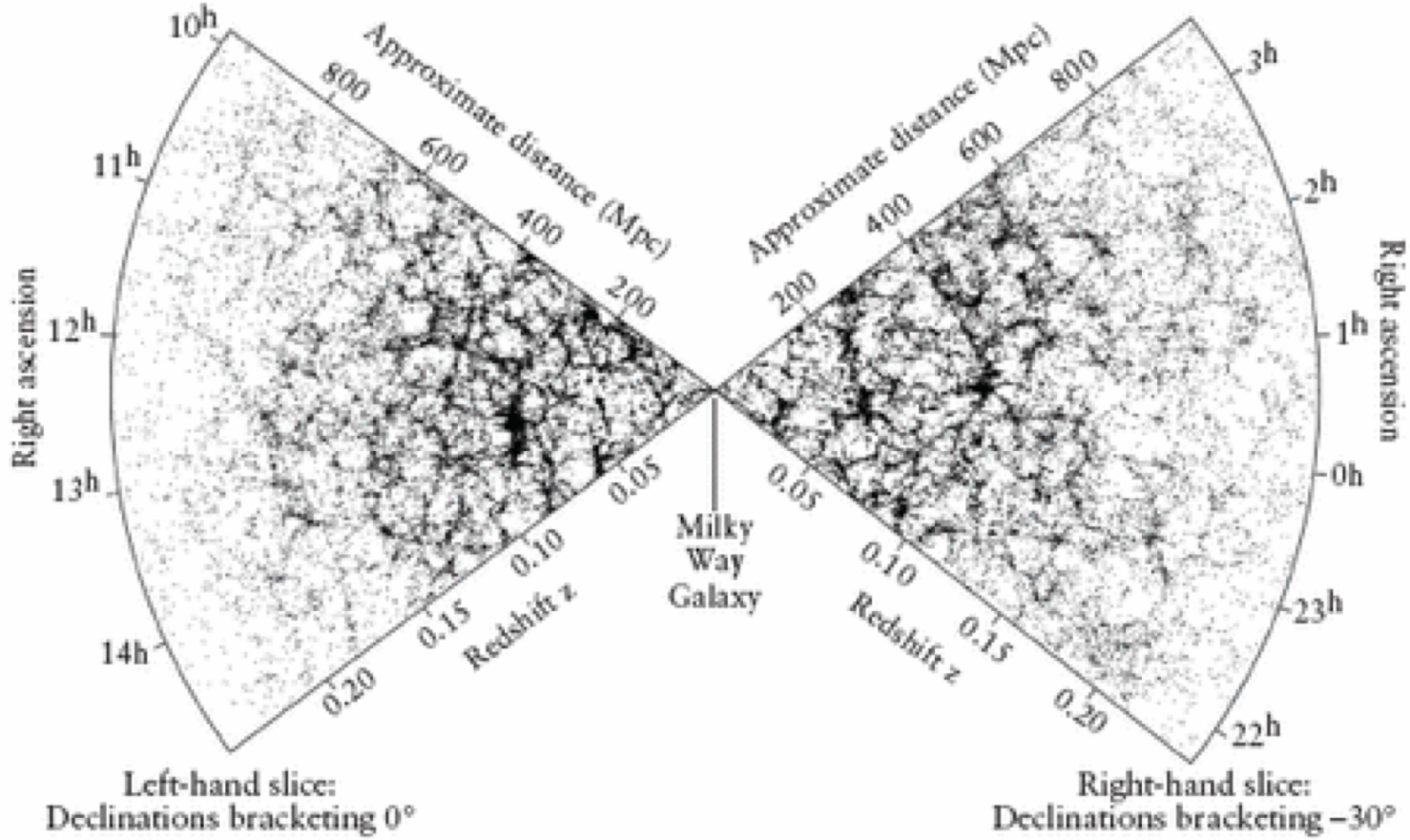
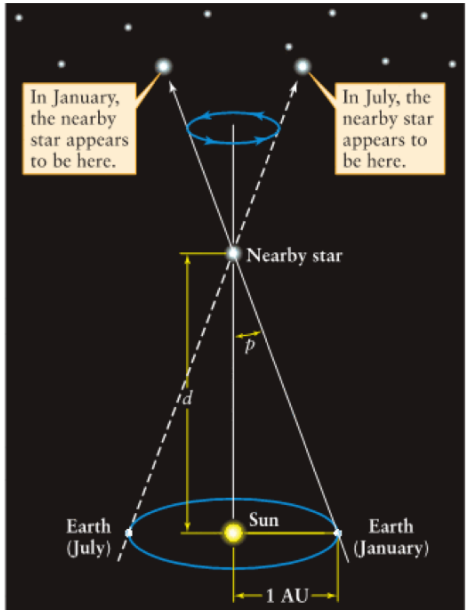
The Structure of the Universe



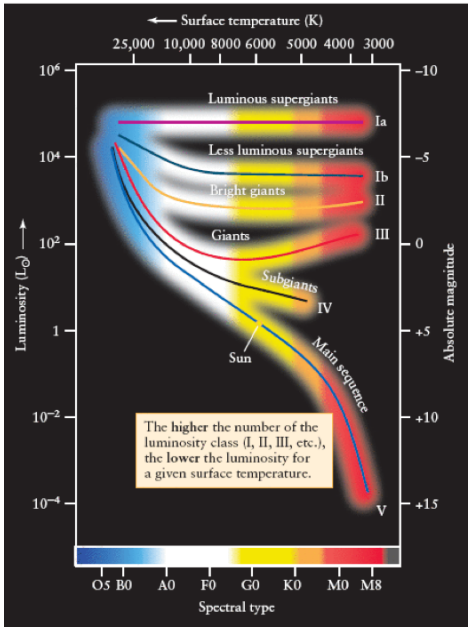
(a) The 2dF galaxy survey

Measuring the Distances to Galaxies

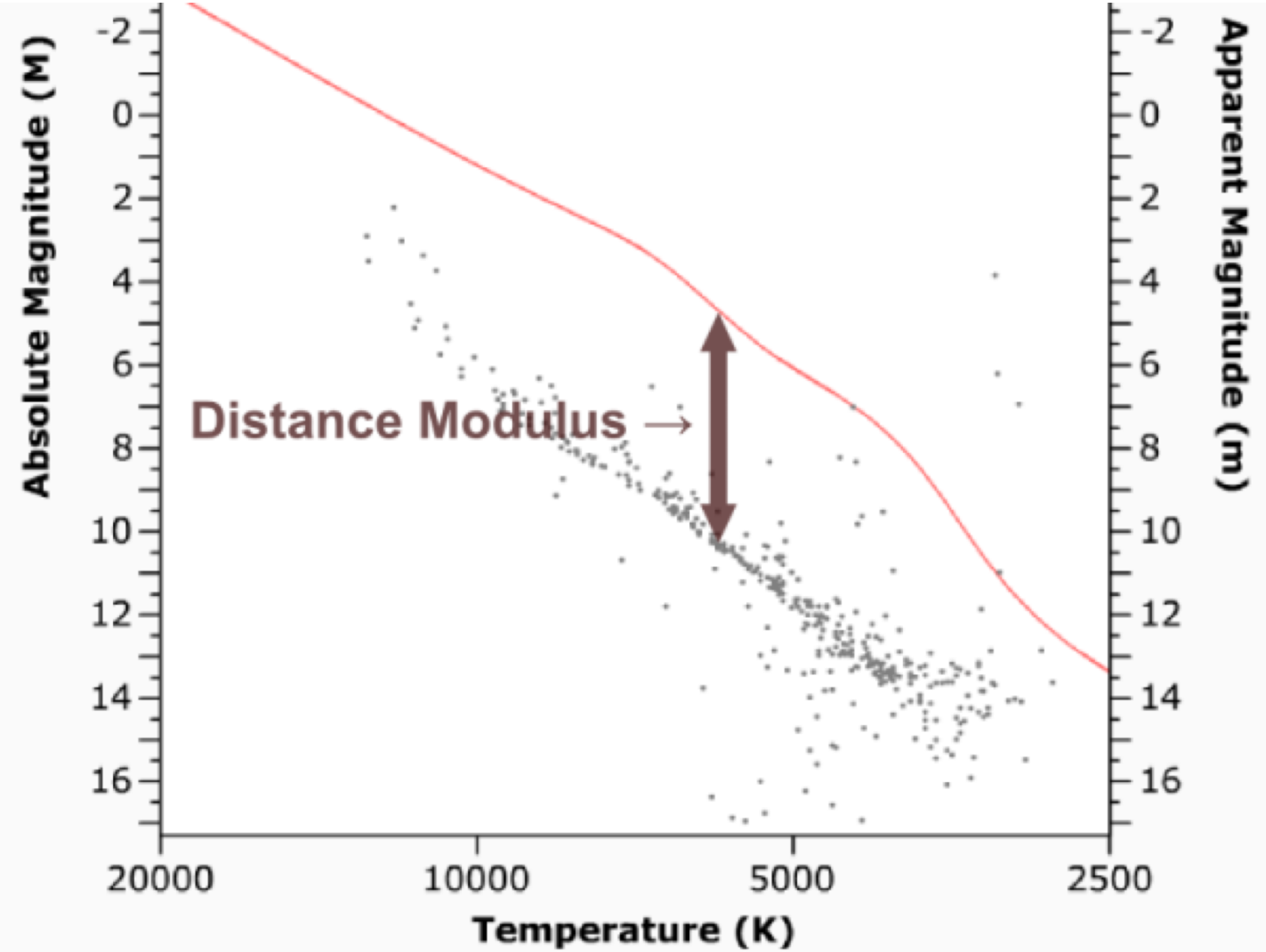
Parallax methods cannot be used to measure the distances to galaxies since they can only be used to measure objects relatively nearby.
The Hipparchos satellite can measure parallax angles as small as ~ 0.001arcsec.
d = (1/p) parsec, p in arcsec.



