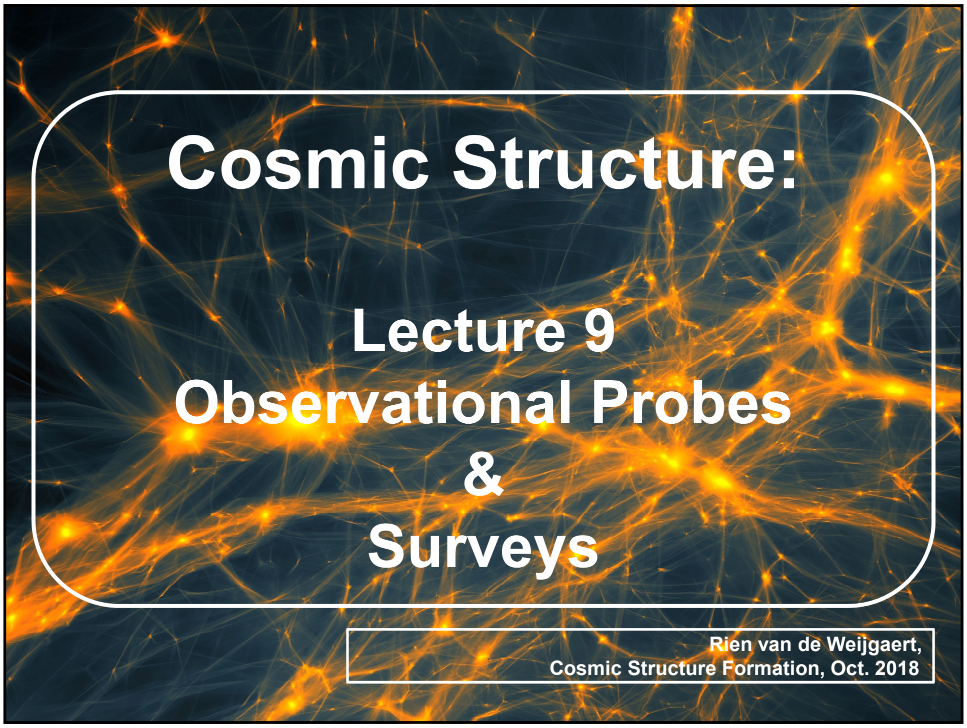
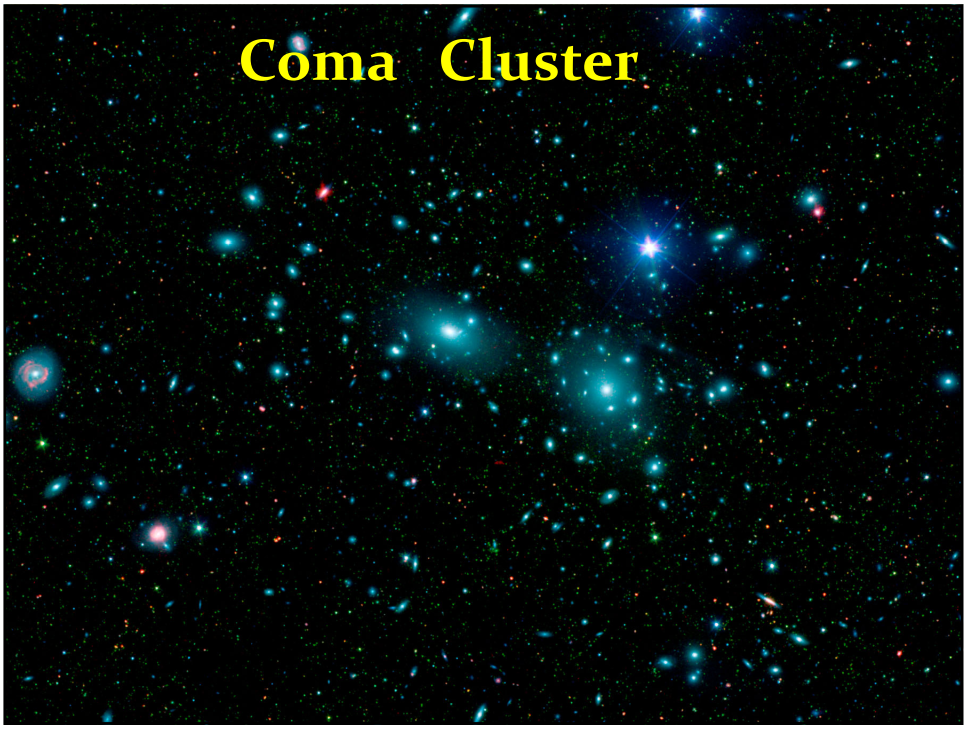


Galaxy & Cluster Distribution

Map of the Universe

How to map the structures and patterns in the Universe ?

- Use galaxies as beacons
- Map of Galaxy positions
- Tracing of structures from distribution of galaxies



Galaxy Surveys:

Luminosity Function
&
Survey Depth

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 □(r,□,□,□,T):
    sampling rate of galaxies at
    - distance r
    - sky position □,□
    - frequency □
    - 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

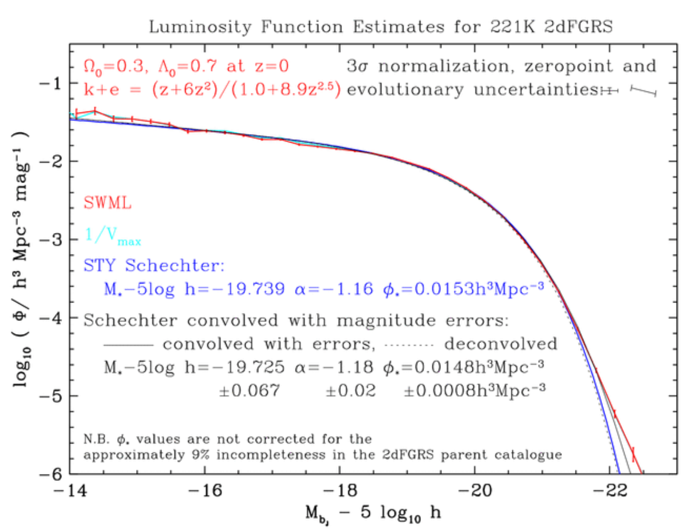
Very good approximate expression for the galaxy luminosity distribution:

- 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 $\alpha < -1$
    (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:

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

- 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

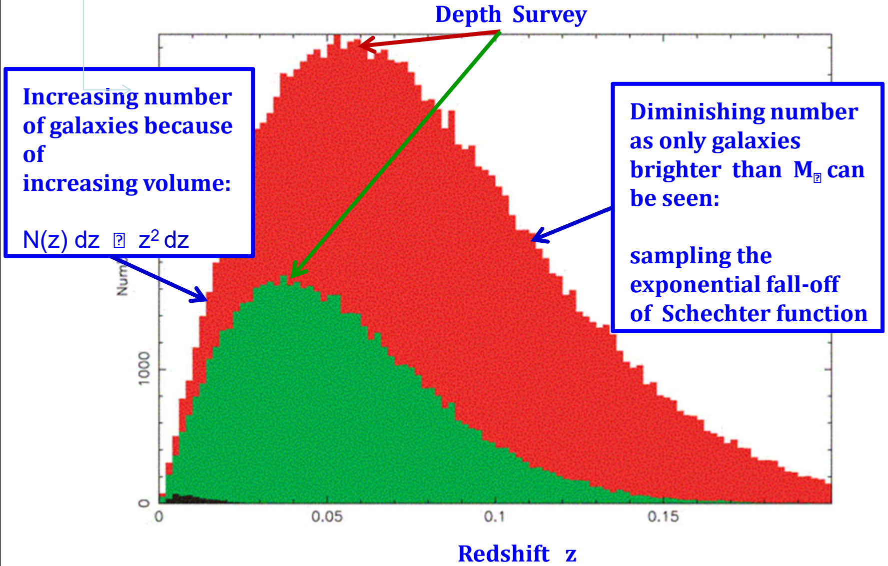
- For a survey with magnitude limit m_{lim}:
- At distance d_L (Mpc) one can see galaxies brighter than:

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

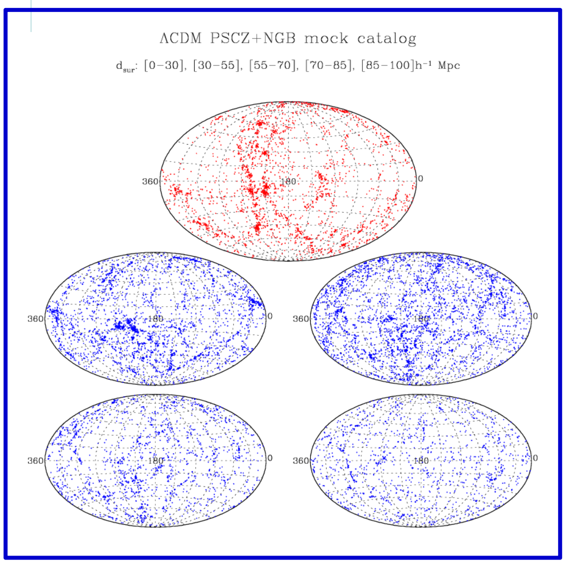
- Survey Depth d_{sur}:
  distance out to which one can see an M_* galaxy:

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

Survey Depth



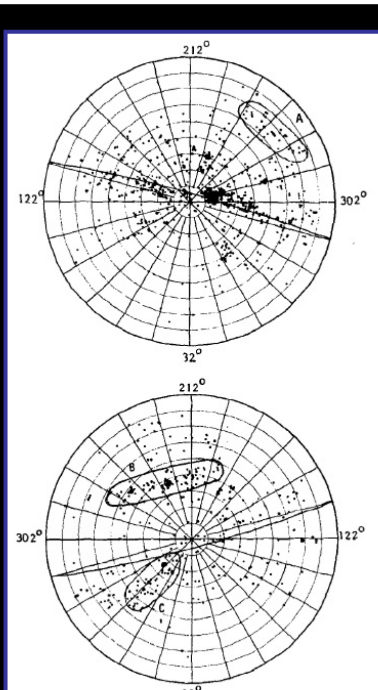
Survey Depth



Theoretical Example:

Galaxies in PSCz catalogue, at different depths

Galaxy Sky Maps



Shapley-Ames

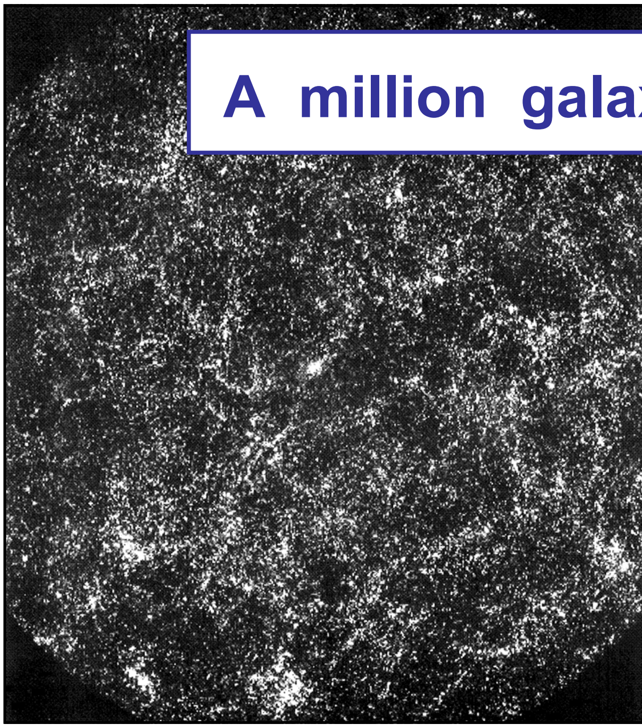
Shapley-Ames catalog (1932) of nearby galaxies:

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)

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 Galaxy Survey

Sky map:

2×10^6 galaxies

$17 < m < 20.5$

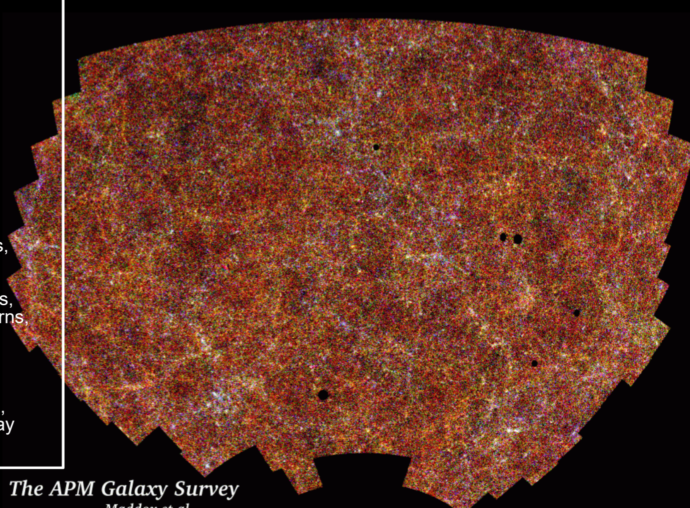
Uniformly defined

- Sky region:
  4300 sq. deg.

  185 UK Schmidt plates,
  $6^o \times 6^o$

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

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

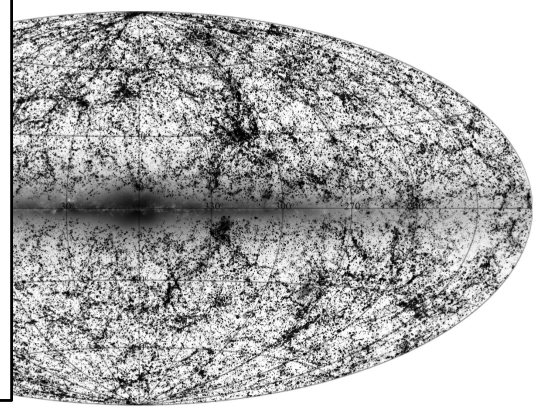


2MASS Cosmic Web

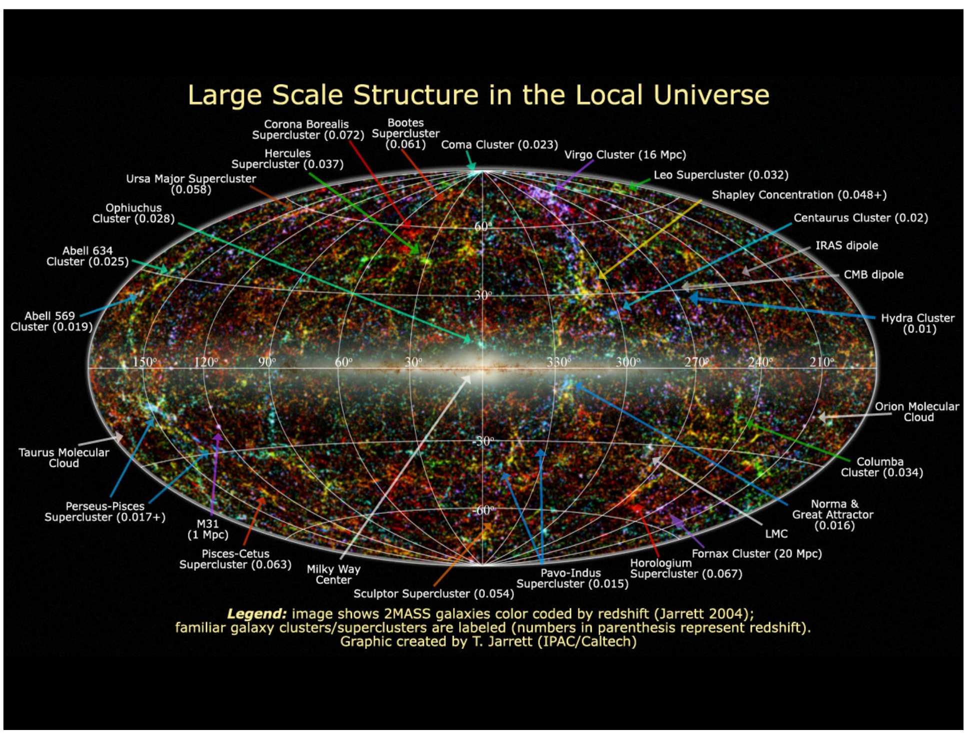
2MASS all-sky survey:

- 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



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



Galaxy Redshift Surveys

Galaxy Redshift Surveys

- For obtaining 3D maps of the galaxy distribution:

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

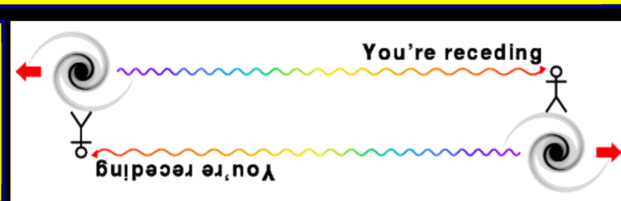
⍰ Determination real distance r of galaxy very cumbersome, reasonably accurate estimates only for nearby gal's …

⍰ Common approximate method:
exploit Hubble expansion of the Universe

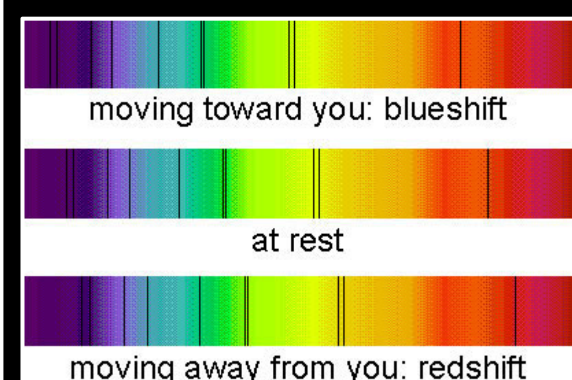
Galaxy Redshift Surveys

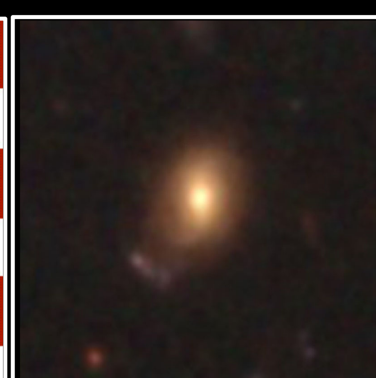
$$1 + z = \frac{1}{a} \quad \Longleftarrow \quad \begin{cases} \lambda_{em} = \lambda_0 \\ \lambda_{obs} = \dfrac{a(t_{obs})}{a(t_{em})} \lambda_0 \end{cases}$$

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



Redshifted Galaxy





Galaxy Redshift Surveys

- Hubble Expansion:

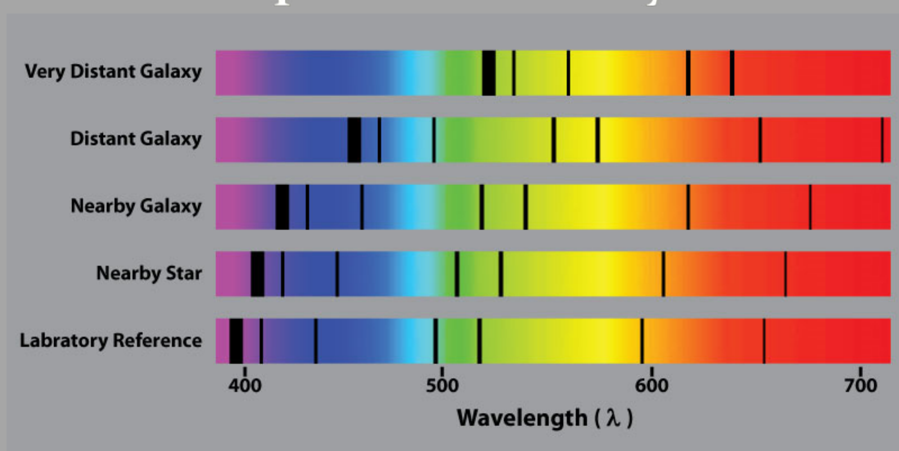
$$cz = Hr \quad (z \ll 1)$$

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

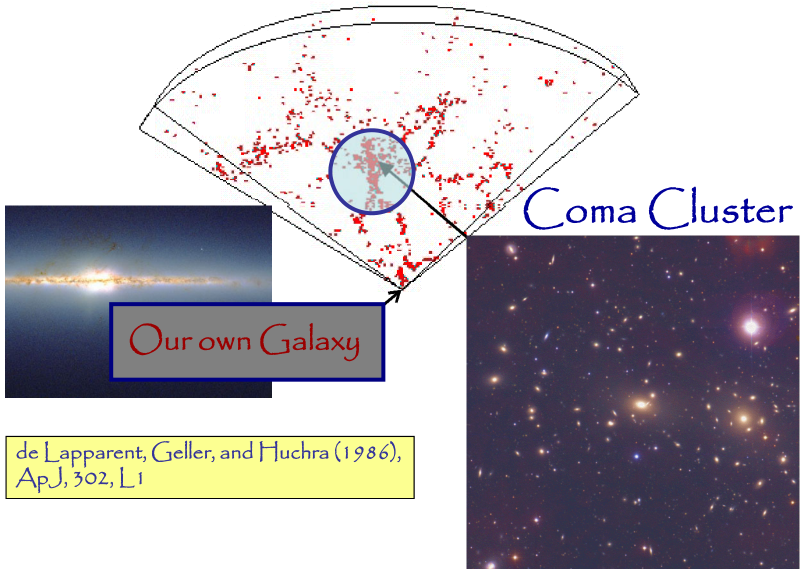
Hubble Expansion & Galaxy Redshift



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

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

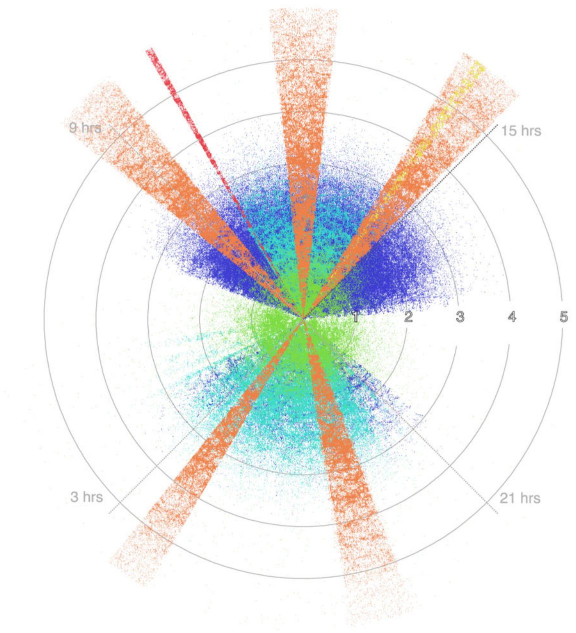
Mapping the Universe



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

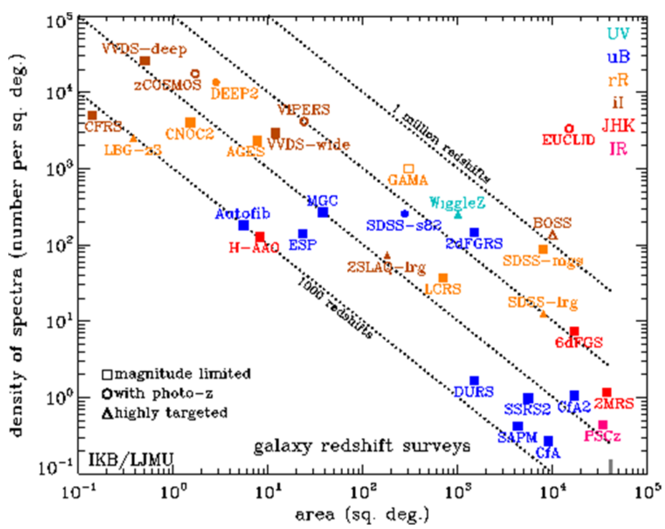
Galaxy Surveys:

