Large Scale 20 **Structure:** Basic 10 **Observations** and Ω Redshift Surveys -10



Large-Scale Structure

- Density fluctuations evolve into structures we observe: galaxies, clusters, etc.
- On scales > galaxies, we talk about the Large Scale
 Structure (LSS); groups, clusters, filaments, walls, voids, superclusters are the elements of it
- To map and quantify the LSS (and compare with the theoretical predictions), we need redshift surveys: mapping the 3-D distribution of galaxies in the space
 Today we have redshifts measured for ~ 2 million galaxies
- While the existence of clusters was recognized early on, it took a while to recognize that galaxies are not distributed in space uniformly randomly, but in coherent structures

Discovery of the Large Scale Structure

- 1930's: H. Shapley, F. Zwicky, and collab.
- 1950's: Donald Shane, Carl Wirtanen, others
- 1950's 1970's: Gerard de Vaucouleurs, first redshift surveys
- 1970's 1980's: CfA, Arecibo, and other redshift surveys



6000 Brightest Galaxies on the Sky



How would the picture of the 6000 brightest stars on the sky look?



The Local Supercluster

- Hinted at by H. Shapley (and even earlier), but really promoted by G. de Vaucouleurs
- Became obvious with the first modern redshift surveys in the 1980's
- A ~ 60 Mpc structure, flattened, with the Virgo cluster at the center; the Local Group is at the outskirts
- Its principal axes define the supergalactic coordinate system (XYZ)
- Many other superclusters known; and these are the largest (~ 100 Mpc) structures known to exist



The Local



~15000 brightest galaxies on the sky, in Galactic coordinates. Solid line defines the Supergalactic plane



Representative Galaxy Catalogs/Surveys

- 1970 Lick (Shane-Wirtanen)
- 1990 APM
- 1995 DPOSS
- 2005 SDSS
- 2015? LSST

1 M galaxies 2 M 50 M 200 M 2000 M

Representative Local Redshift Surveys

- 1985 CfA
- 1992/5 IRAS
- 1995 CfA2
- 1996 LCRS
- 2003 2dF
- 2005 SDSS

2,500 galaxies 9,000 20,000 23,000 250,000 800,000

Stepping Out in Redshift Slices



Stepping Out in Redshift Slices





The Nearby Superclusters



The PSCz Redshift Survey: One of several redshift

surveys which used the IRAS satellite (IR) selected galaxy catalogs, in

order to avoid the extinction effects







The 2nd generation redshift surveys were often done in slices which were thin in Dec and long in RA, thus sampling a large dynamical range of scales. This also helped reveal the large-scale topology (voids, walls, filaments). **Coma cluster:**

Note the "finger of God" effect, due to the velocity disp. in the cluster

Real space distribution The effect of cluster The effect of infall

velocity dispersion

Redshift space apparent distrib.





Up until then, redshift surveys revealed structures as large as can be fitted within the survey boundaries - but 100 Mpc turned out to be about as large as they come.

The next generation of surveys sampled 3-D volumes (rather than thin slices), sometimes with a sparse sampling (measure redshift of every *n*-th galaxy), and often used multi-object spectrographs.

Tools of the Trade: Multiobject Spectrographs





2dF multifiber spectrograph



Las Campanas Redshift Survey



Huge Redshift Surveys

- The 2dF (2 degree Field) redshift survey done with the 3.9-m Anglo-Australian telescope by a UK/Aus consortium
 - Redshifts of ~ 250,000 galaxies with B < 19.5 mag, covering 5% of the sky reaching to $z \sim 0.3$
 - Spectrograph can measure 400 redshifts at a time
 - Also spectra of ~ 25,000 QSOs out to z ~ 2.3
- The Sloan Digital Sky Survey (SDSS) done with a dedicated 2.5-m telescope at Apache Point Observatory in New Mexico
 - Multicolor imaging to r ~ 23 mag, and spectra of galaxies down to r < 17.5 mag, reaching to z ~ 0.4, obtaining ~ 600 (now ~ 1,000) spectra at a time, covering ~ 14,000 deg²
 - As of 2012 (SDSS III, DR 9): > 900 million detected sources,
 ~ 1.5 million galaxy spectra, ~ 670,000 stellar spectra, ~ 230,000 quasar spectra (reaching out to z ~ 6.4)

2dF Galaxy Redshift Survey







Pencil Beam Surveys

- To probe structure at higher redshifts is generally done with deep "pencil beam" surveys in small patches of the sky, but going very deep, using big telescopes
- 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 they're not ... probably a signature of the baryonic oscillations scale at ~ 100 Mpc
 - The same qualitative structure and scale of voids and walls we see locally seems to continue out to $z \sim 1$
- Even deeper surveys done with Keck (DEEP) and VLT (VIRMOS) of the Hubble Deep Field and several other deep surveys show the same effects
- These surveys map out evolution of field galaxies and LSS out to $z \sim 1 2$

Structures in Deep Redshift Surveys



Comparing Redshift Surveys





Next: Galaxy Clustering: The Two-Point Correlation Function

