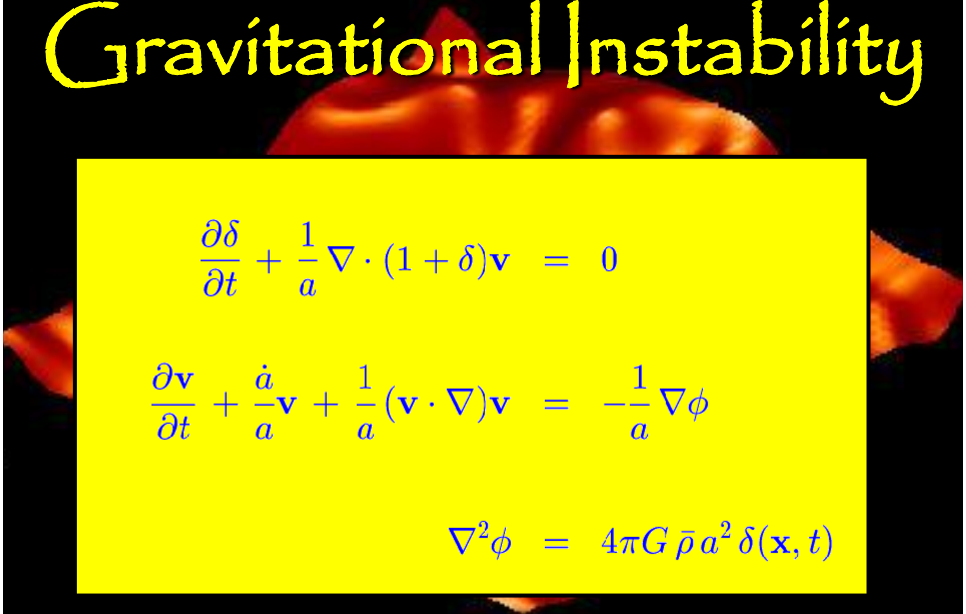
Cosmic Flows

Lecture course
University Groningen
Apr. 2009-July 2009

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

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

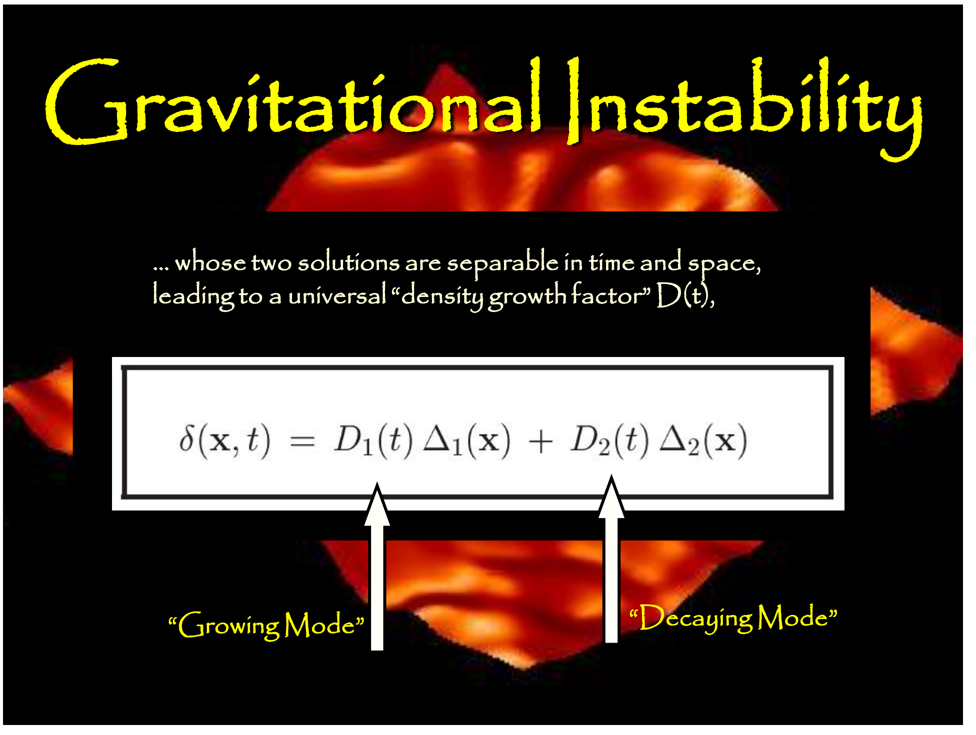
$$\frac{\partial \mathbf{v}}{\partial t} + \frac{\dot{a}}{a}\mathbf{v} = -\frac{1}{a}\,\nabla \phi$$

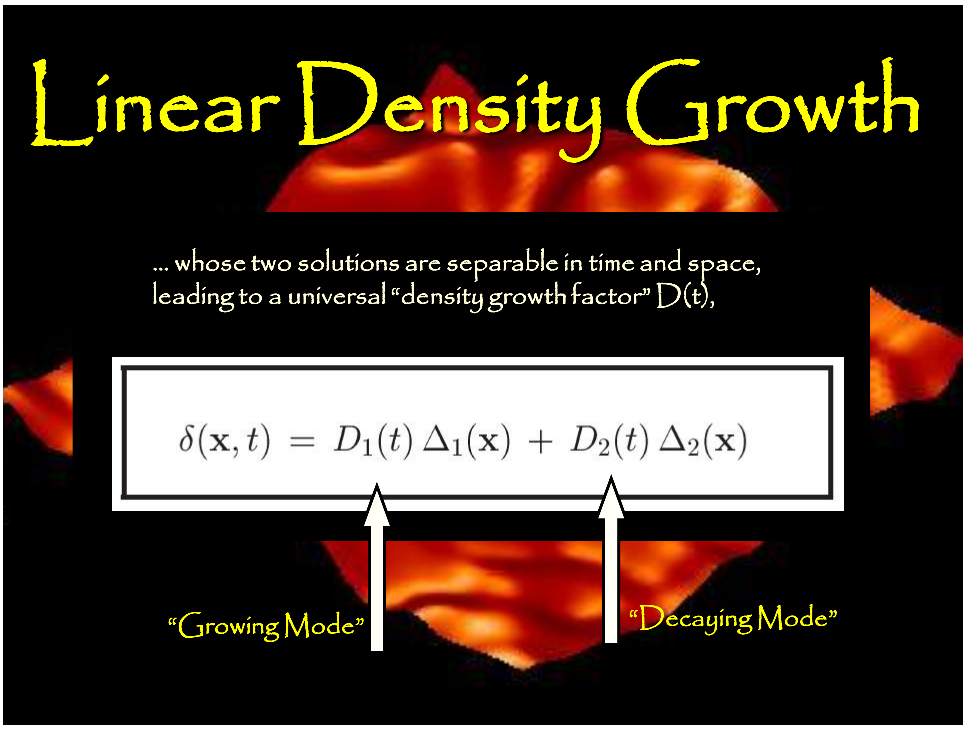
$$\nabla^2 \phi = \frac{3}{2}\Omega H^2 a^2\ \delta(\mathbf{x}, t)$$

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
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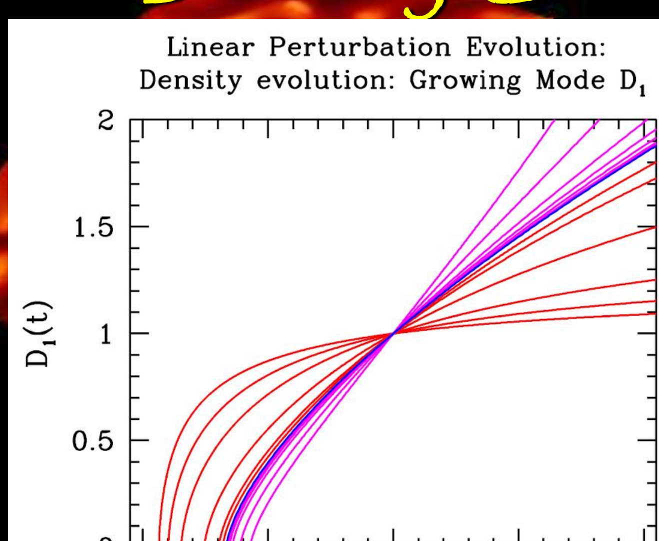
$\delta(\mathbf{x},t) = D_1(t)\,\Delta_1(\mathbf{x}) + D_2(t)\,\Delta_2(\mathbf{x})$
"Growing Mode"
"Decaying Mode"

