What universe do we live in?

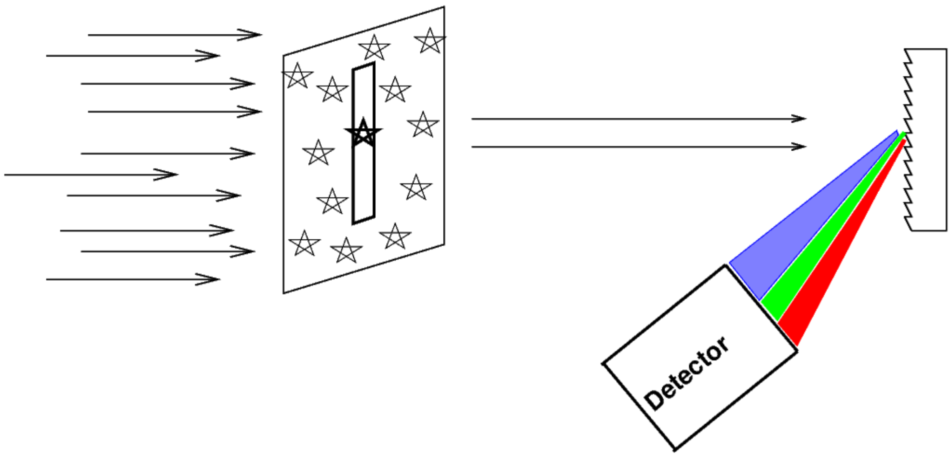
- Galaxy redshift surveys
  - How to do
  - Normalization of power spectrum
  - Shape of power spectrum
- Peculiar velocities
- Cosmological parameters from clusters

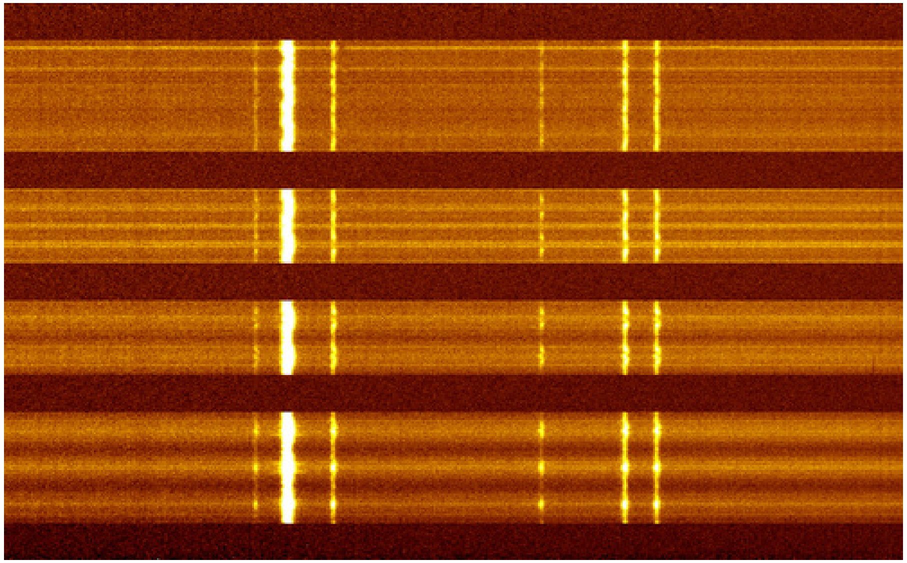
Galaxy surveys

- The dominant component of matter in the universe is dark matter, but it is very hard to see, so let's look at luminous matter in the optical band, e.g. galaxies, first.
- What properties of a galaxy can one measure? For a survey, the most fundamental property is the galaxy's position in space. We can measure the galaxy's position on the sky using an image, but need to obtain a spectrum to measure its distance.
- Steps to doing a galaxy survey:
  - Select fields on the sky.
  - Obtain images of those fields in one or more bands.
  - Pick out the galaxies on the images, e.g. by use color-color diagrams. Also, need to pick a limiting magnitude. Thus, most surveys are flux limited – it is impossible to form a volume limited sample before having the redshift measurements.
  - Obtain a spectrum of each galaxy and measure its redshift
  - Make cool maps of the galaxy positions, usually as “wedge diagrams”.

Measuring redshifts

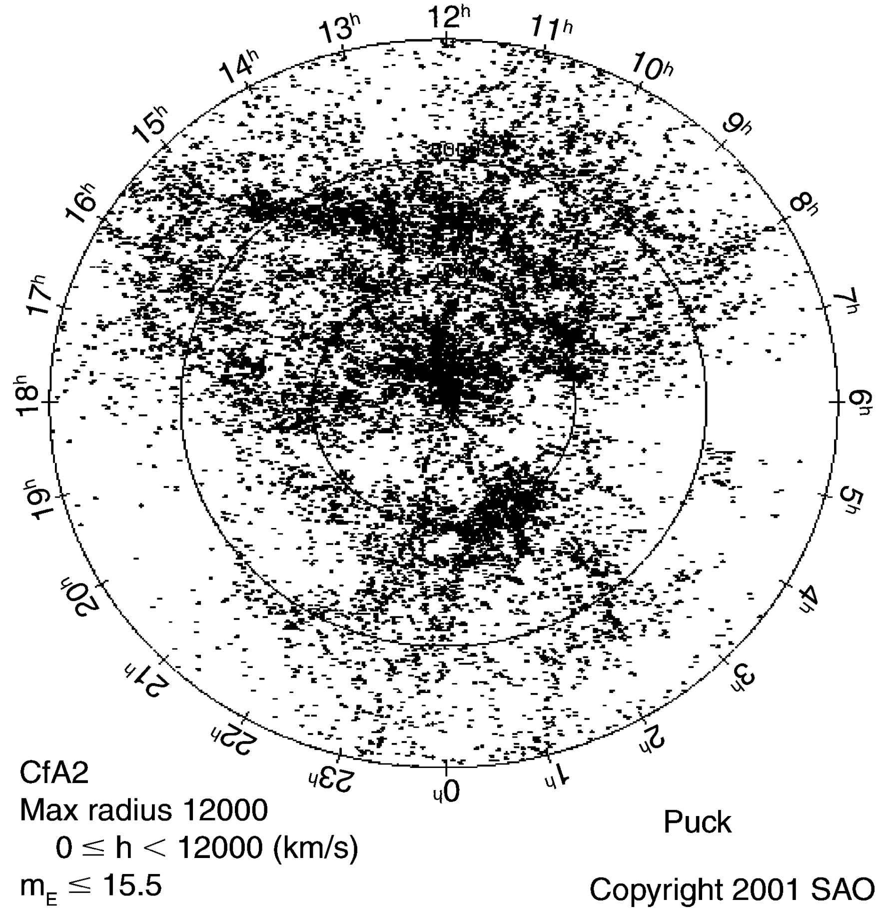
- The hard part is measuring a spectrum for each selected galaxy
- Traditional optical spectrographs take a spectrum of one object at a time using a slit to pick out the object. Need a slit because dispersive element (grating or prism) spreads light from target over one dimension. Without slit, spectra from nearby objects would overlap.
- Early redshift surveys, e.g. CfA survey, were done this way.
- Wasteful because the light from most other objects in the field is discarded.
- Modern instruments use fiber-fed spectrographs. Fiber is placed at object position and spectra of multiple objects can be recorded in each observation.





