Structure of the Universe on Large Scales

- The cosmological principle: a fractal model as an alternative
- probes of large scale structure
  - QSO spectra & galaxy surveys
  - large scale motions
    - the cosmic velocity field
    - inference of cosmological
    - dynamical analysis methods

The cosmological principle

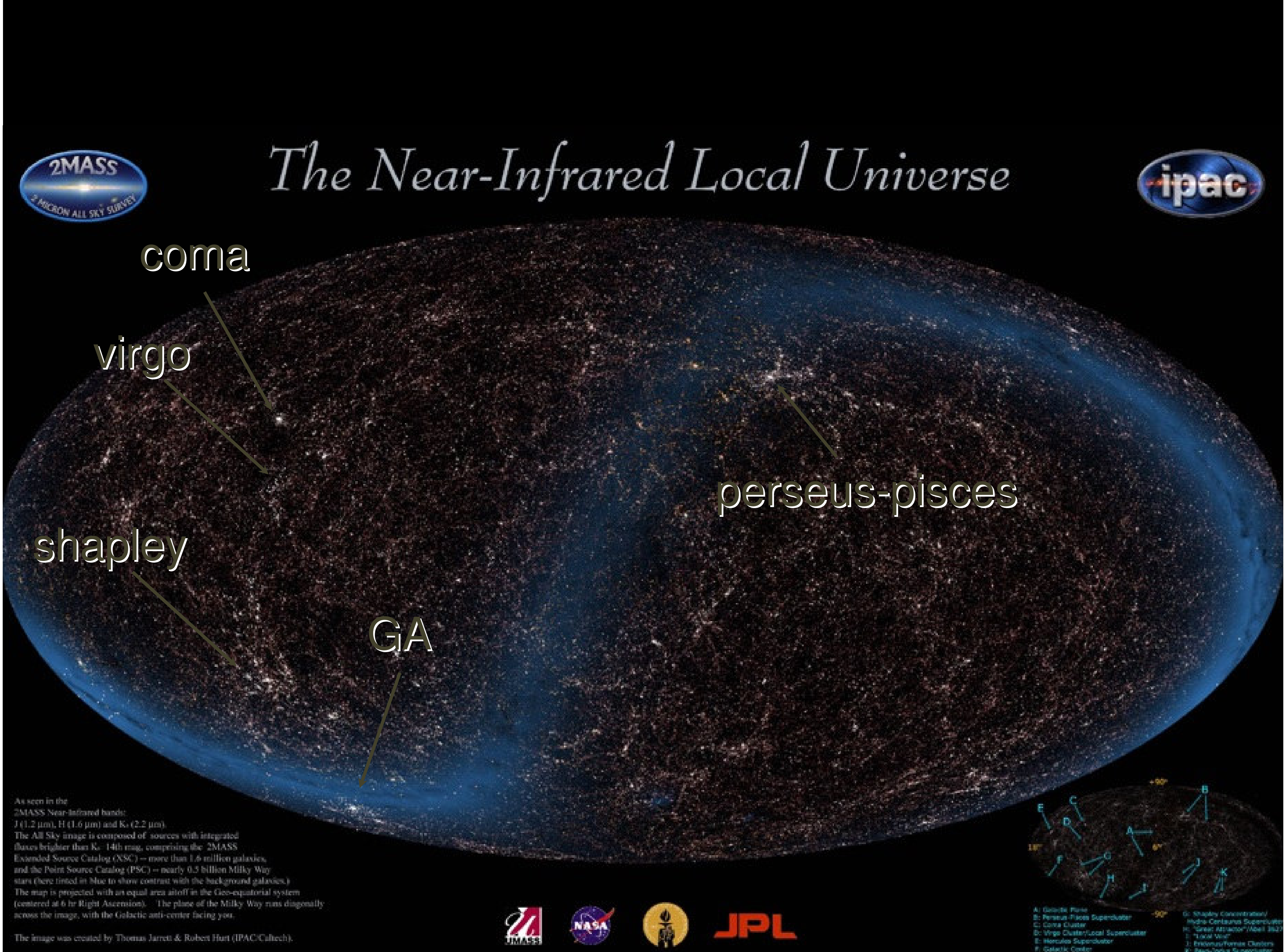
Viewed on sufficiently large distance scales, there are no preferred directions or preferred places in the Universe.

OR

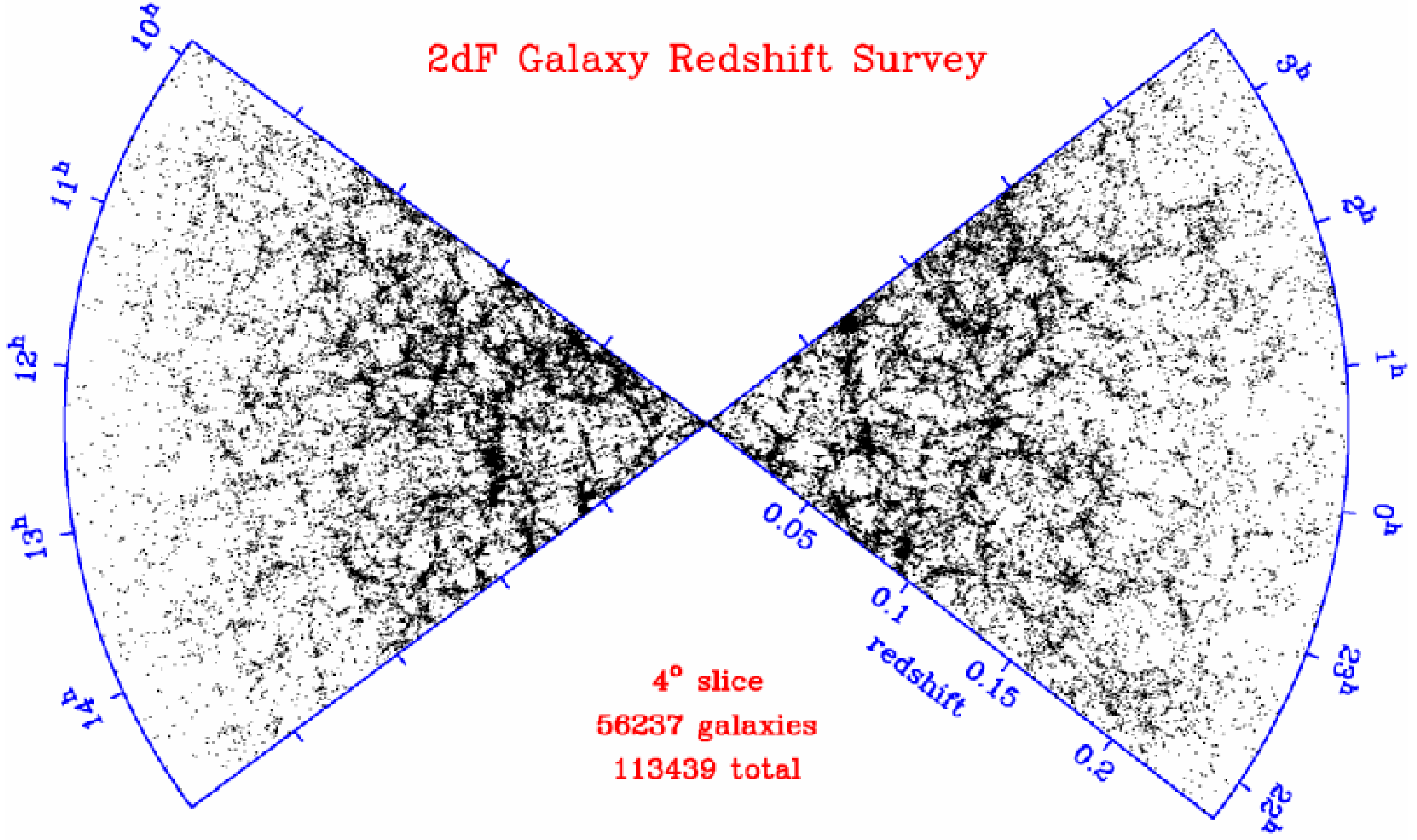
The Universe is homogeneous and isotropic when viewed on large scales.

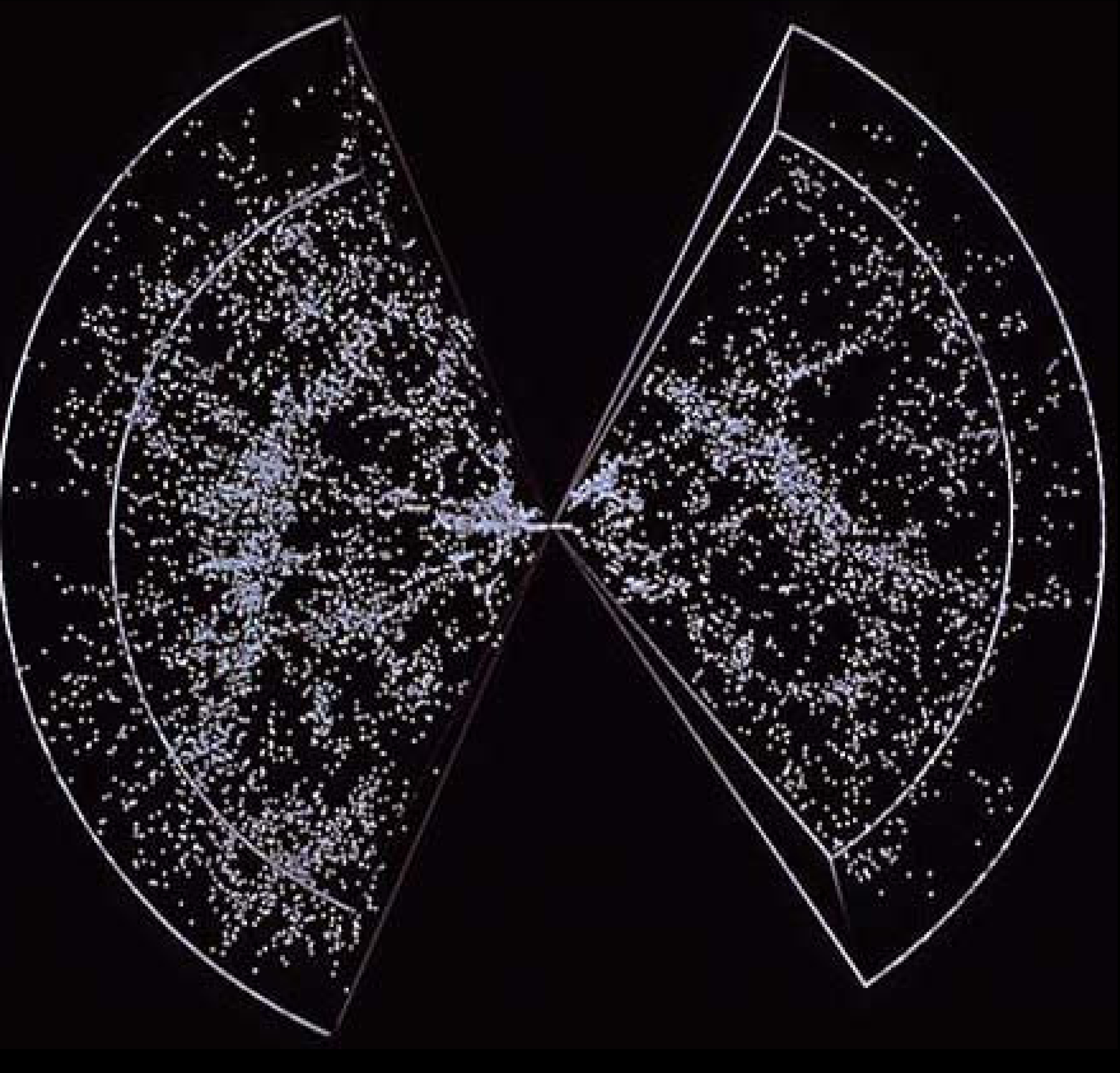
$$N(< R) = \bar{N}\tfrac{4\pi}{3}R^3$$

QuickTime™ and a
decompressor
are needed to see this picture.


The Near-Infrared Local Universe
2MASS
2 MICRON ALL SKY SURVEY
ipac
coma
virgo
shapley
GA
perseus-pisces
As seen in the
2MASS Near-Infrared bands:
J (1.2 μm), H (1.6 μm) and Ks (2.2 μm).
The All Sky image is composed of sources with integrated
fluxes brighter than Ks 14th mag, comprising the 2MASS
Extended Source Catalog (XSC) -- more than 1.6 million galaxies,
and the Point Source Catalog (PSC) -- nearly 0.5 billion Milky Way
stars (here tinted in blue to show contrast with the background galaxies.)
The map is projected with an equal area aitoff in the Geo-equatorial system
(centered at 6 hr Right Ascension). The plane of the Milky Way runs diagonally
across the image, with the Galactic anti-center facing you.
The image was created by Thomas Jarrett & Robert Hurt (IPAC/Caltech).
JPL
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

Cone diagram: 4-degree wedge





The galaxy distribution from the survey of de Lapparent *et al.* (1986a), using the data of Huchra *et al.*

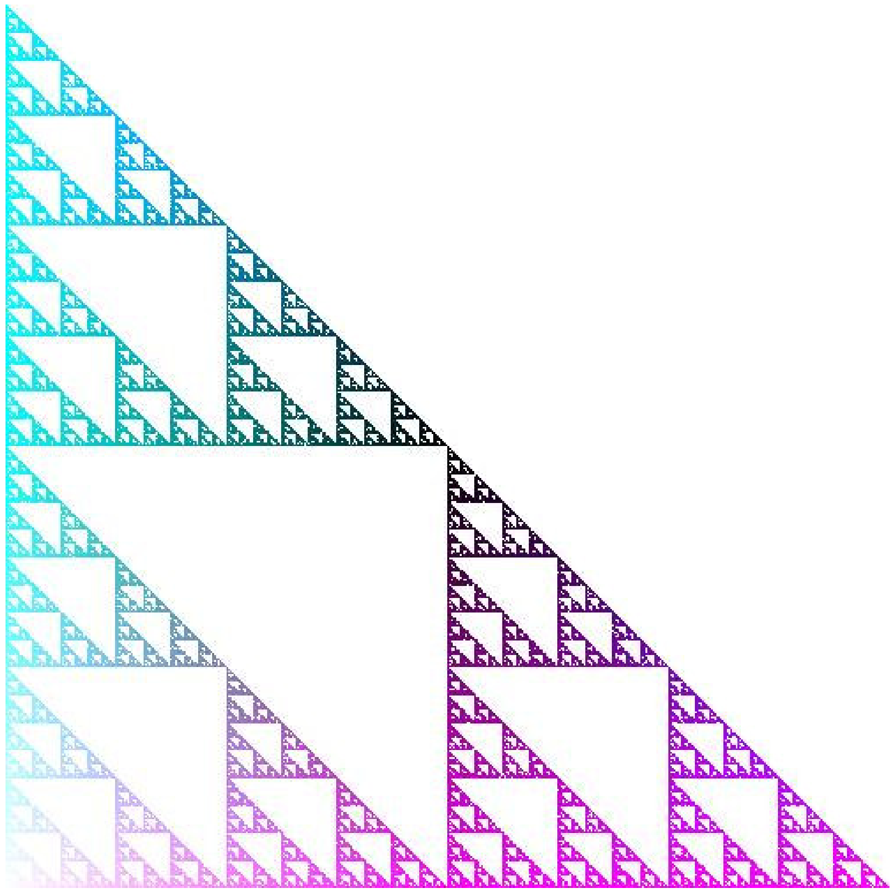
A1367
Coma
A779
7S 224
A569
Hydra
A3581
Cam
Cen
Virgo
Perseus
Fnx Eri
Pavo
7S 206
Pegasus
A194
A2911
A2870

