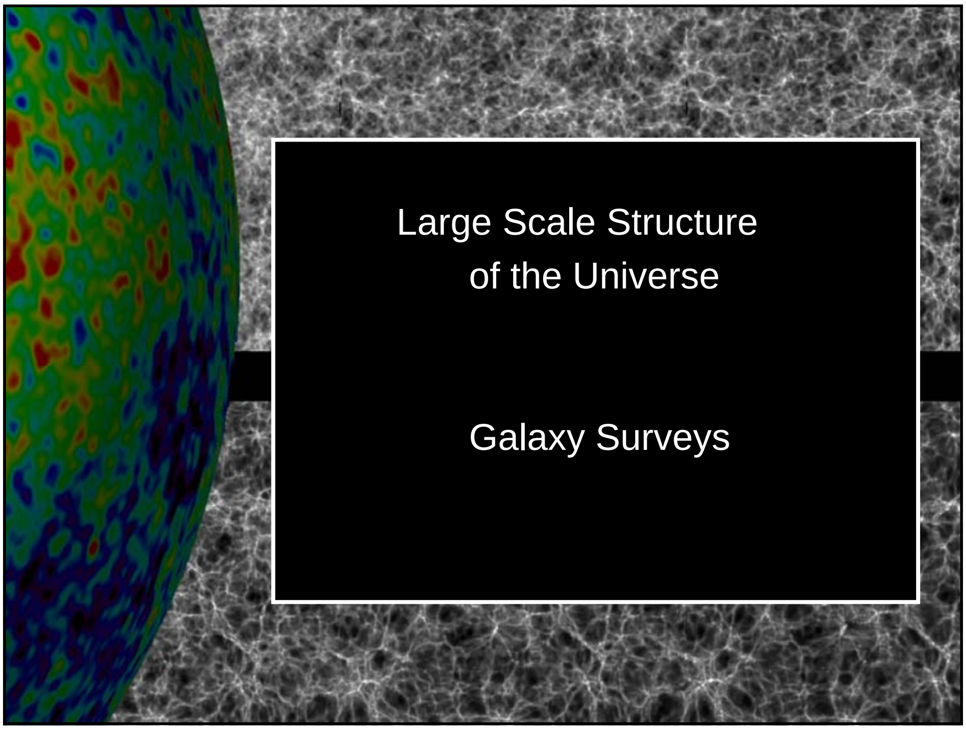


Galaxy Surveys:

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 density of galaxies with luminosity

$$[L, L + dL]$$

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

Schechter Luminosity Function

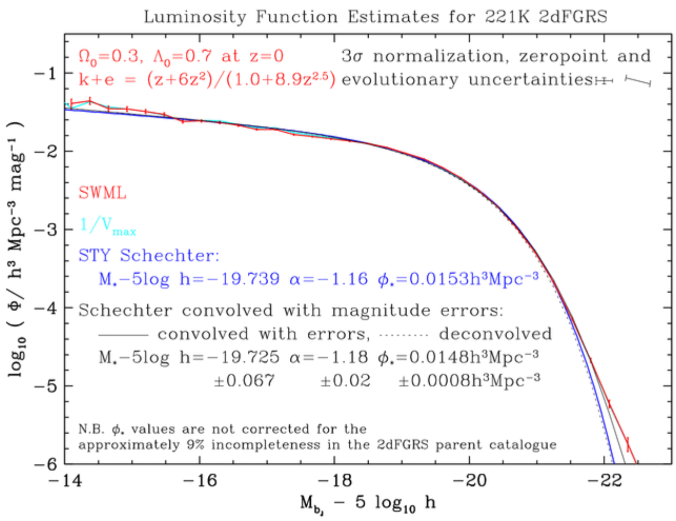
Very good approximate expression for the galaxy luminosity distribution:

- 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:

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

- 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:

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

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

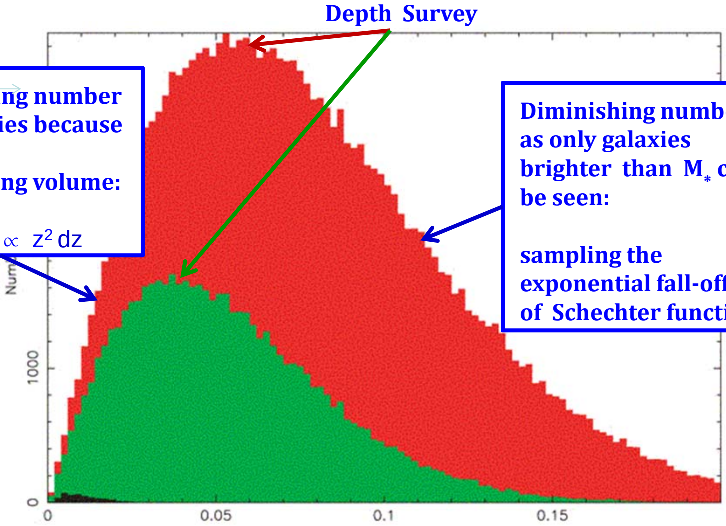
$$\log d_{sur} = 0.2(m_{\lim} - M_*) + 5 + 0.2k(z)$$

Survey Depth

Depth Survey

Increasing number of galaxies because of increasing volume:

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

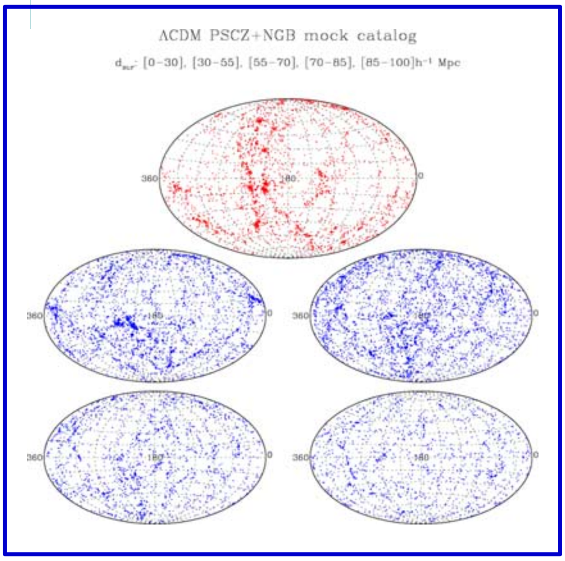


Diminishing number as only galaxies brighter than M_* can be seen:

sampling the exponential fall-off of Schechter function

Redshift z

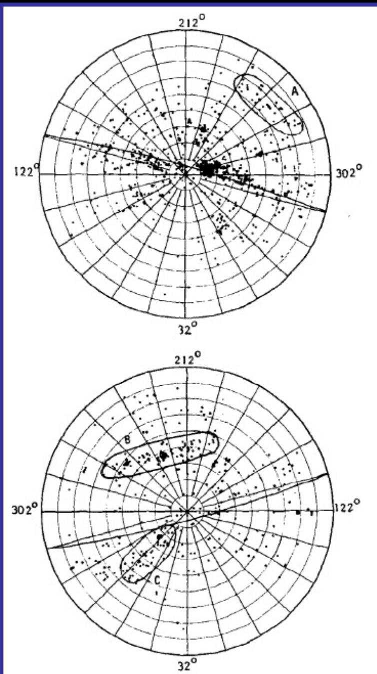
Survey Depth



Theoretical Example:

Galaxies in PSCz catalogue, at different depths

Sky Maps: world all around us



Early Views

Shapley-Ames catalog (1932) of nearby galaxies:

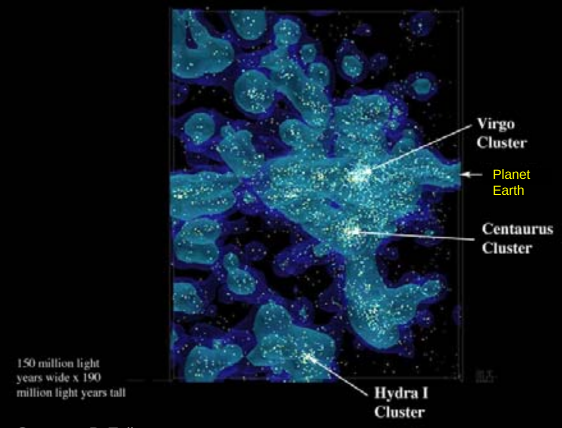
All-sky survey of galaxies to m=18.3

$\delta > -23^o$

- 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:



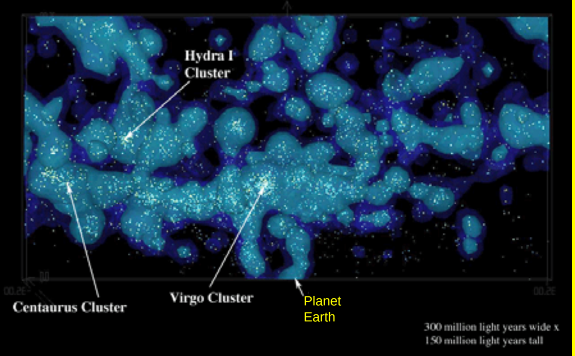
Courtesy: B. Tully

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:



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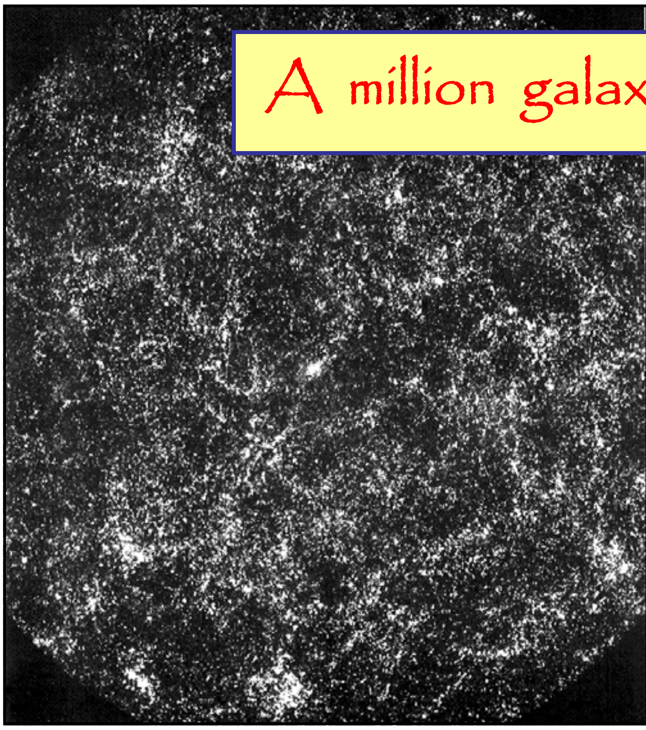
- centered on one rich cluster, the Virgo cluster

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:

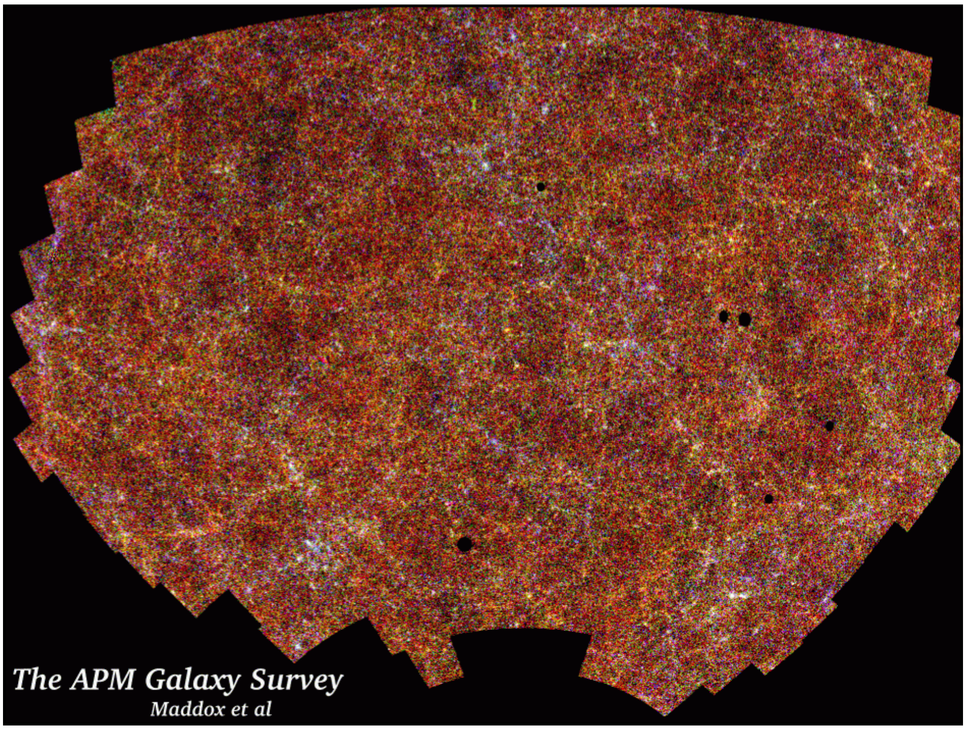
  2×10^6 galaxies

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

  185 UK Schmidt plates, 6° x 6°

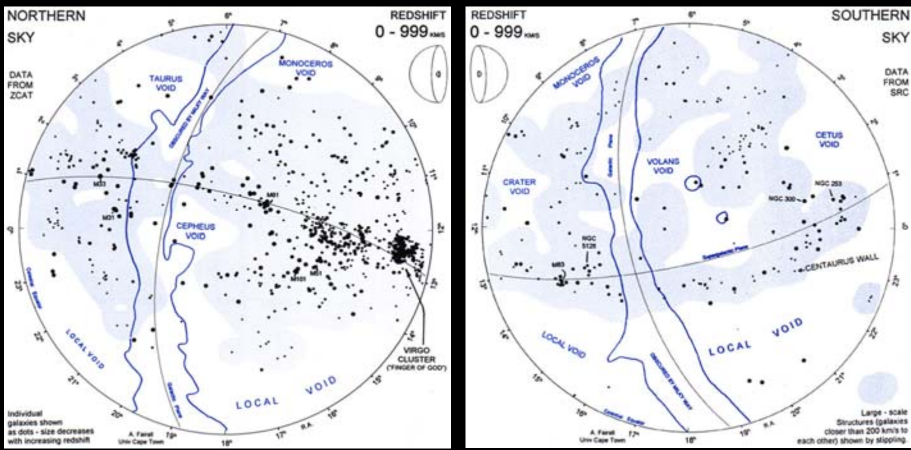
- Large inhomogeneities, hints of weblike patterns, with clusters at densest regions.

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



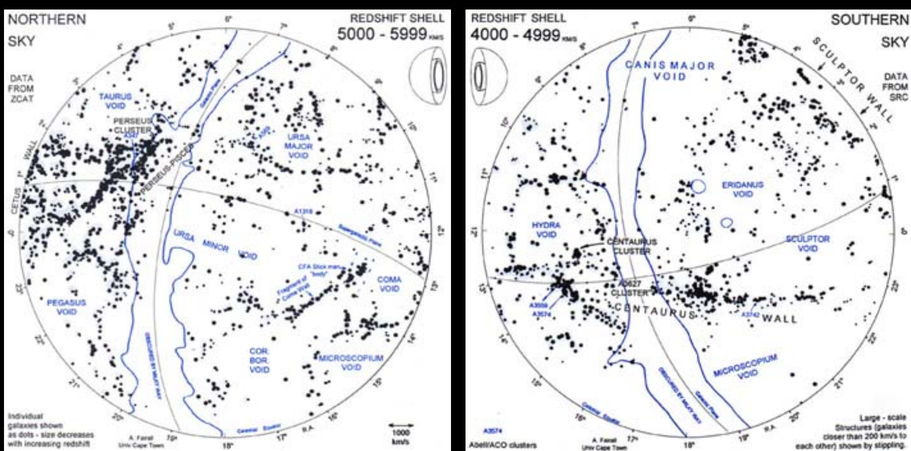
Maps of the Local Universe

Local Views

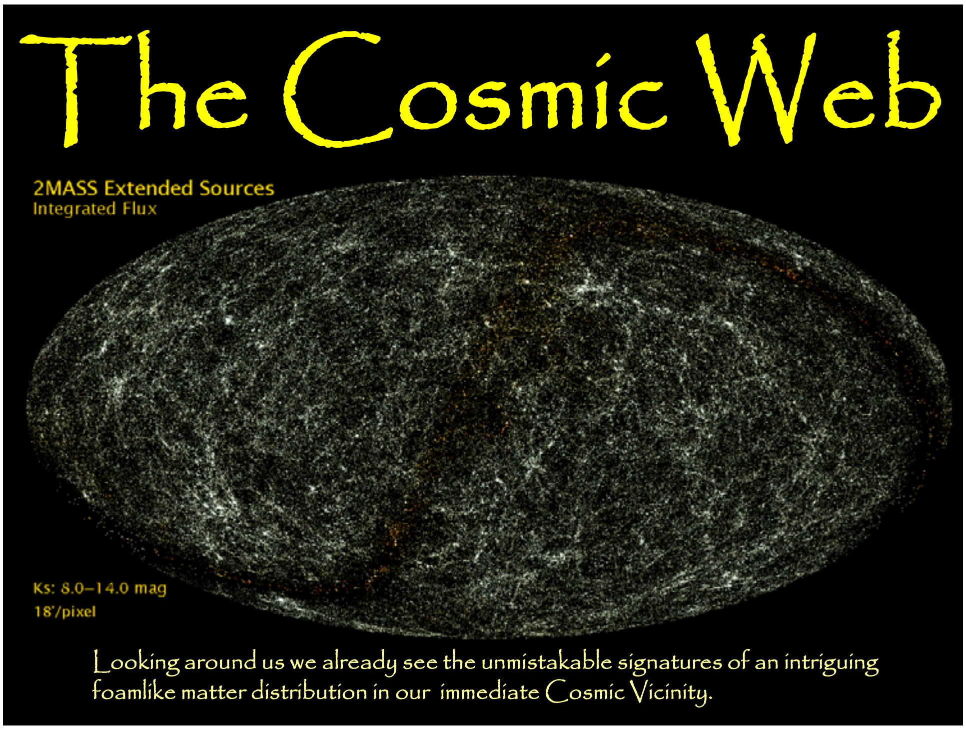


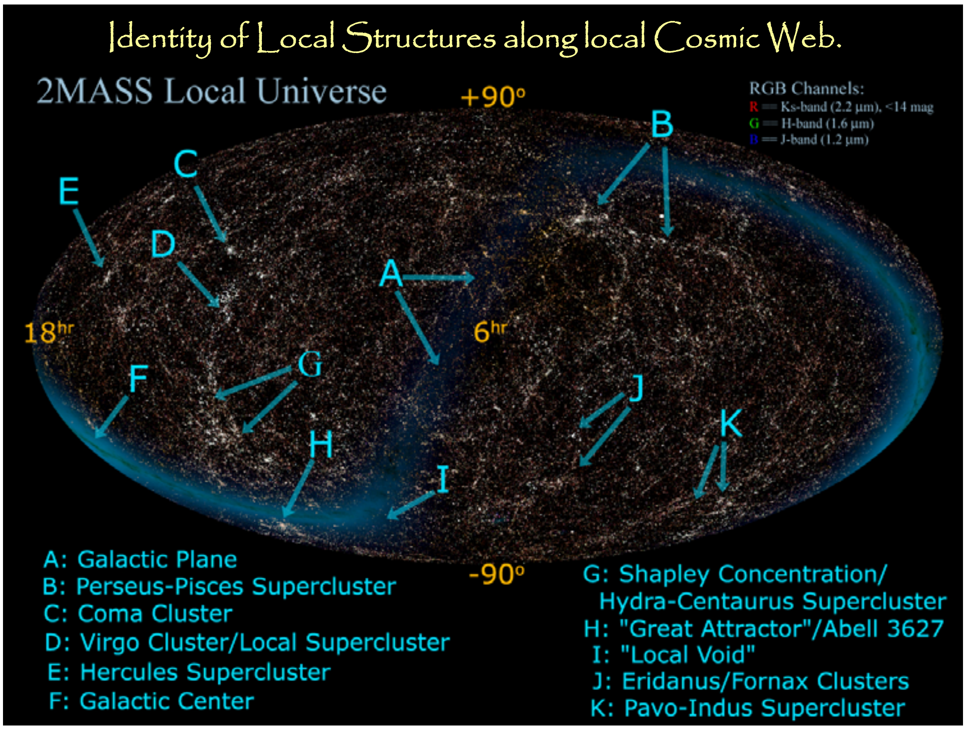
Tony Fairall's nearby LSS map: Local Supercluster clearly visible at v < 999 km/s

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.

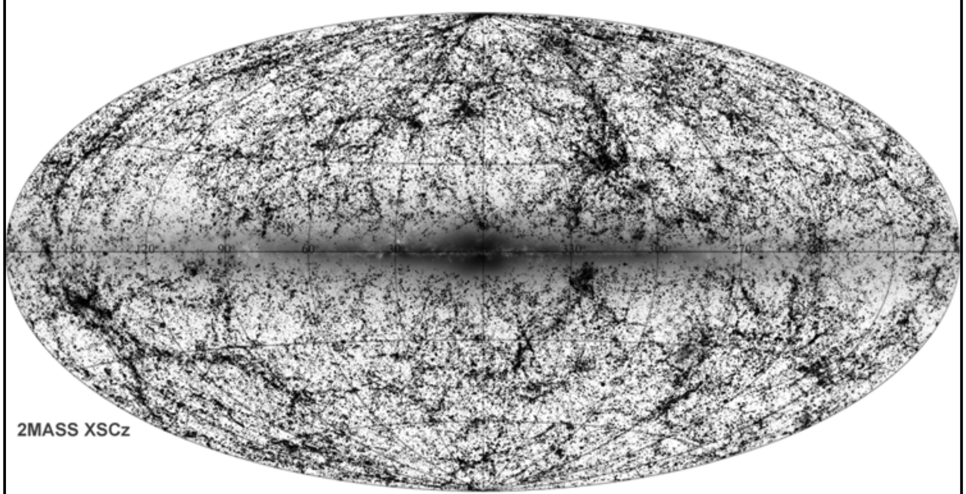

Identity of Local Structures along local Cosmic Web.
2MASS Local Universe
+90°
RGB Channels:
R == Ks-band (2.2 μm), <14 mag
G == H-band (1.6 μm)
B == J-band (1.2 μm)
B
C
E
D
A
18hr
6hr
G
F
H
I
J
K
-90°
A: Galactic Plane
B: Perseus-Pisces Supercluster
C: Coma Cluster
D: Virgo Cluster/Local Supercluster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

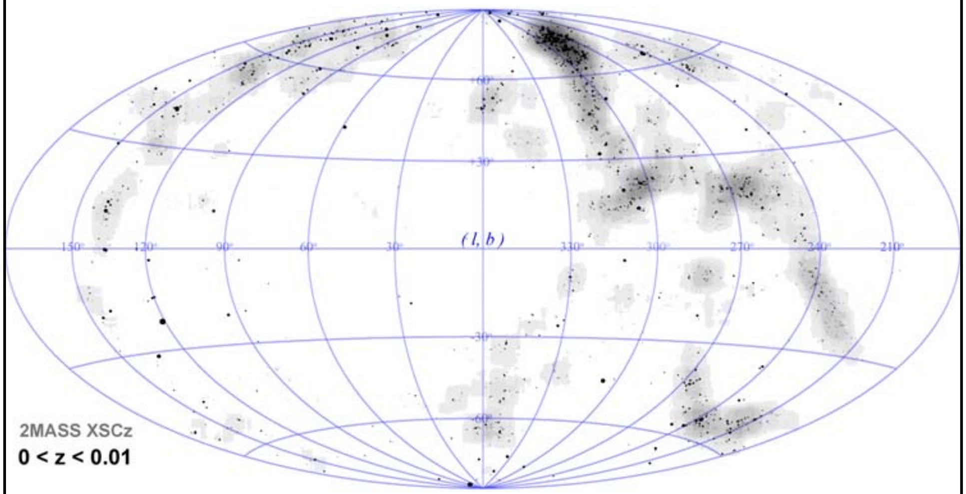
courtesy: T. Jarrett

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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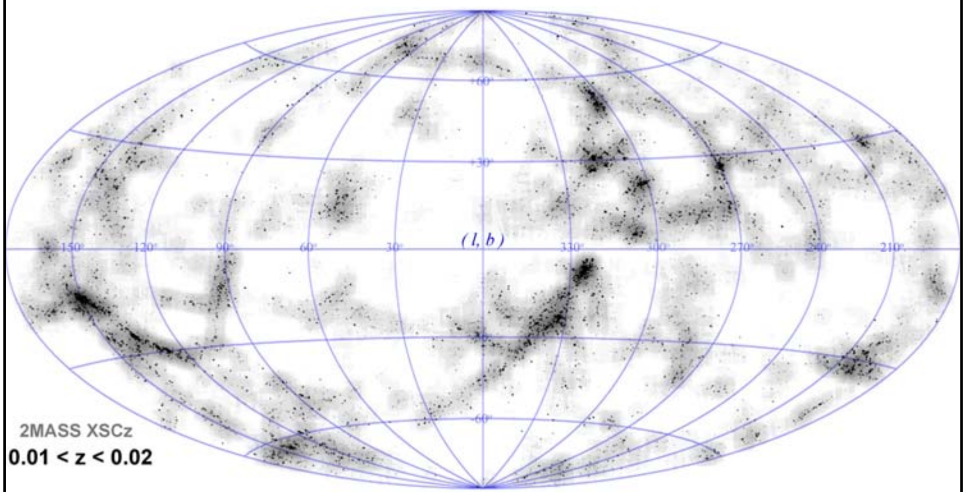

