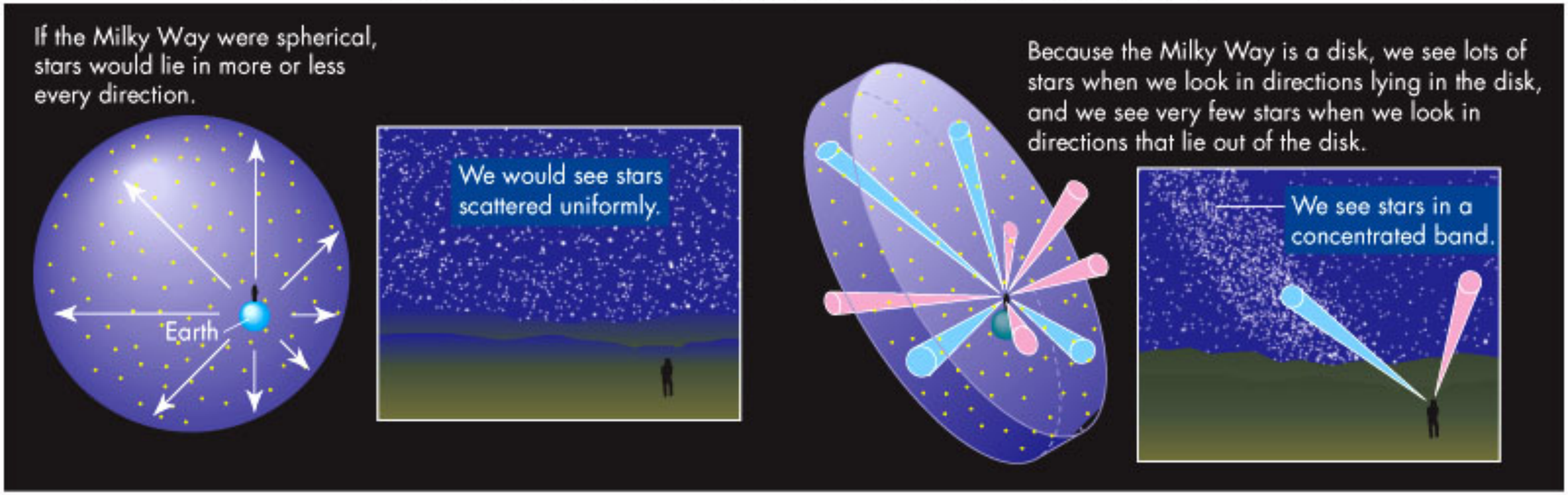
The Milky Way Galaxy and other Galaxies Part 1

The Milky Way

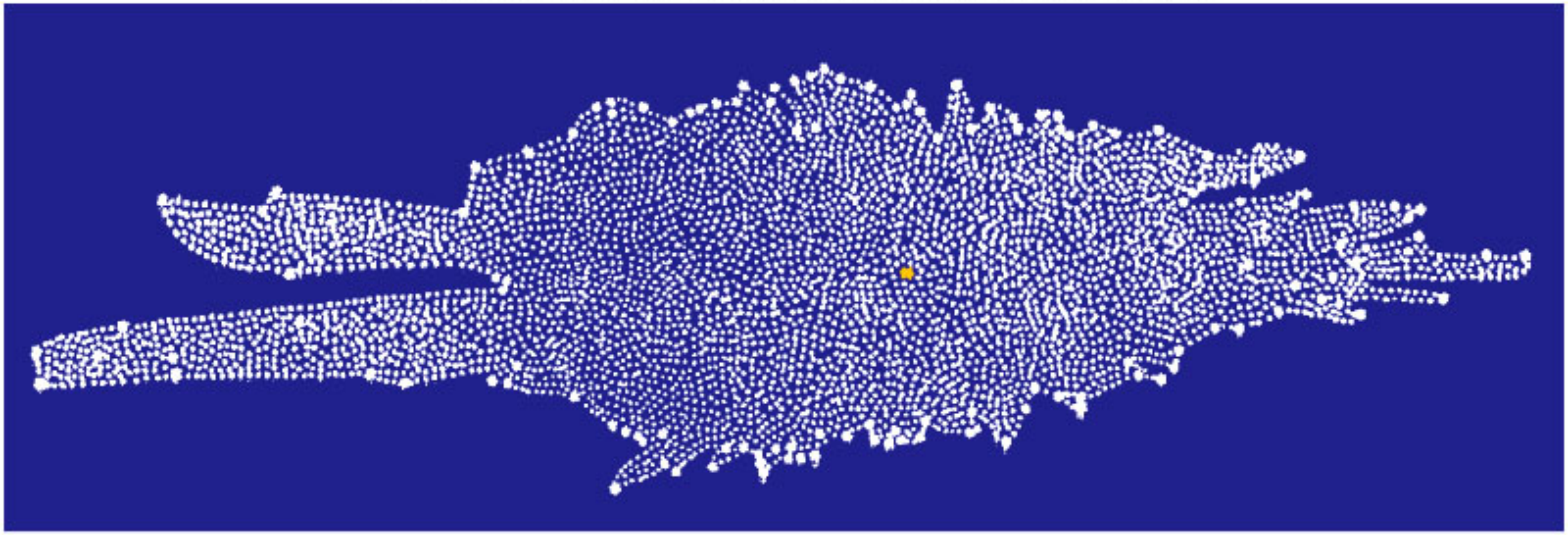
- The pale band of light spangled with stars stretching across the sky is the ***Milky Way,*** a swath of light named by the ancient Greeks
- In the 17th century, Galileo showed the Milky Way is millions of stars too dim to see individually
- Today we know the Milky Way is a slowly revolving disk of stars, a galaxy
- We also know today that the Milky Way is filled with stars of various sizes, many of them found in clusters, and clouds of gas and dust

Shape of the Milky Way



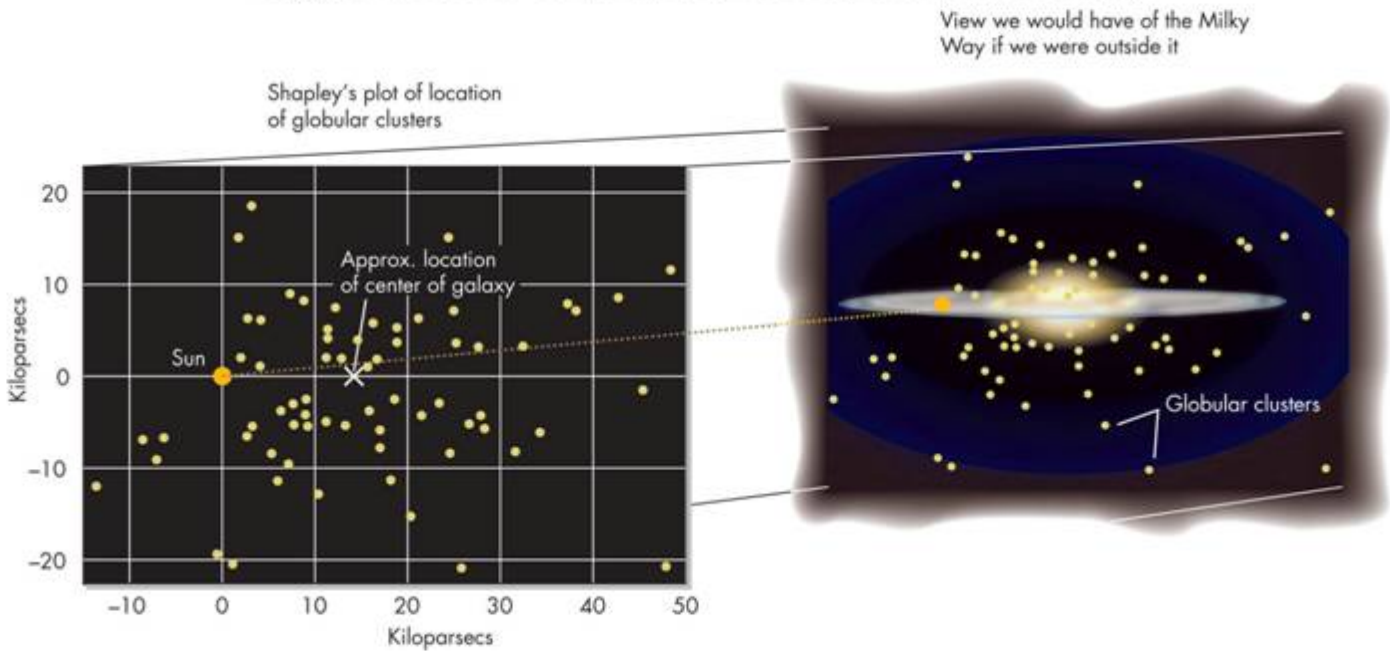
- Uniform distribution of stars in a band across the sky lead Thomas Wright, Immanuel Kant, and William Herschel in the 18th century to suggest the Milky Way is a disc distribution of stars with the Sun near the center

Shape of the Milky Way



- William Herschel's sketch of the Milky Way, from 1748. This sketch led Herschel (and others) to believe the Milky Way was disk-shaped (correct), and that the solar system was near the center of that disk, at the position of the yellow dot (incorrect)

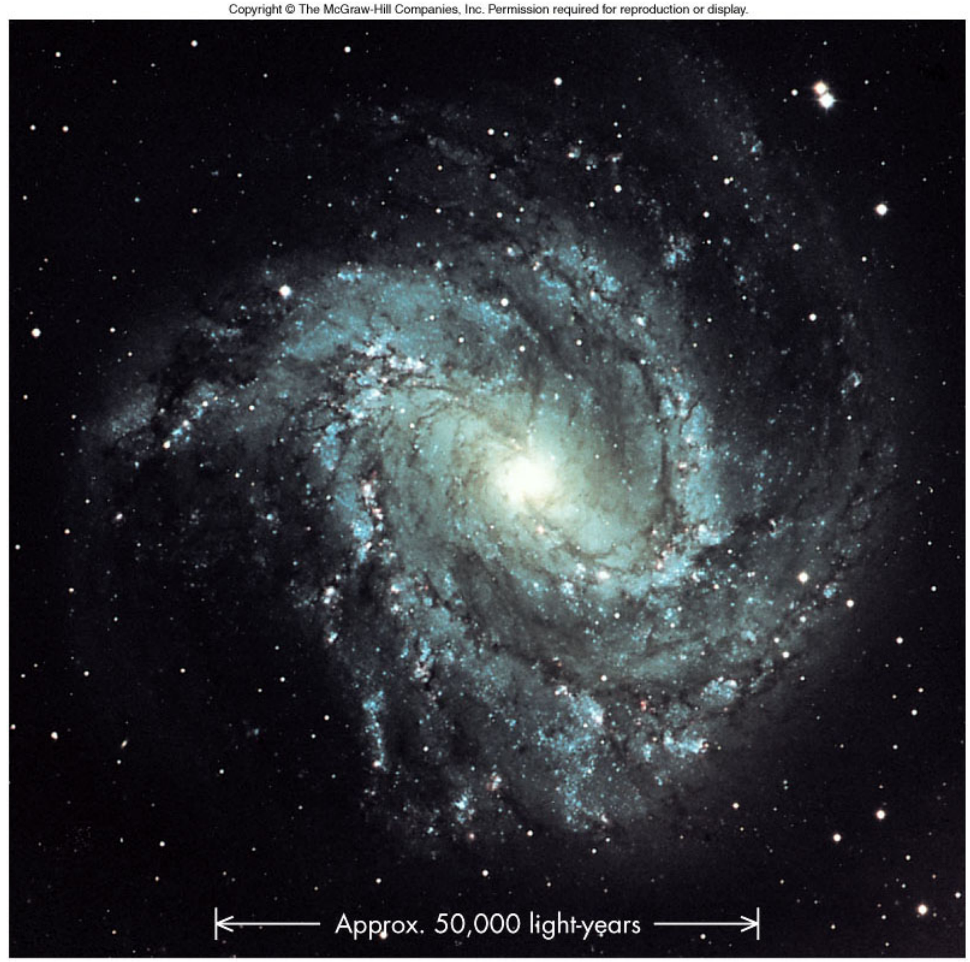
Size of the Milky Way



- Jacobus Kapteyn determined the diameter of the Milky Way to be 20 kpc with the Sun near the center
- Harlow Shapley found the diameter to be 100 kpc with the Sun 2/3 from the center
- Both were not aware of the dimming effects of dust
- Shapley, using globular star clusters for distances, did not distinguish RR Lyrae from Cepheid variables

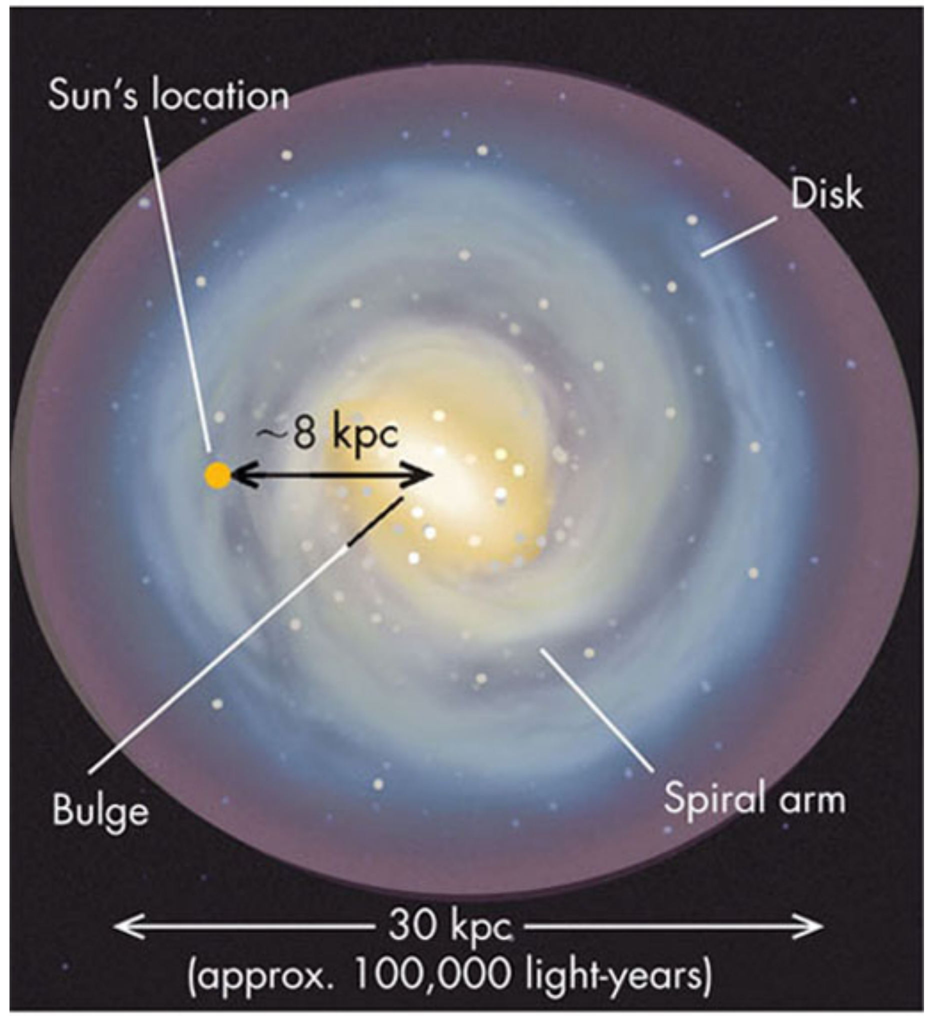
Size of the Milky Way

- Correcting for dust effects and variable star types, astronomers conclude the disc has a 30 kpc diameter with the Sun 2/3 from the center
- Discovery that nearly all disc-shaped galaxies have spiral arms implied Milky Way is a spiral too.



Structure and Contents of the Milky Way

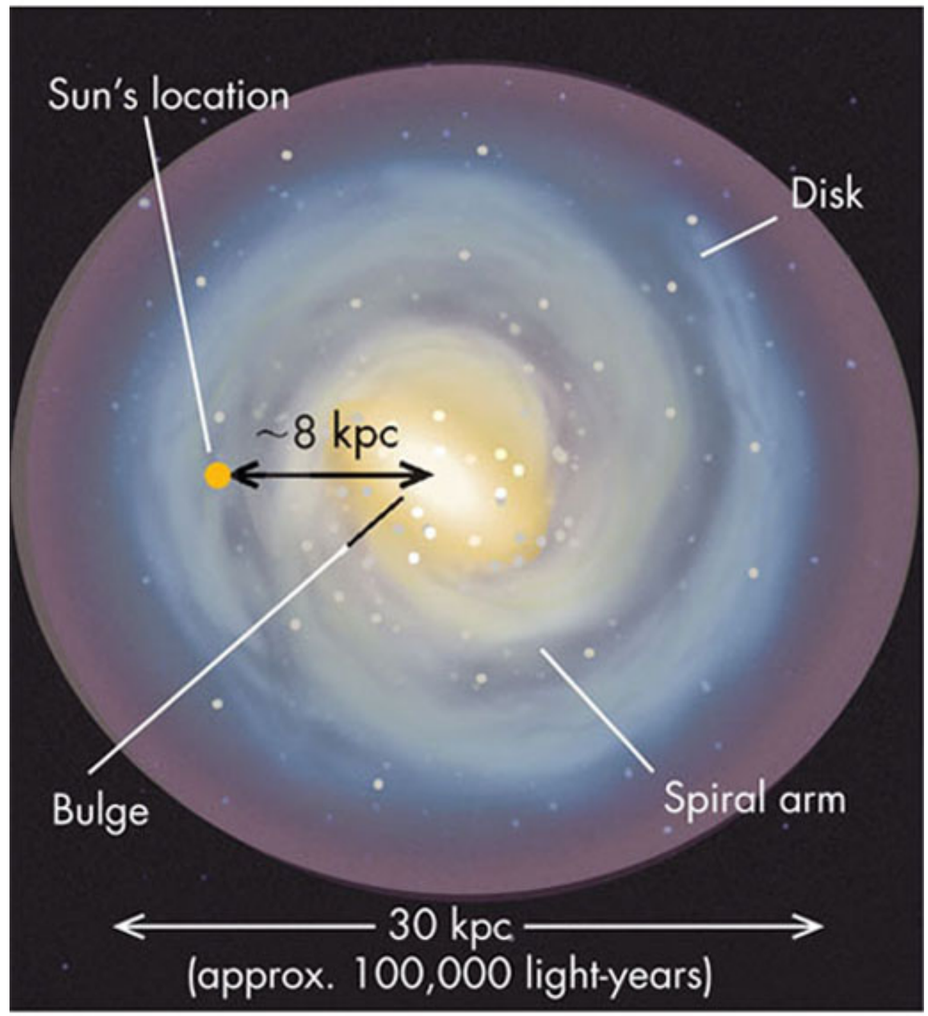
- The ***Disk***
  - ***Spiral arms*** distribution of stars, gas, and dust with a diameter of about 30 kpc (100,000 light-years) and plane tilted with respect to Earth's orbit around Sun
  - Differential rotation with all objects circling in the same direction: 240 million-year period at 220 km/sec at the Sun's orbit (about 8.5 kpc out from center)



Top view

Structure and Contents of the Milky Way

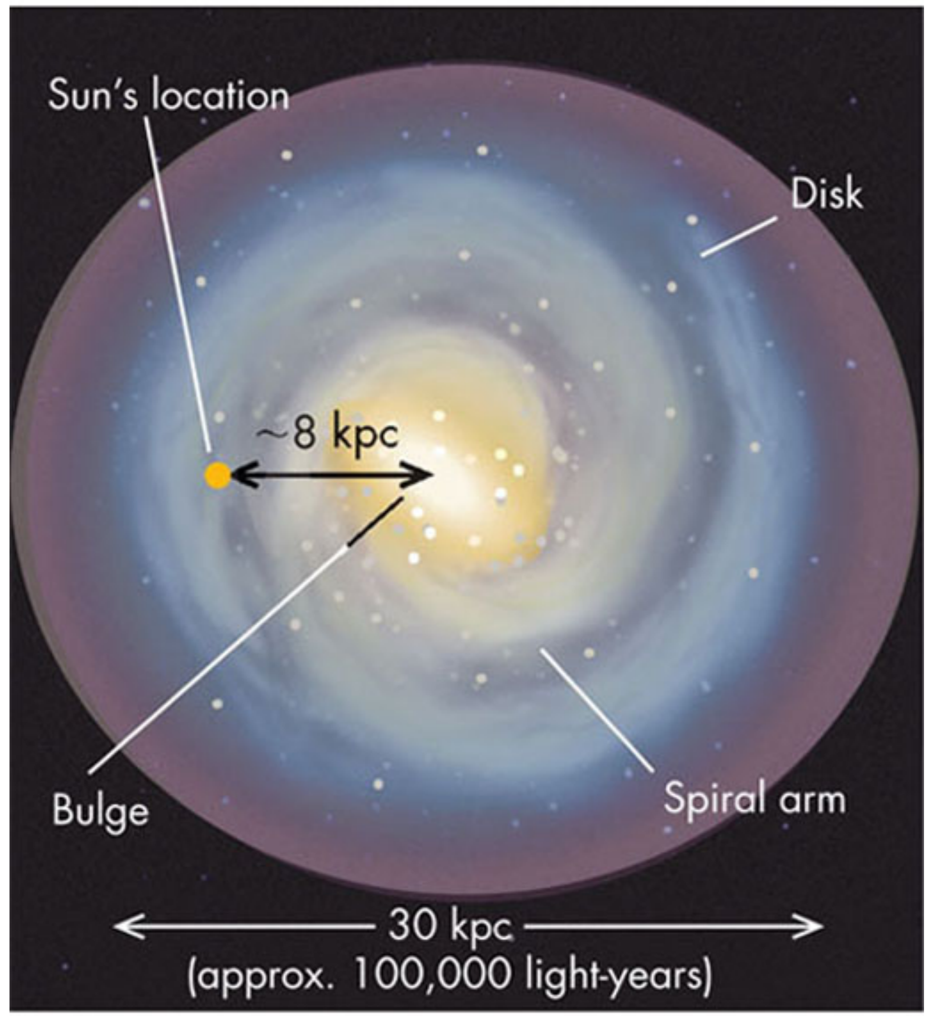
- The ***Disk***
  - High density of stars near center (10 million stars per cubic light-year) to low density farther out (0.003 stars per cubic light-year at Sun)
  - Dust and gas is nearly 15% of the disc's mass



