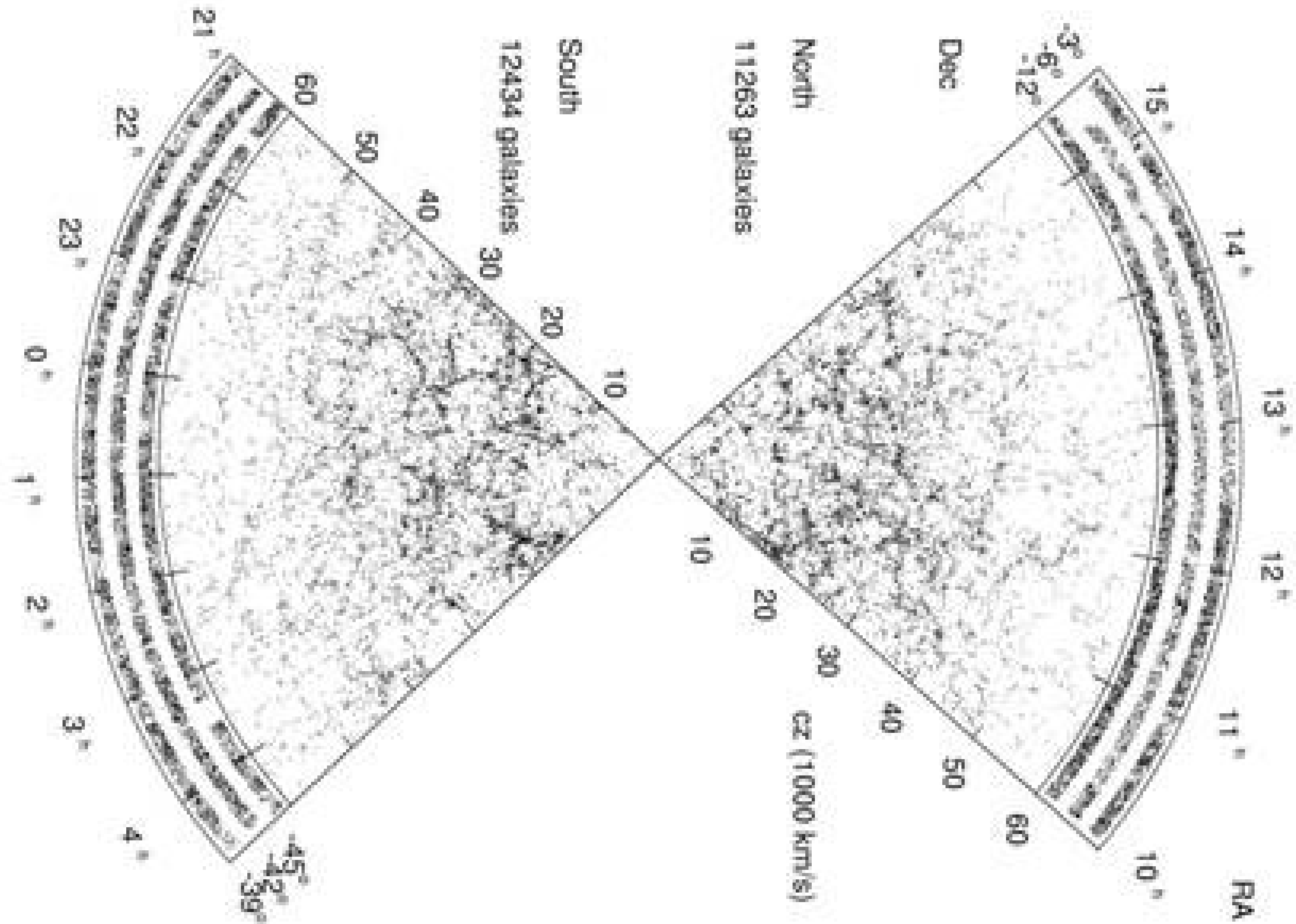
Clusters of Galaxies

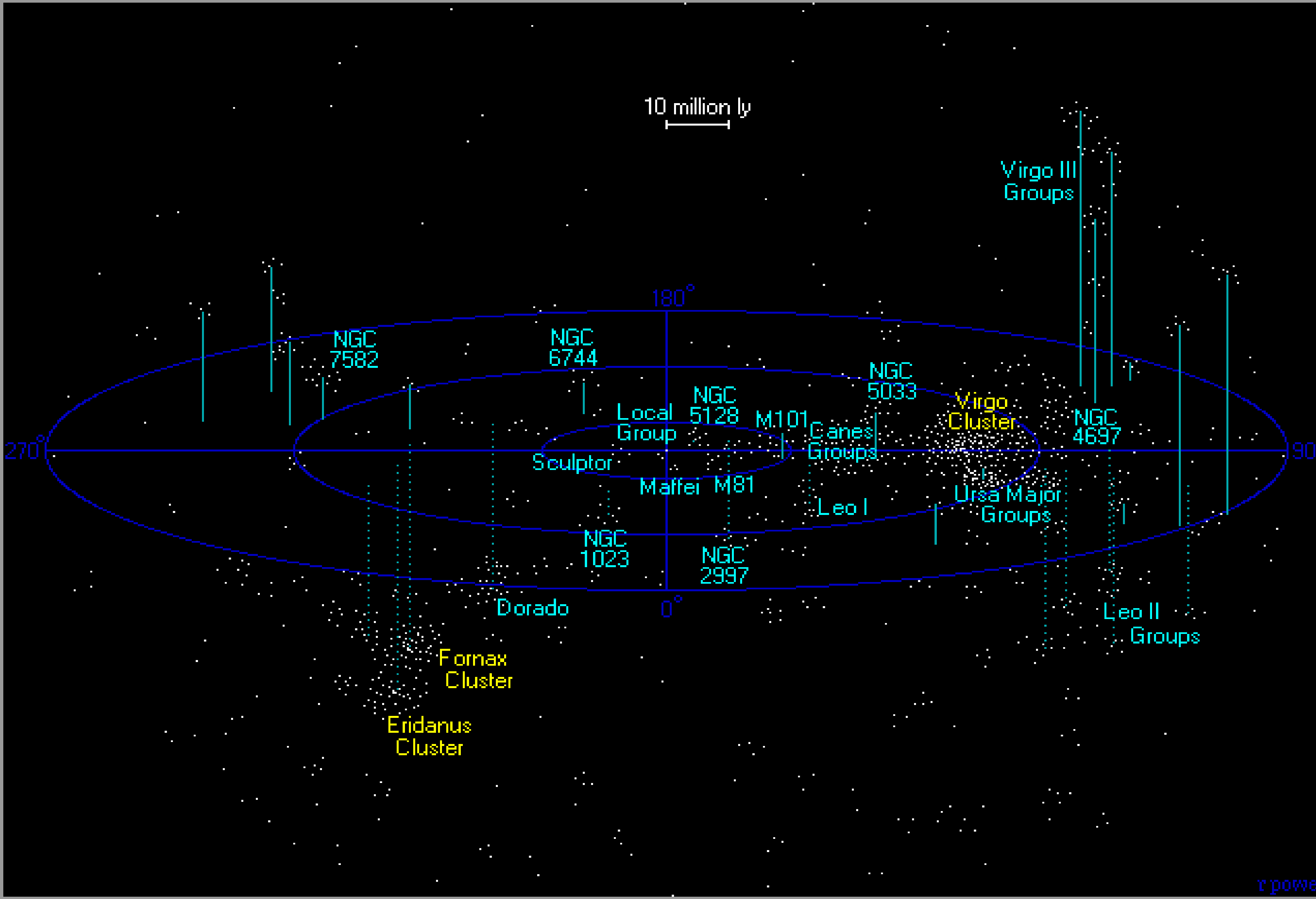
Abell 2218 (HST image)

- Galaxies are not uniformly distributed on the “small” scale.
  - ~90% of all galaxies are in clusters or groups of galaxies.
  - These structures form sheets and filaments on the sky
  - Groups contain 3 – 50 galaxies
    - Masses are 10^{12} – 10^{13} M_{sun}
  - Clusters can have more than 1000 galaxies
    - Masses up to 10^{15} M_{sun}

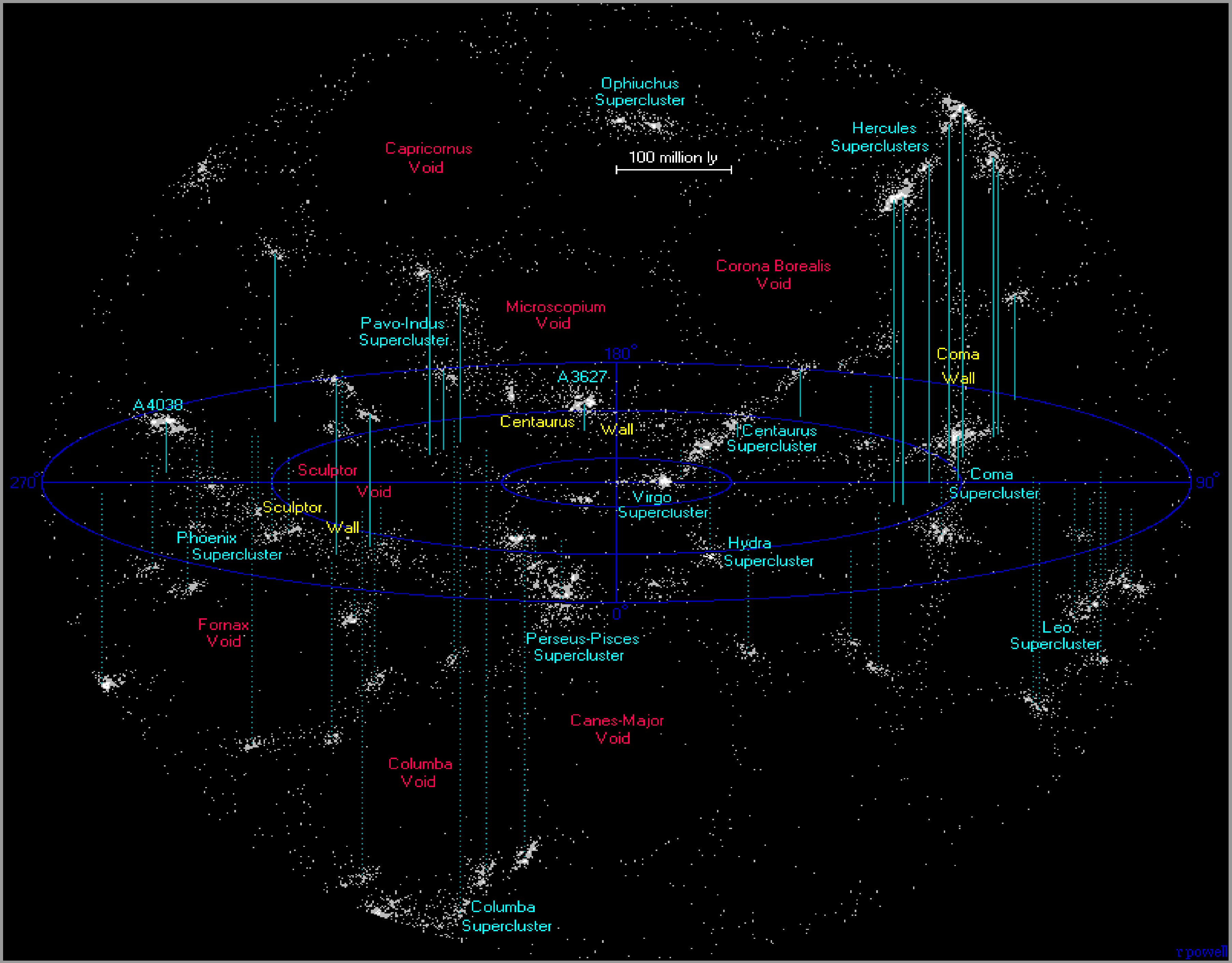
- Clusters and groups have very similar sizes.
  - Clusters span 1-3 Mpc
  - Groups span 0.25-1 Mpc
- In general Clusters a much denser environments
  - Compact groups can be as dense as clusters


RA
Dec
-3°
-6°
-12°
North
11263 galaxies
South
12434 galaxies
cz (1000 km/s)
10 20 30 40 50 60
10 h
11 h
12 h
13 h
14 h
15 h
21 h
22 h
23 h
0 h
1 h
2 h
3 h
4 h
-45°
-42°
-39°

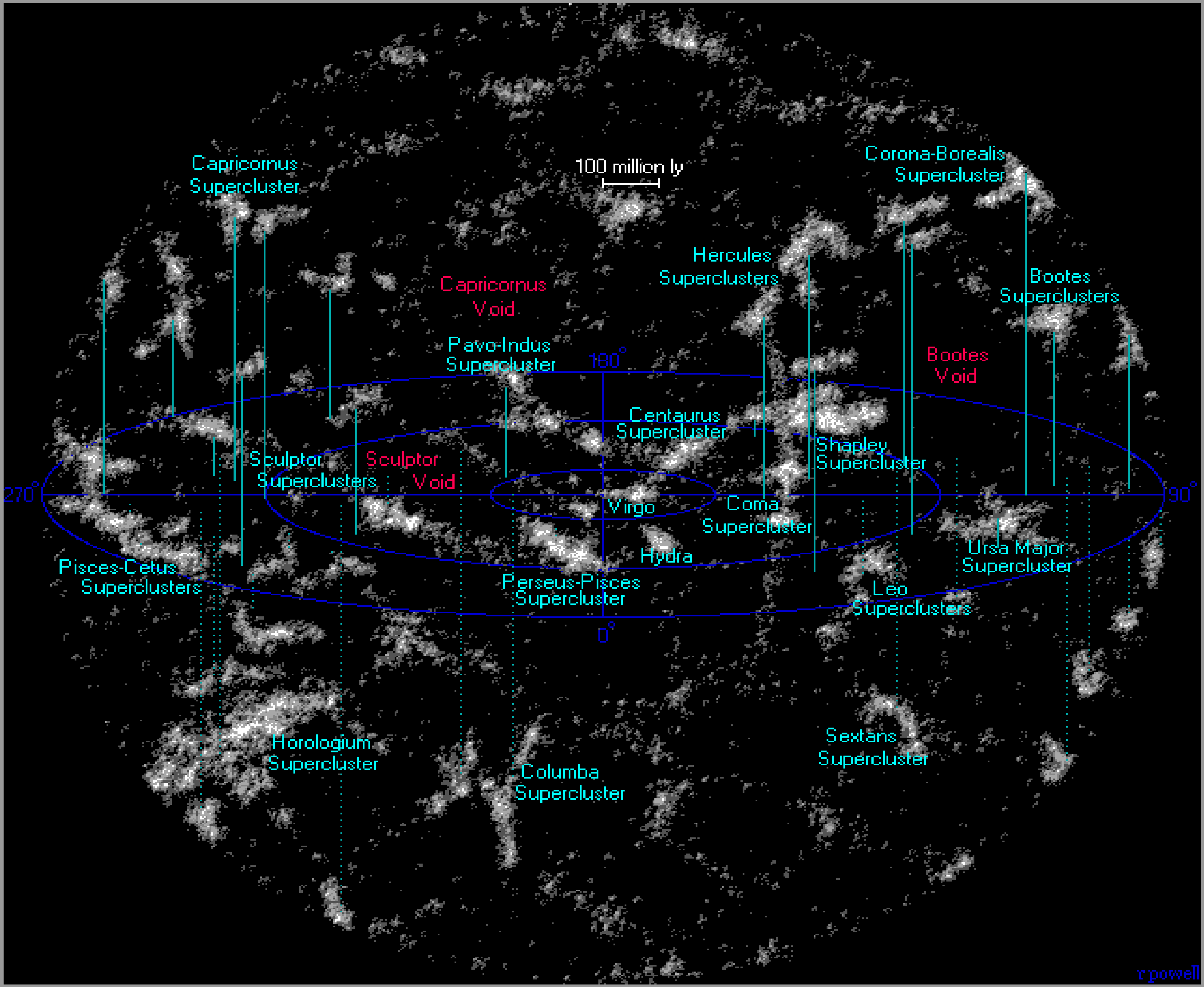
- These large scale structures cause peculiar velocities, deviations from the Hubble flow, due to their gravitational attraction.
- We can use large galaxy redshift surveys to trace the mass distribution of the universe and measure Ω_m
- The amount of clustering we observe also provides strong constraints on the amount and type of dark matter in the universe and the energy density.



