

Cosmic Flows

Lecture course
University Groningen
Nov. 2014-Jan 2015

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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"Growing Mode"

"Decaying Mode"

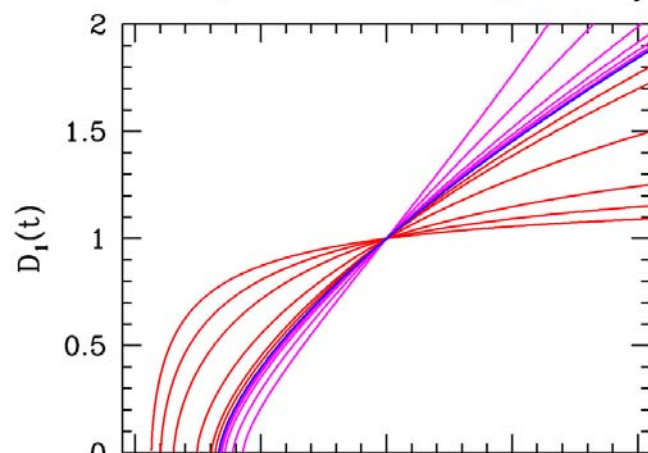
Linear Density Growth

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

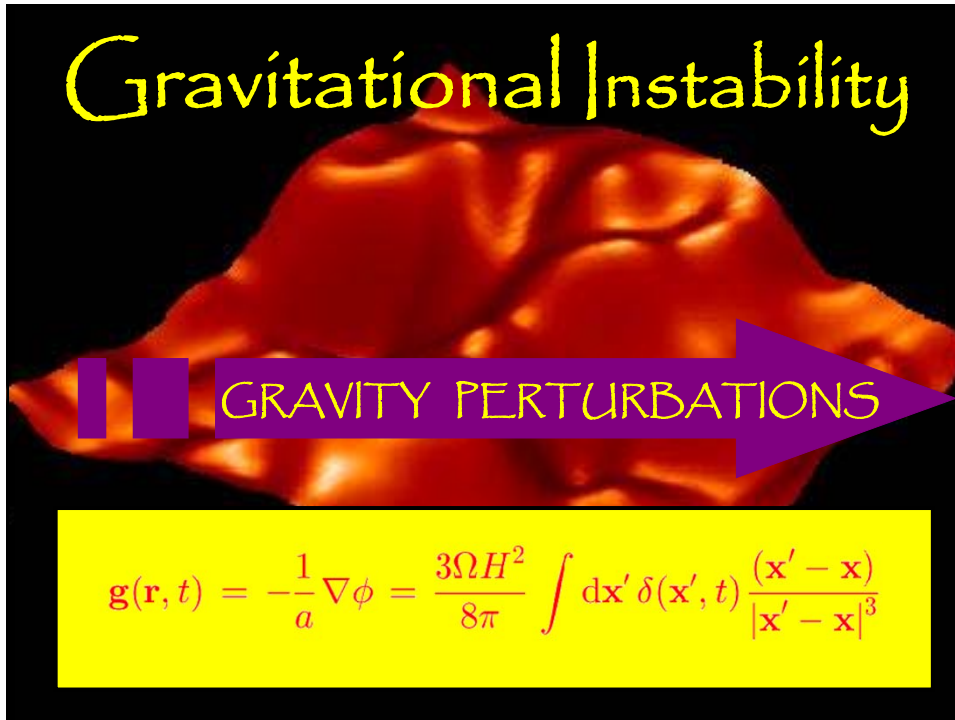
$$D(t) \approx H(t) \int \frac{dt}{a^2 H^2(t)}$$

Linear Density Growth

Linear Perturbation Evolution:
Density evolution: Growing Mode D_1

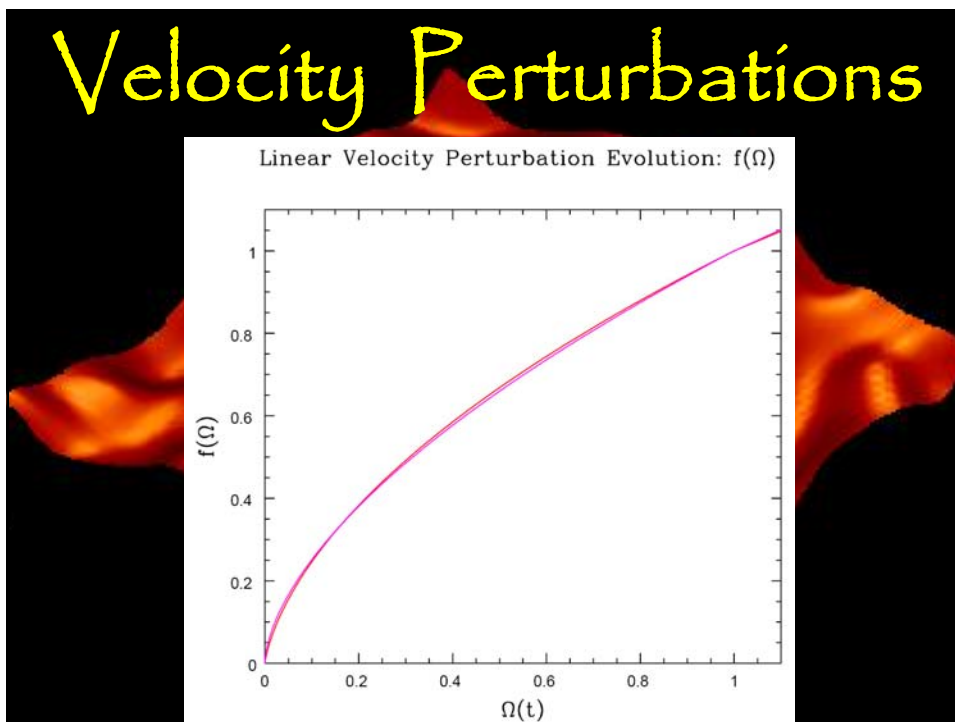


Gravitational Instability



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

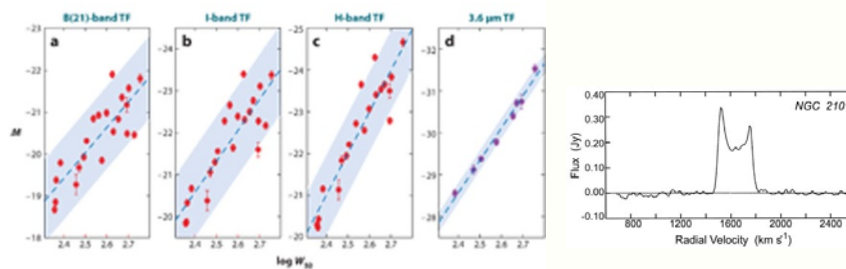
Velocity Perturbations



Distance & Measures

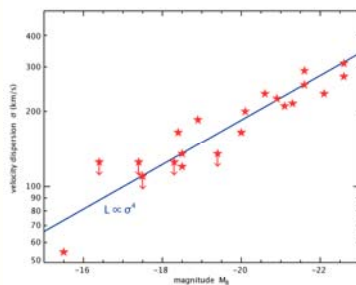
Tully-Fisher

- Spiral galaxies:
relation between rotation velocity (measured by HI velocity width)
&
Luminosity of galaxy
- $L \propto \Delta V^4$



Faber-Jackson

- Early-type galaxies:
relation between velocity dispersion
&
Luminosity of galaxy
- $L \propto \sigma^\gamma$



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

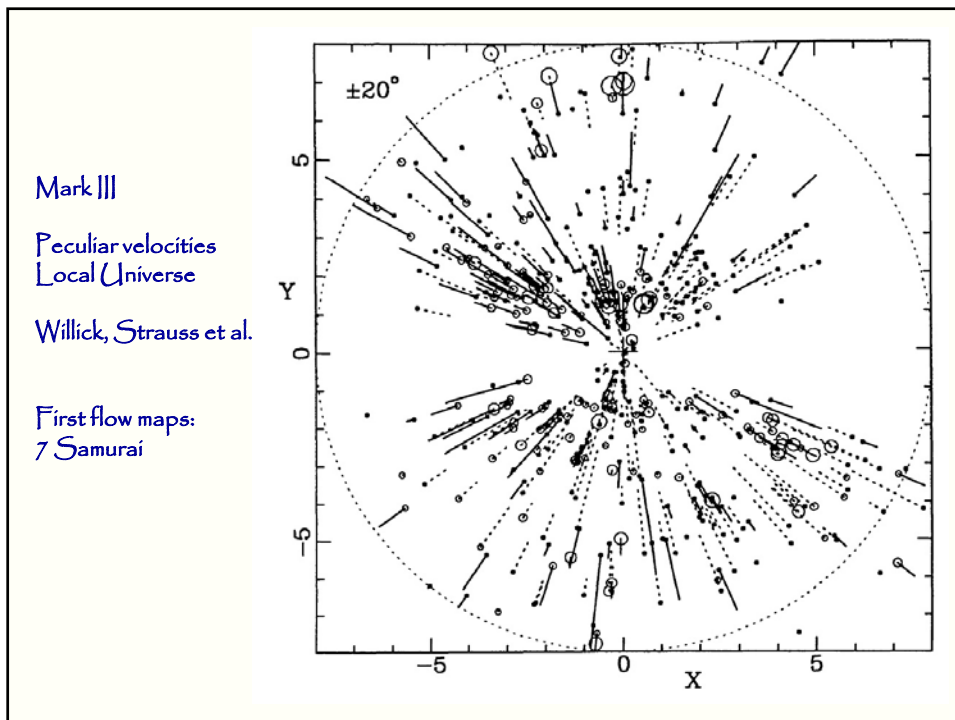
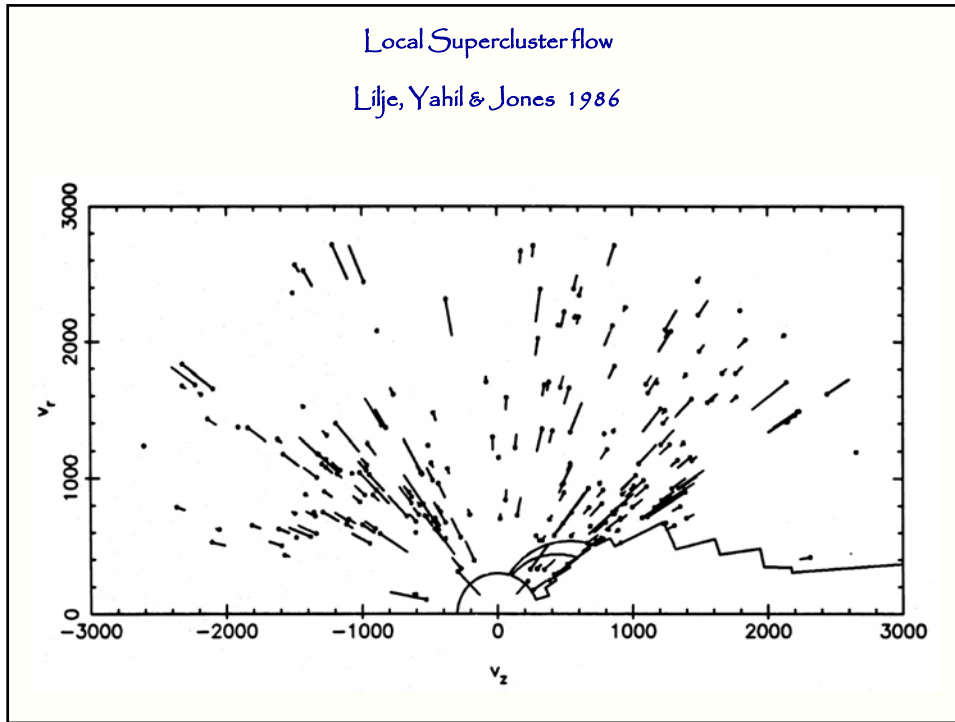
It relates of a E-SO galaxy

