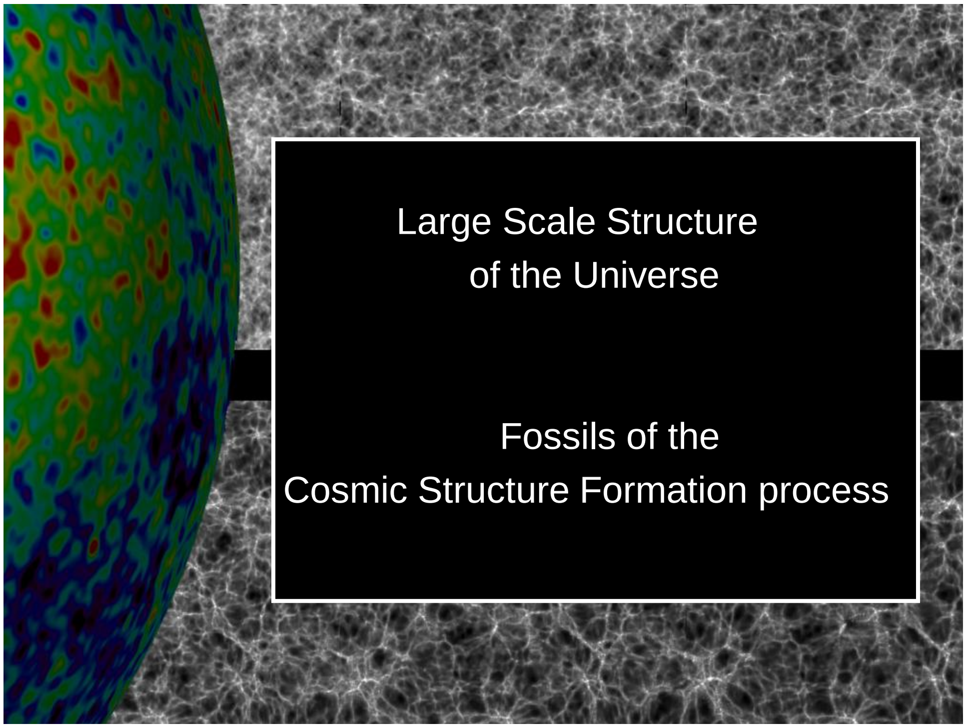
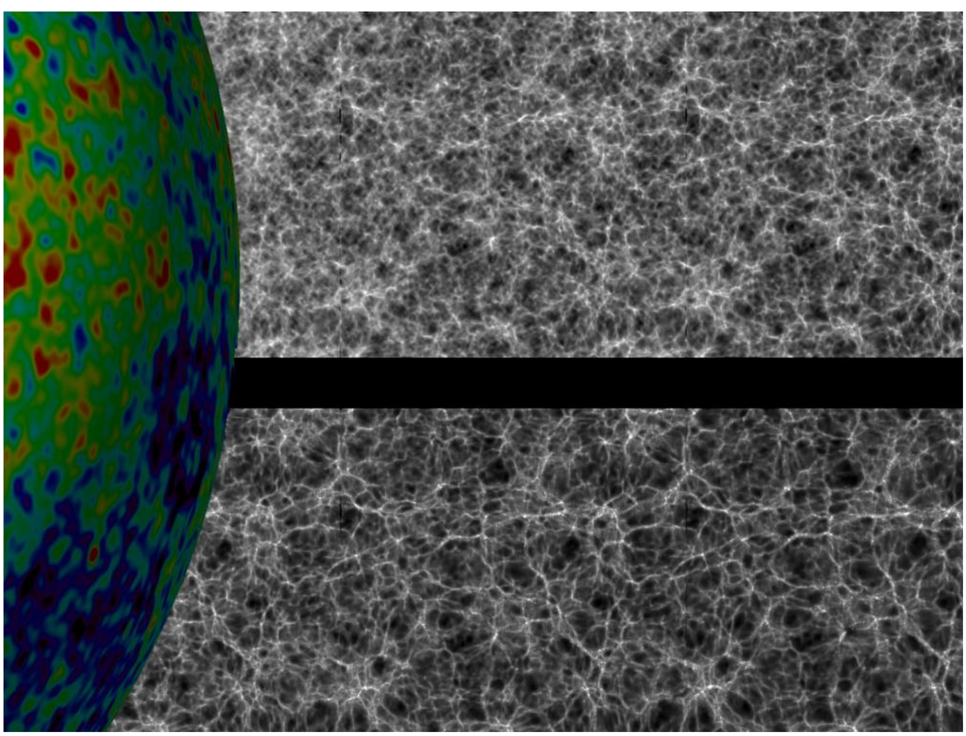

Large Scale Structure
of the Universe
Fossils of the
Cosmic Structure Formation process



Central Theme:

Cosmic Enigma

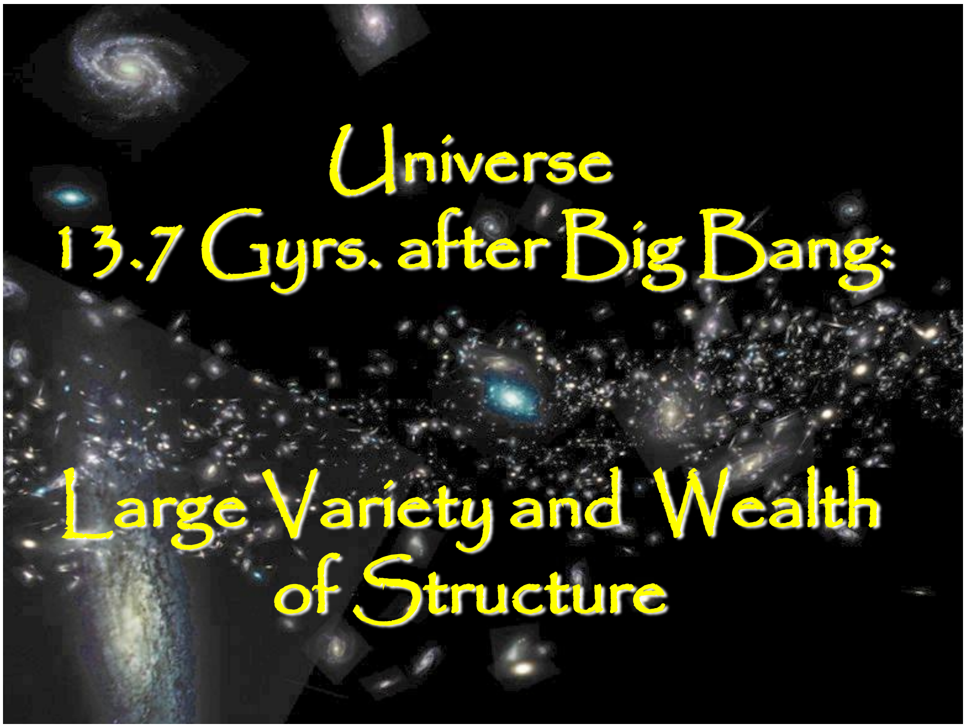
Universe

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:

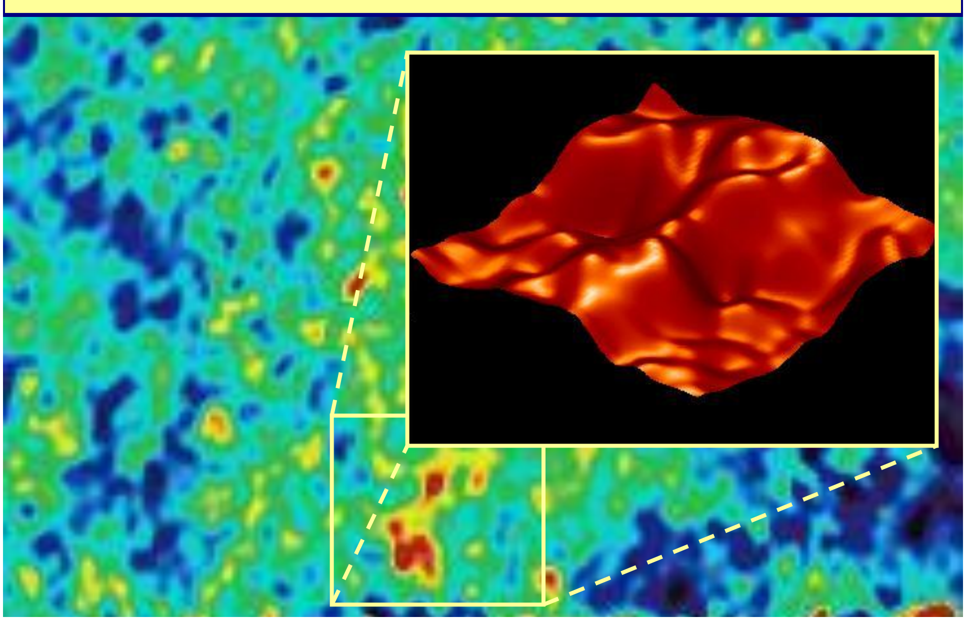
Almost perfectly homogeneous and isotropic,
without any discernable structure ...

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

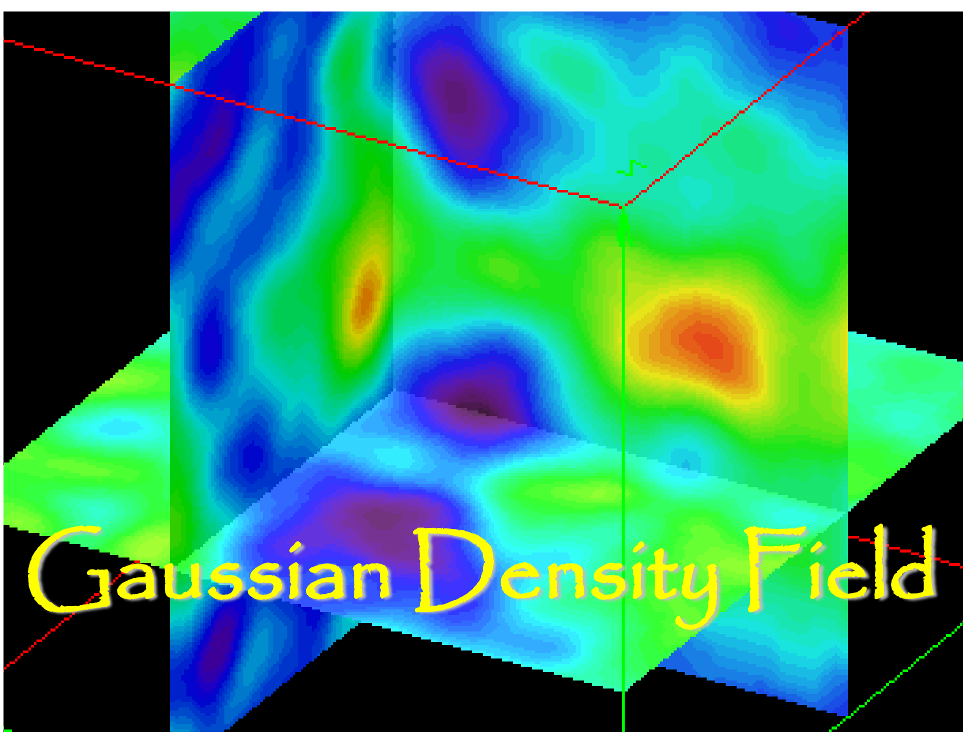
Cosmic Paradigm:

Gravitational Instability

Primordial Gaussian Perturbations




Gaussian Density Field


Gaussian Density Field

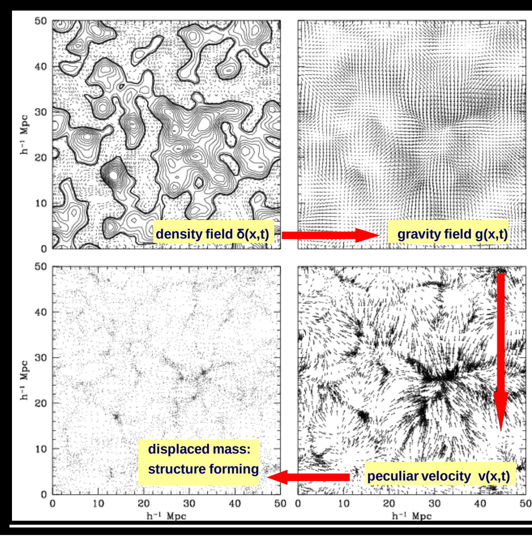
Cosmic Structure Formation

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.

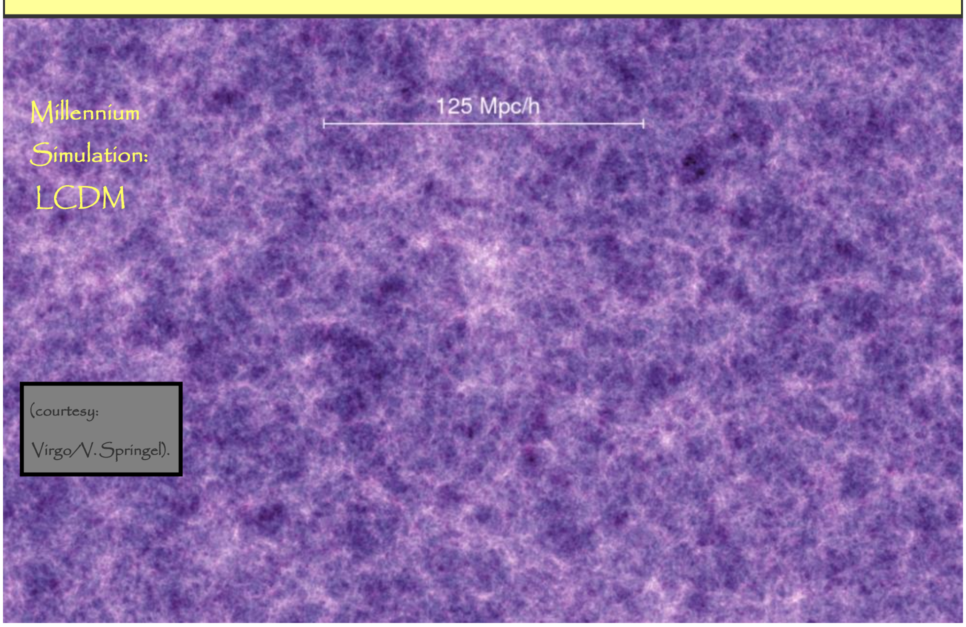


Millennium Simulation

Millennium

Simulation:

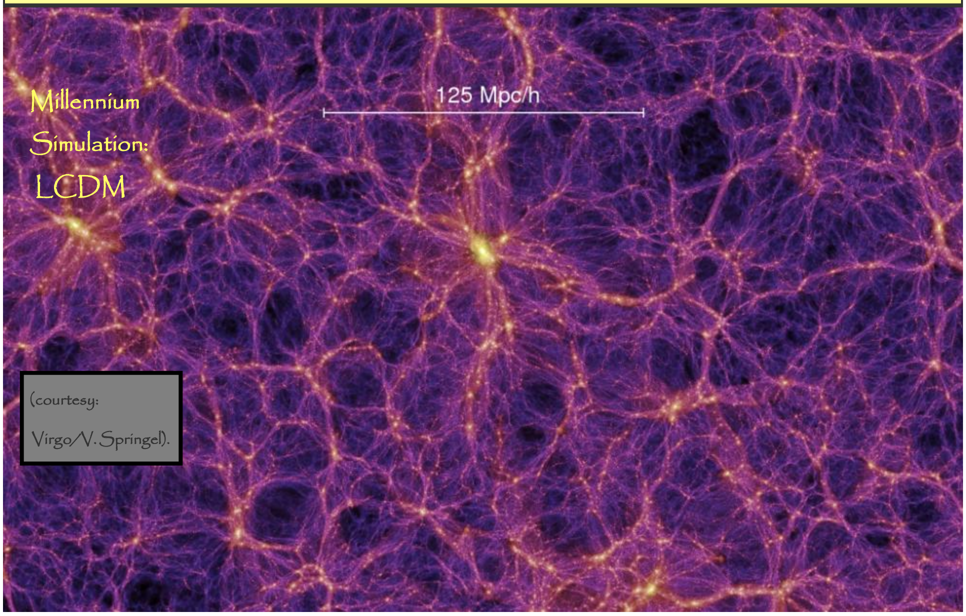
LCDM



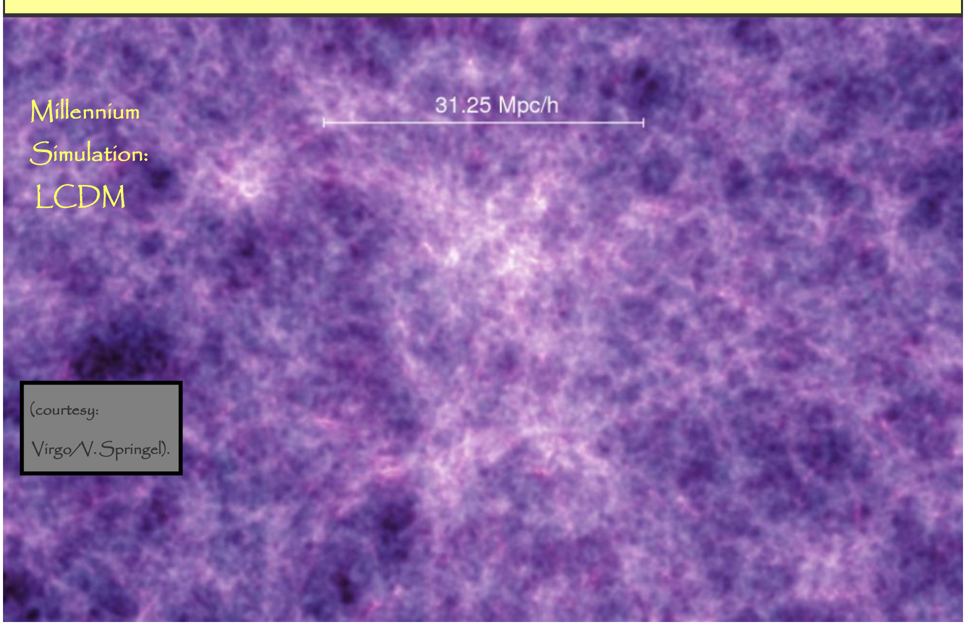
(courtesy:

Virgo/V. Springel).

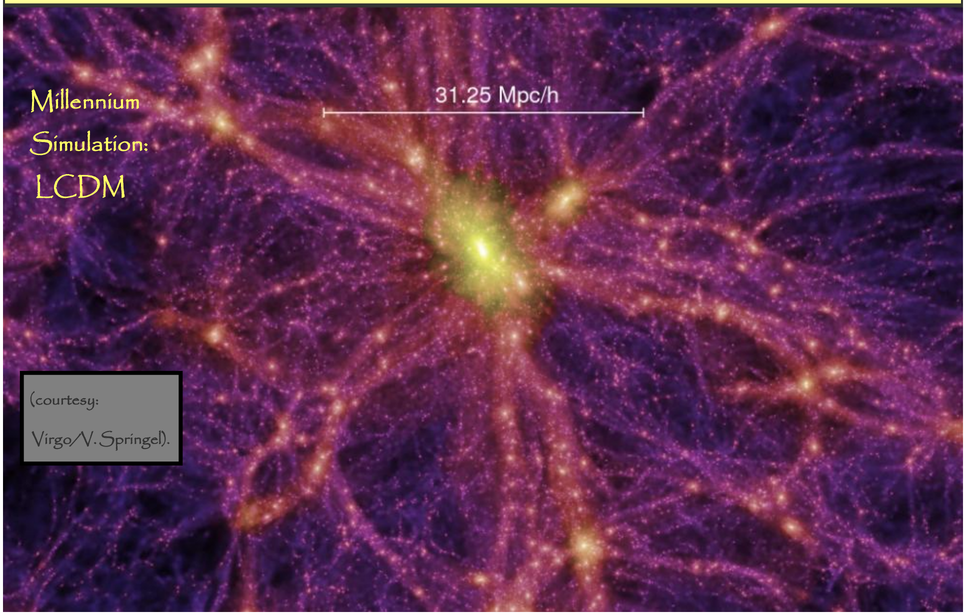
Millennium Simulation



Millennium Simulation



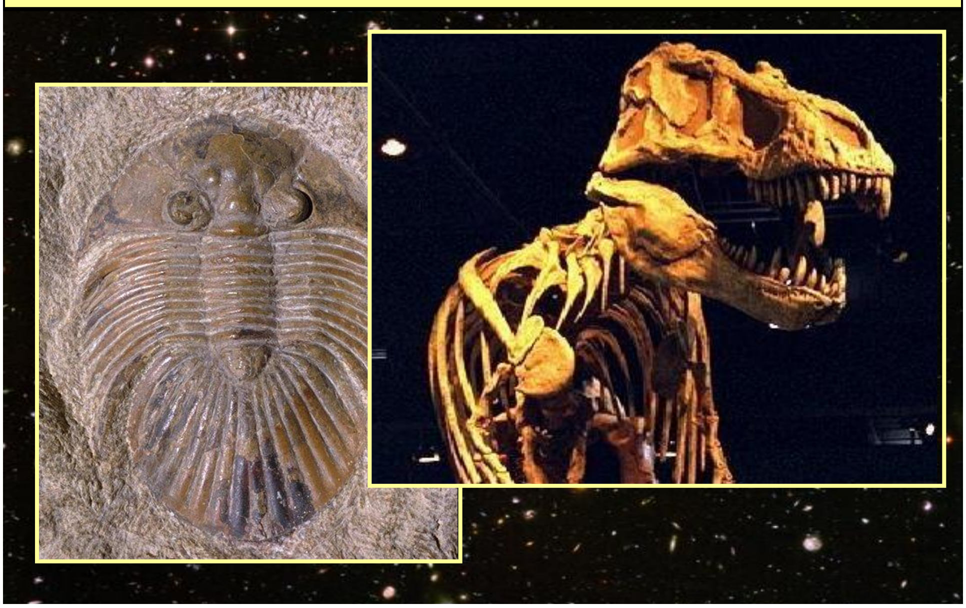
Millennium Simulation



Cosmic

Fossils

Cosmic Fossils ?



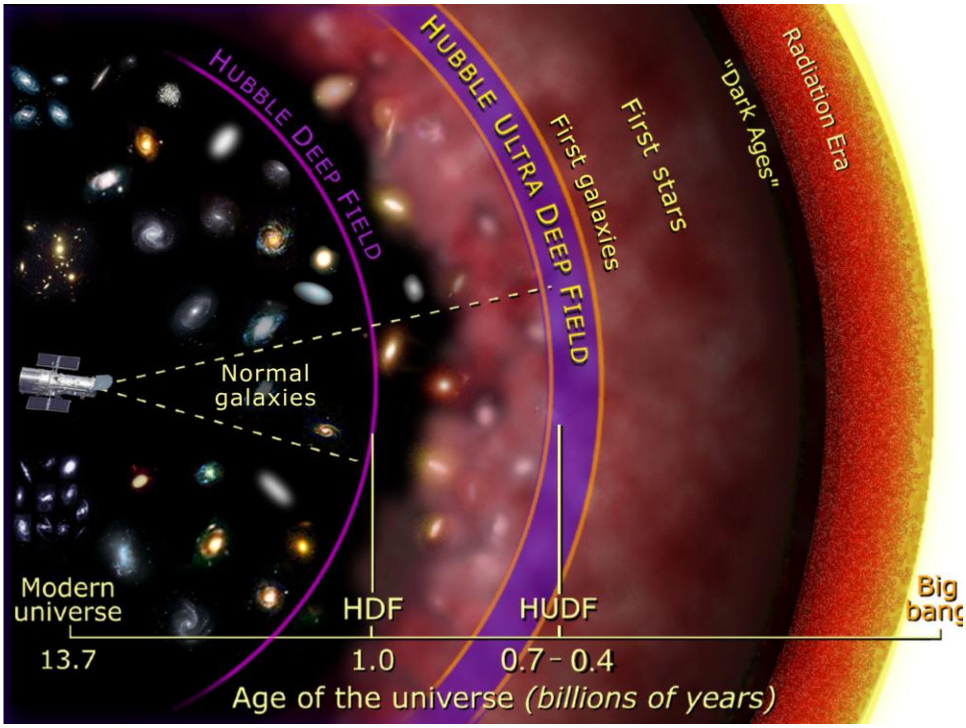
Cosmic Fossils

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

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



- <u>Primordial Conditions:</u>
  - temperature fluctuations in microwave background radiation
  - polarization Cosmic Microwave Background
  - treasure trove cosmological information
- <u>Dynamics:</u>
  - 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.
- <u>Mass Distribution:</u>
  - 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

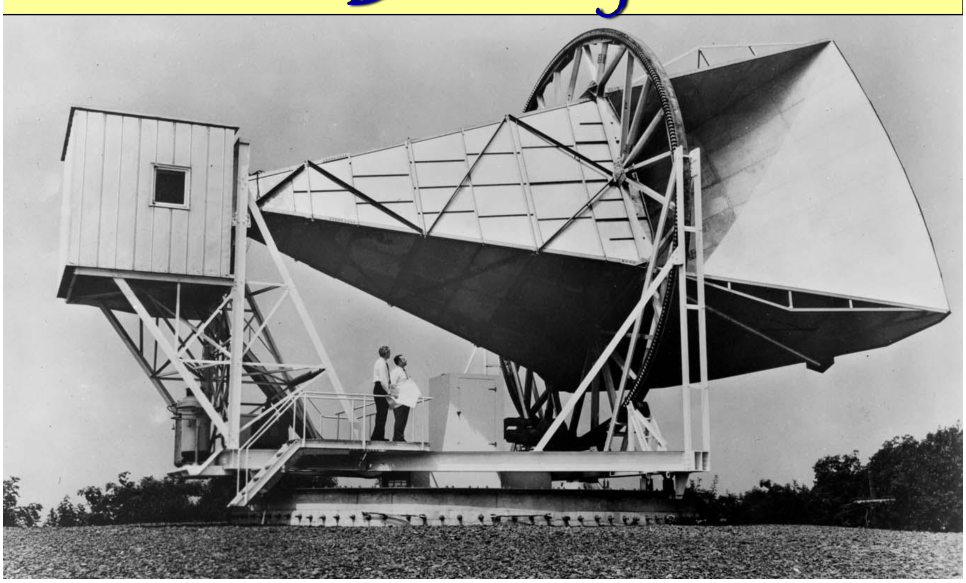
---

- 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

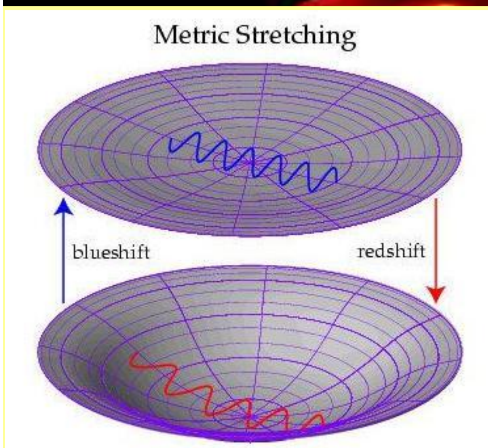
Embryonic Structure:

CMB:
Rippling the Photons

Cosmic Microwave Background: Discovery

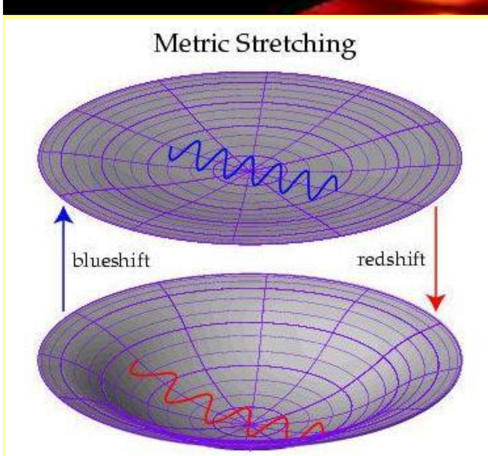


CMB Perturbations



- 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

Cosmic Microwave Background

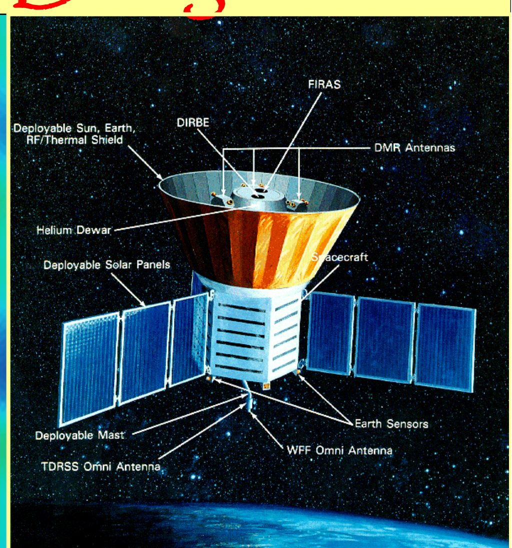
COBE (1992):

Three instruments:

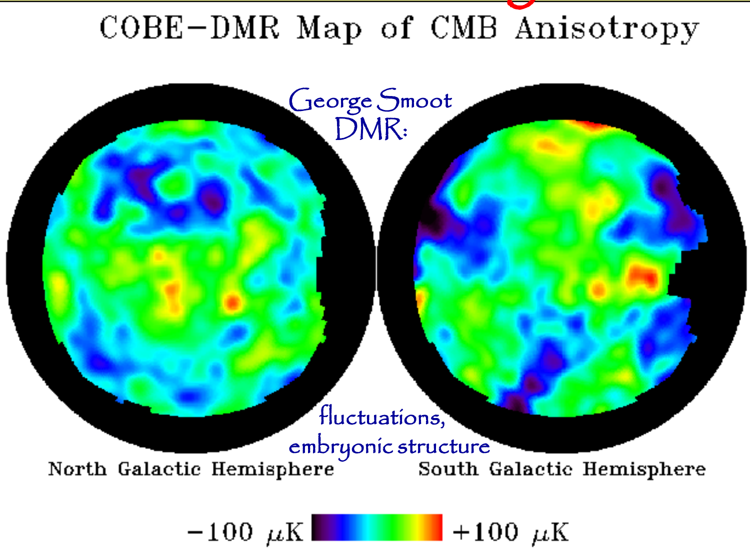
FIRAS: Mather
Far-Infrared Absolute
Spectrophotometer

DIRBE: Hauser
Diffuse Infrared Background
Experiment

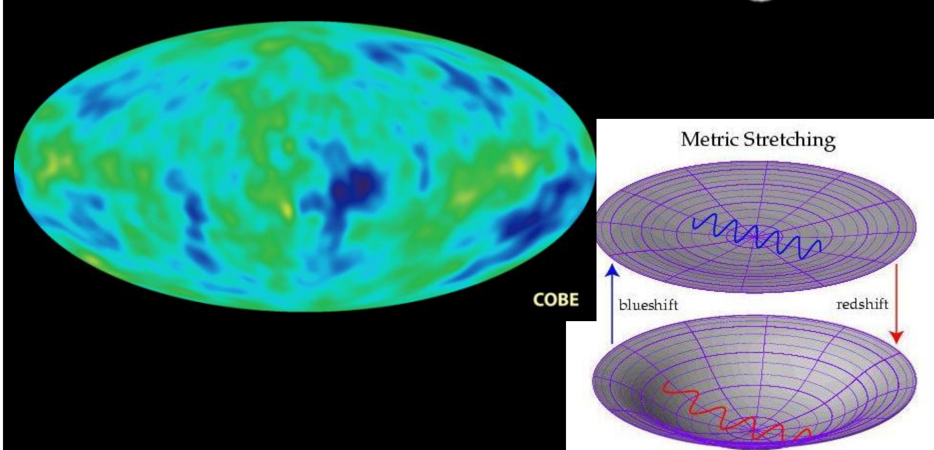
DMR: Smoot
Differential Microwave
Radiometer



