Chapter 17

Galaxies

Galaxies

- Beyond the Milky Way are billions of other galaxies
- Some galaxies are spiral like the Milky Way while others are egg-shaped or completely irregular in appearance
- Besides shape, galaxies vary greatly in the star, gas, and dust content and some are more “active” than others
- Galaxies tend to cluster together and these clusters appear to be separating from each other, caught up in a Universe that is expanding
- The reason for all this diversity is as yet unanswered

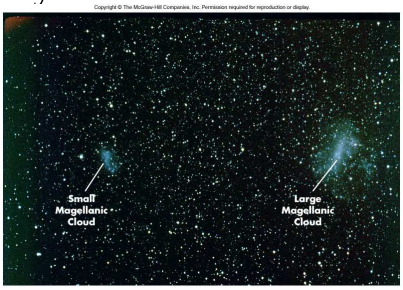
Galaxies

- A ***galaxy*** is an immense and relatively isolated cloud of hundreds of millions to hundreds of billions of stars, and vast clouds of interstellar gas
- Each star moves in its own orbit guided by the gravity generated by other stars in the galaxy

Early Observations of Galaxies

- Since galaxies are so far away, only a few can be seen without the aid of a telescope: Andromeda and the Large and Small Magellanic Clouds
- In 18th century, Charles Messier cataloged several “fuzzy” objects to be avoided in comet searches – many turned out to be galaxies (M31 = Andromeda)

Early Observations of Galaxies



- In 19th century, William Hershel and others systematically mapped the heavens creating the New General Catalog (NGC) which included many galaxies (M82 = NGC 3034)

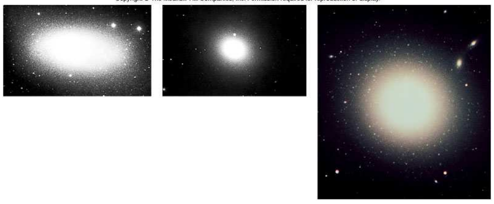
Types of Galaxies

- By the 1920s, Edwin Hubble demonstrated that galaxies could be divided on the basis of their shape into three types, and two sub-types

Spiral Galaxies

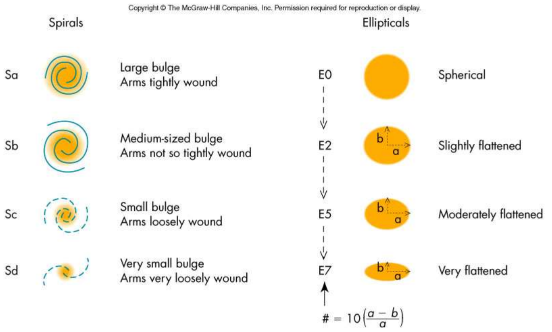
- Two or more arms winding out from center
- Classified with letter S followed by a letter (a-d) to distinguish how large the nucleus is and/or how wound up the arms are

Elliptical Galaxies



- Smooth and featureless appearance and a generally elliptical shape
- Classified with letter E followed by a number (0-7) to express “flatness” of elliptical shape

Learning the Hubble Classification Scheme



Irregular Galaxies

- Neither arms or uniform appearance - generally, stars and gas clouds scattered in random patches
- Classified as Irr

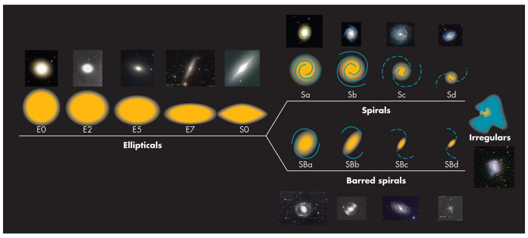
Barred Spirals

- Arms emerge from ends of elongated central region or bar rather than core of galaxy
- Classified with letters SB followed by the letters (a-d)
- Thought by Hubble to be a separate class of object from normal S spirals, computer simulations show bar may be result of a close encounter between two galaxies
- The Milky Way is probably an SB galaxy

S0 Galaxies

- Disk systems with no evidence of arms
- Thought by Hubble to be intermediate between S and E galaxies, several theories now vie to explain their appearance (e.g., an S0 lacks gas to produce O and B stars to light up any spiral arms that may exist)

The Hubble "Tuning Fork"



- Hubble proposed the "tuning fork" diagram as a hypothesis for galactic *evolution* – today it is believed this interpretation is incorrect. However, we still use his classification scheme.