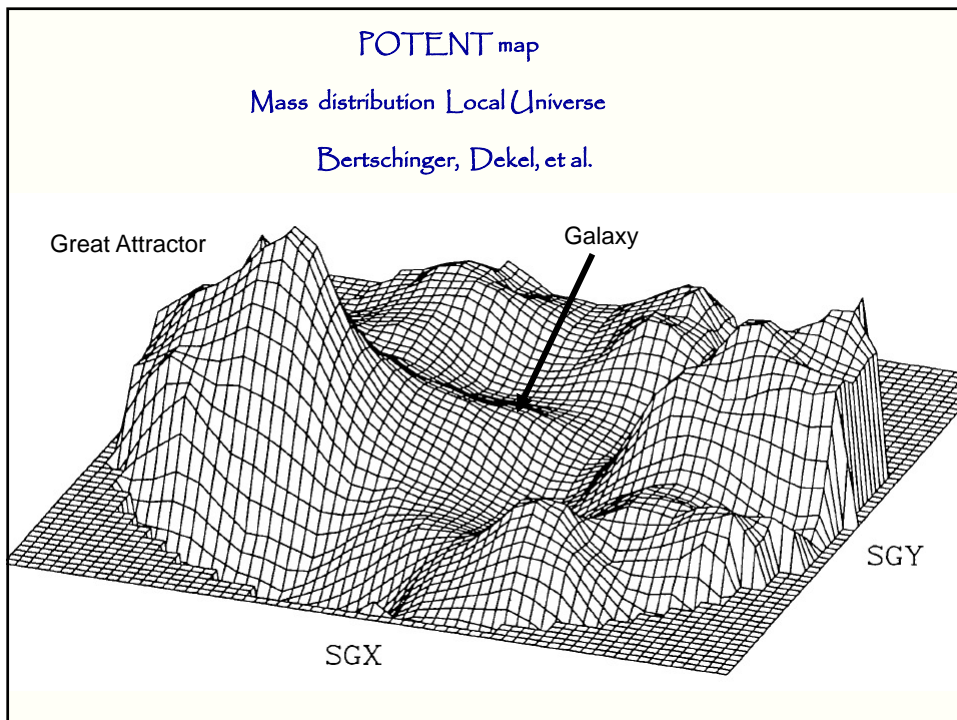
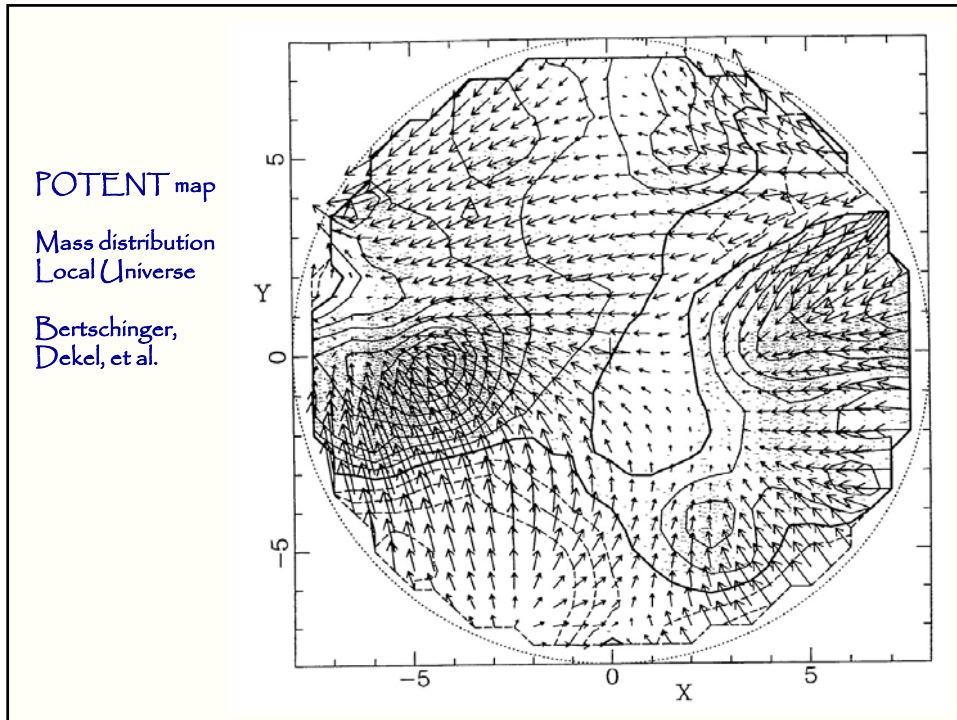
$$L \propto r_e^\alpha \sigma^\gamma$$

Luminosity, effective radius & velocity dispersion

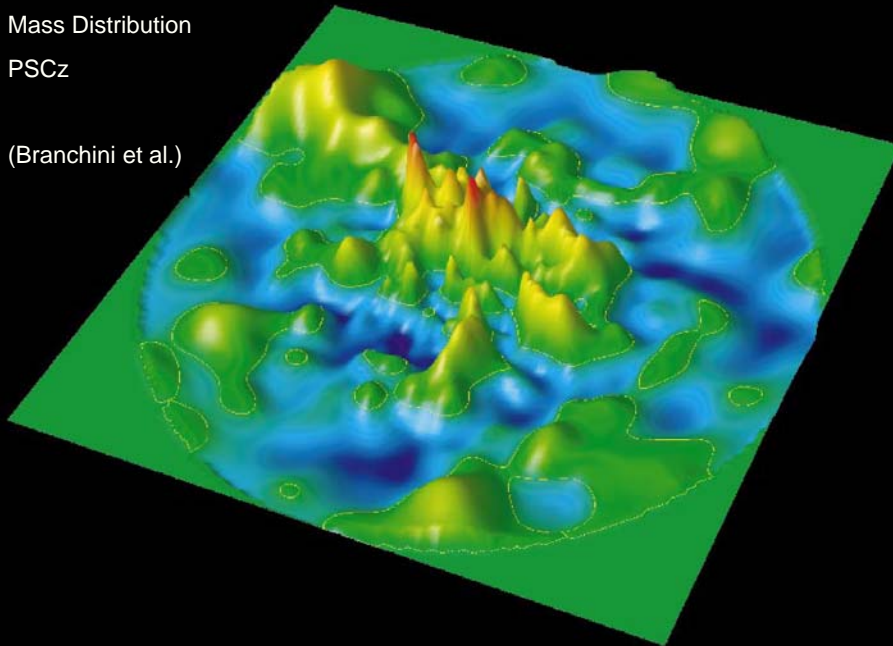
It is a reflection of the virial equilibrium of such a galaxy

Local Universe
Peculiar Velocities

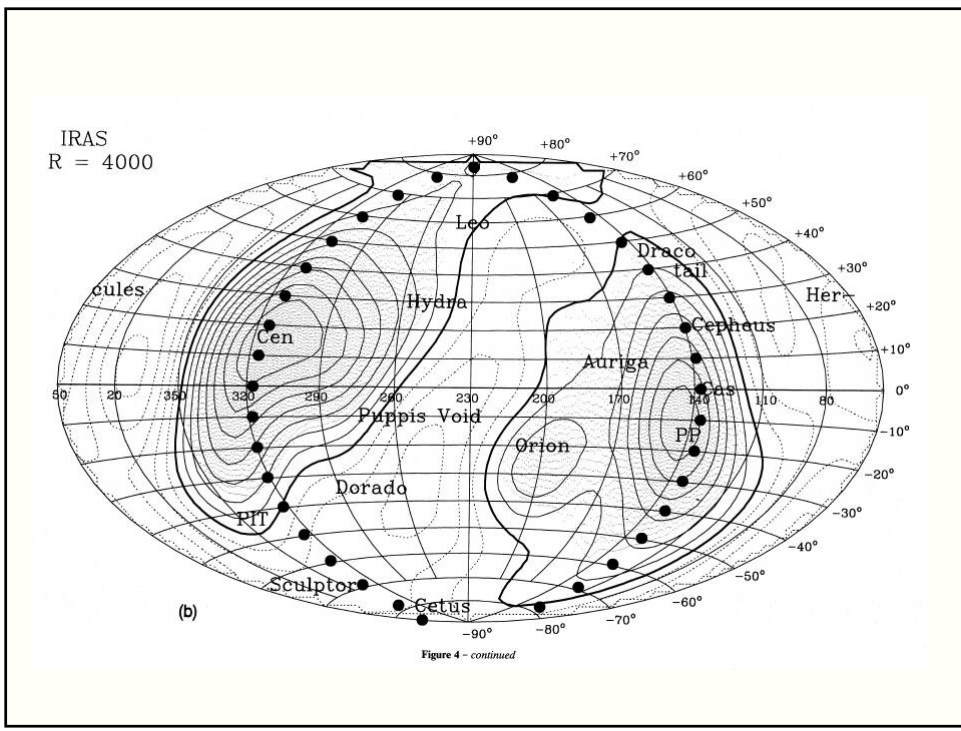
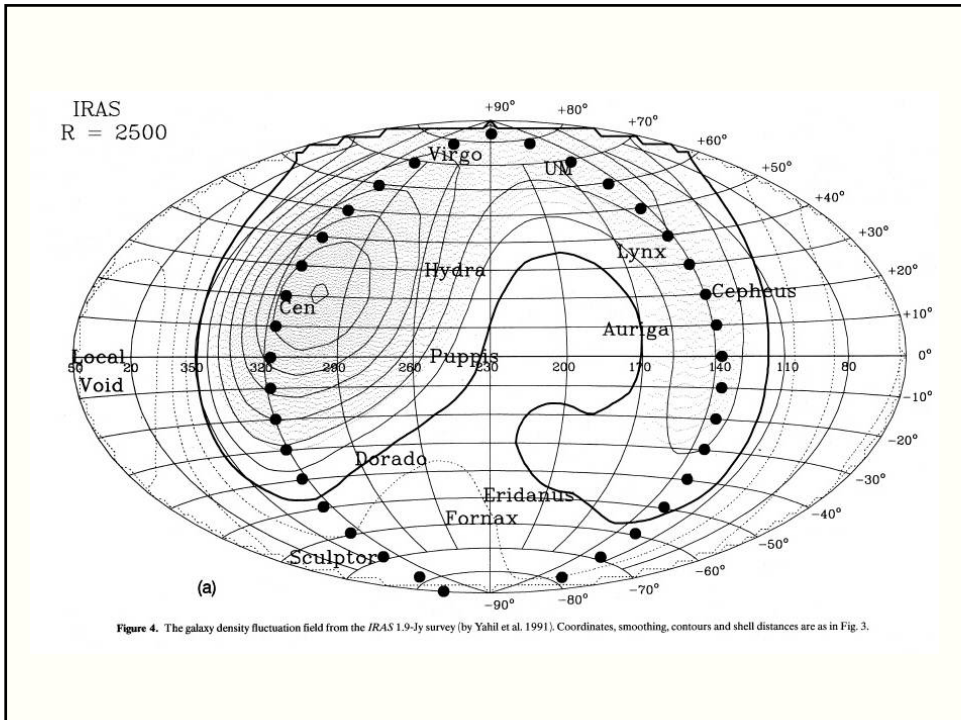