Overview & Developments



Galaxy Redshift Surveys:

some statistics



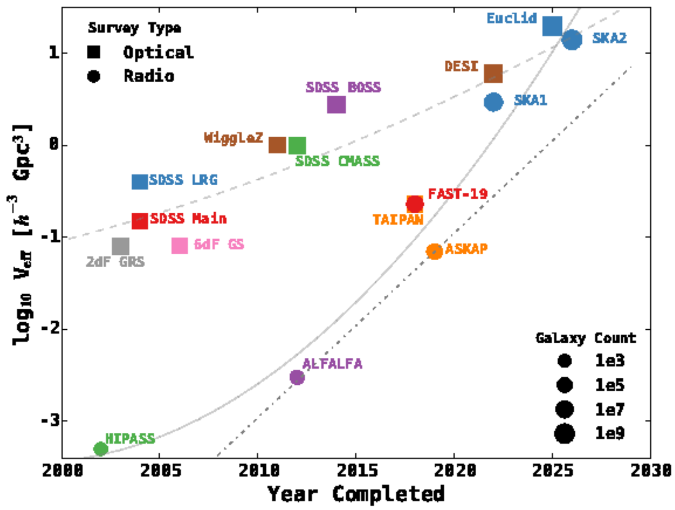
Comparing Galaxy/Cluster

Redshift Surveys

Angular number density vs. Sky area

Galaxy Redshift Surveys:

some statistics



Comparing Optical & Radio surveys

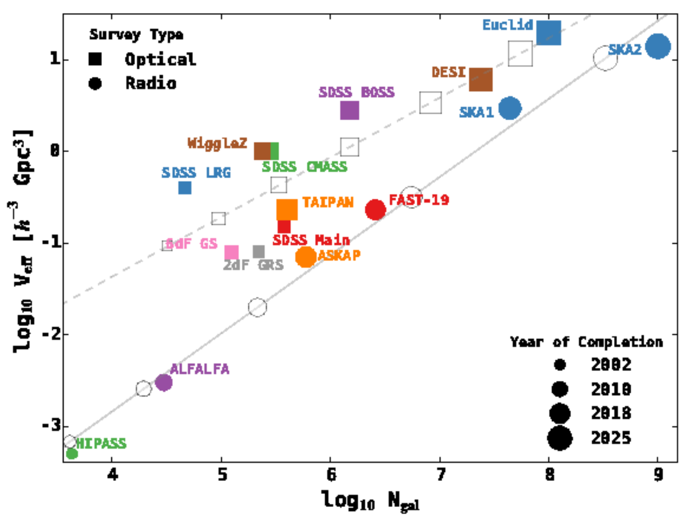
Year completion

Vs.

Effective survey volume

Galaxy Redshift Surveys:

some statistics



Comparing Optical & Radio surveys

Number survey galaxies

vs.

Effective survey volume

Galaxy Surveys:

Redshift Space Distortions

Redshift Space Distortions

When measuring the redshift of galaxies,you do only approximately determine its distance.

- 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, their peculiar velocity

$$\vec{v}_{tot}(\vec{r}) = H\vec{r} + \vec{v}_{pec}$$

$$cz = \vec{v}_{tot} \cdot \vec{e}_r = Hr + \vec{v}_{pec} \cdot \vec{e}_r$$

- Because it is very hard to disentangle the real distance term r and the peculiar velocity term,
- As a result, maps on the basis of galaxy redshift do not reflect the galaxy's true spatial distribution,
- they involve a distortion, the RSD or *redshift space distortion*.

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:

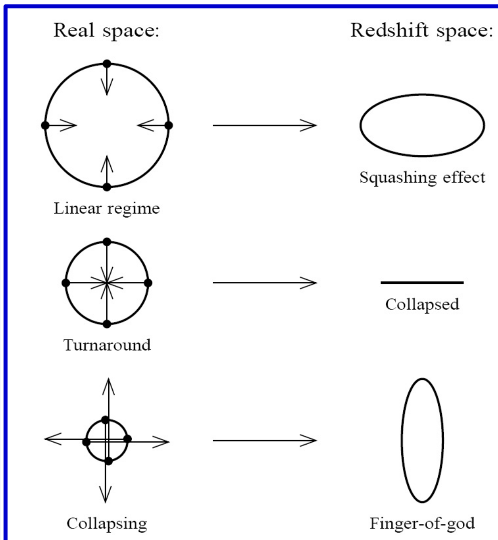
three regimes

- 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

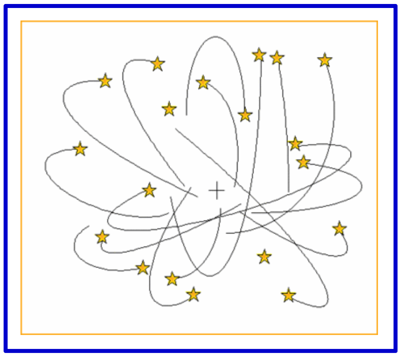
- Large scales: (linear, quasi-linear) cosmic flow, manifestation of structure growth

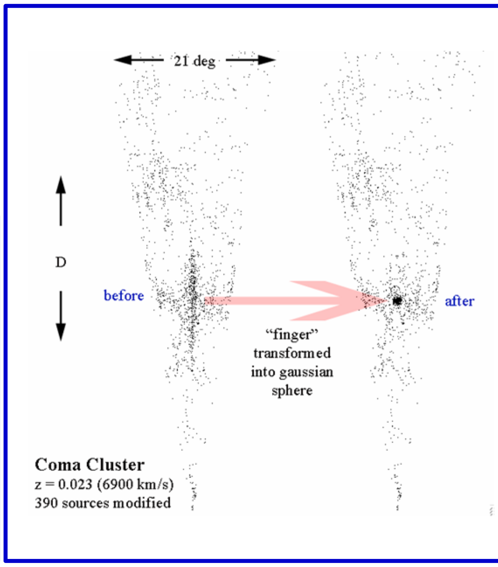


Fingers of God

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

Galaxy velocity component along line of sight





Fingers of God

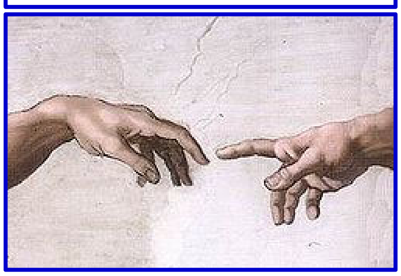
Clusters of galaxies:

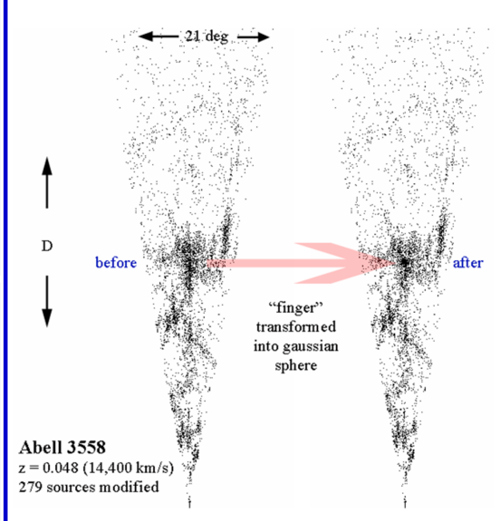
Mass: 10^{14}-10^{15} $M_{□}$
Radius: ~ 1.5 Mpc
Overdensity □ ~ 1000

Thermal velocity: ~ 1000 km/s

Internal cluster galaxy velocities visible in projection along line of sight

→ "Finger of God"





Nonlinear Infall Pattern

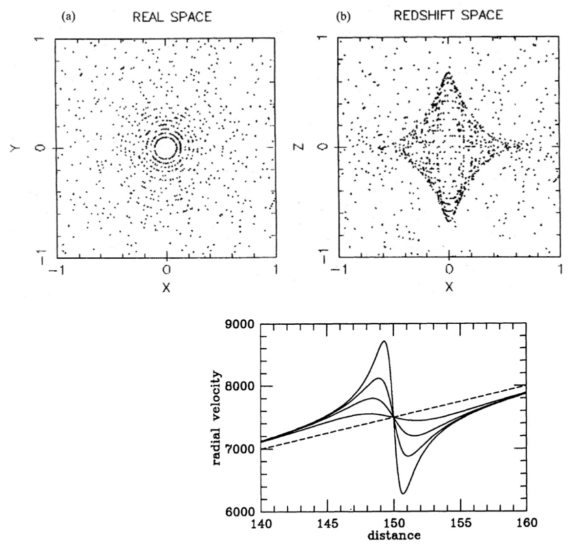
Cluster Infall:

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

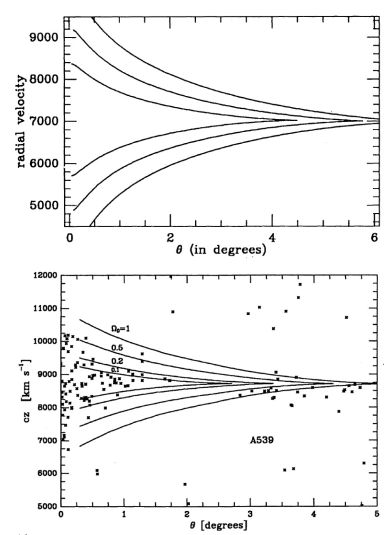
Cluster Caustics:

Three-value region cluster infall:

Projection onto restricted cone-shaped redshift space regions around clusters

Enclosed within caustic surfaces

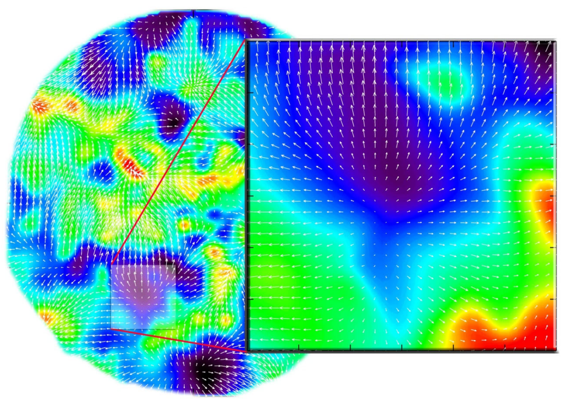
Position caustics dependent on Ω_m



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



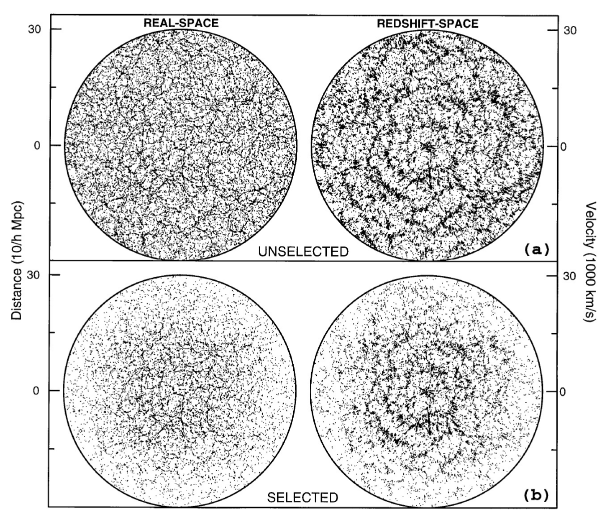
$$\mathbf{v}(\mathbf{x},t) = \frac{H}{4\pi}\frac{f(\Omega_m)}{b}a\int d\mathbf{x}'\,\delta_{gal}(\mathbf{x}',t)\,\frac{(\mathbf{x}'-\mathbf{x})}{|\mathbf{x}'-\mathbf{x}|^3}$$

Large Scale Flows

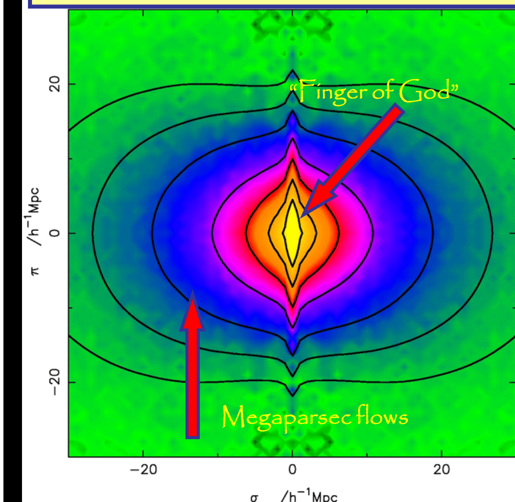
Large-Scale Flows:

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:

$$cz = H\,r + v_{pec}$$

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"

Galaxy Surveys:

Magnitude vs. Volume-Limited

Magnitude vs. Volume limited Surveys

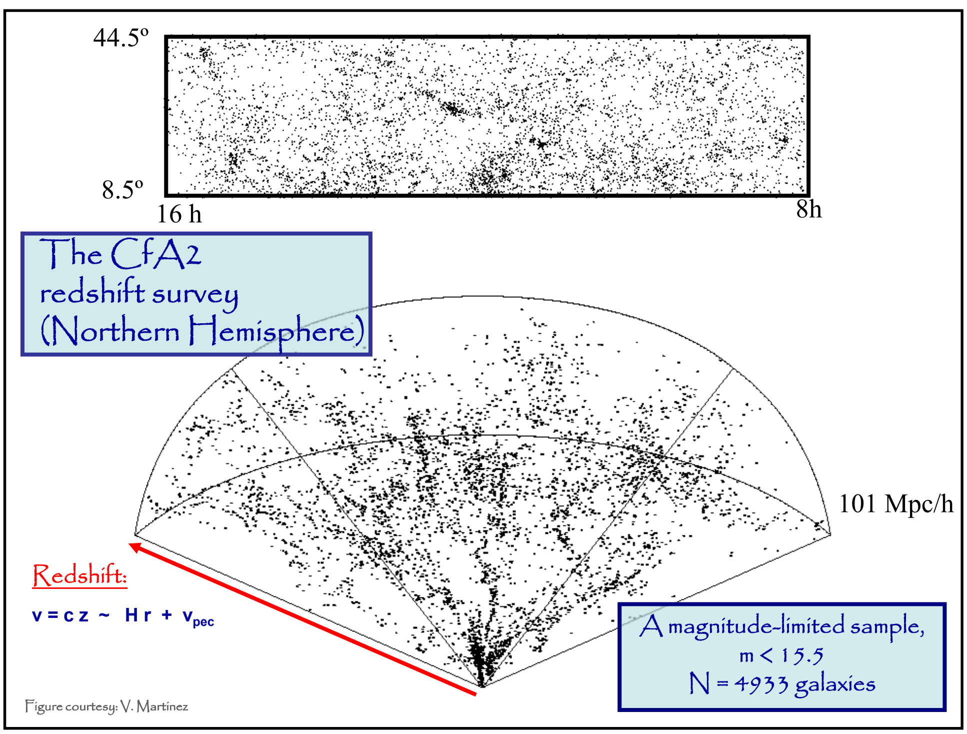
- Two different sampling approaches for analysis spatial structure from galaxy redshift catalogue:

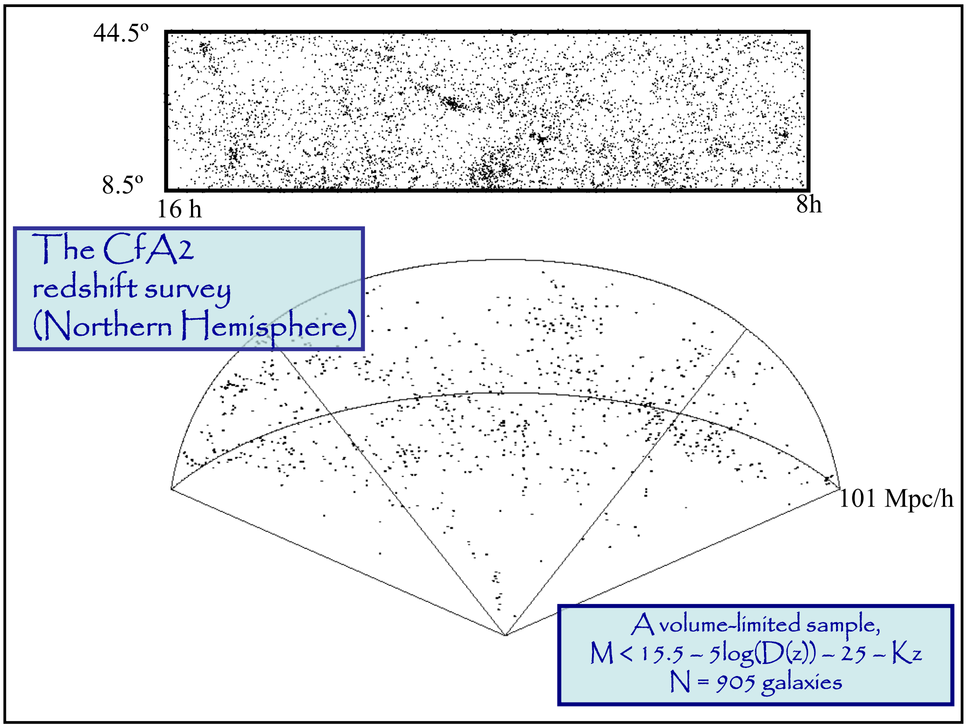
- Volume-limited surveys:
  - uniform spatial coverage, including all galaxies within volume to depth d_s
  - all galaxies with an absolute brightness > survey limit M_s

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

  - 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



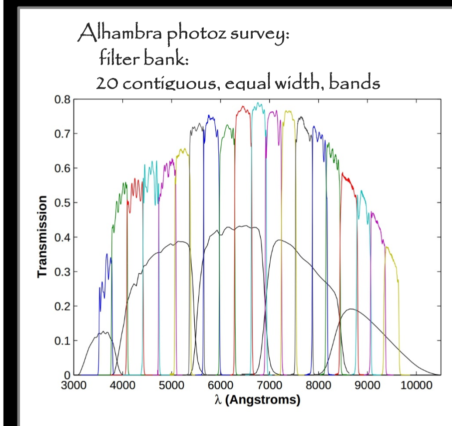


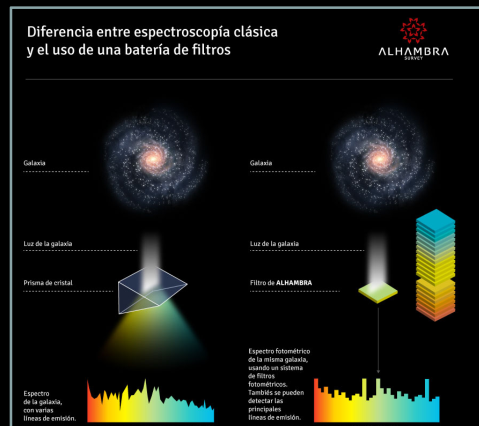
Galaxy Surveys:

Photometric Surveys

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.





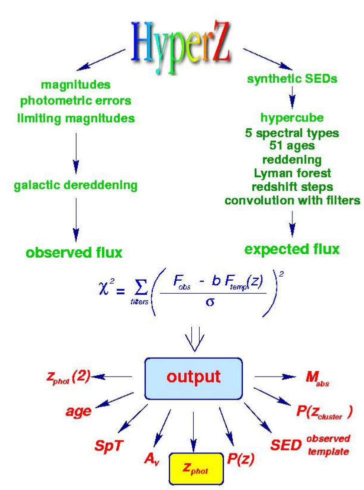
Photometric Redshifts

Practical Implementation:

 Photometric redshifts determined by fitting to standard SED
(SED: spectral energy distribution)

 Taking into account:
- spectral type
- reddening
- Lyman forest (high z!)
- filters

 Accuracy (typical):
- z ~ 0.1



$$\chi^2 = \sum_{filters} \left(\frac{F_{obs} - b\,F_{temp}(z)}{\sigma} \right)^2$$

widely used Hyperz package

Photometric Redshifts

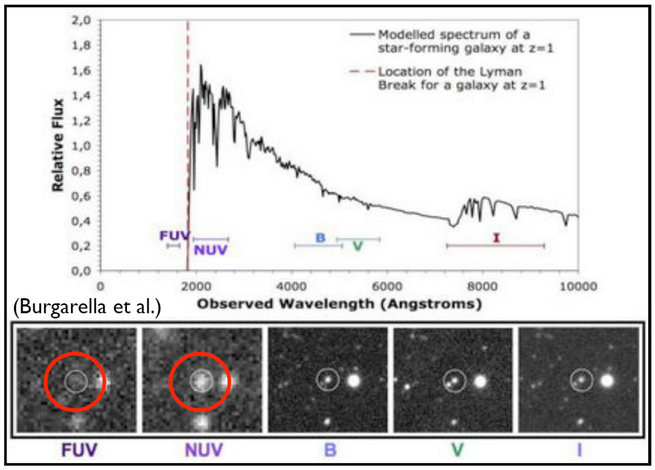
Photometric Redshifts

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



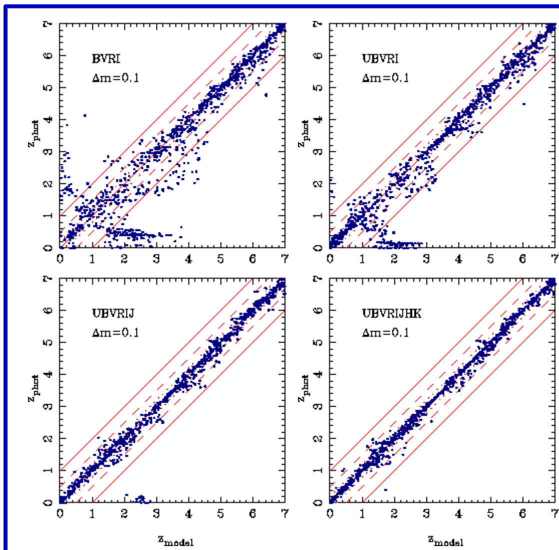
(Burgarella et al.)