Stellar and Gas Content of Galaxies

- Spirals
  - Star types: Mix of Pop I and Pop II
  - Interstellar content: 15% by mass in disk
- Ellipticals
  - Star types: Only Pop II, blue stars rare
  - Interstellar content: Very low density, very hot gas
- Irregulars
  - Star types: blue stars common
  - Interstellar content: As much as 50% by mass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Stellar and Gas Content of Galaxies

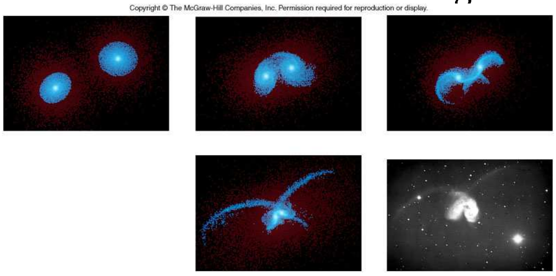
- Other items of note:
  - Ellipticals have a large range of sizes from globular cluster sizes to 100 times the mass of the Milky Way
  - Census of galaxies nearby: Most are dim dwarf E and dwarf Irr sparsely populated with stars
  - Census of distant galaxies: In clusters, 60% of members are spirals and S0, while in sparsely populated regions it is 80%
  - Early (very young) galaxies are much smaller than Milky Way – merging of these small galaxies is thought to have resulted in the larger galaxies of today

Approx. 700,000 light-years

The Cause of Galaxy Types

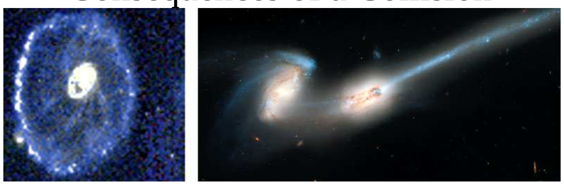
- Computer simulations show galaxies formed from gas clouds with large random motions becoming ellipticals, whereas small random motions become spirals
- Ellipticals had a high star formation rate in a brief period after their birth, while spirals produce stars over a longer period – did the rate cause the type of the reverse?
- Dark matter halo spin rate – fast for spirals, slow for ellipticals
- Density wave or SSF model for creating spiral arms

Galactic Collisions and Mergers



- Could galaxy's type change with time?
  - Computer simulations show a galaxy's shape can change dramatically during a close encounter with another galaxy

Consequences of a Collision



- Individual stars are left unharmed
- Gas/dust clouds collide triggering a burst of star formation
- A small galaxy may alter the stellar orbits of a large spiral to create a "ring galaxy"
- Evidence (faint shell-like rings and dense clumps of stars) of spirals colliding and merging into ellipticals

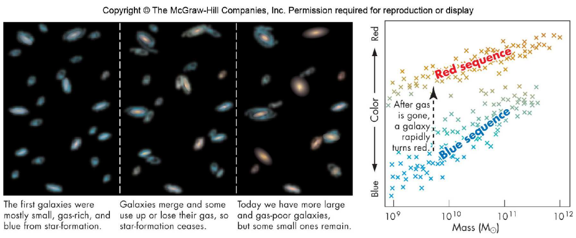
Galactic Collisions and Mergers

- Evidence for galaxy type change via collisions/mergers over time
  - On a large scale, small galaxies may be captured and absorbed by a large galaxy in a process called ***galactic cannibalism***
    - Explains abnormally large ellipticals in center of some galaxy clusters
    - Milky Way appears to be "swallowing" the Magellanic Clouds, while Andromeda shows rings and star clumps of "swallowed" galaxies

