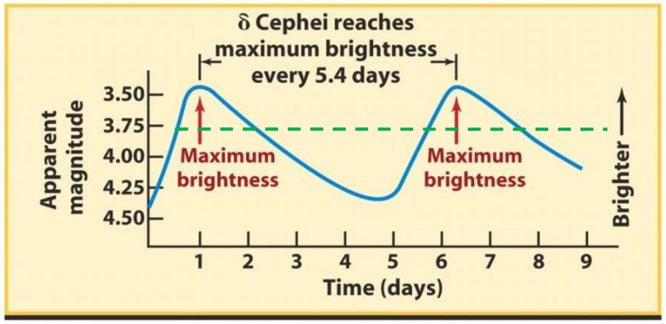
Distances to galaxies

- Cepheids – used by Hubble, 1924 to show that "spiral nebulae" like M31 were further from the Sun than any part of the Milky Way, therefore galaxies in their own right.

Review of Cepheids

• Cepheids are very bright (100's-10,000's x L☉), massive, variable stars. Can be isolated in nearby galaxies.



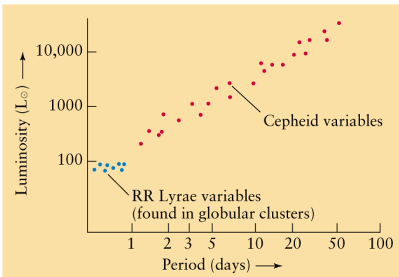
The light curve of δ Cephei (a graph of brightness versus time)

• The light curve yields average incident flux *F* (or apparent magnitude *m*), and the period, *P*.

- From Cepheids whose distances are independently known, can convert average incident flux to luminosity.
- Find that *P* and *L* are related.

Henrietta Leavitt

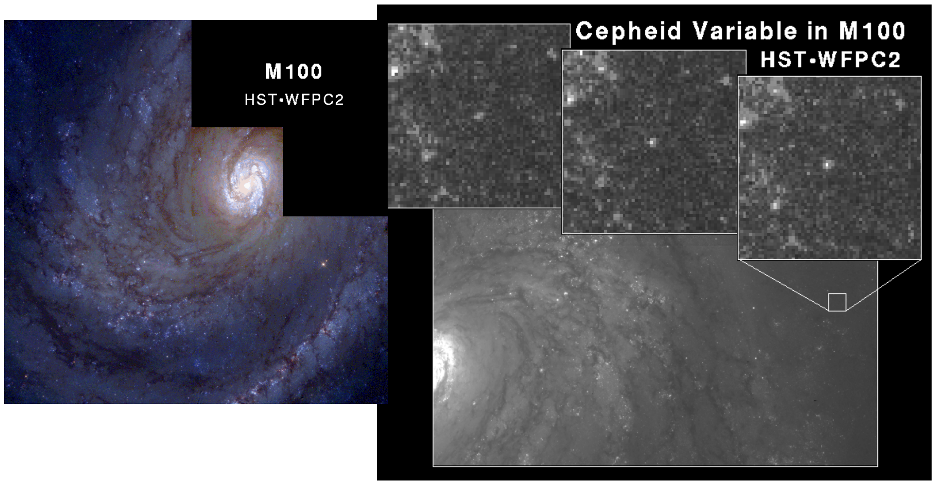
• The modern calibration of the P-L relation (also now known as the Leavitt Law) is from Cepheids in the Milky Way (with very recent HST trig parallax distances), and the Large Magellanic Cloud, whose distance we can estimate independently. Thus "bootstrapping".



• Thus, if they can be identified in nearby galaxies, measure their period and average incident flux. *P-L* relation gives luminosity, and thus distance:

$$D = \sqrt{\frac{L}{4\pi F}}$$

- A key goal of the Hubble Space Telescope was to measure Cepheids in more distant galaxies than is possible from the ground. Successful to about 30 Mpc. Gives distances with about 10% accuracy.

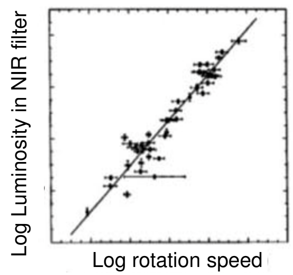


Are there other ways to estimate distances? Yes.