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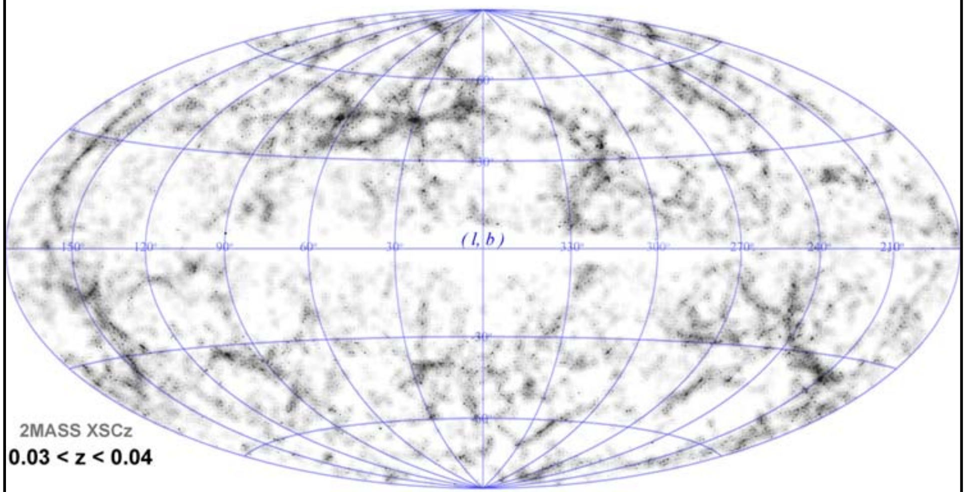

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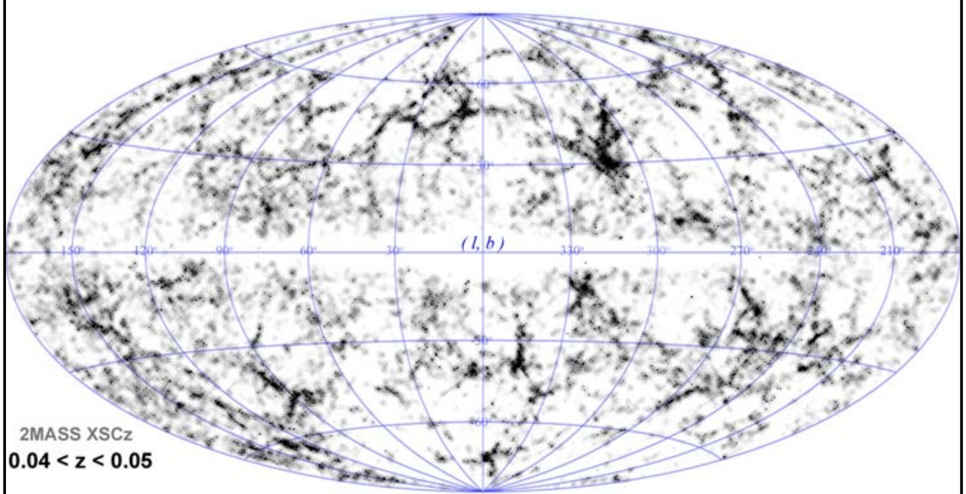

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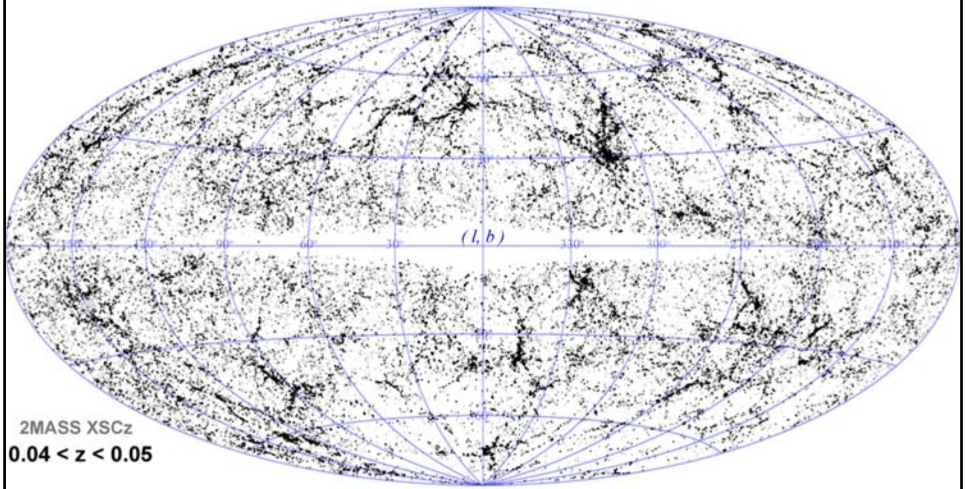

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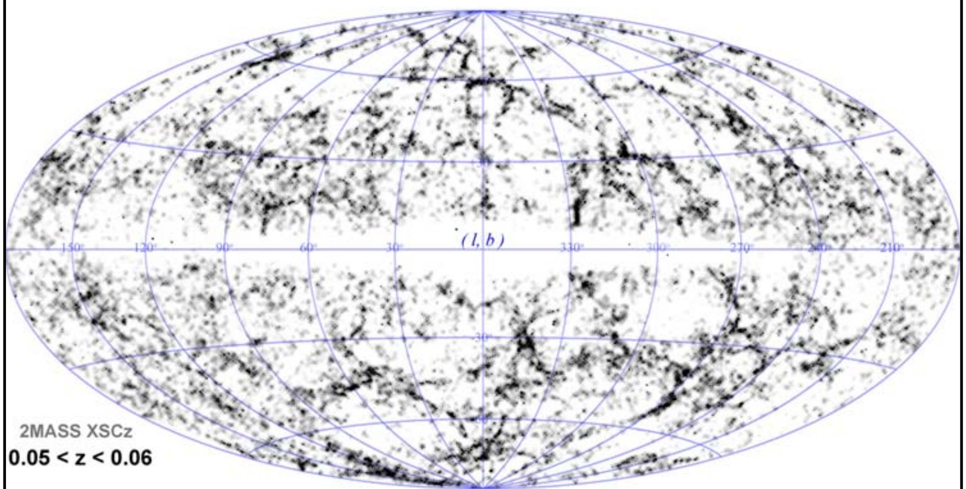

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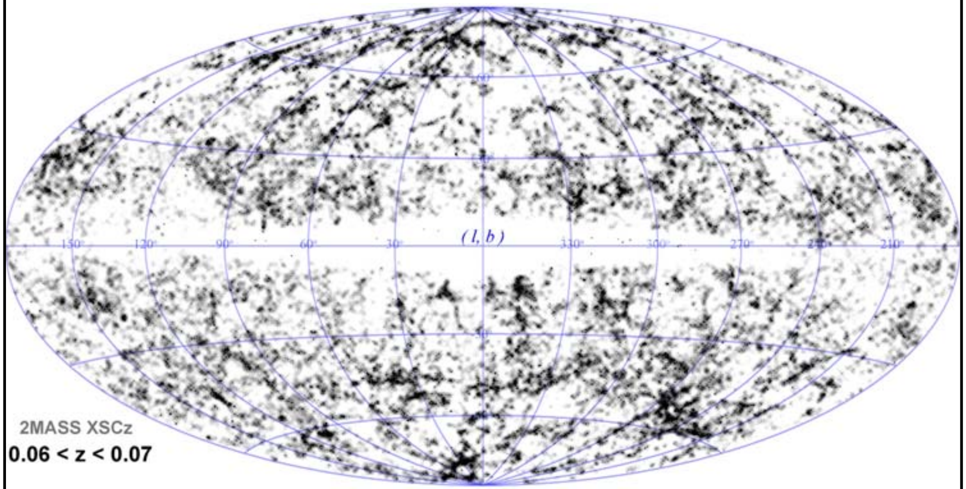

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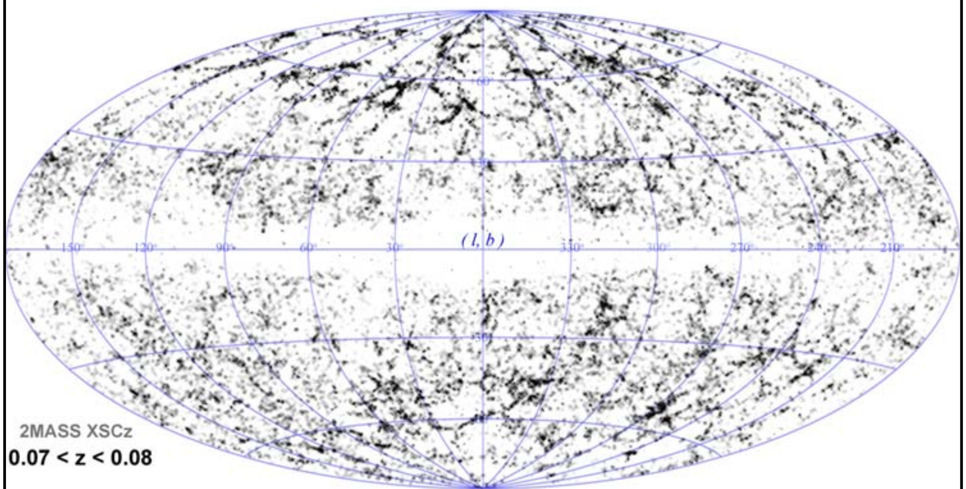

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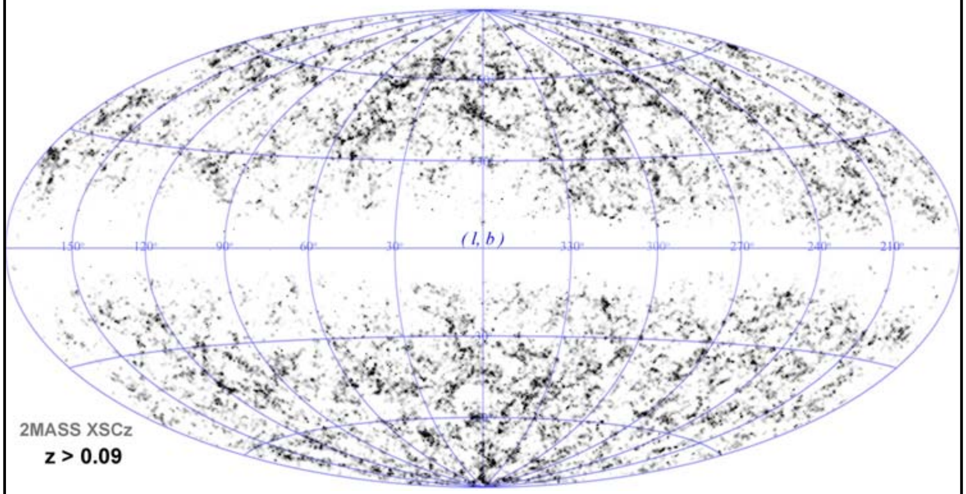

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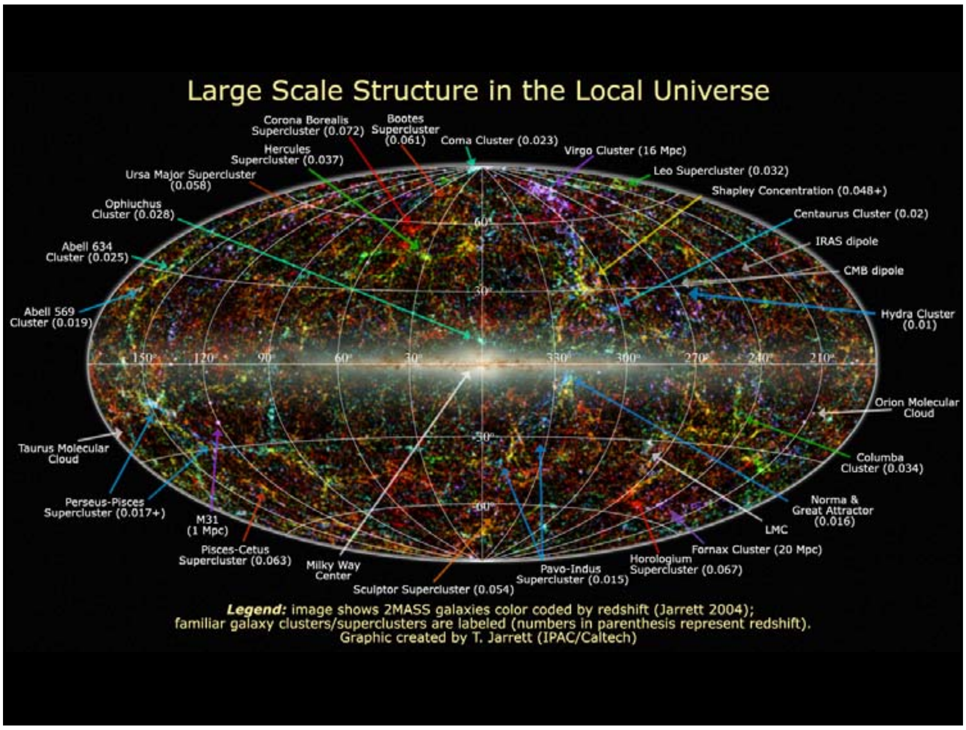


Galaxy Redshift Surveys

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

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

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

Galaxy Redshift Surveys

- Hubble Expansion:

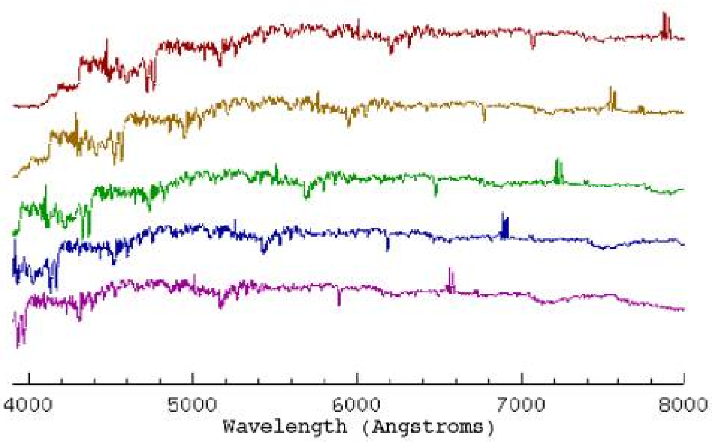
$$cz = Hr \quad (z \ll 1)$$

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

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

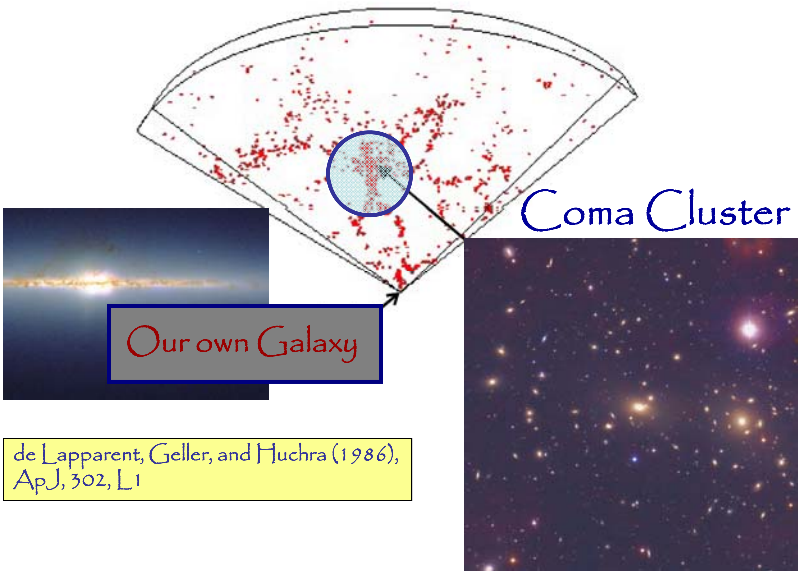
Galaxy Spectrum

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:

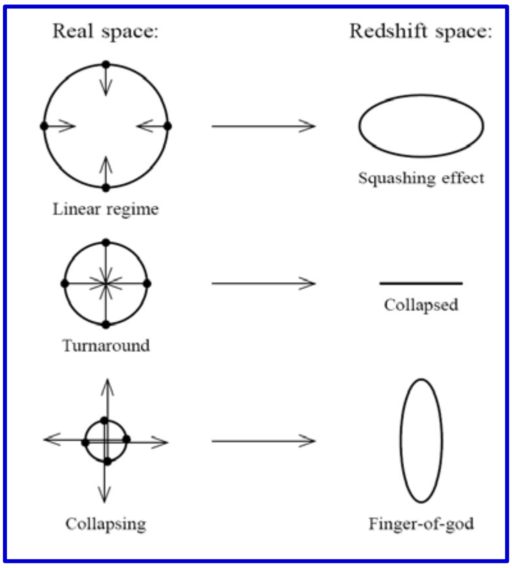
three regimes

- 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

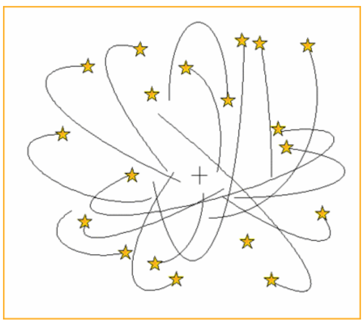
- Large scales: (linear, quasi-linear) cosmic flow, manifestation of structure growth

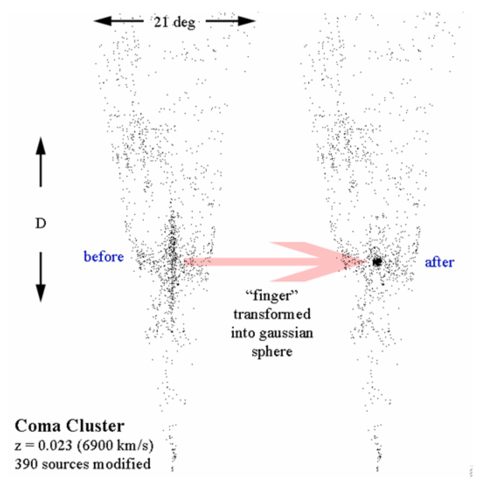


Fingers of God

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

Galaxy velocity component along line of sight





Fingers of God

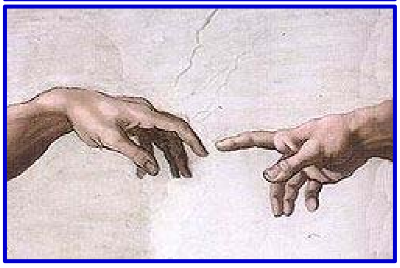
Clusters of galaxies:

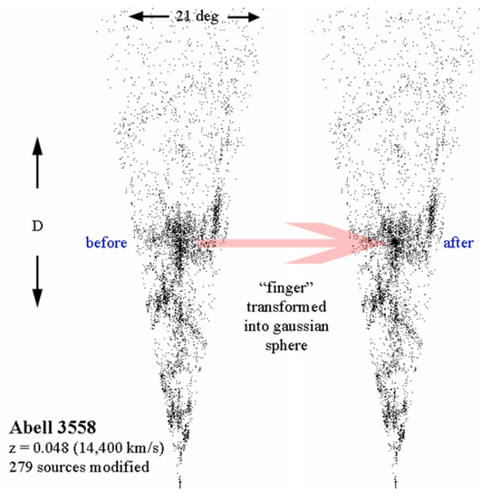
Mass: 10^{14}-$10^{15} M_{\odot}$
Radius: ~ 1.5 Mpc
Overdensity Δ ~ 1000

Thermal velocity: ~ 1000 km/s

Internal cluster galaxy velocities visible in projection along line of sight

→ "Finger of God"





Nonlinear Infall Pattern

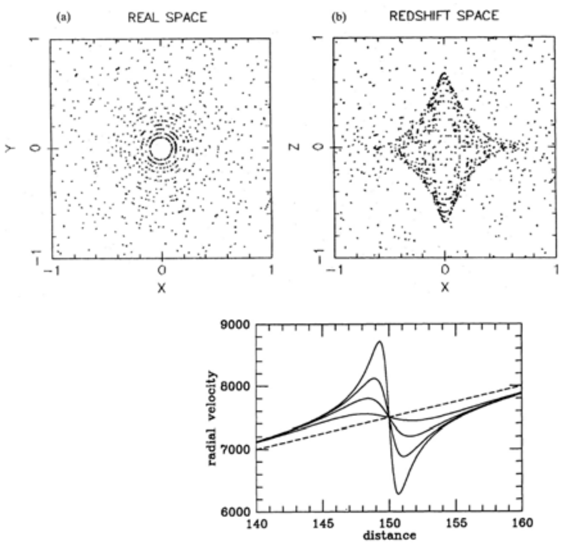
Cluster Infall:

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

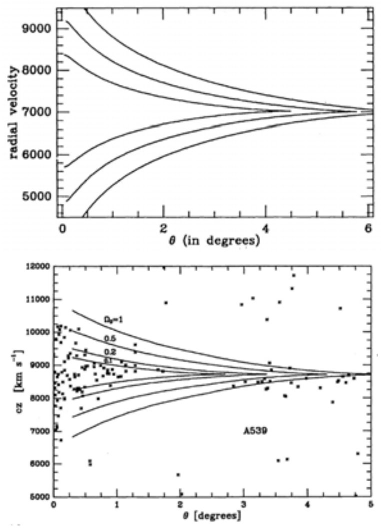
Cluster Caustics:

Three-value region cluster infall:

Projection onto restricted cone-shaped redshift space regions around clusters

Enclosed within caustic surfaces

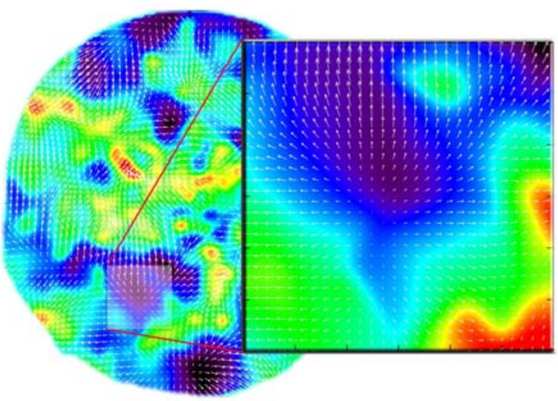
Position caustics dependent on Ω_m



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



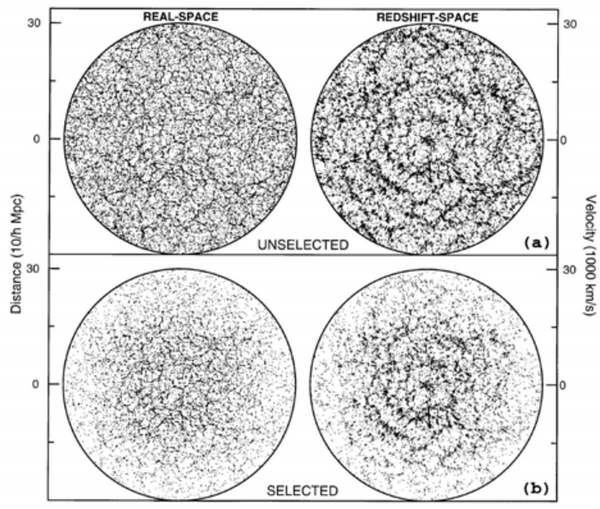
$$\mathbf{v}(\mathbf{x},t) = \frac{H}{4\pi}\frac{f(\Omega_m)}{b}a\int d\mathbf{x}'\,\delta_{gal}(\mathbf{x}',t)\,\frac{(\mathbf{x}'-\mathbf{x})}{|\mathbf{x}'-\mathbf{x}|^3}$$

Large Scale Flows

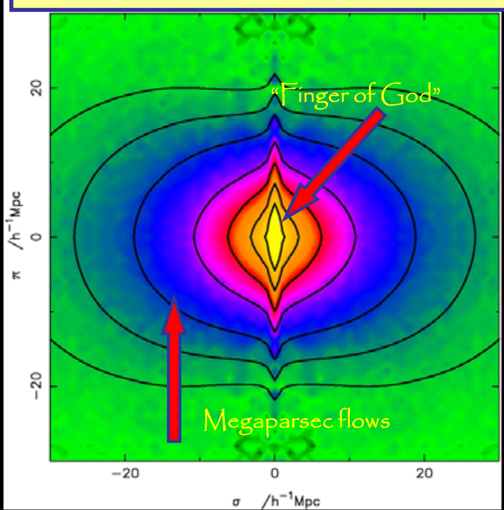
Large-Scale Flows:

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

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



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"