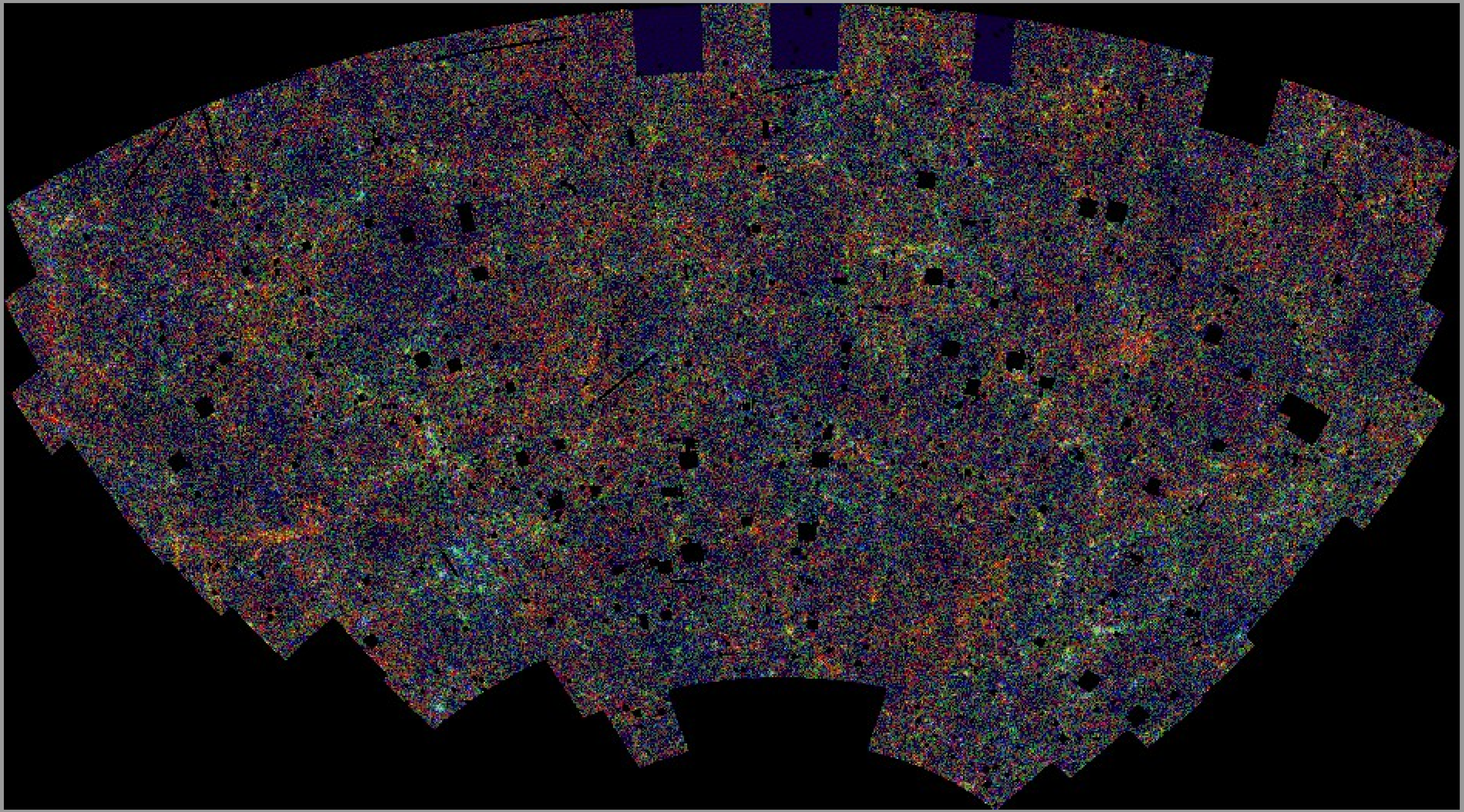
Local Supercluster



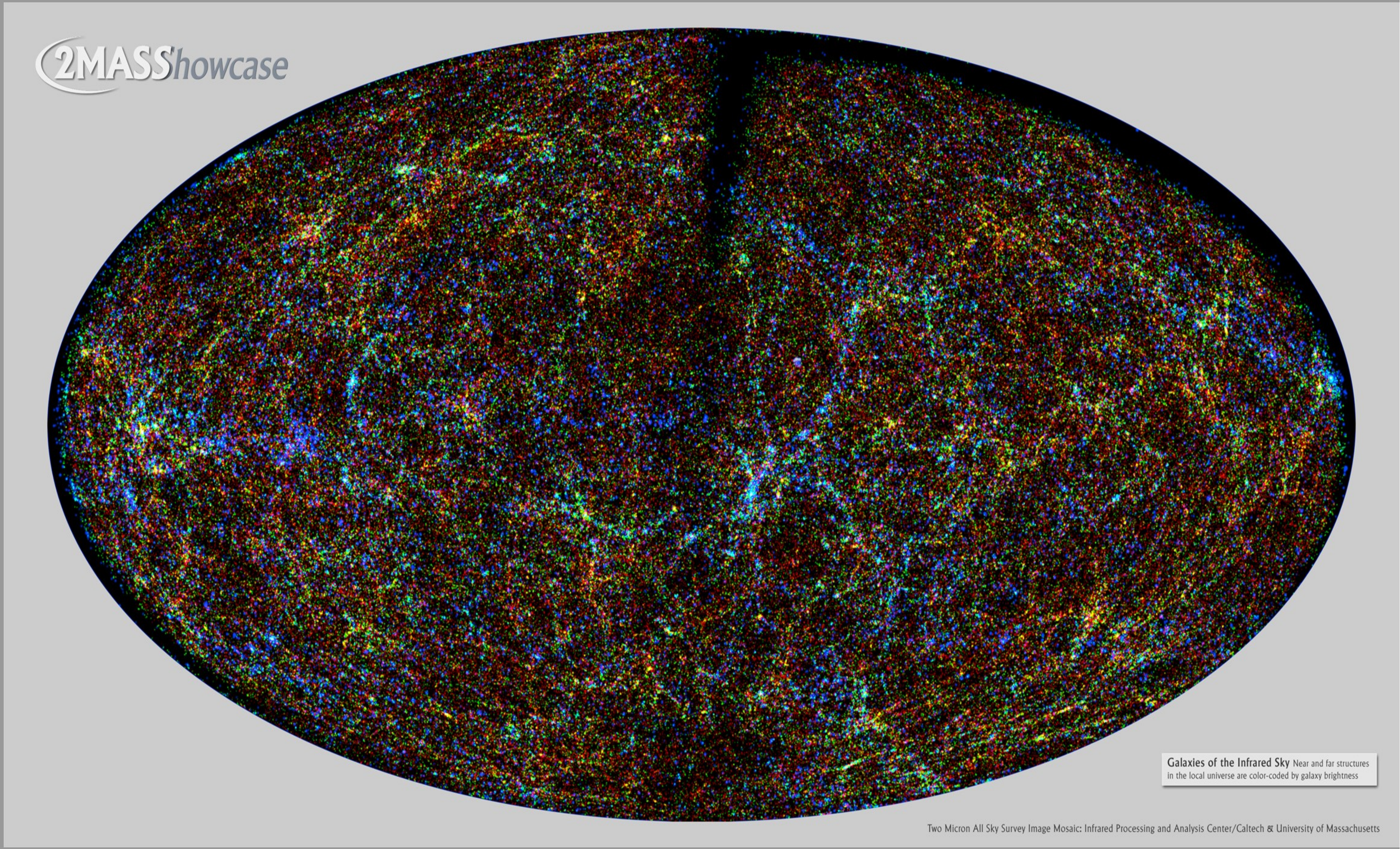
Superclusters



Superclusters cont.



APM galaxy survey (Maddox et al. & Astrophysics Dept, Oxford University) showing large scale structure for 2 million galaxies. The image shows more clustering at large scales that standard CDM models.



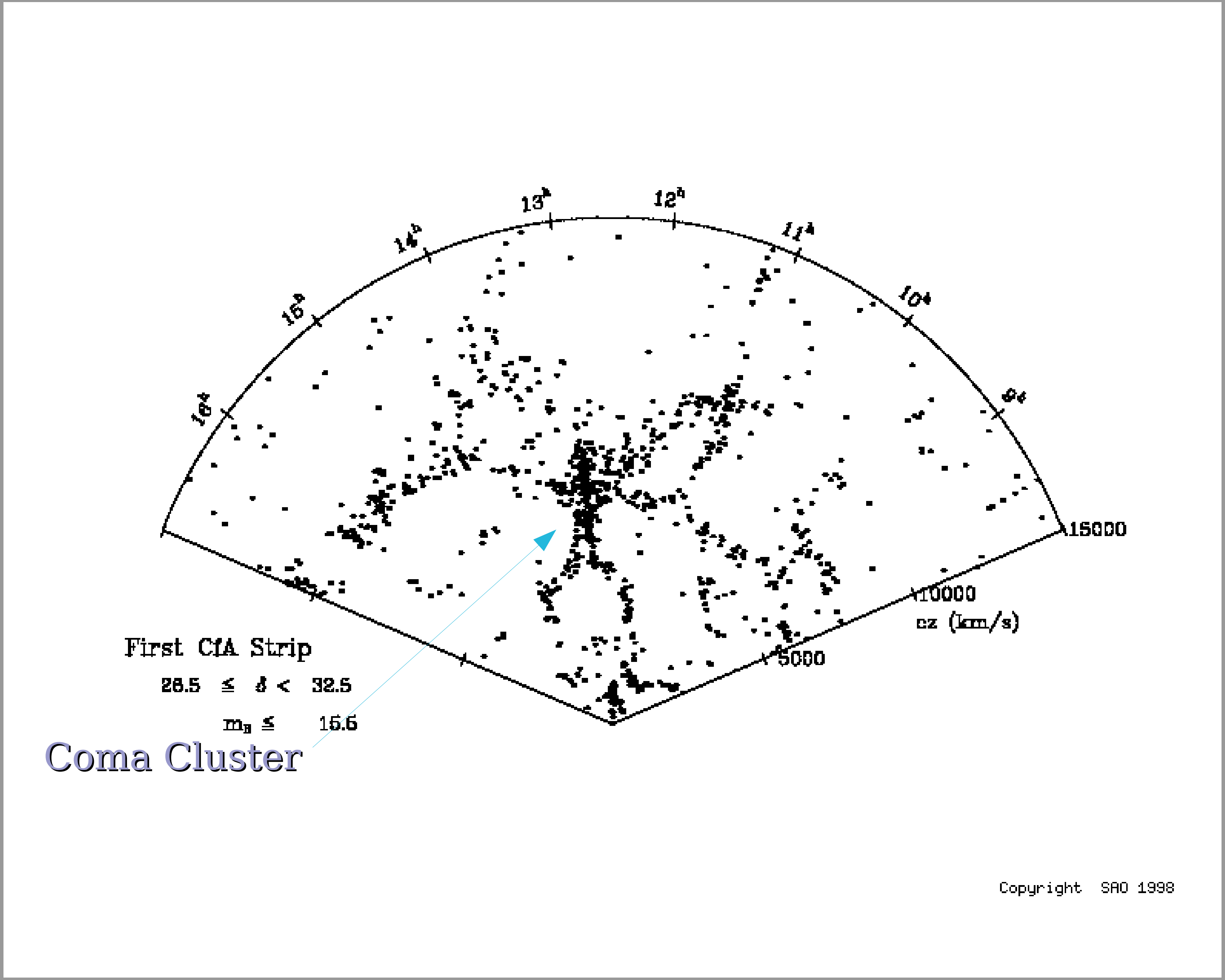
Clustering the in the 2MASS survey

Redshift Surveys

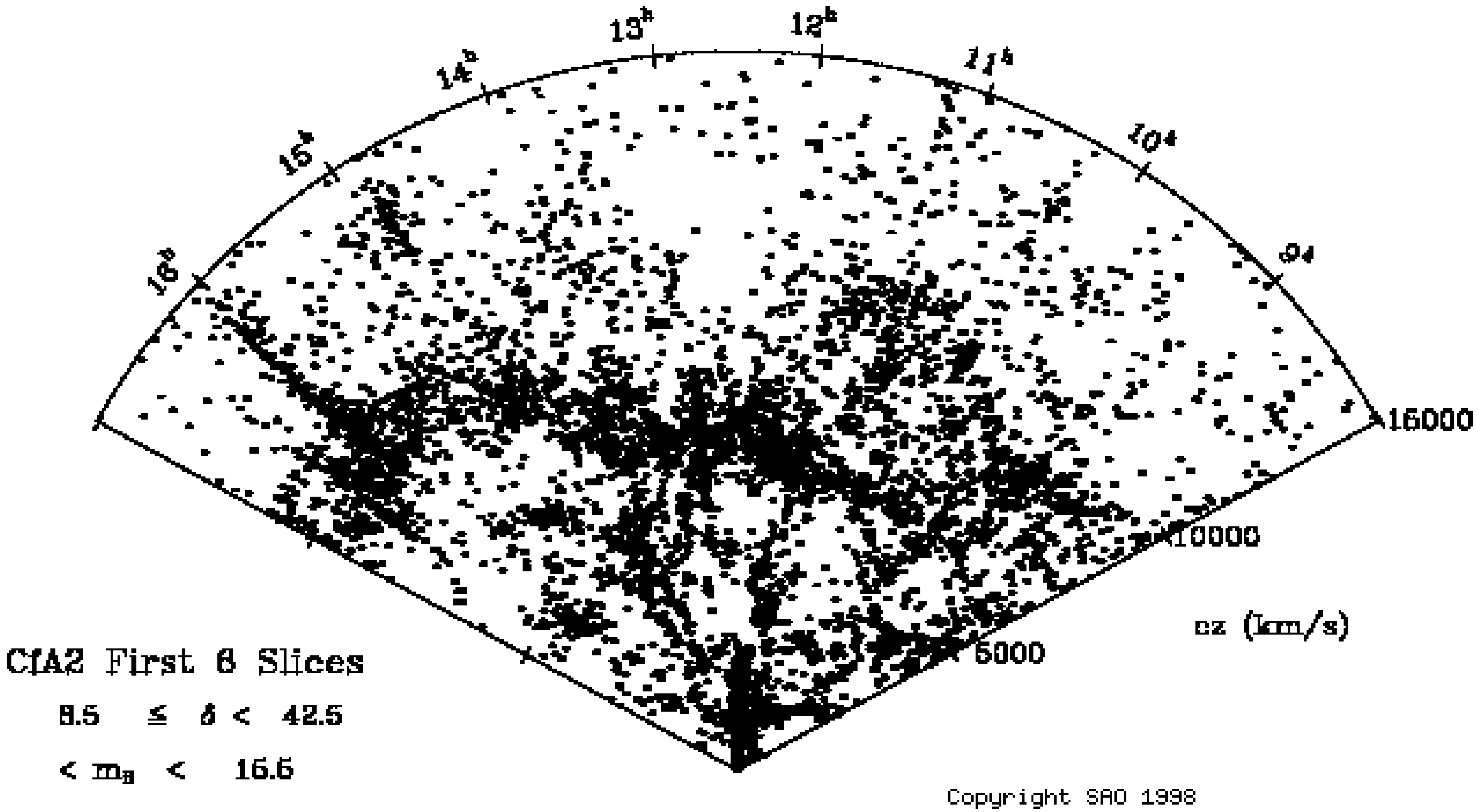
- In the 1980's large scale redshift surveys, allowed us to measure clustering in 3 dimensions, instead of just two
- The first large scale redshift survey was the CfA2 (Center for Astrophysics) survey led by Margaret Geller & John Huchra started in 1984 to 1995.
  - There was a CfA1 survey 1977-1982, 2500 galaxies with b<14.5 (Huchra, Davis, Latham, & Tonry)
- CfA2 observed 20,000 galaxies brighter than B=15.5 with a 1.5 m telescope.
  - This was done one redshift at a time, a massive undertaking!
- Later the Las Campanas Redshift Survey was done in the south (with multiobject spectroscopy), ~25000 galaxies covering 700 square degrees of the sky to r=17.5. Finished in the mid-1990's.

Redshift Surveys cont.