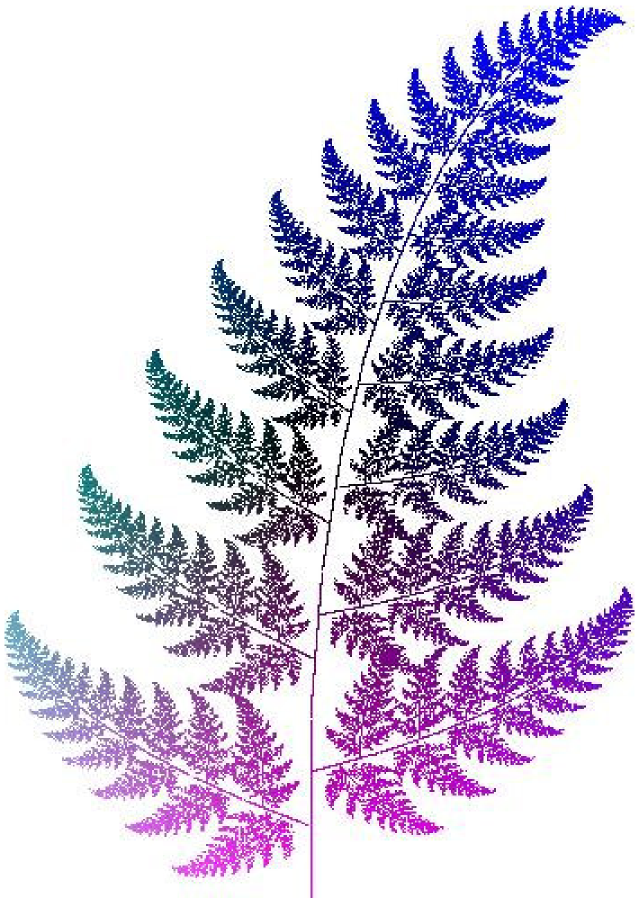
An alternative cosmology: a fractal Universe

$$N(< R) \sim R^D$$

D = the fractal dimension and it is < 3.

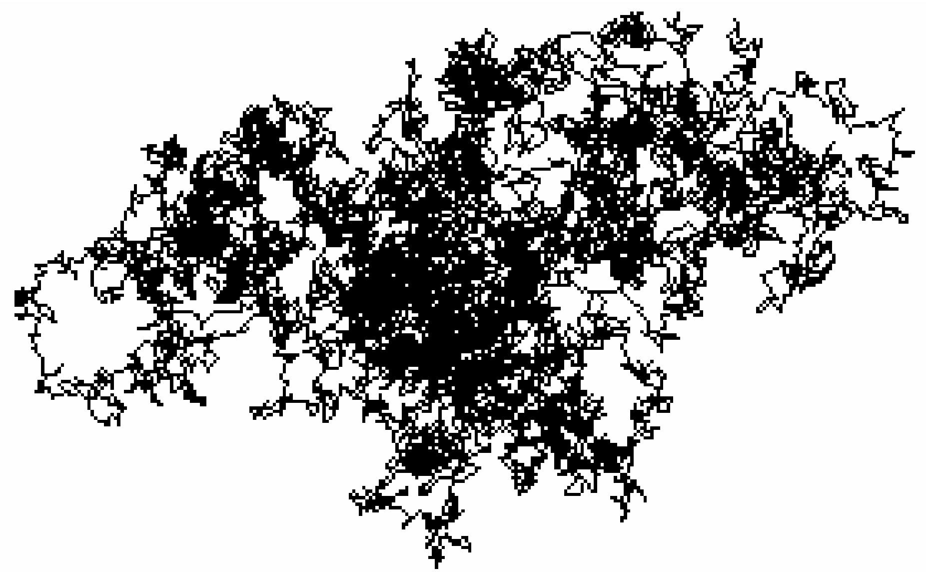
Fractals



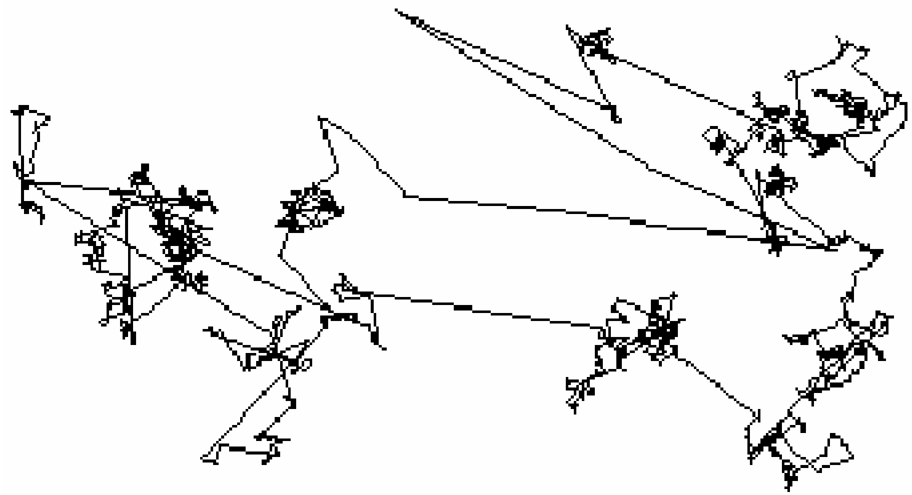


random fractals

Brownian motion



Rayleigh-Levy flight



The Rayleigh-Levy flight

Lengths of steps are chosen according to

$$P(l) = \left(\frac{l}{l_0}\right)^{-\alpha} \quad \text{for} \quad l > l_0$$

$$= 1 \quad \text{otherwise}$$

For $\alpha > 2$ the variance $< l^2 >$ is finite.
For $\alpha < 2$ the variance diverges.

The Fractal Dimension

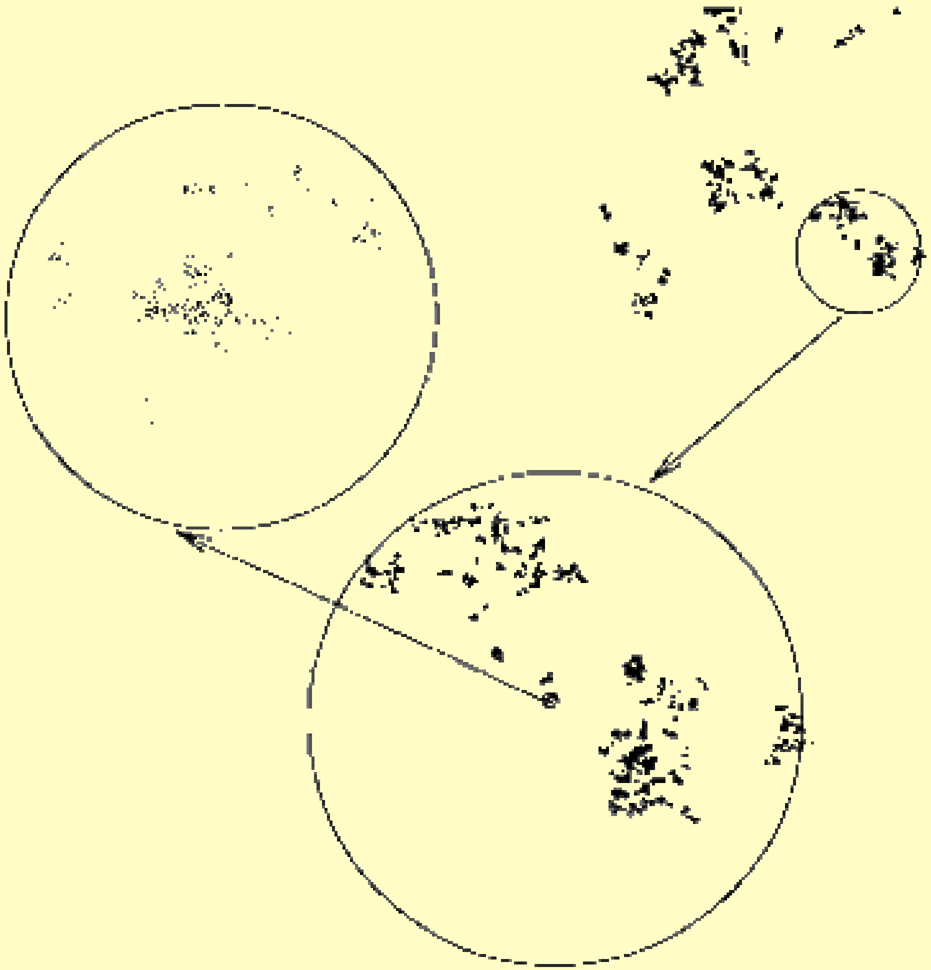
The fractal dimension, D, of a random distribution of points is

$$N(< R) \sim R^D$$

The fractal dimension of a Rayleigh-Levy distribution $(P(l) \sim l^{-\alpha})$ is

$$D = \alpha < 3.$$

A fractal Universe!?



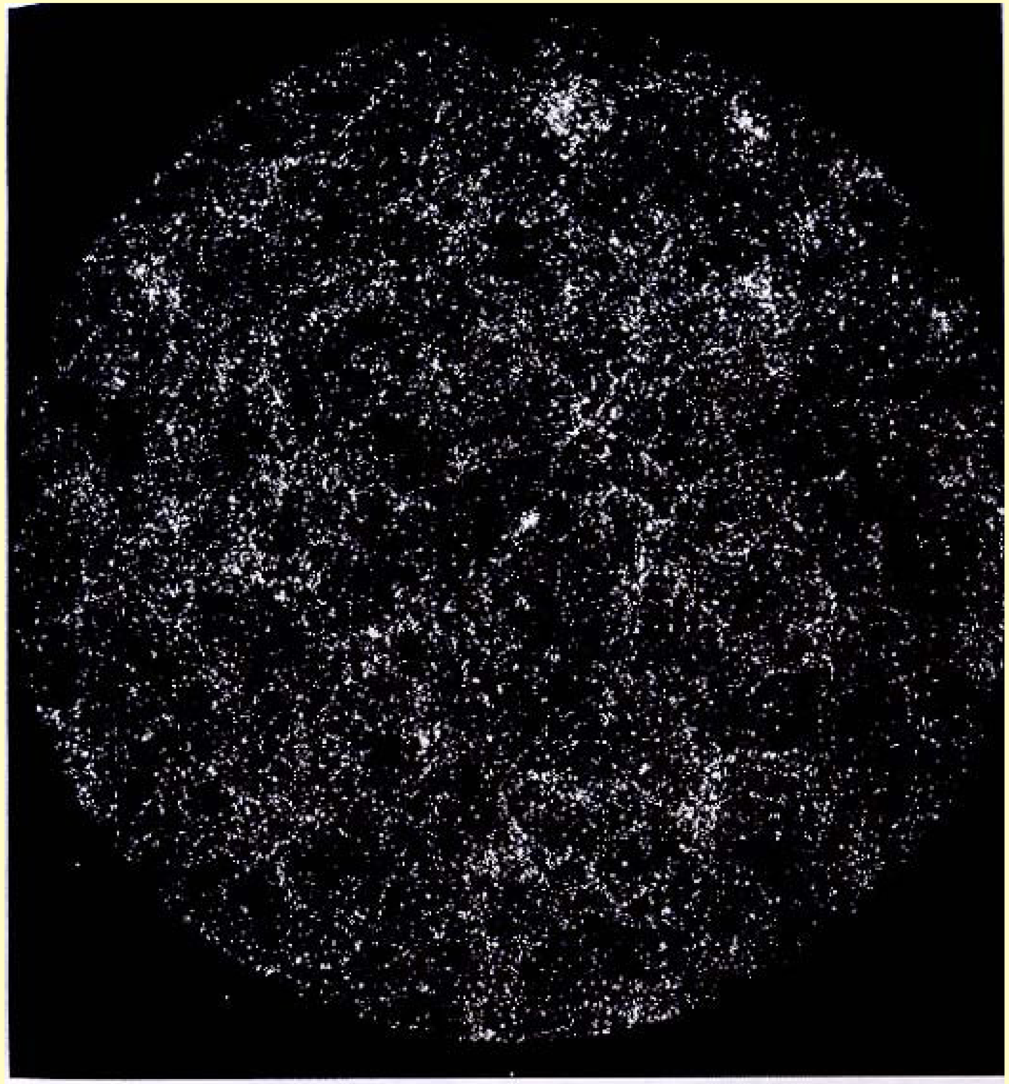
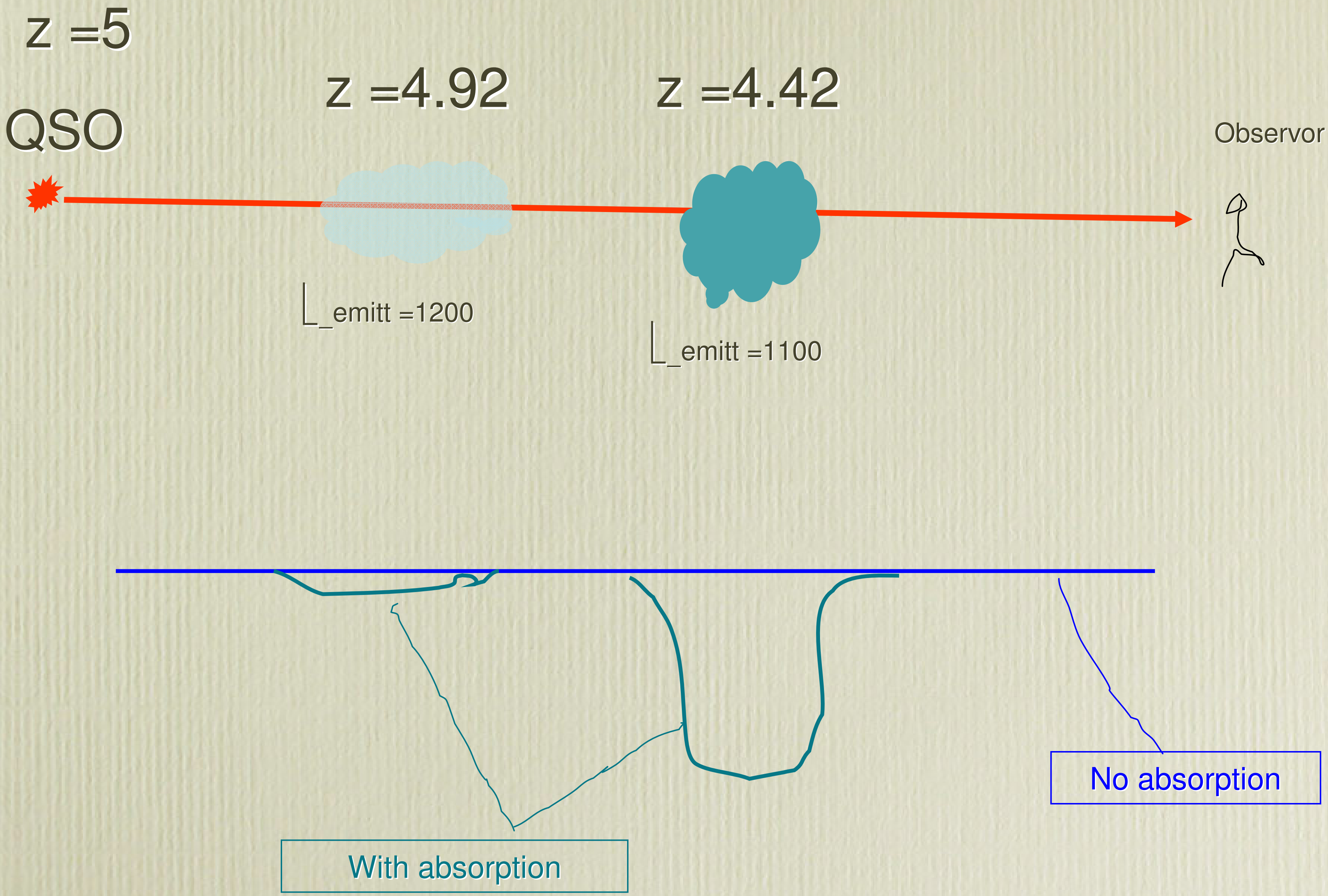
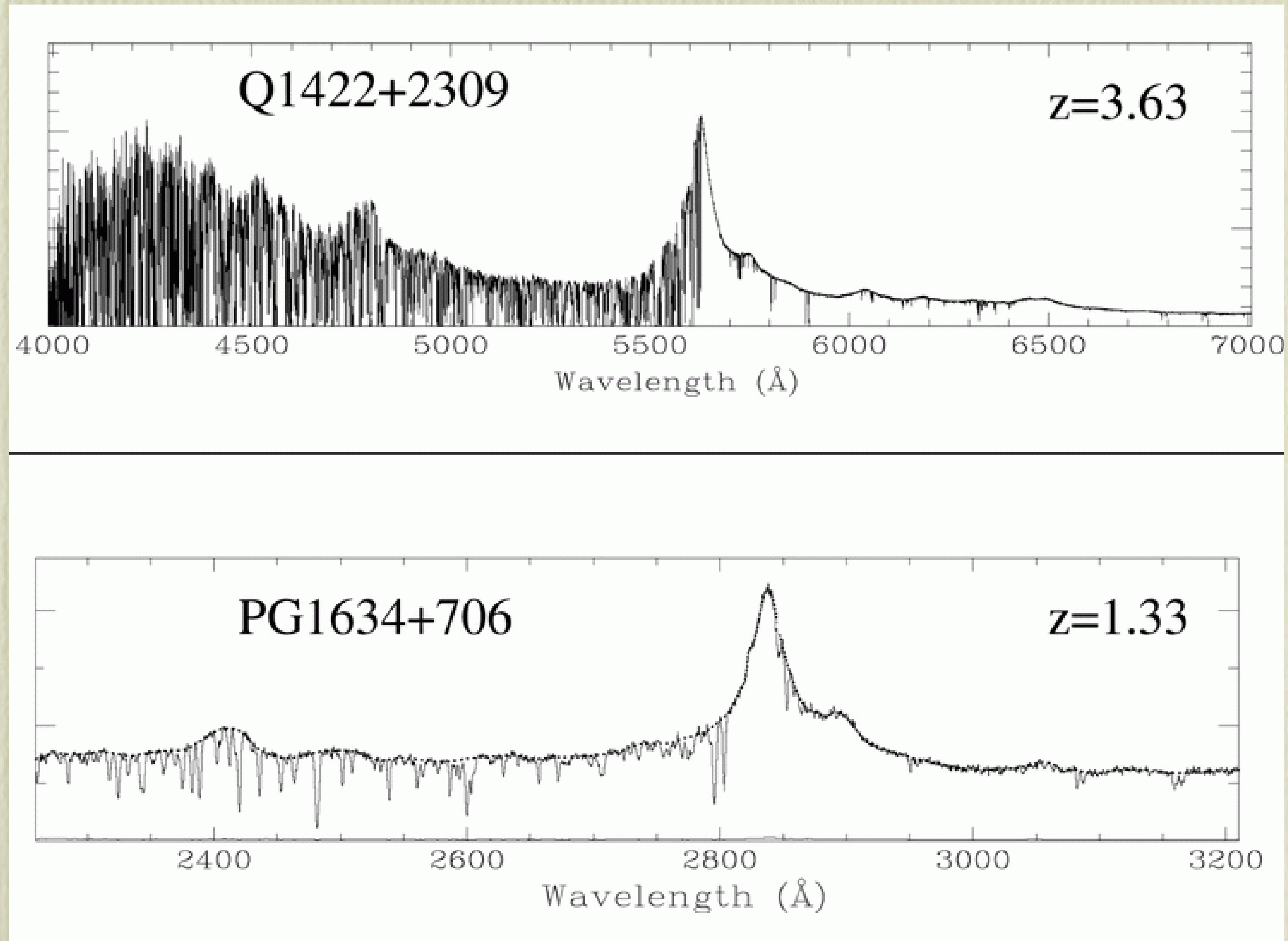