Top view

Structure and Contents of the Milky Way

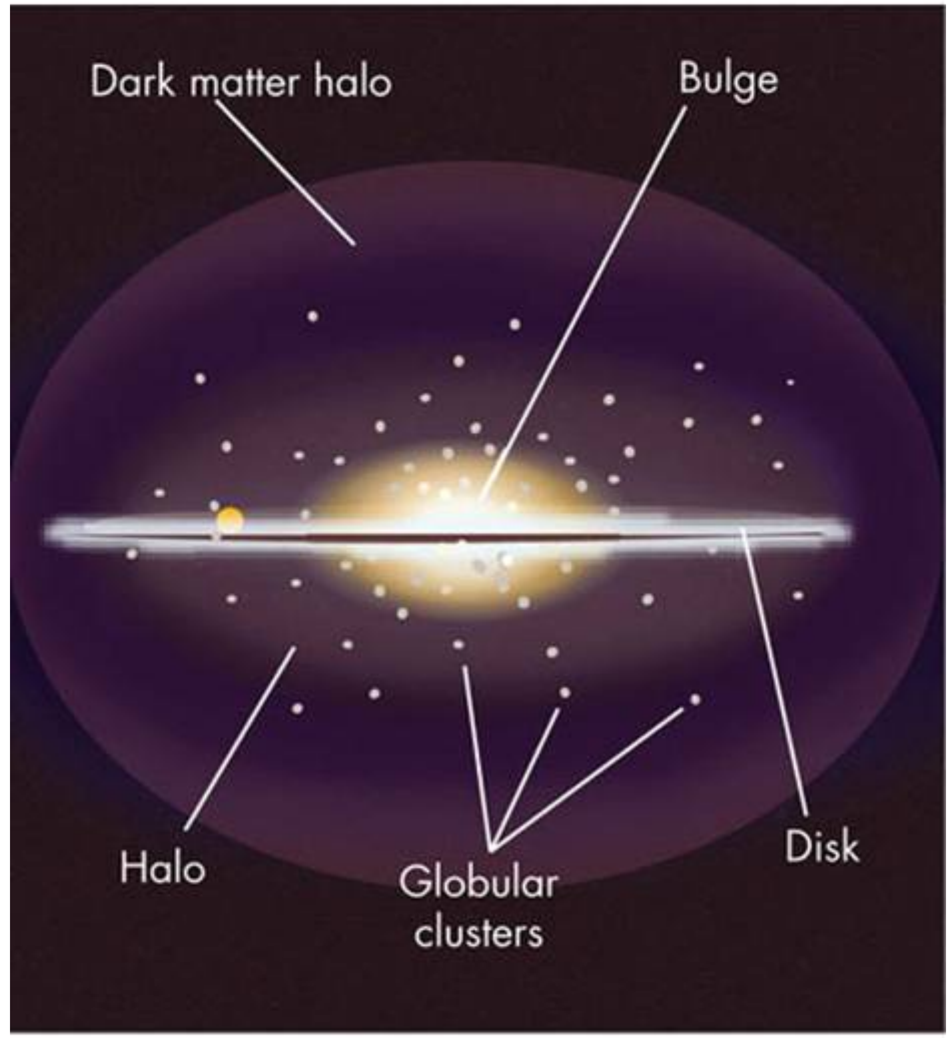
- The ***Disk***
  - Most of galaxy is hidden from Earth due to dust obscuration including the central ***nucleus*** with its dense swarm of stars and gas in which a massive black hole may reside
  - Radio and infrared telescopes can “see” entire galaxy: Radio observations suggest larger warped disc of gas (out to nearly 40 kpc)



Top view

Structure and Contents of the Milky Way

- ***Halo***
  - Roughly spherical region with disk embedded
  - Contains mainly old stars, such as globular clusters
  - Large amounts of dark matter may also be present
- ***Bulge***
  - Flattened collection of stars surrounding dense core of galaxy
  - About 1/3 the diameter of the galaxy



Side view

Mass and Population of the Milky Way

- From its rotation and effects on nearby galaxies, mass of Milky Way is $2 \times 10^{12}\ M_{\odot}$
- From large difference between this mass and what is observed, astronomers conclude Milky Way is embedded in vast halo of material that emits no radiation (at any wavelength) – ***dark matter***
- Assuming that the average star has a mass similar to that of the Sun, then based on the Milky Way's mass, there are roughly 100 billion stars

Age of the Milky Way

- Using stellar aging techniques, astronomers had estimated the galaxy's most ancient stars to be about 15 billion years old
- More recent model calculations and observations suggests the old star ages are more like 13 billion years
- A rough estimate of the Milky Way then is about 13 billion years

Stars of the Milky Way

- Stellar Censuses
  - Counts that list all known stars of a given type in a region of space is called a stellar census
    - All star types are represented in the Milky Way
    - By analyzing the relative numbers of stars of each type, deducing the galaxy's history is possible

Stars of the Milky Way

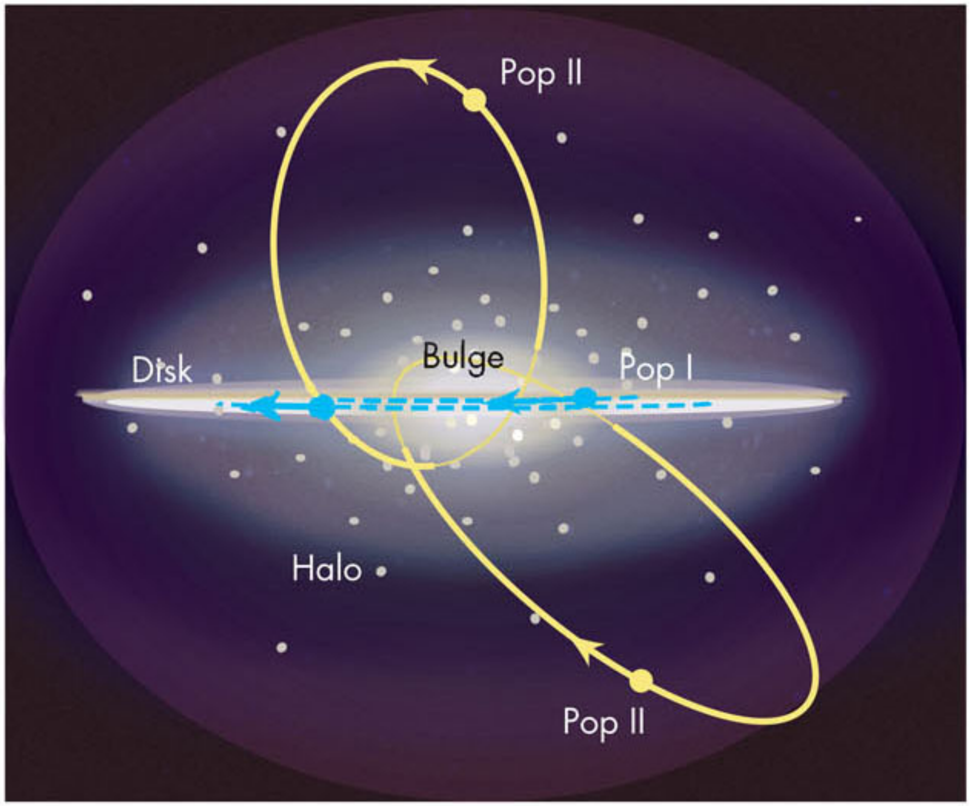
- The Mass Function
  - From a stellar census one can derive the number of stars of each mass, technically known as the ***mass function***
    - Mass determines the life cycle of a star
    - The evolution of the Milky Way will then depend on:
      - How many stars of each type it contains (A galaxy with only massive stars will evolve quickly)
      - How fast each type is created (Fast creation will quickly deplete gas resources)

Stars of the Milky Way

- Some results:
  - Dividing the number of stars in the Milky Way by its age gives a star creation rate of 3-5 stars per year
  - Most numerous stars turn out to be dim, cool, red dwarfs (mass about 0.5 $M_{\odot}$)
  - The average mass for Milky Way stars is ~1 $M_{\odot}$
  - Stars more massive than 100 $M_{\odot}$ are rare
  - Current research suggests that brown dwarfs ("failed stars" of mass less than 0.08 $M_{\odot}$) are more numerous than ordinary stars
  - It is important to be aware of "selection effects" when interpreting data: "Absence of evidence is not evidence of absence"; i.e., there may be things there you cannot see)

Two Stellar Populations

- ***Population I***
  - Age: generally young (10^6 to a few times 10^9) years
  - Color: blue (generally)
  - Location: disk and concentrated in arms
  - Orbit: approximately circular in disk
  - Heavy-element content: high (similar to Sun)

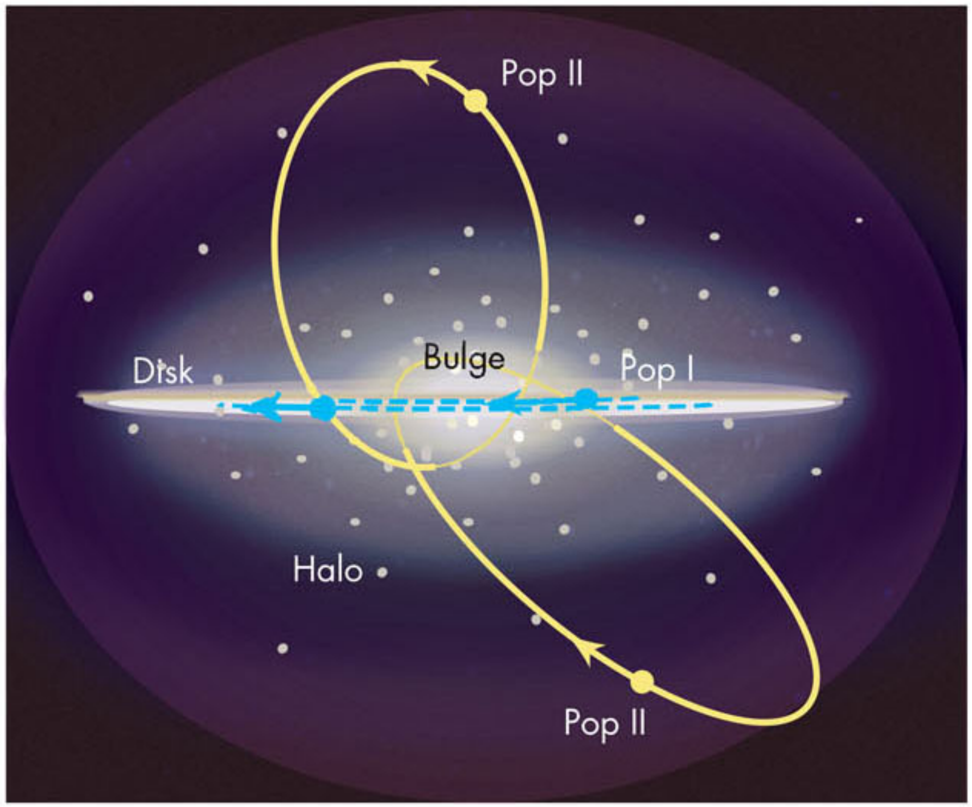


Side view

A

Two Stellar Populations

- ***Population II***
  - Age: old (about 10^{10}) years
  - Color: red
  - Location: halo and bulge
  - Orbit: plunging through disk
  - Heavy-element content: low (10^{-2} to 10^{-3} Sun)

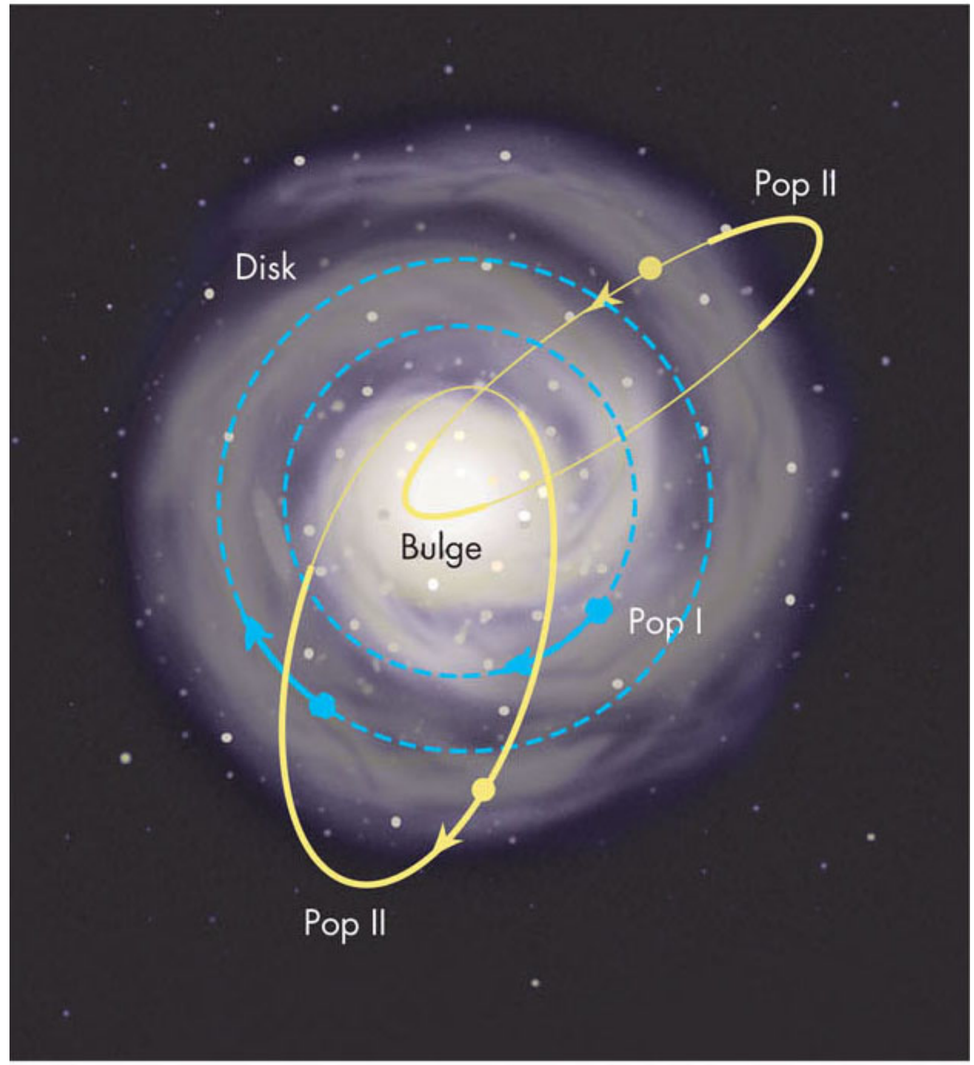


Side view

A

Two Stellar Populations

- Division of stars into two groups can be oversimplification
  - Sun does not fit in either category, but is usually considered a Pop I star
  - Inspires creating sub-groups
    - Subdivide each population into *extreme* and *intermediate*
    - *Old-disk population* sometimes used for stars like the Sun

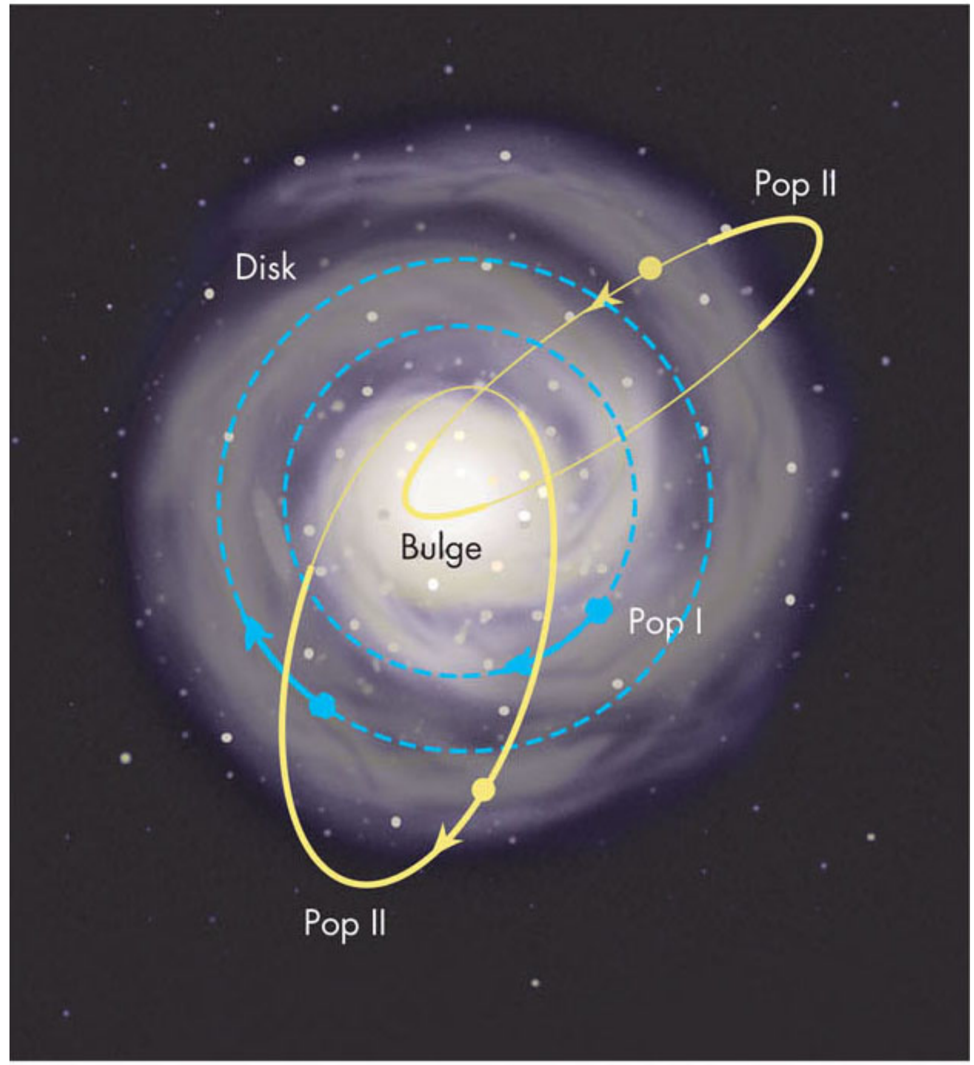


Top view

B

Two Stellar Populations

- The two populations show that star formation has not occurred continuously
  - Pop II formed in major burst at galaxy's birth during its initial collapse
  - Pop I formed much later and are still forming today
- Pop I stars used to map spiral arms in vicinity around Sun



Top view

B

Star Clusters

- Some of the Milky Way's stars are gravitationally bound together in groups called ***star clusters***
- There are two types of star clusters
  - Open Clusters
  - Globular Clusters

Open Clusters

- Contain up to a few hundred members in a volume of typically 7-20 light-years across
- Pleiades (or the Seven Sisters) is an excellent example
- Also called “galactic clusters” since most lie in galactic disk
- Formed when interstellar gas clouds are compressed and collapse upon entering the Milky Way’s spiral arm
- About 20,000 open clusters currently exist, many of them obscured by the dust of the galactic disk

Open Clusters

- Within spiral arms, very young stars may group together in loose ***associations*** a few hundred light-years across
  - Single large open cluster near their center
  - Birthing gas and dust still present
- After hundreds of millions of years, the stars gradually leave and the cluster dissipates

Open Clusters

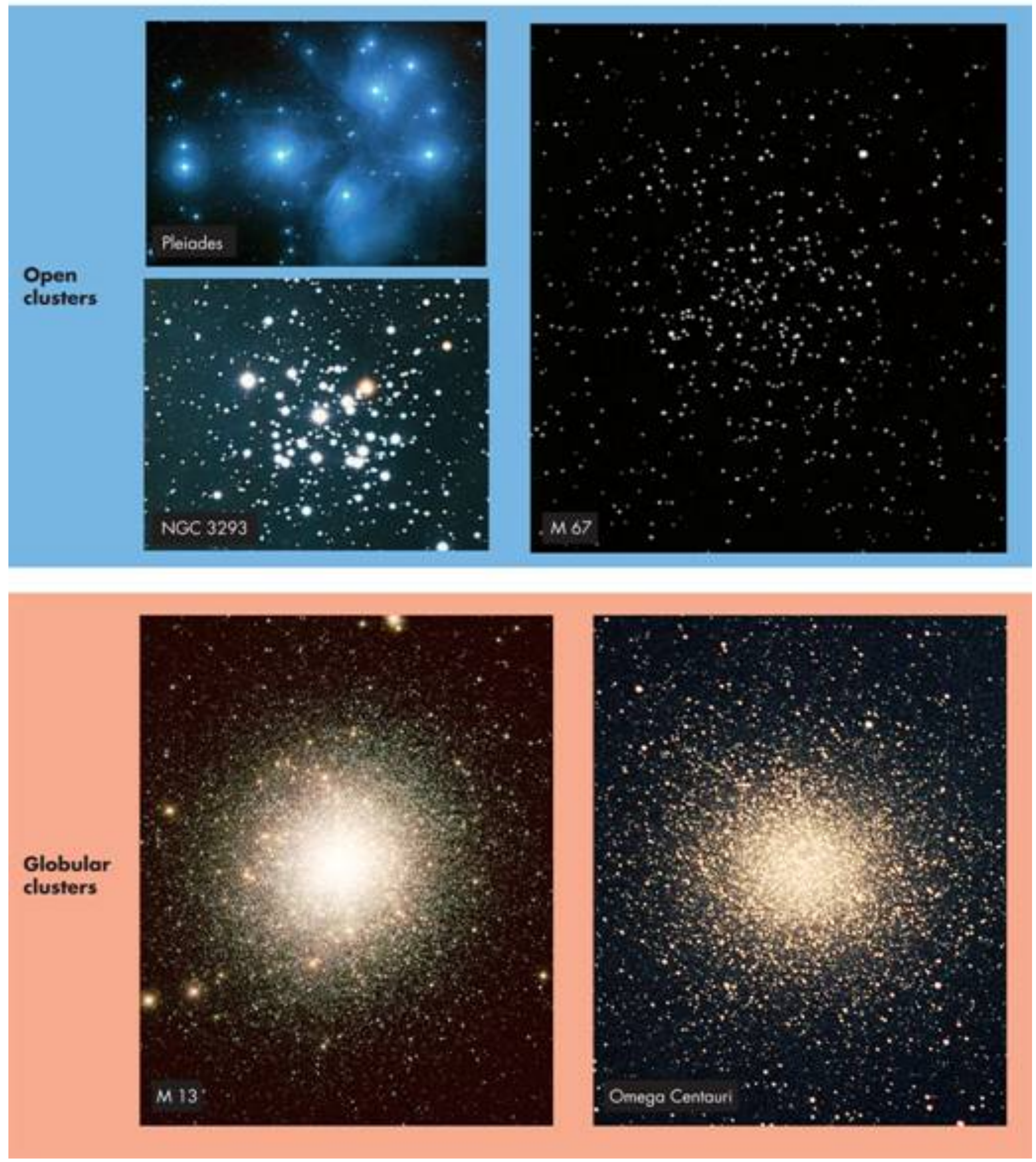
Globular Clusters

- Contain far more stars than open clusters, from a few hundred thousand to several million per cluster
- Have large radii, 40-60 light-years across
- The strong gravity pulls the stars into a ball denser than that found in open stars
- About 150-200 globular clusters outline the halo and bulge of the Milky Way

Globular Clusters

Star Clusters

- Open and globular clusters reflect the properties of Pop I and II stars – Open clusters are generally Pop I and globular clusters are always Pop II

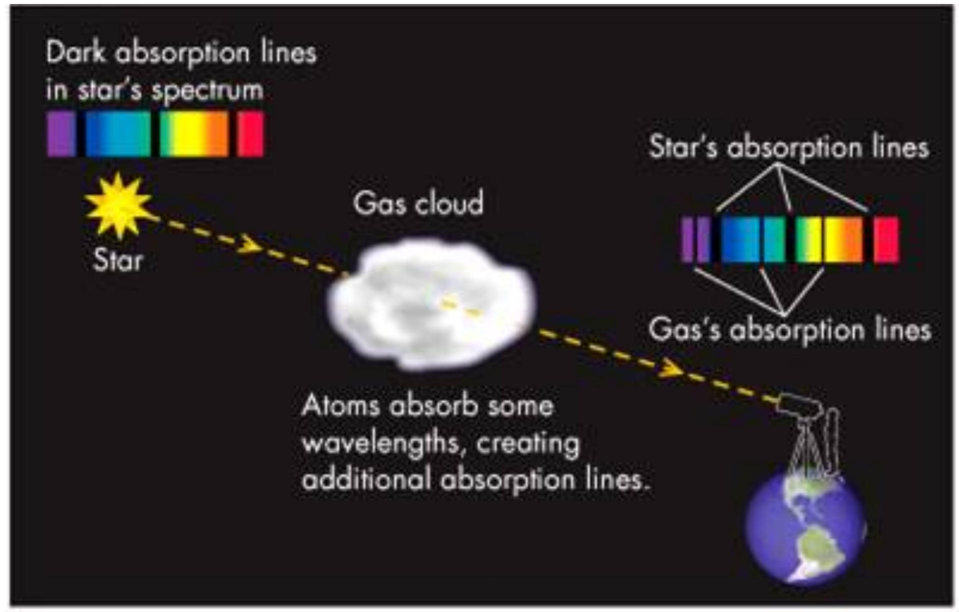


Gas and Dust in the Milky Way

- The space between stars is not empty: it contains ***interstellar matter*** composed of gas and dust
  - Most of the gas and dust exists in the galactic plane
  - Even here it clumps into clouds a few light-years to a few hundred light-years across
  - Typical densities are a few gas atoms per cubic centimeter (air has 10^{19} atoms per cubic centimeter