Magnitude vs. Volume Limited

Magnitude vs. Volume limited Surveys

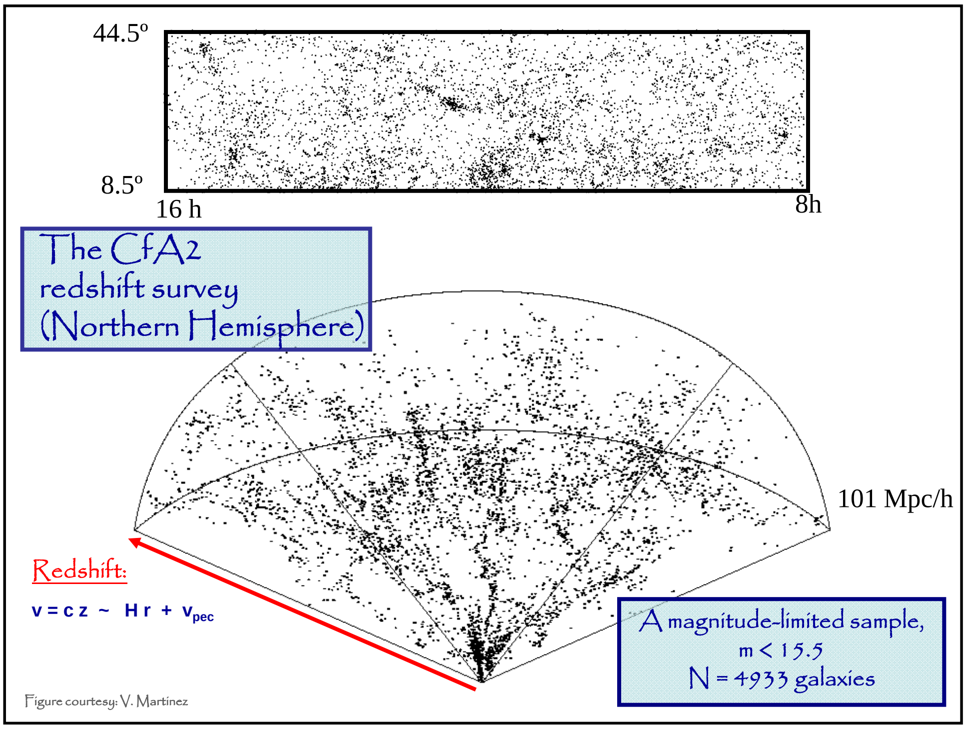
- Two different sampling approaches for analysis spatial structure from galaxy redshift catalogue:

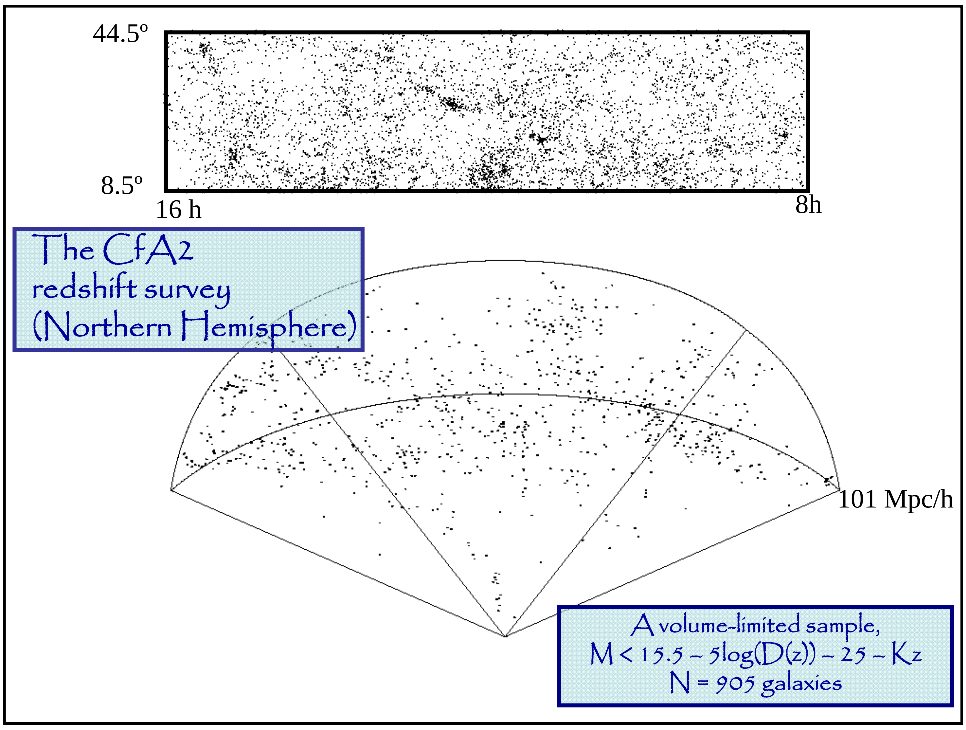
- Volume-limited surveys:
  - uniform spatial coverage, including all galaxies within volume to depth d_s
  - all galaxies with an absolute brightness > survey limit M_s

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

  - 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

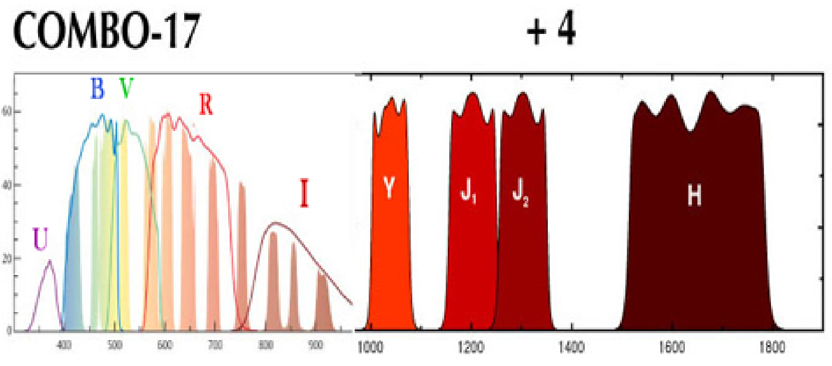

44.5°
8.5°
16 h
8h
The CfA2
redshift survey
(Northern Hemisphere)
101 Mpc/h
Redshift:
v = c z ~ H r + v_pec
A magnitude-limited sample,
m < 15.5
N = 4933 galaxies
Figure courtesy: V. Martinez


44.5°
8.5°
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

Photometric Redshifts

Photometric Redshifts

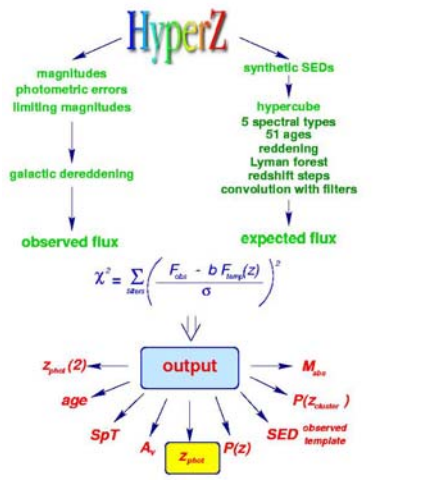
- Instead of measuring the electromagnetic spectrum of the galaxies in a survey, one may get a good estimate of the redshift on the basis of the photometry and colours of the objects.



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):
  - Δz ~ 0.1



widely used Hyperz package

Photometric Redshifts

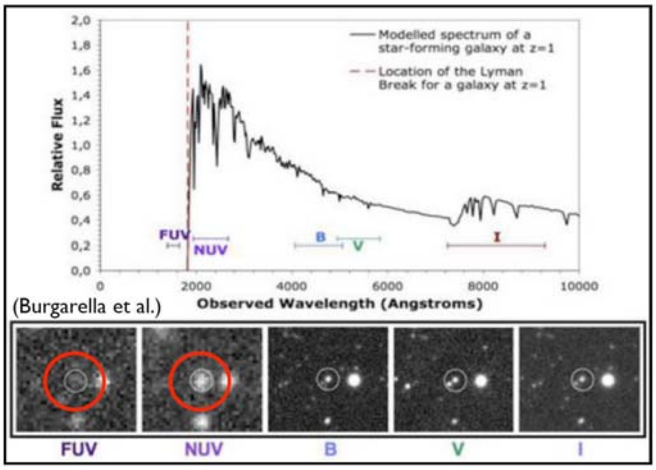
Photometric Redshifts

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



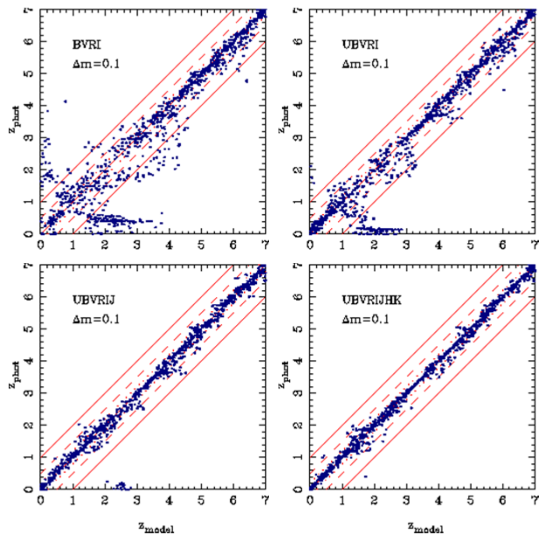
(Burgarella et al.)

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

Photometric Redshifts

Photometric Redshifts:

- Accuracy (typical): $\sim\Delta z \sim 0.1$
- 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

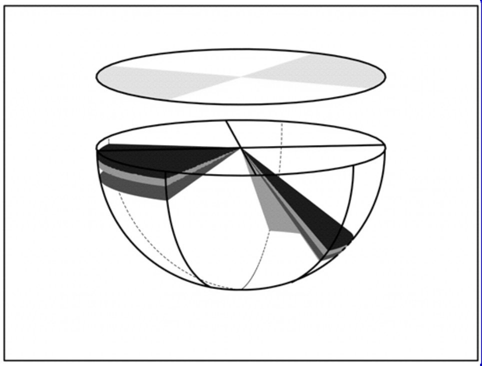
Practical Limitations

- 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



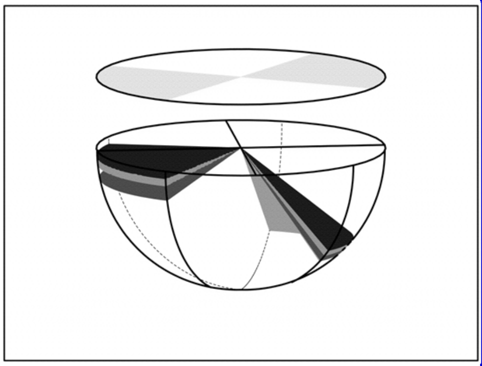
Sky Location
2-D LCRS survey slices

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)



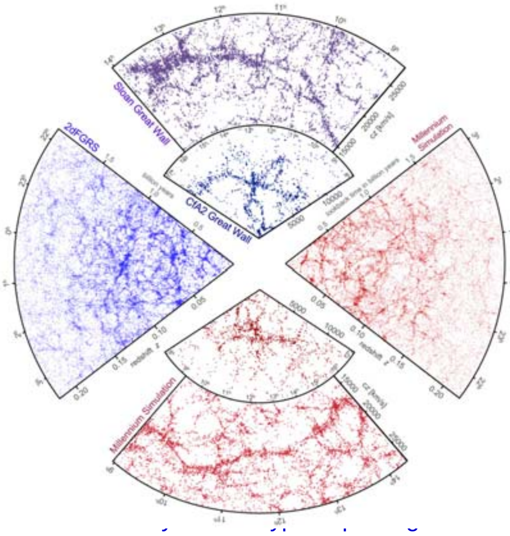
Sky Location
2-D LCRS survey slices

Survey Geometries

Examples of

Slice Redshift Surveys:

From
CfA2-2dFGRS-SDSS

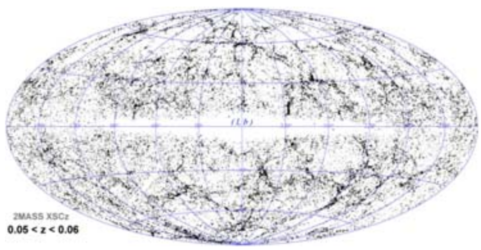


Survey Geometry

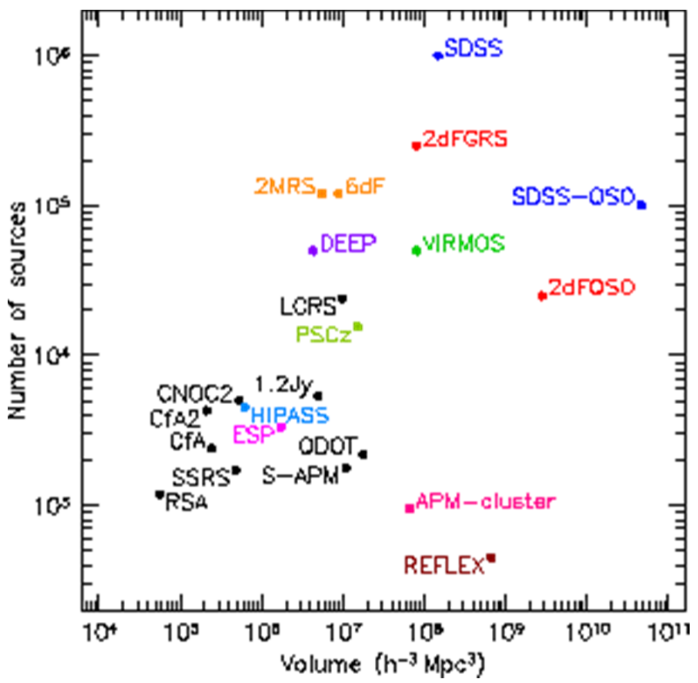
Survey Geometry:

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

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



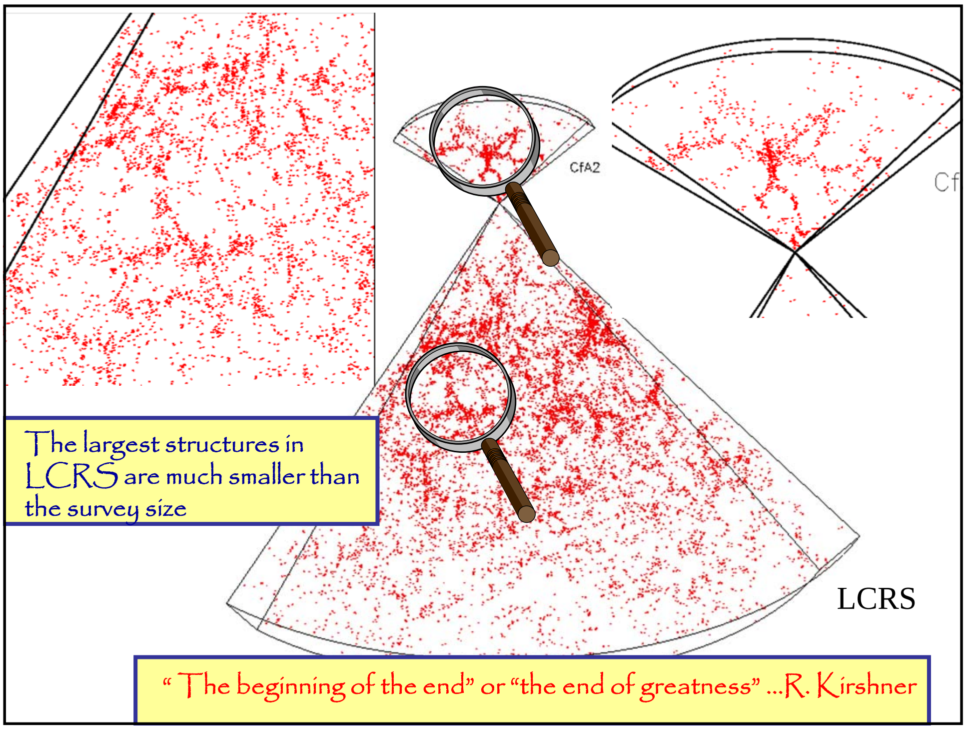
Galaxy Redshift Surveys: Overview

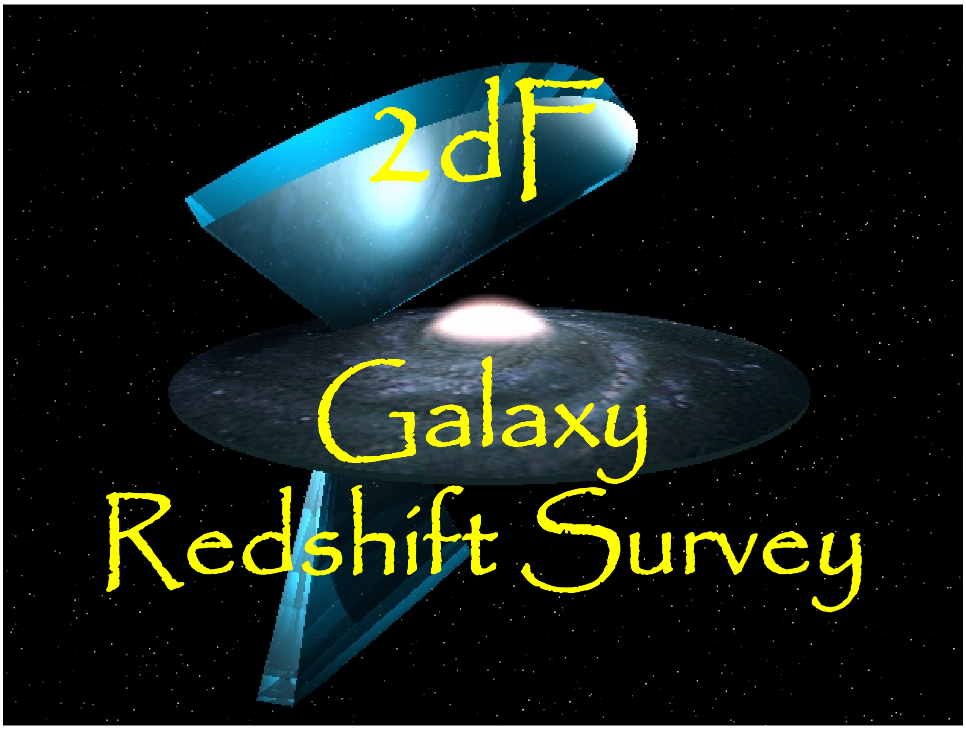


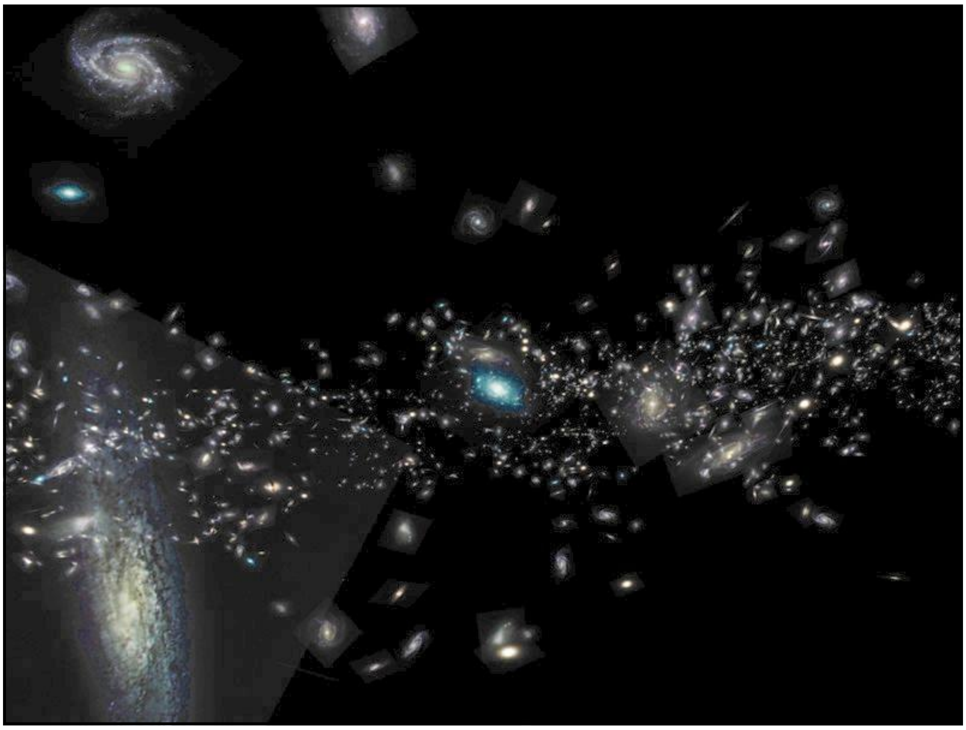
Comparing Galaxy/Cluster

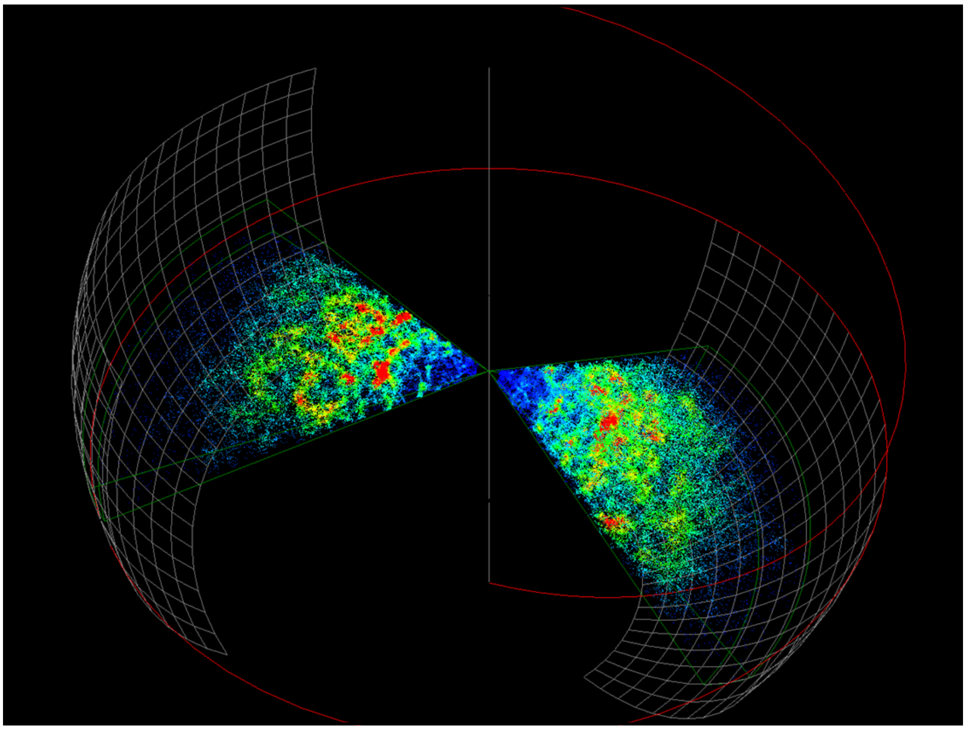
Redshift Surveys

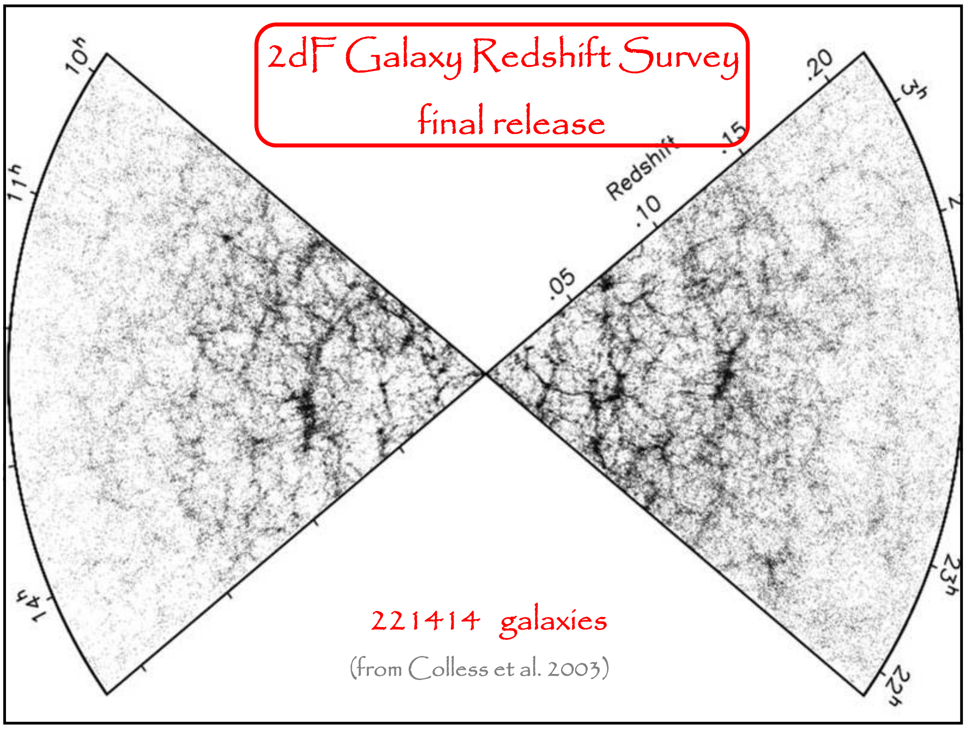
“Sensitivity”
vs.
Extent

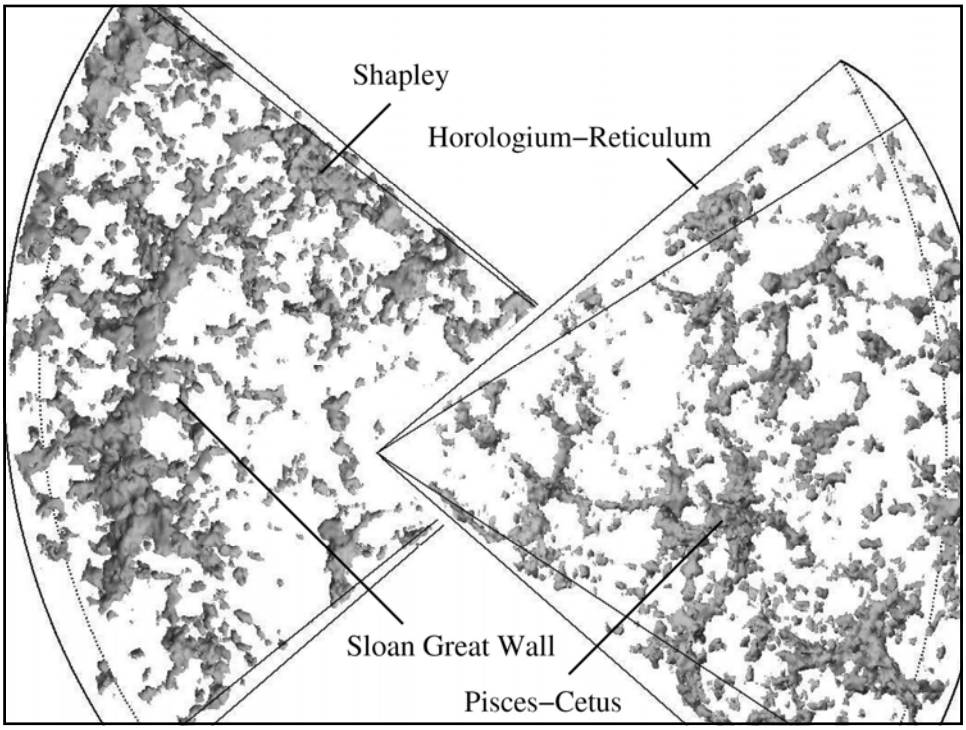

CfA2
Cf
LCRS
The largest structures in LCRS are much smaller than the survey size
" The beginning of the end" or "the end of greatness" ...R. Kirshner