Linear Density Growth

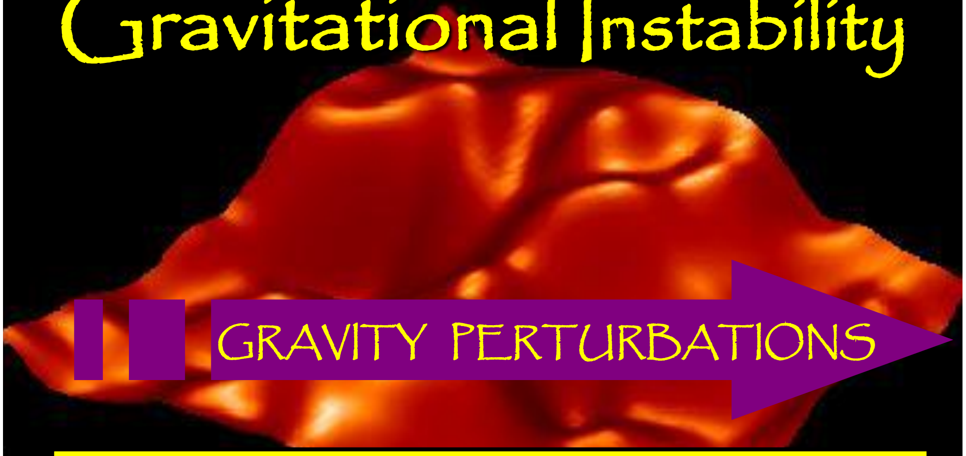
… The universal "density growth factor" D(t) can be computed for any cosmology through the integral

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

Linear Density Growth

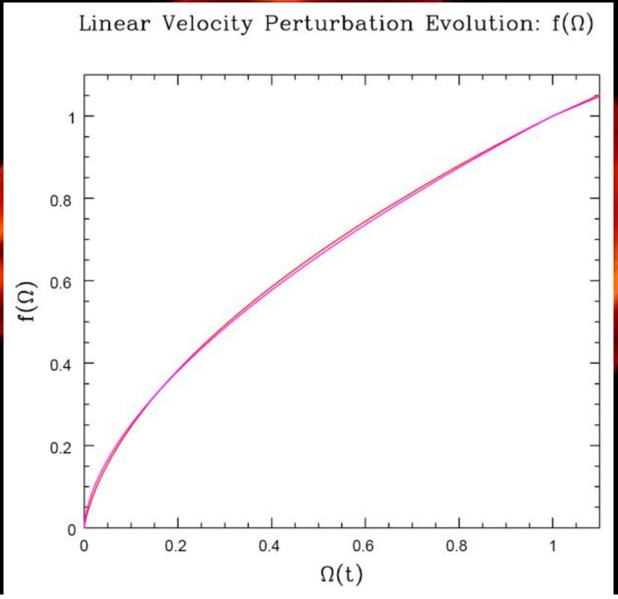


Gravitational Instability



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

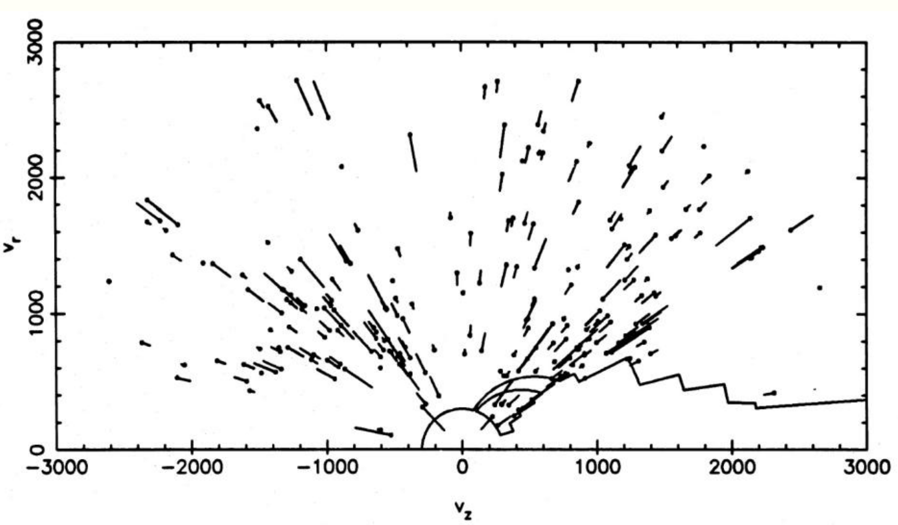
Velocity Perturbations



Local Universe Peculiar Velocities

Local Supercluster flow

Lilje, Yahil & Jones 1986

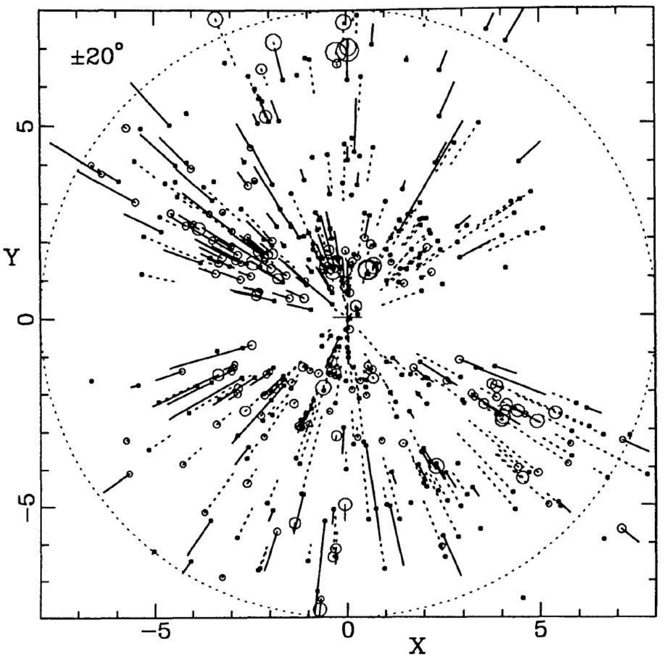


Mark III

Peculiar velocities
Local Universe

Willick, Strauss et al.

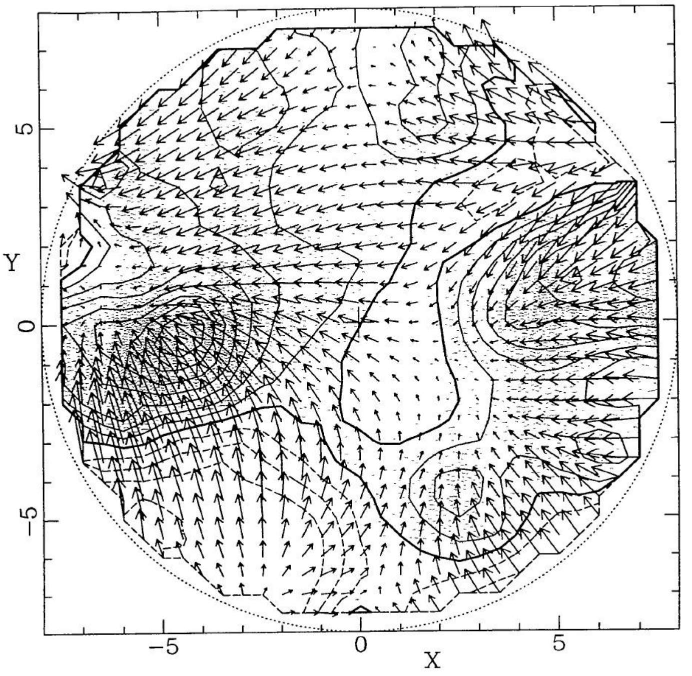
First flow maps:
7 Samurai



POTENT map

Mass distribution
Local Universe

Bertschinger,
Dekel, et al.