Figure 3.9. The Lick galaxy counts in a circle of radius 50° centered on the north galactic pole (Seldner et al. 1977).

QSO spectra as cosmological probes


z =5
QSO
z =4.92
z =4.42
Observor
L_emitt =1200
L_emitt =1100
With absorption
No absorption


Q1422+2309
z=3.63
4000
4500
5000
5500
6000
6500
7000
Wavelength (Å)
PG1634+706
z=1.33
2400
2600
2800
3000
3200
Wavelength (Å)

Physics of the forest

- In the post-reionization universe, a background of UV radiation forms. This background maintains a tiny HI fraction in the moderate density intergalactic medium.

- The (tiny) neutral hydrogen fraction is determined by photoionization-recombination equilibrium

- Gas traces the dark matter on scales larger than the Jeans scale $\Rightarrow \quad n_{H}(x) \propto \rho_{dm}(x)$

- Putting it the physics together $\rightarrow \quad n_{HI} = \propto \rho_{dm}^{2}$

- The observations provide, F, the amount of light absorbed by intervening HI along the line-of-sight to the QSO. The quantity F is given by

$$F = \exp(-\tau)$$

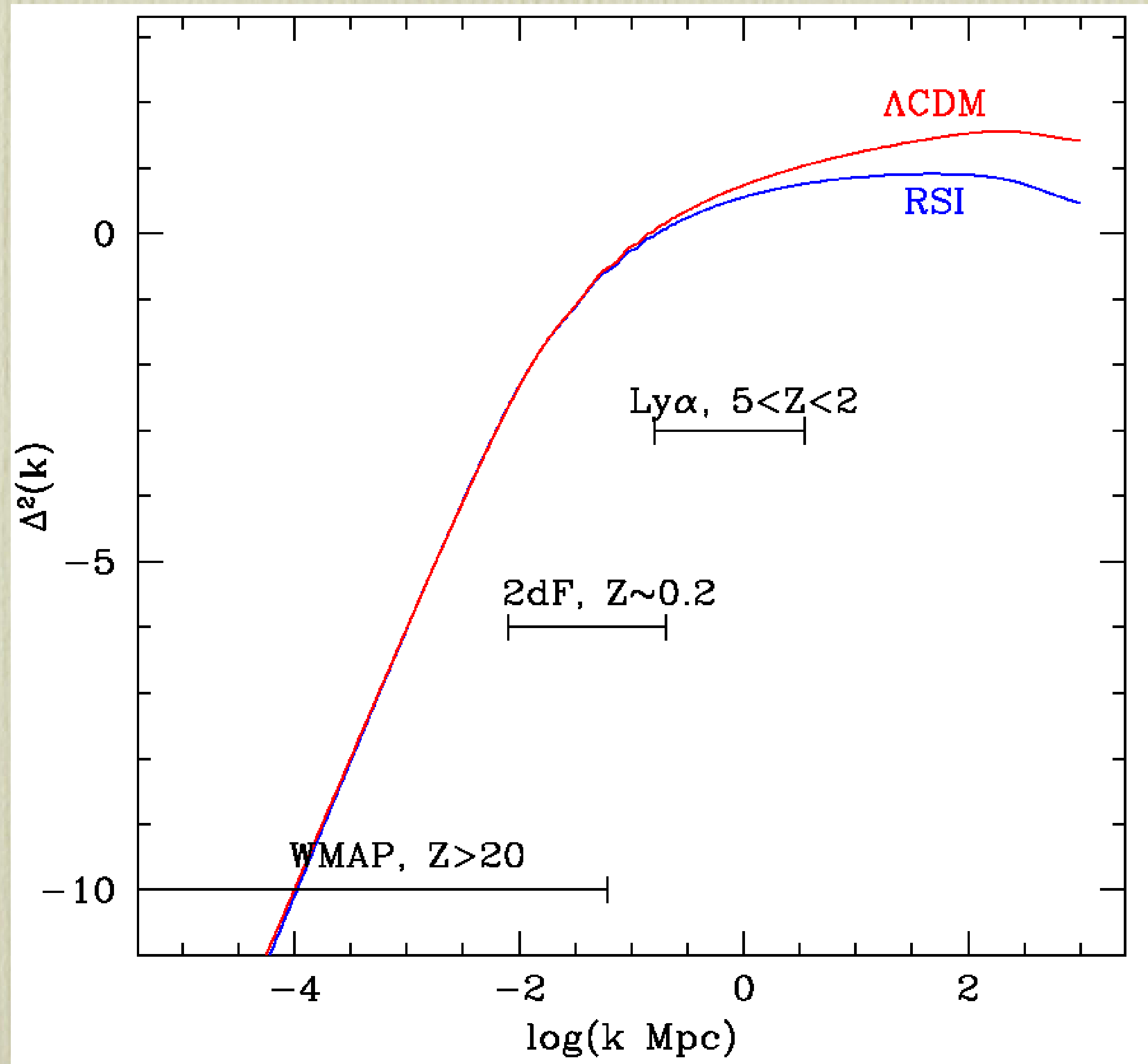
where $\tau \approx A n_{HI}$.

Why QSO spectra?

The Lyα absorption features are

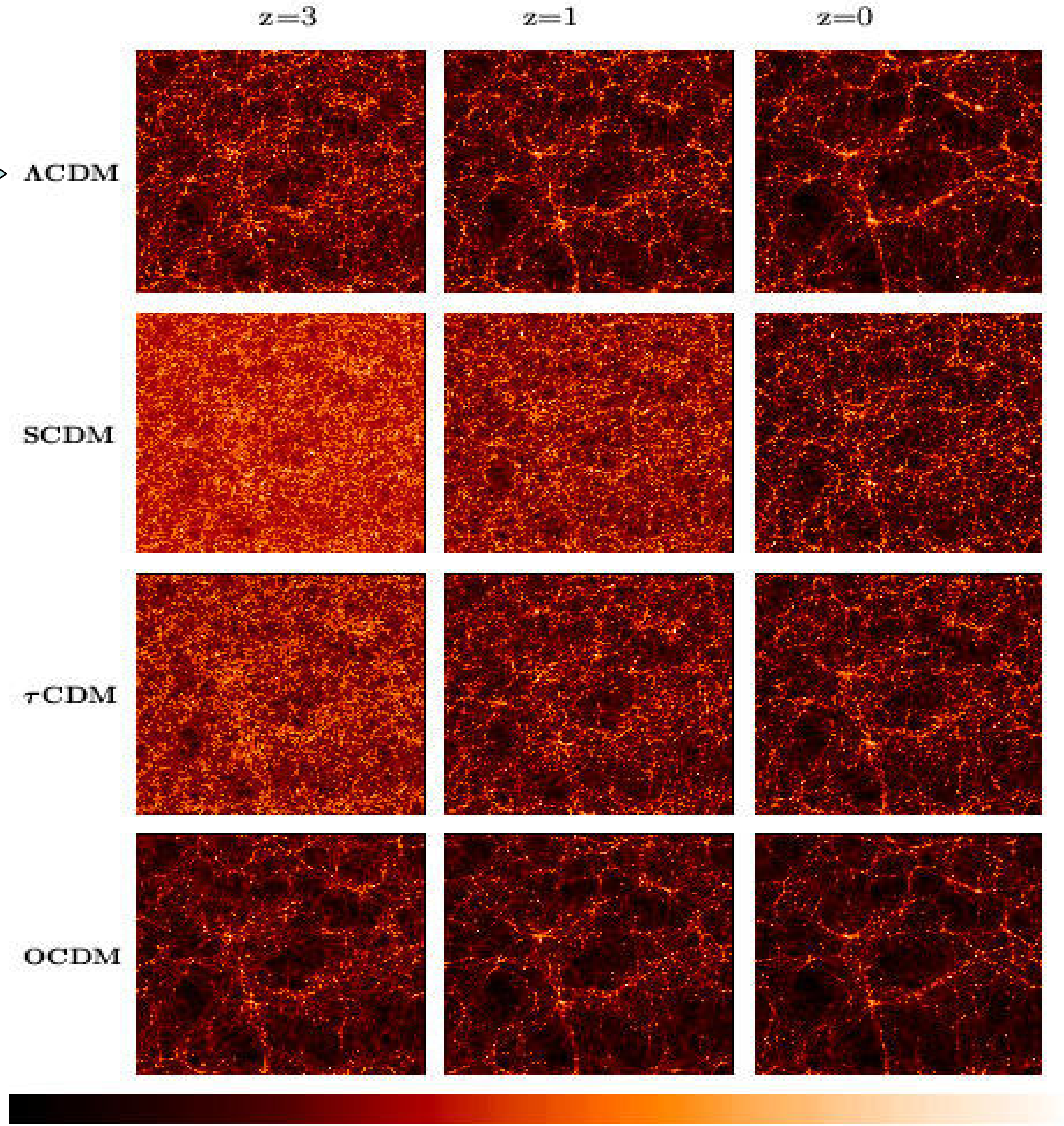
- not affected by selection effects like galaxy surveys
- trace a continuous distribution of matter
- relatively simple physics
- are available at a wide range of redshifts

