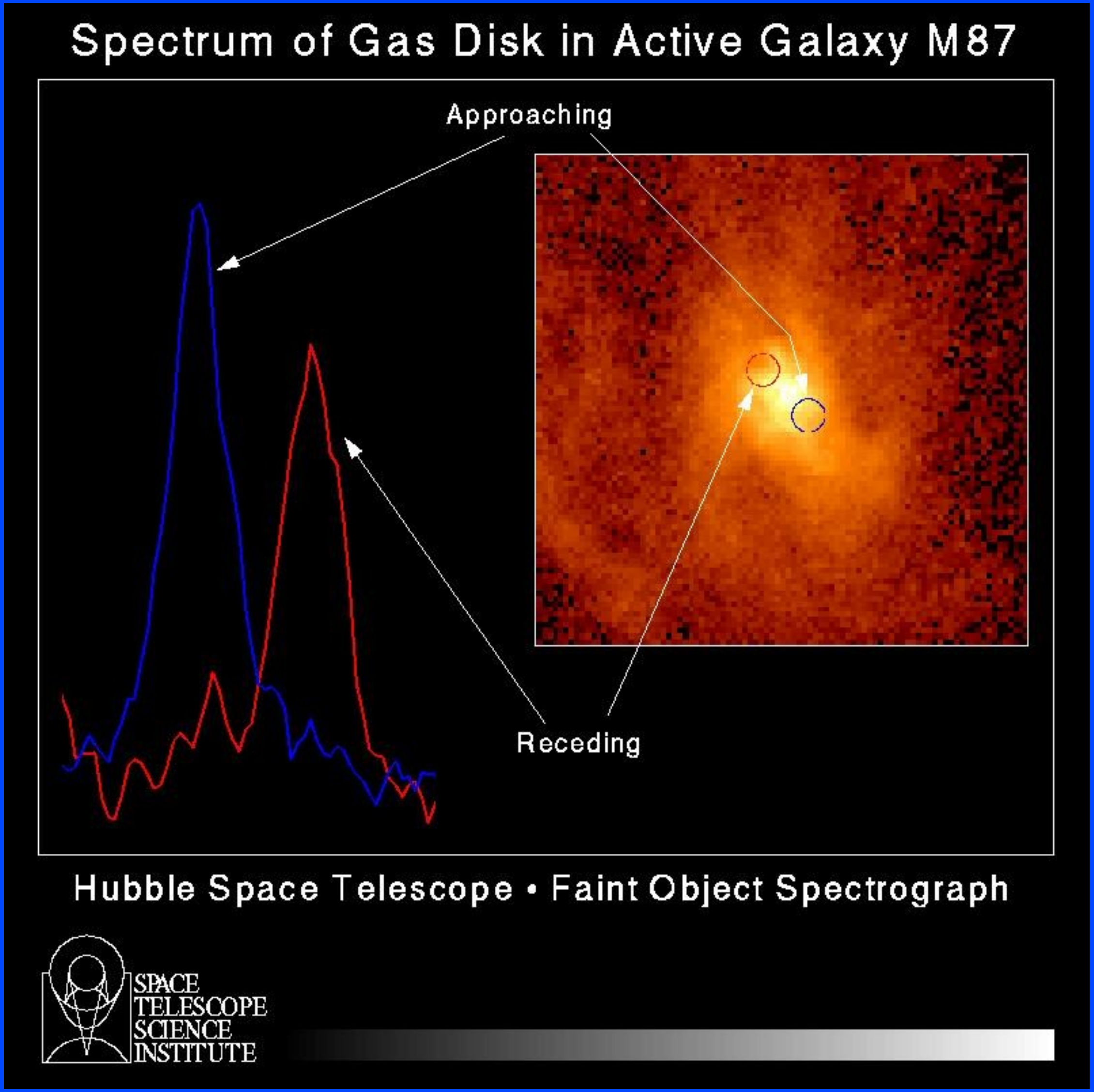
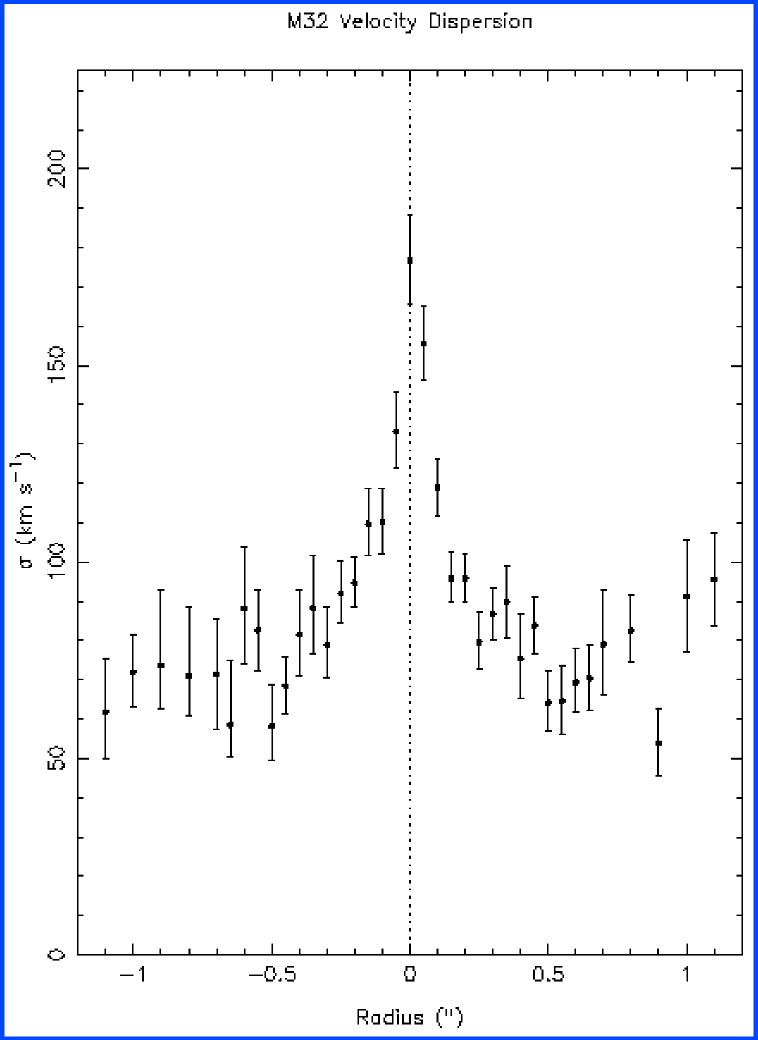
Black Holes in Ellipticals



The first direct detection of gas being drawn into a BH. (Ford et al. 1994)

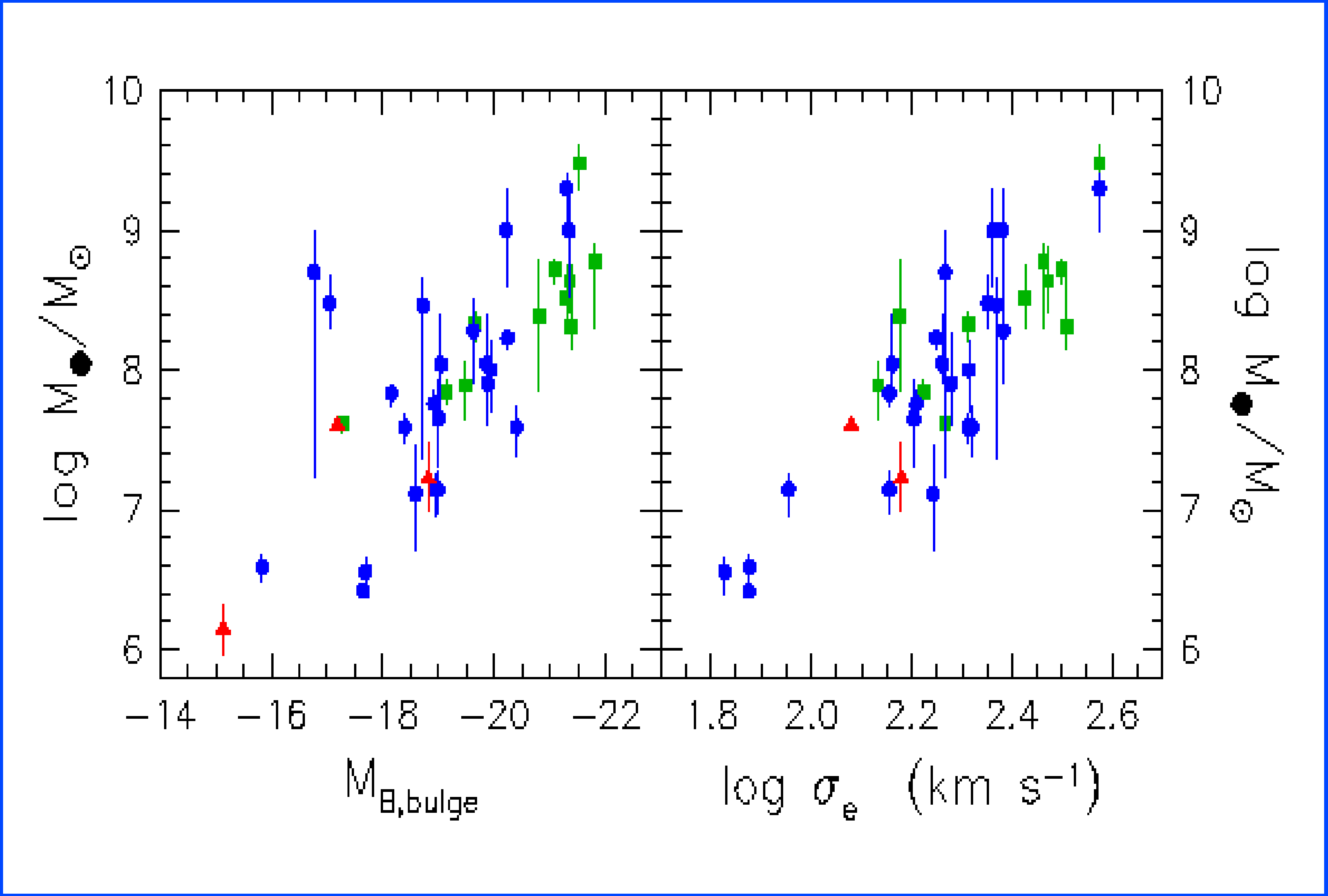
Black Holes in Ellipticals cont.



We can also infer the presence of a BH by looking at the stellar velocity dispersion in the nuclear region (M32).

Black Holes in Ellipticals cont.

- Currently there are at least 40 BH candidates in nearby ellipticals and in the bulges of spirals
- There is a strong correlation between black hole mass and galaxy luminosity and velocity dispersion



Black Hole mass vs bulge mass and σ (Kormendy 2003)

Why is this correlation so good?