- The CfA2 redshift survey revealed surprising amounts of large scale structure (LSS) in the universe
- There are filaments, walls, and voids
  - Voids are “3500-5000 km/s” in diameter or >50h^{-1} Mpc across
  - The “Great Wall” stretches for 100h^{-1} Mpc or ¼ of the way across the sky!
  - The universe is like a sponge or perhaps a pile of soap bubbles!
- Note that walls appear thinner in redshift space than they really are.
- Clusters (like Coma) appear elongated – this is the “Finger of God” effect.



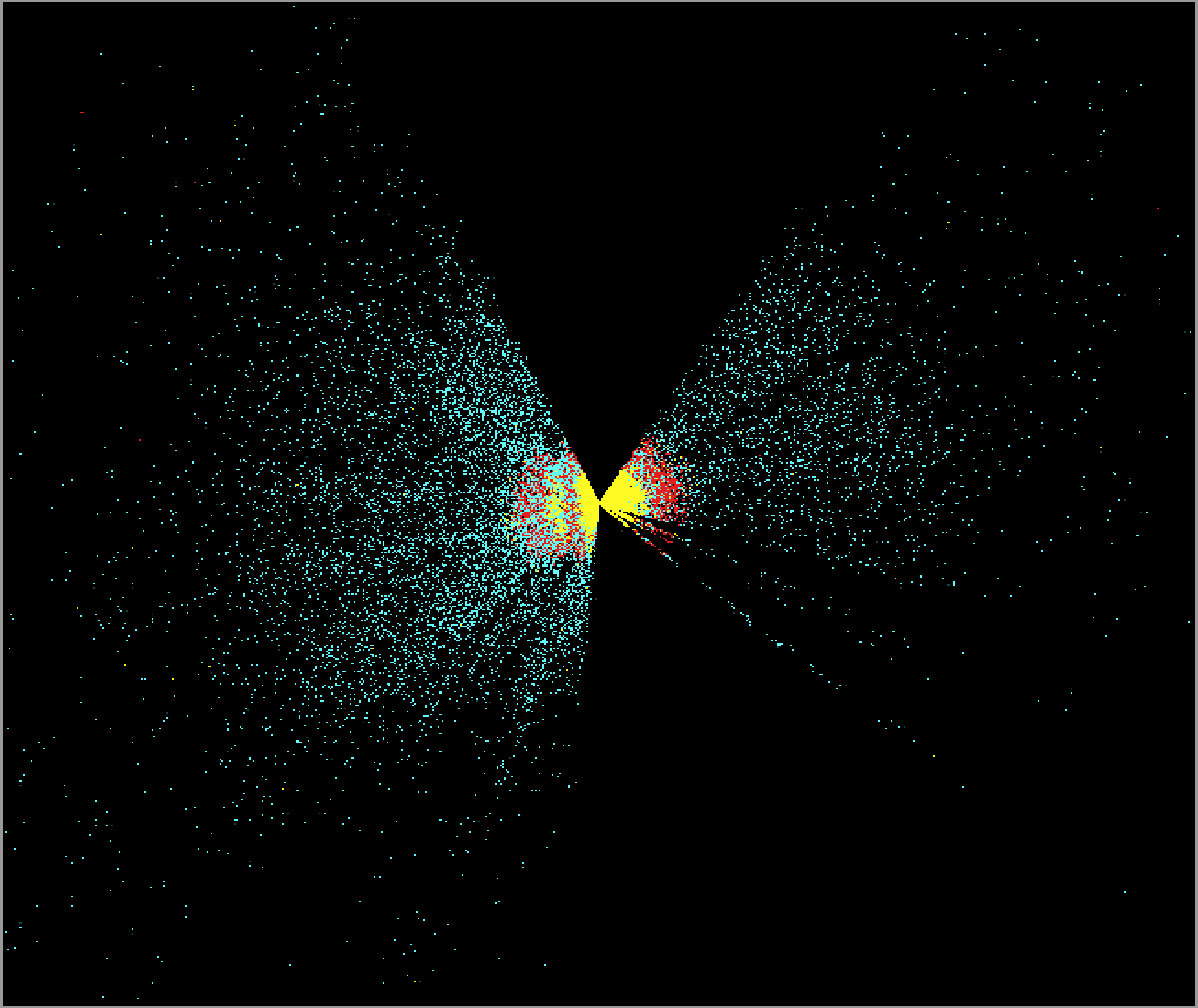
de Lapparent, Geller, & Huchra et al 1985



Geller & Huchra et al 1989

Redshift Surveys cont.

- Recently there have been two large redshift surveys undertaken
- The 2dF (2 degree Field) redshift survey done with the Anglo-Australian telescope
  - ~220,000 galaxies covering 5% of the sky reaching to z~0.3 with B<19.5
  - Their spectrograph can measure 400 redshifts at a time
- The Sloan Digital Sky Survey (SDSS) which uses a dedicated 2.5m telescope at Apache Point Observatory in New Mexico
  - Does multicolor imaging to r=22.5 and spectra of galaxies down to r<17.5 reaching to z~0.4, ~500 redshifts at a time
  - To date (~930,000 redshifts DR7), total goal is 1 million
  - Also measuring redshifts of quasar candidates out to much higher redshifts (Schneider et al.)

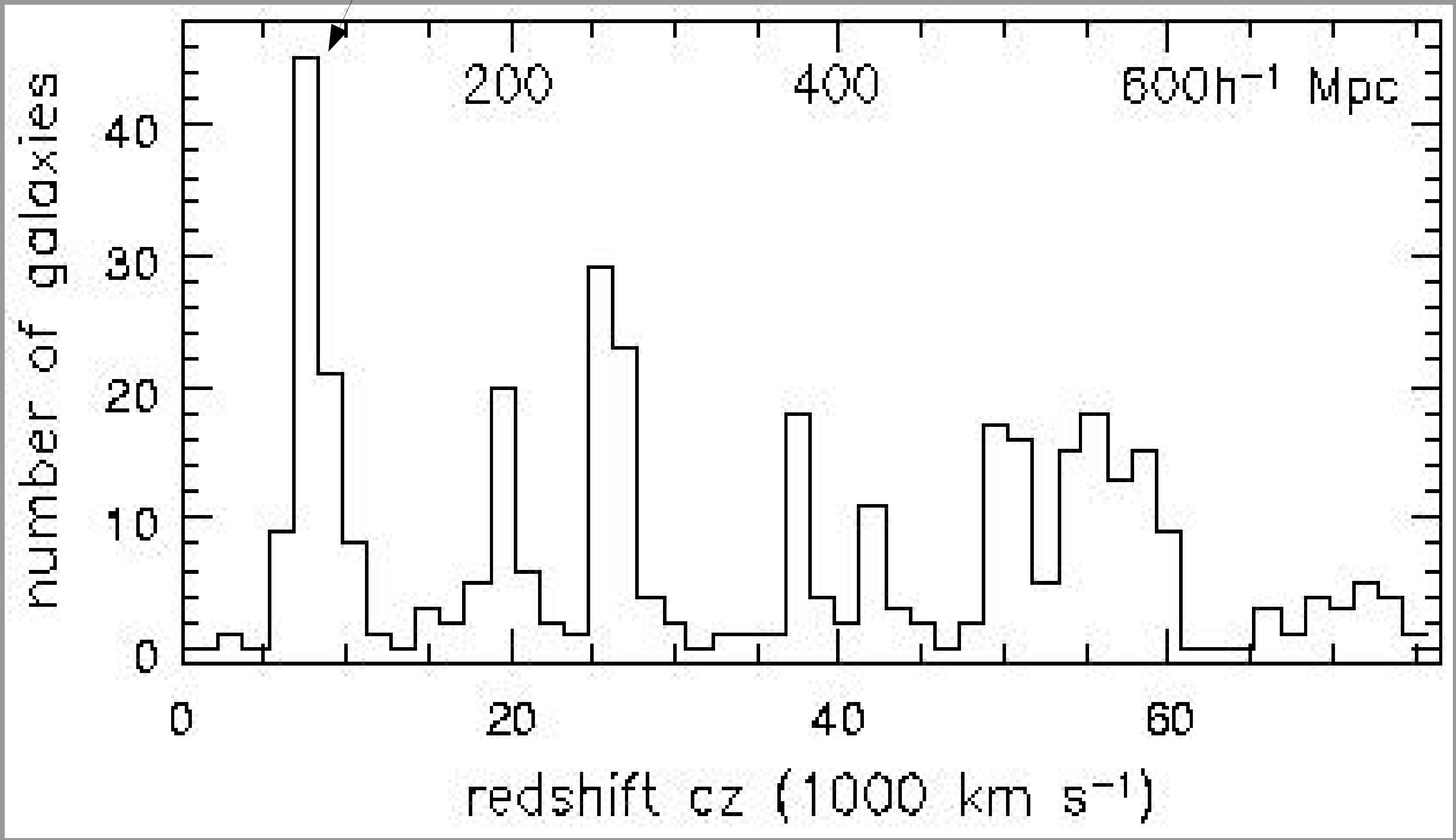


SDSS galaxy data

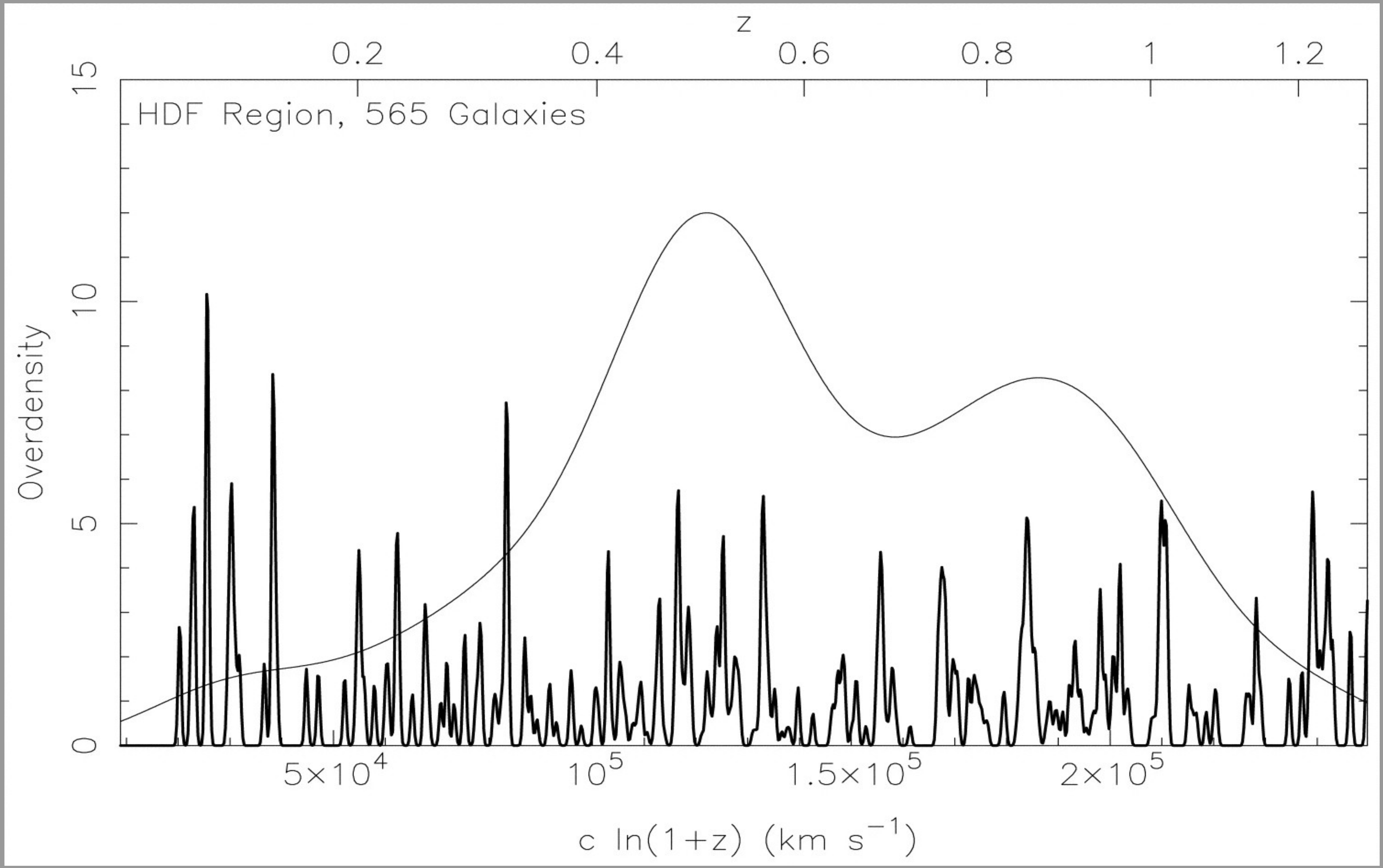
Deeper Surveys

- Probing structure at higher redshifts is generally done with deep "pencil beam" surveys in small patches of the sky.
- Original pencil beam surveys done by David Koo, Richard Kron, & collaborators in early 1990's showed walls showing up at large redshifts
  - Originally thought to be periodic, but but this turned out not to be true
  - The voids & walls we see locally seems to continue out to z~1
- Even deeper surveys done with Keck of the Hubble Deep Field and several other deep surveys show the same thing

Great Wall



Pencil beam survey, Willmer & Koo 1996



The thick curve shows the overdensity as a function of the local velocity, while the thin curve denotes the heavily smoothed distribution of galaxies scaled by a constant.
Hubble Deep Field Redshifts, Cohen et al. 2000

How to measure the amount of clustering?

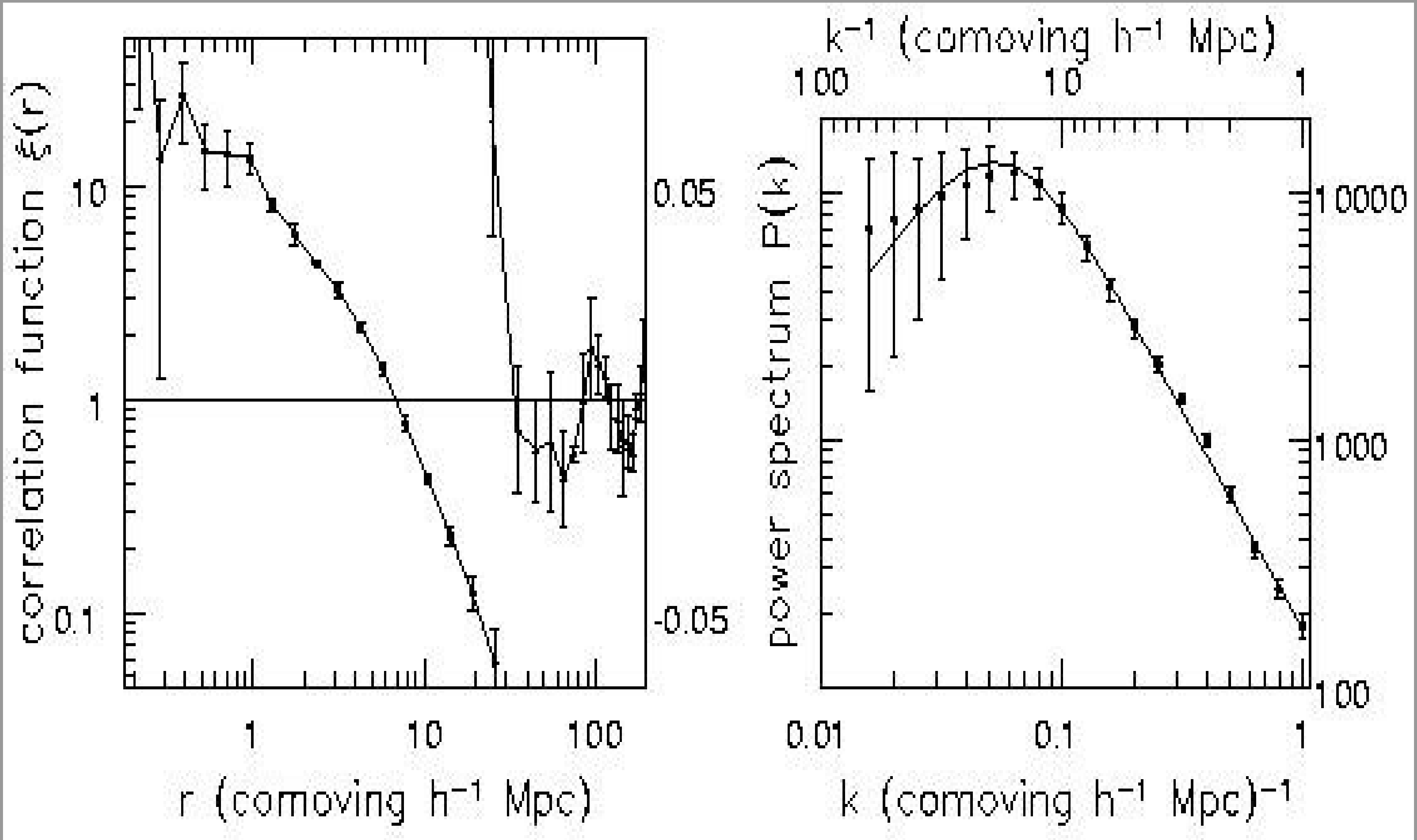
- We want a way to quantify the amount of structure that we see on various scales
- One common way of doing this is to measure the two-point correlation function $\xi(r)$
- We calculate the correlation function by estimating the galaxy distances from their redshifts, correcting for any distortions due to peculiar velocities, and counting the number of galaxies within a given volume
- We can write the probability of finding a galaxy within a volume ΔV_1 and a volume ΔV_2 is
    - $\Delta P = n^2[1+ \xi(r_{12})]\Delta V_1 \Delta V_2$
  - Where n is the average spatial density of galaxies (number per Mpc^3) and r_{12} is the separation between the two regions

Clustering cont.