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)

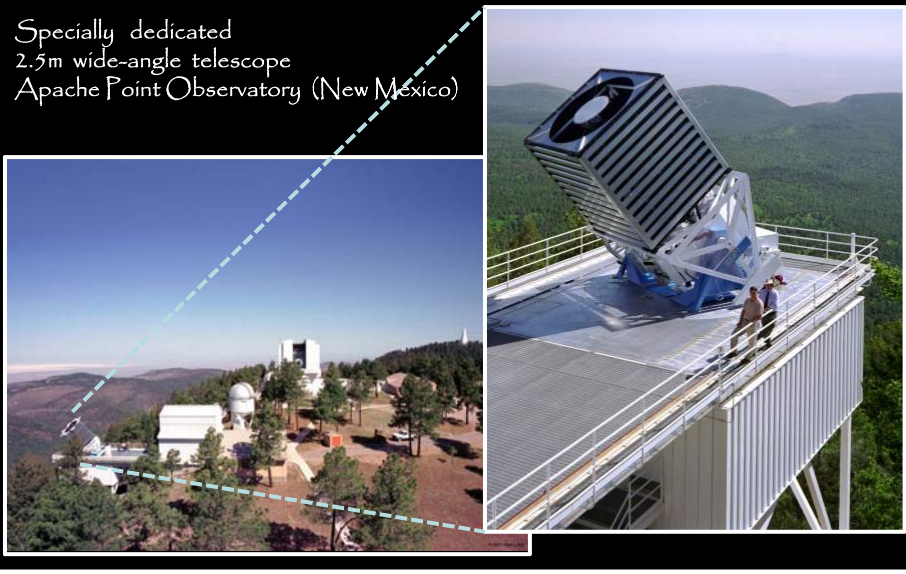

Shapley
Horologium–Reticulum
Sloan Great Wall
Pisces–Cetus

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 has produced 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

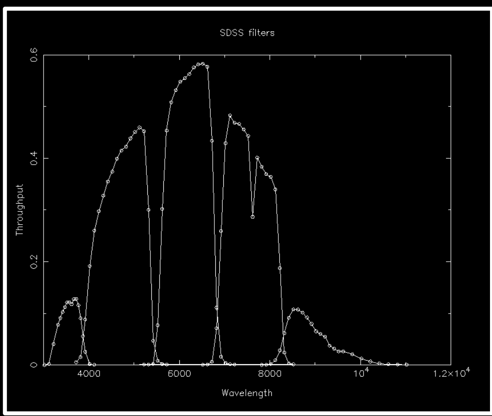
Aims to sample 25% of the sky:
DR7 - 8423 sq. deg.

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



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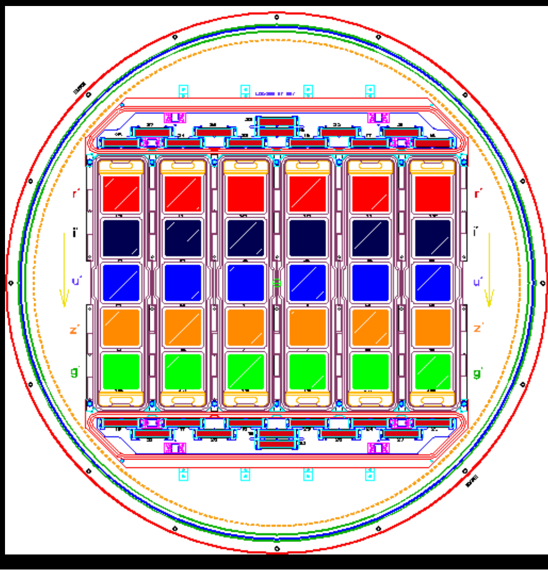
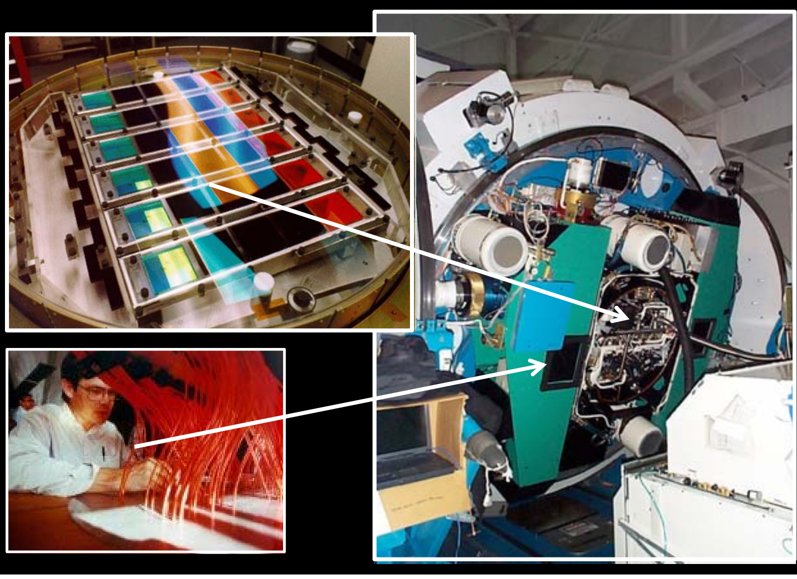


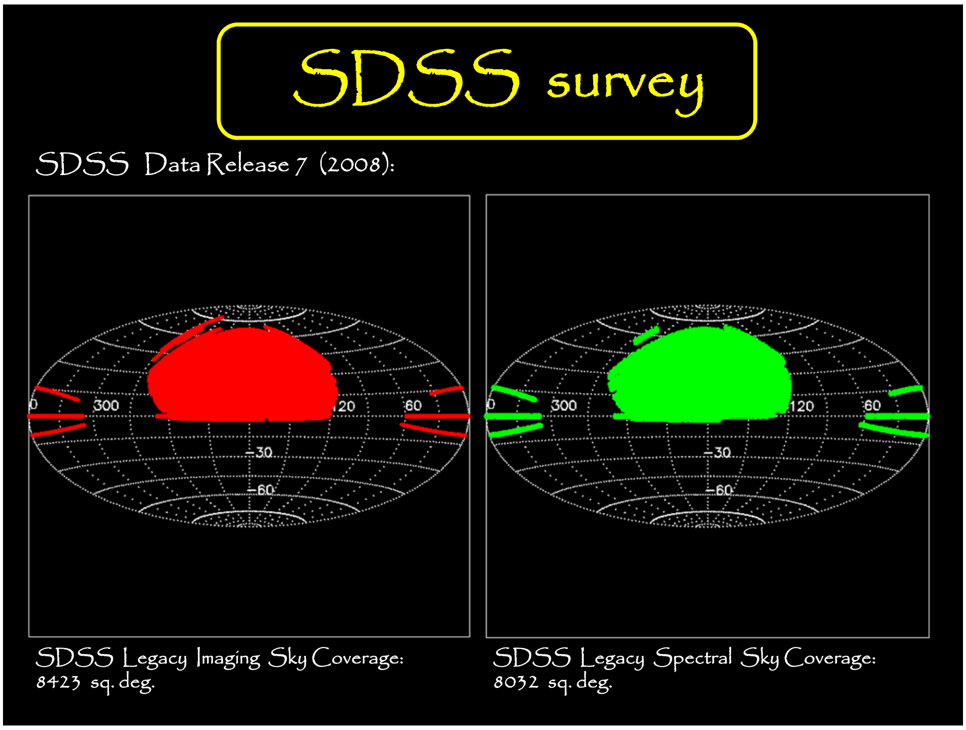
SDSS survey

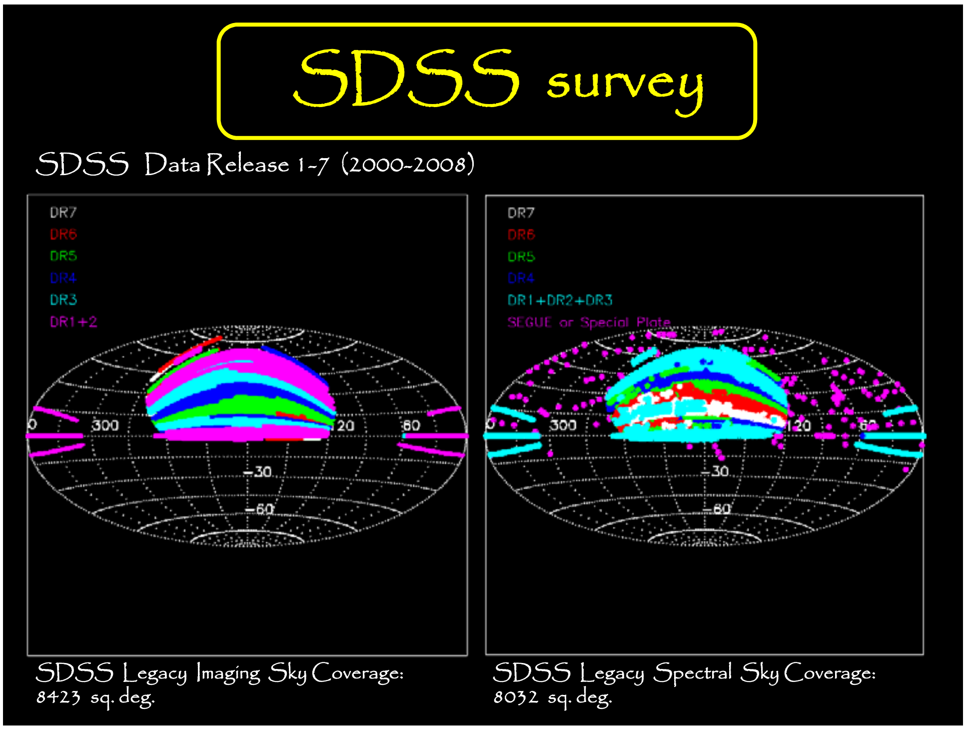
5-color Camera

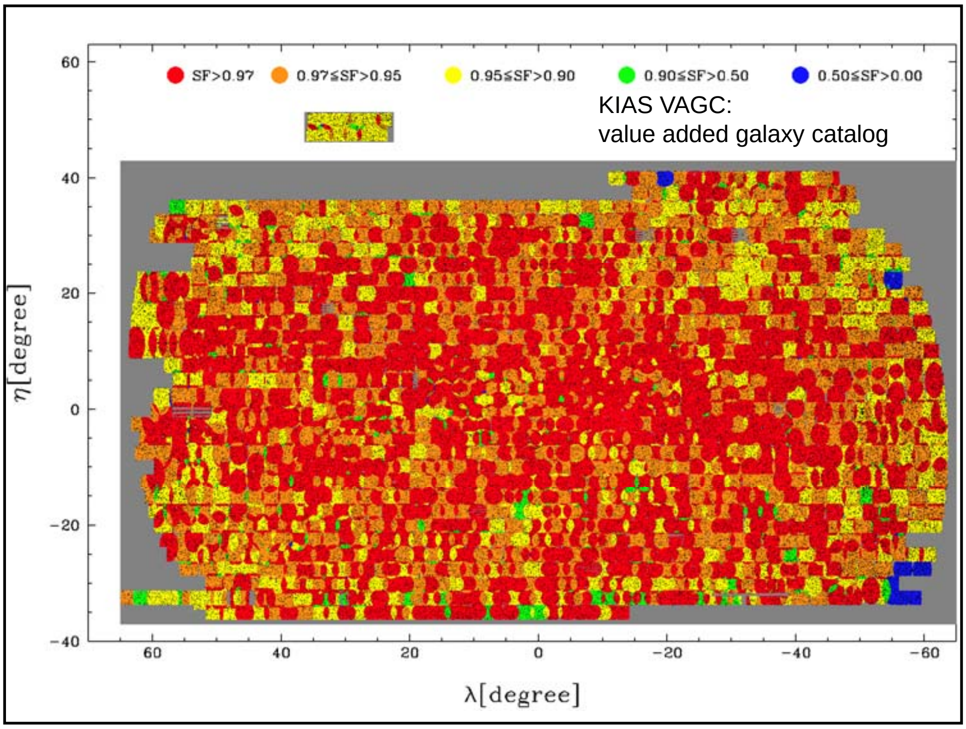
30 CCD chips

Fiber Spectrograph

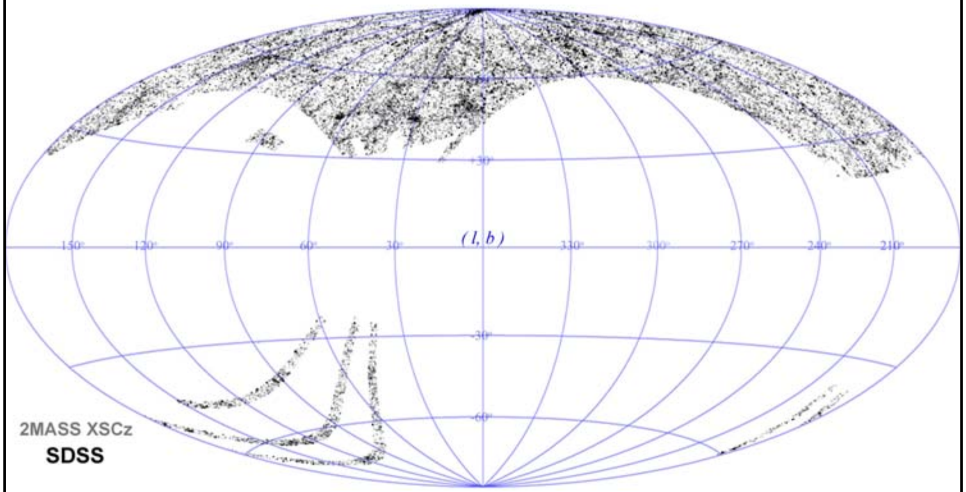



SDSS survey
SDSS Data Release 7 (2008):
300
120
60
-30
-60
SDSS Legacy Imaging Sky Coverage:
8423 sq. deg.
SDSS Legacy Spectral Sky Coverage:
8032 sq. deg.

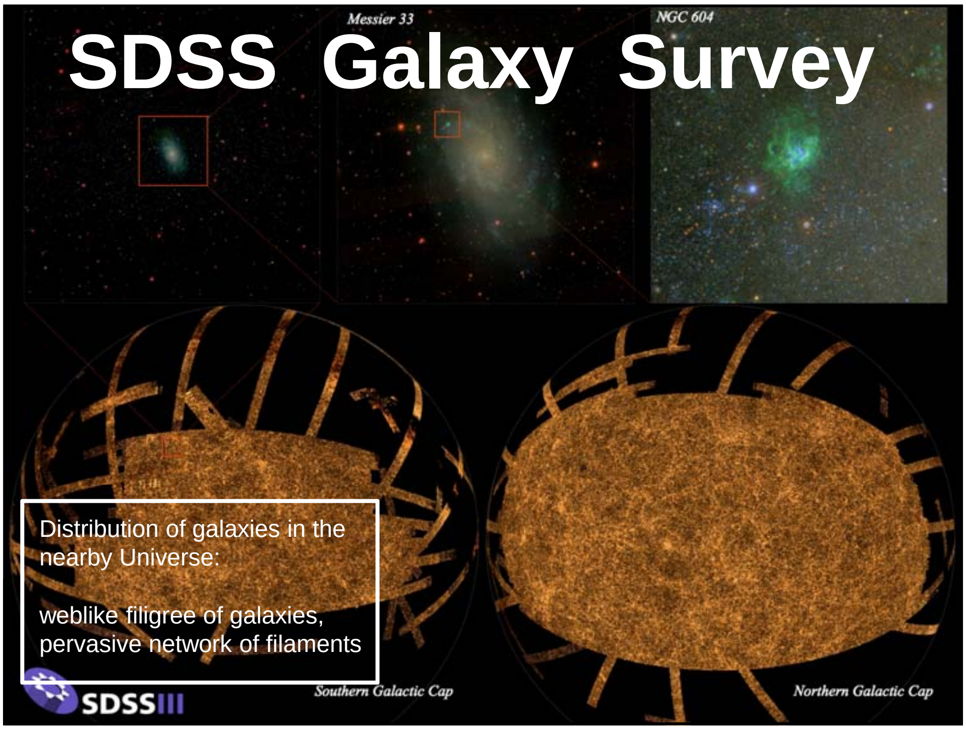

SDSS survey
SDSS Data Release 1-7 (2000-2008)
DR7
DR6
DR5
DR4
DR3
DR1+2
DR7
DR6
DR5
DR4
DR1+DR2+DR3
SEGUE or Special Plate
300
120
60
-30
-60
SDSS Legacy Imaging Sky Coverage:
8423 sq. deg.
SDSS Legacy Spectral Sky Coverage:
8032 sq. deg.

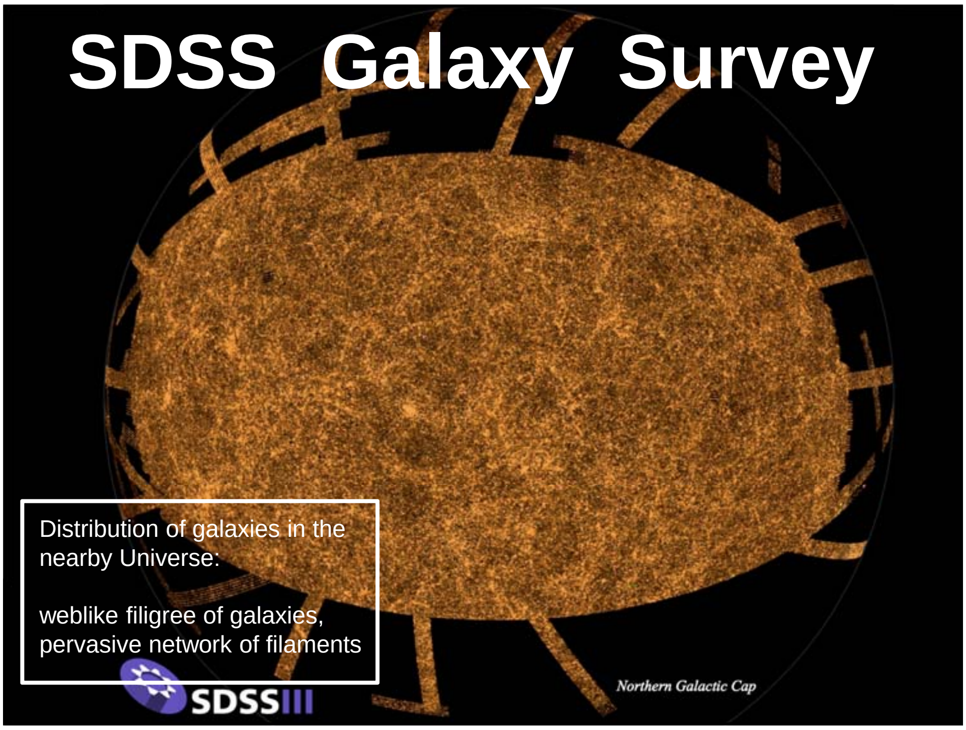


SDSS Galactic region



comparison 2MASS


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


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

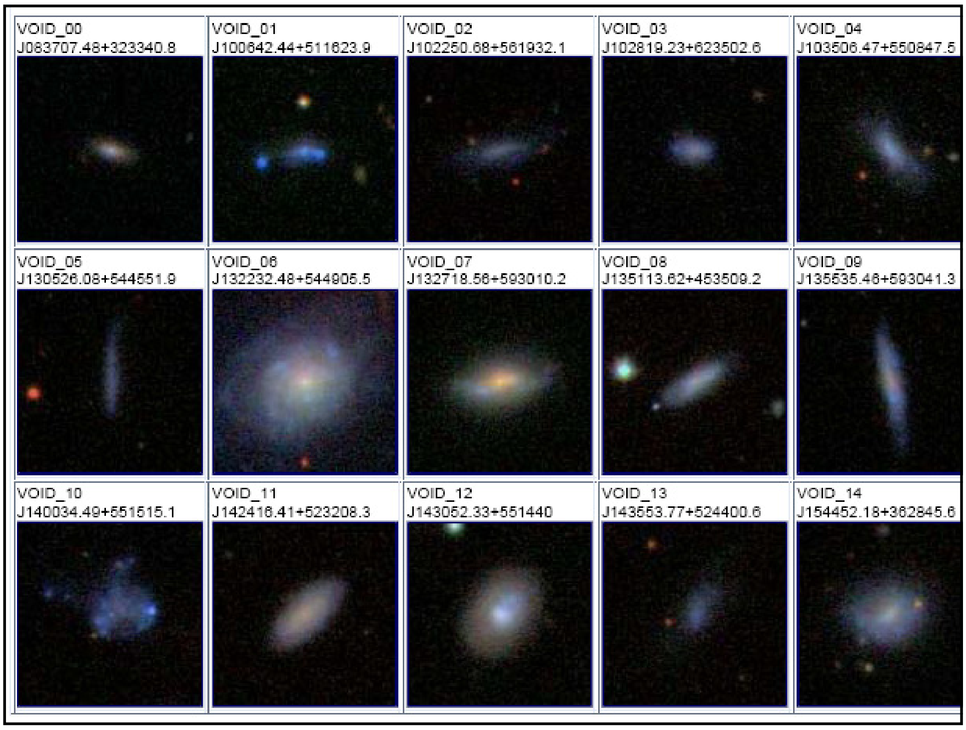
SDSS survey

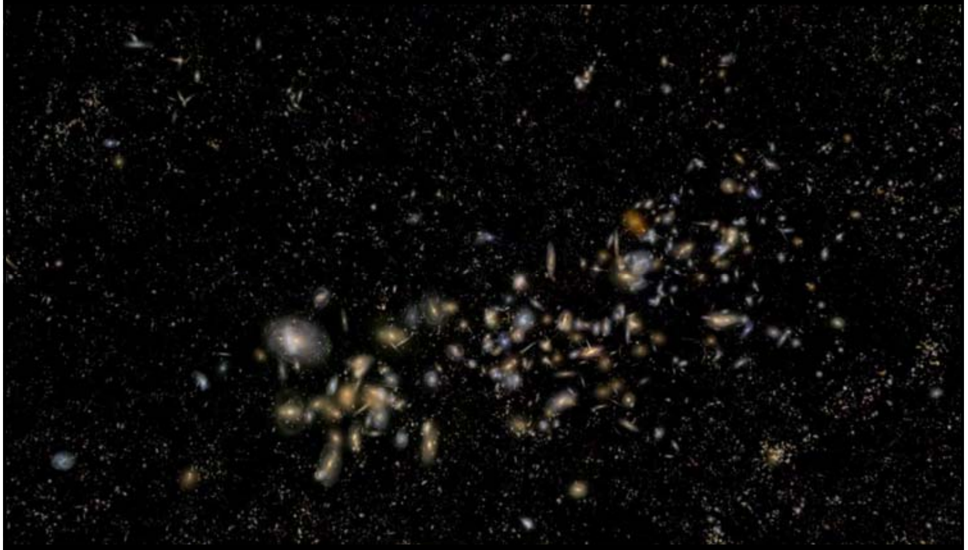
- Imaging:
  230 million objects

- Spectroscopic (Redshift) survey:

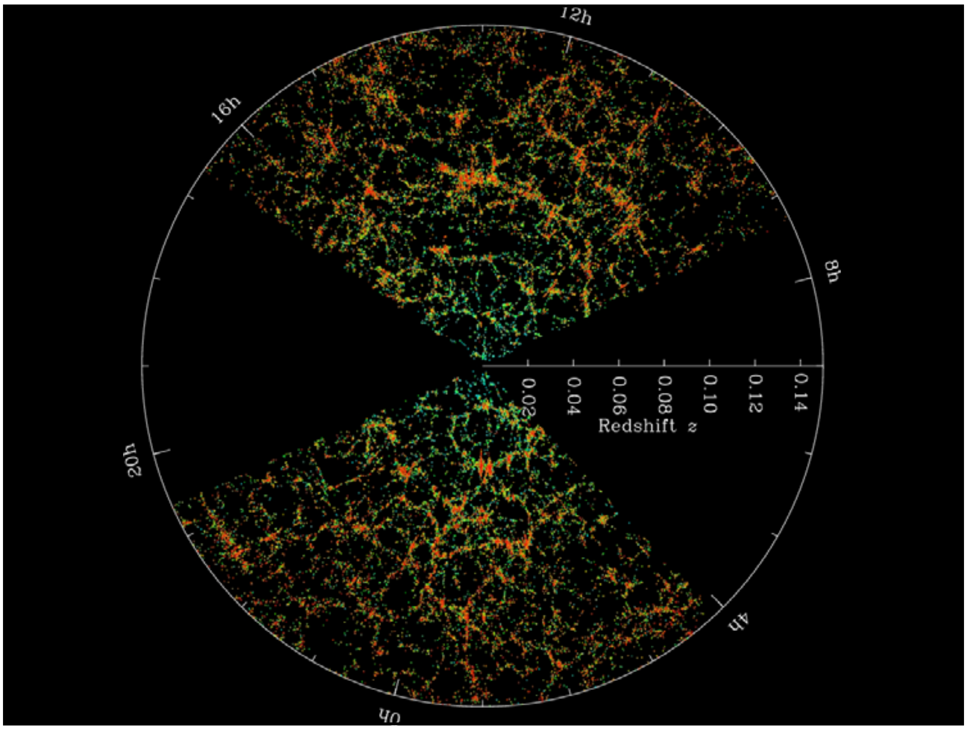
  magnitude limit:
  galaxies: (Petrosian) $r < 17.7$
  quasars $i < 19.1$ / $i < 20.2$ ($z > 2.3$)

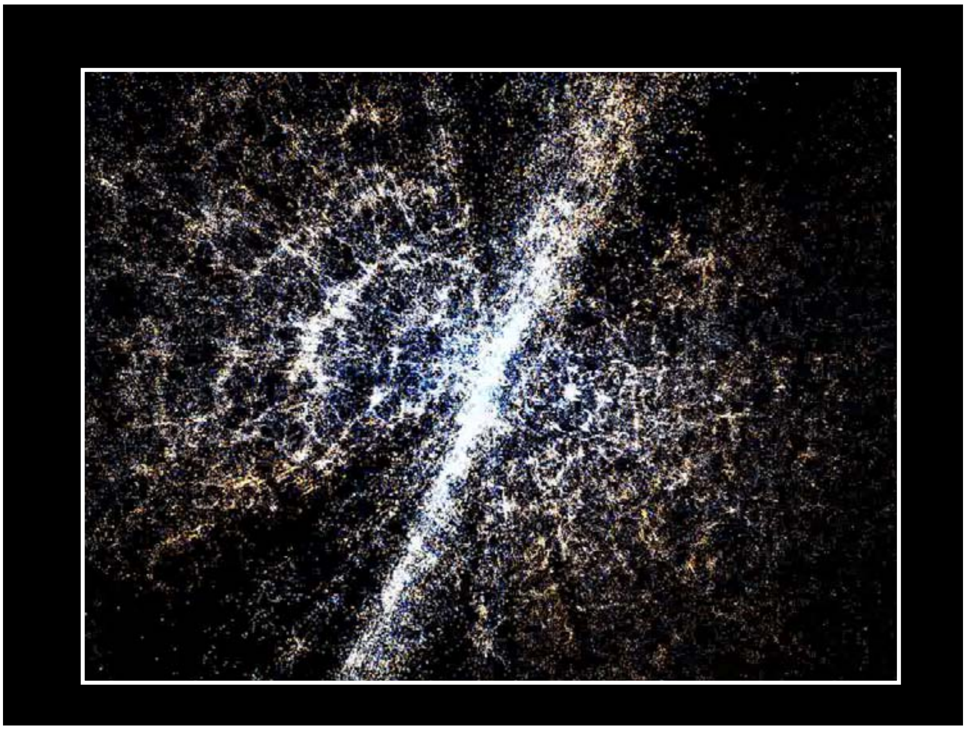
  objects: 928,567 galaxies
  109,862 quasars $z < 2.3$
  8,802 quasars $z > 2.3$





Mapping the Galaxy Distribution





Clusters

Clusters of Galaxies

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

Clusters of Galaxies

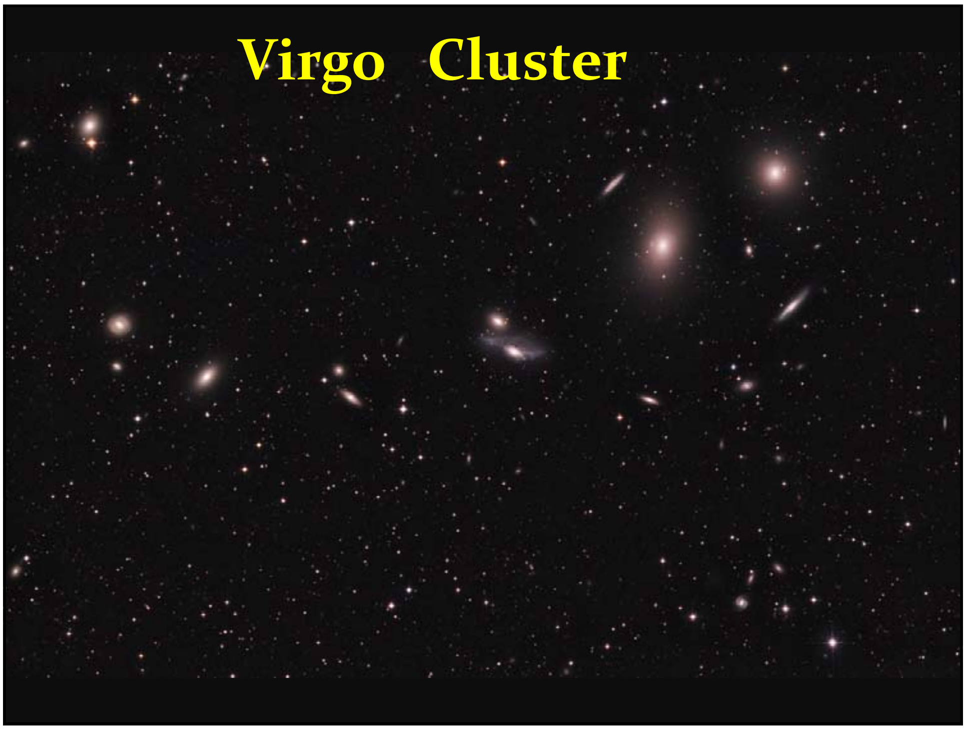
Courtesy:
O. Lopez-Cruz

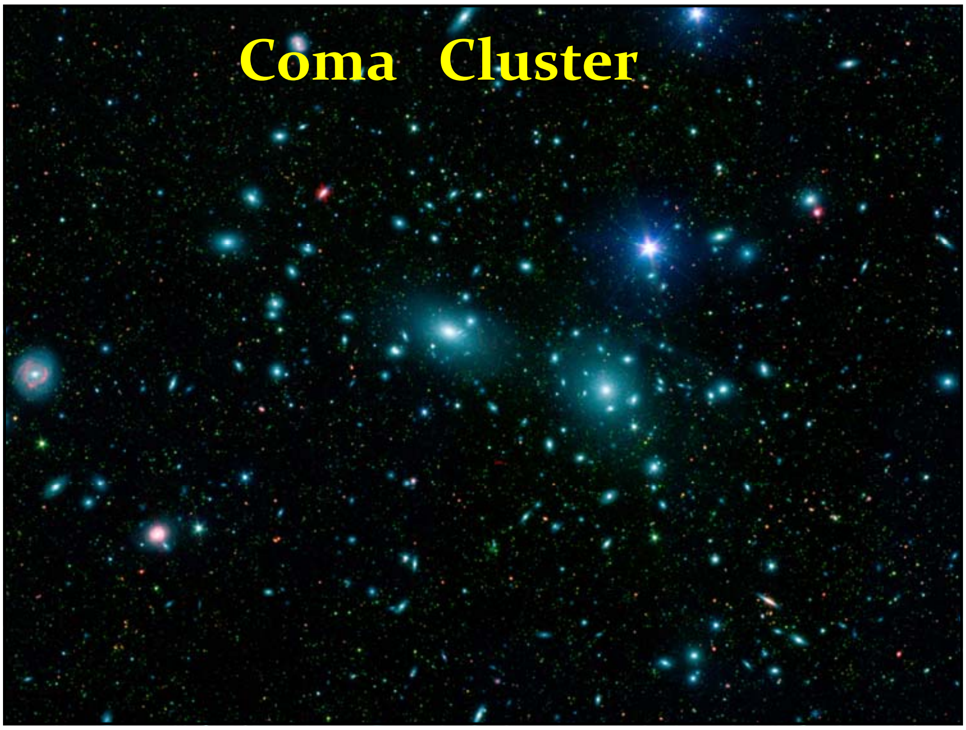
Coma Cluster

Studying Clusters

Includes many different aspects of these versatile astrophysical laboratories:

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


Virgo Cluster


Coma Cluster

Clusters of Galaxies

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

I. Clusters are Halos of Dark Matter:

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

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

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

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

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

Clusters of Galaxies: X-ray intracluster gas

Baryonic matter in clusters is not only confined to galaxies:

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

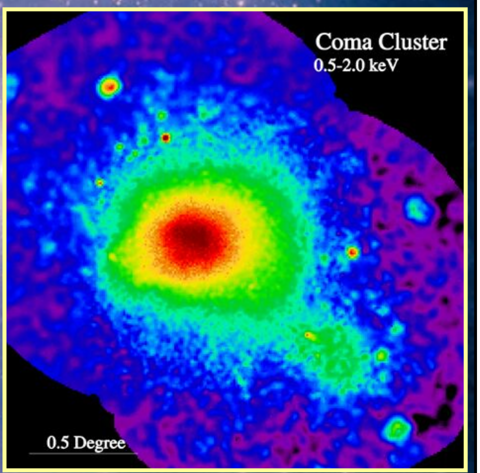
Intracluster Gas,

trapped and heated to a temperature of the order of

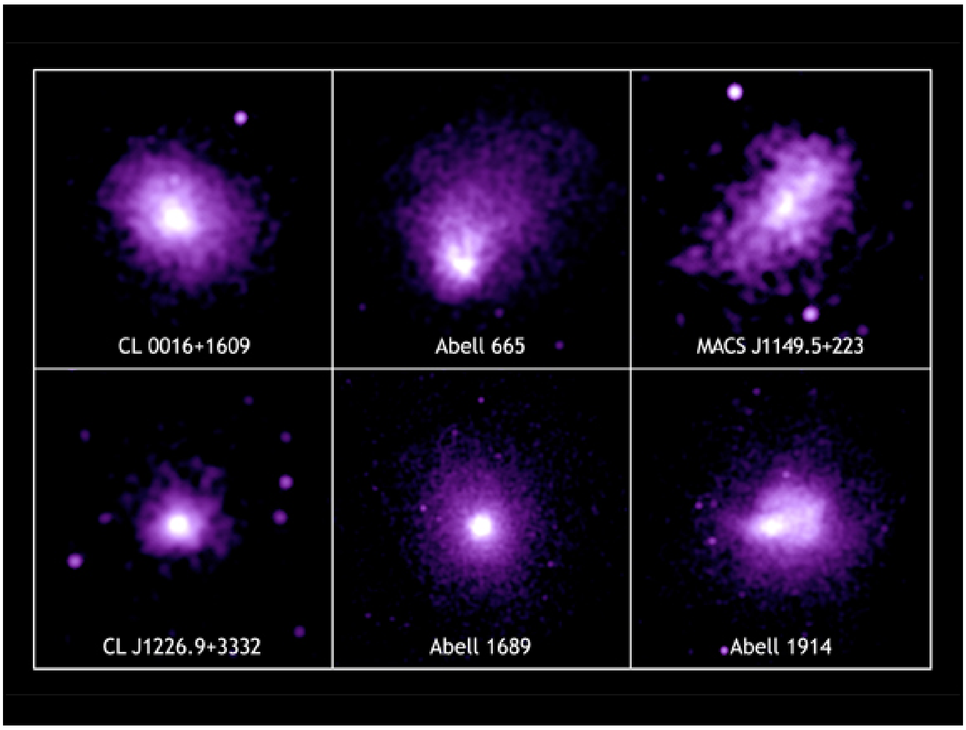
$T \sim 10^8$ K

by the gravitational potential of the cluster.

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



ROSAT X-ray image Coma Cluster



Cluster Mass: X-ray intracluster gas

Hydrostatic Equilibrium:

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

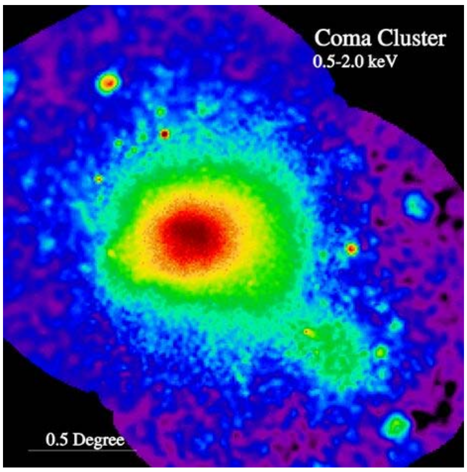
Determination Mass from X-ray observations:

-assumption:

Isothermal: $T(r)=T_o$

-density profile:

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



ROSAT X-ray image Coma Cluster

Clusters of Galaxies: Gravitational Lenses

A highly promising method to determine the amount and distribution of

matter in the Universe

looks at the way it affects

the trajectories of photons

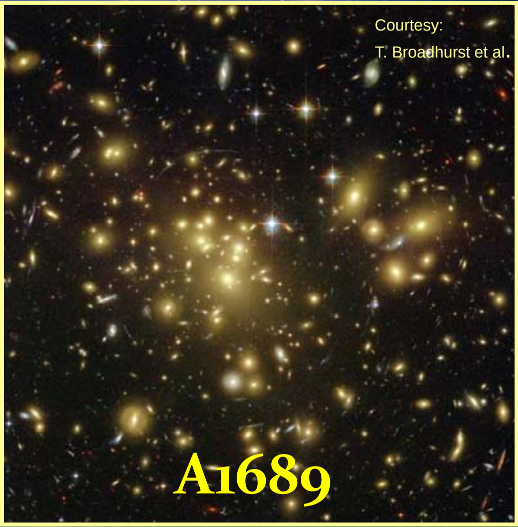
According to

Einstein's theory of

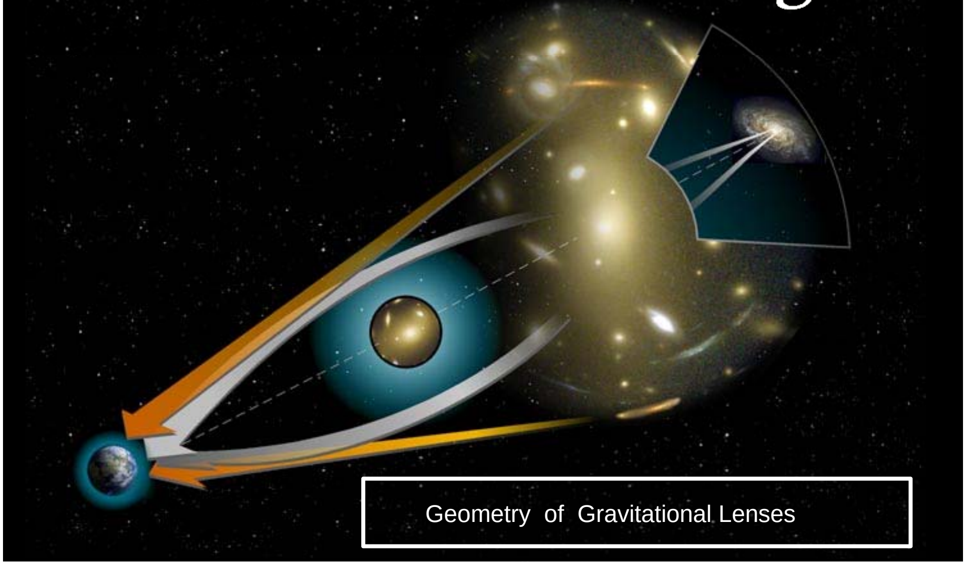
General Relativity,

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

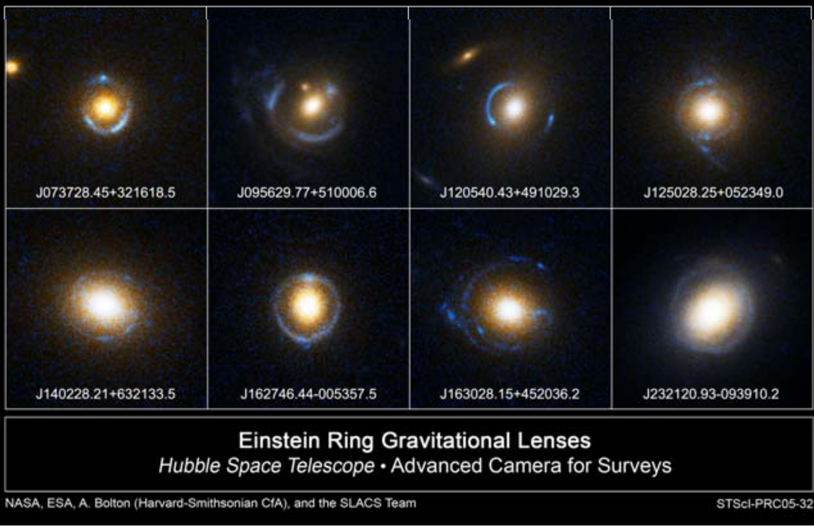
Gravitational Lens



Clusters: Gravitational Lensing



Gravitational Lensing: Einstein Ring

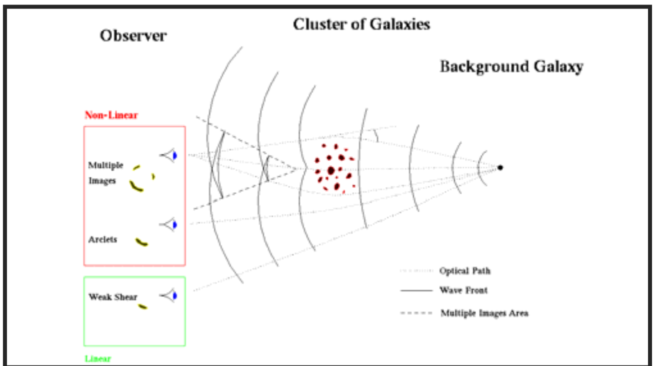


Gravitational Telescopes: Weak vs. Strong Lensing

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

Two kinds of lensing:

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

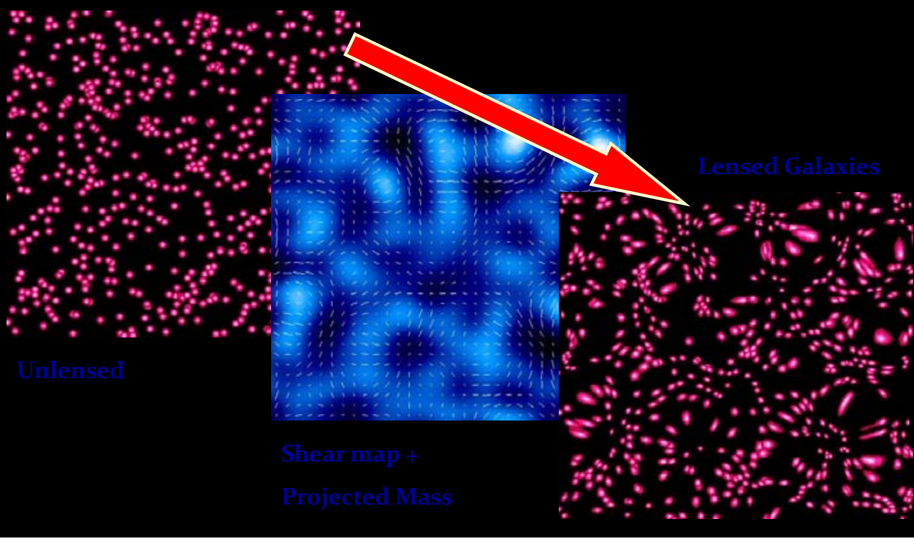


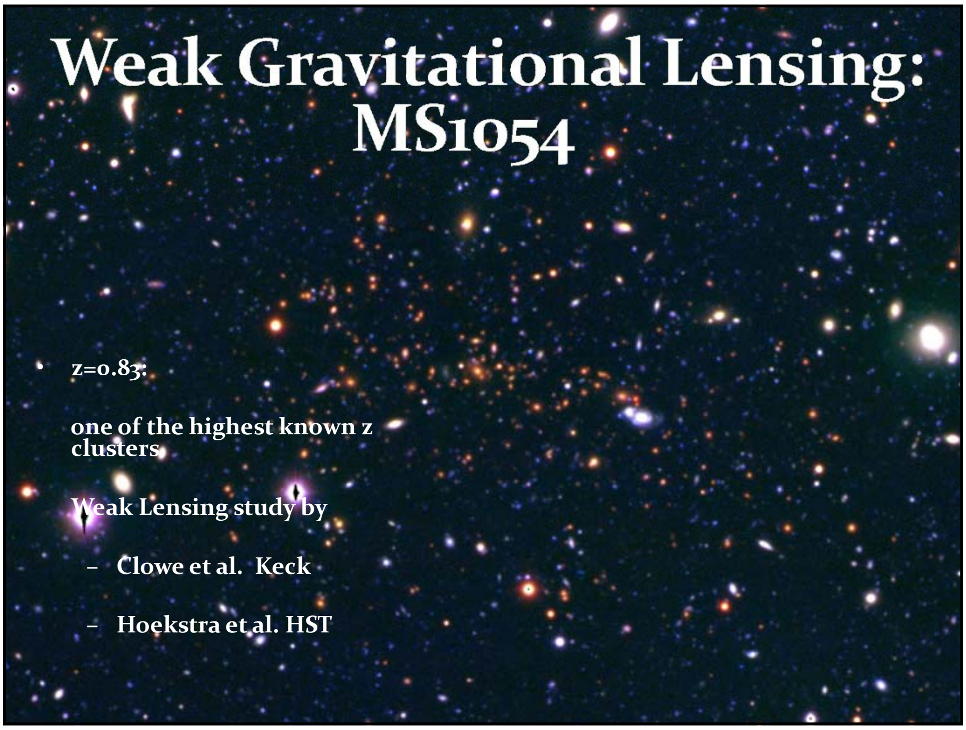
Cluster Mass determination:

Weak Lensing: Linear Inversion Distortion Field

Strong Lensing: Complex Modeling density distribution. non-trivial

Weak Gravitational Lensing





Clusters of Galaxies: Dark Matter Map

A highly promising method to determine the amount and distribution of

matter in the Universe

looks at the way it affects

the trajectories of photons.

According to

Einstein's theory of

General Relativity,

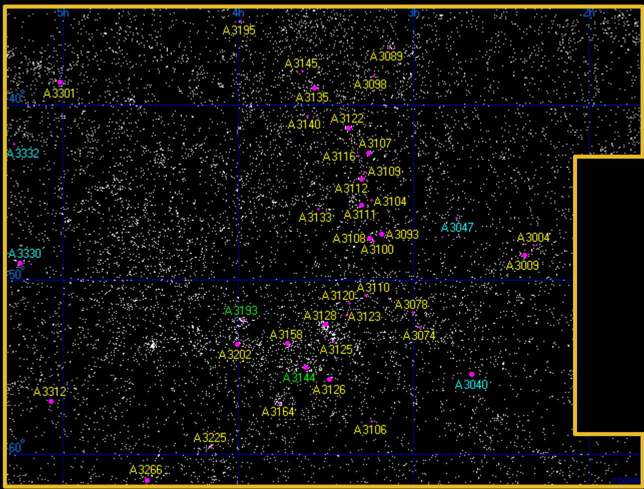
gravitational potential wells will bend and focus light. Dark matter concentrations act as a

Gravitational Lens.