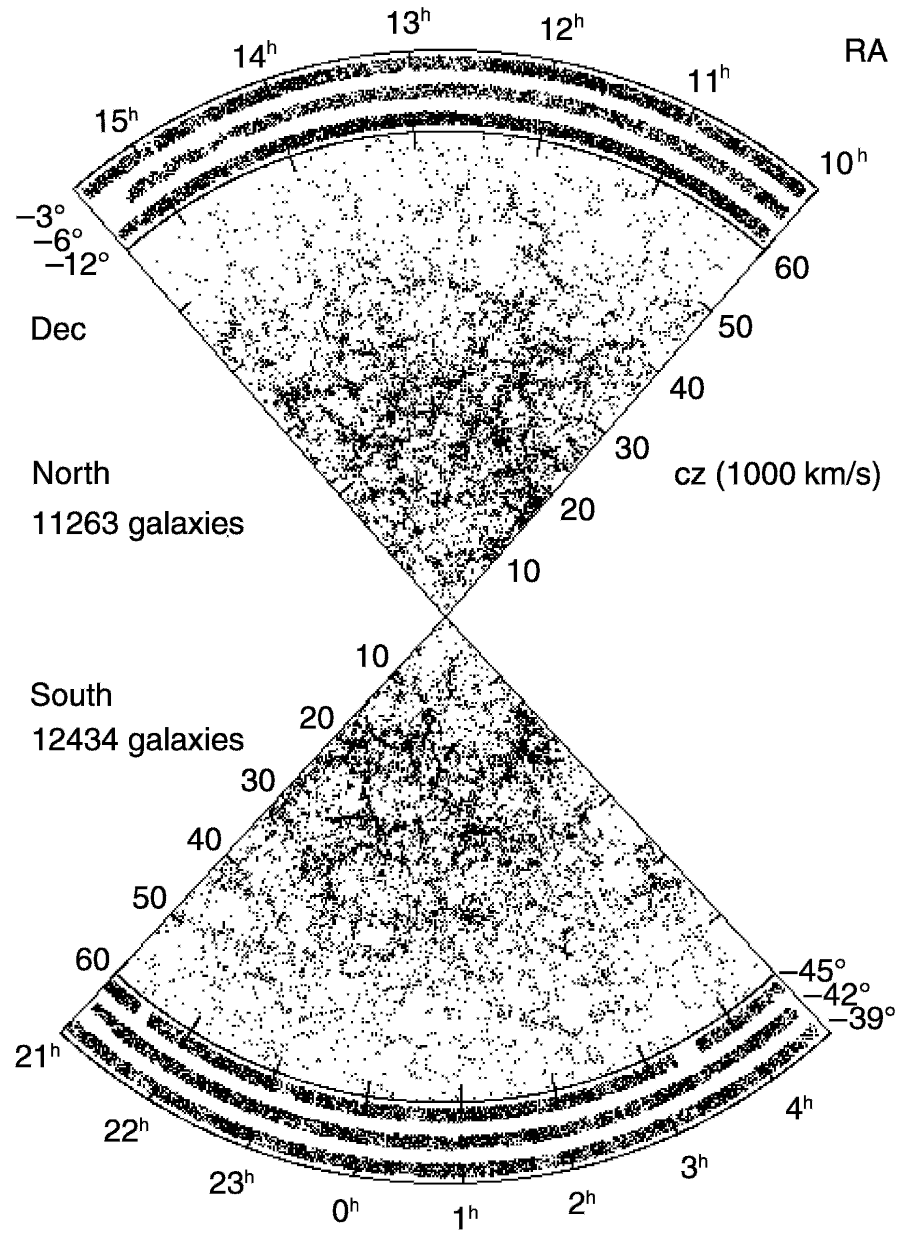
CfA redshift survey

- First big survey done by Harvard-Smithsonian Center for Astrophysics (1989) using a 60 inch telescope to get spectra.
- Led to discovery of the "Great Wall" (at RA = 9 to 15 hours that includes Coma cluster at 13 hours. Perseus-Pisces supercluster is at 1 hours.
- Surprising that there were structures on scales as large as the extent of the survey – implies that survey is not large enough to see a representative sample of the observable universe.
- Redshifts to 12,000 km/s, but good completeness to ~9,000 km/s or ~120 Mpc.
- We are at the center of the circles.