Spectroscopic parallax can measure objects accurately up to about 10 kpc. (From a stellar spectrum obtain the spectral type and luminosity class. Then use the HR diagram to infer luminosity or absolute magnitude. Combine absolute and apparent magnitude to determine distance using :
$m - M = 5\log d - 5$



Main Sequence Fitting

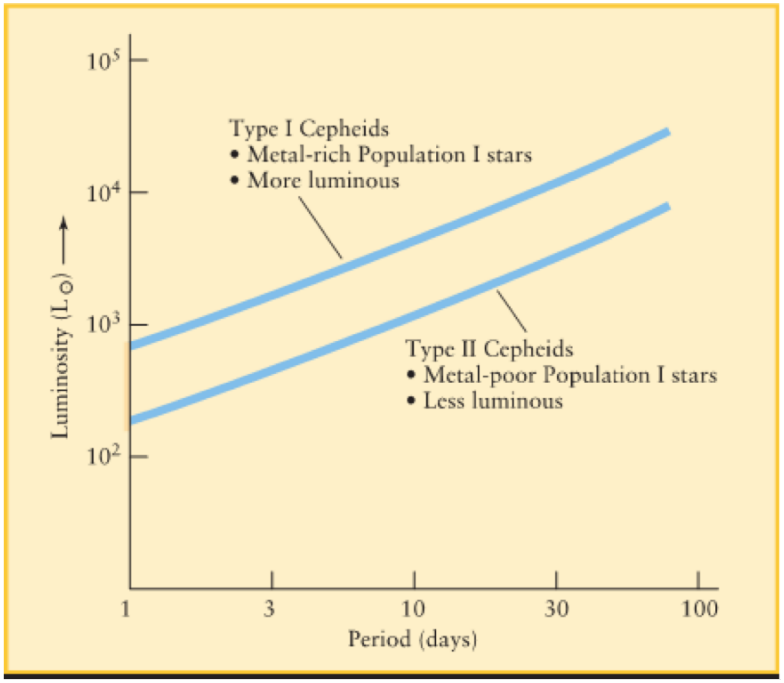


Period-Luminosity Relations of Cepheids

Hubble was able to measure the distance to Andromeda by using the Cepheid method.

A measurement of the apparent magnitude (or flux) of an object combined with its absolute magnitude (or luminosity) that is inferred from the **Period-Luminosity relation** of Cepheids provides the distance to the object.

Distance to Andromeda~ 2.5×10^6 light-years!



Period-Luminosity Relations for Cepheids. The greater the average luminosity of a Cepheid variable, the longer its period. There are two distinct period-luminosity relations—one for Type I Classical Cepheids and one for Type II Cepheids.

Distance to galaxy IC 4182

Example: Galaxy IC 4182

A metal rich Cepheid variable in IC 4182 has a period of 42 days. The period-luminosity relation gives a luminosity of 33,000$L_\odot$ which corresponds to an absolute magnitude of -6.5.

Observations indicate the apparent magnitude of this Cepheid to be m = +22.0. The distance to the Cepheid variable in IC 4182 is:

$m - M = 5\log d - 5$

$d = 10^{(m-M+5)/5}$ parsec = 5×10^6 parsec

$M_{\langle V \rangle} = -3.53\log_{10} P_d - 2.13 + 2.13(B - V)$

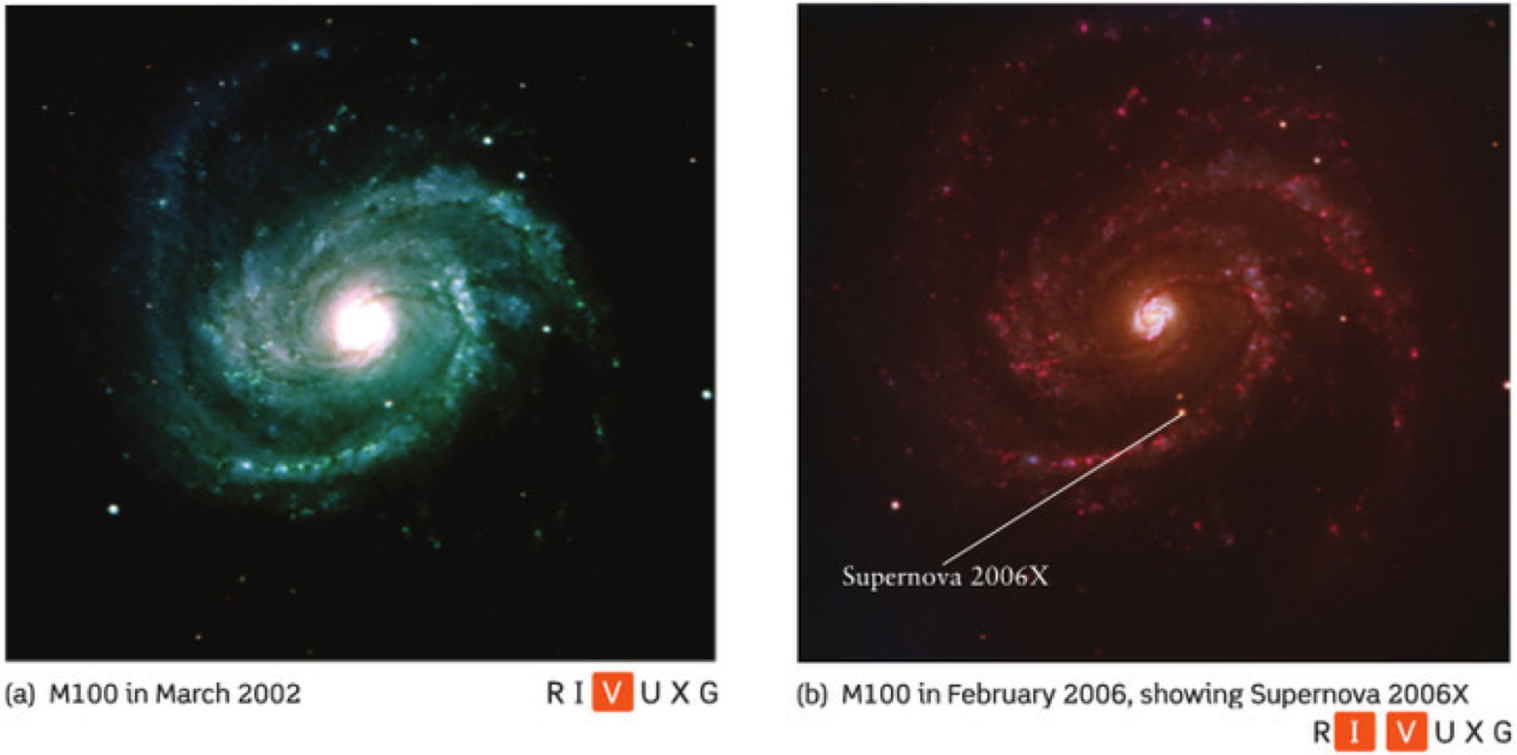
Measuring the Distances to Galaxies

Standard Candles: Objects of known luminosity.
1.) *Cepheid Variables* : Supergiant pulsating stars where their periods are a function of their average luminosity.
Can be used to determine distances up to 100 Mly.

2.) *RR Lyrae Variables* : Pulsating horizontal branch stars of spectral class A with a period of less than a day. They are old, relatively low mass, metal-poor Population II stars.
Can be used to determine distances up to 300,000 ly.

3.) *SN Type Ia*: these supernovae occur when a white dwarf in a close binary system accretes enough matter from its companion to blow itself apart when $M > 1.4\ M_{\odot}$. Their spectra lack hydrogen emission but contain a strong Si absorption line.
Can be used to determine distances up to 3×10^9 ly.

Measuring distances to Galaxies with SN Type Ia



VLT images of M100 (a) before and (b) after a Type Ia supernova exploded within the galaxy in 2006. The distance to M100 (~55 Mly) is also known from observations of Cepheid variables, so this particular supernova can help calibrate Type Ia supernovae as distance indicators.

Estimating the distances to Spiral Galaxies

Tully and Fischer found that the width of the hydrogen 21-cm line of a spiral galaxy is related to its luminosity. This is the **Tully-Fisher relation**.

The reason is that the faster a galaxy rotates the broader the 21 cm line becomes because of Doppler shifts of the receding and approaching sides of the galaxy.

Galaxies with faster rotational speeds are more massive according to Newton's form of Kepler's third law and the more massive galaxies contain more stars and are therefore more luminous. **Consequently, the width of a galaxy's 21-cm line is directly related to its luminosity.**

The Tully-Fisher relation can be used to determine the distance to spiral galaxies up to 100 Mpc.

Estimating the distances to Elliptical Galaxies

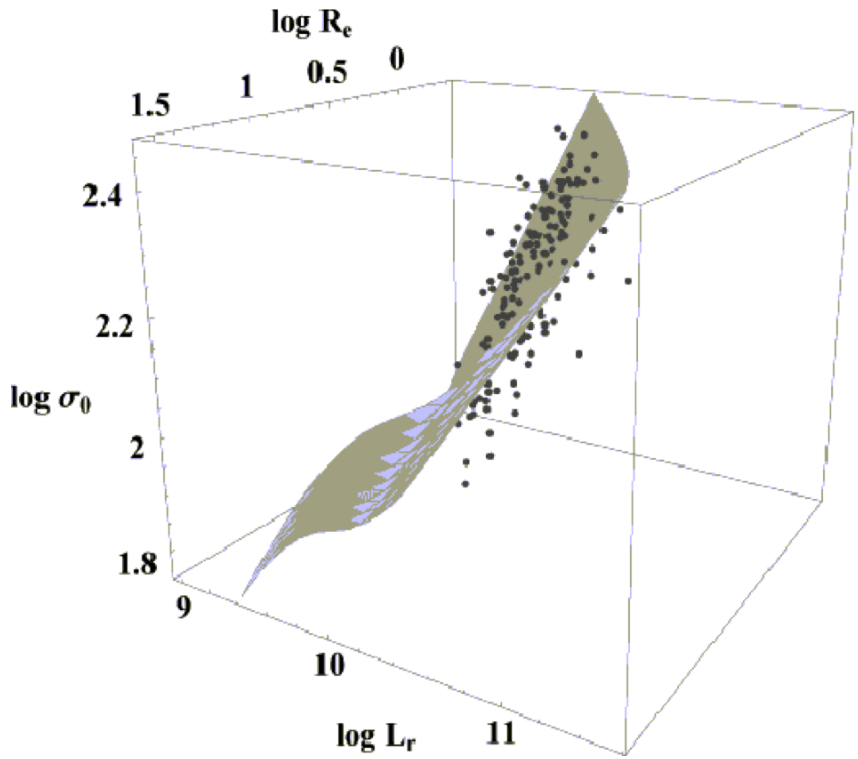
The fundamental plane is an empirical relation between the effective **size**, the average surface **brightness** and the central **velocity dispersion of the central stars** found in elliptical galaxies.