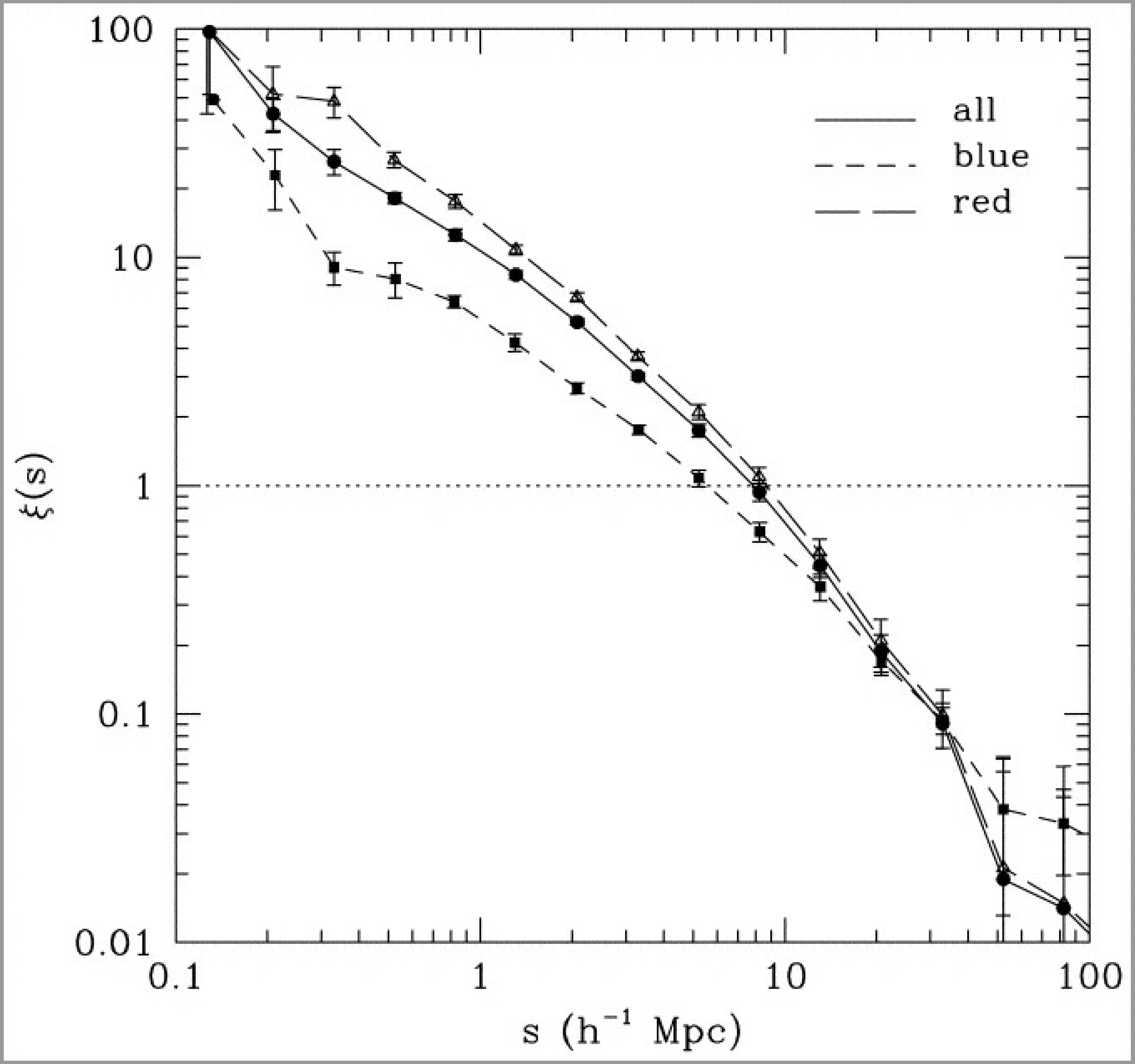
- $\Delta P = n^2[1+\xi(r_{12})]\Delta V_1 \Delta V_2$
    - If $\xi(r) > 0$, then galaxies are clustered
    - If $\xi(r) < 0$, then galaxies avoid each other
    - On scales of < $50h^{-1}$ Mpc, we can represent the correlation function as a power-law: $\xi(r) \sim (r/r_0)^{-\gamma}$ with $\gamma > 0$
- The probability of finding one galaxy within a distance r of another is significantly increased (over random) when $r < r_0$. r_0 is the "correlation length".
- Note that the 2 point correlation function isn't good for describing one-dimensional filaments or two-dimensional walls. We need 3 and 4 point correlation functions for those. These don't work very well.
- From the SDSS: $r_0 = 6.1 \pm 0.2\ h^{-1}$ Mpc, $\gamma = 1.75$ over the scales 0.1 – 16 h^{-1} Mpc

Clustering cont.

- Clustering is a function of galaxy luminosity:
  - Fainter galaxies are less strongly clustered than brighter ones
- And on galaxy color:
  - Bluer galaxies are less strongly clustered than redder ones
- This is presumably telling us something fundamental about galaxy formation, luminous redder galaxies (ellipticals?) like to form in areas of higher mass density



Correlation function and power spectrum from Las Campanas Redshift Survey data (Lin & Tucker.



Correlation function from the SDSS data (Zehavi et al. (2002).

$\xi\ (r_p)$

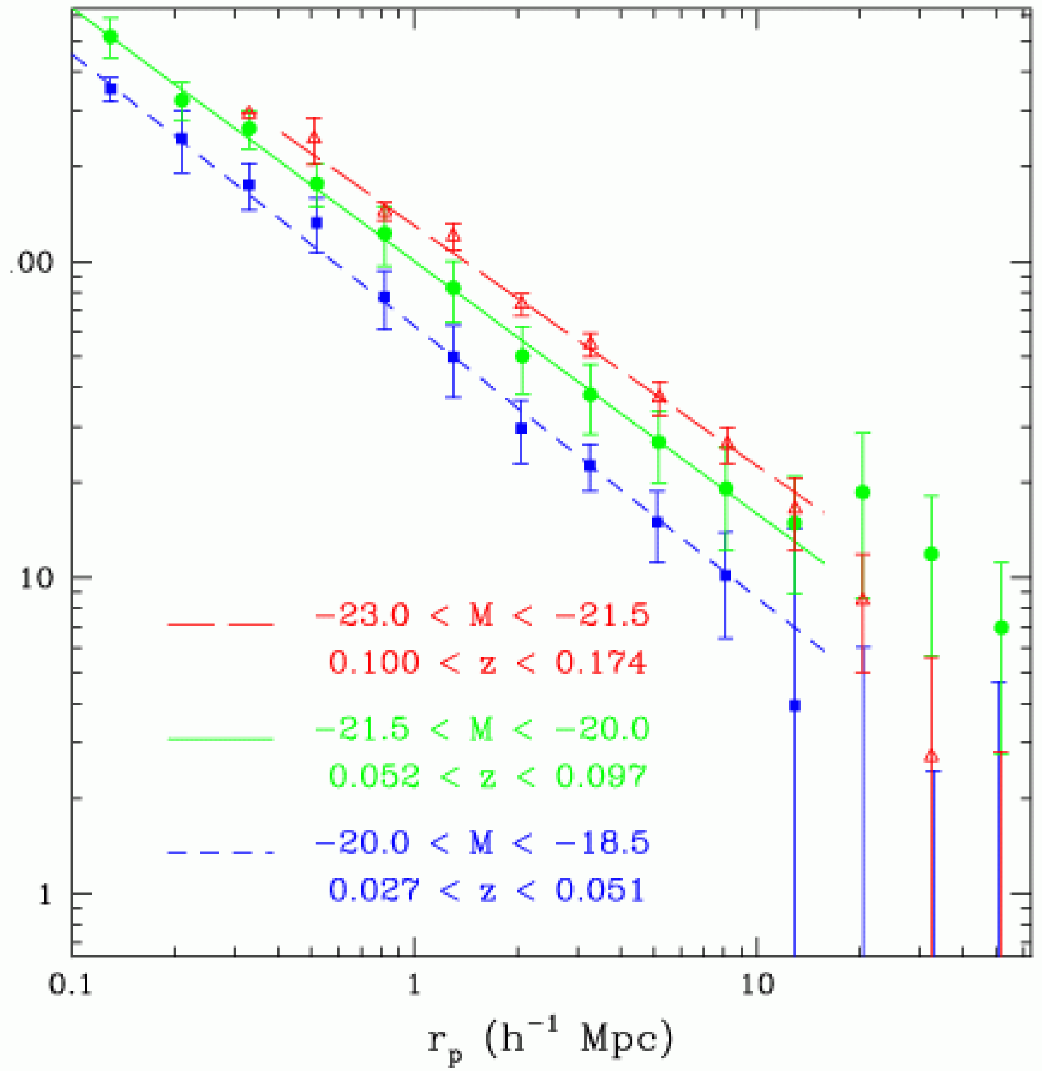
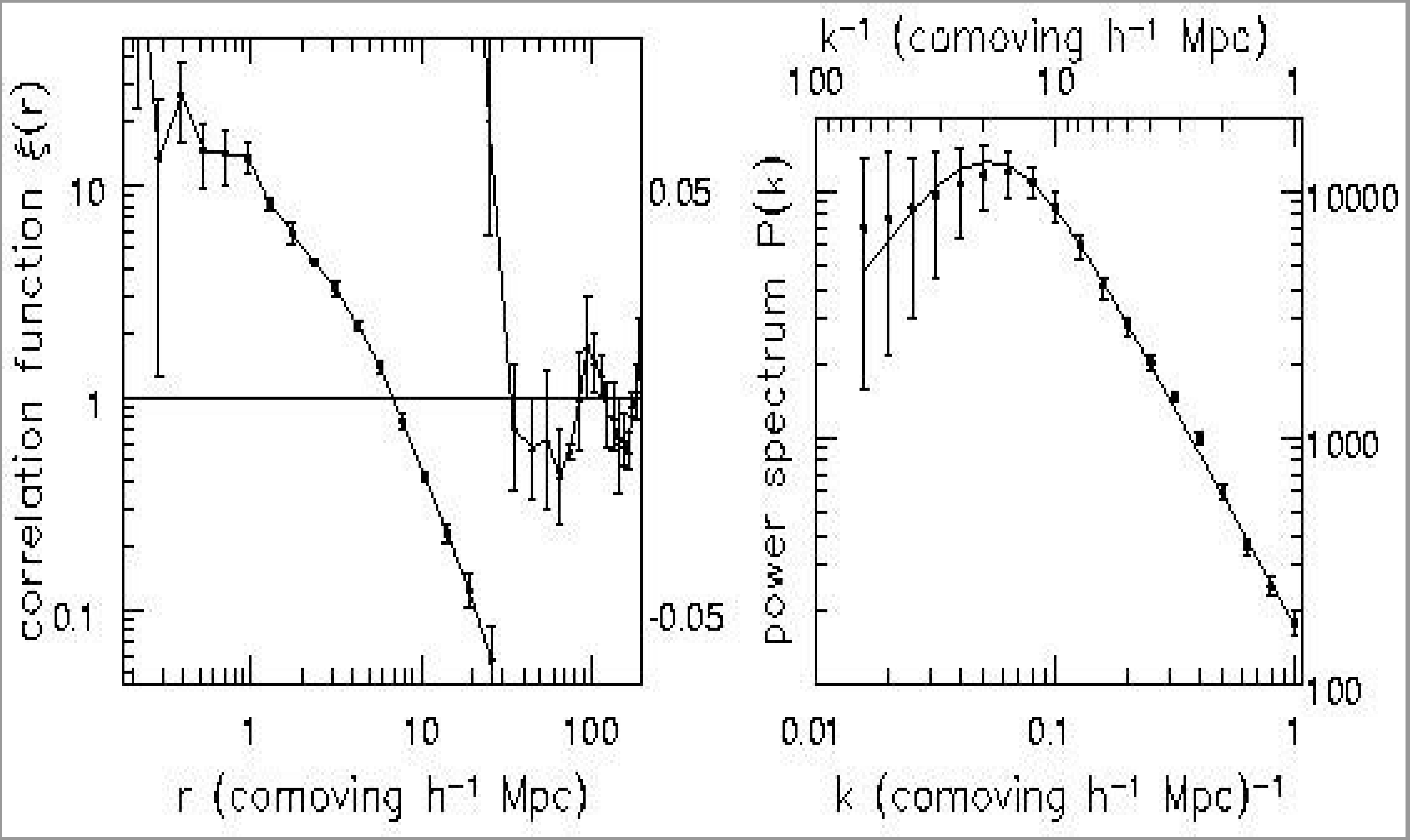


Fig. 1.4. Galaxy clustering depends on luminosity. Changing the luminosity changes the amplitude, but not the slope, of the correlation function. (From Zehavi et al. 2002.)

Correlation function from the SDSS data (Zehavi et al. (2002).

Clustering cont.