Galactic Collisions and Mergers

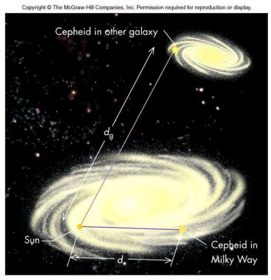
- Evidence for galaxy type change via collisions/mergers over time
  - Very distant clusters have a higher proportion of spirals than near clusters
  - Distant clusters contain more galaxies within a given volume
  - Distant galaxies show more signs of disturbance by neighboring galaxies (odd shapes, bent arms, twisted disks), what astronomers call "harassment"

Galactic Evolution



Galaxy Distances

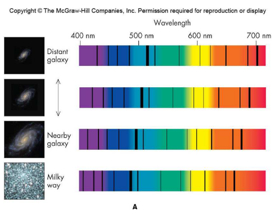
- Galaxy distances are too far to employ the parallax technique
- The method of "standard candles" is used
- The standard candles are usually Cepheid variables, supergiant stars, planetary nebulas, supernovas, etc.



$$\frac{B_*}{B_g} = \left(\frac{d_g}{d_*}\right)^2 \quad \text{or} \quad \frac{d_g}{d_*} = \sqrt{\frac{B_*}{B_g}}$$

The Hubble Law

- In 1911, it was discovered that all galaxies (with but a few exceptions) were moving away from the Milky Way
- Edwin Hubble found that these radial speeds, calculated by a Doppler shift analysis and called a ***recessional velocity,*** increased with a galaxy's distance

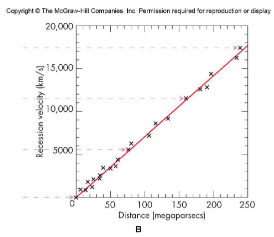


The Hubble Law

- From a plot of several galaxies' known recessional velocities (V) and distances (D), Edwin Hubble, in 1920, discovered a simple formula:

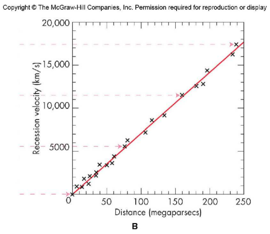
$$V = H \times D$$

- Today, this expression is called the ***Hubble law*** and H is called the ***Hubble constant***



The Hubble Law

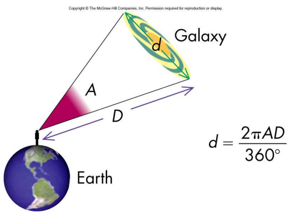
- Although not completely agreed upon, H is about 72 km/sec/Mpc (Mpc = ***megaparsecs***)
- With H known, one can turn this around and determine a galaxy's unknown distance by measuring its recessional velocity and assuming a value for H



Galaxy Distances

- Two other useful methods
  - Image "graininess" – The smoother the distribution of stars in a galaxy the farther away it is
  - Tully-Fisher Method – The higher the rotational speed of a galaxy, the more luminous it is
  - The interrelationship of all the distance measuring methods is called the distance ladder

Measuring the Diameter of Galaxies



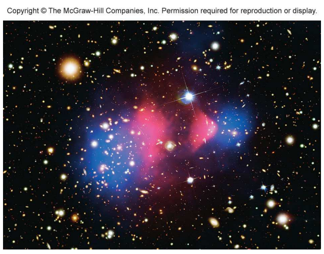
- Astronomers measure a galaxy's diameter (*d*) using a standard geometric formula
- where *A* is the angular size of the galaxy on the sky (in degrees) and *D* is the distance to the galaxy
- To use the equation, *A* must be measured and *D* must be determined by a standard candle technique or from the Hubble law

Measuring the Mass of Galaxies

- The mass of a galaxy is determined from the modified form of Kepler's third law
- To use this method, one concentrates on some stars or gas on the outer fringes of the galaxy
- The semimajor axis distance used in Kepler's third law is simply half the galaxy's pre-determined diameter
- For the orbital period used in the third law, one uses Doppler analysis of the galaxy's spectral lines to determine orbital speed and this speed used with the galaxy's diameter gives the period