Primordial Anisotropies CMB sky

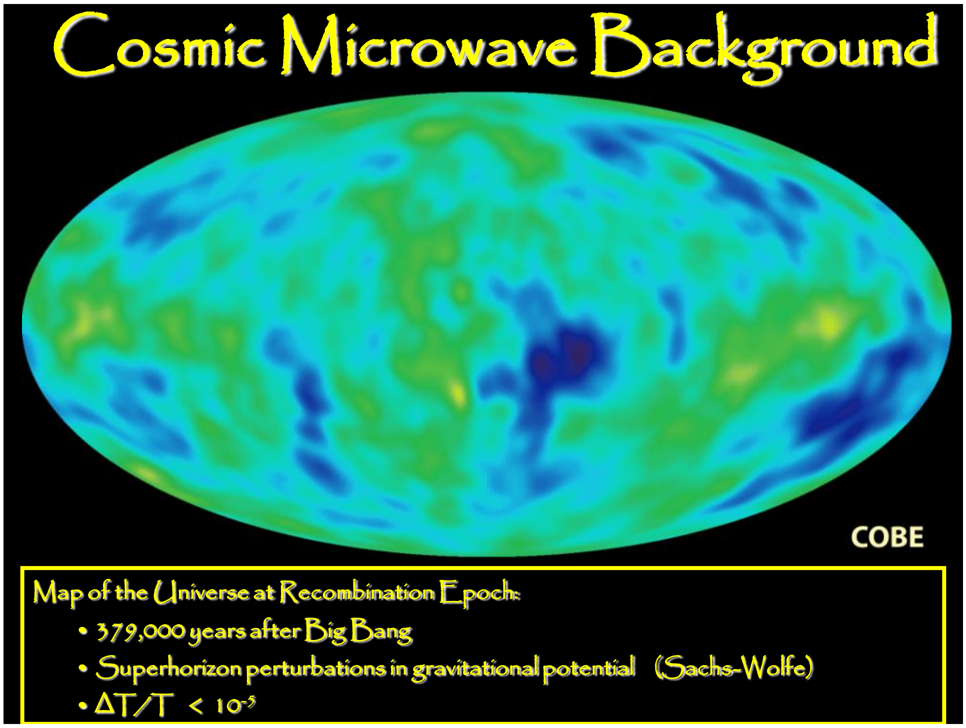


Cosmic Microwave Background



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
COBE
Map of the Universe at Recombination Epoch:
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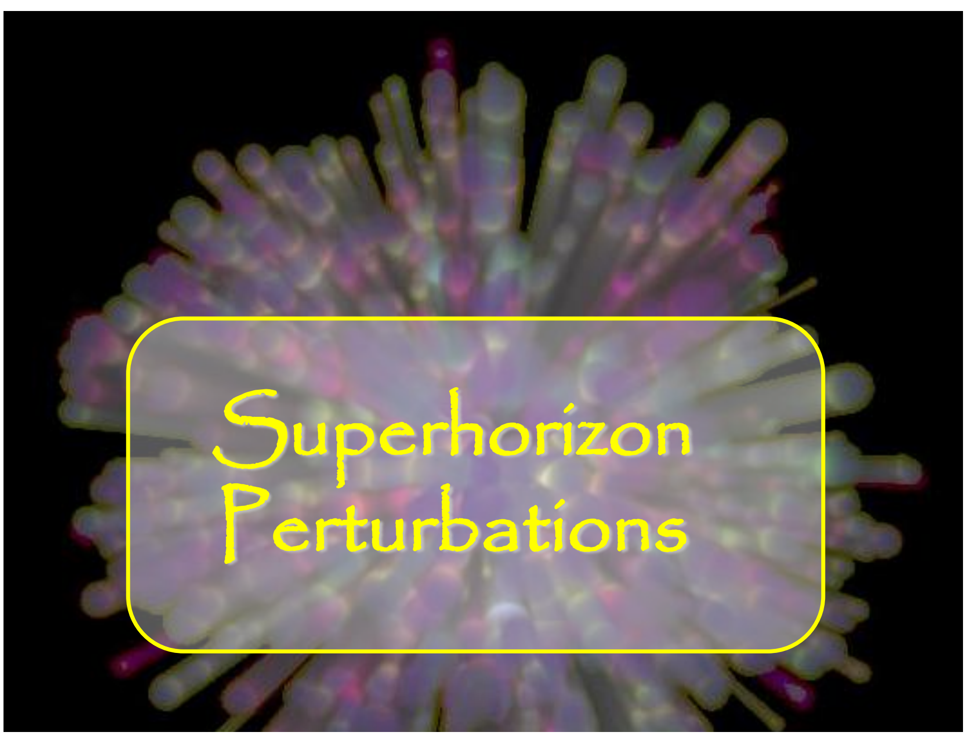
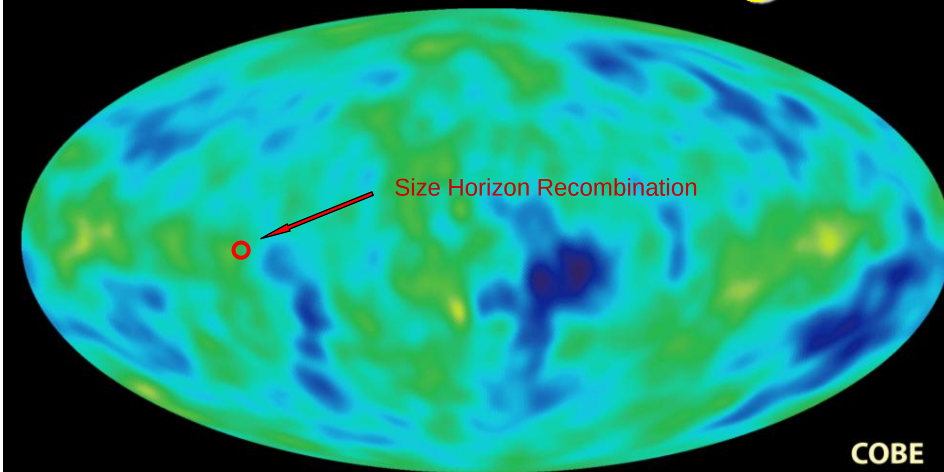
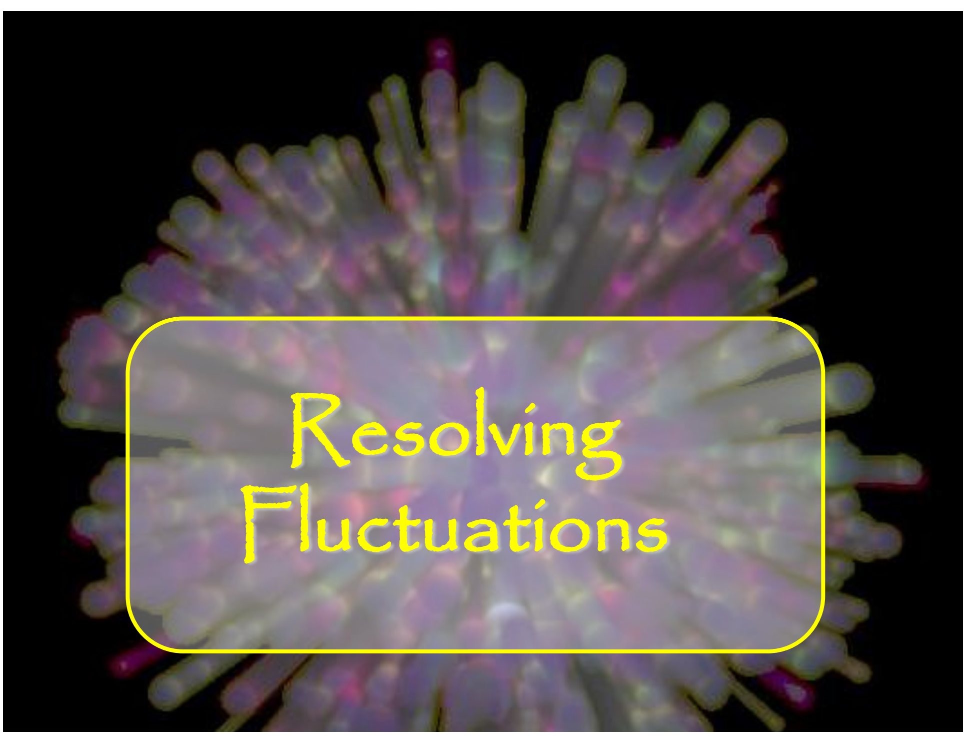

Superhorizon
Perturbations

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 ?

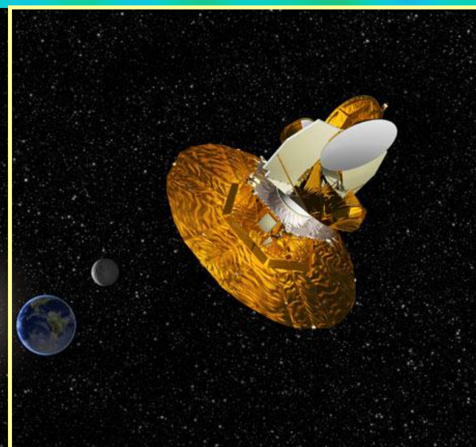


Cosmic Microwave Background

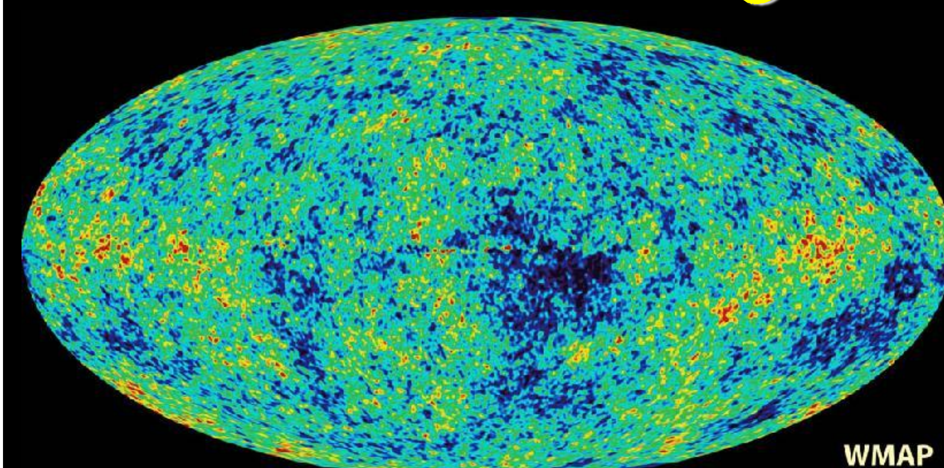
WMAP (2001):

Detailed map sub-degree angular temperature perturbations ($\theta < 1^o$)

Angular Power Spectrum: Precision Cosmology



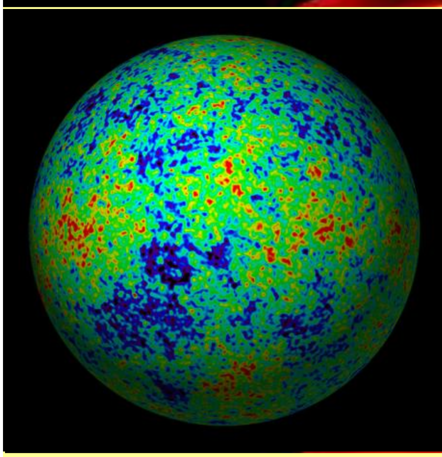
Cosmic Microwave Background



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

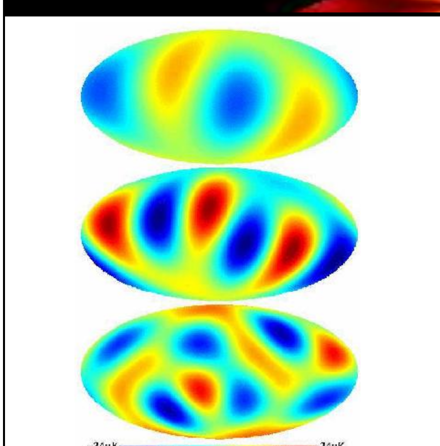


Temperature Perturbations in terms of Spherical Harmonics:

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

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

Temperature Anisotropies



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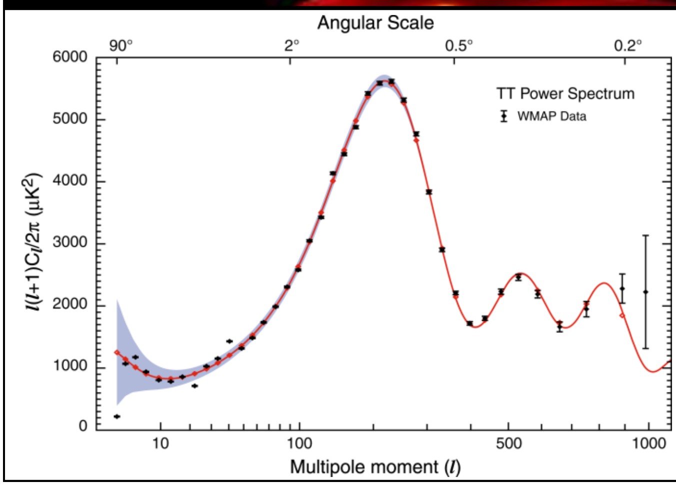
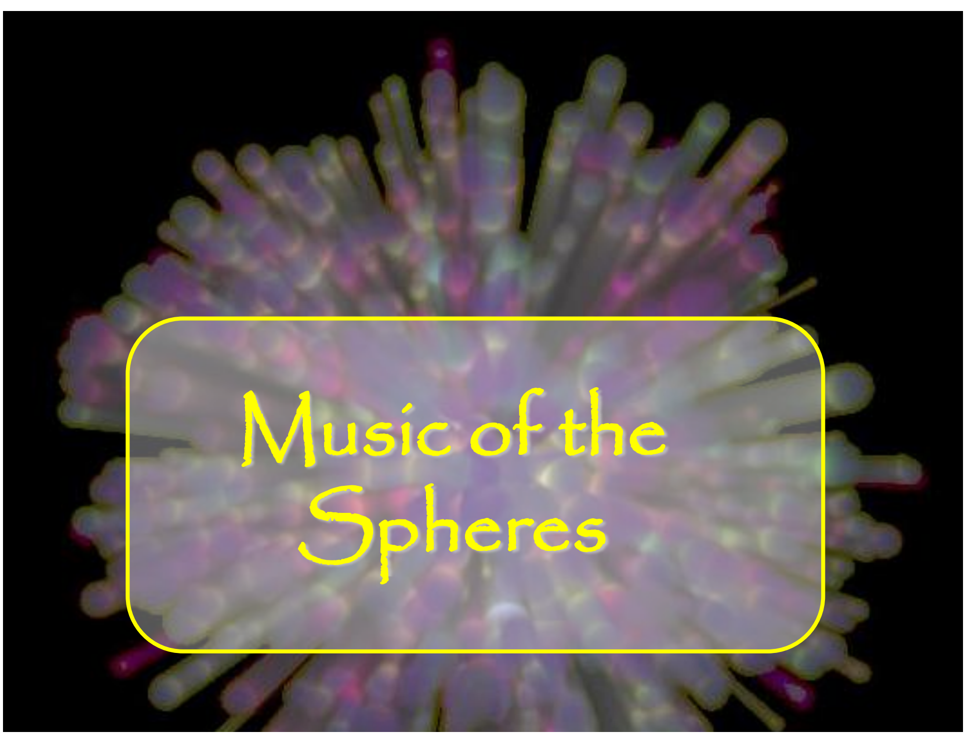
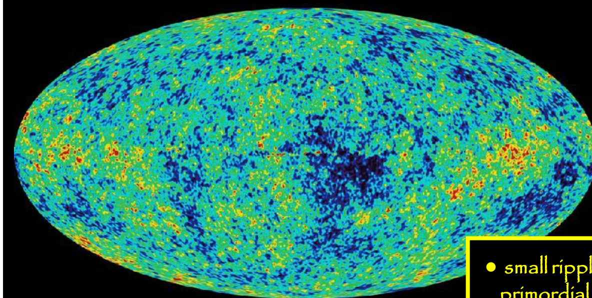
CMB Power Spectrum

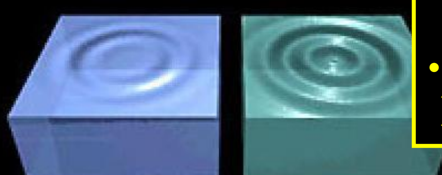


$$T(\theta,\phi)=\sum_{l,m} a_{lm} Y_l^m(\theta,\phi)$$

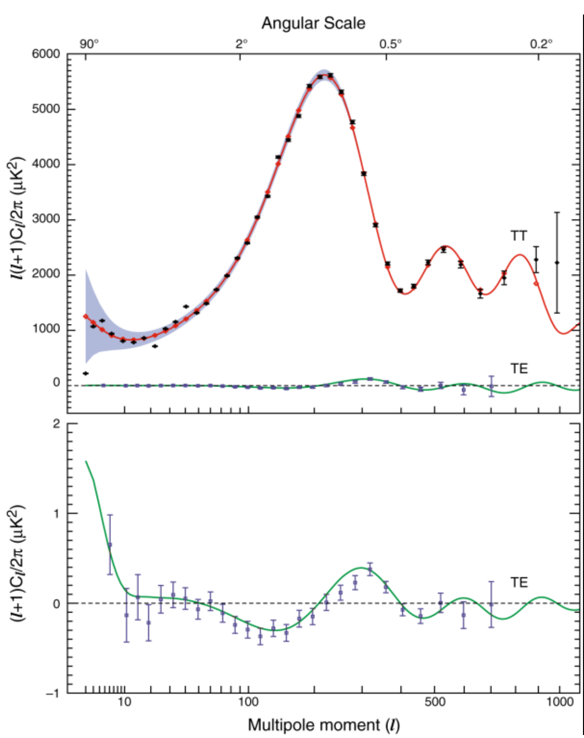


Cosmic Microwave Background





- 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



CMB

Angular power spectrum

WMAP3

Temperature fluctuations

Temperature-Polarization

$$C_l \propto \langle a_{lm} a^*_{lm} \rangle$$

$$C_l \propto l(l+1)$$

$$P(k) \propto k$$

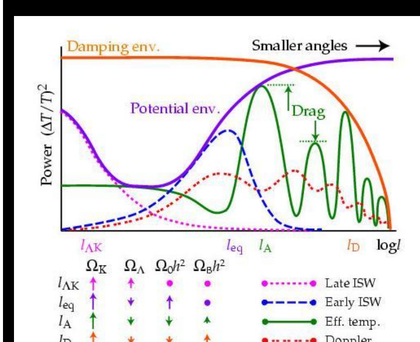
Harmonic Signature

- Identify structure and composition of the Universe
  - through detailed examination of the pattern of overtones on the fundamental frequency
  - much like using them for a music instrument

- Observed frequency spectrum consistent with inflationary origin:
  - spectrum of cosmic sound has harmonics at integer ratios of fundamental

- Without inflation, fluctuations should have been generated at intermediate times
- This would have destroyed the harmonic structure of the peaks (like drilling holes in an organ pipe)

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

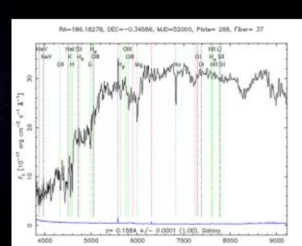
Used as point tracers of underlying cosmic density field.

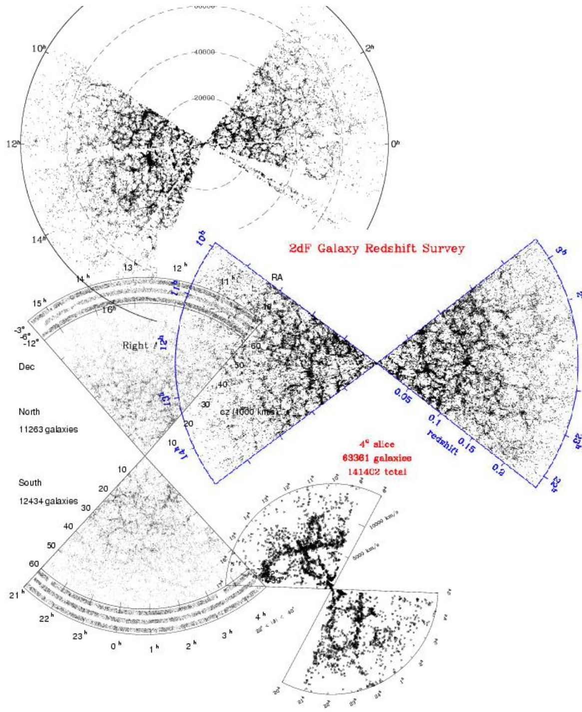
Intention is to map this cosmic matterfield on Megaparsec scales.

"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

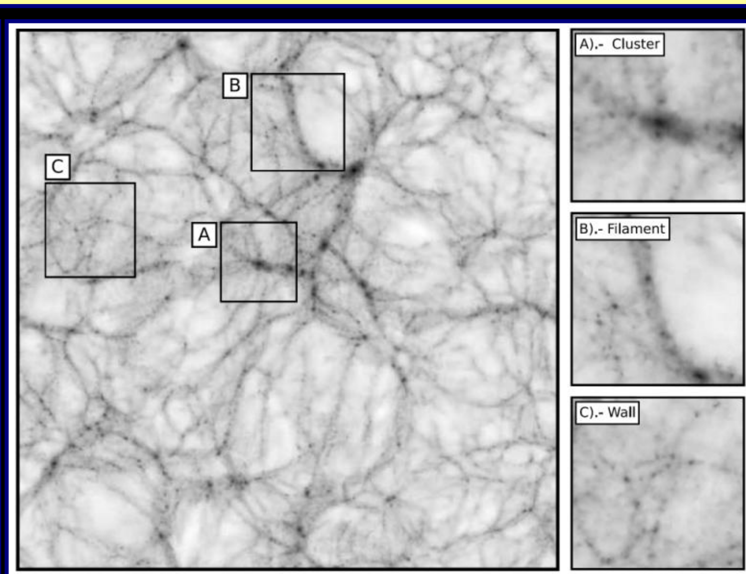
Stochastic Spatial Pattern of

- Clusters,
- Filaments &
- Walls

around

- Voids

in which matter, (DM, gas, gal's) has agglomerated



Galaxy Surveys:

Luminosity Function

Galaxy Surveys

- Galaxies , Groups, Clusters & Superclusters:

  Tracers of Structure in the Universe

- discrete tracers of underlying density field:

$$n(\vec{x}) \leftrightarrow \rho(\vec{x})$$

- Fair or Biased Tracer ?

Galaxy Surveys

- Ideal Sample:
  - all sample points have exactly the same properties over complete "survey volume"
- However ...
  galaxies have different luminosities, sizes, etc.:
  - systematic influence on distribution as function of depth
  - do galaxy properties depend on environment ?

Galaxy Surveys

- Various selection criteria:
  - + magnitude-limited
  - + angular diameter – limited
- Galaxy distribution as tracer cosmic structure:
  - + requirement to understand selection $\psi(r,\theta,\varphi,\nu,T)$:
    - sampling rate of galaxies at
      - distance r
      - sky position θ,φ
      - frequency ν
      - galaxy type T
- Most convenient and best controlled:
  - + selection on basis luminosity/brightness

Luminosity Function

Large variety of galaxies

- ranging from dwarfs to giant ellipticals
- large range of luminosity/brightness

Luminosity distribution:

$$dn(L) = \phi(L)dL$$

number of galaxies with luminosity

$$[L, L + dL]$$

PS. Luminosity distribution may depend on various galaxy properties, such as morphological type

Schechter Luminosity Function

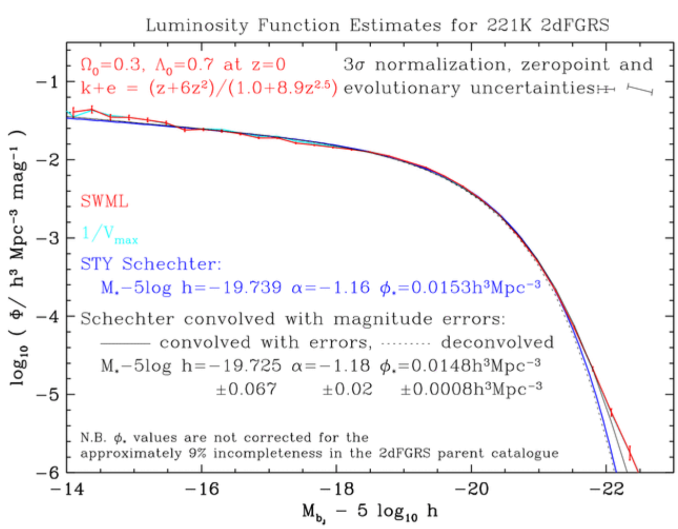
Very good approximate expression for the galaxy luminosity distribution:

- Schechter Luminosity Function:

$$\phi(L)dL = \phi^{*}\left(\frac{L}{L_{*}}\right)^{\alpha} e^{-L/L_{*}} d\left(\frac{L}{L_{*}}\right)$$

- Parameterized by 3 parameters:
  - ϕ^* : normalization density parameter
  - L_* : characteristic luminosity
  - α : faint-end slope

Schechter Function



Schechter Luminosity Function

- Mean space density gal's:

$$n(L)dL = \int_0^\infty \phi(L)dL = \phi^* \int_0^\infty s^\alpha e^{-s} ds = \phi^* \Gamma(\alpha+1)$$

– Gamma function: $\Gamma(z) = \int_0^\infty t^{z-1} e^{-t} dt$

– Notice: divergent if α<-1
(infinite contribution faint gal's)

- Mean Luminosity (from cosmic volume)

$$\langle L \rangle = \int_0^\infty L\phi(L)dL = \phi^* L_* \int_0^\infty s^{(\alpha+1)} e^{-s} ds = \phi^* L_* \Gamma(\alpha+2)$$

- divergent only if α<-2

Schechter Luminosity Function

- 2dFGRs luminosity function:

$$M_* = -19.725$$
$$\alpha = -1.18$$
$$\phi^* = 0.0148\ Mpc^{-3}$$

- Faint Galaxies dominate number density !!!!!

Bright Galaxies determine the luminosity (stars) in a cosmic volume !!!!!

Survey Depth

- Most galaxy surveys defined by apparent magnitude limit m_{lim}
- All galaxies having an apparent brightness higher than that corresponding to m_{lim} are included in survey
- Depends on
  - intrinsic brightness/absolute magnitude M
  - (luminosity) distance d_L
  - (- k-correction: shift galaxy spectrum as function redshift z)
- Absolute Magnitude ⟷ Apparent Magnitude

$$M = m - 5\log d_L(z) - 25 - k(z)$$

Survey Depth

- For a survey with magnitude limit m_{lim}:
- At distance d_L (Mpc) one can see galaxies brighter than:

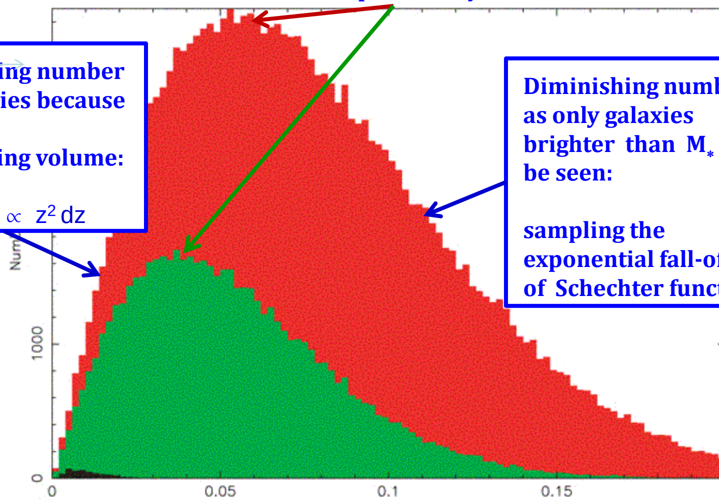
$$M = m_{\lim} - 5\log d_L(z) - 25 - k(z)$$

- Survey Depth d_{sur}: distance out to which one can see an M_* galaxy:

$$\log d_{sur} = 0.2(m_{\lim} - M) + 5 + 0.2k(z)$$

Survey Depth

Depth Survey



Redshift z

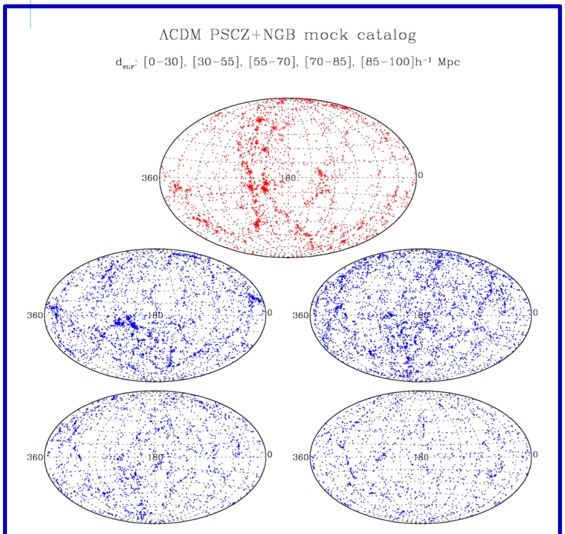
Increasing number of galaxies because of increasing volume:

$N(z)\,dz \propto z^2\,dz$

Diminishing number as only galaxies brighter than M_* can be seen:

sampling the exponential fall-off of Schechter function

Survey Depth

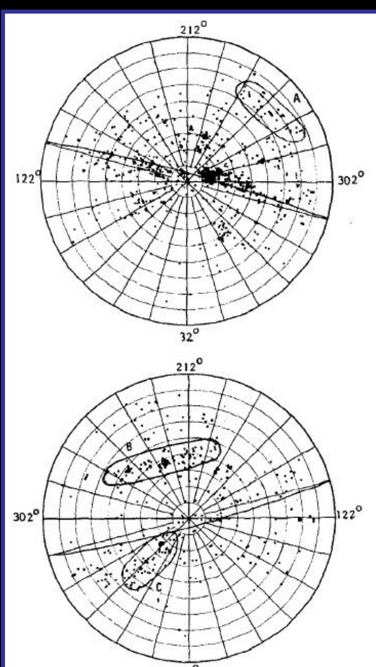


Theoretical Example:

Galaxies in PSCz catalogue, at different depths

Sky Maps: world all around us

Early Views



Shapley-Ames catalog (1932) of nearby galaxies:

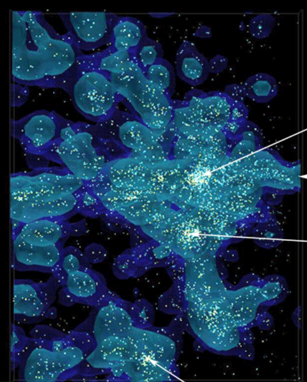
All-sky survey of galaxies to $m=18.3$

$\delta > -23^o$

- 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:



150 million light years wide x 190 million light years tall

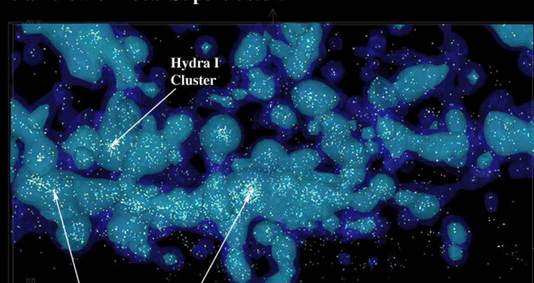
Courtesy: B. Tully

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:



300 million light years wide x 150 million light years tall

Courtesy: B. Tully

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

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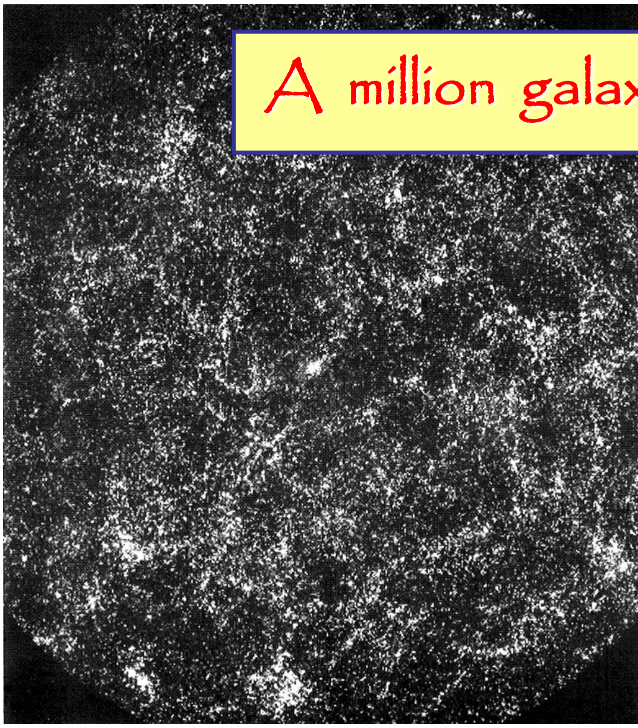


A million galaxies

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:

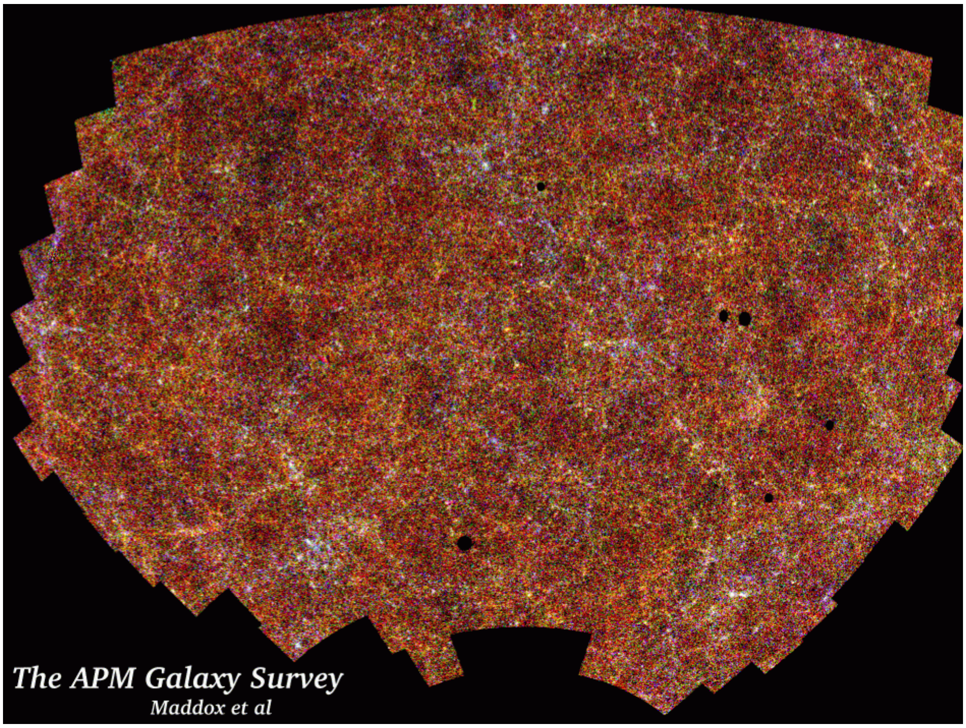
  2×10^6 galaxies

  $17 < m < 20.5$
- Uniformly defined
- Sky region: 4300 sq. deg.