Tully-Fisher relation

- For nearby spirals, (flat) rotation speed correlates with optical or near-IR luminosity (distances known from, e.g., Cepheids). Reasons not well understood (good to think about why), but correlation good.
- So measure distant galaxy's rotation speed, infer luminosity. Measure incident flux. Distance again from:

$$D = \sqrt{\frac{L}{4\pi F}}$$

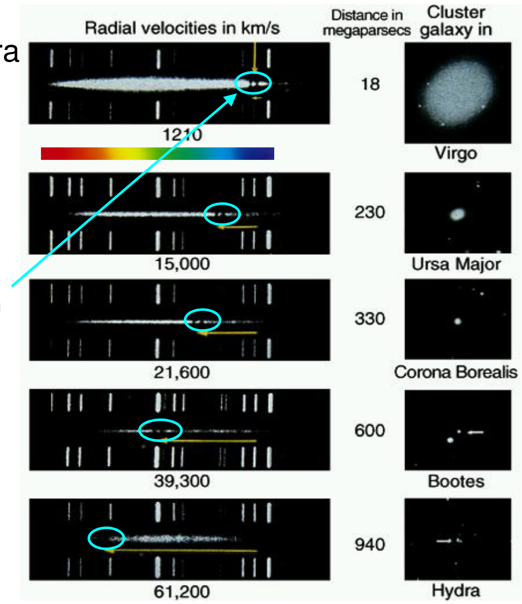


- Successful to >100 Mpc.

Hubble's Law

In 1912, Slipher used spectra of "spiral nebulae" to find essentially all of them are receding from us, that is, show "redshifted" spectral lines.

Calcium absorption lines



The redshift

- The redshift is denoted by z

$$z = \frac{\lambda - \lambda_0}{\lambda_0} = \frac{\Delta\lambda}{\lambda_0}$$

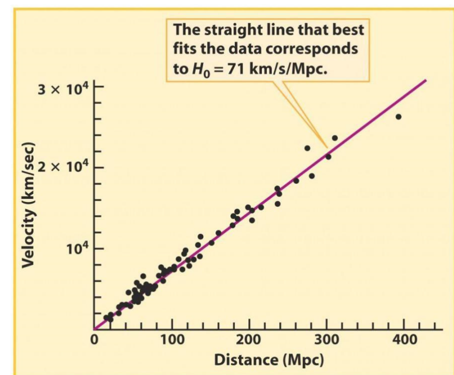
where z is the redshift, λ_0 is the rest wavelength of the spectral line, and λ is the observed (shifted) line from the galaxy.

- The recession "velocity" is then $V = cz$ (but is it really a velocity through space? We'll come back to that), which is valid for small redshifts < 0.3 or so, beyond which General Relativity must be considered.

- Slipher's result mysterious until Hubble estimated distances using Cepheids. Found redshifts and distances are related:
- Hubble's Law:

$$V = H_0 d$$

where the slope H_0 is Hubble's constant. Units of H_0 are km/s/Mpc.



Best modern value is ~70 km/s/Mpc.

- Now can find distance to a galaxy by measuring redshift. Works to much further distances than Cepheids or Tully-Fisher.
- Note: at such large distances, now looking well into past.

Implications of Hubble's Law

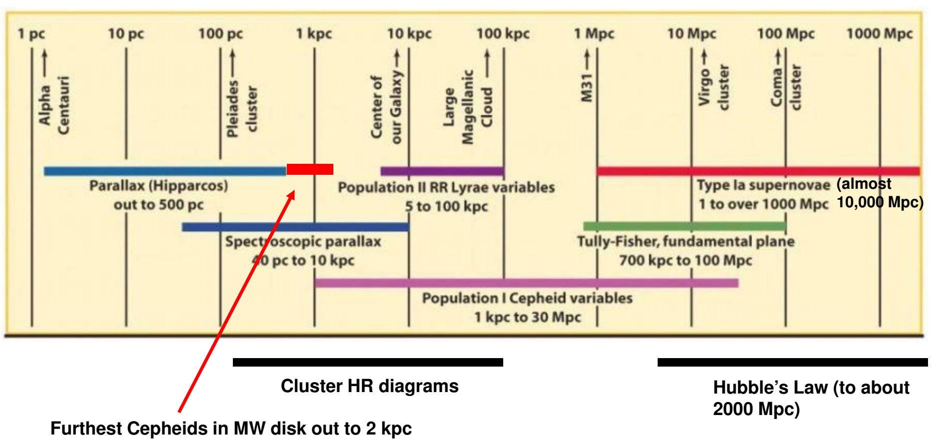
1. A new way to find distance and thus the scale of the Universe.
2. The Universe is expanding.
3. The Universe has an age. Long ago the Universe was compact – the Big Bang.