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

Photometric Redshifts

Photometric Redshifts:

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



J-Pas survey

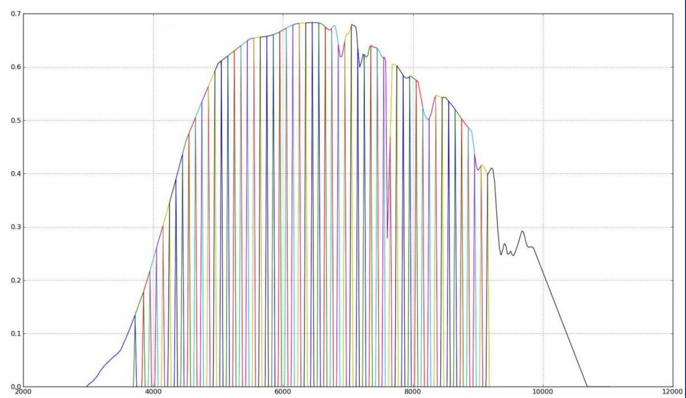
J-PAS survey:

56 narrow band filters
2.5 m. telescope, 7° field of view (OAJ, Javalambre, Spain):

8000 deg2

accurate redshifts out to z~1

14 million red, luminous galaxies



Galaxy Surveys:

Survey Geometry

Survey Geometry

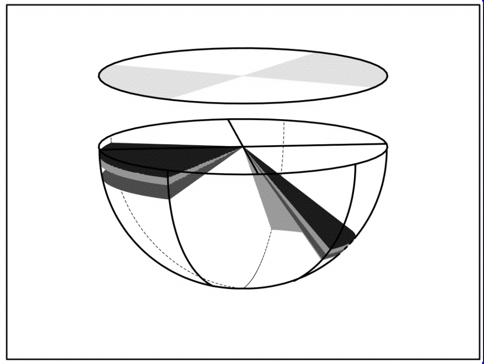
Practical Limitations

- 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



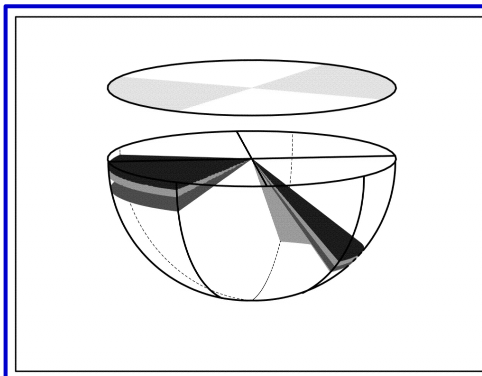
Sky Location
2-D LCRS survey slices

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)



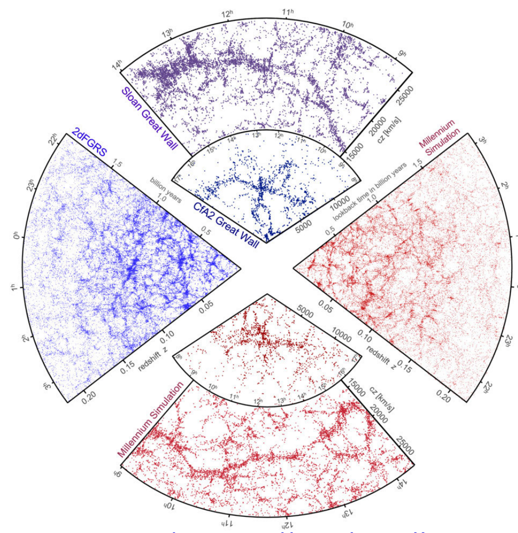
Sky Location
2-D LCRS survey slices

Survey Geometries

Examples of

Slice Redshift Surveys:

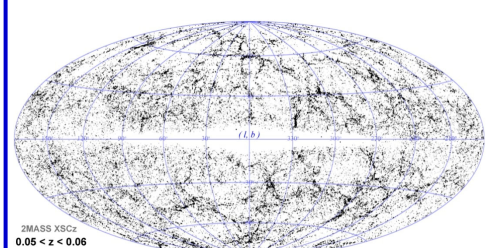
From
CfA2 -2dFGRS - SDSS



Survey Geometry

Survey Geometry:

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



Galaxy Surveys:

SDSS

Sloan Digital Sky Survey

SDSS survey

- Largest and most systematic (digital !) sky survey in history of astronomy.
- Images sky in 5 photometric bands !!!!
  Down to apparent magnitude r~23.1
- Covers ~ 25% of the sky: 8452 sq. deg.
- With 2dFGRS, the SDSS 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

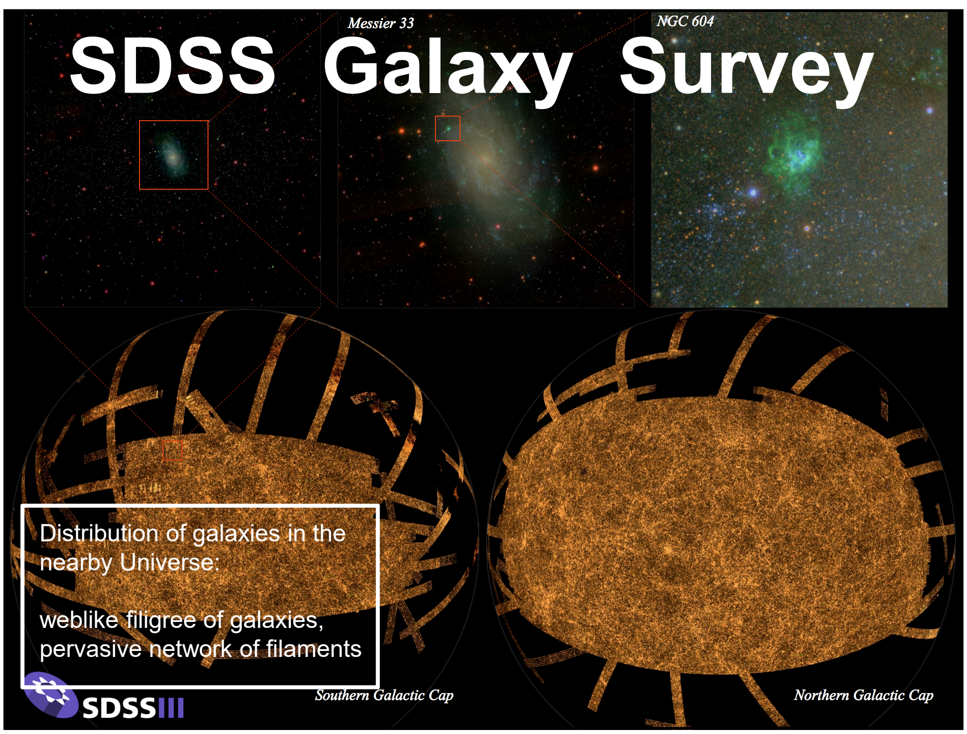
SDSS survey

- Imaging:
  230 million objects

- Spectroscopic (Redshift) survey:

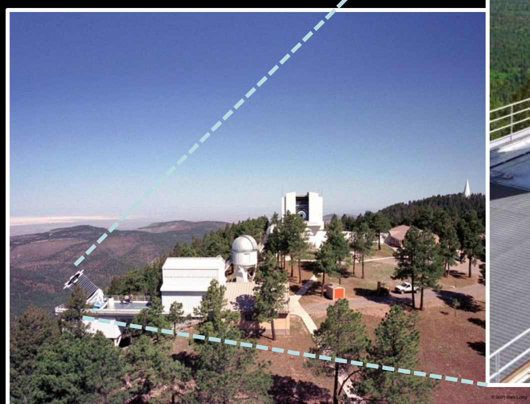
  magnitude limit:
  galaxies: (Petrosian) $r < 17.7$
  quasars $i < 19.1$ / $i < 20.2$ ($z > 2.3$)

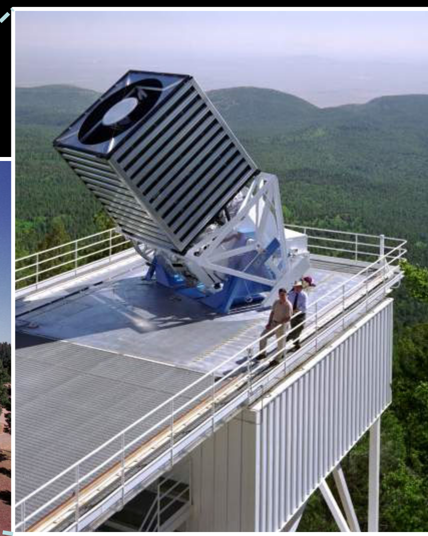
  objects: 928,567 galaxies
  109,862 quasars $z < 2.3$
  8,802 quasars $z > 2.3$



SDSS survey

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





SDSS survey

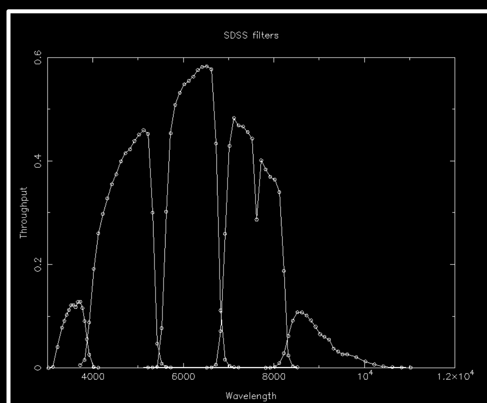
Aims to sample 25% of the sky:
DR7 - 8423 sq. deg.

Photometric system 5 filters:

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

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

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



SDSS survey

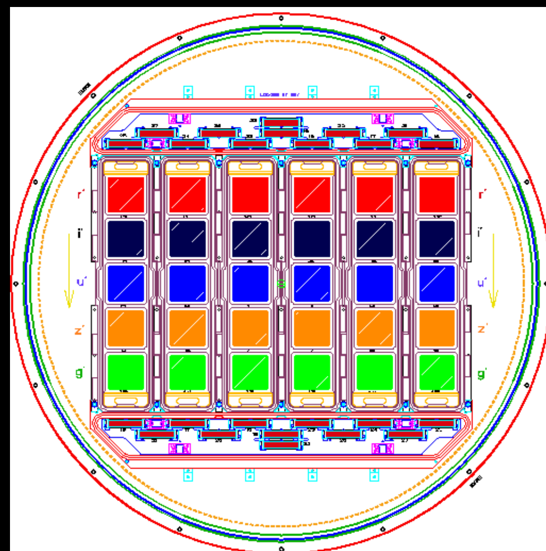
Aims to sample 25% of the sky:
DR7 ~ 8423 sq. deg.

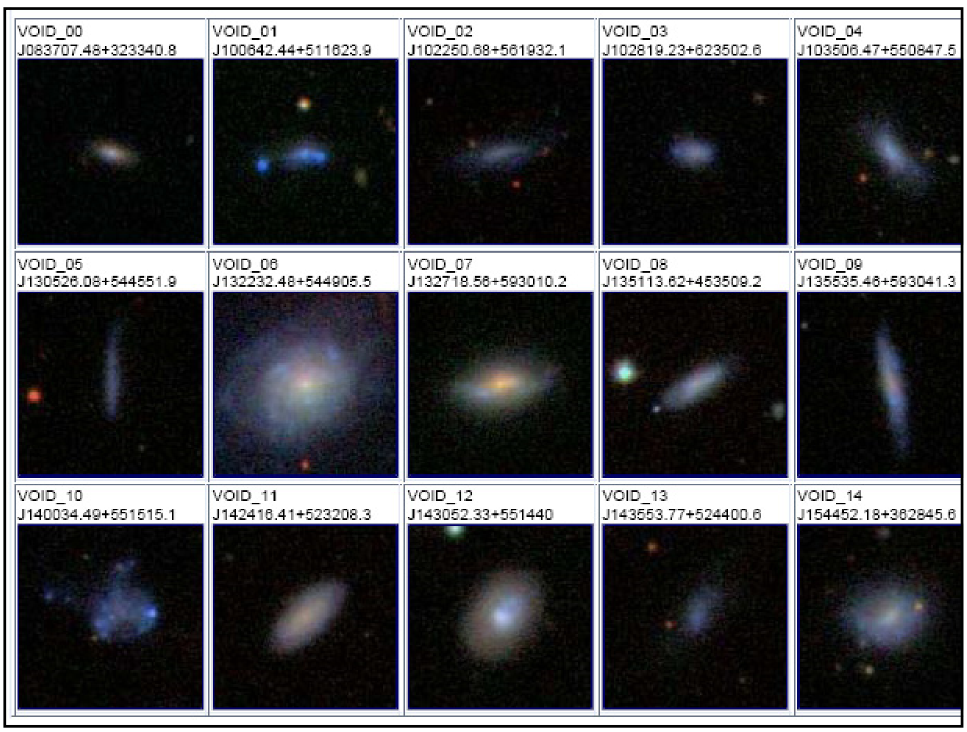
Photometric system 5 filters:

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

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

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



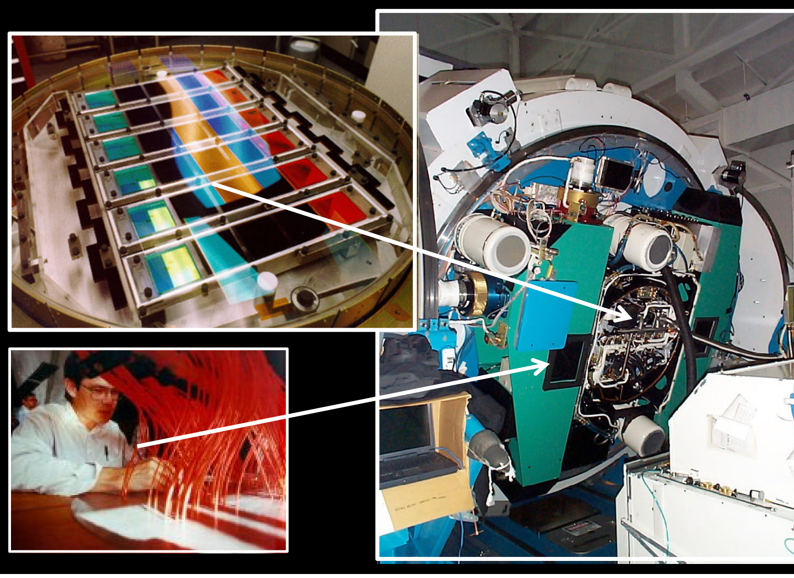


SDSS survey

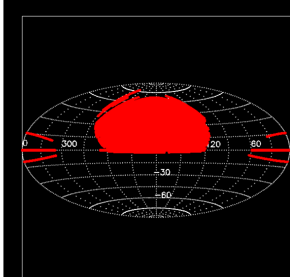
5-color Camera

30 CCD chips

Fiber Spectrograph



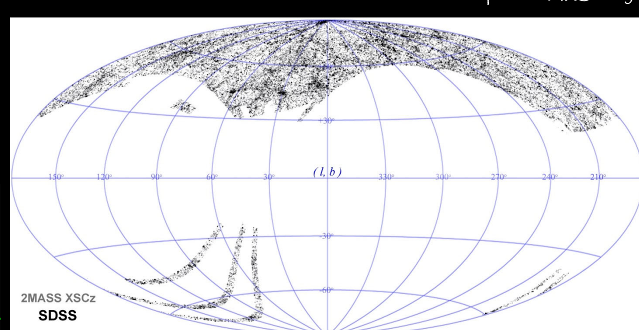
SDSS survey

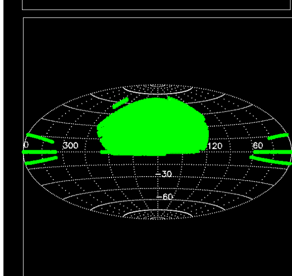


SDSS Legacy Imaging Sky Coverage: 8423 sq. deg.

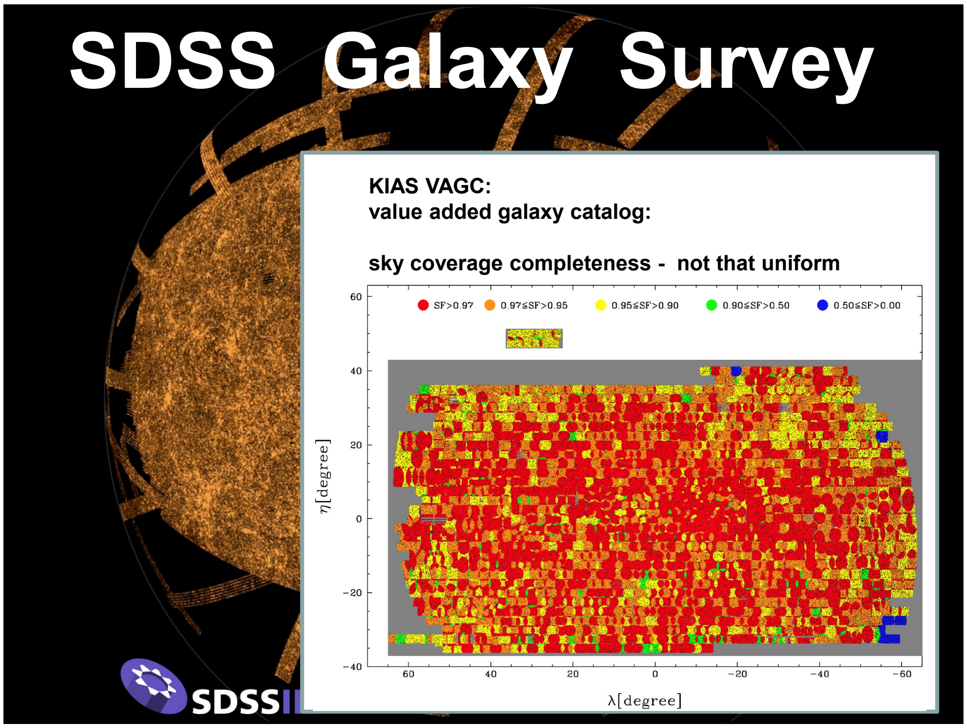
SDSS region, Galactic coordinates

compare to 2MRS surey

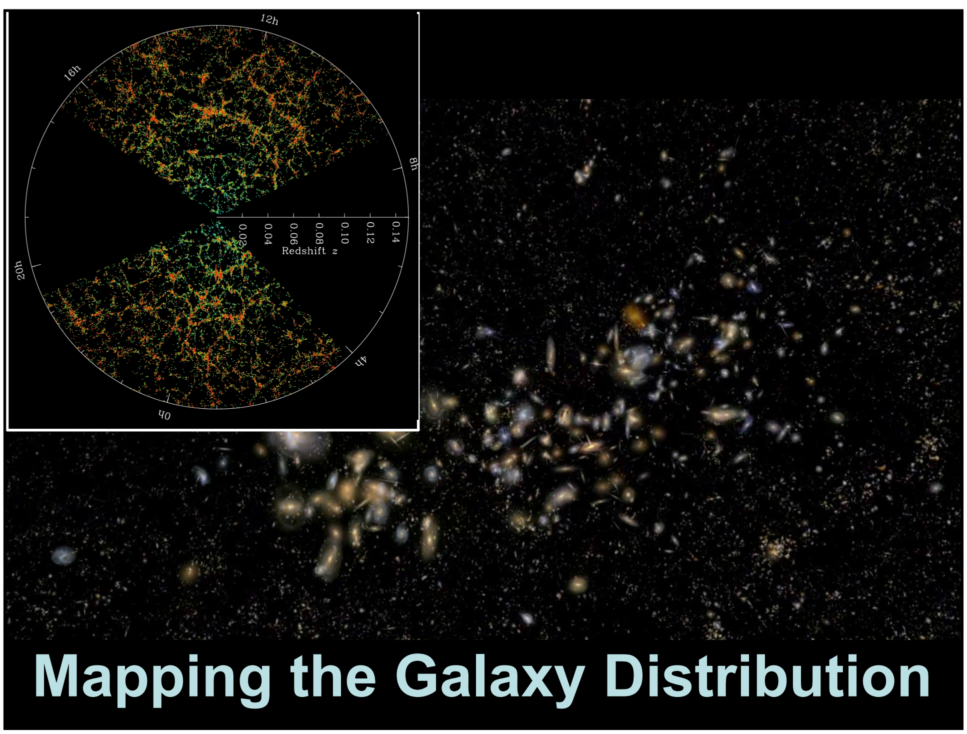




SDSS Legacy Spectral Sky Coverage: 8032 sq. deg.



