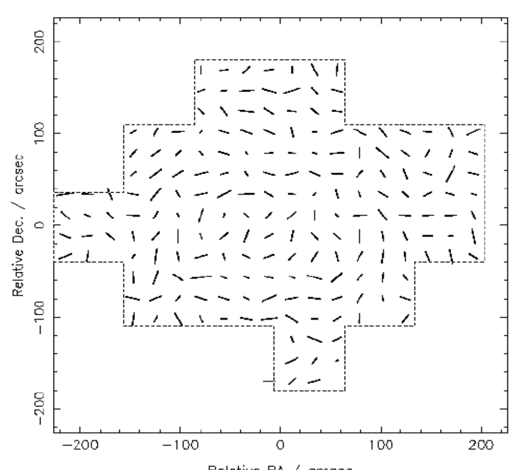
$$\phi(\mathbf{r}) = \frac{2}{c^2}\int_0^r dr'\,\Phi(\mathbf{r}')\left(\frac{1}{r} - \frac{1}{r'}\right)$$



Clusters: Gravitational Lensing

MS1054

- z=0.83 one of the highest z clusters
- Studied by
  - Clowe et al. Keck
  - Hoekstra et al. HST



Shear map

Clusters: Gravitational Lensing

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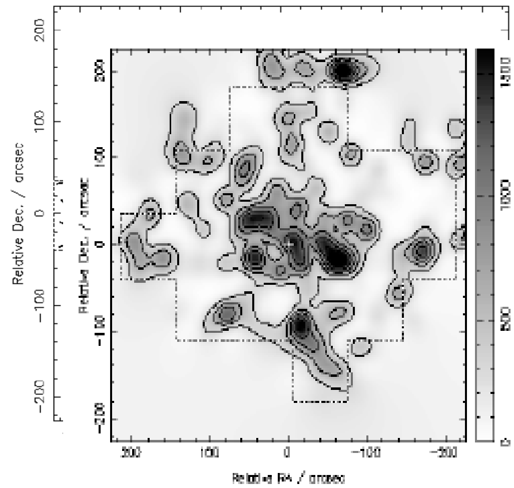
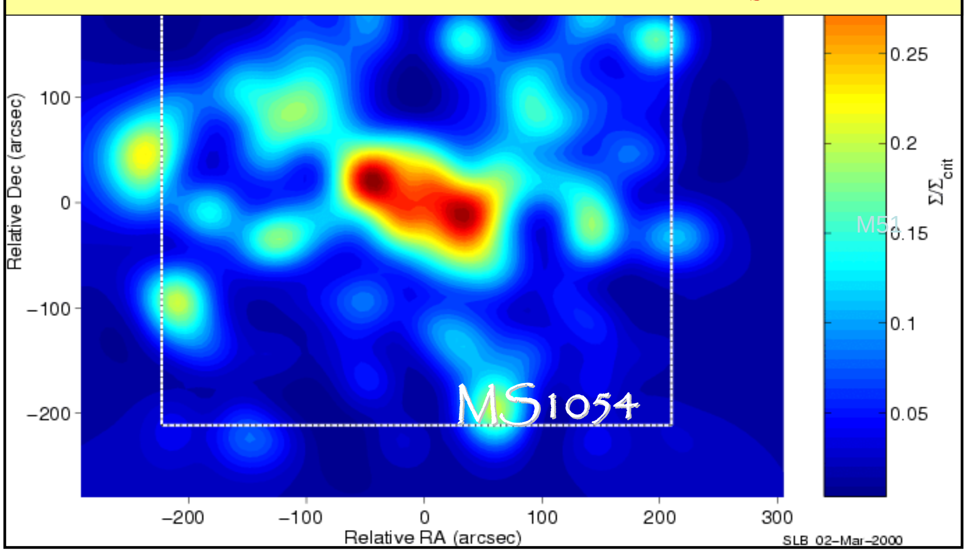
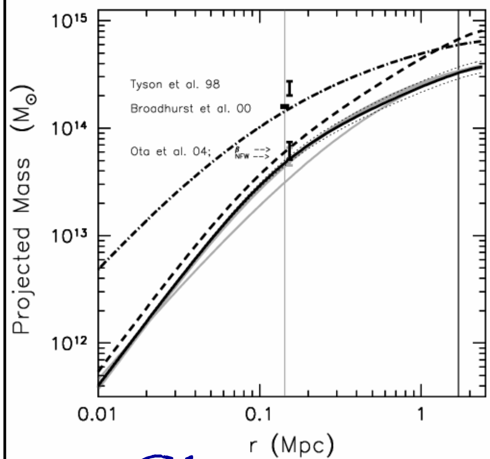