If one measures these three quantities for many elliptical galaxies and plots them they find that the points fall on a plane called the fundamental plane.

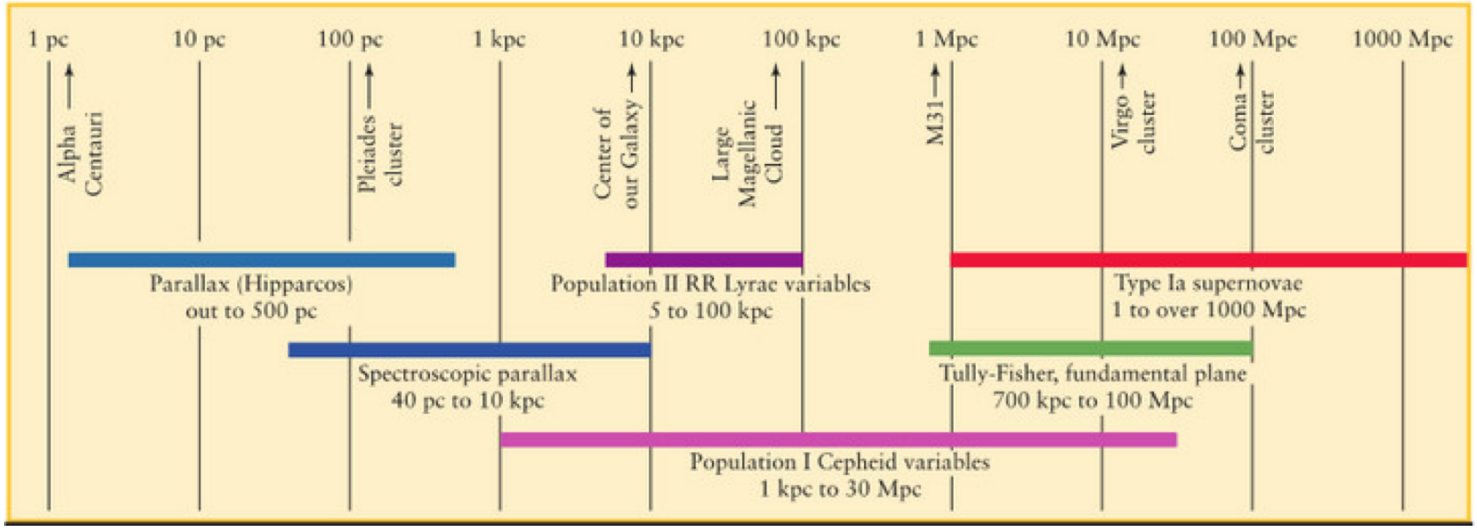
Estimating the distances to Elliptical Galaxies

Having found the fundamental plane for nearby galaxies one can estimate the distance to remote elliptical galaxies:

First one measures the velocity dispersion of the stars and the average surface brightness. Then using the fundamental plane one can infer the actual size of the galaxy and use the small angle formula to estimate the distance.



Distance Ladder



Astronomers use a sequence of methods to determine the distance to very remote objects. This approach is called the **distance ladder**.

Objects are found where their distances can be measured both with the accurate parallax method and the less accurate spectroscopic parallax and calibrate the spectroscopic method so it can be used at larger distances.

Next objects are found where their distance can be measured both with the spectroscopic parallax method and with Cepheid variables and calibrate the luminosities of the Cepheid variables and so on.

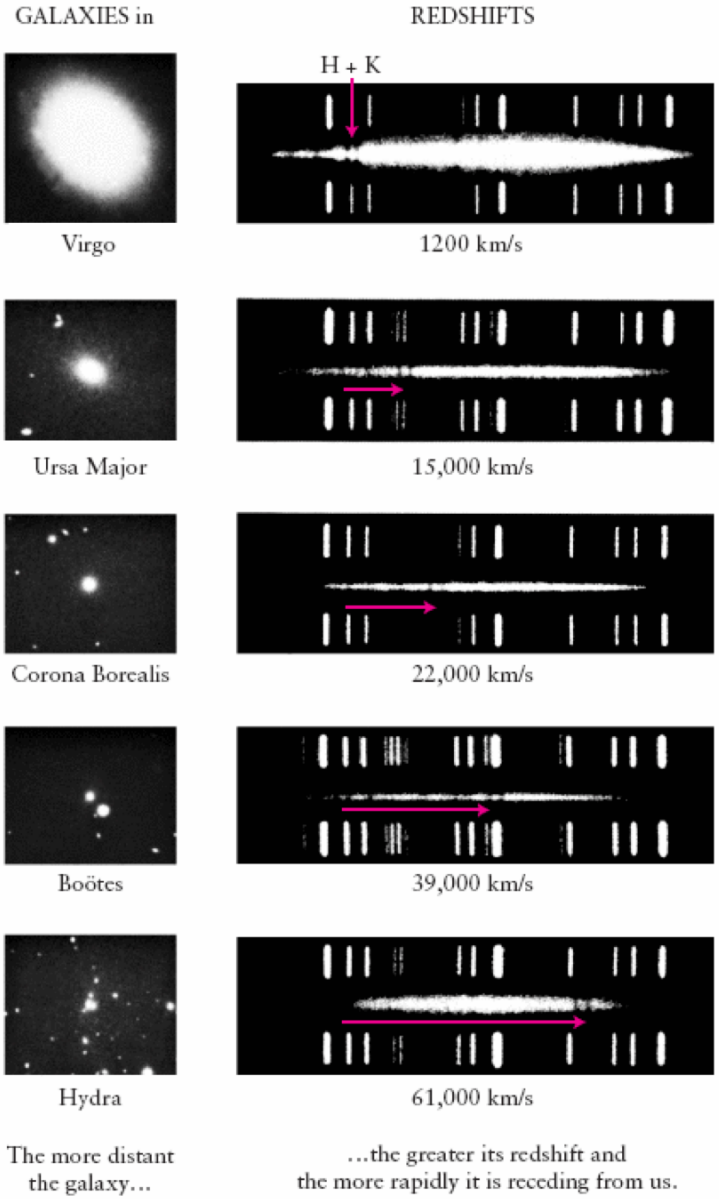
Redshift

$$\frac{\lambda_{obs} - \lambda_0}{\lambda_0} = z$$

λ_{obs} = *the observed wavelength*
λ_0 = *the rest-frame wavelength*
z = *the redshift of the object*

Figure: Each galaxy's spectrum is a bright band with dark absorption lines.

The bright lines above and below it are a comparison spectrum taken on Earth. The horizontal red arrows show how much the H and K lines of singly ionized calcium are redshifted in each galaxy's spectrum. Below each spectrum is the recessional velocity calculated from the redshift.



The Hubble Law

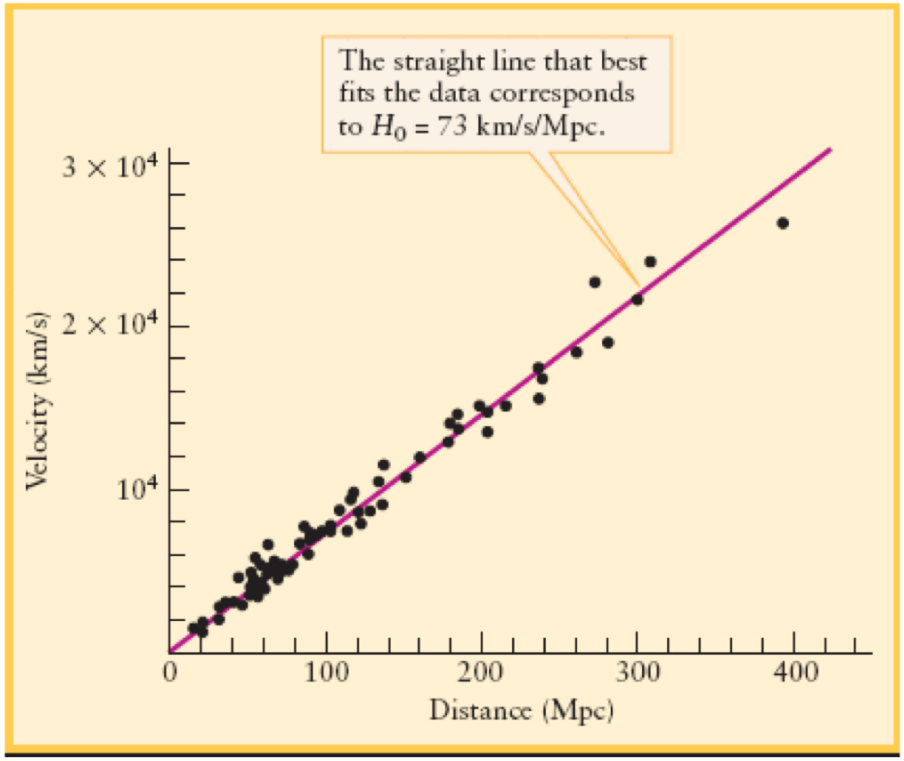
The Hubble Law:

$$v = H_0 \, d$$

v = recessional velocity of a galaxy, H_0 = Hubble constant
d = distance to the galaxy

H_0 = 70 +/- 3 km/s/Mpc

Note that this is not a real velocity as in the Doppler effect but the apparent velocity due to the expansion of space. For low redshift $z \sim v/c$



Hubble measured the recession velocities (from redshifts) and distances to galaxies (using Cepheid variable stars) and found that the more distant the galaxy the greater its recession velocity.