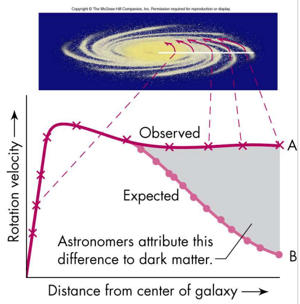
Dark Matter

- ***Dark matter*** is the material predicted to account for the discrepancy between the mass of a galaxy as found from the modified Kepler's third law and the mass observed in the form of gas and dust

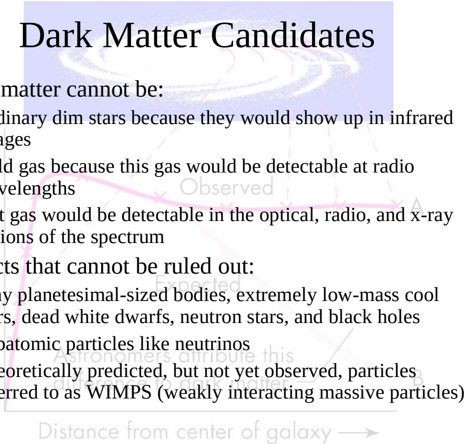


Dark Matter

- The amount of matter needed to resolve this discrepancy is as much as 10× the visible mass
- The strongest evidence that dark matter exists comes from galaxy rotation curves, which do not show diminishing speeds at large distances from the galaxy's center

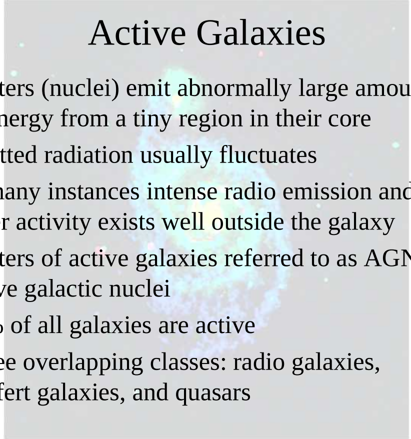


Dark Matter Candidates



- Dark matter cannot be:
  - Ordinary dim stars because they would show up in infrared images
  - Cold gas because this gas would be detectable at radio wavelengths
  - Hot gas would be detectable in the optical, radio, and x-ray regions of the spectrum
- Objects that cannot be ruled out:
  - Tiny planetesimal-sized bodies, extremely low-mass cool stars, dead white dwarfs, neutron stars, and black holes
  - Subatomic particles like neutrinos
  - Theoretically predicted, but not yet observed, particles referred to as WIMPS (weakly interacting massive particles)

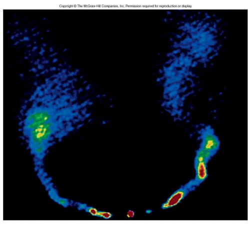
Active Galaxies



- Centers (nuclei) emit abnormally large amounts of energy from a tiny region in their core
- Emitted radiation usually fluctuates
- In many instances intense radio emission and other activity exists well outside the galaxy
- Centers of active galaxies referred to as AGNs – active galactic nuclei
- 10% of all galaxies are active
- Three overlapping classes: radio galaxies, Seyfert galaxies, and quasars

Radio Galaxies

- Generally elliptical galaxies
- Emit radio energy
  - Energy comes from core and regions symmetrically located outside of galaxy
    - Outside regions are called "radio lobes" and span hundreds of millions of light-years
    - Core source is less than a light-month across



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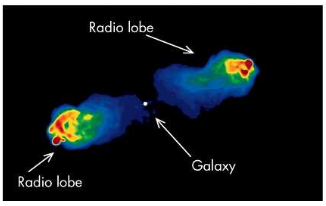
Lobes can be swept into arcs or plumes as they interact with intergalactic matter