Models, scales, redshifts



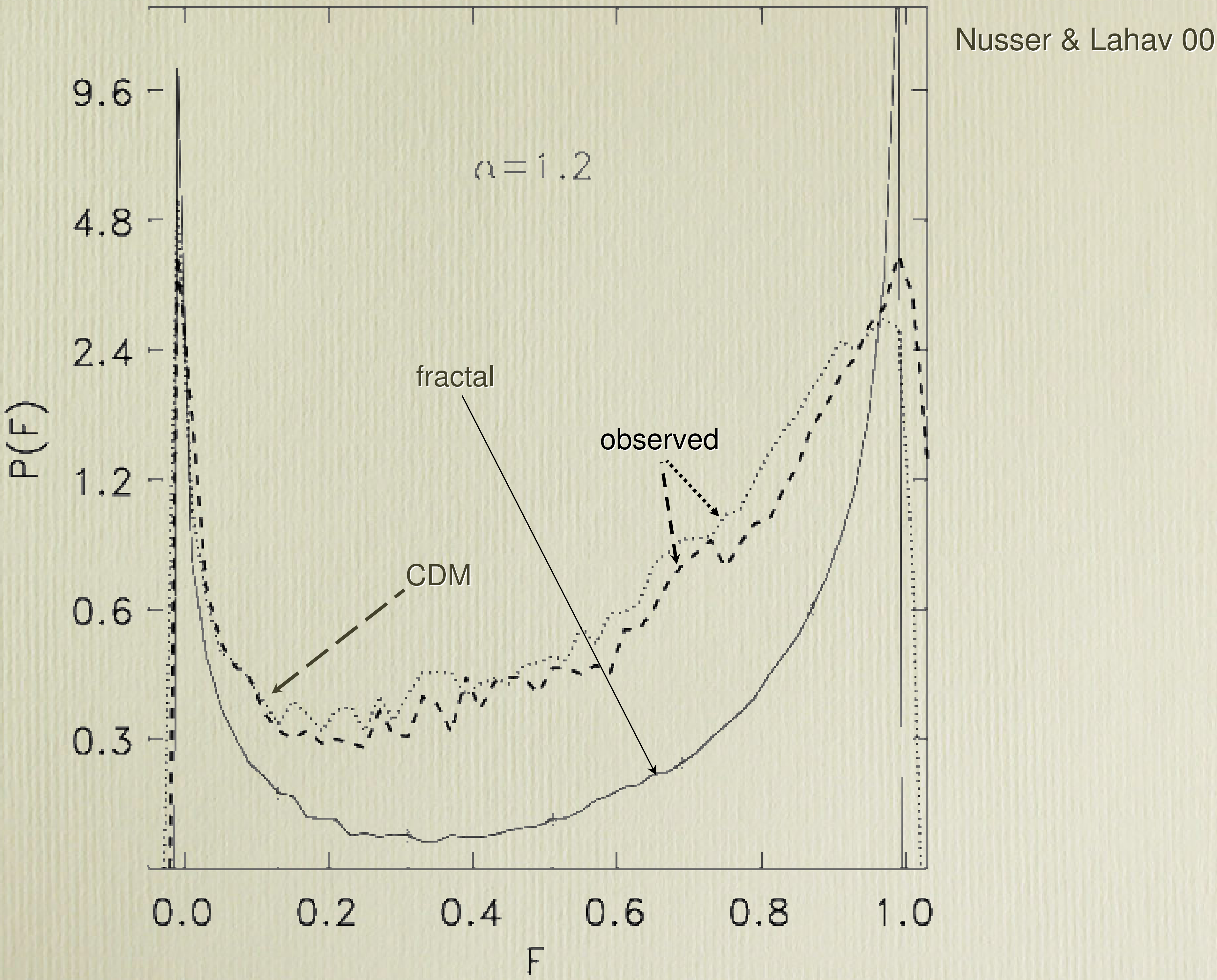
ignorance

Vacuum energy dominated universe



The VIRGO Collaboration 1996

Let $P(F)$ be the distribution function of F.

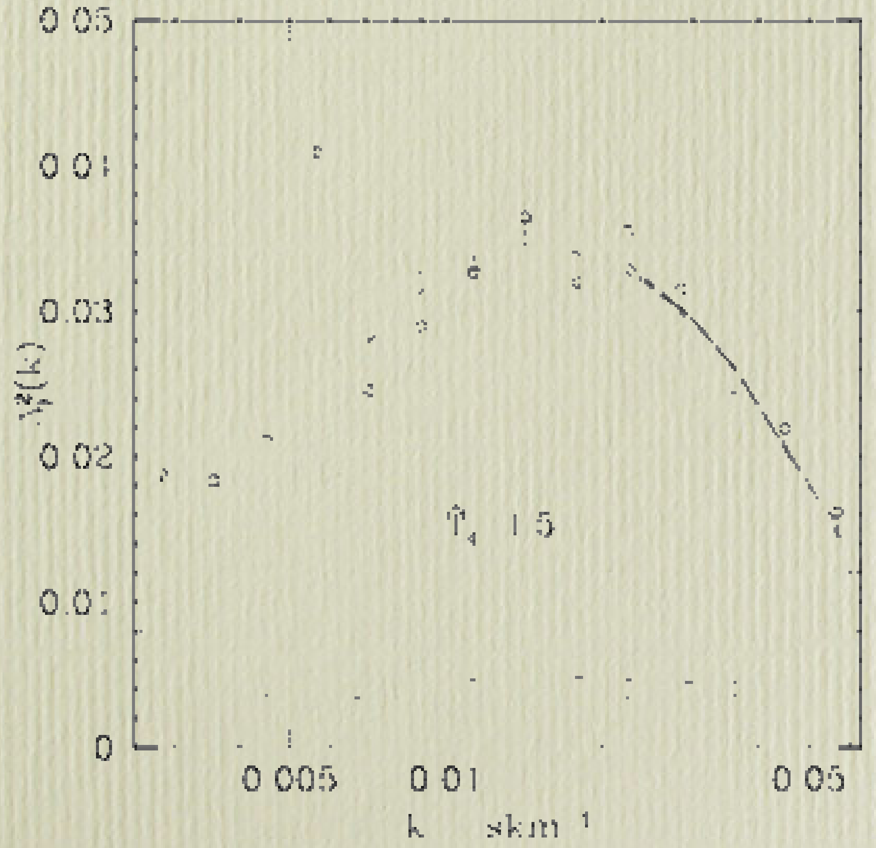


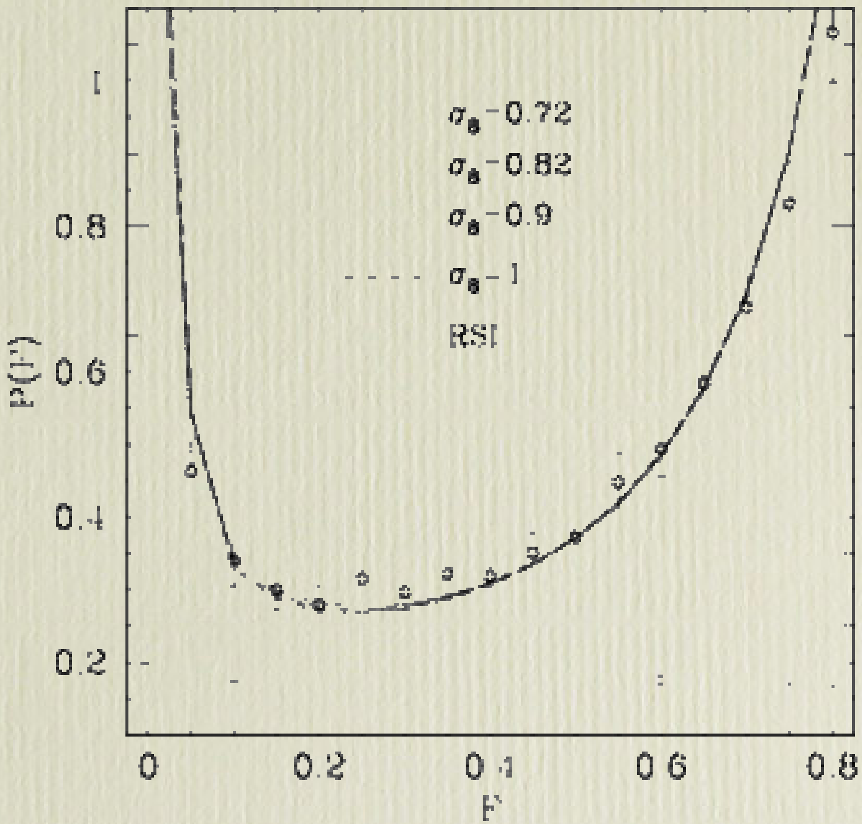
Nusser & Lahav 00
α=1.2
fractal
observed
CDM
P(F)
9.6
4.8
2.4
1.2
0.6
0.3
0.0
0.2
0.4
0.6
0.8
1.0
F

Joint modelling of the probability distribution function and power spectrum of the Lyα forest: comparison with observations at $z = 3$

Vincent Desjacques[1]* and Adi Nusser[1,2]*

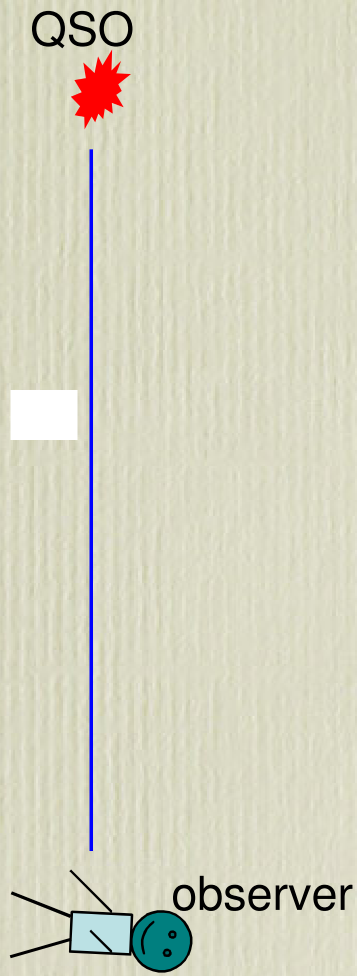
Our joint analysis suggests that σ_8 is likely to be in the range 0.7–0.9 for a temperature $1 \times 10^4 \lesssim T \lesssim 2 \times 10^4$ K and a reasonable reionization history.





The environment of galaxies: galactic winds

QSO spectra are ideal for studying the environment of galaxies



The impact of galactic winds from Lyman-break galaxies on the intergalactic medium

Vincent Desjacques,[1]* Martin G. Haehnelt[2] and Adi Nusser[1]

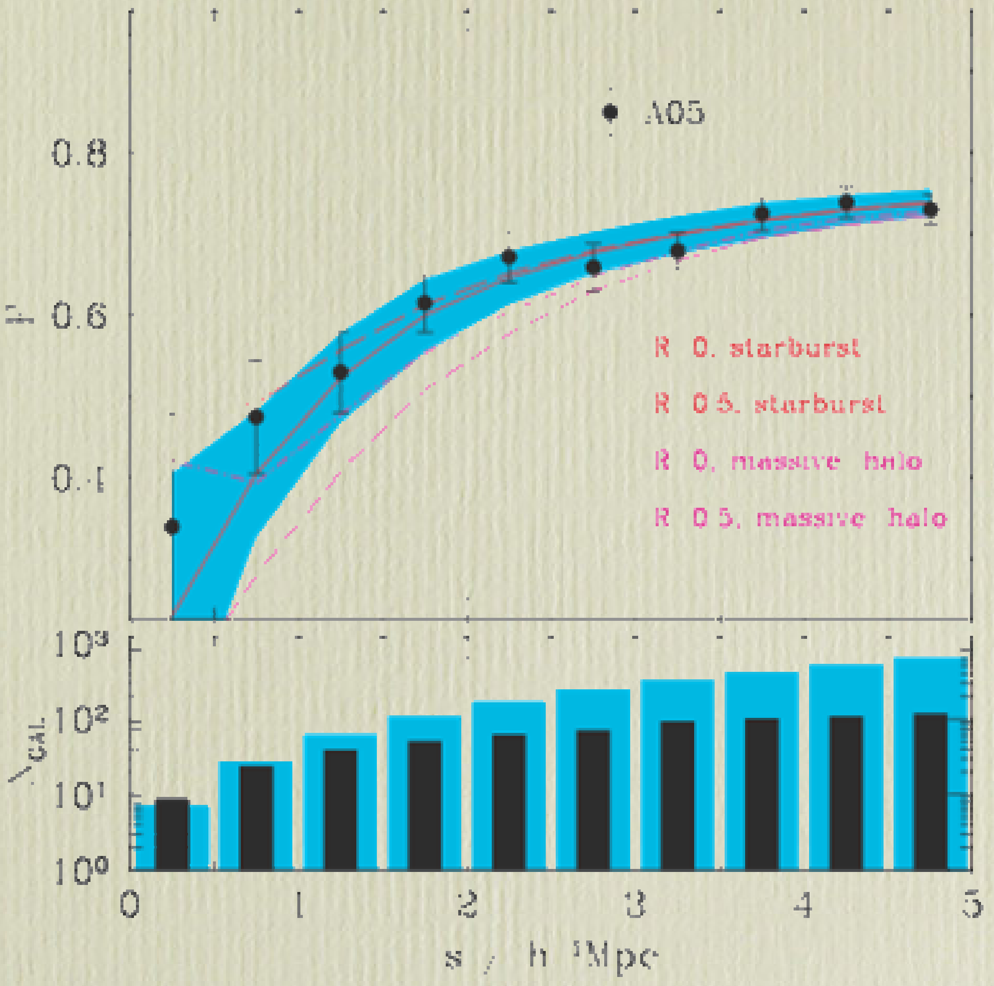


Figure 1. The mean flux $\bar{F}$ as a function of the distance s to the nearest halo in the starburst and massive-halo models for bubble radii of 0 and 0.5 h^{-1} Mpc (top panel). The horizontal dashed line shows the mean transmissivity $\langle f \rangle = 0.765$ of the observed sample. The blue shaded area is our cosmic variance estimate for the model without galactic winds calculated from the cumulative distribution N_{GAL} shown as the light (blue) histogram at the bottom. The filled symbols (top) and the dark bars (bottom) show $\bar{F}$ and N_{GAL} of the observed sample of A05.

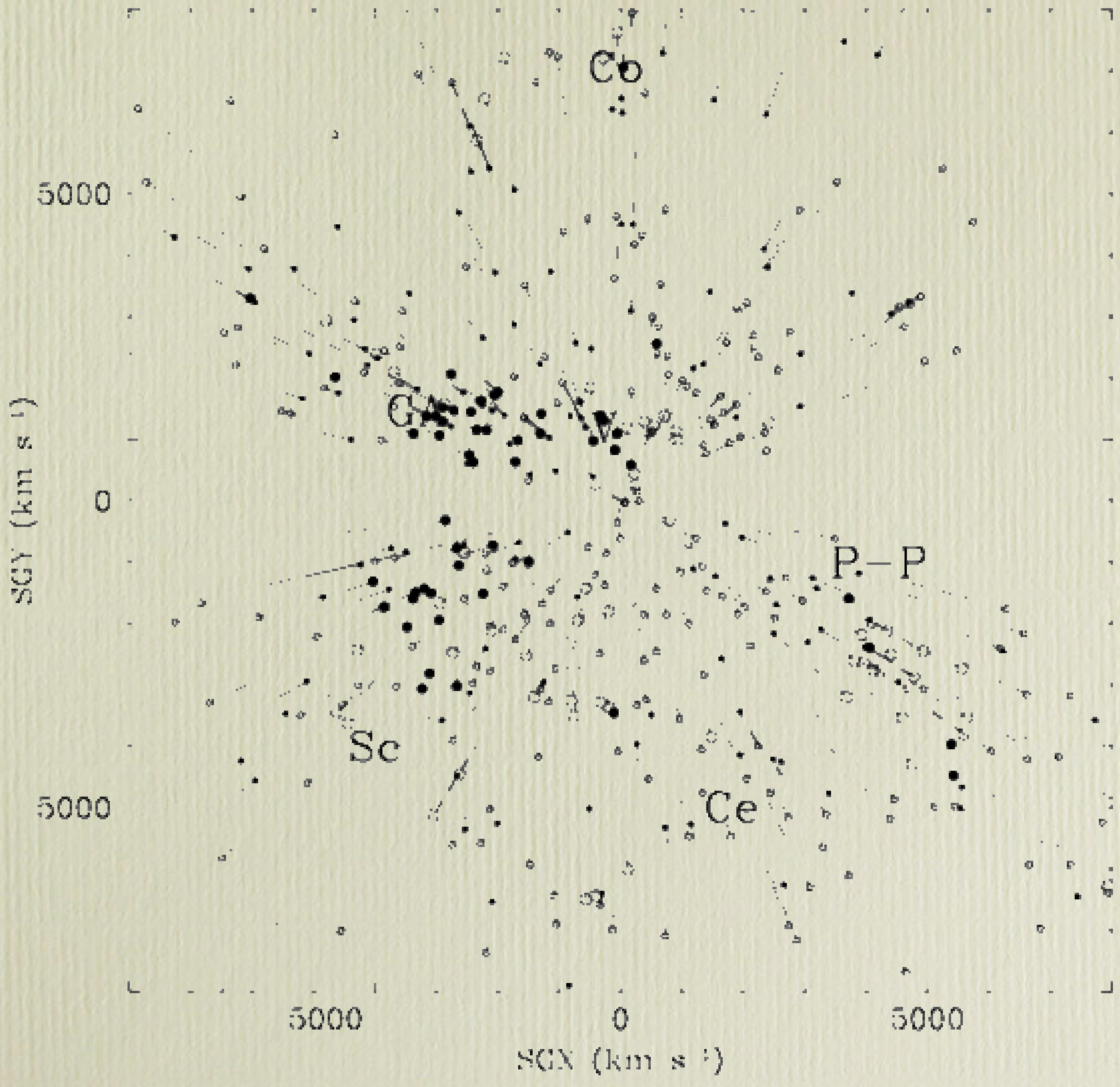
Large scale motions

Cosmic inhomogeneities formed by gravitational amplification of tiny initial conditions. During this process matter moves from voids to regions of positive density contrast.