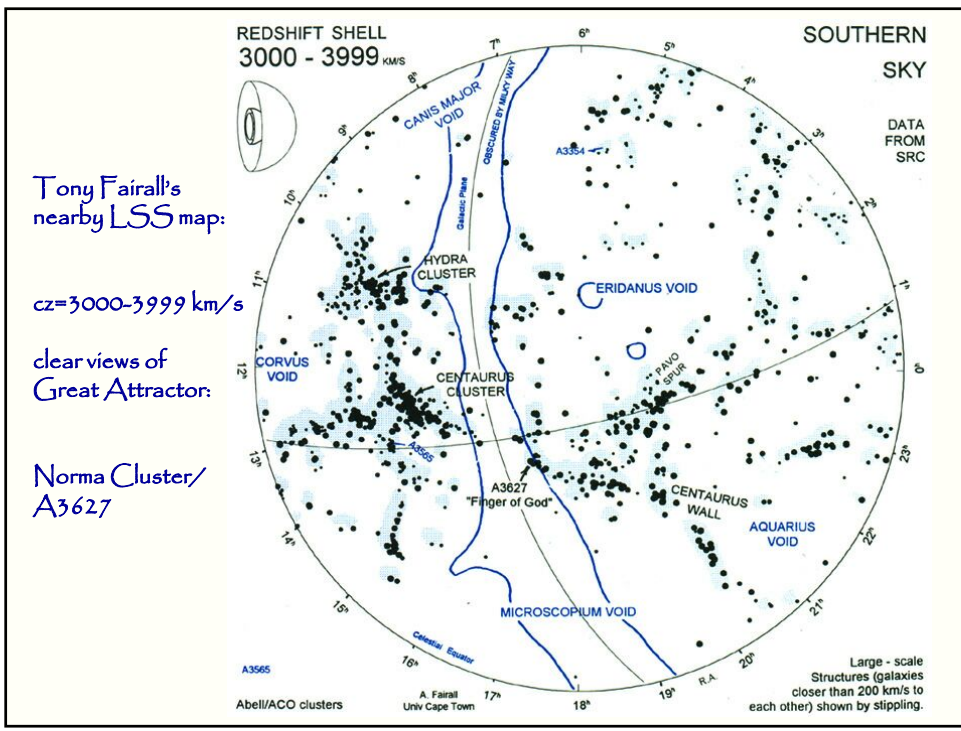
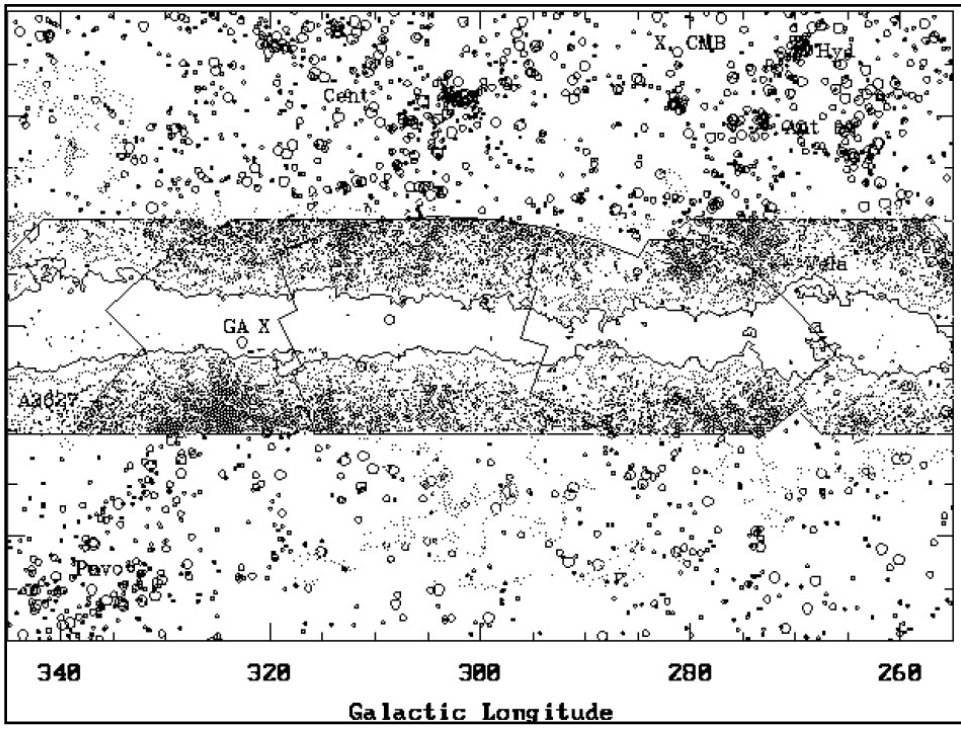


Local Universe
Mass Distribution
PSCz
(Branchini et al.)



Great Attractor



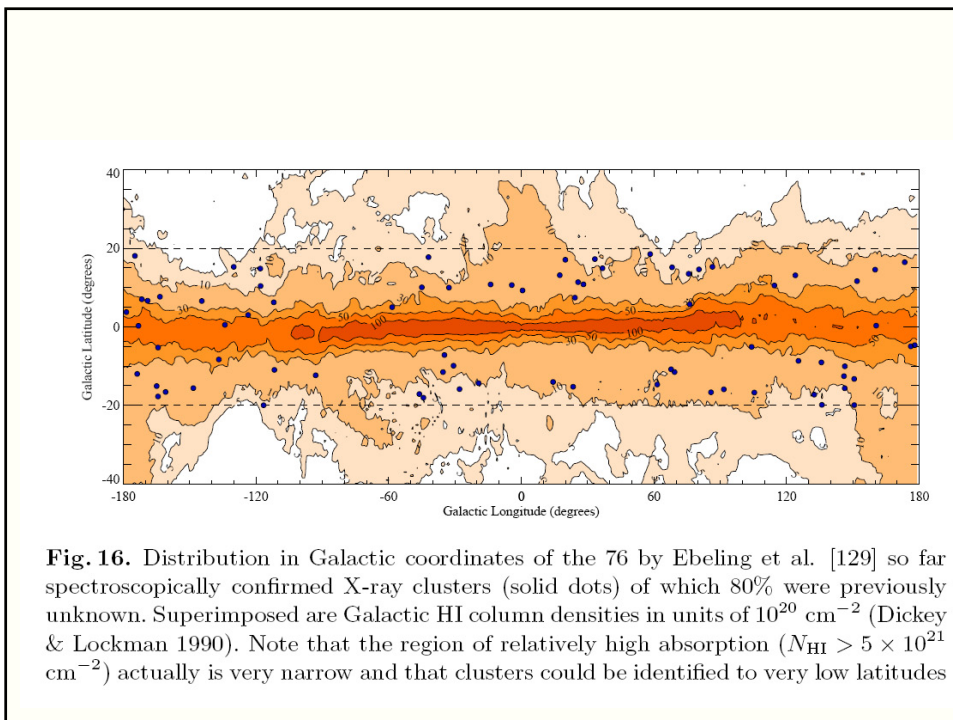
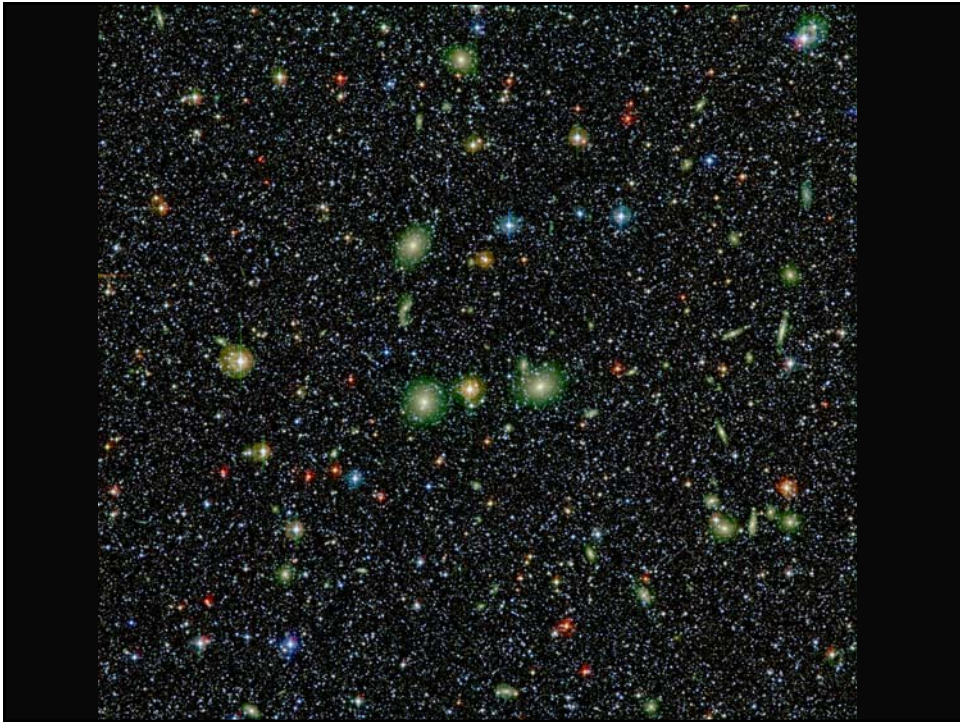


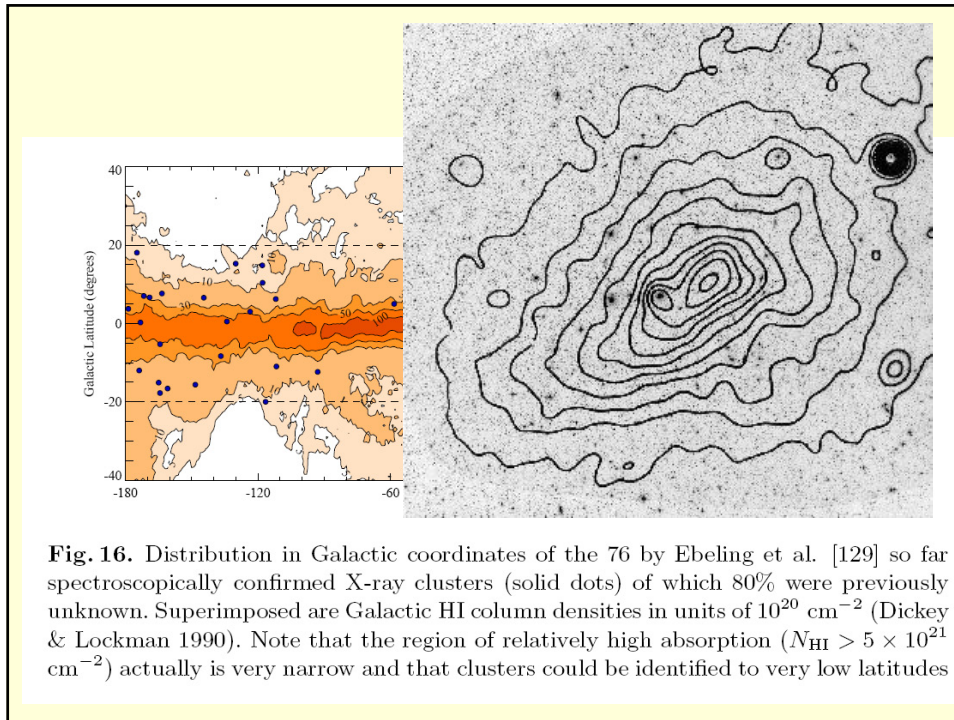
Tony Fairall's nearby LSS map:

$cz=3000-3999$ km/s

clear views of Great Attractor:

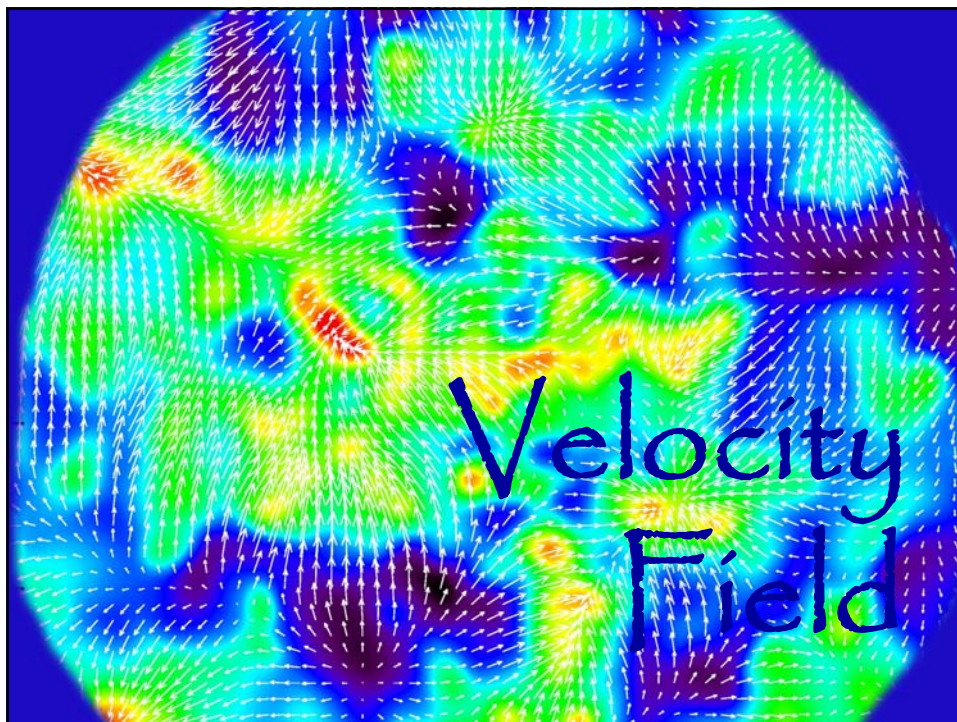
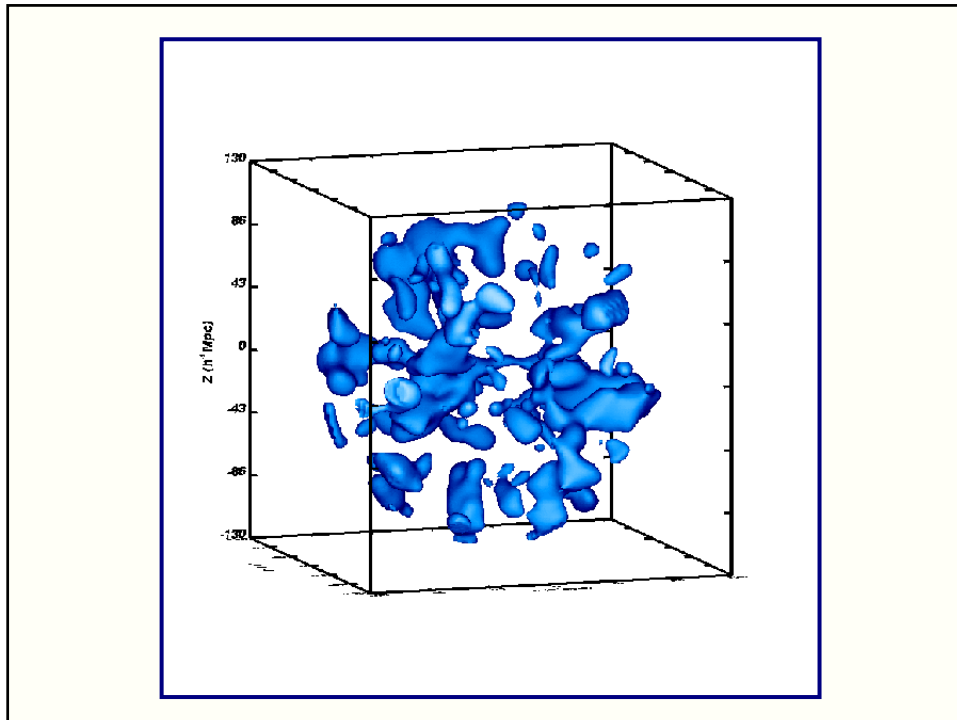
Norma Cluster/
A3627

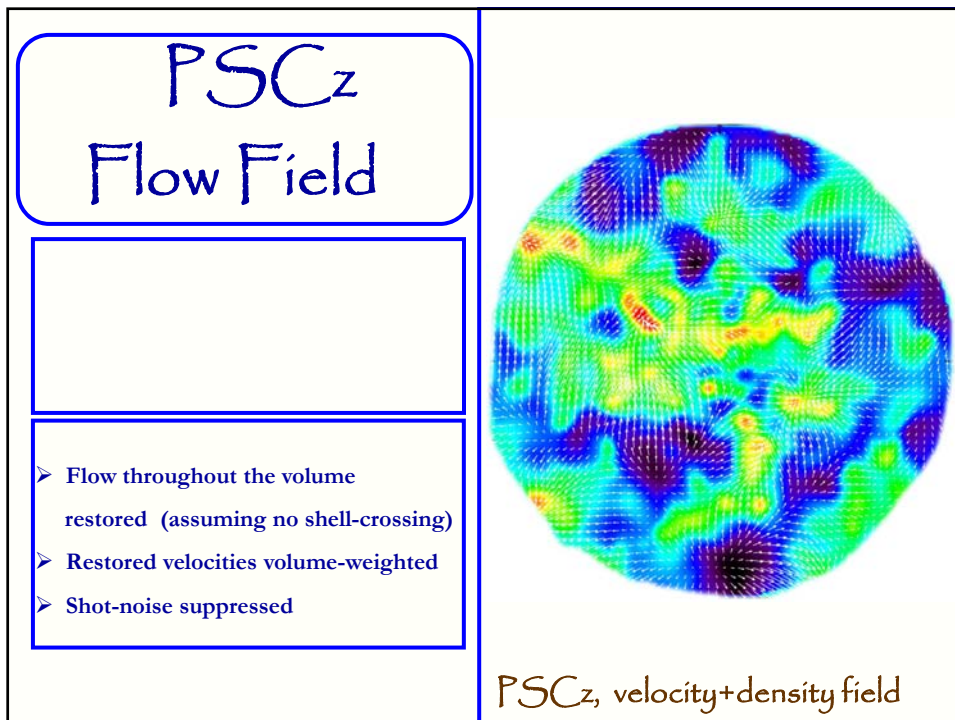
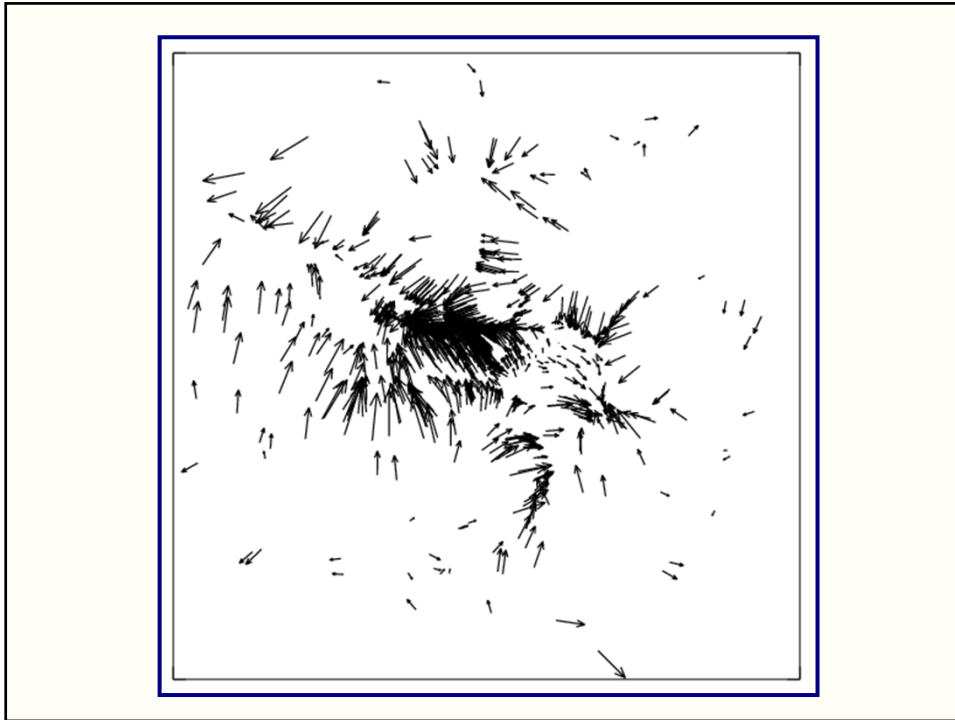


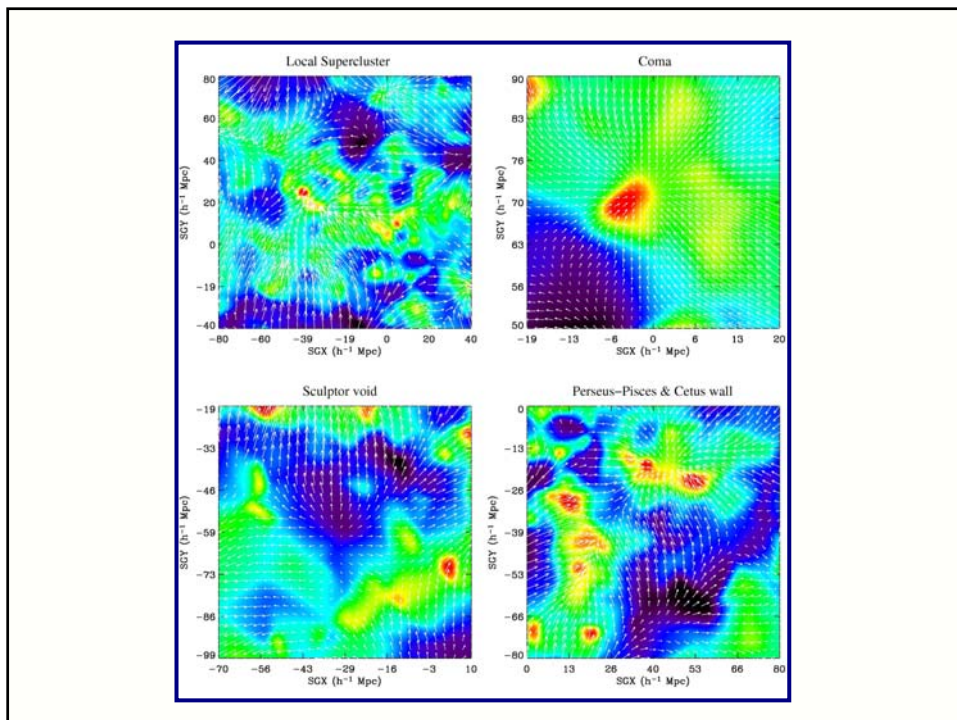
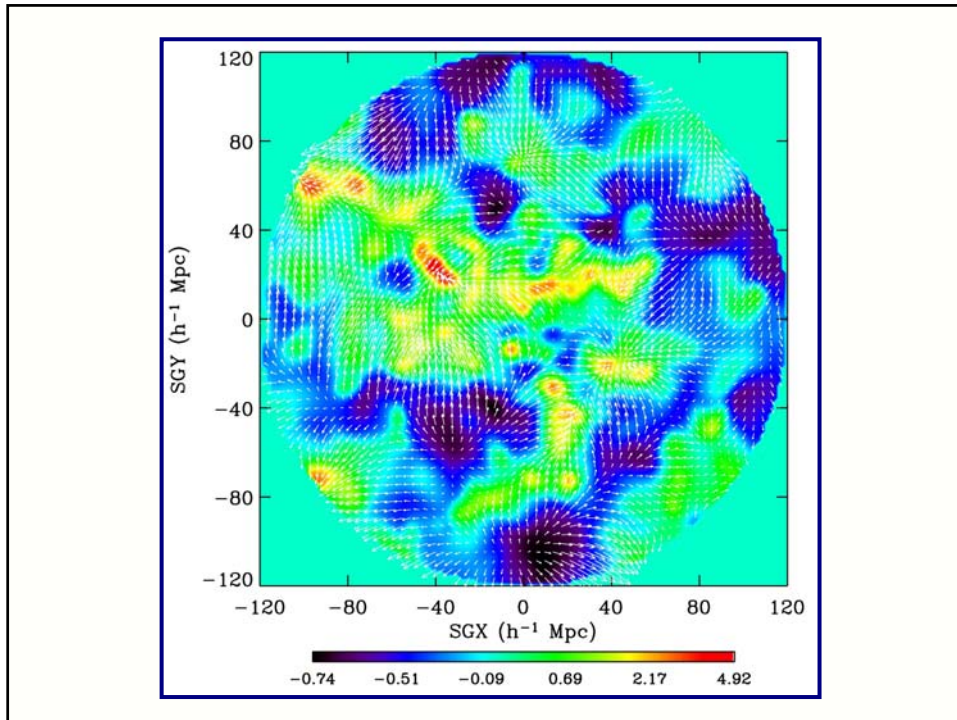