Gas and Dust in the Milky Way

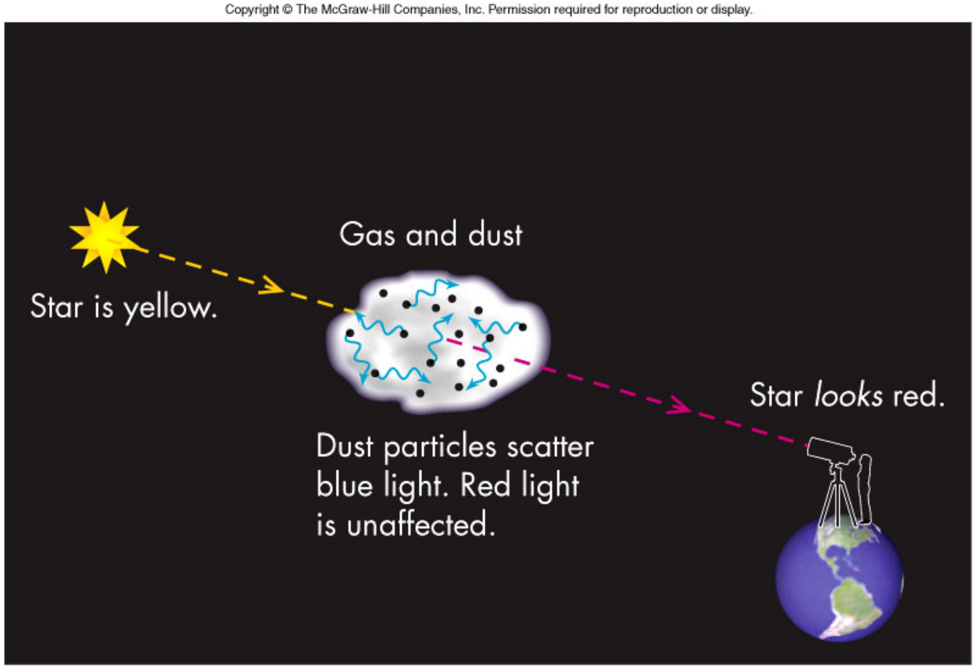
- Interstellar clouds seen directly or detected by their effect on light from distant stars
  - Gas and dust imprint narrow absorption lines on starlight passing through interstellar clouds: such lines can give cloud's composition, temperature, density, and speed
  - Gas found to be 71% H, 27% He, 2% heavy elements



A

  - Dust is μm to nm in size, made of silicates and carbon compounds, and perhaps coated with ices of water, carbon monoxide, and methyl alcohol

Scattering



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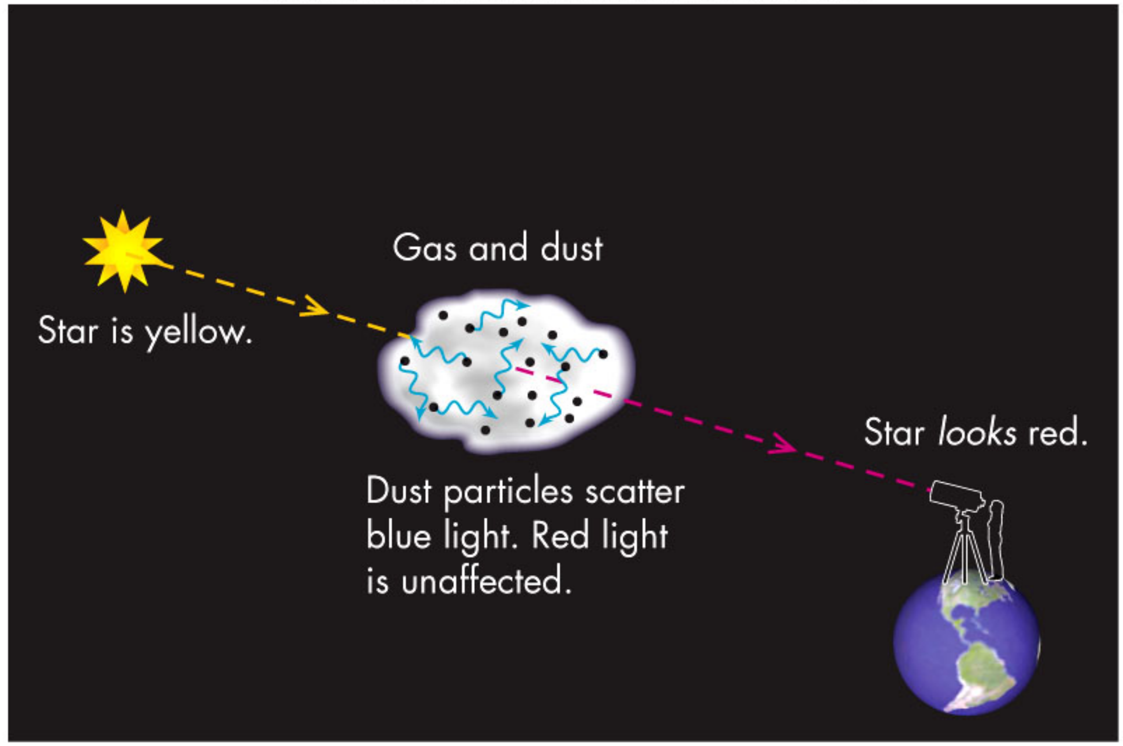
- The light from a star dims and reddens as it passes through an interstellar cloud with dust
- Light is randomly reflected from the dust surfaces in a process called ***scattering***

Scattering

- This scattering is most effective when the light's wavelength is smaller than the dust grain
- The optimum scattering for interstellar dust and molecules in the Earth's atmosphere is for blue and ultraviolet light



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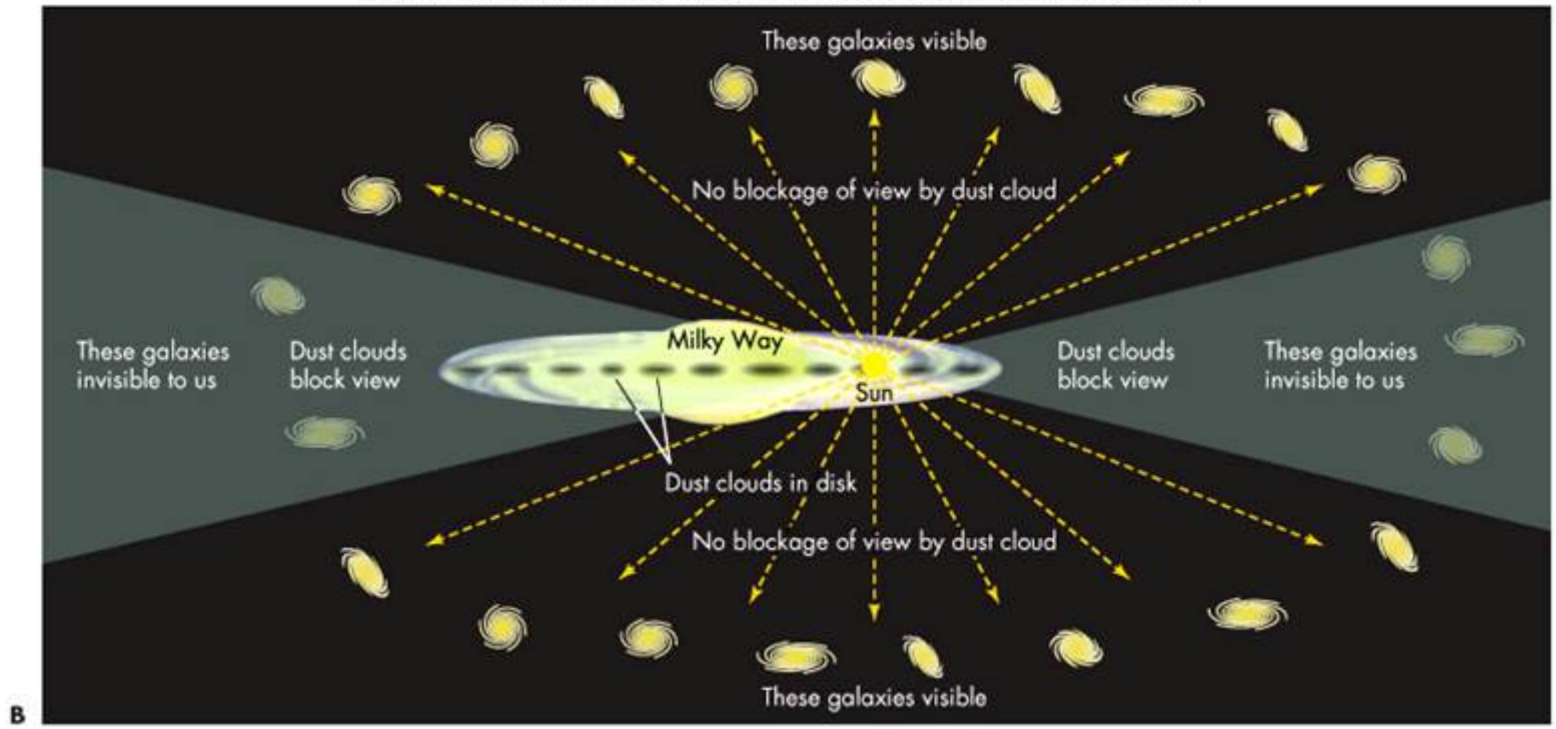
- Earth's sky is blue and the setting Sun red because of scattering

Reddening

Dark nebula

- The loss of blue light from a star due to scattering in an intervening cloud is called ***reddening***
- An interstellar cloud that completely obscures the stars behind it is called a ***dark nebula***

Reddening and Obscuration



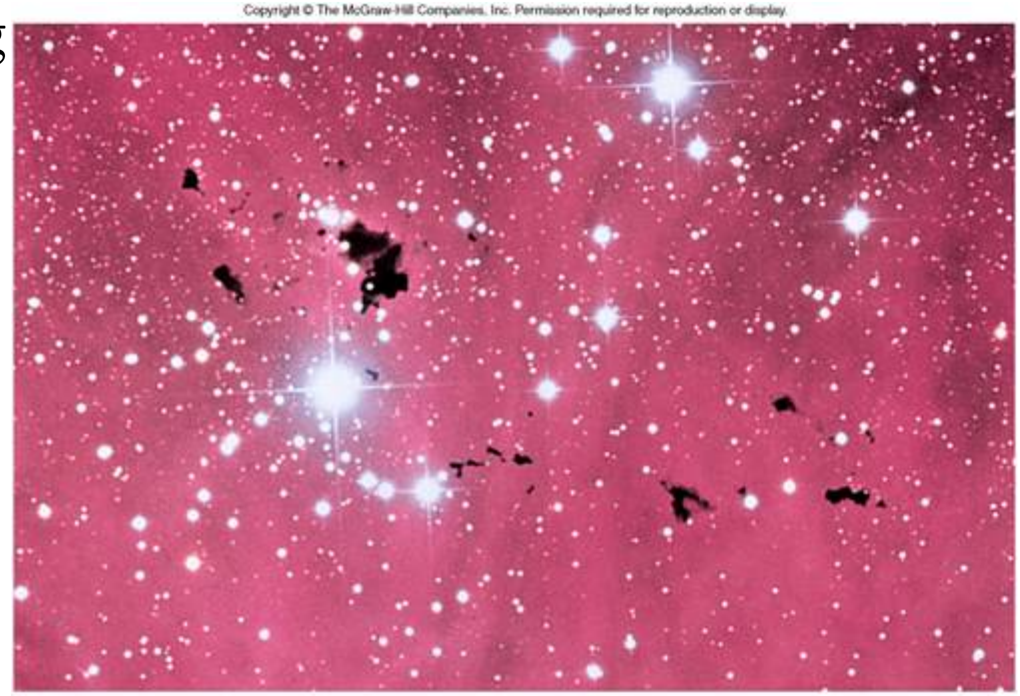
- The large amount of dust in the galactic plane reduces almost to zero the number of distant galaxies that can be seen – this region of the sky is called the ***zone of avoidance*** (the galaxies can still be "seen" in the radio and infrared)

Reflection Nebula

- A nebula may be seen in the visible as the result of starlight reflecting off the dust – such a nebula is called a ***reflection nebula***

Interstellar Gas

- Interstellar gas plays a crucial role in providing material for creating stars and a repository for matter blown out by dying stars
- Interstellar gas also helps astronomers map the Milky Way since molecules within the clouds emit at wavelengths that can penetrate dust
- And, of course, the visible wavelengths of many gas clouds provide spectacular images



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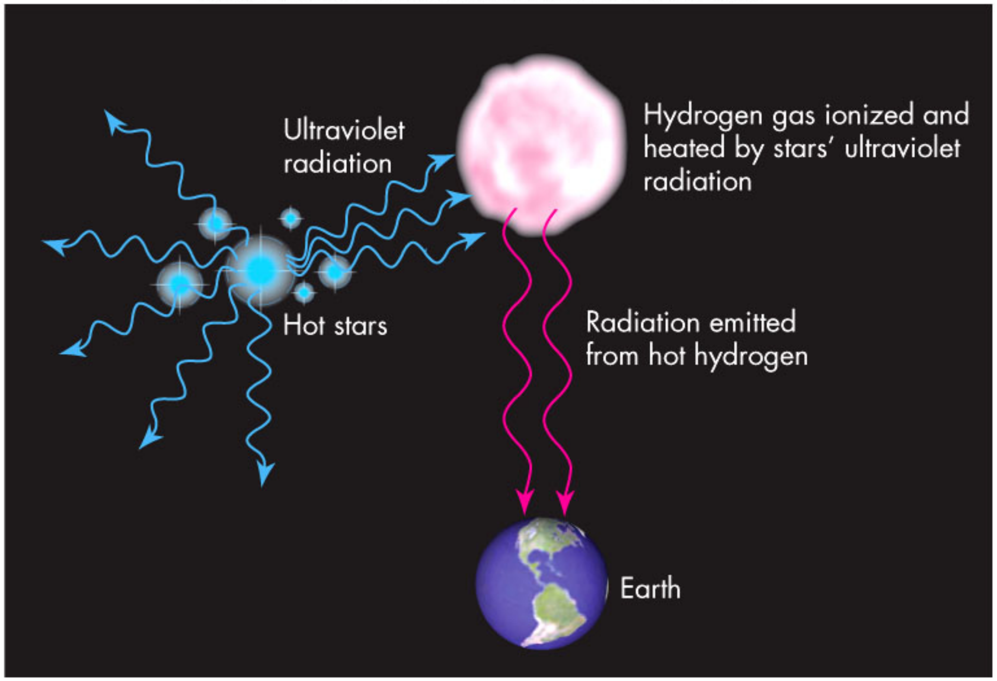
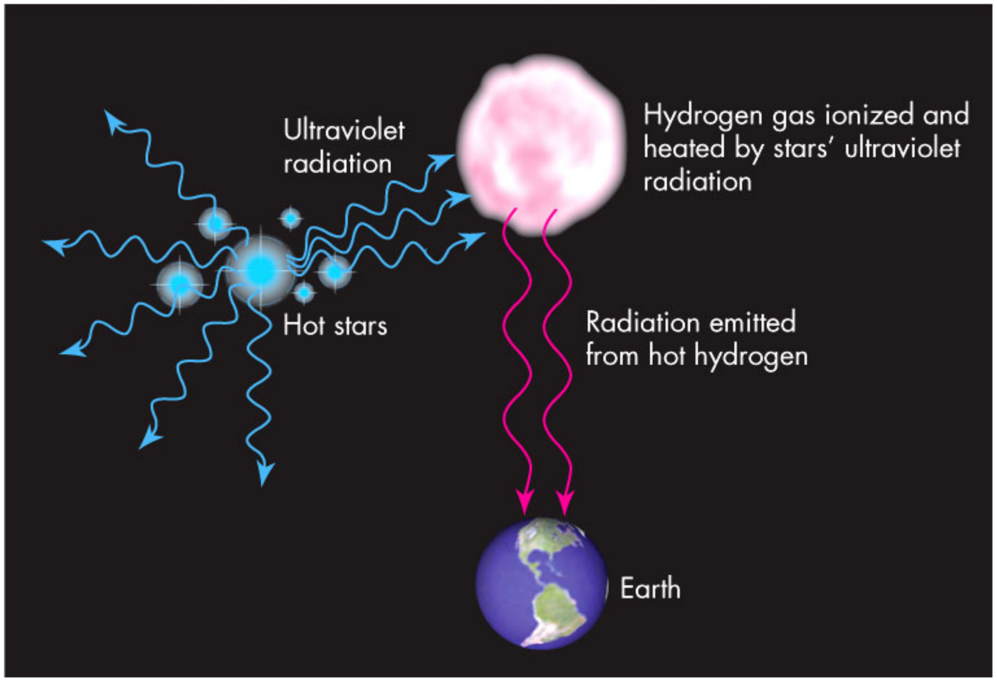
Interstellar Gas



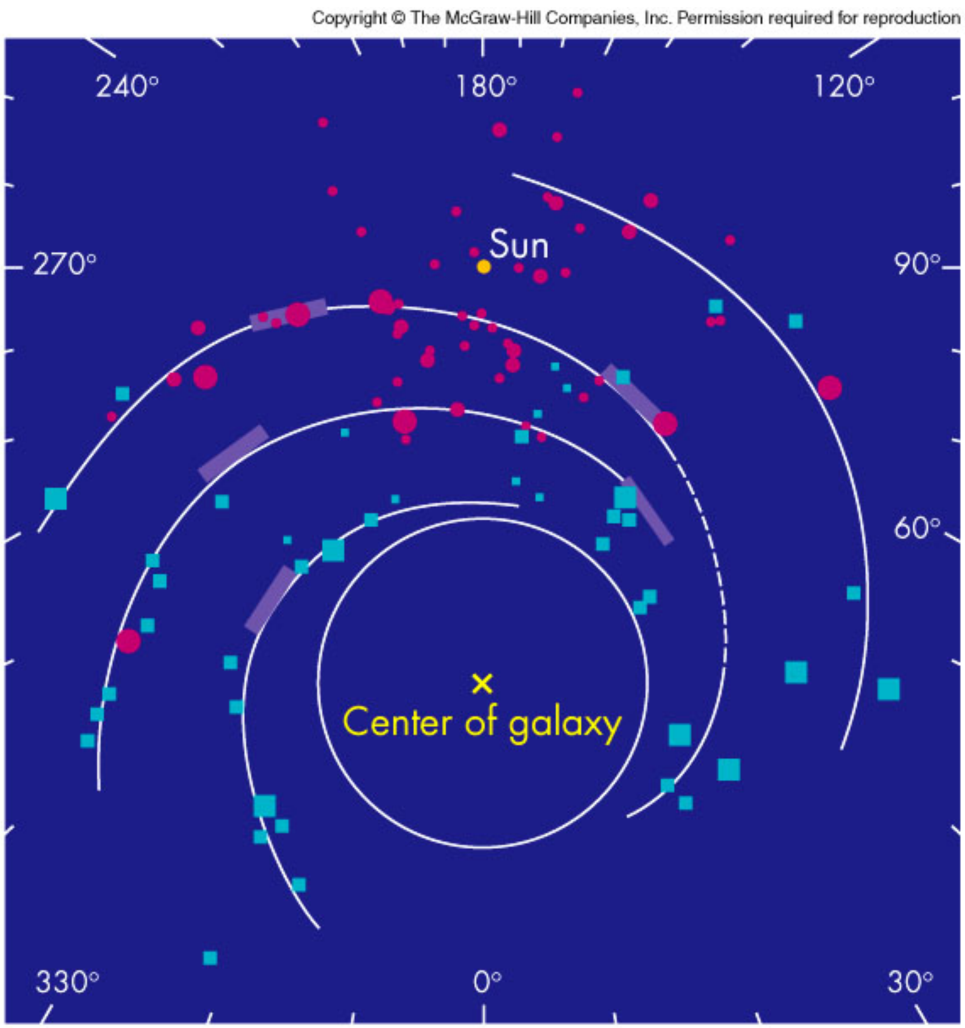
- Interstellar gas clouds that emit visible light are called ***emission nebulas***
  - To emit this light, the cloud must have a source of energy, usually a nearby star
  - Hot, blue stars are especially effective at energizing a gas cloud

Interstellar Gas



- Clouds that are hot enough to ionize hydrogen will give off a very characteristic red color as electrons recombine with protons – these clouds are called ***HII regions*** (the II indicating ionization)

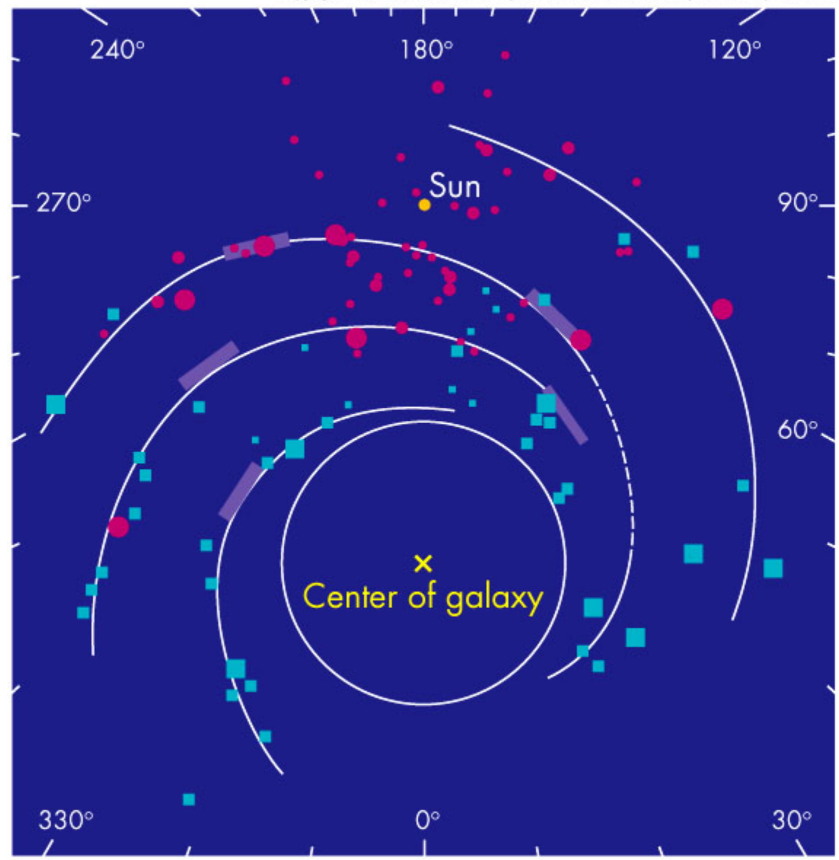
Interstellar Gas



- Maps of radio and optical observations of HII regions are the best evidence we have that the Milky Way is a spiral galaxy