QuickTime™ and a
decompressor
are needed to see this picture.

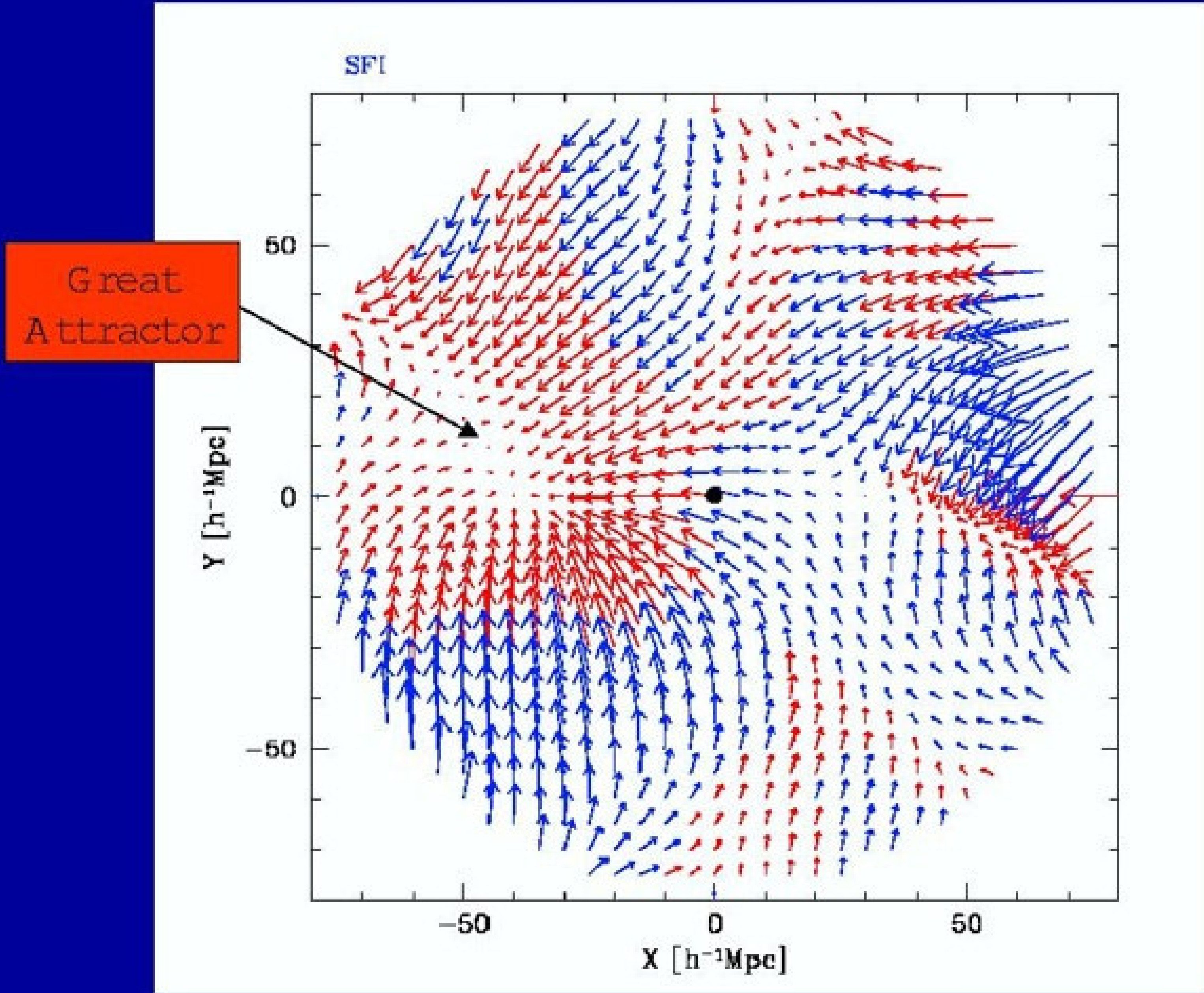
The deviations from a pure Hubble flow are called peculiar motions. The (peculiar) motions seen in the simulations have their counterpart in reality.

Mark III Velocity Field in Supergalactic Plane: CMB Frame



Dekel, Bertschinger, Faber

Cosmic Flows - POTENT



peculiar velocities

The total line-of-sight velocity of a galaxy is

$$V_{tot} = Hd + v$$

v = the peculiar velocity along the line-of-sight to the galaxy.

The Doppler shift readily gives us the total velocity

$$z = \frac{\lambda_{obs}}{\lambda_{emit}} - 1 = \frac{V_{tot}}{c}$$

$$\Longrightarrow \boxed{v = cz - Hd}$$

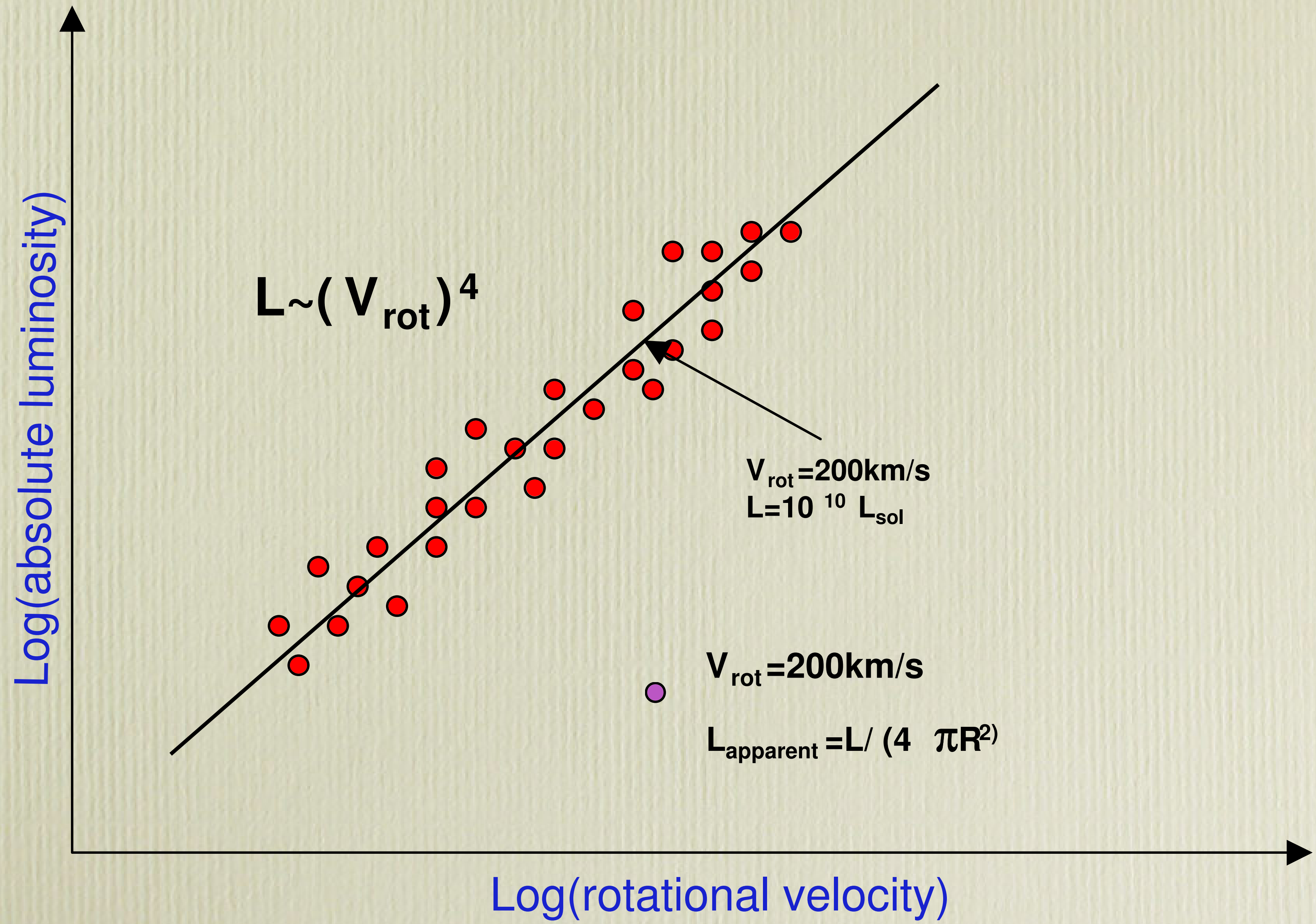
i.e. to get v one needs the distance

Distance measurements

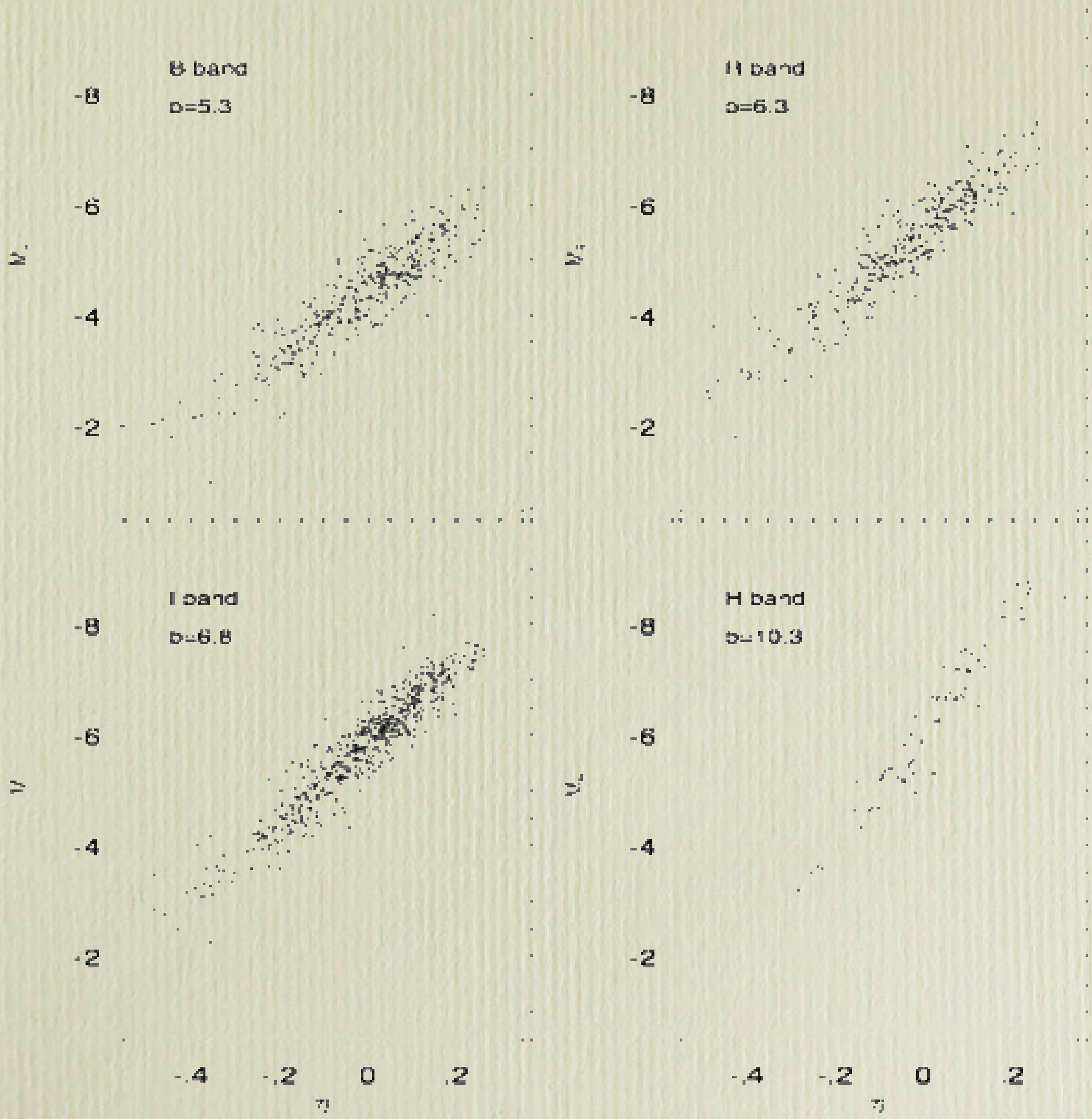
Refs: Lynden-Bell, Faber, Burstein, Davies, Dressler, Terlevich, Wegner 88, ApJ; Strauss & Willick 95, Ph.Rep

Distances can be estimated using empirical relations between intrinsic properties of galaxies. For spirals: the Tully-Fisher relation. For ellipticals: the $D_n - \sigma$ relation.

The Tully-Fisher relation



Tully-Fisher Relations in 4 Bands



What can we do with peculiar velocities?

- Comparisons of velocities with predictions of models (e.g. CDM). One important statistics is the bulk motion as a function of distance.
- Comparisons with velocities obtained from galaxy surveys.

