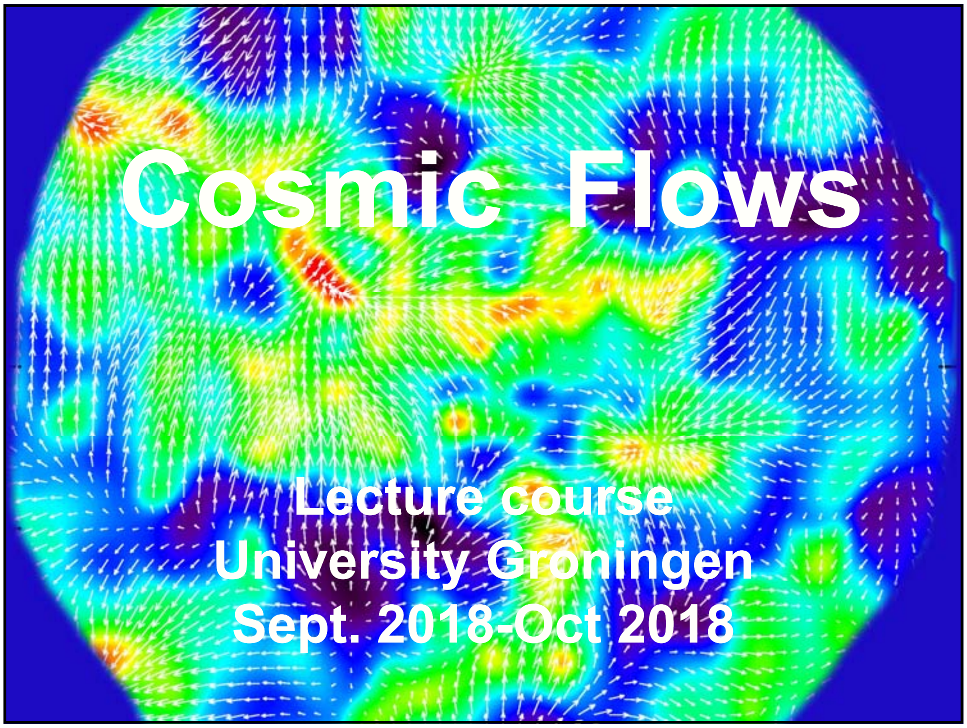
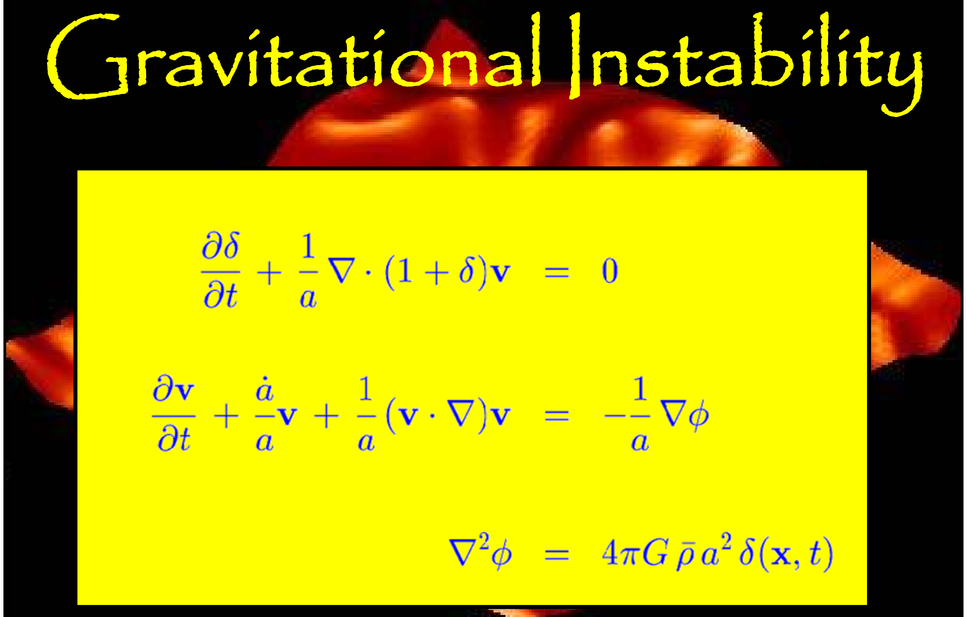


Cosmic Flows

Lecture course
University Groningen
Sept. 2018-Oct 2018

Gravitational Instability



$$\frac{\partial \delta}{\partial t} + \frac{1}{a}\nabla\cdot(1+\delta)\mathbf{v} = 0$$

$$\frac{\partial \mathbf{v}}{\partial t} + \frac{\dot{a}}{a}\mathbf{v} + \frac{1}{a}(\mathbf{v}\cdot\nabla)\mathbf{v} = -\frac{1}{a}\nabla\phi$$

$$\nabla^2\phi = 4\pi G\,\bar{\rho}\,a^2\,\delta(\mathbf{x},t)$$

Gravitational Instability

$$\frac{\partial \delta}{\partial t} + \frac{1}{a}\,\nabla \cdot \mathbf{v} = 0$$

$$\frac{\partial \mathbf{v}}{\partial t} + \frac{\dot{a}}{a}\mathbf{v} = -\frac{1}{a}\,\nabla \phi$$

$$\nabla^2 \phi = \frac{3}{2}\Omega H^2 a^2\, \delta(\mathbf{x}, t)$$

Gravitational Instability

The linear system of structure growth equations can be written in terms of a second order differential equation,

$$\frac{\partial^2 \delta}{\partial t^2} + 2\frac{\dot{a}}{a}\frac{\partial \delta}{\partial t} = \frac{3}{2}\Omega_0 H_0^2\, \frac{1}{a^3}\,\delta$$

Gravitational Instability

… whose two solutions are separable in time and space, leading to a universal "density growth factor" D(t),

$$\delta(\mathbf{x},t) \;=\; D_1(t)\,\Delta_1(\mathbf{x}) \;+\; D_2(t)\,\Delta_2(\mathbf{x})$$

"Growing Mode"

"Decaying Mode"

Linear Density Growth

… whose two solutions are separable in time and space, leading to a universal "density growth factor" D(t),

$$\delta(\mathbf{x},t) \;=\; D_1(t)\,\Delta_1(\mathbf{x}) \;+\; D_2(t)\,\Delta_2(\mathbf{x})$$

"Growing Mode"

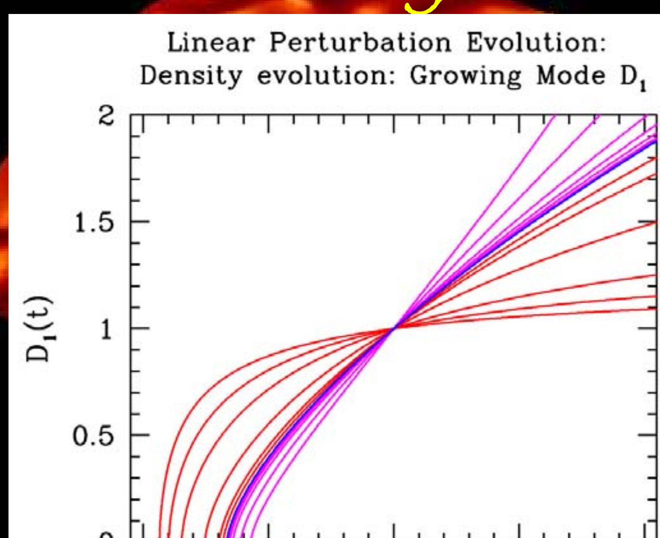
"Decaying Mode"

Linear Density Growth

... The universal "density growth factor" D(t) can be computed for any cosmology through the integral

$$D(t) \approx H(t) \int \frac{dt}{a^2 H^2(t)}$$

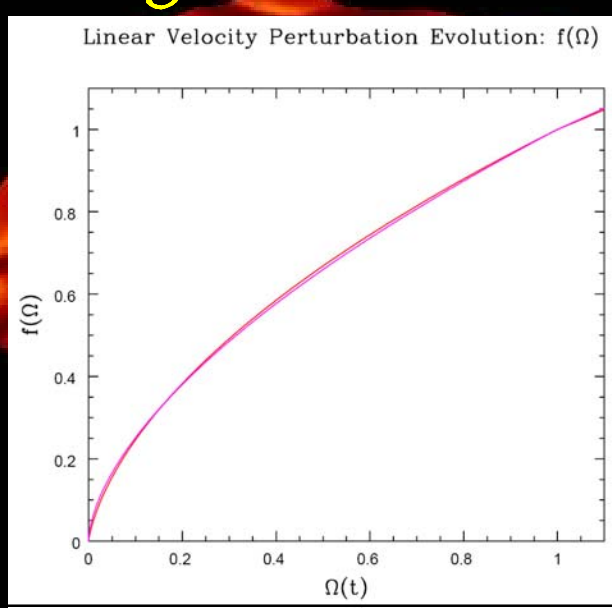
Linear Density Growth



Gravitational Instability

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

Velocity Perturbations



Measuring Distances

Distance & Velocity Measurements

To measure peculiar velocities of galaxies, one needs to know their real distance r:

- ie. the distance independent of redshift, ie. of the use of the Hubble relation:

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

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

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

- to determine the (radial component) of the peculair velocity, one would need to measure independently the distance r.
- Determining reliable distances directly is still one of the main challenges of observational cosmology.