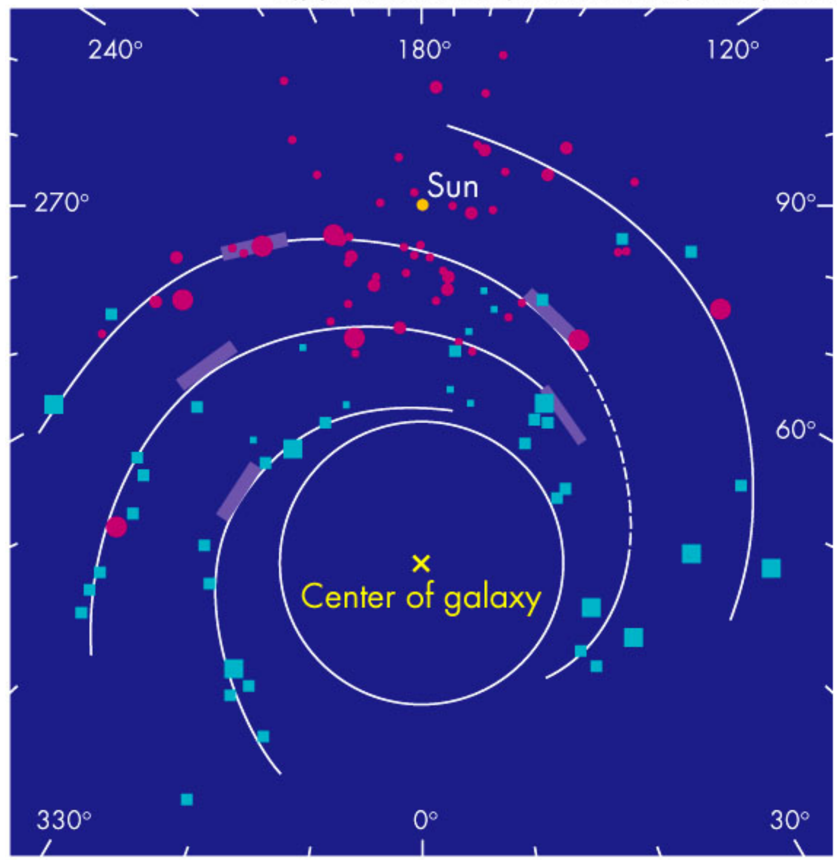
Mapping the Milky Way

- Most interstellar gas clouds are too remote from hot stars to be seen in the visible
  - We detect these clouds by measuring their radio output
  - For hydrogen, the ***21-centimeter radiation*** is the radio emission that comes from the "spin flip" of the bound electron



Mapping the Milky Way

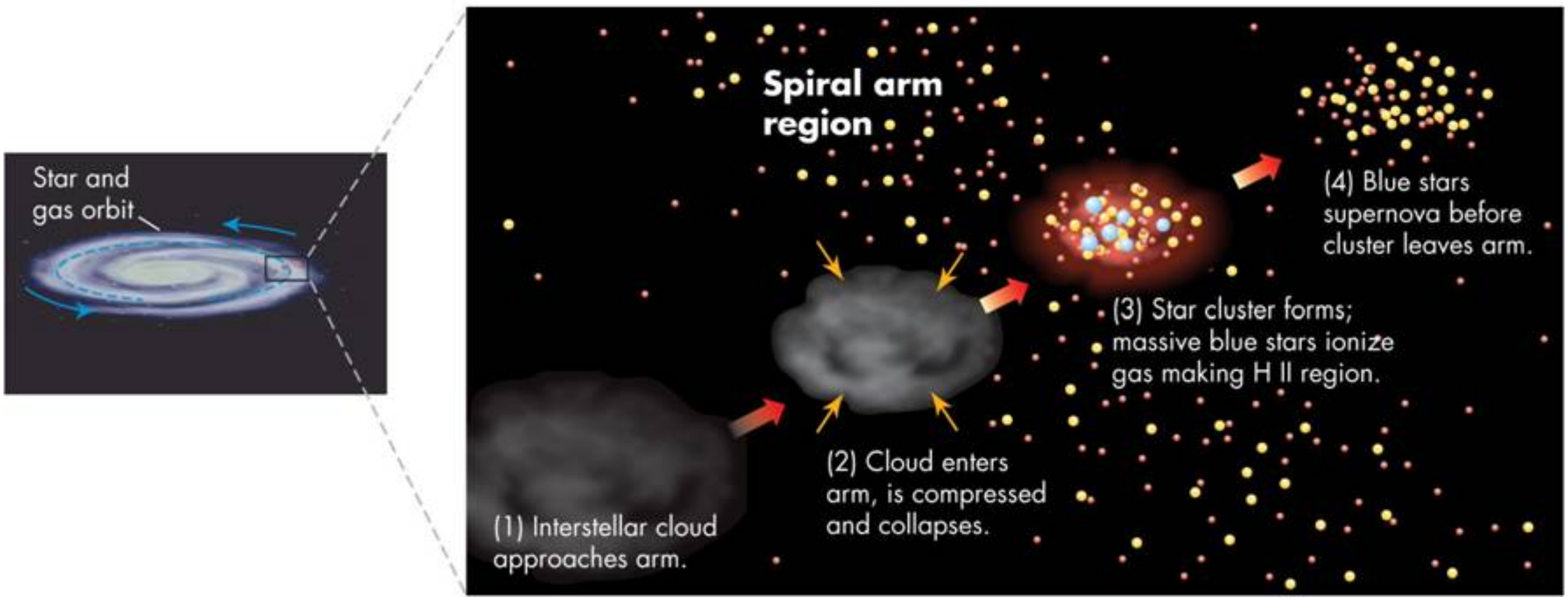
- Radio emissions are not only valuable for mapping gas distributions in the galaxy, but also for identifying the types of molecules that exist in space
  - Examples: H_2 (molecular hydrogen), OH (hydroxyl radical), CN (cyanogen radical), CO (carbon monoxide), H_2O (water), NH_3 (ammonia), HCOH, (formaldehyde), HCOOH (formic acid), CH_3CH_2OH (ethyl alcohol or ethanol)



Spiral Arm Models

- ***Density-wave model***
  - Stars travel around the center of the galaxy in their own orbits
  - Stars and gas traveling in the disc will bunch up as they enter an arm and will spread out as they leave
  - This bunching is similar to that of cars on a freeway except gravity causes the bunching of the stars
  - Gas entering the arm is compressed initiating star formation
  - The newly created and very luminous O and B stars illuminate the gas and dust in the arms
  - Having very small lifetimes, the O and B stars die before leaving the arm region thus making the spiral arms more conspicuous than surrounding regions
  - Theory has difficult time explaining longevity of spiral arms, but observed aging of O and B stars across the arms is consistent with the theory

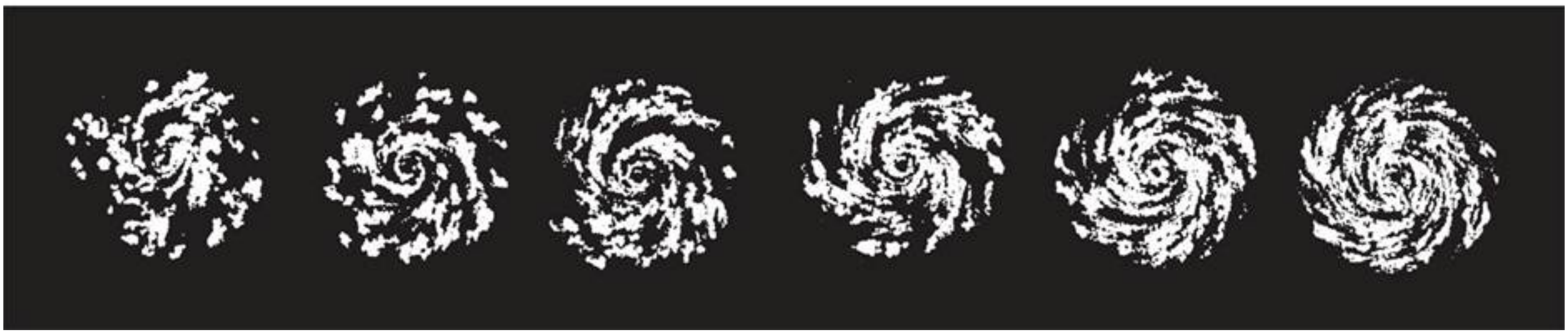
Density-Wave Model



Spiral Arm Models

- ***Self-propagating star formation*** model
  - This theory proposed to explain ragged-appearing arms of some galaxies
  - Star formation begins at some random location in the galaxy creating a collection of stars
  - As these stars heat the gas around them and the larger ones explode, the disturbance sets off a star formation in an adjoining gas cloud
  - The process continues as long as there are enough large stars and gas to propagate the star formation process
  - Differential rotation of the galaxy then spreads the stars out into a spiral arm
  - The random nature of the triggering star formation should give a spiral galaxy a ragged look and this is observed in some galaxies

Self-Propagating Star Formation

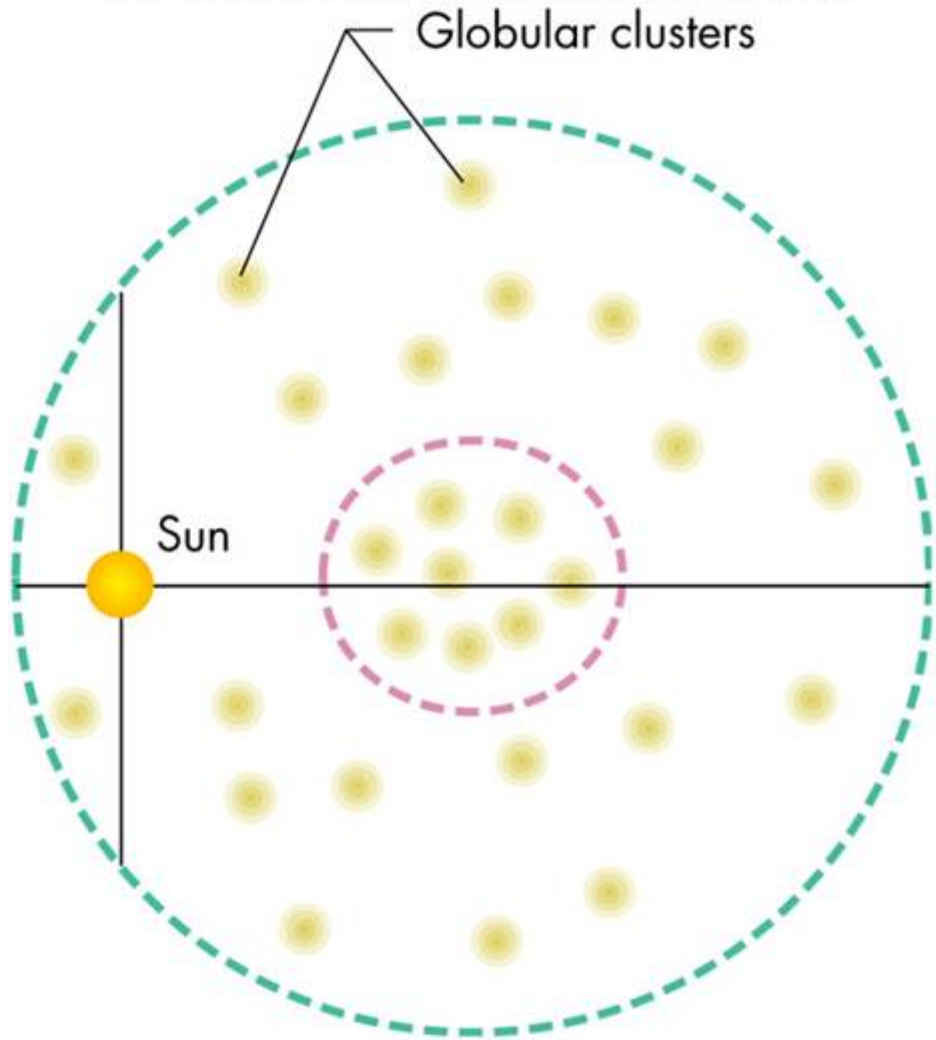


Diameter of the Milky Way

- All methods to determine the Milky Way's diameter depend on Sun's distance to center
- Red giant maser method
  - Red giant maser radio sources common in inner bulge
  - Stars near galactic center move in random directions
  - Assume in a given volume a star moving radially has the same speed as one moving across the line of sight
  - Use Doppler shift of radial maser source to determine speed and use this with transverse maser angular motion to determine distance
  - Geometric center of masers gives Sun distance of 7 kpc

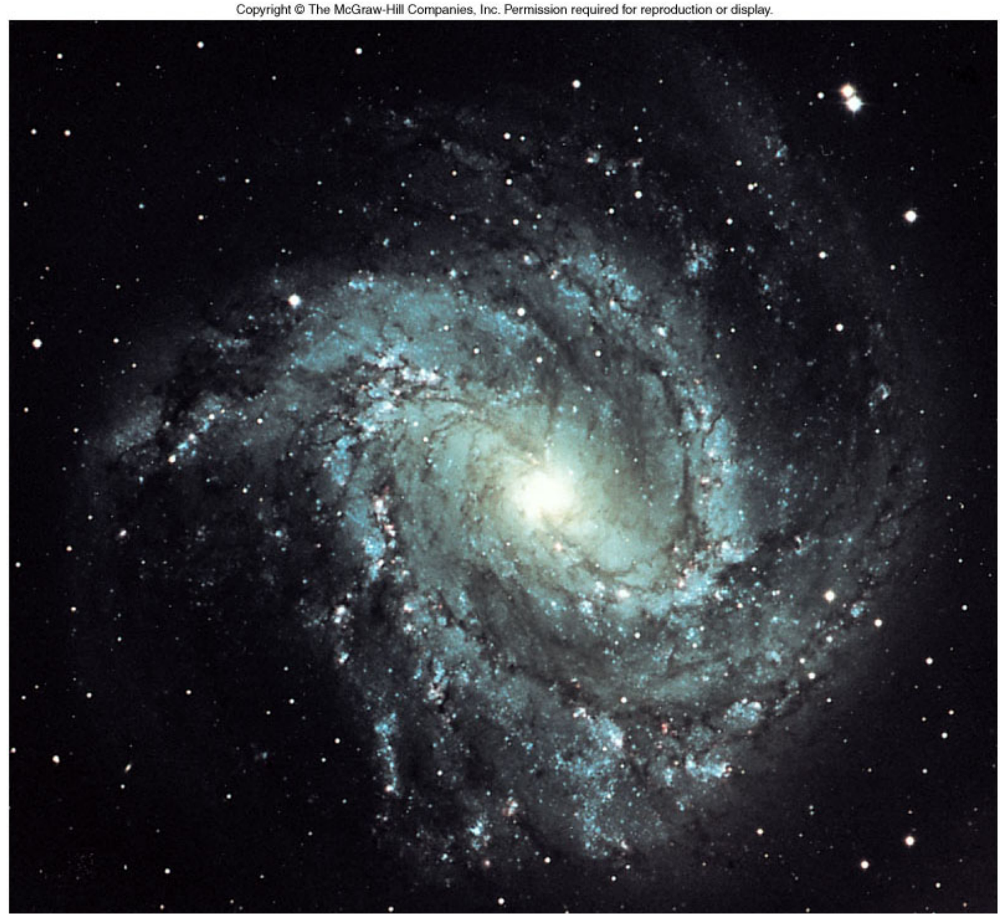
Diameter of the Milky Way

- Globular cluster method
  - Globular cluster distances and directions determined using period-luminosity relation for variable stars
  - Geometric center of globulars then marks the center
  - Distance to center from Sun is then found to be 8.5 kpc

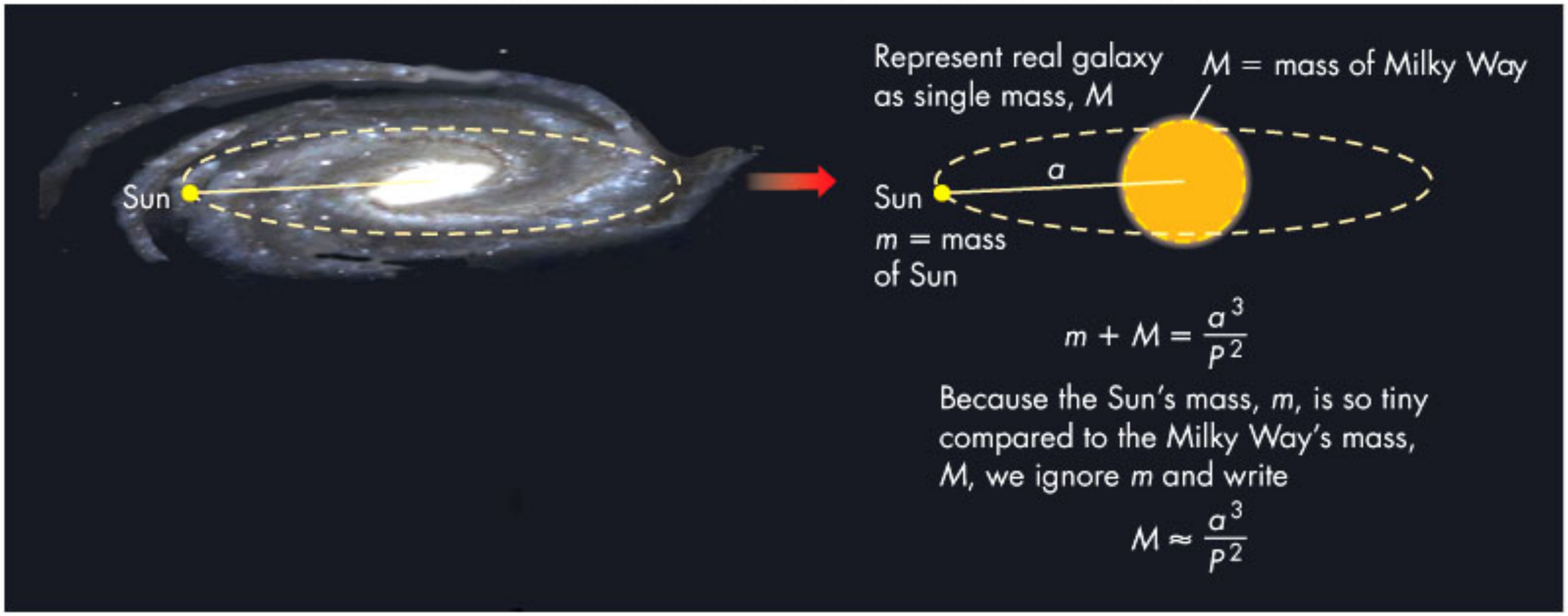


Diameter of the Milky Way

- Once distance to center from Sun found, this is added to distance to outer edge from Sun to arrive at the Milky Way's diameter – a value of about 40 kpc or more

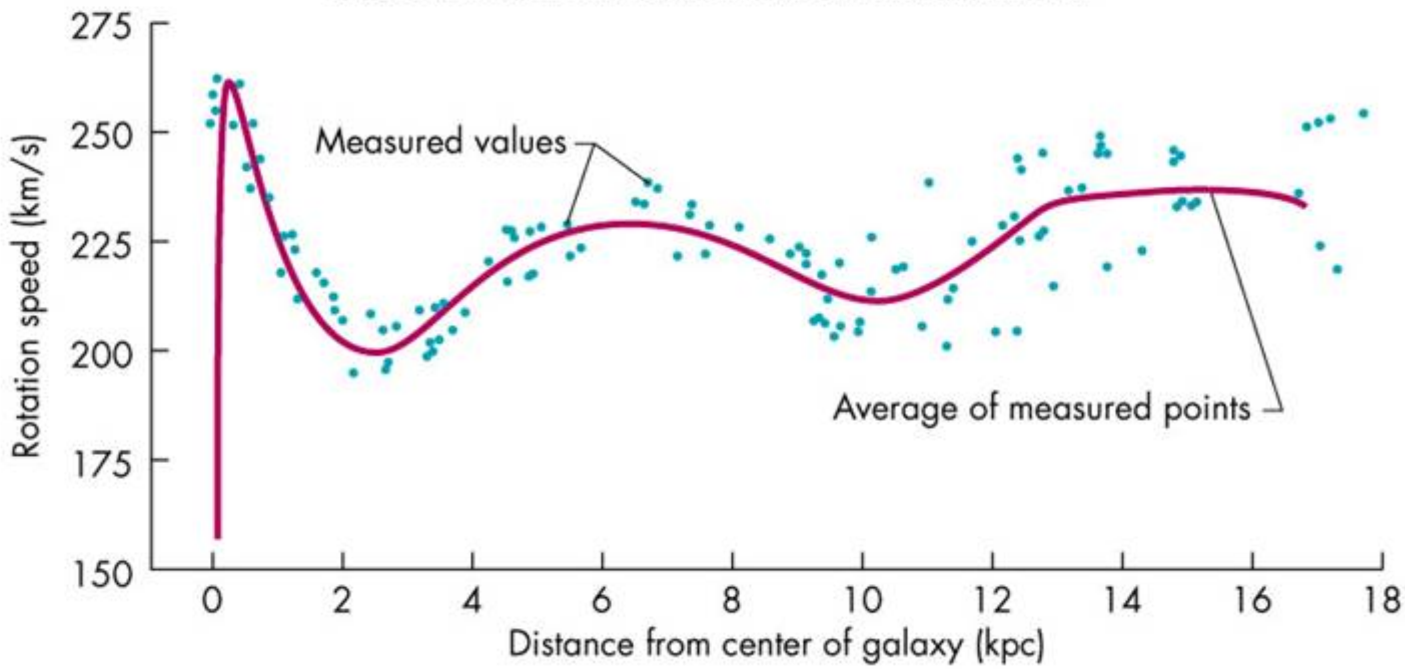


Mass of the Milky Way



- The mass of the Milky Way is determined by using Kepler's modified third law
- Using the Sun's distance to the center and its period of revolution, the mass interior to the Sun's orbit is at least $10^{11}\ M_\odot$

Mass of the Milky Way

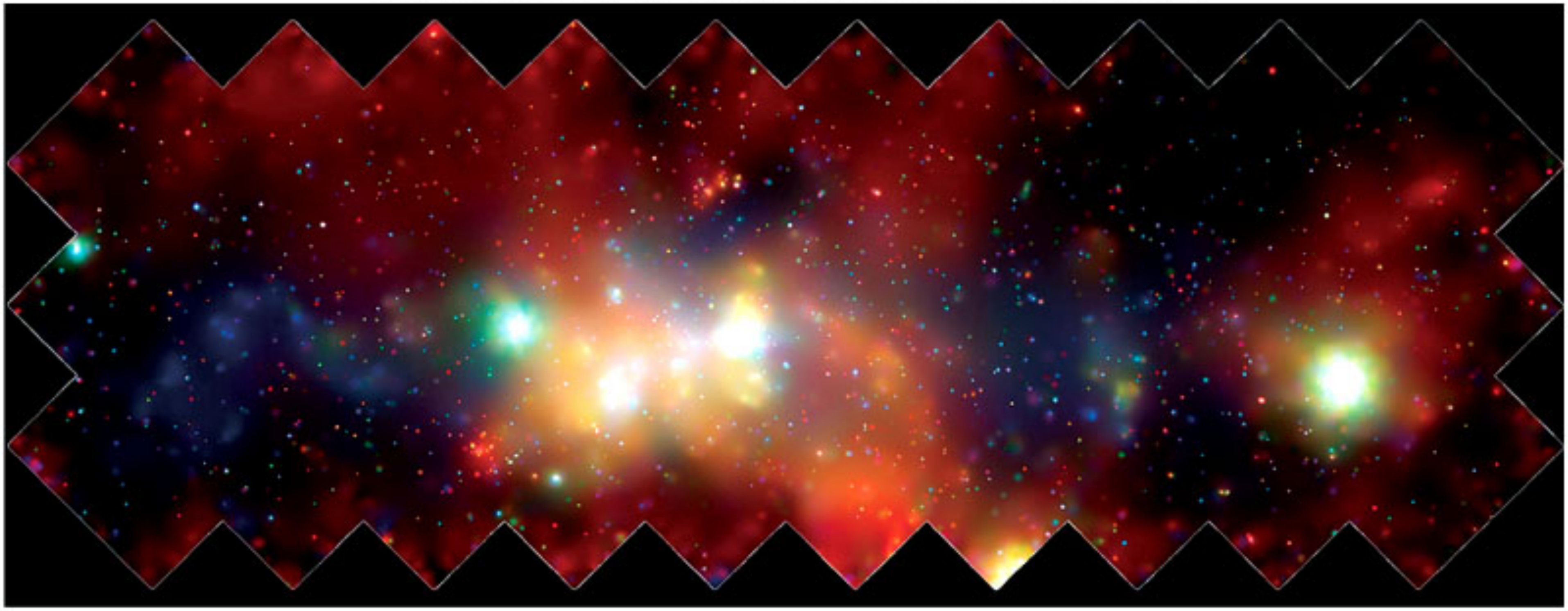


- A more refined technique uses the rotation speeds of stars at a variety of distances from the center (the so-called ***rotation curve***)
- This technique can more accurately determine the mass of the entire galaxy – the Sun method only estimates the mass interior to its orbit