Bulk Motions of Spiral Galaxies

Yu.N.Kudrya[1], V.E.Karachentseva[1], I.D.Karachentsev[2], S.N.Mitronova[2] and W.K.Huchtmeier 2005

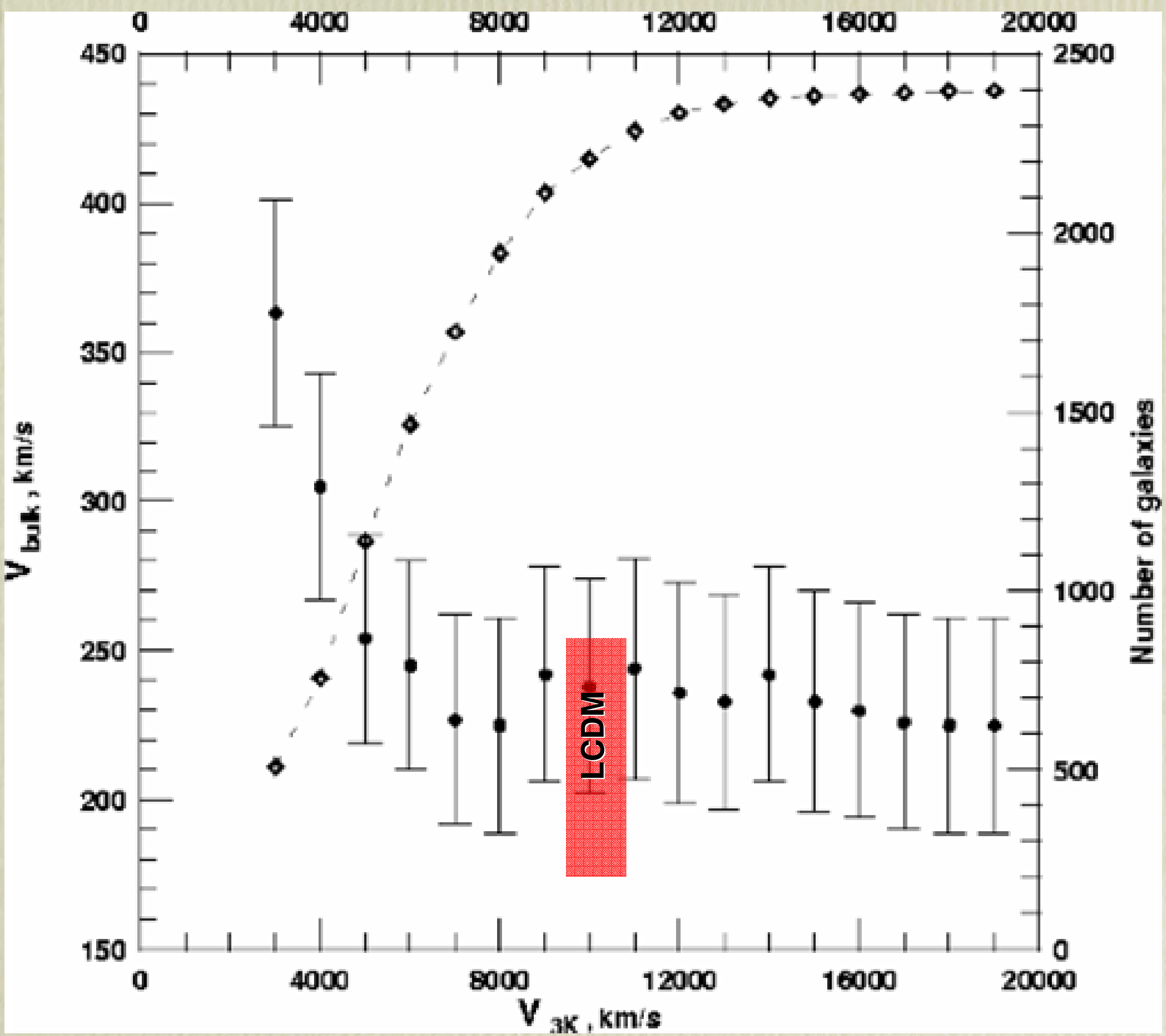
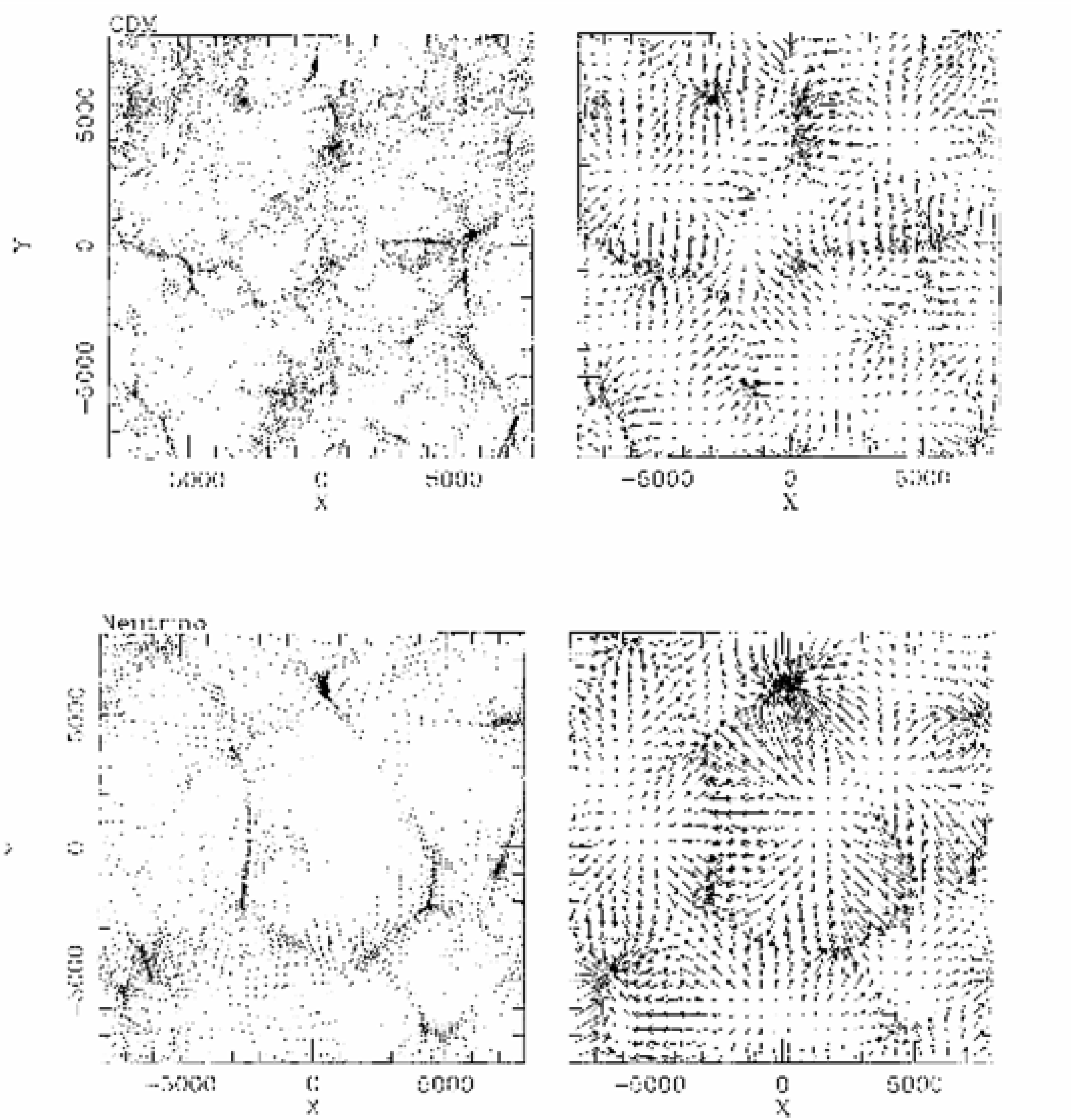
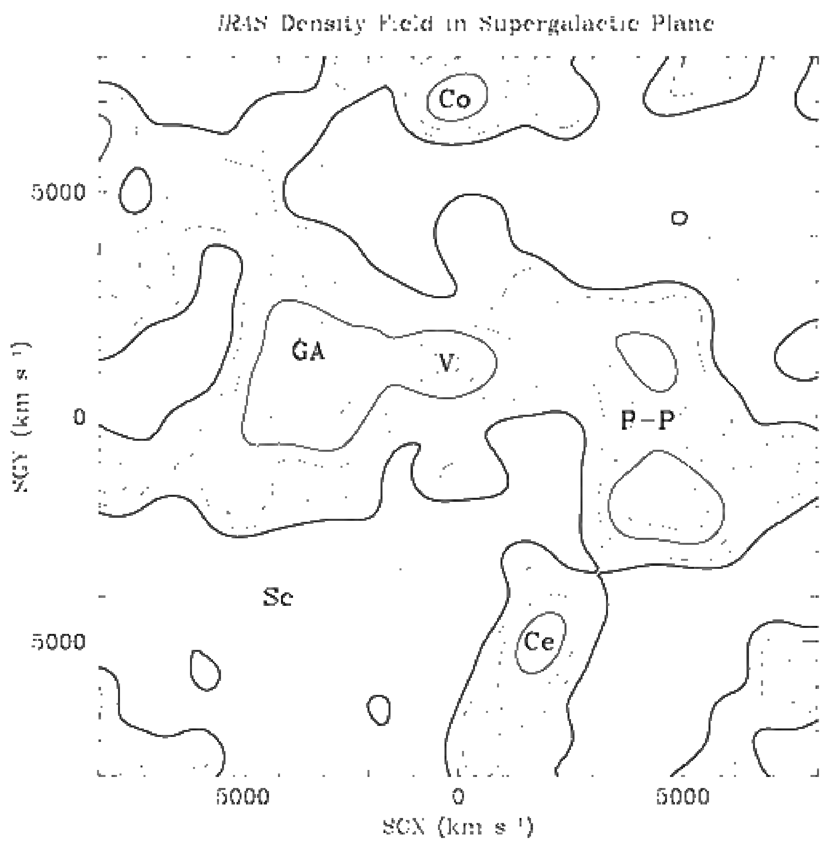
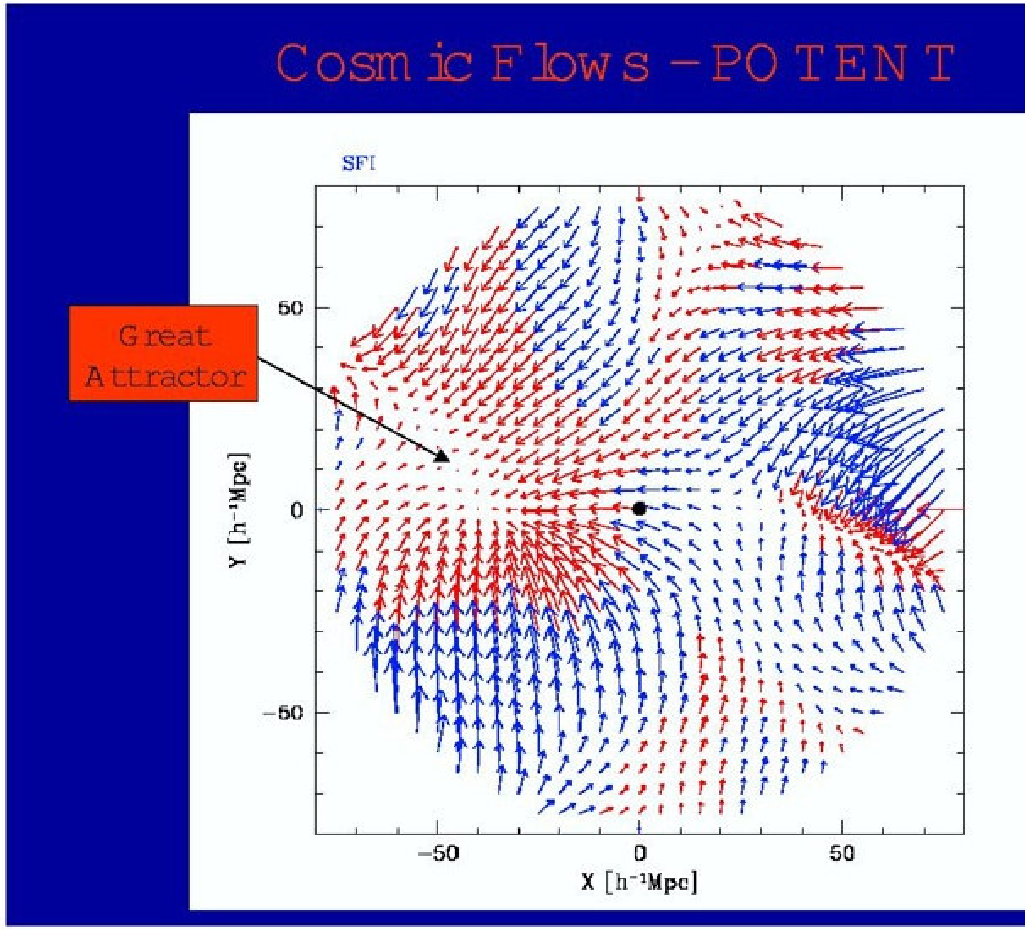


Figure 4: Magnitude of the bulk velocity (dots with bars, left vertical scale) versus depth and the sample size to a given depth (open diamonds, right vertical scale).

Velocity from particle distribution




IRAS Density Field in Supergalactic Plane
Co
GA
V
P-P
Sc
Ce
SGY (km s⁻¹)
SGX (km s⁻¹)
5000
0
5000


Cosmic Flows - POTENT
SFI
Great Attractor
Y [h⁻¹Mpc]
X [h⁻¹Mpc]
50
0
-50

Lets discuss now in some detail how to get the velocity from a given particle distribution.

Dynamics

The dynamics of gravitationally interacting particles in an expanding Universe is governed by

$$\frac{\mathrm{d}\mathbf{v}_i}{\mathrm{d}t} + H\mathbf{v}_i = \mathbf{g}_i$$

$$\mathbf{g}_i = \frac{G}{a^2}\sum_j m_j \frac{\mathbf{x}_j - \mathbf{x}_i}{|\mathbf{x}_j - \mathbf{x}_i|^3} + \frac{4}{3}\pi G\bar{\rho}a\mathbf{x}_i$$

- $\mathbf{x} = \mathbf{r}/a$ = comoving coordinate
- $H = \dot{a}/a$ is the Hubble function

Velocity from density according to linear theory

This theory is valid when the matter distribution is still nearly uniform. Assume straight orbits $\Rightarrow$

$$\mathbf{v}_i = b(t)\mathbf{v}_0$$

$$\Rightarrow \qquad \mathbf{v}_i = t\mathbf{g}_i\, c(t)$$

The exact relation is $\boxed{\mathbf{v}_i = \frac{2}{3}\frac{f(\Omega,\Lambda)}{H\Omega}\mathbf{g}_i}$ $\quad \Omega = \frac{\rho}{\bar{\rho}}$ and $f(\Omega,\Lambda) \approx f(\Omega) \approx \Omega^{0.6}$

Linear theory

$$\mathbf{v}_i = \frac{2}{3}\frac{f(\Omega,\Lambda)}{H\Omega}\mathbf{g}_i$$

where

$$\Omega = \frac{\rho}{\bar{\rho}} \quad \text{and} \quad f(\Omega,\Lambda) \approx f(\Omega) \approx \Omega^{0.6}$$

Remarks:

- If $\Omega = 1$, then $H = 2/3t \Rightarrow \mathbf{v}_i = t\mathbf{g}_i \quad (\text{for} \quad \Omega = 1)$
- $\mathbf{g} \sim \Omega$ for a given particle distribution $\Rightarrow \mathbf{v}_i \sim f(\Omega)$.