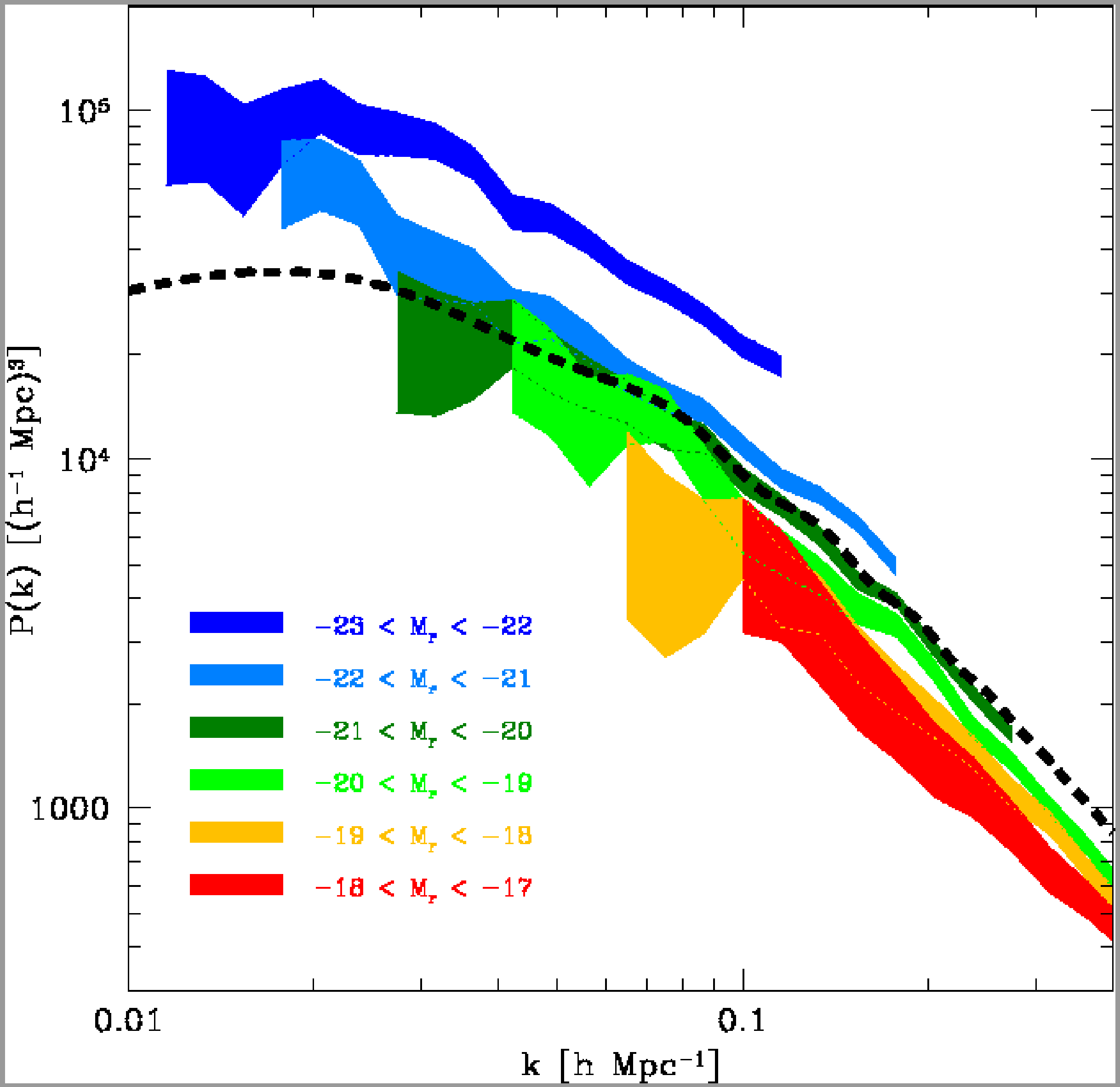
- The Fourier transform of $\xi(r)$ is the power spectrum $P(k)$, $P(k) = 4\pi \int \xi(r) [\sin(kr)/kr] r^2 dr$
- k is the wavenumber, small values of k correspond to large physical scales
- P(k) has the dimensions of volume. It will be at maximum close the radius r where $\xi(r)$ drops to zero.
- Roughly speaking the power spectrum is a power-law at large k (small physical scales) and turns over at small k (large physical scales)
- We can combine information from different measurements (redshift surveys, CMB, Lyα forest, weak lensing) to trace P(k) over a large range of physical scales
- The power spectrum provides strong constraints on the amount and type of dark matter and dark energy in the universe



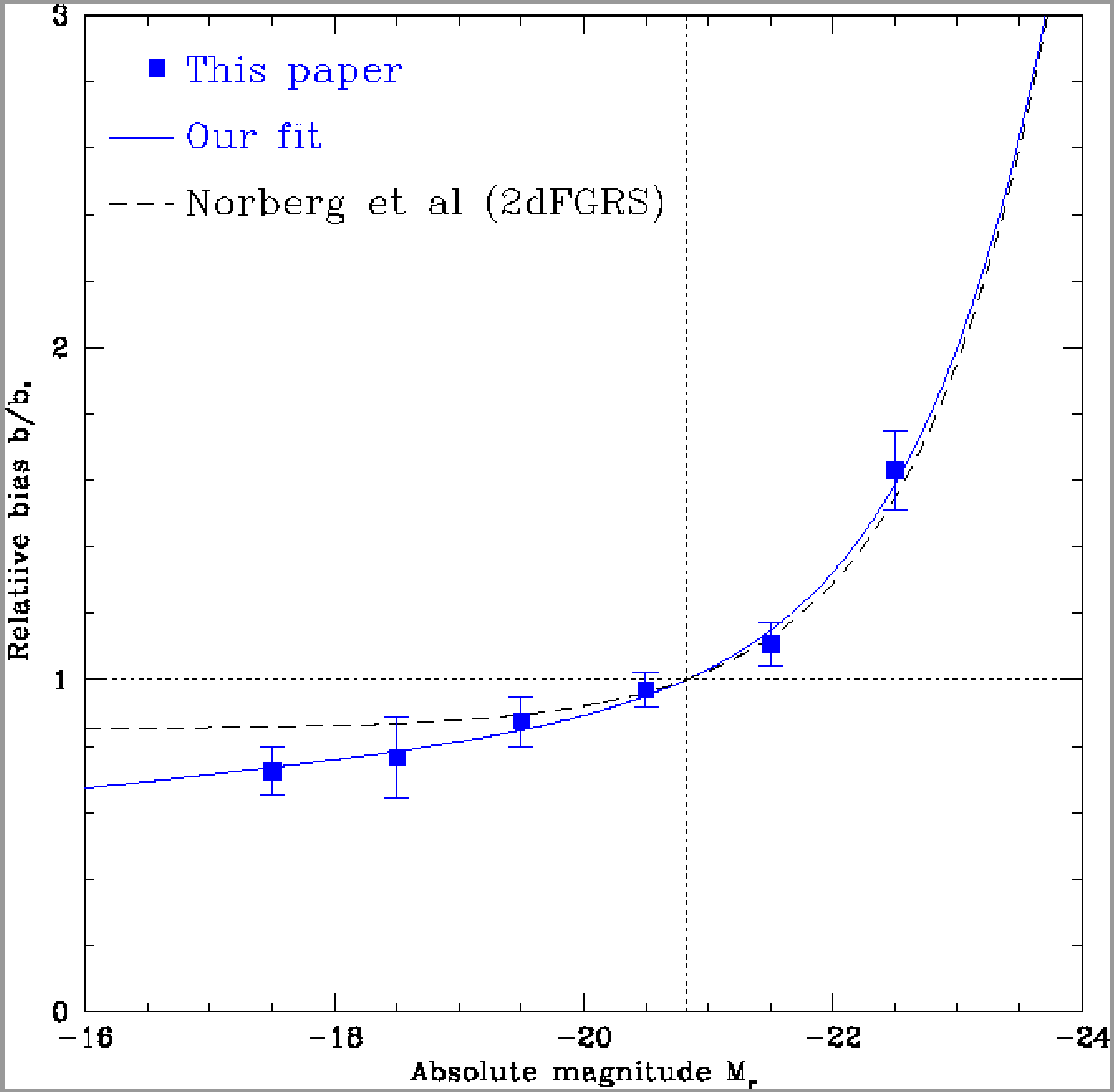
Correlation function and power spectrum from Las Campanas Redshift Survey data (Lin & Tucker.

Clustering cont.

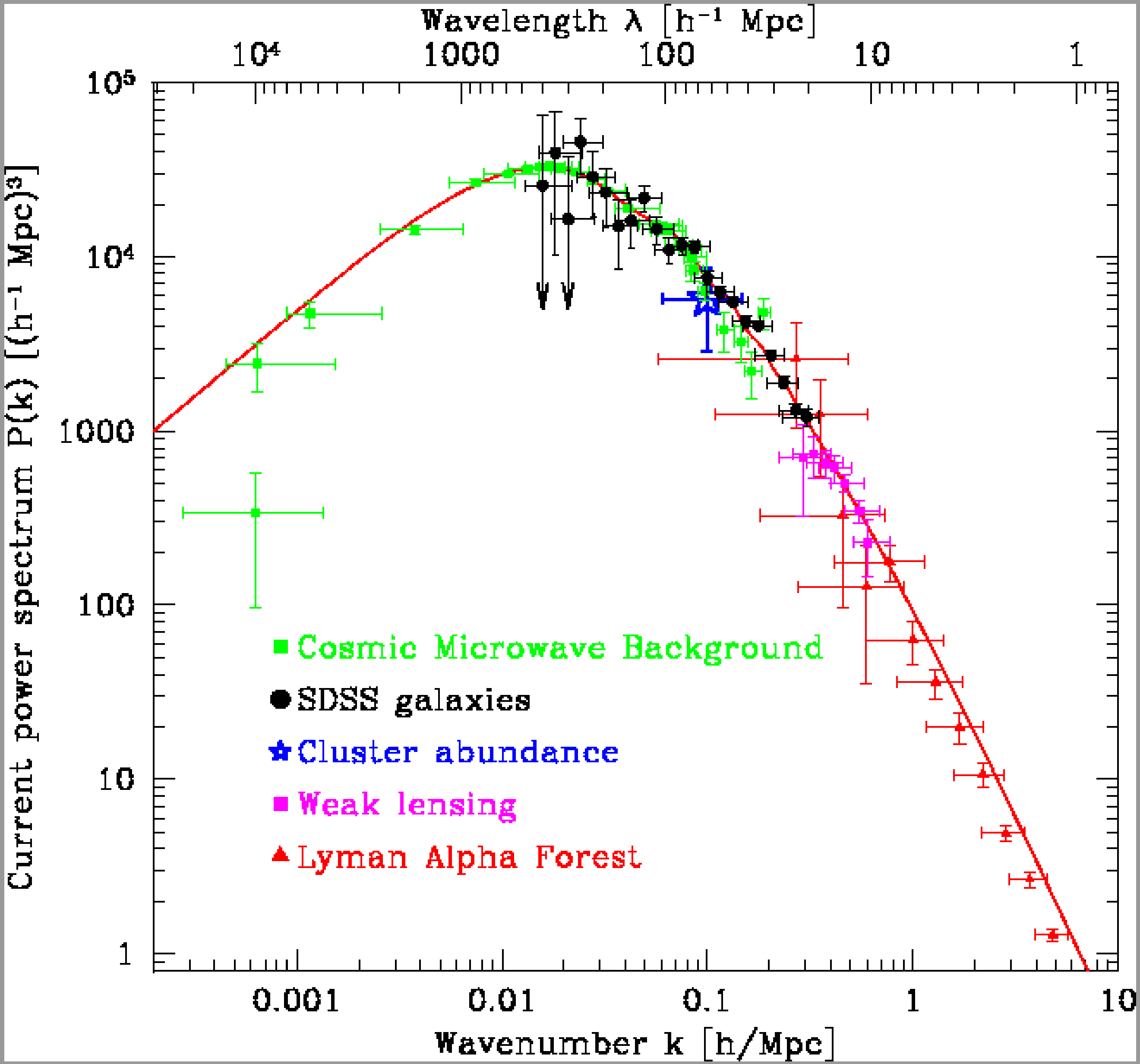
- We would also like to know how well the galaxies trace the mass distribution, or how biased are the galaxies relative to the dark matter
- We generally assume that the two densities are linearly related such that:
  - Let $\delta_x = (\rho_x - \rho_{avg})/\rho_{avg}$ be the density fluctuation of a given population
  - Linear biasing for galaxies implies $\delta_{galaxies} = b\delta_{dm}$
  - Biasing may be a function of scale and of galaxy luminosity
- We can measure relative biasing by measuring the power spectrum of different populations



Power Spectrum from the SDSS data, Tegmark et al (2004)



Biasing in the SDSS data, Tegmark et al (2004)



Combined power spectrum, Tegmark et al (2004)

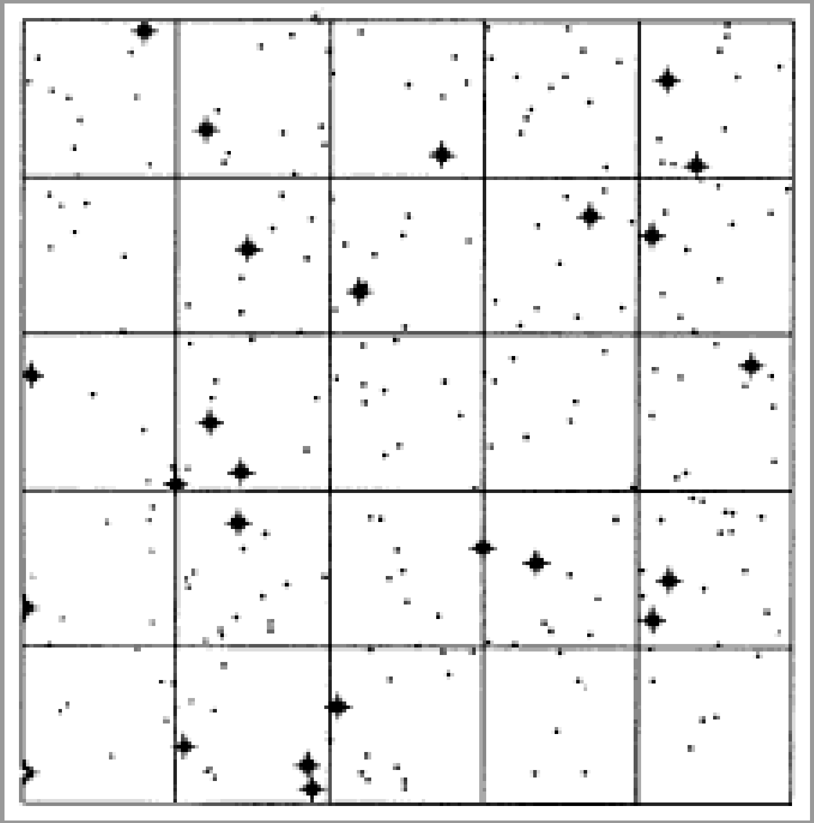
Peculiar velocities & Bulk Flows

- Large scale structure causes peculiar velocities (deviations from the Hubble Flow)
- We can measure these if we have accurate distances to the galaxies by:
  - $V_r = H_0 d + V_{pec}$ – so if we measure distance and radial velocity (and assume the Hubble Constant) we can measure the peculiar velocity of a galaxy
- We are falling into the Virgo cluster at ~270 km/s, this is called the “Virgocentric infall”
- We also measure a dipole anisotropy in the cosmic microwave background which implies that the local group is moving at ~620 km/s towards b=27, l=268.
- This is due to a combination of our infall towards Virgo and the entire Local Supercluster moving towards the general direction of the Hydro-Centaurus Supercluster (the Great Attractor)
  - Flows of superclusters are known as “bulk flows”
  - Measurements of the velocity field of galaxies can help put constraints on the underlying mass field

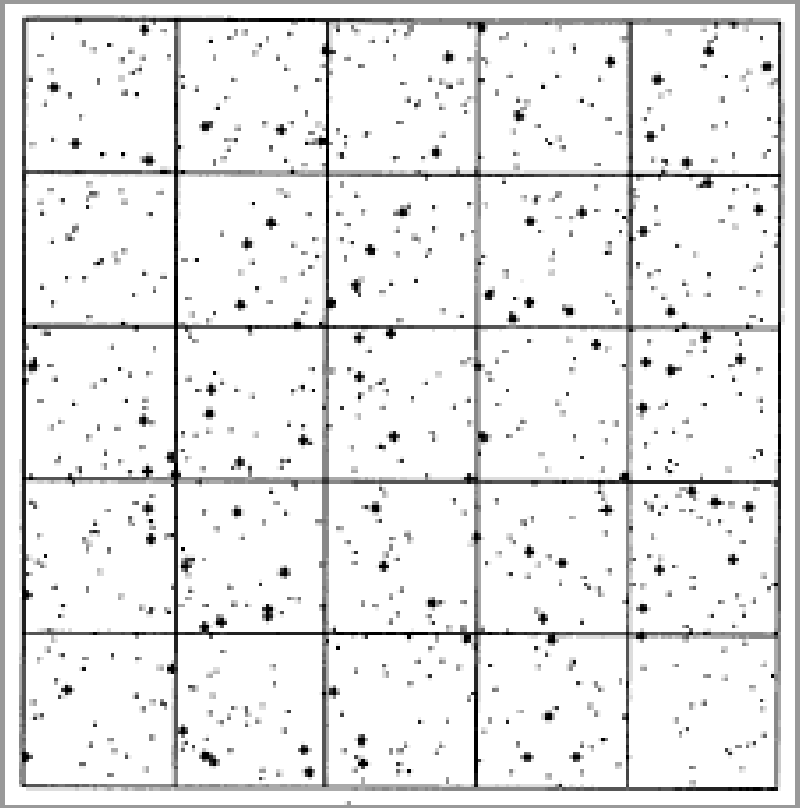
Surface Brightness fluctuations

- Surface brightness fluctuations for old stellar populations (E's, SO's and bulges) are based primarily on their giant stars
- Assume typical average flux per star <f>, the average flux per pixel is then N<f>, and the variance per pixel is $N\langle f^2 \rangle$. But N (number of stars per pixel) scales as d^2 and the flux per star decreases as d^{-2}. Thus the variance scales as d^{-2} and the RMS scales as d^{-1}. Thus a galaxy twice as far away appears twice as smooth. The average flux <f> can be measured as the ratio of the variance and the mean flux per pixel. If we know the average L (or M) we can measure the distance).
- <M> is roughly the absolute magnitude of a giant star and can be calibrated empirically (using the bulge of M31)
- But there is a color-luminosity relation, so
  - $\langle M_I \rangle = -1.74 + 4.5[(V-I)_0 - 1.15]$
- Have to model and remove contamination from foreground stars, background galaxies, and globular clusters
- Can be used out to ~100 Mpc in the infrared using NICMOS on HST