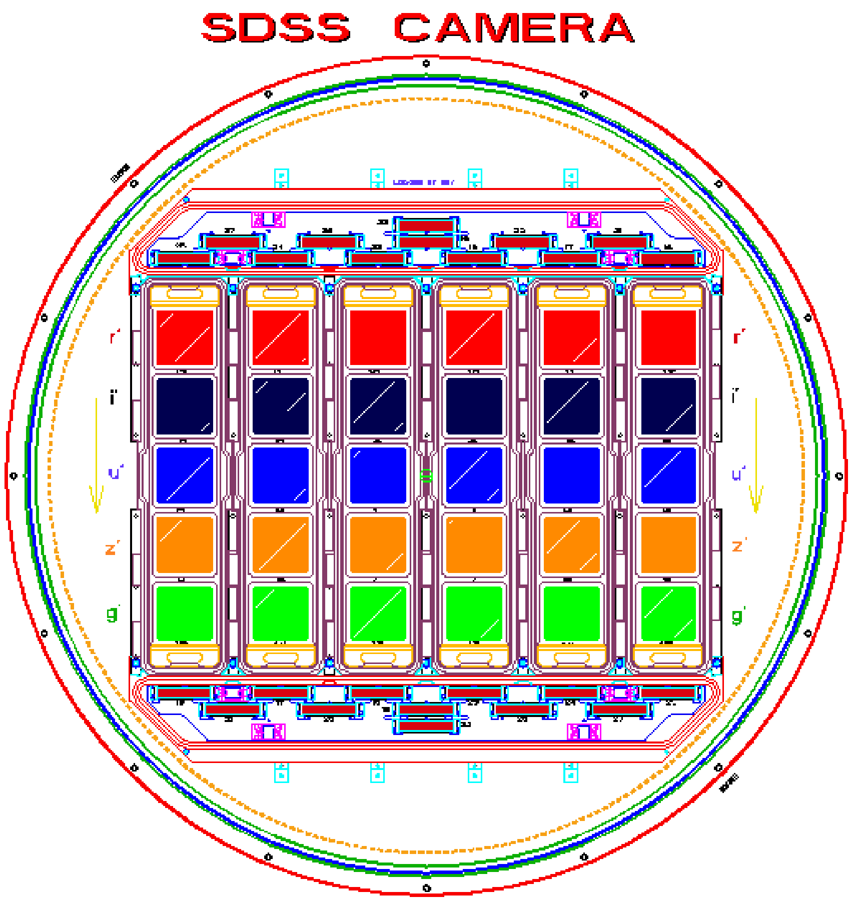
Las Campanas survey

- First survey deep enough to see homogeneity.
- Reasonably complete to 40,000 km/s or about 500 Mpc.
- Redshifts for 26,000 galaxies with average redshift z ~ 0.1 = 30,000 km/s.
- Used 2.5 meter du Pont telescope (98 inch) and one of the earliest fiber-fed spectrographs.



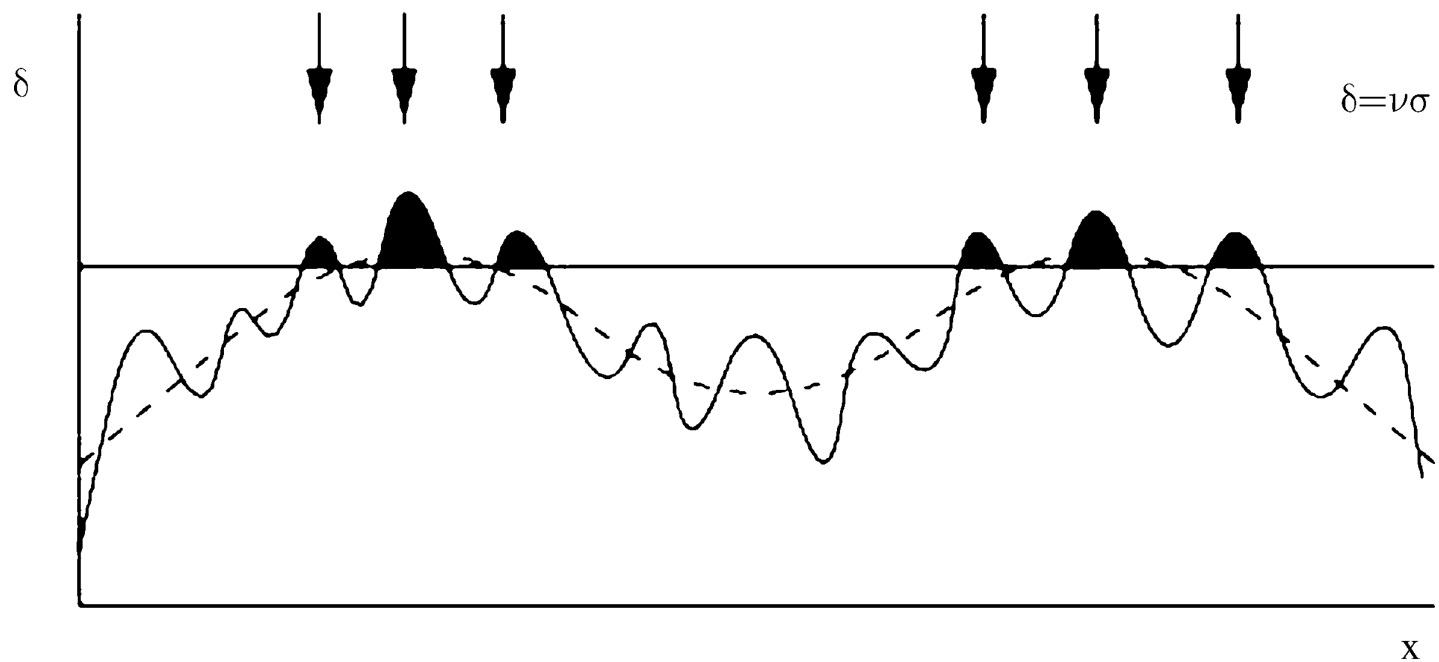
2dF survey and SDSS

- Two-degree field galaxy redshift survey (2dFGRS) used a 4-meter telescope with 400 fiber spectrograph to measure redshifts of 230,000 galaxies over fields (two very large and 100 small) covering 1900 square degrees.
- Sloan digital sky survey (SDSS) has a dedicated 2.4-meter telescope with 120 megapixel imager and 600 fiber spectrograph.
- SDSS-II obtained spectra for 930,000 galaxies in a field covering 8,400 square degrees. SDSS-III is now underway and will complete in 2014.
- Data from SDSS are public.



