

## 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  $\theta, \varphi$
    - frequency  $\nu$
    - 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:

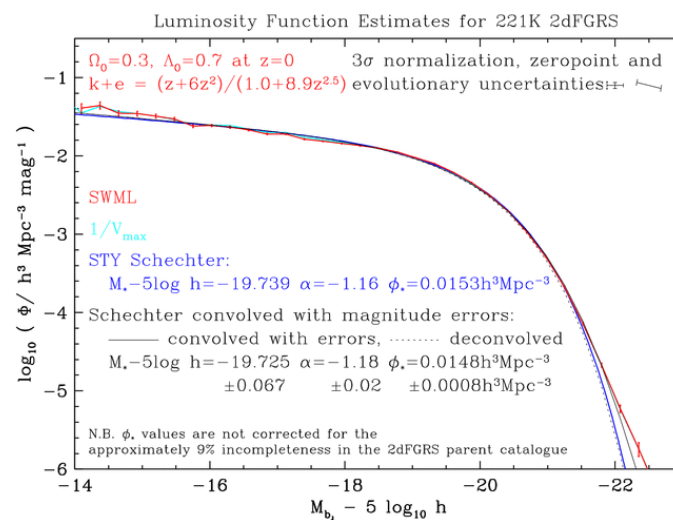
- Schechter Luminosity Function:

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

- Parameterized by 3 parameters:

$\phi^*$ : normalization density parameter  
 $L_*$ : characteristic luminosity  
 $\alpha$ : 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  $\alpha < -1$   
(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  $\alpha < -2$

## Schechter Luminosity Function

- 2dFGRs luminosity function:

$$M_* = -19.725$$

$$\alpha = -1.18$$

$$\phi^* = 0.0148 \text{ Mpc}^{-3}$$

- Faint Galaxies dominate number density !!!!!

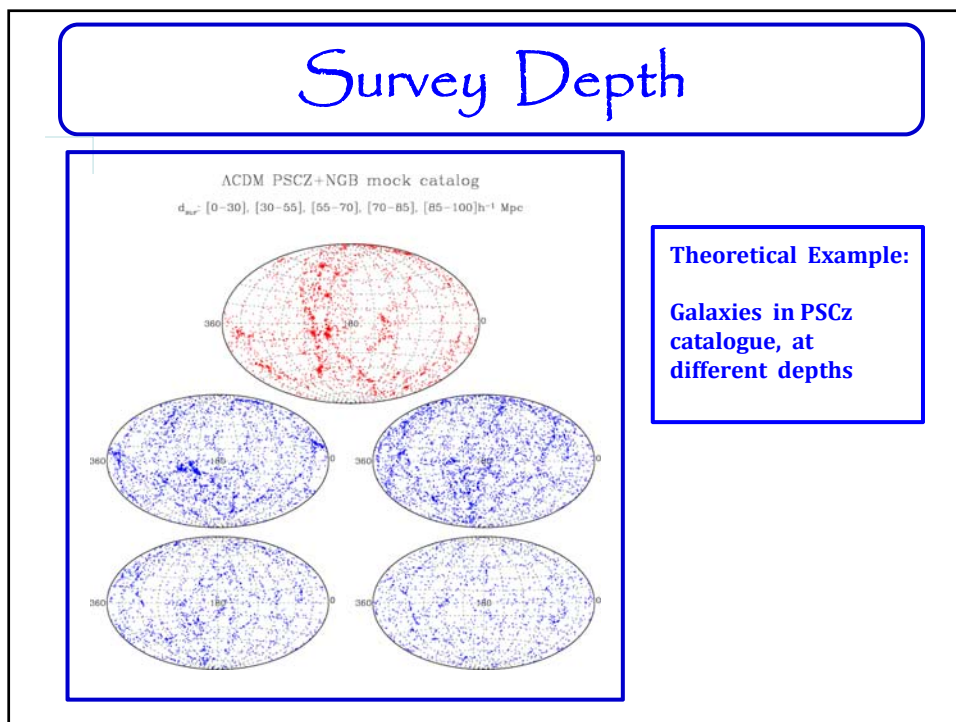
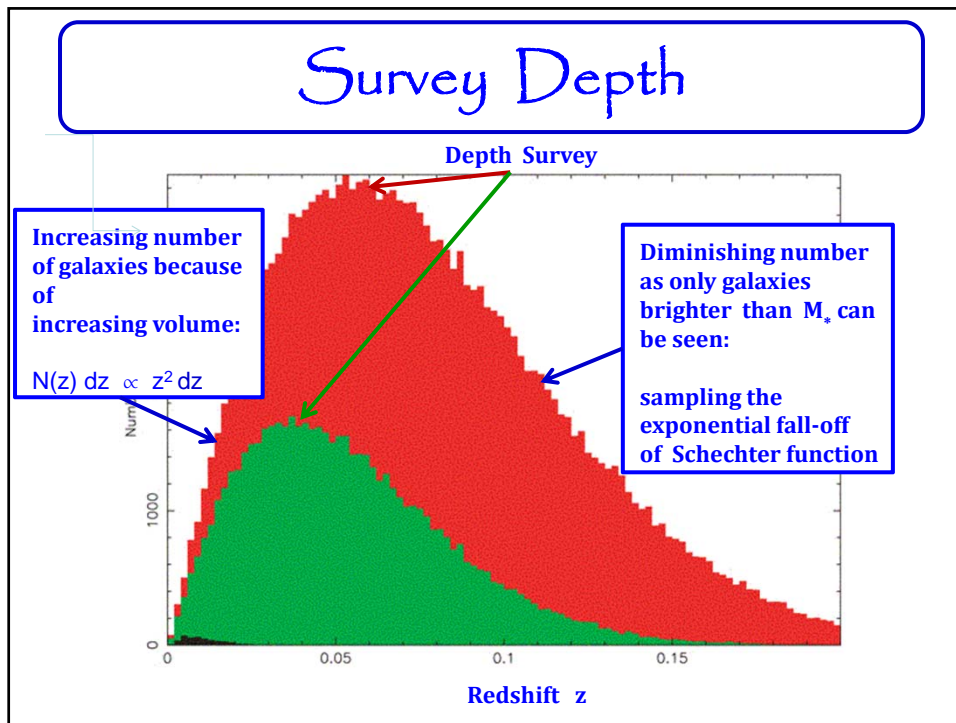
Bright Galaxies determine the luminosity (stars)  
in a cosmic volume !!!!!

## Survey Depth

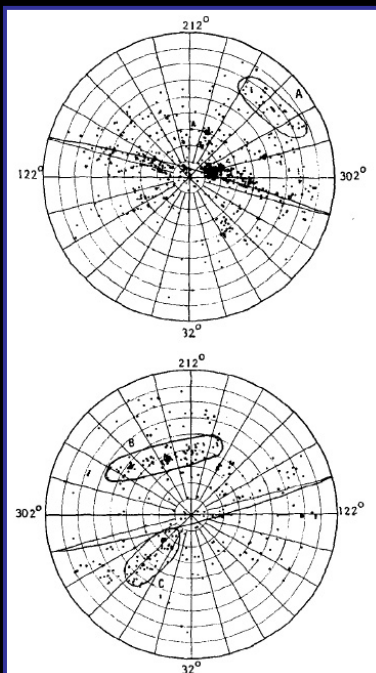
- Most galaxy surveys defined by apparent magnitude limit  $m_{\text{lim}}$
- All galaxies having an apparent brightness higher than that corresponding to  $m_{\text{lim}}$  are included in survey
- Depends on
  - intrinsic brightness/absolute magnitude  $M$
  - (luminosity) distance  $d_L$
  - (- k-correction: shift galaxy spectrum as function redshift  $z$ )
- Absolute Magnitude  $\longleftrightarrow$  Apparent Magnitude
 
$$M = m - 5 \log d_L(z) - 25 - k(z)$$

## Survey Depth

- For a survey with magnitude limit  $m_{\text{lim}}$ :
- At distance  $d_L$  (Mpc) one can see galaxies brighter than:
 
$$M_{\text{lim}} = m_{\text{lim}} - 5 \log d_L(z) - 25 - k(z)$$
- Survey Depth  $d_{\text{sur}}$ :  
distance out to which one can see an  $M_*$  galaxy:
 
$$\log d_{\text{sur}} = 0.2(m_{\text{lim}} - M_*) + 5 + 0.2k(z)$$



# Sky Maps: world all around us



## Early Views

Shapley-Ames catalog (1932) of nearby galaxies:

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

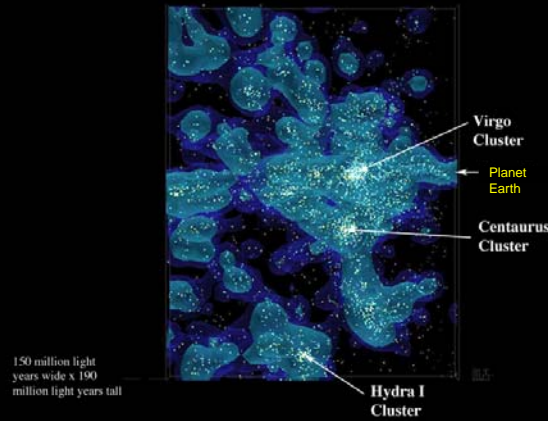
$$\delta > -23^\circ$$

- 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:

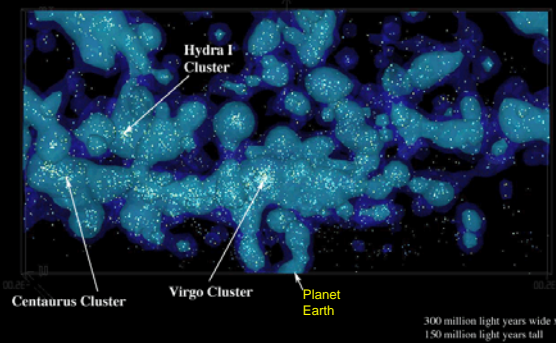


Our Local Group finds itself located at the outer region of a large supercluster region,

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

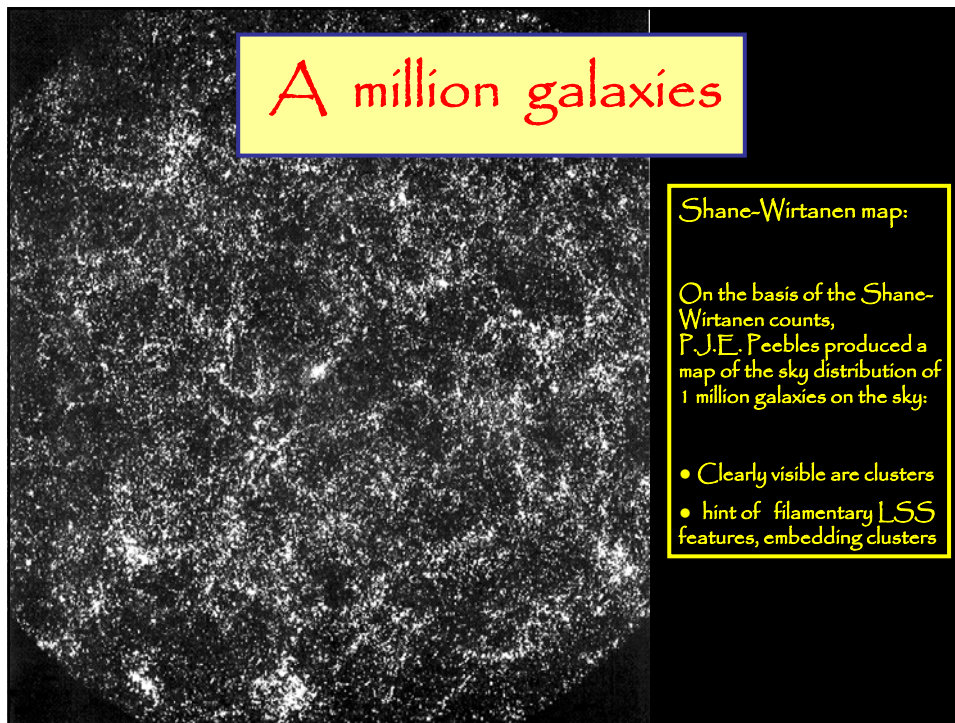
# The Local Supercluster

Polar View of Local Supercluster:



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

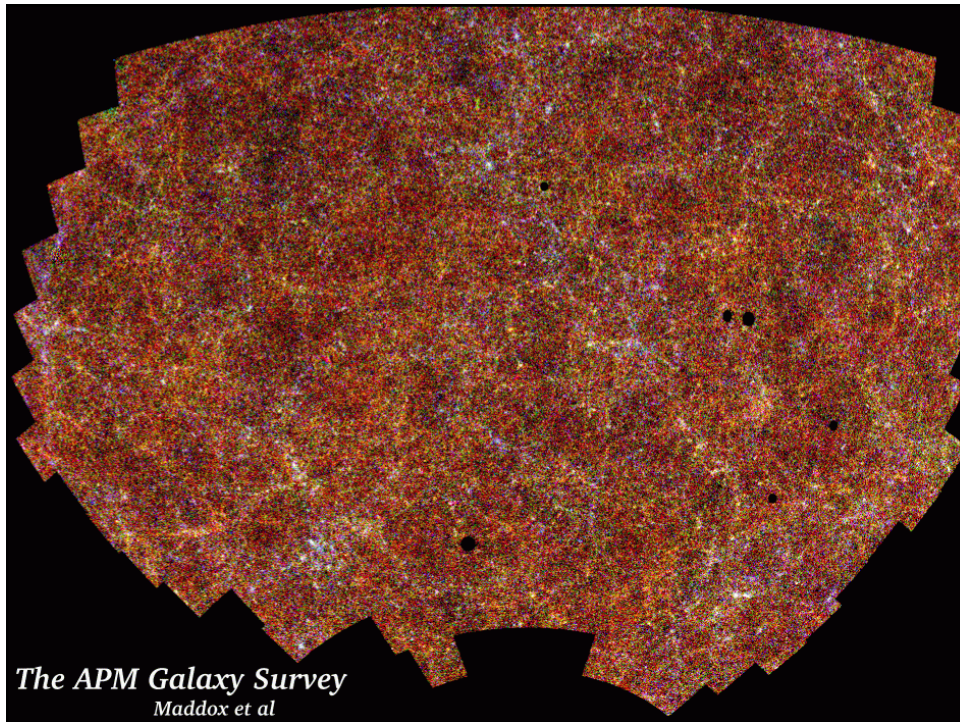
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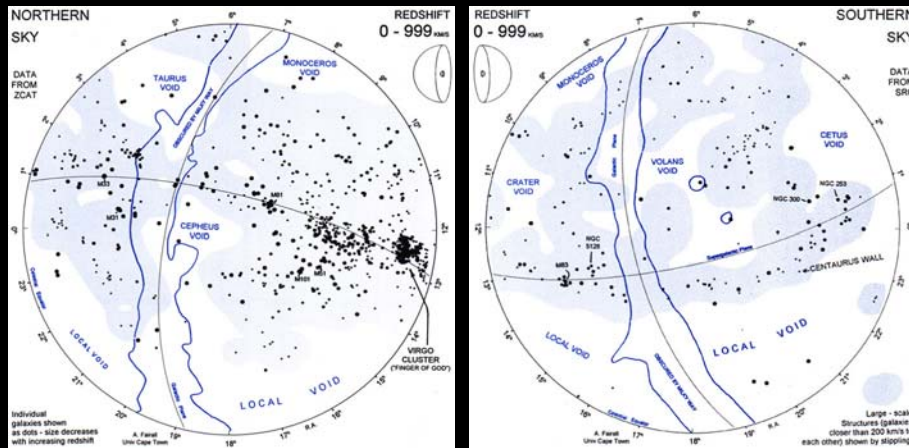
## APM survey

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

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

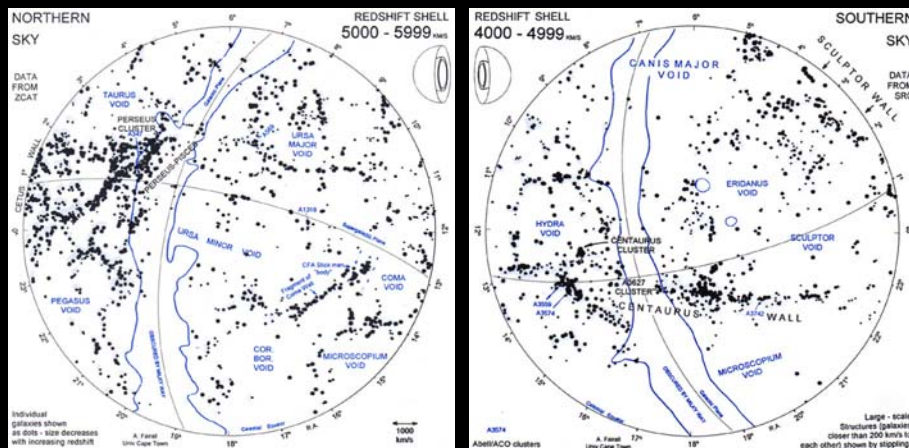


# Local Views

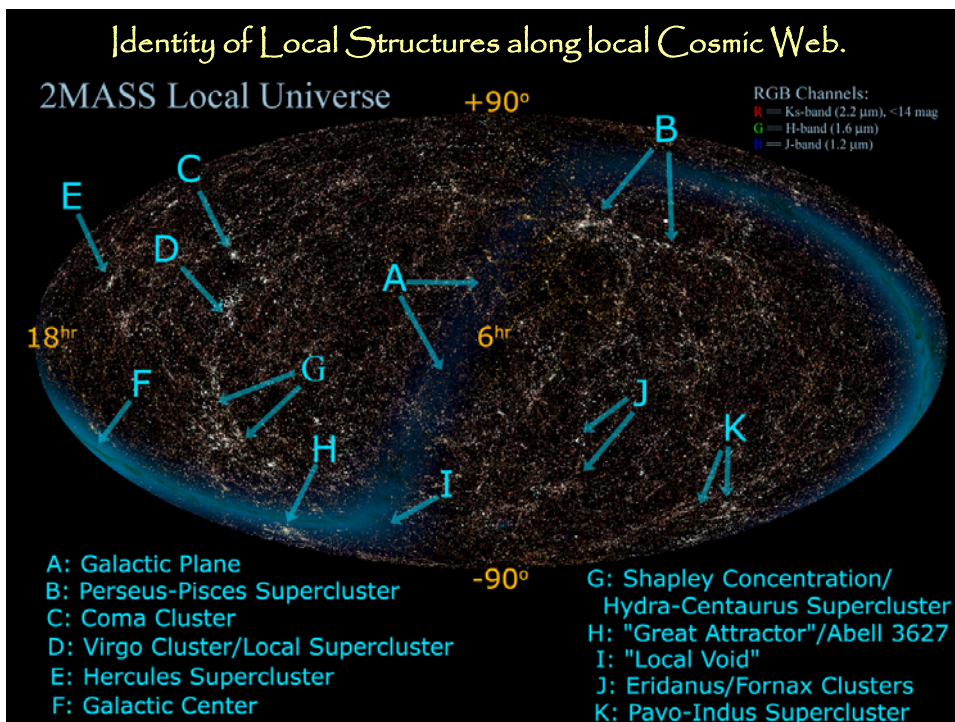
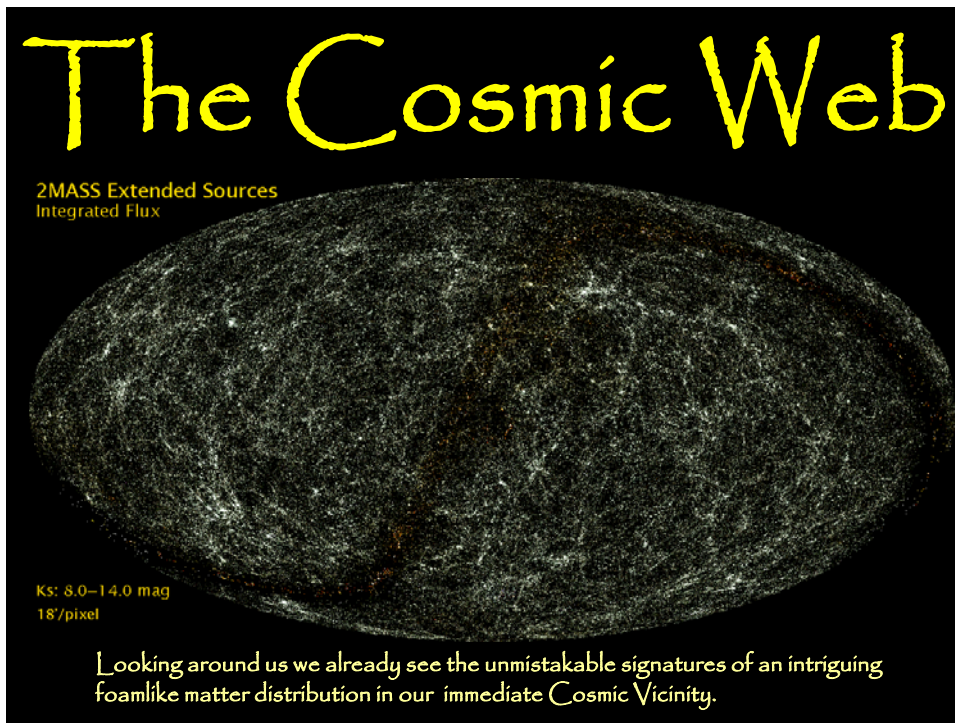


Tony Fairall's nearby LSS map: Local Supercluster clearly visible at  $v < 999$  km/s

# Local Views: Moving into Foam



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

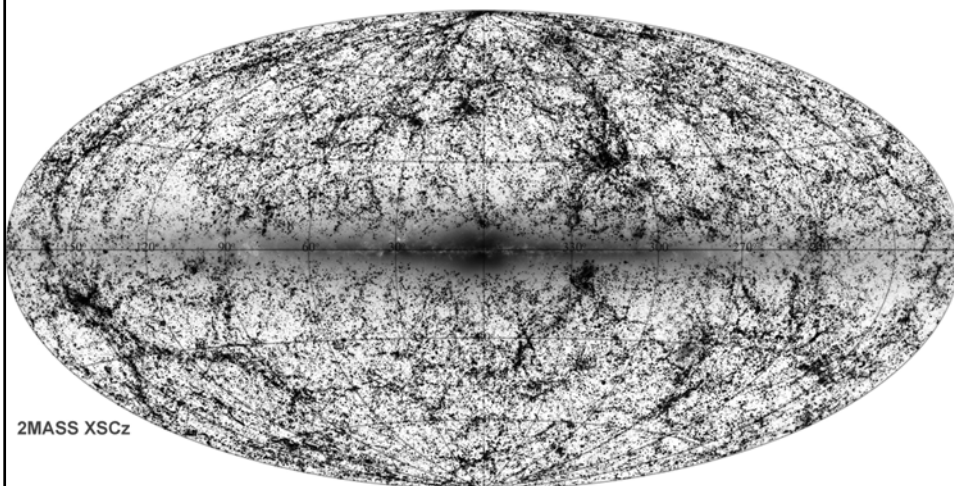


## 2MASS survey

- 2MASS all-sky survey:  
ground-based near-infrared survey whole sky,  
J( $1.2\ \mu\text{m}$ ), H( $1.6\ \mu\text{m}$ ), K( $2.2\ \mu\text{m}$ )
- 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.

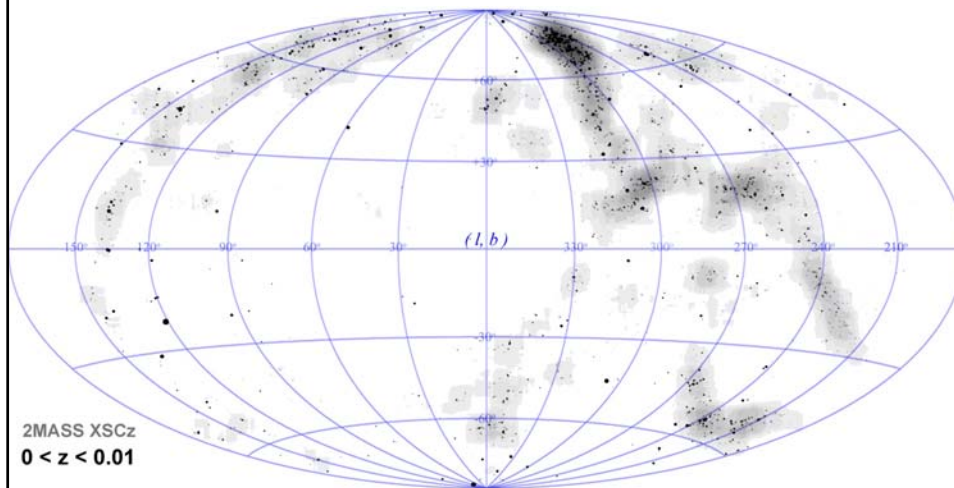
courtesy: T. Jarrett

## 2MASS Cosmic Web



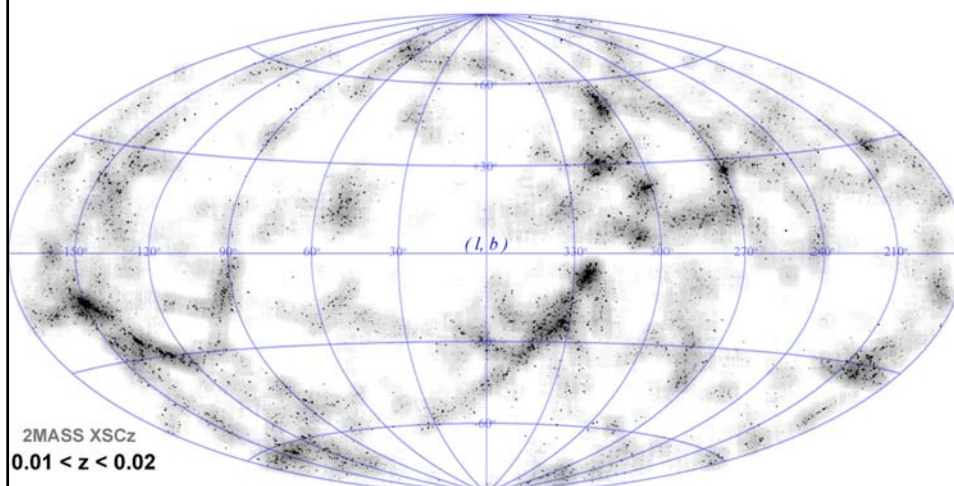
Looking around us we already see the unmistakable signatures of an intriguing  
weblike matter distribution in our immediate Cosmic Vicinity.