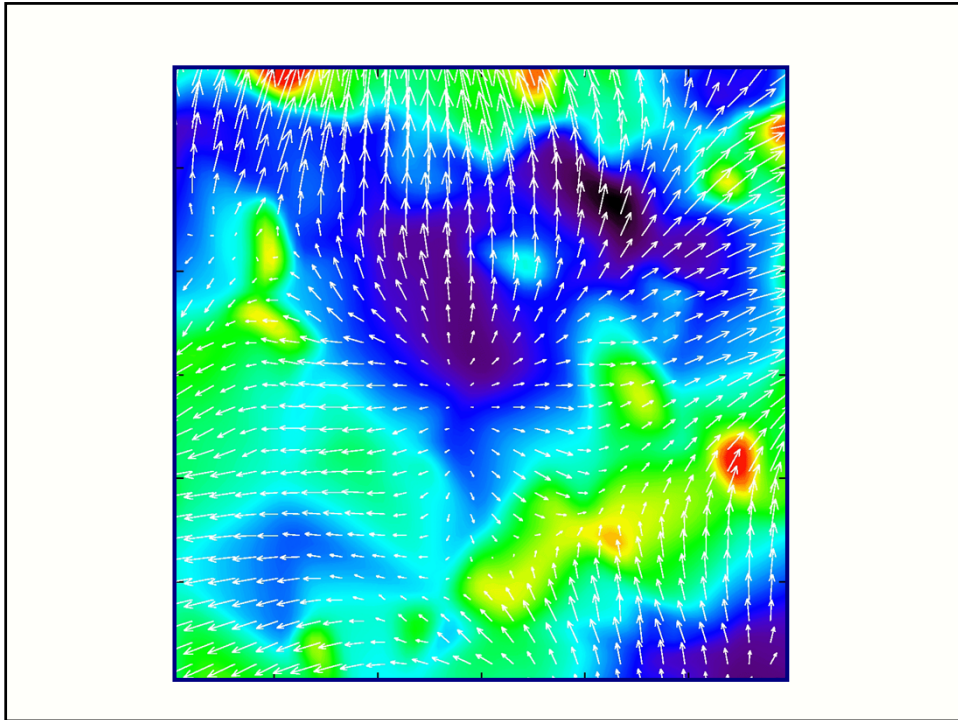
PSCz Survey

Dynamics:

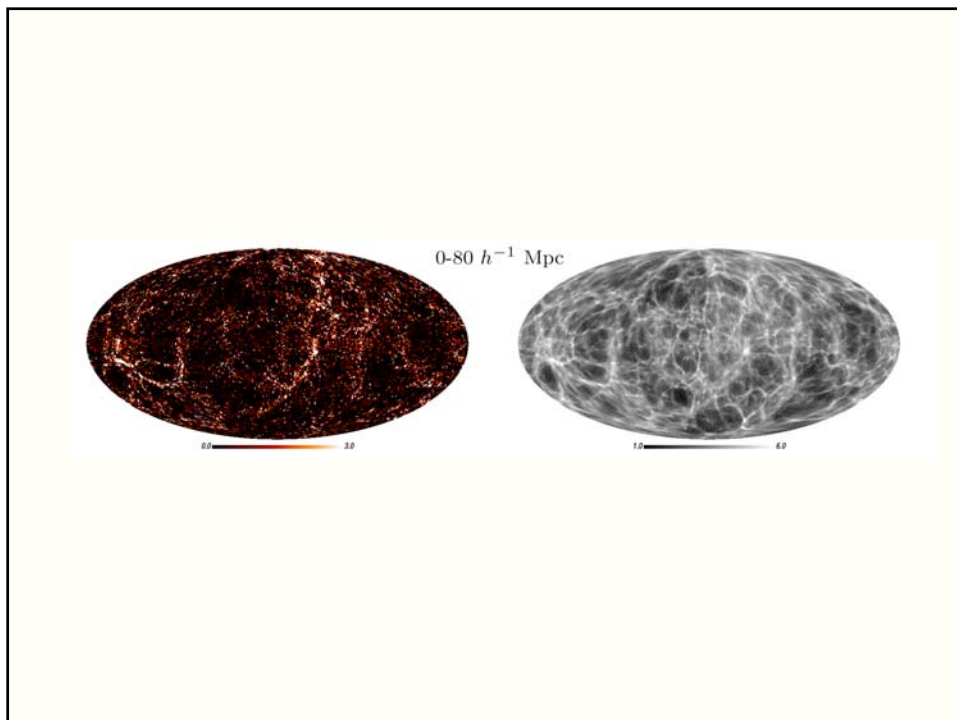
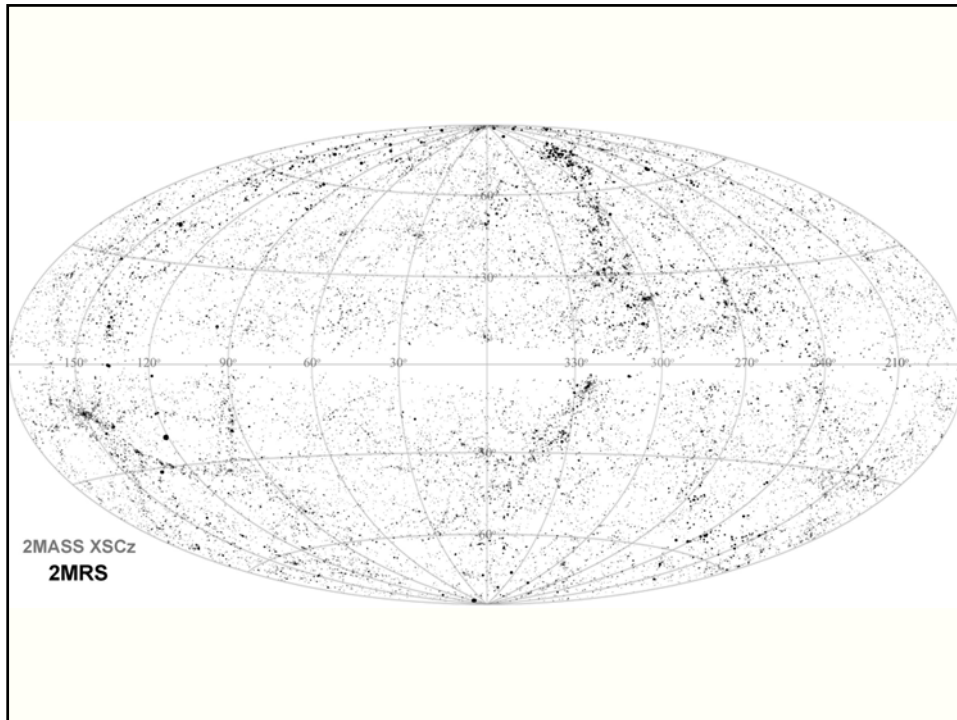


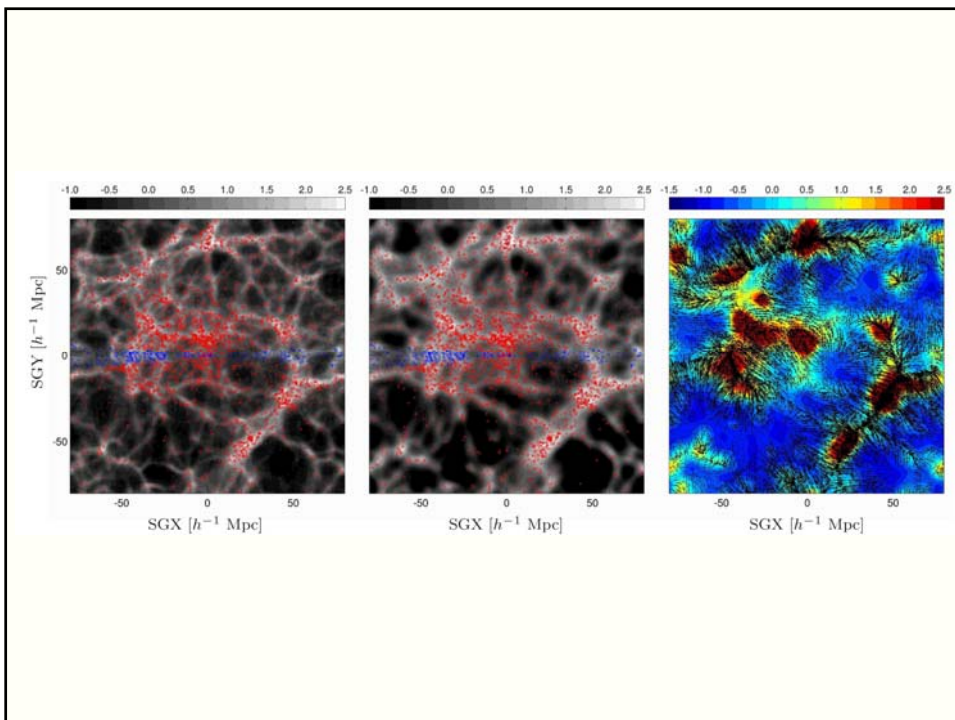
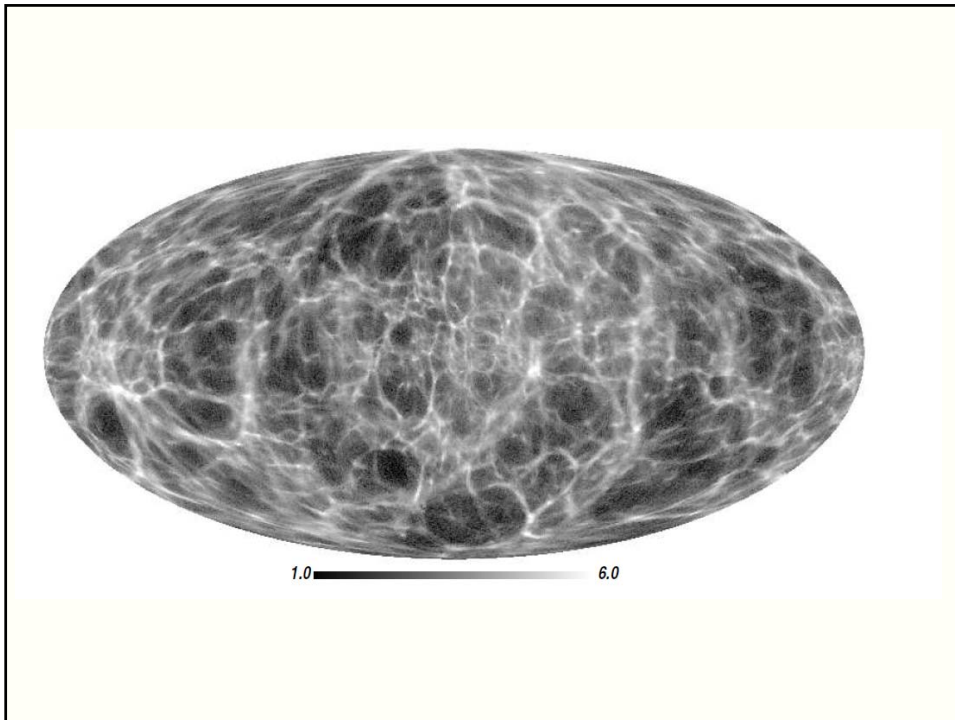