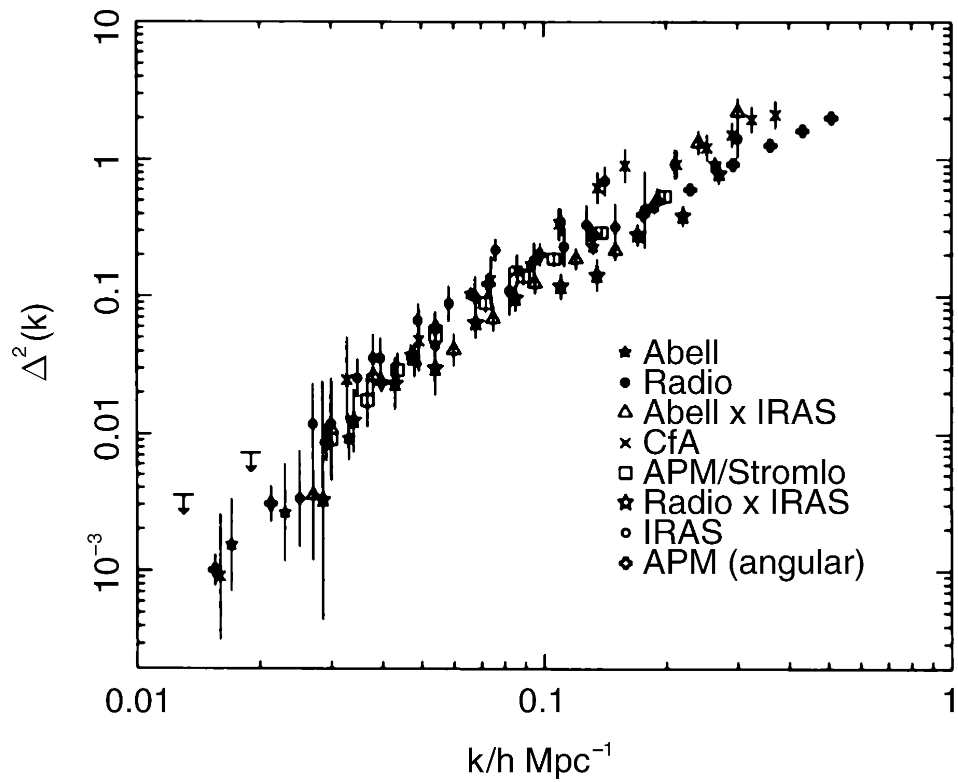
Bias factor

- Distribution of luminous matter may not match that of dark matter.
- E.g. perhaps galaxies form only if matter density reaches some threshold value.
- Introduce linear bias factor b, $\delta_g = \Delta n/\bar{n} = b(\Delta\rho/\bar{\rho}) = b\delta$, b may vary with length scale.
- Statistical fluctuations in n, $\sigma \sim \sqrt{n}$.
- Correlation of luminous matter may also differ from that of dark matter.



Normalization of power spectrum

- The normalization of the power spectrum can be fixed by choosing a particular length scale and then finding the amplitude of fluctuations at that length scale.
- Standard length scale is R = $8h^{-1}$ Mpc.
- Optically selected galaxies have a fluctuation amplitude ~ 1 on this length scale, $\sigma_{8,g}{}^2 = \langle(\Delta n/\bar{n})^2\rangle_8 \sim 1$.
- Dark matter $\sigma_8{}^2 = \langle\delta^2\rangle_8$
- Thus, $\sigma_8 = \sigma_{8,g}/b \sim 1/b$
- Note if $b \sim 1$, then $\sigma_8 \sim 1$ on length scales of $8h^{-1}$ Mpc and $\delta \sim 1$ meaning non-linear fluctuations.
- Need to go to larger length scales to apply linear perturbation theory.