POTENT map

Mass distribution Local Universe

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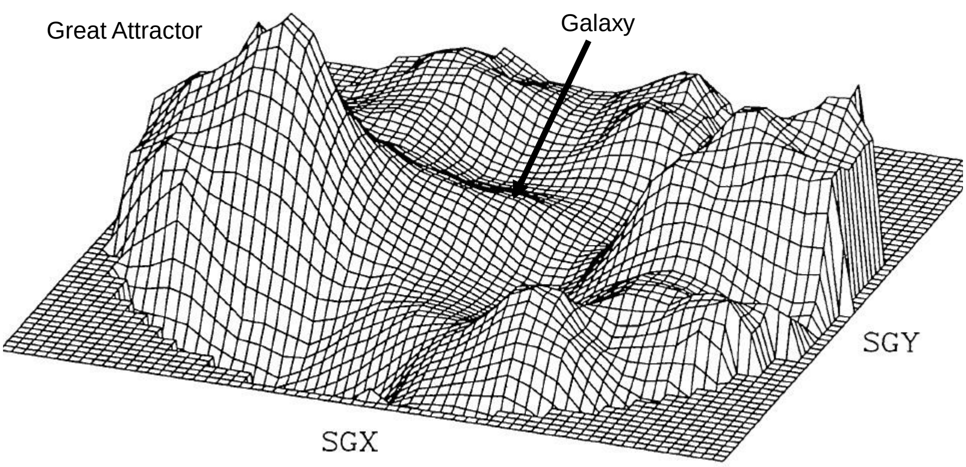
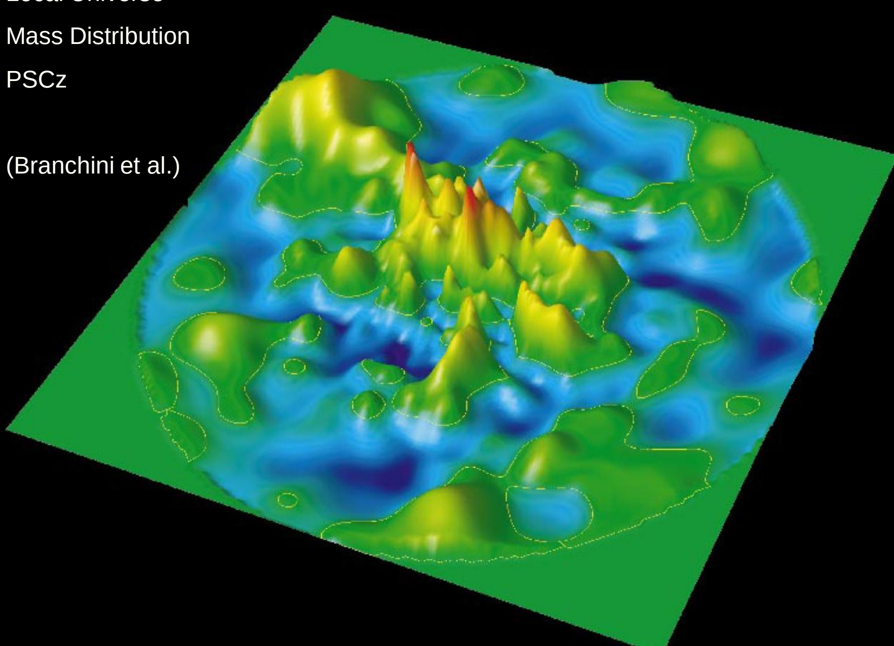


Local Universe

Mass Distribution

PSCz

(Branchini et al.)



Great Attractor

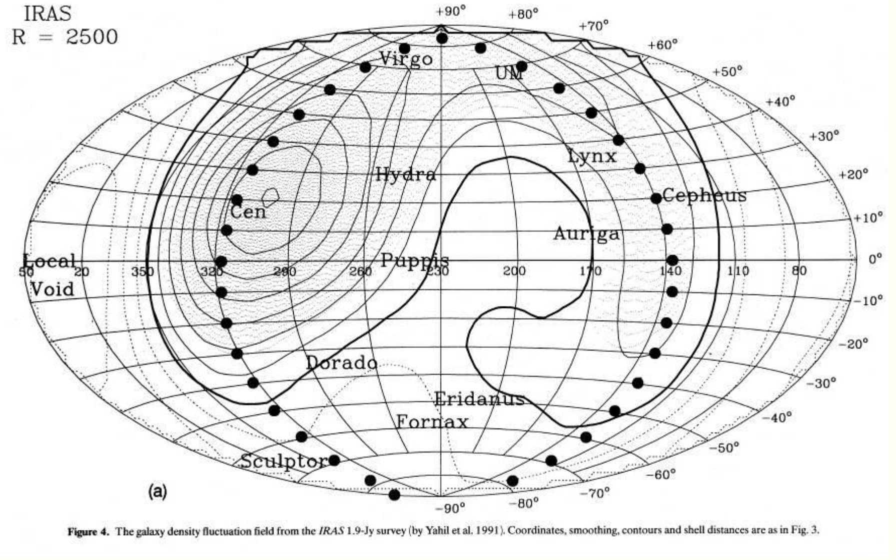


Figure 4. The galaxy density fluctuation field from the *IRAS* 1.9-Jy survey (by Yahil et al. 1991). Coordinates, smoothing, contours and shell distances are as in Fig. 3.

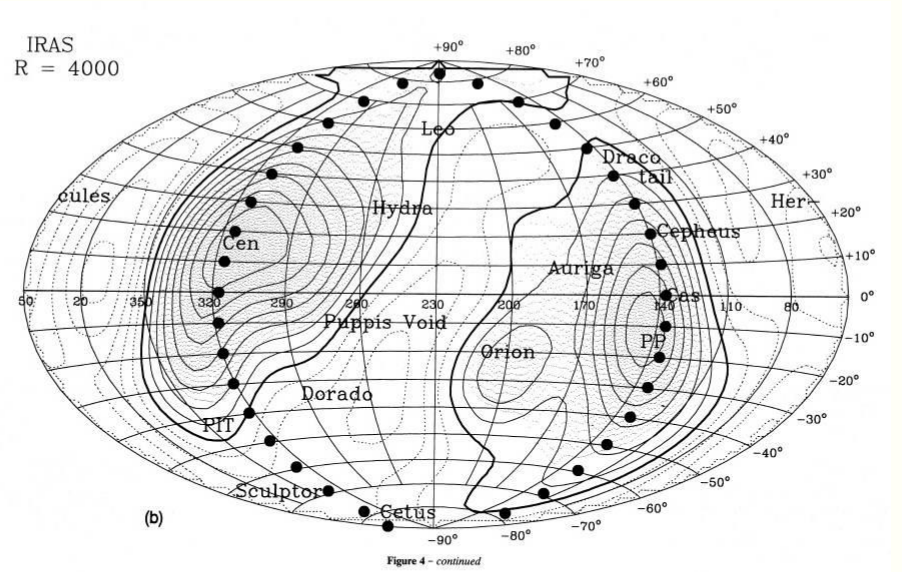
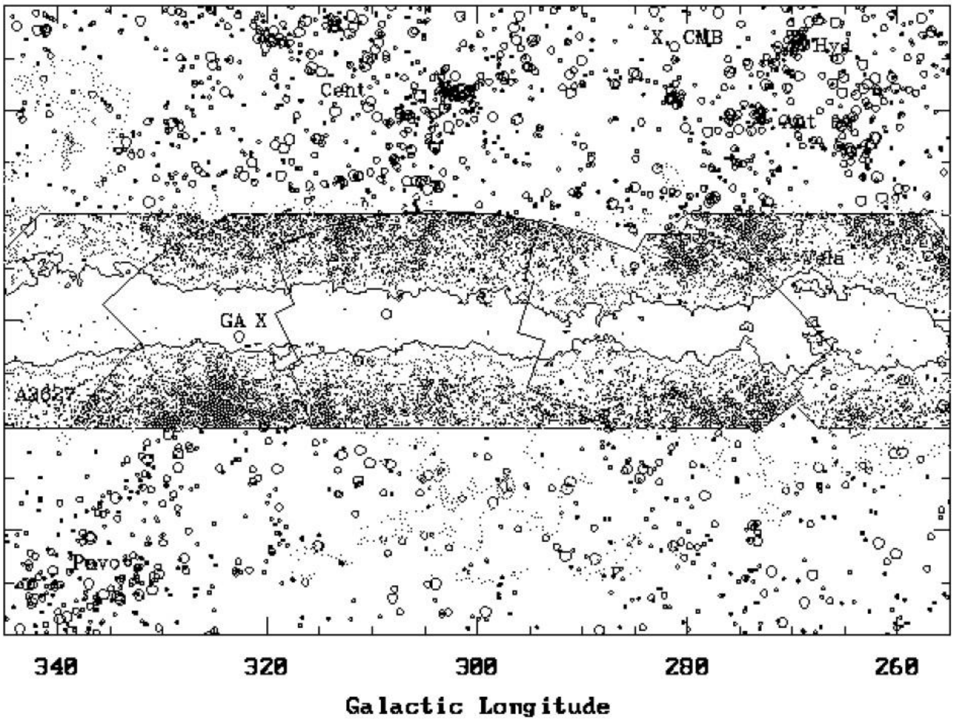