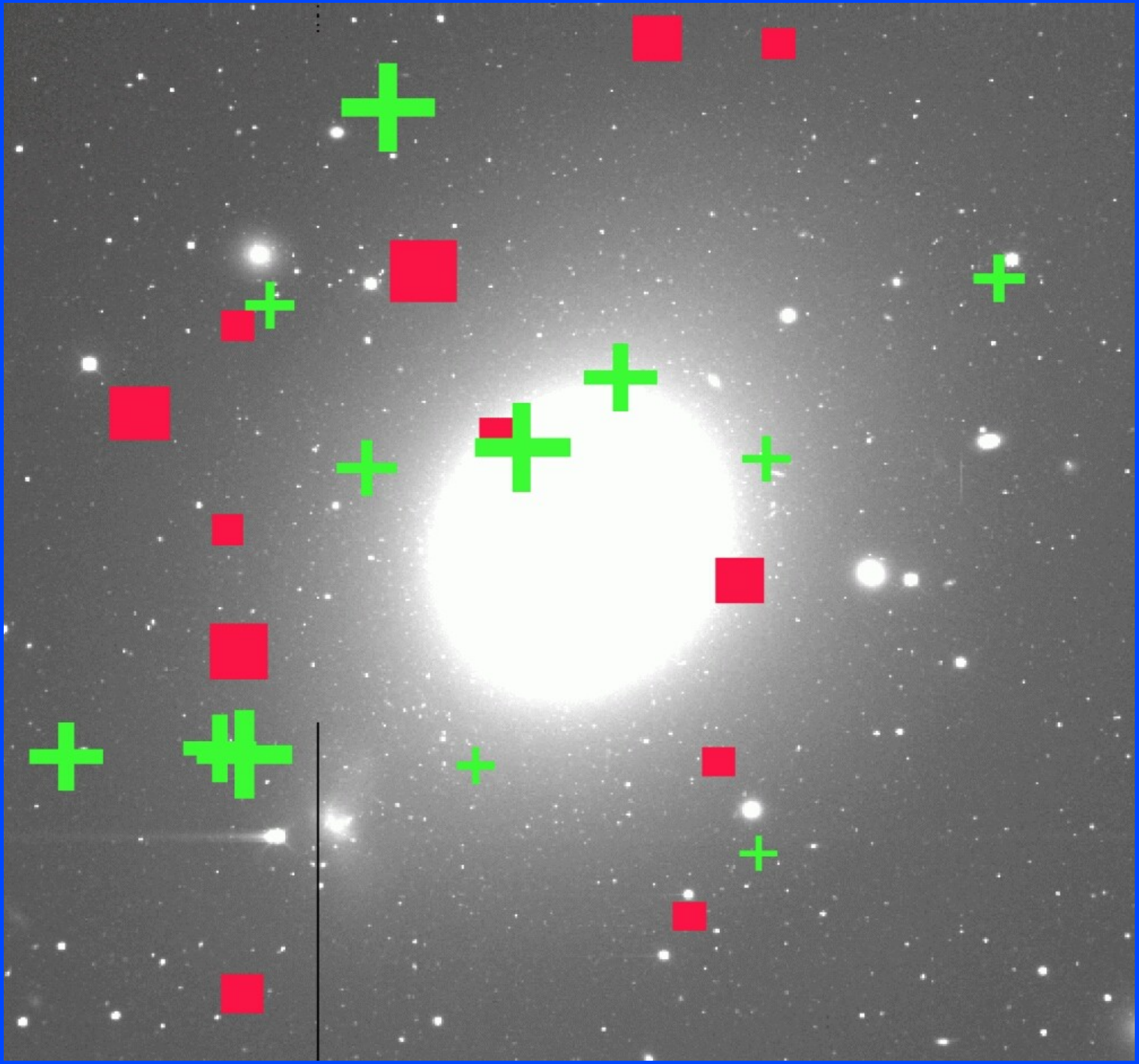
- Observations imply BH mass 'knows' about the formation of bulges and ellipticals
  - All proto-galaxy clumps harbored a BH with the BH mass proportional to the bulge mass and BHs merged as the galaxy formed
  - BH started out small and grew as galaxy formed – e.g., central BH is fed during process of formation
    - Maybe this acts as the seed for the formation process (implies ->all galaxies have BHs

Dark Matter in Elliptical Galaxies

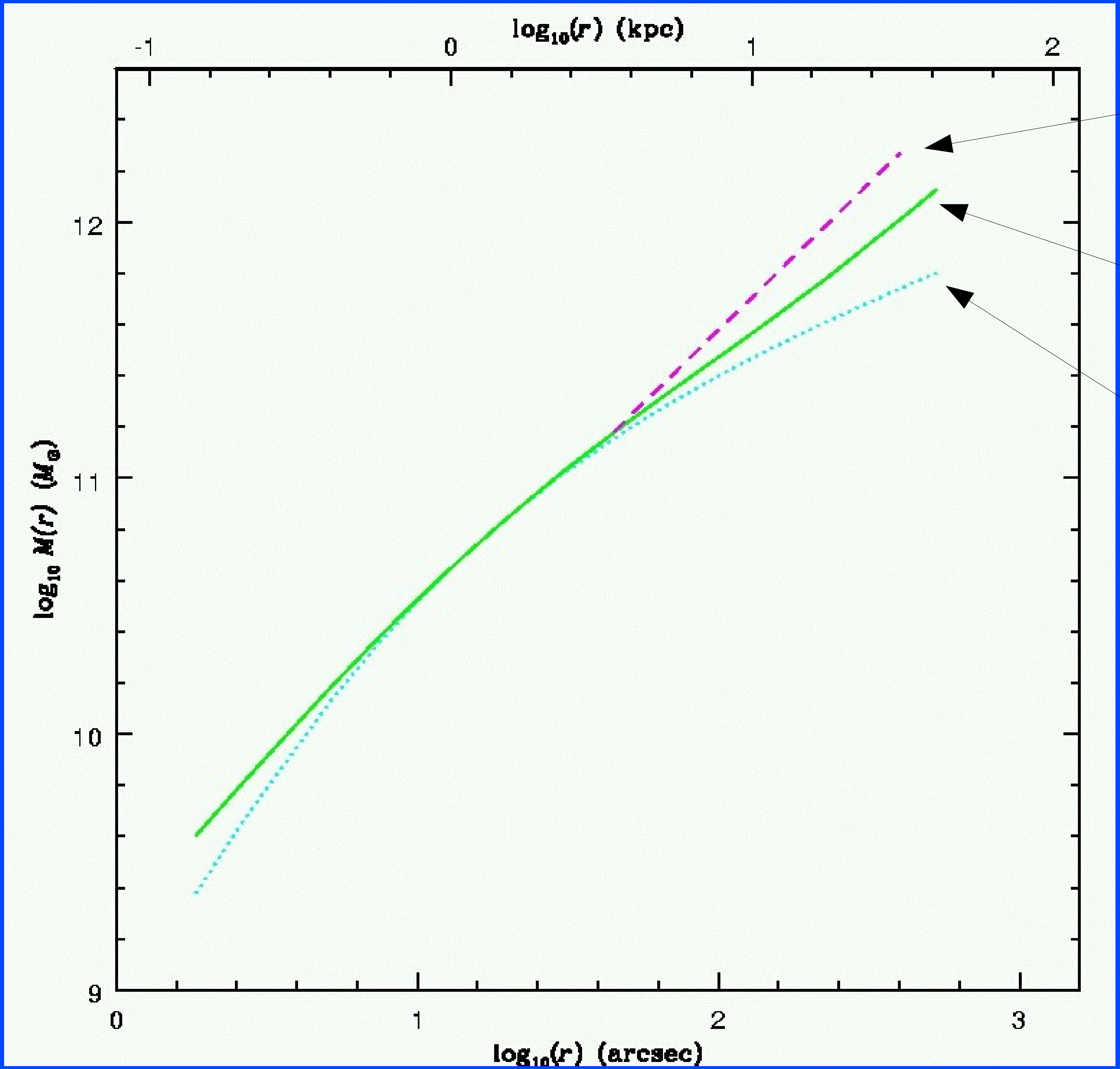
- Looking at just the stars we expect the mass to light ratio of the stellar population to be $M/L_V \sim 3\text{-}5$
- Orbital motions of the stars in the centers of ellipticals imply they are not dark matter dominated
- In the few ellipticals containing cold gas, we can measure the orbit of the gas we find M/L ~ 10 –20
  - But are these galaxies typical of all E's?
- Also can use the amount of mass required to retain the hot x-ray gas, find M/L~100 for galaxies with large x-ray halos
  - Mostly Luminous and mid-sized ellipticals

Dark Matter in Elliptical Galaxies cont.

- Are there any other ways to look at velocities?
  - globular clusters and planetary nebulae
  - Recent results of PN dynamics around (a few) elliptical galaxies show NO dark matter, the galaxies are “naked”
  - Recent results of GC dynamics around (a few) elliptical galaxies show large dark halo.



PN velocities in NGC 4472, + is blueshifted, red is redshifted. (Romanowsky 2001)

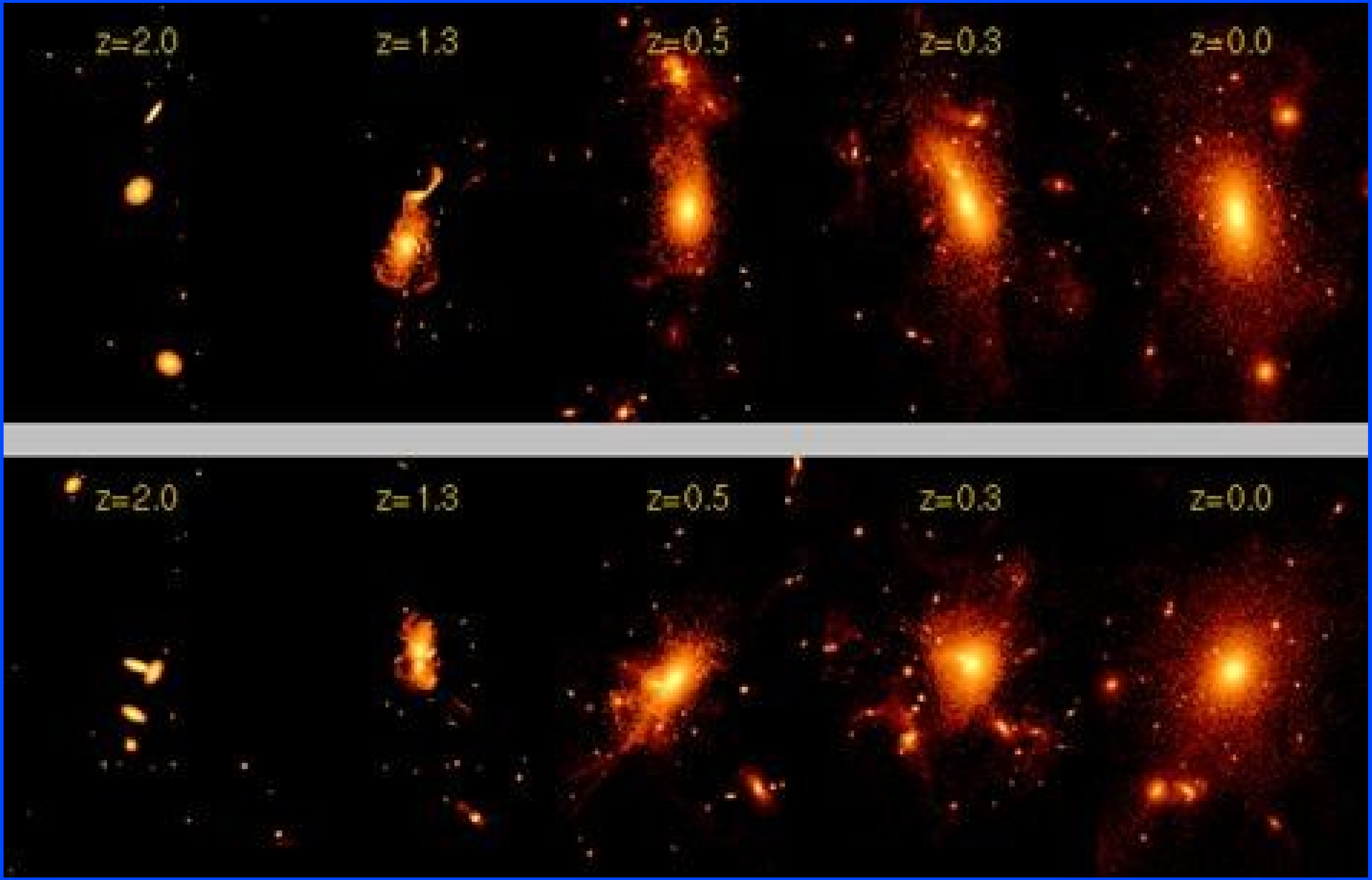


Mass from
Stars & M/L

Mass from
PN & Stars

Mass from
GC velocites

Formation of Ellipticals



Formation of Ellipticals cont.