Distance & Velocity Measurements

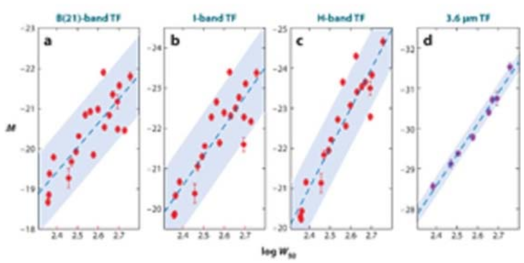
$$\vec{v}_{pec} \cdot \vec{e}_r = cz - Hr$$

- Determining reliable distances directly is still one of the main challenges of observational cosmology.
- In practice, one makes use of *galaxy scaling relations,* which relates an observable *intrinsic characteristic* of a galaxy – such as velocity dispersion or rotation velocity – with an observable *distance dependent characteristic* whose intrinsic value is physically related to the intrinsic characteristic.
- The 2 main examples are the Tully-Fisher (TF) relation – for late-type galaxies – and the Faber-Jackson (FJ) relation – for early-type galaxies. Both are relations based on the dynamics of galaxies, relating the mass M of the galaxy to their rotation velocity (TF) or velocity dispersion (FJ) of galaxies.
- Main obstacle: accuracy/measurement errors of peculiar velocities still only 20%, at best 10%

Tully-Fisher

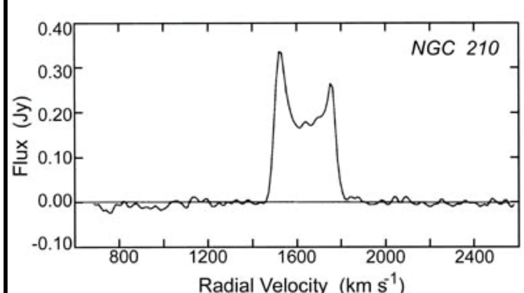
- Spiral galaxies:

  relation between rotation velocity v (measured by HI velocity width) and absolute luminosity L of galaxy
- $L \propto v^4$



- Measure rotation velocity v from linewidth 21cm line of galaxy:

  TF → L
- Measure apparent magnitude, ie. apparent luminosity l:
- Distance r: $r = \sqrt{\frac{L}{l}}$



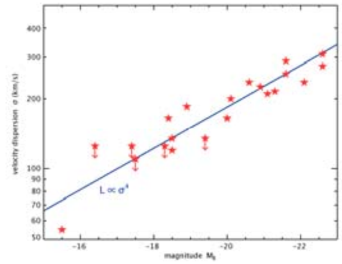
Faber-Jackson

- Early-type galaxies:

  relation between
  velocity dispersion σ_v

  Luminosity L of galaxy

- $L \propto \sigma_v^{\,4}$



- Measure velocity dispersion σ_v of galaxy:

  FJ → L

- Measure apparent magnitude, ie. apparent luminosity l:

- Distance r: $r = \sqrt{\frac{L}{l}}$

The FJ relation is a projection of a higher dimensional relation, the Fundamental Plane (FP)

The FP relates, for E and SO galaxies, the surface brightness I_e, effective radius R_e & velocity dispersion σ_v of a galaxy

$$\log R_e = -0.82 \log I_e + 1.24 \log \sigma_v + C_{FP}$$

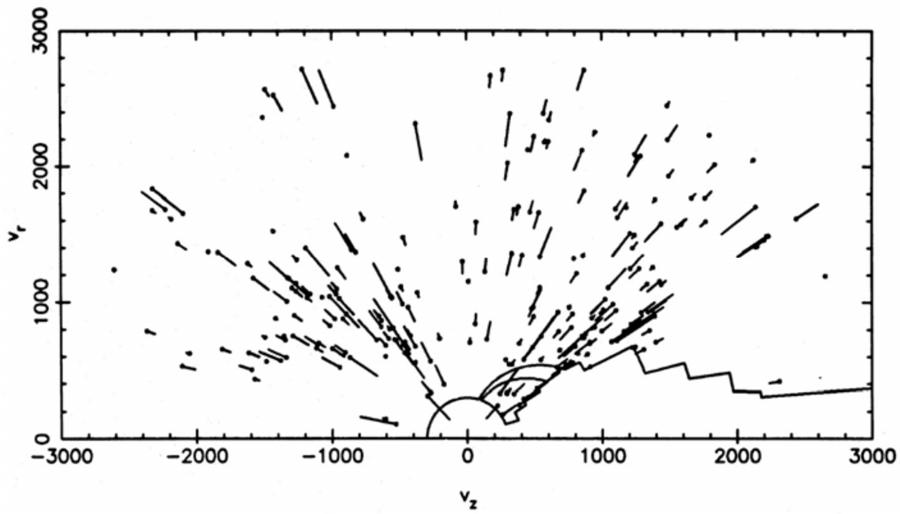
The FP is a reflection of the virial equilibrium of such a galaxy

Peculiar Velocities

Local Universe

Local Supercluster flow

Lilje, Yahil & Jones 1986

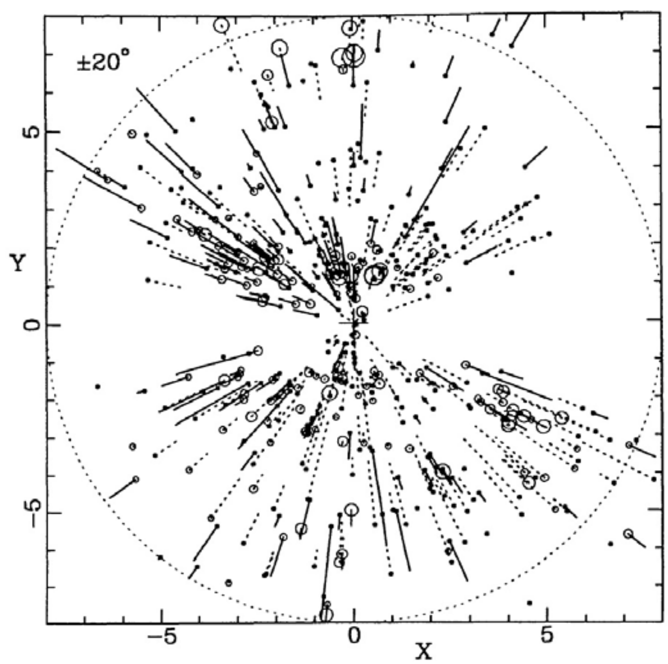


Mark III

Peculiar velocities Local Universe

Willick, Strauss et a

First flow maps: 7 Samurai



POTENT

velocity reconstruction
mass density distribution

- Surveys of galaxy peculiar velocities only give a sample of RADIAL velocities of galaxies,
- irregularly sample – at discrete galaxy locations – in sample volume

- Bertschinger & Dekel (1989++) proposed a beautiful idea to convert this into a map of the mass distribution in this volume.

- Their method, POTENT, is based on the realization that the flow on large scales is a a potential flow, so that once can compute the velocity potential Φ_v:

$$v_{pec,r} = \vec{v}_{pec} \cdot \vec{e}_r = cz - Hr$$

$$\Phi_v(r) = \int_0^r v_{pec,r}(x)\, dx$$

- From this one can then simply get the FULL 3-D velocity flow:

$$\vec{v}(r) = \vec{\nabla}\Phi_v(r)$$

POTENT

velocity reconstruction
mass density distribution

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- From this one can then simply get the FULL 3-D velocity flow:

$$\vec{v}(r) = \vec{\nabla}\Phi_v(r)$$

- The density field δ(r) then simply follows from the linear continuity eqn.

$$\vec{\nabla} \cdot \vec{v} = -Haf(\Omega)\,\delta(\vec{r})$$

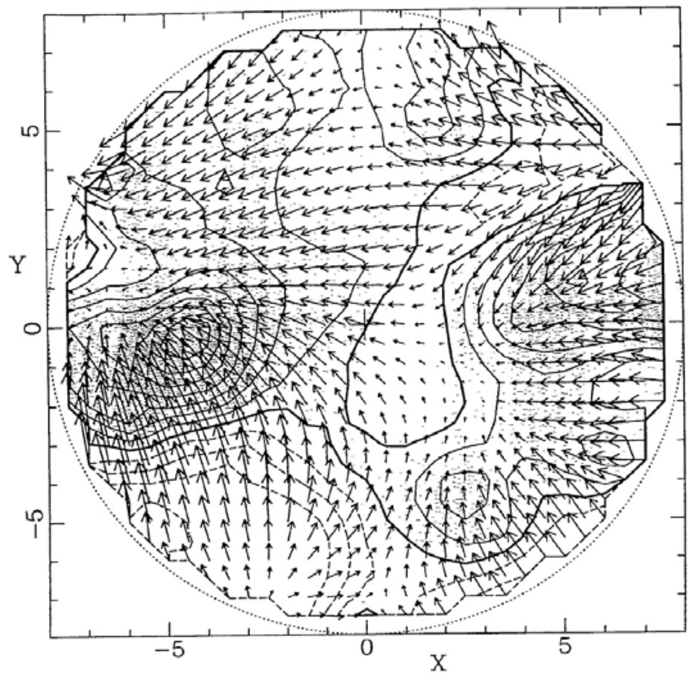
$$\Downarrow$$

$$\delta(\vec{r}) = -\frac{\vec{\nabla} \cdot \vec{v}}{Haf(\Omega)}$$

POTENT map

Mass distribution Local Universe

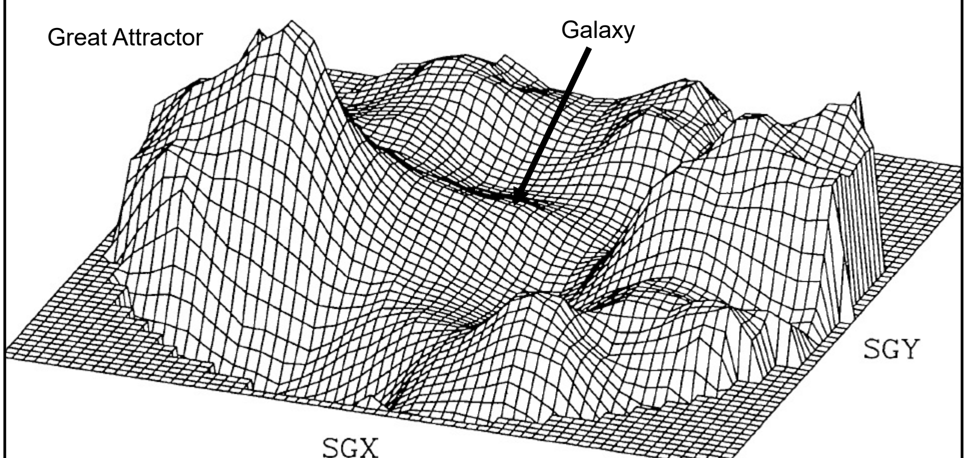
Bertschinger, Dekel, et al.

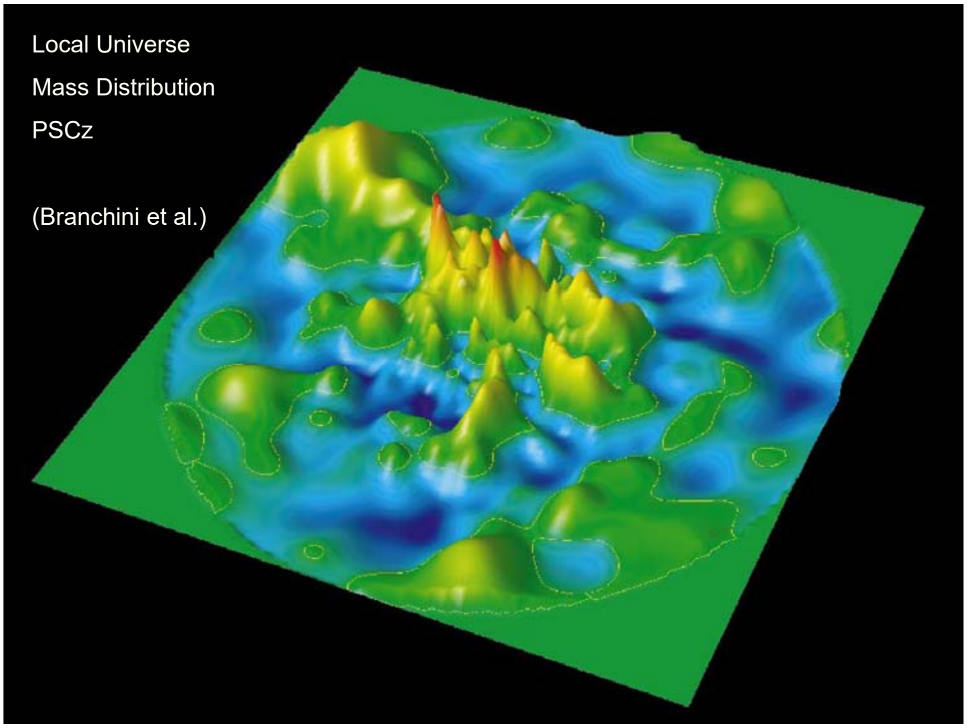


POTENT map

Mass distribution Local Universe

Bertschinger, Dekel, et al.