  185 UK Schmidt plates, 6° x 6°

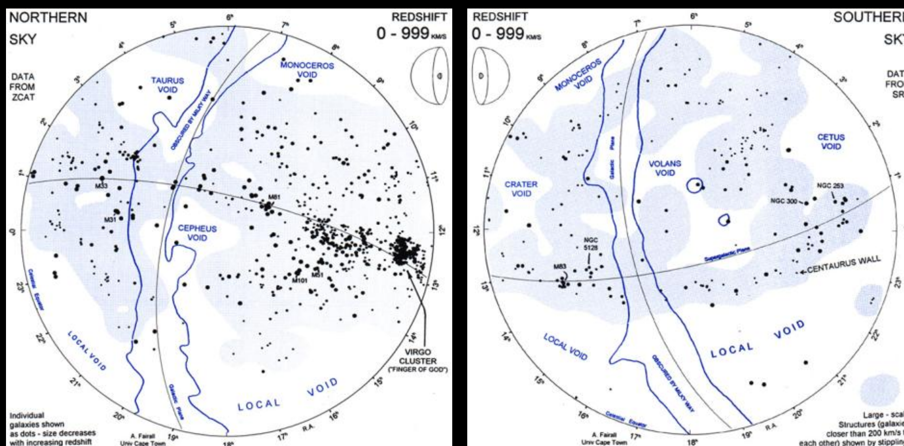
- Large inhomogeneities, hints of weblike patterns, with clusters at densest regions.

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



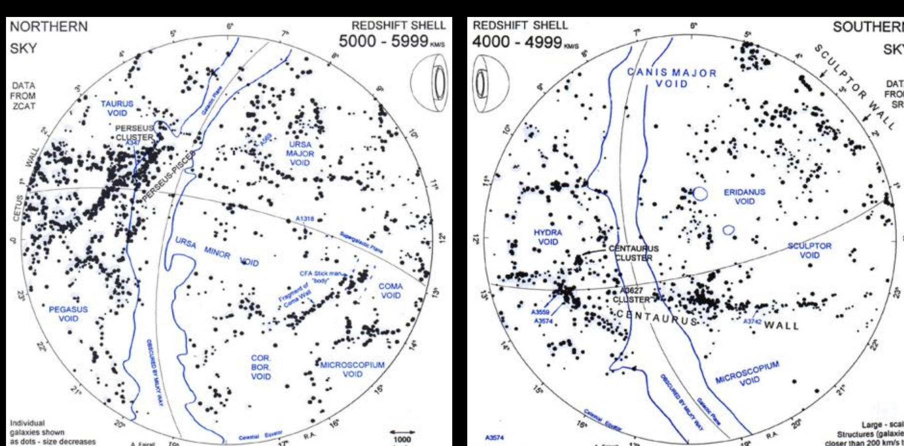
Maps of the Local Universe

Local Views

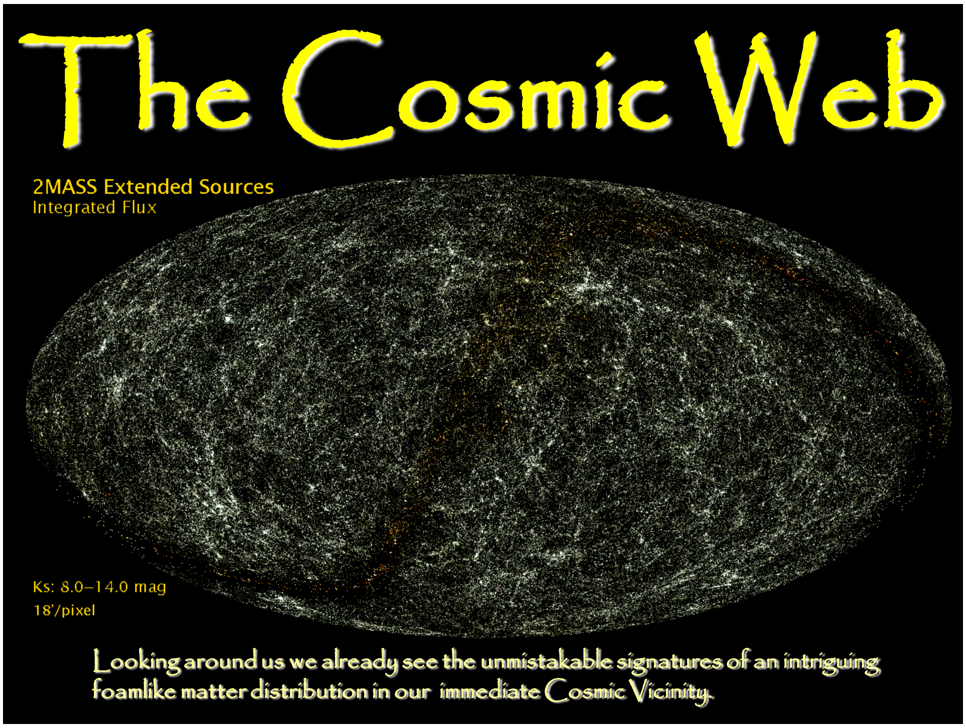


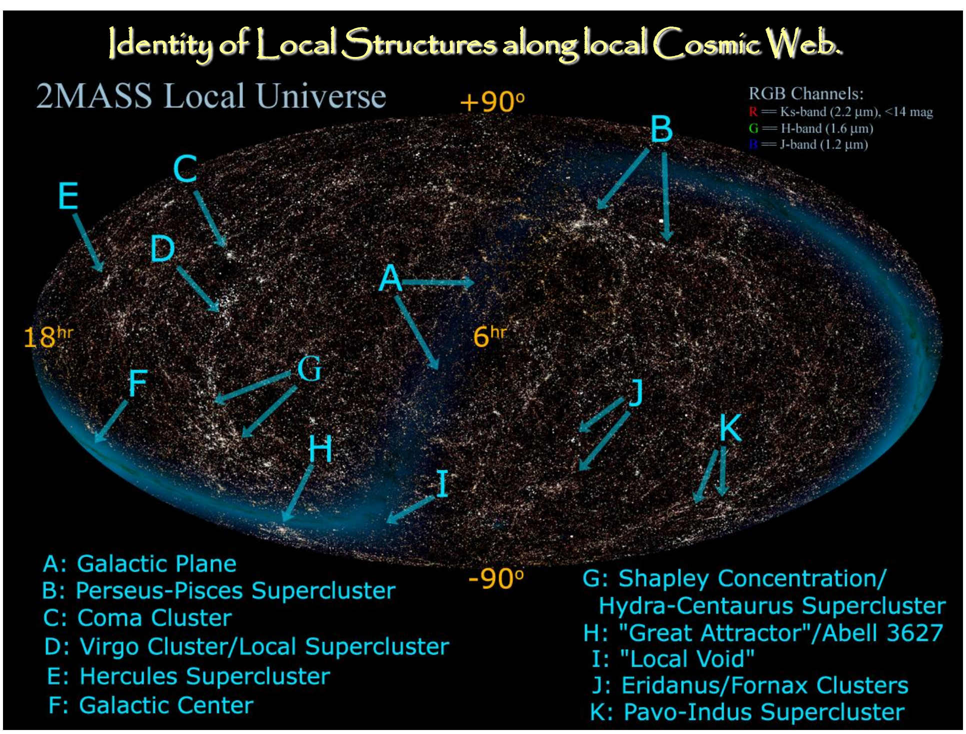
Tony Fairall's nearby LSS map: Local Supercluster clearly visible at v < 999 km/s

Local Views: Moving into Foam



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


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.

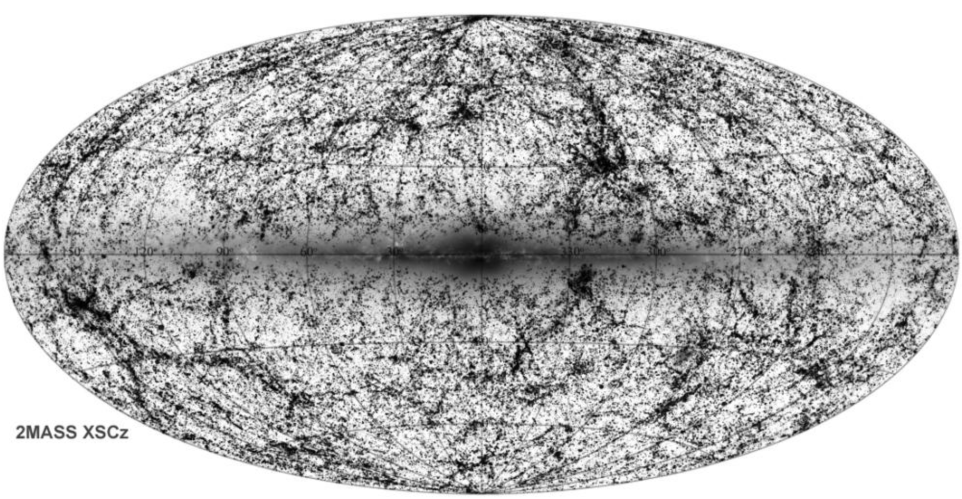

Identity of Local Structures along local Cosmic Web.
2MASS Local Universe
+90°
RGB Channels:
R = Ks-band (2.2 μm), <14 mag
G = H-band (1.6 μm)
B = J-band (1.2 μm)
B
C
E
D
A
18hr
6hr
F
G
J
K
H
I
-90°
A: Galactic Plane
B: Perseus-Pisces Supercluster
C: Coma Cluster
D: Virgo Cluster/Local Supercluster
E: 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

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.

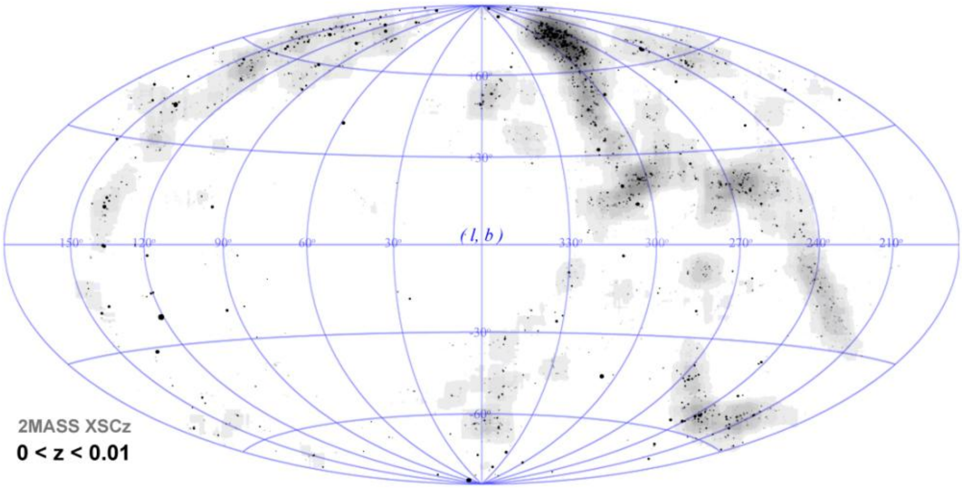
courtesy: T. Jarrett

2MASS Cosmic Web



Looking around us we already see the unmistakable signatures of an intriguing weblike matter distribution in our immediate Cosmic Vicinity.

2MASS Cosmic Web



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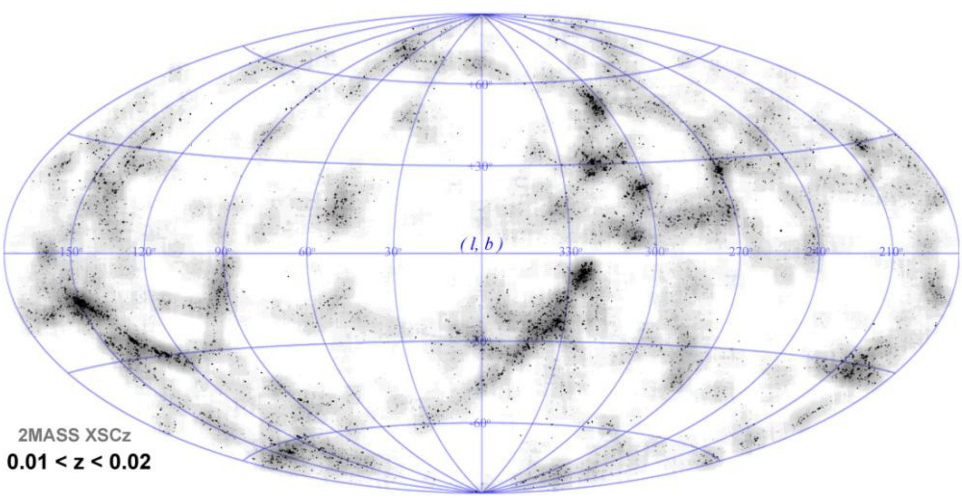
2MASS Cosmic Web



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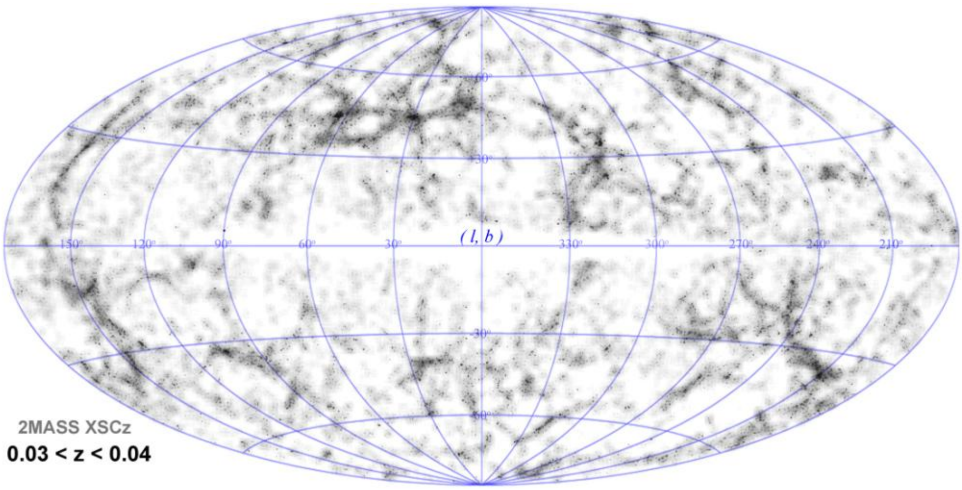
2MASS Cosmic Web



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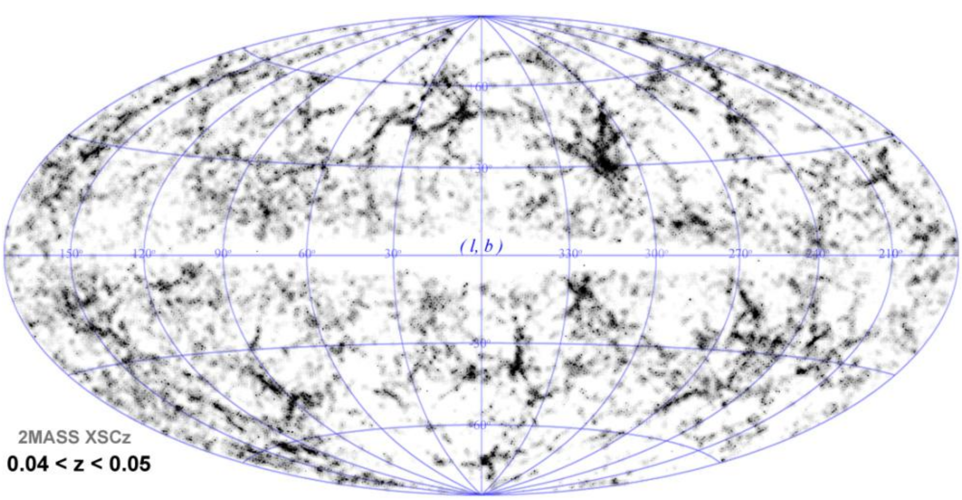
2MASS Cosmic Web



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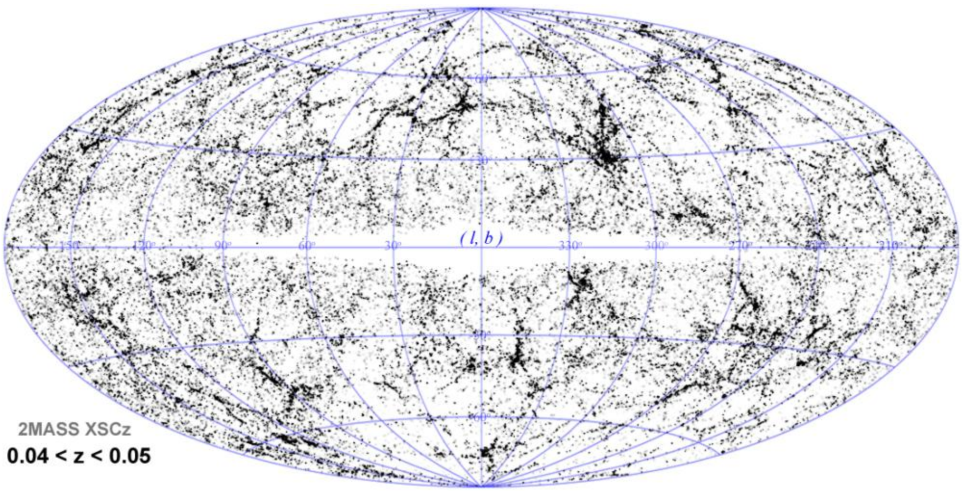
2MASS Cosmic Web



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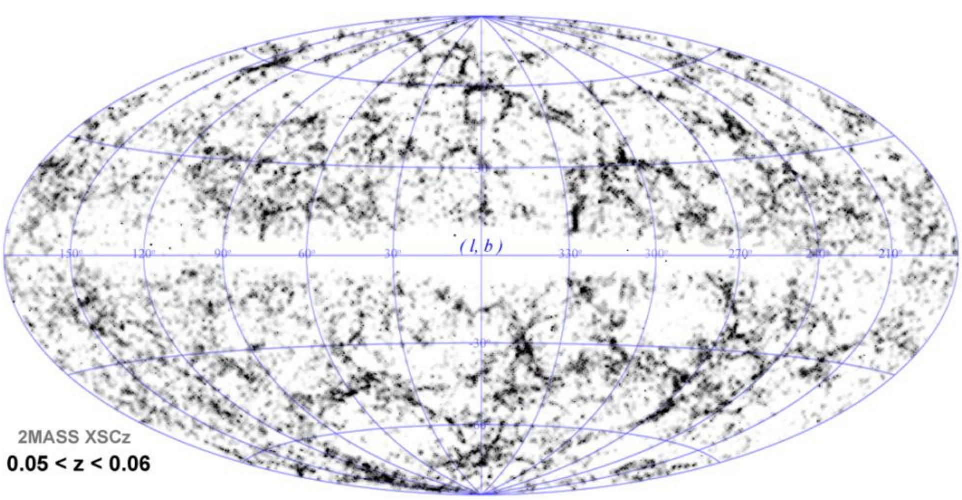

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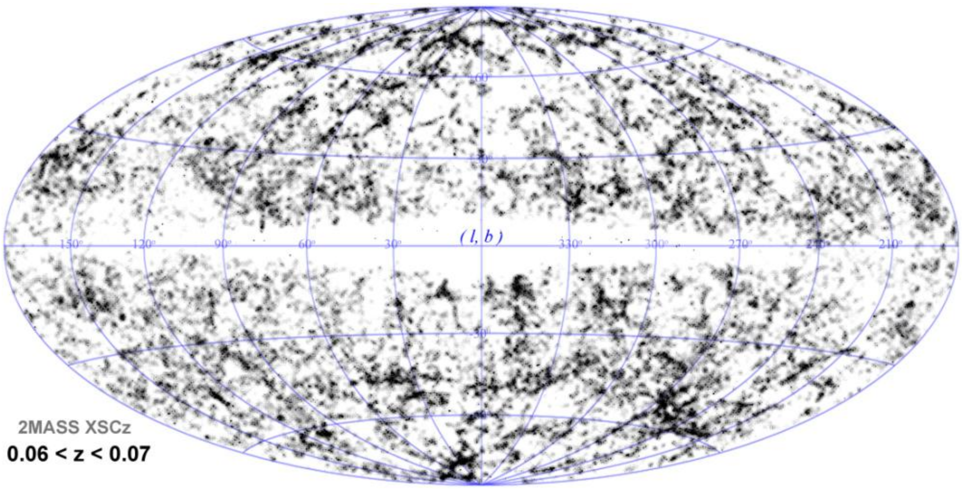

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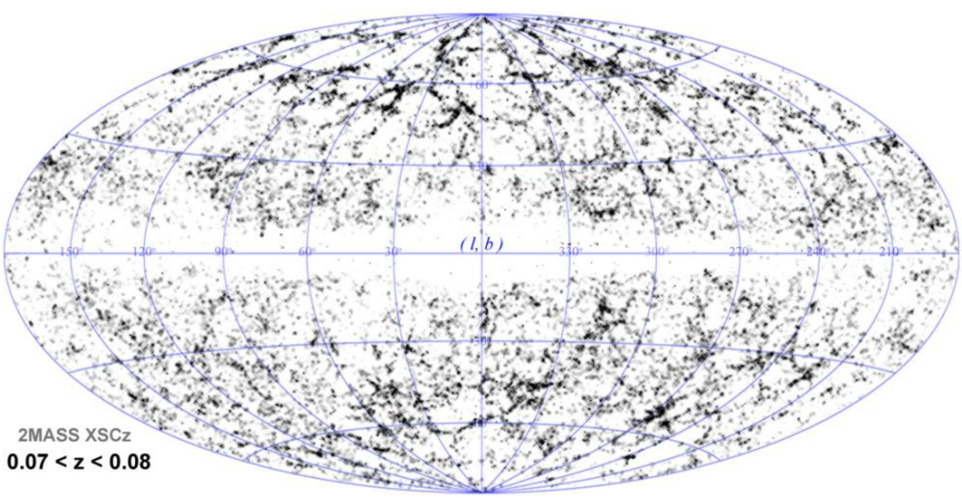

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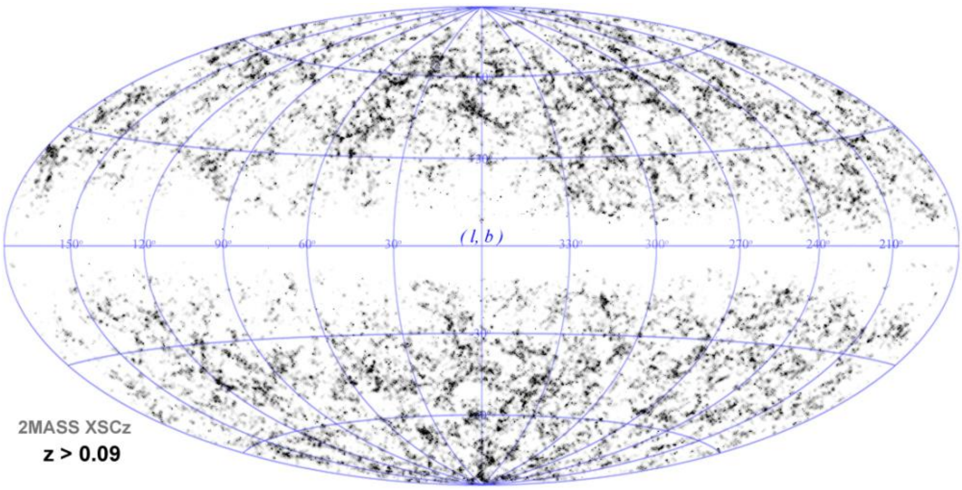

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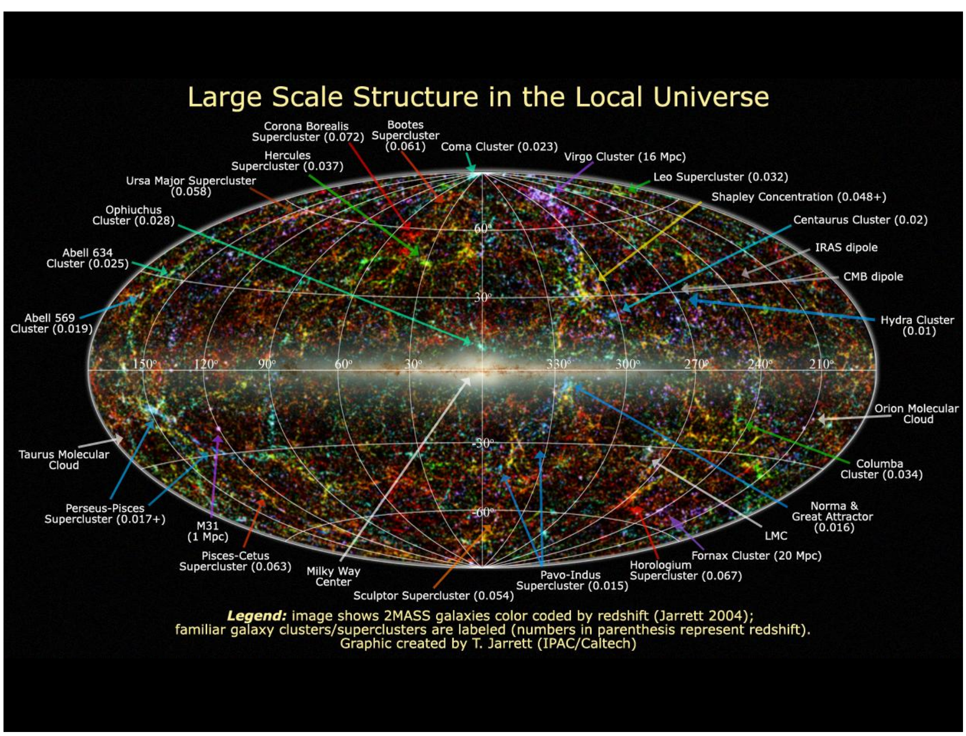


Galaxy Redshift Surveys

Galaxy Redshift Surveys

- For obtaining 3D maps of the galaxy distribution:

  measure spatial location of galaxies:
  - position on the sky (α,δ)
  - distance r

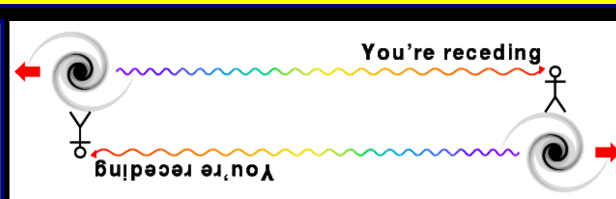
- Determination real distance r of galaxy very cumbersome, reasonably accurate estimates only for nearby gal's ...

- Common approximate method:
  exploit Hubble expansion of the Universe

Galaxy Redshift Surveys

$$1 + z = \frac{1}{a} \Longleftarrow \begin{cases} \lambda_{em} = \lambda_0 \\ \lambda_{obs} = \dfrac{a(t_{obs})}{a(t_{em})} \lambda_0 \end{cases}$$

$$z \equiv \frac{\lambda_{obs} - \lambda_{em}}{\lambda_{em}}$$



Galaxy Redshift Surveys

- Hubble Expansion:

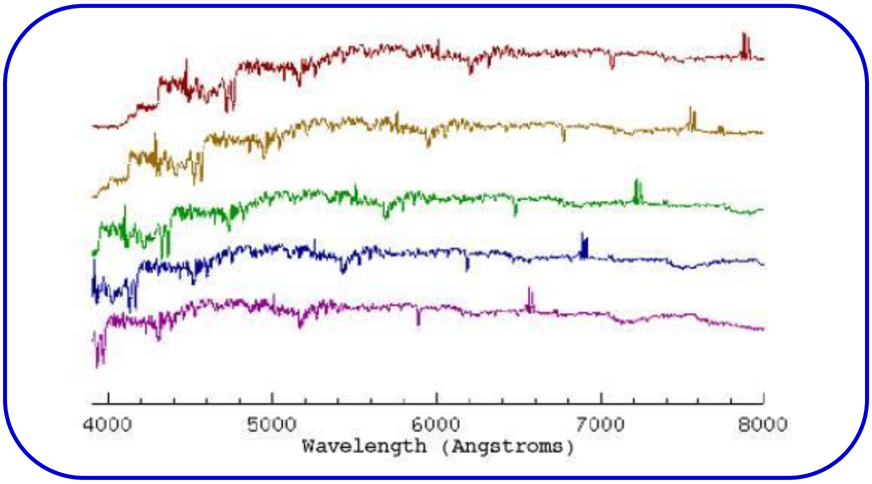
$$cz = Hr \quad (z \ll 1)$$

galaxy at distance r
has redshift z
(c: vel. light; H: Hubble constant)

- Redshift of galaxies can be much more easily determined than distance:

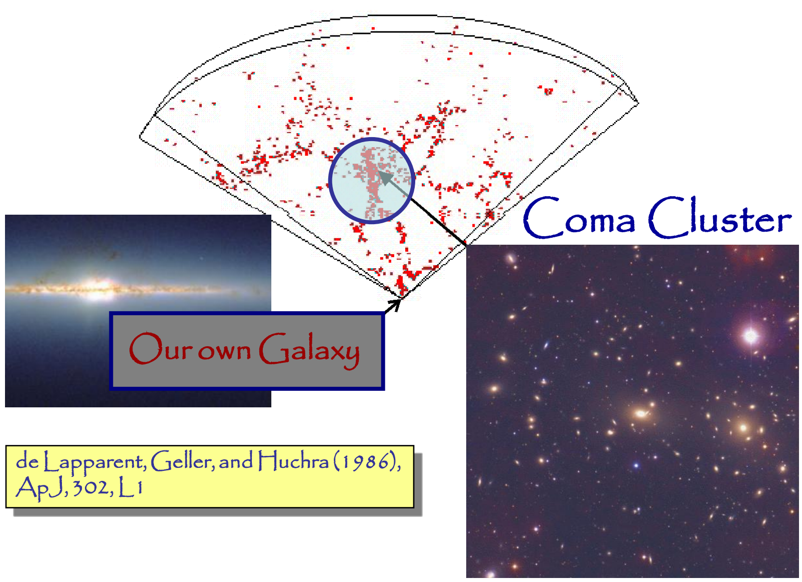
Galaxy Spectrum

Galaxy Redshift Surveys



Examples of redshifted galaxy spectra

Mapping the Universe



Redshift Space Distortions

Redshift Distortions

- In reality, galaxies do not exactly follow the Hubble flow:

  In addition to the cosmological flow, there are locally induced velocity components in a galaxy's motion:

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

  the galaxy's peculiar velocity v_{pec}

- As a result, maps on the basis of galaxy z do not reflect the galaxies' true spatial distribution

Redshift Distortions

Origin of peculiar velocities:

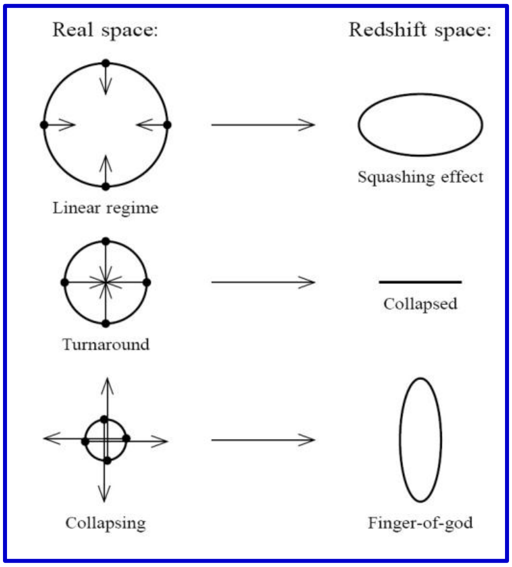
three regimes

- very high-density virialized cluster (core) regions: "thermal" motion in cluster, up to > 1000 km/s

  "Fingers of God"

- collapsing overdensity (forming cluster): inflow/infall velocity

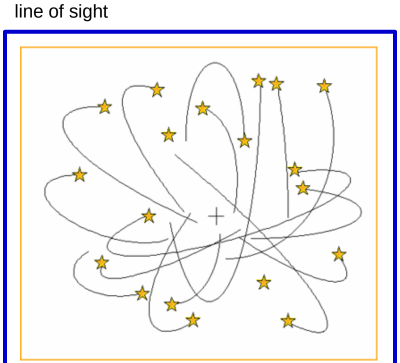
- Large scales: (linear, quasi-linear) cosmic flow, manifestation of structure growth

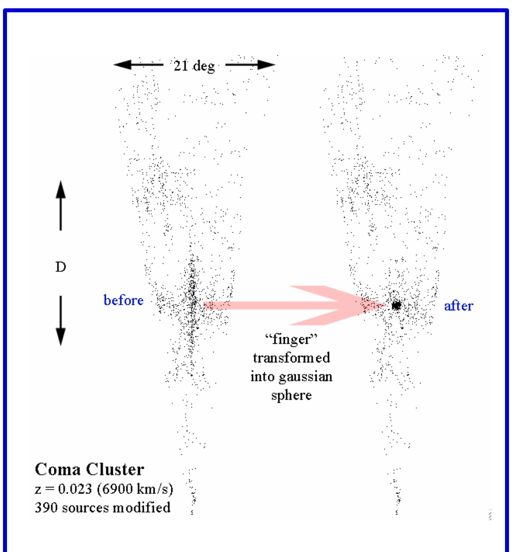


Fingers of God

$$cz = Hr_{clust} + \frac{\vec{v}_{gal} \cdot \vec{r}_{gal}}{r_{gal}}$$

Galaxy velocity component along line of sight





Fingers of God

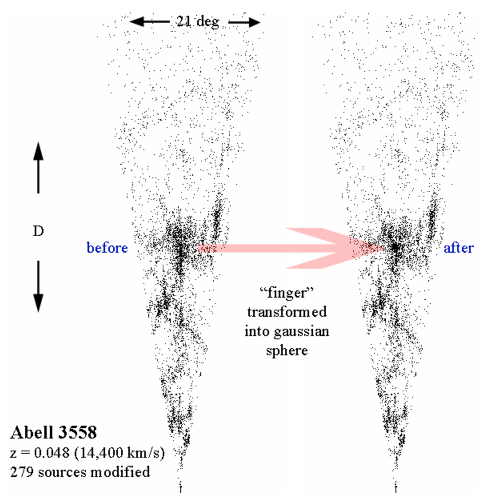
Clusters of galaxies:

Mass: 10^{14}-$10^{15} M_\odot$
Radius: ~ 1.5 Mpc
Overdensity Δ ~ 1000

Thermal velocity: ~ 1000 km/s

Internal cluster galaxy velocities visible in projection along line of sight

→ "Finger of God"



Nonlinear Infall Pattern

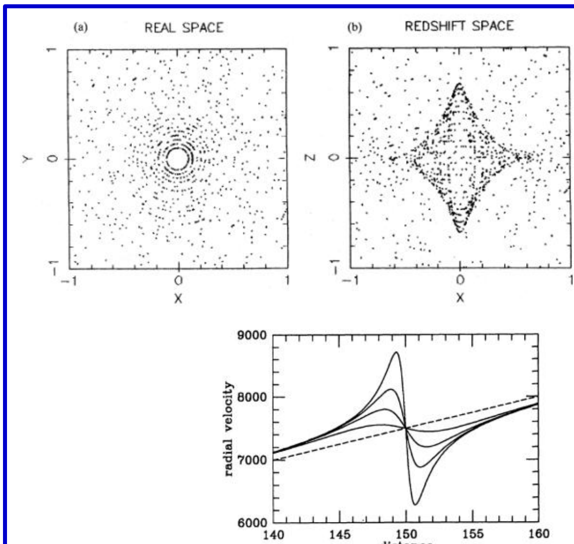
Cluster Infall:

Matter in surroundings falling in onto cluster:

- infall velocities up to 1000 km/s radially declining:
- velocities decrease as distance to cluster centre increases
- projected radial velocity function of angle & distance wrt. cluster centre.