Superclusters

Superclusters

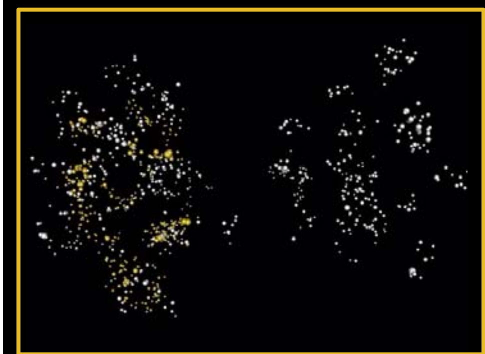
Large groups of clusters & galaxies (1-dozens)



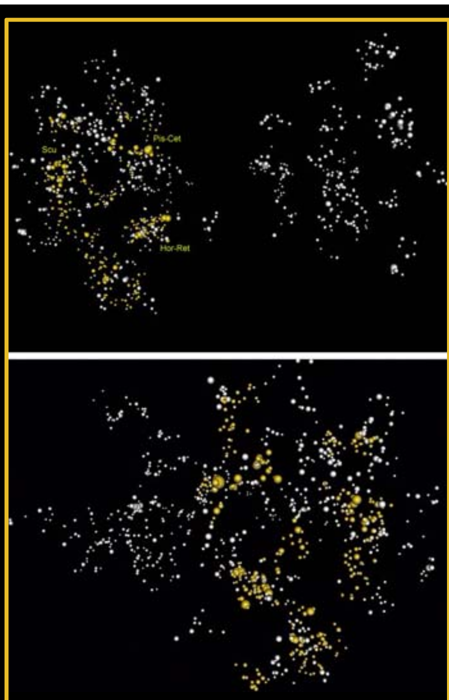
$M \sim 10^{15}$-$10^{16}\ M_{\odot}$
$L \sim$ few-100 Mpc
irregular shaped
mild overdensity Δ~few

Superclusters:

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

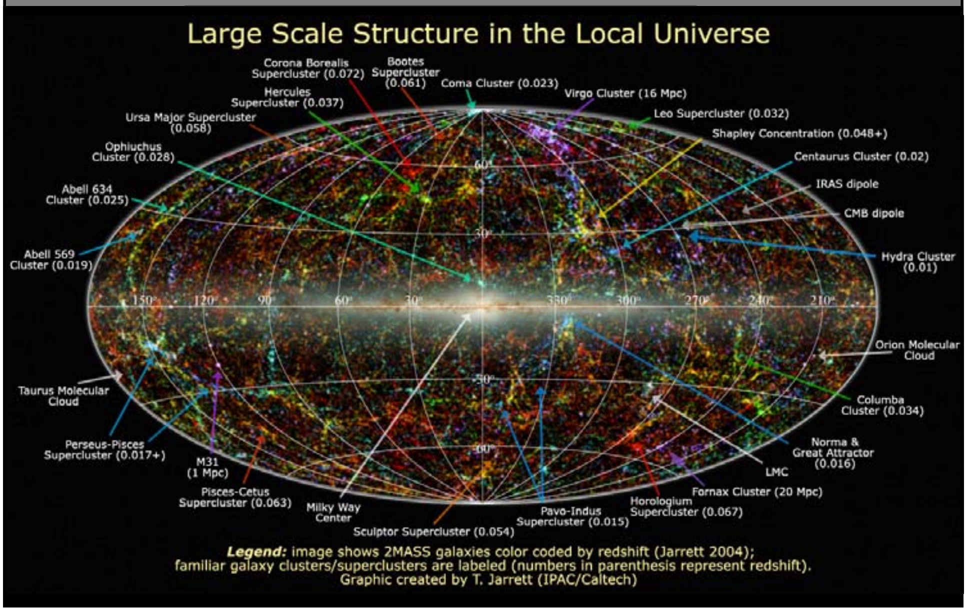


superclusters are not isolated single objects,
but integral components in the pervasive
Cosmic Web




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

Cosmic Web


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

Voids

Nature Vol. 300 2 December 1982 **407**

REVIEW ARTICLE

Giant voids in the Universe

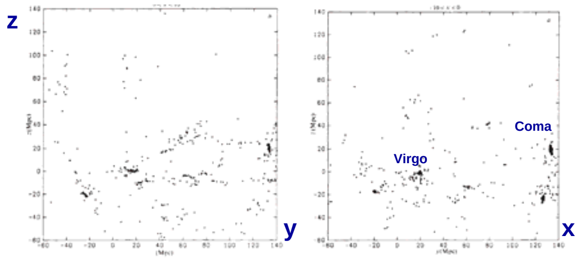
Ya. B. Zeldovich*, J. Einasto†‡ & S. F. Shandarin*

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

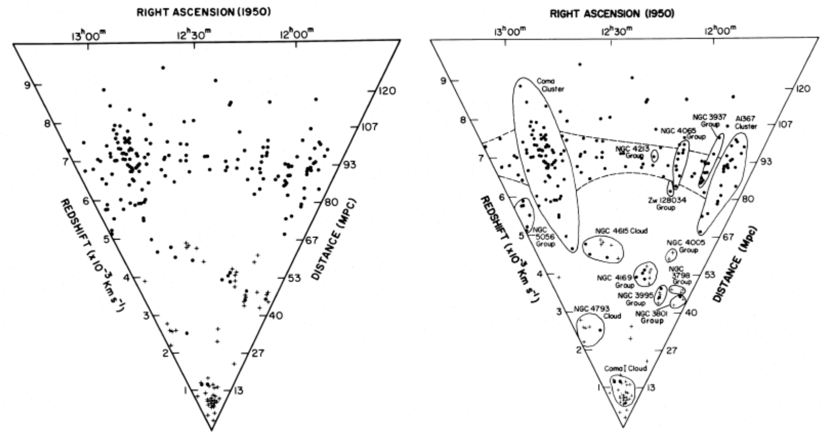
Recent observations indicate that most galaxies are concentrated in superclusters consisting of galaxies, and clusters of galaxies, aligned along strings. Giant volumes exist between superclusters which are almost empty of visible objects. Theories of galaxy formation predict the formation of non-spherical superclusters and giant voids. Large-scale structure changes very slowly, so the currently observed structure reflects the whole history of galaxy formation and structural evolution.

Zeldovich, Einasto & Shandarin 1982:

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



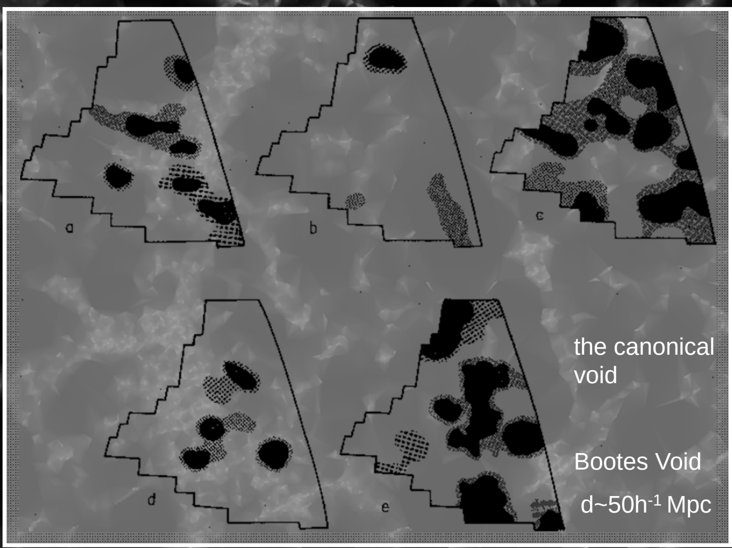
First Voids



Gregory & Thompson 1978:
redshift survey of Coma/A1367 supercluster region revealed existence of large near-empty regions of space.

Bootes Void

Kirshner, Oemler, Schectman, Schechter (KOSS) 1981, 1987

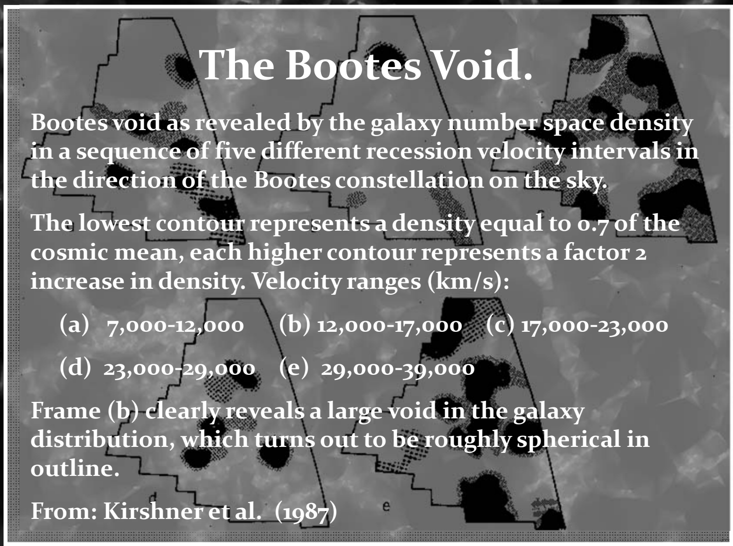


the canonical void

Bootes Void

d~50h^{-1} Mpc

Bootes Void



The Bootes Void.

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

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

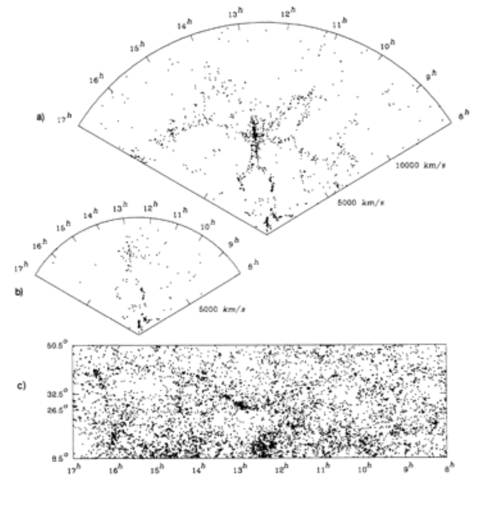
(a) 7,000-12,000 (b) 12,000-17,000 (c) 17,000-23,000

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

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

From: Kirshner et al. (1987)

Voids & the Cosmic Web

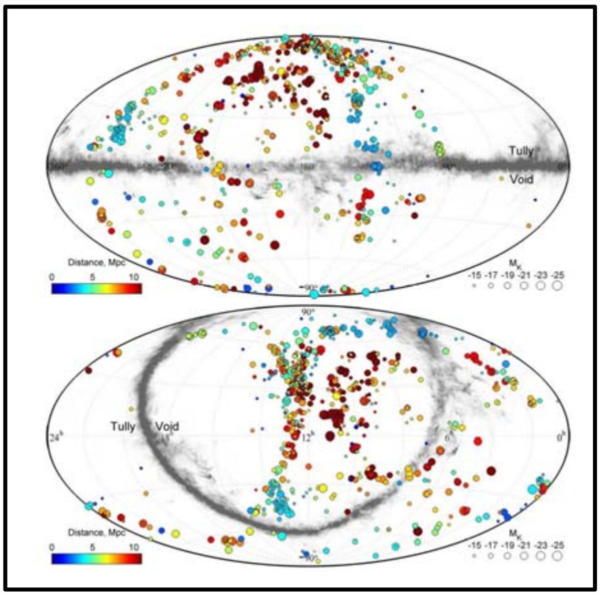


deLapparent, Geller & Huchra, 1986:

"a slice of the Universe"

Voids appear to be an integral part of a complex weblike arrangement of galaxies

local Cosmic Web: Local Void



Karachentsev etal.

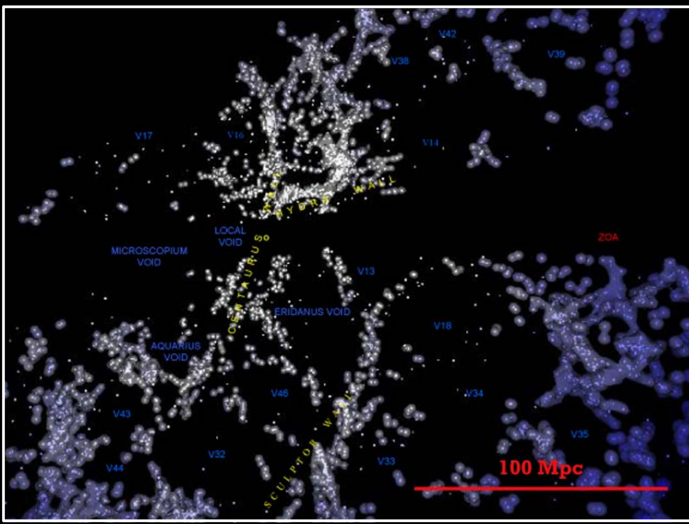
LV catalog:
galaxies within 10 Mpc reveal
beautifully the magnificent

Local Void – Tully Void

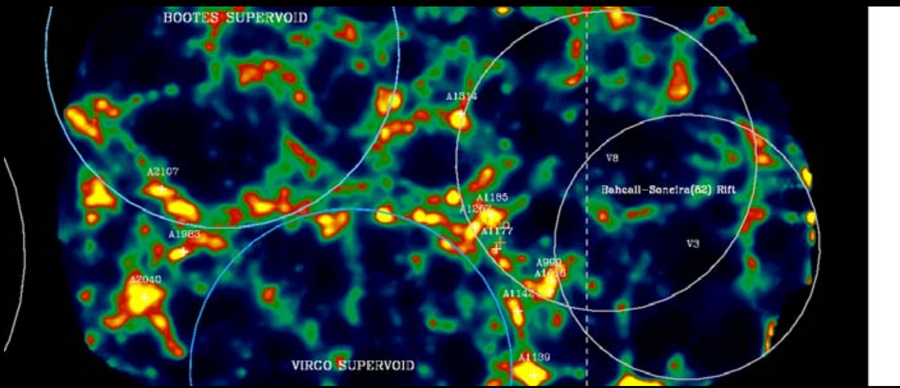
Fairall Void Catalogue

6dF based
catalogue

of 526
visually identified
voids.

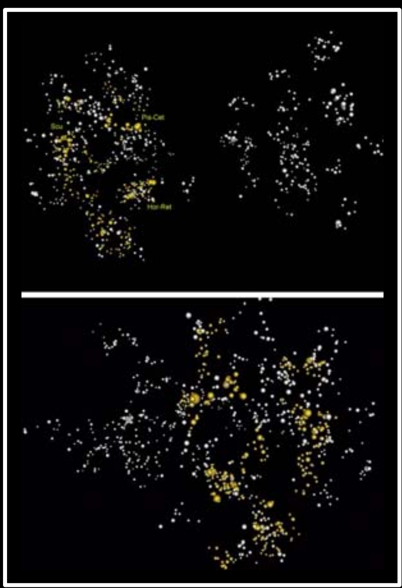


Bootes Void: Substructure



Platen et al. 2009

Voids & Clusters



Einasto, Saar et al. (1990s)

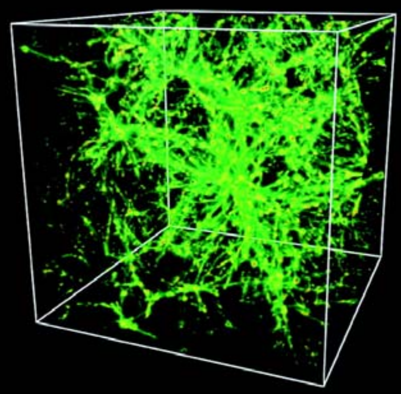
- Superclustering in Abell/APM clusters catalog

- Finding of characteristic scale ~140 Mpc, corresponding to large voids in the cluster distribution

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

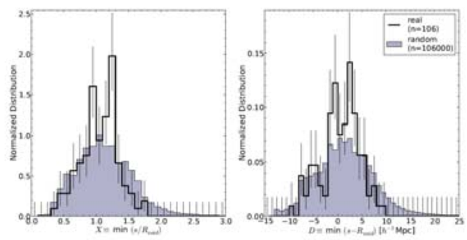
(see talk by Collins).

Voids & the Gaseous Web

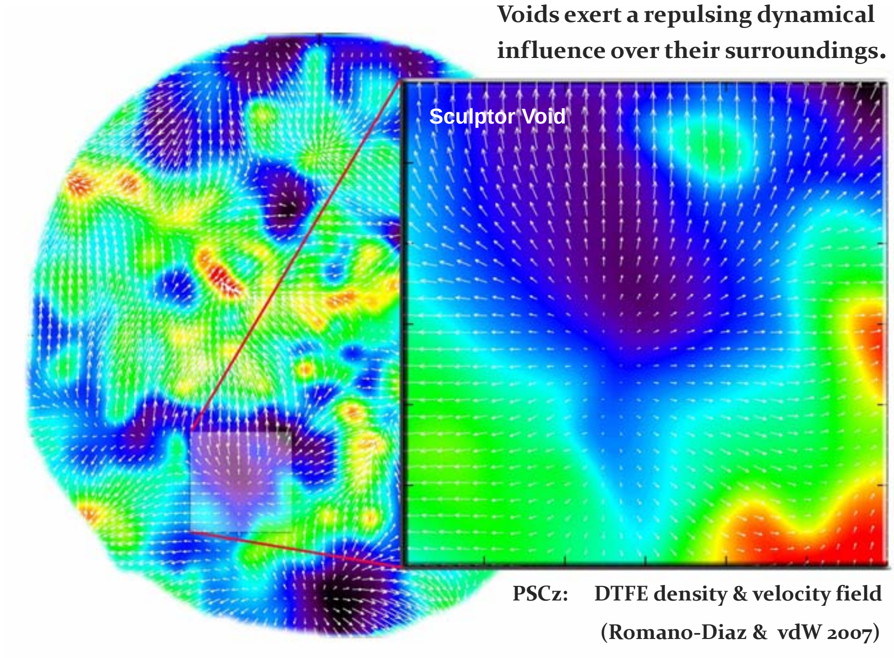


Tejos et al. 2012:

HI Lyα absorption systems clearly delineate voids

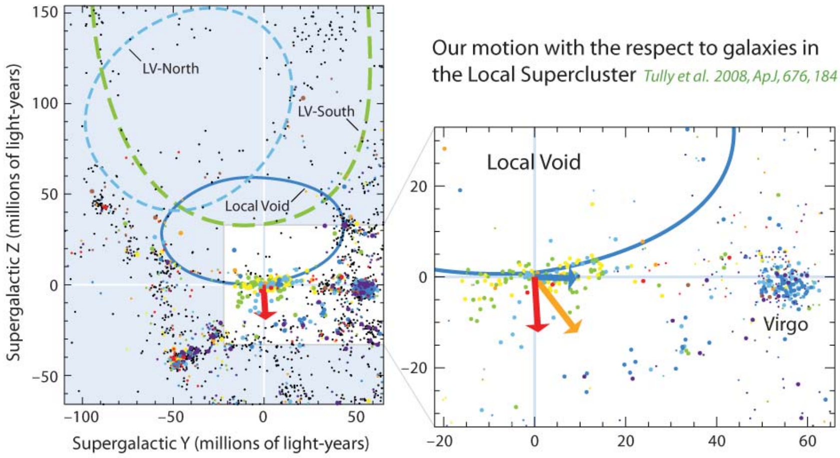


Voids exert a repulsing dynamical influence over their surroundings.



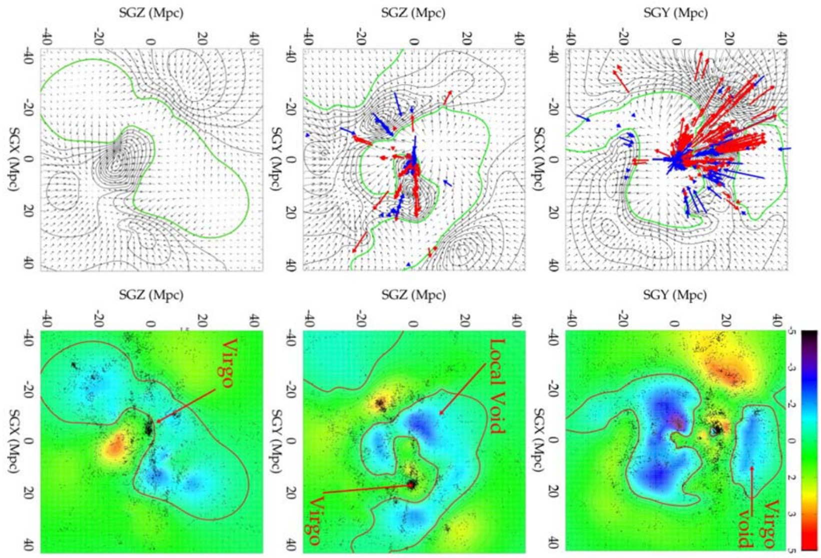
PSCz: DTFE density & velocity field (Romano-Diaz & vdW 2007)

Push of the Local Void



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

Void Dynamics: Local Void

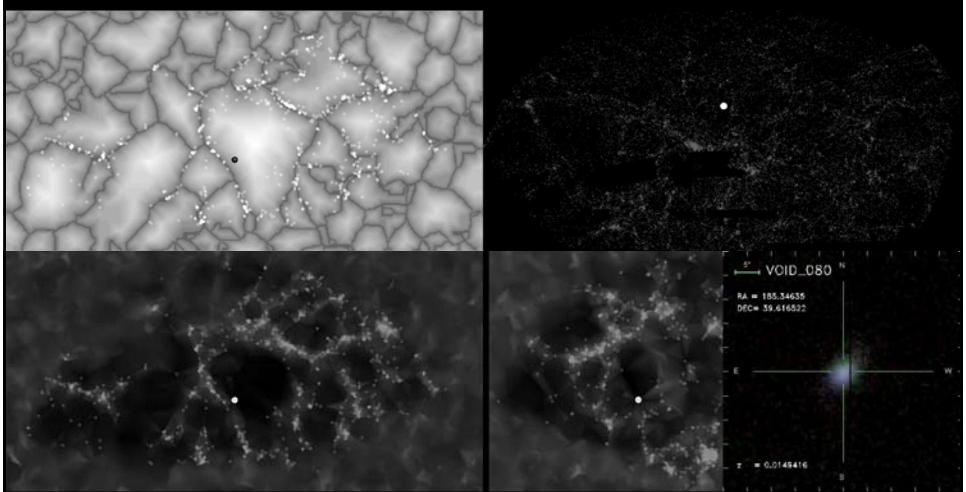


Voids:
Identification & Catalogues

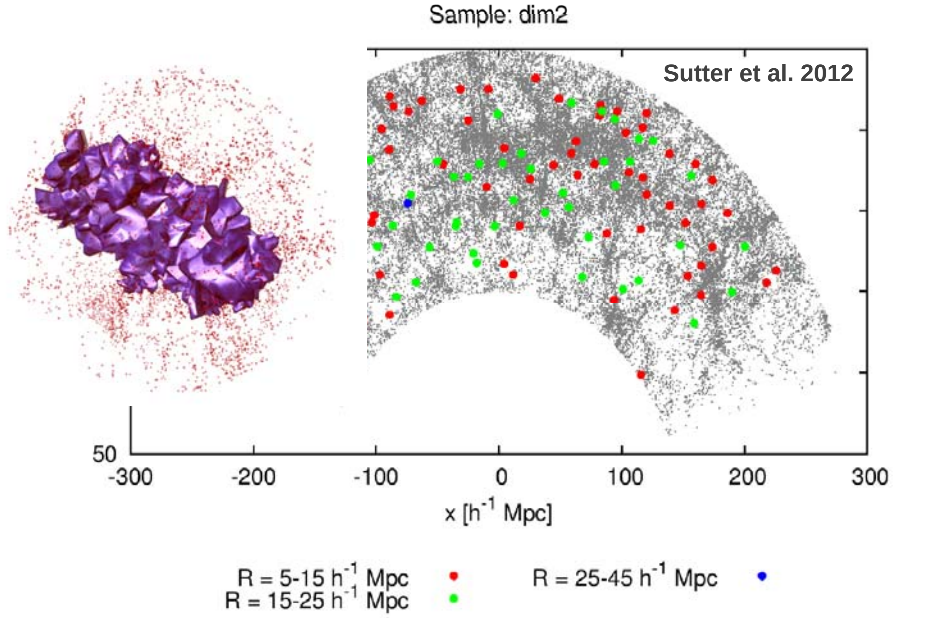
- Voids are not easily defined
  not as cleanly & objectively identifiable objects as clusters
- range of criteria & identifiers,
  often conflicting see Colberg et al. 2008
- increased interest due to cosmological/dark energy
  information contained in voids

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

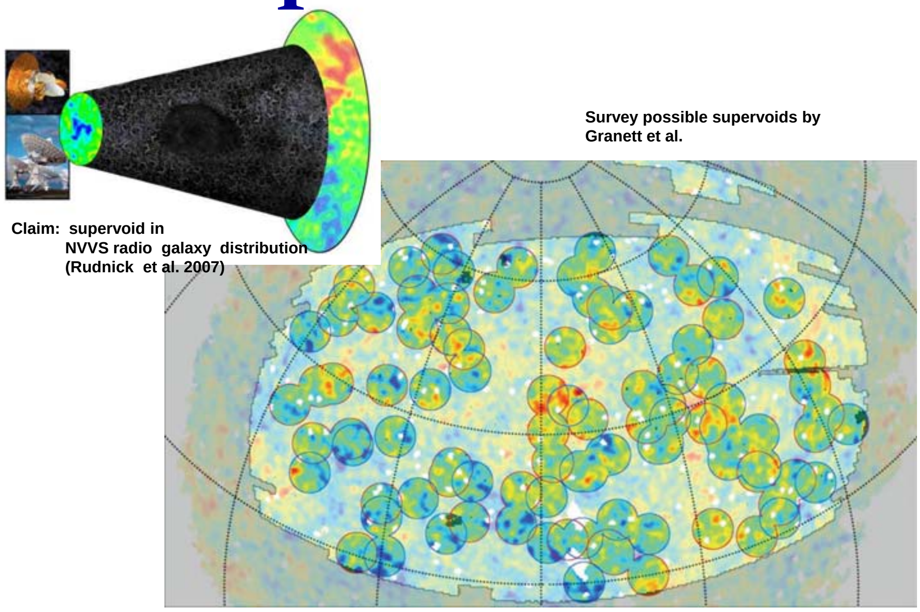
SDSS Voids



SDSS Multiscale Watershed Void Catalog



Supervoids ???