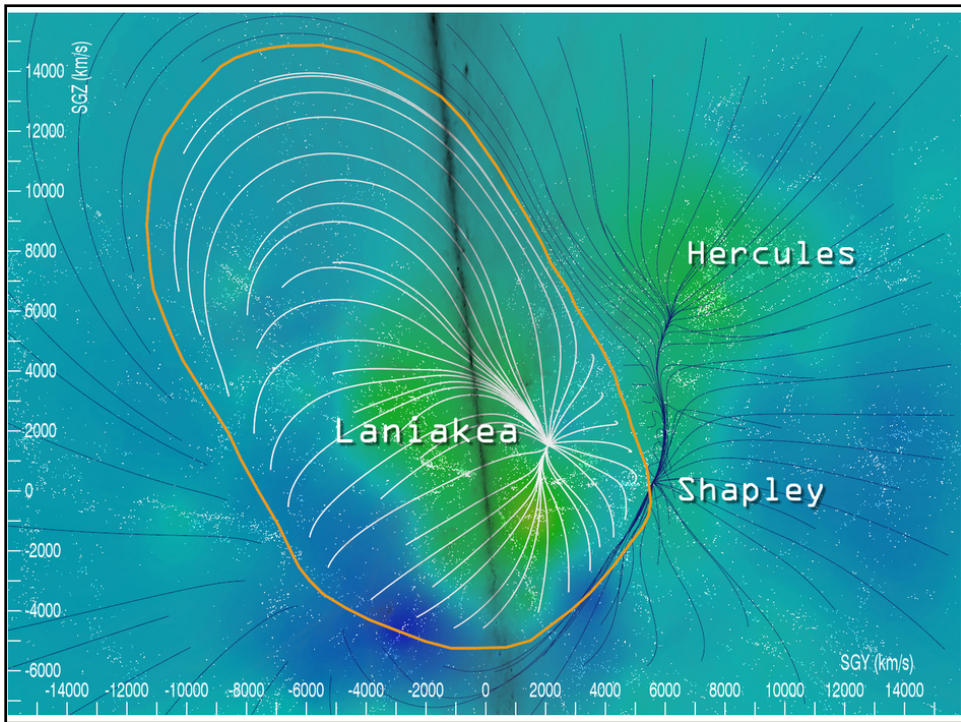




2MRS Survey
Dynamics





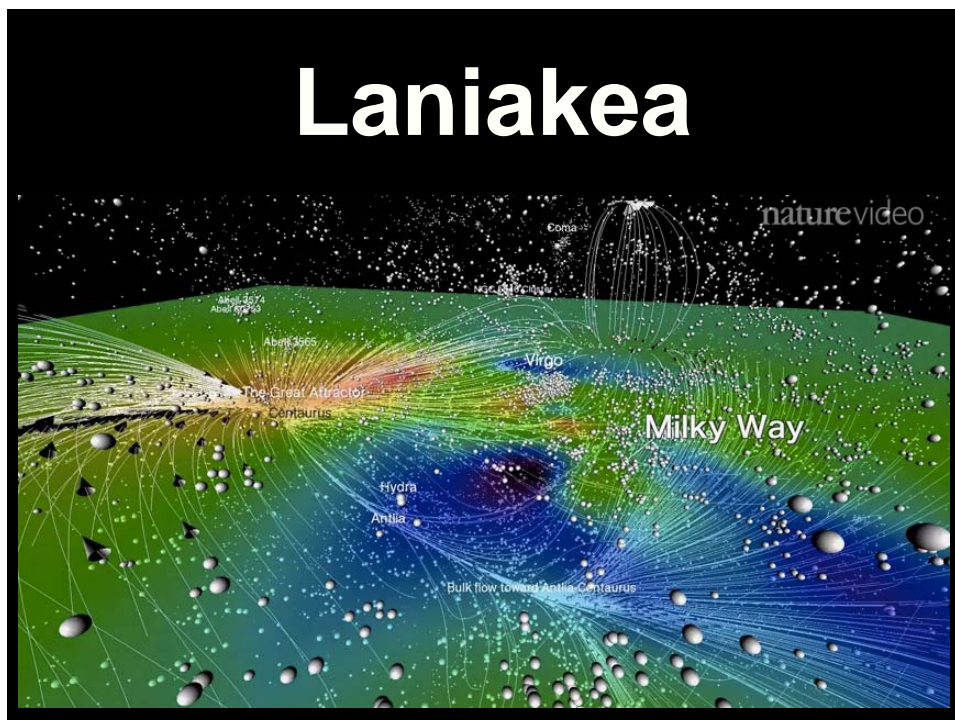


Laniakea

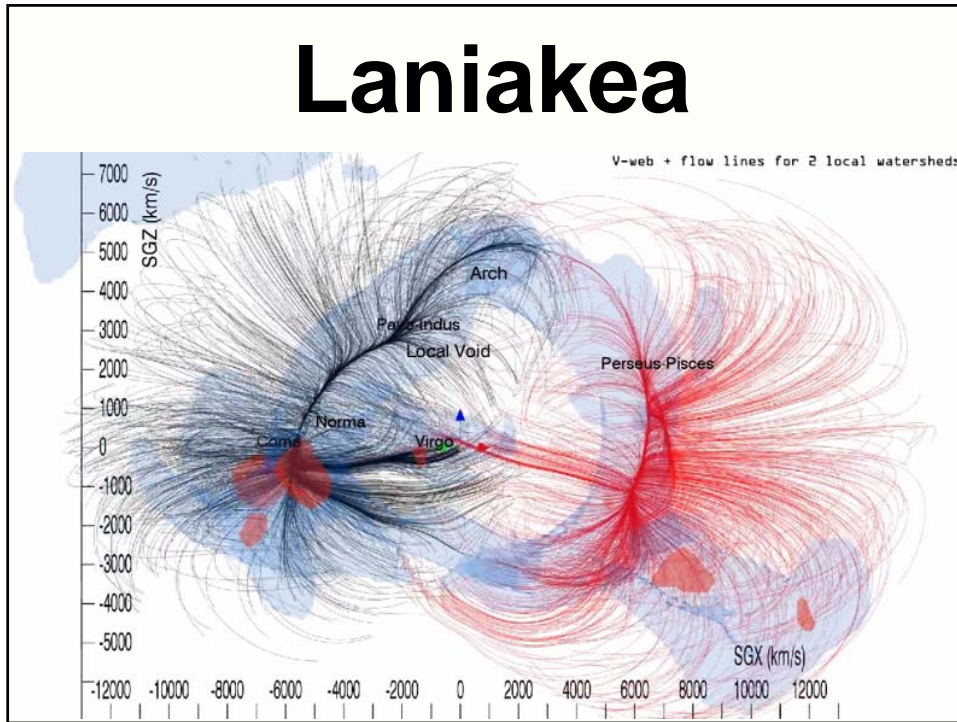
- Cosmicflows-2 catalogue
(Tully, Courtois et al. 2013)

compilation of distances & peculiar velocities 8000 galaxies

- most:
 - spirals: Tully-Fisher relation
 - E/SO: Fundamental plane
- 1000 galaxies
 - accurate distance: Cepheids, tip giant branch, SN Ia, surface brightness fluctuations