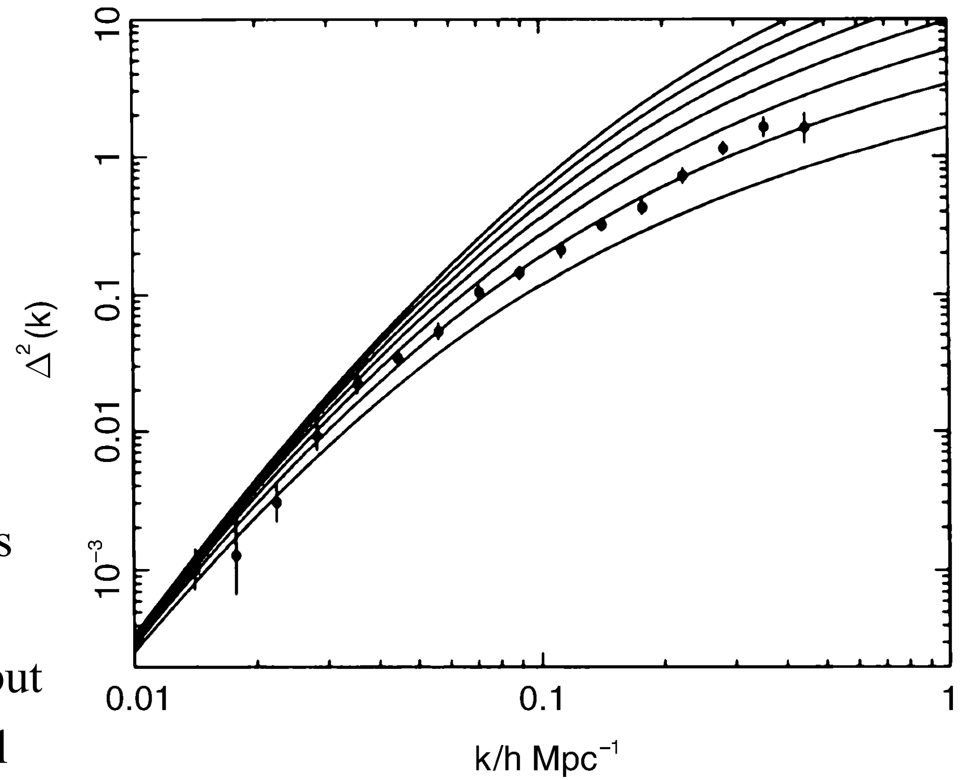


Shape of power spectrum

- Power spectrum at beginning of the matter-dominated phase is $P_0(k) = \mathrm{A}\, k^n\, T^2(k)$
- We found $T(k) \sim 1$ for $k << 1/L_0$ and $T(k) \sim (kL_0)^{-2}$ for $k >> 1/L_0$ where L_0 = horizon size at start of matter dominated era when matter and radiation densities were equal, z_{eq}.
- Thus, the shape of the $T(k)$ and therefore of $P_0(k)$ depend on kL_0
- Note $L_0 = 12\, (\Omega_m h^2)^{-1}$ Mpc, so $kL_0 \sim k(\Omega_m h^2)^{-1}$
- Distances from redshifts are h^{-1} Mpc, so $k \sim h$, and $kL_0 \sim h(\Omega_m h^2)^{-1} \sim (\Omega_m h)^{-1}$
- Define shape parameter $\Gamma = h\Omega_m$
- We can then fit to the shape of the power spectrum to find Γ if b does not vary with k.
- Consider only scales longer than 10 h^{-1} Mpc.

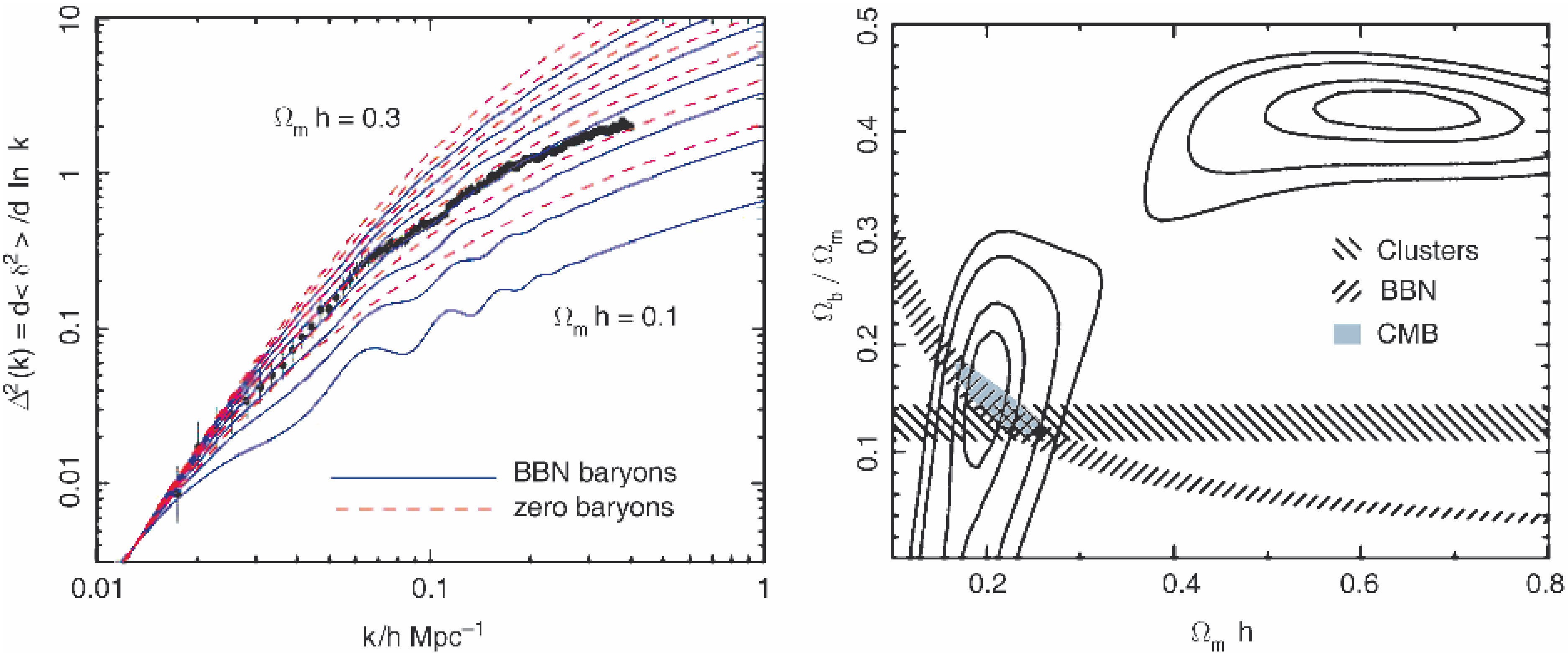
Shape of power spectrum

- Points show averages of data on previous plot.
- Curves show $\Gamma = 0.2, 0.25, \ldots 0.5$ from bottom to top.
- Find $\Gamma \sim 0.25$.



- Discussion on previous slide ignored effects of baryonic matter.
- Matter-radiation equilibirum at $z_{eq} \sim 3000$, but baryons didn't decouple from radiation until recombination $z_{rec} \sim 1100$.
- During that period, evolution of density fluctuations in baryonic matter was affected by radiation.