Type Ia Supernovae

- All should have about same *L* since all result from detonation of WD of about same mass. Indeed true in nearby galaxies.
- Extremely luminous (peak at a few x 10^9 $L_\odot$). Can see in galaxies a few times 10^9 parsecs away, where light has taken billions of years to reach us!
- Like Cepheids, these are "standard candles".

- Why useful? Can look for deviations from Hubble's Law at great distances (i.e. early times).

The "Distance Ladder"



Structures of Galaxies

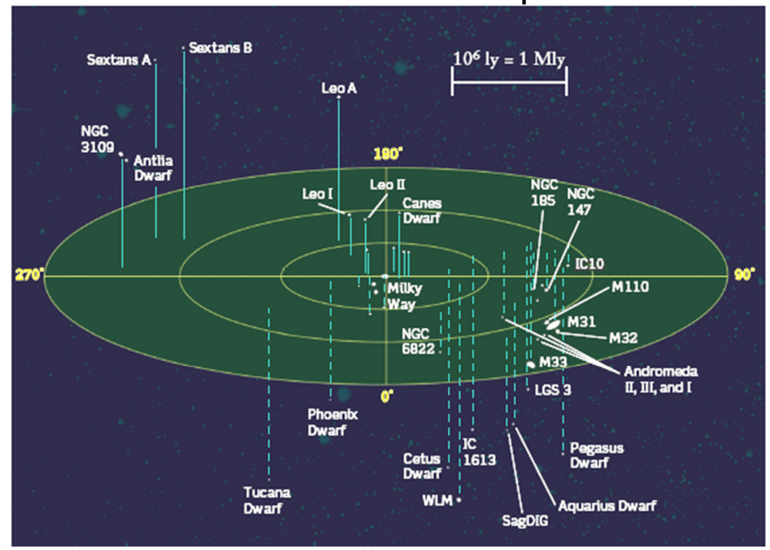
- Galaxies tend to form groups and clusters. Rough dividing line: 100 members.

The Local Group

- The MW and Andromeda are the two giant galaxies in a loose collection of more than 100 galaxies.
- Many orbit the MW, and many orbit M31. The rest have orbits governed by the entire gravity of the Local Group.
- Almost all galaxies in the Local Group are dwarfs. New ones still being found. Many found with Sloan Digital Sky Survey in NM!

Leo I, a dwarf Elliptical orbiting the Milky Way

The Local Group



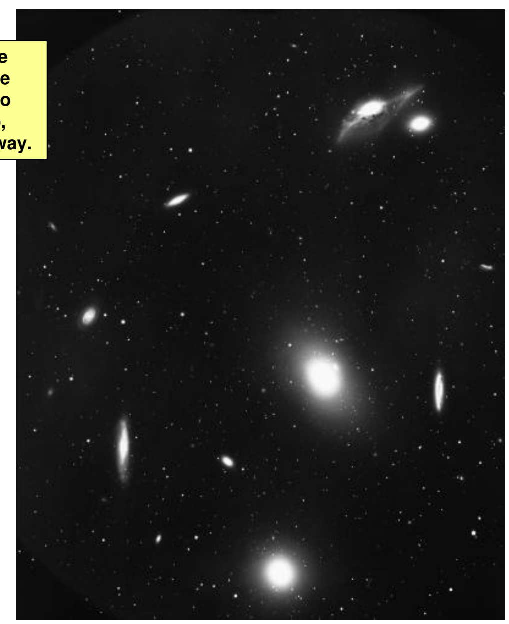
Groups have irregular structure. (Does not show all the recently found dwarfs).