Figure 4 – *continued*

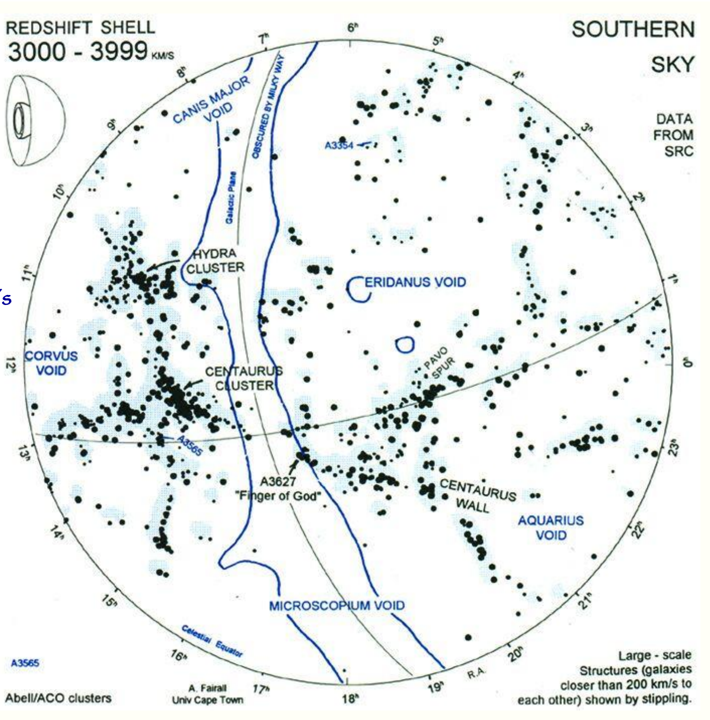


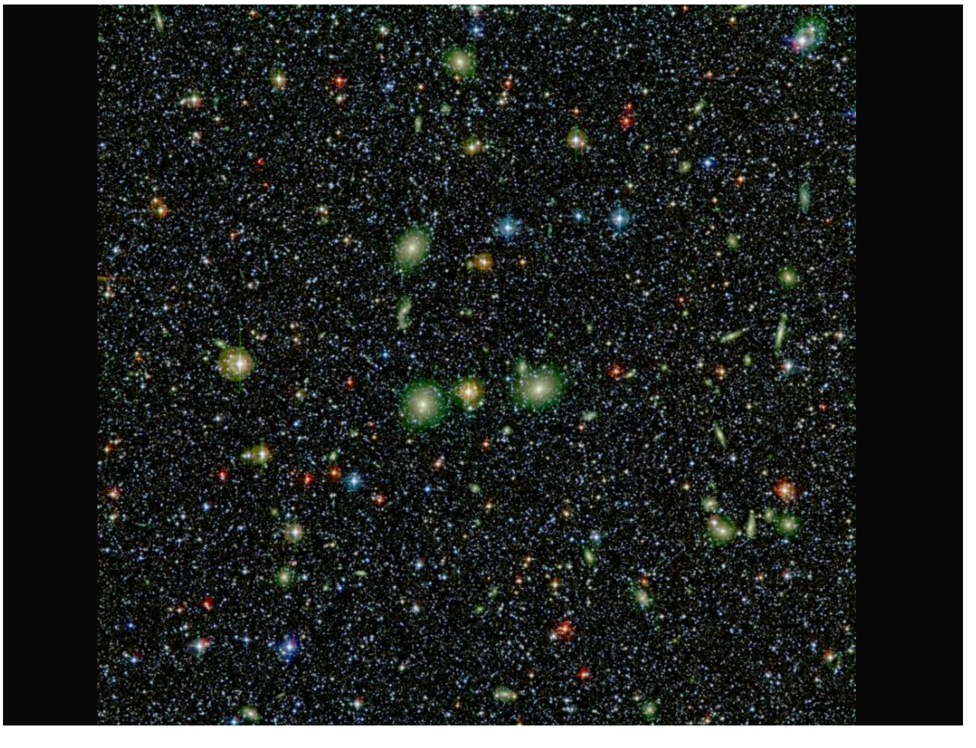
Tony Fairall's nearby LSS map:

cz=3000-3999 km/s

clear views of Great Attractor:

Norma Cluster/ A3627





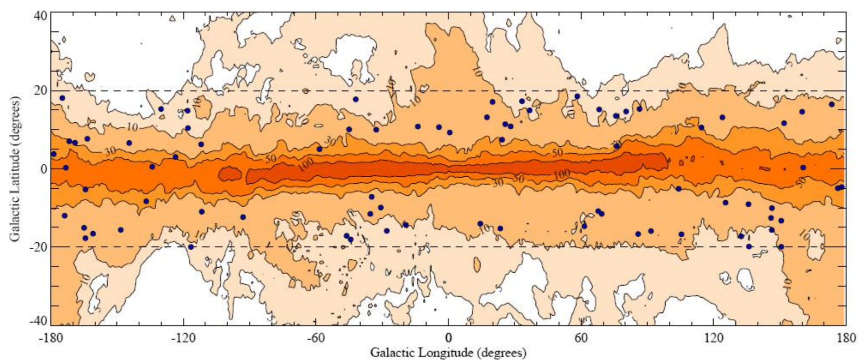
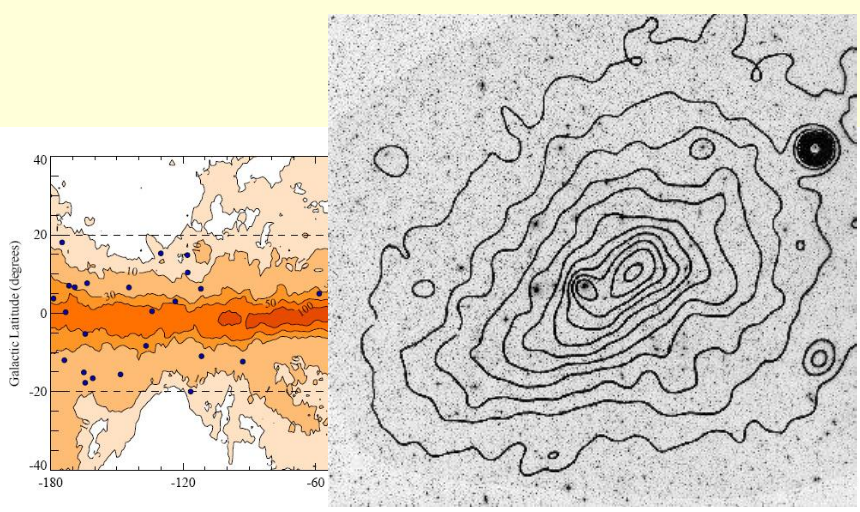


Fig. 16. Distribution in Galactic coordinates of the 76 by Ebeling et al. [129] so far spectroscopically confirmed X-ray clusters (solid dots) of which 80% were previously unknown. Superimposed are Galactic HI column densities in units of 10^{20} cm^{-2} (Dickey & Lockman 1990). Note that the region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