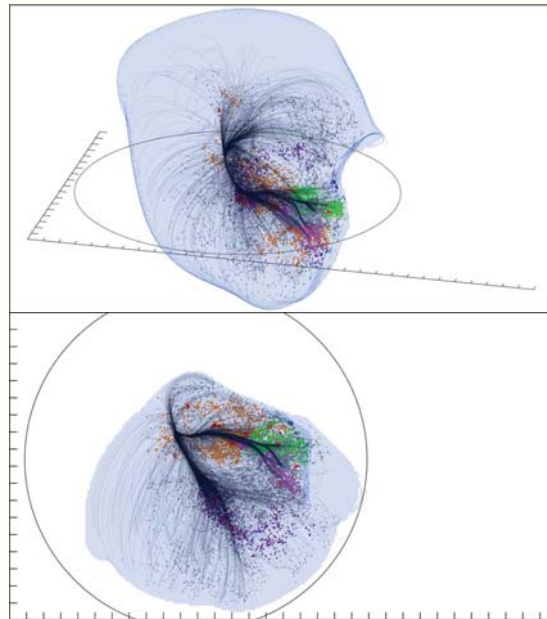


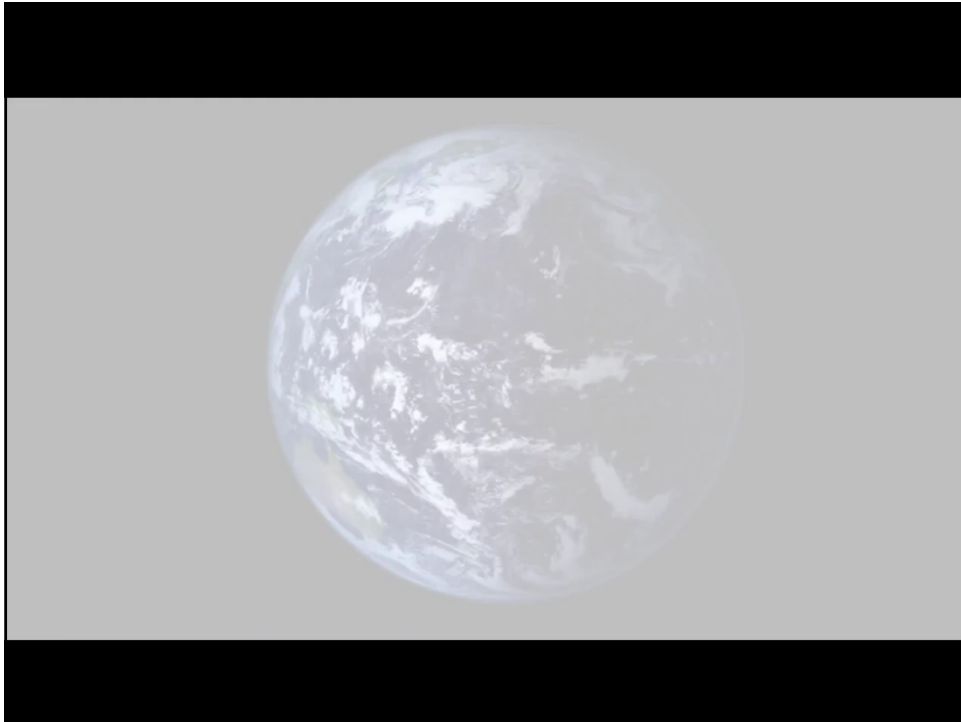
Laniakea



Laniakea

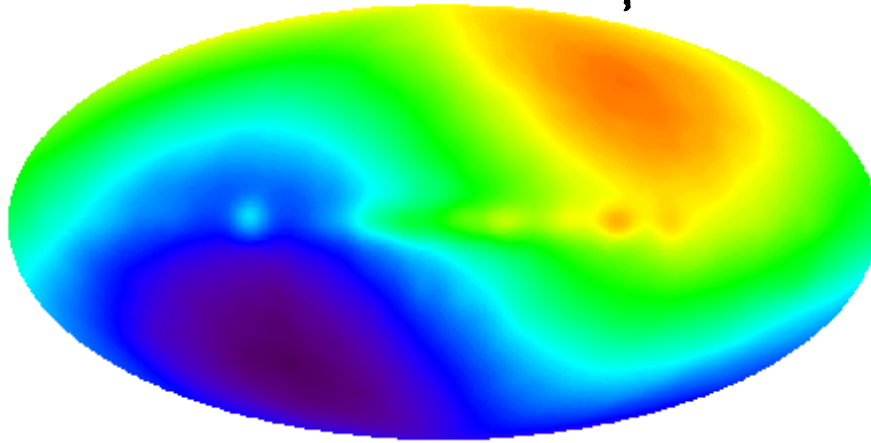
Laniakea
seen from 2 different angles





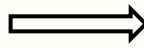
Cosmic Dipoles

The CMB Dipole



$$\Delta T = 3.36 \text{ mK}$$

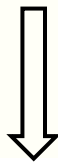
$$(l, b) = (264.3^\circ, 48.1^\circ)$$



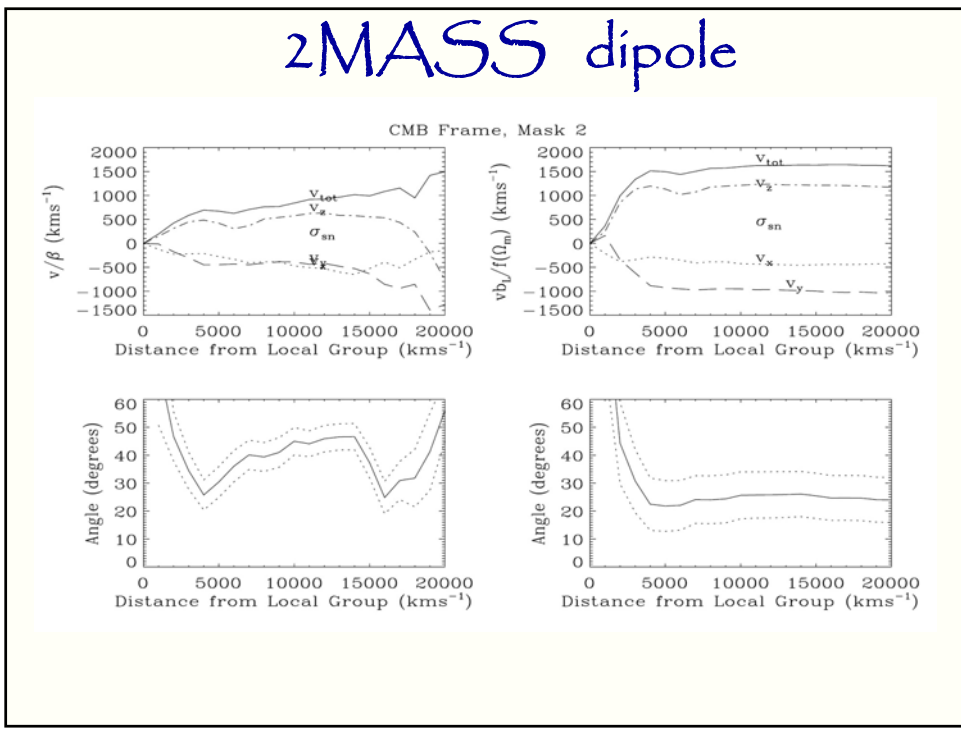
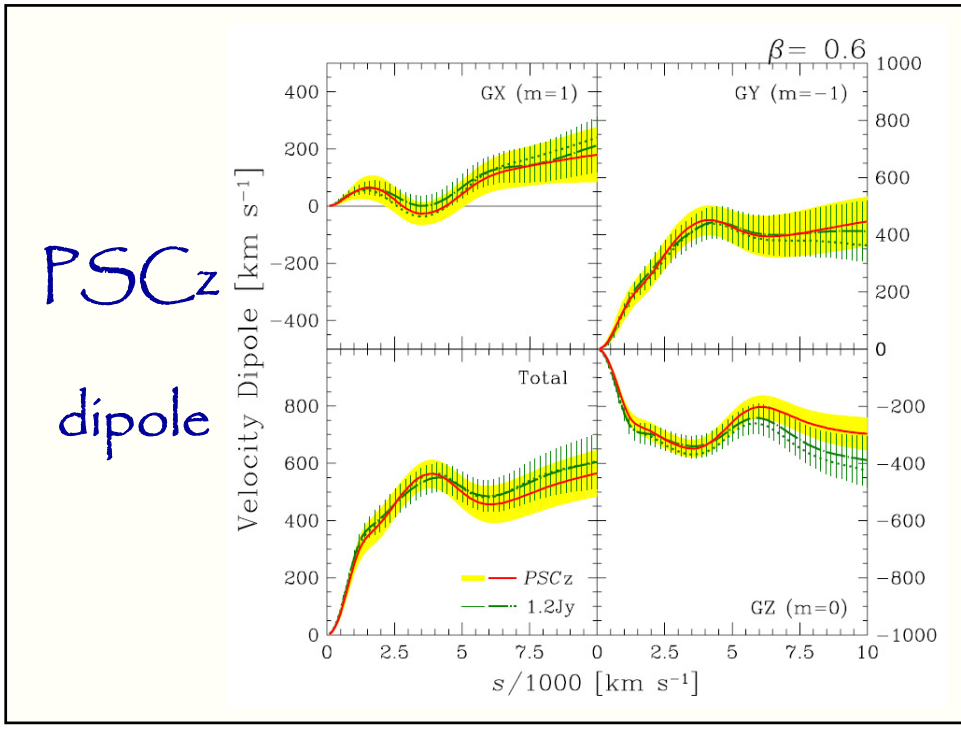
$$v_{\text{LG}} = 627 \pm 22 \text{ km/s}$$

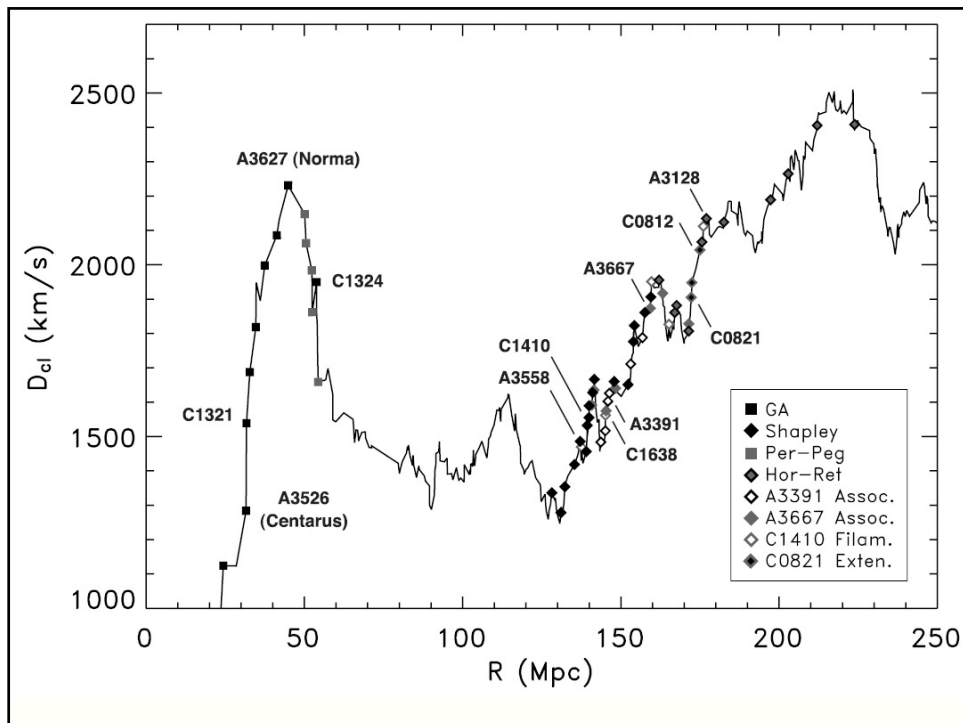
$$(l, b) = (276^\circ, 30^\circ)$$

$$\mathbf{v}_{\text{LG}} = \frac{H_0 \beta}{4\pi} \int_r^\infty d^3 \mathbf{r}' \delta_g(\mathbf{r}') \frac{\mathbf{r}' - \mathbf{r}}{|\mathbf{r}' - \mathbf{r}|^3}$$



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



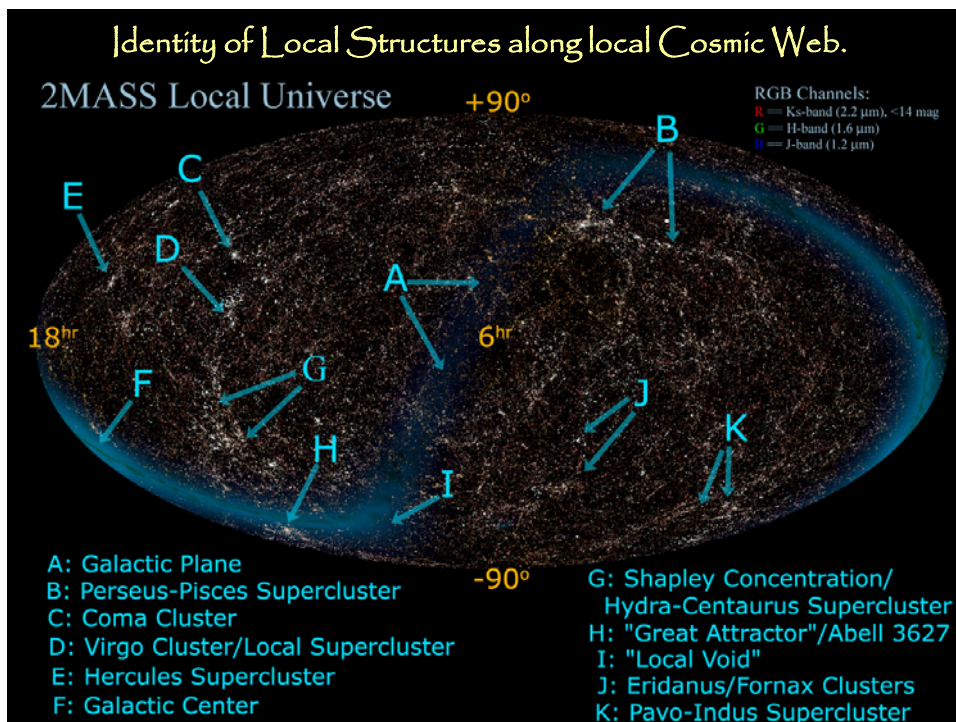
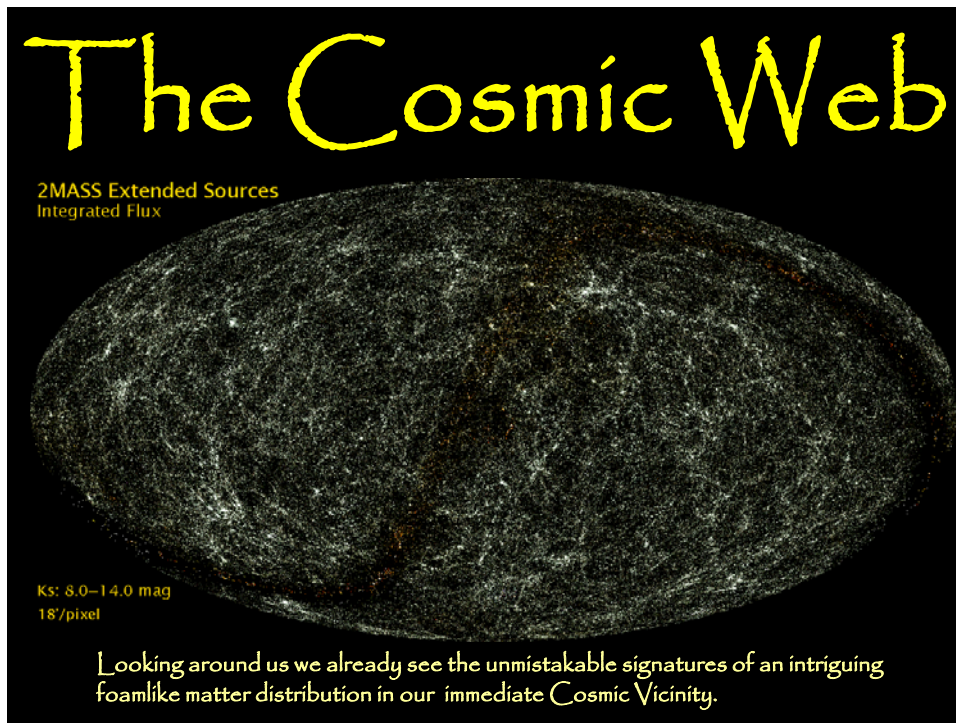