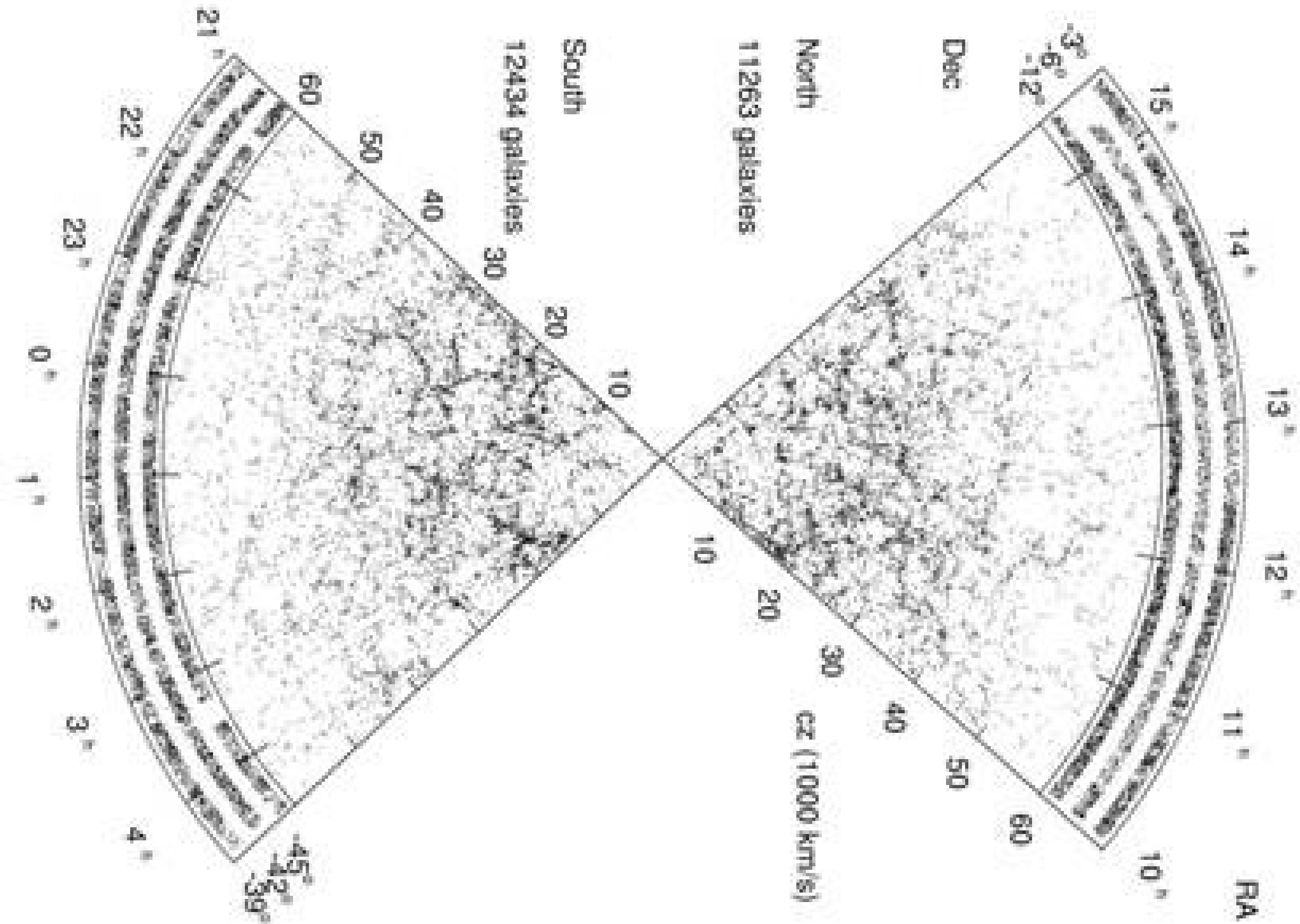
- Equal mass mergers can account for the massive ellipticals with boxy isophotes and little rotation
- Unequal mass mergers can explain less massive ellipticals with disky isophotes and higher rotation

Clusters of Galaxies

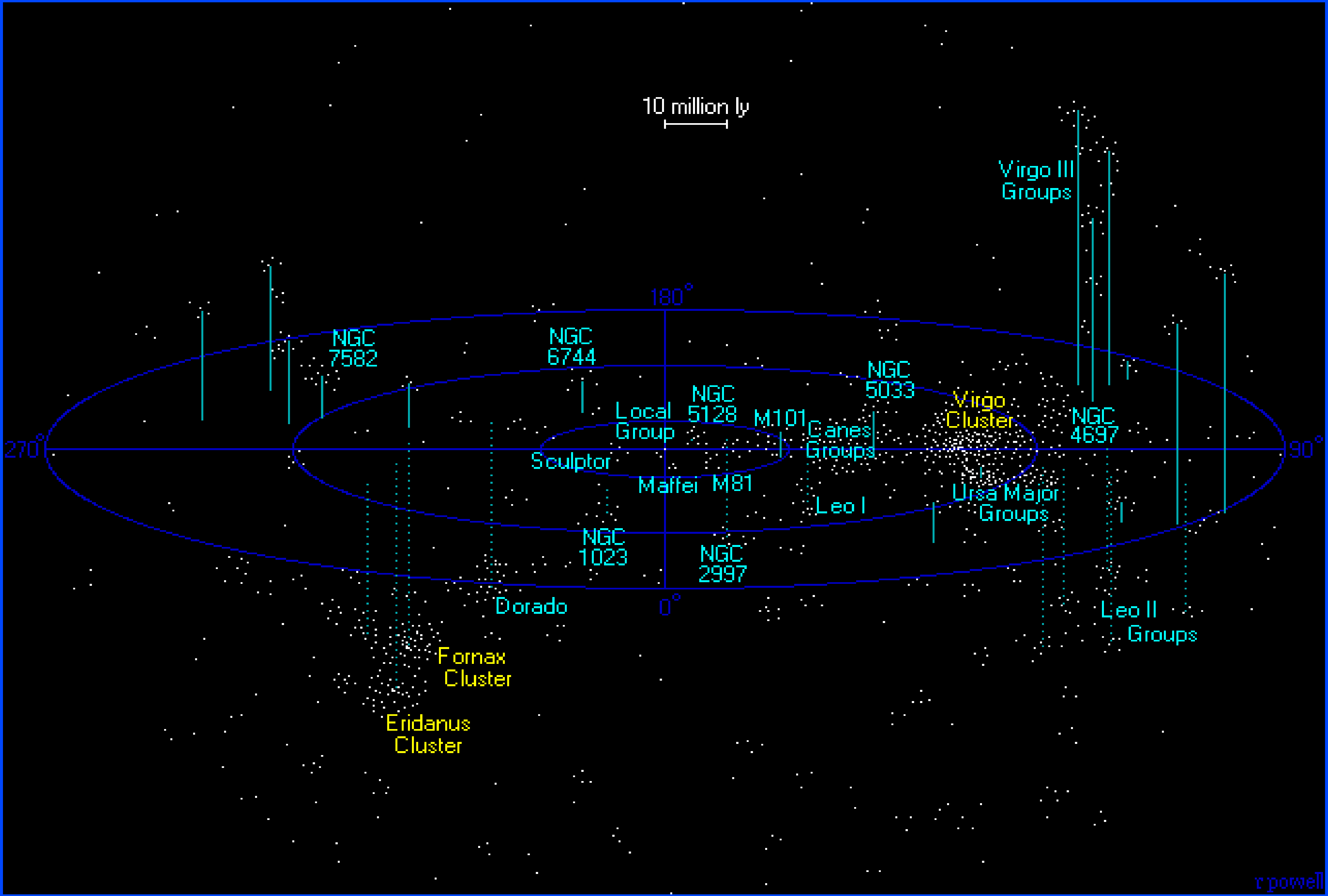
Abell 2218 (HST image)

- 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}

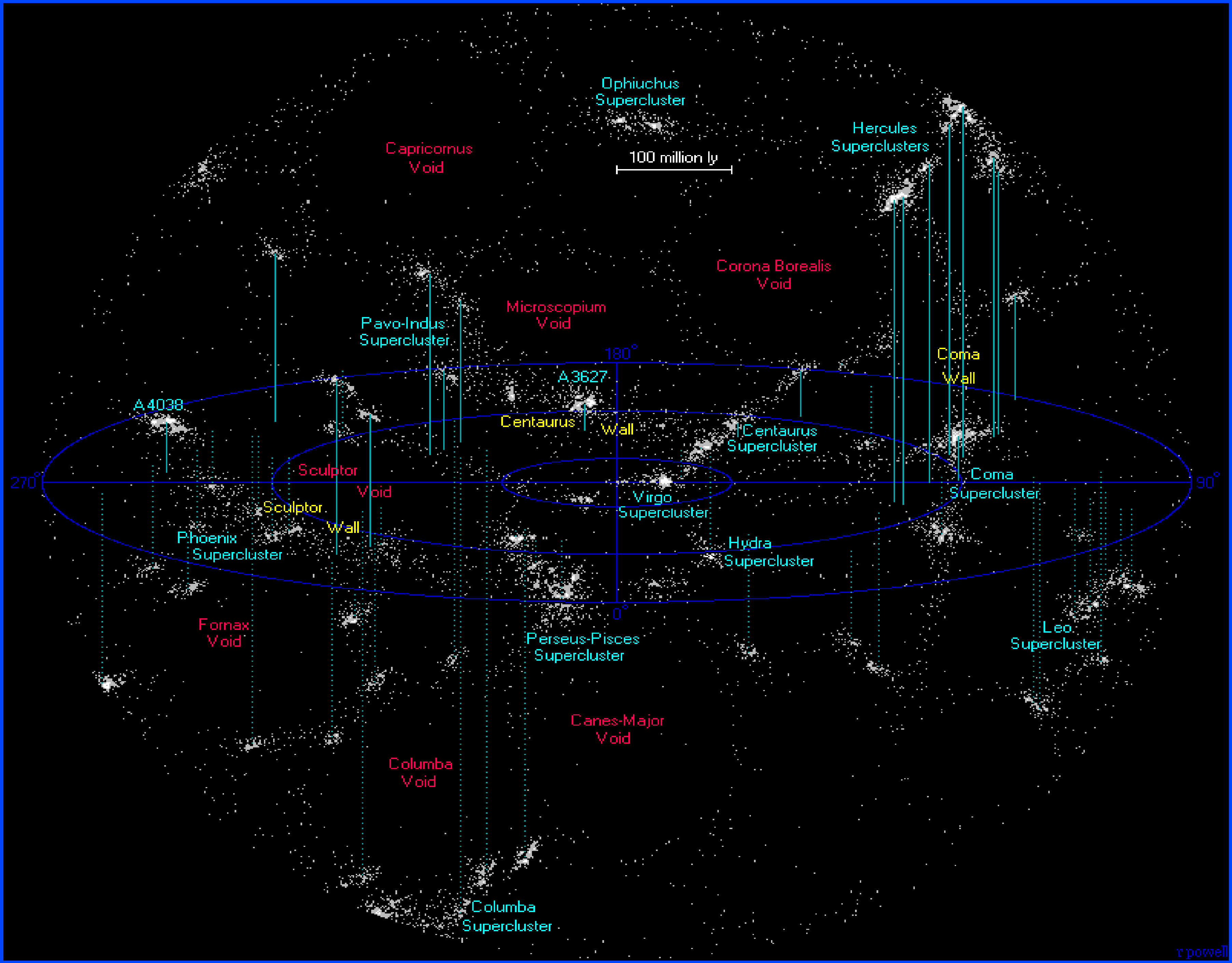
- Clusters and groups have very similar sizes.
  - Clusters span 1-3 Mpc
  - Groups span 0.25-1 Mpc
- In general Clusters a much denser environments
  - Compact groups can be as dense as clusters


RA
Dec
-3°
-6°
-12°
-45°
-42°
-39°
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

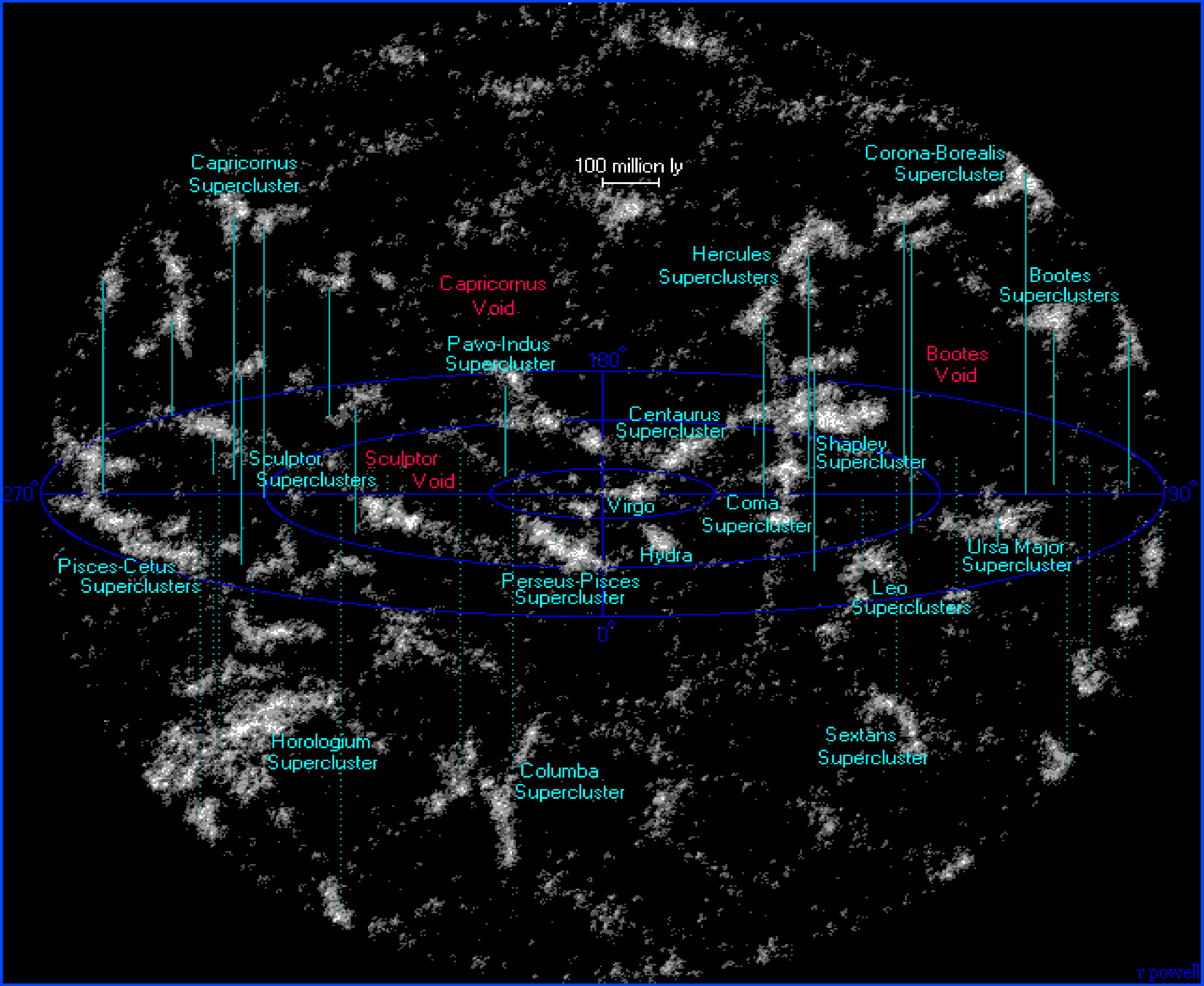
- These large scale structures cause peculiar velocities, deviations from the Hubble flow, due to their gravitational attraction.
- We can use large galaxy redshift surveys to trace the mass distribution of the universe and measure Ω_m
- The amount of clustering we observe also provides strong constraints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