→

- triple-value region redshift space:
  - within turnaround radius, a particular redshift z may correspond to 3 spatial positions



Nonlinear Infall Pattern

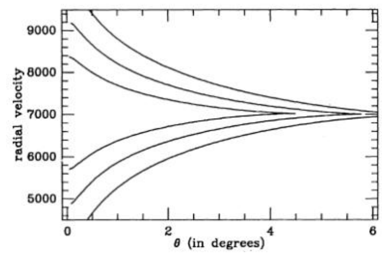
Cluster Caustics:

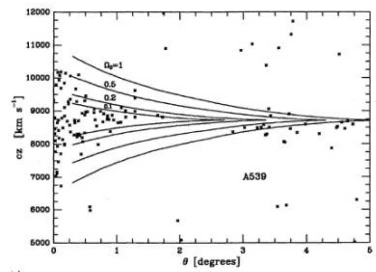
Three-value region cluster infall:

Projection onto restricted cone-shaped redshift space regions around clusters

Enclosed within caustic surfaces

Position caustics dependent on Ω_m

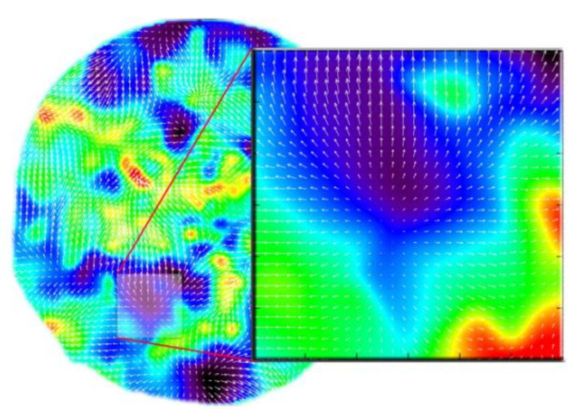




Large Scale Flows

Large-Scale Flows:

- On large (Mpc) scales, structure formation still in linear regime
- Structure buildup accompanied by displacement of matter: - Cosmic flows
- Directly related to cosmic matter distribution
- In principle possible to correct for this distortion, ie. to invert the mapping from real to redshift space
- Condition: entire mass distribution within volume should be mapped



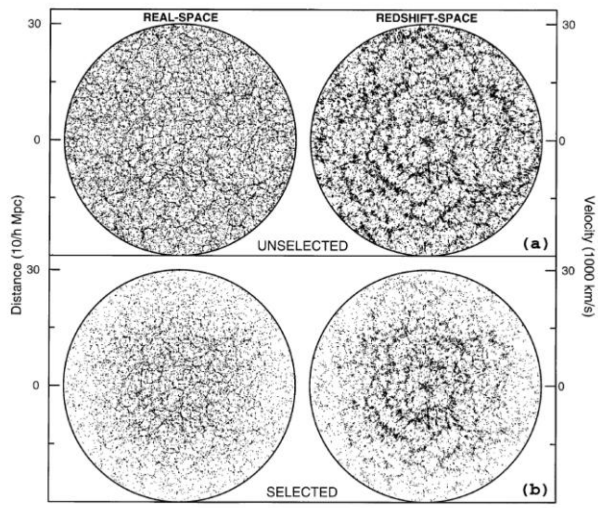
$$\mathbf{v}(\mathbf{x},t) = \frac{H}{4\pi}\frac{f(\Omega_m)}{b}\, a \int d\mathbf{x}'\, \delta_{gal}(\mathbf{x}',t)\, \frac{(\mathbf{x}'-\mathbf{x})}{|\mathbf{x}'-\mathbf{x}|^3}$$

Large Scale Flows

Large-Scale Flows:

The induced large scale peculiar velocities translate into extra contributions to the redshift of the galaxies

Compare
"real space" structure vs.
"redshift space" structure



Magnitude vs. Volume Limited

Magnitude vs. Volume limited Surveys

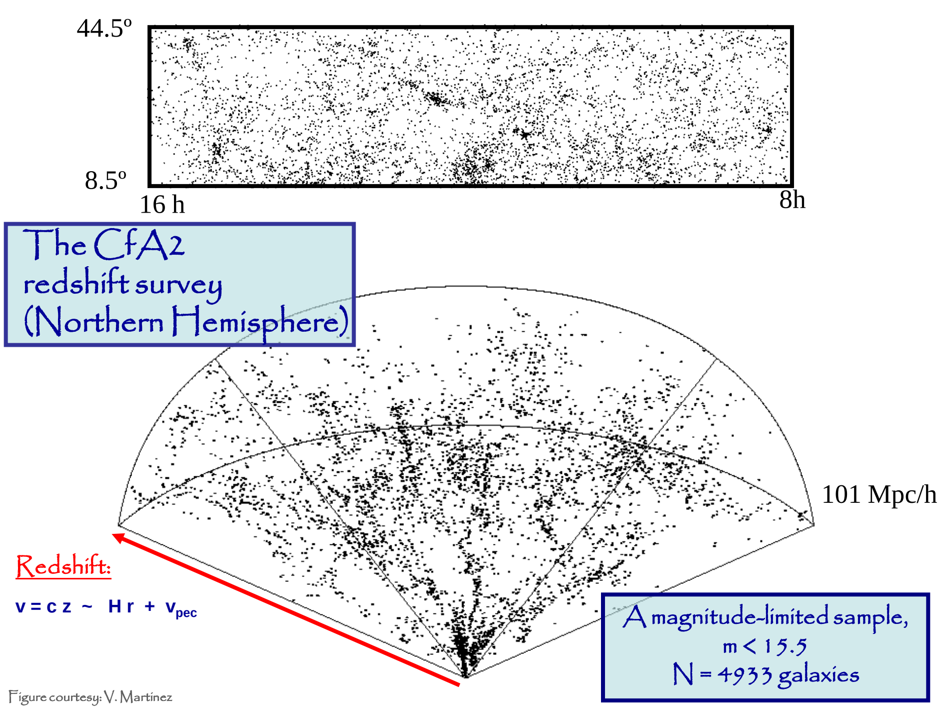
- Two different sampling approaches for analysis spatial structure from galaxy redshift catalogue:

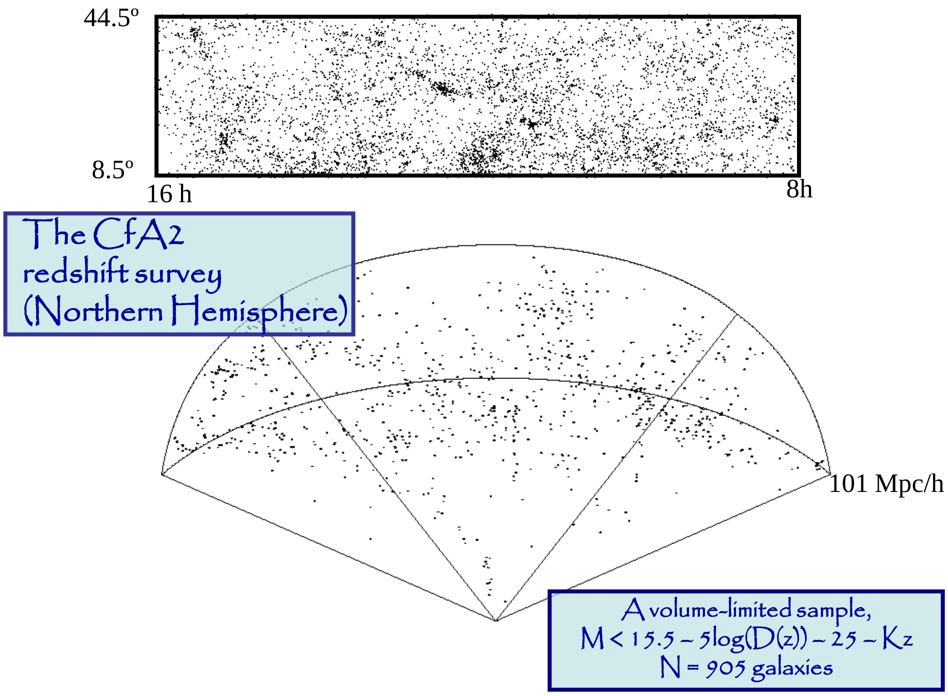
- Volume-limited surveys:
  - uniform spatial coverage, including all galaxies within volume to depth d_s
  - all galaxies with an absolute brightness > survey limit M_s

$$M_s = m_{\lim} - 5\log d_s - 25 - k(z)$$

  - diminishing sampling density & spatial resolution as one wishes to include larger volume (excluding all galaxies $M>M_s$)

- Magnitude-limited survey
  - include all galaxies with apparent magnitude brighter than m_s
  - assures optimal use of spatial galaxy catalogue
  - at the price of an non-uniform spatial coverage & diminishing resolution towards higher depths

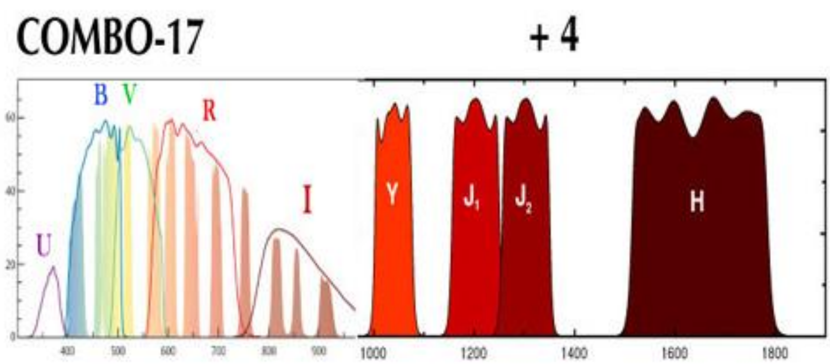




Photometric Redshifts

Photometric Redshifts

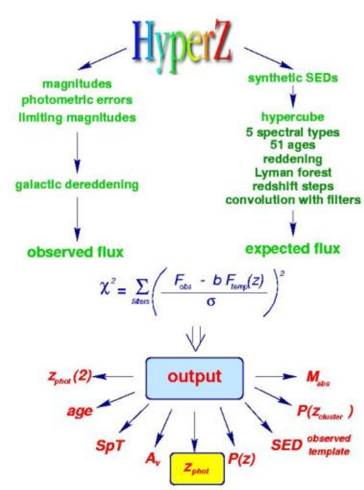
- Instead of measuring the electromagnetic spectrum of the galaxies in a survey, one may get a good estimate of the redshift on the basis of the photometry and colours of the objects.



Photometric Redshifts

Practical Implementation:

- Photometric redshifts determined by fitting to standard SED
  (SED: spectral energy distribution)
- Taking into account:
  - spectral type
  - reddening
  - Lymanα forest (high z!)
  - filters
- Accuracy (typical):
  - $\Delta z \sim 0.1$



widely used Hyperz package

Photometric Redshifts

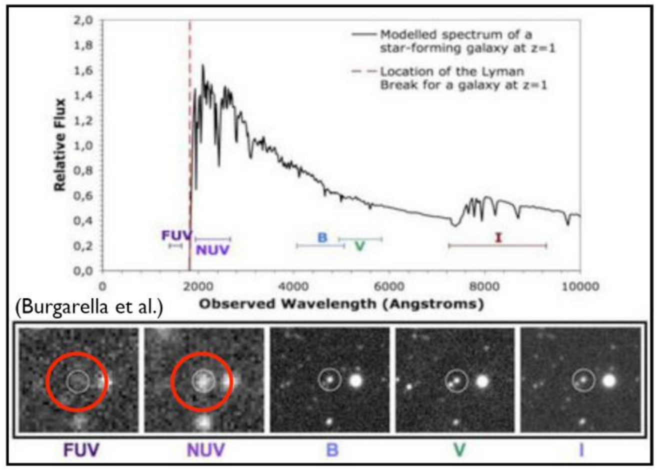
Photometric Redshifts

Technique widely used for identifying high z objects

For example, Lyman break results

in

FUV-NUV dropouts (1400-1800 A)
for z ~ 0.5-1.0

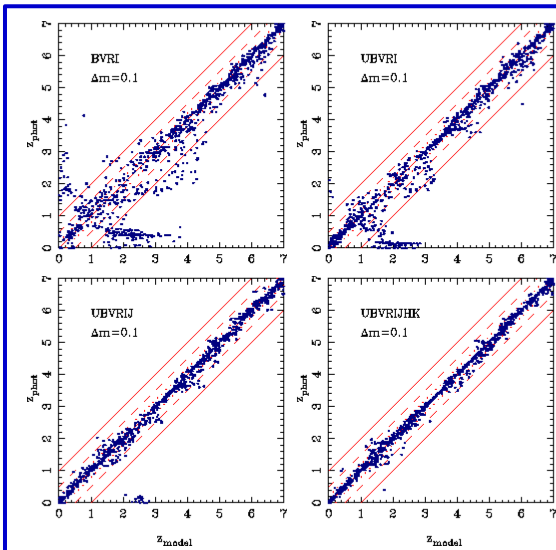


Below the Lyman break at 912 A, hydrogen absorbs galaxy light

Photometric Redshifts

Photometric Redshifts:

- Accuracy (typical):
  - $\Delta z \sim 0.1$
- Accuracy higher as more bands are used
- Bands to be chosen to take into account spectral characteristics/ features
- eg. low z: UV still weak point



Survey Geometry

Survey Geometry

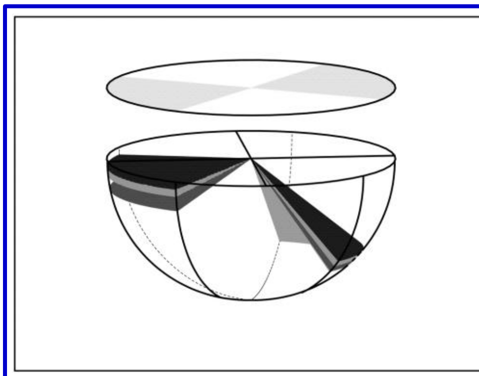
Practical Limitations

- Limited telescope time
- Limited detector sensitivity

• How to optimally sample structure in Universe ?

• Devise survey geometry that reveals optimal amount of Information on question at hand:

- Patterns galaxy distribution
- Distribution high-density peaks
- Density Field



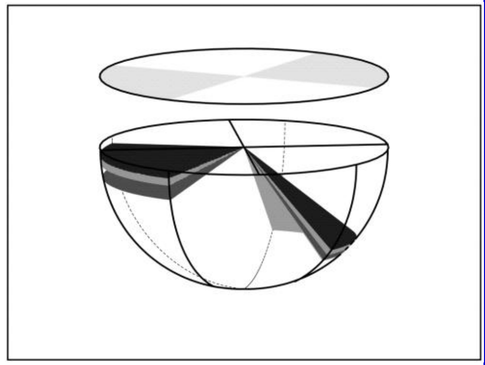
Sky Location
2-D LCRS survey slices

Survey Geometry

Survey Geometry:

•Slice Surveys:
- thin stripe on sky
- very sensitive to reveal patterns galaxy distribution

• Pencil-beam surveys
- very narrow region on sky
- very deep
- strategy to probe largest structures
- structure at high z (early times)



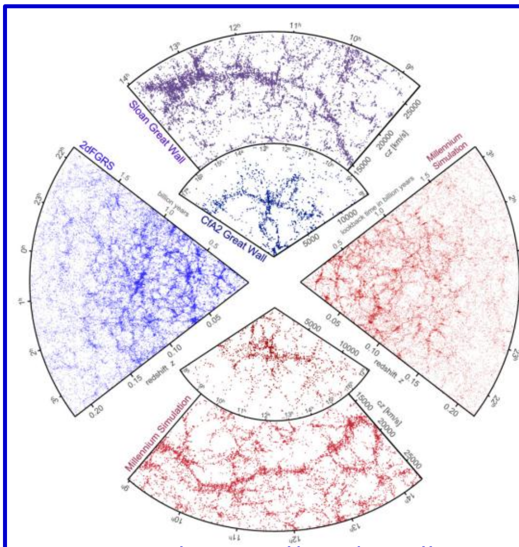
Sky Location
2-D LCRS survey slices

Survey Geometries

Examples of

Slice Redshift Surveys:

From
CfA2-2dFGRS-SDSS

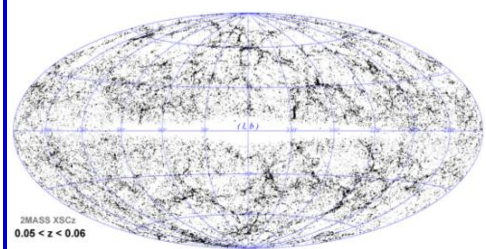


Survey Geometry

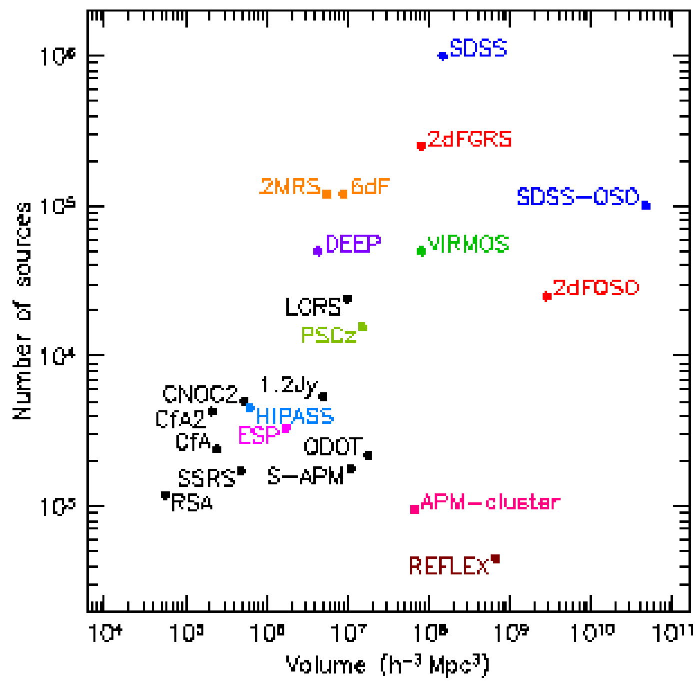
Survey Geometry:

•Sparse Sample:
- sampling density field
- on scales > intergalaxy distance

• Full-sky surveys
- necessary to probe dynamics cosmic regions



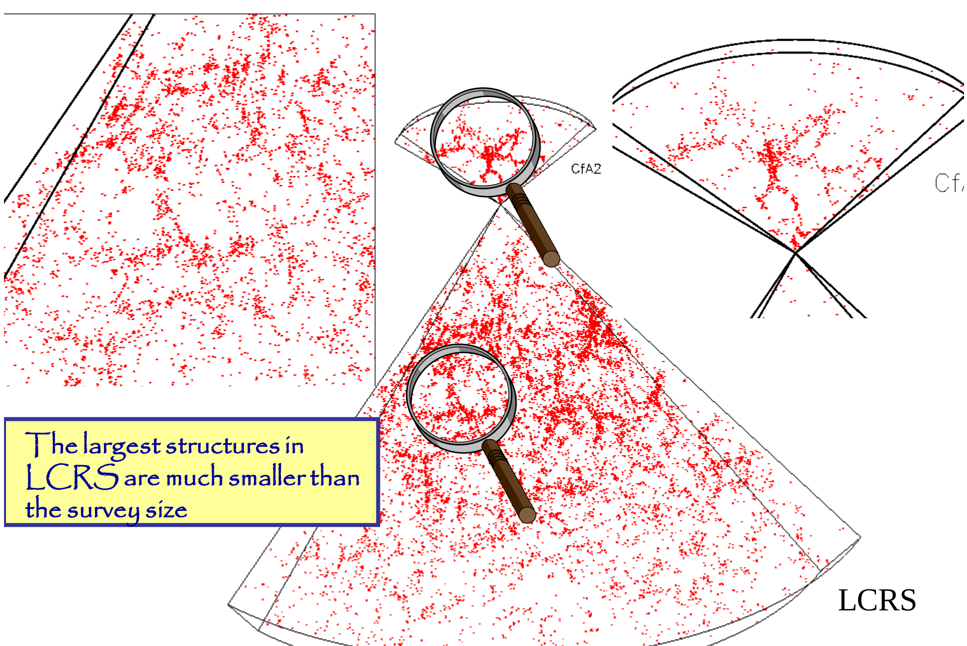
Galaxy Redshift Surveys: Overview



Comparing Galaxy/Cluster

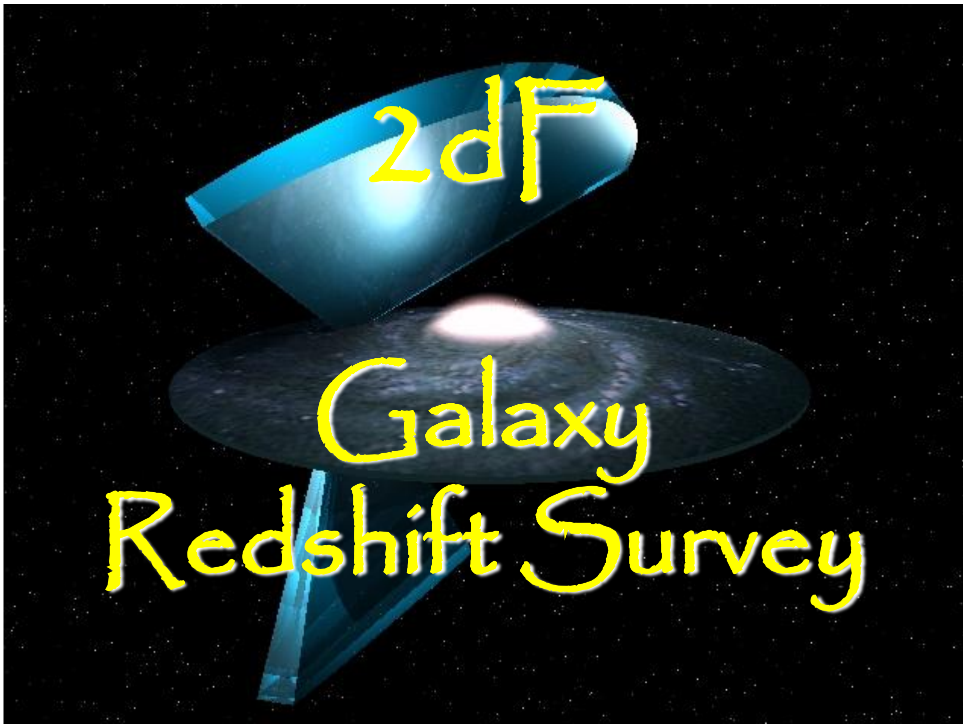
Redshift Surveys

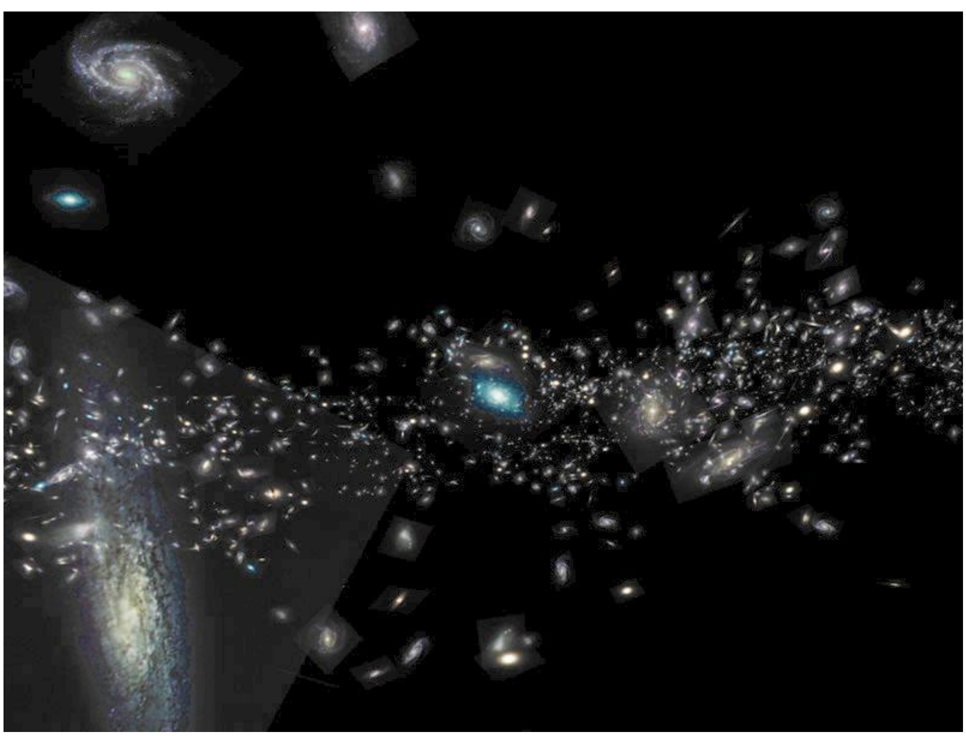
“Sensitivity” vs. Extent

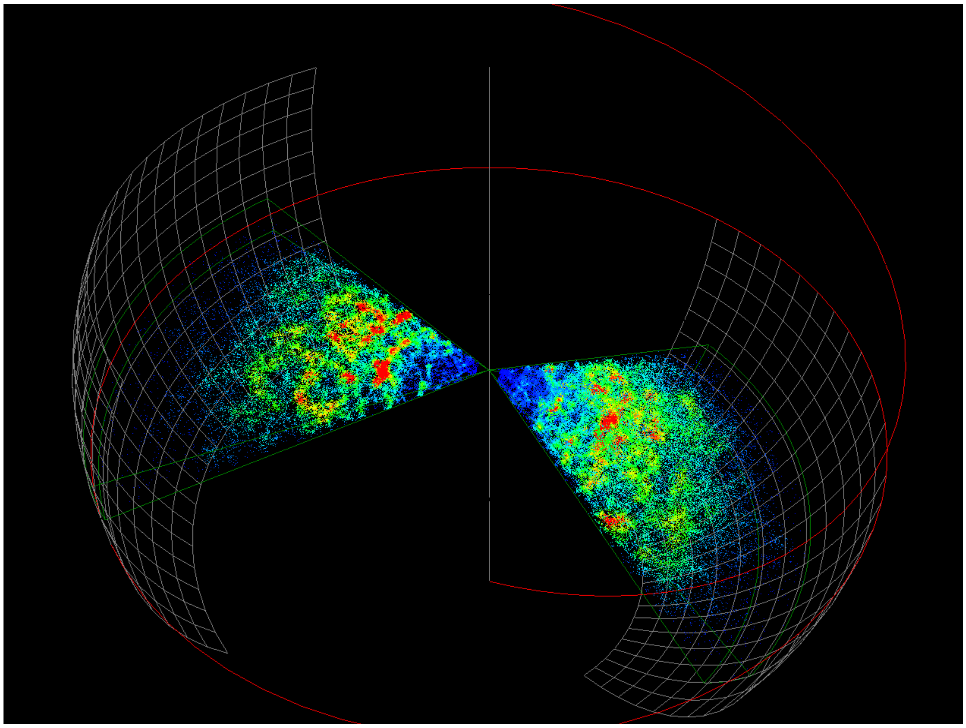


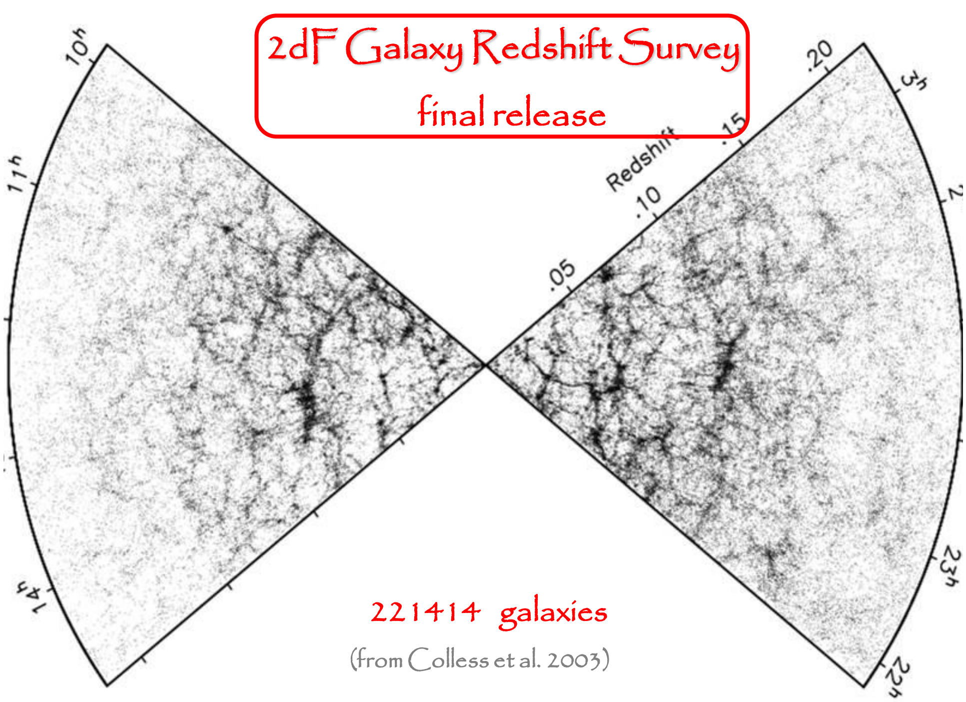
The largest structures in LCRS are much smaller than the survey size

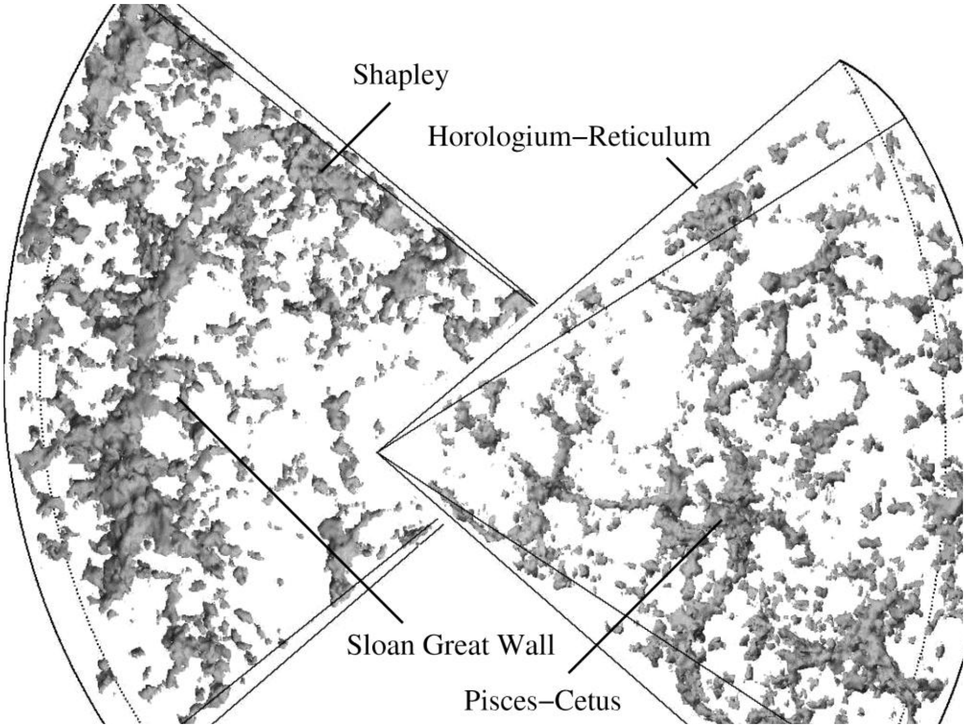
“ The beginning of the end” or “the end of greatness” ...R. Kirshner


2dF
Galaxy
Redshift Survey






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


Shapley
Horologium−Reticulum
Sloan Great Wall
Pisces−Cetus

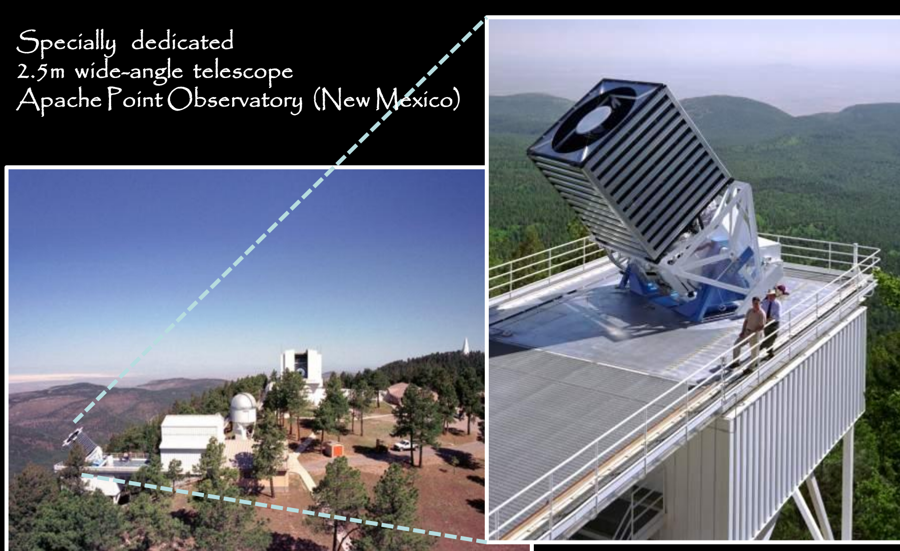

SDSS
Galaxy
Redshift Survey

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

Specially dedicated
2.5m wide-angle telescope
Apache Point Observatory (New Mexico)



SDSS survey

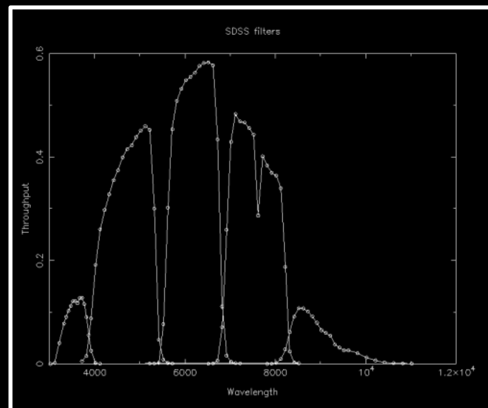
Aims to sample 25% of the sky:
DR7 - 8423 sq. deg.