Radio Galaxies

- Energy is as much as 1 million times more than normal galaxies
- Radio emission is synchrotron radiation
  - High-speed electrons are generated in core and shot out via ***jets*** in general direction of the lobes
  - High-speed electrons eventually collide with surrounding gas and spread out to form lobes



Seyfert Galaxies

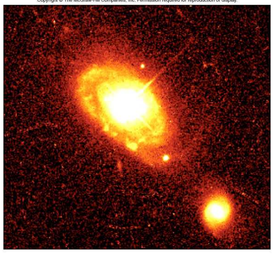
- Spiral galaxies (mostly) with abnormally luminous nucleus
  - As much energy output as the entire Milky Way
  - Region of emission is less than a light-year across
  - Wavelength emissions range from infrared to X-ray
  - Intensity fluctuates rapidly, sometimes changing in a few minutes

Seyfert Galaxies

- Contain gas clouds moving at high speed
  - Occasionally the gas is ejected in small jets
- Rapidly moving gas and small, bright nucleus make Seyfert galaxies similar to radio galaxies, and , in fact, some Seyfert galaxies are radio galaxies as well

Quasars

- Largest redshifts of any astronomical object
  - Hubble law implies they are at great distances (as much as 10 billion light-years away)
  - To be visible at those distances, they must be about 1000× more luminous than the Milky Way



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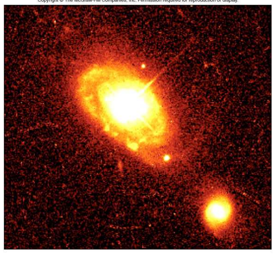
Quasars

- Some similar to radio galaxies in emissions
- Others similar to radio and Seyfert galaxies in that they eject hot gas from their centers
- Superluminal motion in jets indicate extreme high-speed motions



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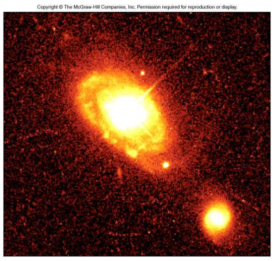
Quasars

- Recent images reveal quasars often lie in faint, fuzzy-looking objects that appear to be ordinary galaxies
- Based on output fluctuations, quasars resemble the AGNs of radio galaxies and Seyfert galaxies in that they are small (fractions of a light-year in some cases)



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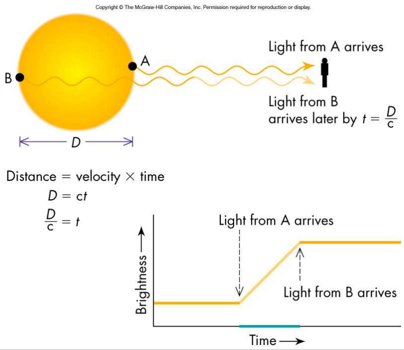
Measuring the Diameter of Astronomical Objects by Using Their Light Variability

- Technique makes three assumptions
  - The rate at which light is emitted from an active region is the same everywhere in that region
  - The emitting region completely defines the object of interest (there are no “dead” areas of significance)
  - The speed of light is finite (a safe bet)
- The light variation then is just a measure of the time it takes light to travel across the active surface
- Multiplying this time by the speed of light gives the size of the emitting object

Measuring the Diameter of Astronomical Objects by Using Their Light Variability

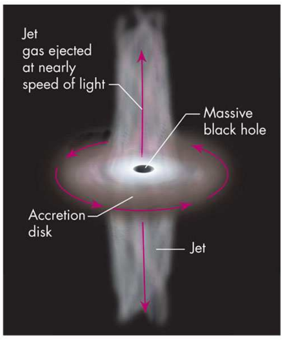


Cause of Activity in Galaxies

- All active galaxies have many features in common – this suggests a single model to explain all of them
  - Such a model must explain how a small region can emit an extreme amount of energy over a broad range of wavelengths
  - Model must be unusual since no ordinary star could be so luminous nor could enough ordinary stars be packed into such a small volume