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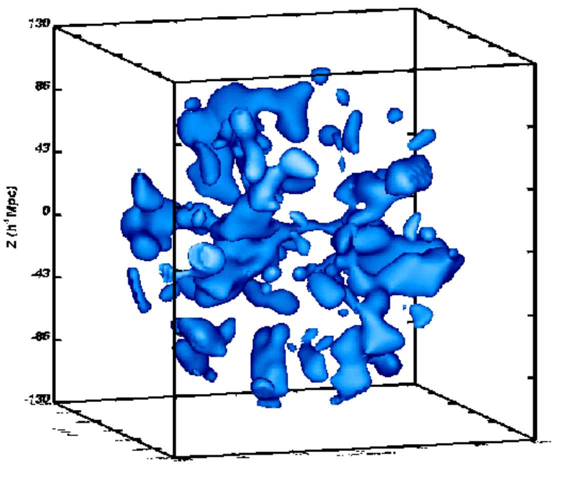
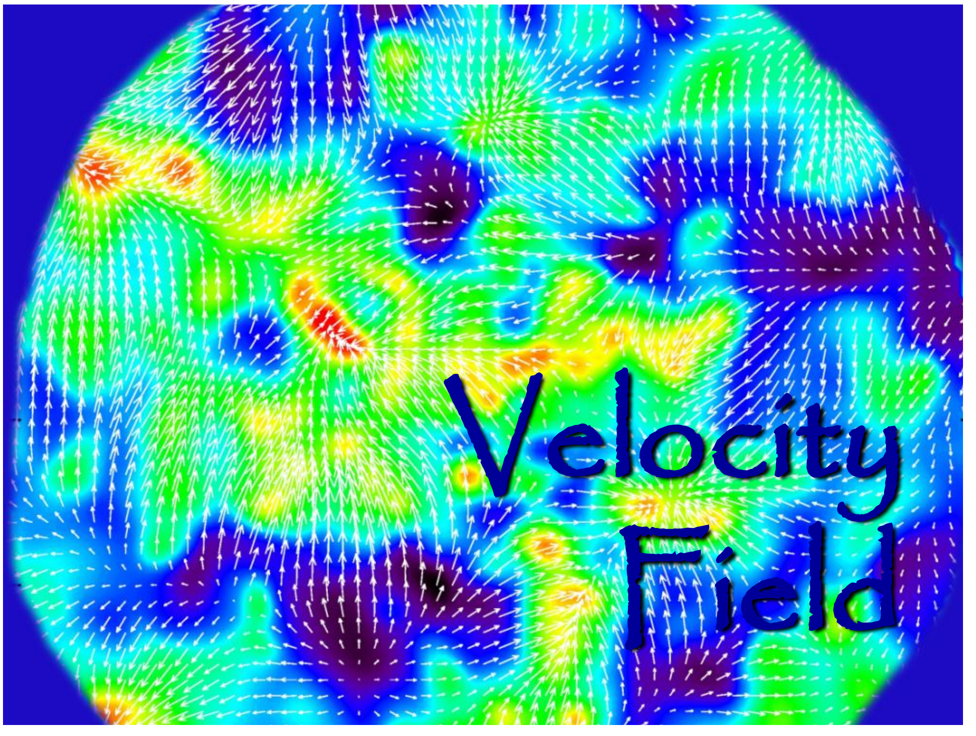
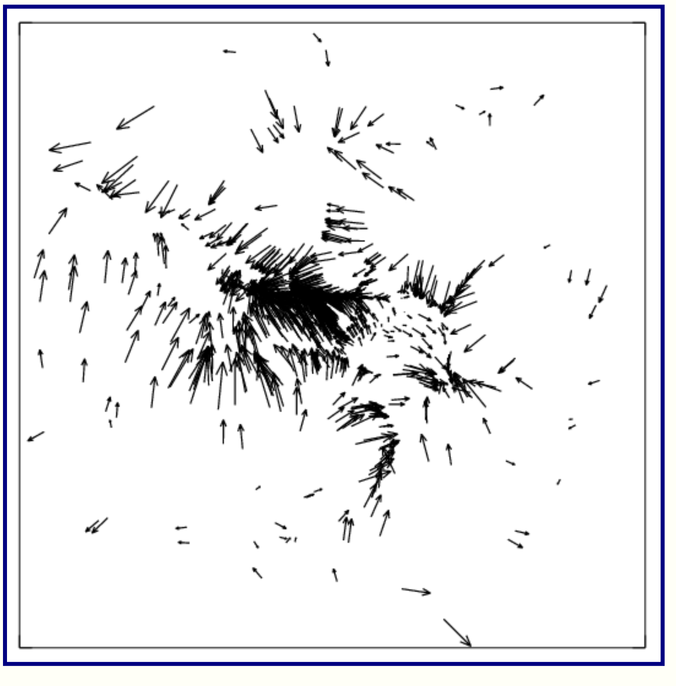
PSCz Survey

Dynamics:

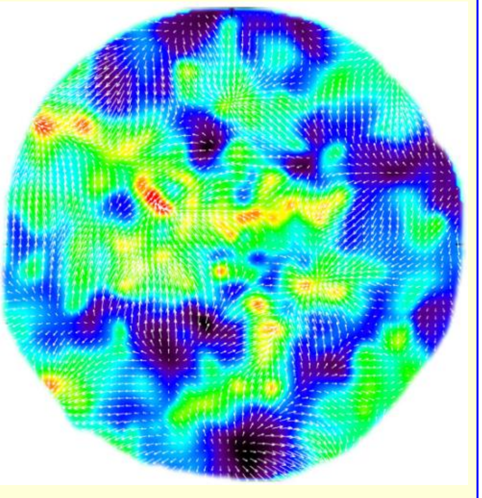



Velocity
Field

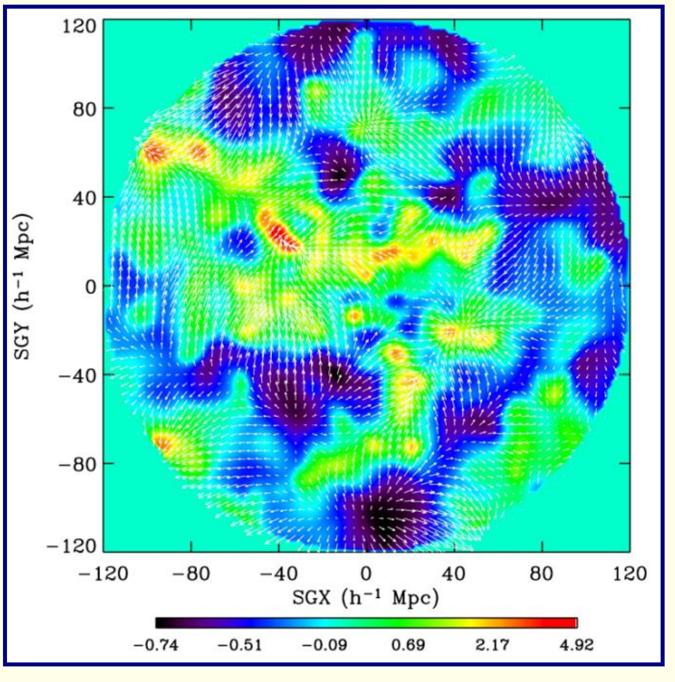


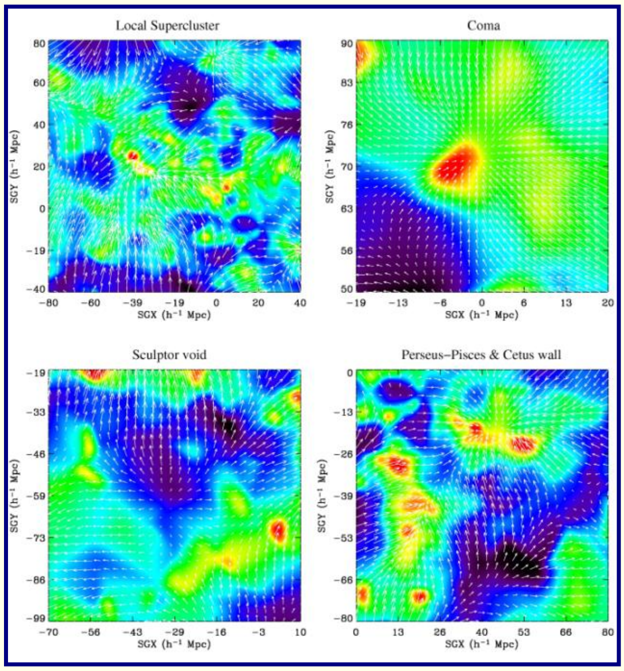
PSCz Flow Field

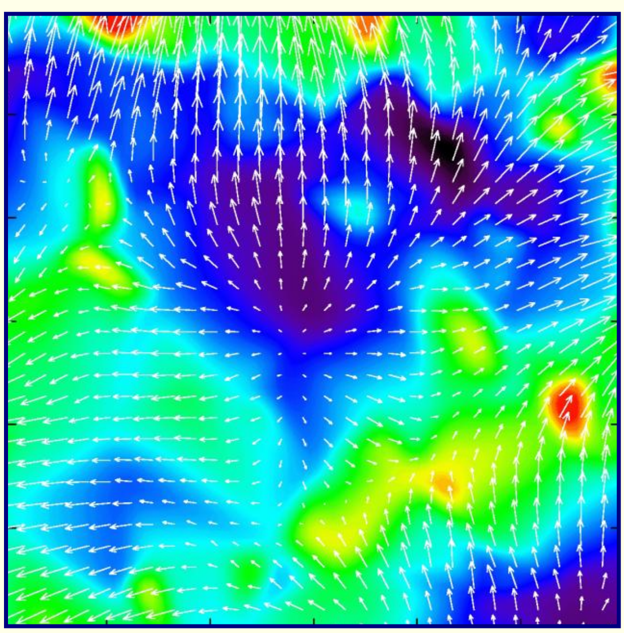
- Flow throughout the volume restored (assuming no shell-crossing)
- Restored velocities volume-weighted
- Shot-noise suppressed