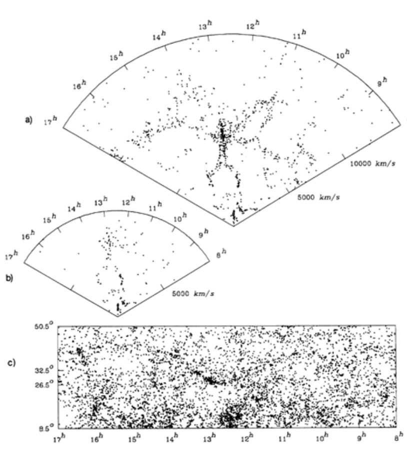
SDSS Galaxy Survey
KIAS VAGC:
value added galaxy catalog:
sky coverage completeness - not that uniform
SF>0.97
0.97≤SF>0.95
0.95≤SF>0.90
0.90≤SF>0.50
0.50≤SF>0.00
η[degree]
λ[degree]
SDSS



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

Cosmic Web

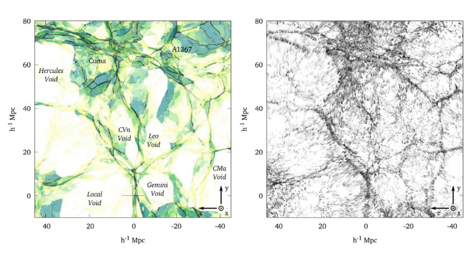
Cosmic Web:
Stickman & Discovery



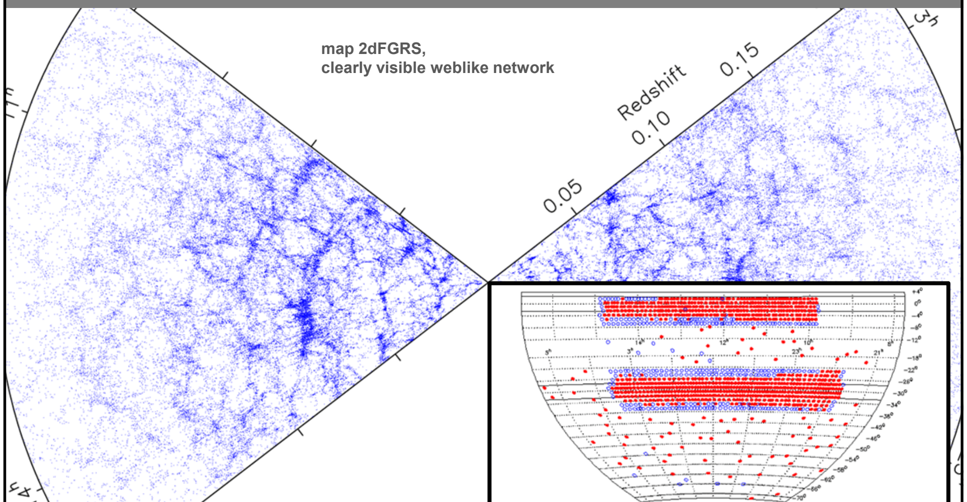
deLapparent, Geller & Huchra, 1986:

“a slice of the Universe”

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

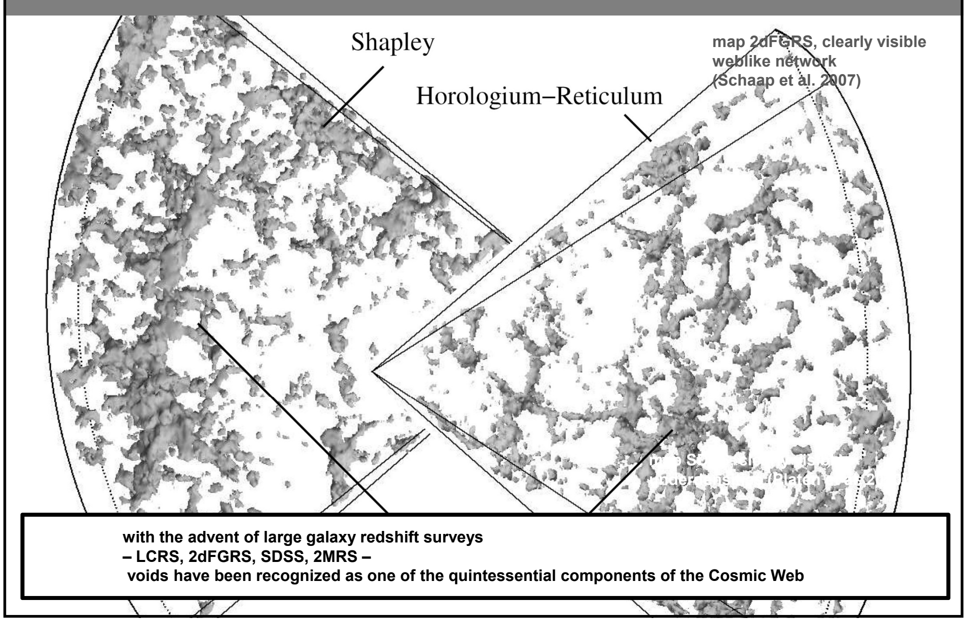


2dFGRS Galaxy Survey



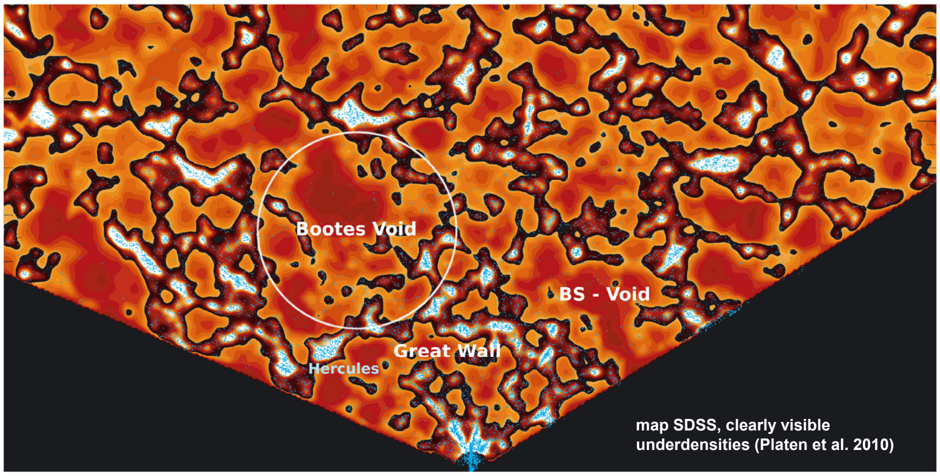
with the advent of large galaxy redshift surveys
– LCRS, 2dFGRS, SDSS, 2MRS –
voids have been recognized as one of the quintessential components of the Cosmic Web

2dFGRS Galaxy Survey



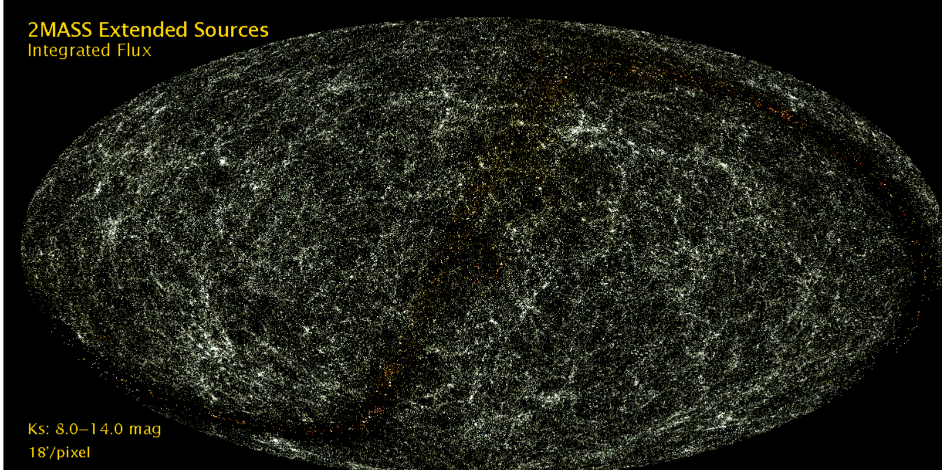
with the advent of large galaxy redshift surveys
– LCRS, 2dFGRS, SDSS, 2MRS –
voids have been recognized as one of the quintessential components of the Cosmic Web

SDSS Galaxy Survey



with the advent of large galaxy redshift surveys
– LCRS, 2dFGRS, SDSS, 2MRS –
voids have been recognized as one of the quintessential components of the Cosmic Web

2MASS: the Local Cosmic Web

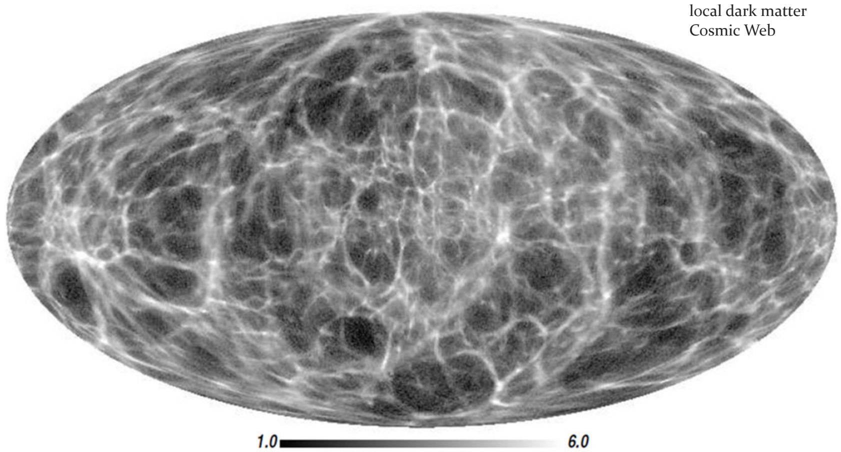


Looking around us we already see the unmistakable signatures of an intriguing foamlike matter distribution in our immediate Cosmic Vicinity.

local Cosmic Web: 2MRS

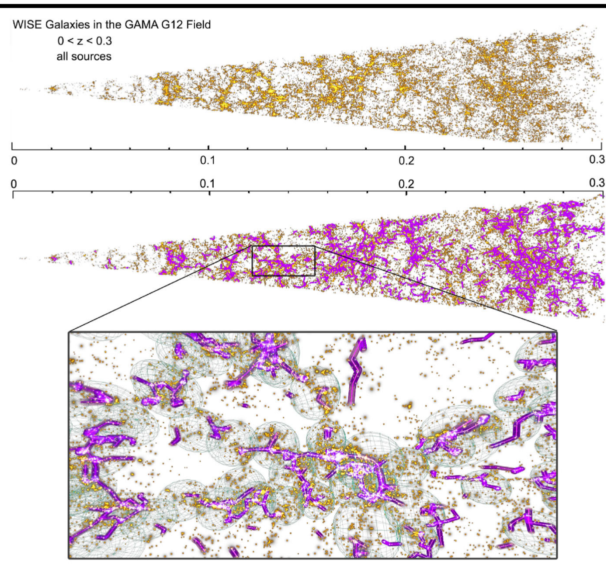
most detailed reconstruction of the

local dark matter Cosmic Web



Courtesy: Francisco Kitaura

GAMA/WISE: Cosmic Web z=0.3



GAMA/WISE

Intermediate redshift

z=0.3

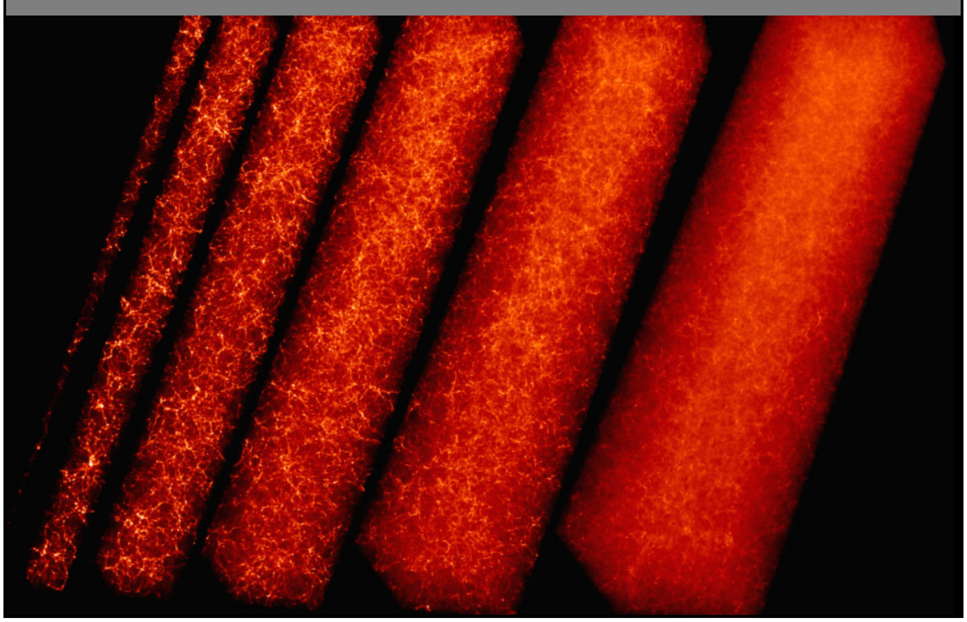
(Jarrett et al. 2017)

GAMA/WISE: galaxy populations in different parts/regions of the Cosmic Web

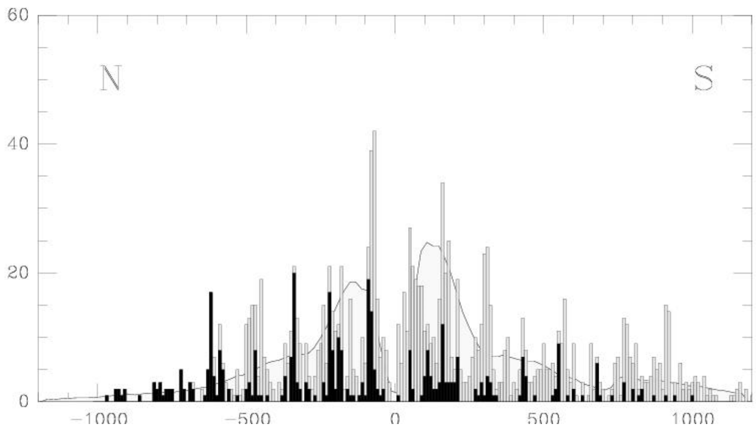
- **bright, early-type galaxies in dense nodes**
- **late-type disk galaxies lowest clustering level (filaments & voids)**

High z Universe

Cosmic Web at High z



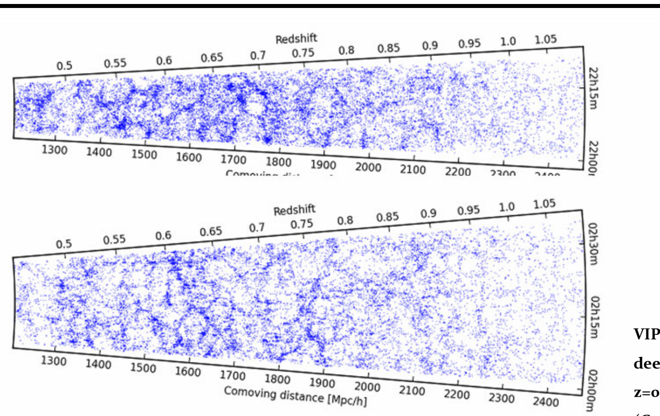
Cosmic Web at High z



Deep pencil beam survey (Broadhurst et al):

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

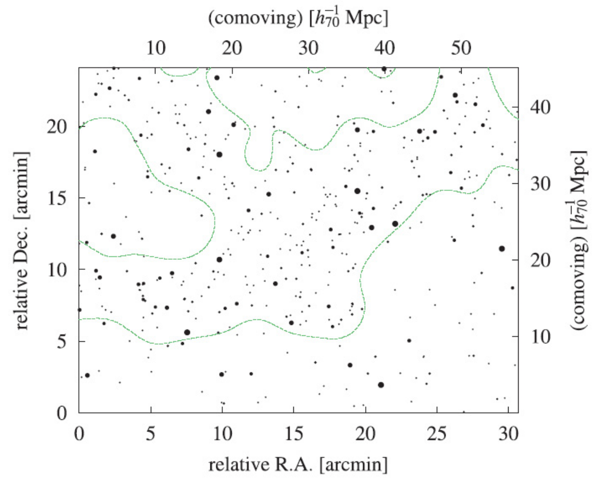
VIPERS: Cosmic Web at High z



VIPERS
deep redshift survey,
z=0.4-1.2
(Guzzo et al. 2014-)

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

Cosmic Web at High z

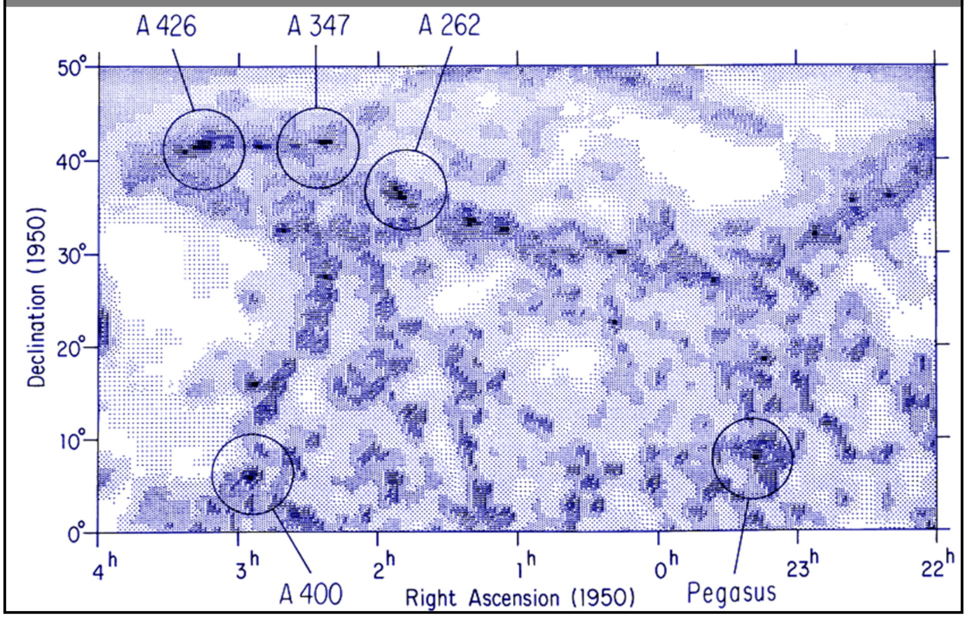


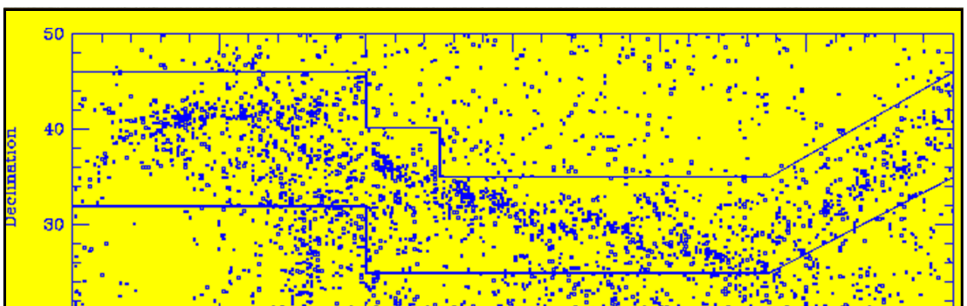
Subaru:

Ly? emitters at z=3 (Ouchi et al. 2005)

Filaments

Pisces-Perseus Supercluster



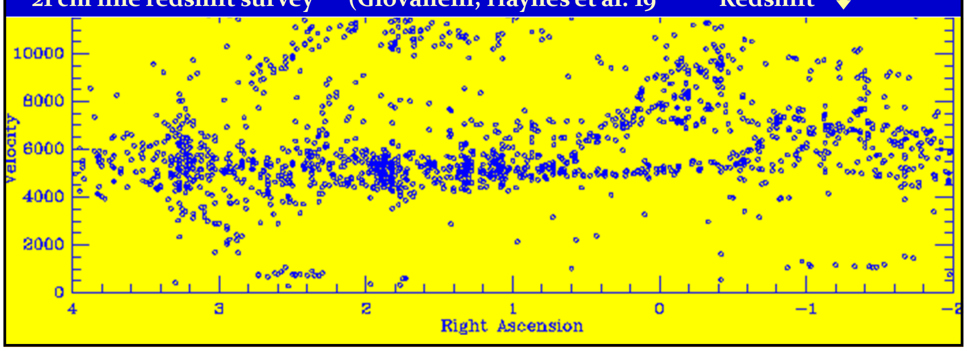


Pisces-Perseus Chain

21 cm line redshift survey (Giovanelli, Haynes et al. 19

Sky

Redshift



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.

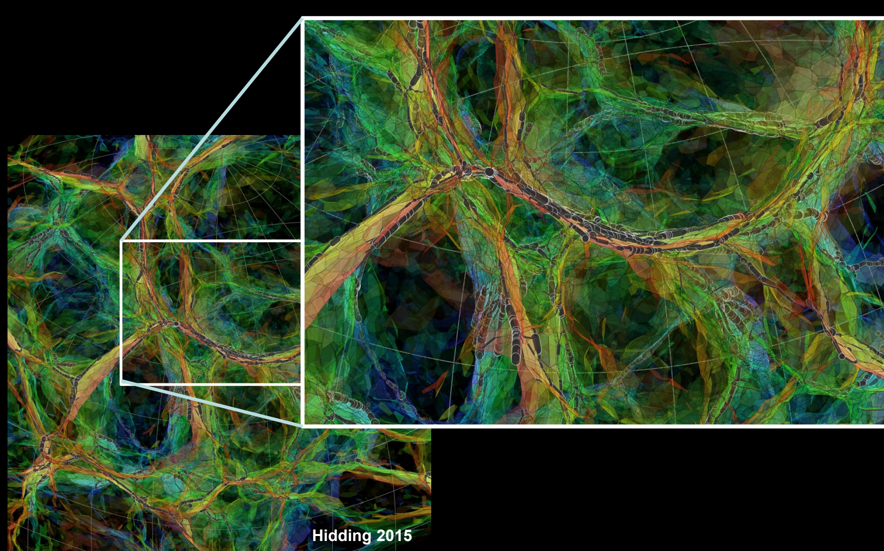
Northern boundary: ridge south-westward of Perseus cluster (A426)

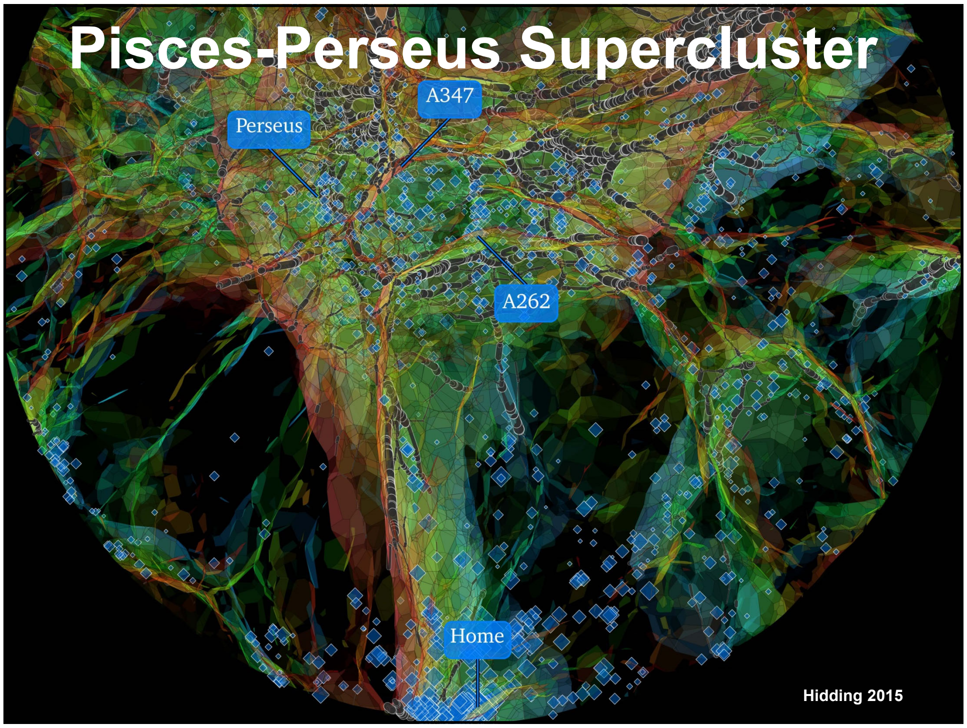
Dimensions Ridge: 5h^{-1} Mpc wide

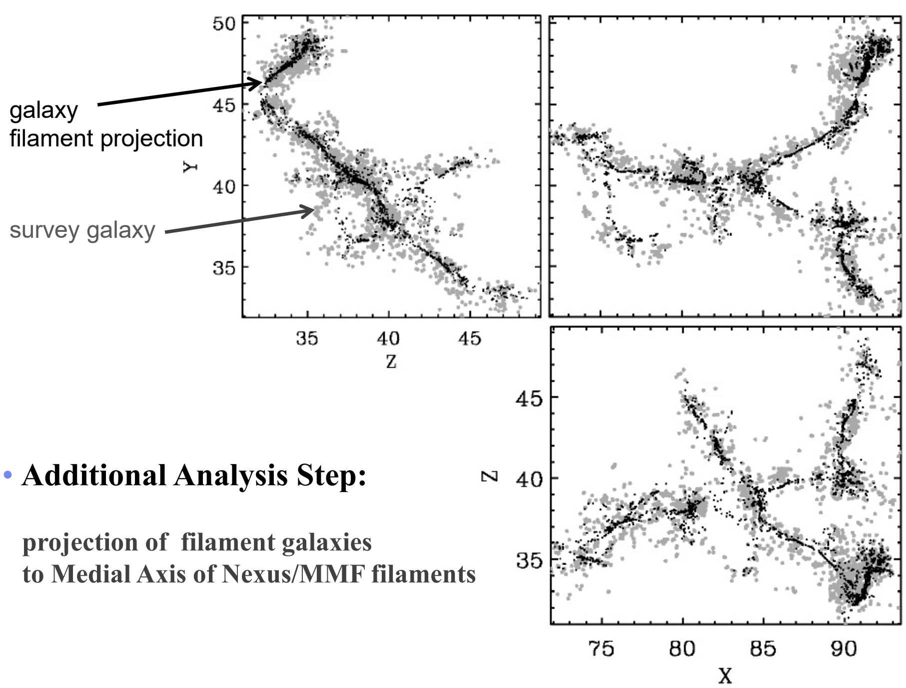
50h^{-1} Mpc length; possible 140h^{-1} Mpc extension