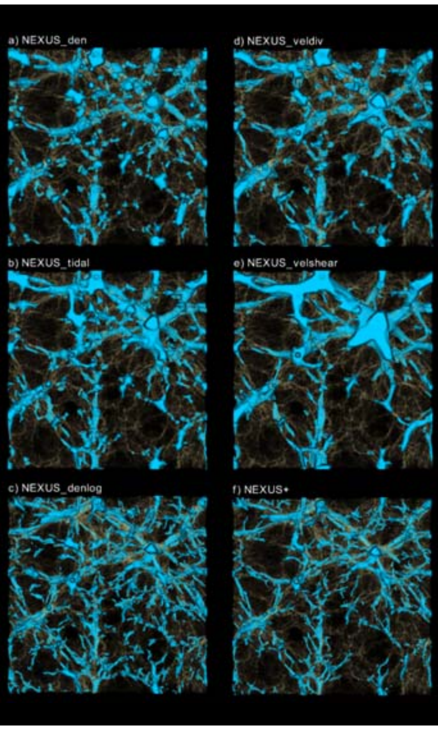


Survey possible supervoids by Granett et al.

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

Filaments

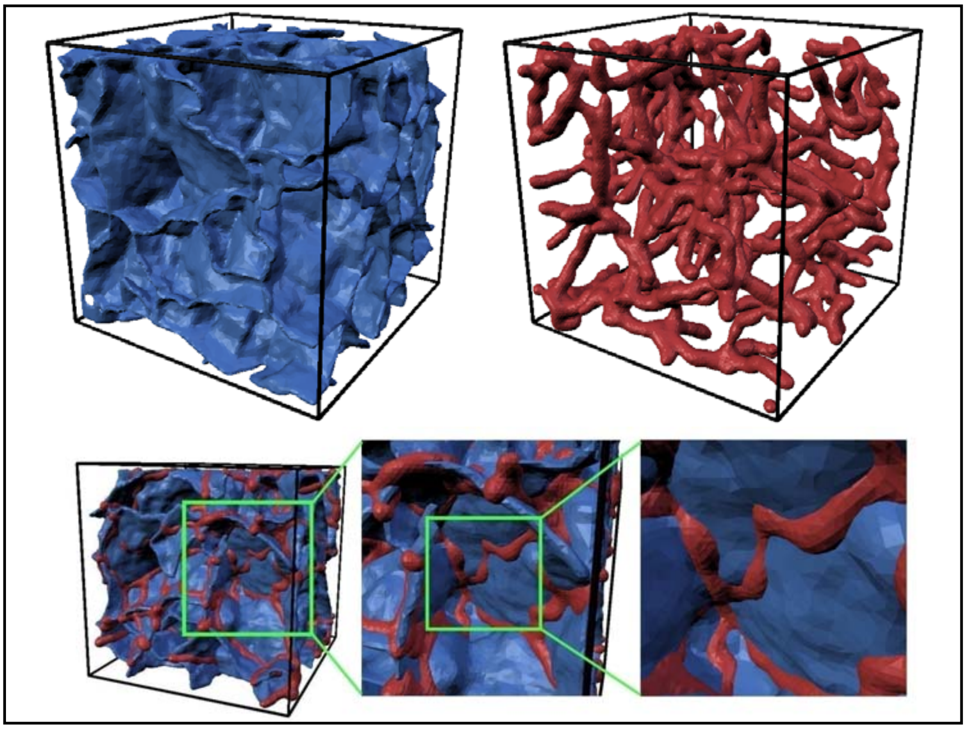
Nexus Filaments



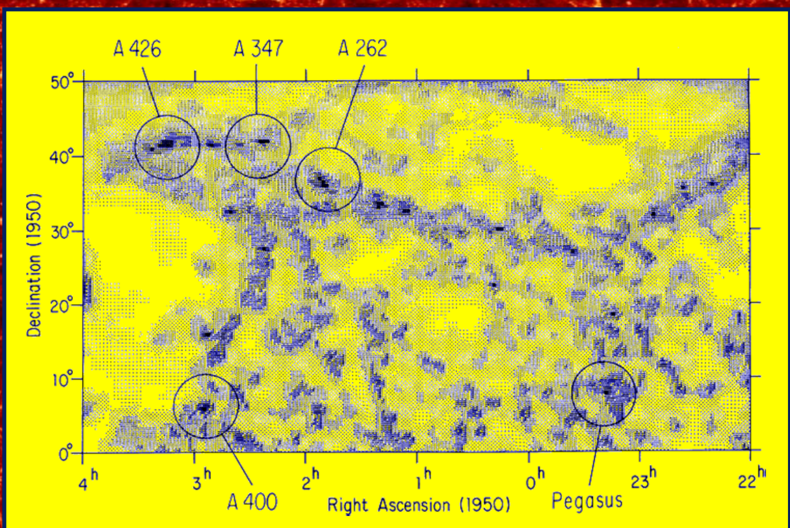
- Nexus identification of filaments (blue)

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

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



Pisces-Perseus Chain



21 cm line redshift survey,
Giovanelli & Haynes

Pisces-Perseus Chain

Canonic example of a strongly flattened supercluster consisting of

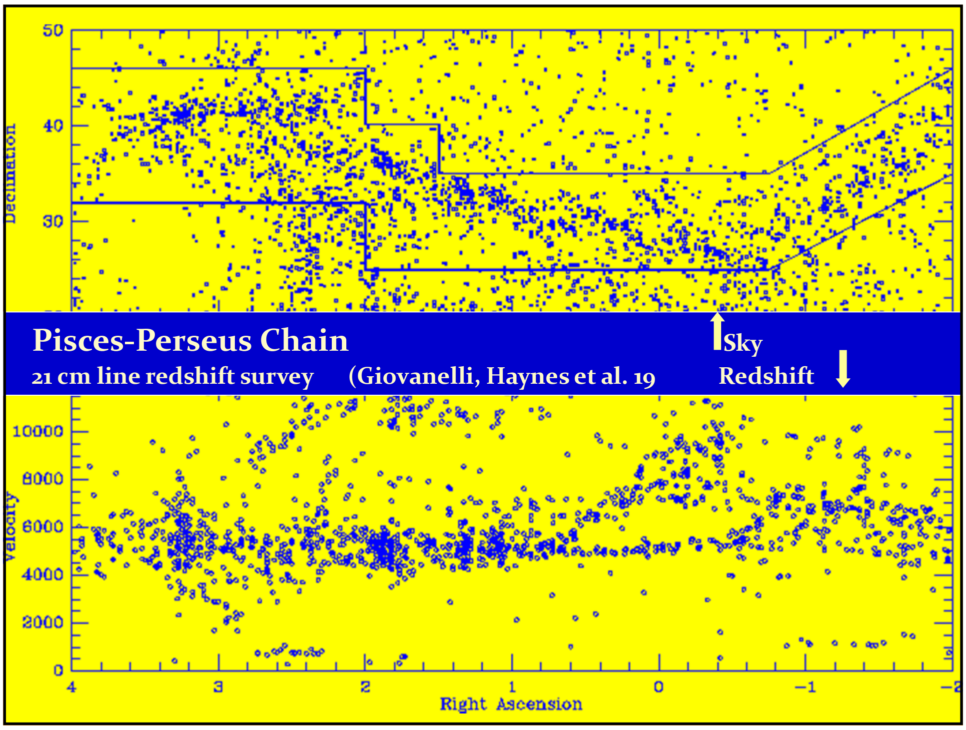
- sheet-like central region, dense filamentary boundary ridge
- Relative proximity (d ~ 55h^{-1} Mpc),
- Characteristic & salient filamentary morphology,
- Favourable orientation.

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

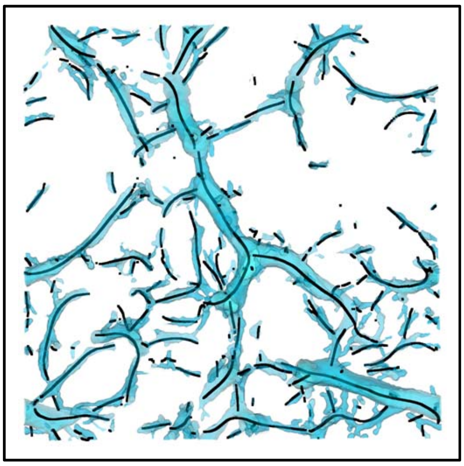
Dimensions Ridge: 5h^{-1} Mpc wide

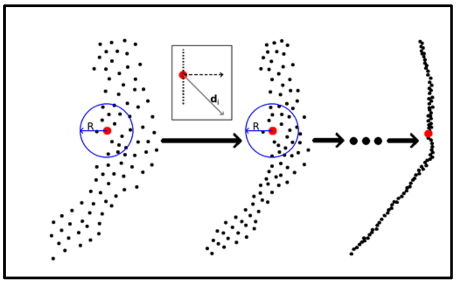
50h^{-1} Mpc length; possible 140h^{-1} Mpc extension

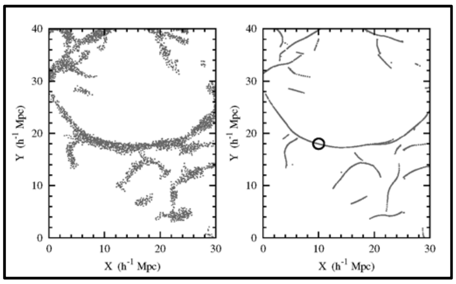
Along Ridge: high density clusters, incl. A462, A347, A262

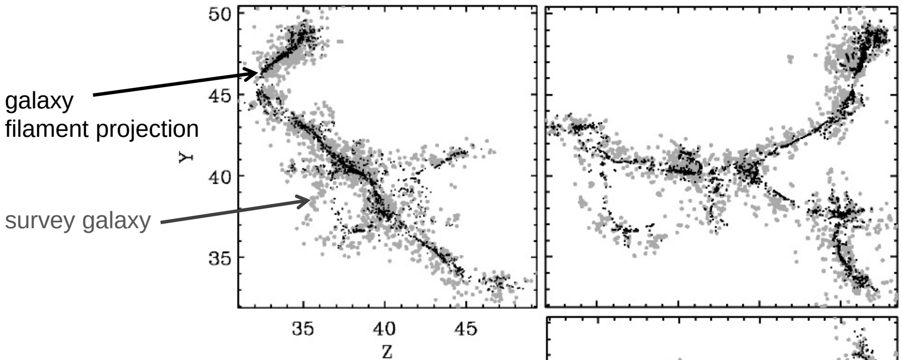


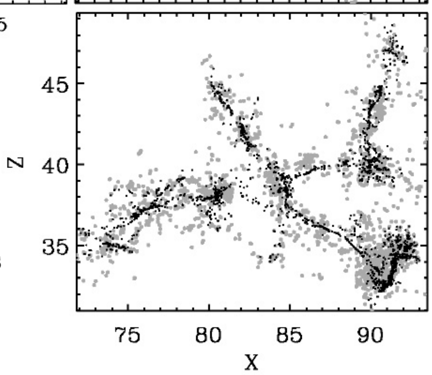
Spine of the Cosmic Web







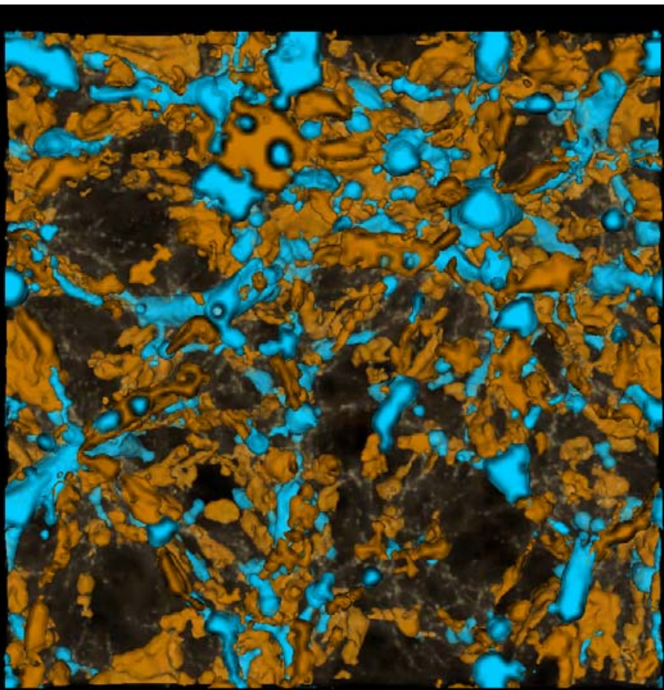




- **Additional Analysis Step:**

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

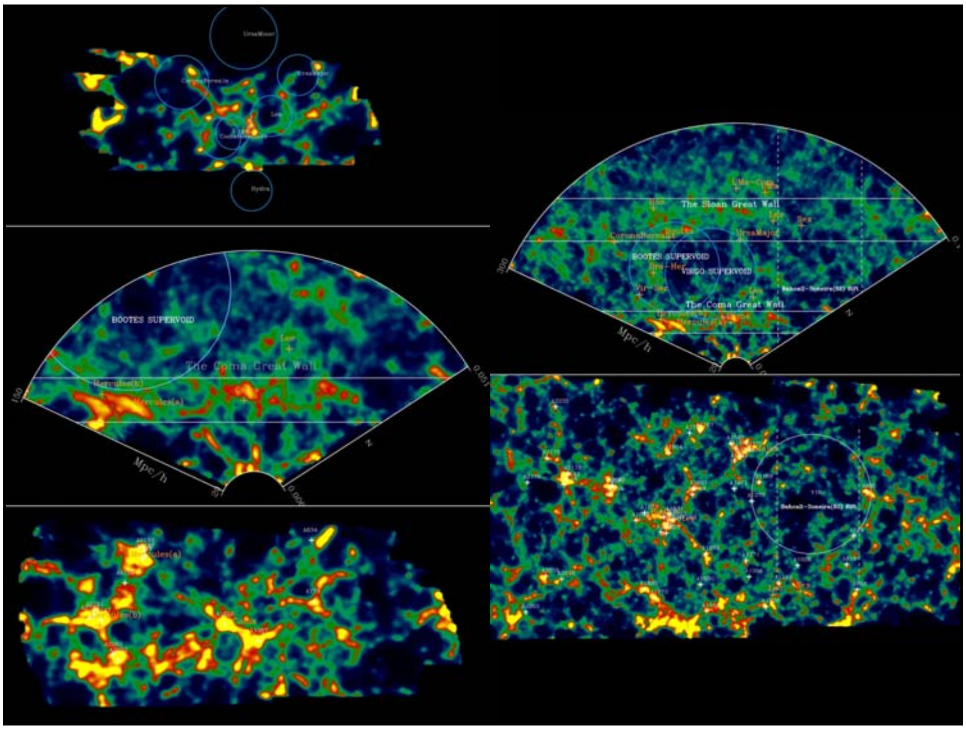
Walls - Sheets

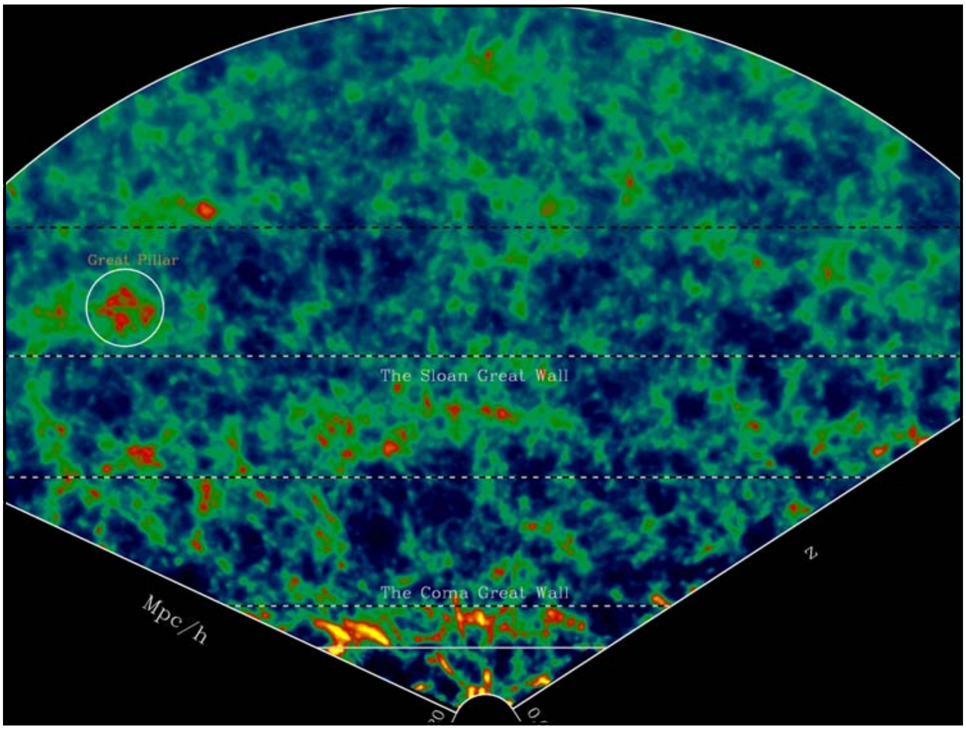


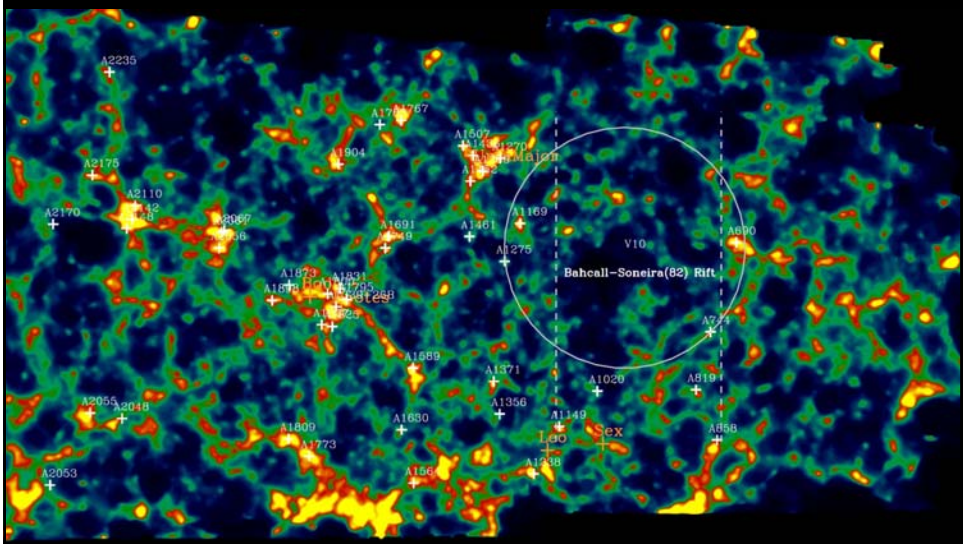
Nexus:

Walls &
Filaments

Cautun et al. 2012

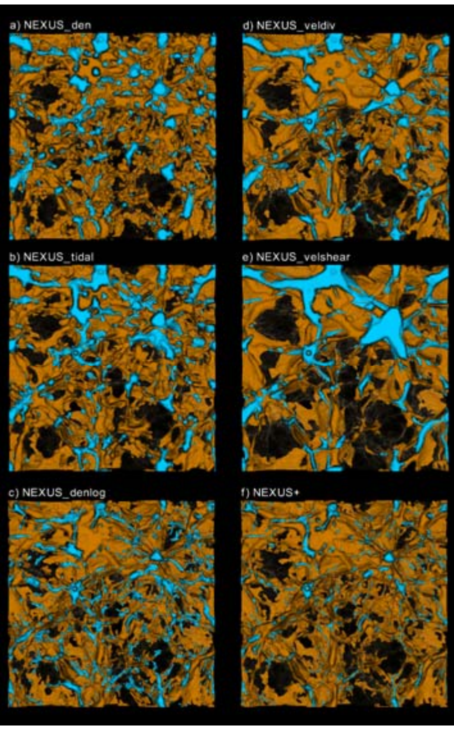

BOOTES SUPERVOID
The Coma Great Wall
Mpc/h
The Sloan Great Wall
VIRGO SUPERVOID
z


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



Sloan Great Wall

Largest Structure
Local Universe
~ 300 x 150 Mpc



Nexus:

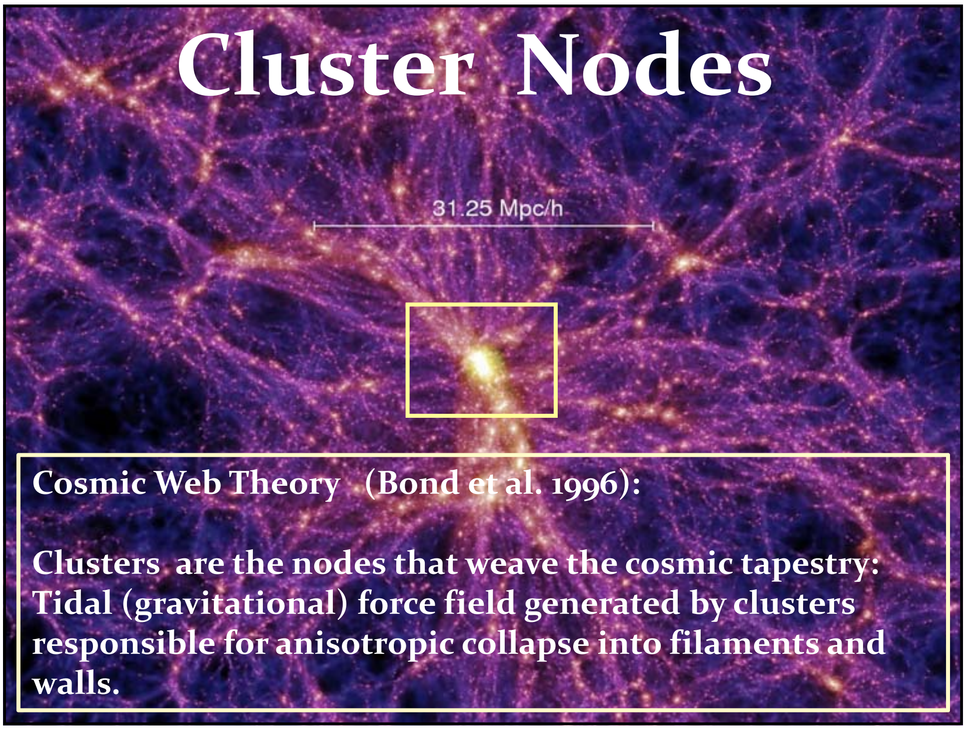
Multiscale Morphology
Identification
Cosmic Web Elements