Cause of Activity in Galaxies

- Basic model
  - Black hole about the size of the Earth with a gas accretion disc tens to hundreds of AU across
  - Most gas drawn into black hole heats to millions K
  - Some gas channeled by magnetic fields into jets
  - Accretion gas replenished by nearby passing stars or material from collision with another galaxy



Cause of Activity In Galaxies

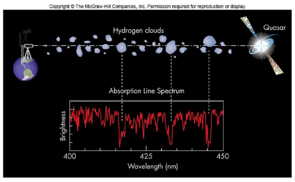
- Creation of massive black hole
  - Massive star in densely populated core of galaxy explodes forming a small black hole of ~5 $M_\odot$
  - Black hole grows from accretion of interstellar matter
  - Radius of black hole increases making capture of more material easier
  - Eventually black hole becomes large enough to swallow entire stars
  - Growth of black hole is exponential until equilibrium with available materials stops growth

Cause of Activity In Galaxies

- Observational "proof" – extremely high speeds of gas and stars at very small distance from galactic center requires huge mass there (at least millions of solar masses), yet this mass emits no radiation of its own
- All galaxies appear to have massive black holes at their centers
- Not all galaxies are active, especially older ones, because central source of material to black hole is diminished
- Highly correlated relationship of central black hole mass to bulge size suggests that they grow at the same rate
- Other theories of AGNs exist, but none is as well accepted as the black hole model

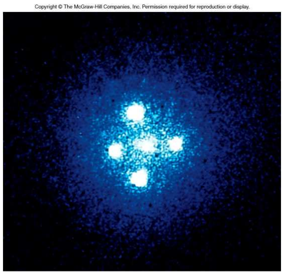
Quasars as Probes of Intergalactic Space

- The immense distances of quasars allow their light to be used as probes of the intervening material
  - Quasar absorption lines have very different Doppler shifts from the emission lines of the quasars themselves – an indicator of cool gas clouds between the quasar and Earth
  - A quasar's light may be affected by a ***gravitational lens***

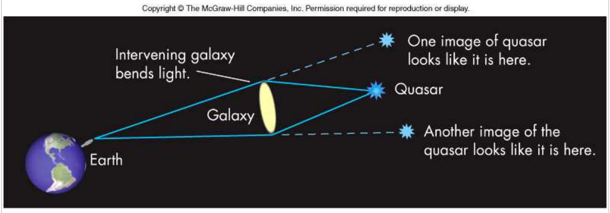


Gravitational Lenses

- Light from a quasar may bend as it passes by a massive object in much the same way light is bent as it passes through a glass lens
- The bending of light by gravity is a prediction of Einstein's general theory of relativity
- The bending light creates multiple quasar images and arcs that can be used to determine the mass of the massive object



Gravitational Lenses



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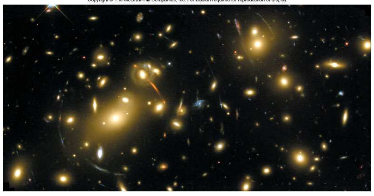
Galaxy Clusters



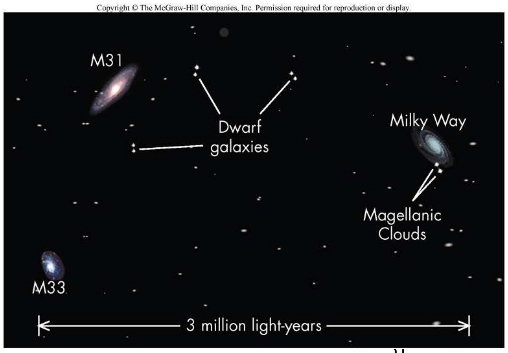
- Galaxies are often found in groupings called ***galaxy clusters***
  - Galaxies within these clusters are held together by their mutual gravity
  - Typical cluster is several million light-years across and contains a handful to several thousand galaxies