## 2MASS Cosmic Web



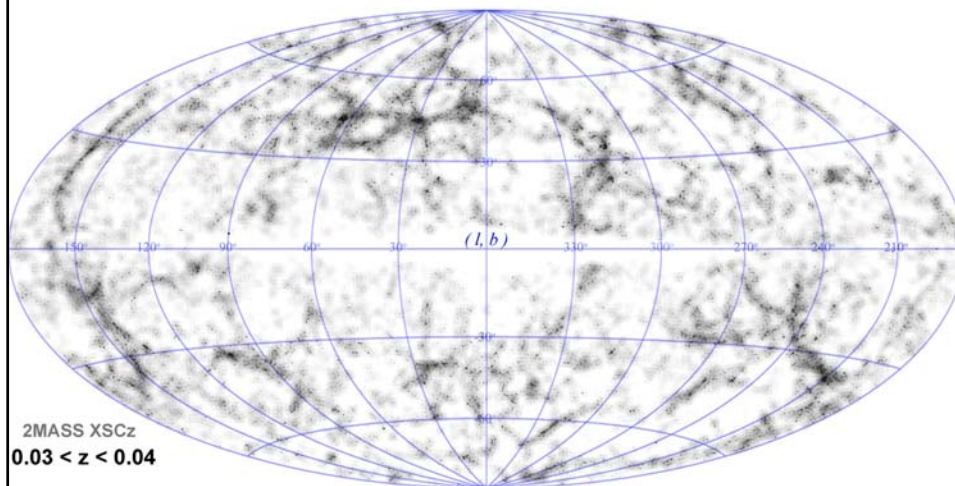
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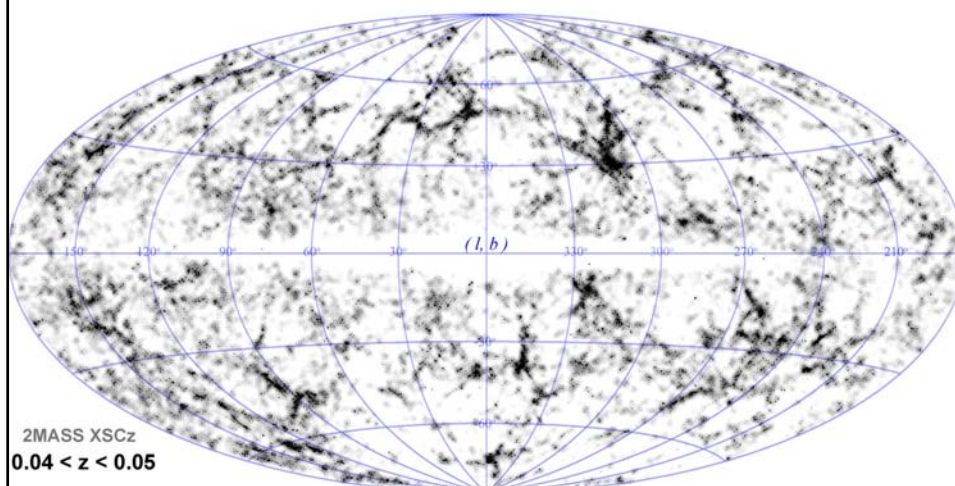
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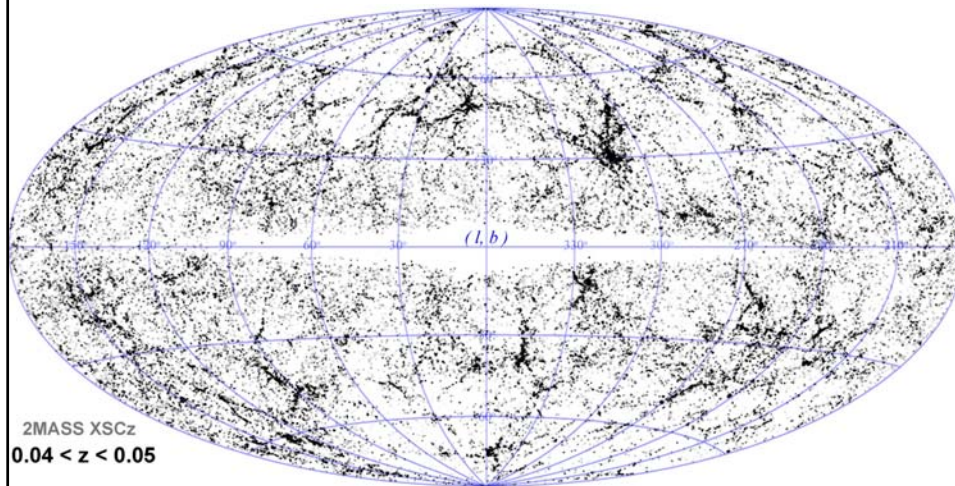
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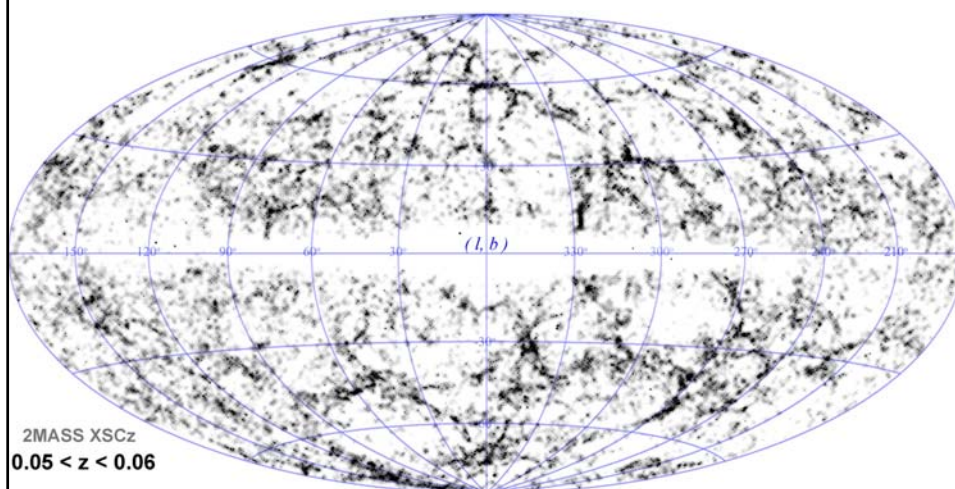
## 2MASS Cosmic Web



2MASS XSCz  
 $0.04 < z < 0.05$

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

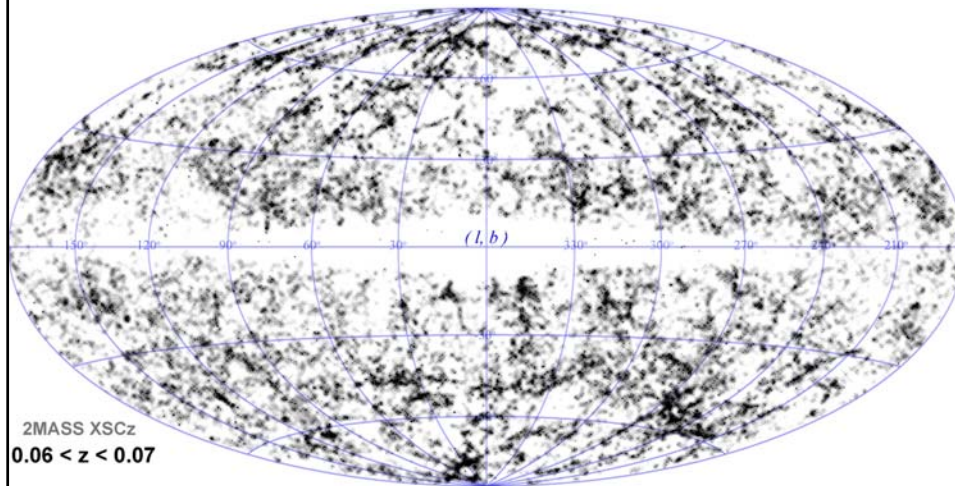
## 2MASS Cosmic Web



2MASS XSCz  
 $0.05 < z < 0.06$

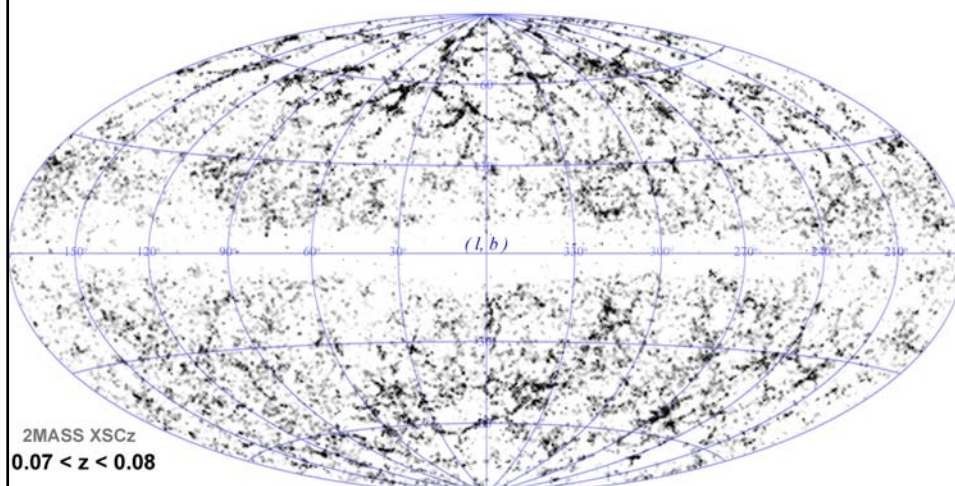
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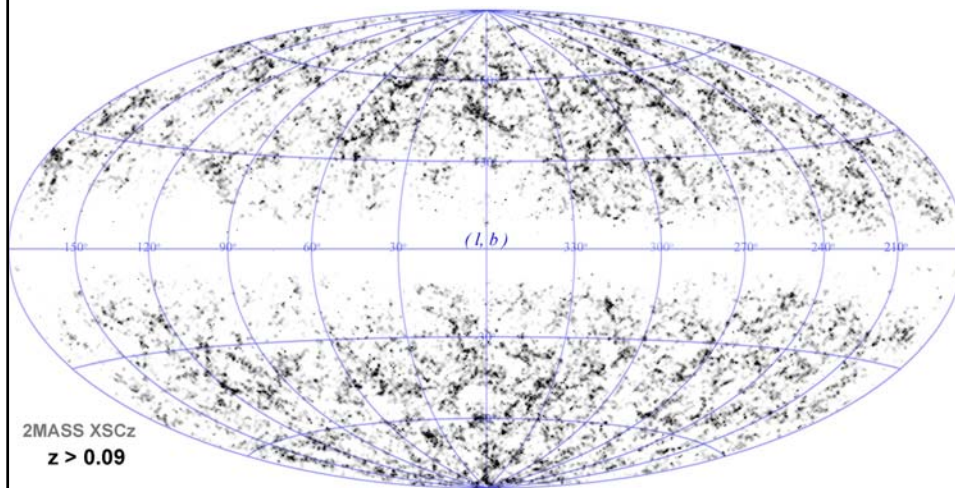
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## 2MASS Cosmic Web



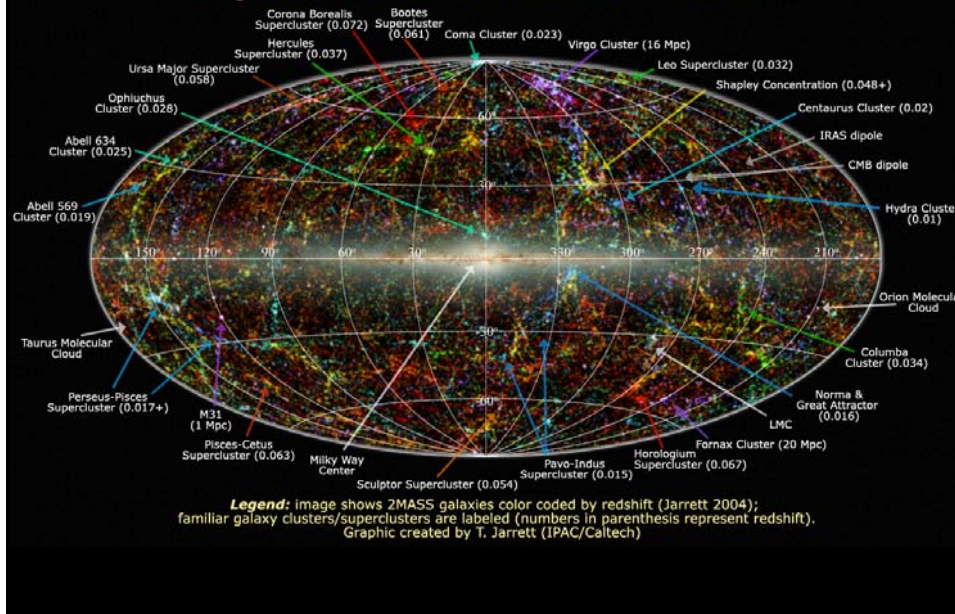
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# 2MASS Cosmic Web



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

## Large Scale Structure in the Local Universe



# Galaxy Redshift Surveys

## Galaxy Redshift Surveys

- For obtaining 3D maps of the galaxy distribution:

measure spatial location of galaxies:

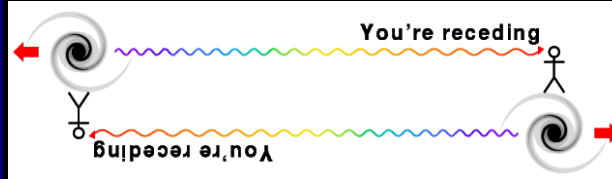
- position on the sky  $(\alpha, \delta)$
- distance  $r$

- 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

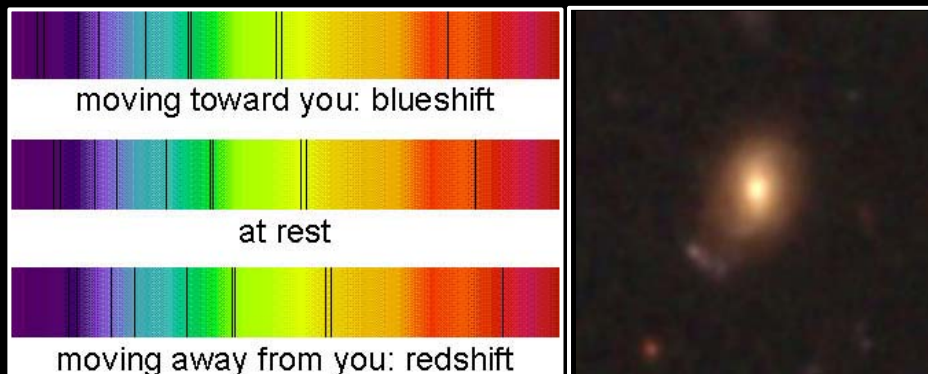
## Galaxy Redshift Surveys

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

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



## Redshifted Galaxy



## Galaxy Redshift Surveys

- Hubble Expansion:

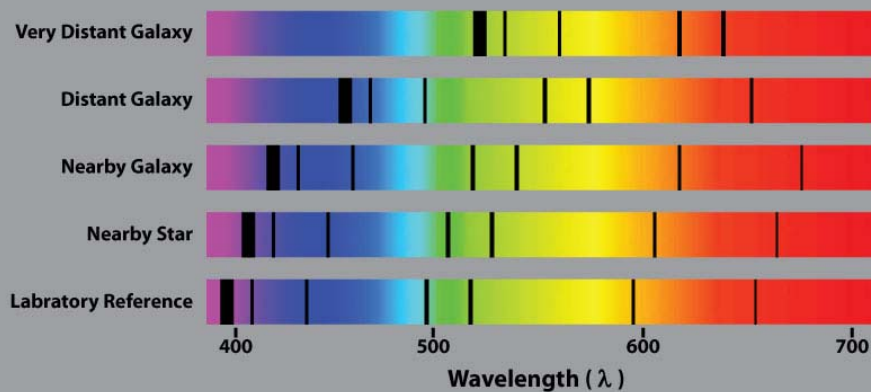
$$cz = Hr \quad (z \ll 1)$$

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

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

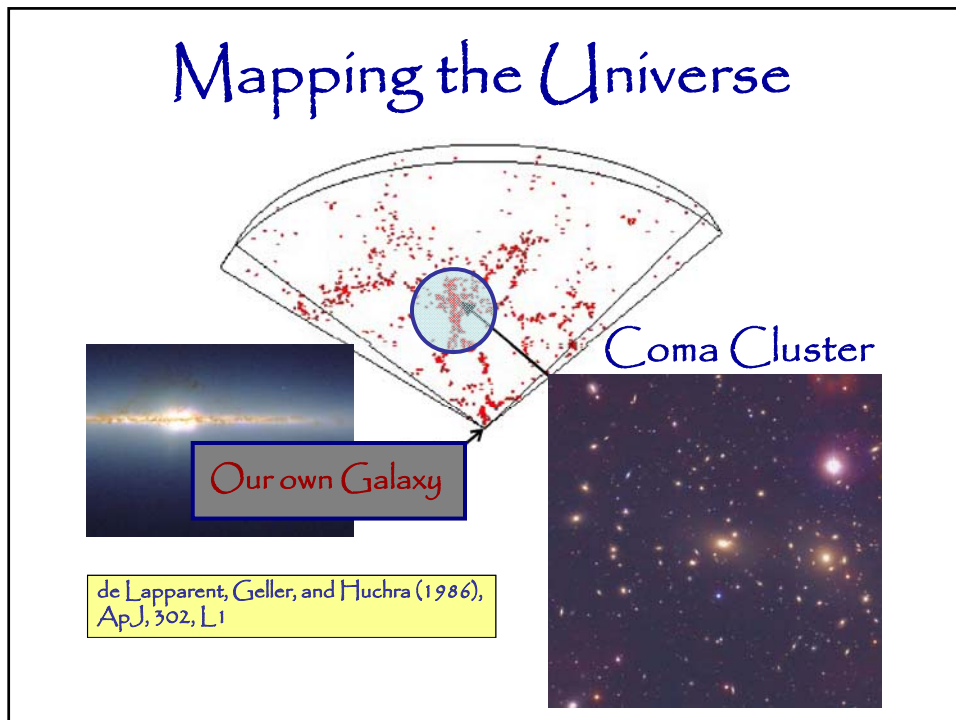
Galaxy Spectrum

## Hubble Expansion & Galaxy Redshift



$$v_{rad} = cz = H_0 r$$

The Hubble law tells us that the further a galaxy is, the more redshifted it is. Moreover, because this is a linear relation, we can even estimate distances to galaxies once we know the value of the Hubble constant !



## 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  $v_{pec}$

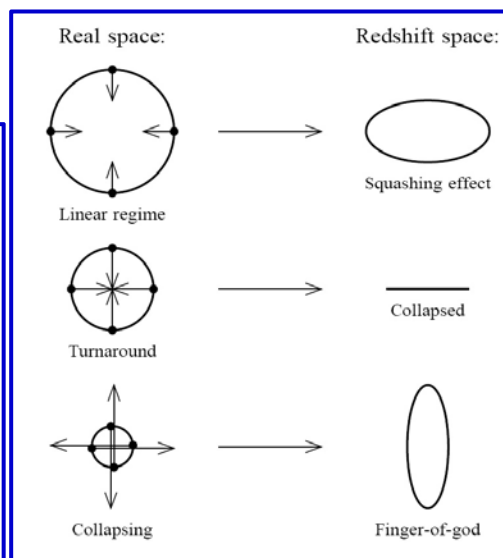
- As a result, maps on the basis of galaxy  $z$  do not reflect the galaxies' true spatial distribution

## Redshift Distortions

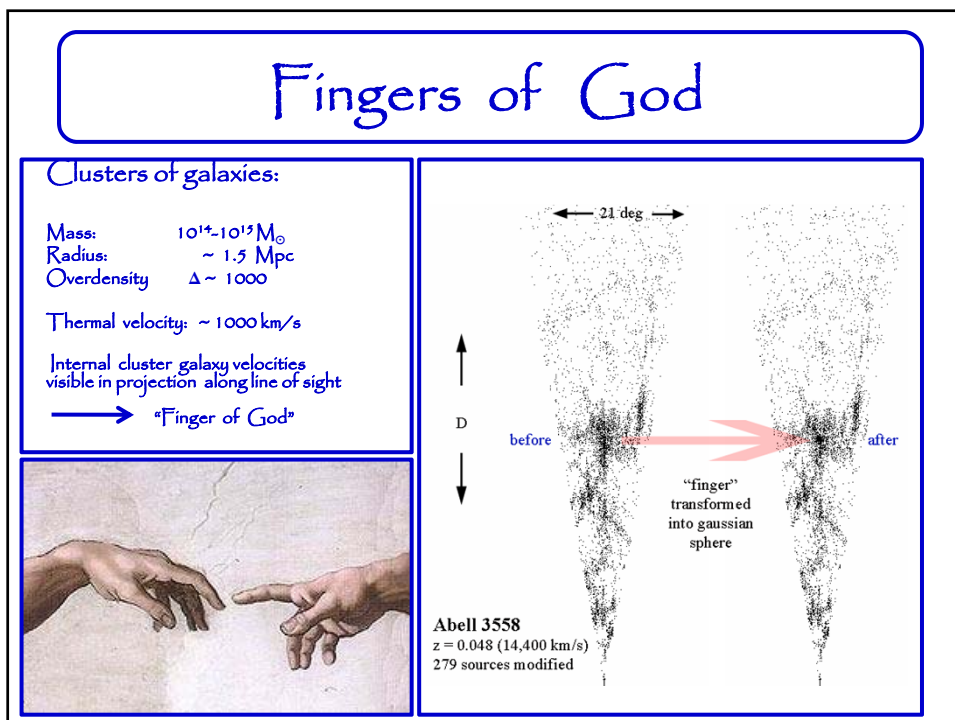
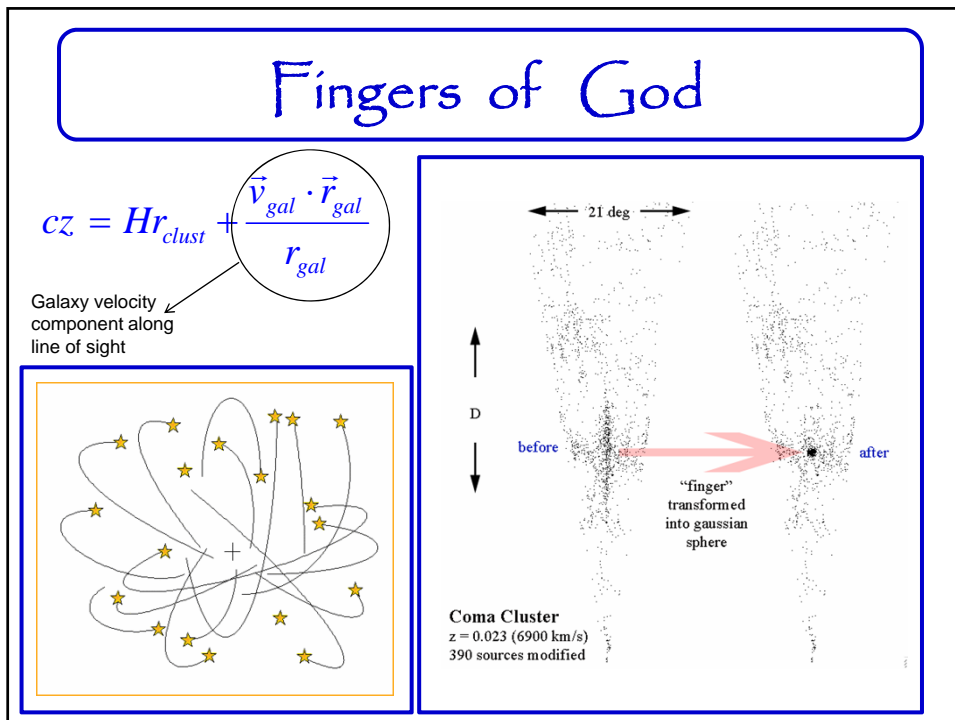
Origin of peculiar velocities:

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







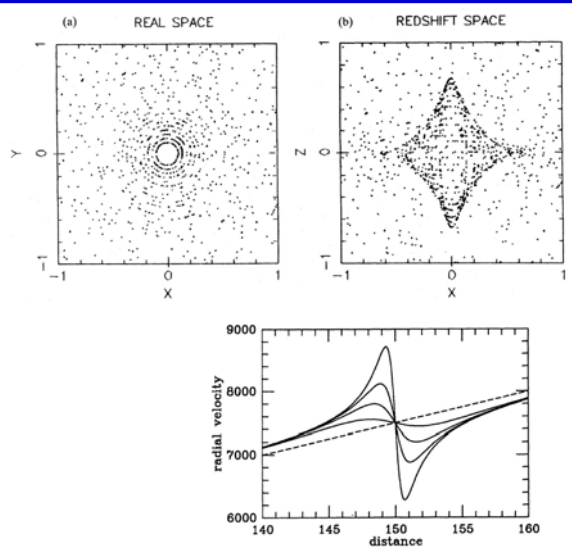
# Nonlinear Infall Pattern

## 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

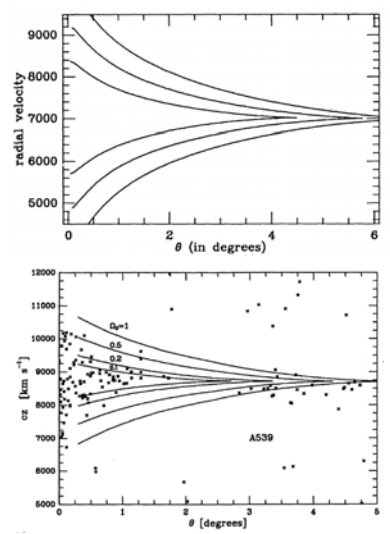
## Cluster Caustics:

Three-value region cluster infall:

Projection onto restricted cone-shaped redshift space regions around clusters

Enclosed within caustic surfaces

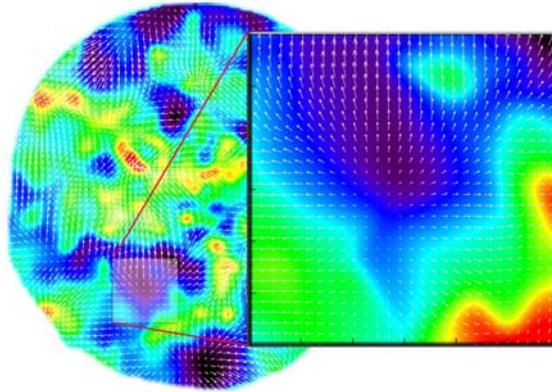
Position caustics dependent on  $\Omega_m$



# 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, i.e. to invert the mapping from real to redshift space
- Condition: entire mass distribution within volume should be mapped



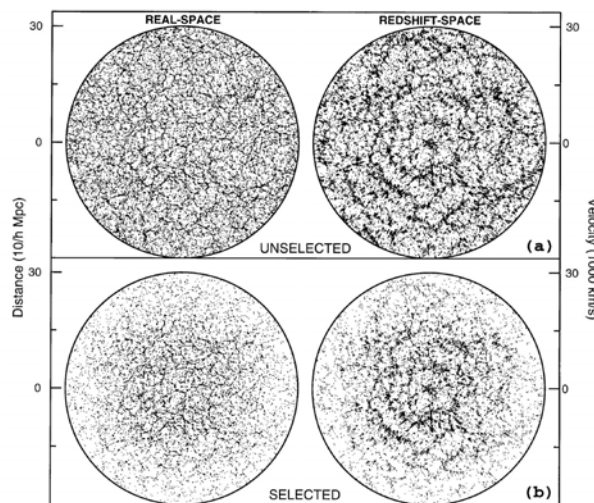
$$\mathbf{v}(\mathbf{x}, t) = \frac{H}{4\pi} \frac{f(\Omega_m)}{b} a \int d\mathbf{x}' \delta_{gal}(\mathbf{x}', t) \frac{(\mathbf{x}' - \mathbf{x})}{|\mathbf{x}' - \mathbf{x}|^3}$$

# Large Scale Flows

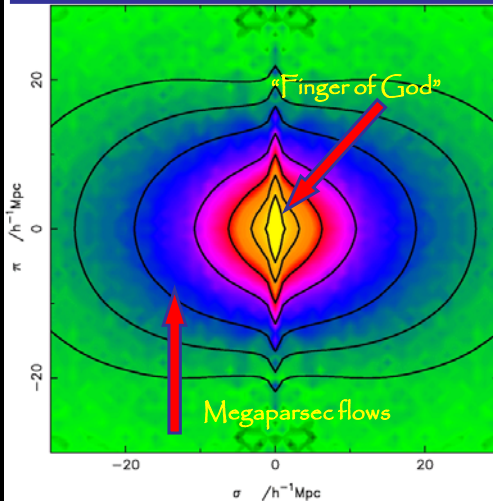
## Large-Scale Flows:

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:

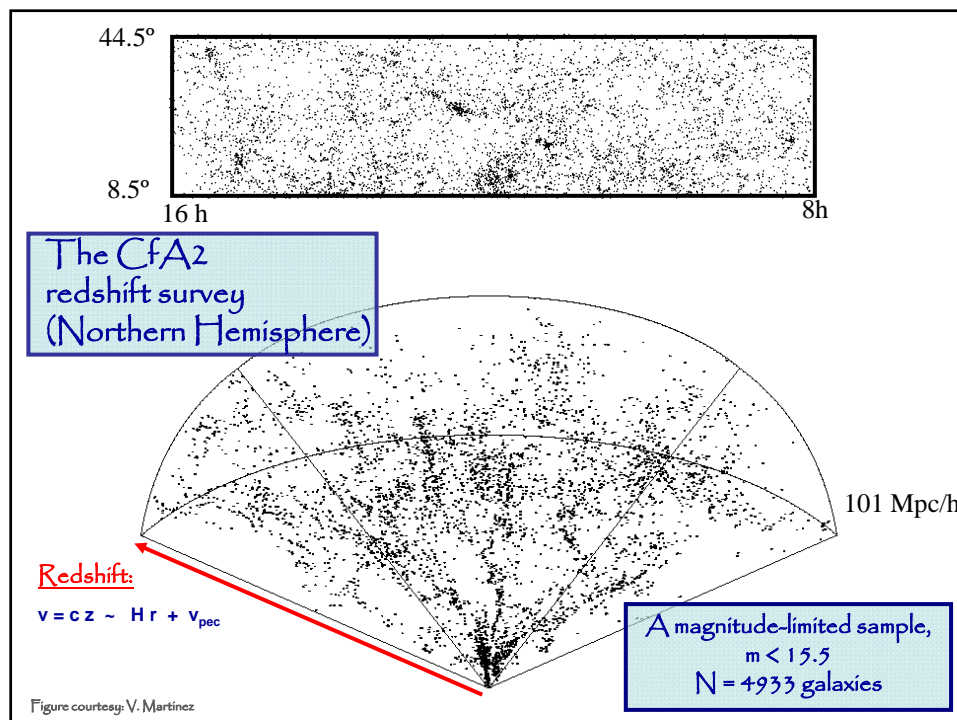
- Flattening along  $z$  as matter flows into Megaparsec features ( $v < 600$  km/s).
- Extension due to thermal motions inside cluster ( $v \sim 1000$  km/s):

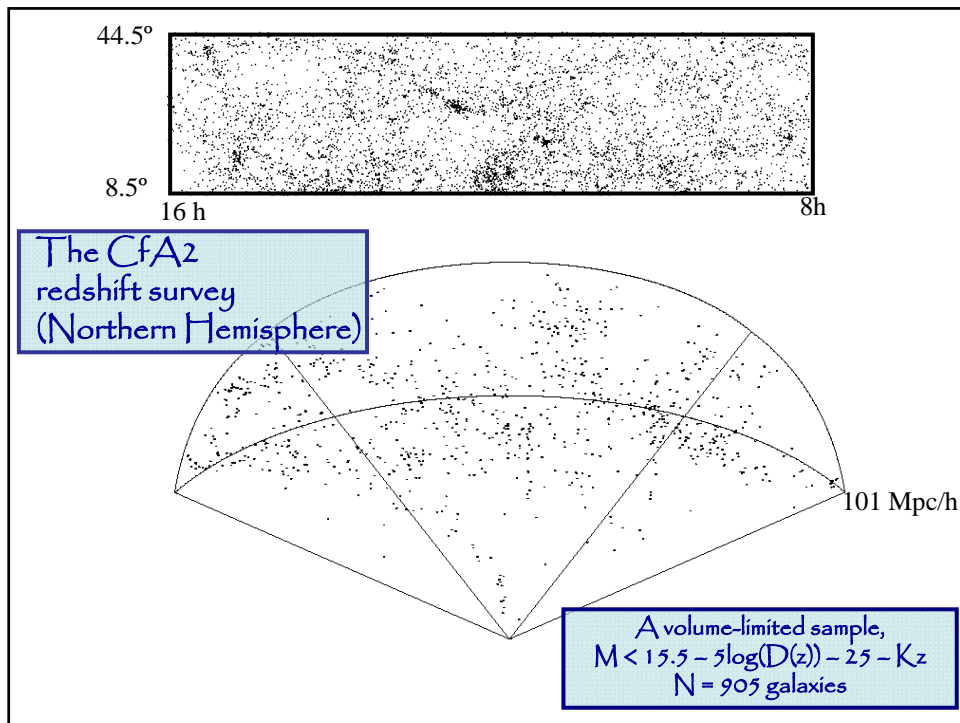
"Fingers of God"

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  $M_s$
$$M_s = m_{\text{lim}} - 5 \log d_s - 25 - k(z)$$
  - 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 a non-uniform spatial coverage & diminishing resolution towards higher depths





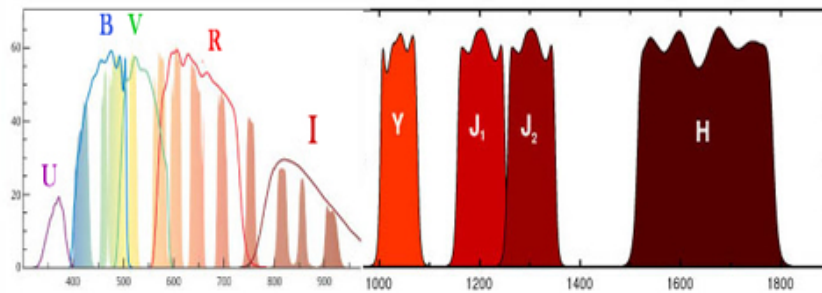
## Photometric Redshifts

# 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.

COMBO-17

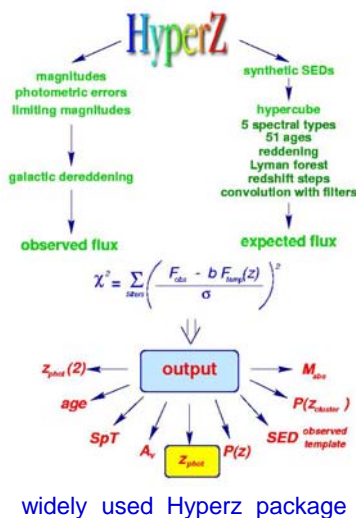
+ 4



# Photometric Redshifts

Practical Implementation:

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



# Photometric Redshifts

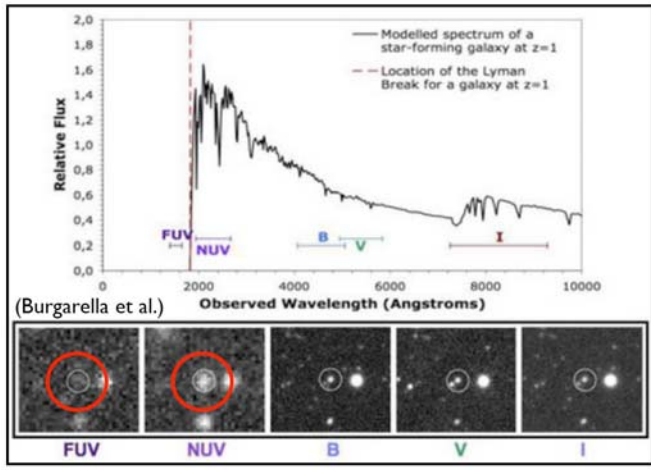
## Photometric Redshifts

Technique widely used for identifying high z objects

For example, Lyman break results

in

FUV-NUV dropouts (1400-1800 Å) for  $z \sim 0.5-1.0$

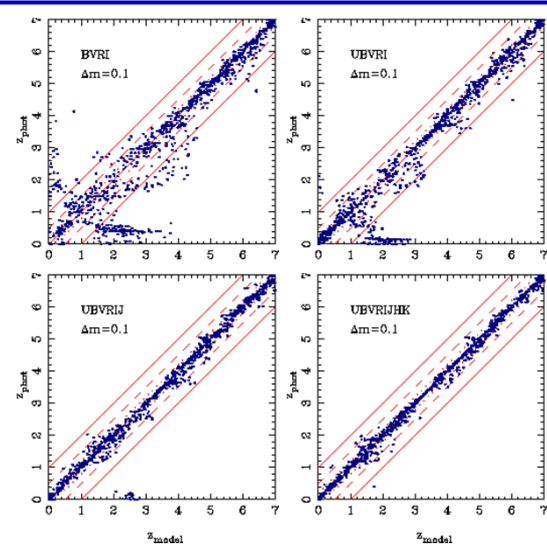


(Burgarella et al.) Below the Lyman break at 912 Å, hydrogen absorbs galaxy light

# 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



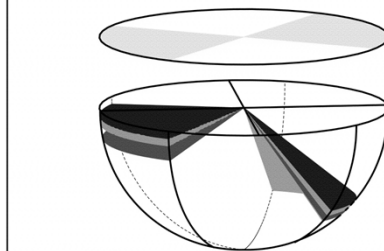


# Survey Geometry

## 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

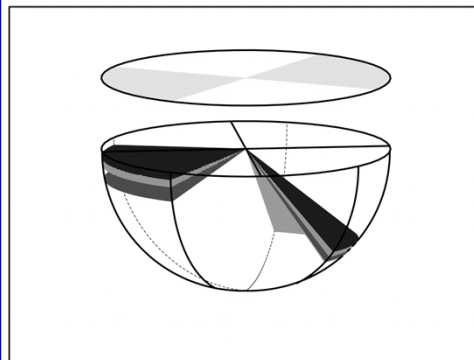


Sky Location  
2-D LCRS survey slices

# 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)

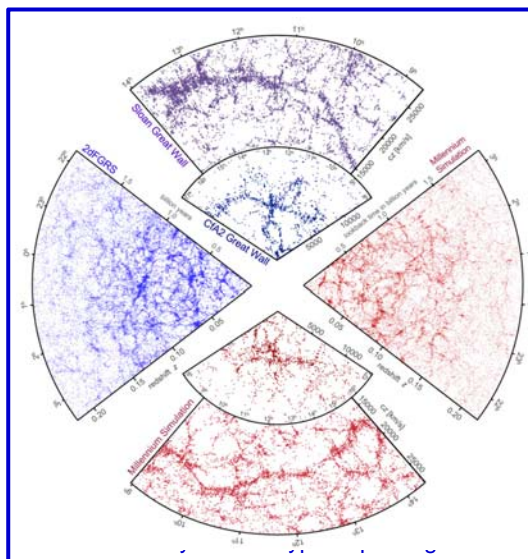


Sky Location  
2-D LCRS survey slices

# Survey Geometries

Examples of  
Slice Redshift Surveys:

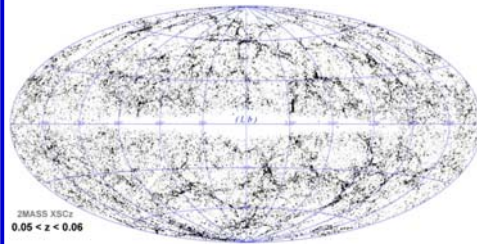
From  
CfA2-2dFGRS-SDSS



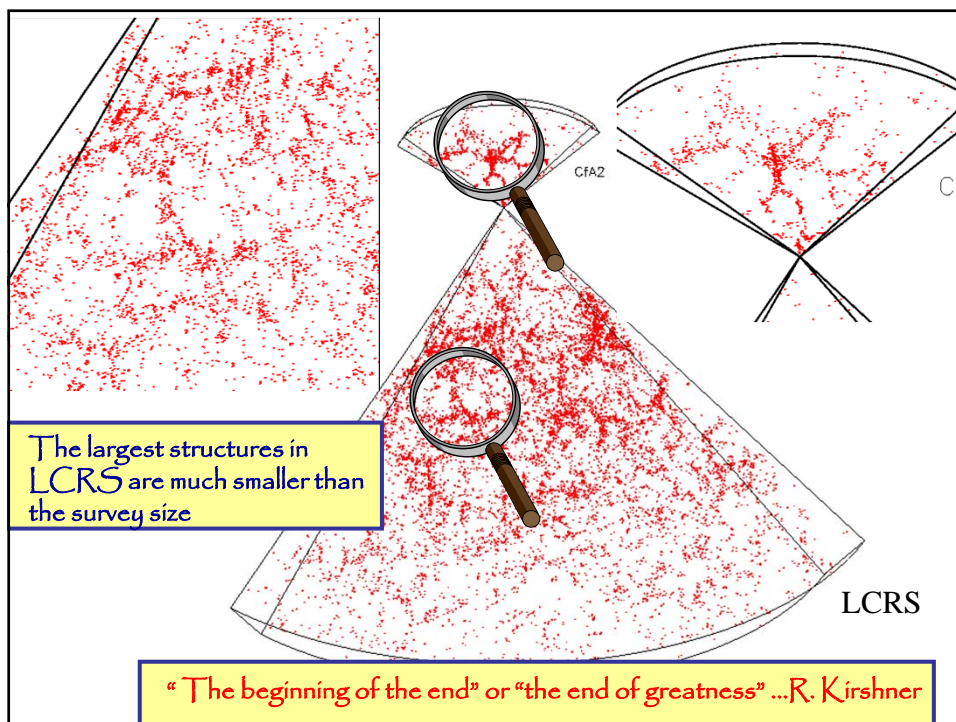
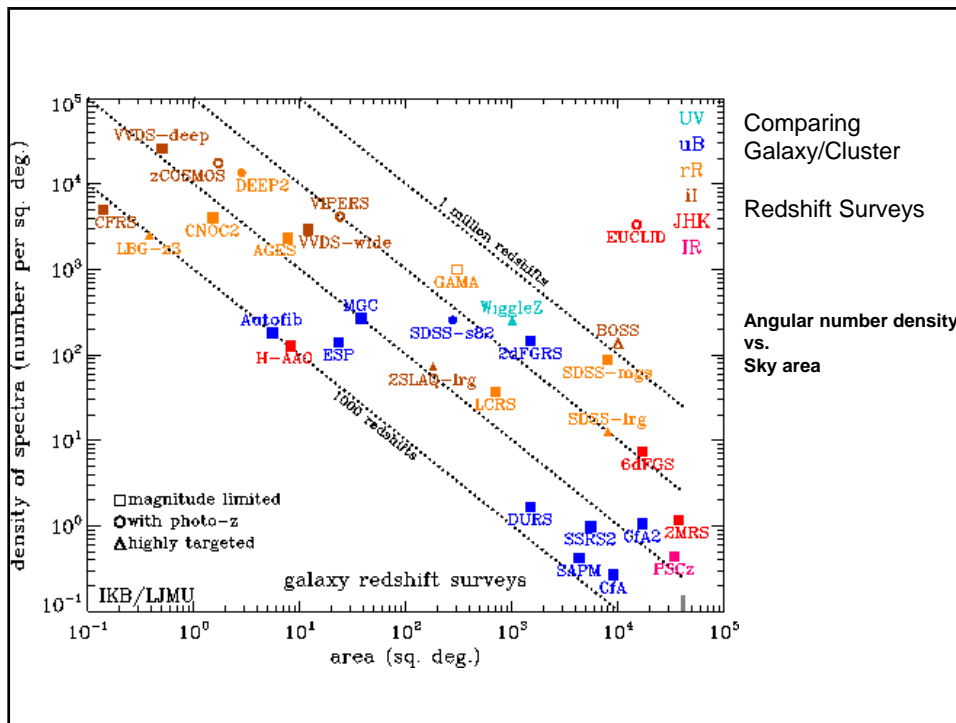
## Survey Geometry

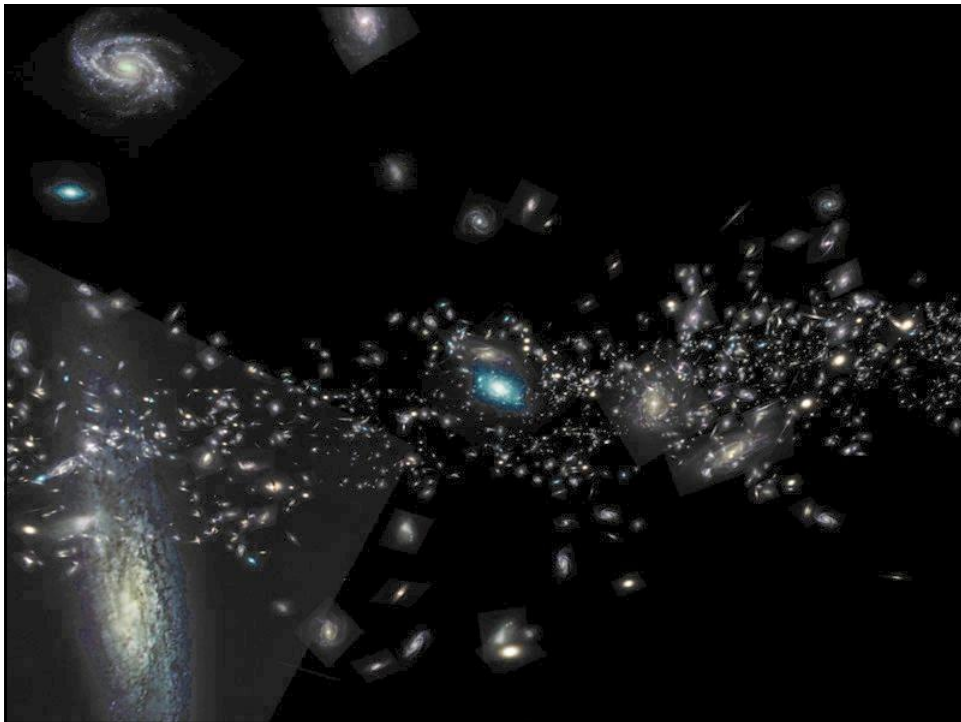
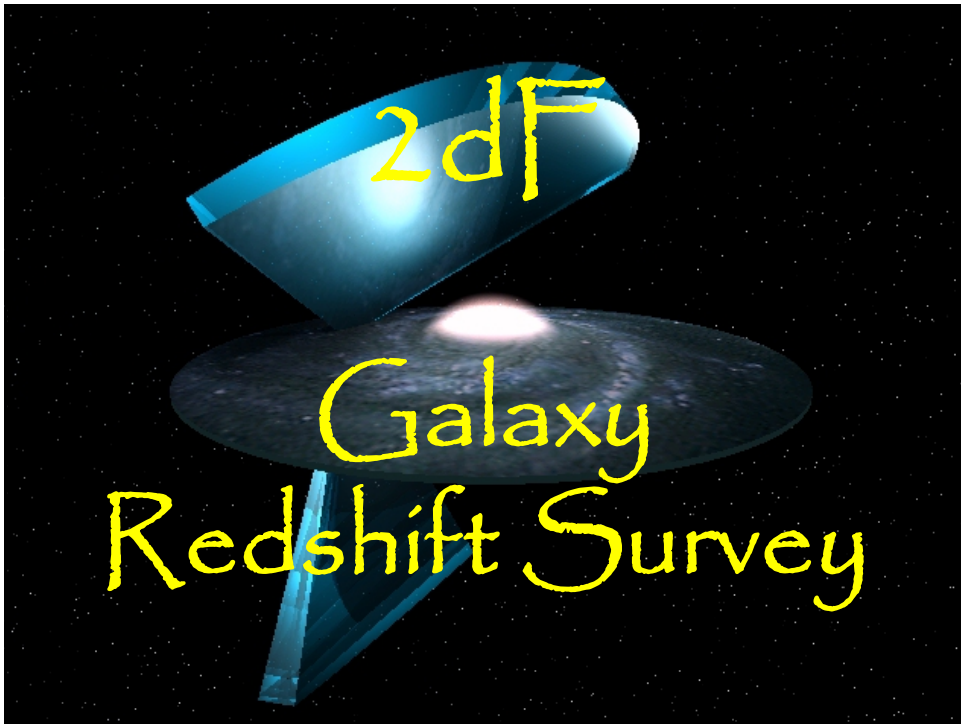
### Survey Geometry:

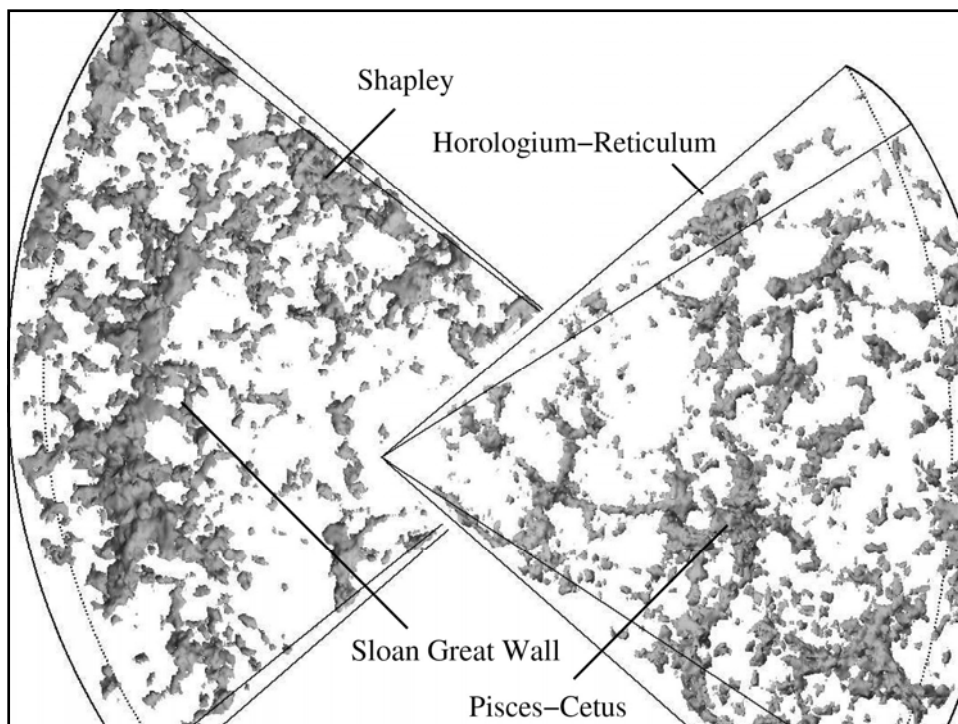
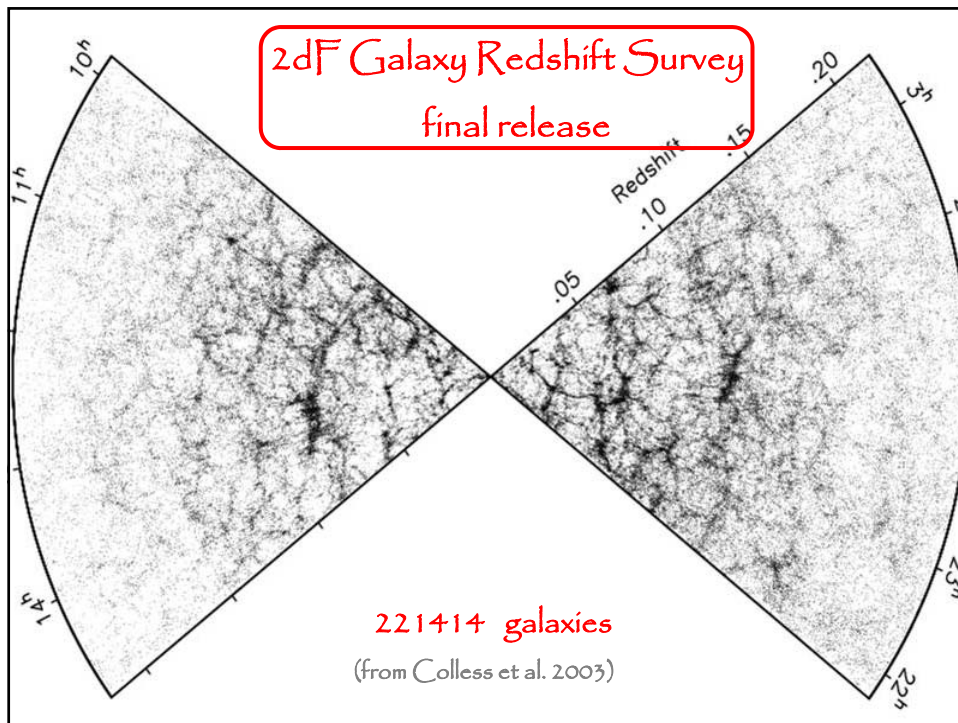
- Sparse Sample:
  - sampling density field
  - on scales  $\gg$  intergalaxy distance
- Full-sky surveys
  - necessary to probe dynamics cosmic regions



## Galaxy Redshift Surveys: Overview









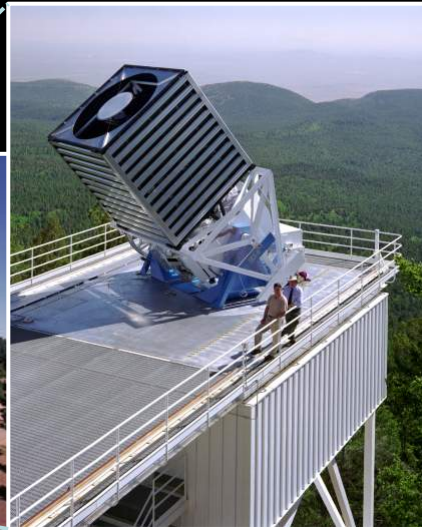
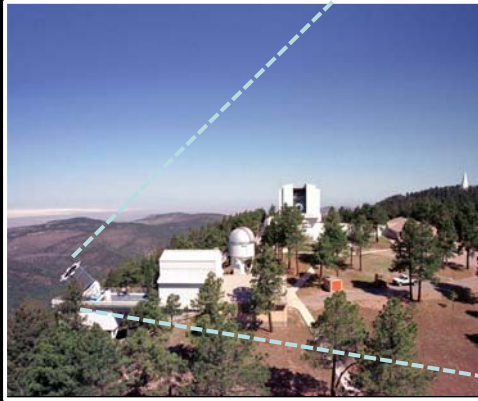
## SDSS survey

- Largest and most systematic (digital!) sky survey in history of astronomy.
- Images sky in 5 photometric bands!!!!  
Down to apparent magnitude  $r \sim 23.1$
- Covers  $\sim 25\%$  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:

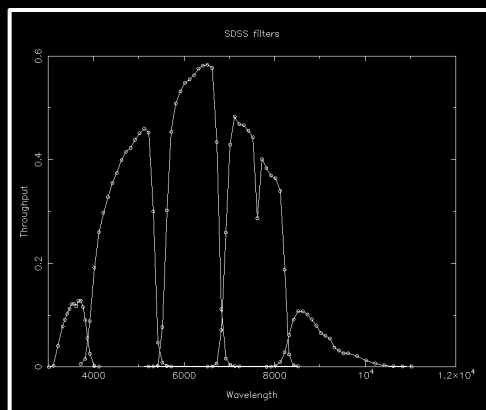
	$\lambda$	$m_{\text{lim}}$
u	354 nm	24.4
g	476 nm	25.3
r	628 nm	25.1
i	769 nm	24.4
z	925 nm	22.9

Driftscan mode

- 5 filters:
- 30 CCD chips, 5 rows of 6
- SN ~ 5
- CCD chip: 2048x2048 pixels  
120 Mbyte

Spectroscopy

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





# SDSS survey

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

Photometric system 5 filters:

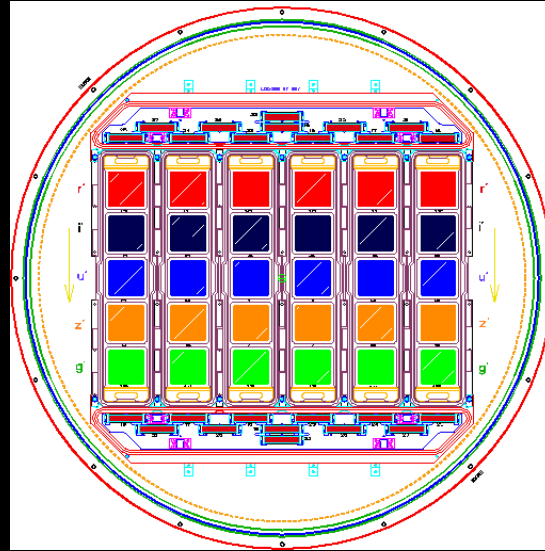
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Spectroscopy

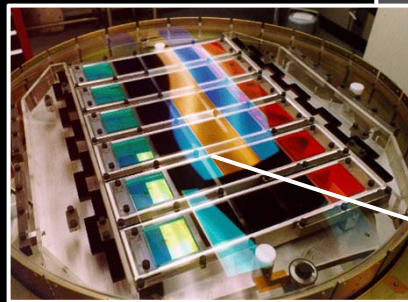
- up to 640 (fibers) per recording
- per night 6-9 recordings



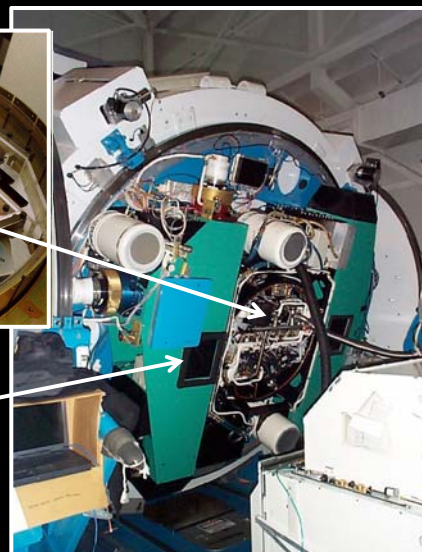
# SDSS survey

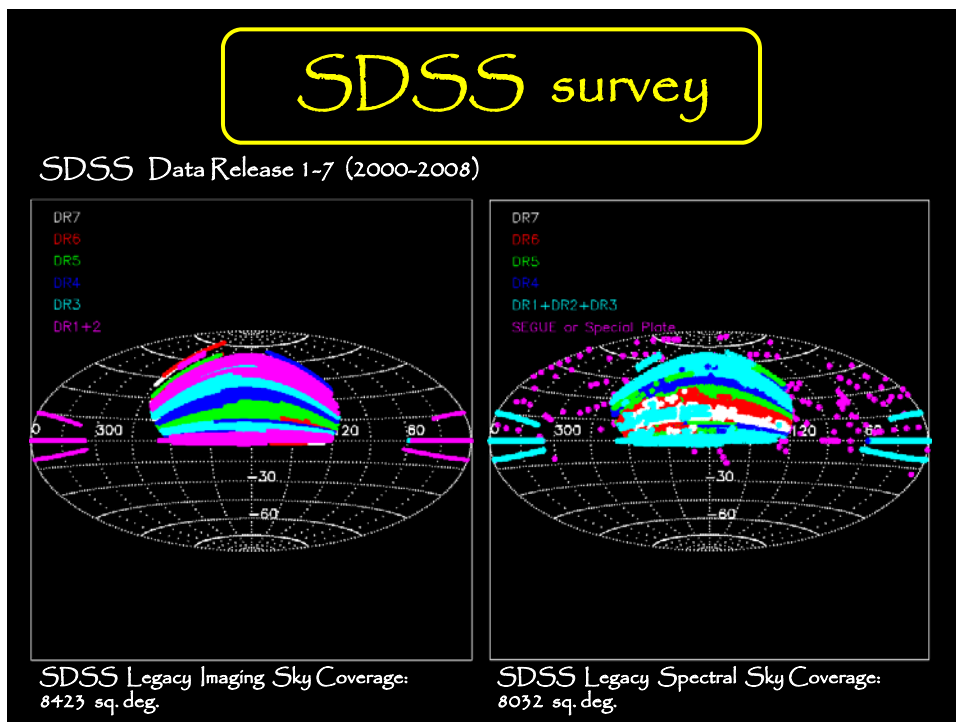
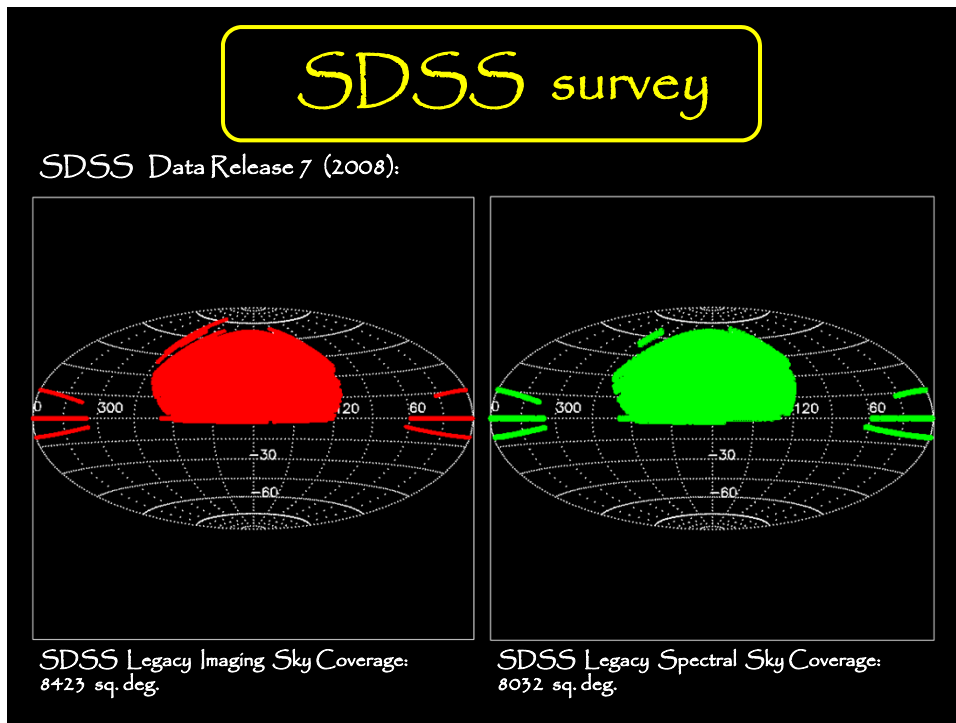
5-color  
Camera

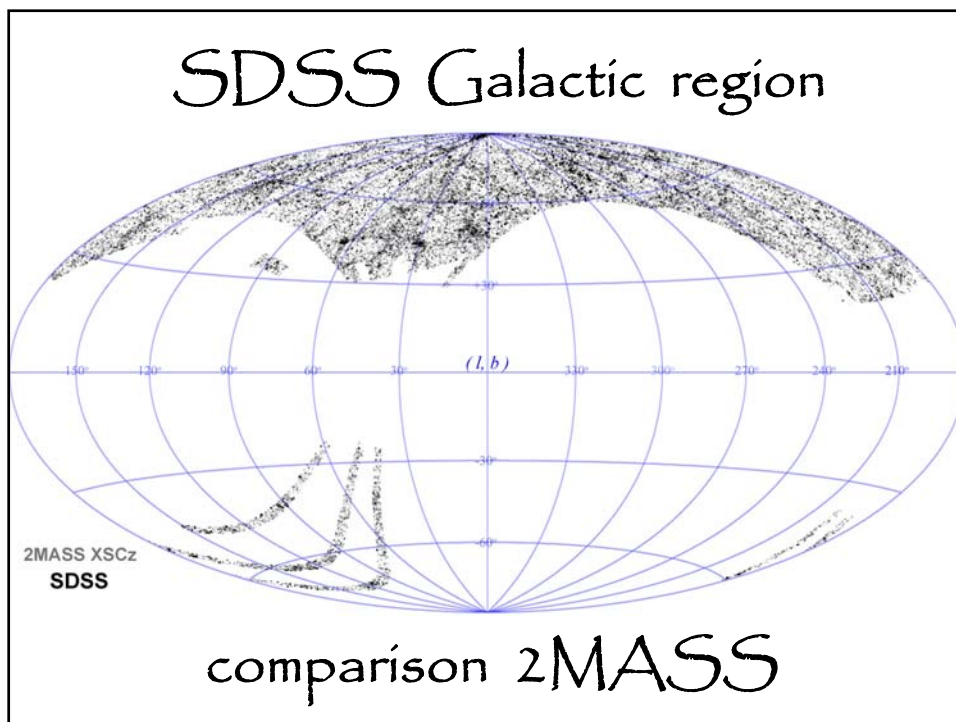
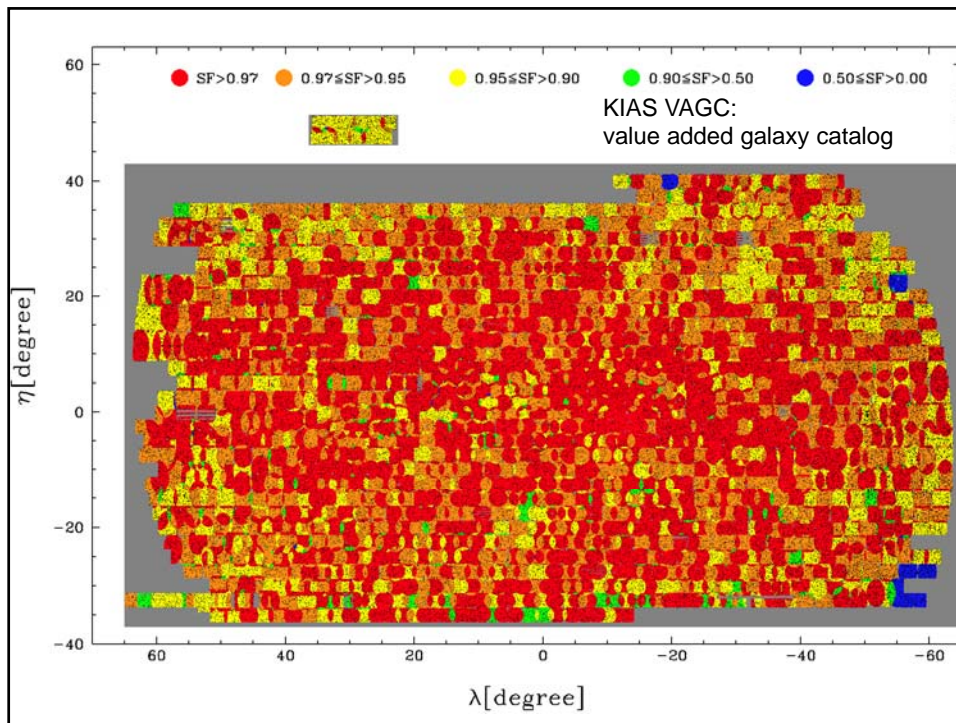
30 CCD  
chips

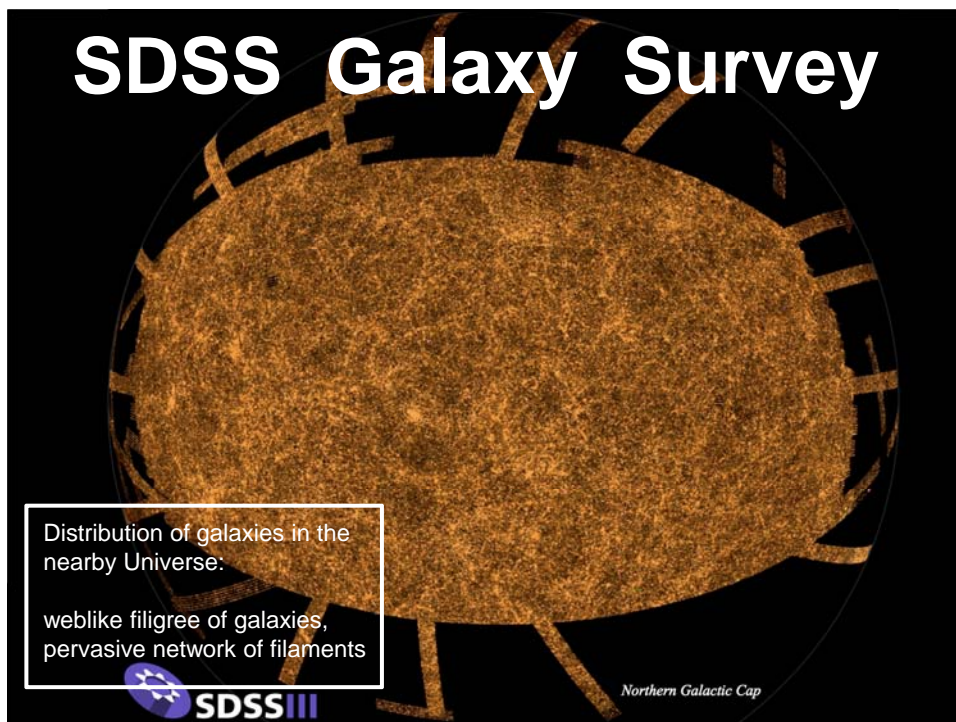
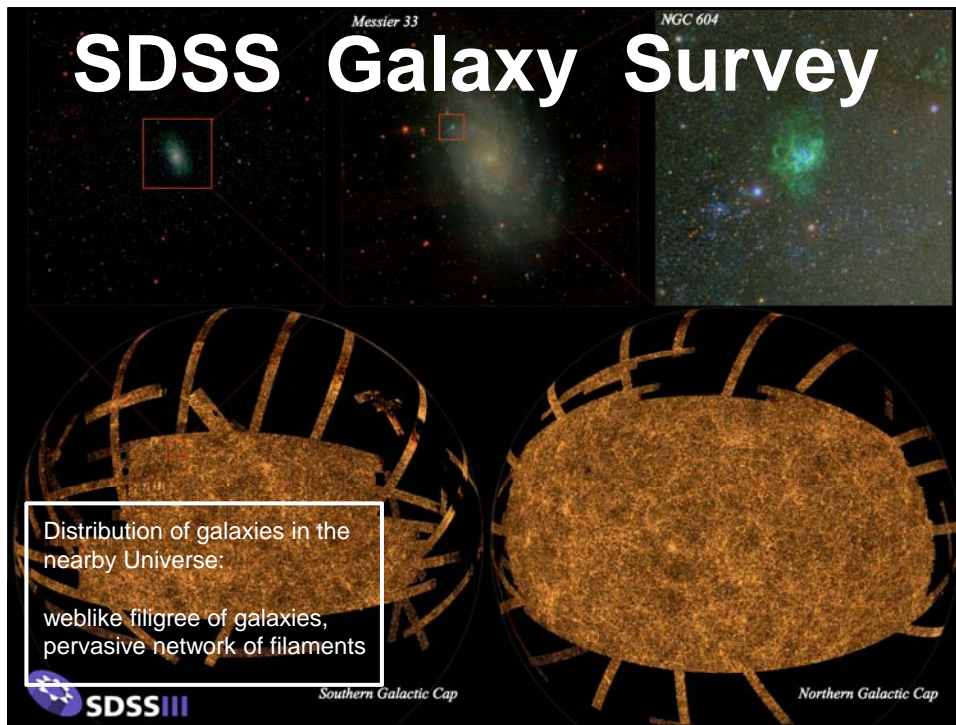


Fiber  
Spectrograph








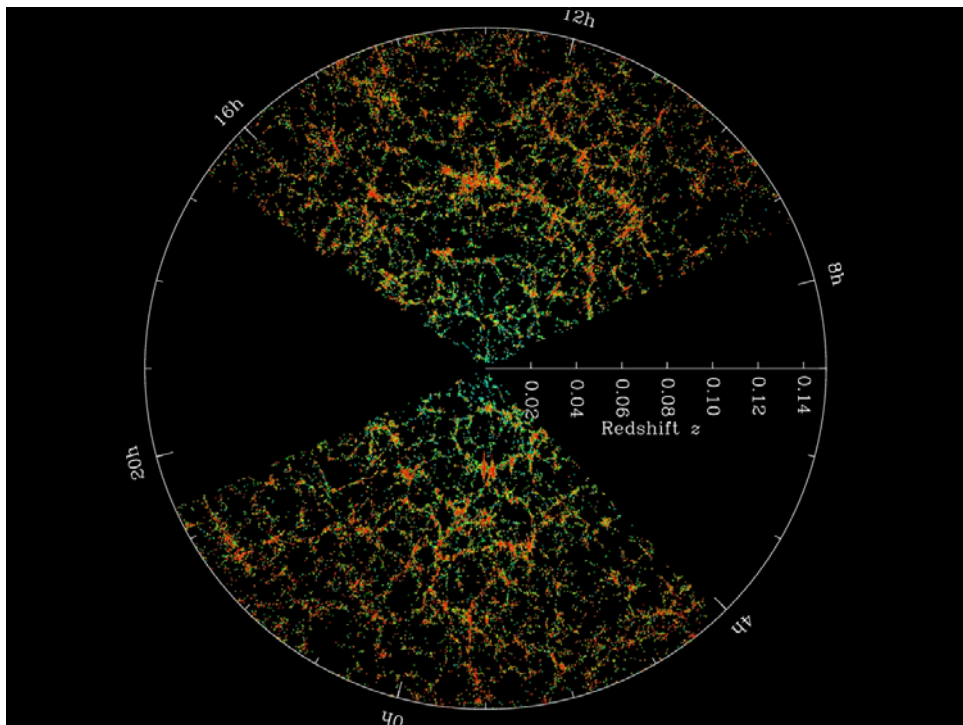


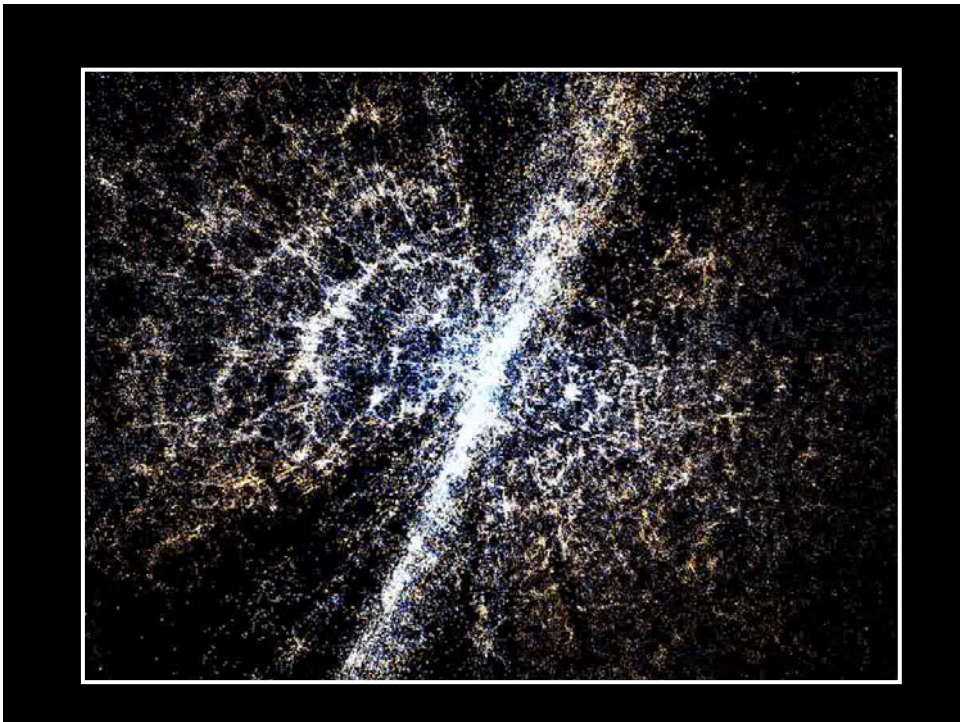
# SDSS survey

- 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  $z > 2.3$



VOID_00 J083707.48+323340.8	VOID_01 J100842.44+511623.9	VOID_02 J102260.68+561932.1	VOID_03 J102819.23+623502.6	VOID_04 J103606.47+550847.6
VOID_05 J130526.08+544651.9	VOID_06 J132232.48+544906.5	VOID_07 J132718.56+593010.2	VOID_08 J135113.62+463509.2	VOID_09 J135635.46+593041.3
VOID_10 J140034.49+551615.1	VOID_11 J142416.41+523208.3	VOID_12 J143052.33+551440	VOID_13 J143653.77+524400.6	VOID_14 J154452.18+382845.6