Clusters

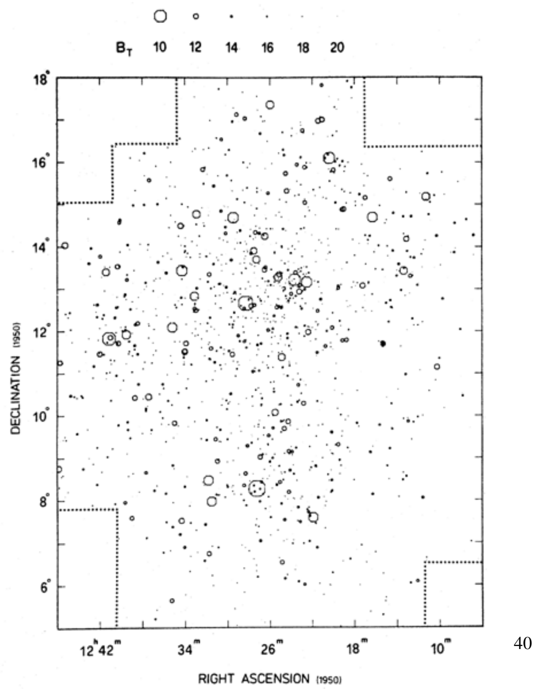
- 10^2 - 10^4 galaxies
- Size a few Mpc
- Larger ones tend to have regular, more spherical structure, like a globular cluster

The Coma cluster

The center of the Virgo cluster, the closest cluster to the Local Group, about 15 Mpc away.



Depiction of all known members (about 2500) of Virgo Cluster



Mass in clusters

- Quasi-spherical: orbits are like stars in a halo or Elliptical. Measure galaxies' Doppler shifts.
- Rough estimate: as we did for MW, for a galaxy of mass m orbiting with speed v in a cluster of mass M:

Then,

$$\frac{GMm}{R^2} = m\frac{V^2}{R}$$

$$M \approx \frac{RV^2}{G}$$

(How do we get good estimate of *V*? How do we get *R*?)

- Result: typical speeds 400-1200 km/s, radii 1-10 Mpc, so masses up to 10^{15} $M_\odot$. Luminous matter 10x less

=> Dark Matter again! First done by Zwicky in 1933.

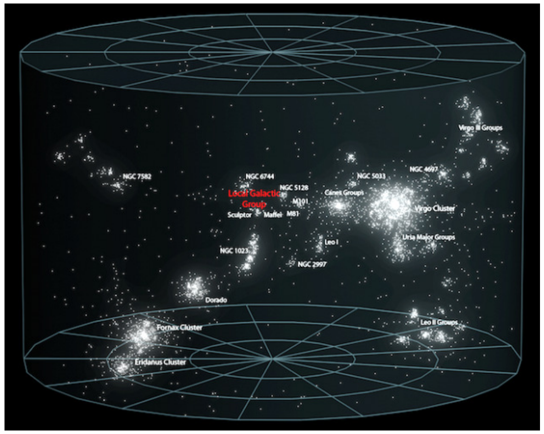
In many clusters, even most of the "normal" matter is not in galaxies, but in hot gas between them (revealed by X-rays).

Superclusters: they contain clusters and groups

- Sizes up to 50 Mpc, 10^{15} - 10^{16} $M_\odot$.
- Often long and filamentary in shape.