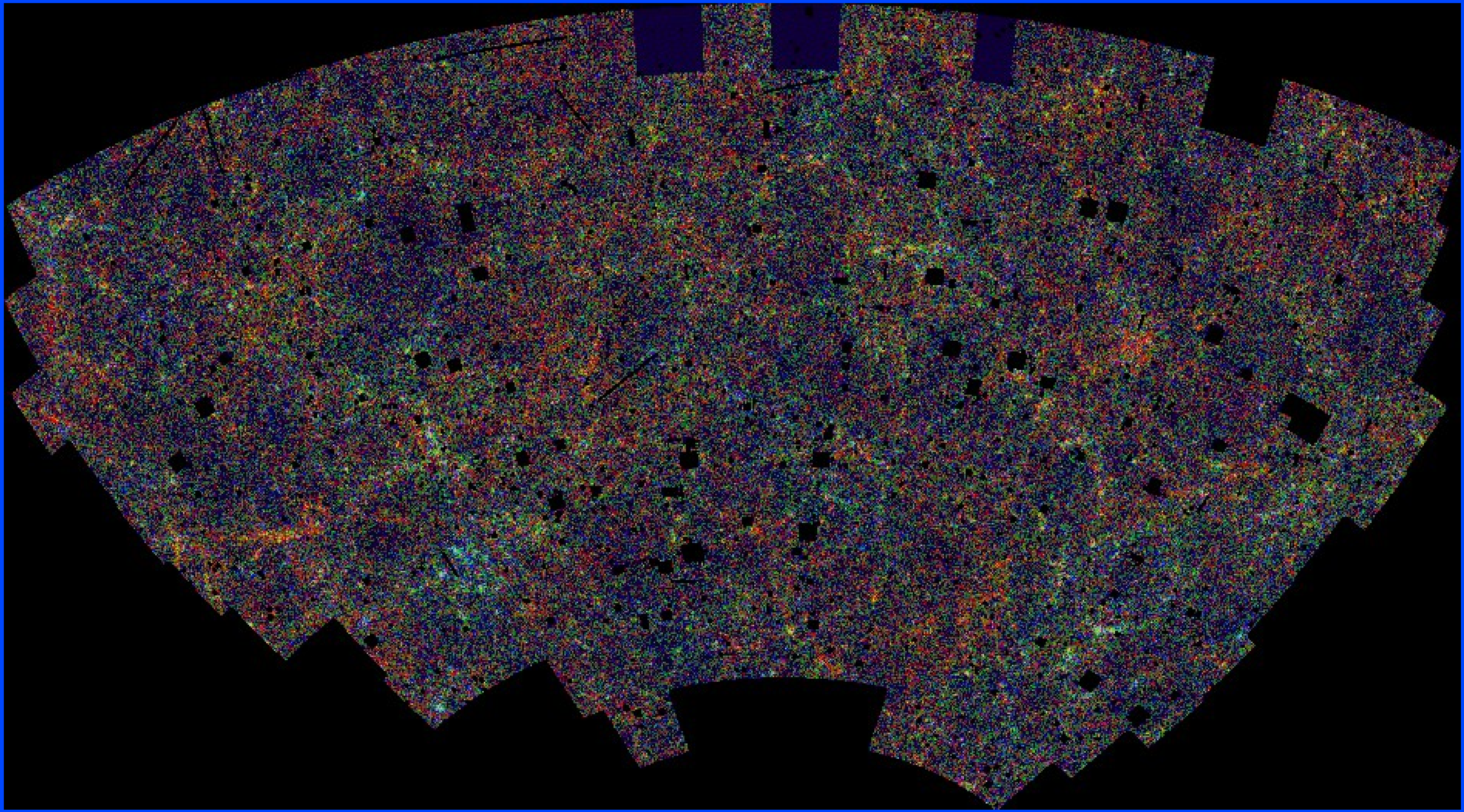
Local Supercluster



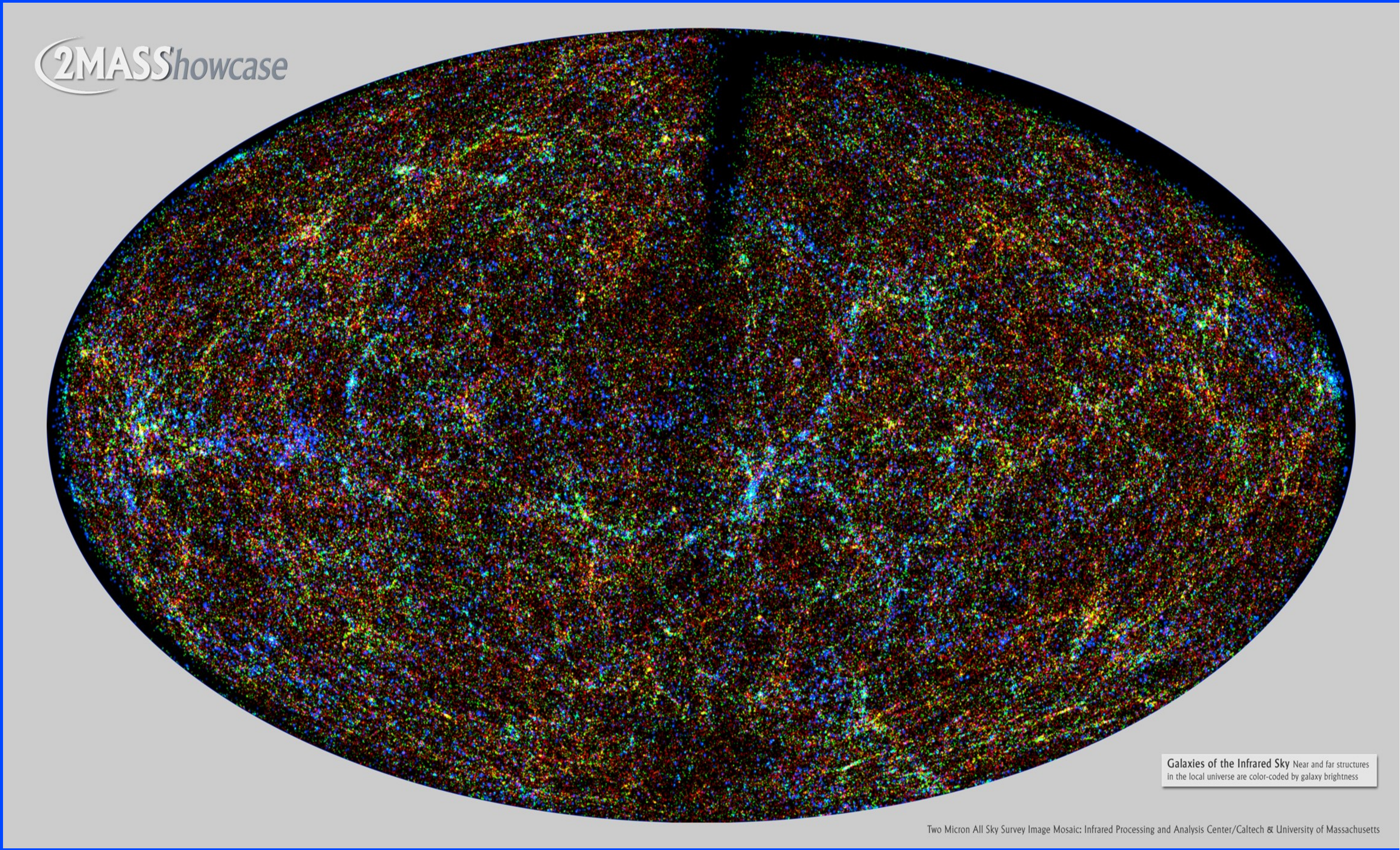
Superclusters



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

Modeling Number Counts

We can model the number counts by using

$$d^2 A(m, z) = \Phi(M)(1+z)^3 \frac{dV}{dz} dm\, dz$$

This gives the number of galaxies between apparent magnitude m and m+dm in the shell defined by the redshift range z to z + dz. Φ(M) is the luminosity function. We can relate the apparent and absolute magnitudes by $m = 5\log(D_L) + M + K(z)$

The number of galaxies per magnitude bin per area on the sky is given by

$$N(m)\,dm = \int_0^{z_{form}} d^2 A(m,z)\,dz$$

Where z_{form} is the redshift at which galaxies form and the luminosity function is given by the Schechter function:

$$\Phi(M) = \Phi e^{-0.92(\alpha+1)(M-M_s)} e^{-0.92(M-M_s)}\,dM$$

Where M_s is the characteristic magnitude and α is the slope at the low luminosity end

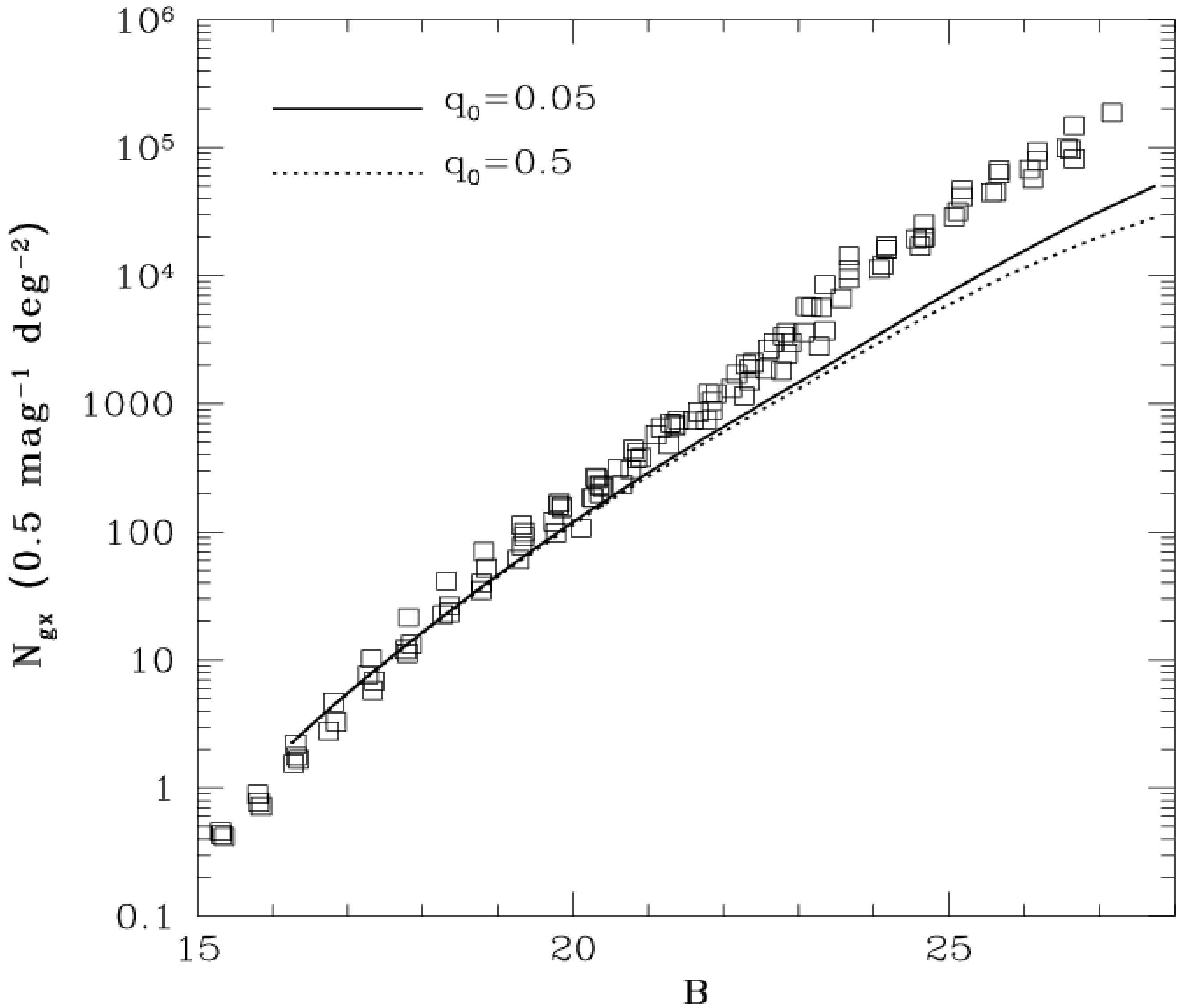


Figure 1. The number counts in the B band. The data has been taken from the literature (see text for references). Also we plot predictions from no-evolution models.