PSCz, velocity+density field

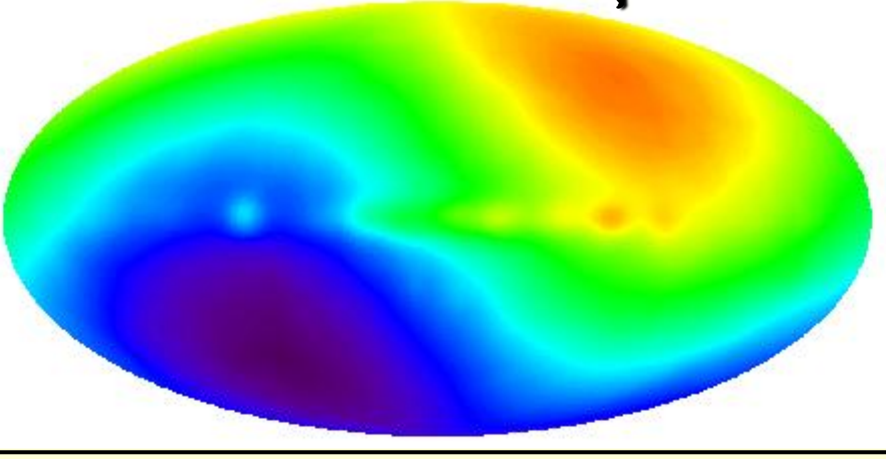



Local Supercluster
Coma
Sculptor void
Perseus−Pisces & Cetus wall
SGY (h⁻¹ Mpc)
SGX (h⁻¹ Mpc)



Cosmic Dipoles

The CMB Dipole



$\Delta T = 3.36$ mK

(l,b)=(264.3°,48.1°)

⇒

$v_{LG} = 627 \pm 22$ km/s

(l,b)=(276°,30°)

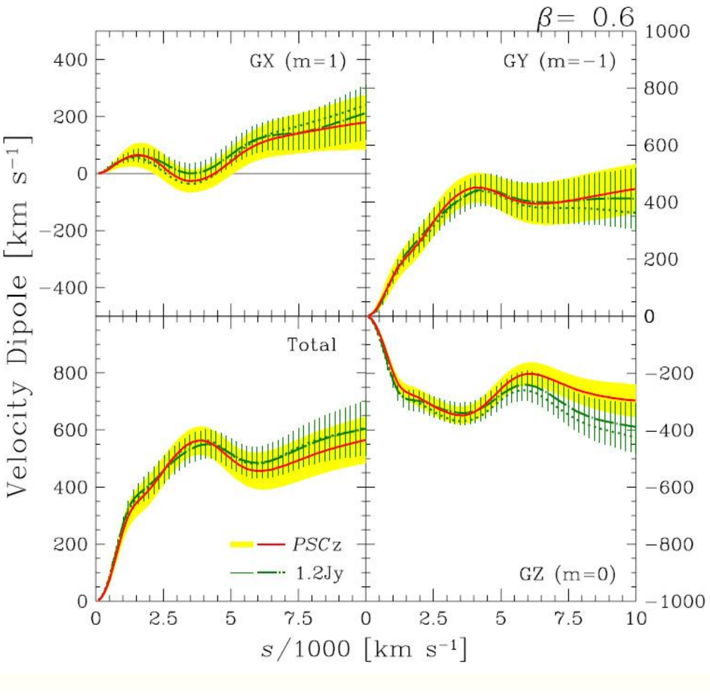
$$\boldsymbol{v}_{\mathrm{LG}} = \frac{H_0\beta}{4\pi} \int_{\boldsymbol{r}}^{\infty} \mathrm{d}^3\boldsymbol{r}'\delta_{\mathrm{g}}(\boldsymbol{r}')\frac{\boldsymbol{r}'-\boldsymbol{r}}{|\boldsymbol{r}'-\boldsymbol{r}|^3}$$

$$\Downarrow$$

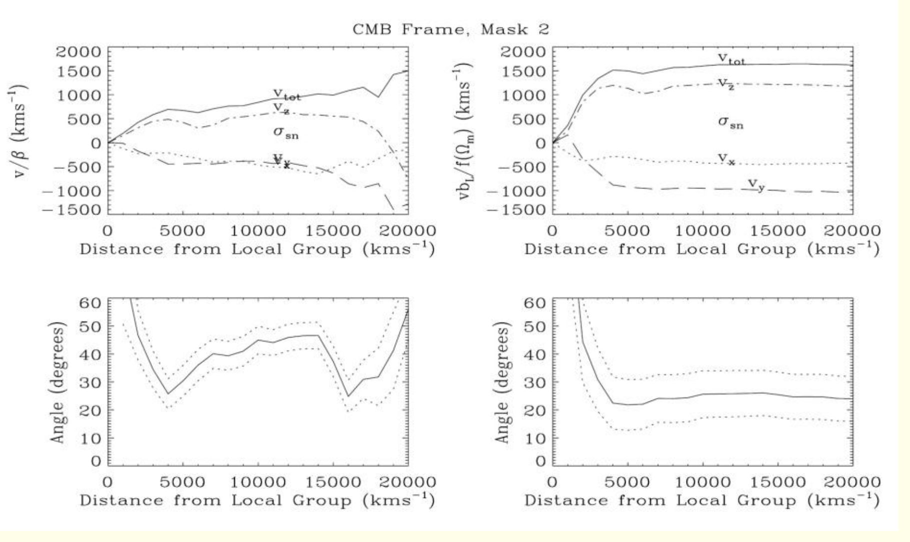
$$\boldsymbol{v}(\boldsymbol{r}) = \frac{H_0\beta}{4\pi\bar{n}} \sum_{i}^{N} \frac{w_i\hat{\boldsymbol{r}}_i}{r_i^2}$$