Clusters: Gravitational Lensing

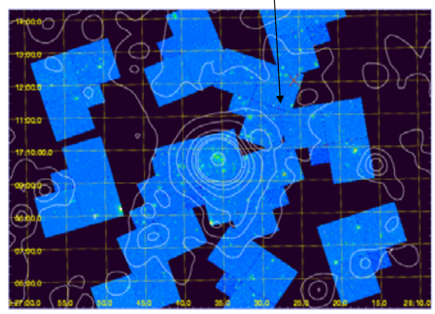


Clusters: Comparison Lensing & X-ray



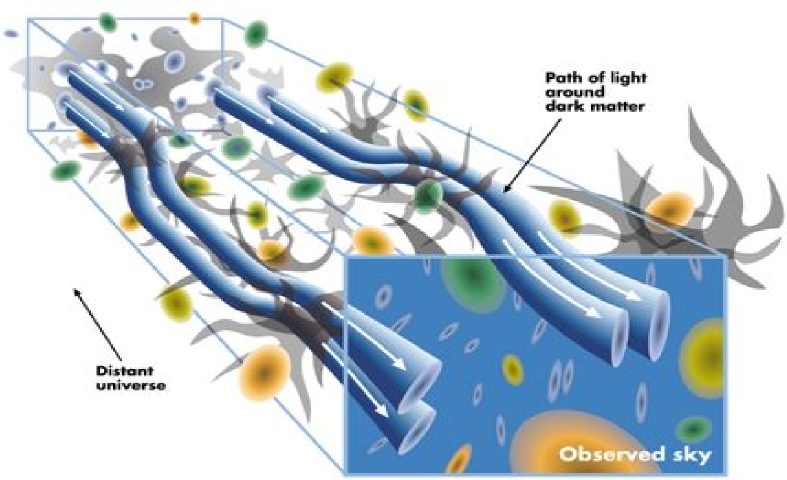
CL0024+17

Same substructure seen in weak lensing and X-rays

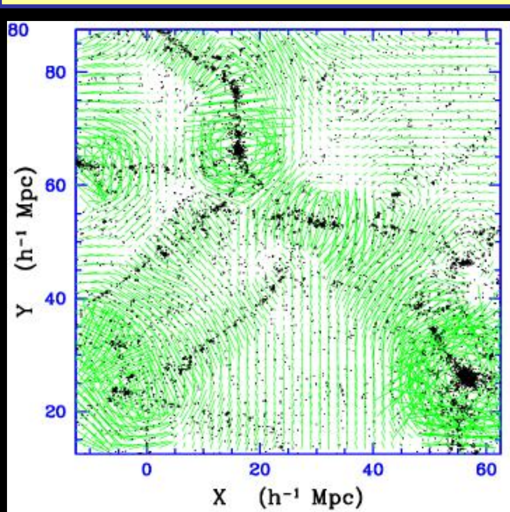


X-ray overlay on HST image

Cosmic Shear



the Web: Shear Distortions & Lensing



Large scale tidal shear distorts the paths of photons as they travel from their source to the observer.

This effect is known as "gravitational lensing". For moderate distortions, outside the Einstein radius ("weak lensing"),

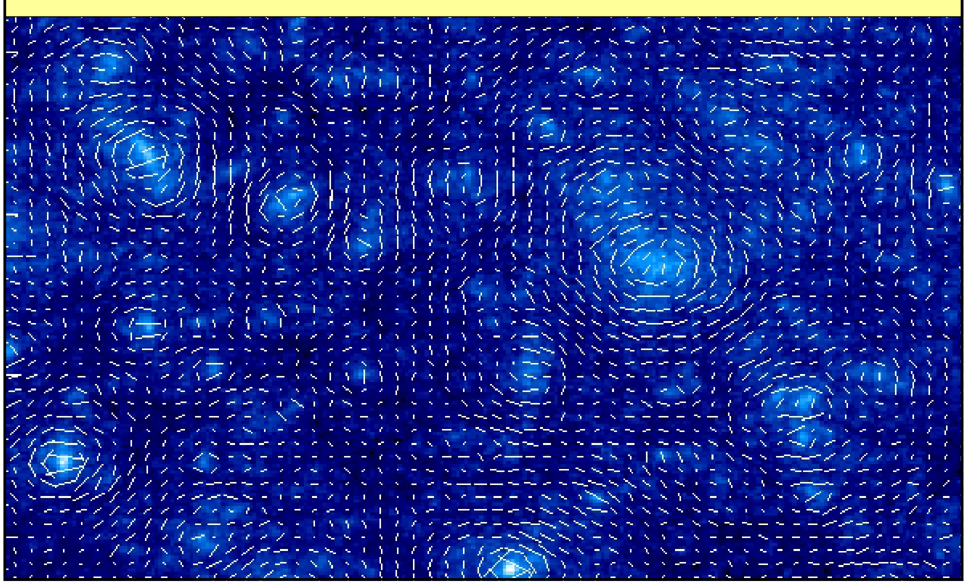
the distortions of galaxy shapes can be measured and inverted to yield the (projected) distorting mass distribution.