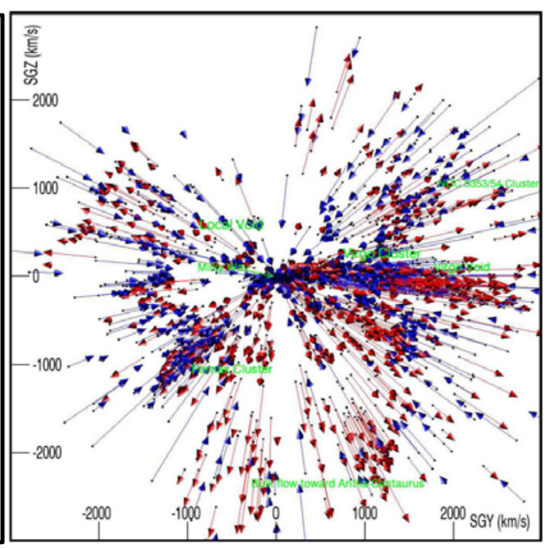


Cosmicflows

- Cosmicflows survey peculiar velocities Local Universe:

Tully & Courtois

Cosmicflows-2 2013
Cosmicflows-3 2017



the Great Attractor

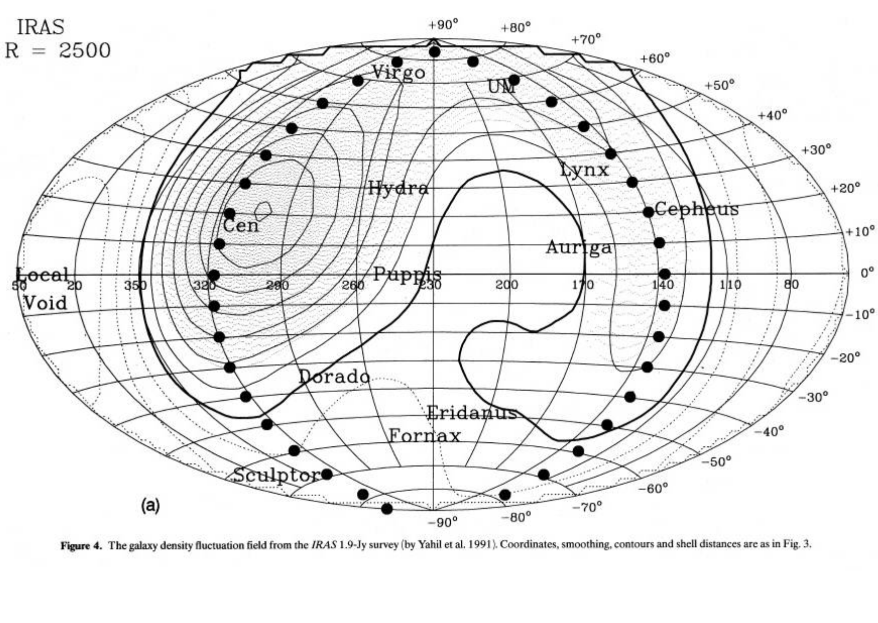
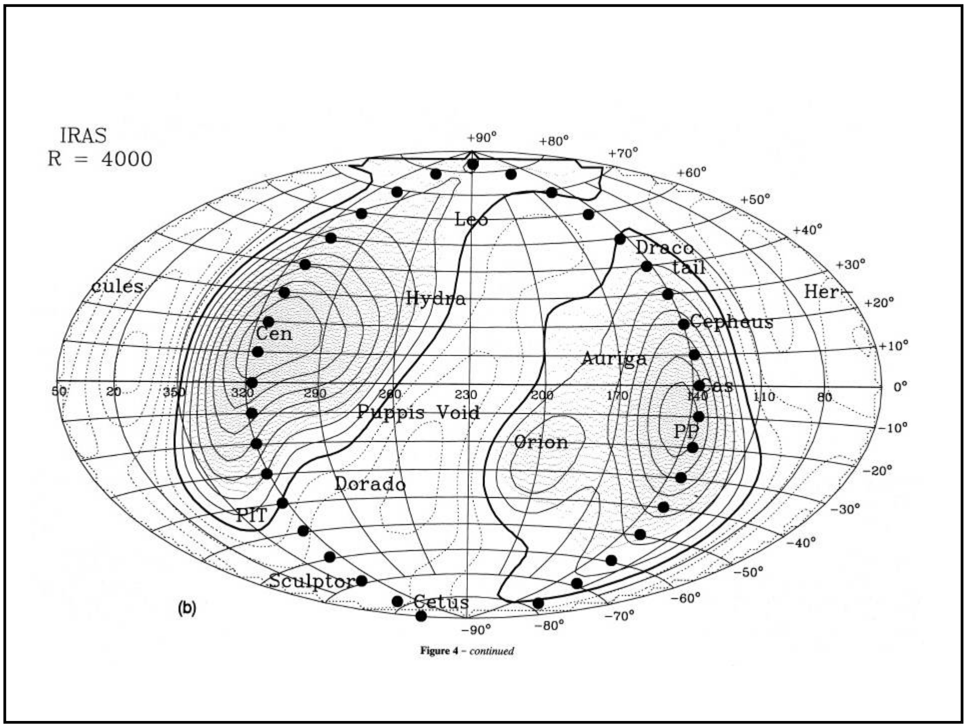
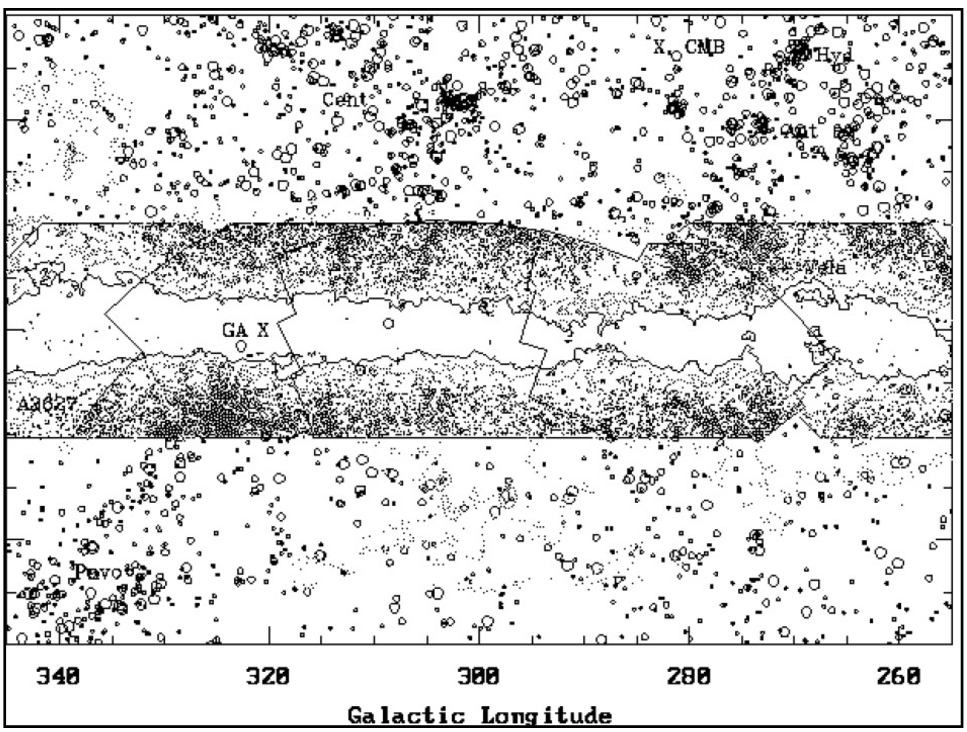
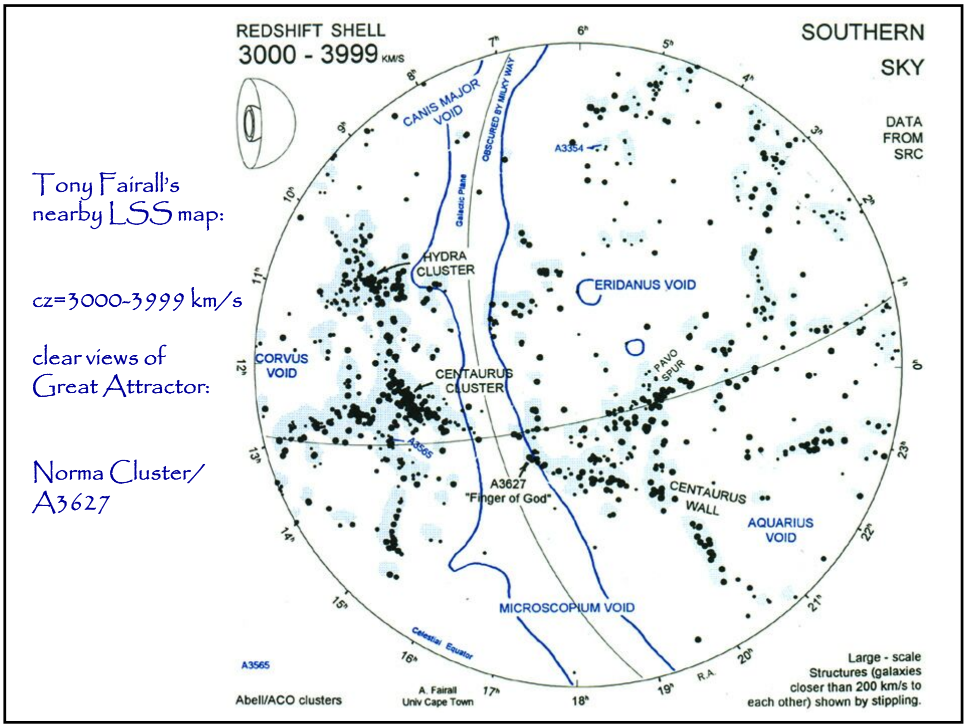


Figure 4. The galaxy density fluctuation field from the *IRAS* 1.9-Jy survey (by Yahil et al. 1991). Coordinates, smoothing, contours and shell distances are as in Fig. 3.