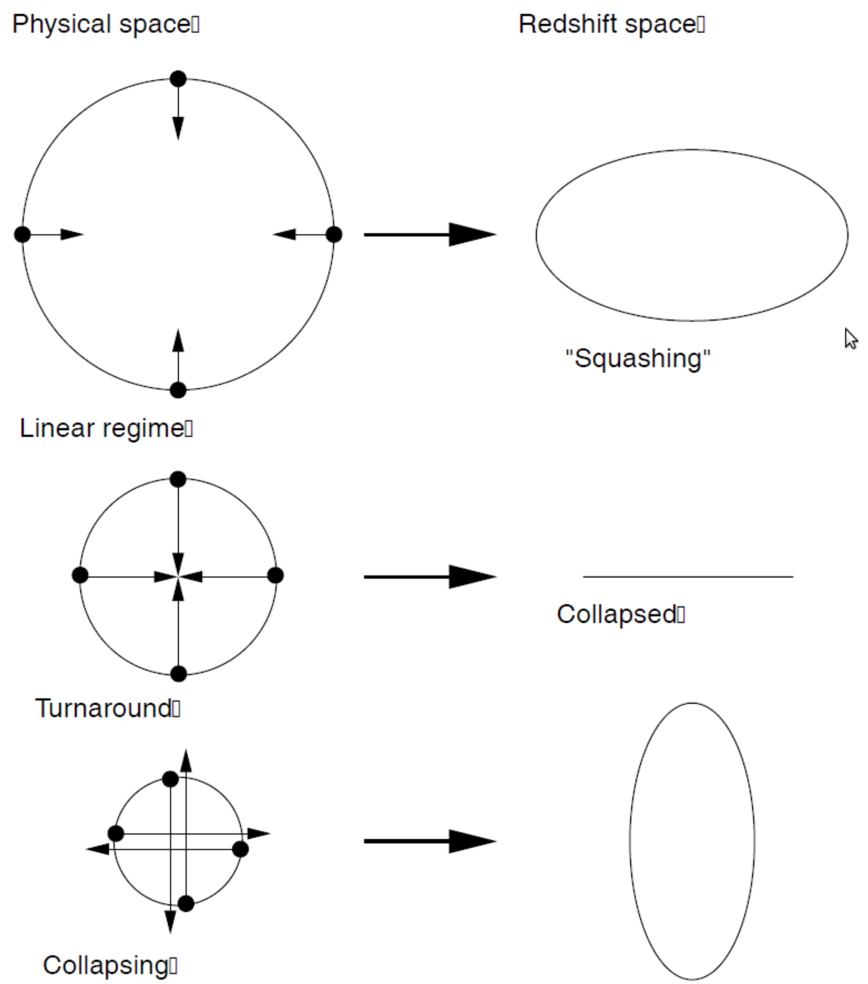
Shape of power spectrum



- Left – black curve shows data. Blue and red curves are models.
- None of the zero baryon curves provide a good fit.
- Find $\Gamma = 0.18 \pm 0.02$ and $\Omega_b/\Omega_m = 0.17 \pm 0.06$ as plotted on right. Also, second allowed range which is excluded by other data.

Peculiar velocities

- Because we use redshift to measure distance, distances are affected by the peculiar velocities, u, of the galaxies, redshift distance $s = D + u/H_0$ where D is the true distance.
- This causes "fingers of God" in collapsed clusters and squashing for low density regions that are still expanding.



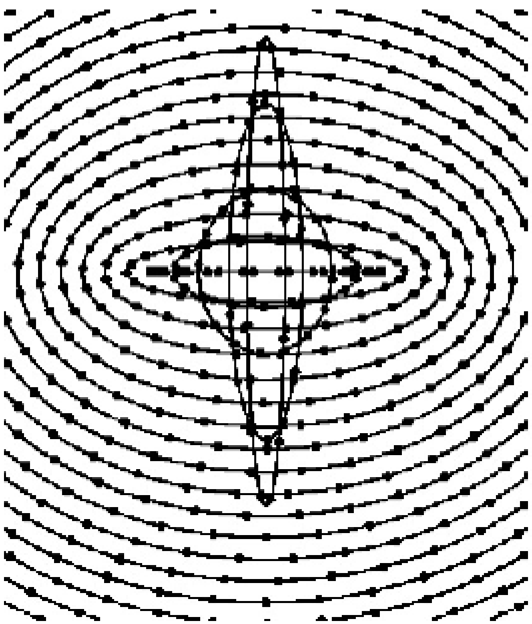
Peculiar velocities

- Peculiar velocities are determined by matter distribution in linear perturbation theory:

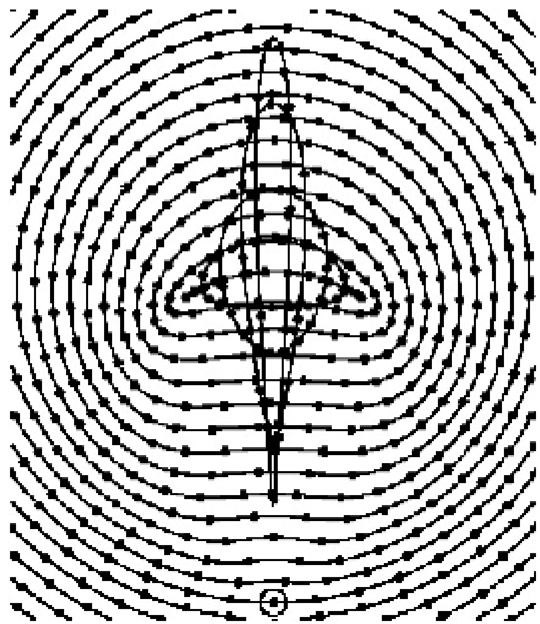
$$\boldsymbol{u}(\boldsymbol{x},t)=\frac{\Omega_m^{0.6}}{4\pi}aH(a)\int d^3y\ \ \delta(\boldsymbol{y},t)\frac{\boldsymbol{y}-\boldsymbol{x}}{|\boldsymbol{y}-\boldsymbol{x}|^3}$$

- In terms of the galaxy distribution $\boldsymbol{u}(\boldsymbol{x})=\beta\frac{H_0}{4\pi}\int d^3y\ \ \delta_g(\boldsymbol{y})\frac{\boldsymbol{y}-\boldsymbol{x}}{|\boldsymbol{y}-\boldsymbol{x}|^3}$ *where* $\beta=\Omega_m^{0.6}/b$
- There is an additional velocity component, σ_p, due to small scale interactions.
- Find $\beta = 0.51\pm0.05$, $\sigma_p \sim 520$ km/s, $b \sim 1$.