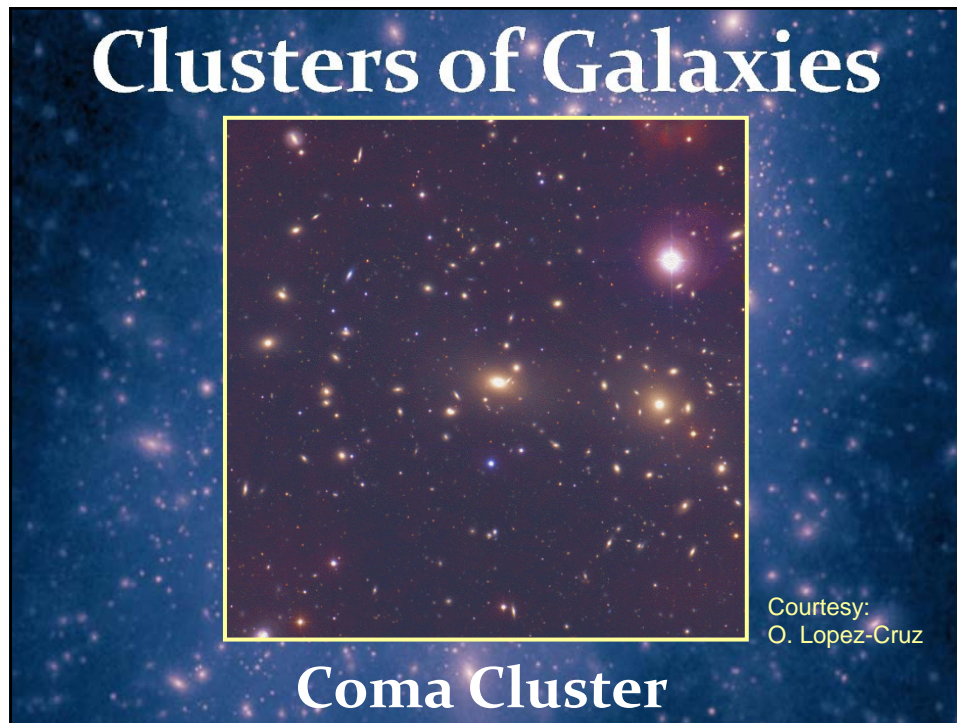




## Clusters of Galaxies

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





# 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
  - synchrotron radiation in shocked, hot, ionized intracluster plasma



# Clusters of Galaxies

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

## I. Clusters are Halos of Dark Matter:

$$M_{\text{DM}}/M_{\text{total}} \sim 82\%$$

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

$$M_{\text{ICM}}/M_{\text{total}} \sim 16-17\%$$

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

$$M_{\text{stars}}/M_{\text{total}} \sim 2\%$$

# 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**

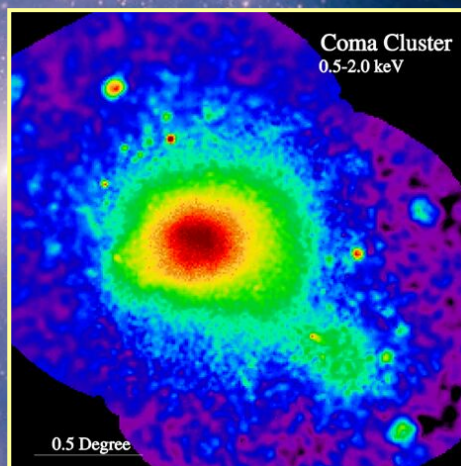
**Intracluster Gas,**

trapped and heated to a temperature of the order of

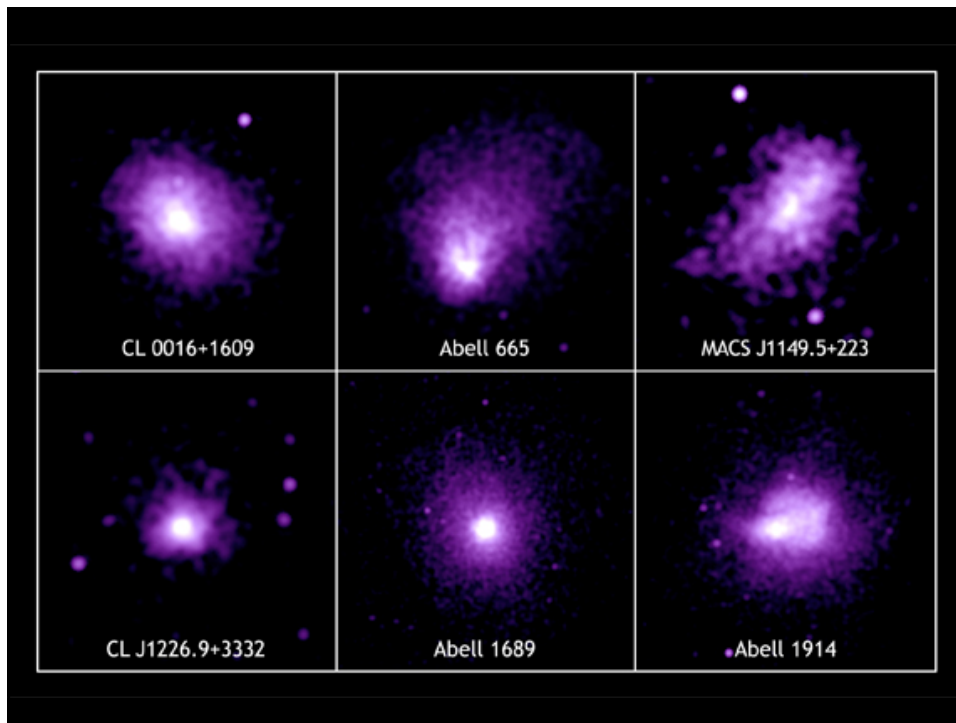
$$T \sim 10^8 \text{ K}$$

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:

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

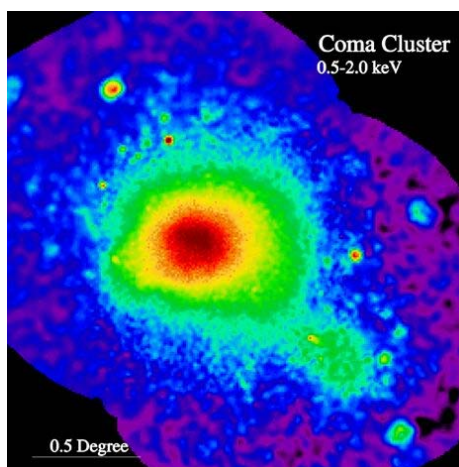
### Determination Mass from X-ray observations:

-assumption:

Isothermal:  $T(r) = T_0$

-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**

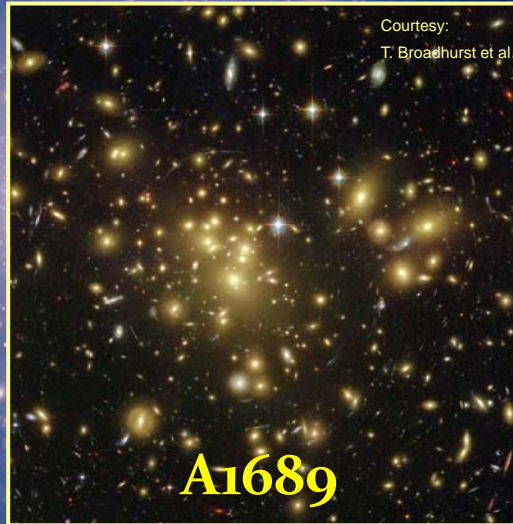
According to

Einstein's theory of

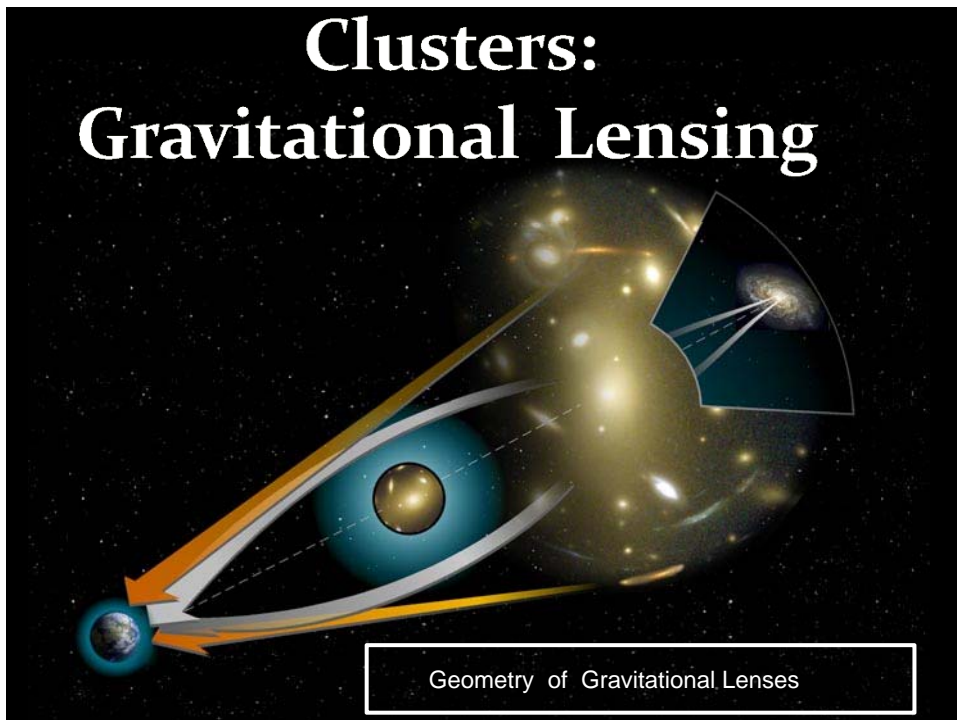
General Relativity,

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

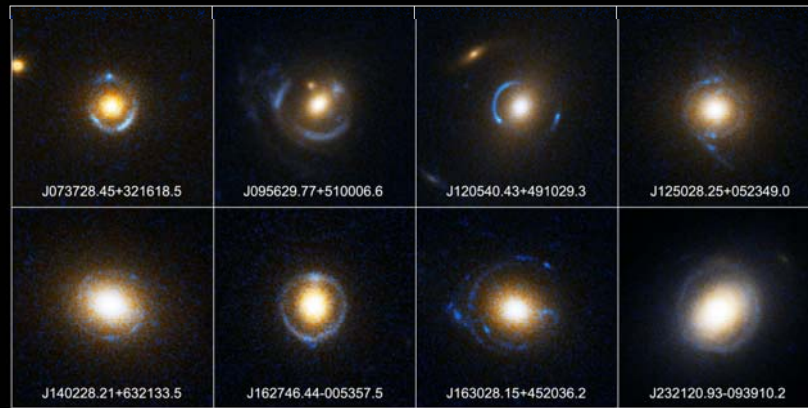
**Gravitational Lens**



# Clusters: Gravitational Lensing



# Gravitational Lensing: Einstein Ring



Einstein Ring Gravitational Lenses  
Hubble Space Telescope • Advanced Camera for Surveys

NASA, ESA, A. Bolton (Harvard-Smithsonian CfA), and the SLACS Team

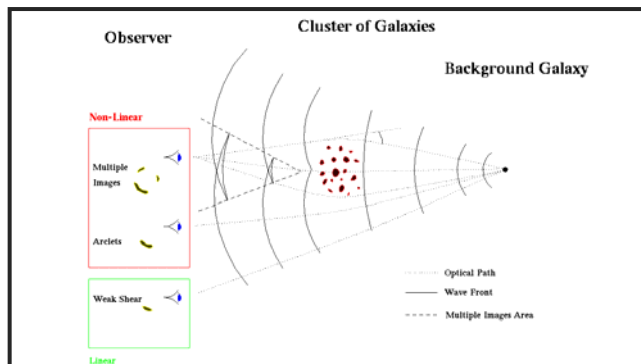
STScI-PRC05-32

## Gravitational Telescopes: Weak vs. Strong Lensing

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

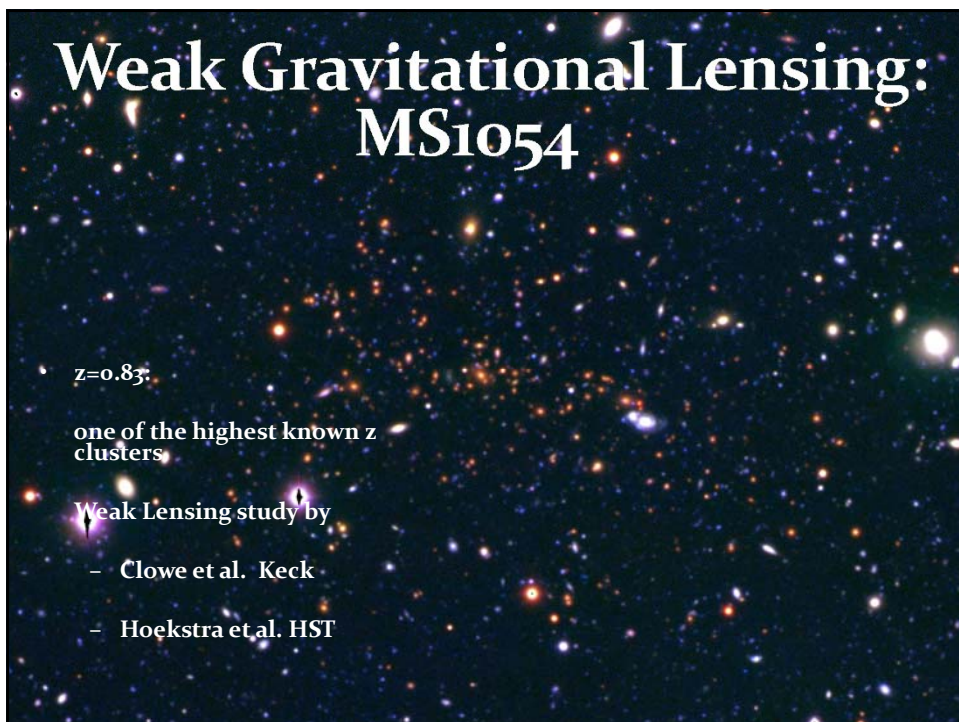
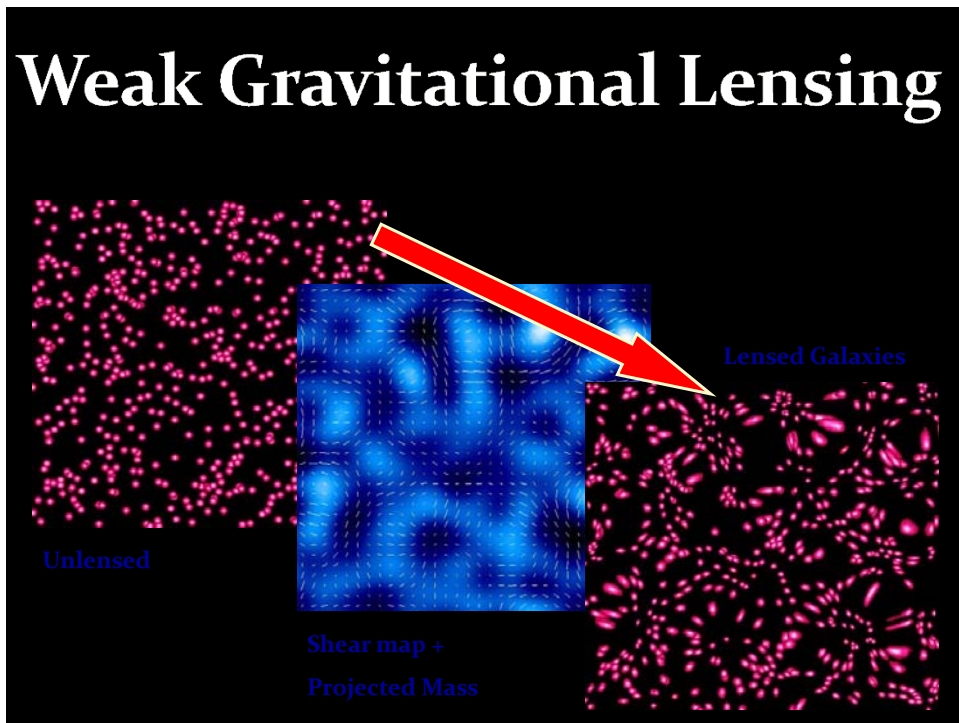
Two kinds of lensing:

- **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      |                       |



# 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.**

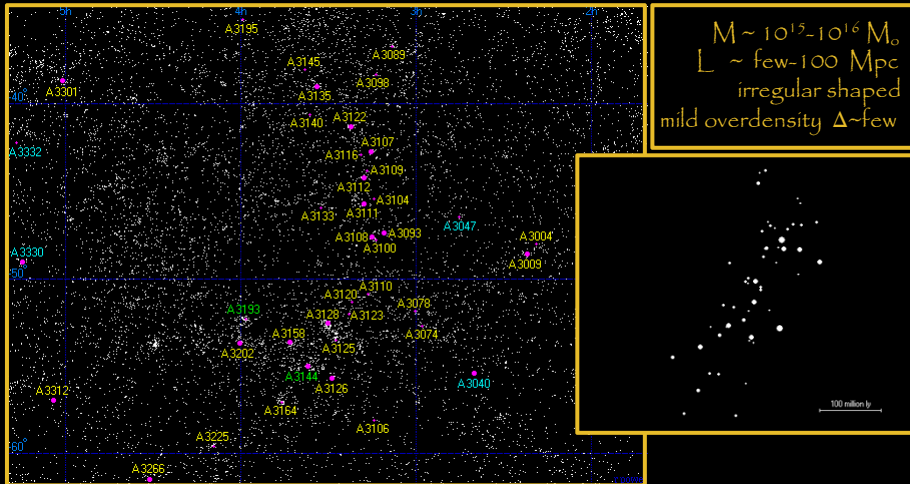


Superclusters



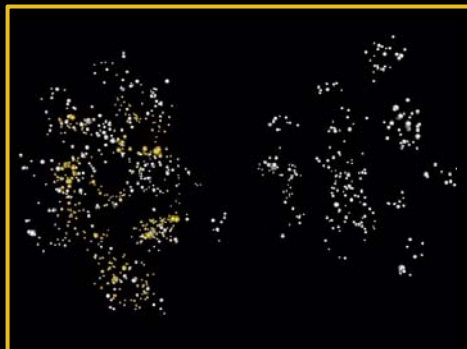
# Superclusters

Large groups of clusters & galaxies (1-dozens)

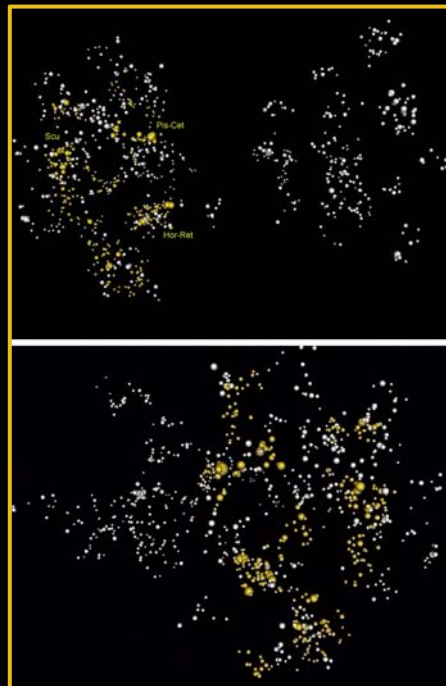


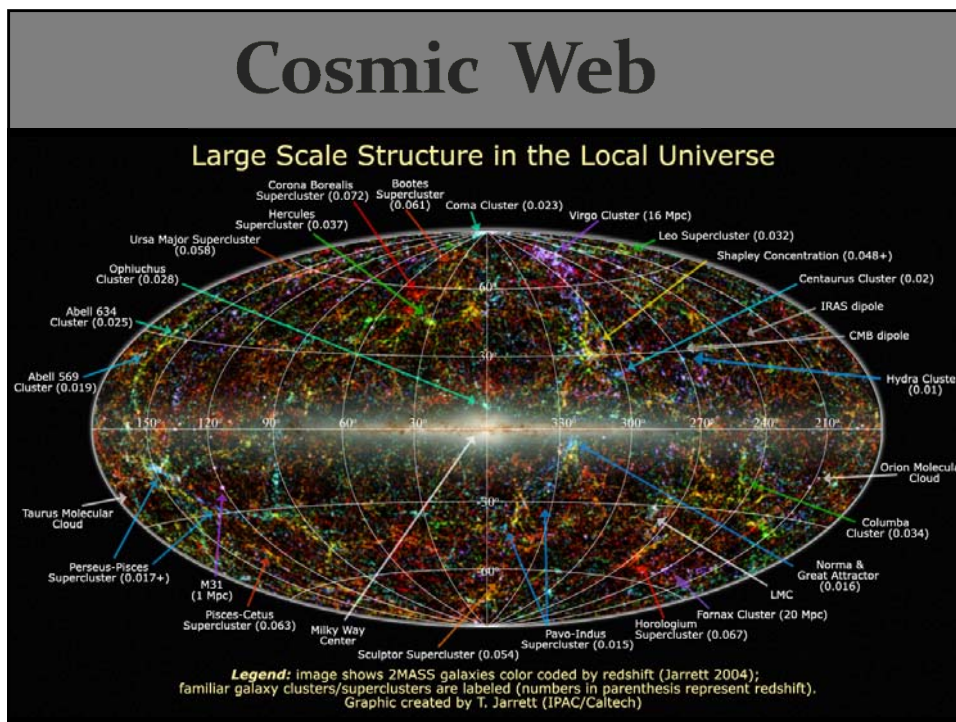
## Superclusters:

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



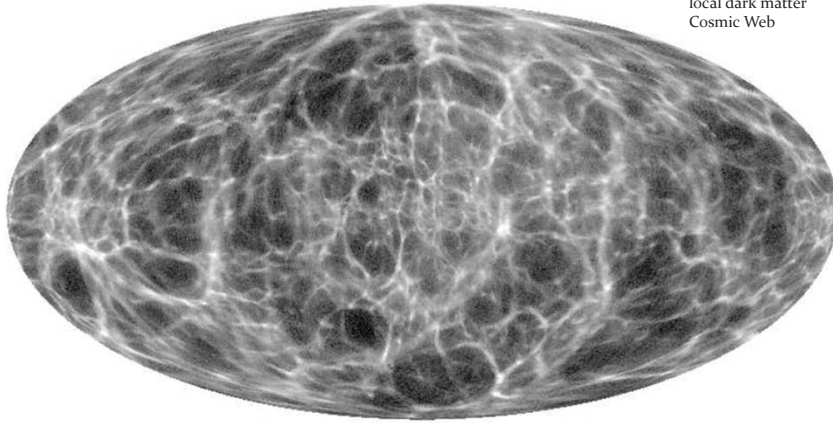
superclusters are not isolated single objects,  
but integral components in the pervasive  
Cosmic Web