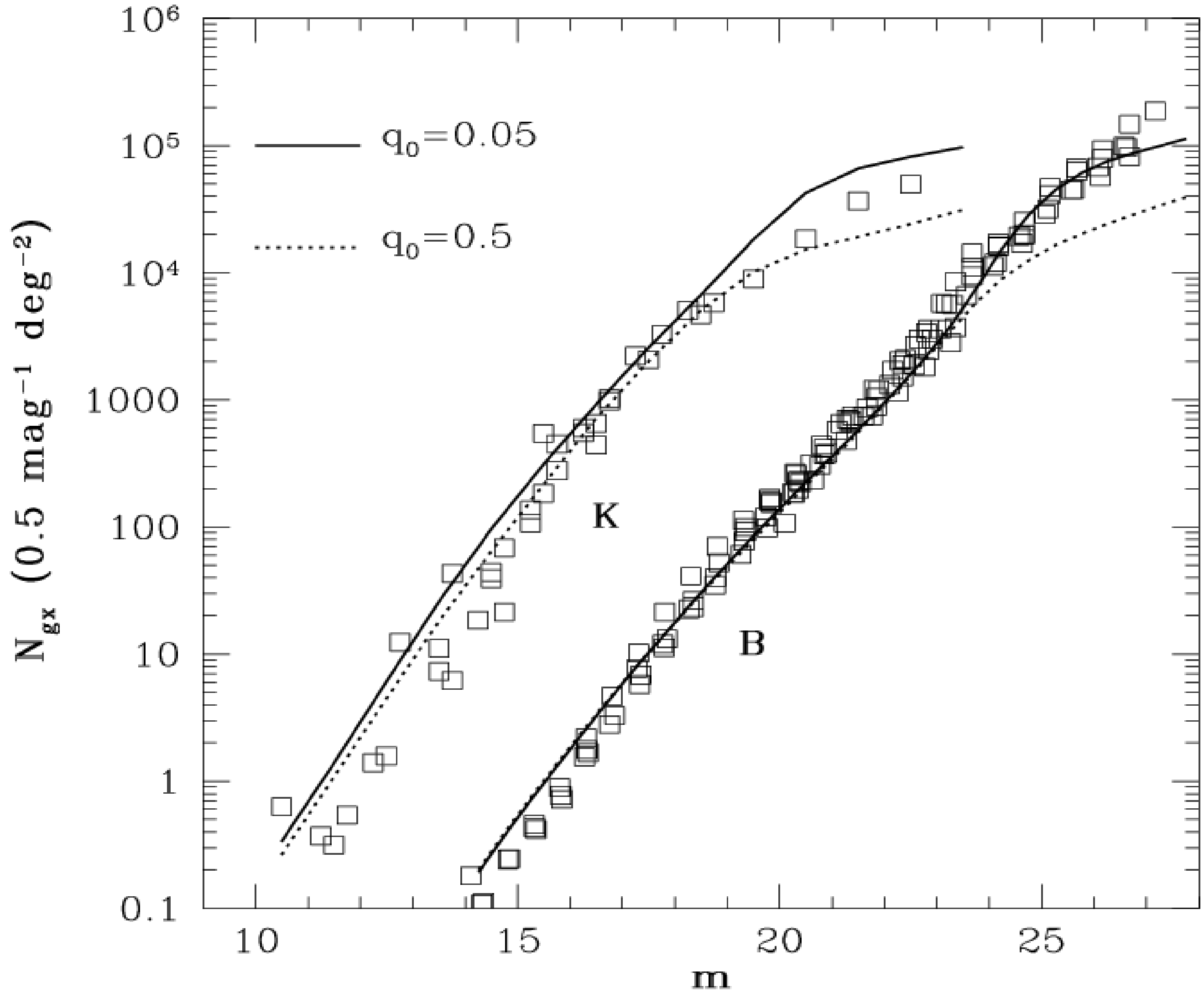


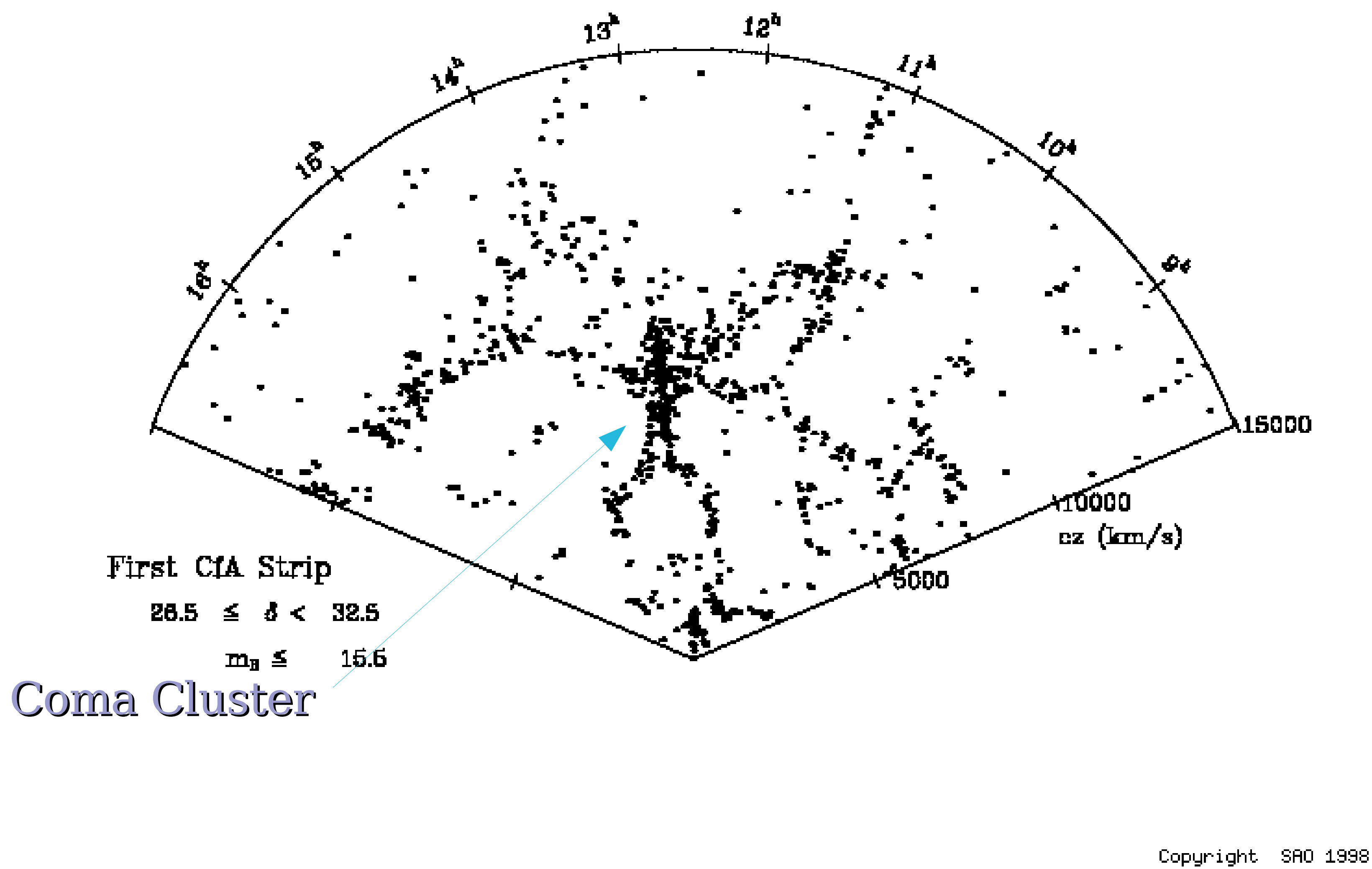
Figure 3. The number counts in the B and K bands, and predictions from luminosity evolution models with dust.

Redshift Surveys

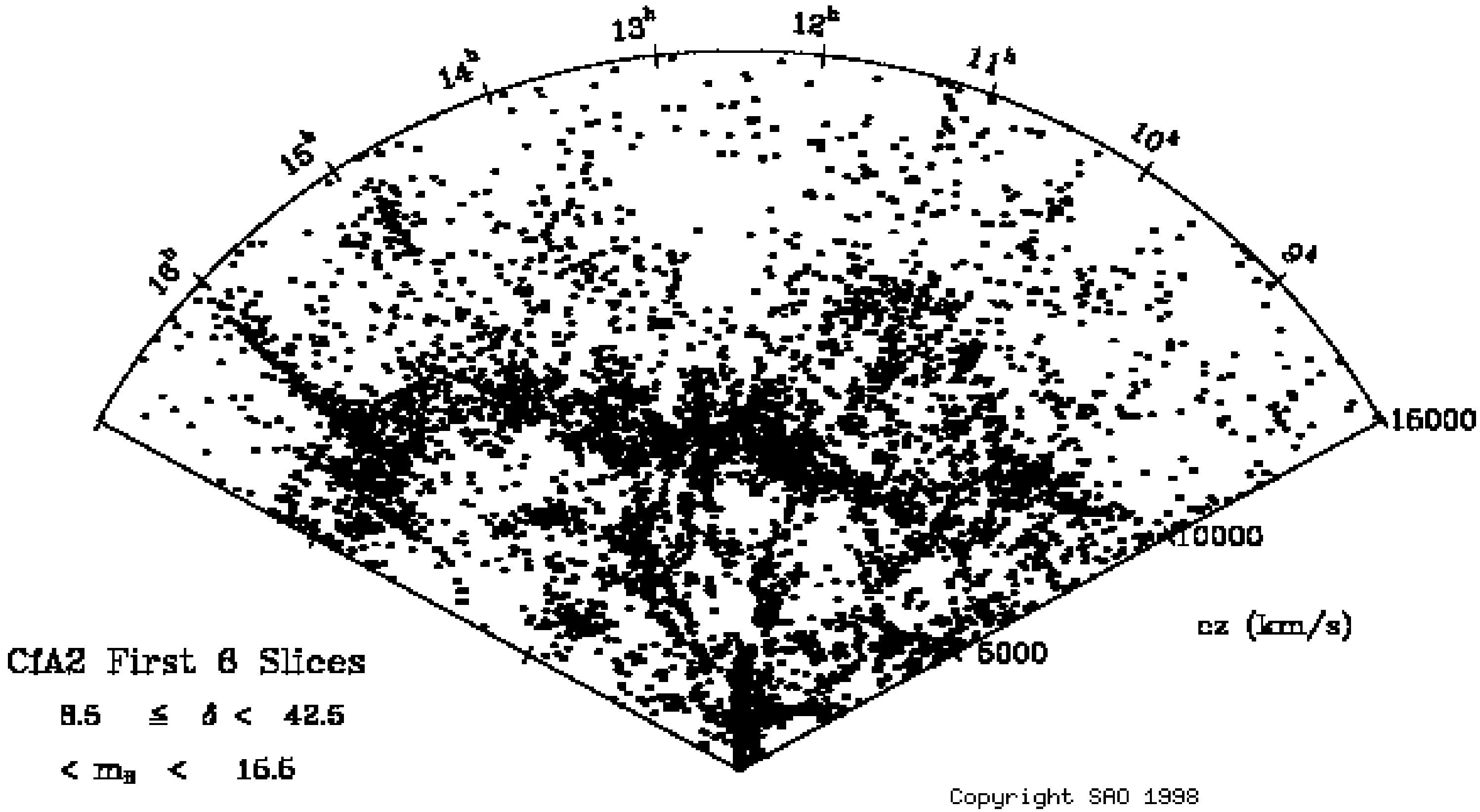
- In the 1980's large scale redshift surveys, allowed us to measure clustering in 3 dimensions, instead of just two
- The first large scale redshift survey was the CfA2 (Center for Astrophysics) survey led by Margaret Geller & John Huchra started in 1984 to 1995.
  - There was a CfA1 survey 1977-1982, 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