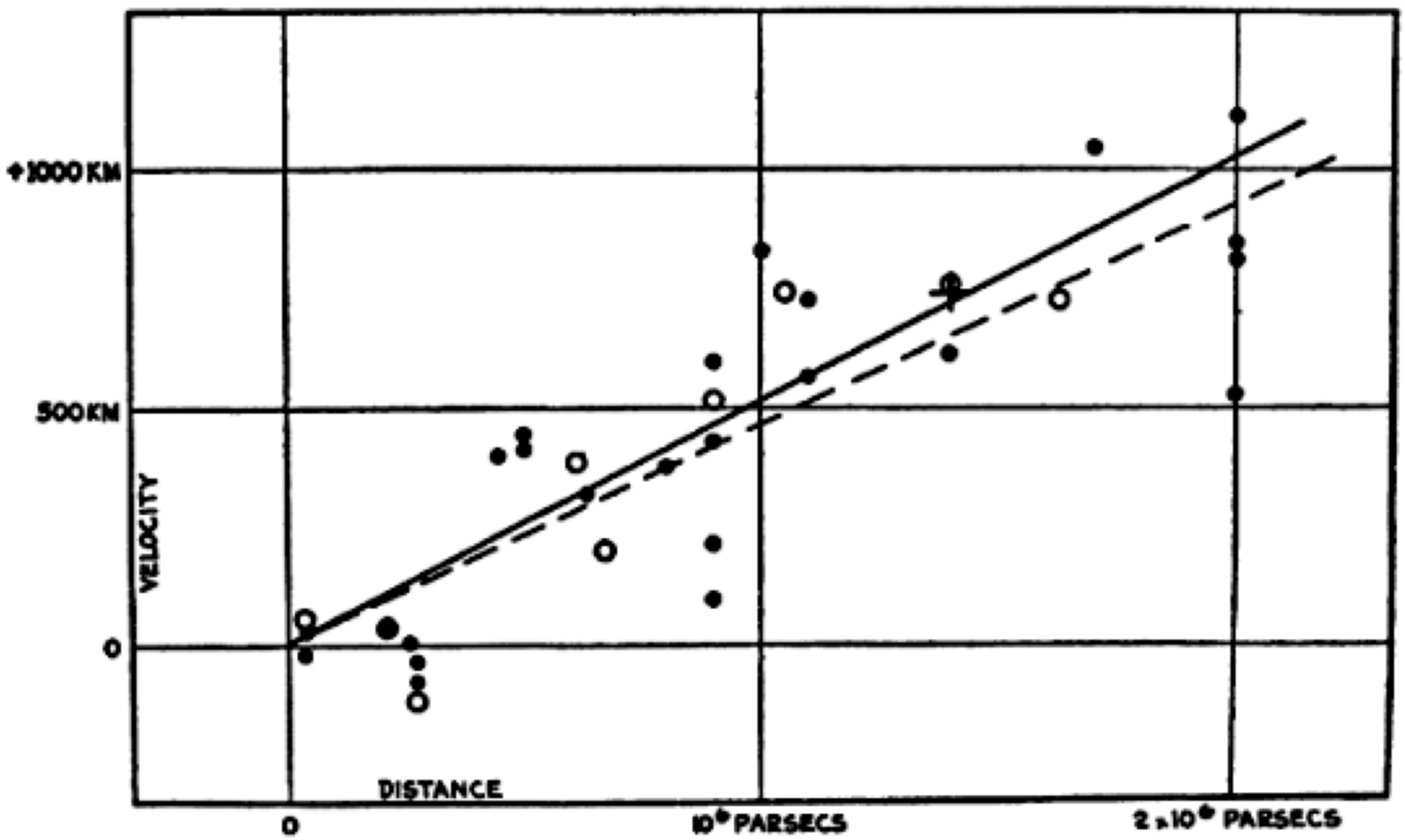


FIGURE 27.7 Hubble's 1936 velocity–distance relation. The two lines use different corrections for the Sun's motion. (Note: The vertical units should be km s^{-1}.) (Figure from Hubble, *Realm of the Nebulae*, Yale University Press, New Haven, CT, ©1936.)

Einstein’s Biggest Blunder?

Einstein's initial formulation of General Relativity implied an **expanding Universe**.

The prevailing theory at the time, however, was that the Universe was static and infinite. Einstein included a constant (Λ) in his equations to make his theory predict a non expanding and static Universe.

Einstein later stated that the inclusion of this constant was the **greatest blunder of his life**.

Hubble showed with observations that the Universe was expanding. Later Einstein visited Hubble and congratulated him on this remarkable discovery.

Hubble's Law and the Expanding Universe

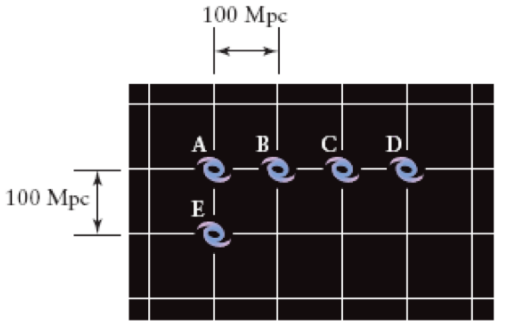
The **Hubble law** states that the recession velocity of a galaxy is proportional to its distance from Earth.

$$v = H_0 d$$

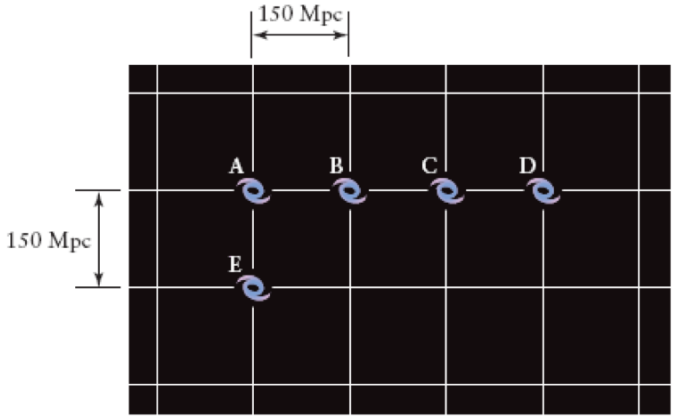
This law applies to any object participating in the expansion of the Universe and for an observer at any location in the Universe.

The currently accepted value of the Hubble constant is :

$$H_0 = (70 +/- 3) \text{ km/s/Mpc}$$



(a) Five galaxies spaced 100 Mpc apart



(b) The expansion of the universe spreads the galaxies apart

	Original distance (Mpc)	Later distance (Mpc)	Change in distance (Mpc)
A–B	100	150	50
A–C	200	300	100
A–D	300	450	150
A–E	100	150	50

Clusters of Galaxies

The Hercules cluster of galaxies just 650 million ly away.

Clusters of galaxies are the largest gravitationally bound objects in the Universe. Based on simulations the smallest structures collapsed first and eventually build the largest structures, such as clusters of galaxies.

Properties of Clusters of Galaxies

Clusters of Galaxies contain between 100 - 2000 galaxies, hot X-ray emitting gas and dark matter. **Mass distribution**:
~5% in galaxies, ~10% in hot gas and ~85 % in dark matter.

- Total mass ~ $10^{14} - 10^{15}$ $M_\odot$
- Diameter of $1 - 2$ Mpc
- Velocity dispersion of $\sigma \sim 1000$ km/s
- $M/L \sim 500$ $M_\odot/L_\odot$

Clusters are classified as **rich** (> 100 members) **or poor** (< 100 members). Poor Clusters are also called **groups**.

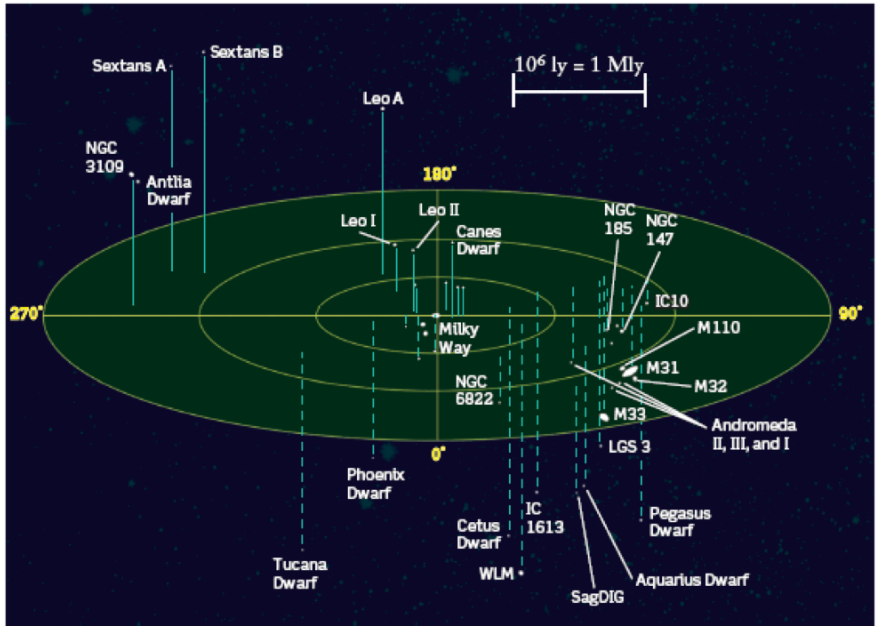
Cluster are also classified as **regular** (spherical shape) and **irregular** (non-spherical shape).

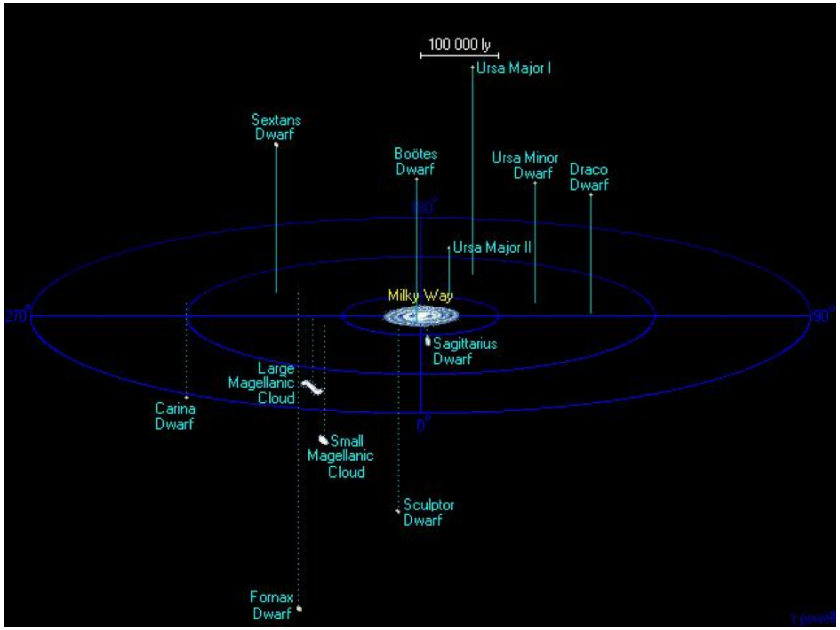
Properties of Groups

-Total mass ~ 10^{13} $M_\odot$
-Velocity dispersion of σ ~ 150 km/s
- M/L ~ 250 $M_\odot/L_\odot$

The Milky Way belongs to the **Local Group**.