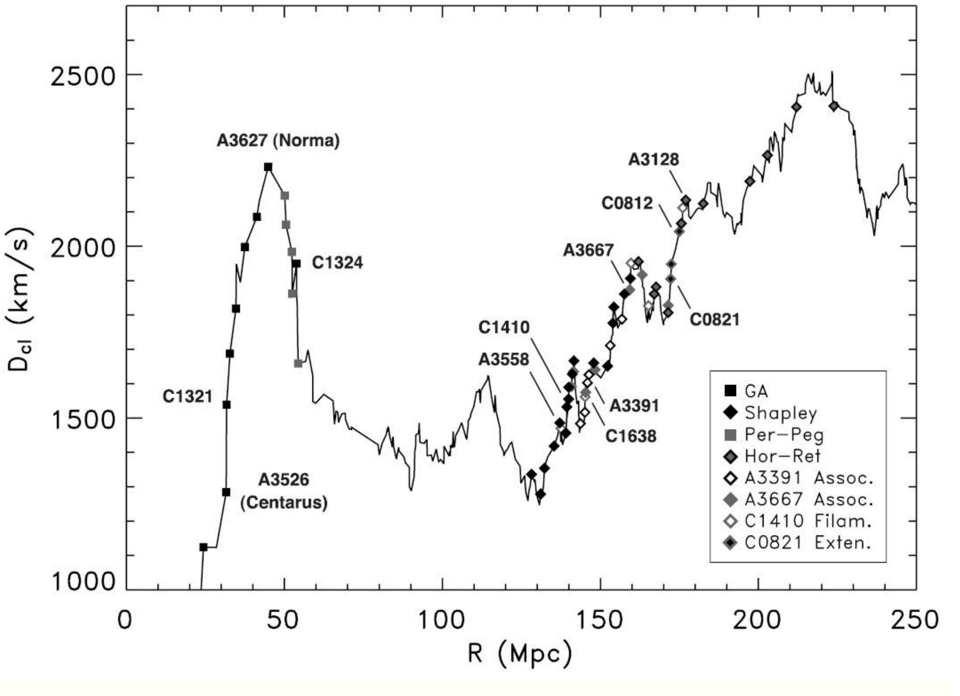
PSCz

dipole



2MASS dipole



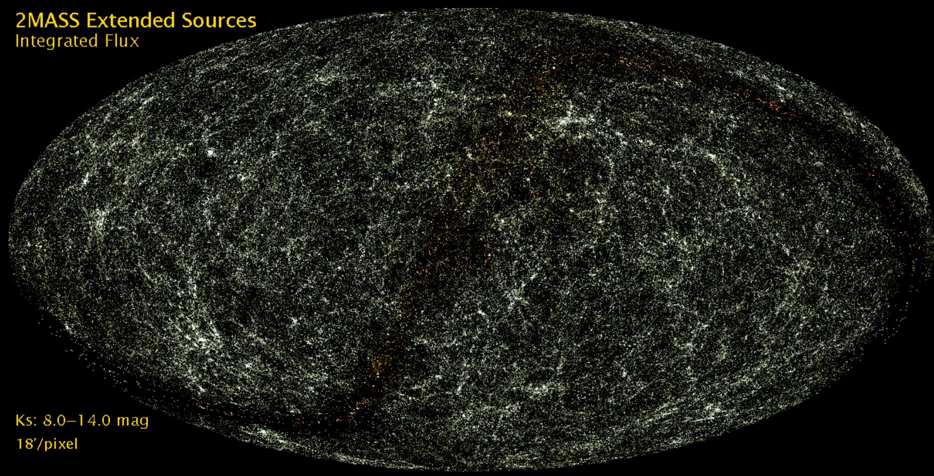


2MASS survey

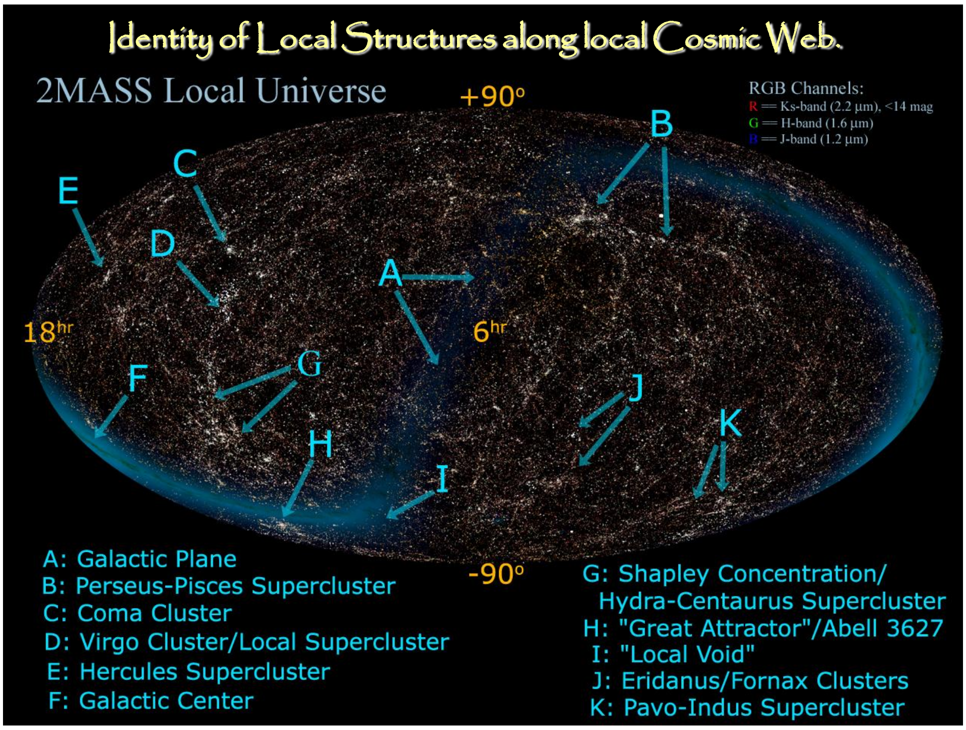
- 2MASS all-sky survey:
  ground-based near-infrared survey whole sky,
  J(1.2 μm), H(1.6 μm), K(2.2 μm)
- 2MASS extended source catalog (XSC):
  1.5 million galaxies
- unbiased sample nearby galaxies
- photometric redshifts: depth in 2MASS maps,
  "cosmic web" of (nearby) superclusters spanning
  the entire sky.