Mass of the Milky Way

- In either method, the speed of stars around the galaxy is crucial and there are many ways to do this – two of them are:
  - Use the Local Group of galaxies as a reference frame since the stars on the Milky Way move much faster
  - Use the distribution of randomly moving globular clusters as on average being at rest
- Analysis of the rotation curve also reveals a dark matter halo with a radius exceeding 100 kpc

The Galactic Center

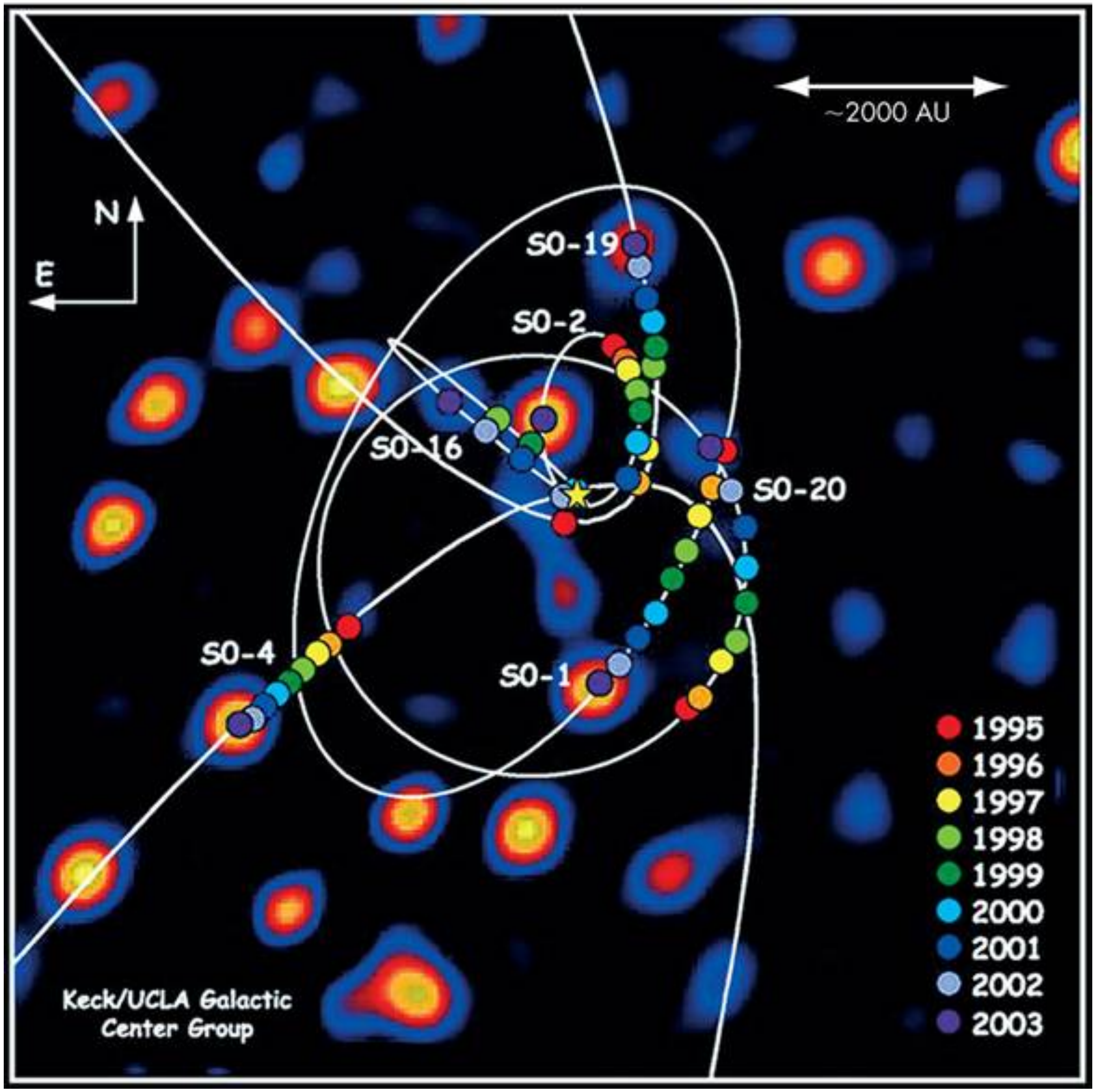


- Because the galactic center is not observable in the visible, astronomers must rely on radio, infrared, X-ray, and gamma-ray observations

The Galactic Center

- At a distance of 3 kpc, an arc of cold hydrogen sweeps outward at a speed exceeding 100 km/sec
- A giant swarm of stars, packed in at millions of stars per cubic light-year, are arranged in an elongated structure about 1000 light-years across
- Some energetic event, perhaps a supernova explosion, violently disturbed the center in the not-to-distant past
- Deep within the core lies an incredibly small (10 AU diameter) radio source known as Sgr A*
- A $5 \times 10^6 \, M_\odot$ black hole may occupy the very center of the galaxy!

A Black Hole?


~2000 AU
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S0-2
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S0-20
S0-4
S0-1
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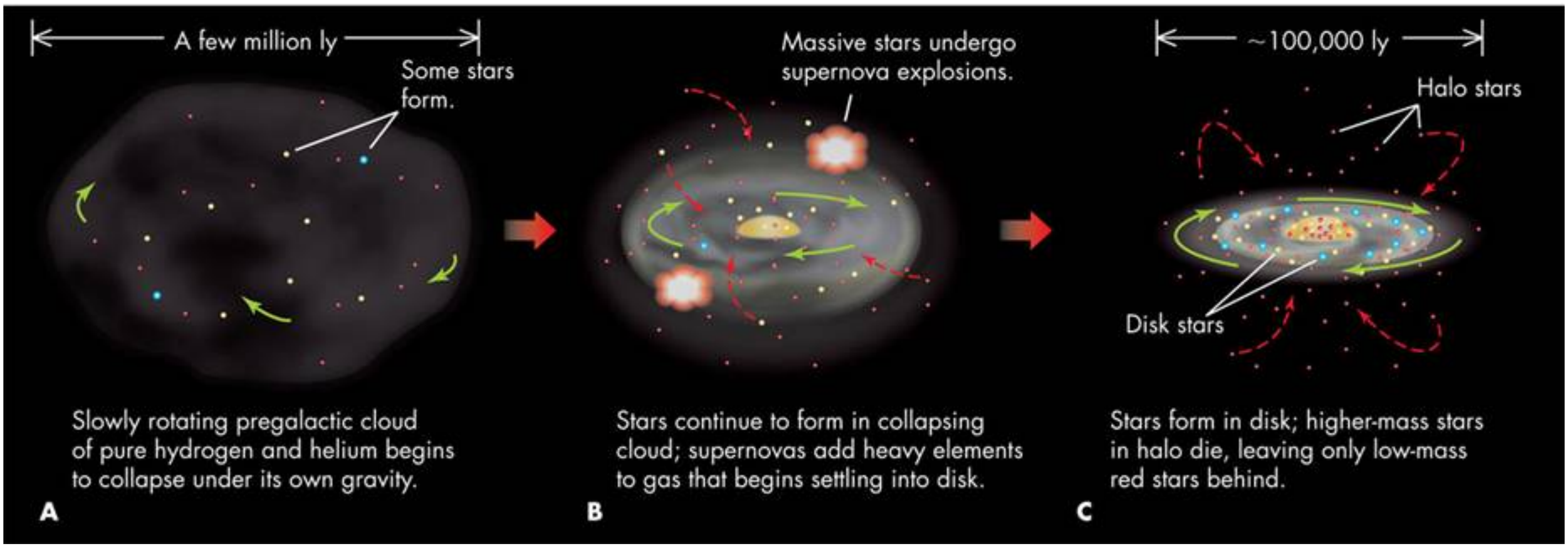
2003
Keck/UCLA Galactic
Center Group

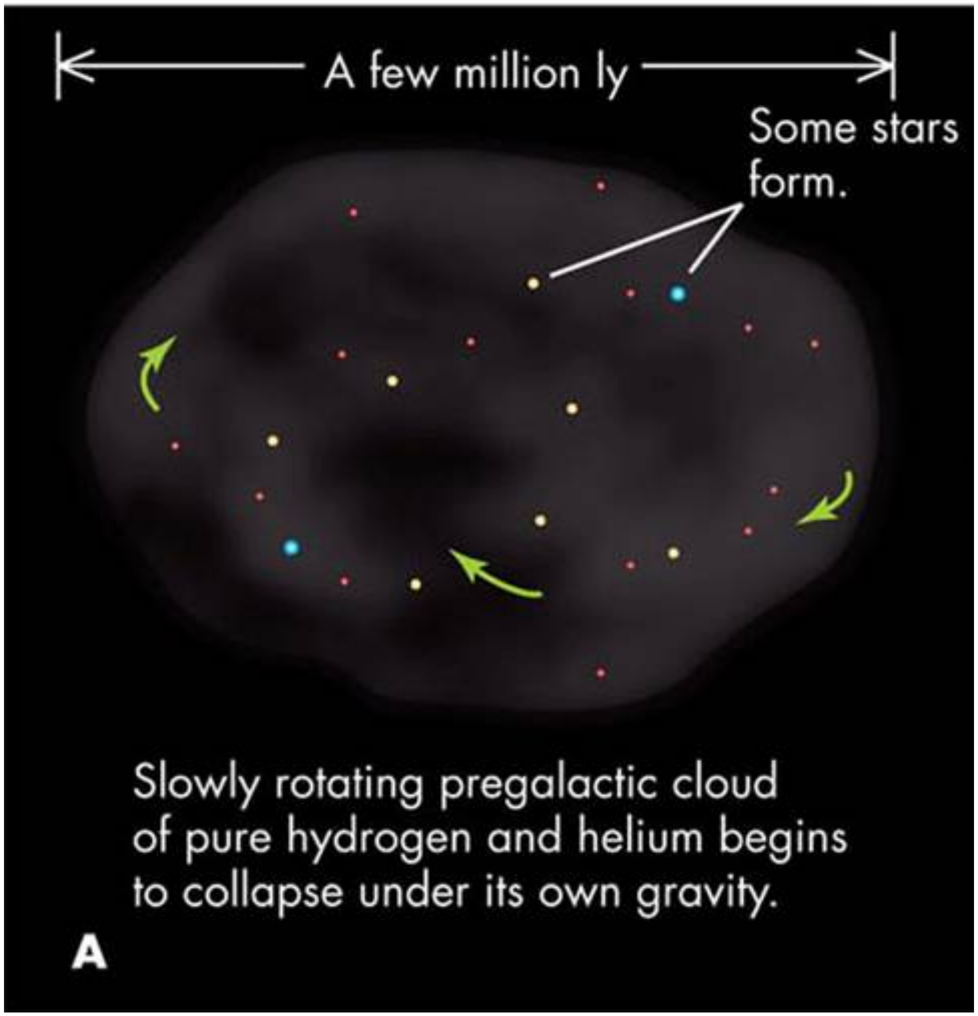
Formation of the Milky Way

- Forming galaxies is still a major unsolved problem
- Originally, it was thought that galaxies form like stars, but only on a larger scale
  - Begin with a million-light-year cloud with 100 billion solar masses of material
  - The cloud gravitationally collapses and breaks up into stars
- Evidence for this galaxy formation process can be found in the Pop I and Pop II stars

Formation of the Milky Way

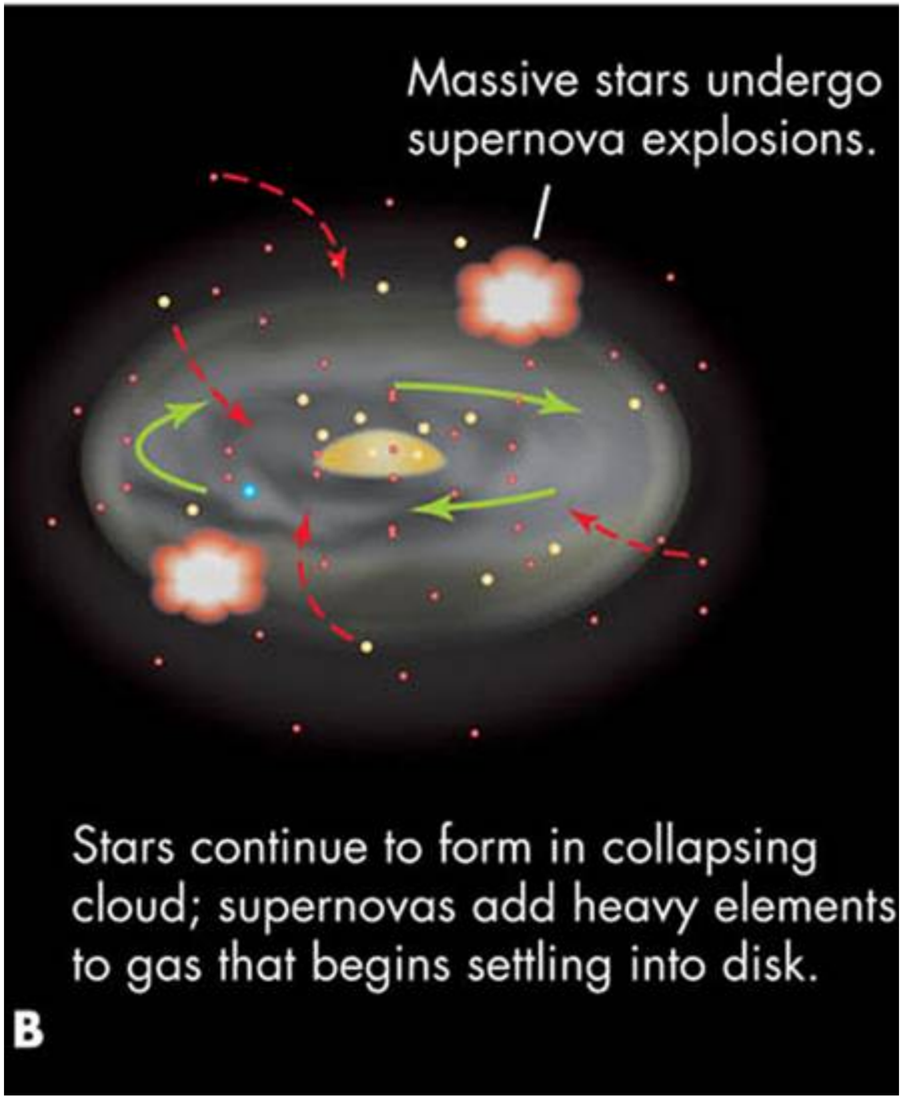


Formation of the Milky Way



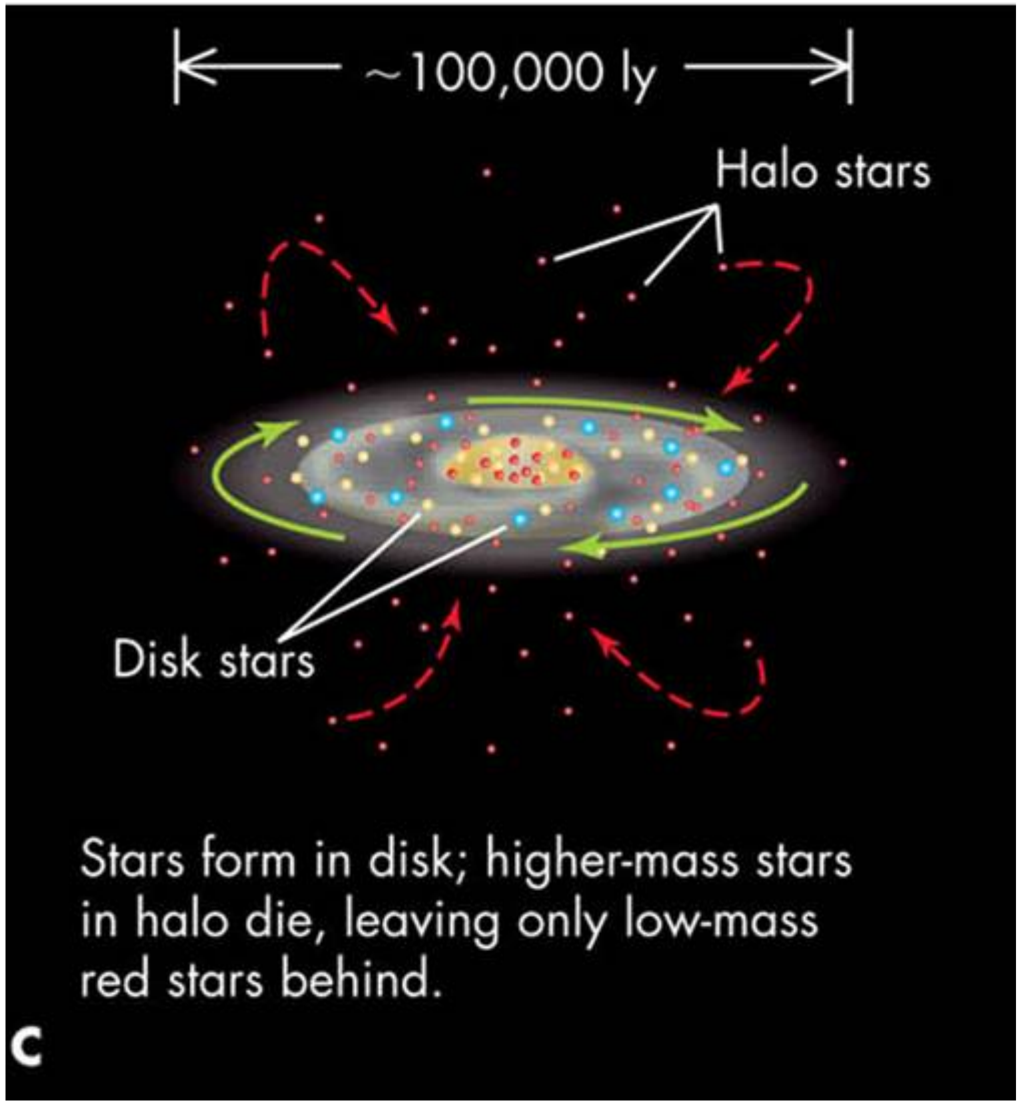
- The proto-Milky Way was a giant cloud of pure hydrogen and helium
- The existence of old Pop II stars with very little heavy elements suggests they formed at the onset of collapse and as they did so, they dropped out of the gas collapse

Formation of the Milky Way

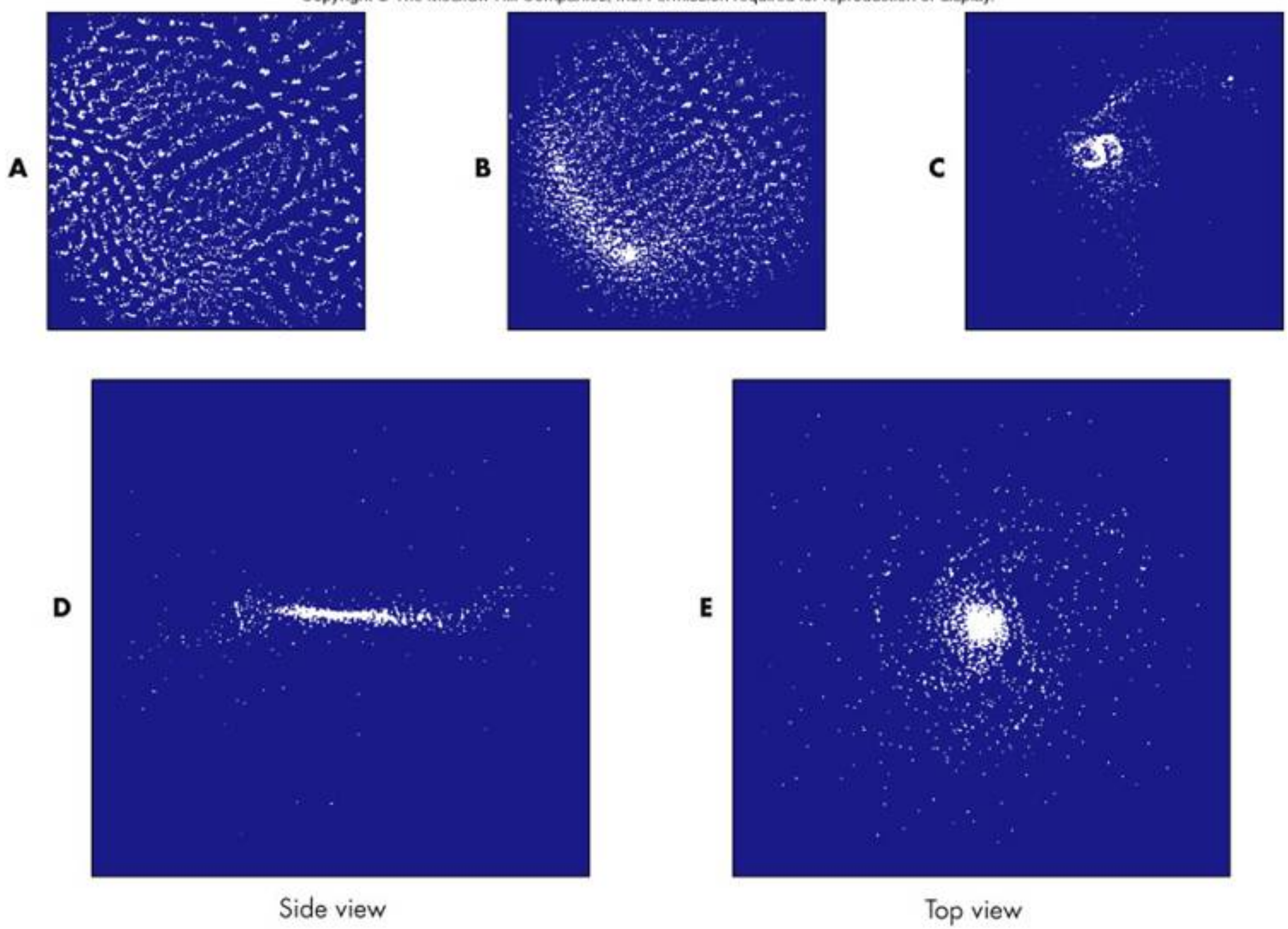


- The massive Pop II stars exploded early on, seeding the galactic cloud with heavy elements
- By the time the cloud collapsed into a disc it was rich enough in heavy elements to generate the Pop I stars we see there today

Formation of the Milky Way



Computer Simulation of Galactic Formation



Formation of the Milky Way

- However, the collapse model fails to explain two important properties of stars
  – Pop II stars appear to have formed over a longer time scale than the collapse model allows
  – Some stars should have virtually no heavy elements, but no such stars have ever been observed