IRAS
R = 4000
Leo
Draco
tail
cules
Hydra
Her-
Cepheus
Cen
Auriga
Cas
Puppis Void
Orion
PP
Dorado
PIT
Sculptor
Cetus
(b)
Figure 4 – continued


X CMB
Hya
Cent
Ant
Vela
GA X
A3627
Pavo
340
320
300
280
260
Galactic Longitude

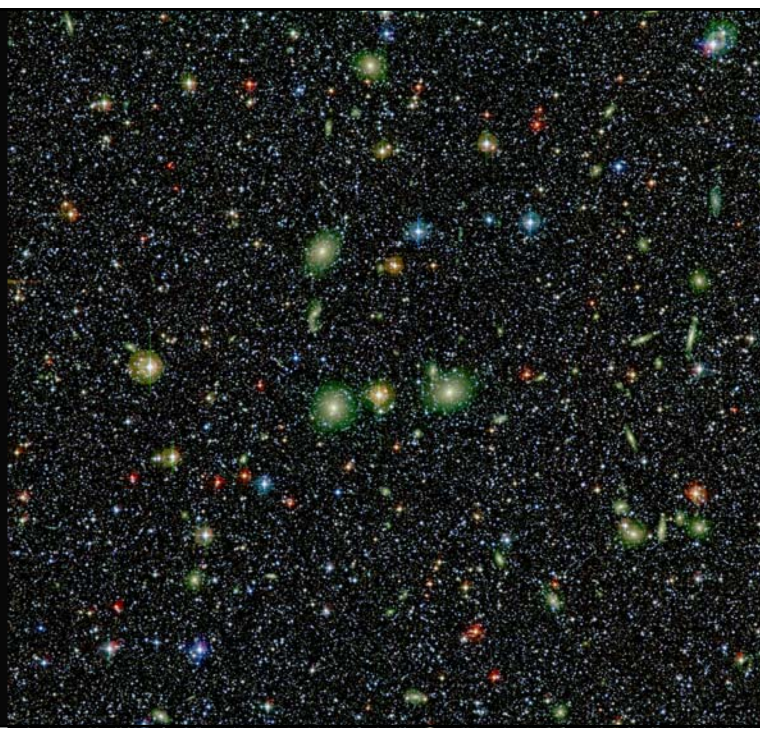


Tony Fairall's
nearby LSS map:

cz=3000-3999 km/s

clear views of
Great Attractor:

Norma Cluster/
A3627



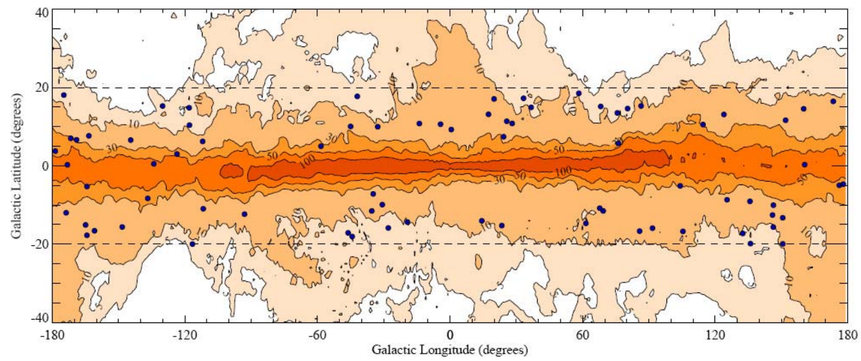
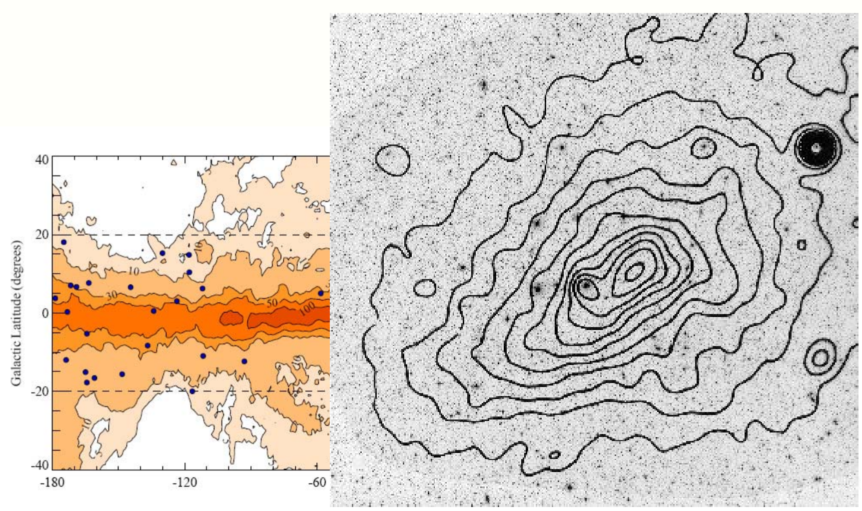


Fig. 16. Distribution in Galactic coordinates of the 76 by Ebeling et al. [129] so far spectroscopically confirmed X-ray clusters (solid dots) of which 80% were previously unknown. Superimposed are Galactic HI column densities in units of 10^{20} cm^{-2} (Dickey & Lockman 1990). Note that the region of relatively high absorption ($N_{HI} > 5 \times 10^{21}$ cm^{-2}) actually is very narrow and that clusters could be identified to very low latitudes



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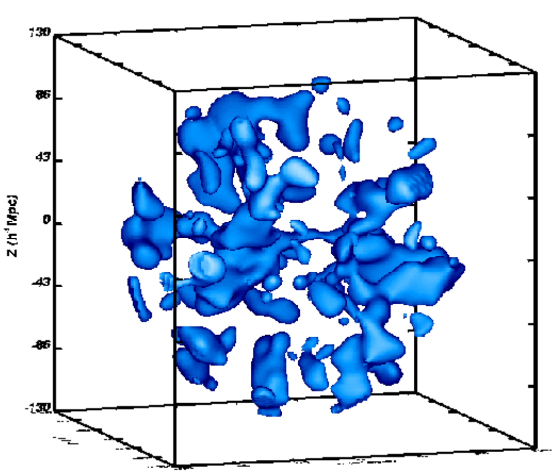
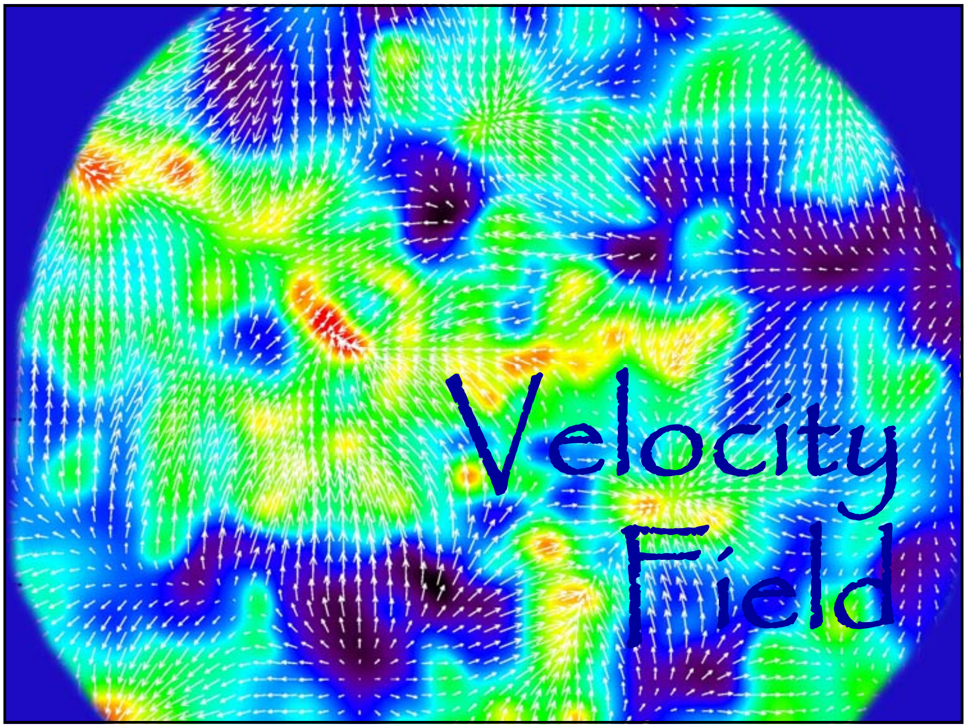
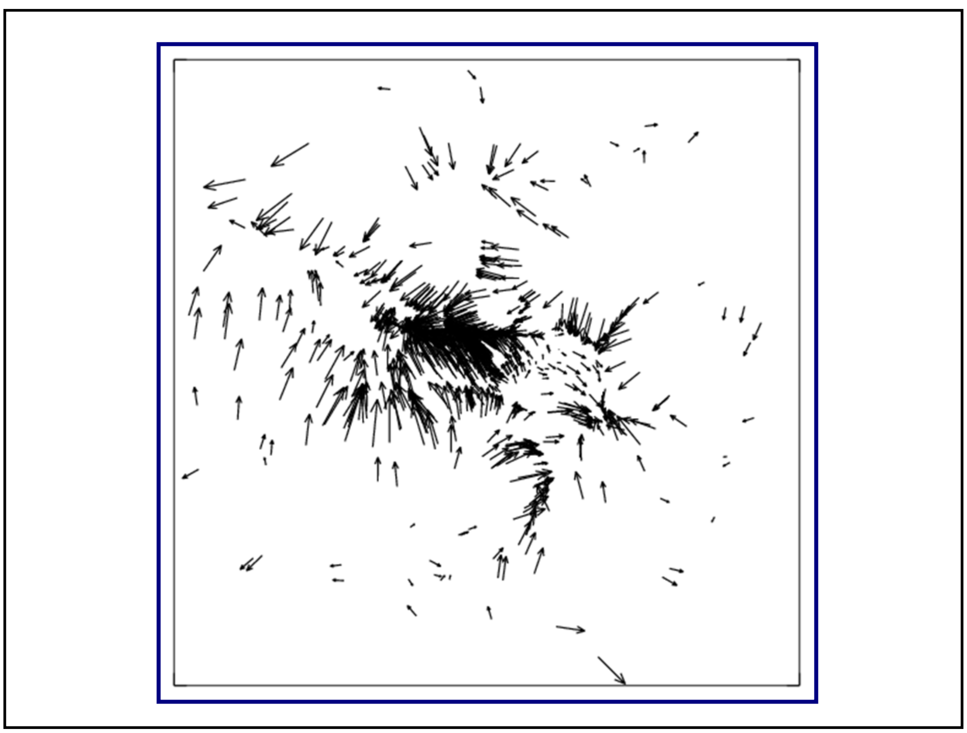
PSCz:

Cosmic Migration Flows

Local Universe

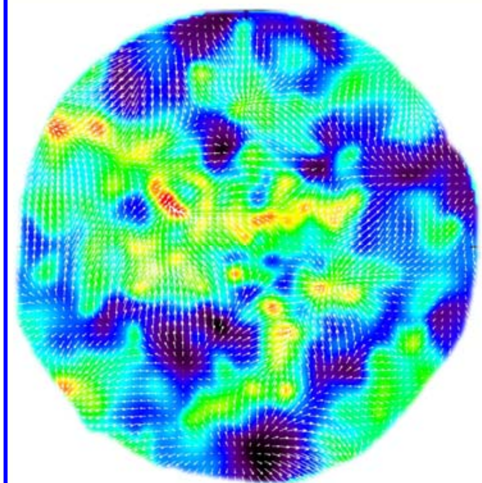



Velocity
Field

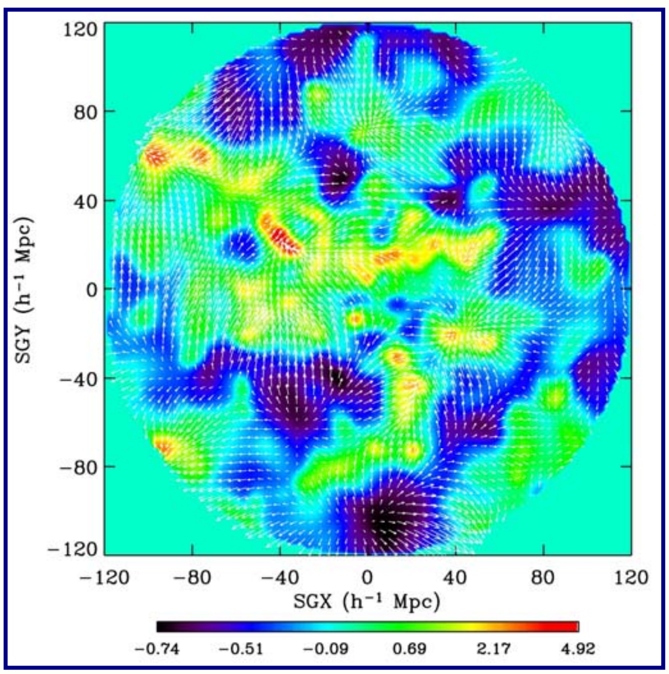


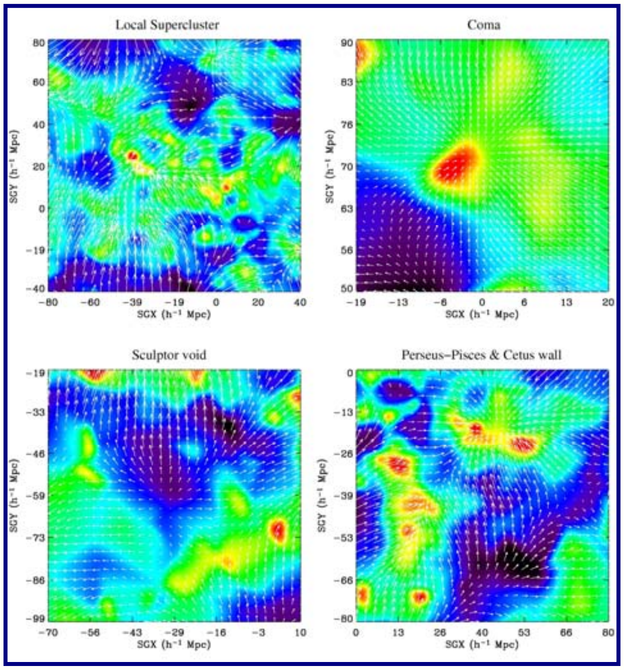
PSCz Flow Field

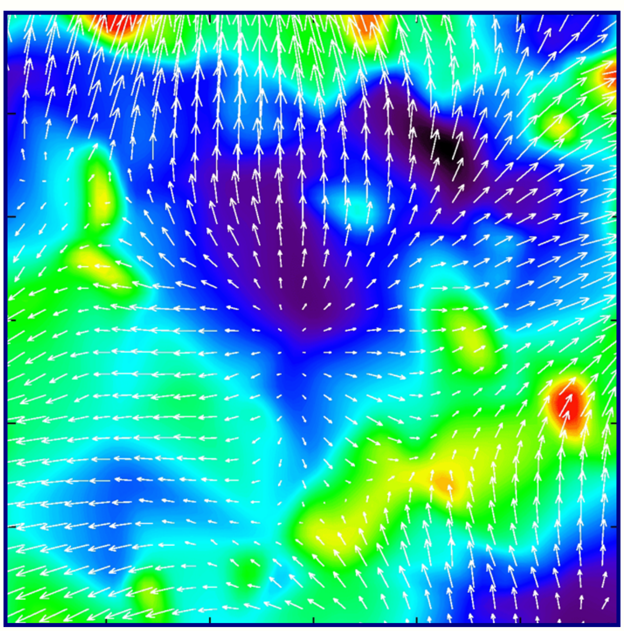
- Flow throughout the volume restored (assuming no shell-crossing)
- Restored velocities volume-weighted
- Shot-noise suppressed



PSCz, velocity+density field




Local Supercluster
Coma
Sculptor void
Perseus–Pisces & Cetus wall
SGX (h^{-1} Mpc)
SGY (h^{-1} Mpc)



Cosmic Web:

Cosmic Migration Flows

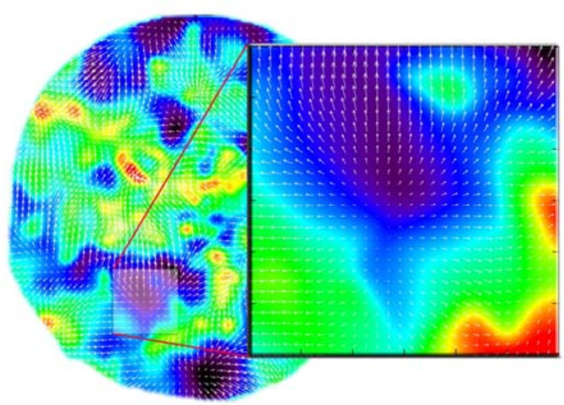
Large Scale Flows

Large-Scale Flows:

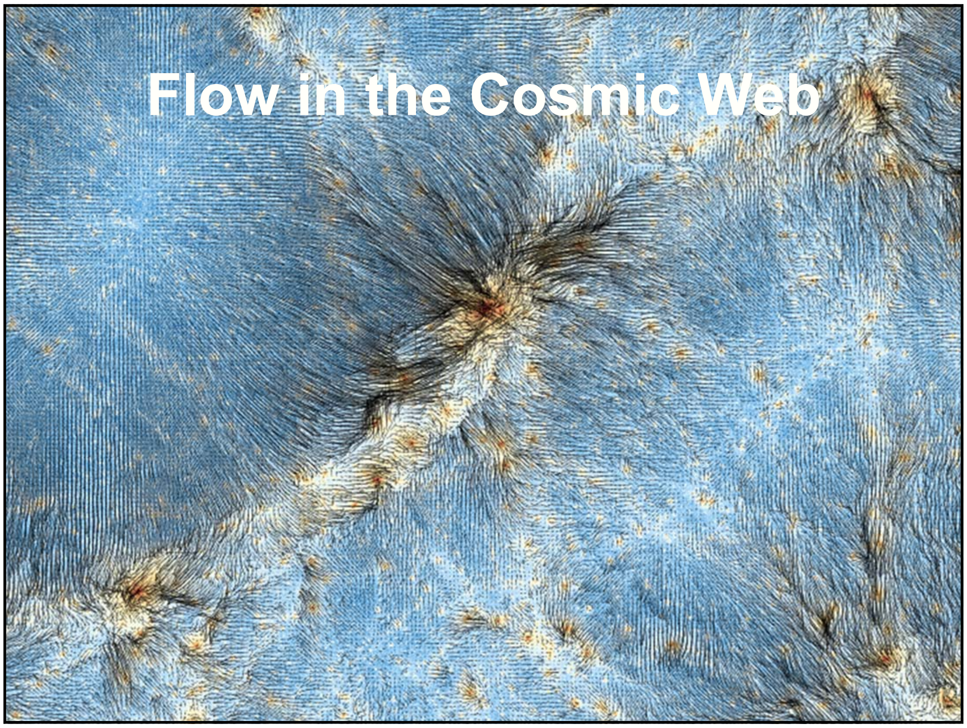
- Structure buildup accompanied by displacement of matter:
  - Cosmic flows
- On large (Mpc) scales, structure formation still in linear regime
- Directly related to cosmic matter distribution
- Note:
  redshift space distortion