Clusters are outstanding, representing major potential wells.

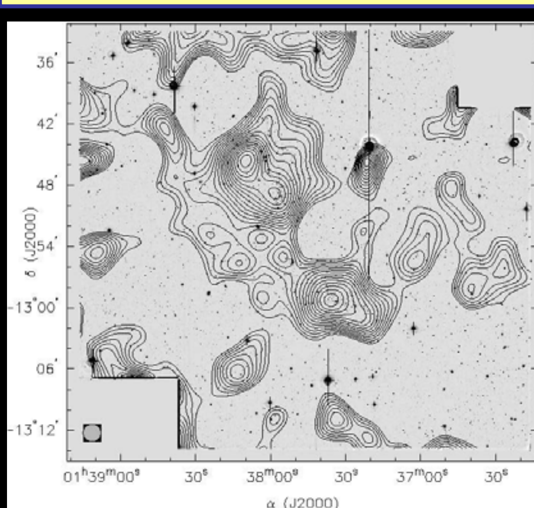
But also the generic Megaparsec matter distribution "lenses":

Cosmic Shear

Cosmic Shear



the Web:
Shear Distortions & Lensing



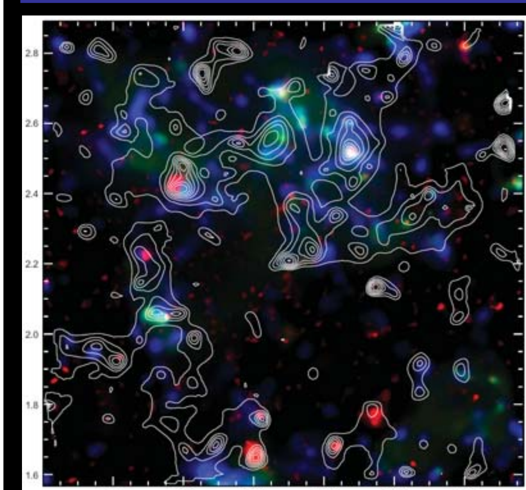
Although the cosmic shear due to a filament is considerably weaker than that of the clusters, recently

Dietrich, Schneider & Romano-Diaz (2004)

succeeded in mapping the filament between A222 and A333 on the basis of the measured lensing.

This shows that filaments are shown to be genuine dynamical entities.

the Web:
Shear Distortions & Lensing

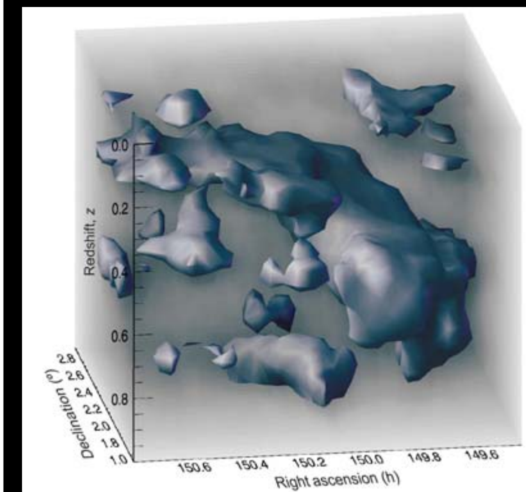


First genuine map
Large Scale
Cosmic Dark Matter distribution
by means of weak lensing:

Clearly visible is the filamentary
Weblike nature of the mass
Distribution.

Massey et al. 2007

the Web:
Shear Distortions & Lensing



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Massey et al. 2007