Formation of the Milky Way

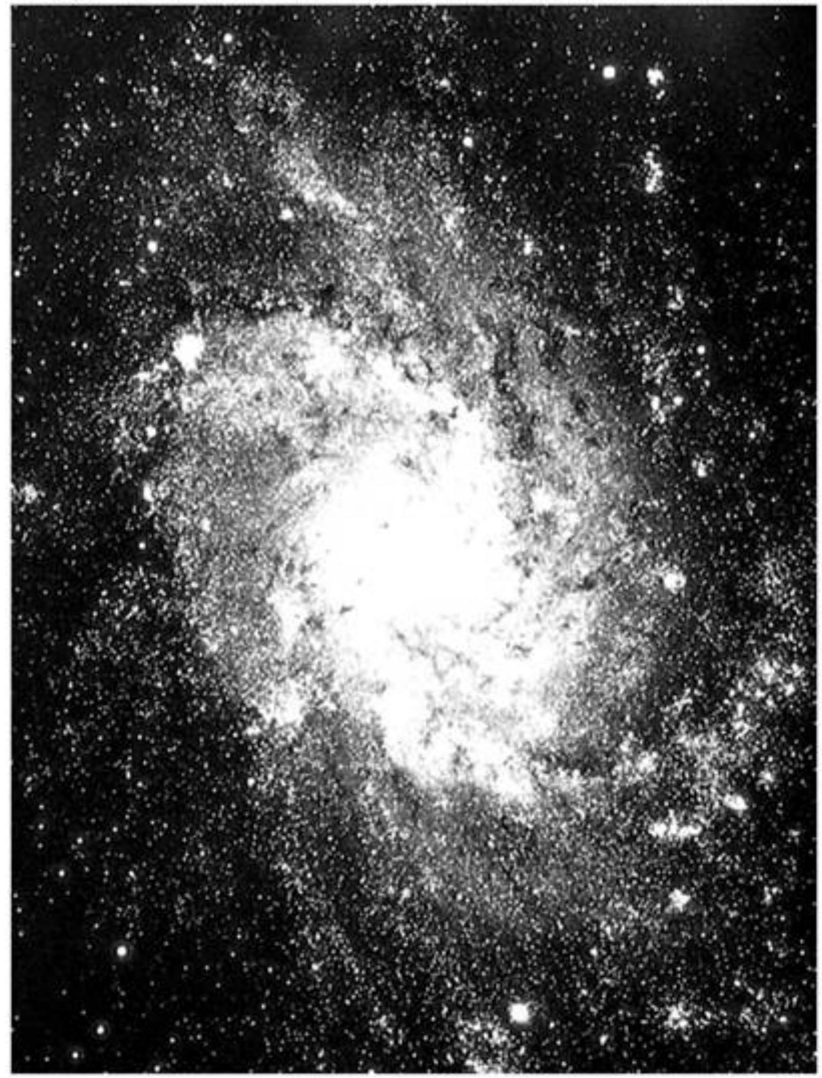
- Today, astronomers also think the collapse model fails to include the effects of galactic mergers on galactic and stellar evolution – merging appears to be the rule, not the exception

Population III Stars

- Despite uncertainties, the basic idea of the initial stars being made of pure hydrogen and helium is still true – so where are they
- These ***population III stars*** may not be observable for three reasons
  - Only short-lived massive population III stars can form – consequently none are left today
  - Population III stars exist, but are masquerading as Pop II since their atmospheres have been contaminated by gas ejected when a more massive star exploded
  - Pop II stars may be rare and hard to find

The Future of the Milky Way

- Eventually all gas finds its way into stars, which in turn will lock up material in stellar remnants
- Hundreds of billions of years from now the Milky Way will fade, slowly spinning in space, a dark disk of stellar cinders



Galaxies
Part 2

Galaxies

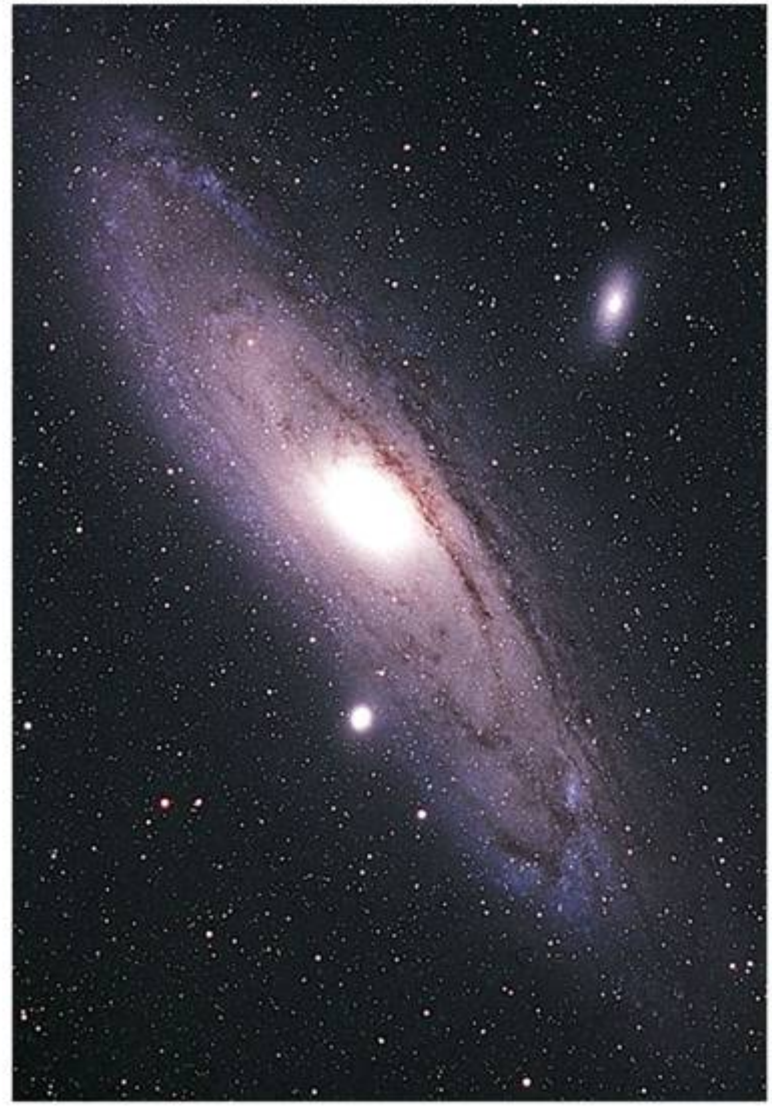
- Beyond the Milky Way are billions of other galaxies
- Some galaxies are spiral like the Milky Way while others are egg-shaped or completely irregular in appearance
- Besides shape, galaxies vary greatly in the star, gas, and dust content and some are more “active” than others
- Galaxies tend to cluster 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

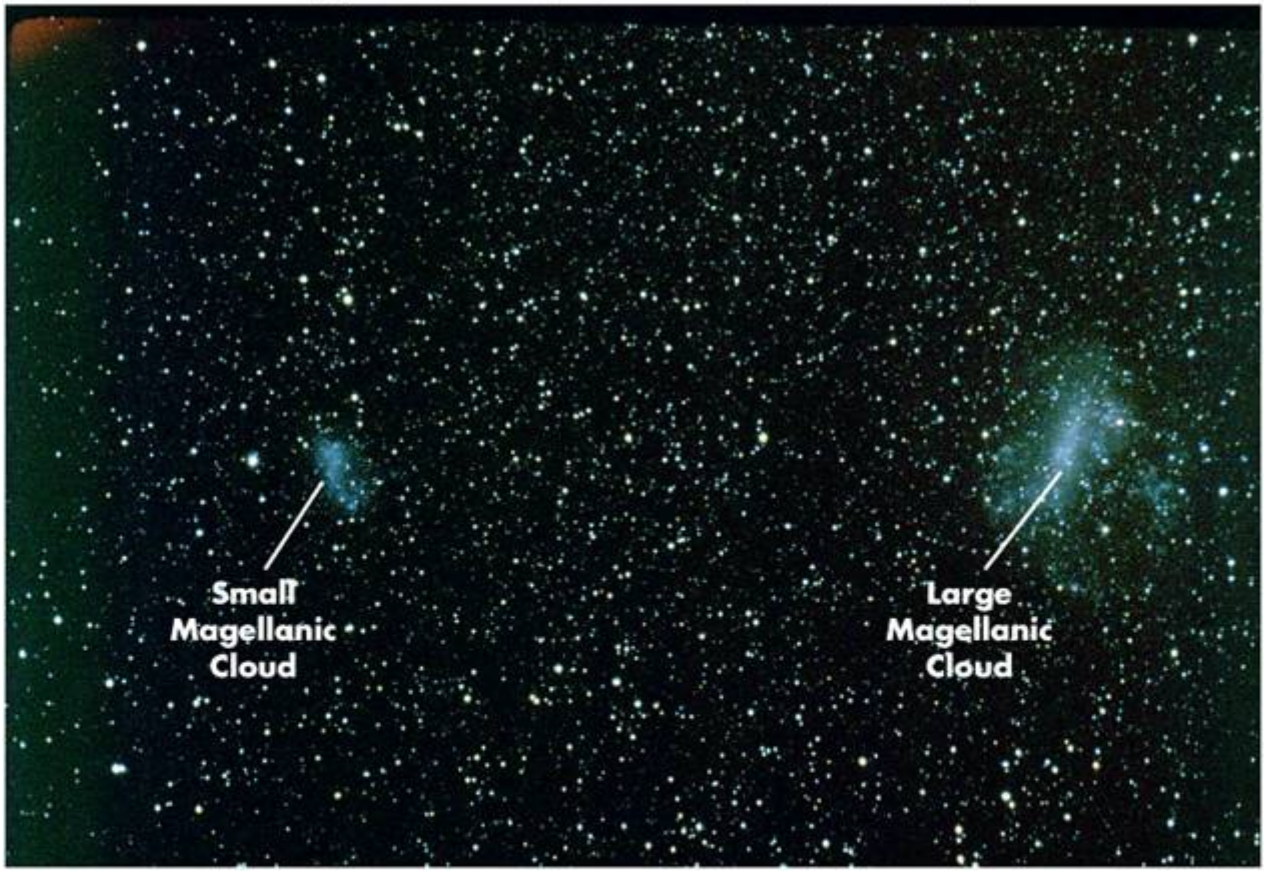
- A ***galaxy*** is an immense and relatively isolated cloud of hundreds of millions to hundreds of billions of stars, and vast clouds of interstellar gas
- Each star moves in its own orbit guided by the gravity generated by other stars in the galaxy

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)

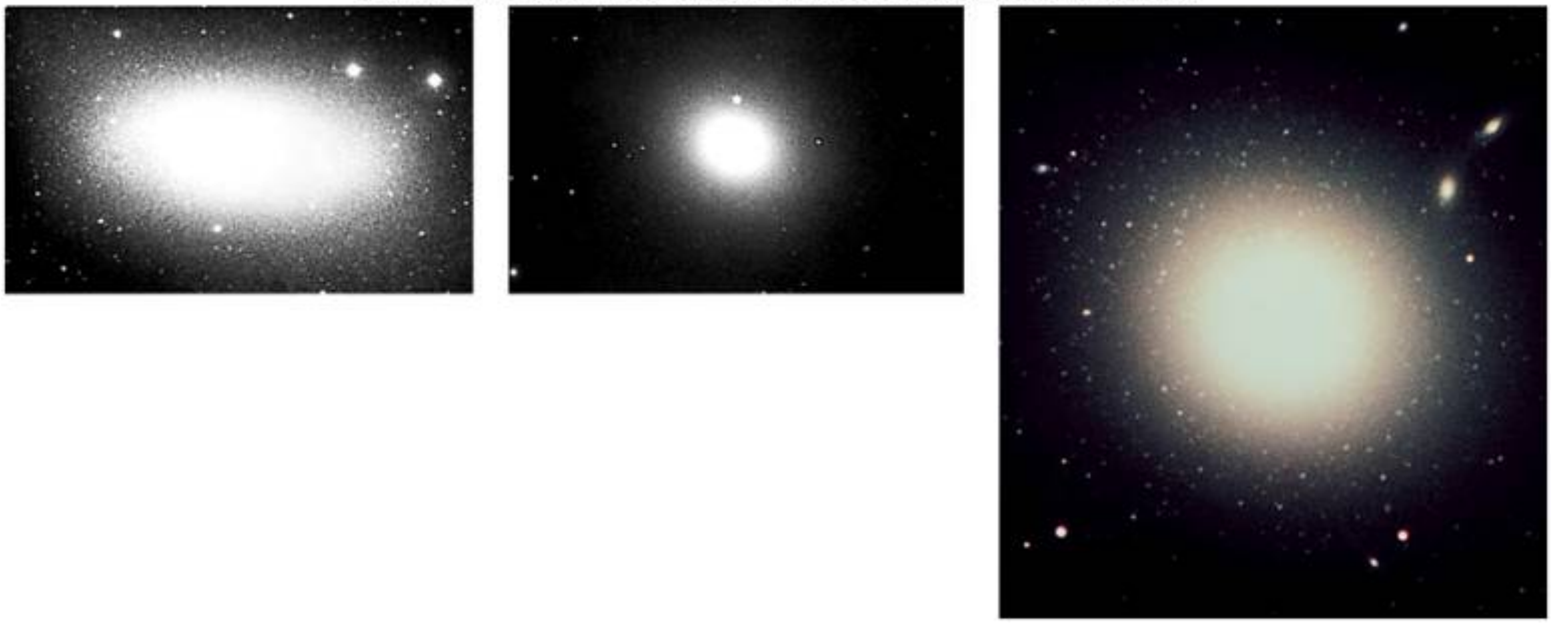
Types of Galaxies

- 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

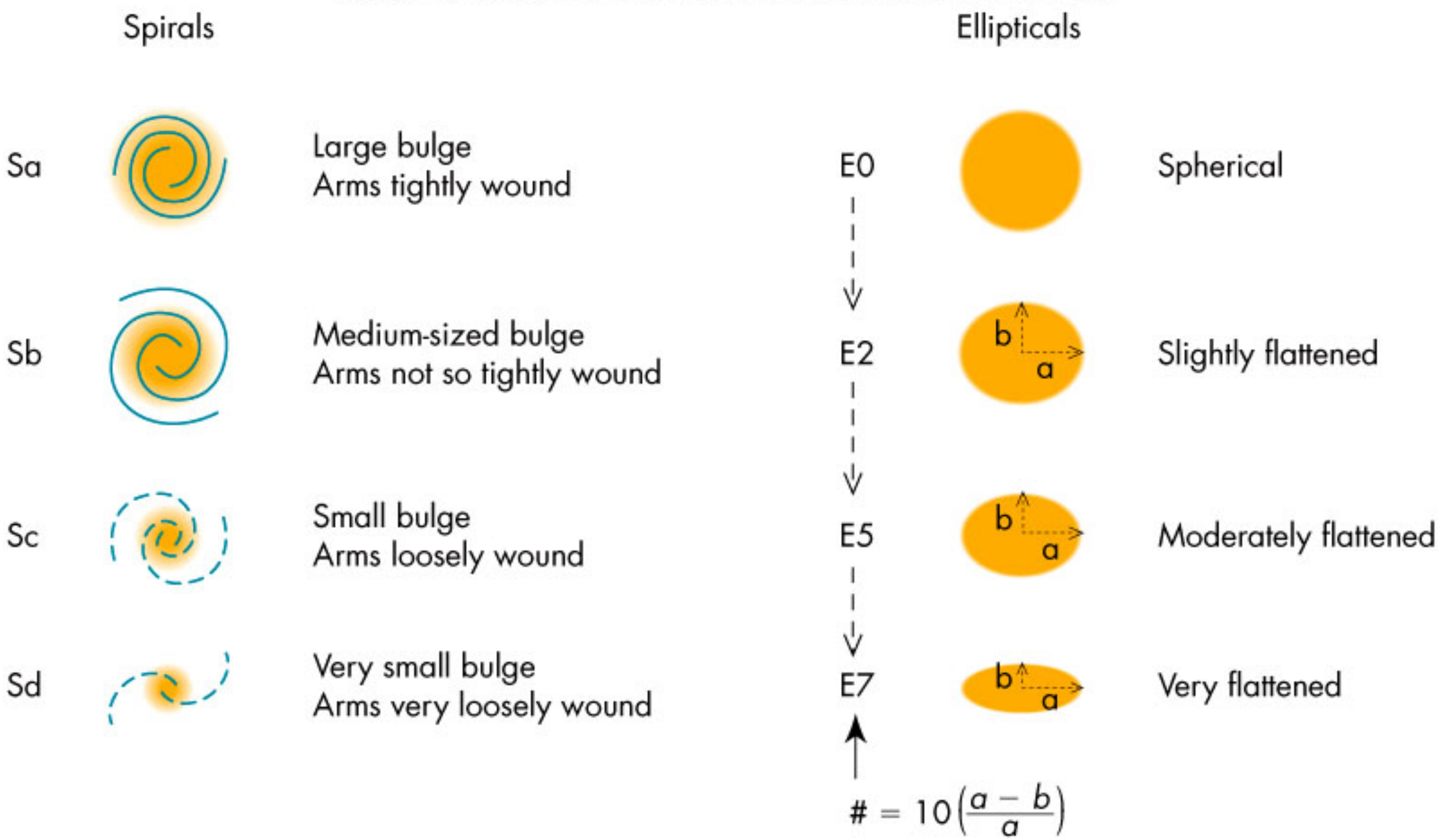
- Two or more arms winding out from center
- Classified with letter S followed by a letter (a-d) to distinguish how large the nucleus is and/or how wound up the arms are

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

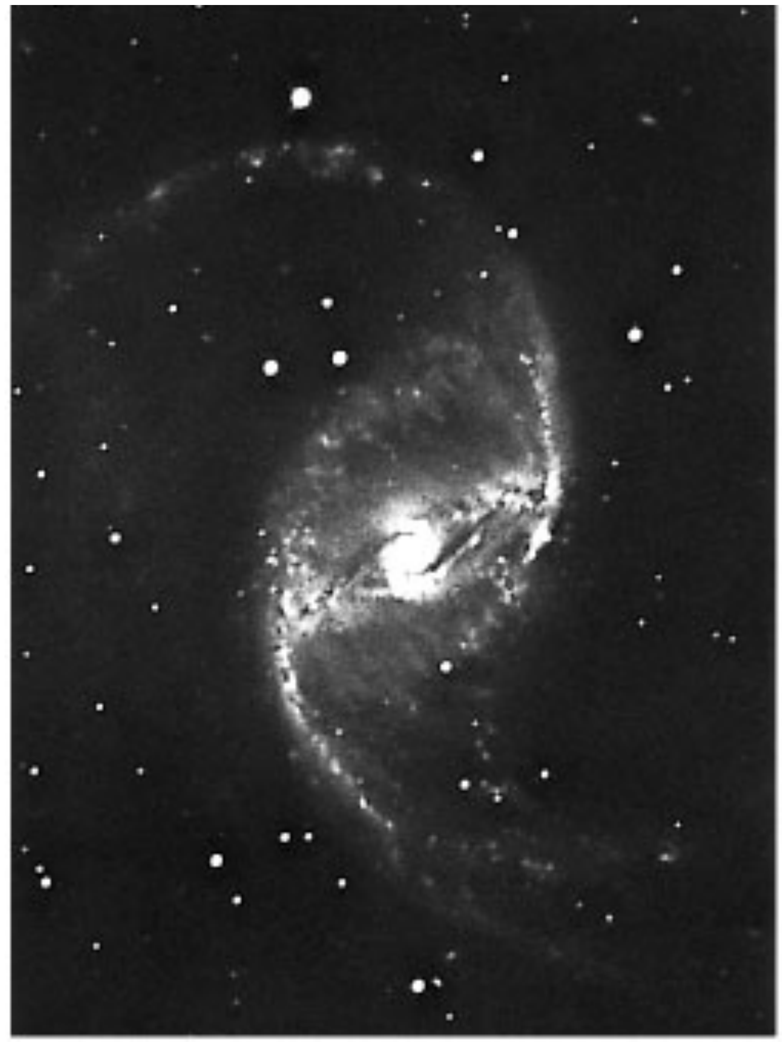


Irregular Galaxies

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

Barred Spirals

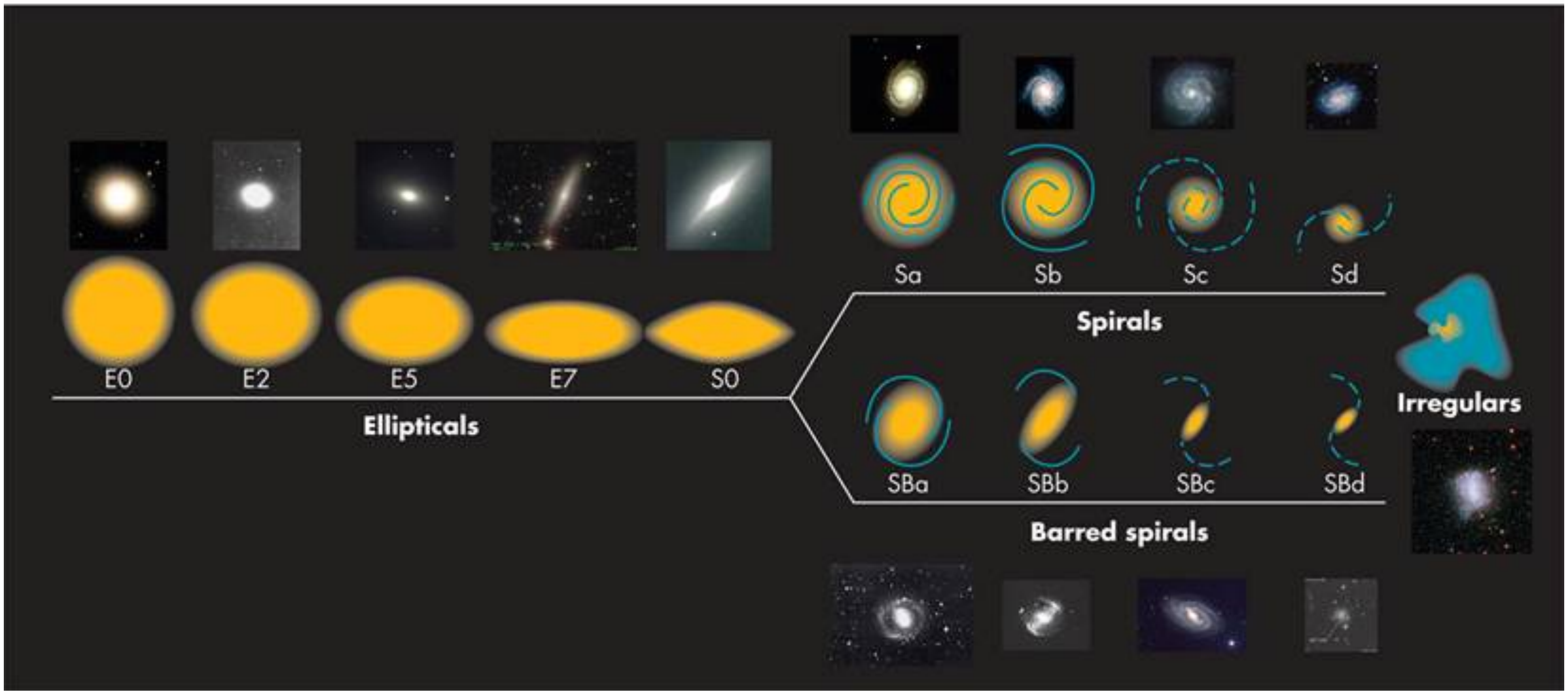
- Arms emerge from ends of elongated central region or bar rather than core of galaxy
- Classified with letters SB followed by the letters (a-d)
- Thought by Hubble to be a separate class of object from normal S spirals, computer simulations show bar may be result of a close encounter between two galaxies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



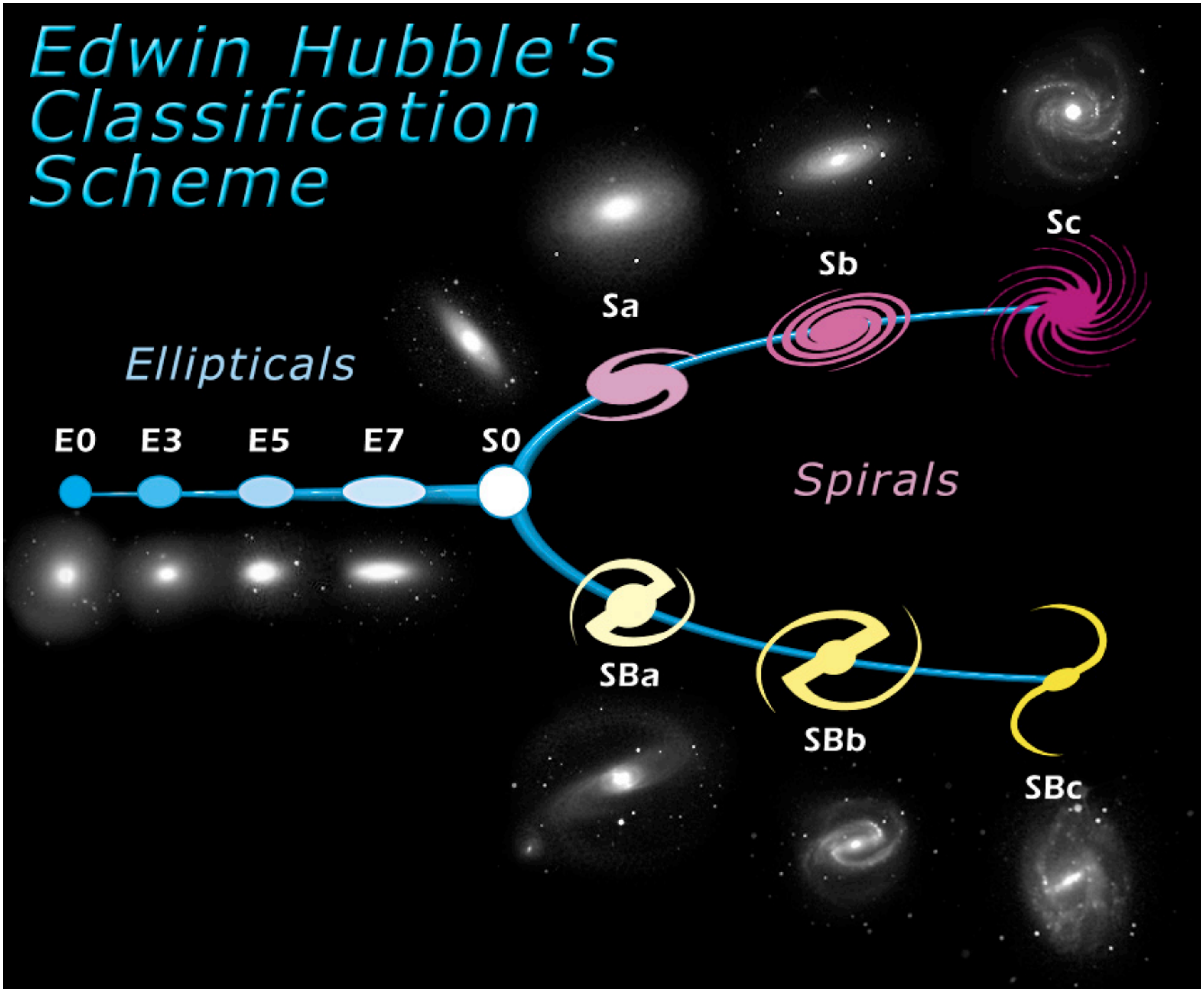
S0 Galaxies

- 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.