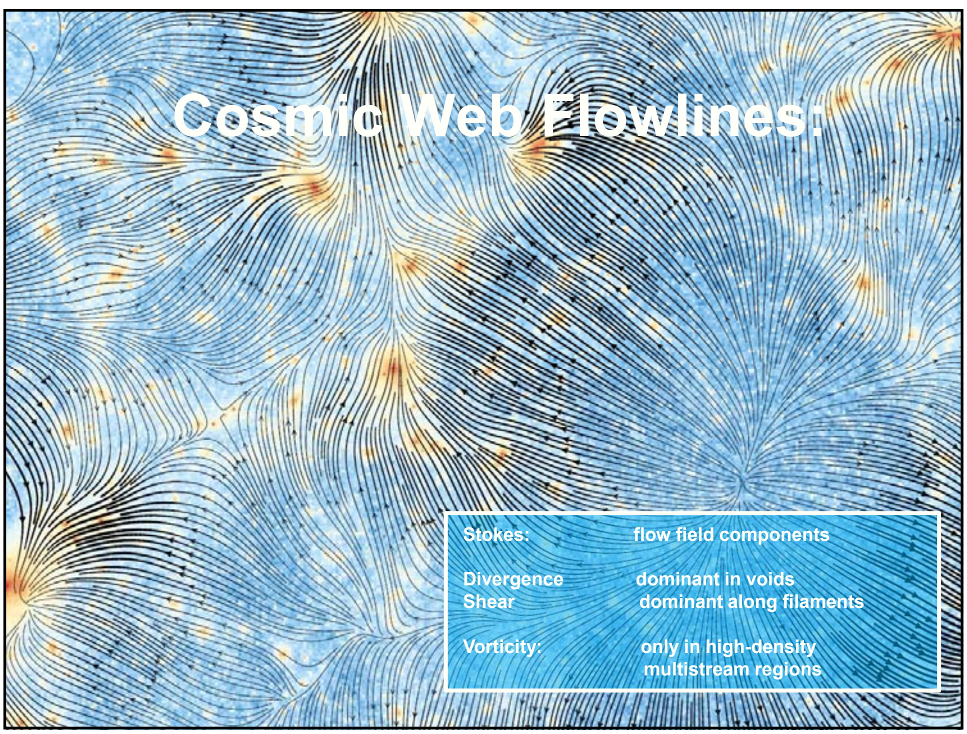
  $cz = Hr + v_{pec}$

  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

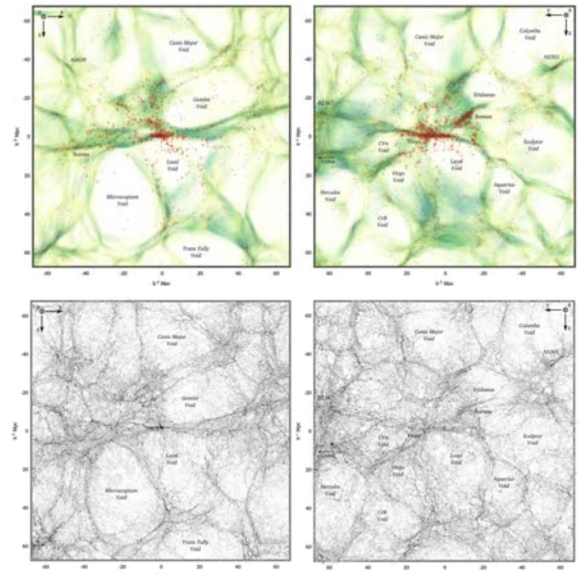


$$\mathbf{v}(\mathbf{x},t) = \frac{H}{4\pi}\frac{f(\Omega_m)}{b}a\int d\mathbf{x}'\,\delta_{gal}(\mathbf{x}',t)\,\frac{(\mathbf{x}'-\mathbf{x})}{|\mathbf{x}'-\mathbf{x}|^3}$$


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

2MRS Local Universe



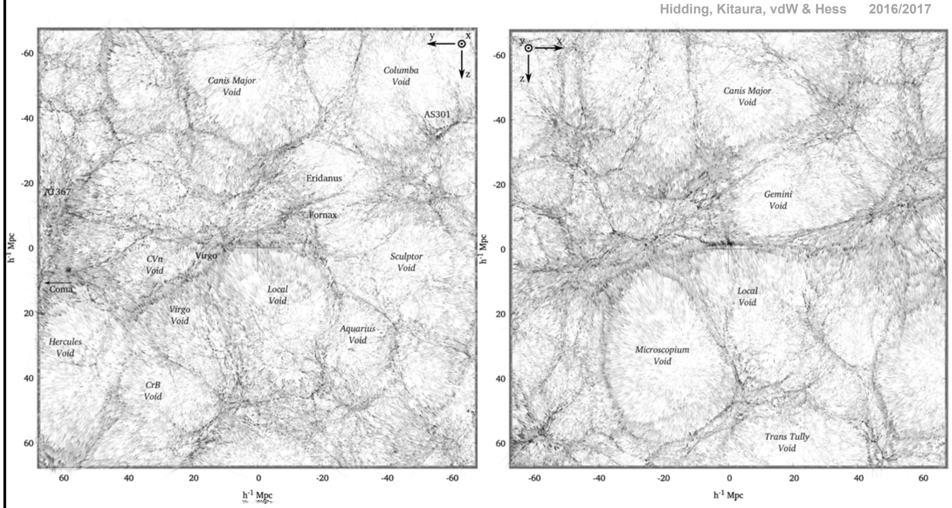
KIGEN-adhesion reconstruction 2MRS

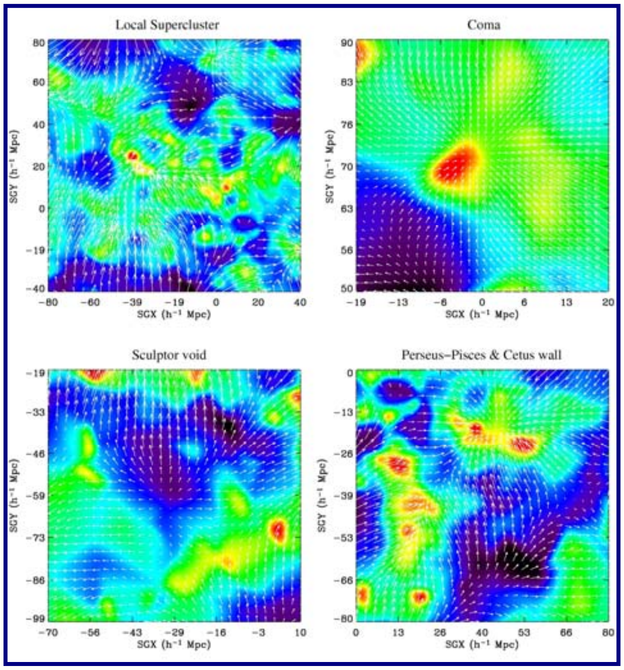
Hidding, vdW, Kitaura & Hess 2018

Supergalactic Plane

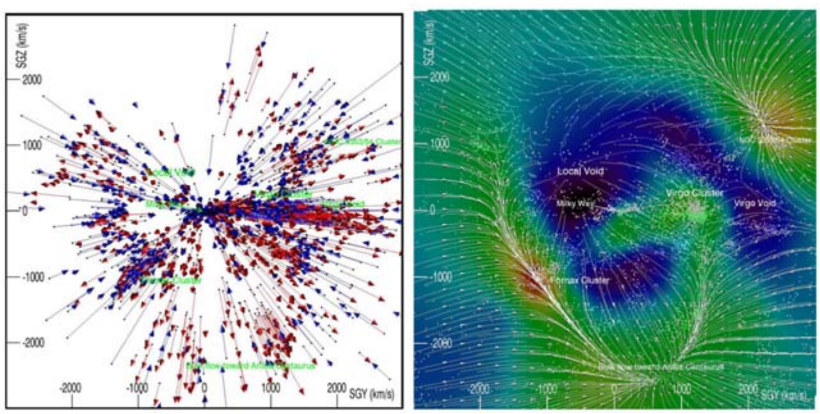
mean KIGEN - adhesion reconstruction

Hidding, Kitaura, vdW & Hess 2016/2017



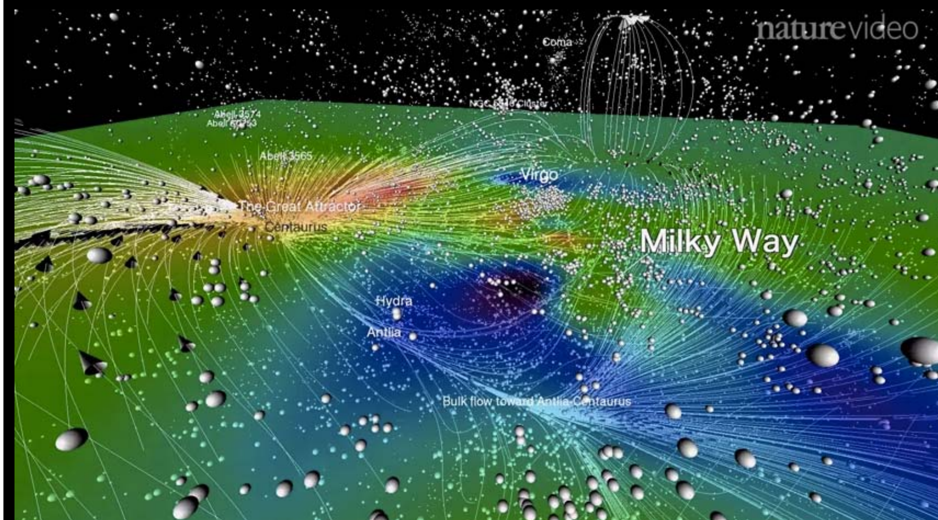


CosmicFlows-2

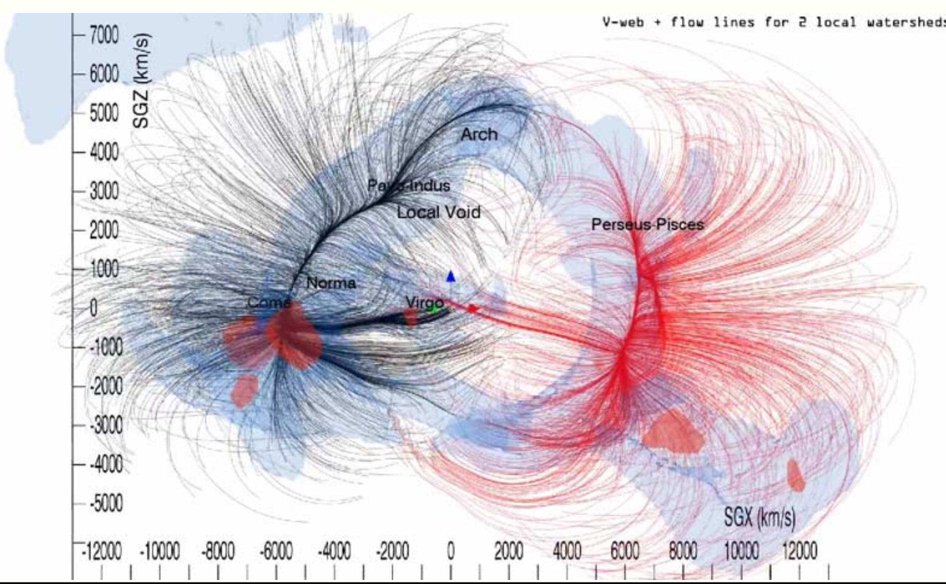


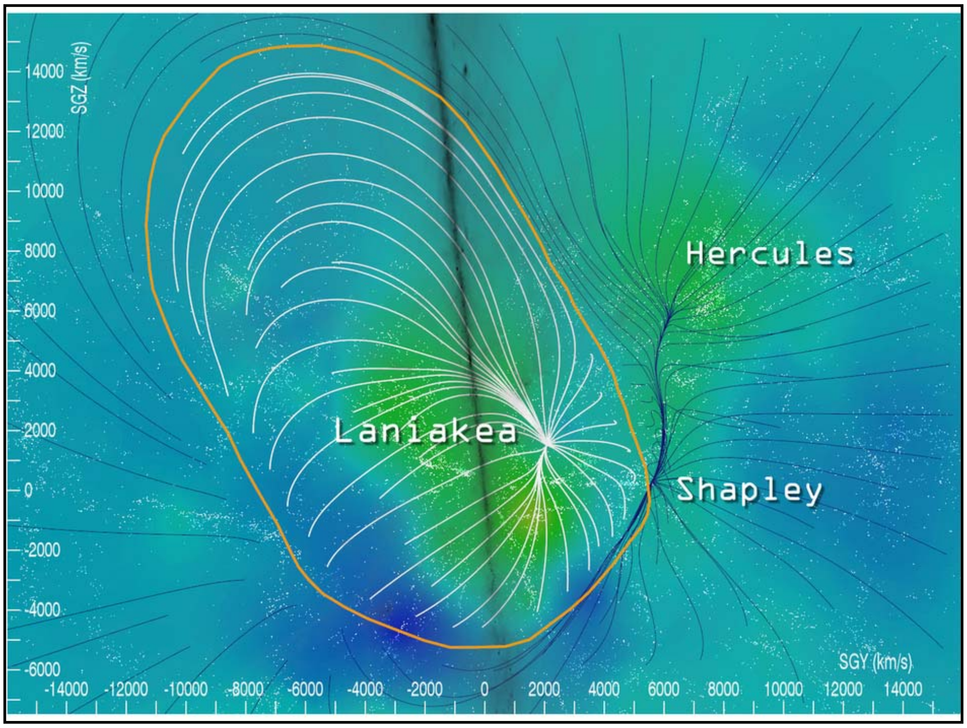
Courtois et al. 2013
Local void expansion in Cosmicflows-2