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

Pisces-Perseus Supercluster



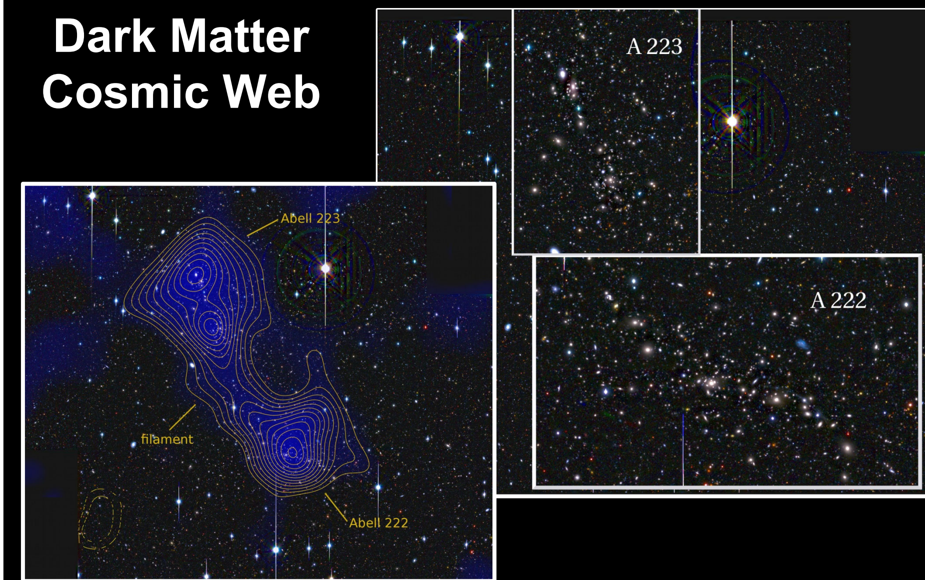




- **Additional Analysis Step:**

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

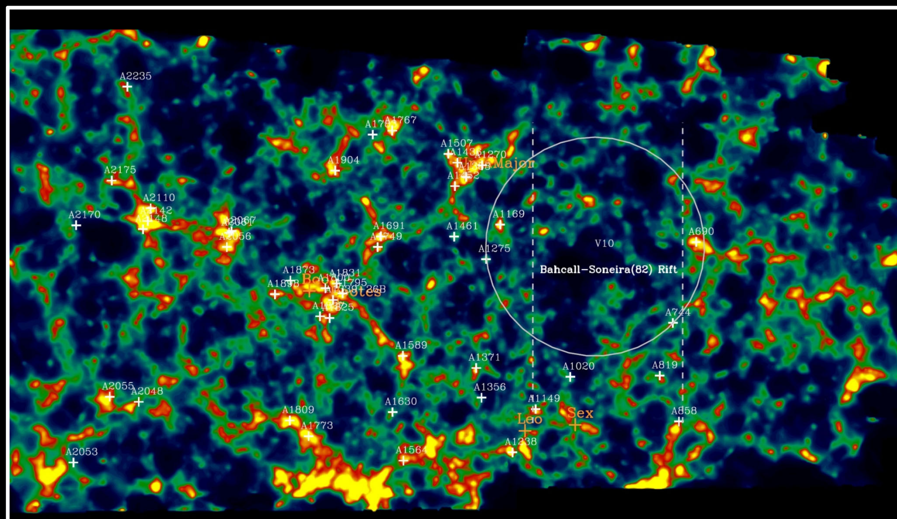
Dark Matter Cosmic Web



A222-A223
Dietrich et al. 2013

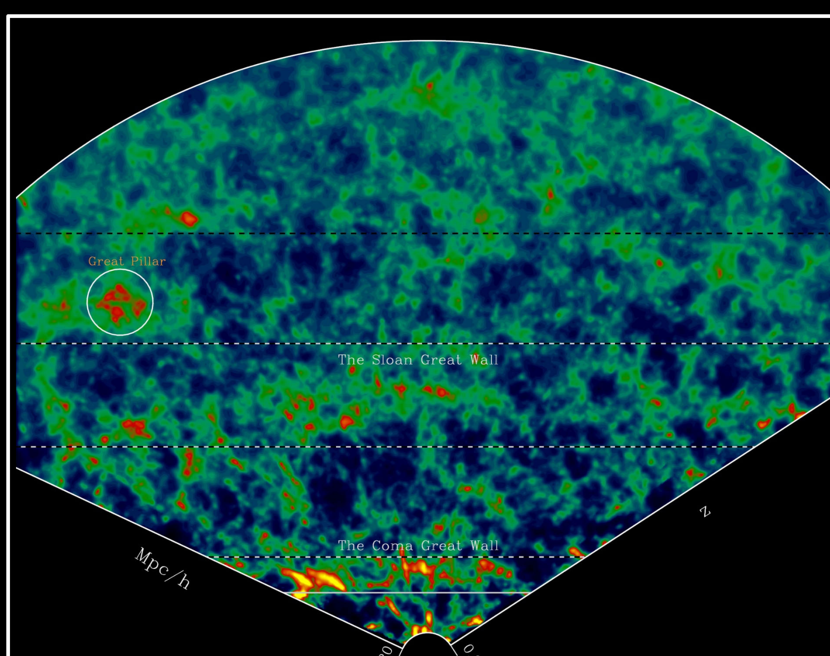
Walls

Sloan Great Wall

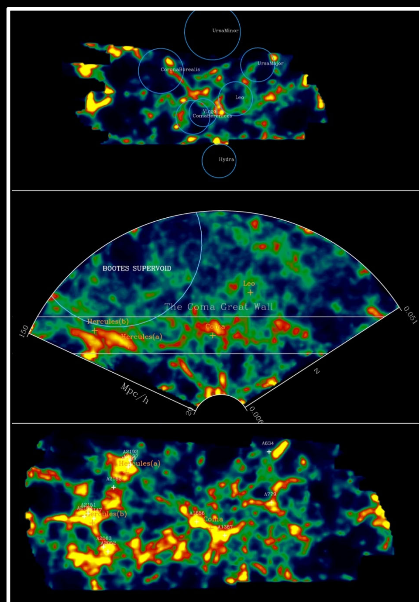


Platen 2009

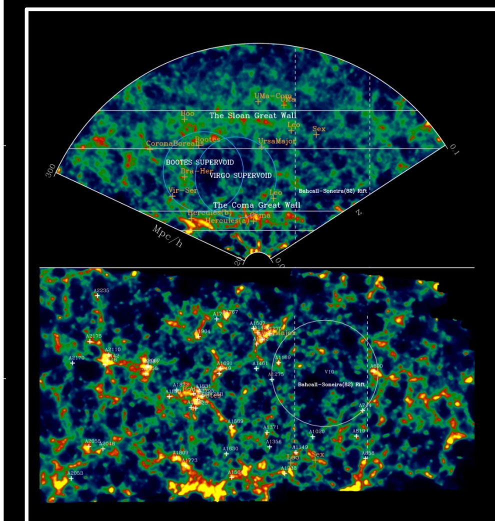
Largest Structure
Local Universe
~ 300 x 150 Mpc



Coma Great Wall



Sloan Great Wall



Platen 2009

Voids

Nature Vol. 300 2 December 1982 407

REVIEW ARTICLE

Giant voids in the Universe

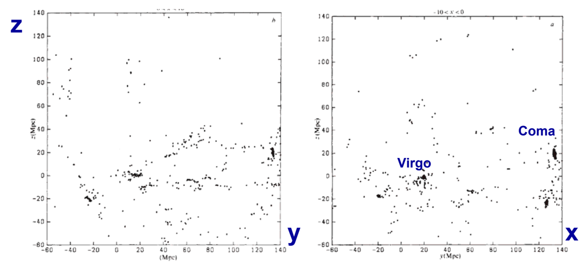
Ya. B. Zeldovich*, J. Einasto†‡ & S. F. Shandarin*

* 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.

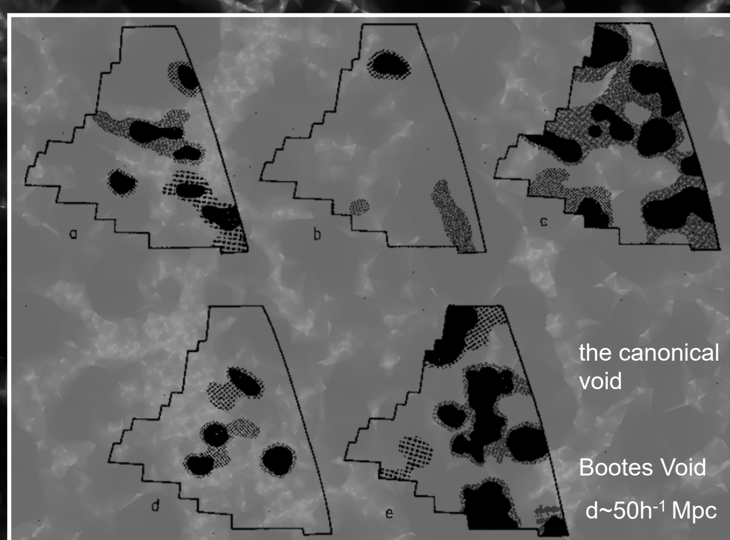
Zeldovich, Einasto & Shandarin 1982:

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

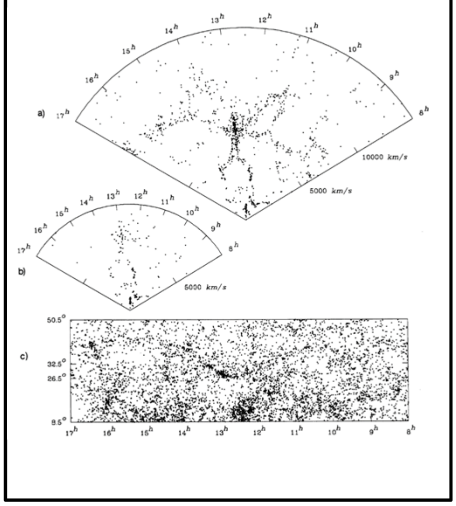


Bootes Void

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



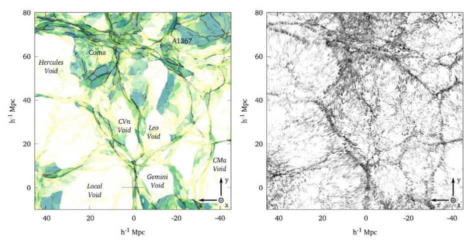
Voids & the Cosmic Web



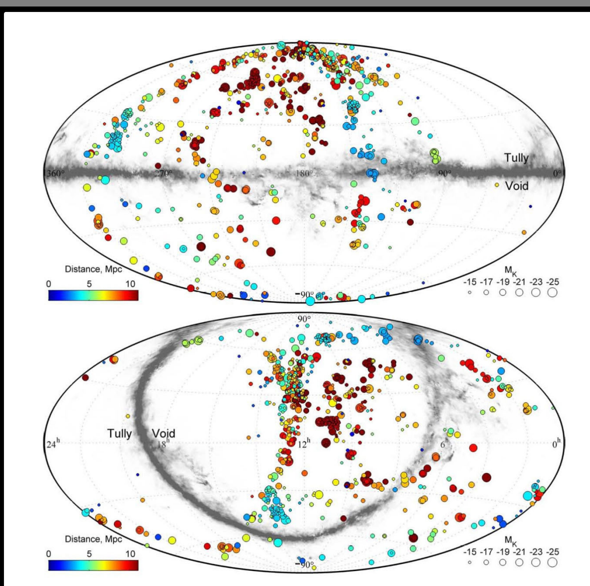
deLapparent, Geller & Huchra, 1986:

"a slice of the Universe"

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



local Cosmic Web: Local Void

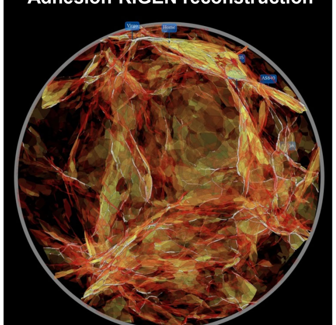


Karachentsev etal.

LV catalog:
galaxies within 10 Mpc reveal beautifully the magnificent

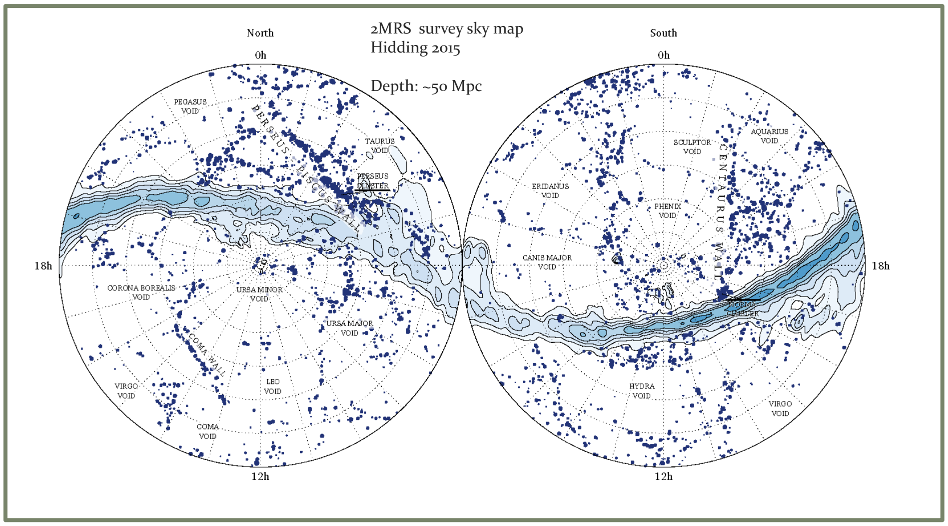
Local Void – Tully Void

Adhesion-KIGEN reconstruction

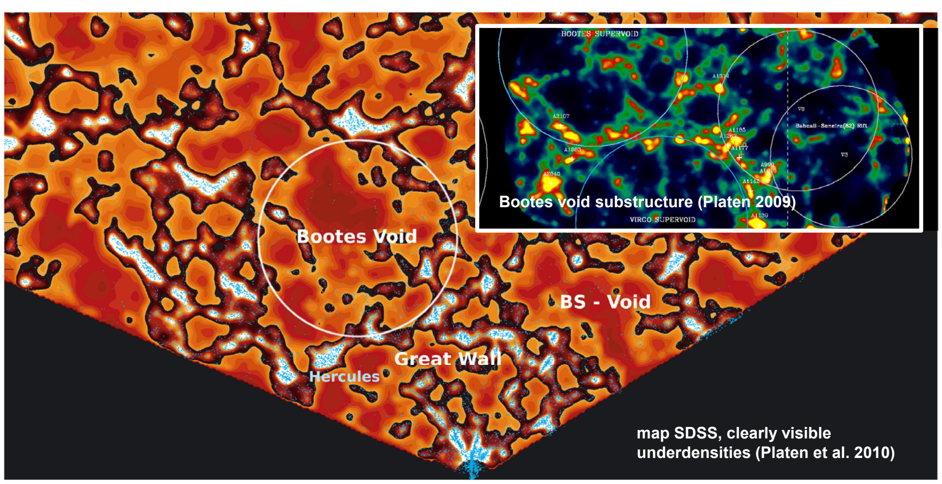


Hidding, vdW, Kitaura & Hess 2015

2MRS Local Universe …

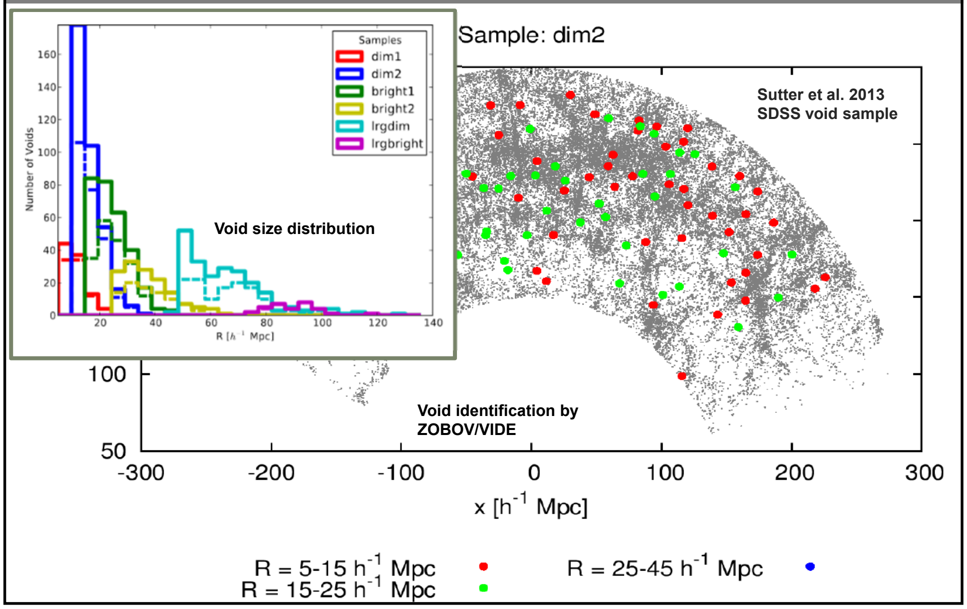


SDSS Galaxy Survey

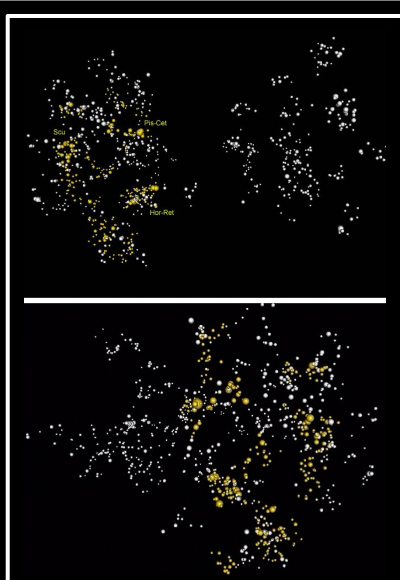


with the advent of large galaxy redshift surveys
– LCRS, 2dFGRS, SDSS, 2MRS –
voids have been recognized as one of the quintessential components of the Cosmic Web

SDSS Void Sample



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

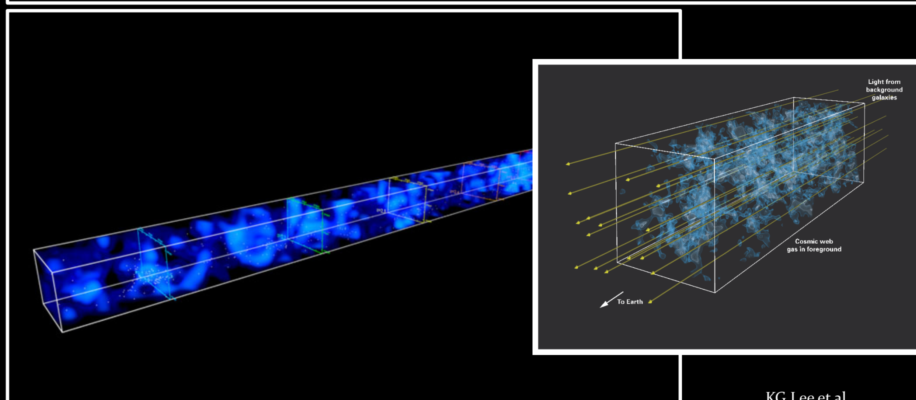
(see talk by Collins).