Local Group



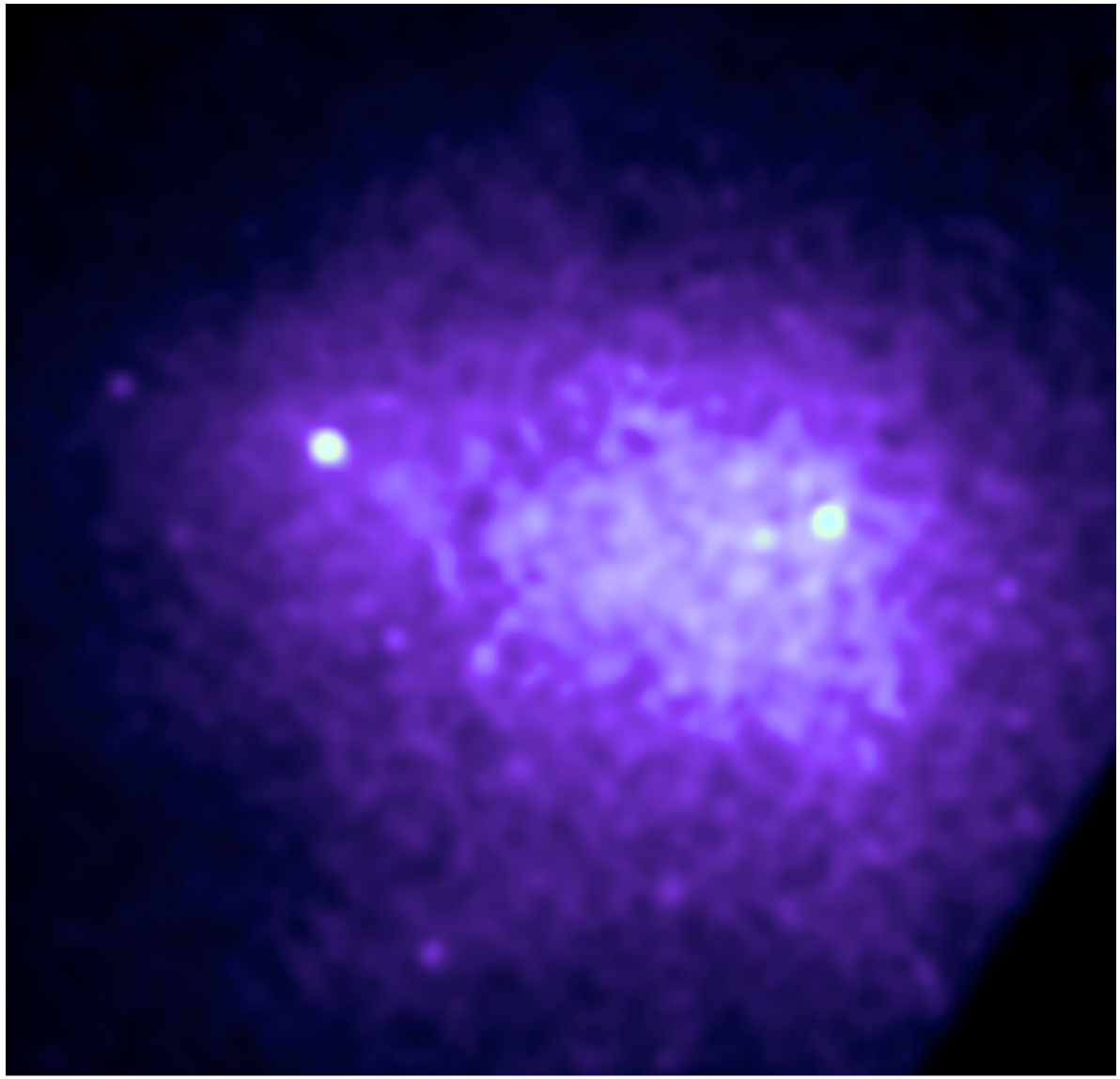


Members of the **Local Group** include:
Milky Way, M31, M33, Large and Small Magellanic Clouds, Leo I and Leo II, Canis Dwarf (only 42,000 ly from the center of the Milky Way) Ursa minor and Major Dwarfs, Sextans Dwarf, Sagittarius Dwarf.

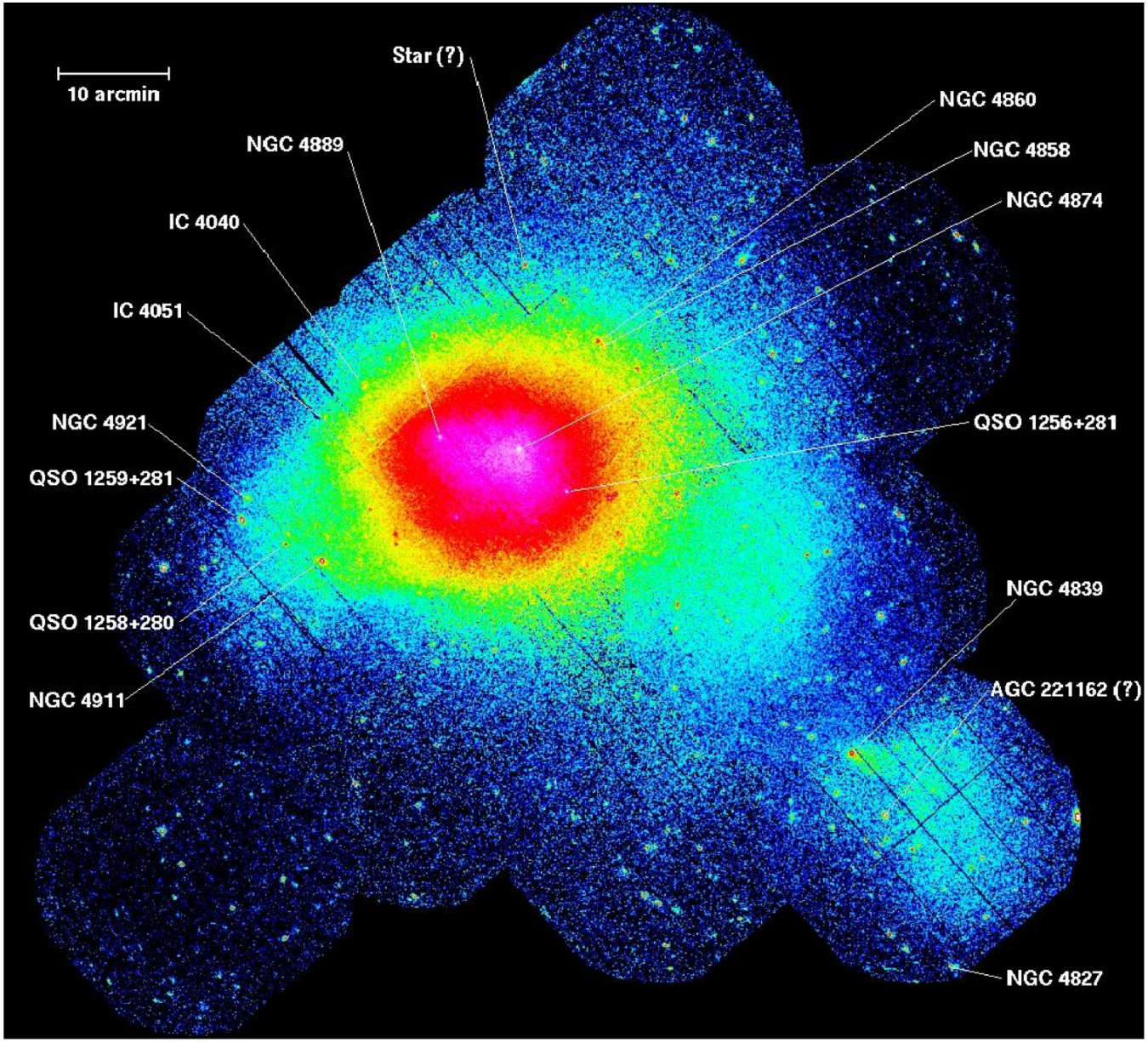
Virgo: A Rich Irregular Cluster of Galaxies

FIGURE 27.13 The center of the Virgo cluster, showing the giant ellipticals M84 (right) and M86 (center). (Courtesy of National Optical Astronomy Observatories.)