# local Cosmic Web: 2MRS

most detailed reconstruction  
of the  
local dark matter  
Cosmic Web



1.0  6.0

Courtesy: Francisco Kitaura

Voids

REVIEW ARTICLE

# Giant voids in the Universe

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

\* Institute of Applied Mathematics, Moscow A-47, 125047, USSR

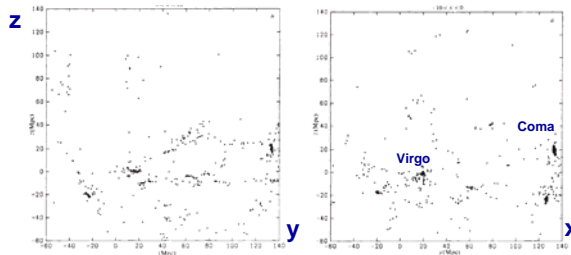
† Tartu Astrophysical Observatory, 202444 Estonia, USSR

‡ European Southern Observatory, 8046 Garching, FRG

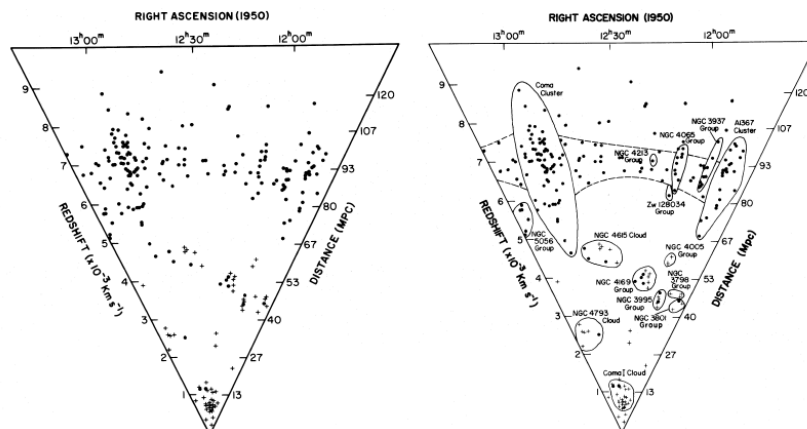
Recent observations indicate that most galaxies are concentrated in superclusters consisting of galaxies, and clusters of galaxies, aligned along strings. Giant volumes exist between superclusters which are almost empty of visible objects. Theories of galaxy formation predict the formation of non-spherical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

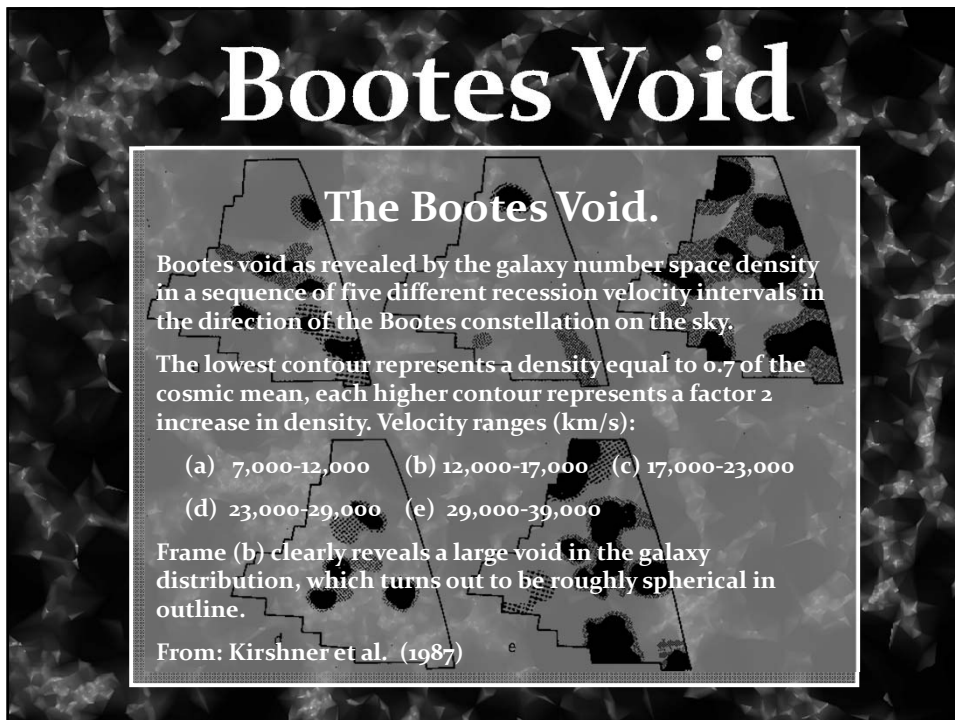
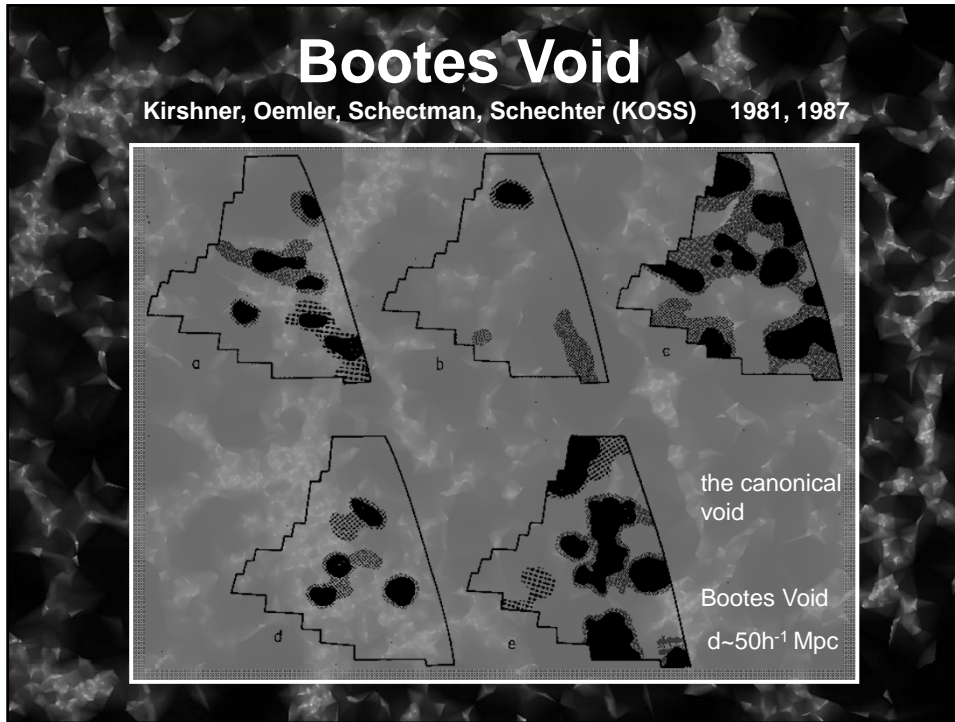
First linking of observationally visible void regions and the theory of cosmic structure formation.



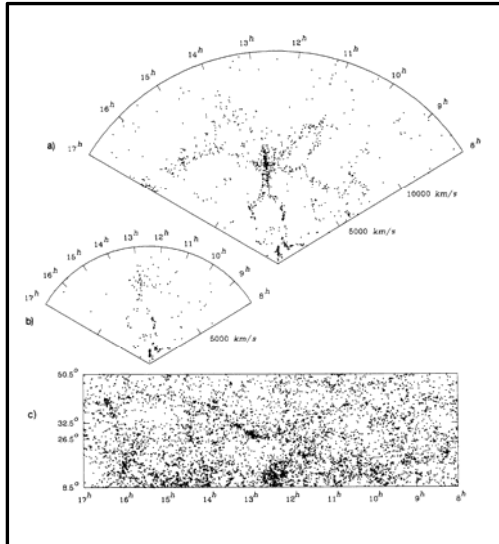
## First Voids



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



# Voids & the Cosmic Web

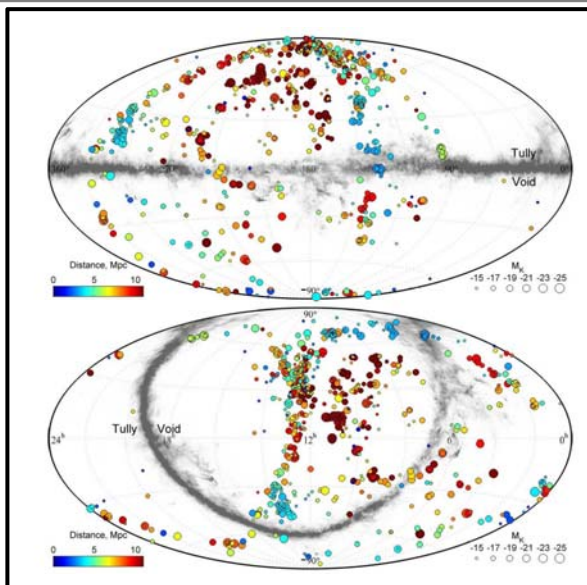


deLapparent, Geller & Huchra, 1986:

“a slice of the Universe”

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

## local Cosmic Web: Local Void

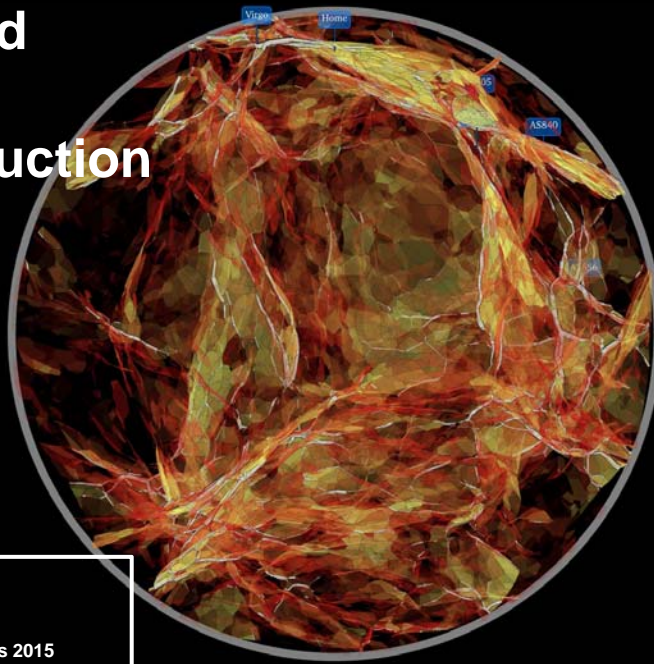


Karachentsev et al.

LV catalog:  
galaxies within 10 Mpc reveal  
beautifully the magnificent

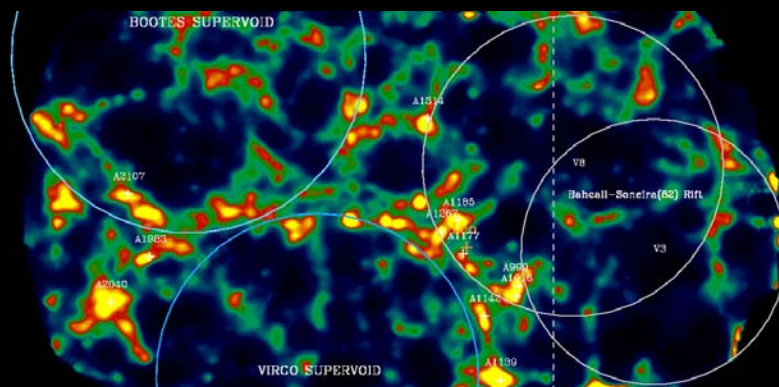
Local Void – Tully Void

# Local Void Adhesion Reconstruction



Local Void Reconstruction:  
Hidding, vdW, Kitaura & Hess 2015

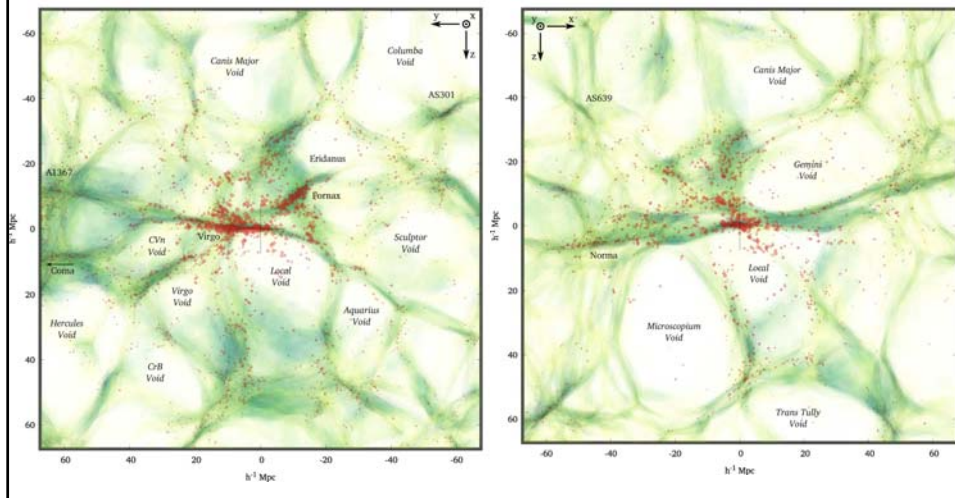
# Bootes Void: Substructure



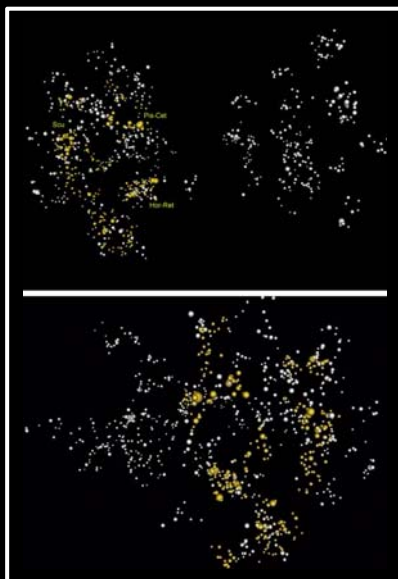
Platen et al. 2009

# ⊥ Supergalactic Plane

mean adhesion reconstruction



## Voids & Clusters



Einasto, Saar et al. (1990s)

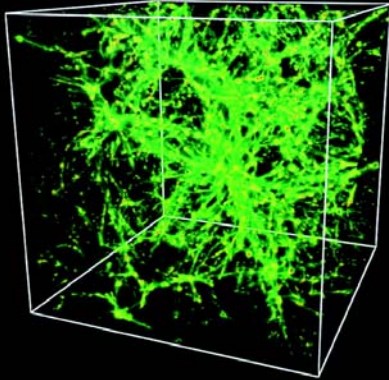
- Superclustering in Abell/APM clusters catalog
- Finding of characteristic scale ~140 Mpc, corresponding to large voids in the cluster distribution

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

(see talk by Collins).

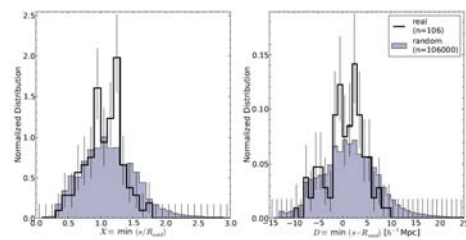


# Voids & the Gaseous Web

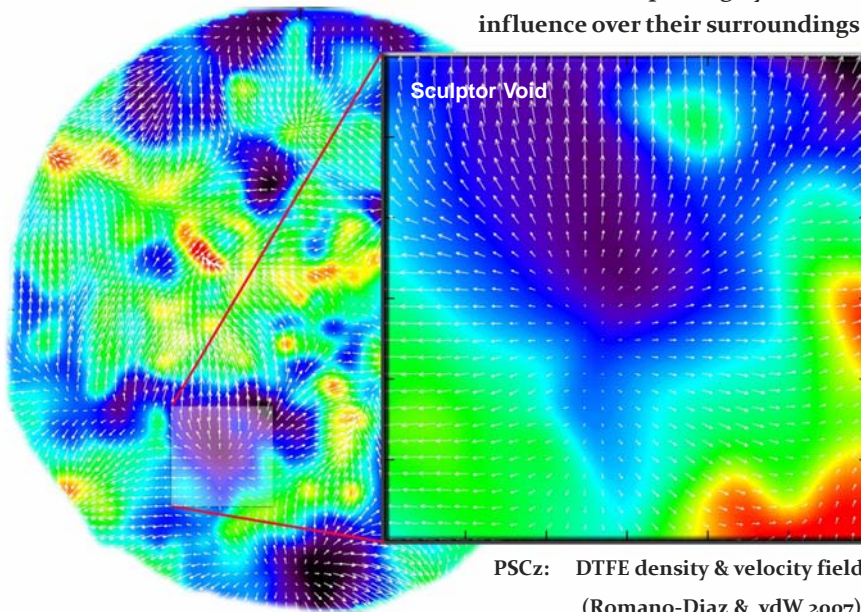


Tejos et al. 2012:

HI Ly $\alpha$  absorption systems clearly delineate voids



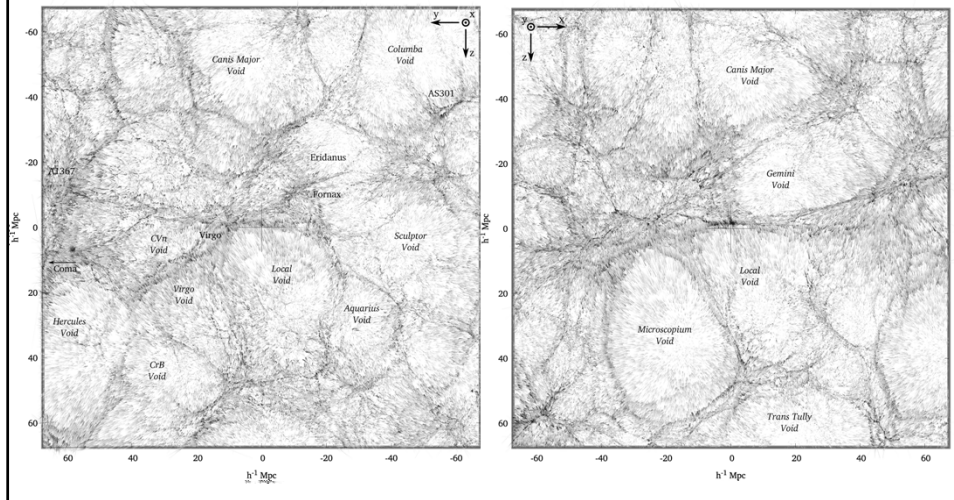
Voids exert a repulsing dynamical influence over their surroundings.



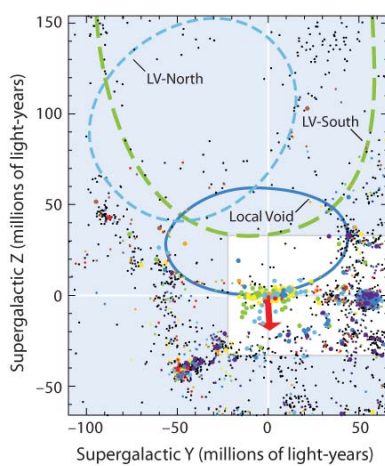
PSCz: DTFE density & velocity field (Romano-Diaz & vdW 2007)

# ⊥ Supergalactic Plane

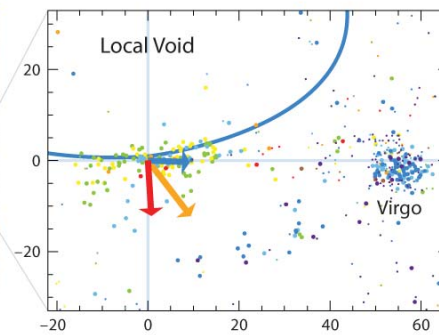
mean adhesion reconstruction



# Push of the Local Void



Our motion with the respect to galaxies in the Local Supercluster *Tully et al. 2008, ApJ, 676, 184*



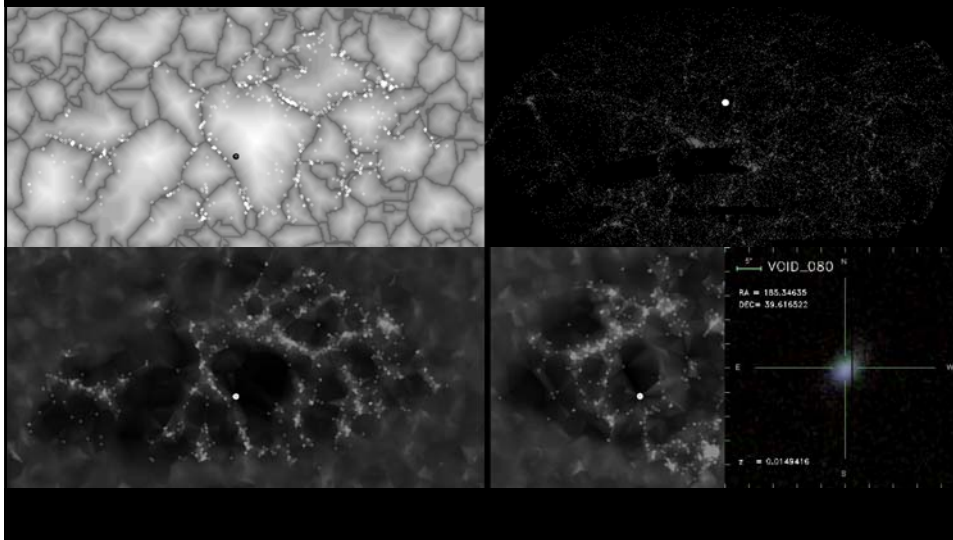
Tully et al. 2008:  
Local Void pushes with ~260 km/s against our local neighbourhood

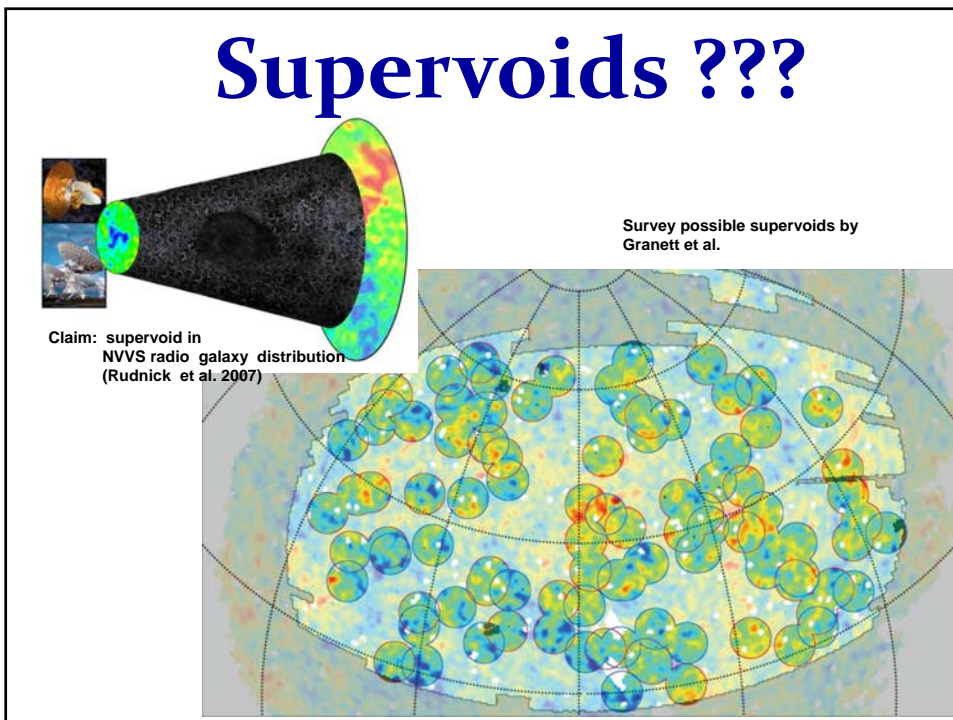
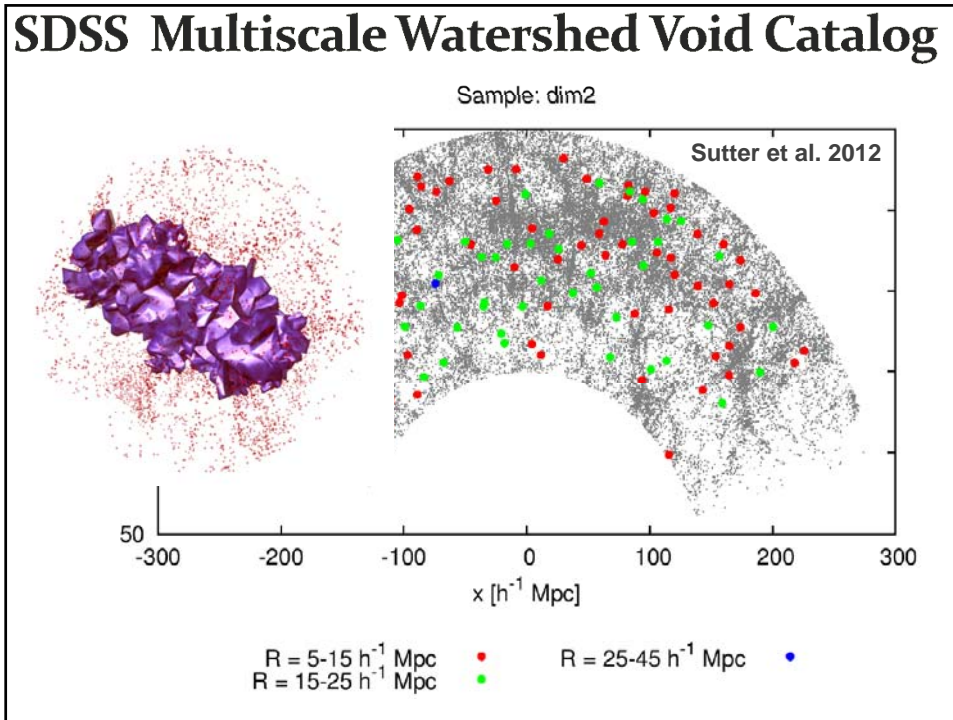
## Voids: Identification & Catalogues