Cosmic Web Tomography
Lyα survey CLAMATO

Mapping the Lyα forest in a densely sampled set of quasar spectra over sky region

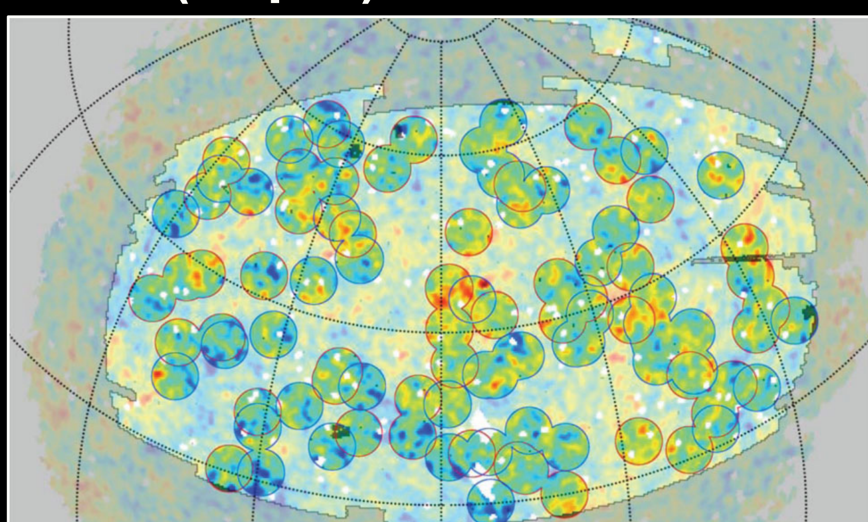
1-D skewers through the gaseous Universe
Reconstruction full 3-D cosmic web, when skewers within correlation scale from each other

First systematic survey: CLAMATO (Lee et al.): identification Lya forest void population



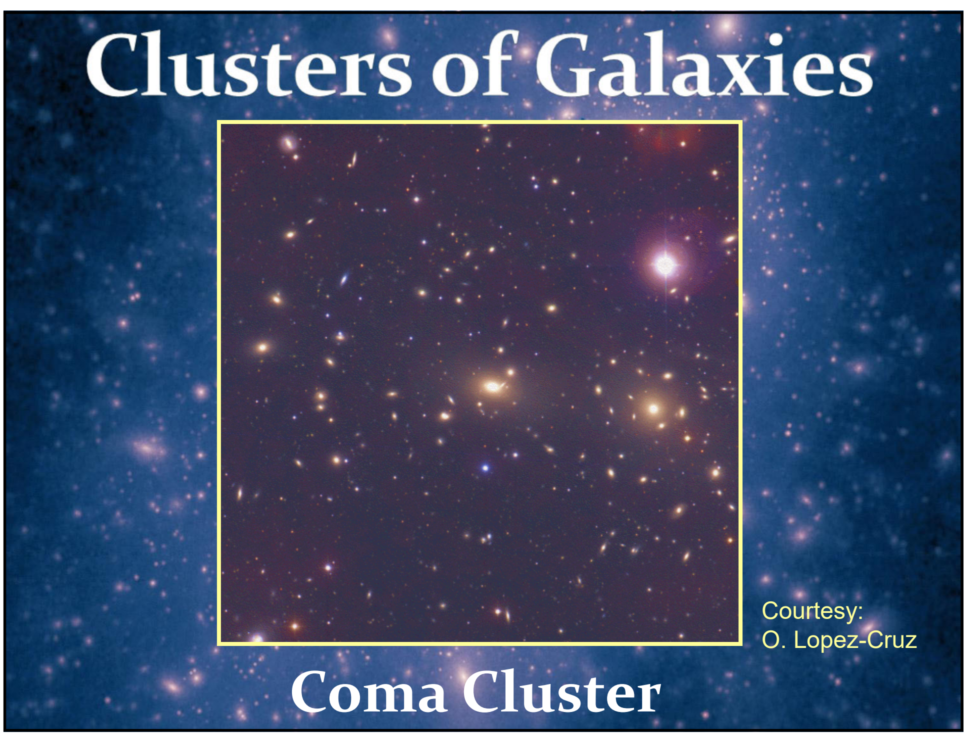
KG Lee et al..

(Super)voids & ISW



Granett et al. 2009
identification of (LRG) supercluster & supervoid
ISW imprint on CMB

Clusters

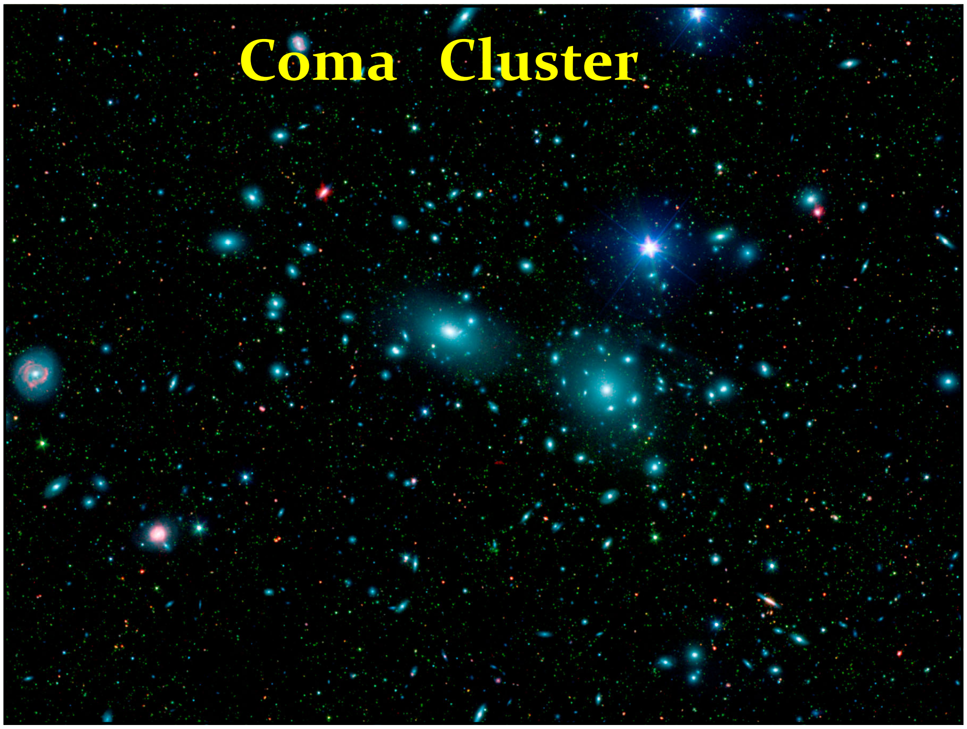


Studying Clusters

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



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

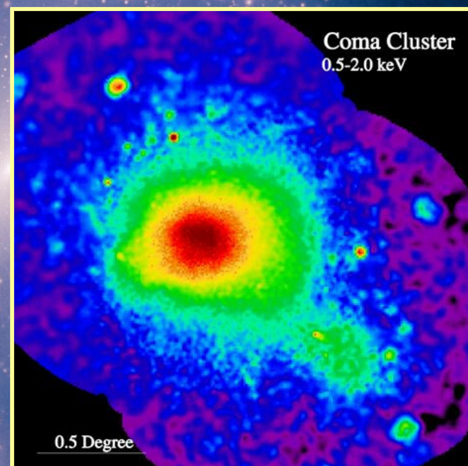
Intracluster Gas,

trapped and heated to a temperature of the order of

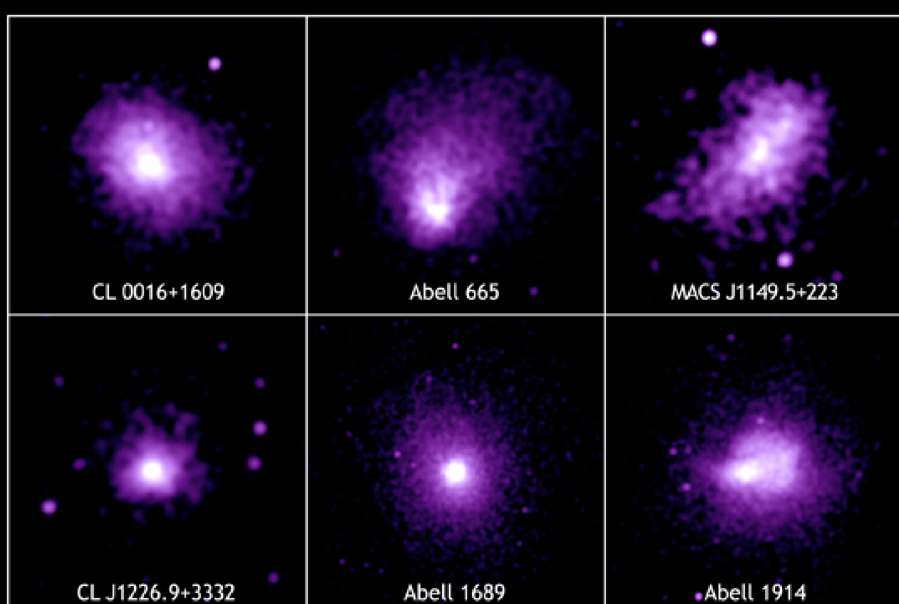
$T \sim 10^8$ K

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:

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

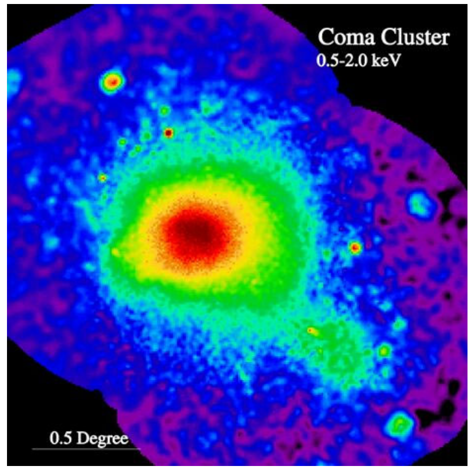
Determination Mass from X-ray observations:

-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

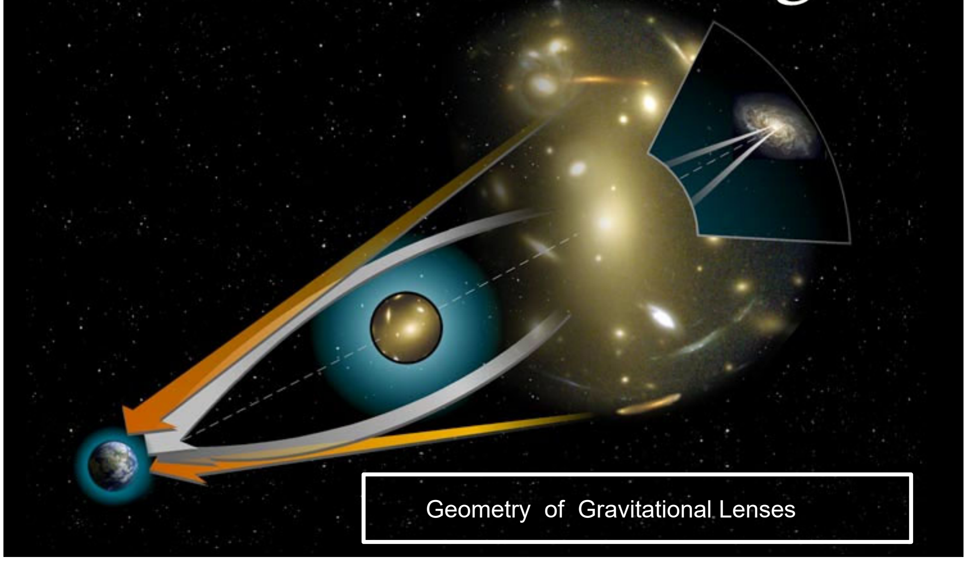
Einstein's theory of

General Relativity,

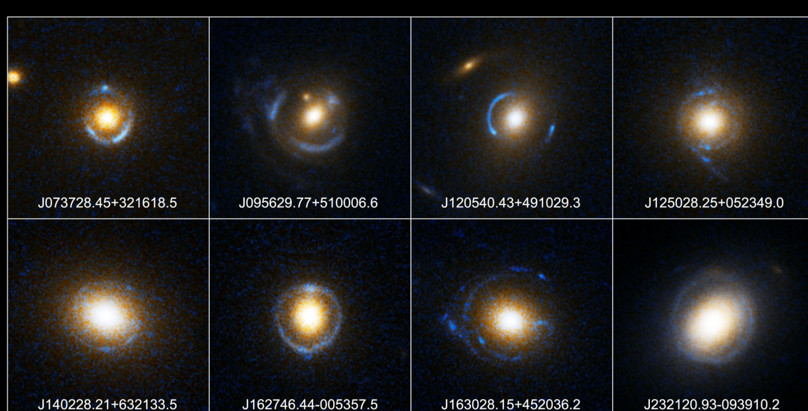
gravitational potential wells will bend and focus light. Dark matter concentrations act as a

Gravitational Lens

Clusters: Gravitational Lensing



Gravitational Lensing: Einstein Ring



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

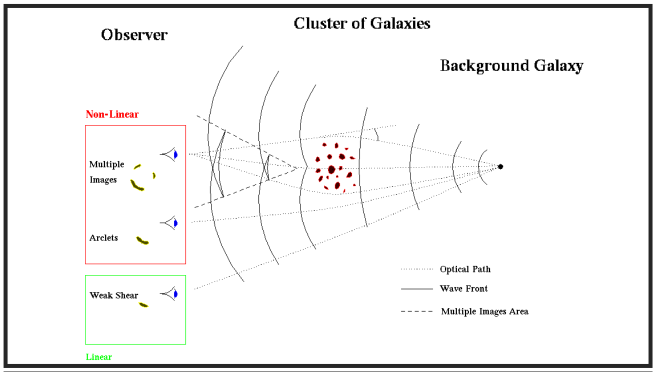
NASA, ESA, A. Bolton (Harvard-Smithsonian CfA), and the SLACS Team STScI-PRC05-32

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:**
  - □ < $□_E$
  - - nonlinear distortions
  - - multiple image
- **Weak Lensing:**
  - □ > $□_E$
  - - linear distortions
  - - sheared images

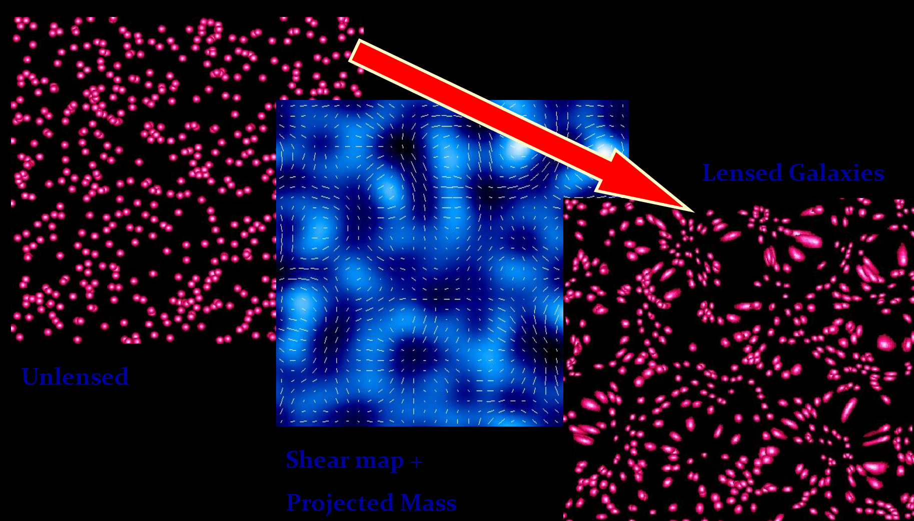


Cluster Mass determination:

Weak Lensing: Linear Inversion Distortion Field

Strong Lensing: Complex Modeling density distribution. non-trivial

Weak Gravitational Lensing



Weak Gravitational Lensing: MS1054

- z=0.83:

  one of the highest known z clusters

  Weak Lensing study by
  - Clowe et al. Keck
  - Hoekstra et al. HST

Clusters of Galaxies: Dark Matter Map

A highly promising method to determine the amount and distribution of

matter in the Universe

looks at the way it affects

the trajectories of photons.

According to

Einstein's theory of

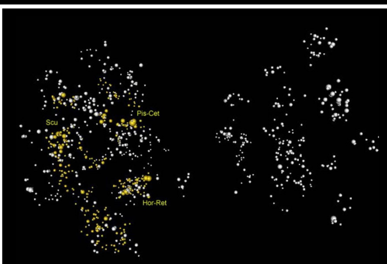
General Relativity,

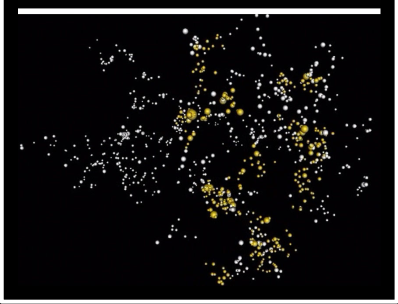
gravitational potential wells will bend and focus light. Dark matter concentrations act as a

Gravitational Lens.

Clusters and Superclusters

Voids & Clusters





Einasto, Saar et al. (1990s)

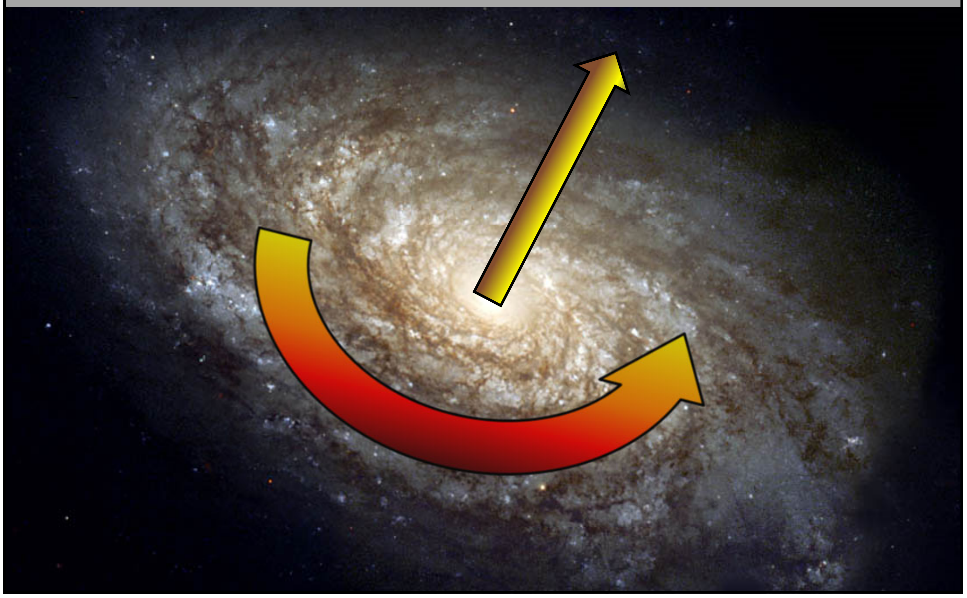
- Superclustering in Abell/APM clusters catalog
- Finding of characteristic scale ~140 Mpc, corresponding to large voids in the cluster distribution

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

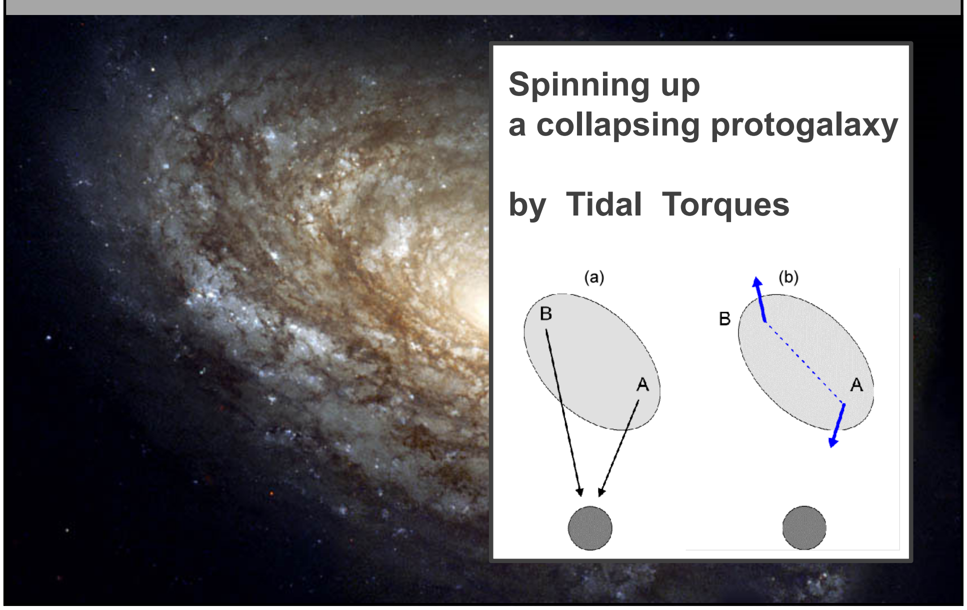
Cosmic Web:

Alignments

Spinning the Galaxies



Spinning the Galaxies



Spinning the Galaxies

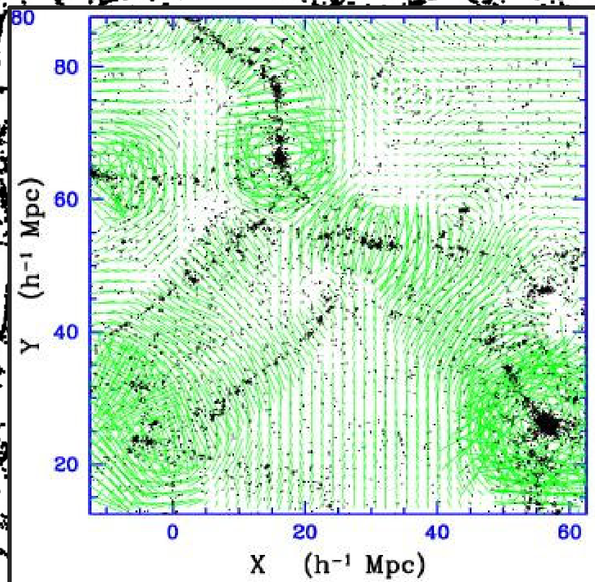
Connection

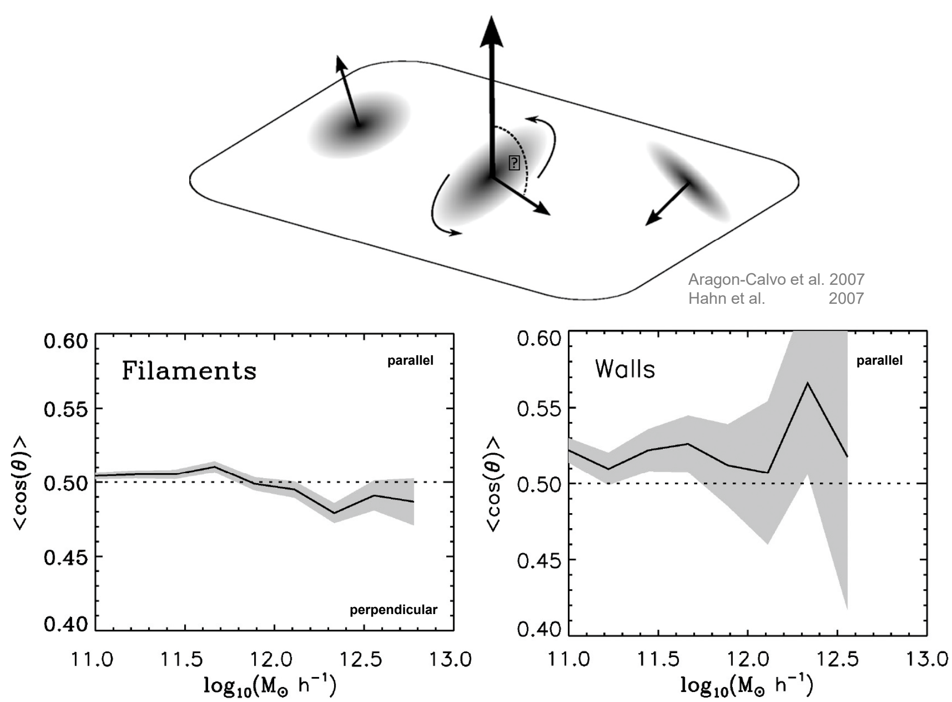
Galaxy Spin

Cosmic Web

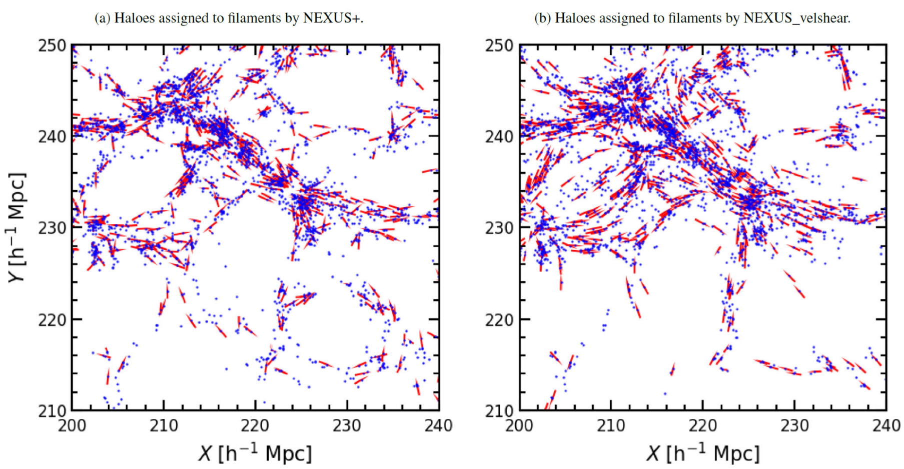
Spinning the Galaxies:

Tidal Forces that also Shape Cosmic Web



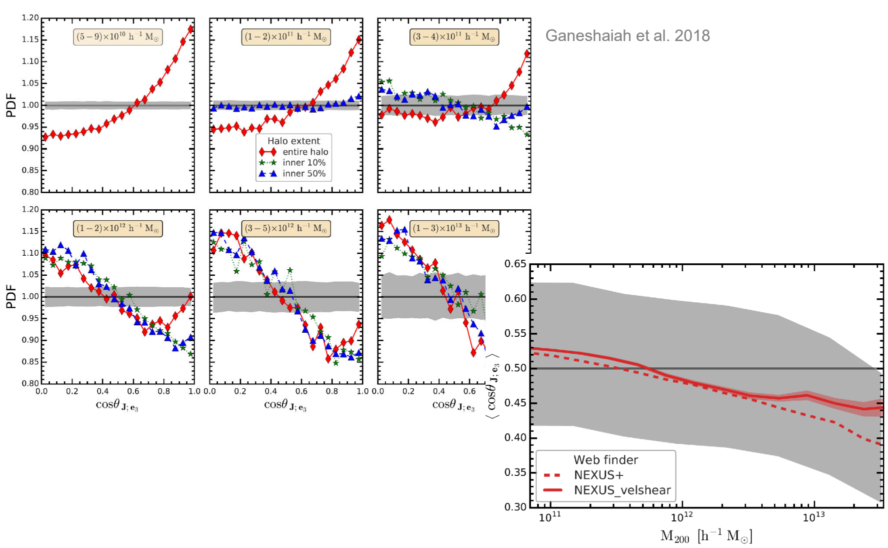


Filament-Halo alignments



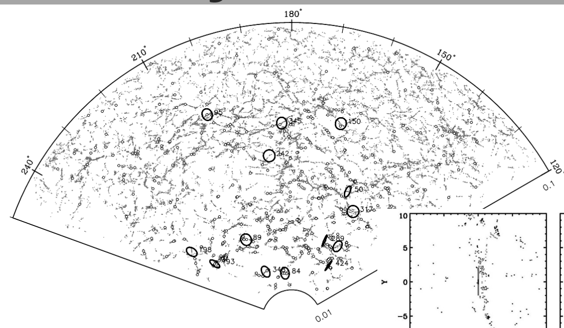
Ganeshaiah et al. 2018

Spin-Flip: mass dependent alignments



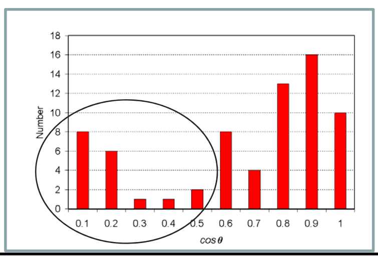
Ganeshaiah et al. 2018

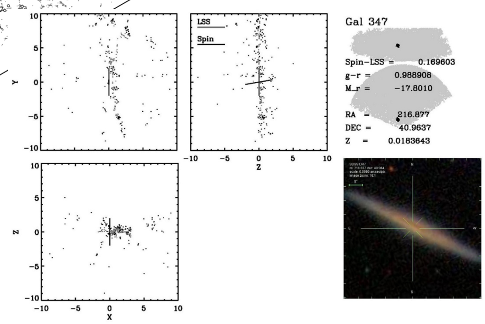
SDSS: Galaxy-Filament alignment



Aragon-Calvo et al. 2010

also see alignment studies by:
- Plionis et al. 1996
- Flin, Biernacka et al.
- Tempel & Libeskind 2014

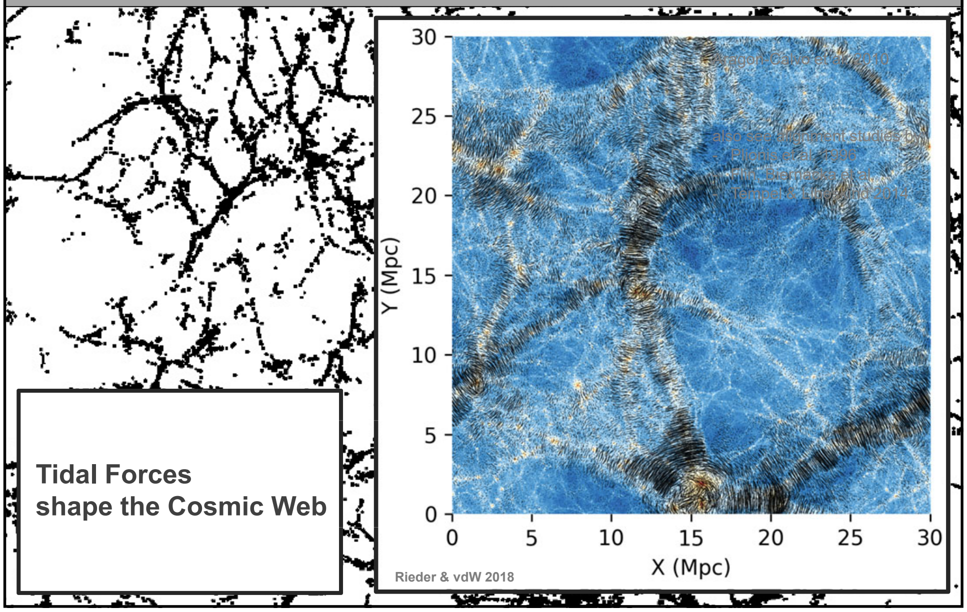




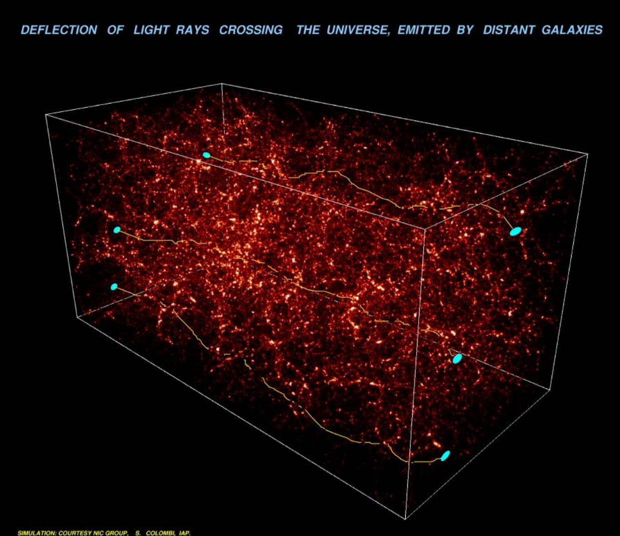
Cosmic Web:

Dark Matter & Grav. Lensing

Tidal Shaping of the Cosmic Web



Dark Matter Cosmic Web



Lensing of background light by dark matter distribution

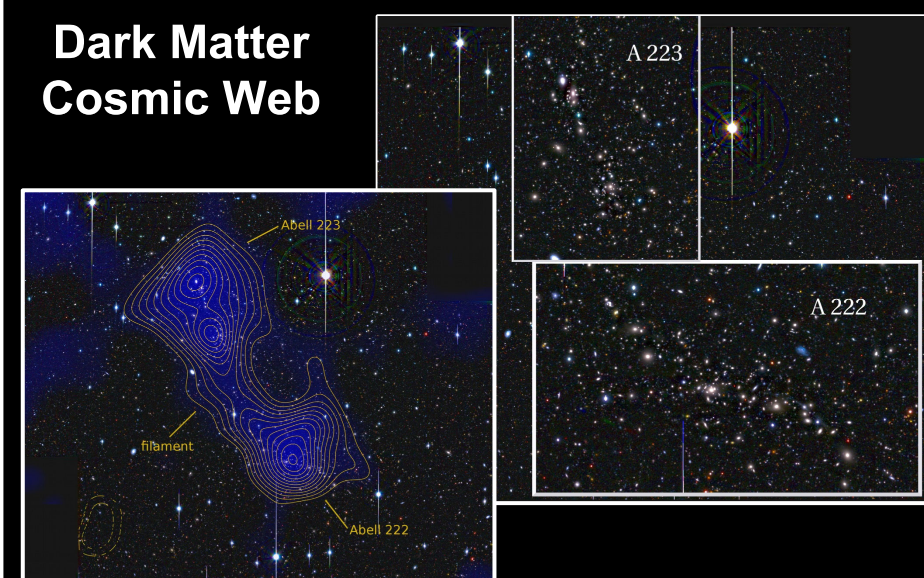
Galaxy Clusters

CL0024+17:

(Jee et al., 2007)

mapping the dark matter
content of
cosmic mass distribution
via
weak gravitational lensing

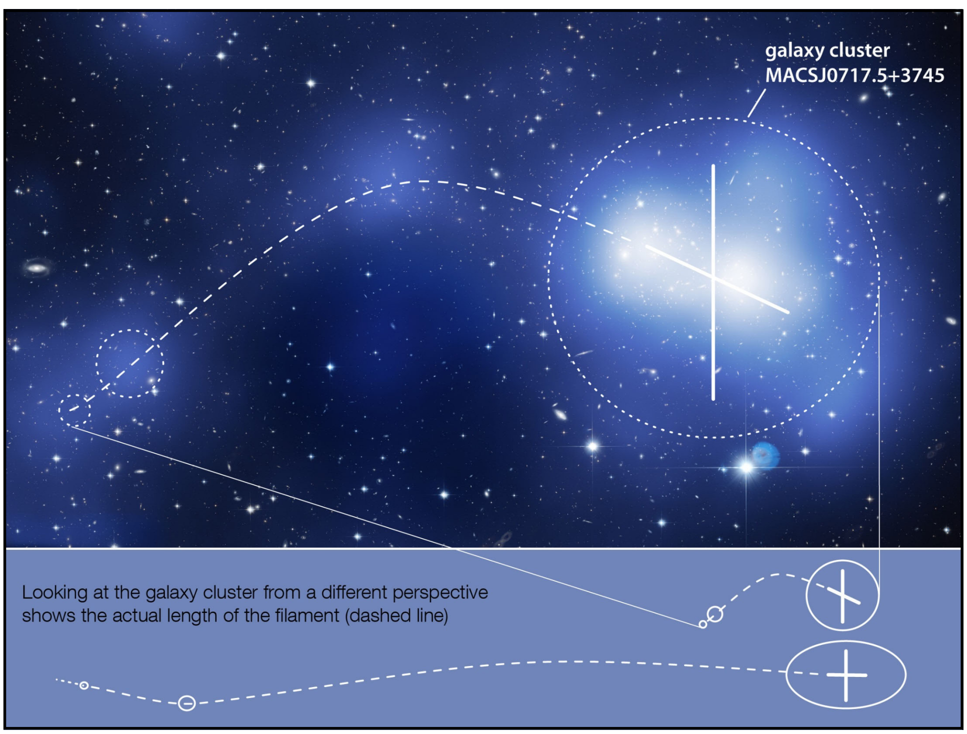
Dark Matter Cosmic Web



A222-A223
Dietrich et al. 2013

Dark Matter Cosmic Web

MACSJ0171.5+3745
Ebeling et al. 2012

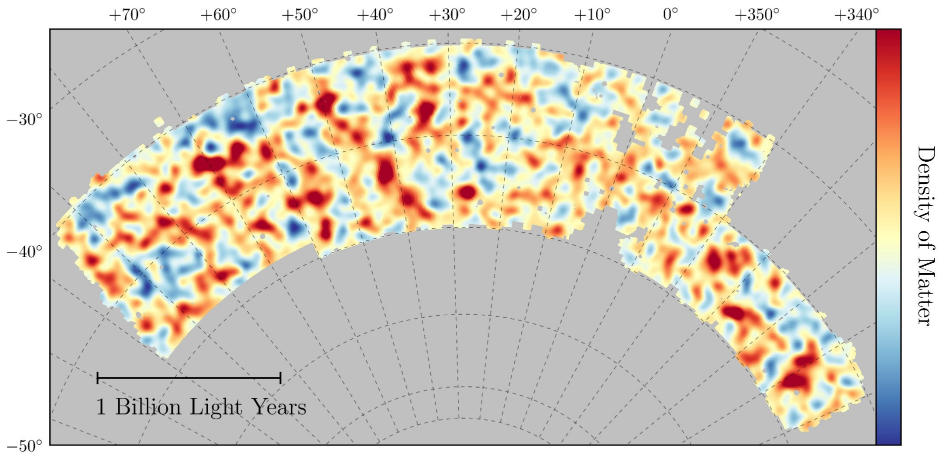


Dark Energy Survey (DES)

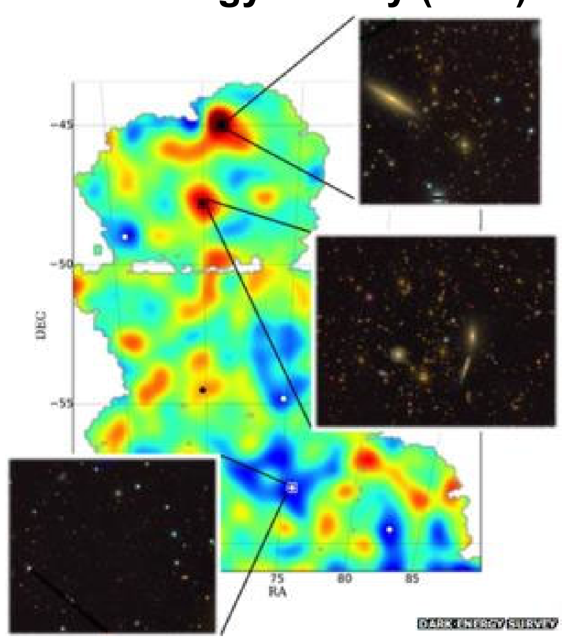
Map of (projected) (dark) matter density:

- **Determined from lensing deformation 28 million galaxies**
- **Red-yellow: overdense**
- **Blue-white: underdense**

Clearly visible: the weblike arrangement of dark matter



Dark Energy Survey (DES)



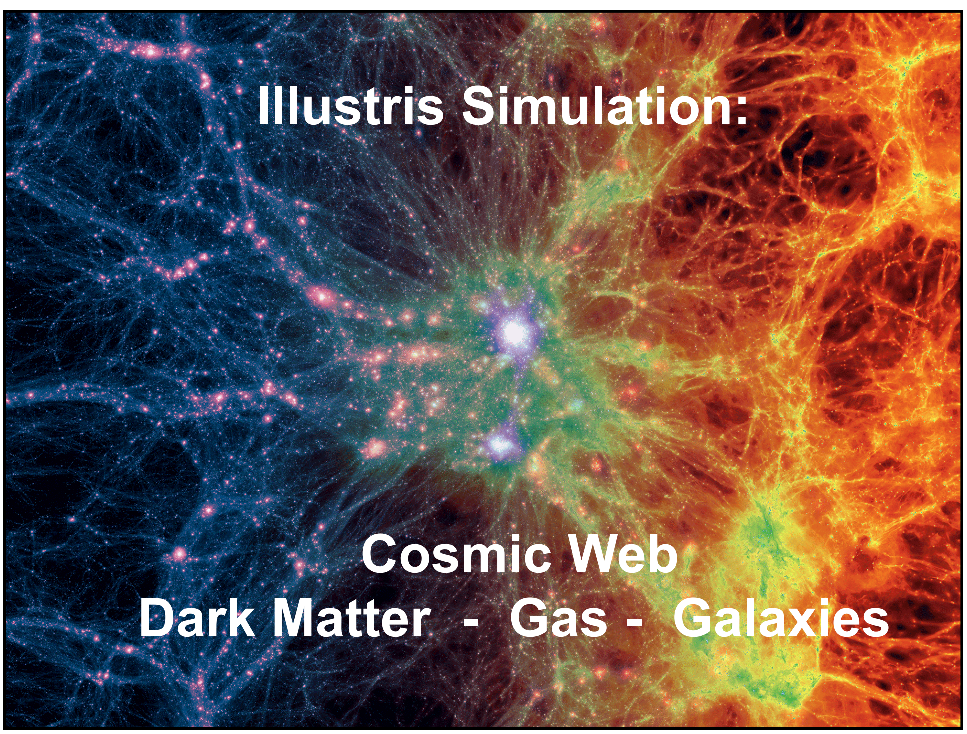
Map of (projected) (dark) matter density:

For reference, elements of the Cosmic Web:

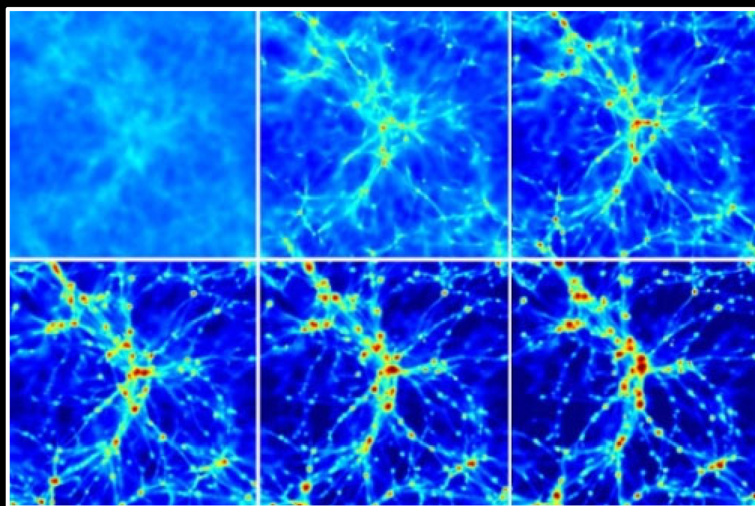
- **Identification 2 clusters**
- **Reveals filamentary extensions**
- **Also noticeable is a void region**

Cosmic Web:

Gas



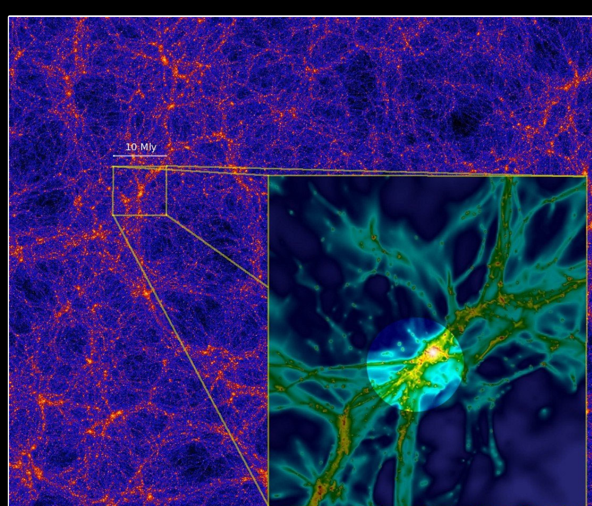
the Gaseous Cosmic Web



Evolution of the gaseous Cosmic Web:

- Gas falls into the potential wells (mainly determined by dark matter web)
- Gas heats up: - extremely hot in cluster nodes (hard Xray emitting gas)
  - warm/hot gas in filamentary extensions (WHIM)

the Gaseous Cosmic Web



Gaseous Cosmic Web:

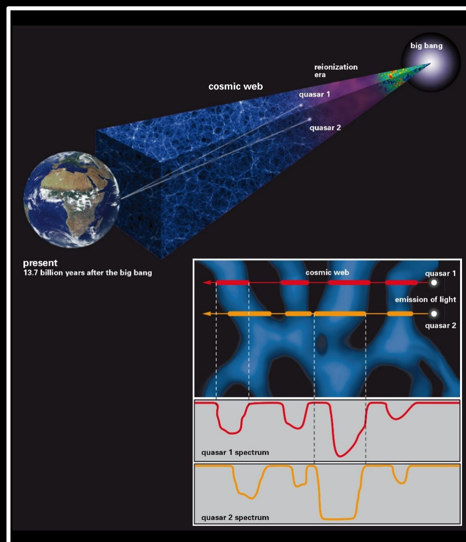
Detection via:

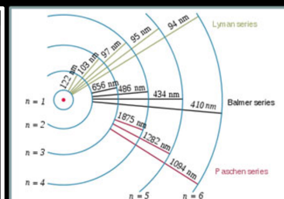
1) Lyα absorption (Lyα forest)
   - neutral hydrogen (cloud)
   - mostly at high redshift
   - absorption against quasar los.
   - possible use as tomographic tool

2) WHIM
   - warm-hot intergalactic medium
   - soft Xray emission of hot gas (10^5 K) very hard to see
   - absorption lines Xray band (eg. OVI)

3) Sunyaev-Zeldovich scattering filaments
   - inverse Compton scattering CMB photons against hot electrons in ICM/IGM
   - has been seen in Planck (80 filam.)