Coma: A Rich Regular Cluster of Galaxies



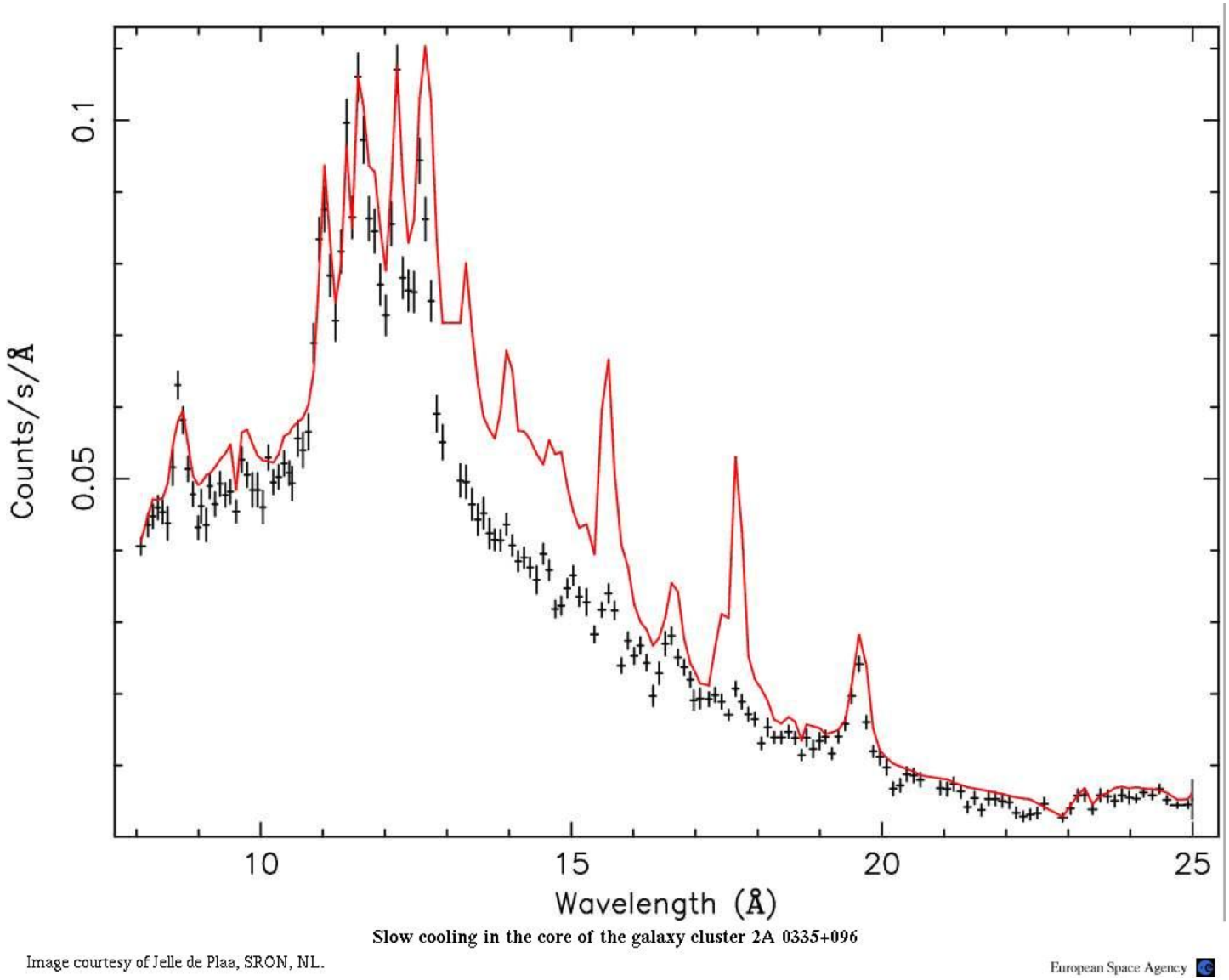
Coma: A Rich Regular Cluster of Galaxies



Coma Cluster of galaxies

Image courtesy of U. Briel, MPE Garching, Germany

European Space Agency



XMM-Newton spectrum of the cluster of galaxies 2A 0335+096. The black crosses are the data points, the red line shows the predicted spectrum according to the previously favored isobaric cooling-flow model. The difference between the two, due to the lack of the expected Fe XVII lines, indicates that the cores of clusters are cooling much slower than predicted.

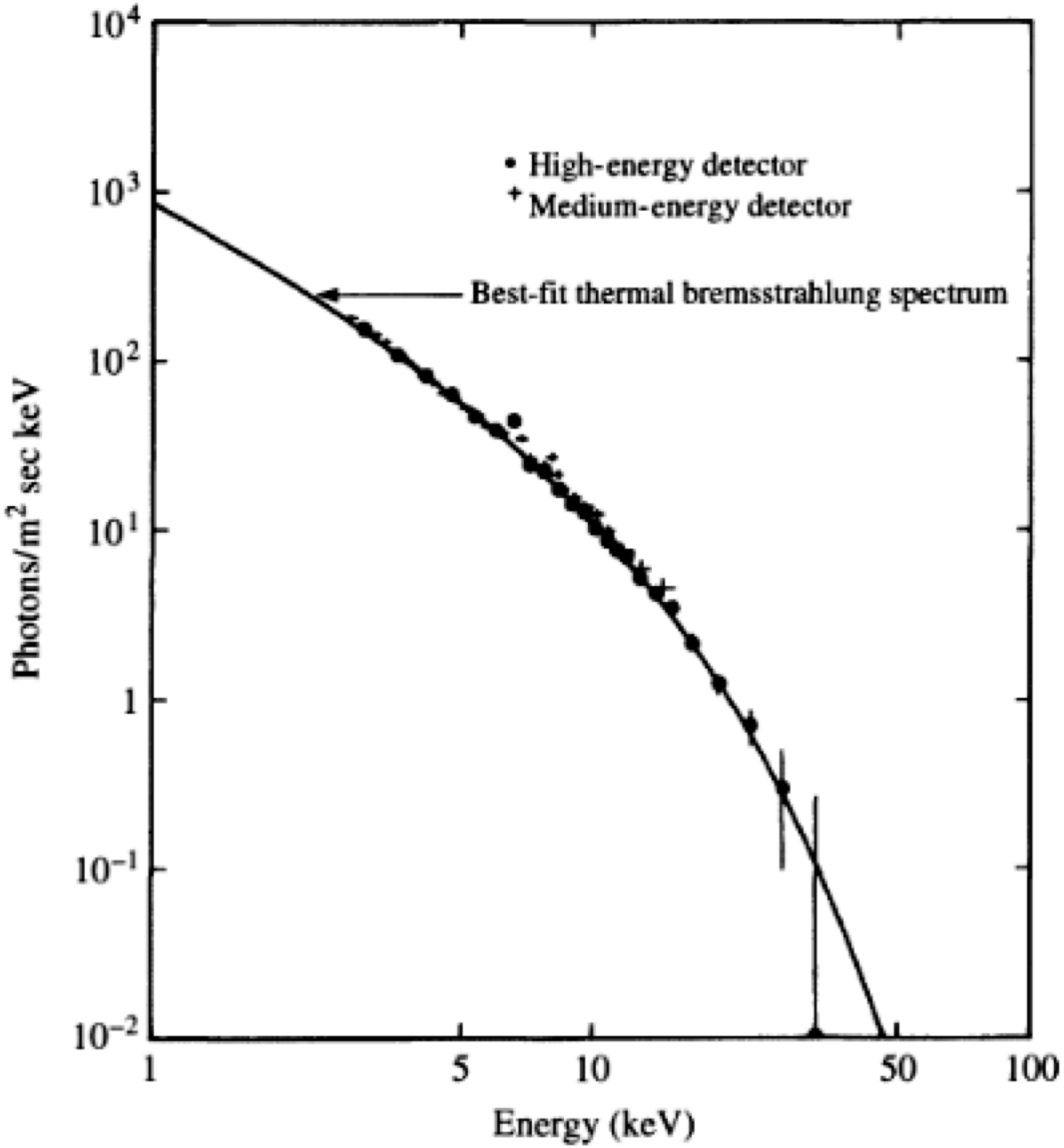
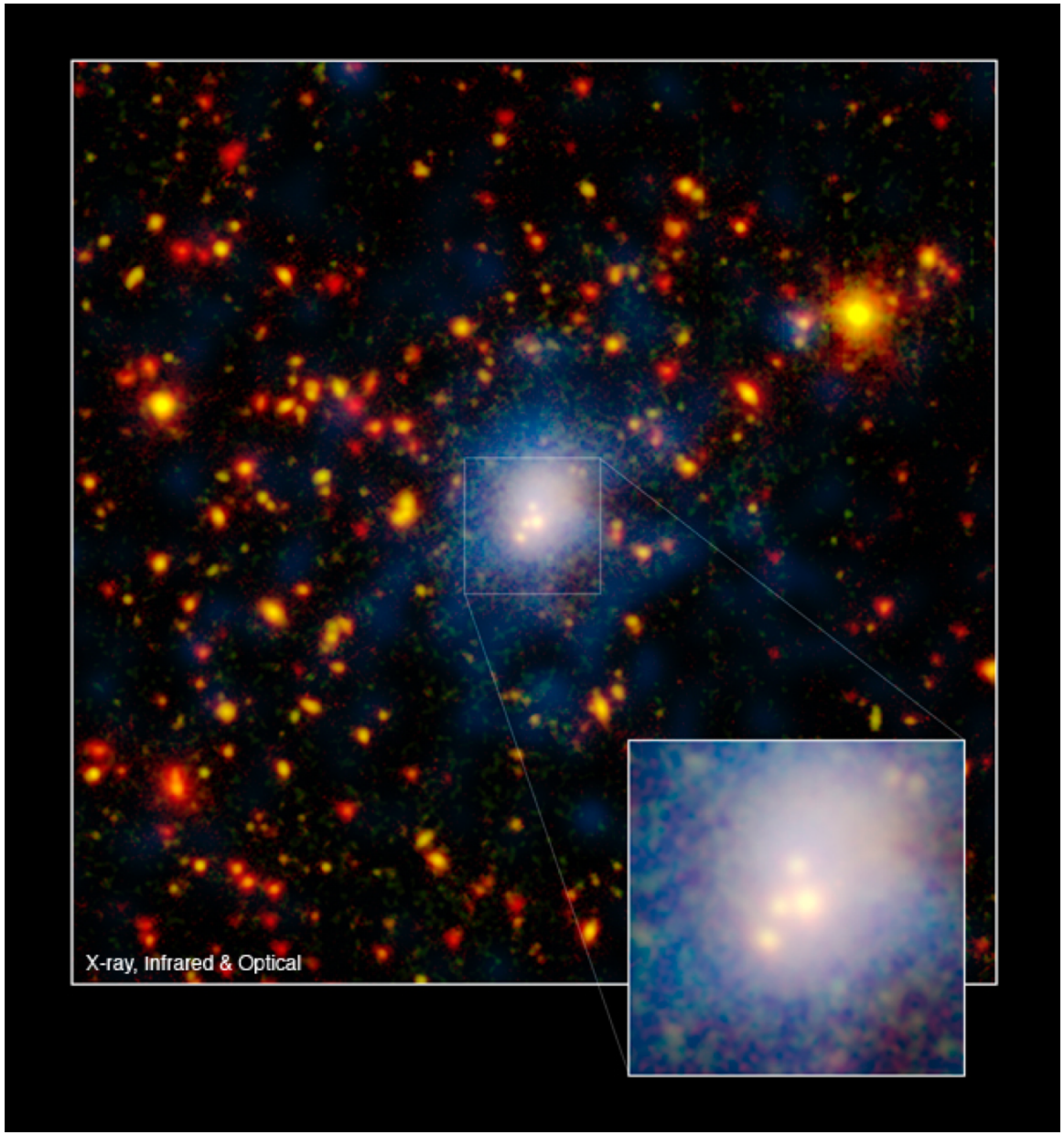