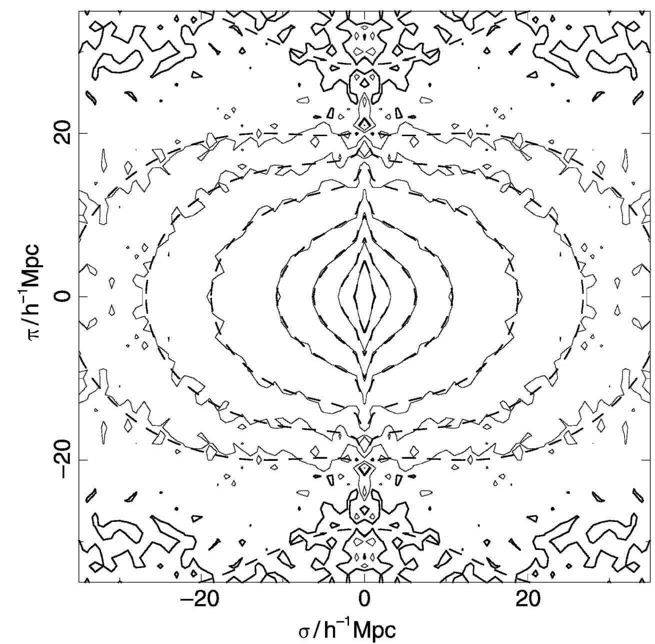
Physical space



Redshift space



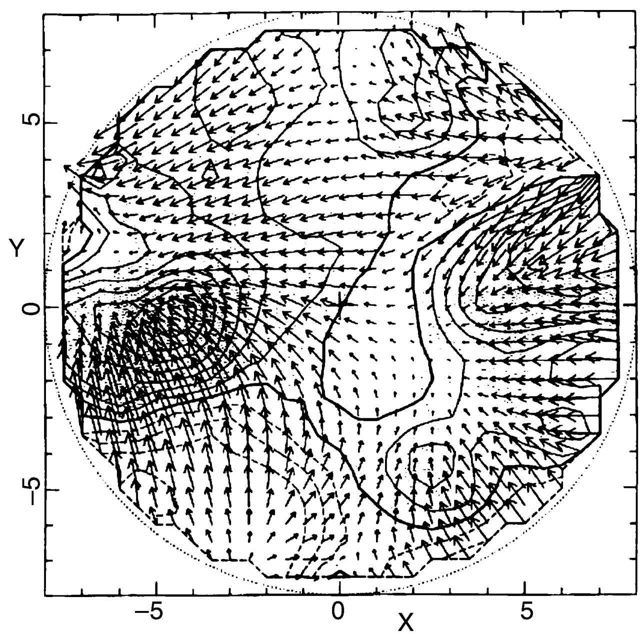
Correlation function

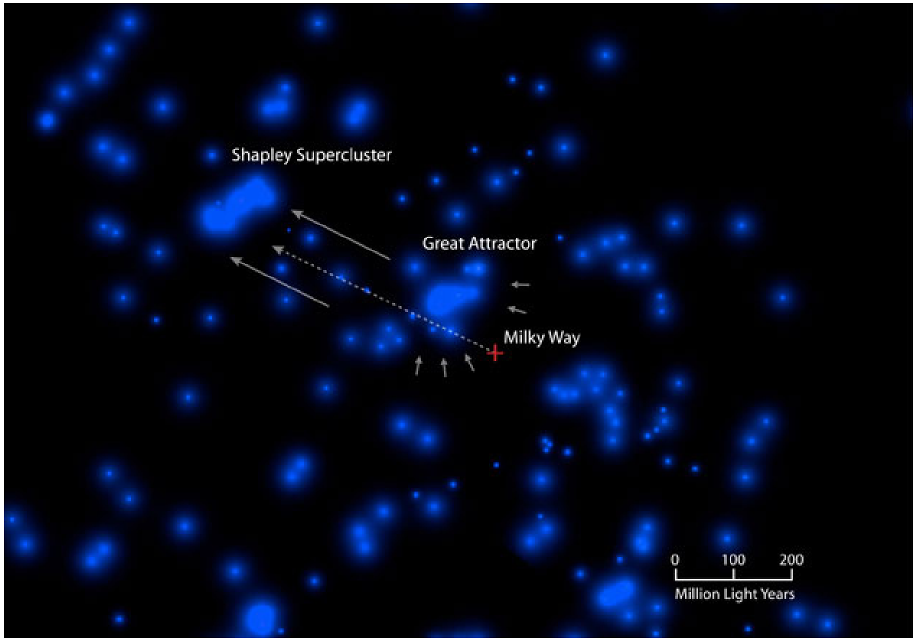


Peculiar velocities

- If one can measure physical distances to galaxies, then one can invert the equation and solve for the mass distribution. This works well for < 100 Mpc.
- Find nearby galaxies are moving toward the "Great attractor" roughly in the direction of the Galactic Center at a distance ~ 80 Mpc. The Shapley Supercluster, with 10,000 L* galaxies, may be the cause instead.
- More useful is to compare velocity of MW relative to CMB with dipole moment of nearby galaxies. Velocity → total mass, light → galaxies, find $\beta = 0.49 \pm 0.04$.