Laniakea

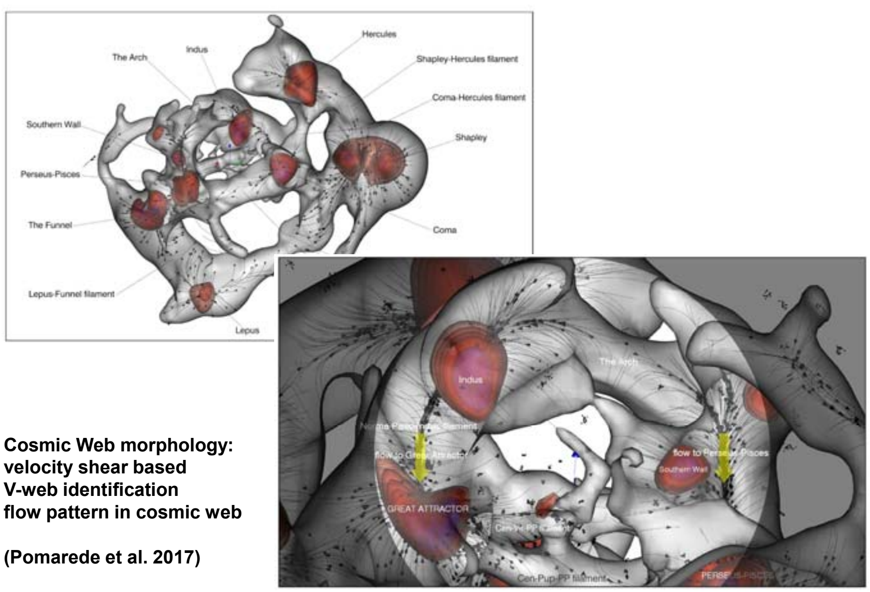


Laniakea





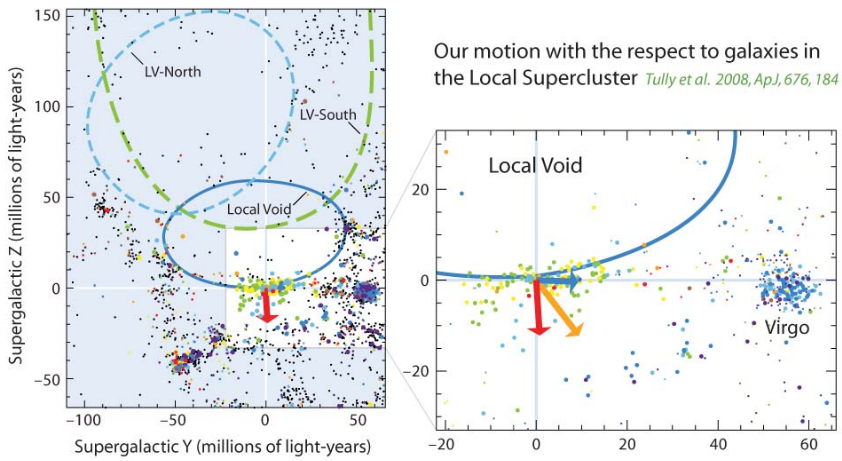
CosmicFlows-3



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

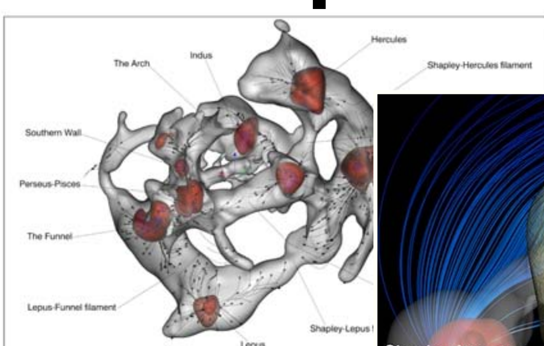
(Pomarede et al. 2017)

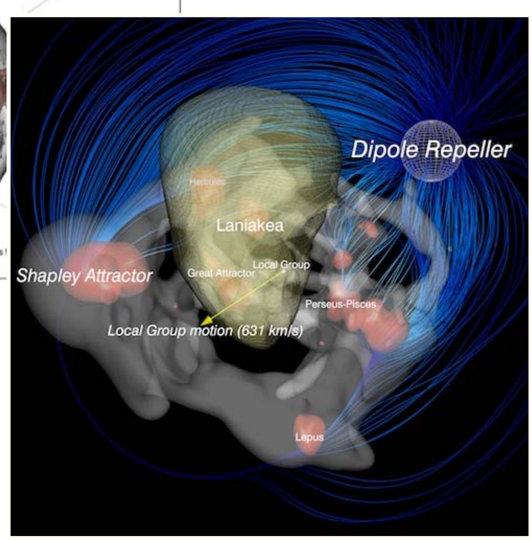
Push of the Local Void



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

Void Dipole Repeller





Cosmicflows-3 Cosmic Web
morphology Local Universe

(Pomarede et al. 2017)

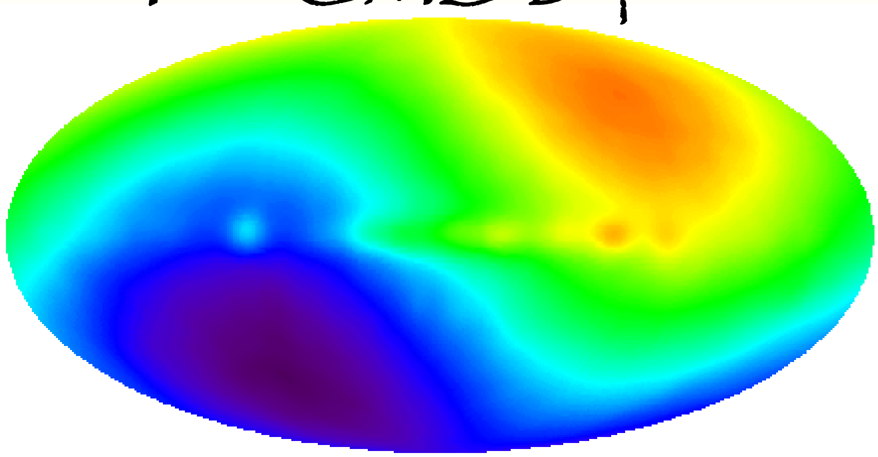
Void Dipole Repeller
dominant dynamical
Presence Local Universe

(Tully et al. 2017)

Cosmic Dipoles:

Motion of the Milky Way

The CMB Dipole



$\Delta T = 3.36$ mK ⟹ $v_{LG} = 627 \pm 22$ km/s

$(l,b) = (264.3°, 48.1°)$ ⟹ $(l,b) = (276°, 30°)$

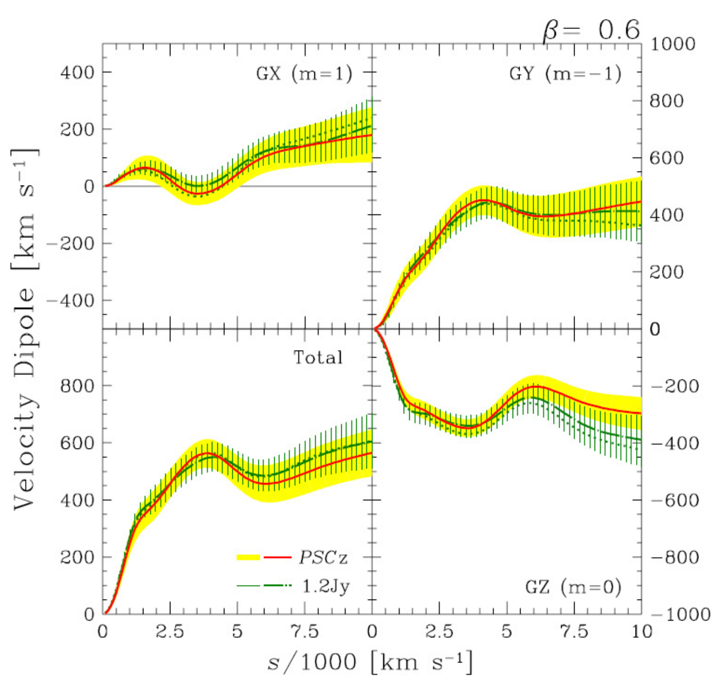
$$v_{\rm LG} = \frac{H_0\beta}{4\pi}\int_{r}^{\infty} {\rm d}^3\boldsymbol{r}'\delta_{\rm g}(\boldsymbol{r}')\frac{\boldsymbol{r}'-\boldsymbol{r}}{|\boldsymbol{r}'-\boldsymbol{r}|^3}$$