FIGURE 27.17 Thermal bremsstrahlung spectrum (line) for 88 million K. The points are observations of X-rays from the Coma cluster's intracluster gas. Photon energy is plotted on the horizontal axis. (Figure adapted from Henriksen and Mushotzky, *Ap. J.*, *302*, 287, 1986.)

z=0.39 CL0958+4702: Spitzer and Chandra Spy Monster Galaxy Pileup

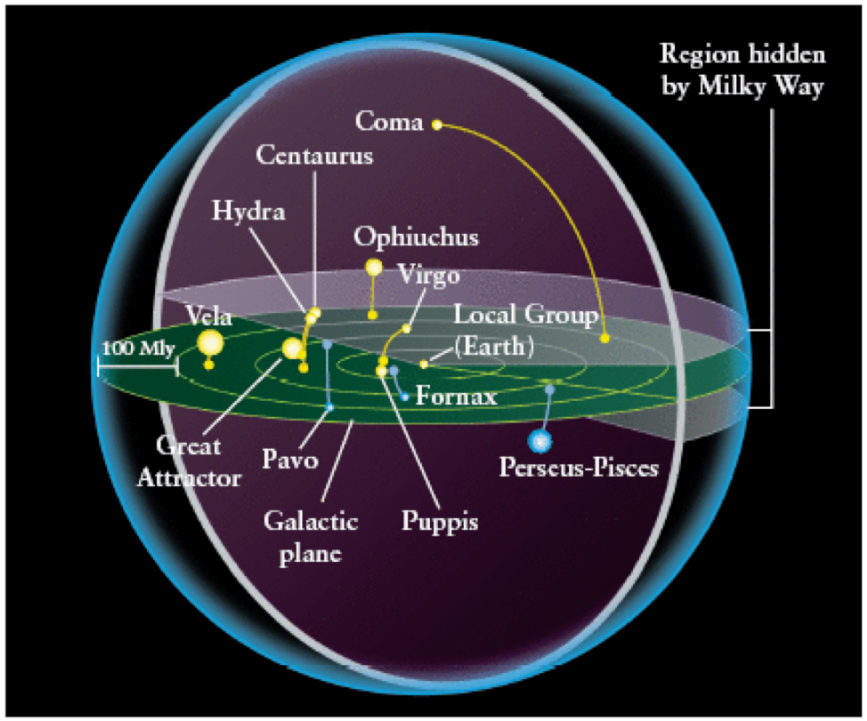


Superclusters

Clusters of galaxies are also grouped in larger structures called **superclusters.**
A supercluster may contain tens of clusters of galaxies.

Superclusters are not bound together by gravity and the distances between members grows as the Universe expands.

The nearest supercluster goes out to Virgo and includes our Local Group and is called the **Virgo Supercluster.**



Nearby clusters of galaxies

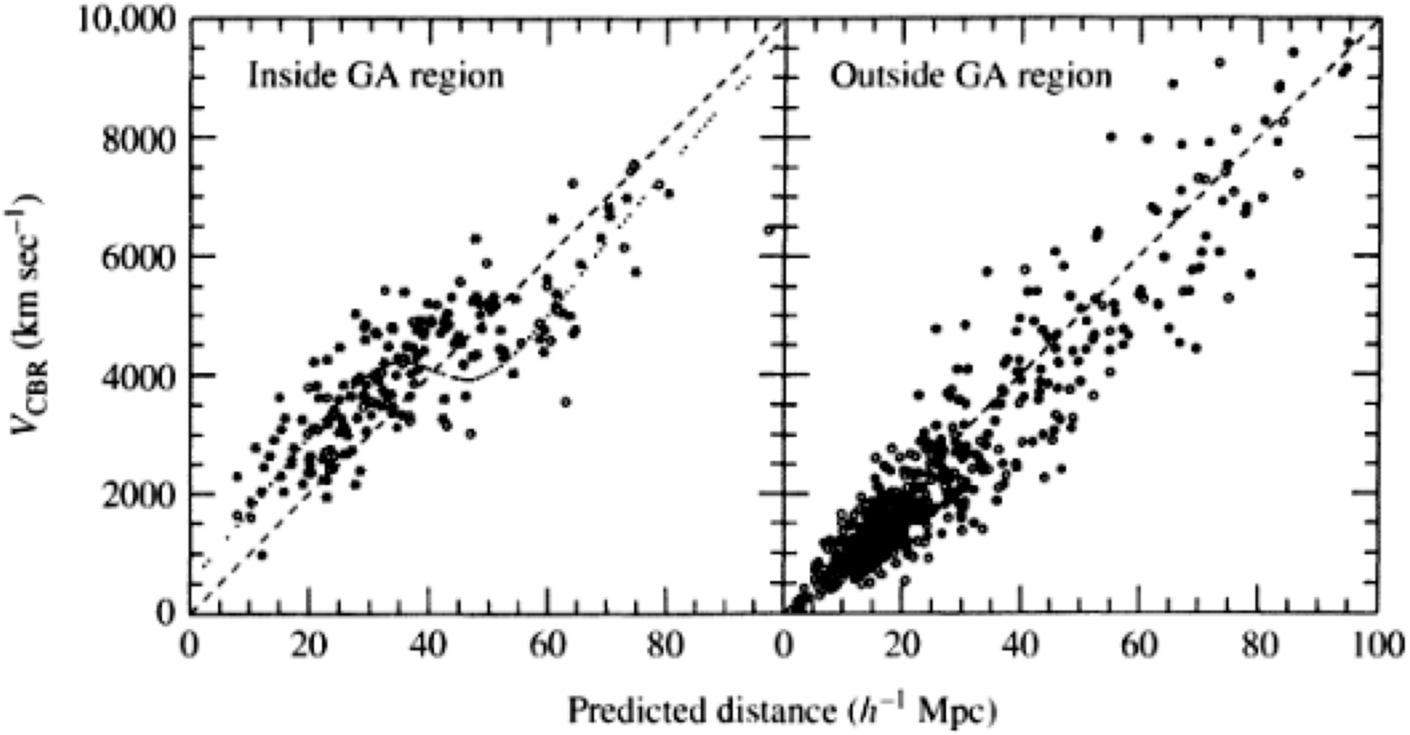


FIGURE 27.19 Left: velocities of galaxies in the Centaurus region, compared with the Hubble flow (dashed line). The dotted line shows the theoretical variation in velocity produced by a model of the Great Attractor. The Hydra–Centaurus supercluster is centered at about $30h^{-1}$ Mpc. Right: comparison figure for galaxies observed in another direction. (Figure adapted from Dressler and Faber, *Ap. J. Lett.*, *354*, L45, 1990.)

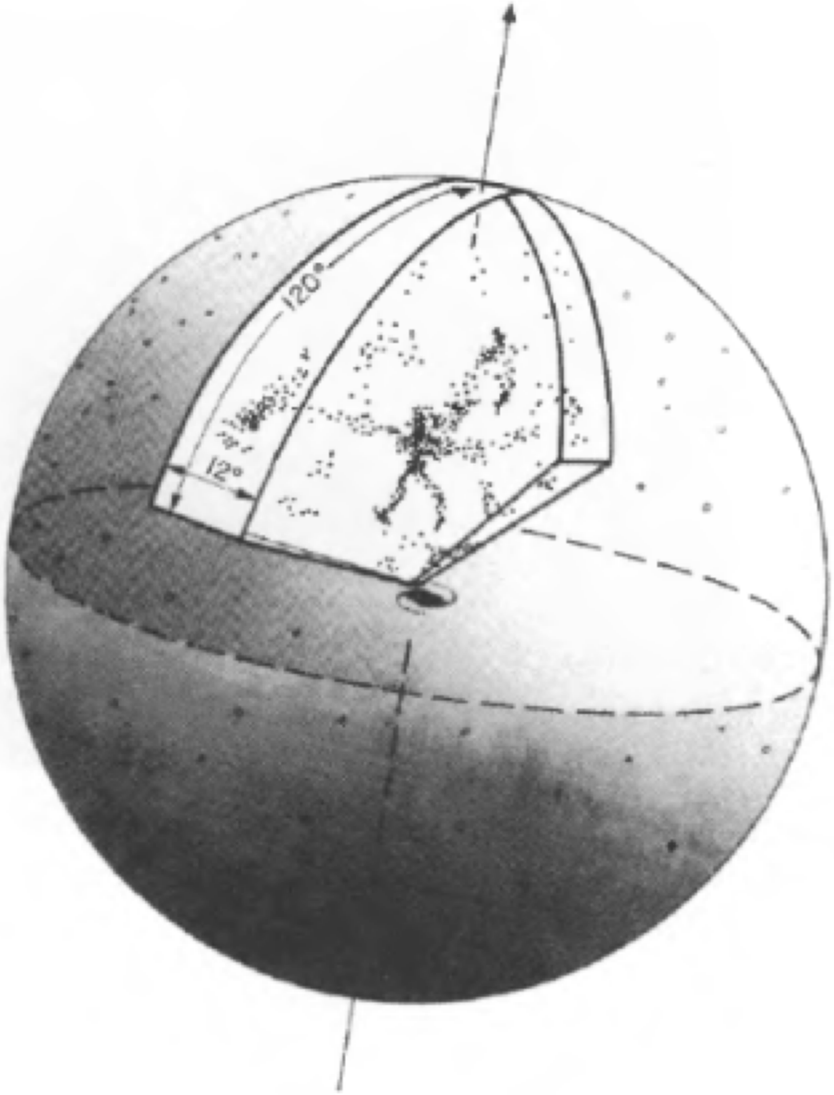


FIGURE 27.22 Two adjacent 6°-wide wedges used in the CfA redshift survey. (Figure from Geller, *Mercury*, May/June 1990.)