Local Supercluster

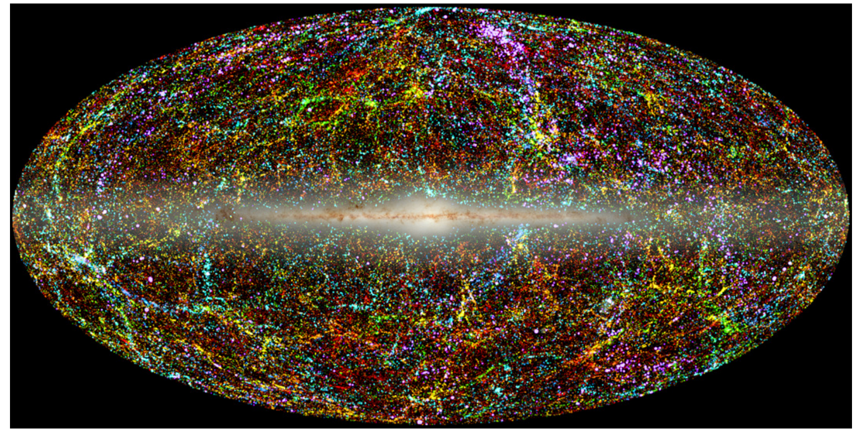
- Dominated by the Virgo Cluster.
- Size: ~30 Mpc, mass: ~$10^{15}\ M_{\odot}$
- The Local Group is on the outskirts of the Local Supercluster, and "falling into" the Virgo Cluster at about 200 km/s now (how do we measure this, and what do we mean by it?)



30 Mpc

Large Scale Structure

- Large scale structure of the Universe ("2MASS" project): redshifts for 45,000 galaxies. Color coded by redshift. Furthest here about 115 Mpc.

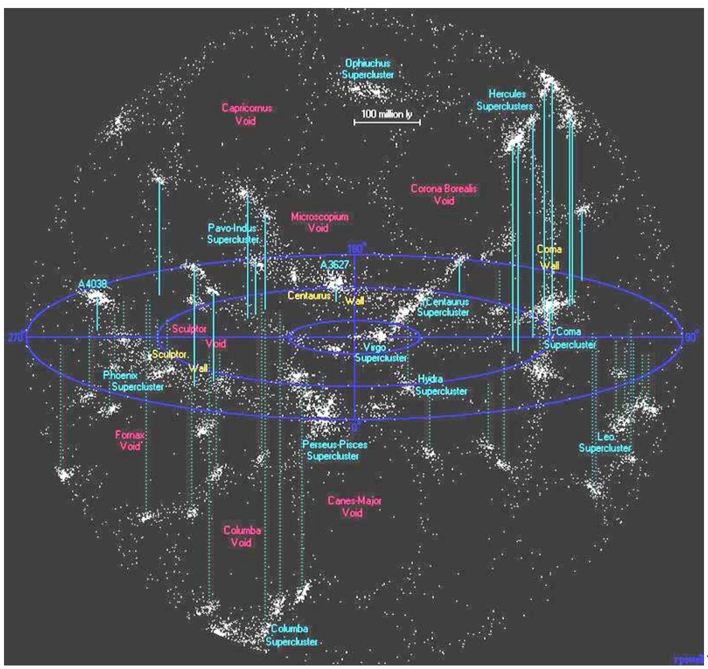


The local Universe:

Filamentary superclusters surrounding almost empty "voids".

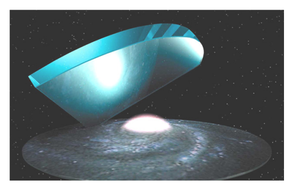
300 Mpc

What about on even larger scales?

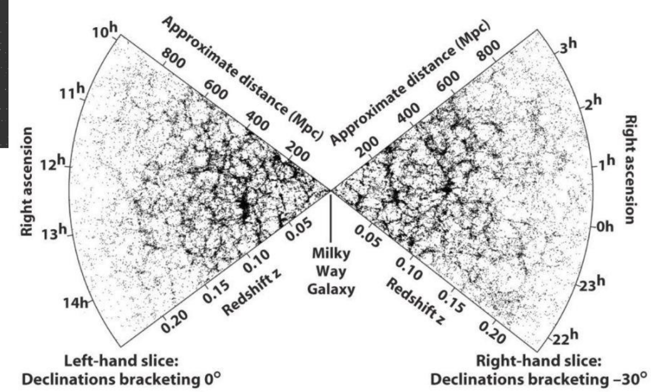


Slices through Large Scale Structure

- Again, filaments of clusters and superclusters, (occupying ~10% of the Universe), surrounding voids of 25-50 Mpc diameter (5-10 times fewer galaxies than in superclusters).



Simulation of growth



The 2dF galaxy survey