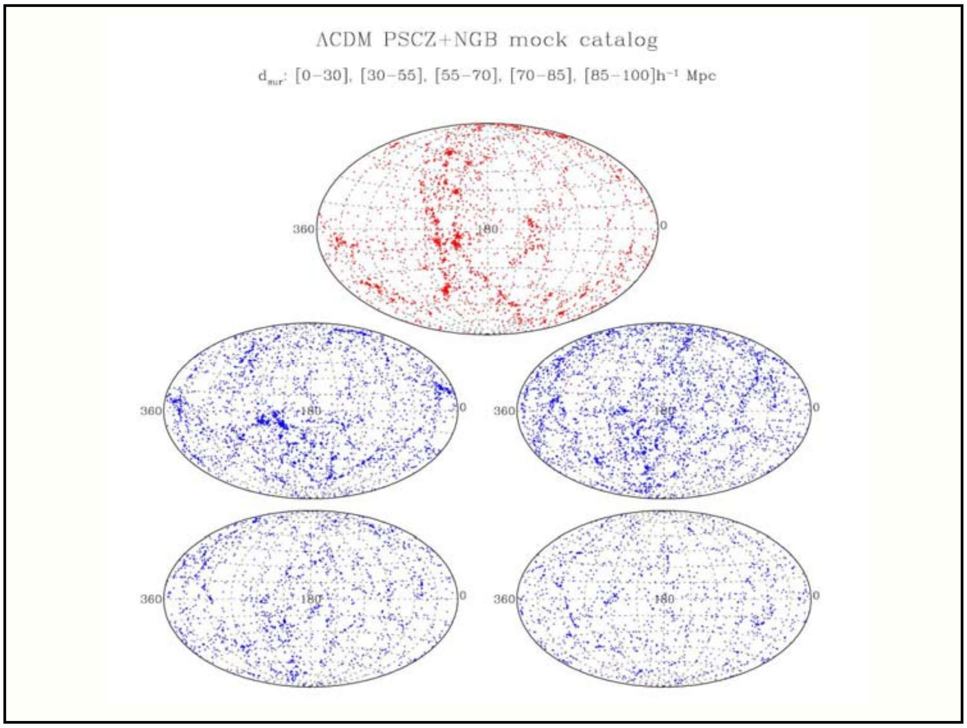
$$\Downarrow$$

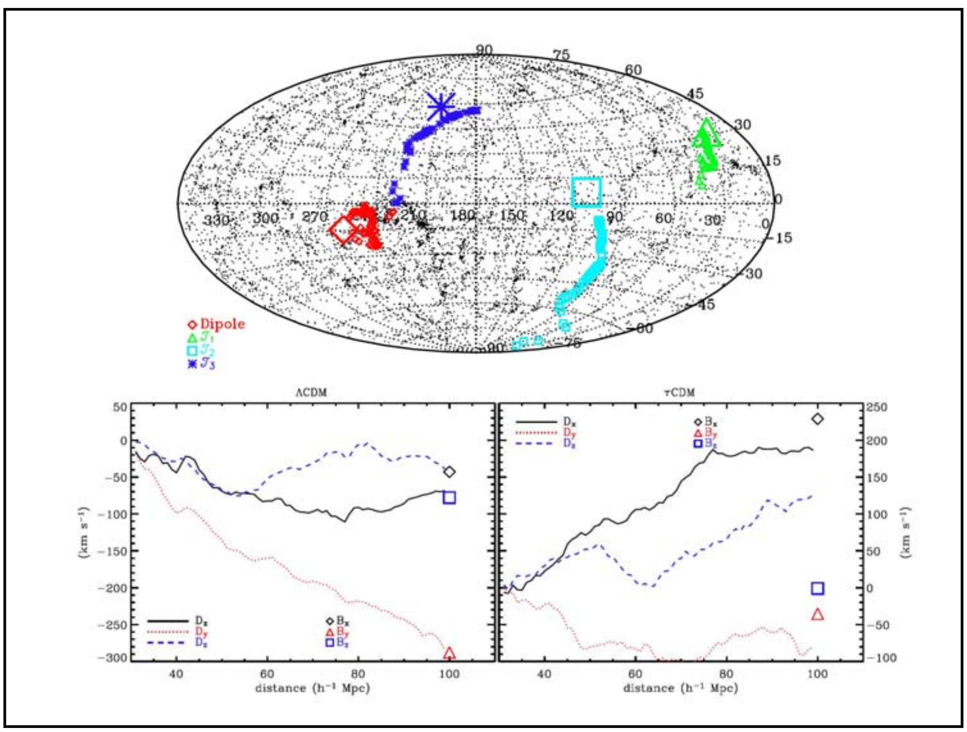
$$\boldsymbol{v}(\boldsymbol{r}) = \frac{H_0\beta}{4\pi\bar{n}}\sum_{i}^{N}\frac{w_i\hat{\boldsymbol{r}}_i}{r_i^2}$$

PSCz

dipole




ΛCDM PSCZ+NGB mock catalog
d_sur: [0-30], [30-55], [55-70], [70-85], [85-100]h⁻¹ Mpc
360
180
0


Dipole
ΛCDM
τCDM
distance (h⁻¹ Mpc)
(km s⁻¹)

2MASS survey

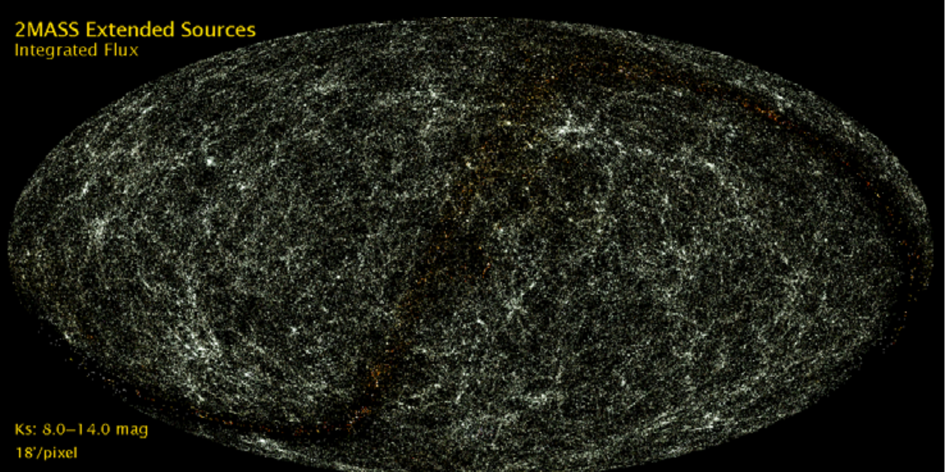
- 2MASS all-sky survey:
  ground-based near-infrared survey whole sky,
  J(1.2 μm), H(1.6 μm), K(2.2 μm)

- 2MASS extended source catalog (XSC):
  1.5 million galaxies

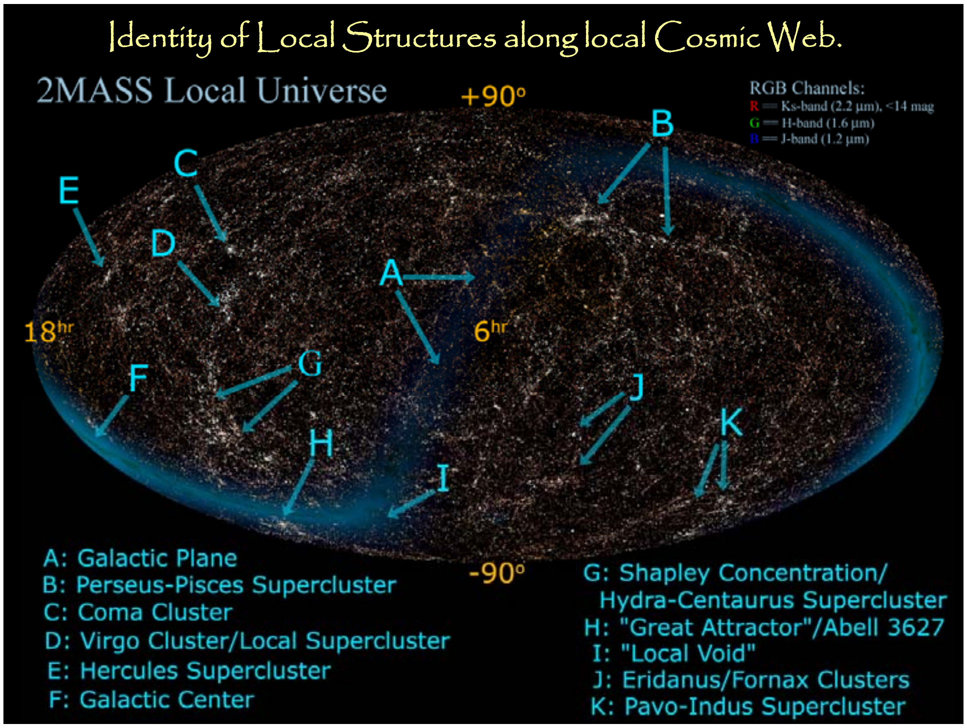
- unbiased sample nearby galaxies
- photometric redshifts:
  depth in 2MASS maps,
  "cosmic web" of (nearby) superclusters spanning the entire sky.

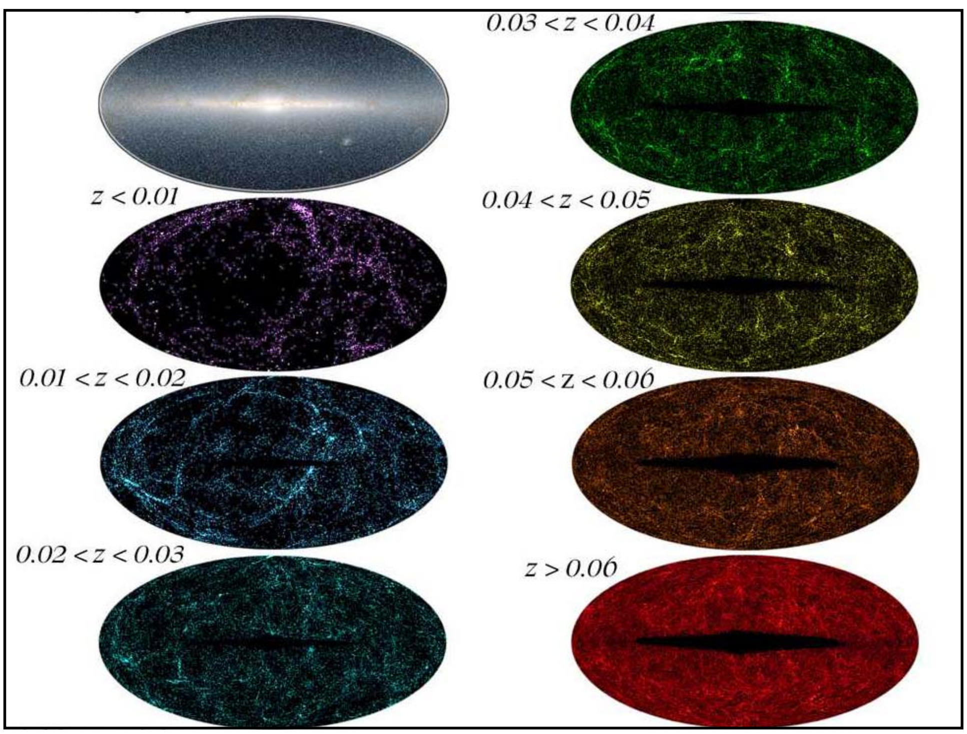
courtesy: T. Jarrett

2MASS Cosmic Web



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


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


z < 0.01
0.01 < z < 0.02
0.02 < z < 0.03
0.03 < z < 0.04
0.04 < z < 0.05
0.05 < z < 0.06
z > 0.06

2MASS dipole