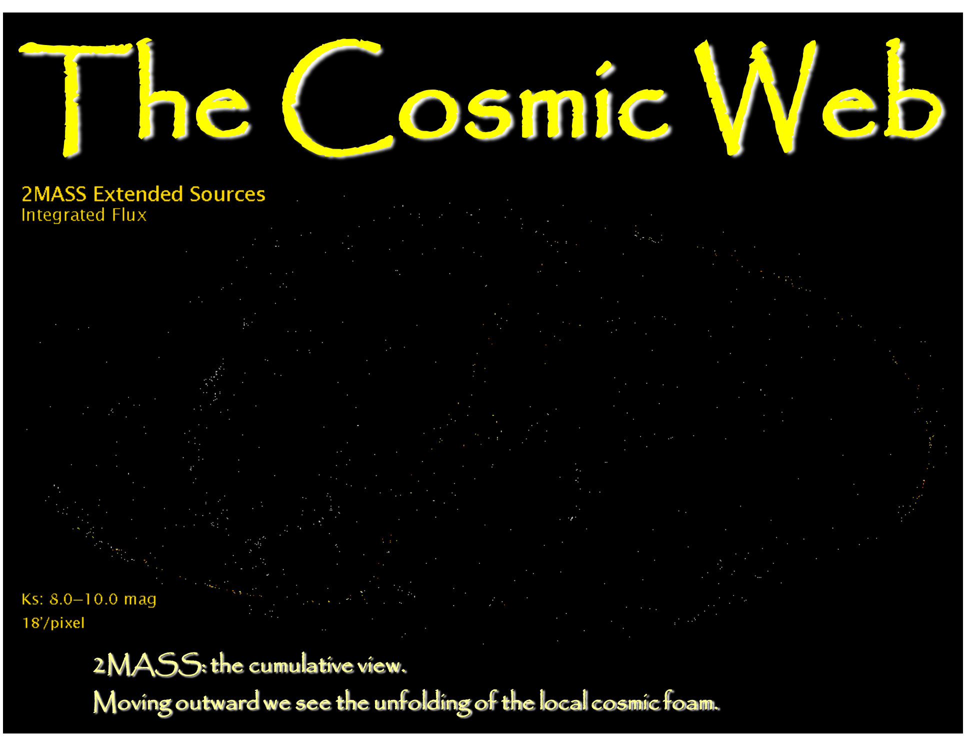
courtesy: T. Jarrett

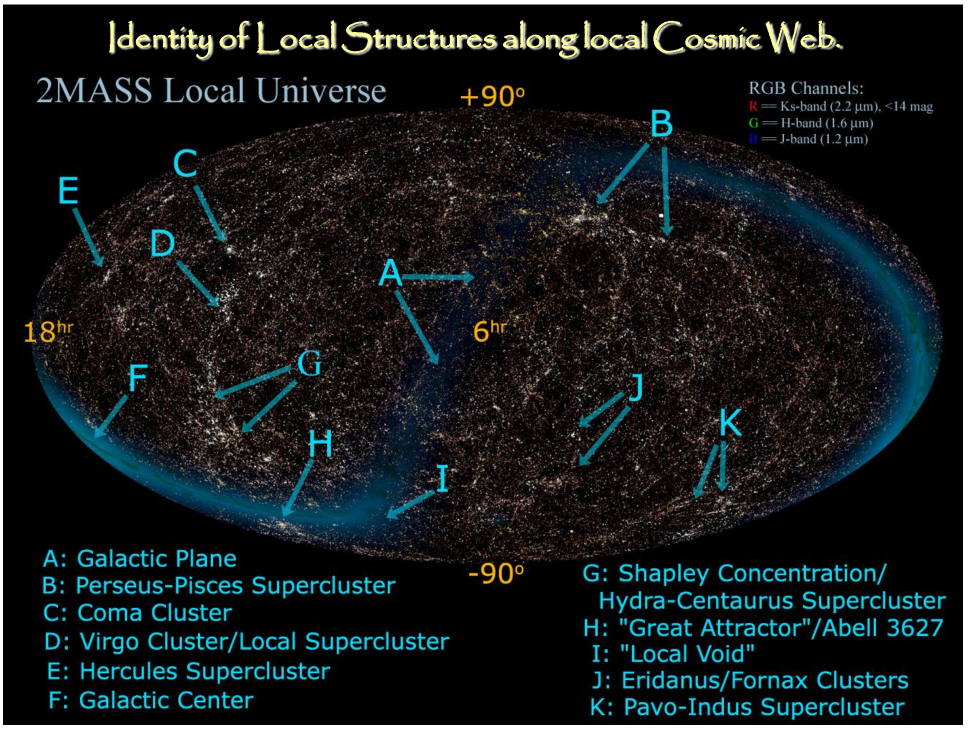
The Cosmic Web



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


The Cosmic Web
2MASS Extended Sources
Integrated Flux
Ks: 8.0–10.0 mag
18'/pixel
2MASS: the cumulative view.
Moving outward we see the unfolding of the local cosmic foam.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2MASS Local Universe
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B
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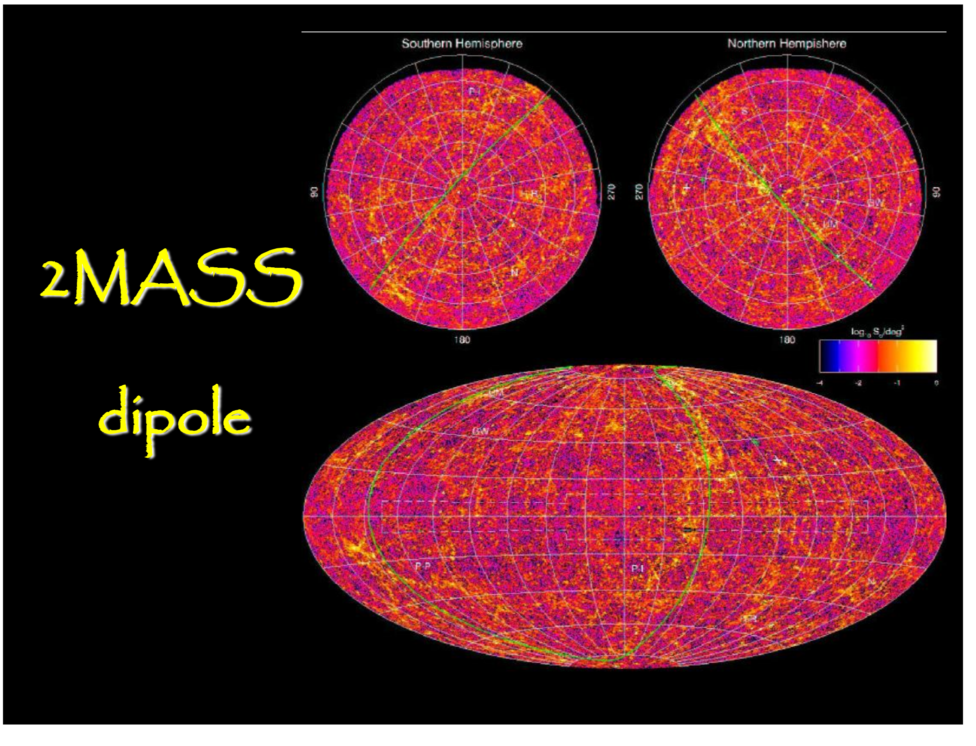
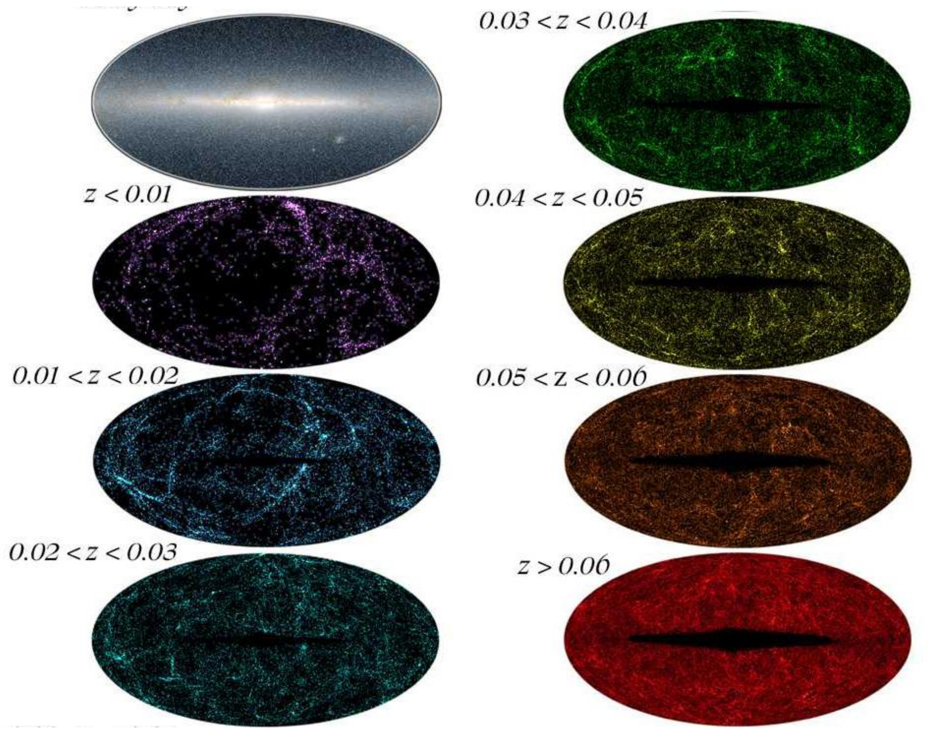
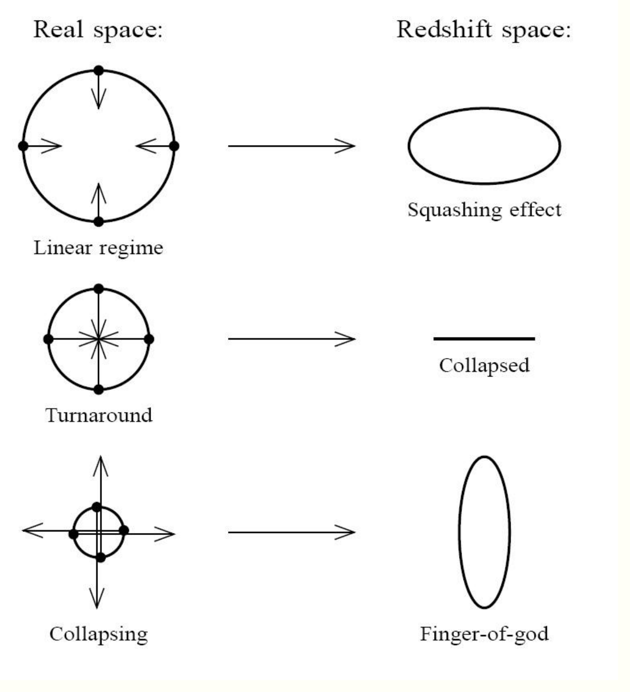
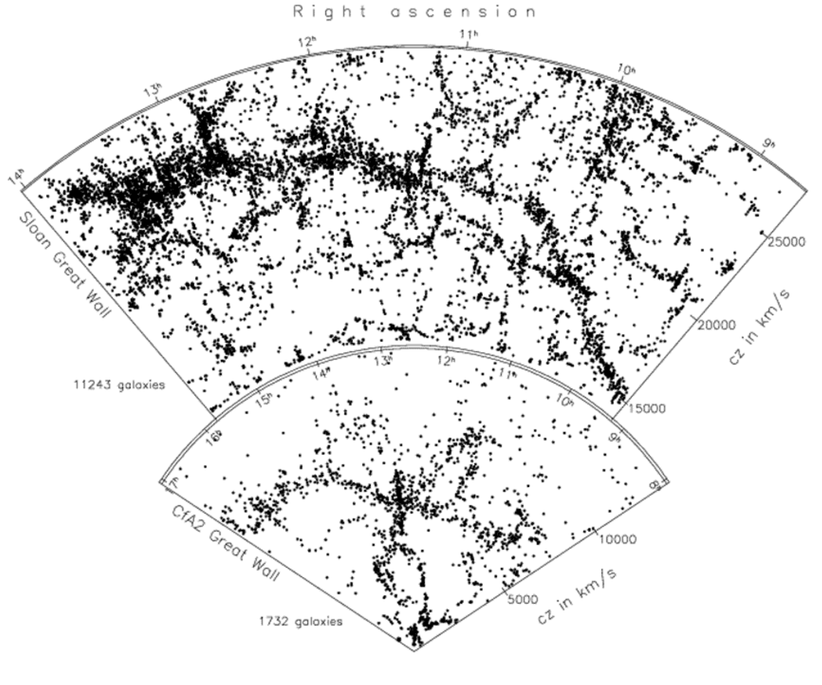

Southern Hemisphere
Northern Hemisphere
2MASS
dipole
90
270
270
90
180
180



Redshift Space Distortions


Real space:
Redshift space:
Linear regime
Squashing effect
Turnaround
Collapsed
Collapsing
Finger-of-god


Right ascension
Sloan Great Wall
11243 galaxies
25000
20000
15000
cz in km/s
CfA2 Great Wall
1732 galaxies
10000
5000
cz in km/s