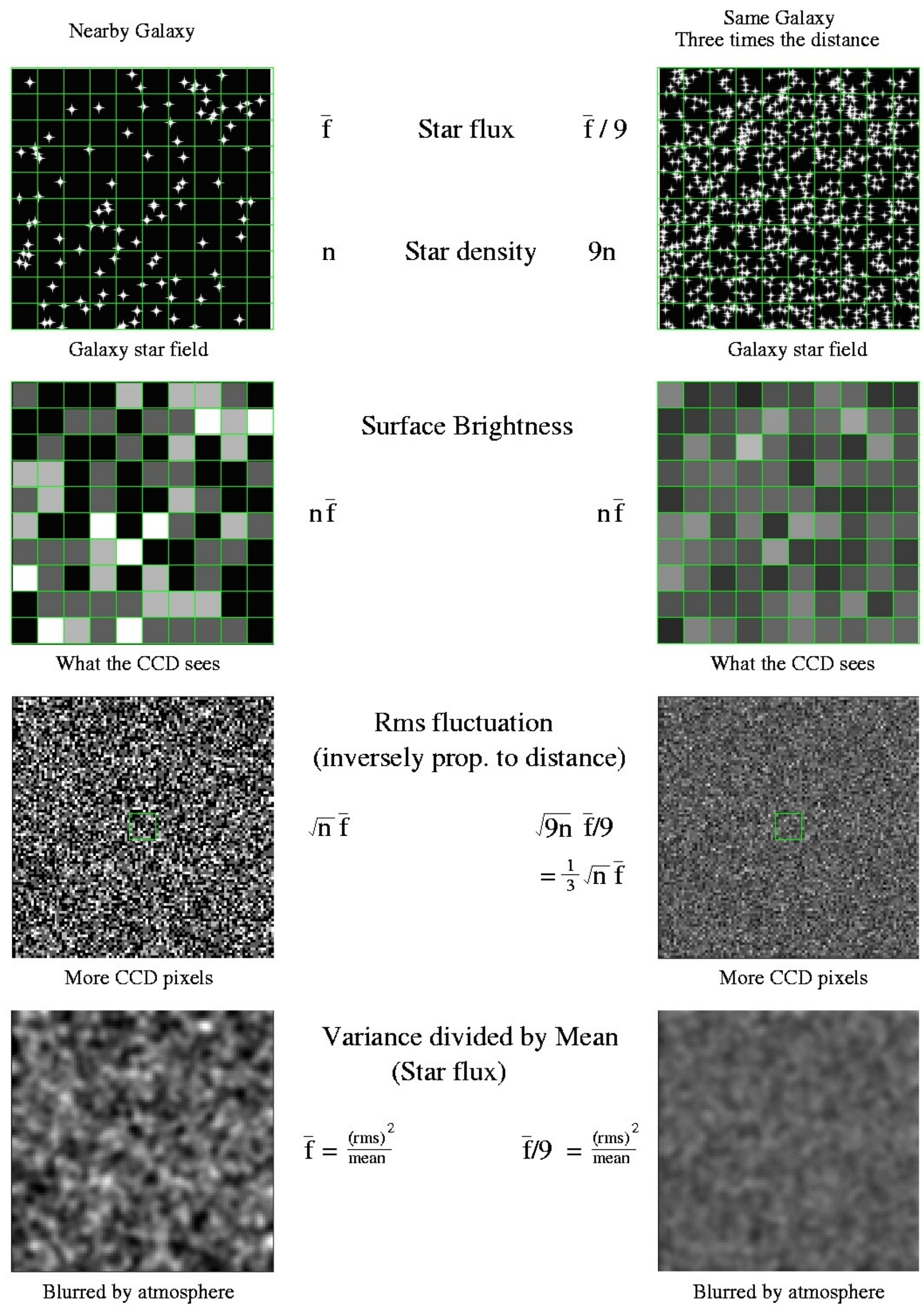
SB fluctuations cont.



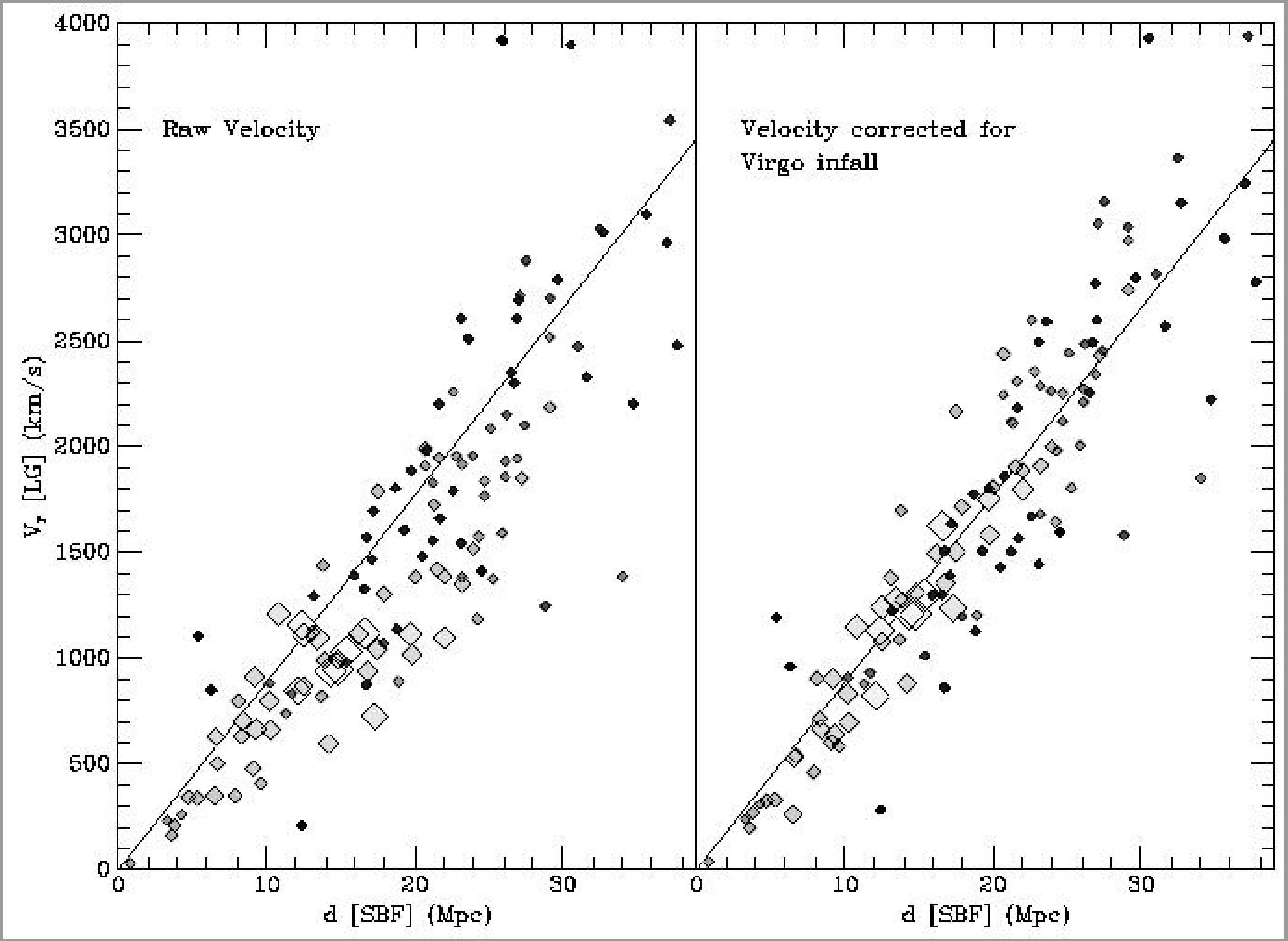
Nearby Galaxy



Same observation for a Galaxy with twice the distance.

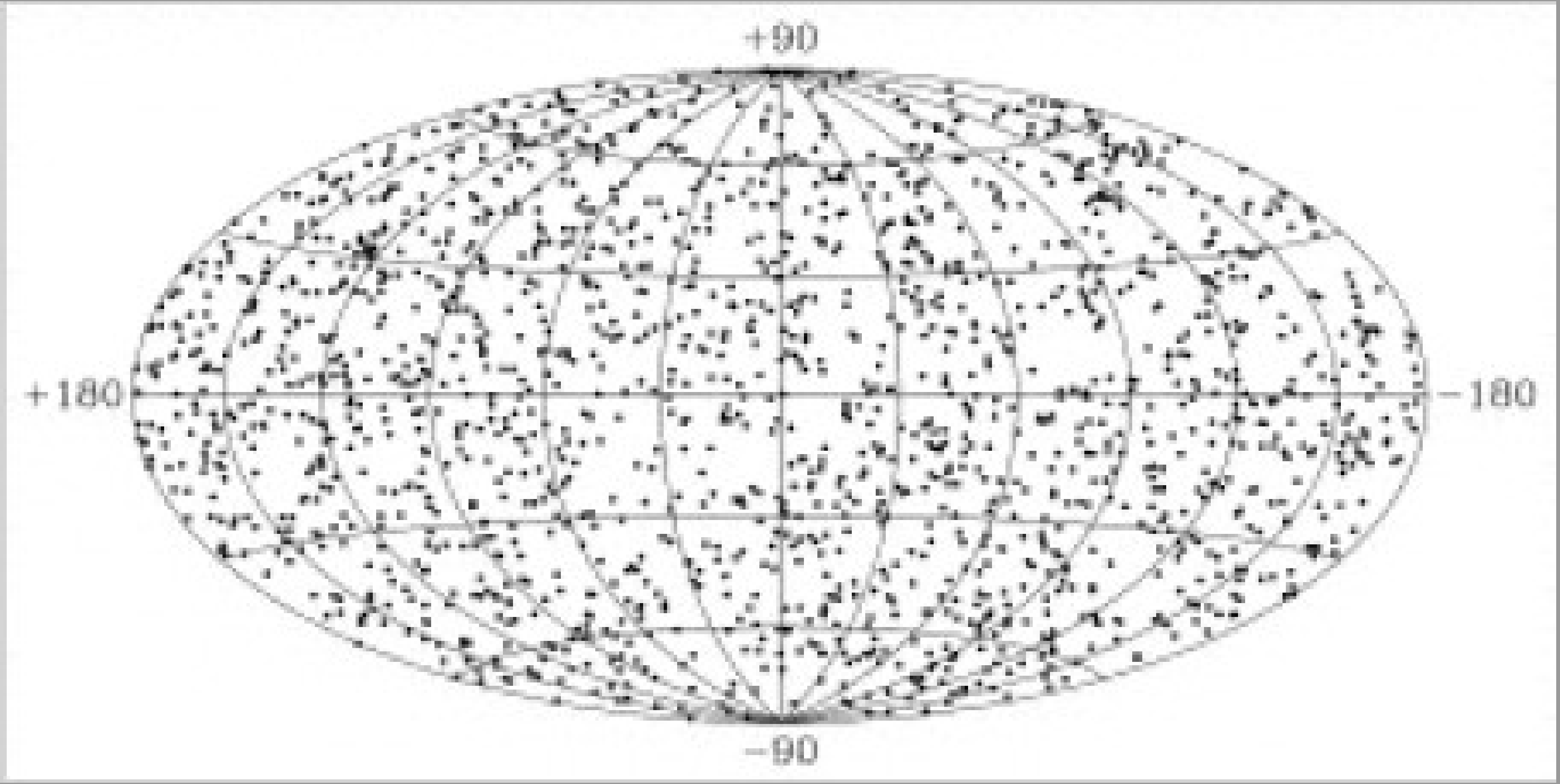


Nearby Galaxy
Same Galaxy
Three times the distance
$\bar{f}$ Star flux $\bar{f}/9$
n Star density 9n
Galaxy star field
Galaxy star field
Surface Brightness
$n\bar{f}$
$n\bar{f}$
What the CCD sees
What the CCD sees
Rms fluctuation
(inversely prop. to distance)
$\sqrt{n}\,\bar{f}$
$\sqrt{9n}\ \bar{f}/9$
$= \frac{1}{3}\sqrt{n}\,\bar{f}$
More CCD pixels
More CCD pixels
Variance divided by Mean
(Star flux)
$\bar{f} = \frac{(\mathrm{rms})^2}{\mathrm{mean}}$
$\bar{f}/9 = \frac{(\mathrm{rms})^2}{\mathrm{mean}}$
Blurred by atmosphere
Blurred by atmosphere

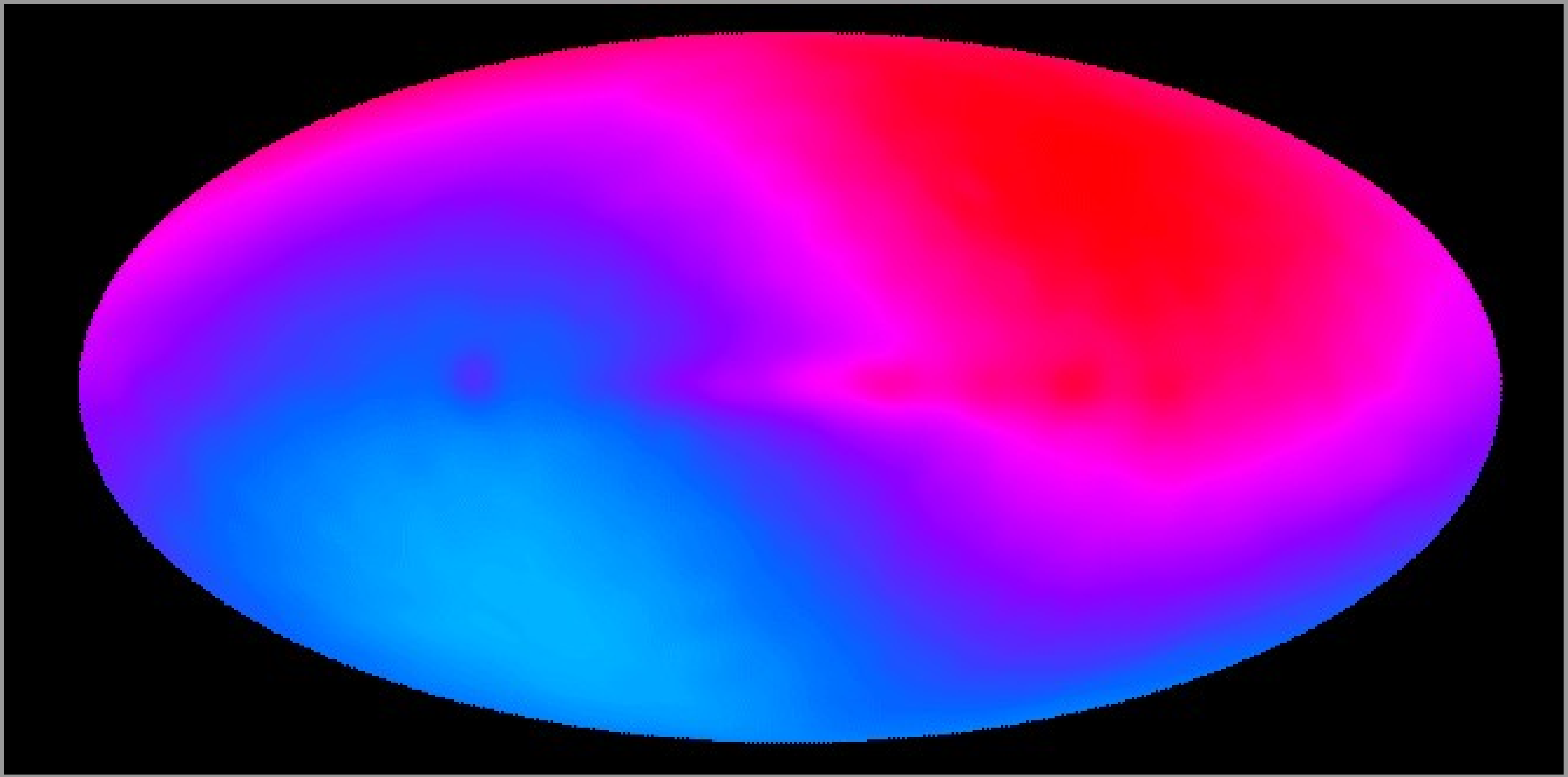


Corrections for Virgo infall, SBF distances, Tonry et al.