- 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

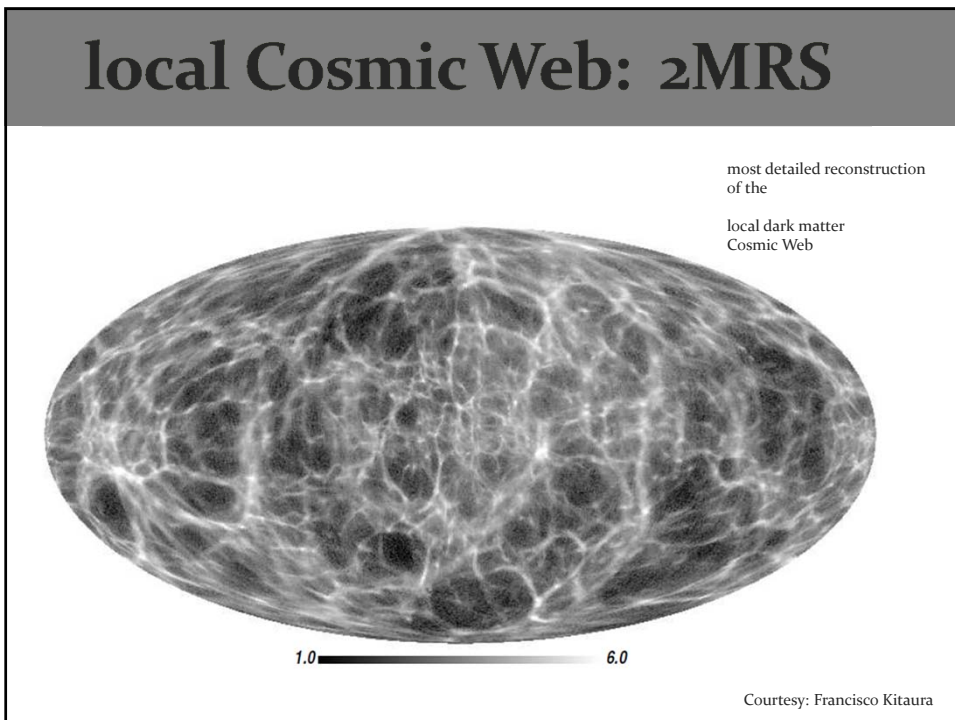
- Catalogues:
  - Fairall 2006 by eye
  - Pan et al. 2012 Hoyle-Vogele algorithm
  - Sutter et al. 2012 Watershed/ZOBOV multiscale

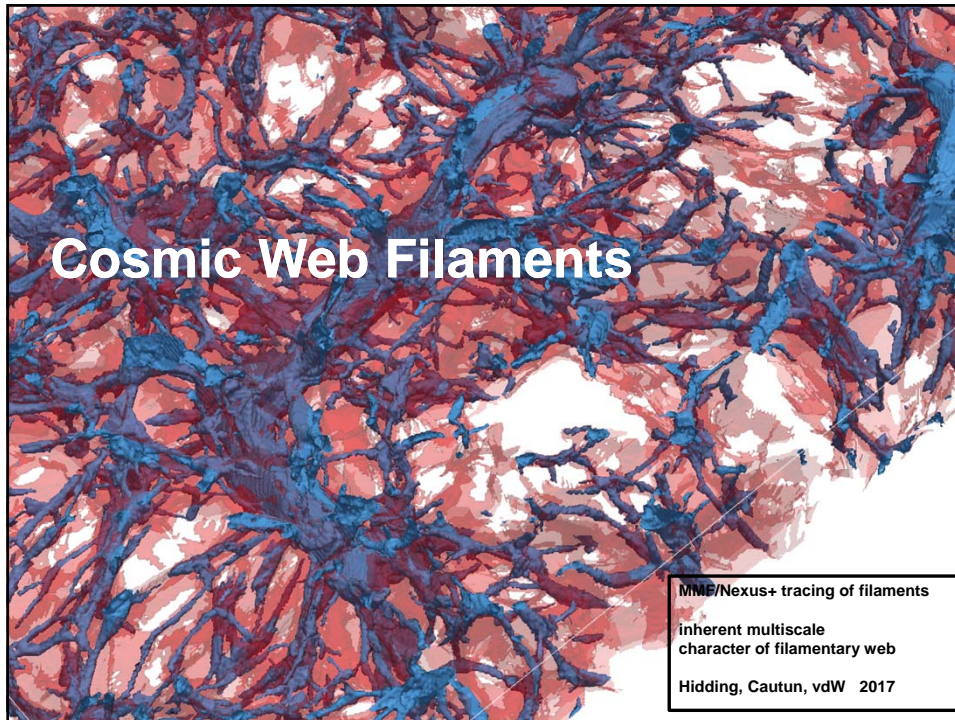
## SDSS Voids





# Filaments





### Nexus Filaments

a) NEXUS\_den

b) NEXUS\_tidal

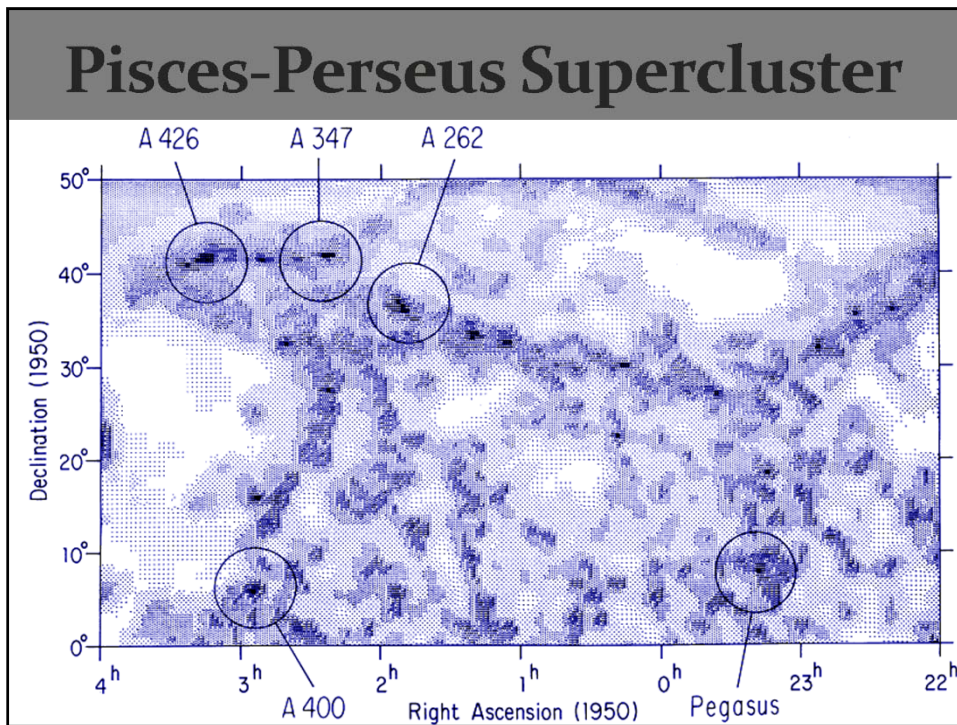
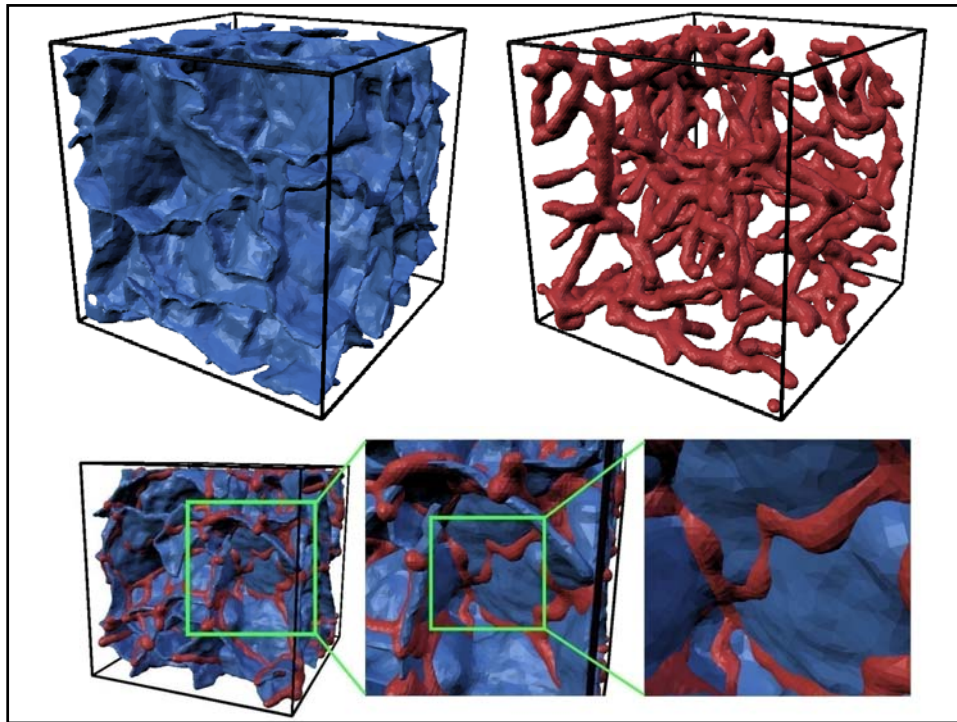
c) NEXUS\_denlog

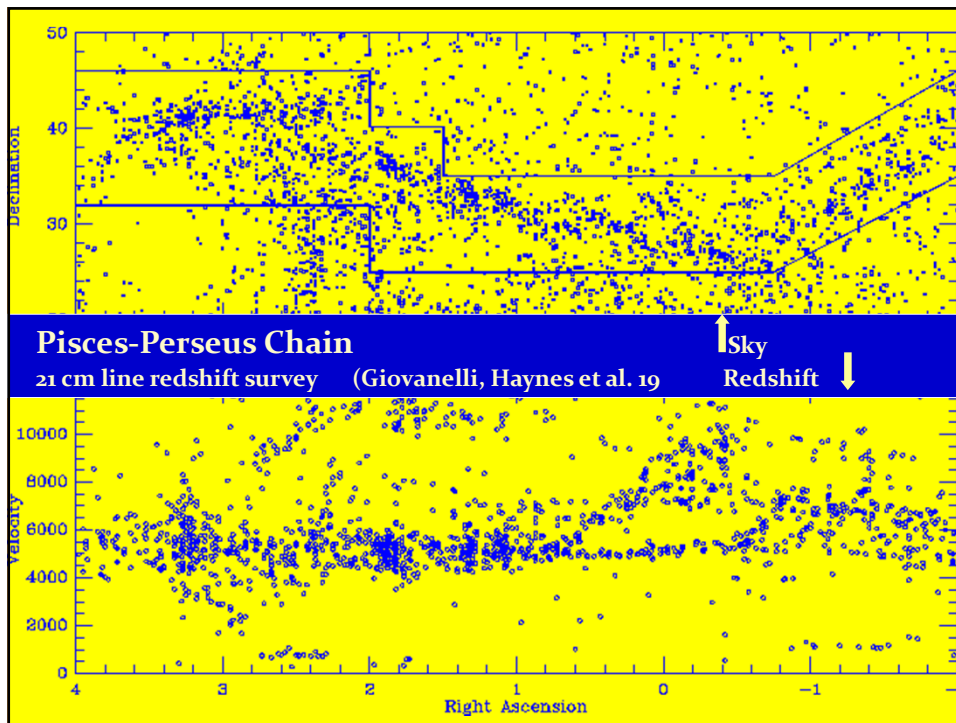
d) NEXUS\_veldiv

e) NEXUS\_velshear

f) NEXUS+

- Nexus identification of filaments (blue)
  
- Identification on the basis of 6 different physical characteristics of the cosmic mass distribution:
  - Density
  - Tidal field
  - Log(density)
  - Velocity Divergence
  - Velocity Shear
  - Nexus+





## Pisces-Perseus Chain

Canonic example of a strongly flattened supercluster consisting of

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

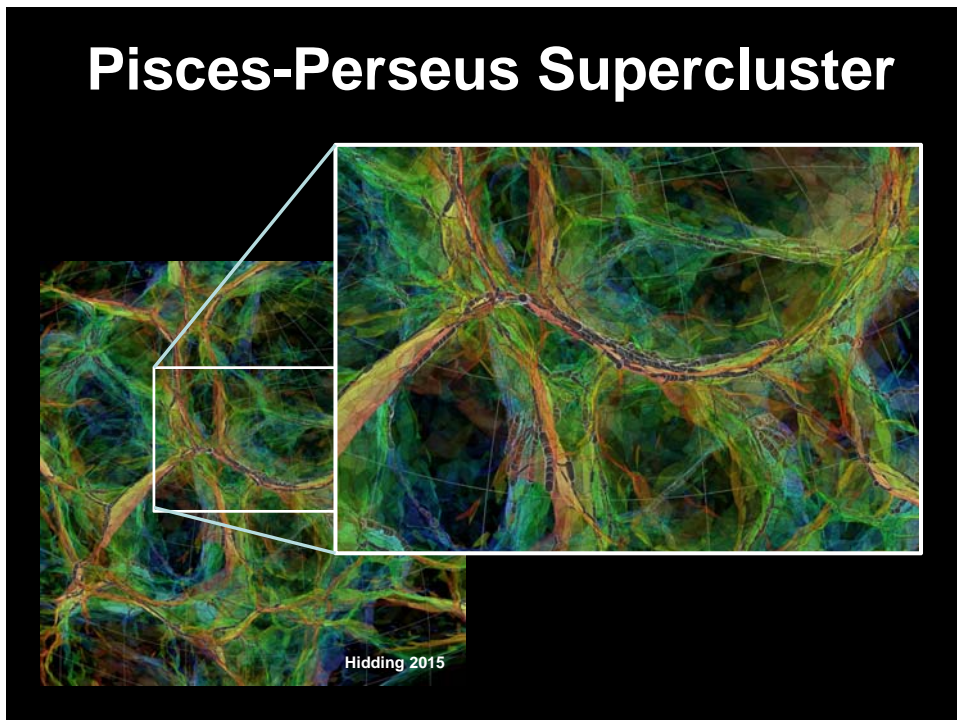
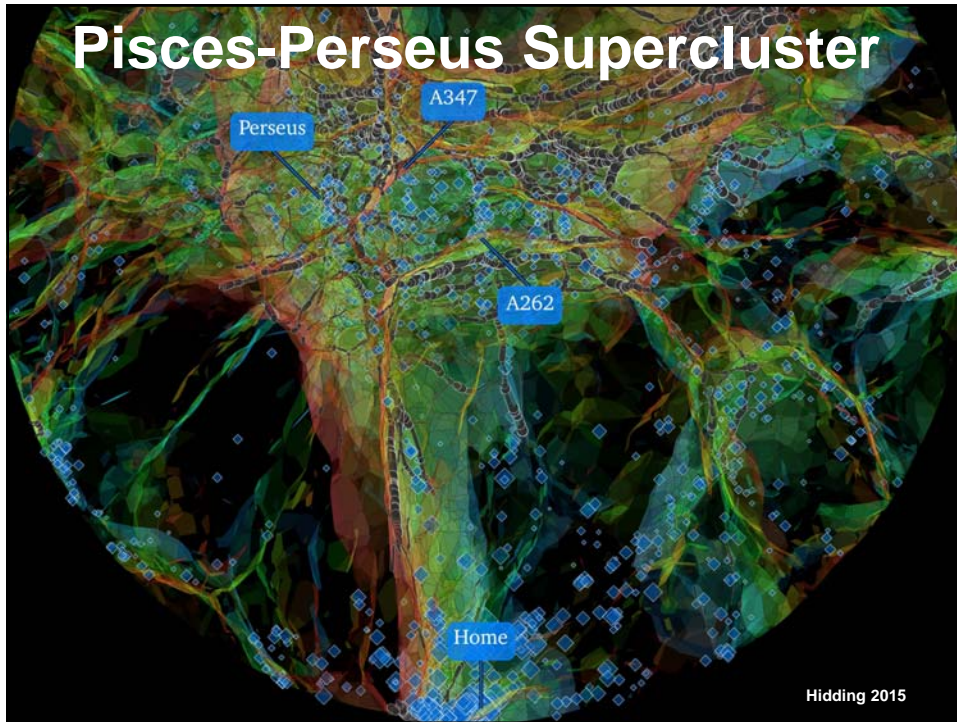
Northern boundary: ridge south-westward of Perseus cluster (A426)

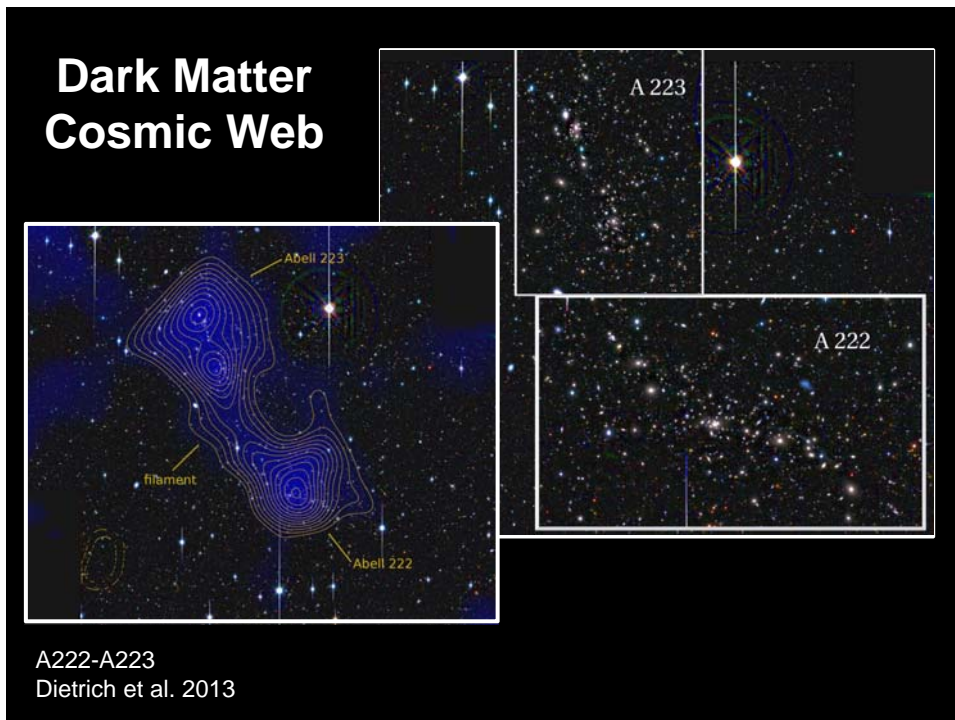
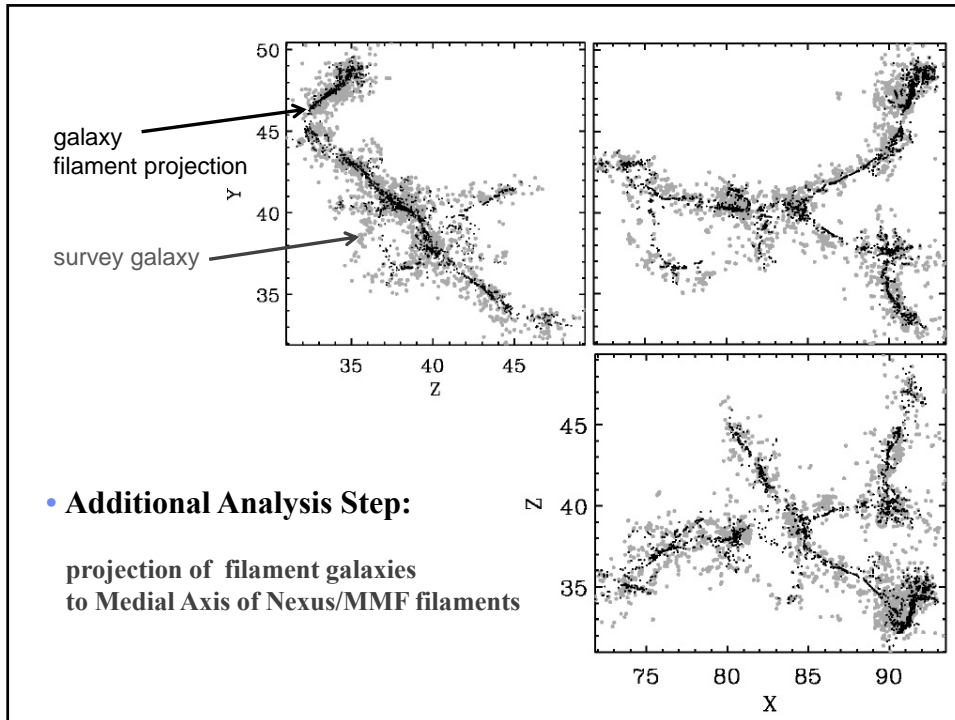
Dimensions Ridge:  $5h^{-1}$  Mpc wide

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

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



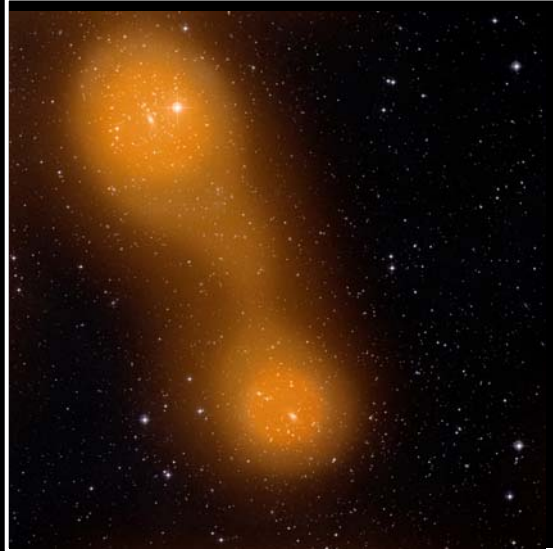




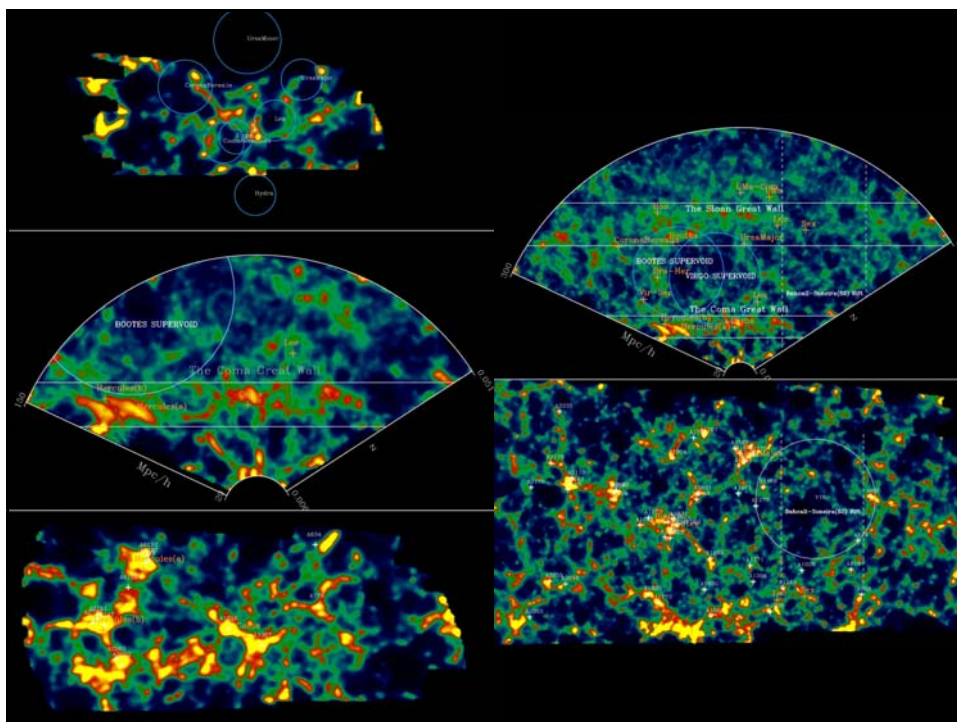
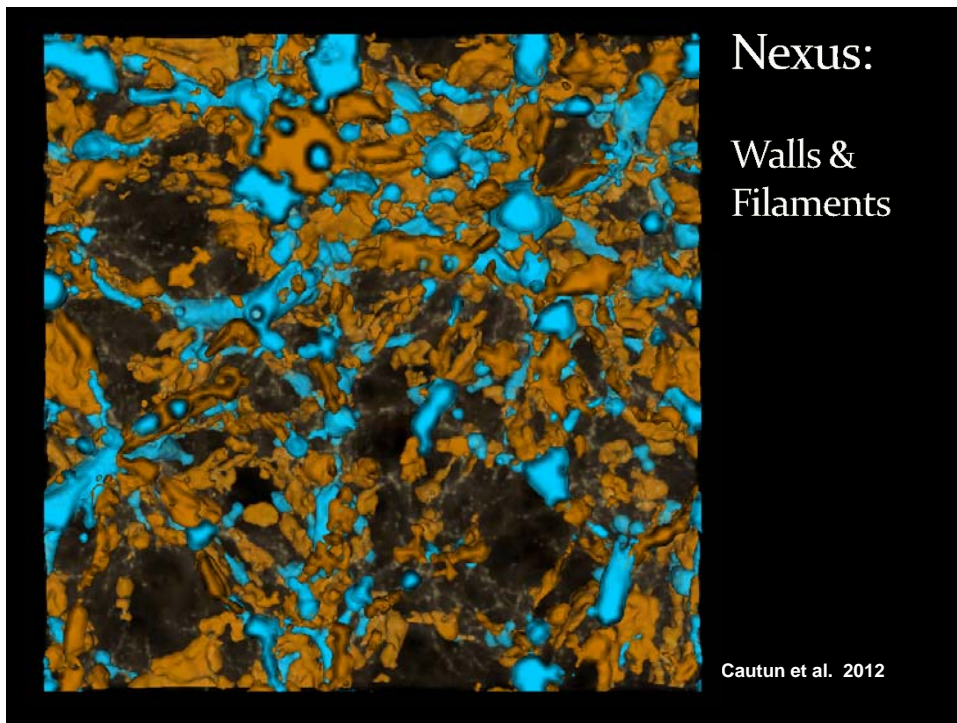
# the Gaseous Cosmic Web