The Gaseous Cosmic Web: Lyα forest

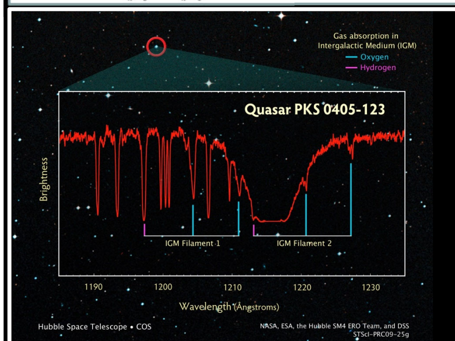




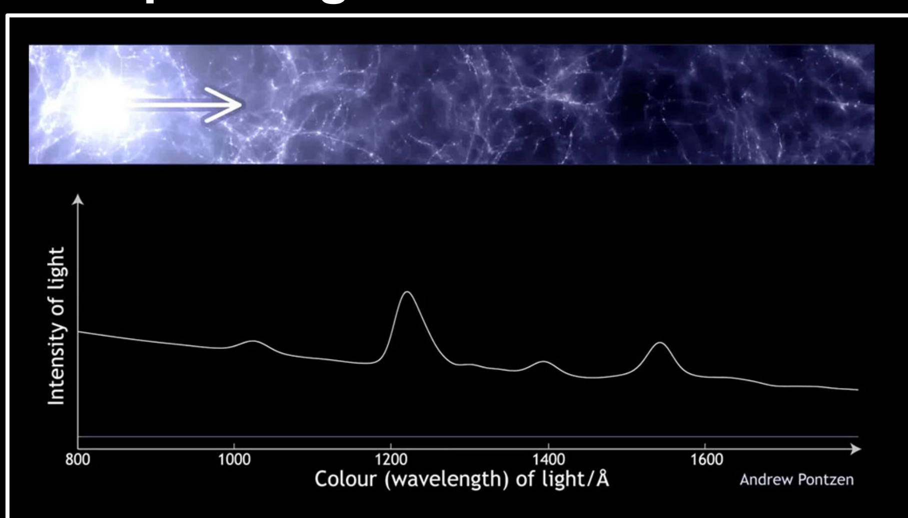
Lyα transition:

absorption line by neutral hydrogen

intervening hydrogen gas



Lyα forest:
piercing the Cosmic Web

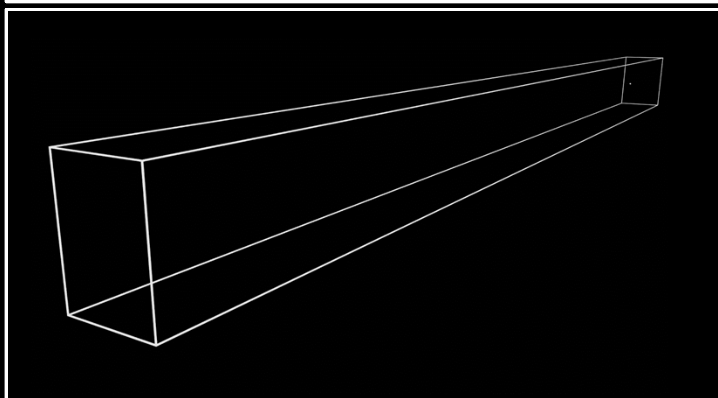


Cosmic Web Tomography
Lyα survey CLAMATO

Mapping the Lyα forest in a densely sampled set of quasar spectra over sky region

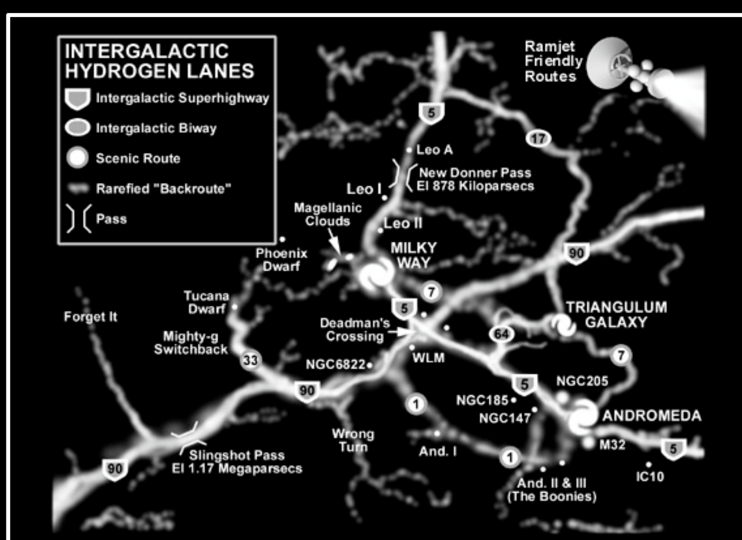
1-D skewers through the gaseous Universe
Reconstruction full 3-D cosmic web, when skewers within correlation scale from each other

First systematic survey: CLAMATO (Lee et al.)



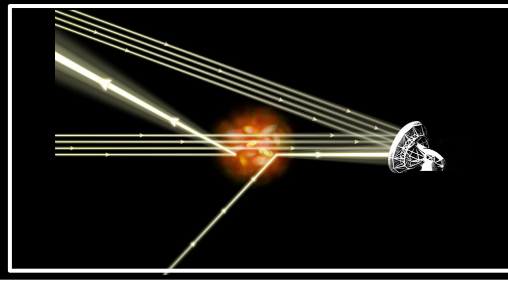
KG Lee et al..

The Gaseous Cosmic Web:
Intergalactic Hydrogen Lanes



J. Cramer

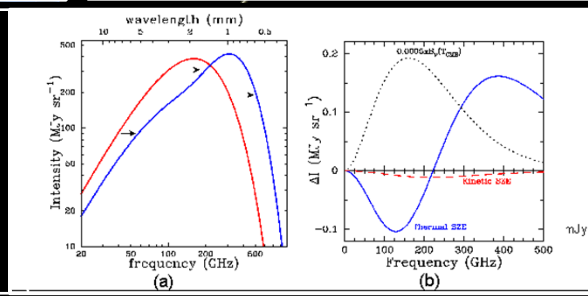
The Gaseous Cosmic Web:
Sunyaev-Zeldovich



Sunyaev-Zeldovich

Inverse Compton scattering of CMB photons:

hot intervening gas:
frequency dependent signature:
- **Absorption**
- **Emission**



The Gaseous Cosmic Web:
Sunyaev-Zeldovich

Sunyaev-Zeldovich detection of

Inter-cluster bridge/filament

in between clusters A401 and A399

ESA/Planck collaboration

Cosmic Web:

Cosmic Migration Flows

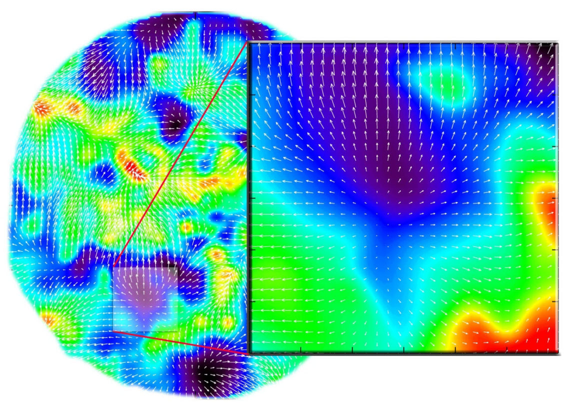
Large Scale Flows

Large-Scale Flows:

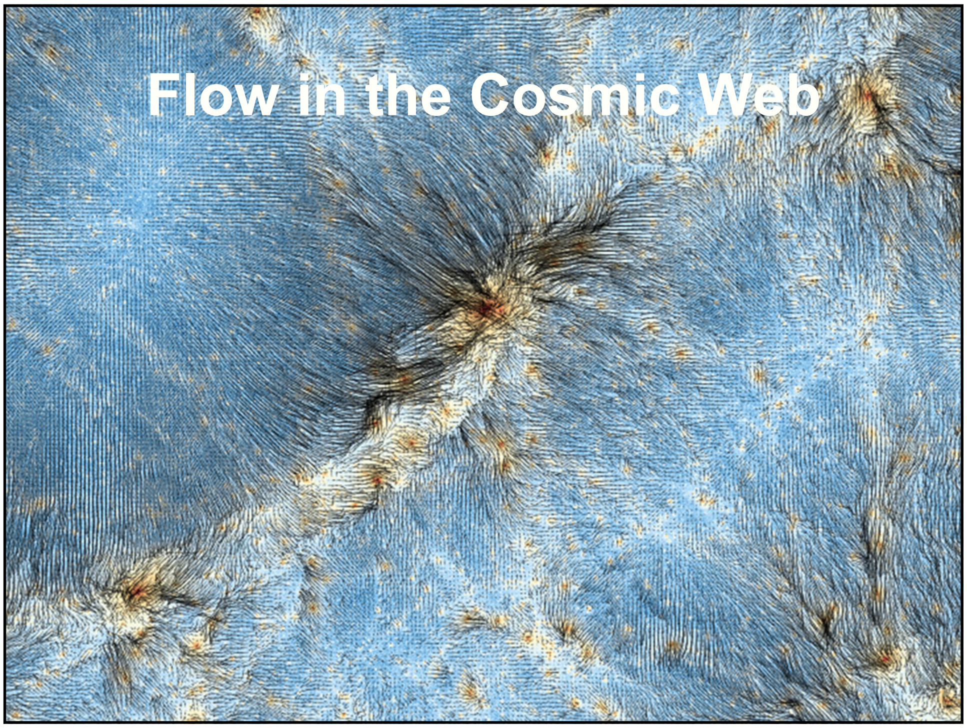
- Structure buildup accompanied by displacement of matter:
  - Cosmic flows
- On large (Mpc) scales, structure formation still in linear regime
- Directly related to cosmic matter distribution
- Note:
  redshift space distortion

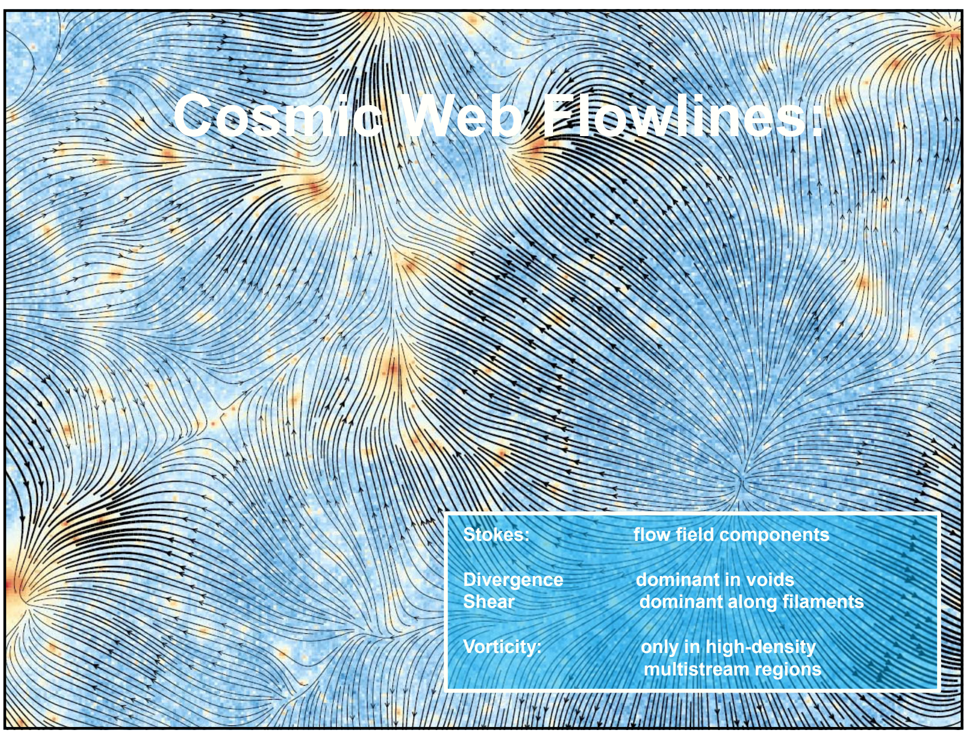
  $cz = Hr + v_{pec}$

  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



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

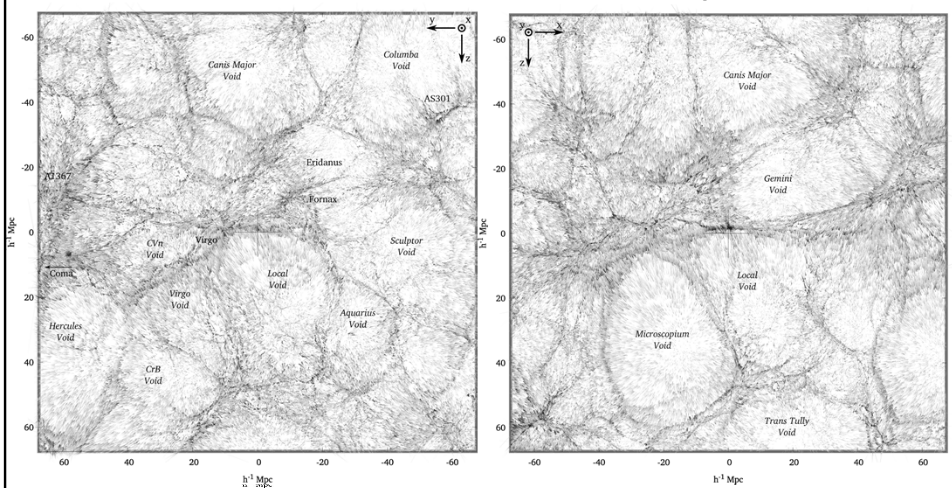

Flow in the Cosmic Web

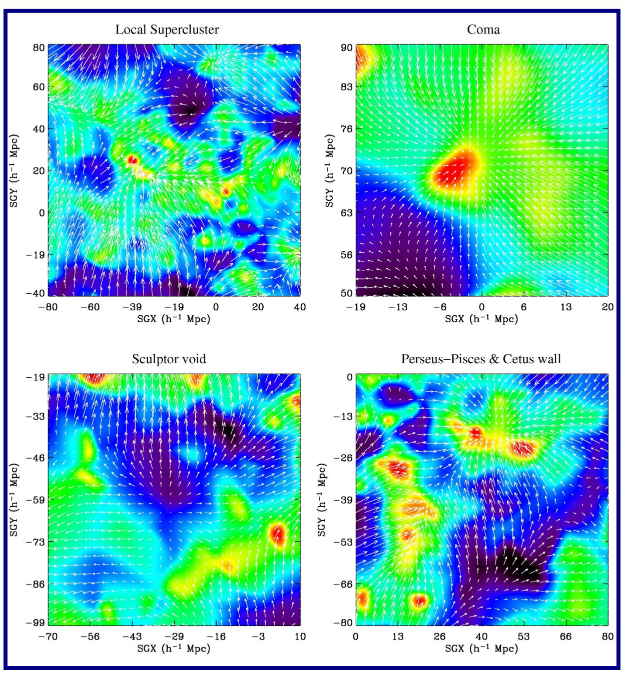

Cosmic Web Flowlines:
Stokes: flow field components
Divergence dominant in voids
Shear dominant along filaments
Vorticity: only in high-density multistream regions

Supergalactic Plane

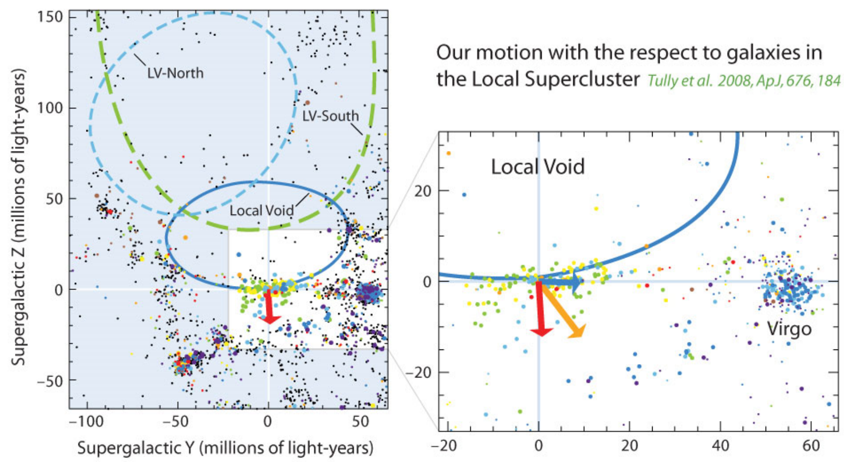
mean KIGEN - adhesion reconstruction

Hidding, Kitaura, vdW & Hess 2016/2017



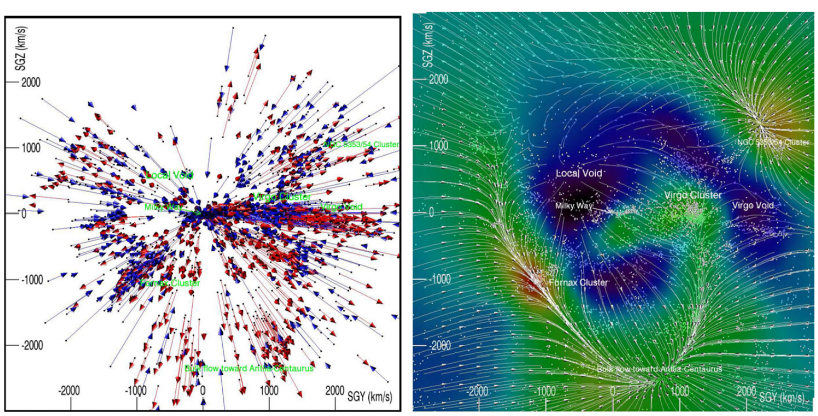


Push of the Local Void



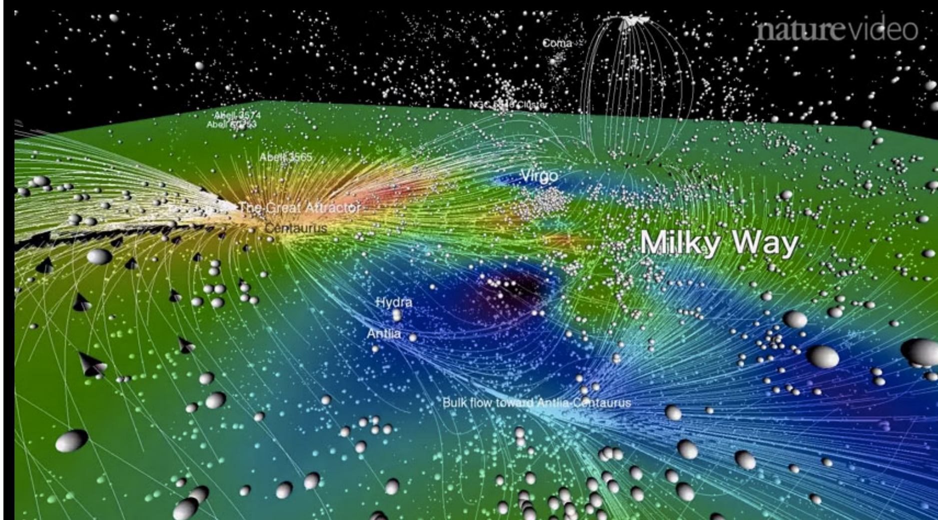
Tully et al. 2008:
Local Void pushes with ~260 km/s against our local neighbourhood

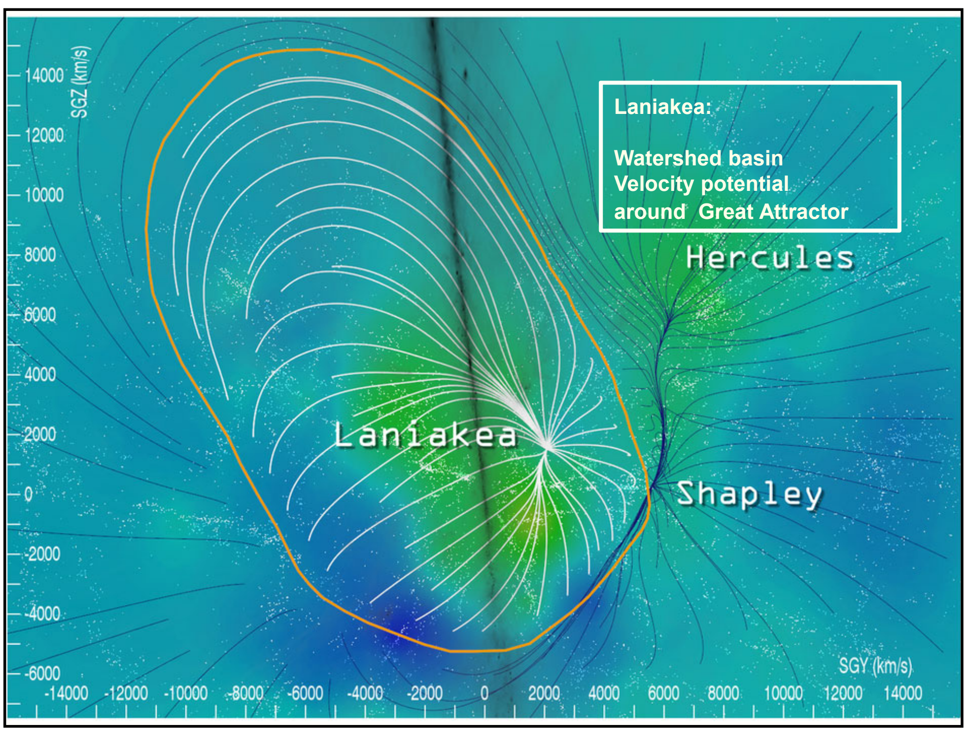
CosmicFlows-2



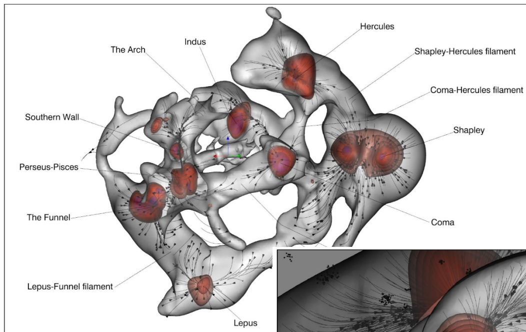
Courtois et al. 2013
Local void expansion in Cosmicflows-2

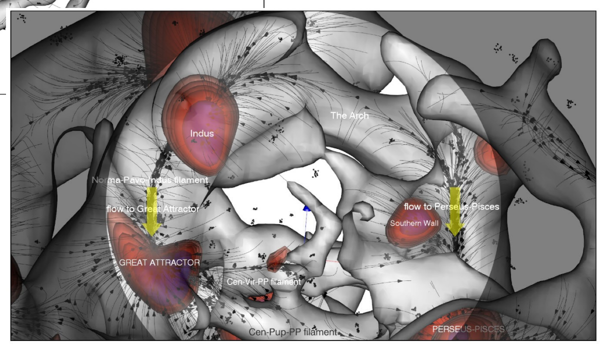
Laniakea


naturevideo
Coma
Abell 3565
Virgo
The Great Attractor
Centaurus
Milky Way
Hydra
Antlia
Bulk flow toward Antlia-Centaurus


Laniakea:
Watershed basin
Velocity potential
around Great Attractor
Hercules
Laniakea
Shapley
SGZ (km/s)
SGY (km/s)
14000
12000
10000
8000
6000
4000
2000
0
-2000
-4000
-6000
-14000 -12000 -10000 -8000 -6000 -4000 -2000 0 2000 4000 6000 8000 10000 12000 14000

CosmicFlows-3





Cosmic Web morphology:
velocity shear based
V-web identification
flow pattern in cosmic web

(Pomarede et al. 2017)