Photometric system 5 filters:

	λ		m_{lim}
u	354	nm	24.4
g	476	nm	25.3
r	628	nm	25.1
i	769	nm	24.4
z	925	nm	22.9

Driftscan mode
- 5 filters:
- 30 CCD chips, 5 rows of 6
- S/N ~ 5
- CCD chip: 2048x2048 pixels
  120 Mbyte

Spectroscopy
- up to 640 (fibers) per recording
- per night 6-9 recordings



SDSS survey

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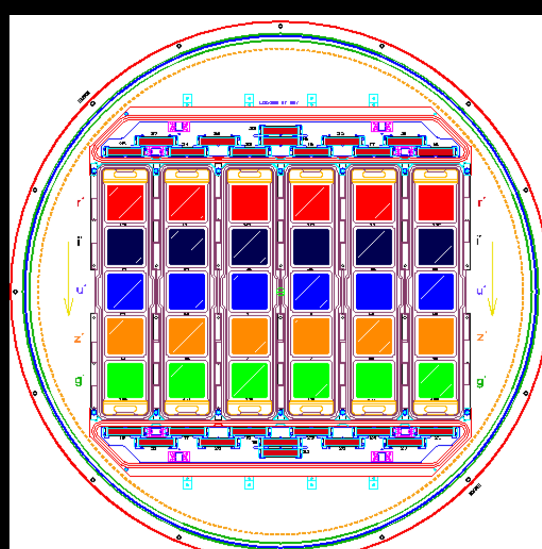
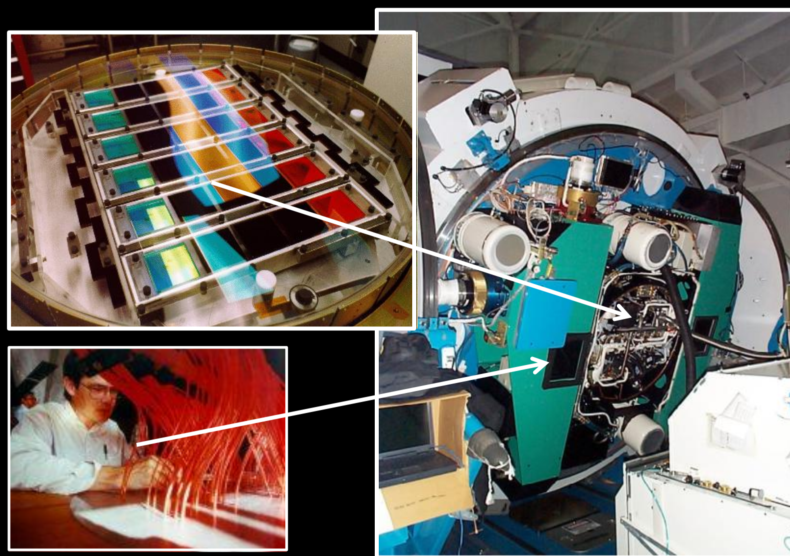


SDSS survey

5-color Camera

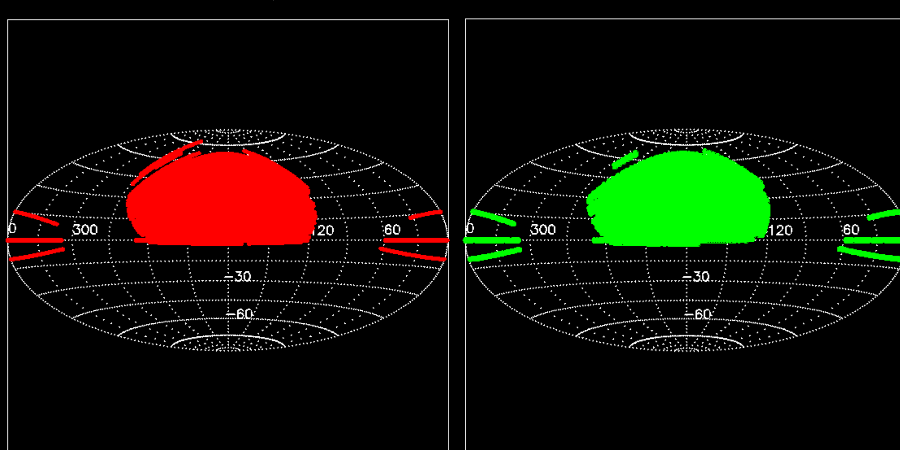
30 CCD chips

Fiber Spectrograph



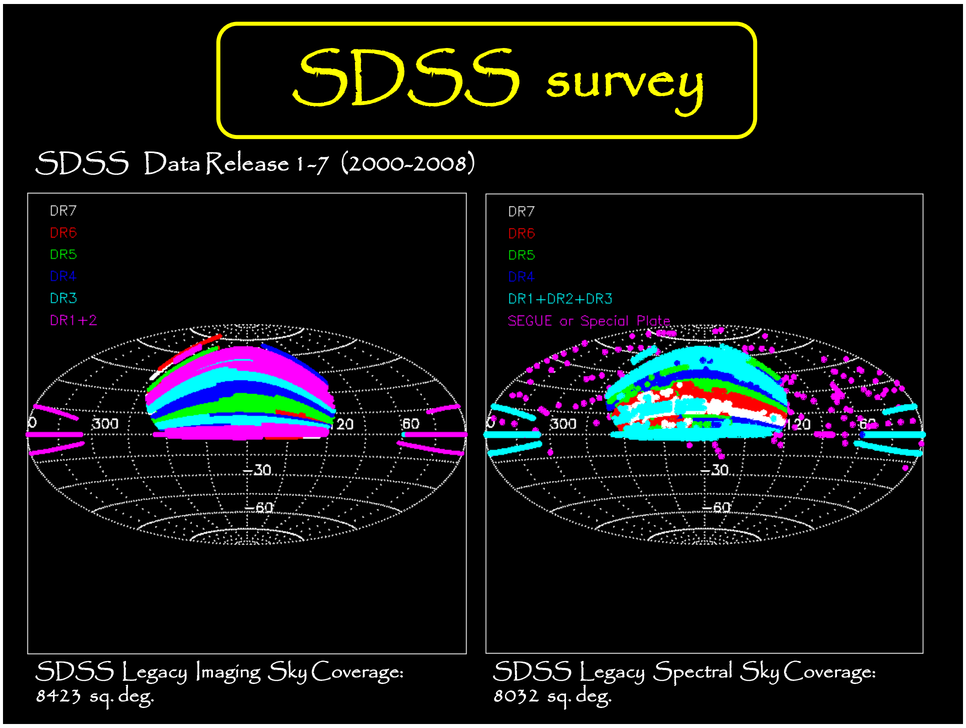
SDSS survey

SDSS Data Release 7 (2008):

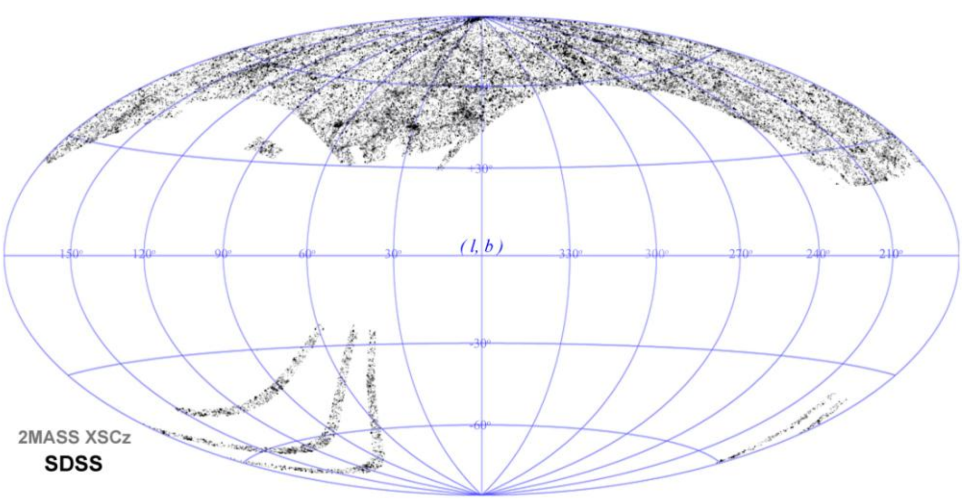


SDSS Legacy Imaging Sky Coverage: 8423 sq. deg.

SDSS Legacy Spectral Sky Coverage: 8032 sq. deg.



SDSS Galactic region



comparison 2MASS

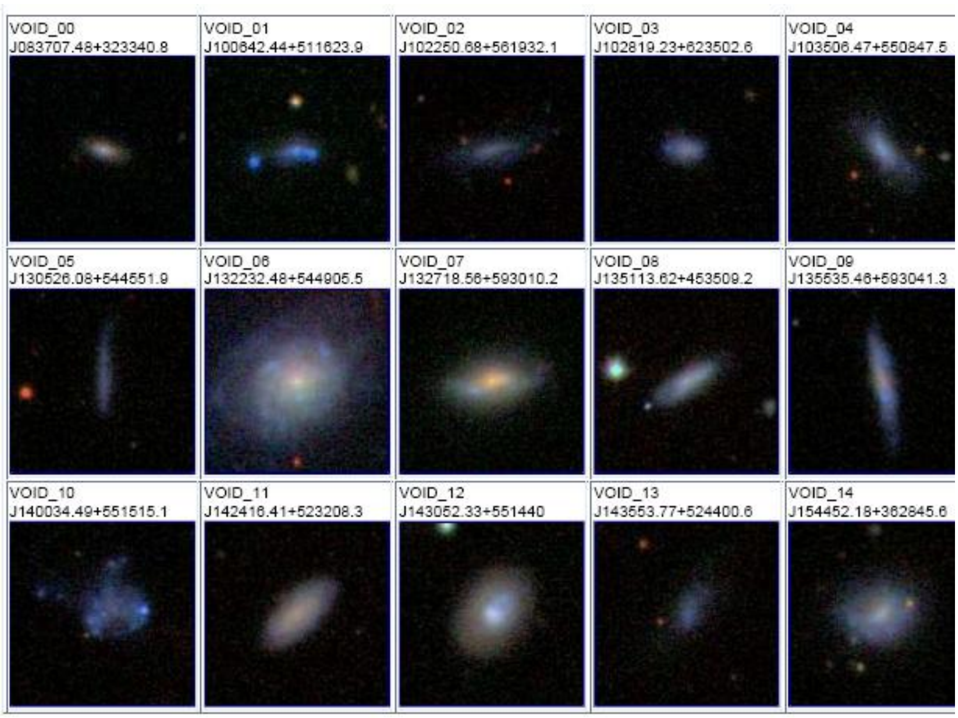
SDSS survey

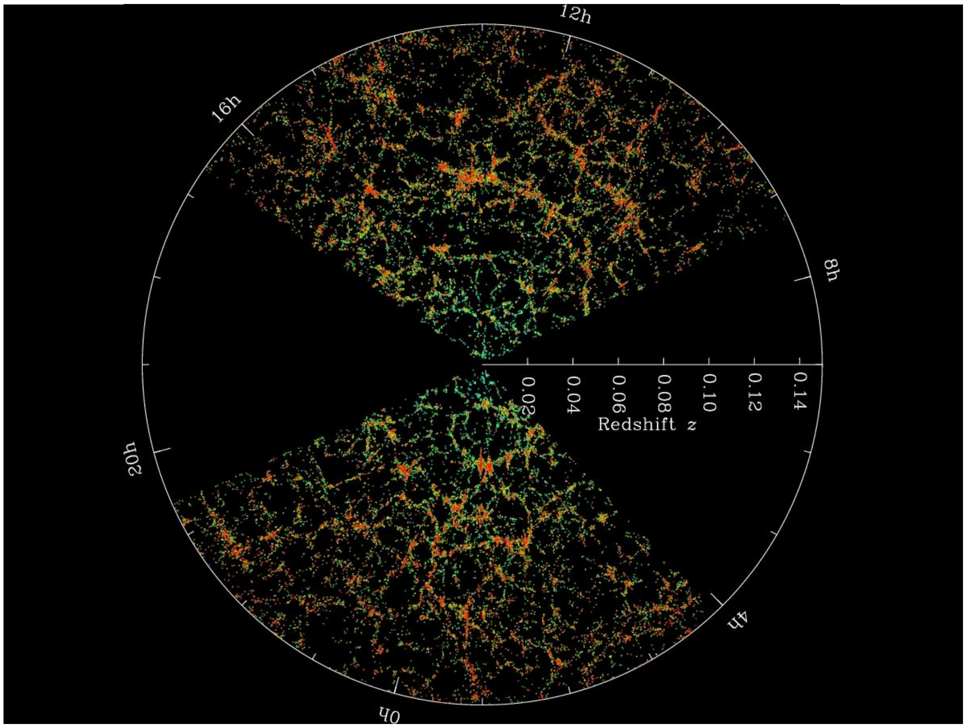
- Imaging:
  230 million objects

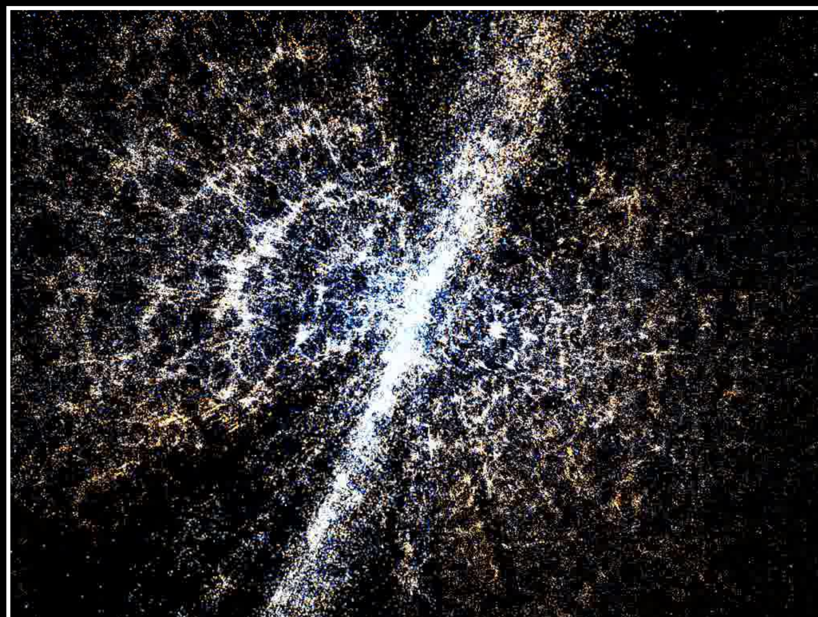
- Spectroscopic (Redshift) survey:

  magnitude limit:
  galaxies: (Petrosian) $r < 17.7$
  quasars $i < 19.1$ / $i < 20.2$ ($z > 2.3$)

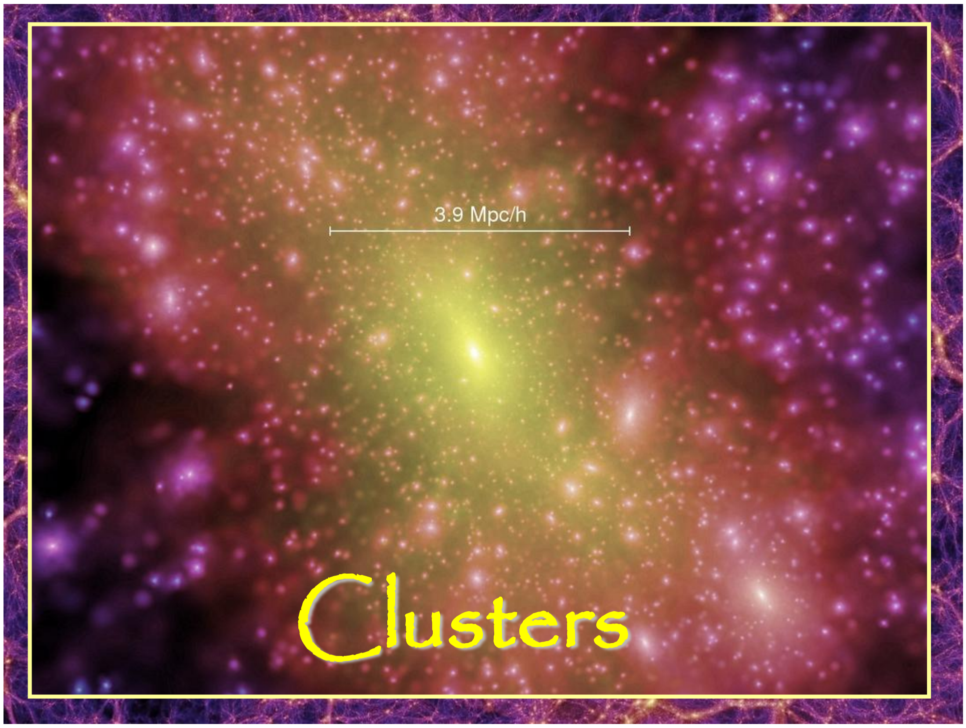
  objects:
  928,567 galaxies
  109,862 quasars $z < 2.3$
  8,802 quasars $z > 2.3$




12h
16h
8h
20h
4h
0h
0.02
0.04
0.06
0.08
0.10
0.12
0.14
Redshift z



The Elements: Clusters


3.9 Mpc/h
Clusters


Sloan SDSS

Clusters of Galaxies

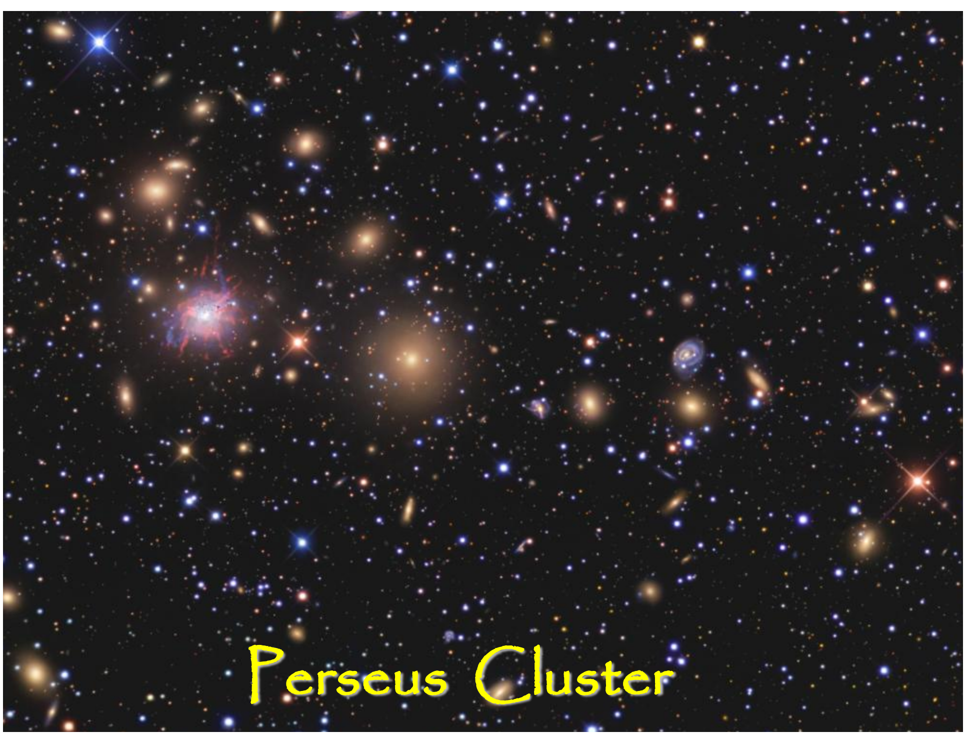
- Assemblies of up to 1000s of galaxies within a radius of only 1.5-2h^{-1} Mpc,
- Representing overdensities of $\delta \sim 1000$
- Galaxy move around with velocities ~ 1000 km/s
- They are the most massive, and most recently, fully collapsed structures in our Universe.

Clusters of Galaxies

Courtesy:
O. Lopez-Cruz

Coma Cluster

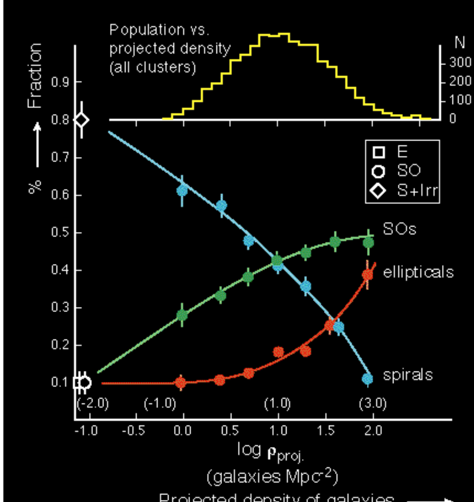

Coma Cluster


Perseus Cluster

Density-Morphology Relation

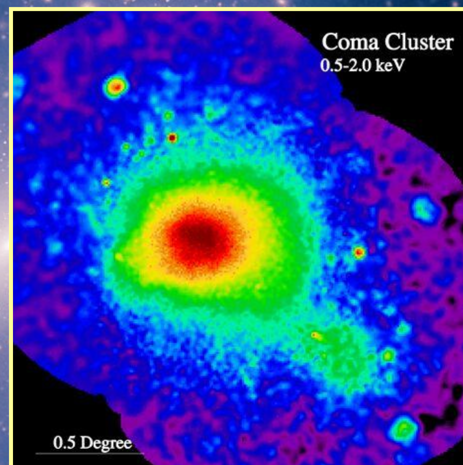
Outstanding relation between cosmic environment and galaxies:

- Density-Morphology Relation
- Dense regions (clusters):
  early-type galaxies
  (ellipticals, SO,...)
- Lower Density areas:
  late-type galaxies
  (spirals, irregulars)
- From clusters to voids
- reflection of effects galaxy interactions (more frequent high densities)

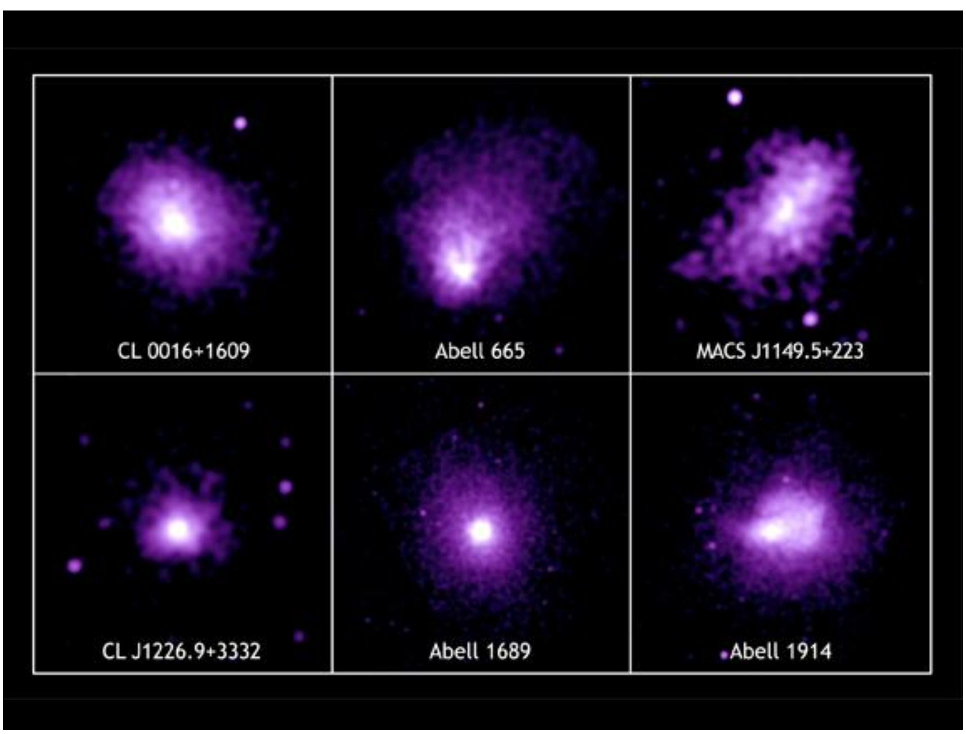


Clusters of Galaxies
X-ray intracluster gas

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 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



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.

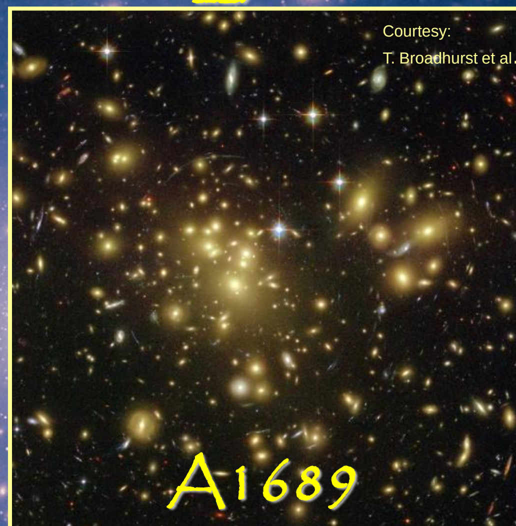
According to

Einstein's theory of

General Relativity,

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

Gravitational Lens.



Clusters 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

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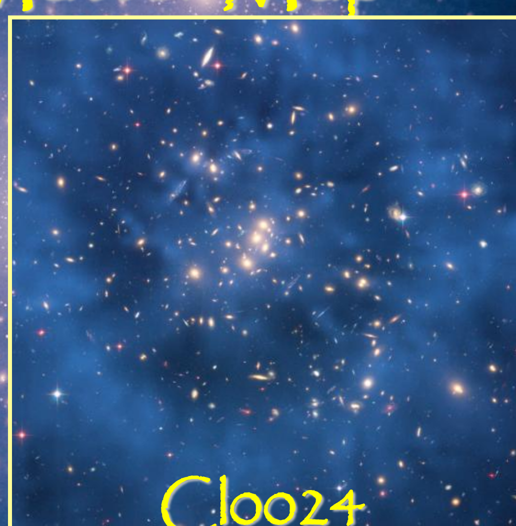
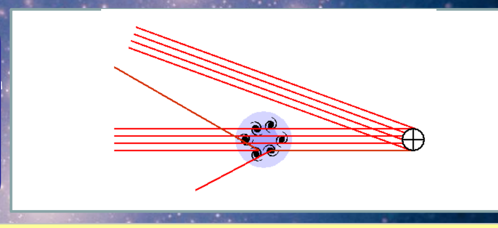
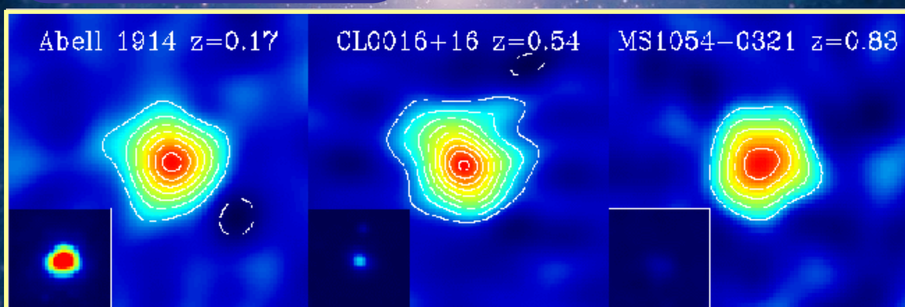


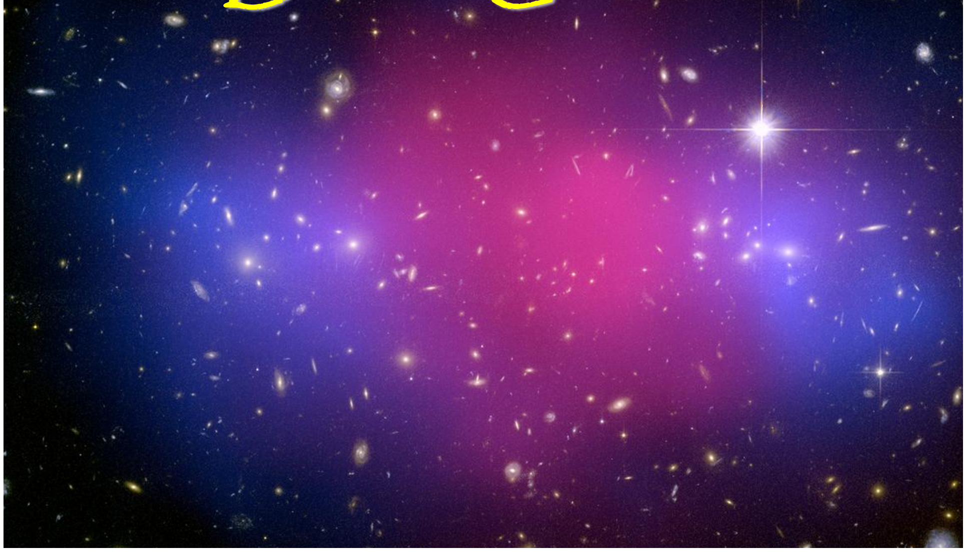
Clusters of Galaxies: Sunyaev-Zeldovich

Sunyaev-Zel'dovich effect:
scattering through inverse Compton
of CMB photons by
hot intracluster electrons





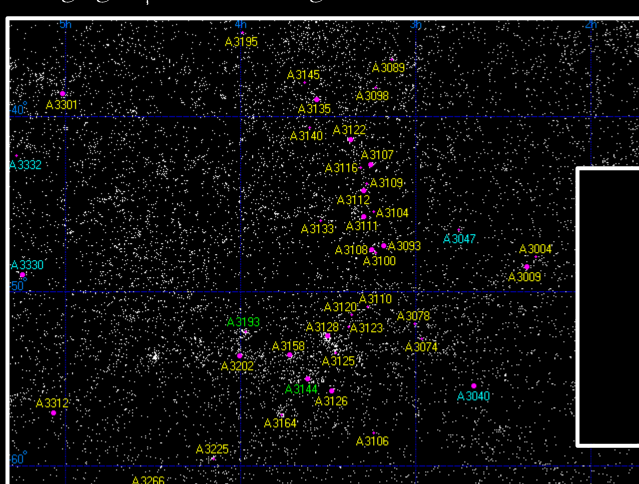
Colliding: Bullet Cluster



The Elements: Superclusters

Superclusters

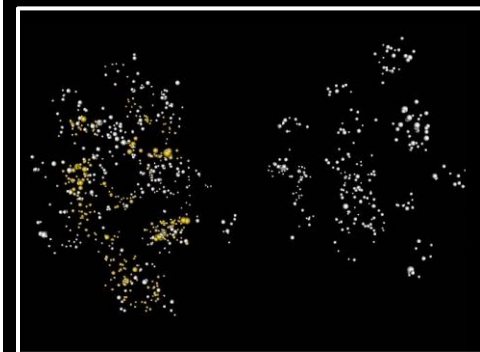
Large groups of clusters & galaxies (1-dozens)