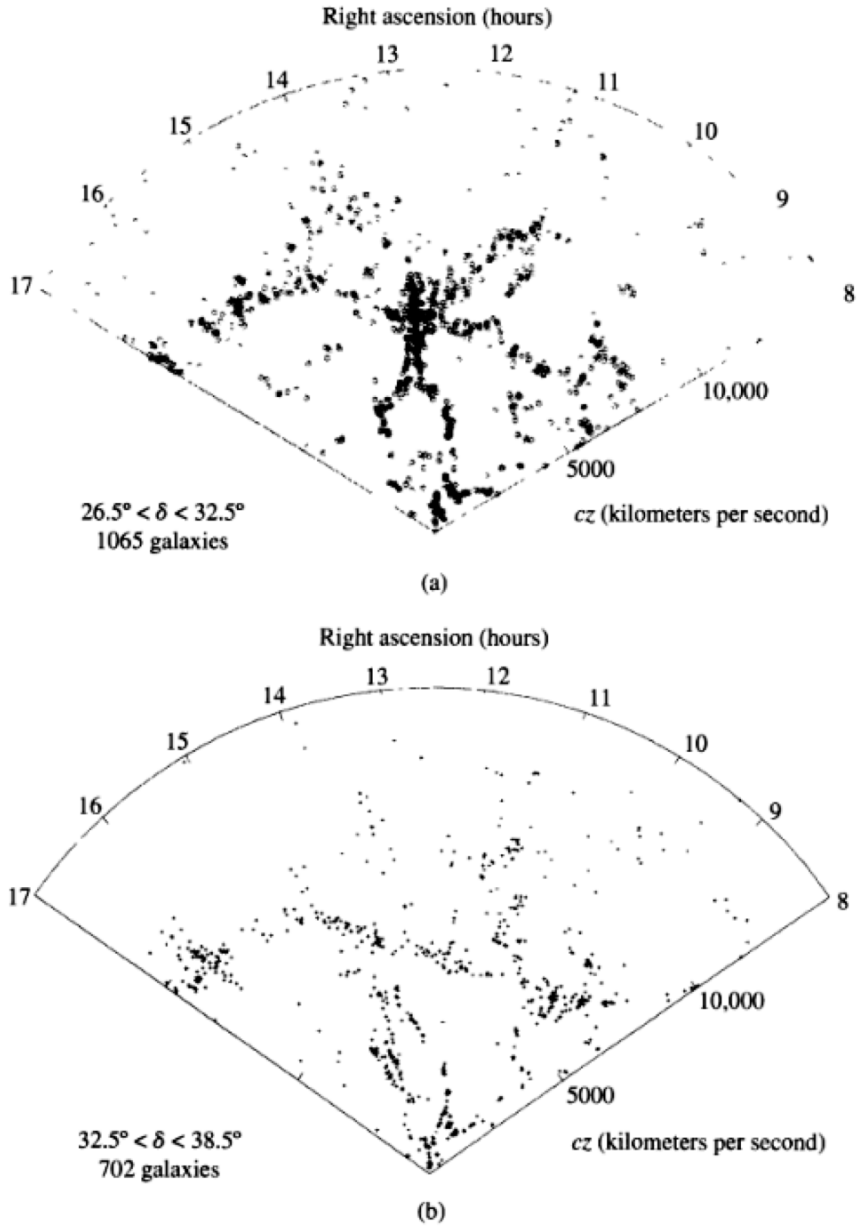
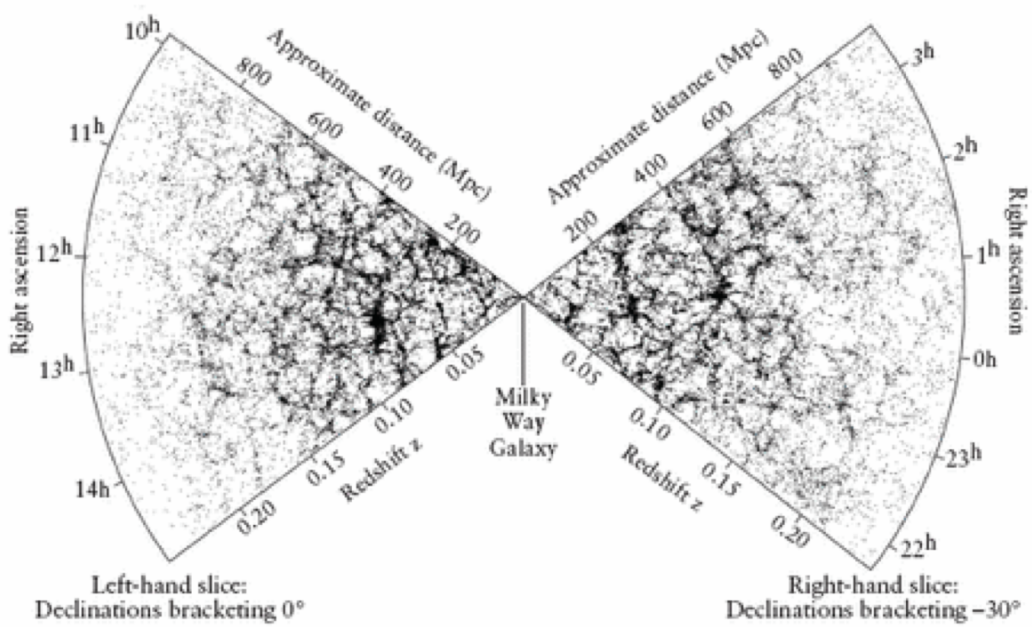
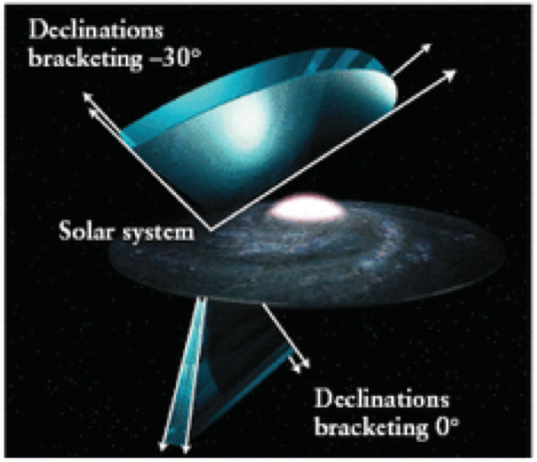


FIGURE 27.23 Two slices from the CfA redshift survey. Right ascension is indicated along the top of each figure. (a) $26.5° < \delta < 32.5°$. (b) $32.5° < \delta < 38.5°$. (Figures adapted from Geller, *Mercury*, May/June 1990.)

Large Scale Distribution of Galaxies: Voids and Sheets



(a) The 2dF galaxy survey

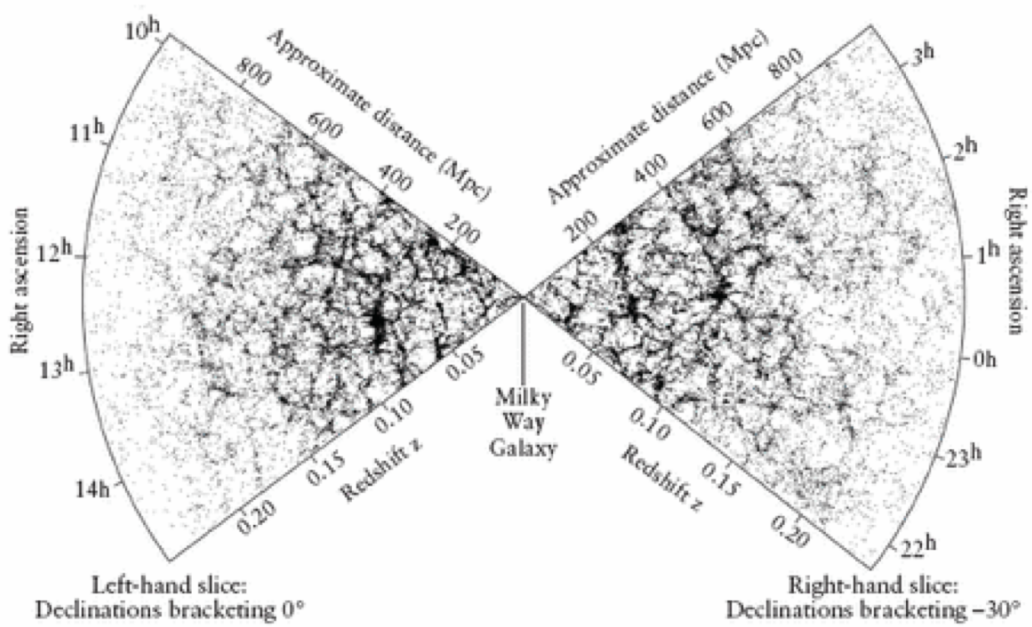


(b) Fields of view in the 2dF survey

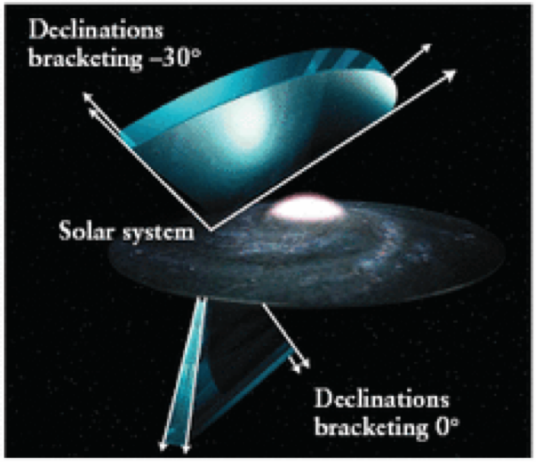
Three dimensional maps of galaxies in the nearby Universe are now available from the **Sloan Digital Sky Survey** (SDSS) and the **two degree field galactic redshift survey** (2dFGRS).

These maps indicate that most galaxies are located on sheets several Mpc thick and separated by voids of sizes ~ 100 Mpc.

Large Scale Distribution of Galaxies: Voids and Sheets



(a) The 2dF galaxy survey



(b) Fields of view in the 2dF survey

This pattern is similar to that of soapsuds in a kitchen sink, with sheets of soap film (analogous to galaxies) surrounding air bubbles (analogous to voids). Voids contain very few galaxies but may contain hydrogen clouds.

On scales much larger than 100 Mpc, the distribution of galaxies in the universe appears to be roughly uniform.