Edwin Hubble's Classification Scheme
Ellipticals
E0
E3
E5
E7
S0
Sa
Sb
Sc
Spirals
SBa
SBb
SBc

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

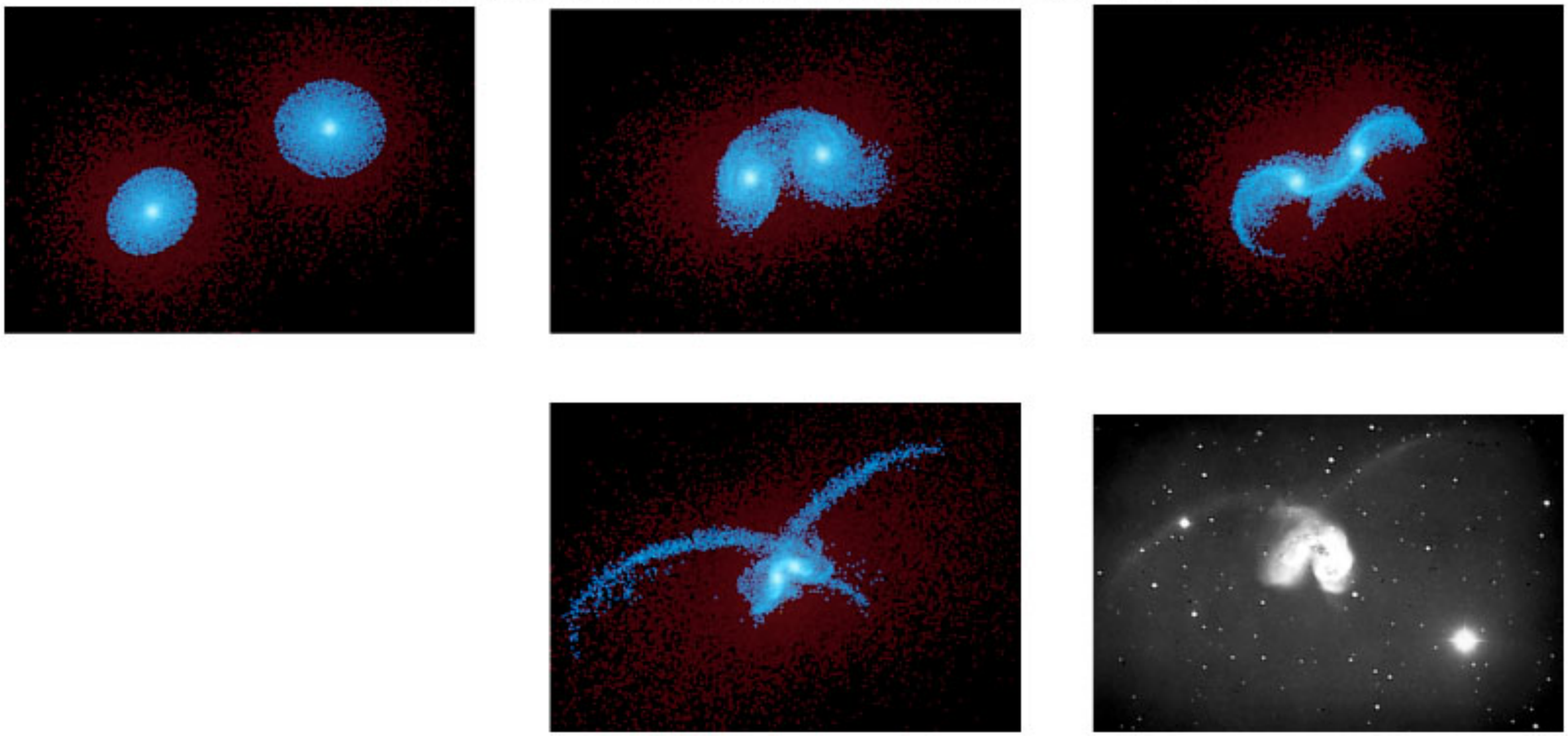
Stellar and Gas Content of Galaxies

- 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

The Cause of Galaxy Types

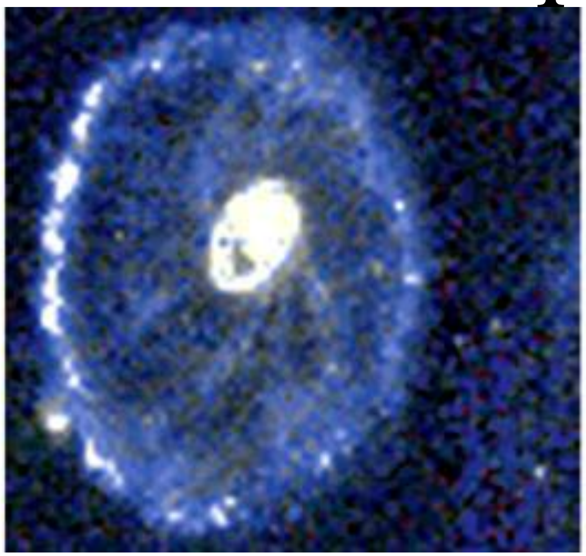
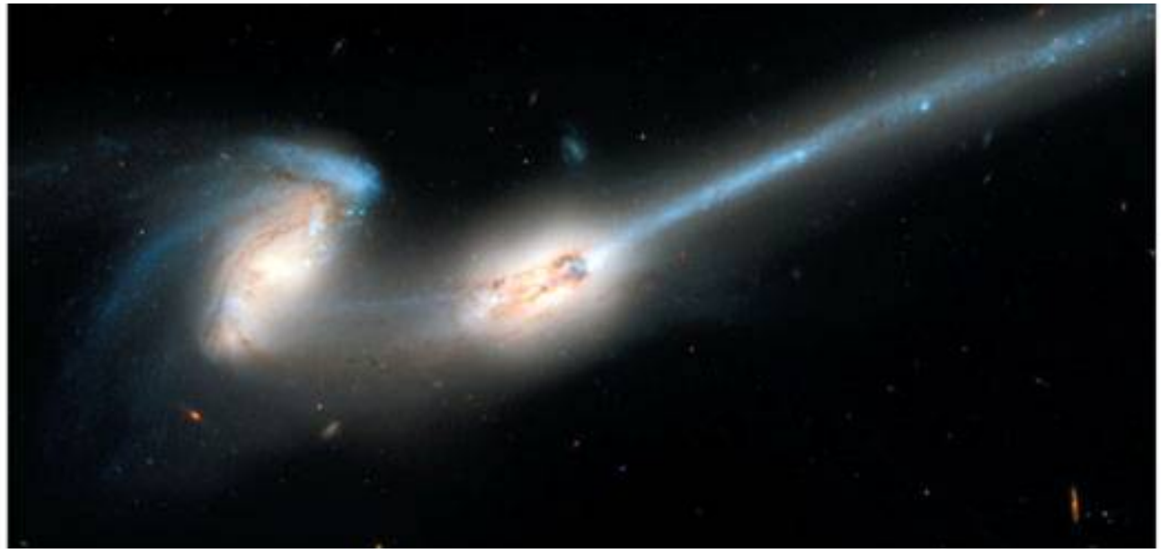
- Computer simulations show galaxies formed from gas clouds with large random motions becoming ellipticals, whereas small random motions become spirals
- Ellipticals had a high star formation rate in a brief period after their birth, while spirals produce stars over a longer period – did the rate cause 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

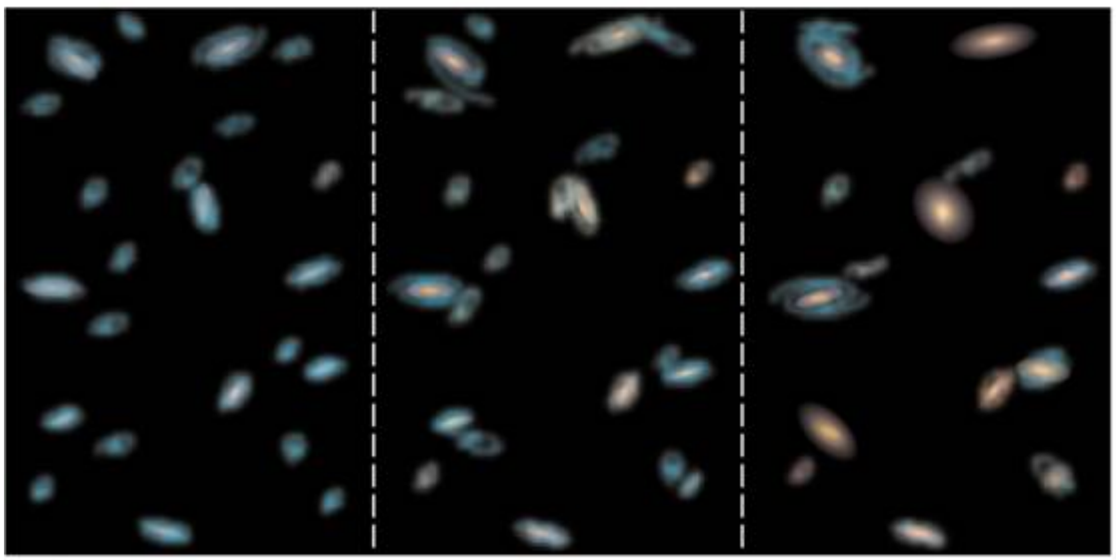
Galactic Collisions and Mergers

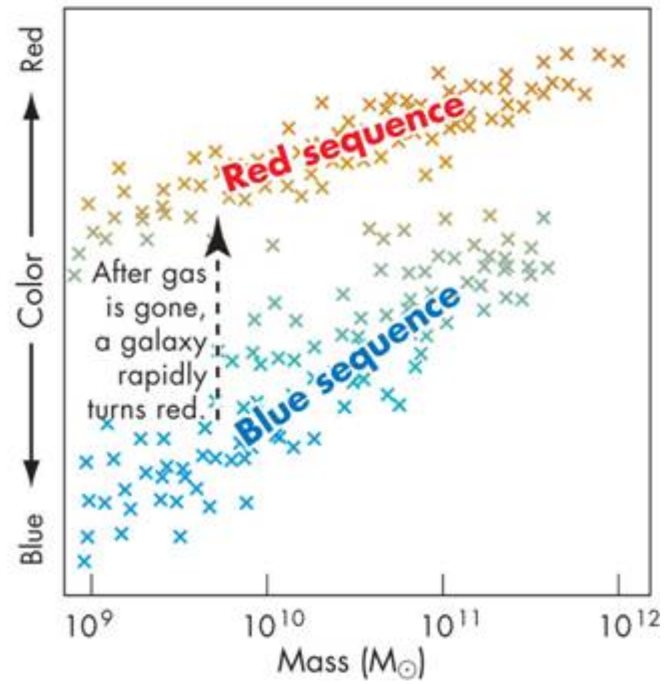
- Evidence for galaxy type change via collisions/ mergers over time
  - On a large scale, small galaxies may be captured and absorbed by a large galaxy in a process called ***galactic cannibalism***
    - Explains abnormally large ellipticals in center of some galaxy clusters
    - Milky Way appears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

Galactic Collisions and Mergers

- Evidence for galaxy change type 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”

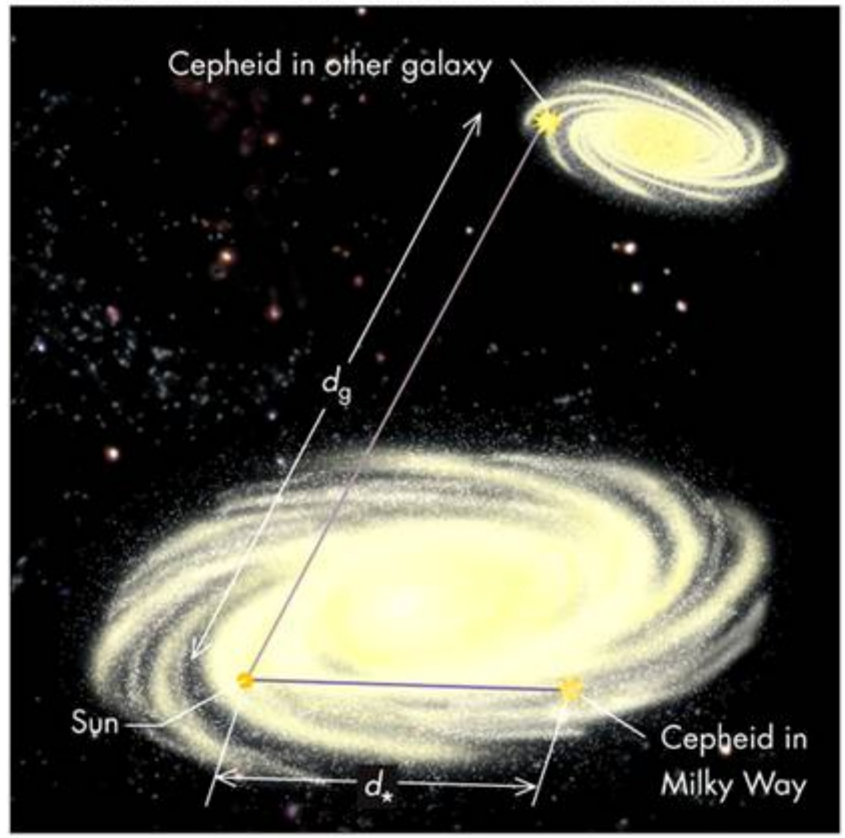
Galactic Evolution


The first galaxies were mostly small, gas-rich, and blue from star-formation.
Galaxies merge and some use up or lose their gas, so star-formation ceases.
Today we have more large and gas-poor galaxies, but some small ones remain.



Galaxy Distances

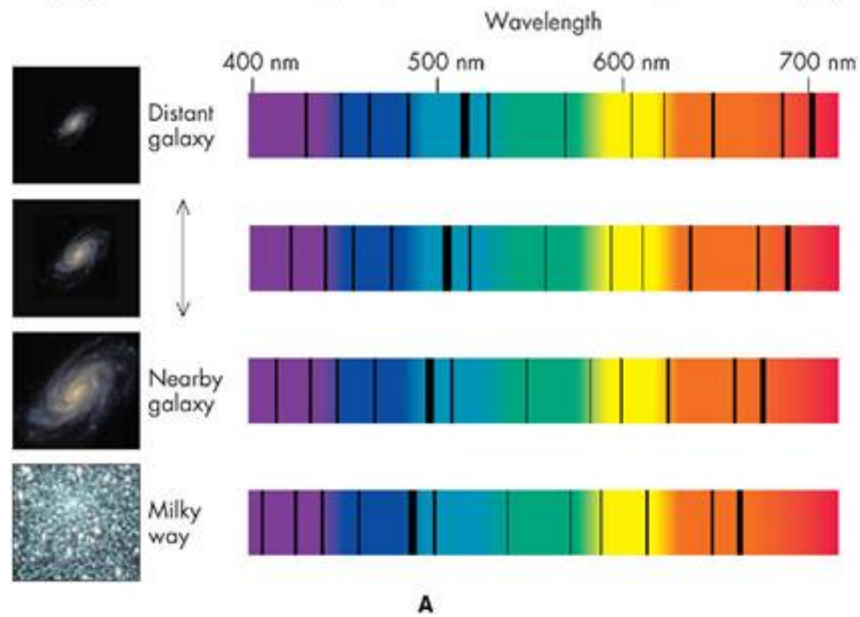
- Galaxy distances are too far to employ the parallax technique
- The method of "standard candles" is used
- The standard candles are usually Cepheid variables, supergiant stars, planetary nebulas, supernovas, etc.



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

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

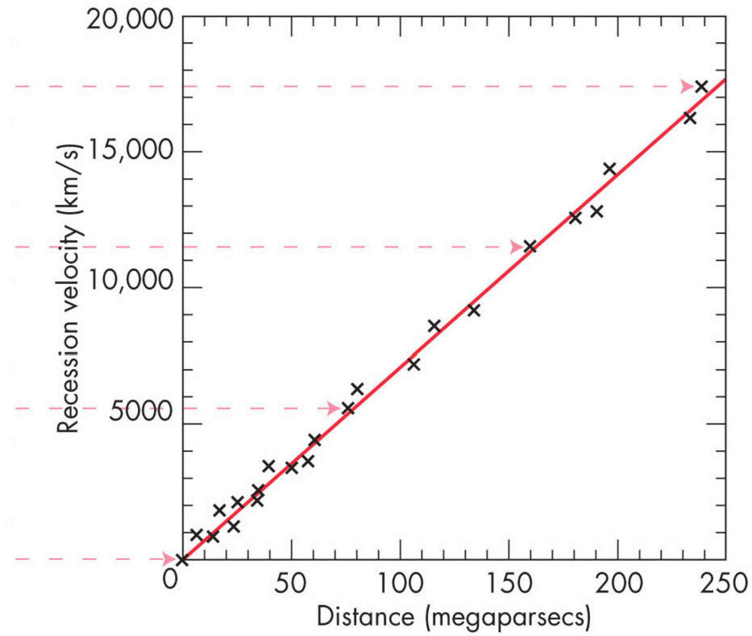


The Hubble Law

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

$$V = H \times D$$

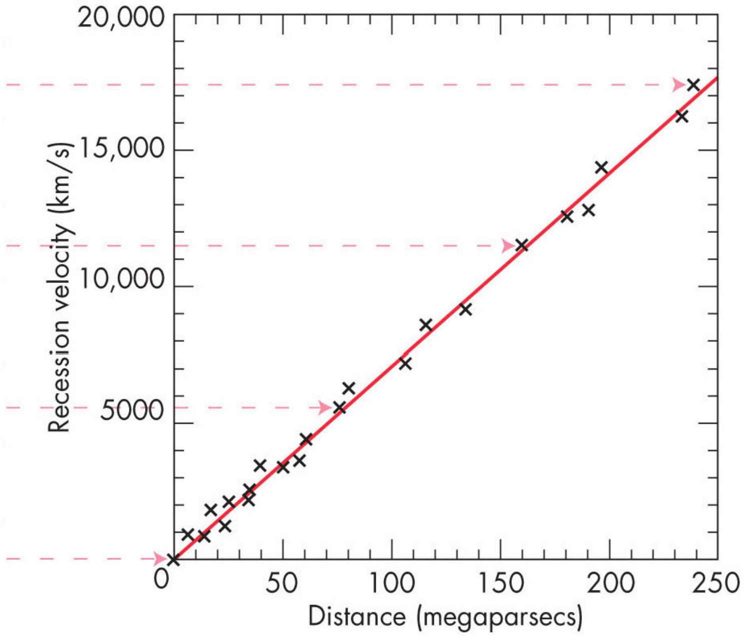
- Today, this expression is called the ***Hubble law*** and H is called the ***Hubble constant***