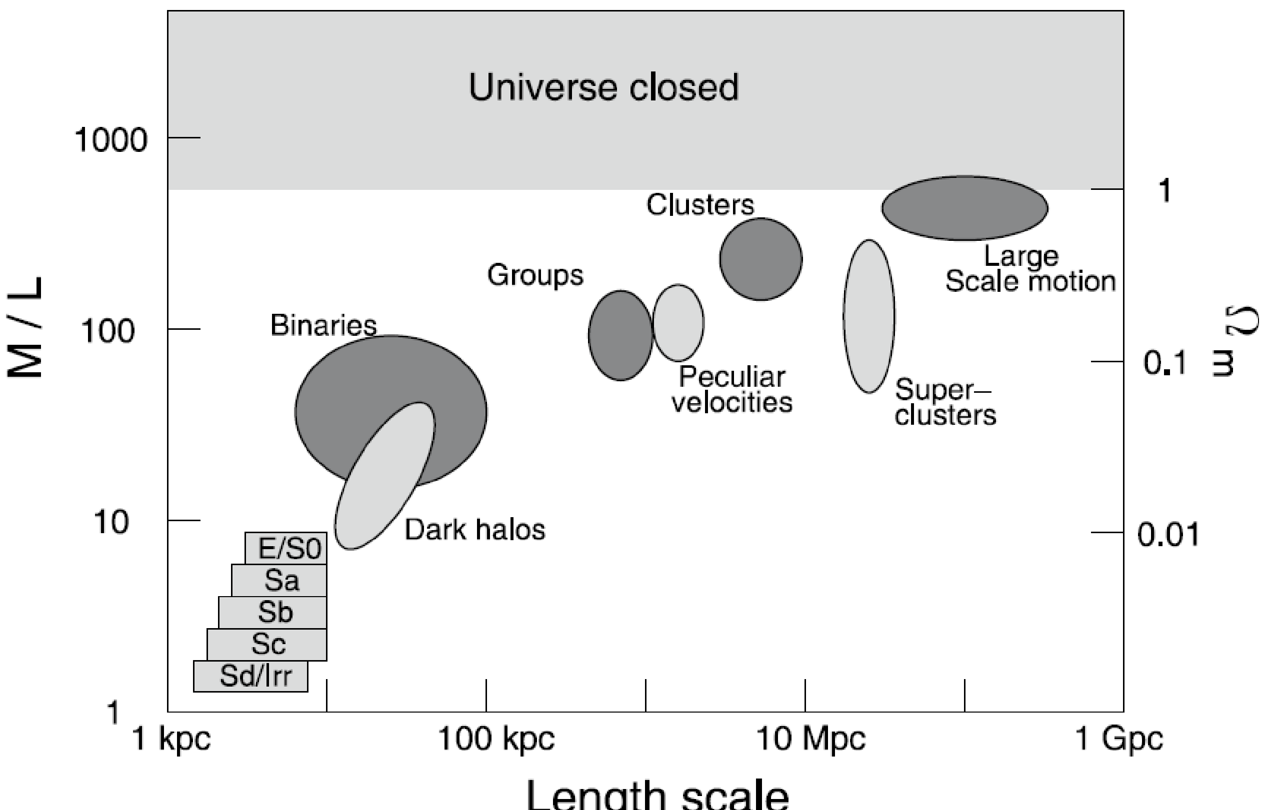
Velocity field





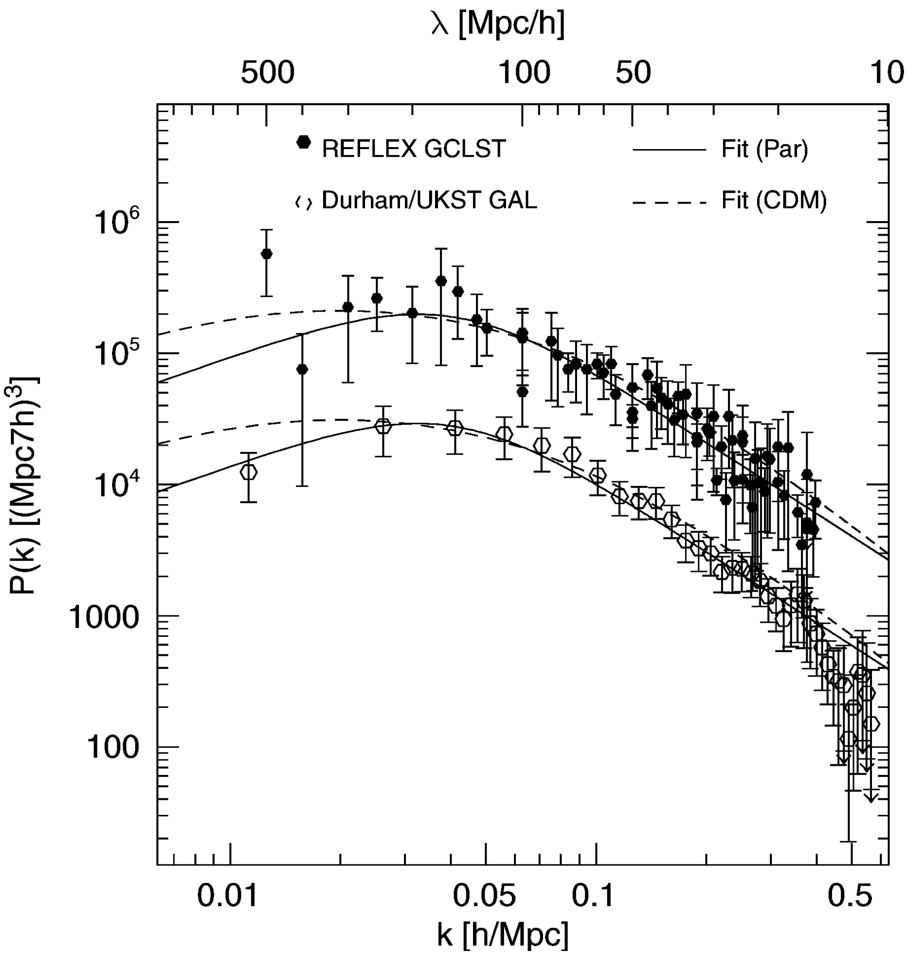
Clusters of Galaxies

- Mass/light ratio increases for objects of increasing size, but saturates on the scale of clusters. Thus, with a measurement of M/L for clusters and a measurement of the luminosity density, one can estimate $\Omega_m \sim 0.2$.
- One can measure the total mass of clusters and their baryon content (mostly in X-ray emitting gas), thus their baryon fraction. Using the cosmic baryon density from primordial nucleosynthesis, $\Omega_m \sim 0.3$.



Clusters of Galaxies

- One can find power spectrum for X-ray clusters (filled circles) and compare with the optical galaxy power spectrum (open).
- Bias is higher for cluster, $b_{clus} \sim 2.6\ b_g$.
- Shape parameter for clusters → $\Omega_m \sim 0.34$.
- Amplitude → $\sigma_8 = 0.71$ (most accurate).



- Multiple means to measure cosmological parameters permit tests of the model.
- The standard cosmological model produces consistent parameter values for many different measurements.

For next class

- Read 8.3-8.7.
- Project presentations on November 5 and 7. Should be full presentations with all results.
- Move presentations to Nov. 12 and 14 and HW #8 to Nov. 5?