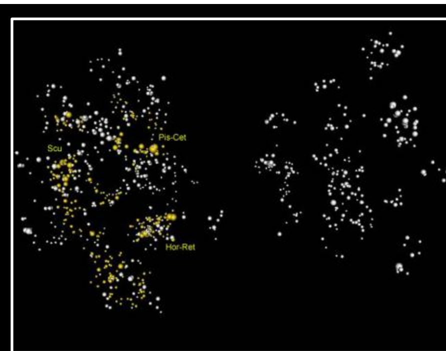


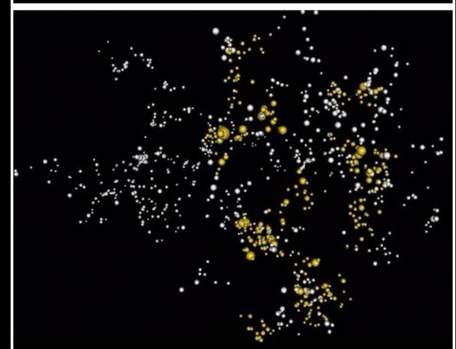
$M \sim 10^{15}$-10^{16} M_{o}
L ~ few-100 Mpc
irregular shaped
mild overdensity Δ~few

Superclusters:

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







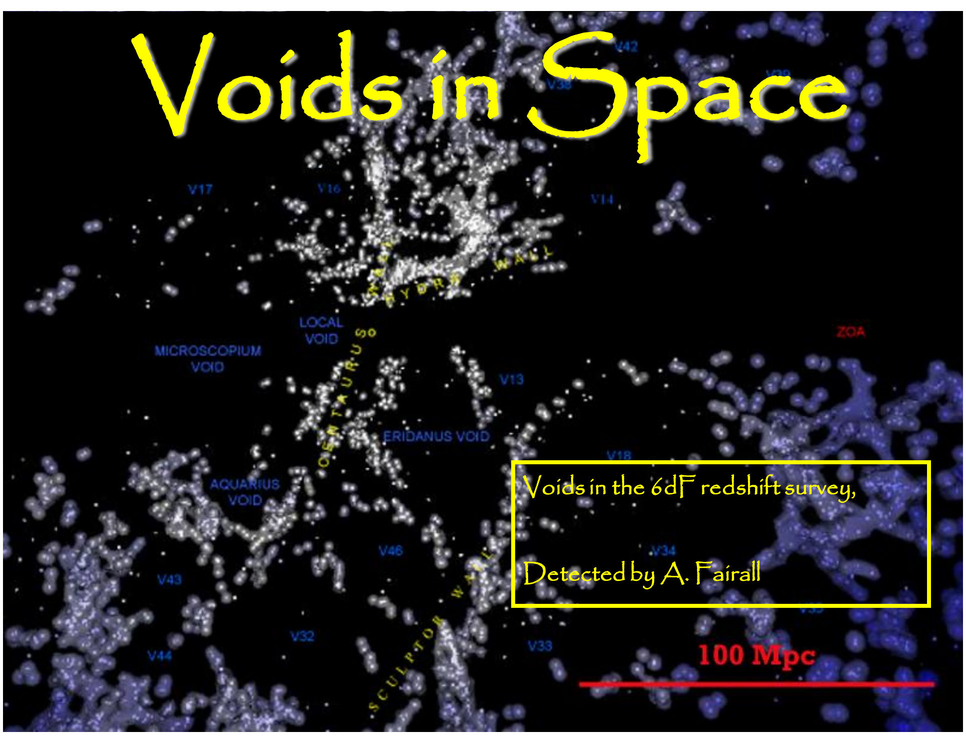
superclusters are not isolated single objects, but integral components in the pervasive Cosmic Web

Abell 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

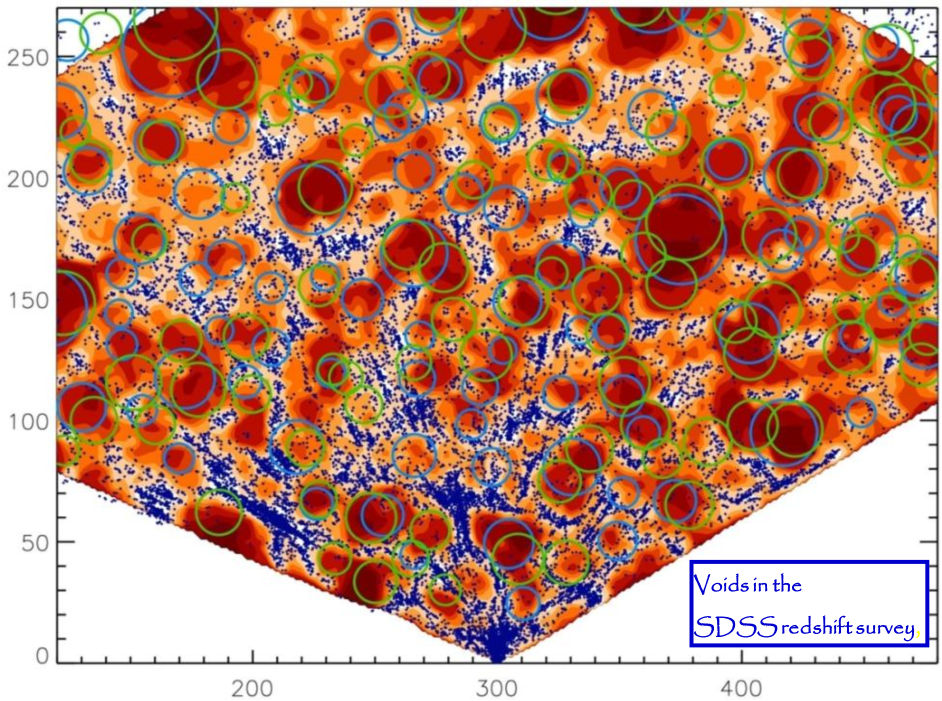
The Elements: Voids

Voids in Space

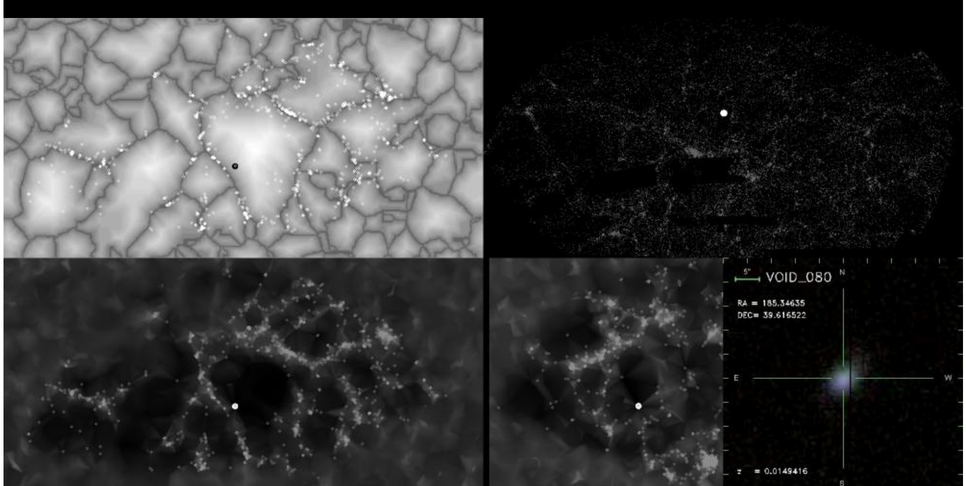


Voids in the 6dF redshift survey,

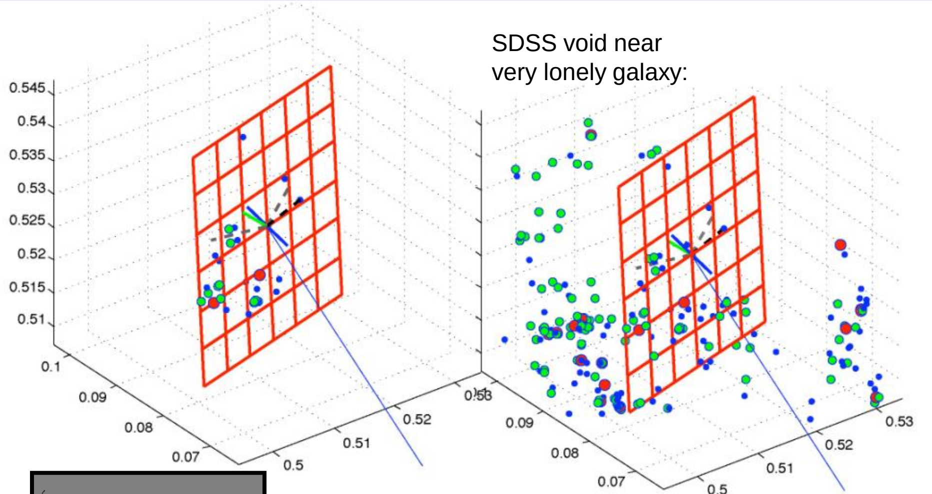
Detected by A. Fairall


Voids in the
SDSS redshift survey
250
200
150
100
50
0
200
300
400

SDSS Voids


VOID_080

SDSS Voids

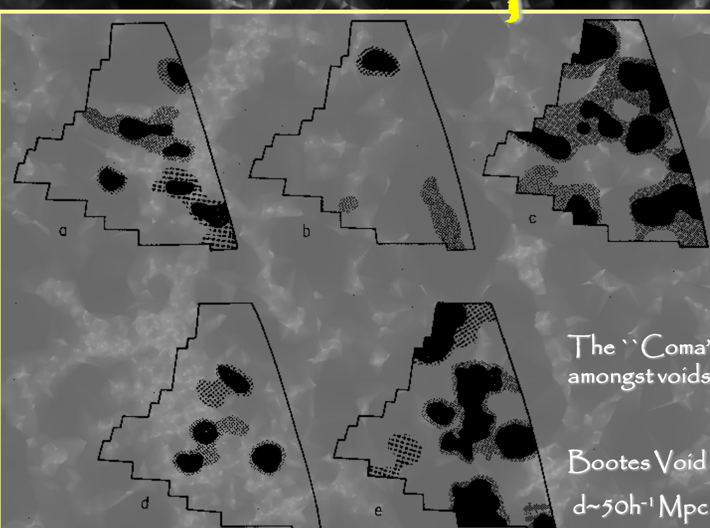


SDSS void near
very lonely galaxy:

sampled by
galaxies different brightness:
no difference

(courtesy:
P.J.E. Peebles & E. Platen)

Voids in Space

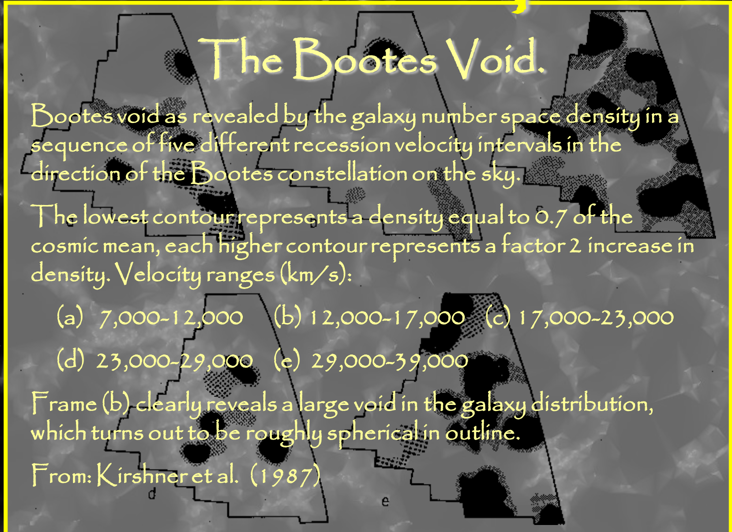


The ``Coma"
amongst voids:

Bootes Void
d~$50h^{-1}$ Mpc

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)

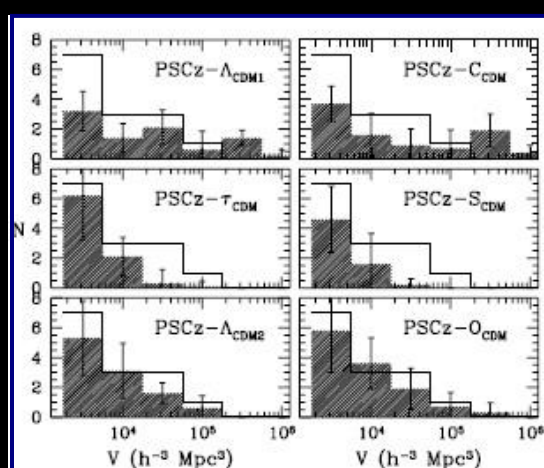
Void Size & Volume

Void Size

Void size distribution dependent on cosmology:

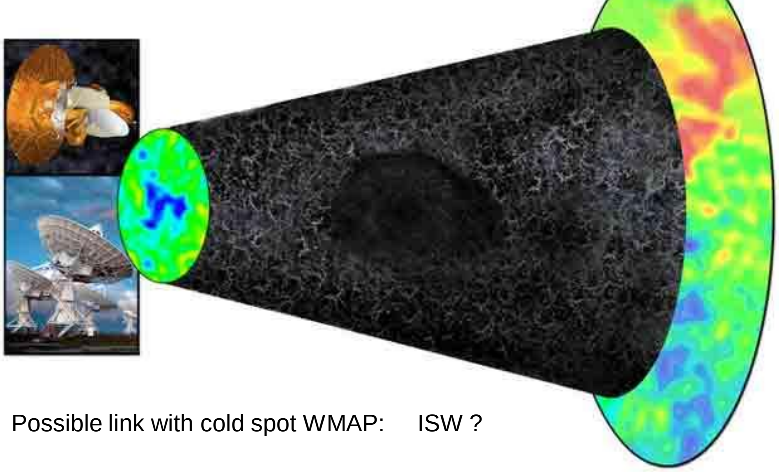
Comparison PSCz & models:

Plionis & Basilakos 2002

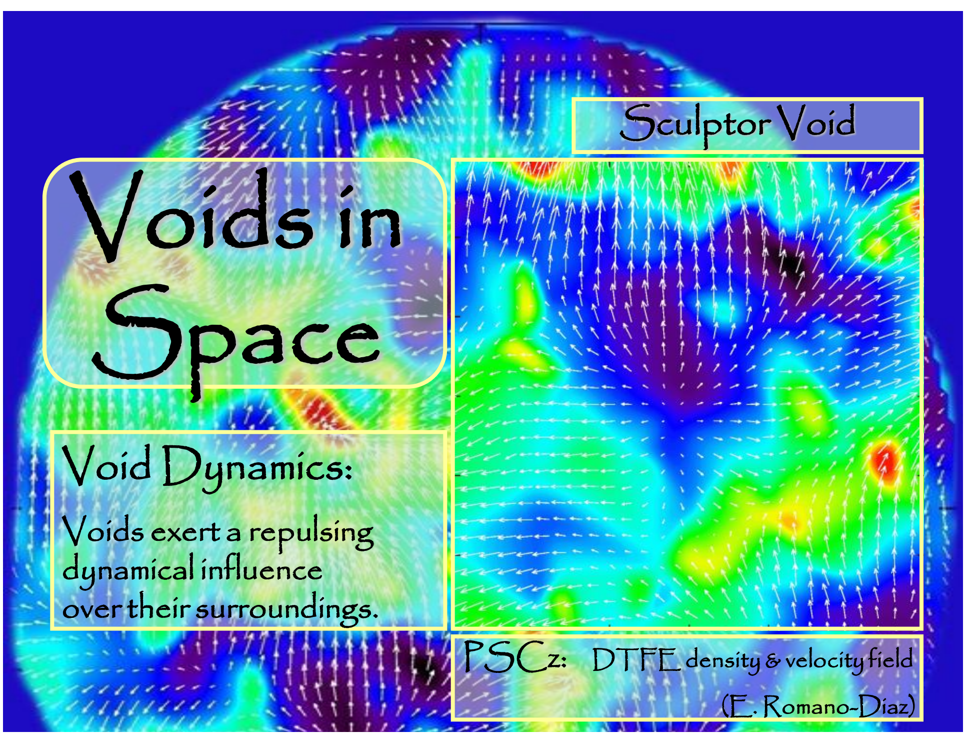


Supervoids ???

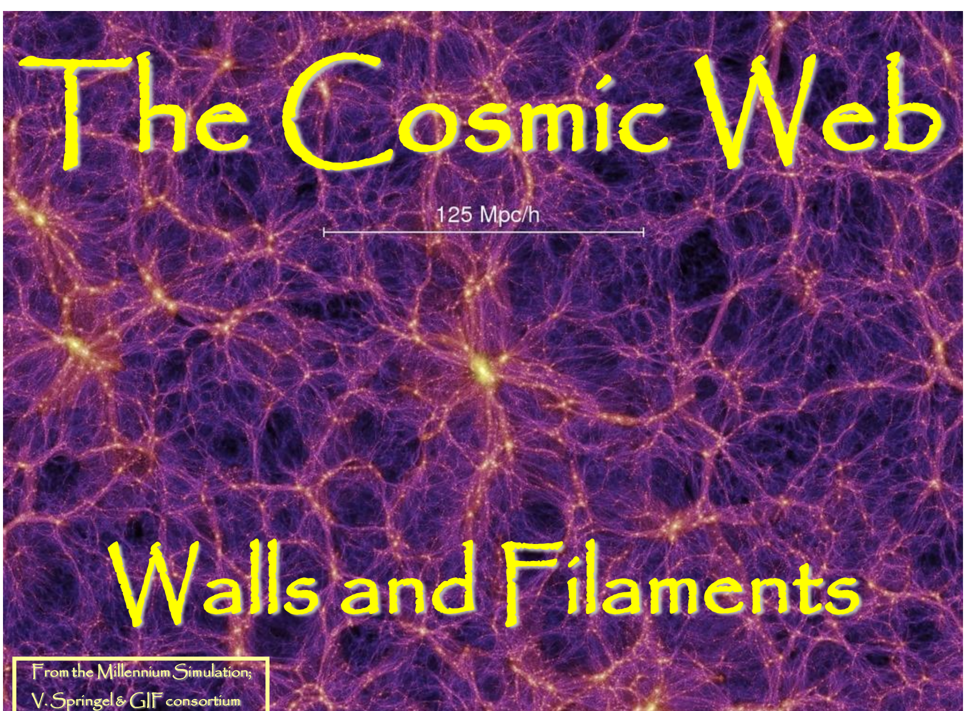
Claim: supervoid in NVVS radio galaxy distribution
(Rudnick et al. 2007)

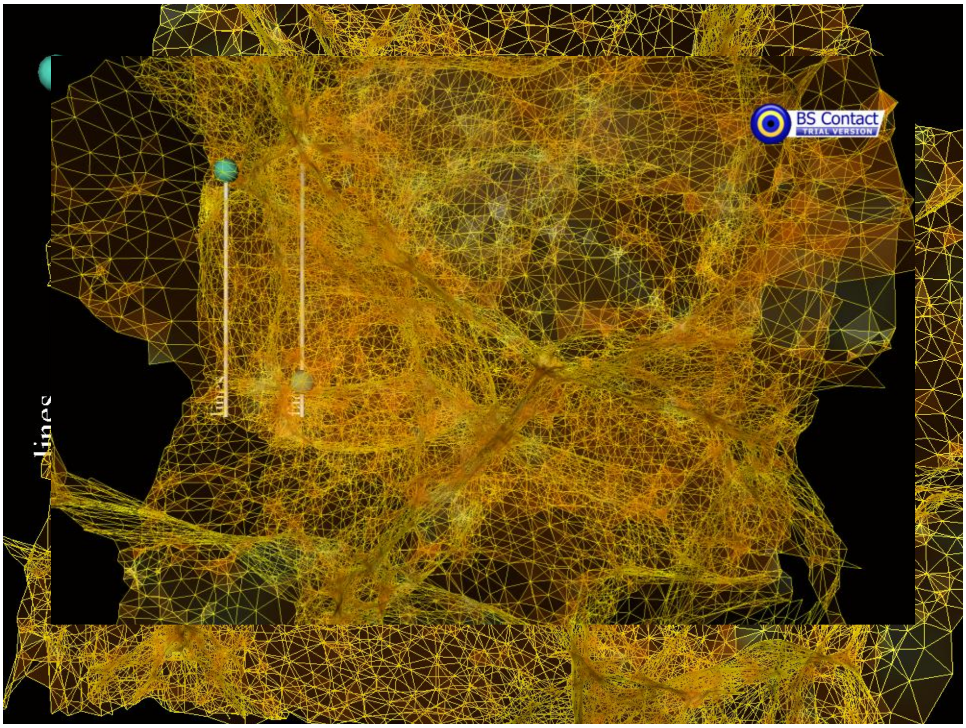


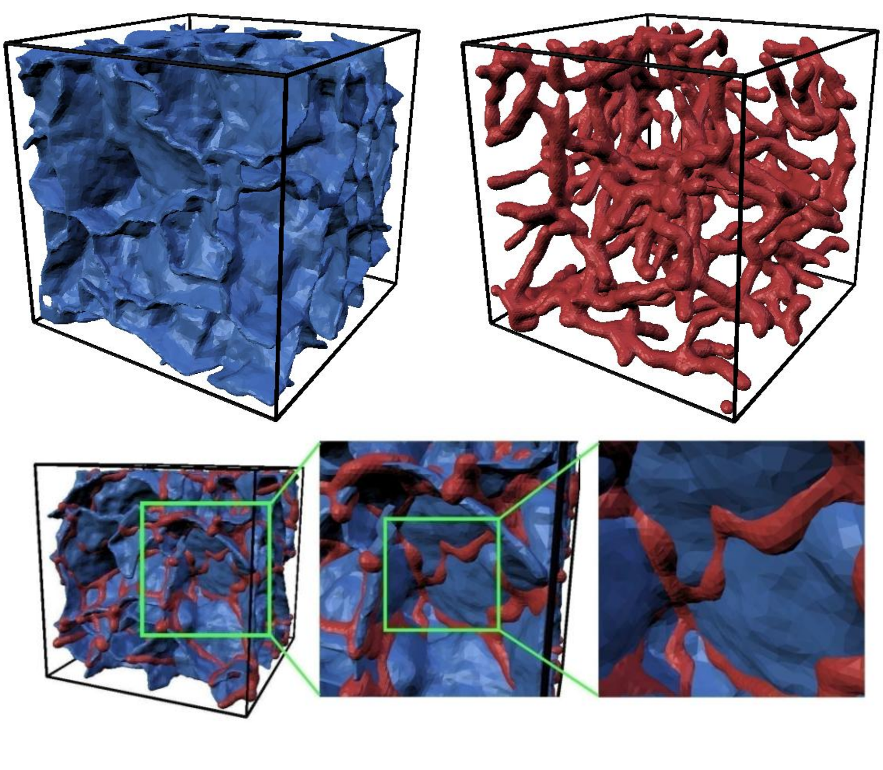
Possible link with cold spot WMAP: ISW ?

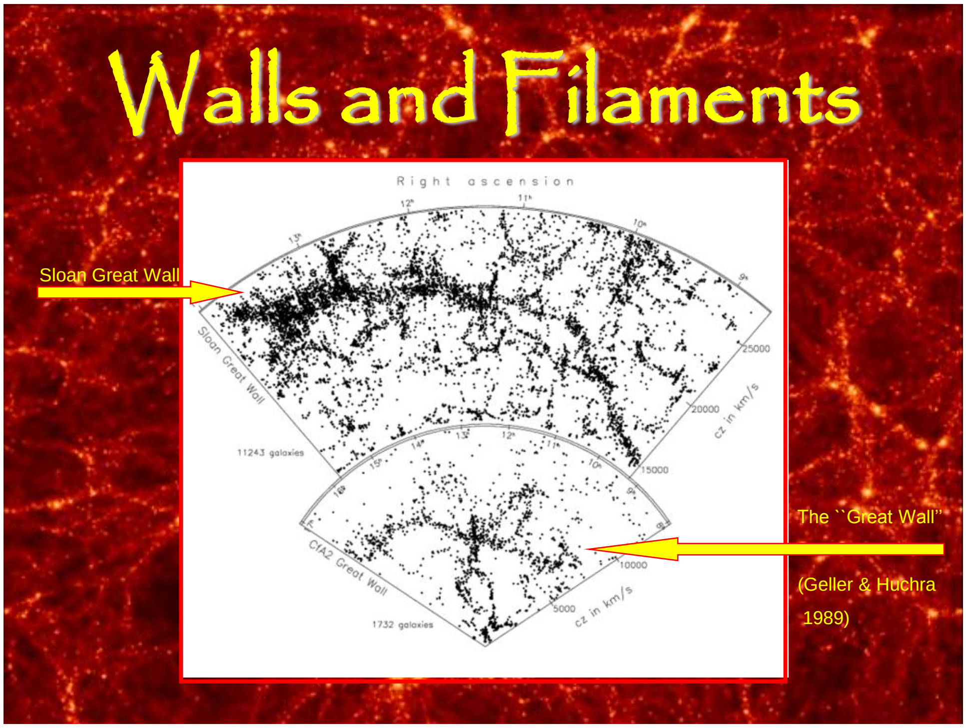


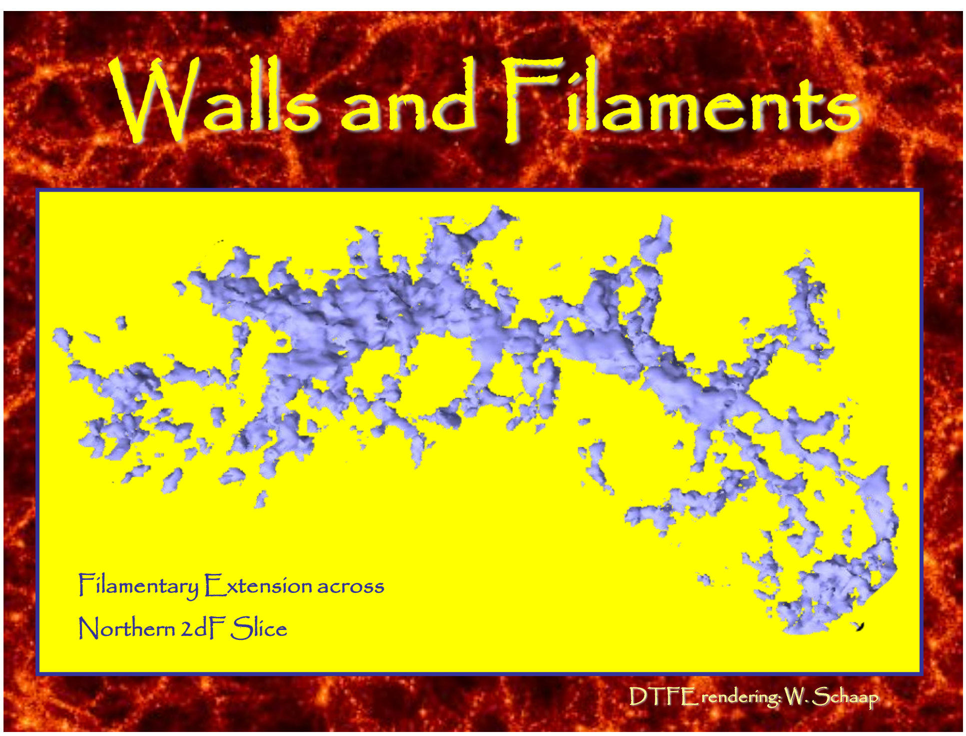
Cosmic Web


The Cosmic Web
125 Mpc/h
Walls and Filaments
From the Millennium Simulation;
V. Springel & GIF consortium


BS Contact
TRIAL VERSION




Walls and Filaments
Sloan Great Wall
Right ascension
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 ~ 55h^{-1} Mpc),
- Characteristic & salient filamentary morphology,
- Favourable orientation.

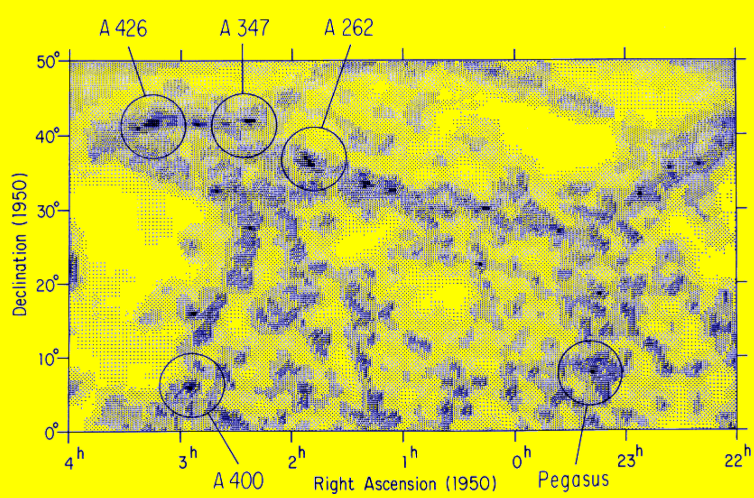
Northern boundary: ridge south-westward of Perseus cluster (A426)

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

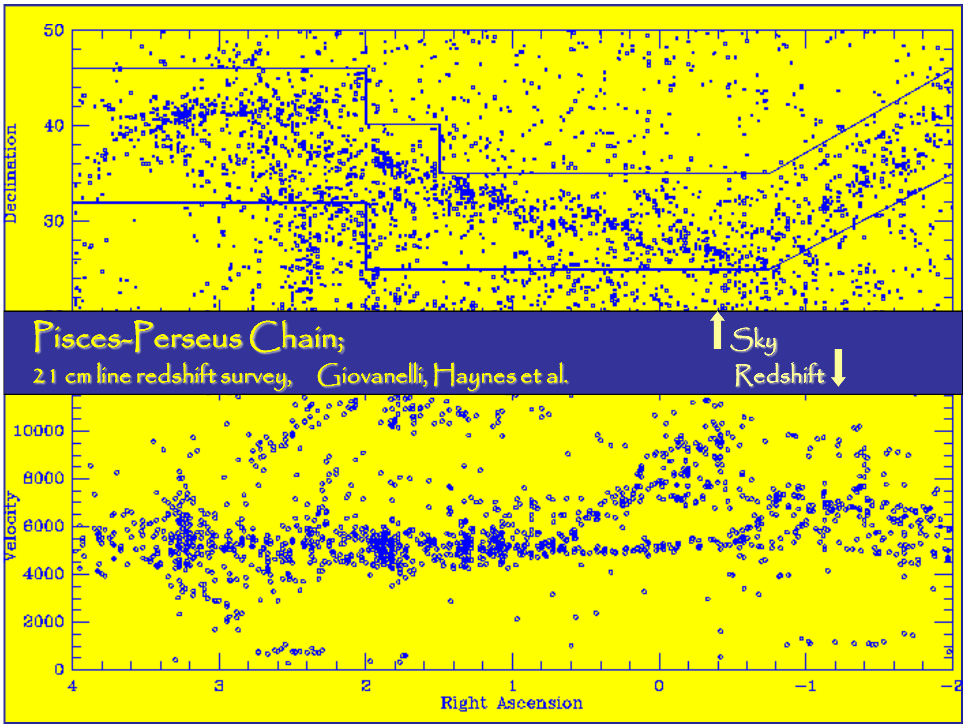
50h^{-1} Mpc length; possible 140h^{-1} Mpc extension

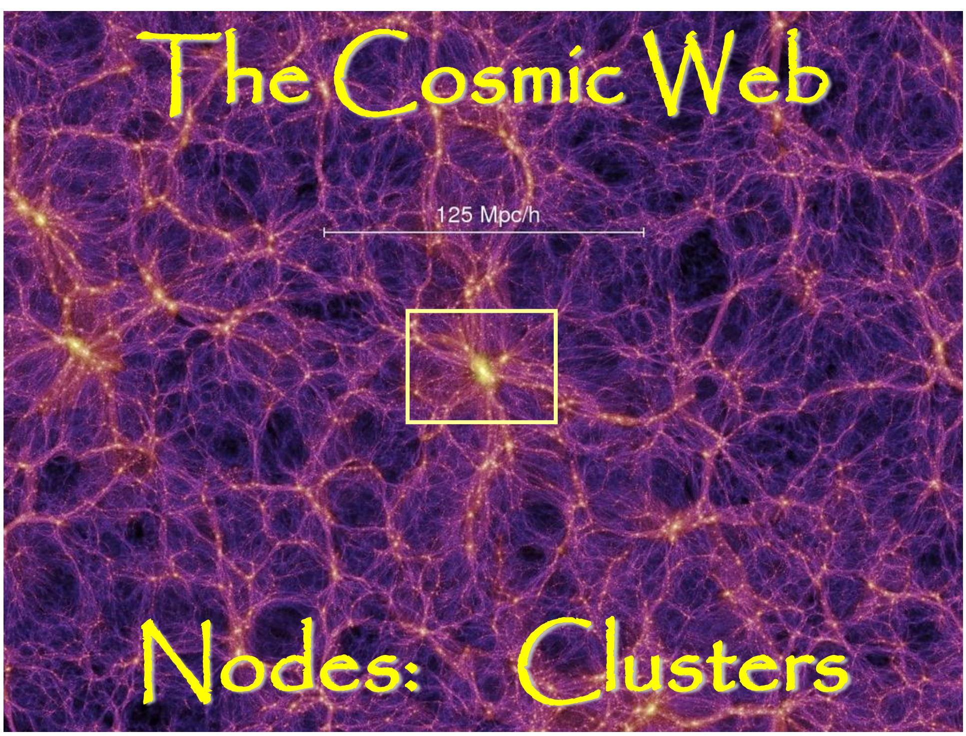
Along Ridge: high density clusters, incl. A462, A347, A262