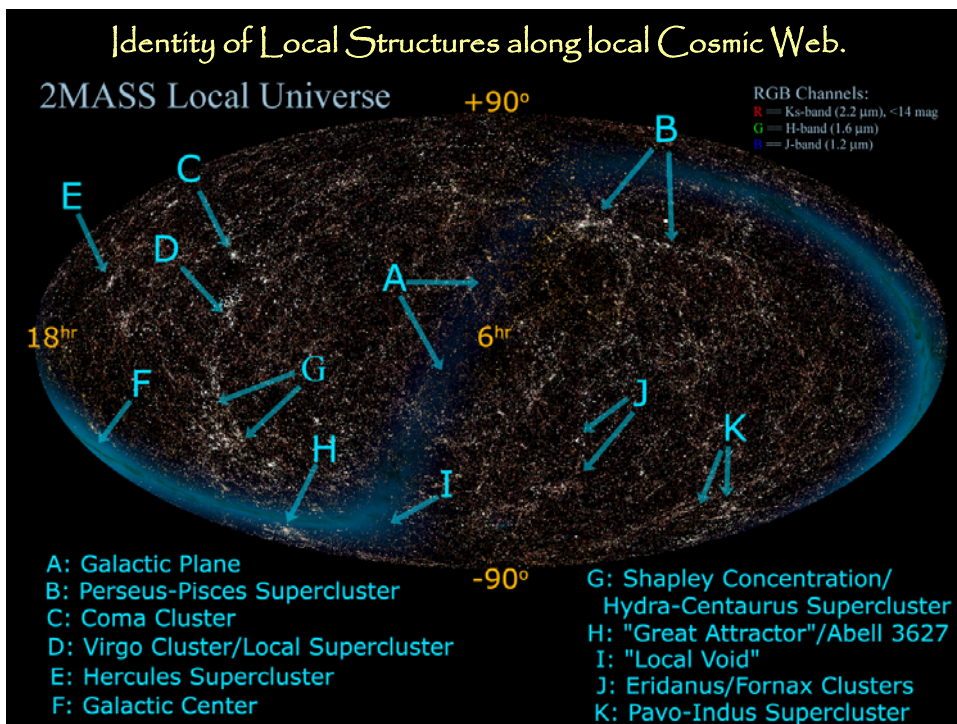
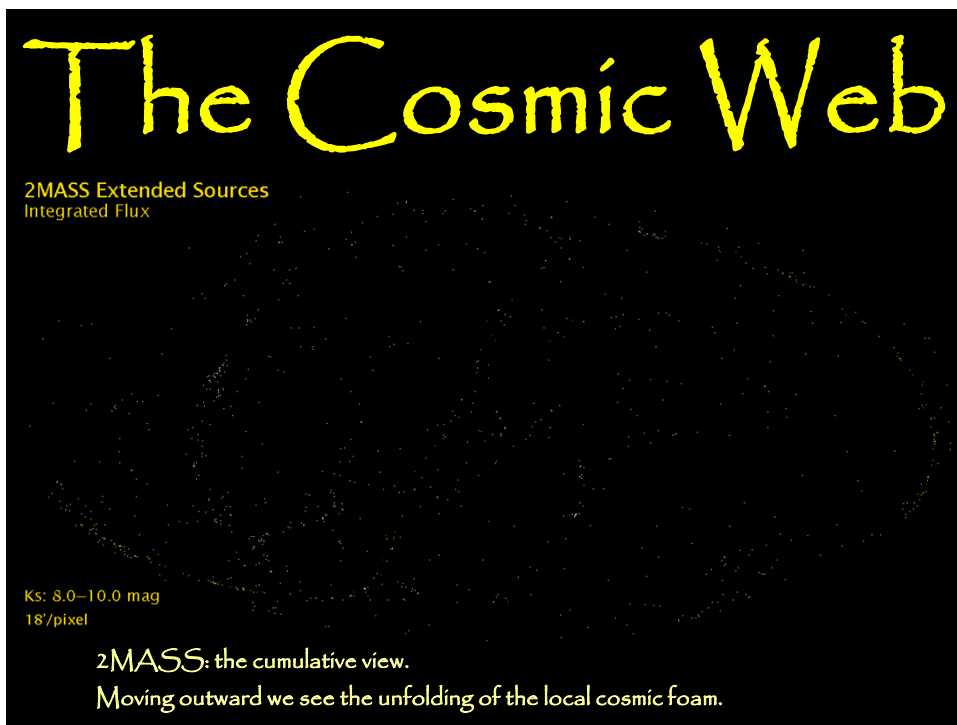
2MASS survey

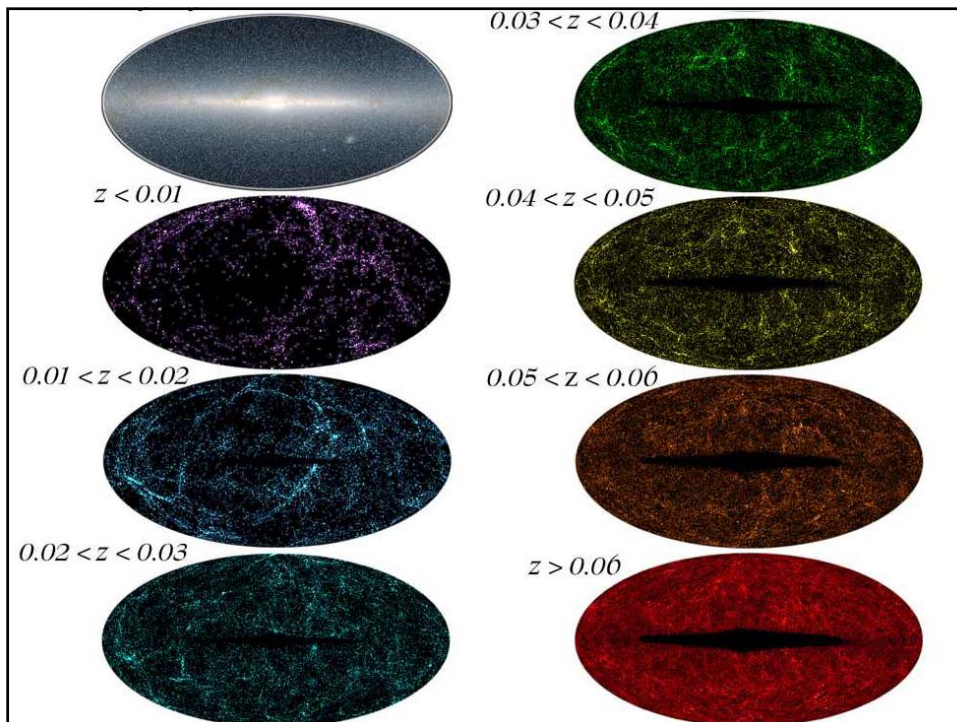
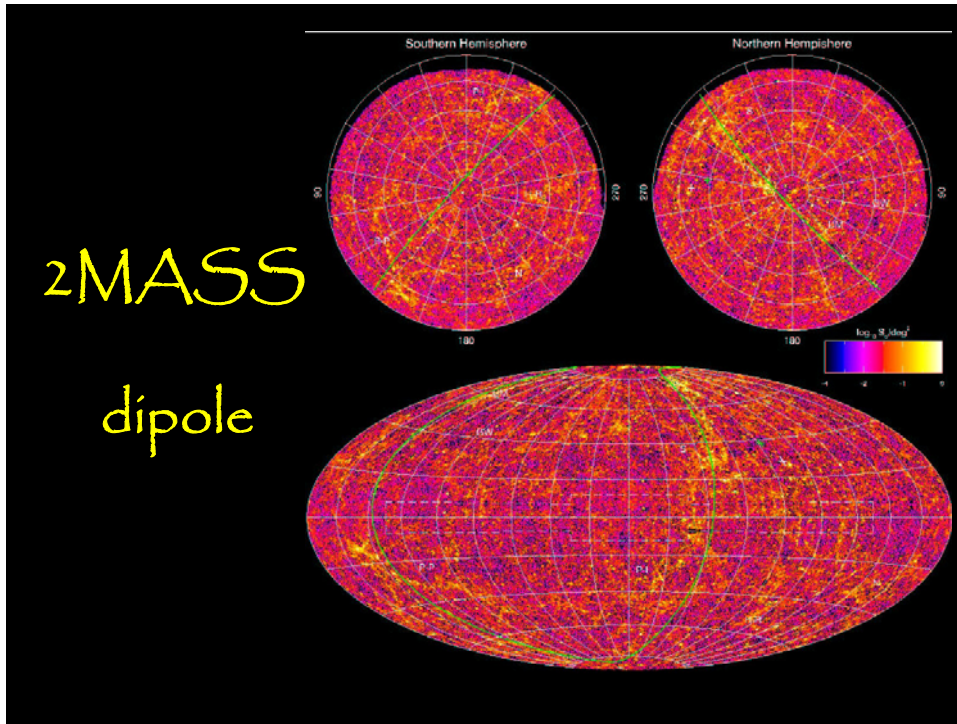
- 2MASS all-sky survey:
ground-based near-infrared survey whole sky,
 $J(1.2 \mu\text{m})$, $H(1.6 \mu\text{m})$, $K(2.2 \mu\text{m})$
- 2MASS extended source catalog (XSC):
1.5 million galaxies
- unbiased sample nearby galaxies
- photometric redshifts: depth in 2MASS maps,
“cosmic web” of (nearby) superclusters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

courtesy:

T. Jarrett







Redshift Space Distortions