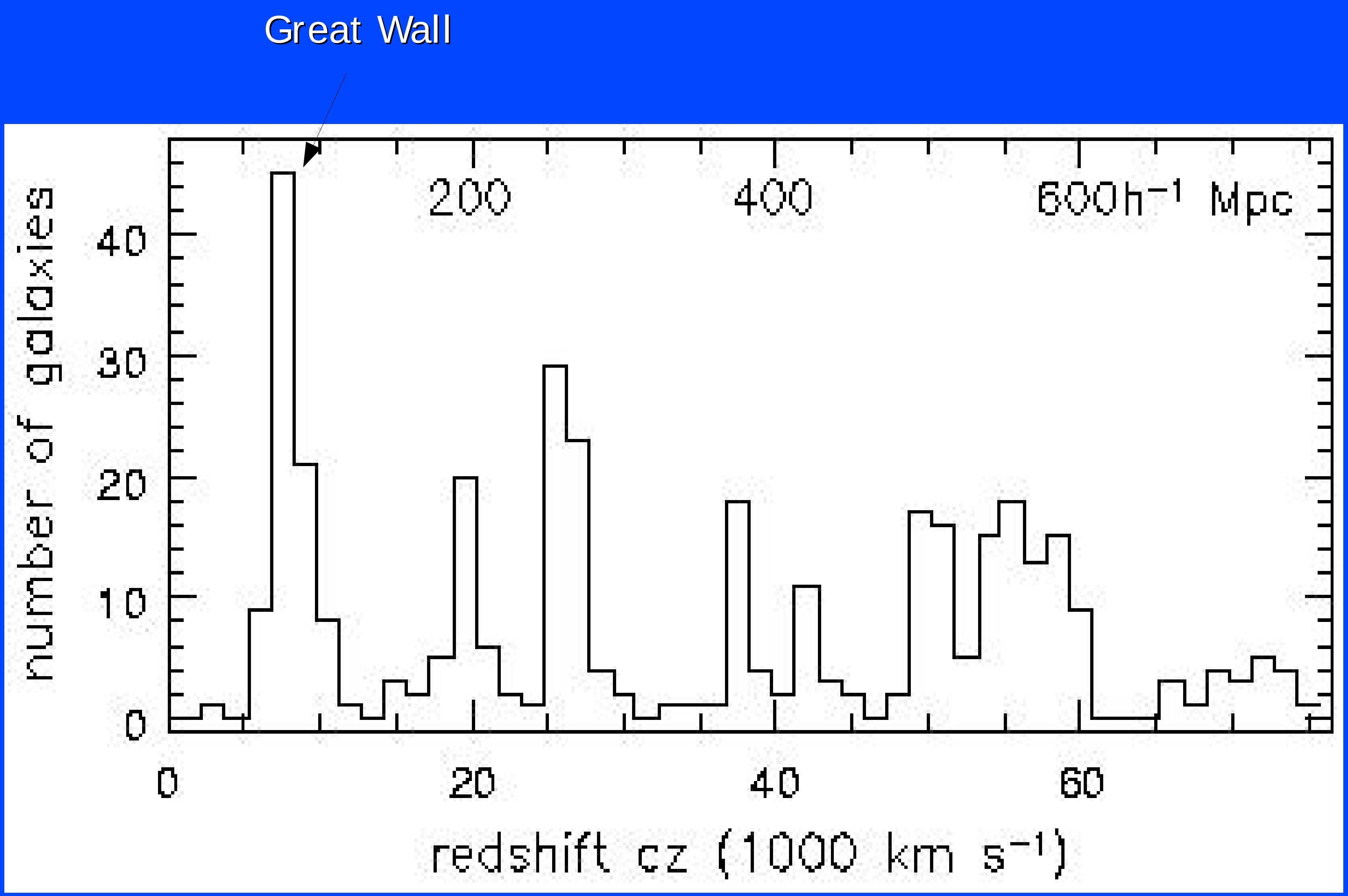
Geller & Huchra et al 1989

Redshift Surveys cont.

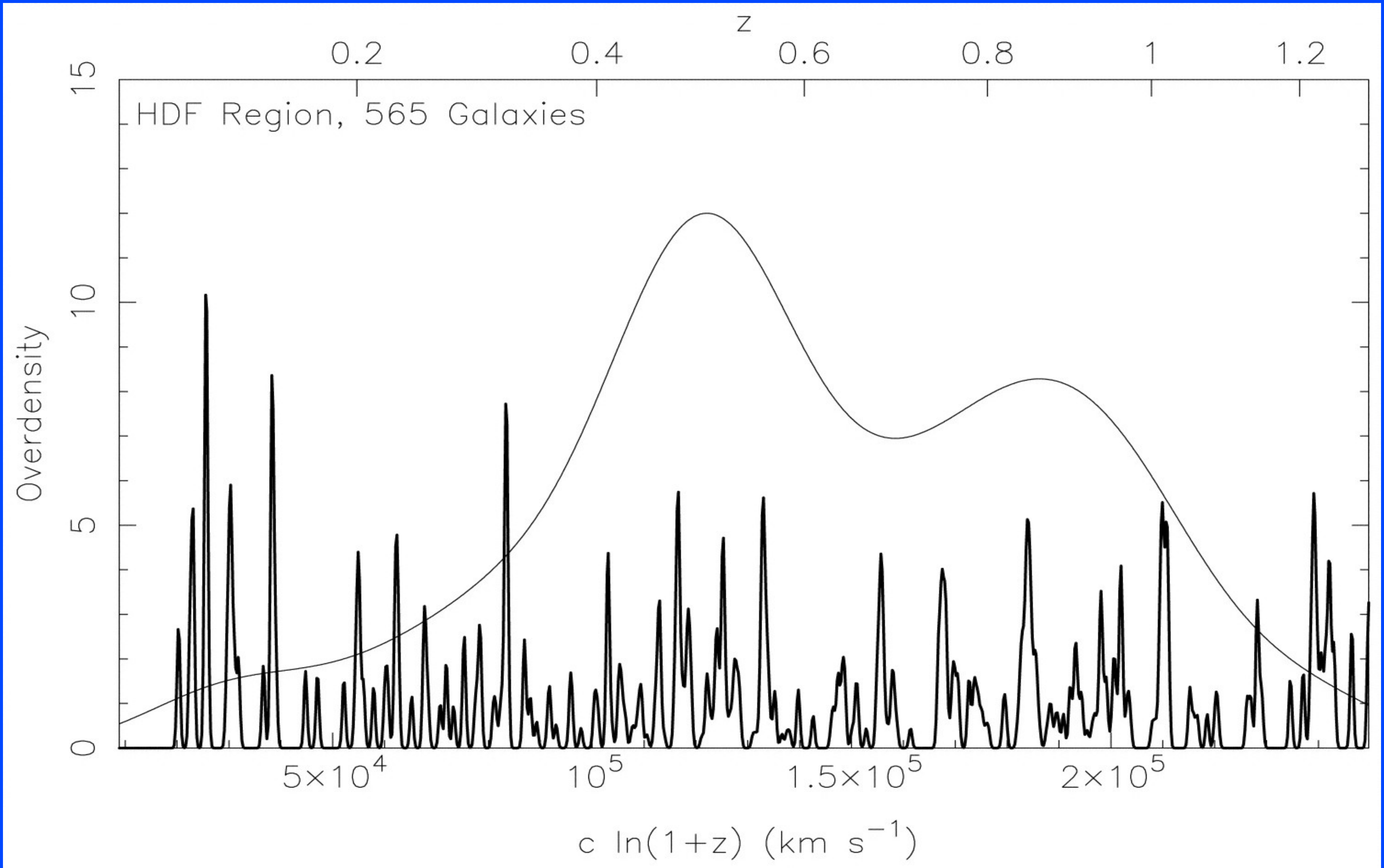
- Recently there have been two large redshift surveys undertaken
- The 2dF (2 degree Field) redshift survey done with the Anglo-Australian telescope
  - ~220,000 galaxies covering 5% of the sky reaching to $z \sim 0.3$ with $B < 19.5$
  - Their spectrograph can measure 400 redshifts at a time
- The Sloan 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 $z \sim 0.4$, ~500 redshifts at a time
  - To date (~375,000 redshifts DR3), total goal is 1 million
  - Also measuring redshifts of quasar candidates out to much higher redshifts (Schneider et al.)

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



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?

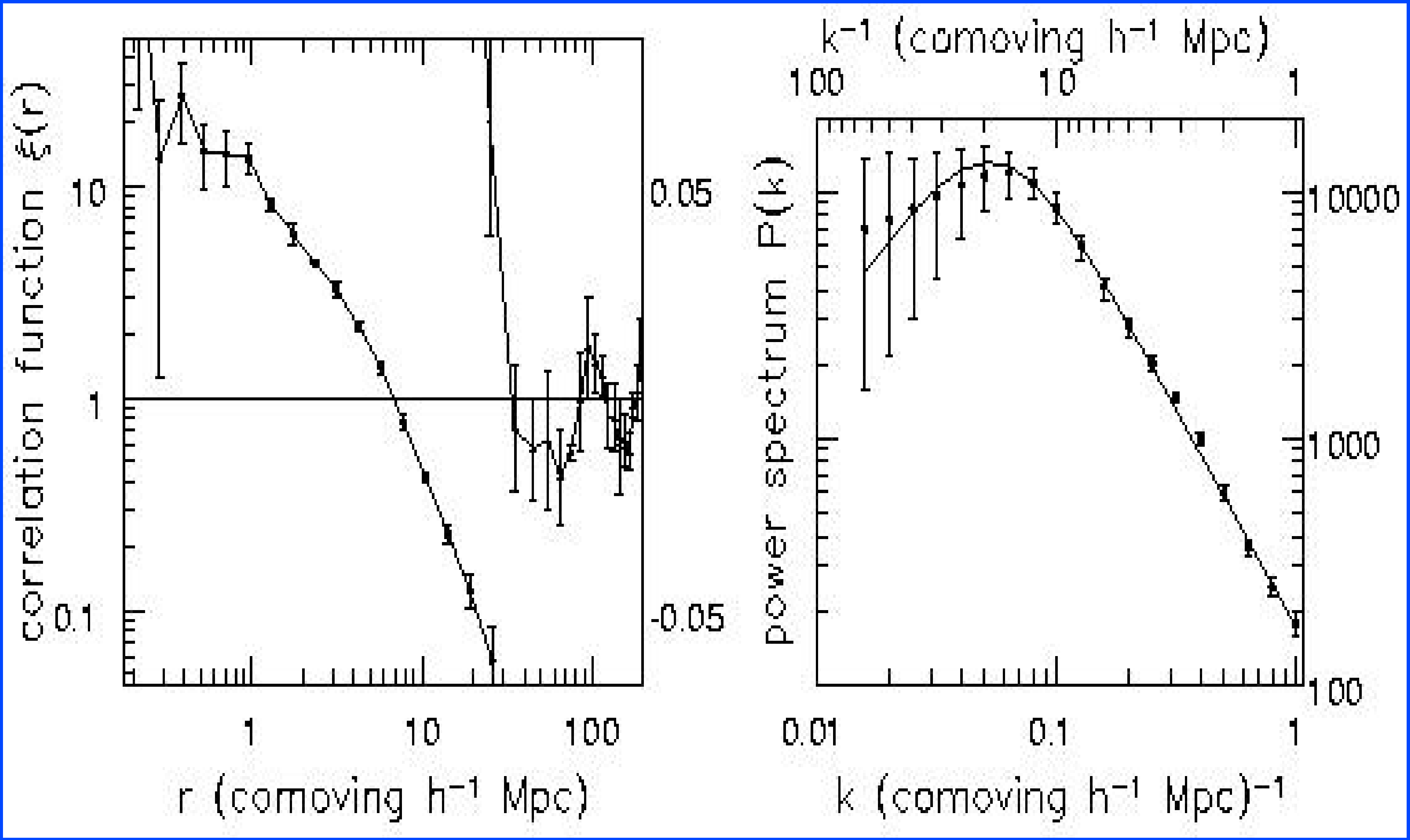
- We want a way to quantify the amount of structure that we see on various scales
- One common way of doing this is to measure the two-point correlation function $\xi(r)$
- We calculate the correlation function by estimating the galaxy distances from their redshifts, correcting for any distortions due 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.