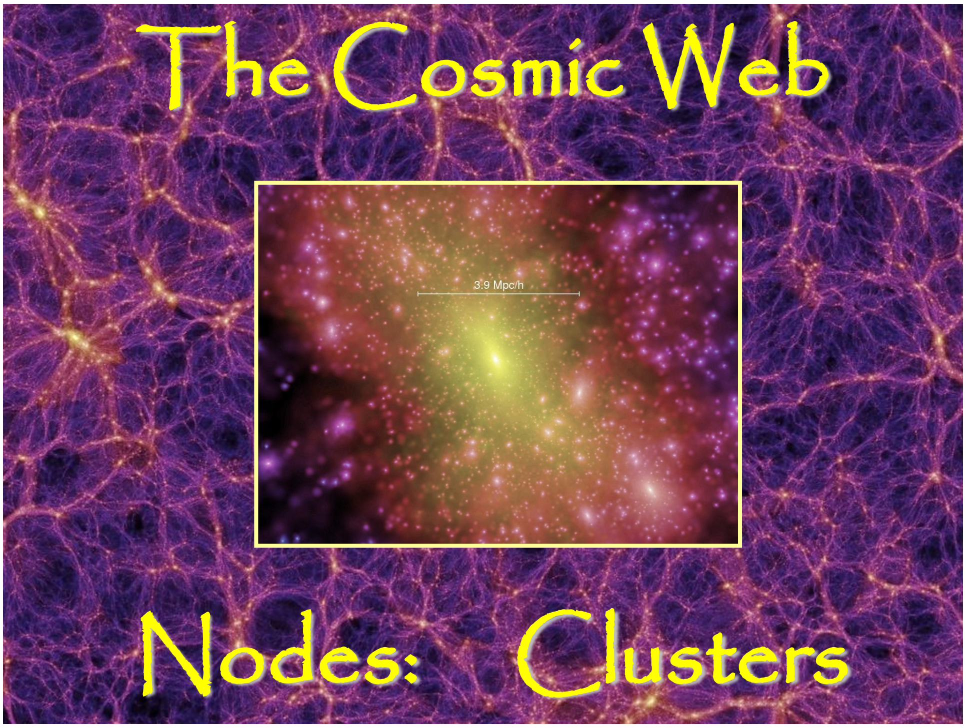
Walls and Filaments

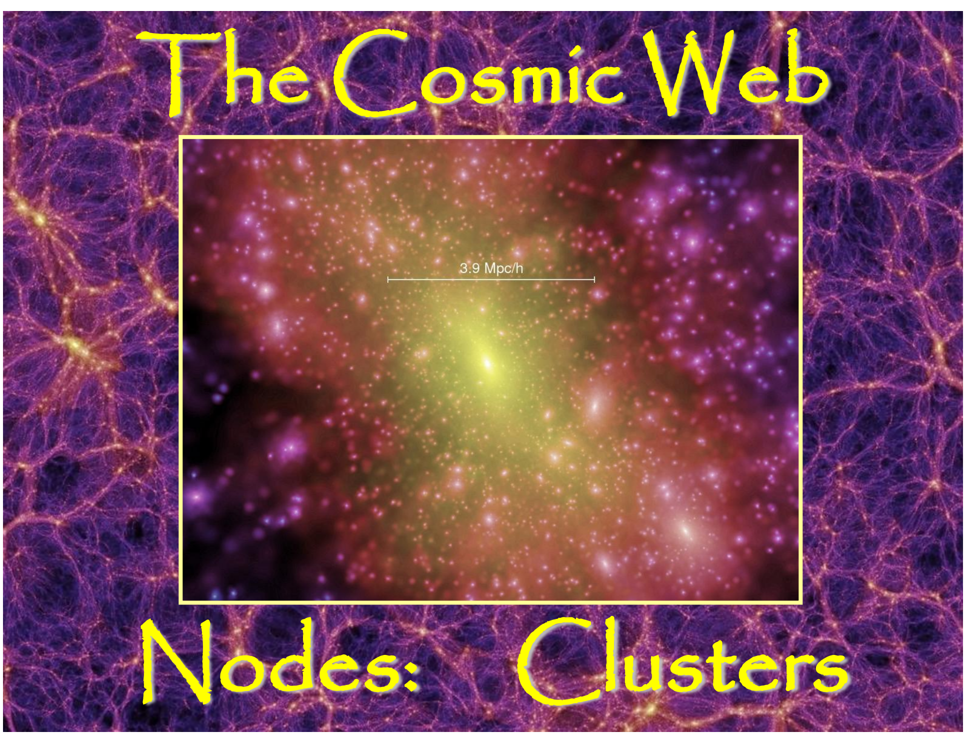


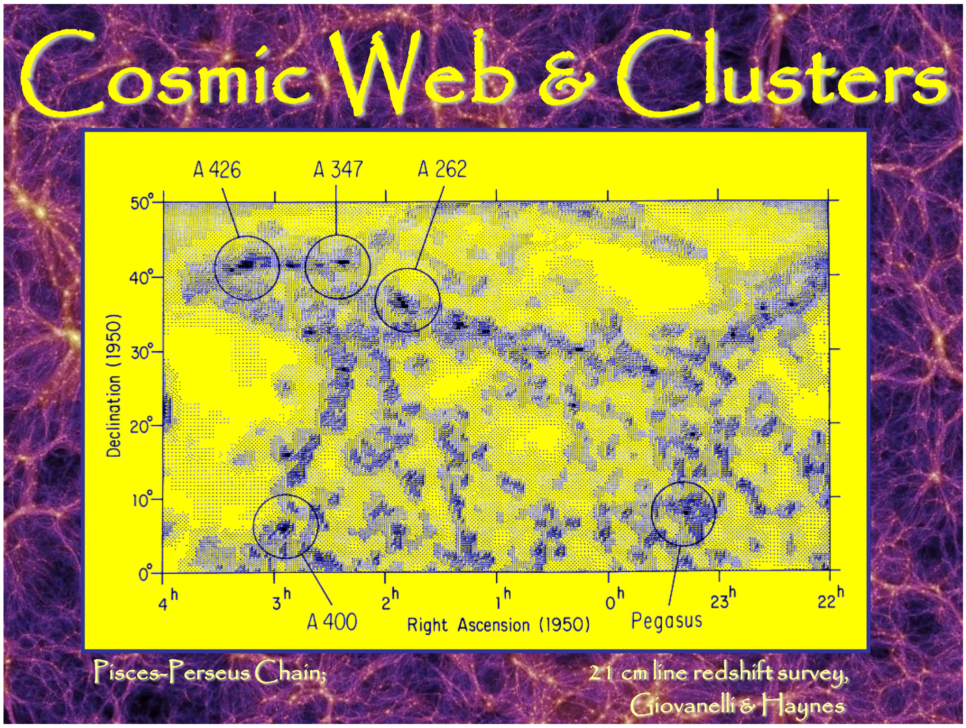
Pisces-Perseus Chain; 21 cm line redshift survey, Giovanelli & Haynes

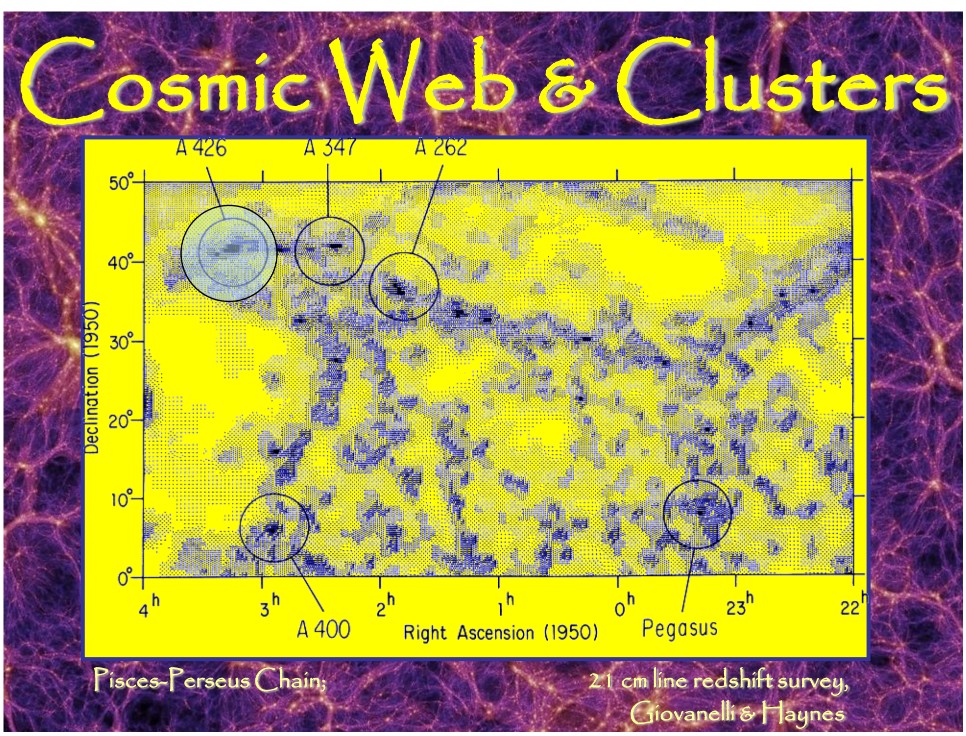

Pisces-Perseus Chain;
21 cm line redshift survey, Giovanelli, Haynes et al.
Sky
Redshift
Declination
Velocity
Right Ascension
50
40
30
10000
8000
6000
4000
2000
0
4
3
2
1
0
−1
−2

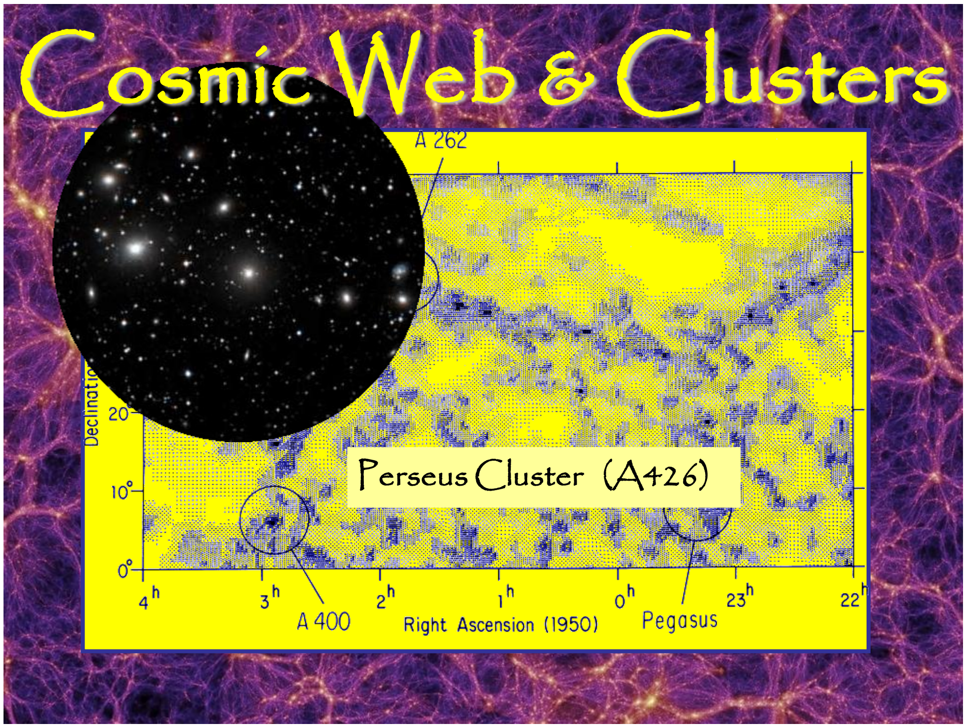

The Cosmic Web
125 Mpc/h
Nodes: Clusters

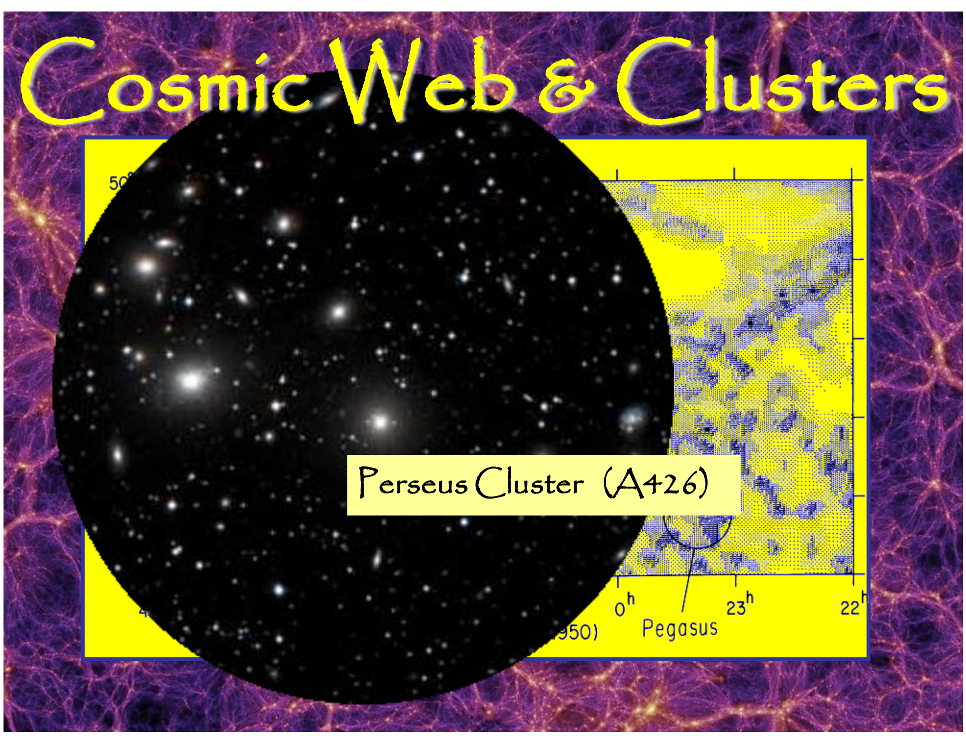

The Cosmic Web
3.9 Mpc/h
Nodes: Clusters


The Cosmic Web
3.9 Mpc/h
Nodes: Clusters

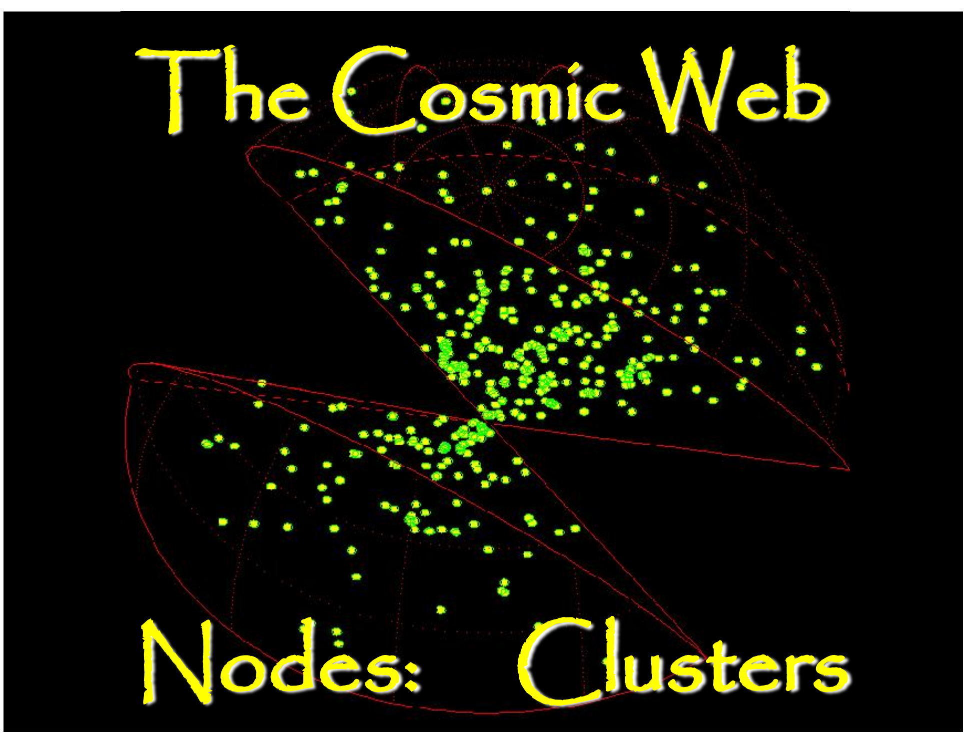

Cosmic Web & Clusters
A 426
A 347
A 262
50°
40°
30°
20°
10°
0°
Declination (1950)
4h
3h
2h
1h
0h
23h
22h
A 400
Right Ascension (1950)
Pegasus
Pisces-Perseus Chain;
21 cm line redshift survey,
Giovanelli & Haynes


Cosmic Web & Clusters
A 426
A 347
A 262
50°
40°
30°
20°
10°
0°
Declination (1950)
4h
3h
2h
1h
0h
23h
22h
A 400
Right Ascension (1950)
Pegasus
Pisces-Perseus Chain;
21 cm line redshift survey,
Giovanelli & Haynes

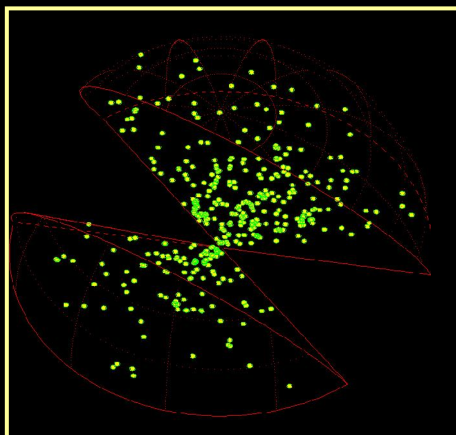

Cosmic Web & Clusters
A 262
Declination
20°
10°
0°
4h
3h
2h
1h
0h
23h
22h
A 400
Right Ascension (1950)
Pegasus
Perseus Cluster (A426)


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


Cosmic Web & Clusters
Perseus Cluster (A426)


The Cosmic Web
Nodes: Clusters

The Cosmic Web



The spatial cluster distribution.

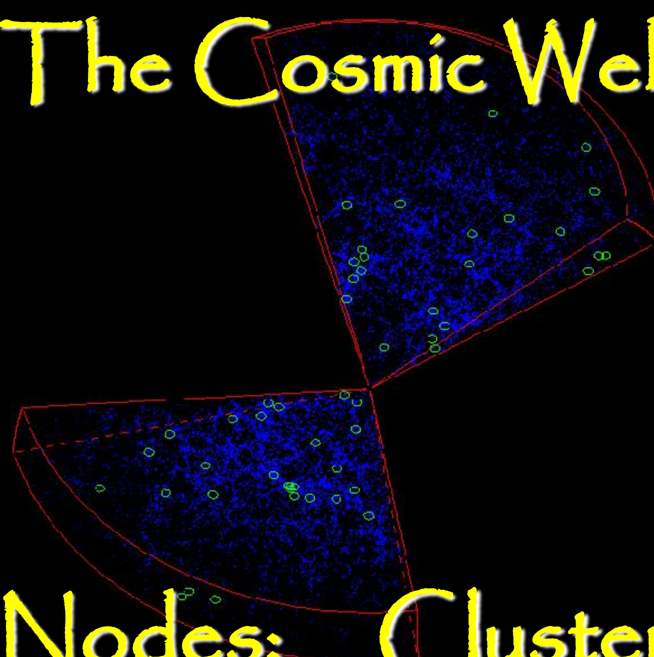
The full volume of the X-ray cluster REFLEX cluster survey within a distance of $600h^{-1}$ Mpc. The REFLEX galaxy cluster catalogue contains all clusters brighter than an X-ray flux of 3x10 ergs cm^{-2} over a large part of the in the southern sky. The missing part of hemisphere delineates the region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

REFLEX: Boehringer et al. (2001)

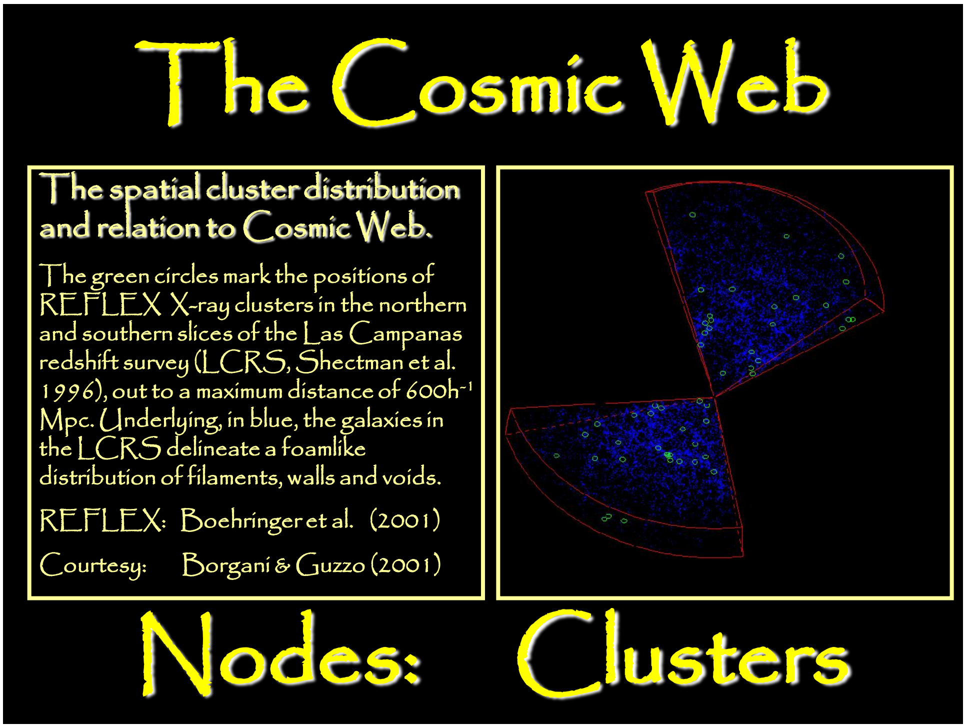
Courtesy: Borgani & Guzzo (2001)

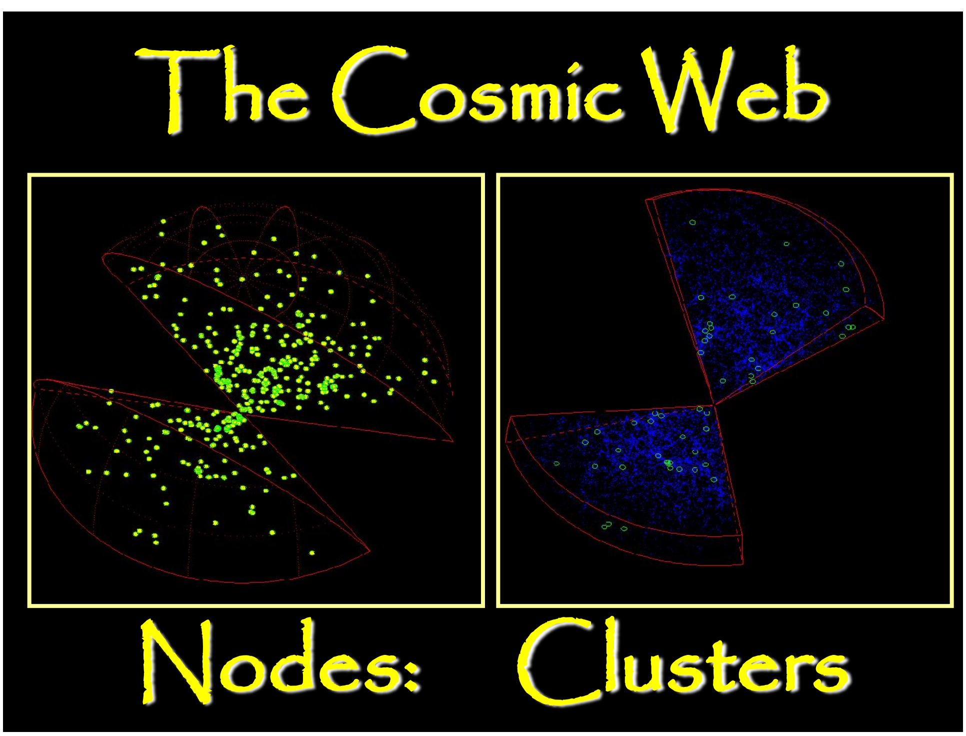
Nodes: Clusters

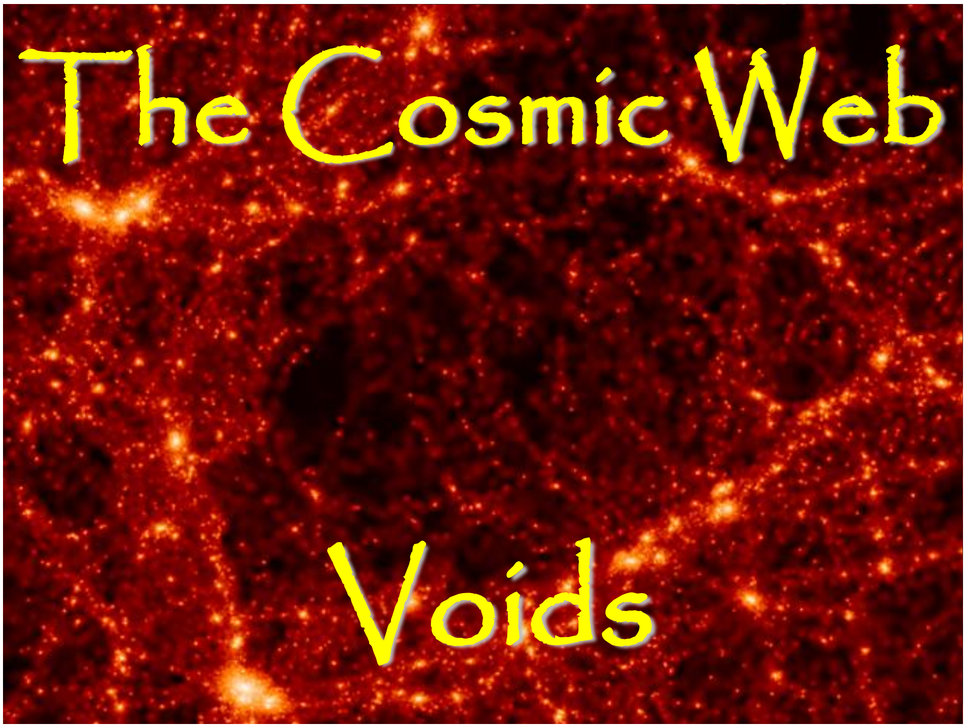
The Cosmic Web



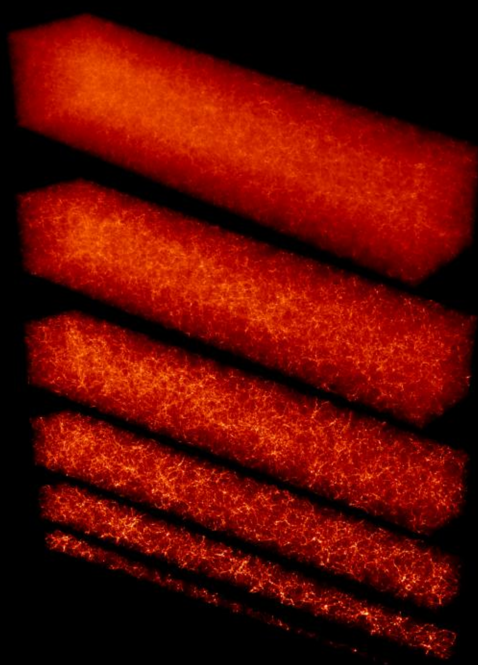
Nodes: Clusters


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



Web in Depth



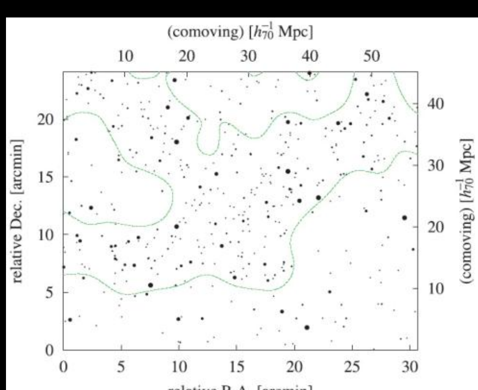
Far Away, Long Ago

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



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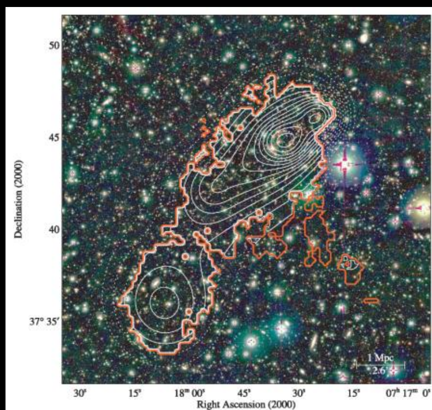
- Is cosmic web truly universal
- What about the scales of the web (characteristic, largest structures, ...)
- Evolution of Megaparsec scale matter distribution.

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

Far Away, Long Ago

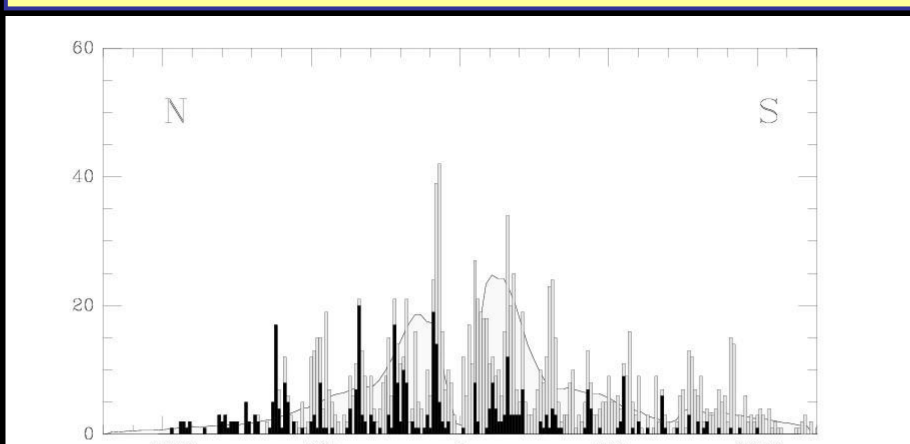


Various surveys are attempting to trace the large scale structure out to large cosmic depths/redshifts.

- 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

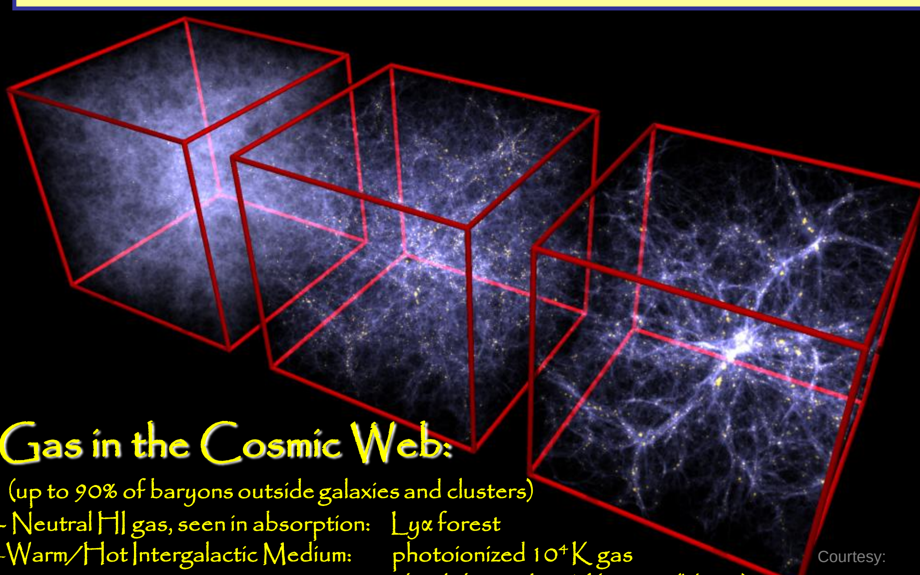


Deep pencil beam survey (Broadhurst et al):

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 $\sim 120 h^{-1}$ Mpc should be ascribed to the 1-D character of the redshift skewer through 3-D structure.