Gamma-ray Bursts



First ~1000 Gamma-ray bursts from BATSE



Dipole anisotropy in the Cosmic Microwave Background from COBE (1992). We are moving wrt. to the CMB at ~620 km/s.

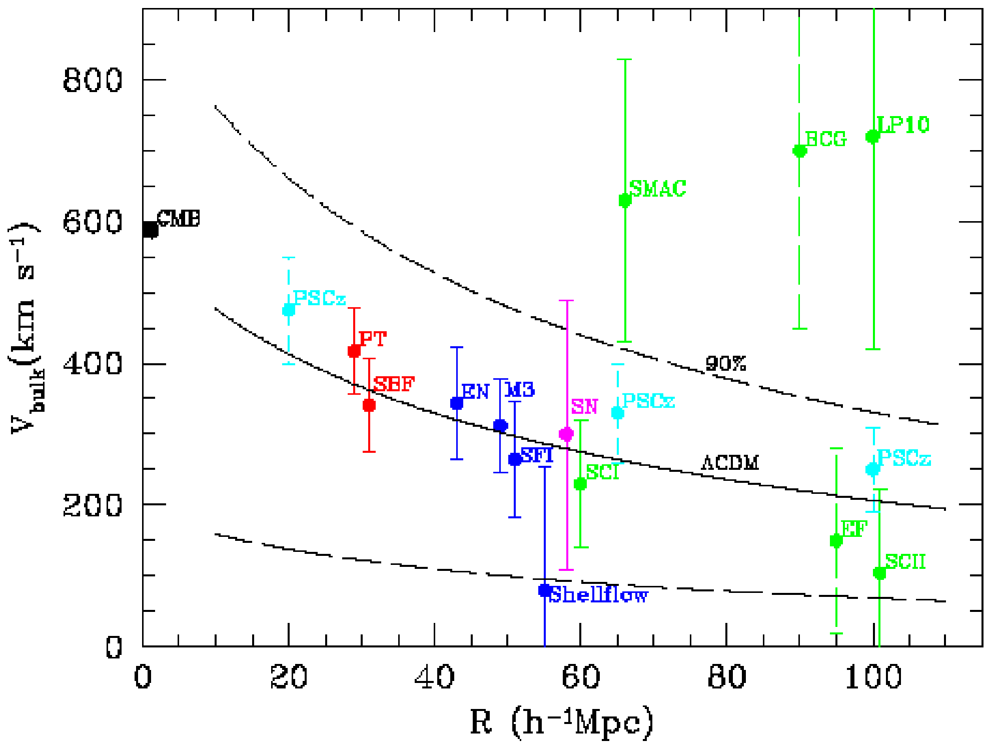


Figure 1. Amplitude of CMB bulk velocity in top-hat spheres about the LG, in comparison with theory. The curves are the predicted rms and cosmic scatter for a ΛCDM model. The measurements, based on the data listed in Table 1, are crudely translated to a top-hat bulk velocity. The error bars are random only. All the non-zero vectors (except BCG) point to $(l, b) = (280°, 0°) \pm 30°$. Shown as well are the LG dipole velocity (labeled "CMB"), and linear estimates from the PSCz redshift survey for $\beta = 0.7$. Care must be exercised when interpreting such plots since directions are not plotted and projected amplitudes (V_X, V_Y, V_Z) may differ substantially (*e.g.* Hudson et al. 2000).

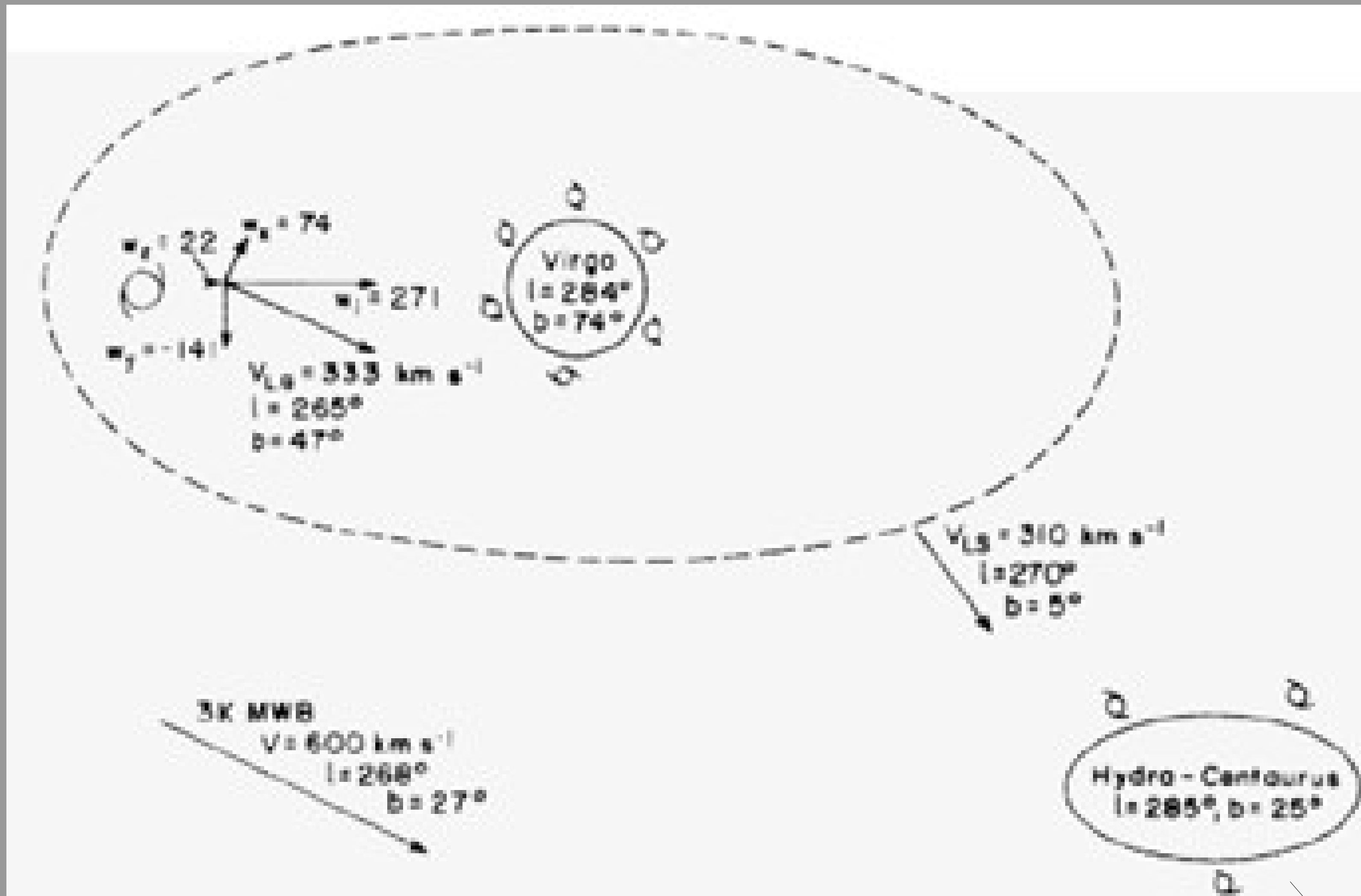
Bulk flows, Courteau & Dekel 2001

Table I. Recent Bulk Flow Measurements[†]

Survey	$R_{\rm eff}$ ($\rm km\,s^{-1}$)	V_B ($\rm km\,s^{-1}$)	Dist. Ind.
Lauer-Postman (BCG)	12500	700	BCG
Willick (LP10K)	11000	700	TF
Hudson et al. (SMAC)	8000	600	FP
Tonry et al. (SBF)	3000	290	SBF
Wegner et al. (ENEAR)	5500	340	D_n-σ
Dekel et al. (POTENT/M3)	6000	350	TF,D_n-σ
Riess et al. (SNIa)	6000	300	SN Ia
Courteau et al. (SHELLFLOW)	6000	70	TF
Dale & Giovanelli (SFI)	6500	200	TF
Colless et al. (EFAR)	10000	170	FP
Dale & Giovanelli (SCI/SCII)	14000	170	TF

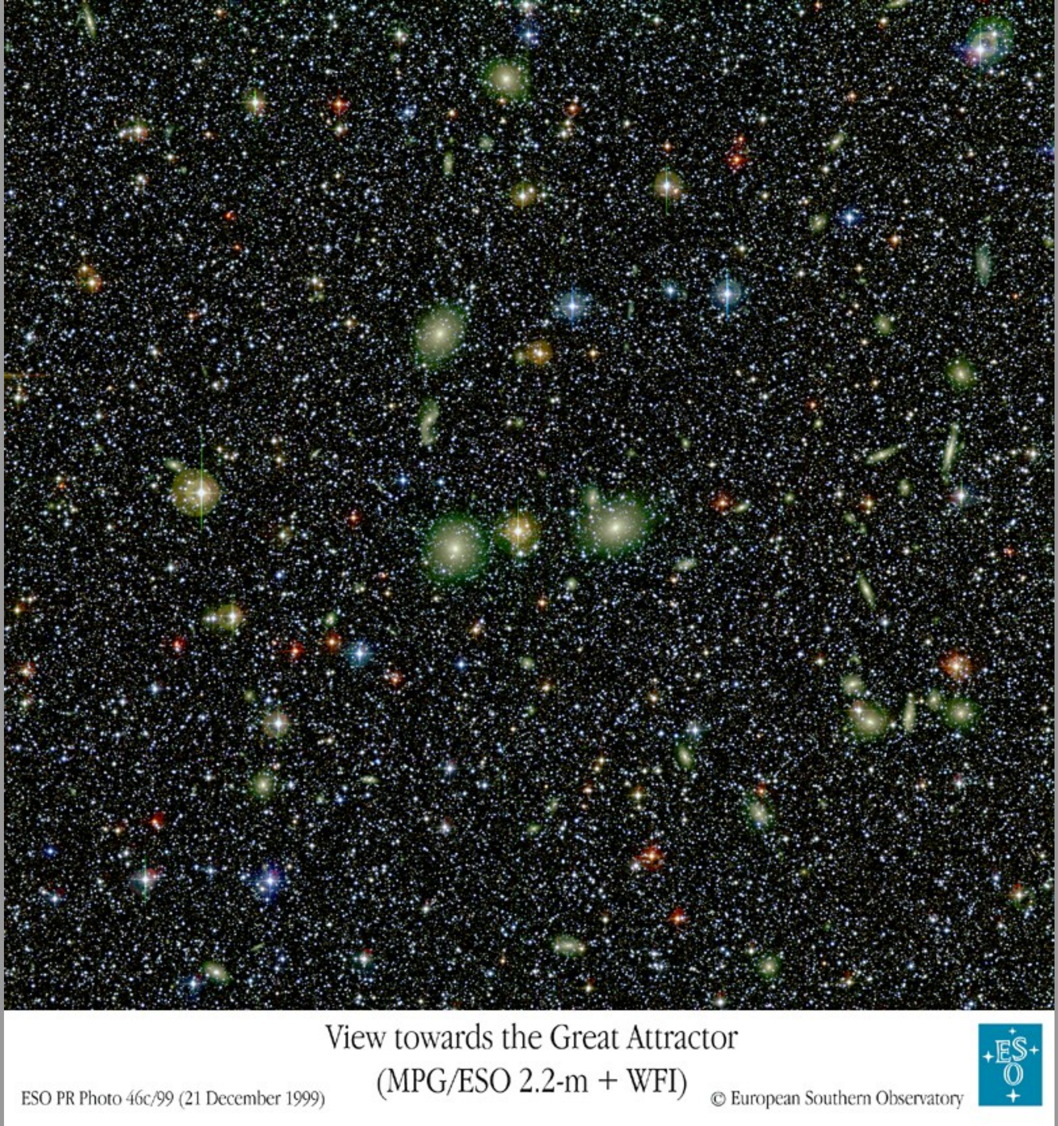
† All references in CFW2000. With the exception of Lauer-Postman (1994), all results are post-1999.