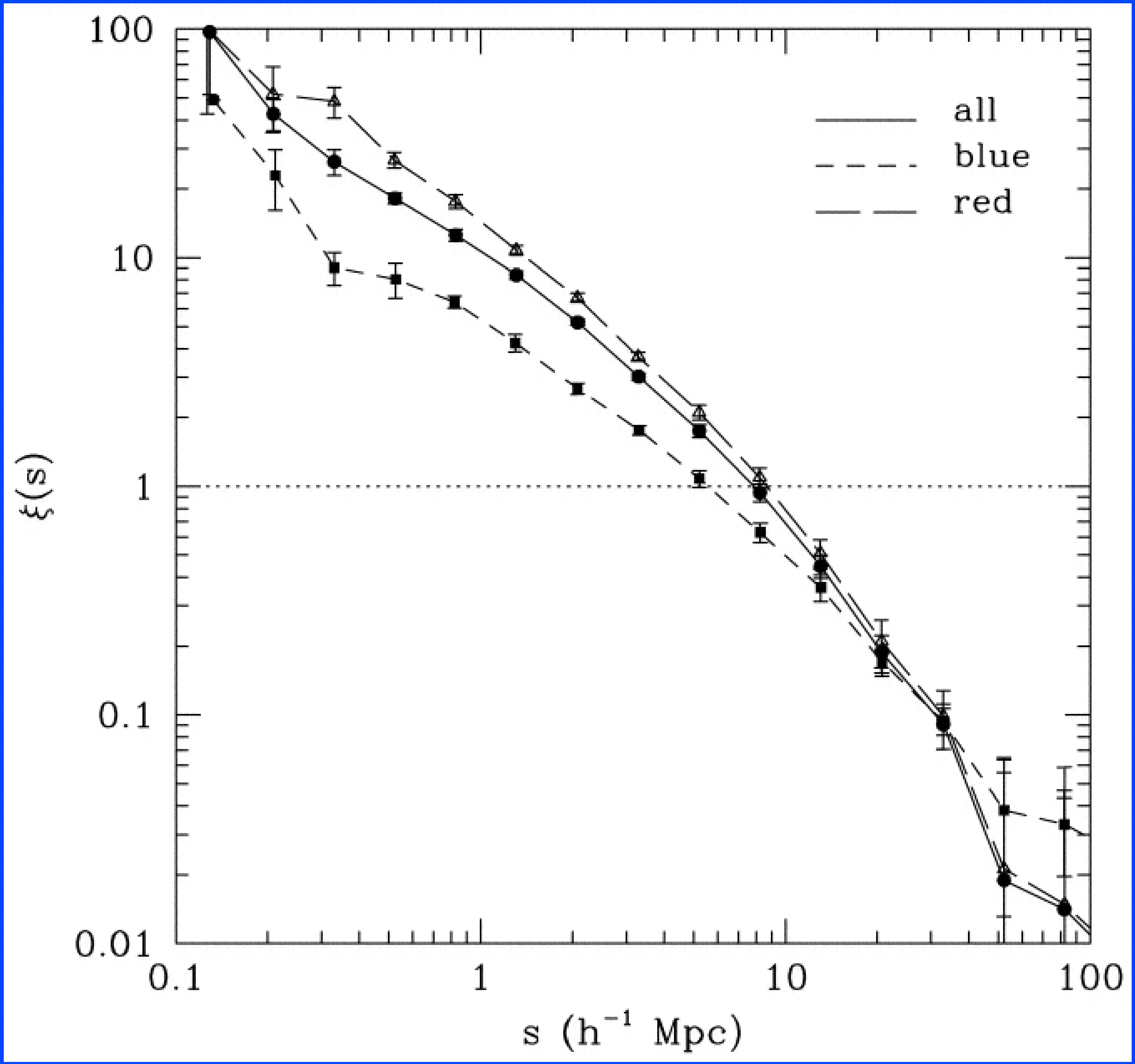
- $\Delta P = n^2[1+\xi(r_{12})]\Delta V_1 \Delta V_2$
- If $\xi(r) > 0$, then galaxies are clustered
- If $\xi(r) < 0$, then galaxies avoid each other
- On scales of < $50h^{-1}$ Mpc, we can represent the correlation function as a power-law: $\xi(r) \sim (r/r_0)^{-\gamma}$ with $\gamma>0$
- The probability 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 ideal for describing one-dimensional filaments or two-dimensional walls. We need 3 and 4 point correlation functions for those. However, these don't work very well.
- From the SDSS: r_0=6.1 +/- 0.2 h^{-1} Mpc, γ=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).

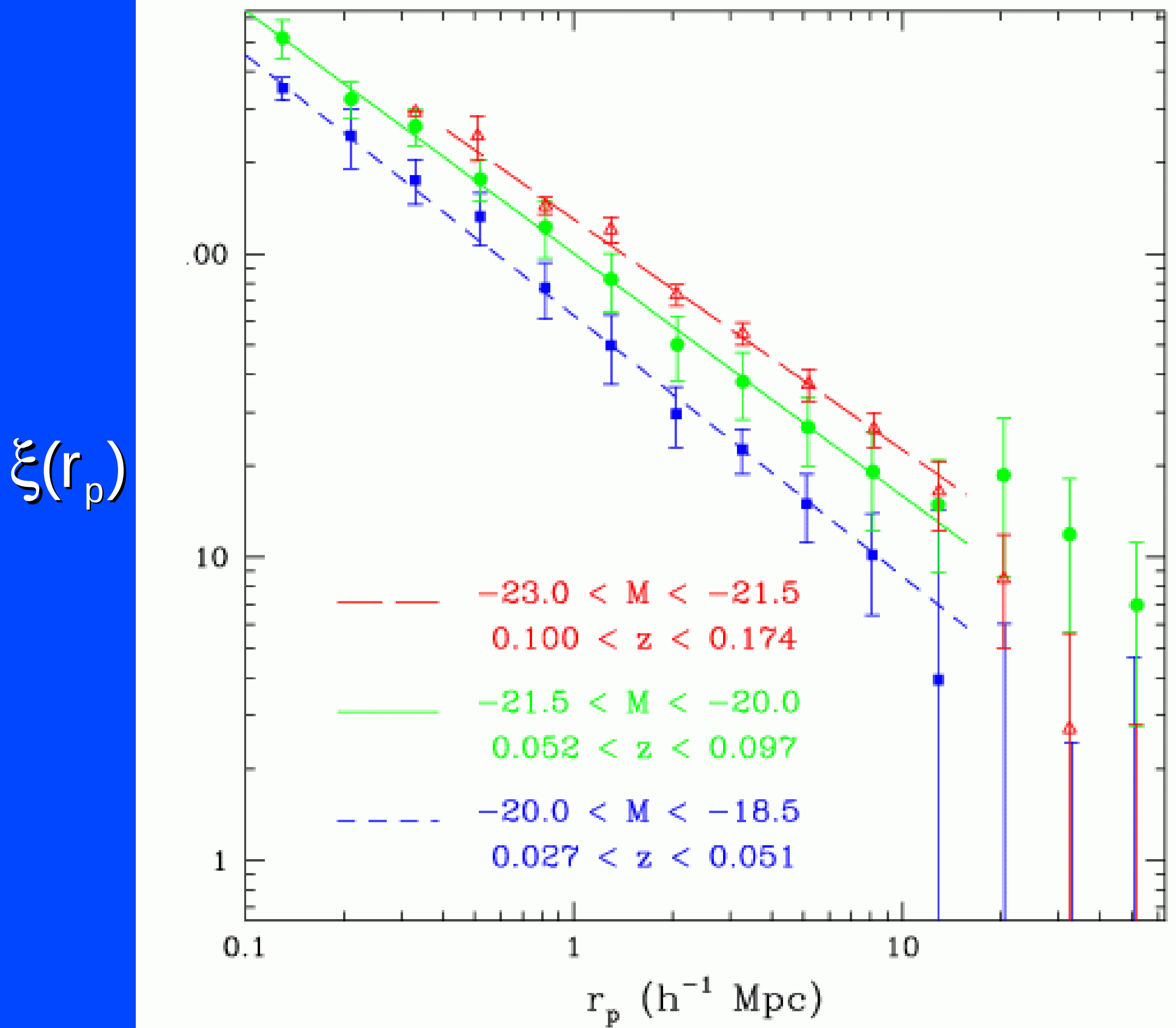
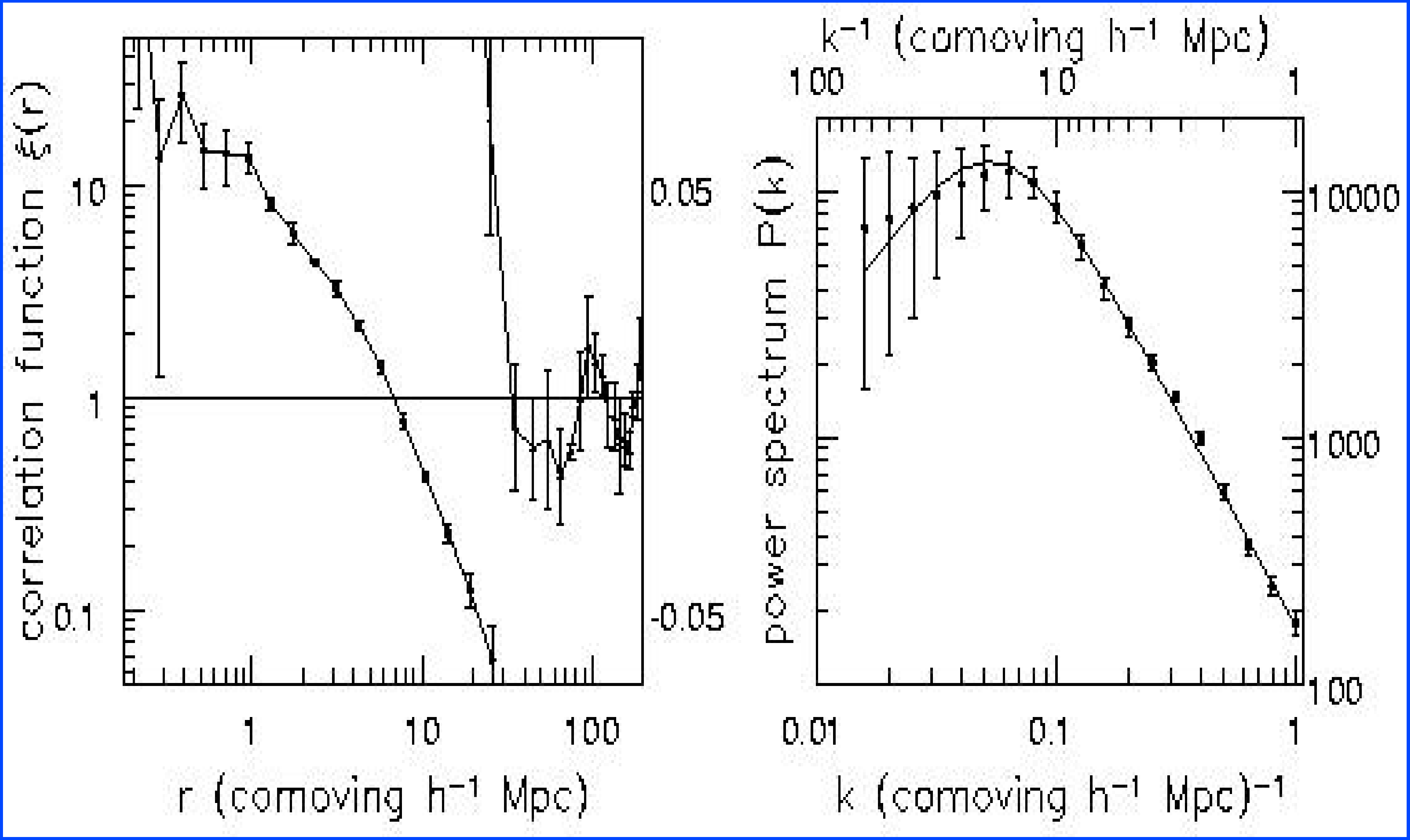


Fig. 1.4. Galaxy clustering depends on luminosity. Changing the luminosity changes the amplitude, but not the slope, of the correlation function. (From Zehavi et al. 2002.)