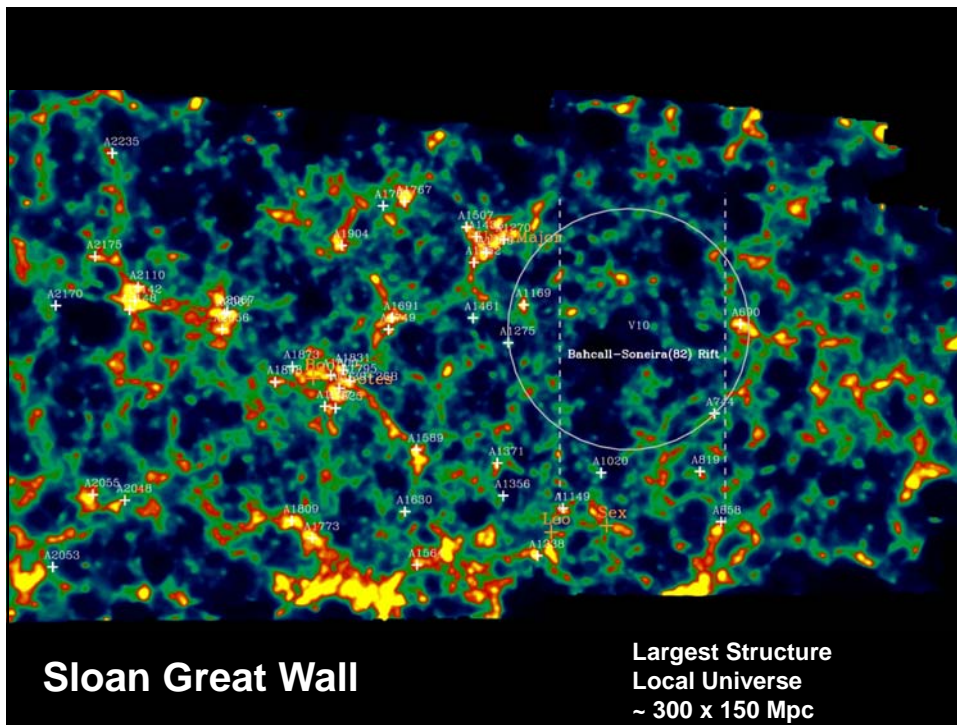
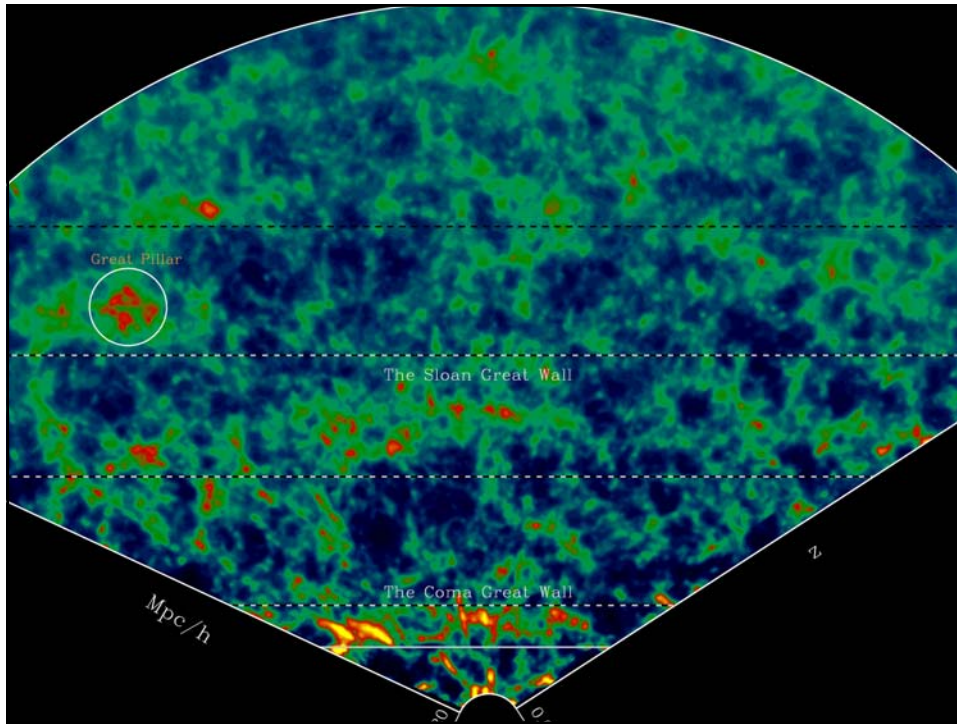
SZ detection of  
Inter-cluster bridge/filament  
in between clusters  
A401 and A399

ESA/Planck collaboration

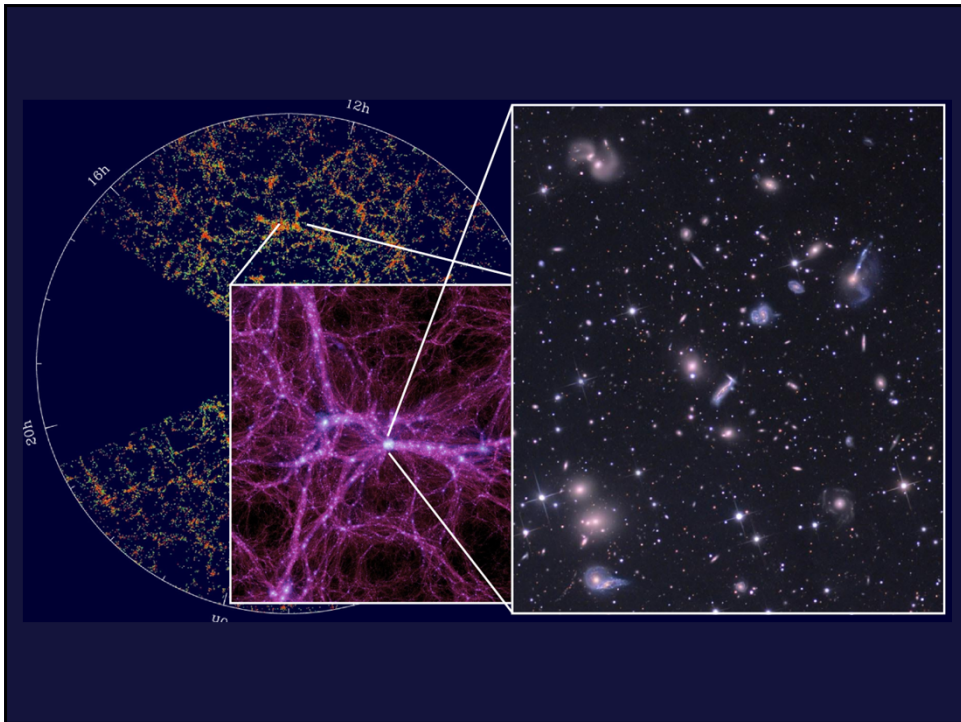


Walls - Sheets

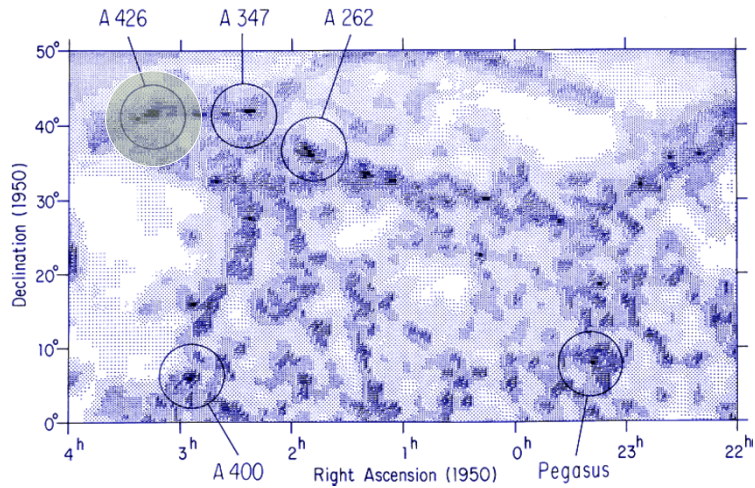




# Cluster Nodes

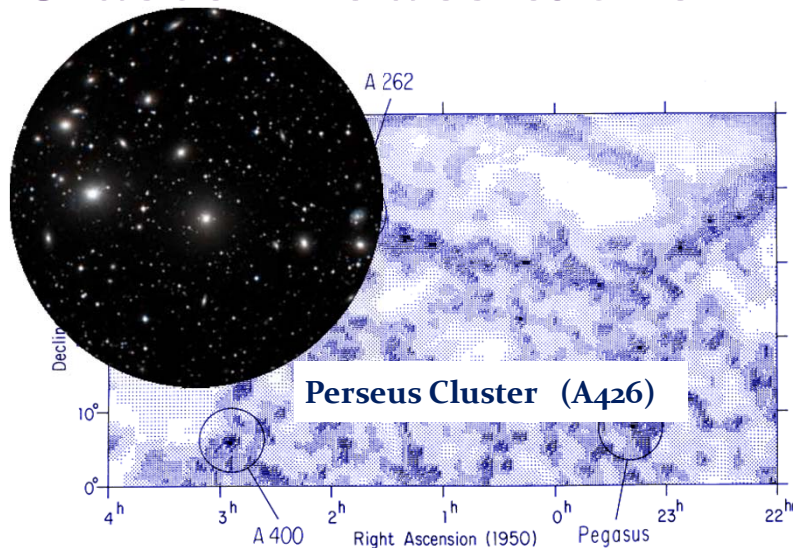


# Cluster Nodes & the Web

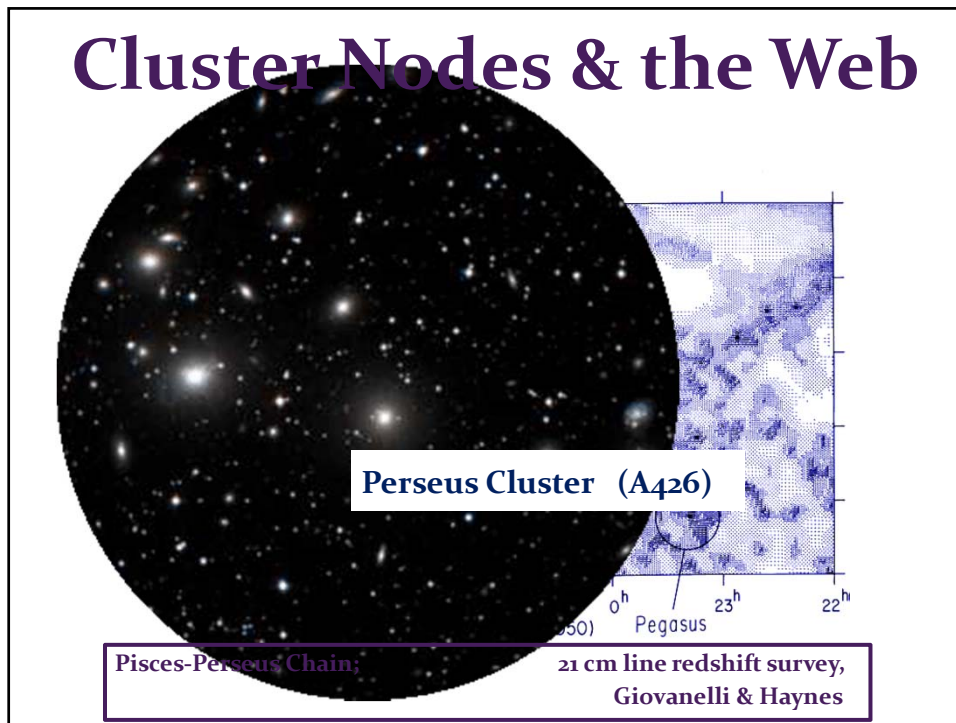


Pisces-Perseus Chain; 21 cm line redshift survey, Giovanelli & Haynes

# Cluster Nodes & the Web

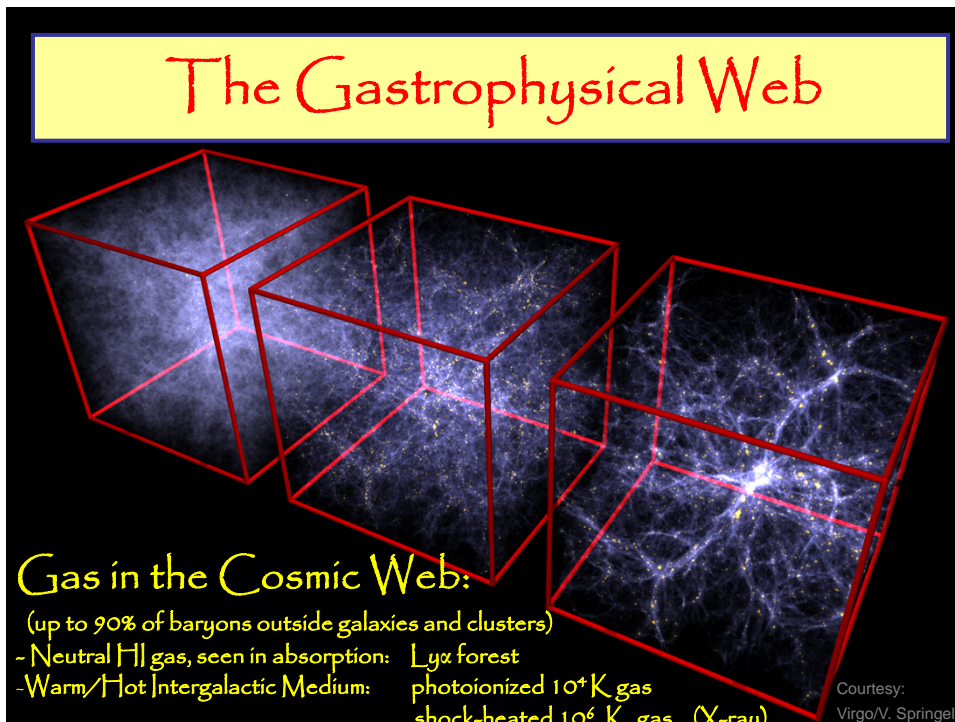
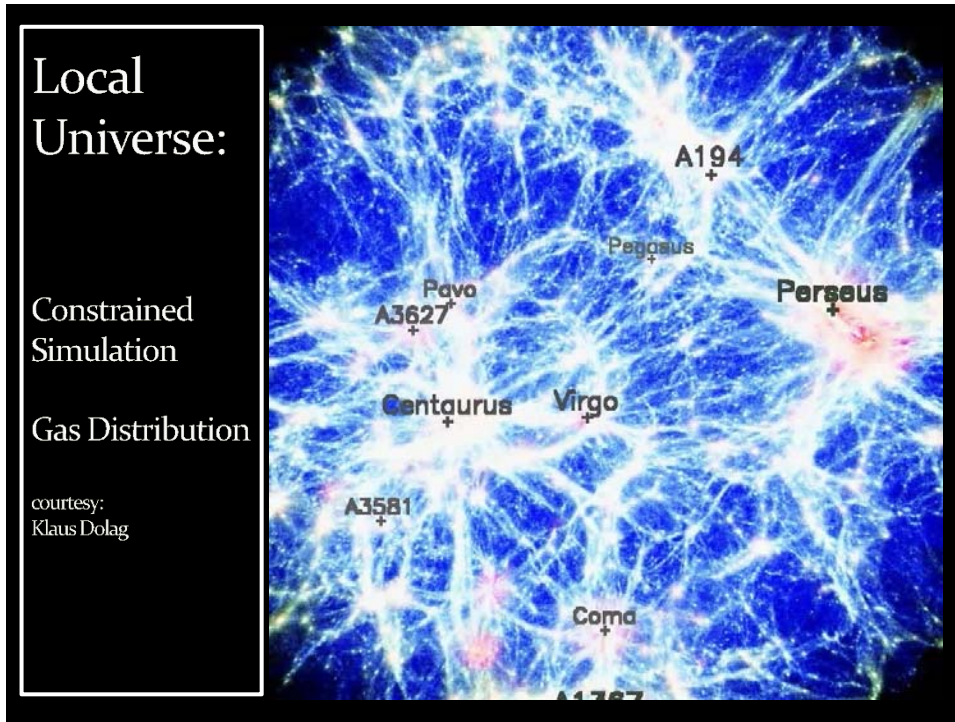


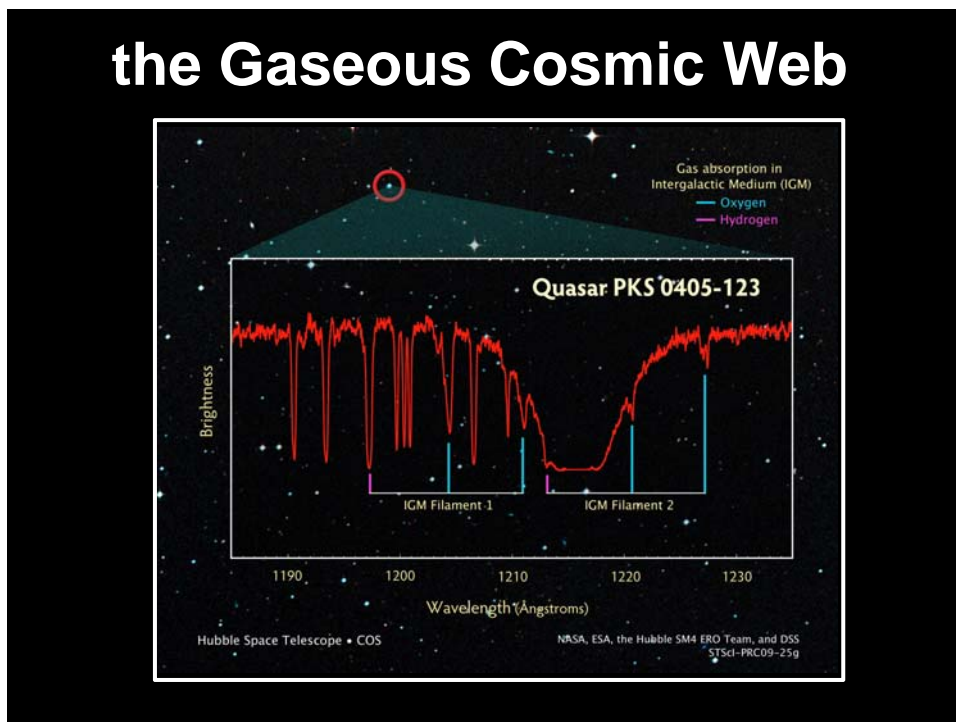
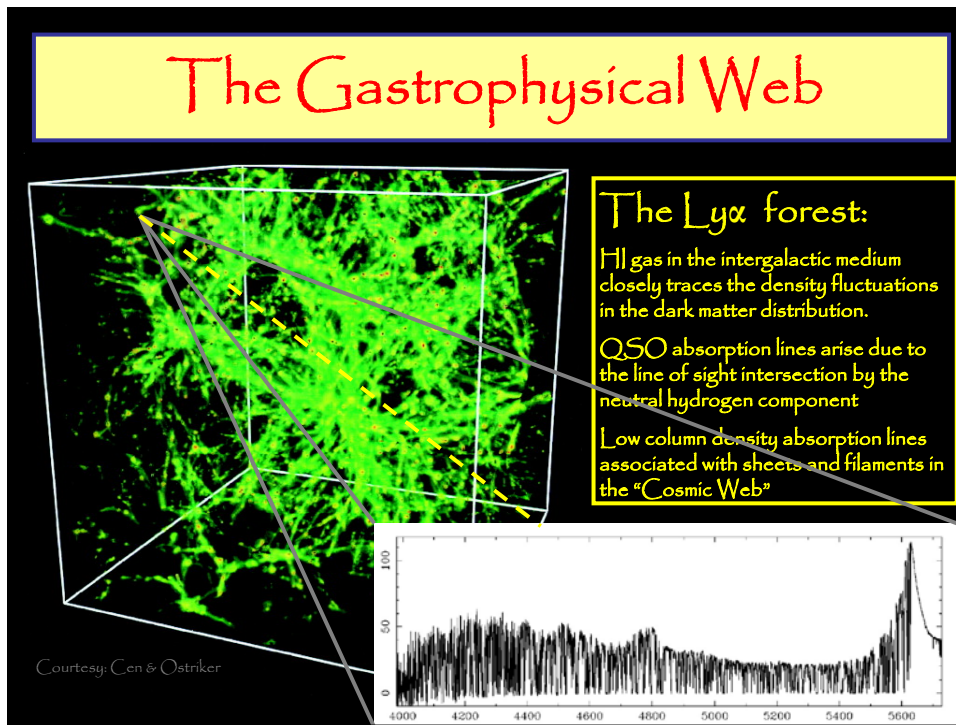
Pisces-Perseus Chain; 21 cm line redshift survey, Giovanelli & Haynes



# Cosmic Web: Gas







# Cosmic Web: in depth



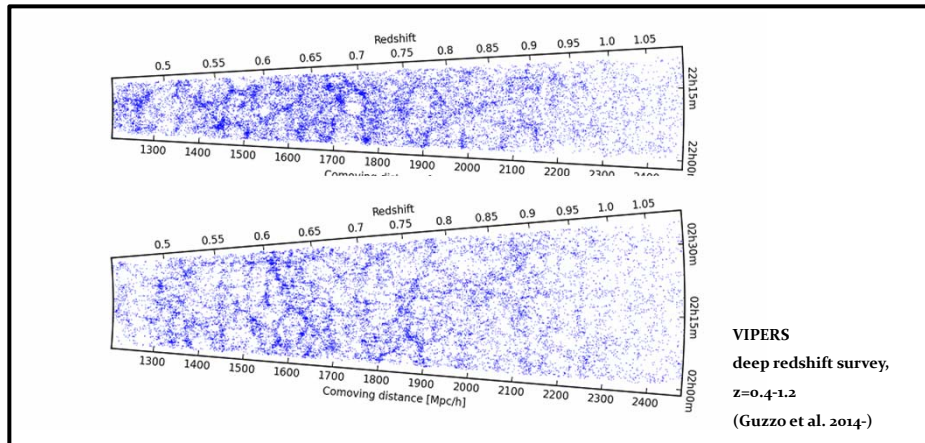
Far Away,  
Long Ago

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.

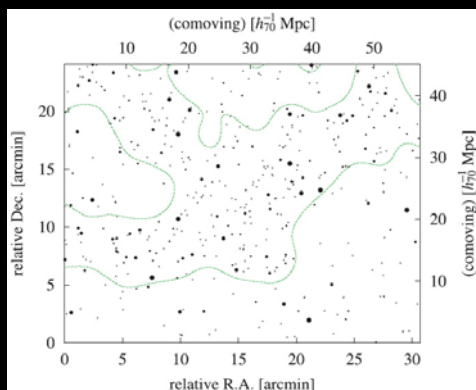
Simulation of VIRMOS redshift survey, web out to large redshift

# VIPERS: Cosmic Web at High z



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

## Far Away, Long Ago

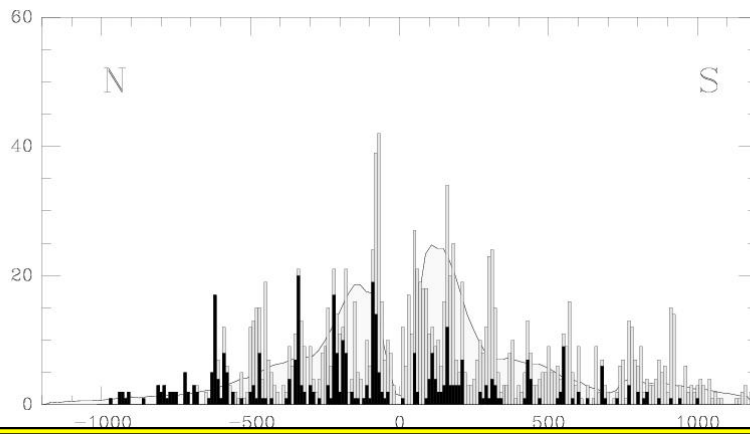


Various surveys are attempting to trace the large scale structure out to large cosmic depths/redshifts.

- 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 Ly $\alpha$  emitting galaxies.  
A filament at redshift  $z \sim 3$ ?

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