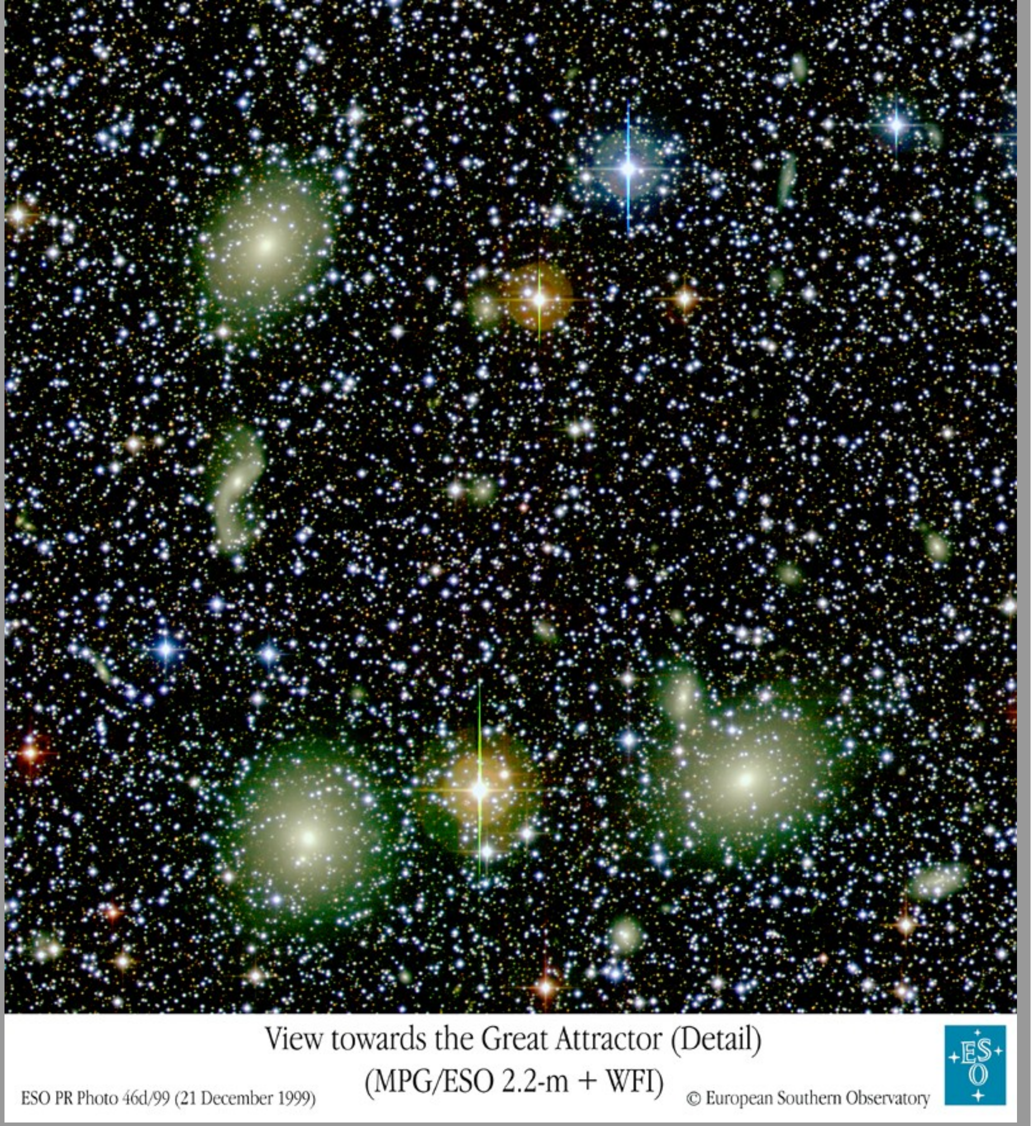
Bulk flows, Courteau & Dekel 2001



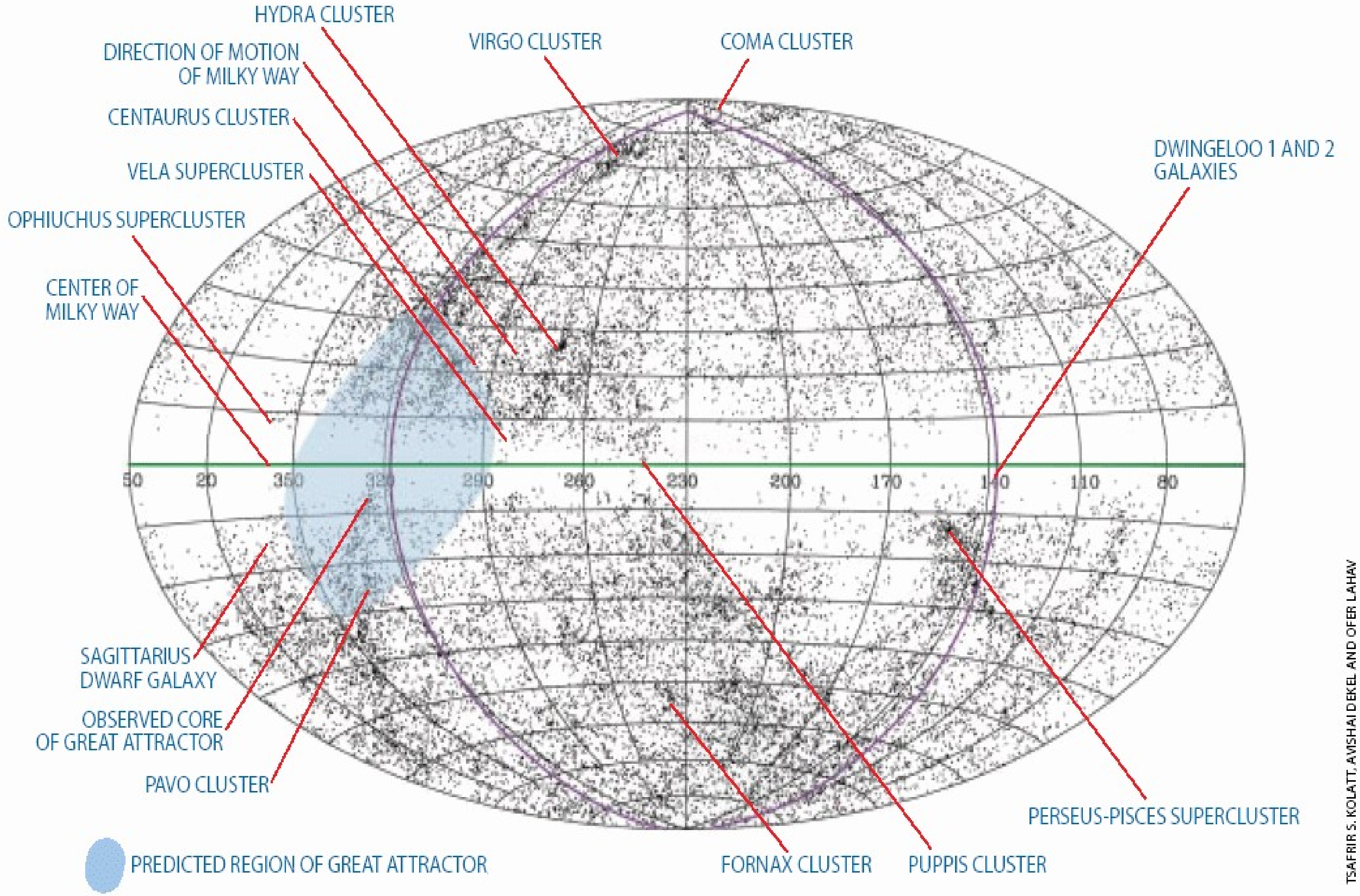
Great Attractor

Bulk flows, Aaronson et al. (1986)





Abell 3627, heart of the Great Attractor?

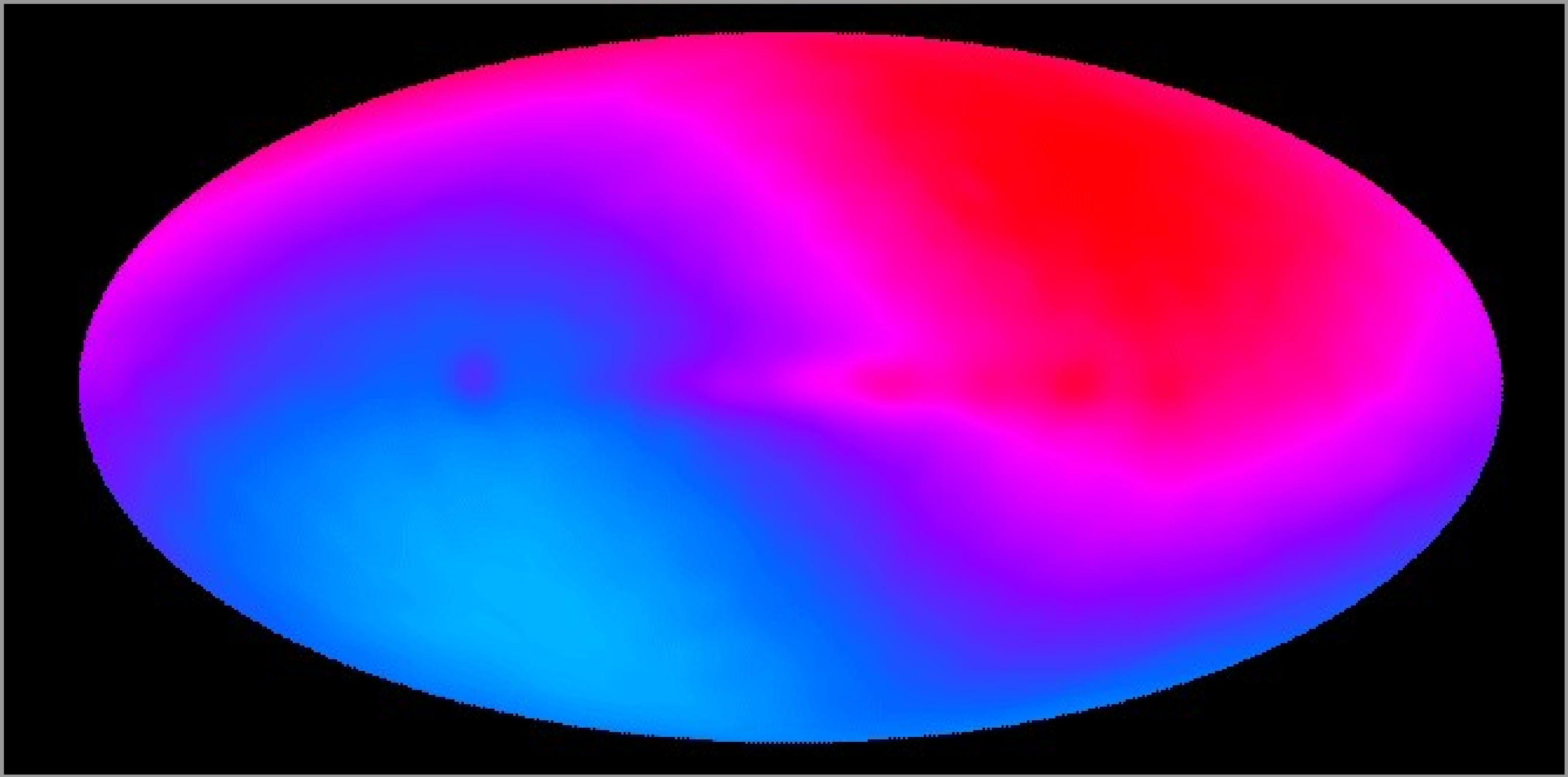


30,000 GALAXIES, culled from three standard astronomical catalogues, are shown as dots on this map. The galaxies appear all over the sky except in the so-called zone of avoidance, which corresponds to the plane of our Milky Way galaxy (*green horizontal center line*). Outside the zone, the galaxies tend to clump near a line that traces out the Supergalactic Plane (*purple line*).

The GA lies in the "zone of avoidance", it's hard to study

Hot Big Bang Model

- Universe is isotropic and homogeneous
  - This is only true when you average over sufficiently large volumes
- This is also know as the Cosmological Principle



Dipole anisotropy in the Cosmic Microwave Background from COBE (1992). We are moving wrt. to the CMB at ~620 km/s. Once you subtract the dipole velocity the CMB is isotropic at a level of 10^{-5} (also must remove the Galactic component).

The Universe is expanding

The distance between particles is increasing with time at the rate

$$\frac{dl}{dt} = H_0 l$$

The constant of proportionality is time dependent and H_0 is the present value, Hubble's constant. The best estimate of H_0 is 72±4 km/s/Mpc (WMAP team).

We can define a Hubble length:

$$c/H_0 \sim 4000 \text{ Mpc}$$

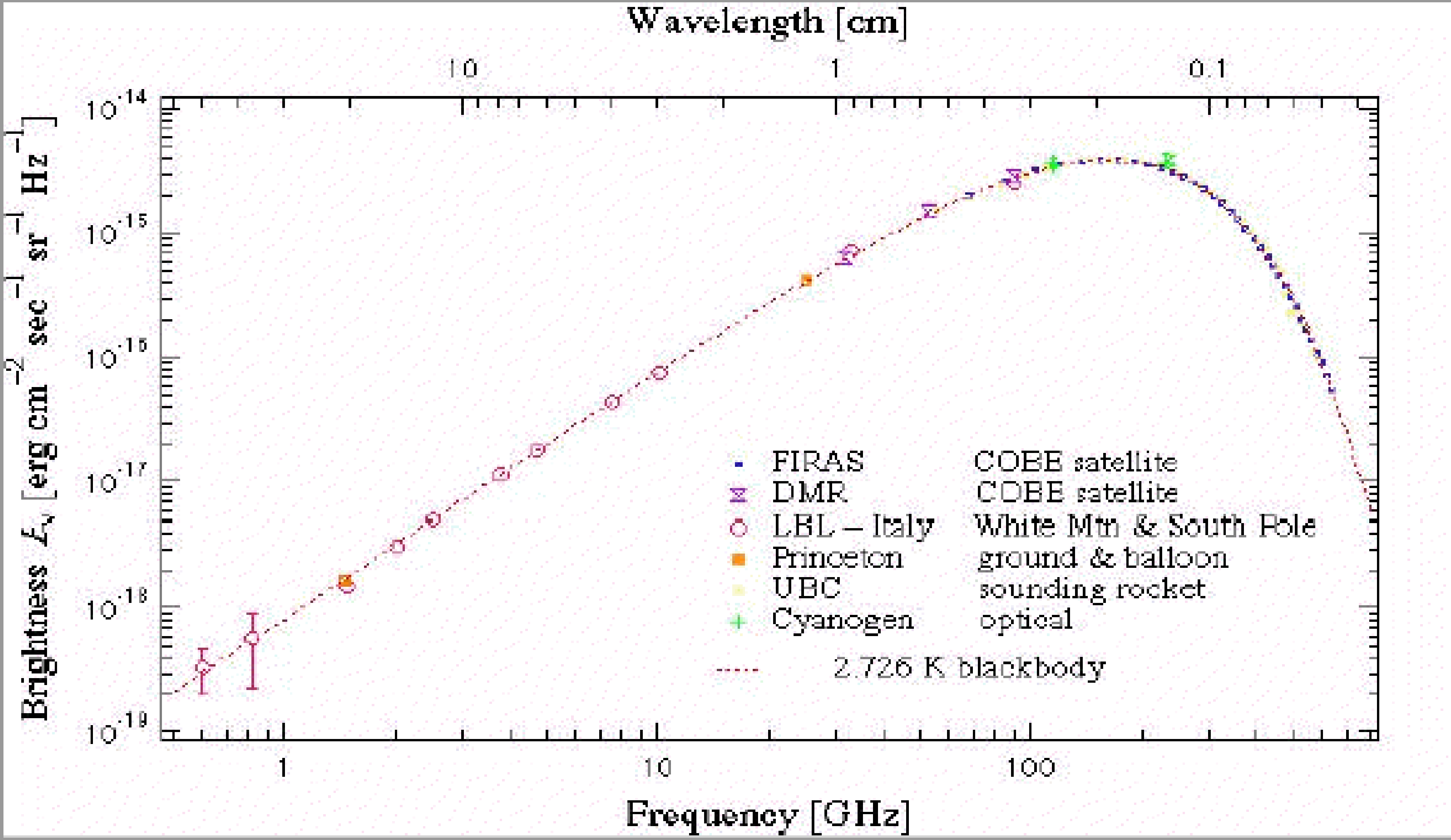
This is the point where the recession velocity is equal to the speed of light. Clearly to do this correctly we need a fully relativistic treatment.

We can also define a Hubble time

$$1/H_0 \sim 10^{10} \text{ years}$$

this gives the age of the universe (to an order of magnitude).

Universe started from a hot dense state



The Robertson-Walker Metric

General relativity is a geometric theory describing the curvature of space time. We want to describe the distance between two events (an event happens at a coordinate in a 4-dimensional spacetime. In 3-dimensional space, we can describe the distance between two points as,

$$ds^2 = du^2 = dx^2 + dy^2 + dz^2$$

The distance between two points is found by integrating along the path. In spacetime the interval between these two points is,

$$ds^2 = c^2 dt^2 - du^2$$

We must integrate along these coordinates to find the distance.

The Robertson-Walker Metric cont.

For an expanding universe, the space distance between two points is,

$$ds^2 = c^2 dt^2 - R^2 du^2$$

Writing this in spherical coordinates in a Cartesian geometry we get,

$$du^2 = dr^2 + r^2 d\theta^2 + r^2 \sin^2\theta \, d\phi^2$$

But space-time isn't necessarily flat, it may have a curvature so,

$$du^2 = \frac{dr^2}{1 - kr^2} + r^2 d\theta^2 + r^2 \sin^2\theta \, d\phi^2$$

The Robertson-Walker Metric cont.

Putting this all together, we obtain

$$\begin{aligned} ds^2 &= c^2dt^2 - R^2du^2 \\ &= c^2dt^2 - R^2\left\{\frac{dr^2}{1-kr^2} + r^2d\theta^2 + r^2\sin^2\theta d\phi^2\right\} \end{aligned}$$

Where r is the co-moving coordinate, R(t) is the scale factor of the expansion, d_p = R(t) x r is the "proper distance", and k is the curvature. This equation depends only on the geometry of the space-time and not on gravitational theory (which determines the factors R(t) and k).

Distance Measures

The proper distance is defined as $d_p = \int R du$. For light, ds = 0, and we can use the RW metric to find,

$$c^2 dt^2 = R^2 du^2 = R^2 \left\{ \frac{dr^2}{1 - kr^2} + r^2 d\theta^2 + r^2 \sin^2\theta \, d\phi^2 \right\}$$

To simplify things, let's put ourselves at the origin, then
The light's path is purely radial ($d\theta = 0$ and $d\phi = 0$).

$$c^2 dt^2 = R^2 \left\{ \frac{dr^2}{1 - kr^2} \right\}$$

Taking the square root of both sides and integrating

$$\int_{t_0}^{t_1} \frac{c}{R} dt = \int_u^0 \frac{dr}{(1 - kr^2)^{1/2}}$$

Distance Measures cont.

$$\int_{t_0}^{t_1} \frac{c}{R} dt = \int_u^0 \frac{dr}{(1-kr^2)^{1/2}}$$

In general this is non-analytic. In a Λ=0 universe,

$$d_p = \frac{c}{H_0 q_0^2 (1+z)} \left\{ q_0 z + (q_0 - 1) \left[(2q_0 z + 1)^{1/2} - 1 \right] \right\}$$

For non-zero Λ,

$$d_p = |\Omega_k|^{-\frac{1}{2}} \sinh \left\{ |\Omega_k|^{\frac{1}{2}} \int_0^z \left\{ (1+z)^2 (1 + \Omega_M z) - \Omega_\Lambda z (2+z) \right\}^{\frac{1}{2}} dz \right\}$$

Assuming $\Omega_k<0$, if $\Omega_k>0$ then the sinh becomes a sin and if $\Omega_k=0$ then the sinh and the Ω_k drop out and all that's left is the integral.

Distance Measures cont.

For a source that has a flux F, and a known luminosity we can define the luminosity distance d_L

$d_L = L/4\pi F$ or we can write

$F = L/4\pi d_L$

There are two effects on photons, comological redshift reduces the energy of a photon by (1+z) and time dilation increases the time between photon arrival time by (1+z)