The Local Group

- The Milky Way belongs to a very small cluster called the ***Local Group***
- The Local Group contains about 30 members with the 3 largest members being the spiral galaxies M31, M33, and the Milky Way
- Most of the Local Group galaxies are faint, small "dwarf" galaxies - ragged, disorganized collection of stars with very little or no gas – that can't be seen in other clusters

4 million light-years

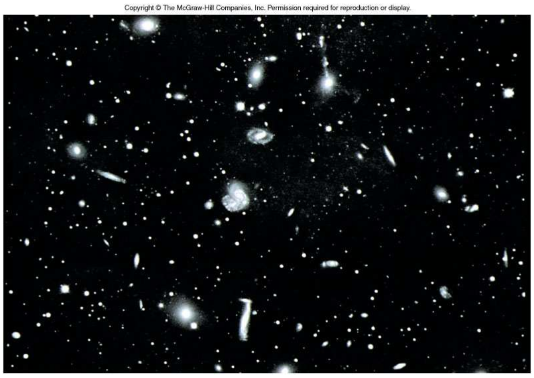
The Local Group



Rich Clusters

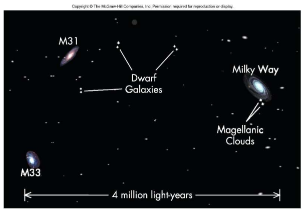
- Largest groups of galaxies - contain hundreds to thousands of member galaxies
- Large gravity puts galaxies into spherical distribution
- Contain mainly elliptical and S0 galaxies
- Spirals tend to be on fringes of cluster
- Giant ellipticals tend to be near center – cannibalism
- Contain large amounts (10^{12} to 10^{14} $M_{\odot}$) of extremely hot X-ray emitting gas with very little heavy elements

The Hercules Cluster



Poor Clusters

- Only a dozen or so member galaxies
- Ragged, irregular look
- High proportion of spirals and irregulars



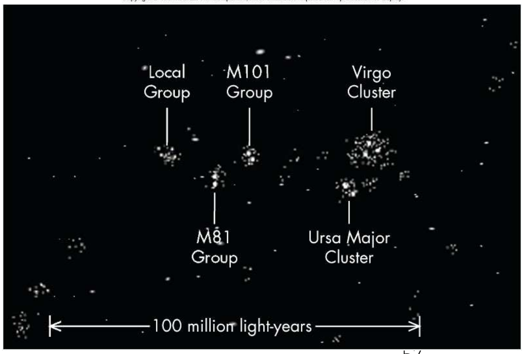
Galaxy Clusters

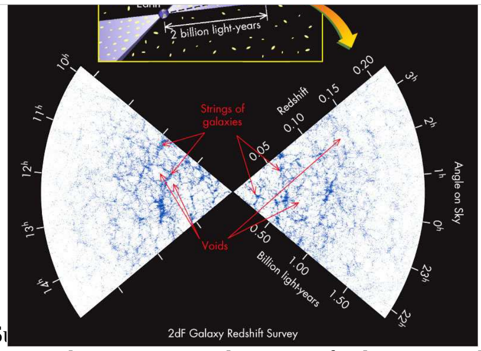
- In general, all clusters need dark matter to explain galactic motions and the confinement of hot intergalactic gas within cluster
- Near clusters appear to have their members fairly smoothly spread out, while far away clusters (and hence younger clusters) are more ragged looking – this suggests that clusters form by galaxies attracting each other into groups as opposed to clustering forming out of a giant gas cloud

Superclusters

- A group of galaxy clusters may gravitationally attract each other into a larger structure called a ***supercluster*** – a cluster of clusters
  - A supercluster contains a half dozen to several dozen galaxy clusters spread over tens to hundreds of millions of light-years (The Local group belongs to the Local Supercluster)
  - Superclusters have irregular shapes and are themselves part of yet larger groups (e.g., the "Great Wall" and the "Great Attractor")

The Local Supercluster





- S surrounding regions nearly empty of galaxies – voids
- Clusters of superclusters and voids mark the end of the Universe's structure we currently see