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

Clustering cont.

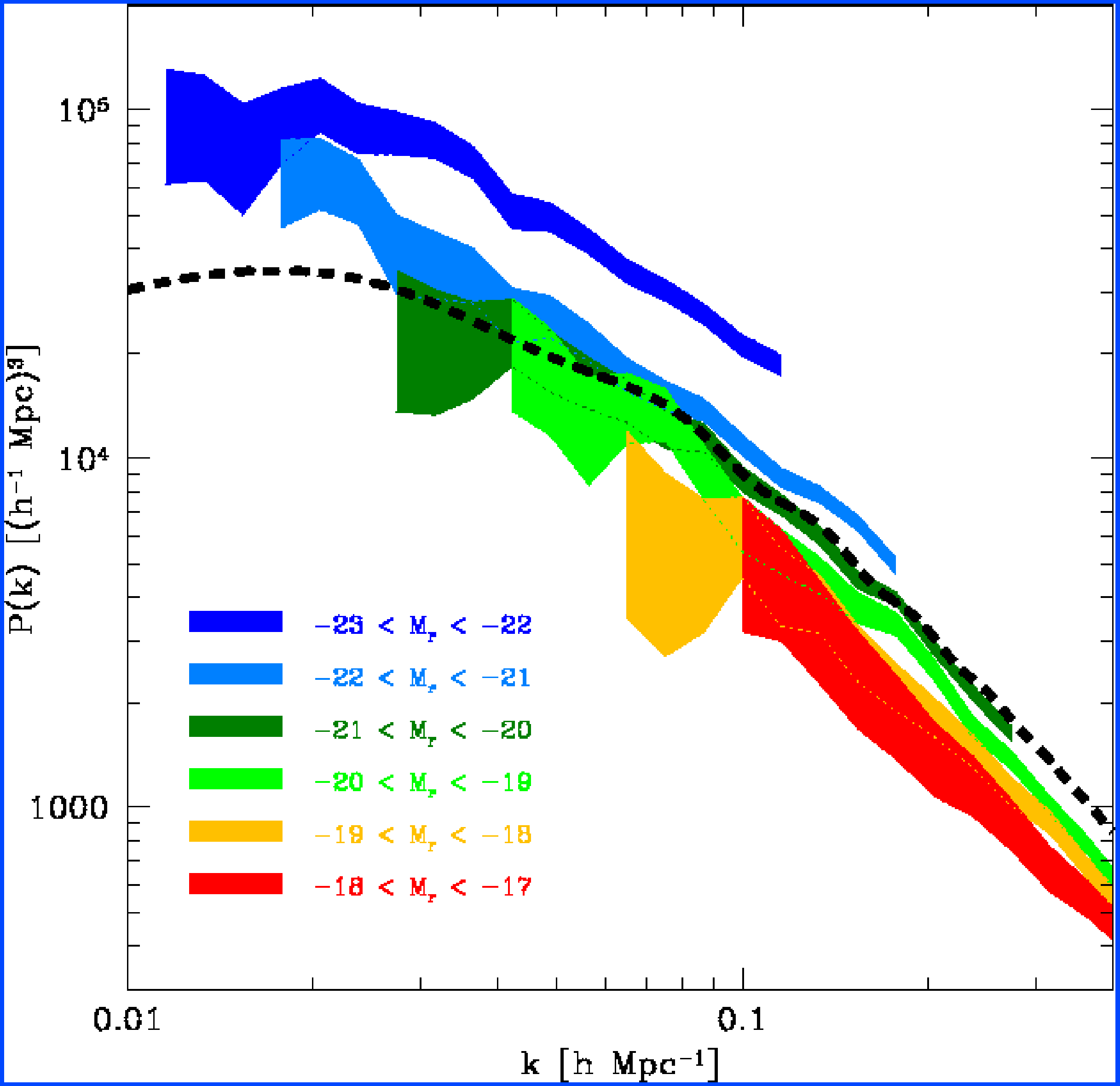
- The Fourier transform of $\xi(r)$ is the power spectrum $P(k)$, $P(k) = 4\pi \int \xi(r) [\sin(kr)/kr] r^2 dr$
- k is the wavenumber, small values of k correspond to large physical scales
- $P(k)$ has the dimensions of volume. It will be at maximum close the radius r where $\xi(r)$ drops to zero.
- 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



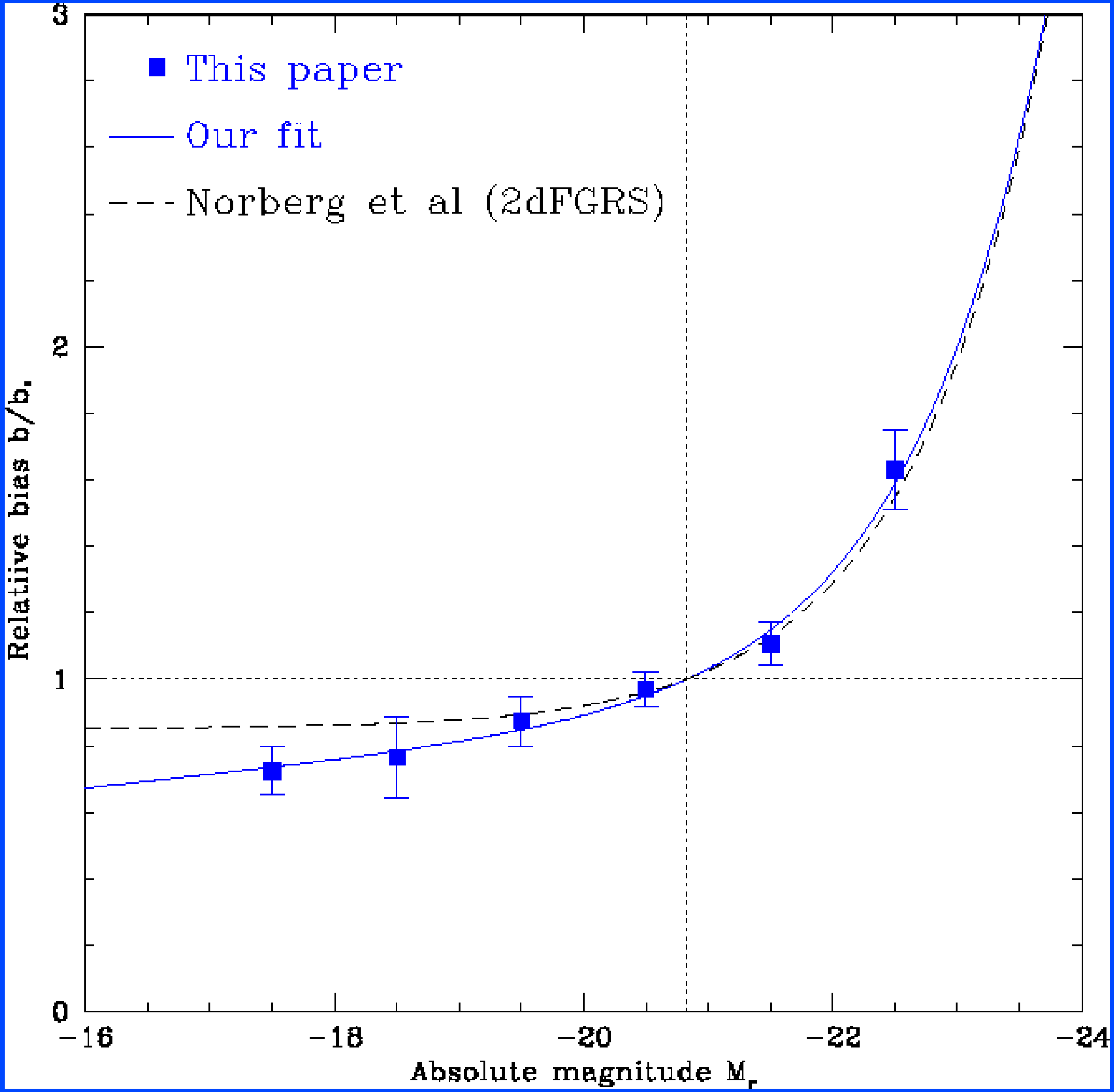
Correlation function and power spectrum from Las Campanas Redshift Survey data (Lin & Tucker).

Clustering cont.

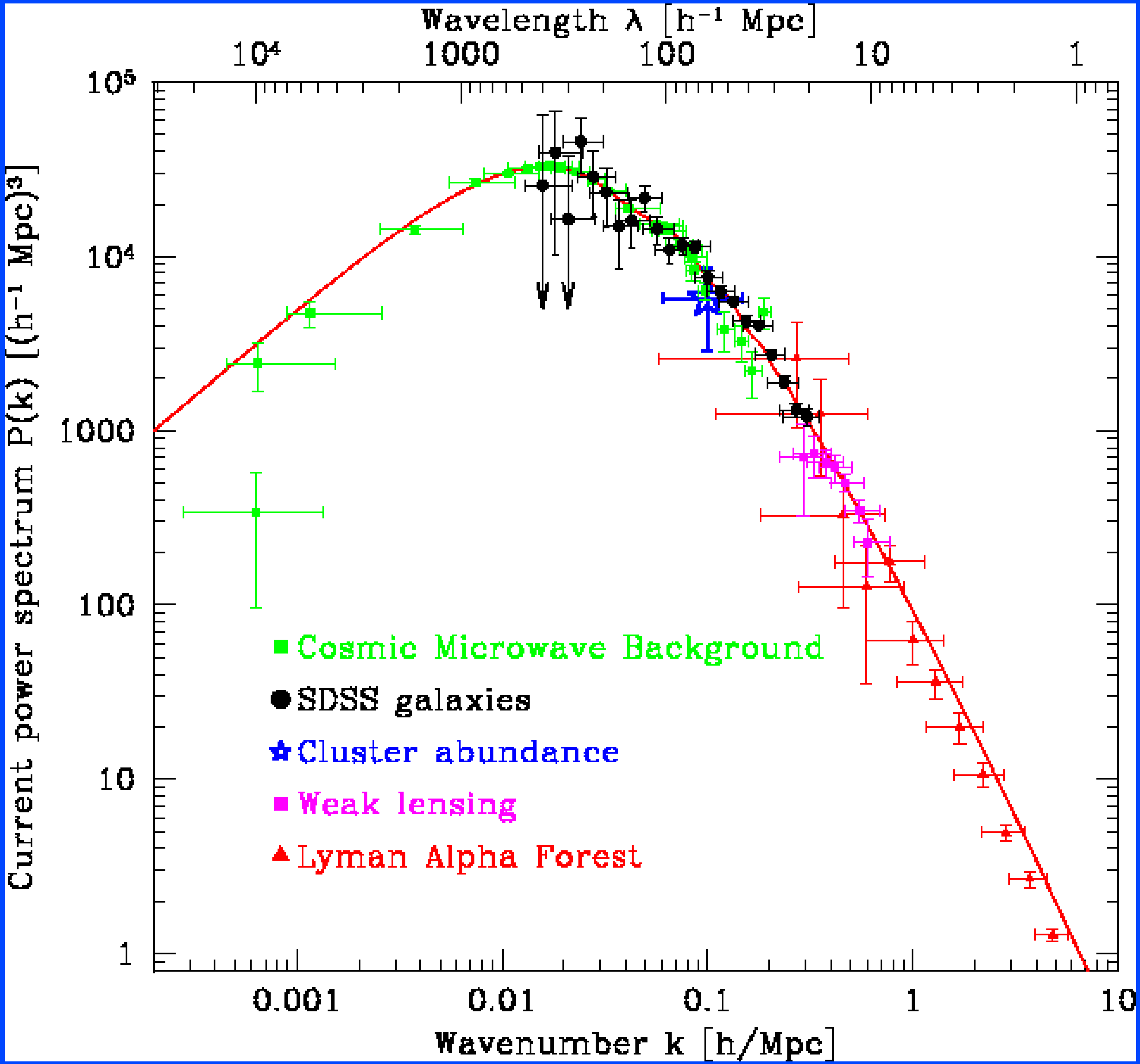
- We would also like to know how well the galaxies trace the mass distribution, or how biased are the galaxies relative to the dark matter
- We generally assume that the two densities are linearly related such that:
  - Let $\delta_x = \delta\rho_x/\rho_x$ be the density fluctuation of a given population
  - Linear biasing for galaxies implies $\delta_{galaxies} = b\delta_{dark\ matter}$
  - 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)