Results of the $v - v$ comparison

from the TF relation)

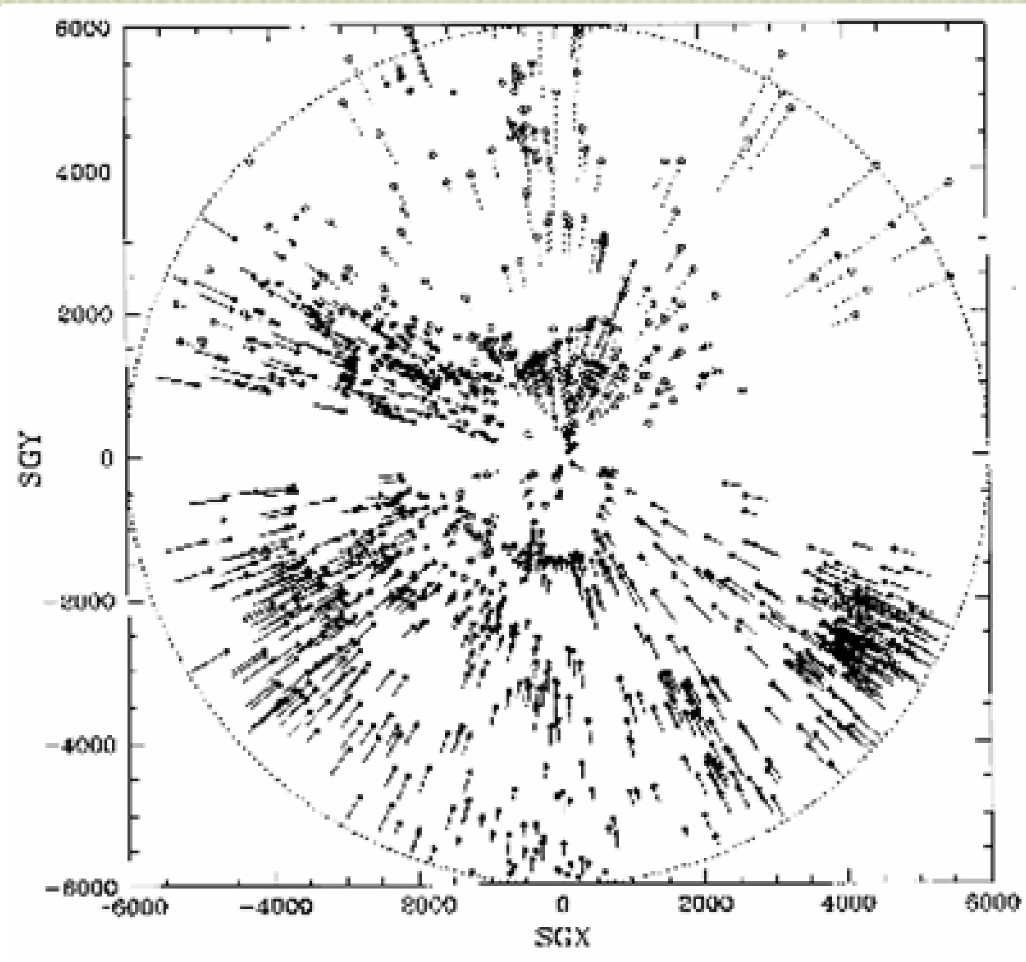


FIG. 9. The ITF velocity field u_{ITF} for Mark III galaxies within 30° of the supergalactic plane, using the same notation as in Fig. 3.

from the galaxy distribution

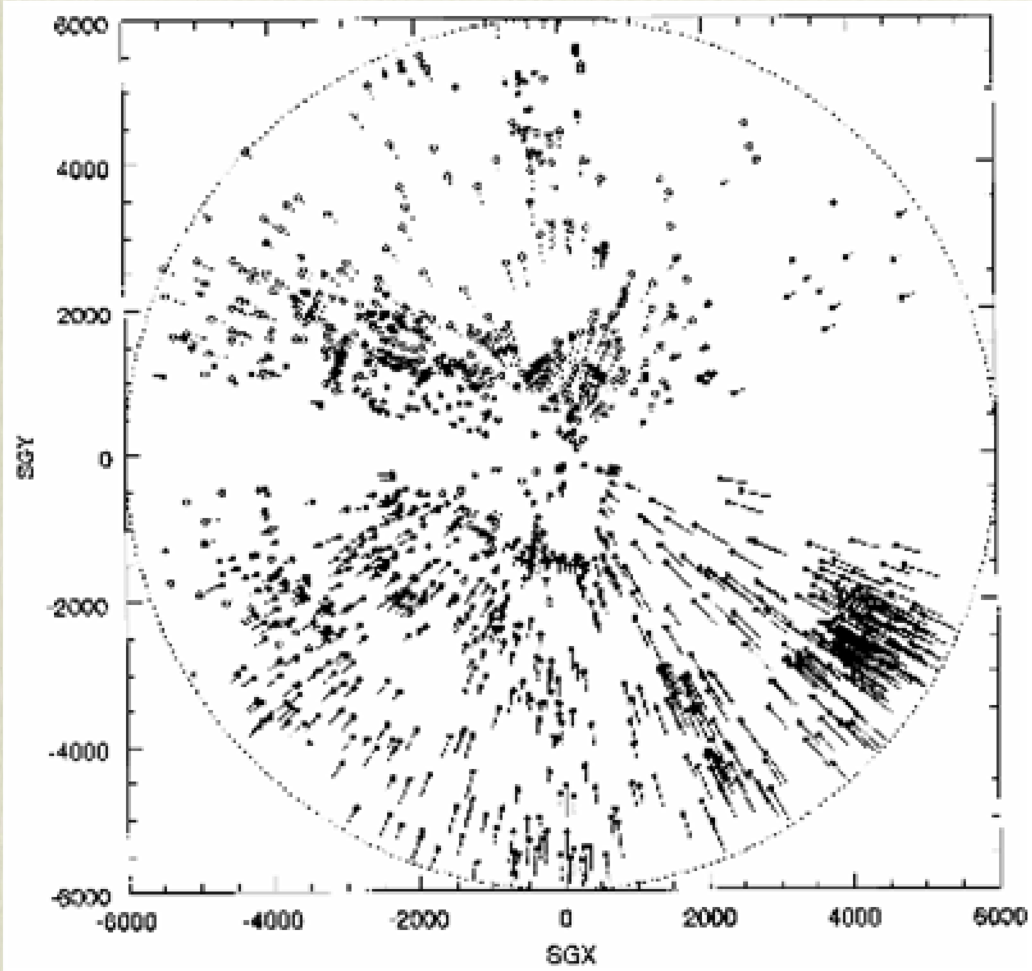
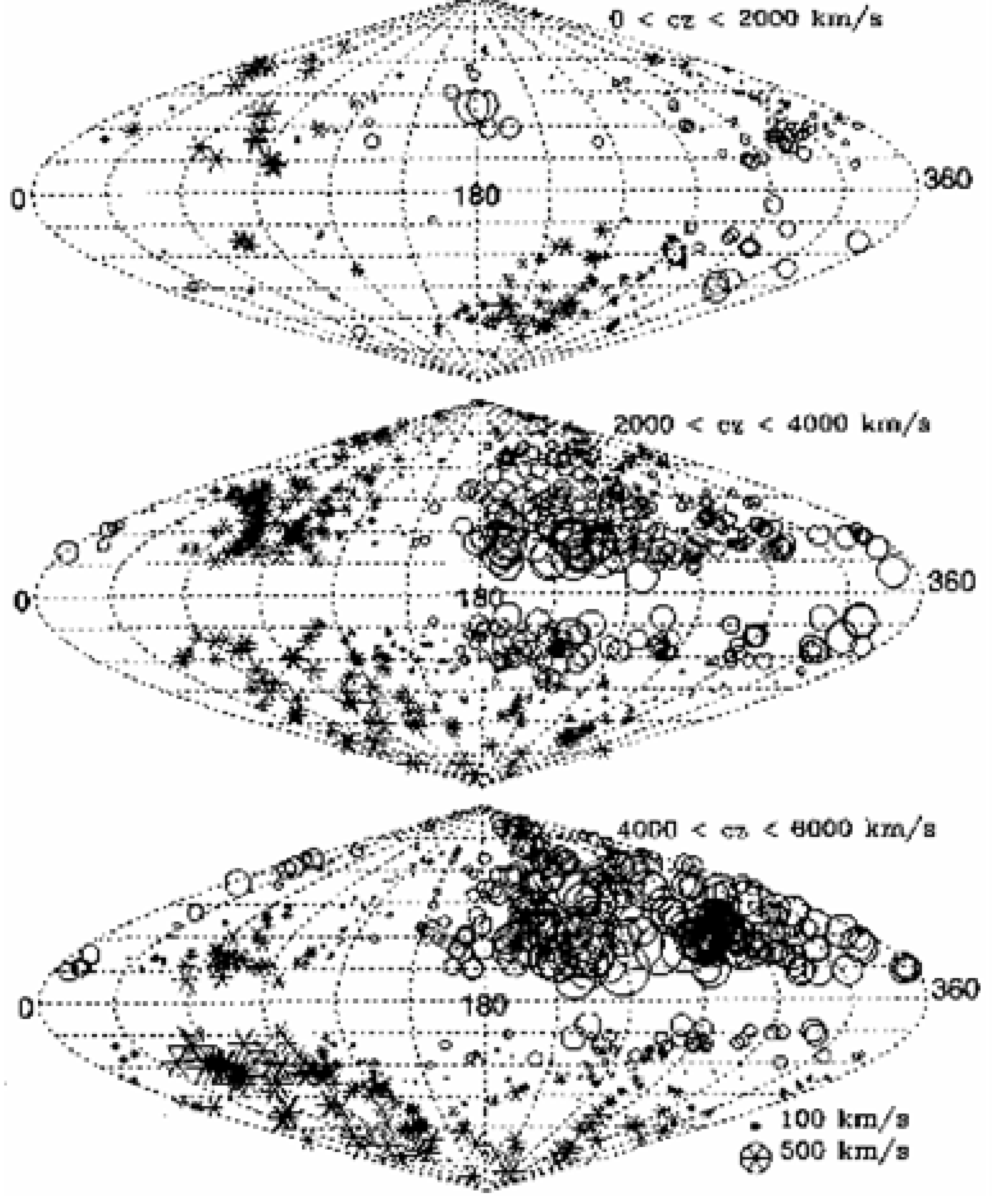
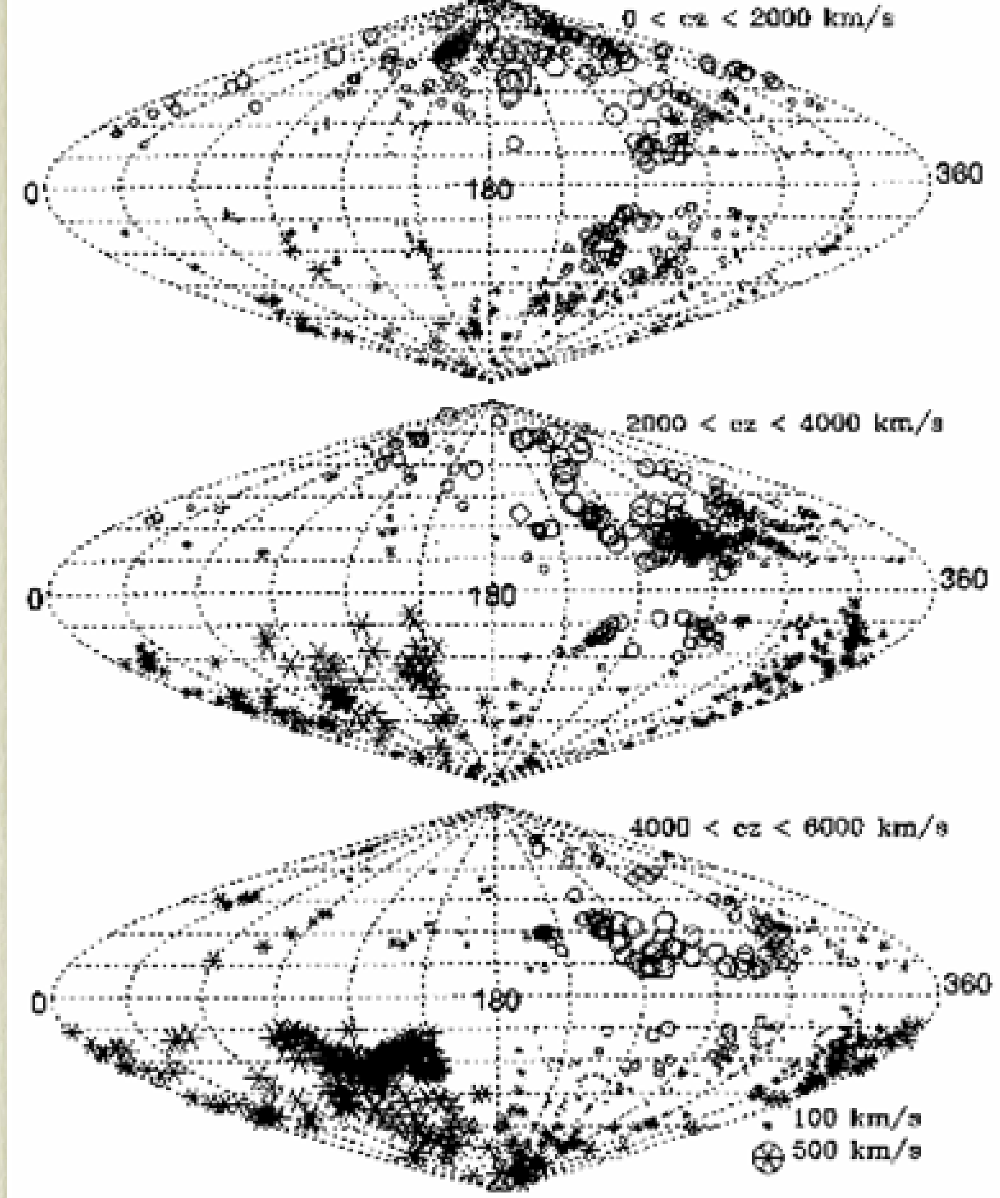


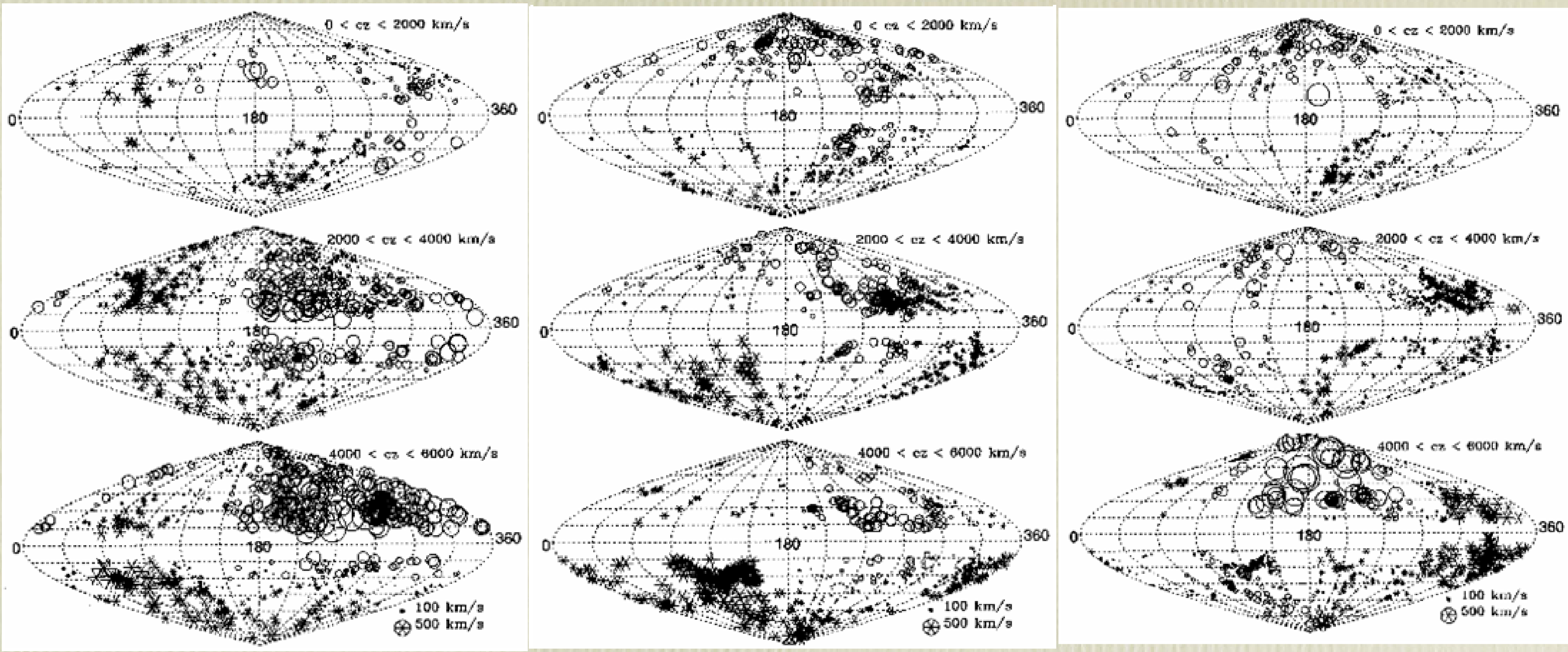
FIG. 11. The supergalactic plane projection for the *IRAS*-predicted flow field u_{iras} for $\beta = 0.4$ for the Mark III galaxies.