The Gastrophysical Web

The Gastrophysical Web



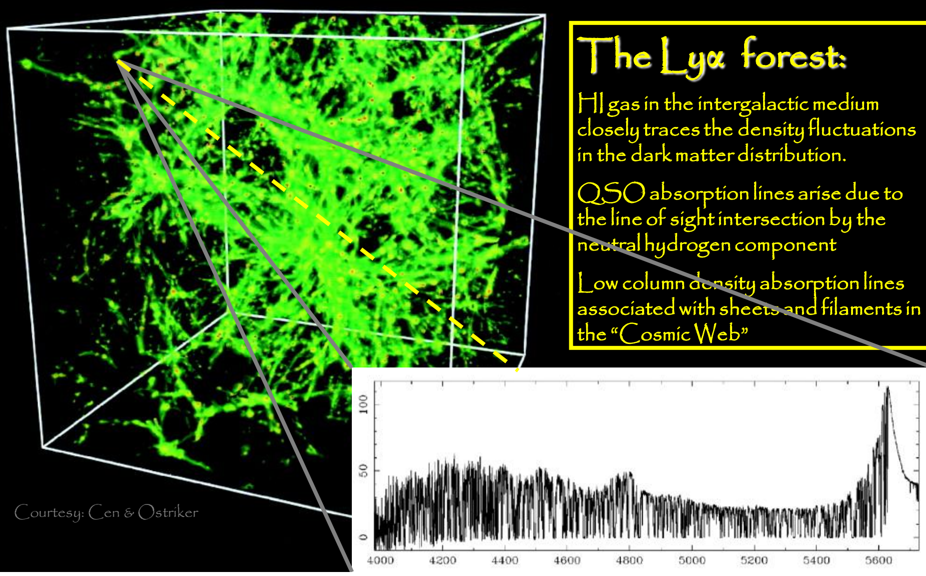
Courtesy: Virgo/V. Springel

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)

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

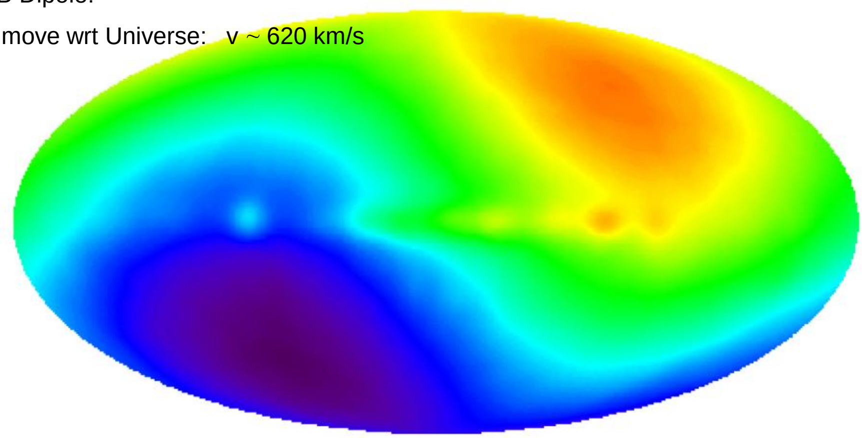
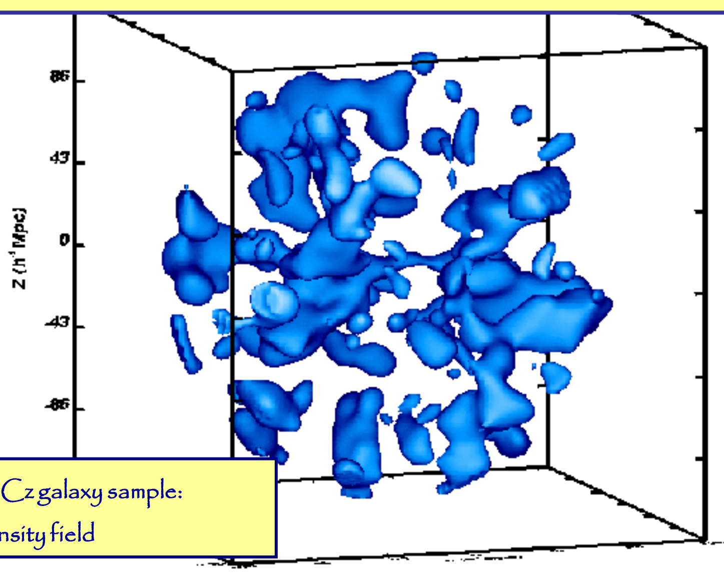


Figure 11. The Cosmic Microwave Background dipole as measured by the DMR instrument of the COBE microwave background satellite (see also Kogut et al. 1993)

Cosmic Migration Flows



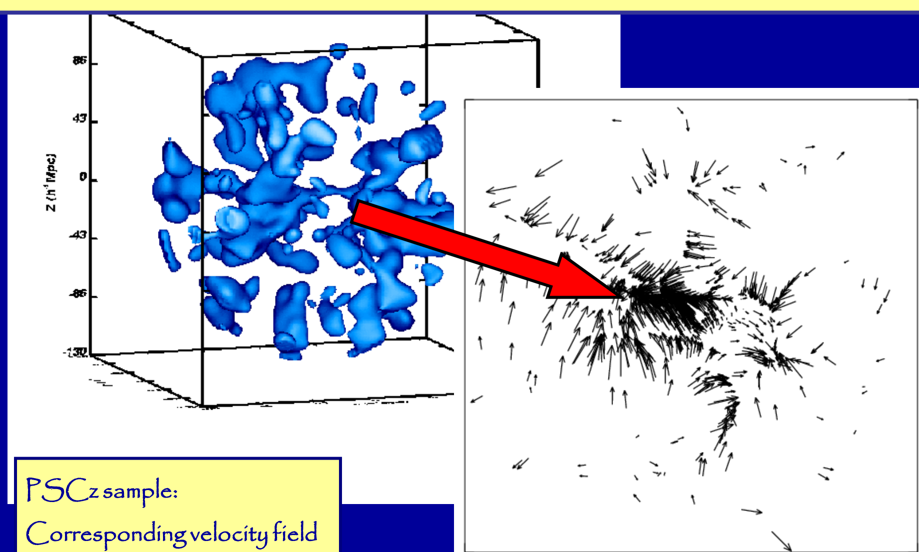
PSCz galaxy sample:
Density field

Cosmic Migration Flows

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

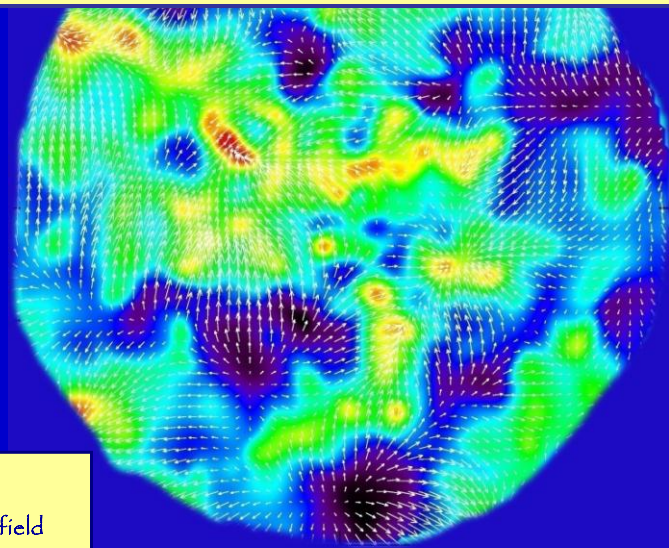
$$\mathbf{v}(\mathbf{x},t) = \frac{H}{4\pi}\frac{f(\Omega_m)}{b}\,a\int d\mathbf{x}'\,\delta_{gal}(\mathbf{x}',t)\,\frac{(\mathbf{x}'-\mathbf{x})}{|\mathbf{x}'-\mathbf{x}|^3} \qquad (158)$$

Cosmic Migration Flows



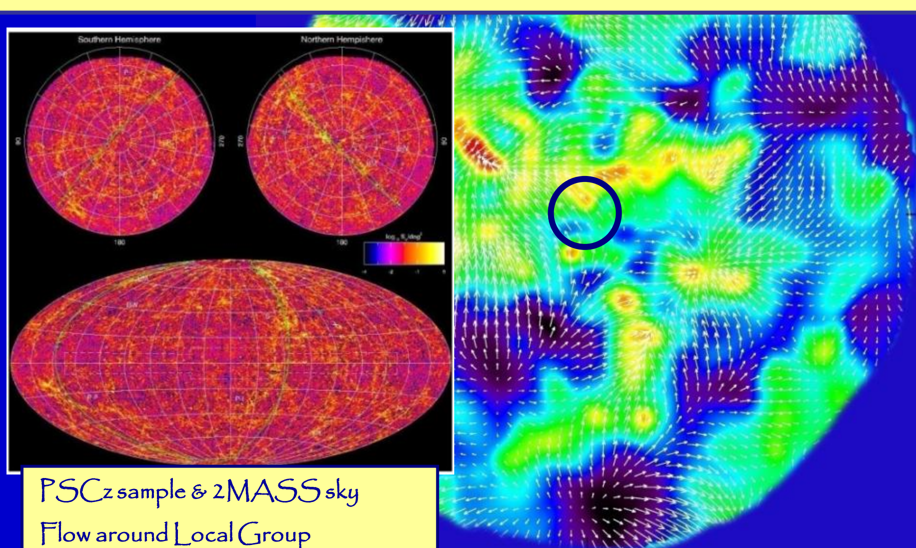
PSCz sample:
Corresponding velocity field

Cosmic Migration Flows



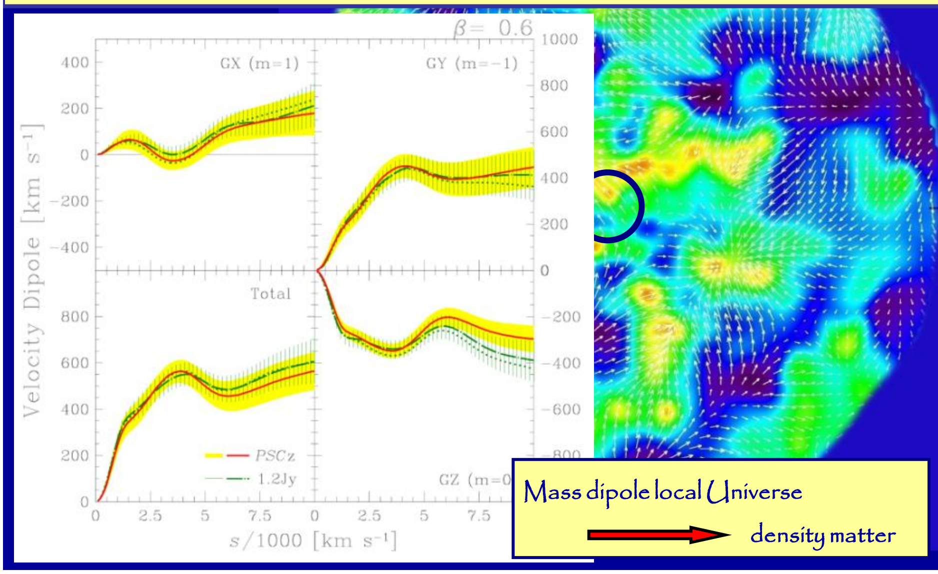
PSCz sample,
Map Density & Flow field

Cosmic Migration Flows



PSCz sample & 2MASS sky
Flow around Local Group

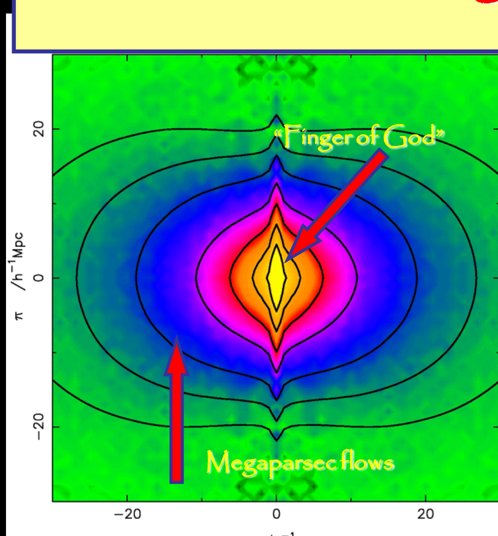
Cosmic Migration Flows



Mass dipole local Universe

→ density matter

the Web: Migration Flows



Large scale flows lead to redshift distortions:

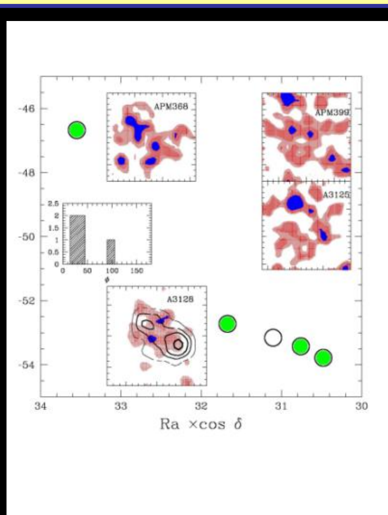
$$cz = Hr + v_{pec}$$

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

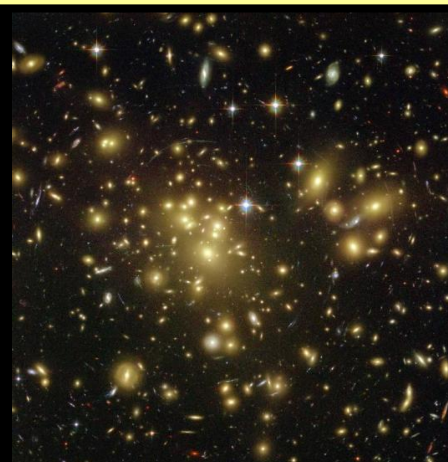
- the motions of galaxies and the intracluster gas,

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:

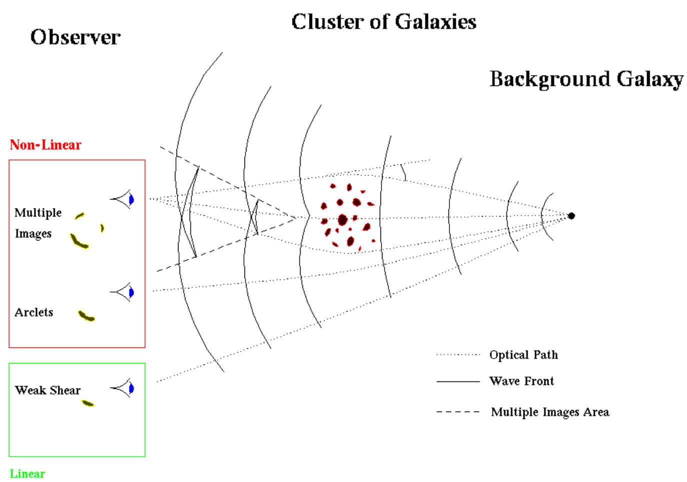
Mass passing in front of background of galaxies, distorting their received images.

Clusters: Gravitational Lensing

Illustration:

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

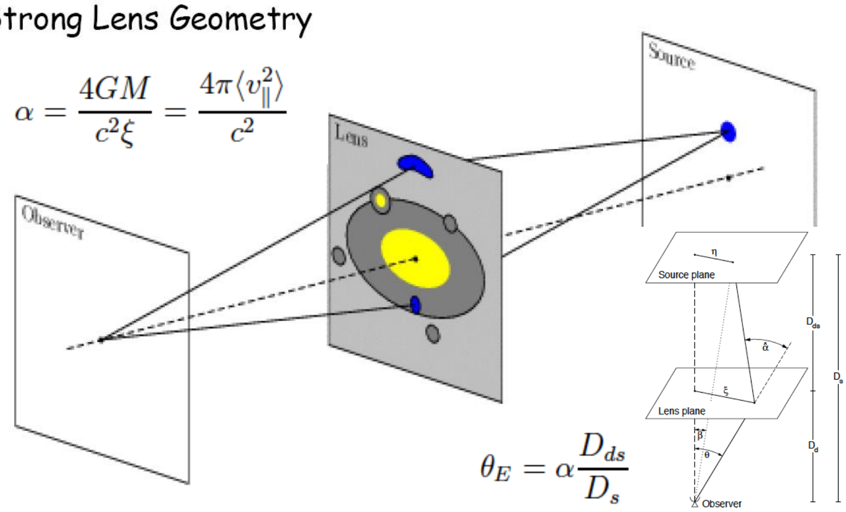
- Strong Lensing: nonlinear distortions
- Weak Lensing: linear distortions



Gravitational Strong Lensing

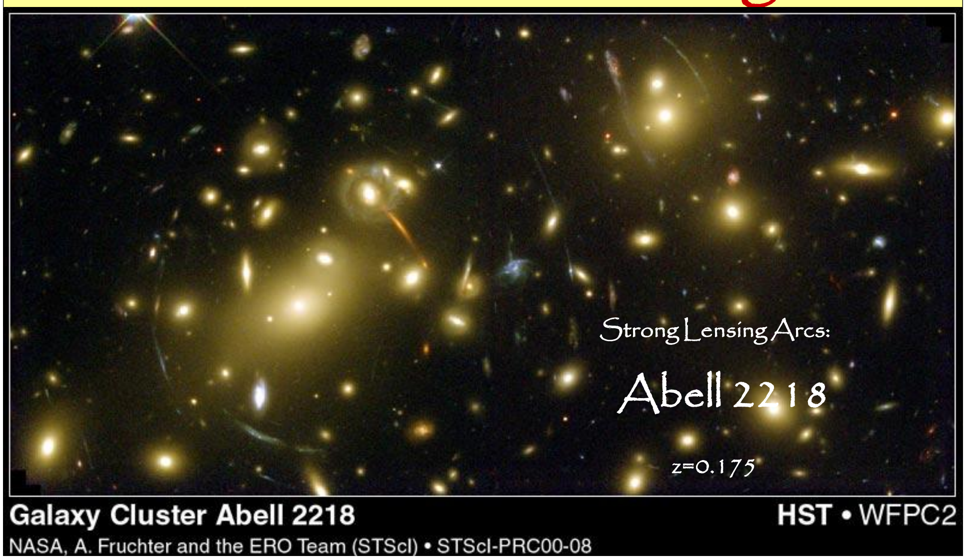
Strong Lens Geometry

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



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

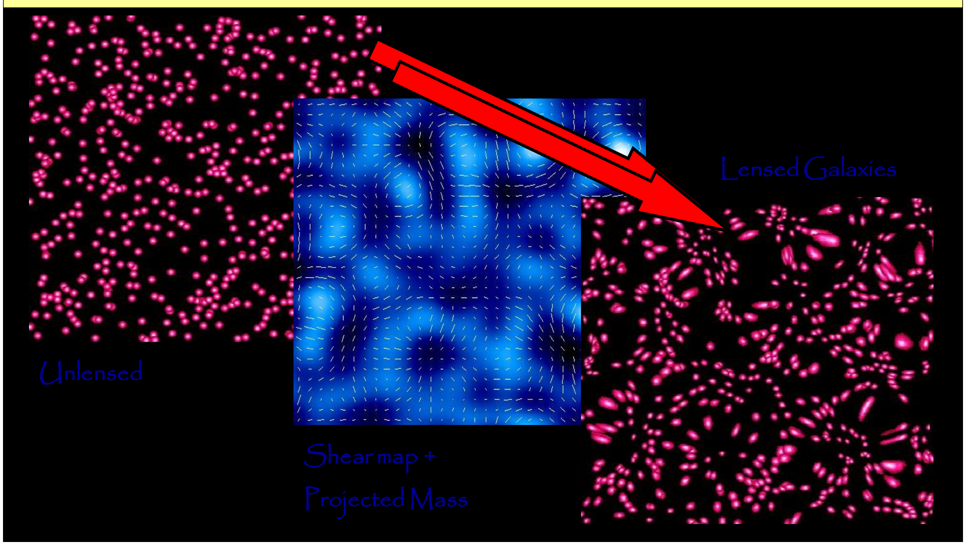
Clusters: Gravitational Lensing



Clusters: Gravitational Weak Lensing

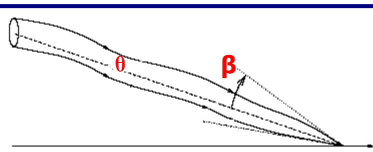
- z=0.83 one of the highest z clusters
- Weak Lensing study by
  - Clowe et al. Keck
  - Hoekstra et al. HST

Gravitational Weak Lensing



Gravitational Lensing

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

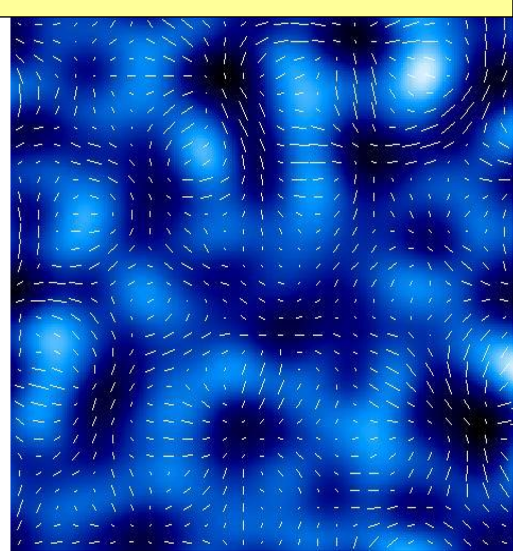


$$\kappa = \frac{1}{2}(\phi_{,11} + \phi_{,22})$$

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

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

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



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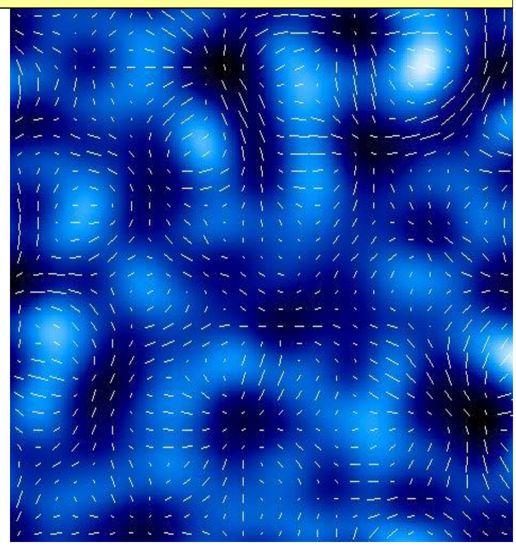
Lensing Potential
related to
Peculiar Gravitational Potential

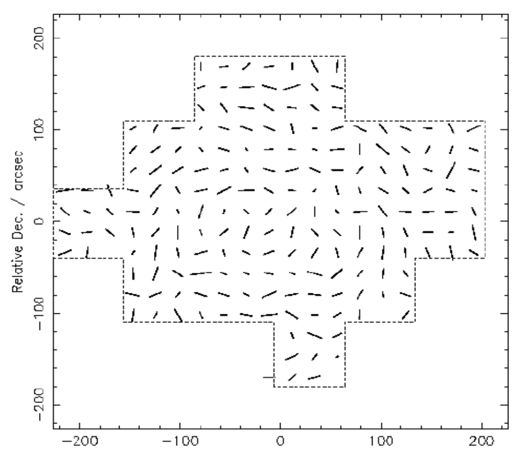
$$\phi(\mathbf{r}) = \frac{2}{c^2}\int_0^r dr'\,\Phi(\mathbf{r}')\left(\frac{1}{r} - \frac{1}{r'}\right)$$



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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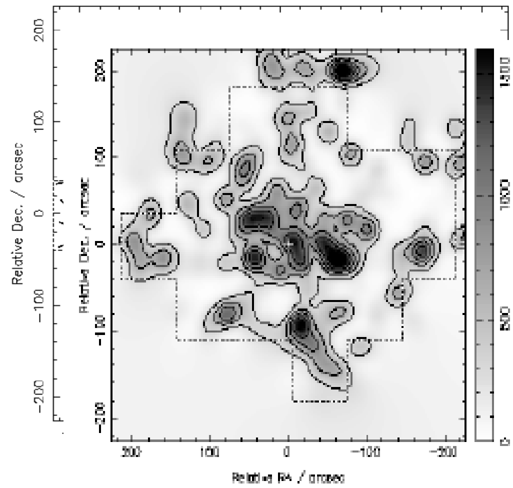
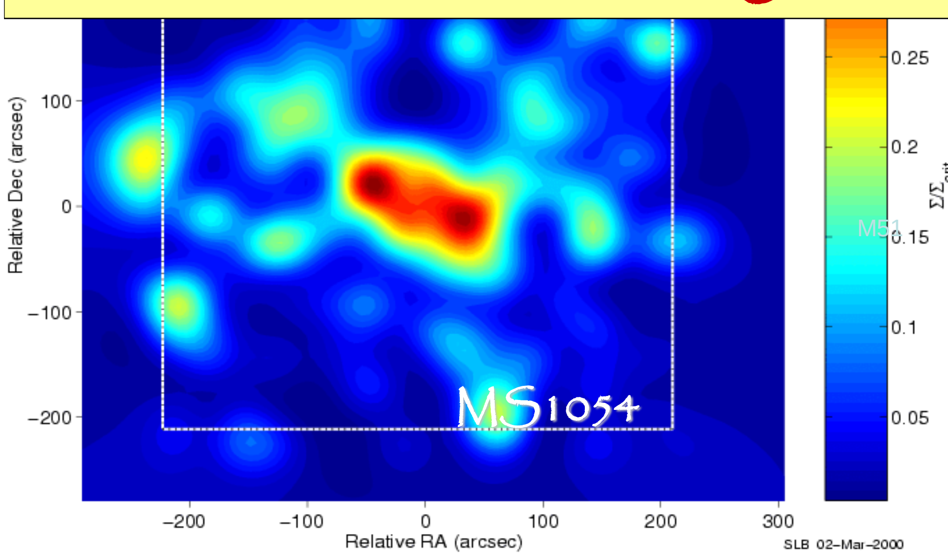
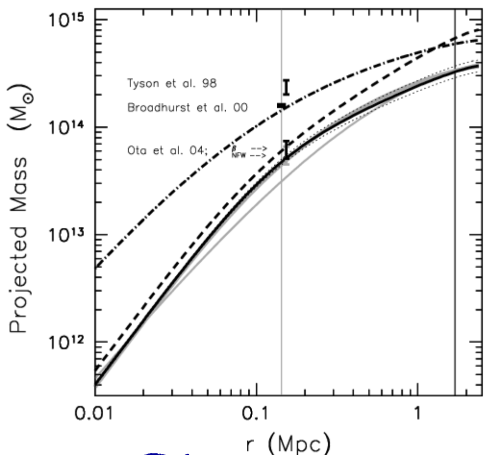


Clusters: Gravitational Lensing

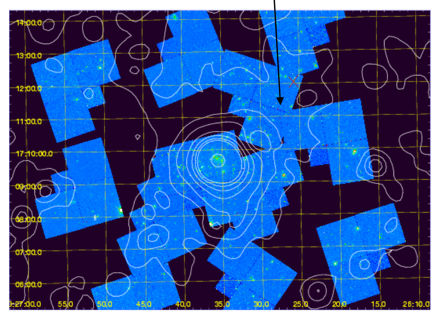


Clusters: Comparison Lensing & X-ray



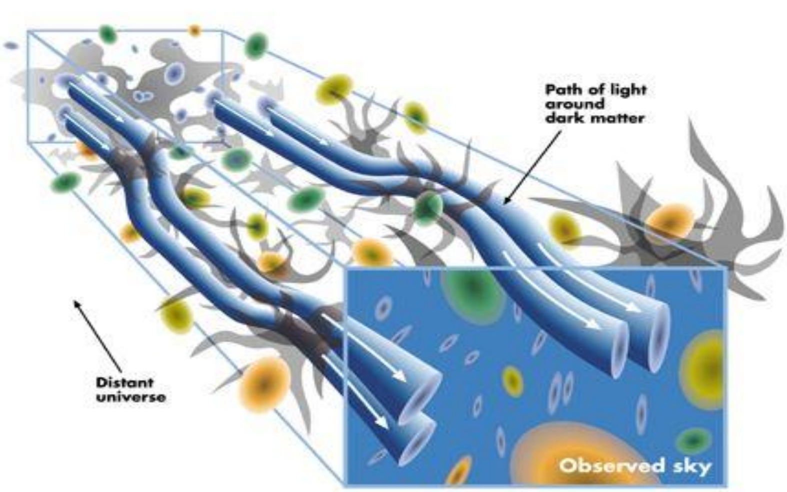
CL0024+17

Same substructure seen in weak lensing and X-rays

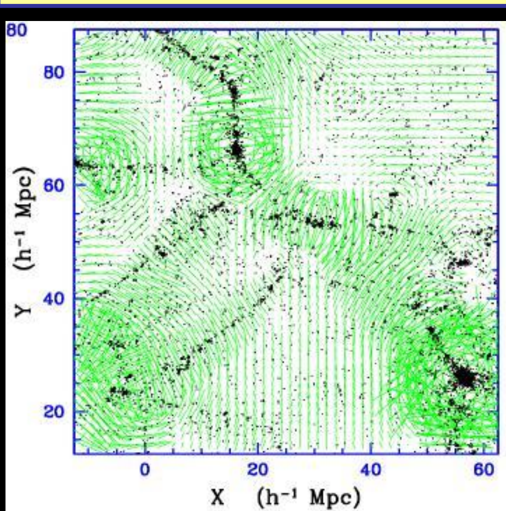


X-ray overlay on HST image

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"),

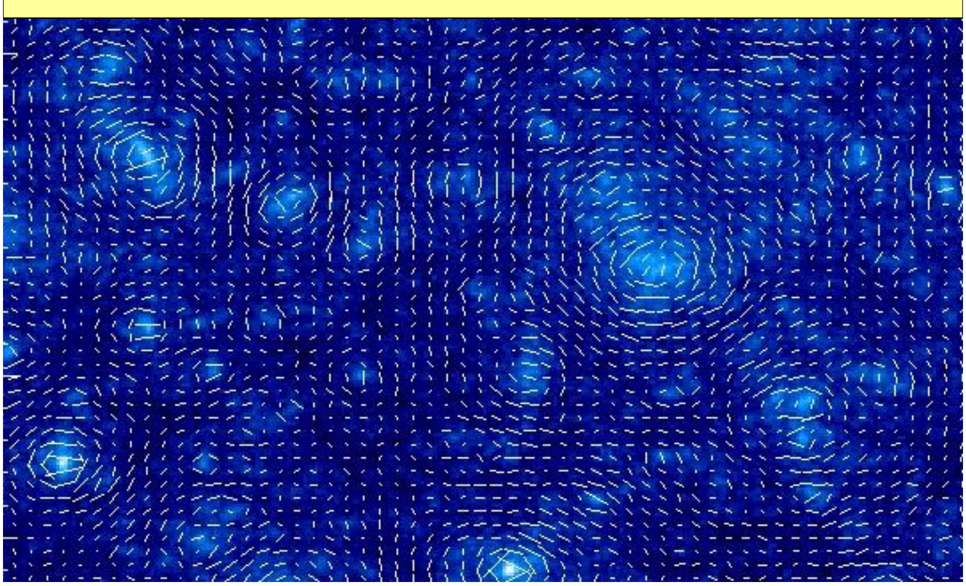
the distortions of galaxy shapes can be measured and inverted to yield the (projected) distorting mass distribution.

Clusters are outstanding, representing major potential wells.

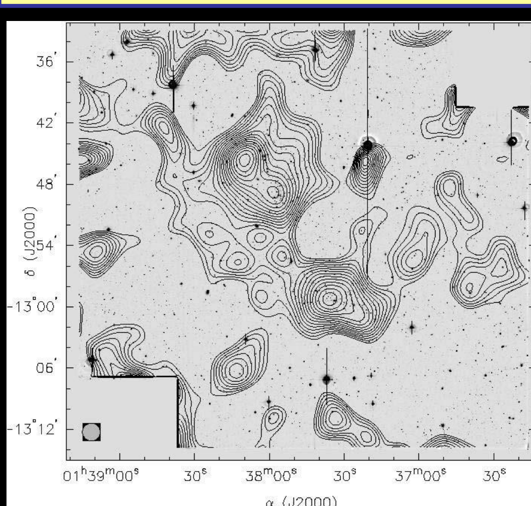
But also the generic Megaparsec matter distribution "lenses":

Cosmic Shear

Cosmic Shear



the Web: Shear Distortions & Lensing



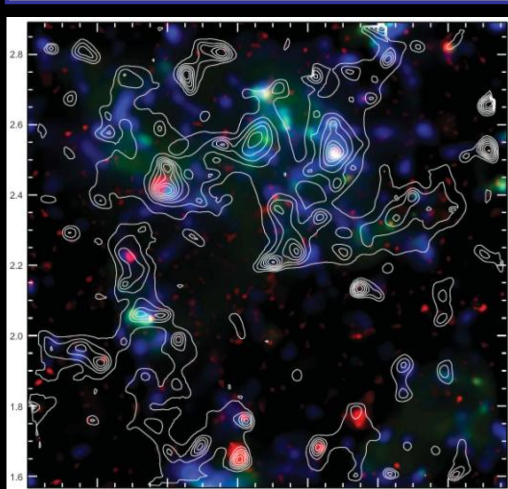
Although the cosmic shear due to a filament is considerably weaker than that of the clusters, recently

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:

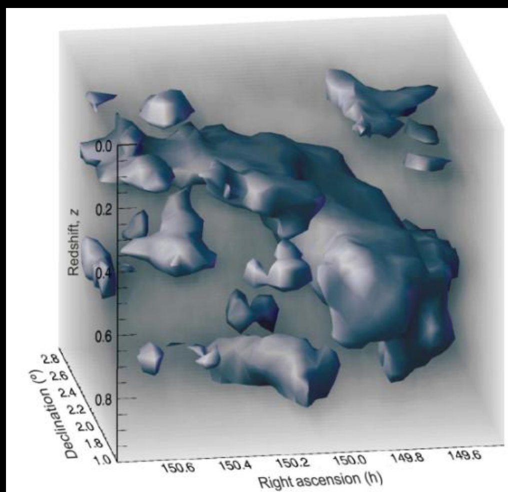
Clearly visible is the filamentary

Weblike nature of the mass

Distribution.

Massey et al. 2007

the Web: Shear Distortions & Lensing



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