Walls

Cautun et al. 2012

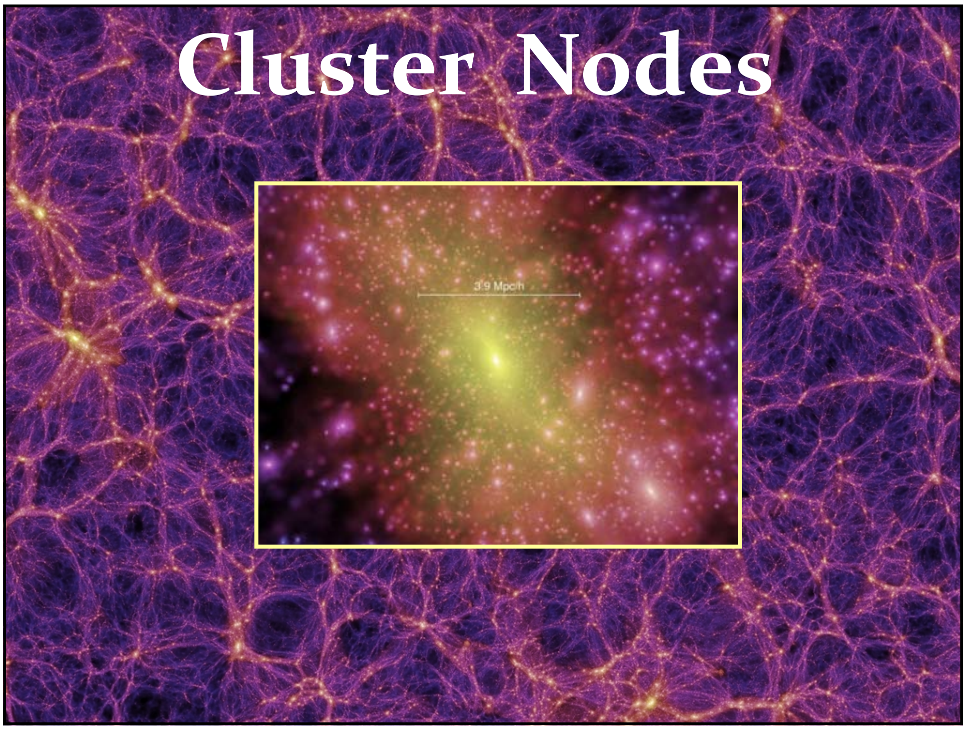
Cluster Nodes

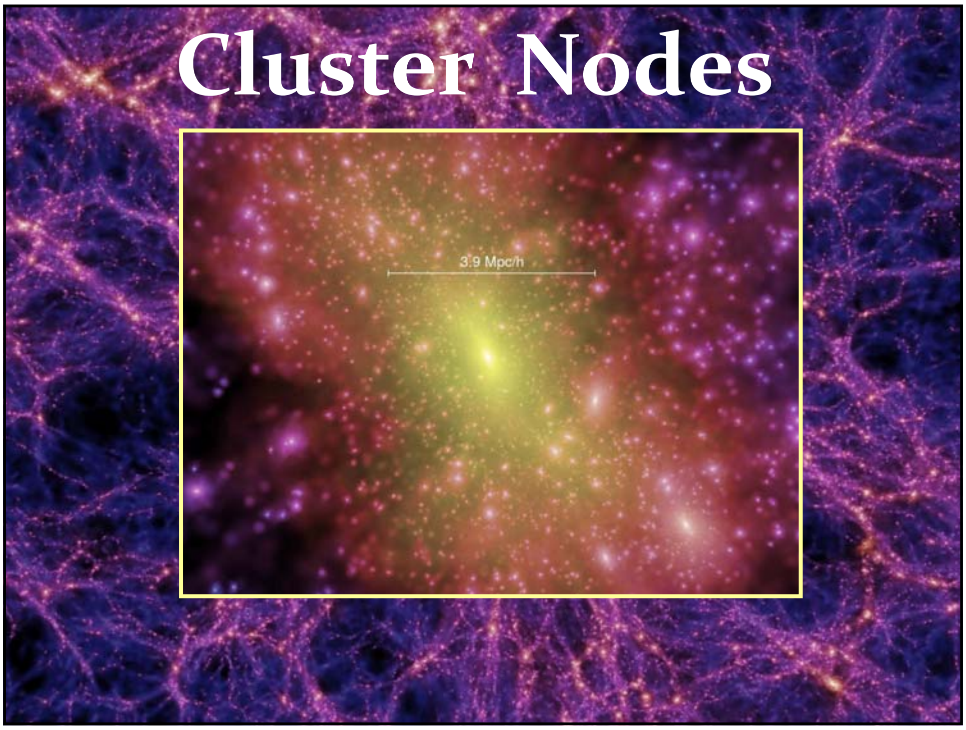
Cluster Nodes



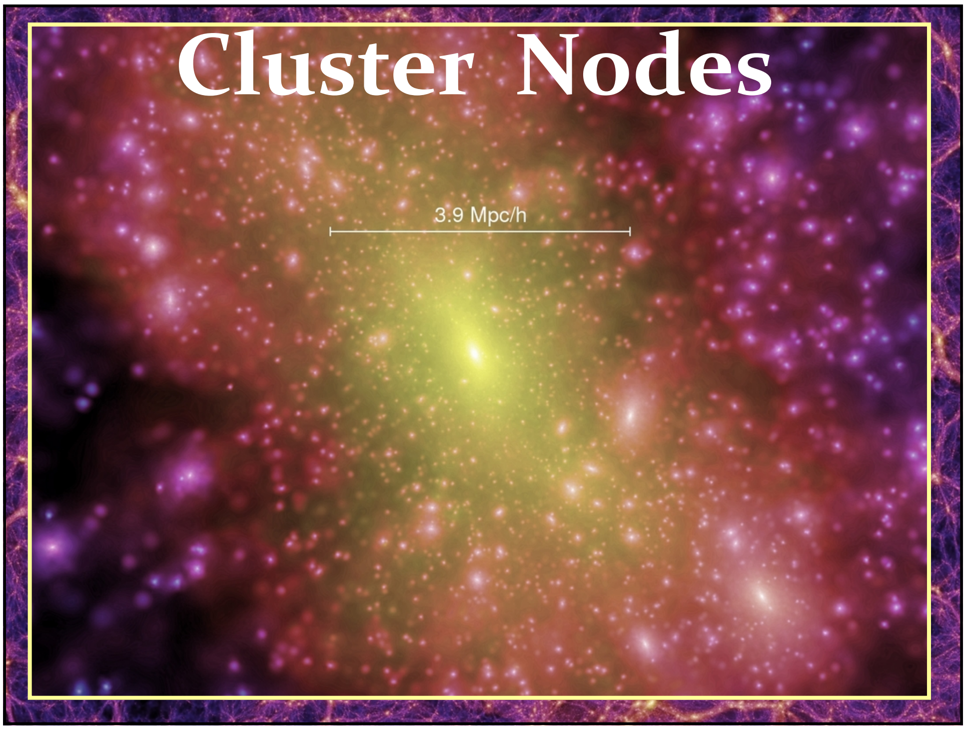
Cosmic Web Theory (Bond et al. 1996):

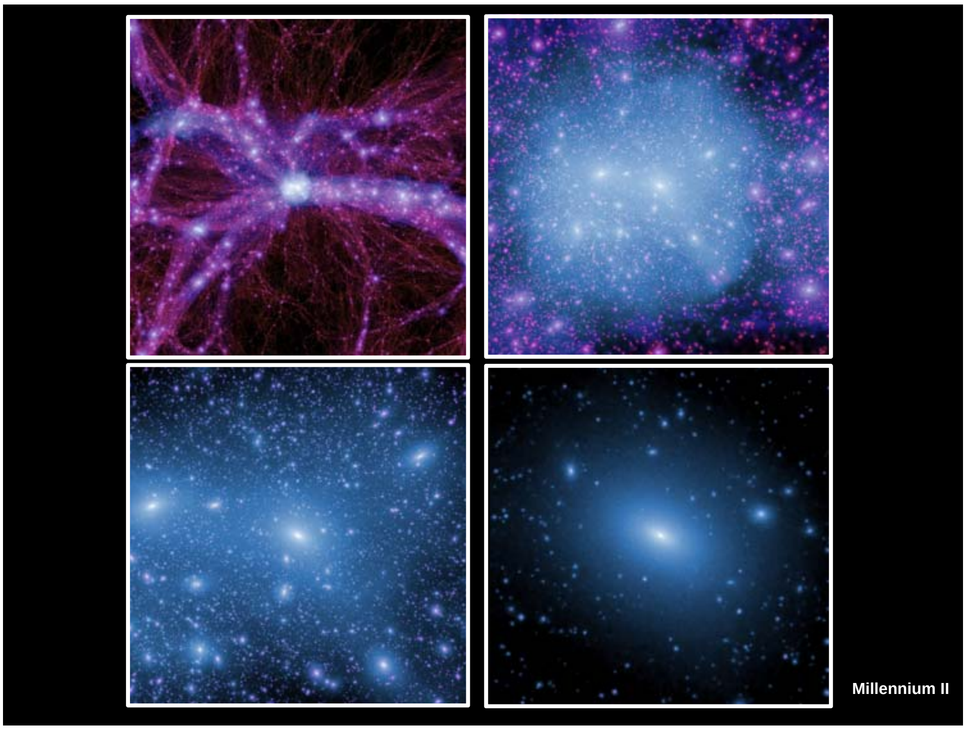
Clusters are the nodes that weave the cosmic tapestry:
Tidal (gravitational) force field generated by clusters responsible for anisotropic collapse into filaments and walls.

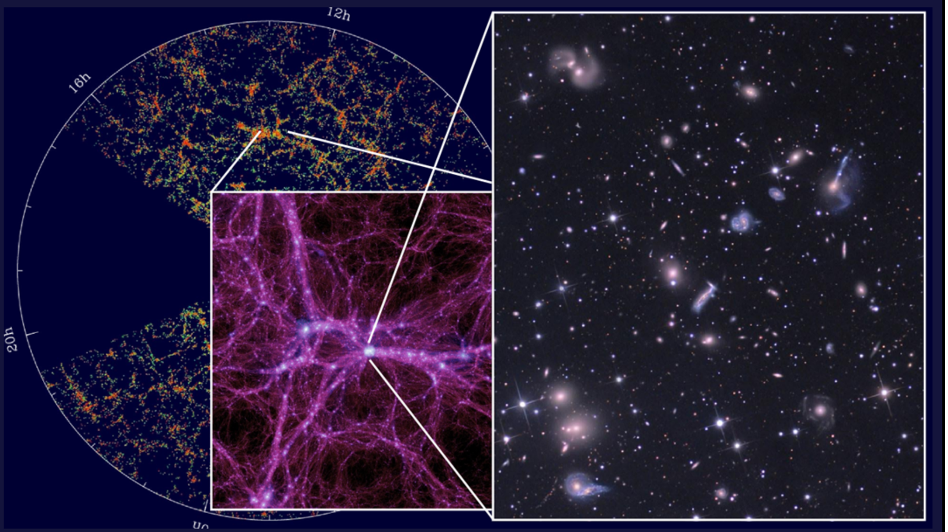

Cluster Nodes
3.9 Mpc/h


Cluster Nodes
3.9 Mpc/h

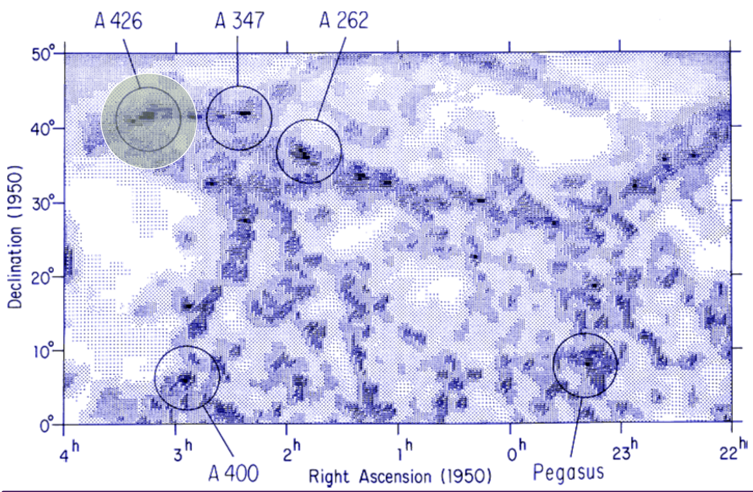
Cluster Nodes





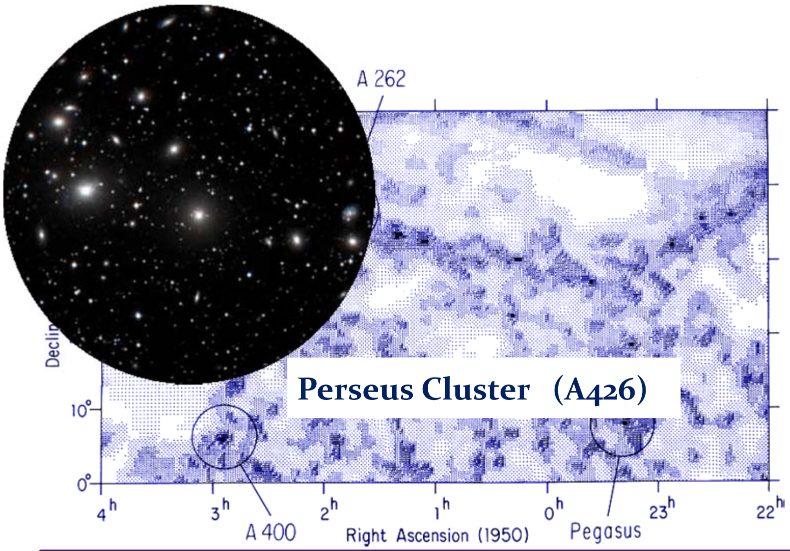


Cluster Nodes & the Web



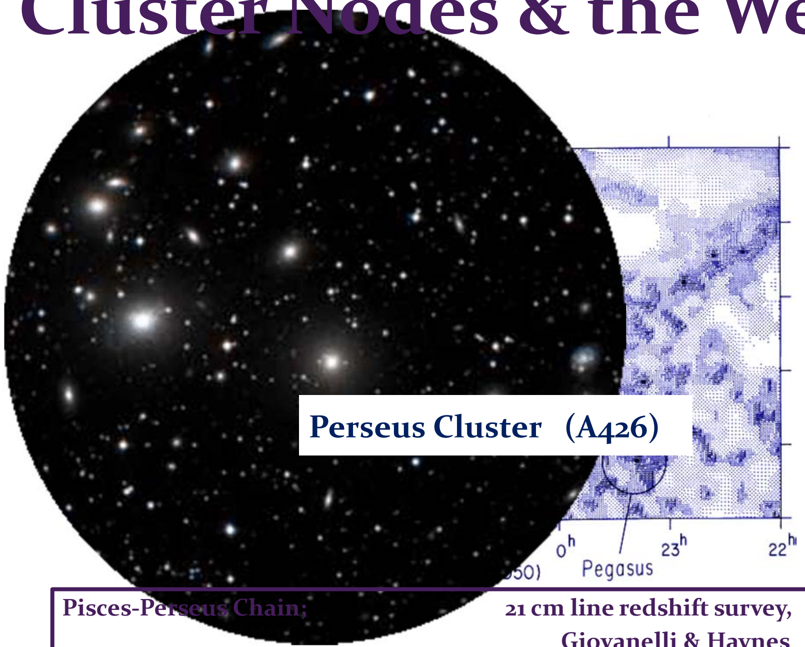
Pisces-Perseus Chain; 21 cm line redshift survey, Giovanelli & Haynes

Cluster Nodes & the Web



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

Cluster Nodes & the Web



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

Cosmic Web:

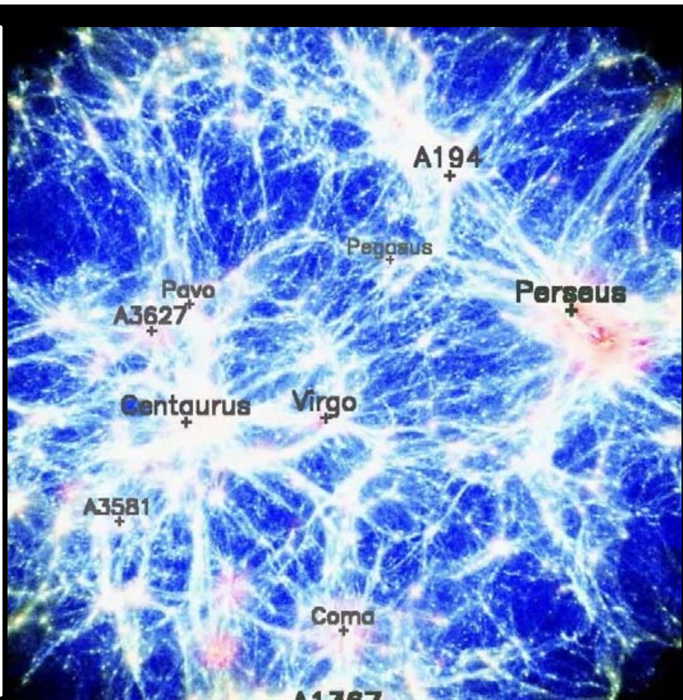
Gas

Local Universe:

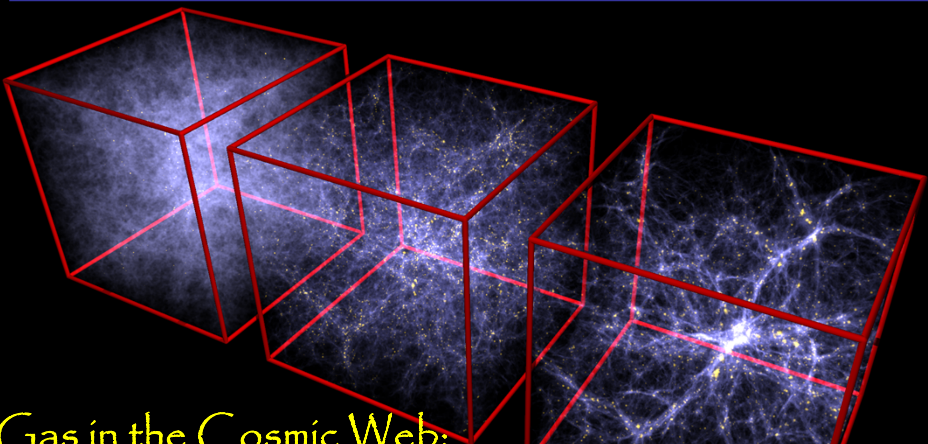
Constrained Simulation

Gas Distribution

courtesy:
Klaus Dolag



The Gastrophysical Web



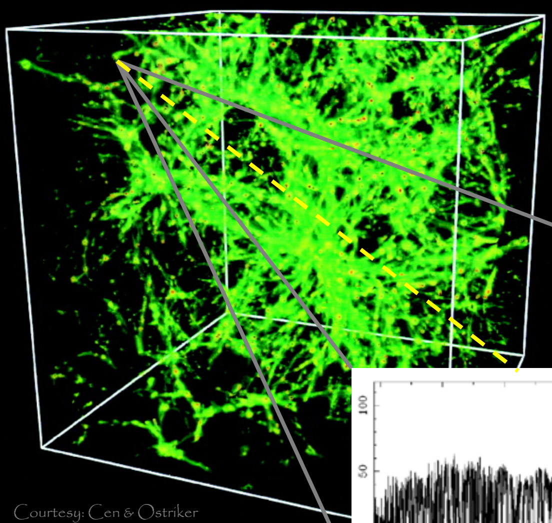
Gas in the Cosmic Web:

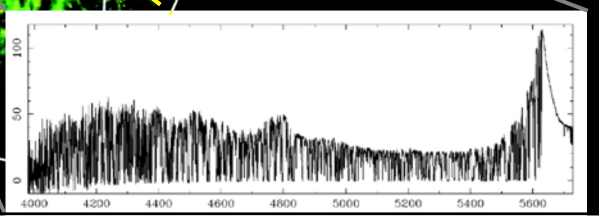
(up to 90% of baryons outside galaxies and clusters)

- 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





Courtesy: Cen & Ostriker

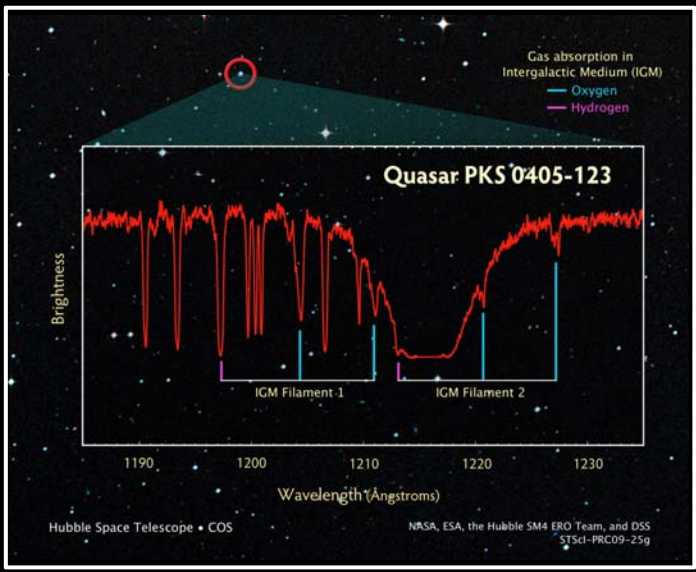
The Lyα forest:

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"

the Gaseous Cosmic Web



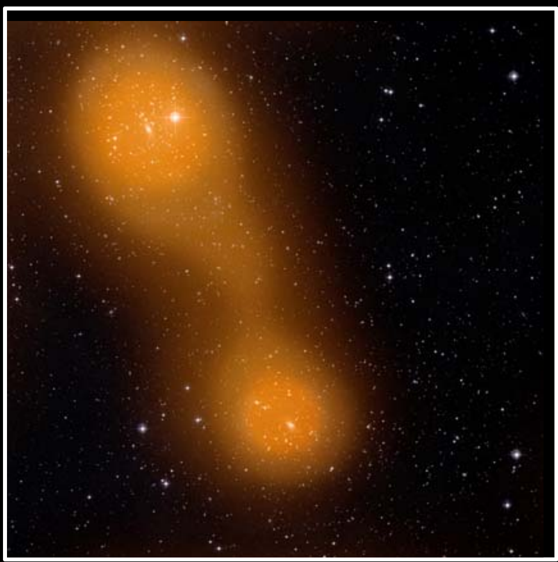
the Gaseous Cosmic Web

SZ detection of

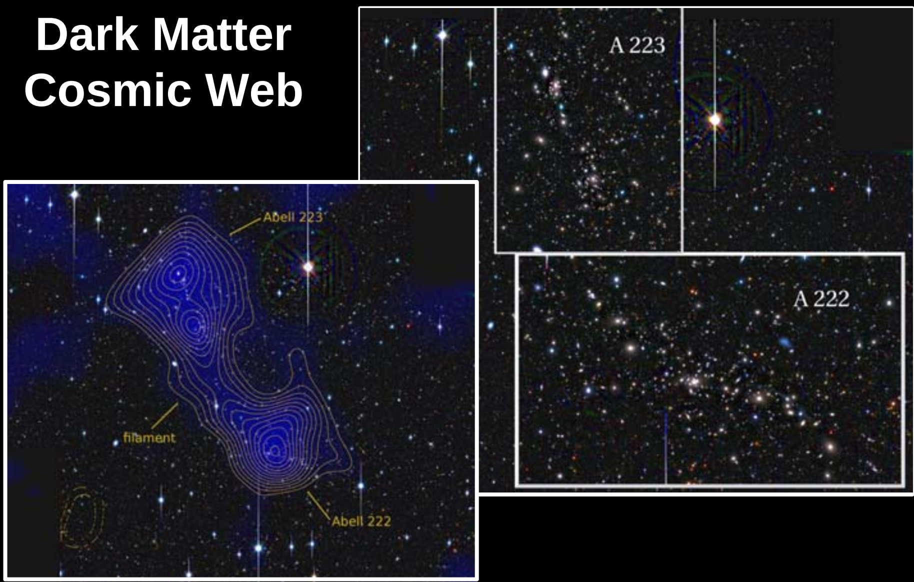
Inter-cluster bridge/filament

in between clusters
A401 and A399

ESA/Planck collaboration



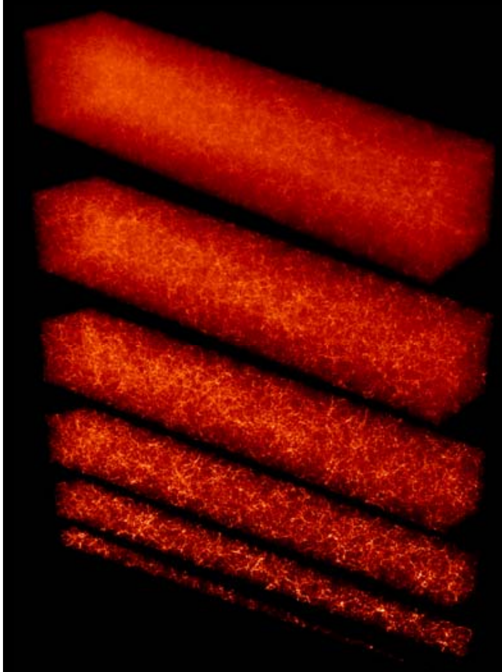
Dark Matter Cosmic Web



A222-A223
Dietrich et al. 2013

Cosmic Web:

in depth



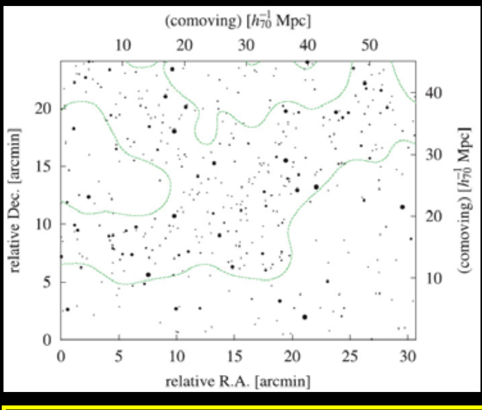
Far Away, Long Ago

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

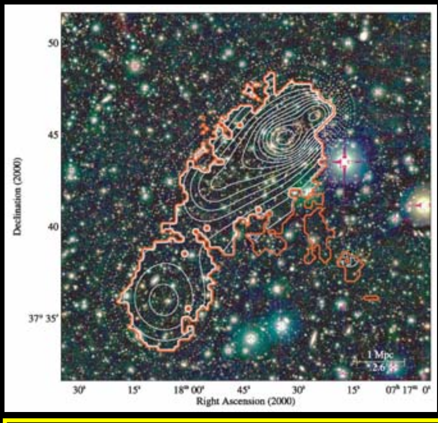


Various surveys are attempting to trace the large scale structure out to large cosmic depths/redshifts.

- 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

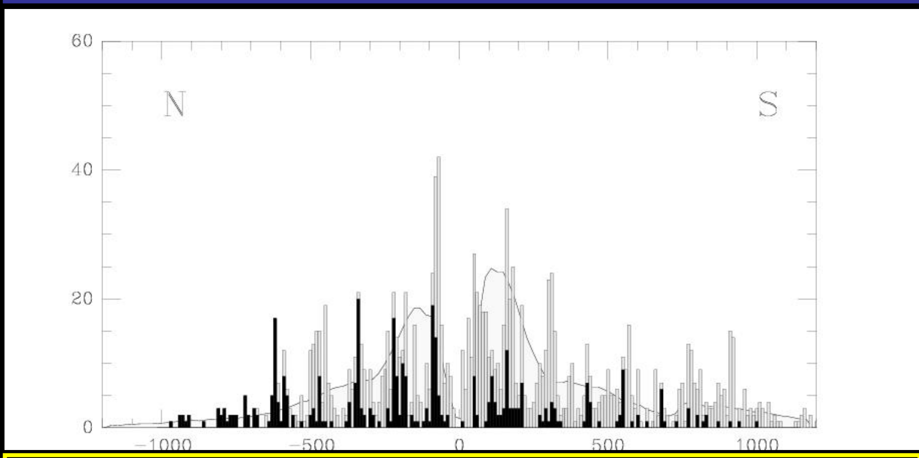


Various surveys are attempting to trace the large scale structure out to large cosmic depths/redshifts.

- 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.