The u_{icr} sky projection as seen in the LG frame for the Mark III catalog, in galactic coordinates. The open circles are points that are flowing inward, and the stars are points flowing outward. The size of the symbols is proportional to the flow velocity, with a key showing 500 km s^{-1} flow. Note the three separate panels of redshift interval. Note also the dominance of the dipole mode, especially for the outer shell. This is the signature of the reflex motion of the LG.



The sky projection of the *IRAS*-predicted flow field u_{iras} for $\beta = 0.4$ for the Mark III galaxies.



The sky projection of the residuals $u_{tf} - u_{iras}$ for $\beta = 0.4$

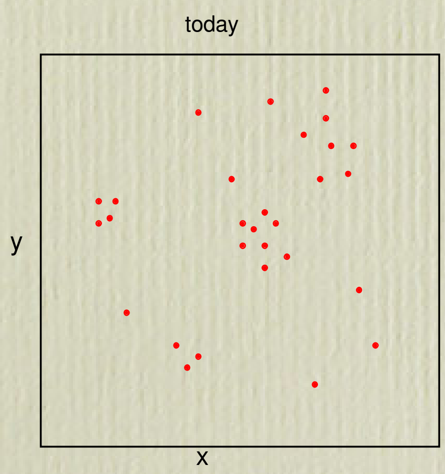
Velocity from density in the nonlinear regime

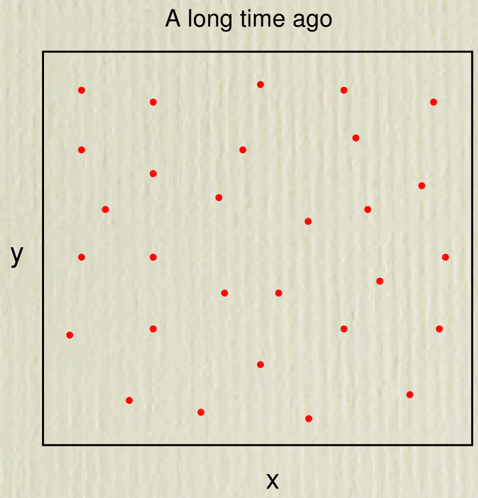
Refs: Peebles 89; Nusser & Branchini 02; Phelps, Desjacques & Nusser 06

Many data sets will probe the mildly nonlinear regime. One needs appropriate methods to deal with these nonlinearities.

The most general approach is to solve the full equations of motion given

1. the positions today
2. homogeneity at some initial time (very high redshift).





This is a boundary value problem!

A boundary value problem may have multiple solutions.

Example: consider a harmonic oscillator

$$\ddot{x} + \omega^2 x = 0$$

Problem: find $x(t)$ such that $x(0) = 0$ and $x(2\pi/\omega) = 0$

Solution 1: $x(t) = 0$ for all t

Solution 2: $x(t) = \sin(\omega t)$

Solution 3: $x(t) = 2.1872\sin(\omega t)$

Numerical schemes to the boundary value problem

All solutions fail in the highly nonlinear regime such as in virialized regions.

In an expanding Universe, initial homogeneity is guaranteed if $\mathbf{v} \sim \mathbf{v}_0 t^{1/3}$ as $t \to 0$. Therefore, the problem is to find orbits such that

$$\mathbf{x}_i(t = t_0) = \mathbf{x}_{i0}$$

and

$$\mathbf{v}_i(t) \propto t^{1/3} \quad \text{for} \quad t \to 0$$

Direct solution by matrix inversion: schematic description only!

$$\dot{v} = F(x) \qquad\qquad \dot{x} = v$$

In discrete form corresponding to time steps: $t^n = n\delta t$

$$v^{(2)} = v^{(1)} + F[x^{(1)}]\Delta t \quad ; \quad x^{(2)} = x^{(1)} + \frac{v^{(2)} + v^{(1)}}{2}\Delta t$$

$$v^{(3)} = v^{(2)} + F[x^{(2)}]\Delta t \quad ; \quad x^{(3)} = x^{(2)} + \frac{v^{(3)} + v^{(2)}}{2}\Delta t$$

$$\cdots$$

$$\cdots$$

$$\cdots$$

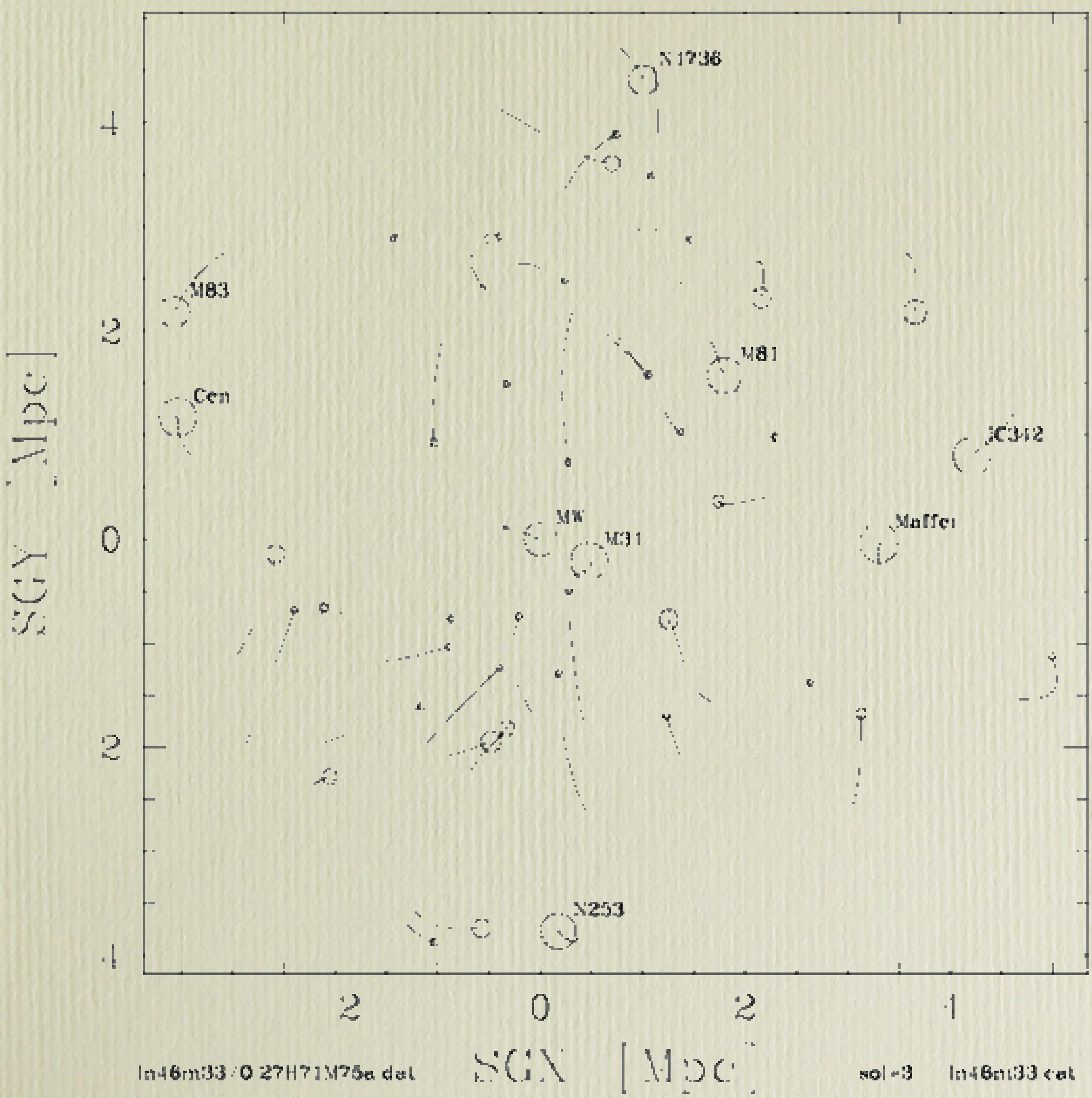
$$v^{(N)} = v^{(N-1)} + F[x^{(N-1)}]\Delta t \quad ; \quad x^{(N)} = x^{(N-1)} + \frac{v^{(N)} + v^{(N-1)}}{2}\Delta t$$

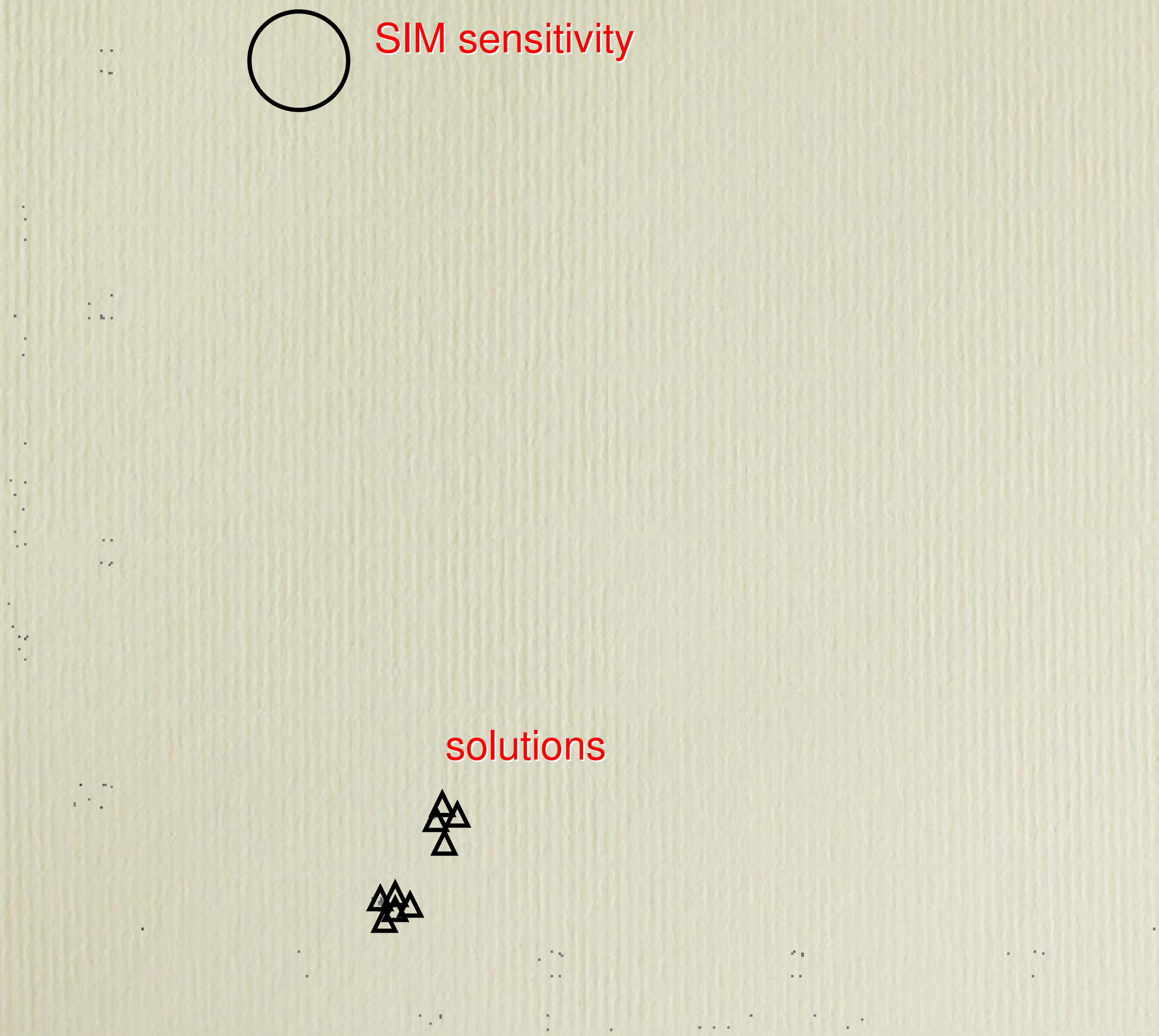
In a boundary value problem: $x^{(N)}$ and $v^{(1)}$ are known. A solution can be found by recasting the problem in terms of boundary conditions.

In an initial value problem: $x^{(1)}$ and $v^{(1)}$ are known. The solution is trivial.

One could also minimize the action subject to the appropriate boundary conditions.

$$\left[-v^{(n+1)} + v^{(n)} + F[x^{(n)}]\Delta t\right]^2 \quad ; \quad \left[-x^{(n+1)} + x^{(n)} + \frac{v^{(n+1)} + v^{(n)}}{2}\Delta t\right]^2$$


N1736
M83
M81
Cen
IC342
MW
M31
Maffei
N253
SGY [Mpc]
SGX [Mpc]
ln46m33/0.27H71M75a.dat
sol=3
ln46m33.cat


SIM sensitivity
solutions

Final Remarks

- Peculiar motions in the local universe pose great puzzles. Is it anomalies in the TF in some parts of the sky? Is it complicated biasing?
- Dynamics of the Local Group can provide a test of gravity in the nonlinear regime. Transverse speeds are likely to be measured in the near future.
- the universe is quite uniform on large scales, but how uniform or what is the power spectrum on hundreds of Mpcs?
- The Lyα forest provides a good consistency check. Should we give it more weight?