B

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



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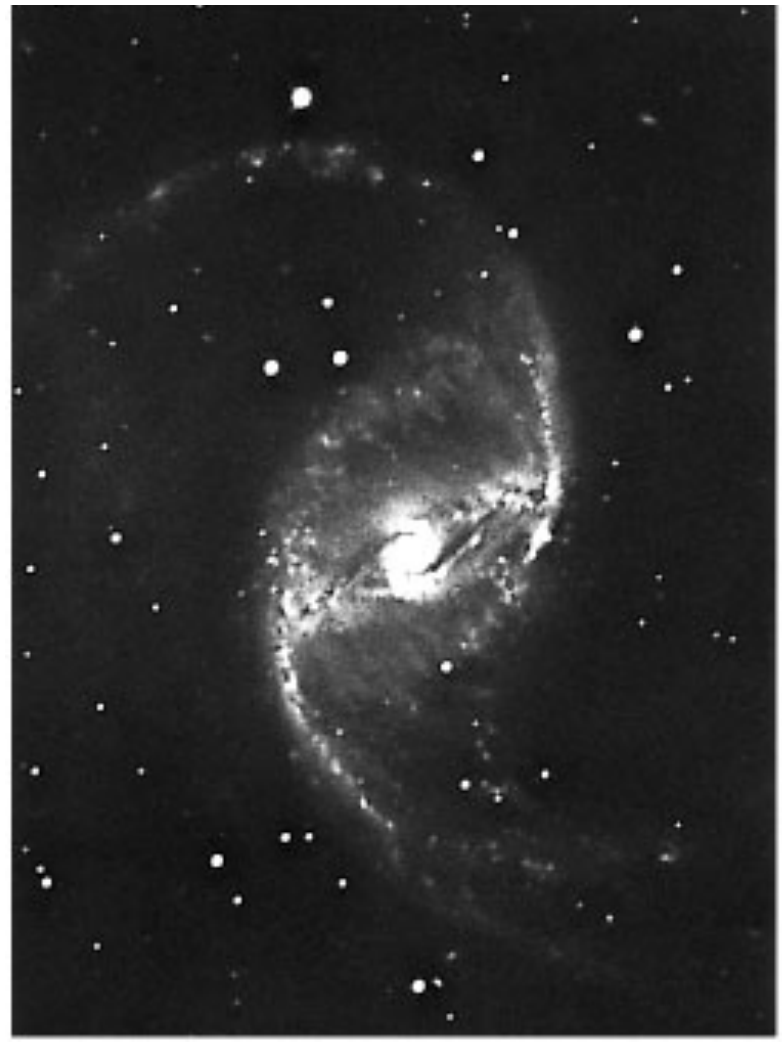
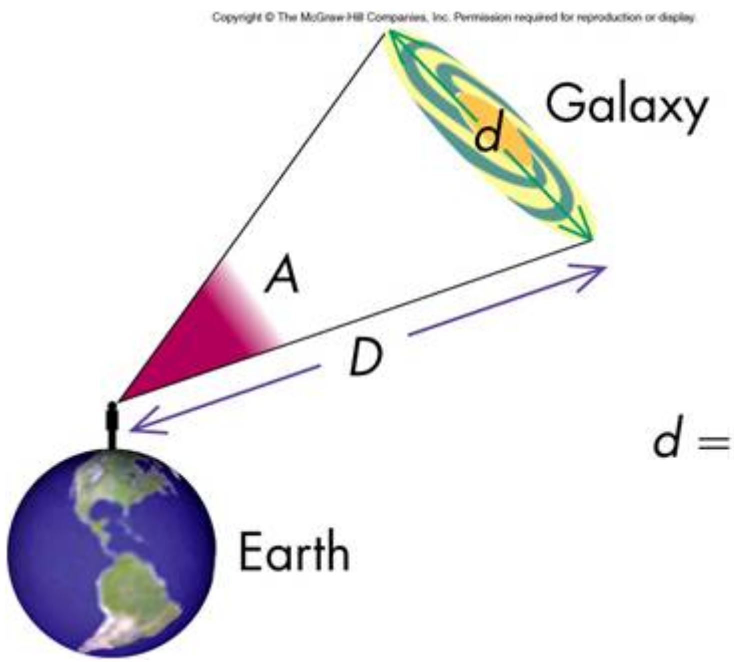
Galaxy Distances

- 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



$$d = \frac{2\pi AD}{360°}$$

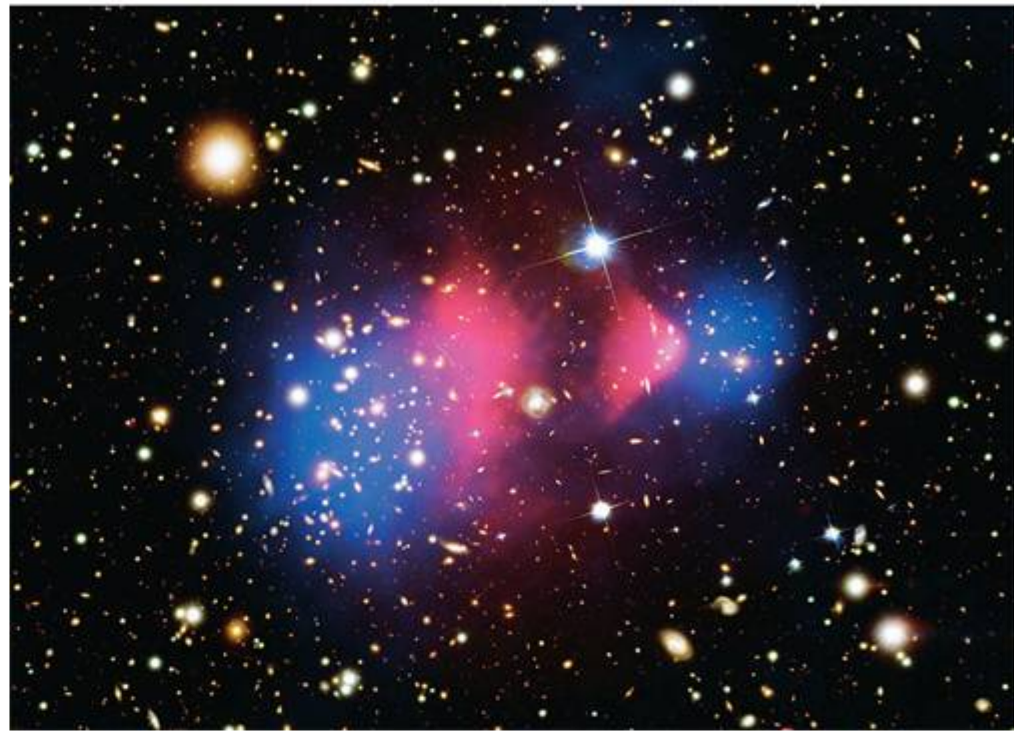
- Astronomers measure a galaxy's diameter (*d*) using a standard geometric formula
- where *A* is the angular size of the galaxy on the sky (in degrees) and *D* is the distance to the galaxy
- To use the equation, *A* must be measured and *D* must be determined by a standard candle technique or from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

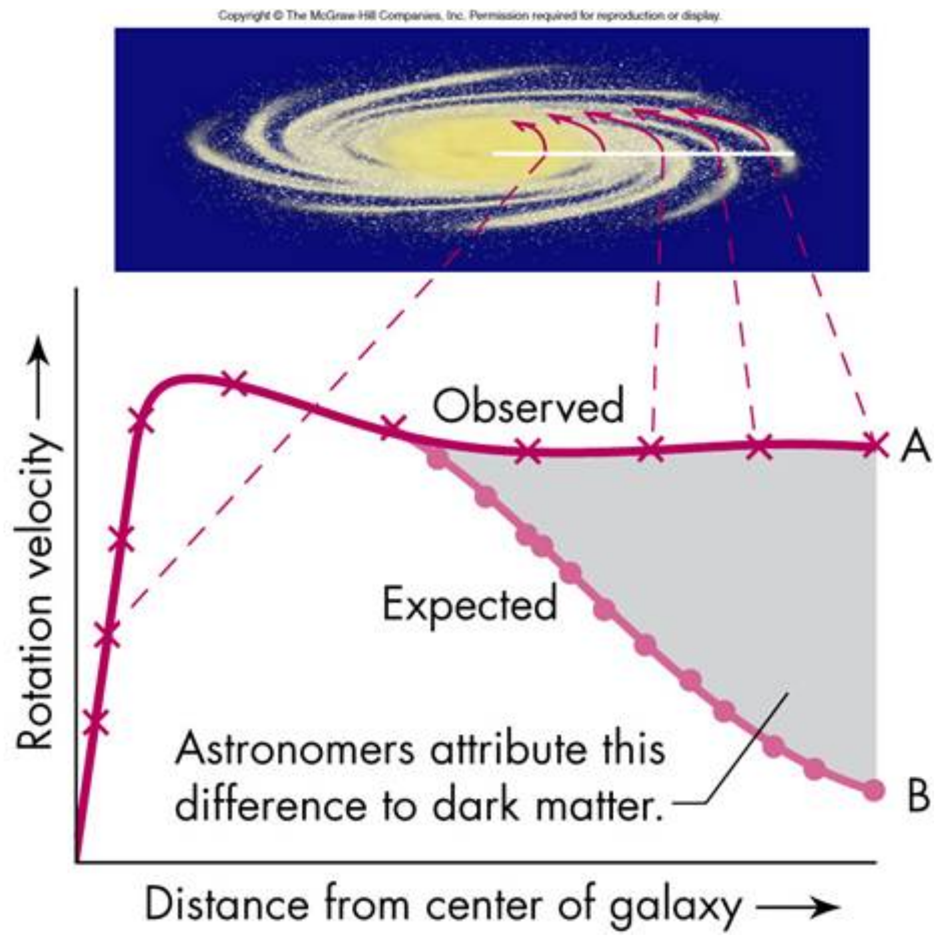
Dark Matter

- ***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

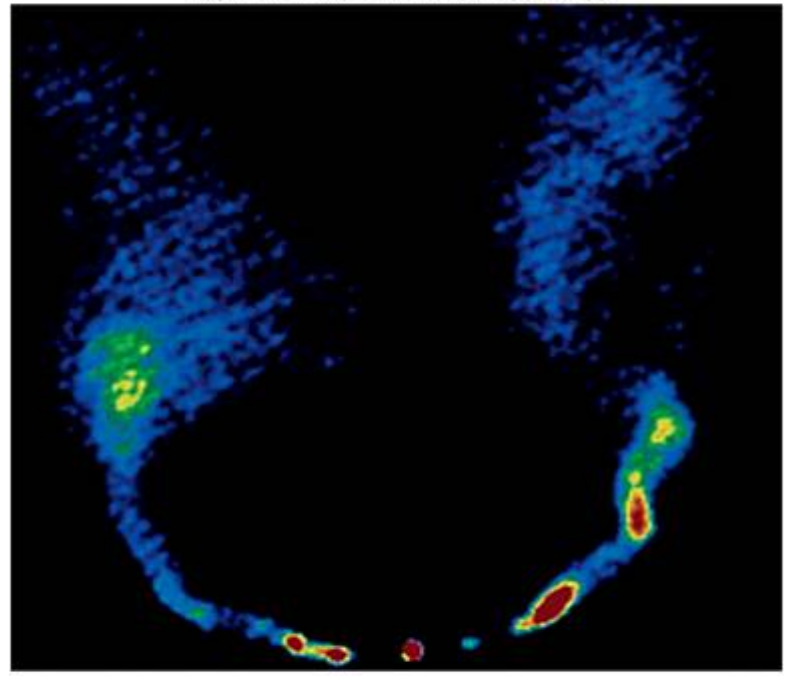
- Dark matter cannot be:
  - Ordinary dim stars because they would show up in infrared images
  - Cold gas because this gas would be detectable at radio wavelengths
  - Hot gas would be detectable in the optical, radio, and x-ray regions of the spectrum
- Objects that cannot be ruled out:
  - Tiny planetesimal-sized 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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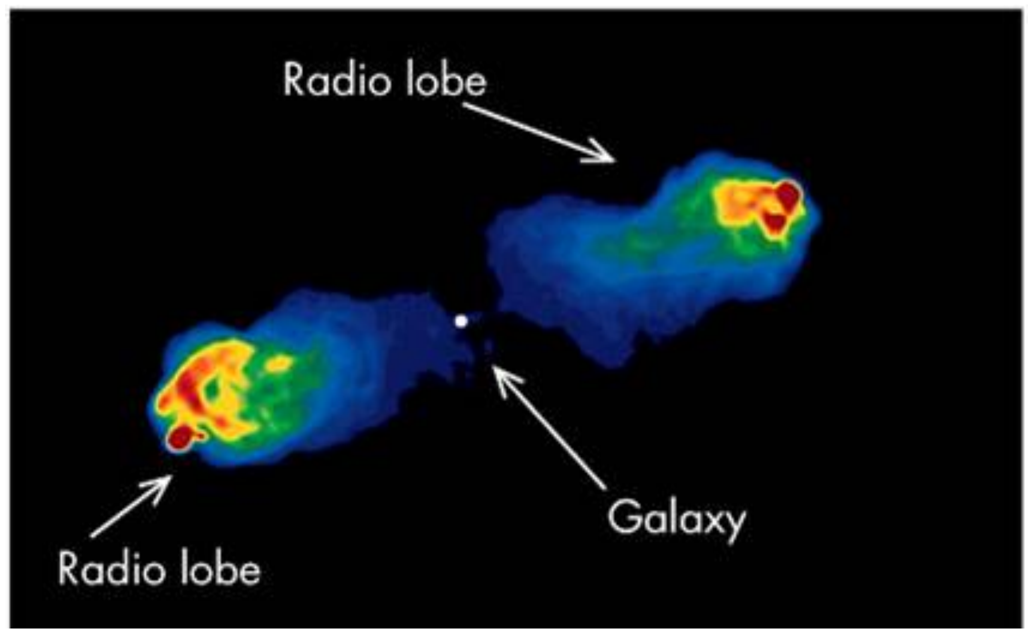
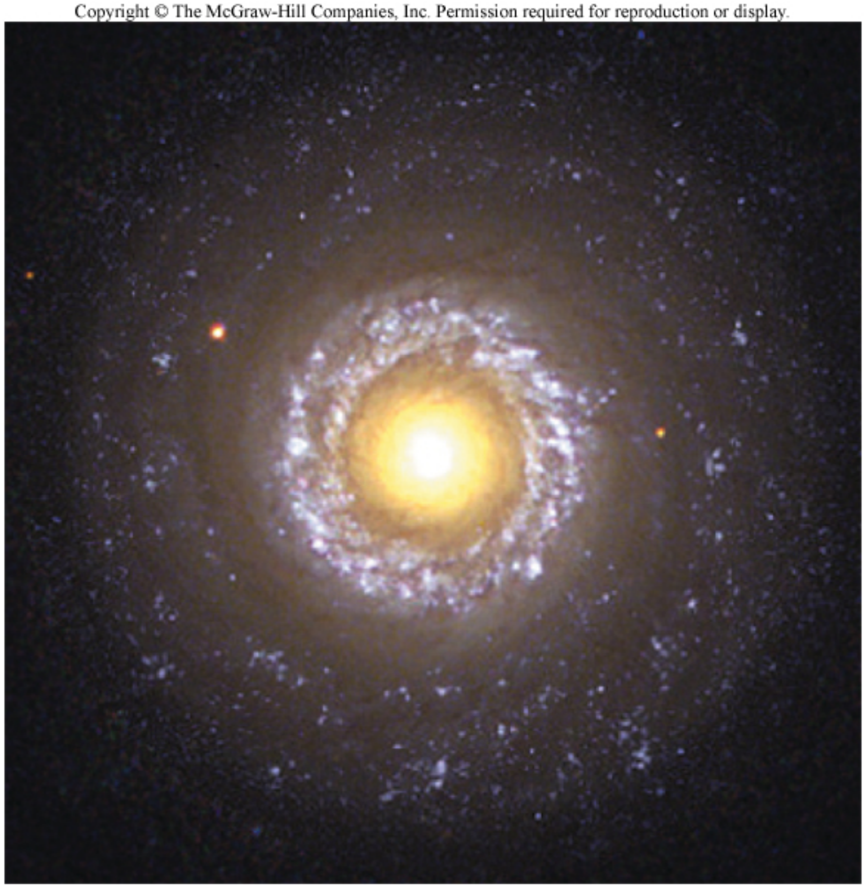
Lobes can be swept into arcs or plumes as they interact with intergalactic matter

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

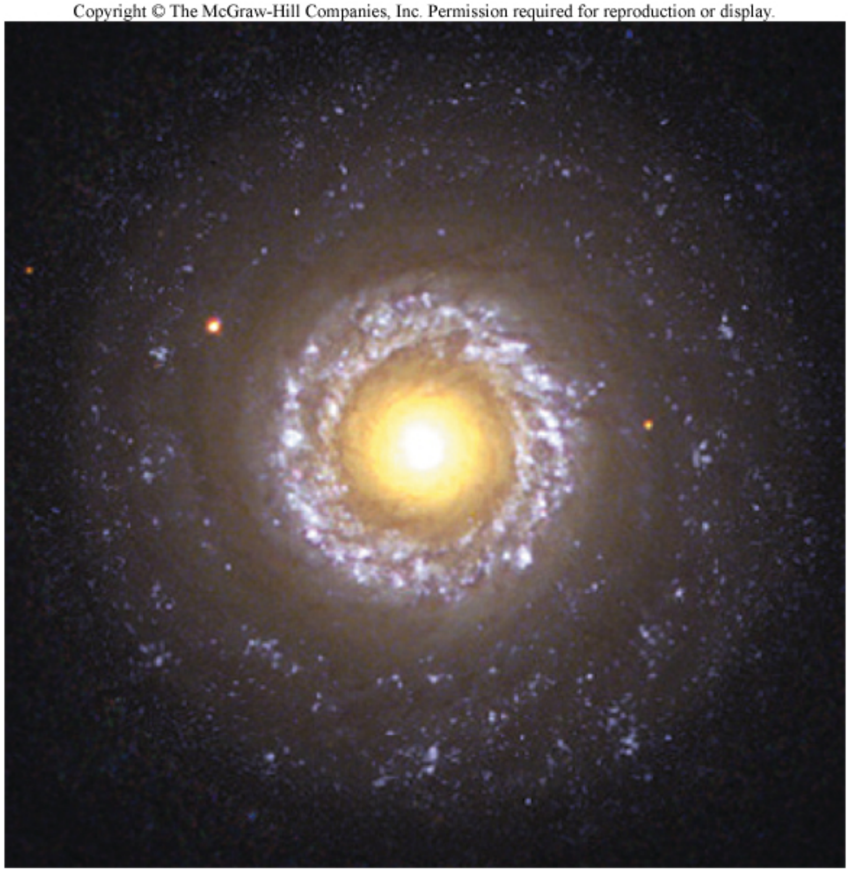


Seyfert Galaxies



- 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

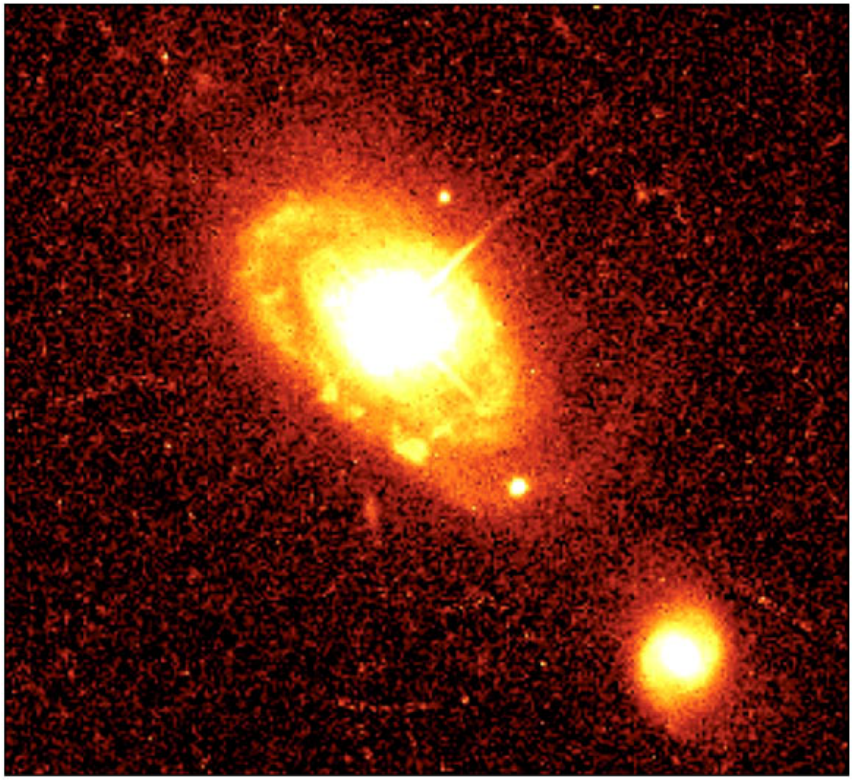
Seyfert Galaxies



- 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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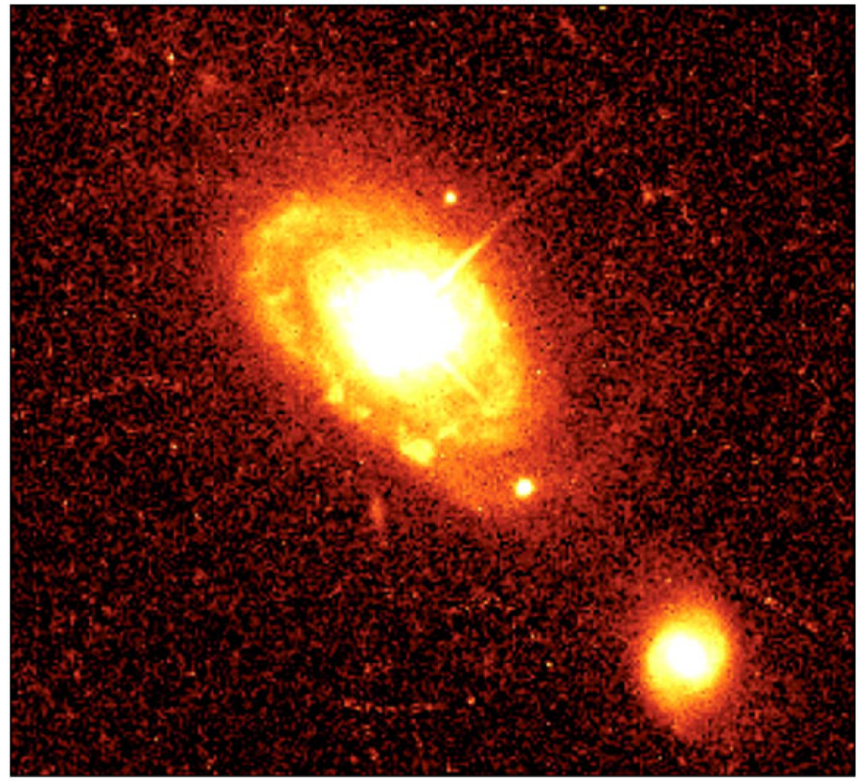
Quasars

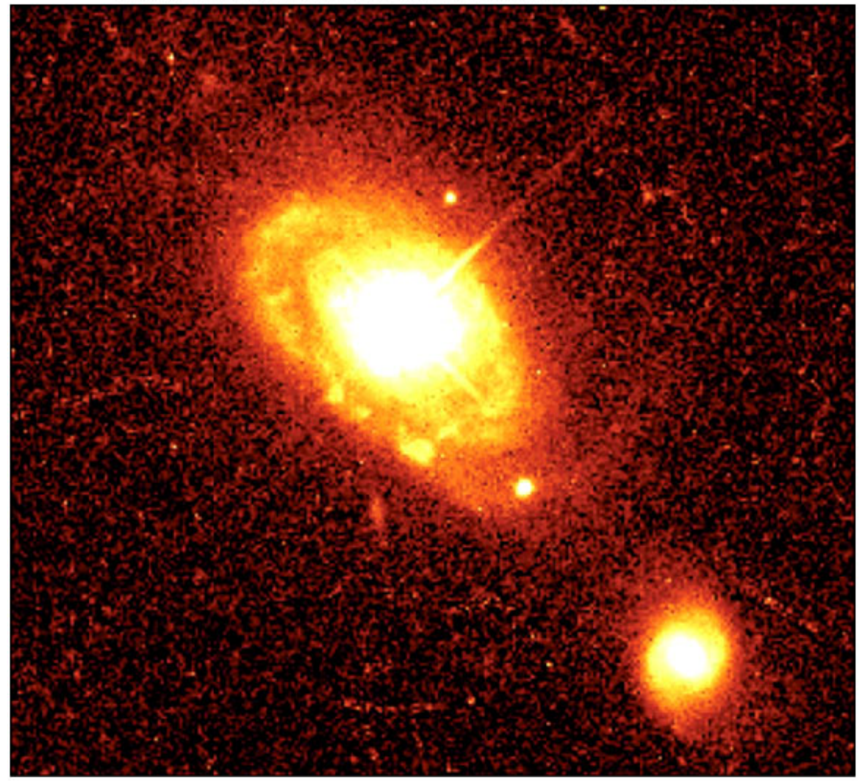
- Some similar to radio galaxies in emissions
- Others similar to radio and Seyfert galaxies in that they eject hot gas from their centers
- Superluminal motion in jets indicate extreme high-speed motions



A

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)

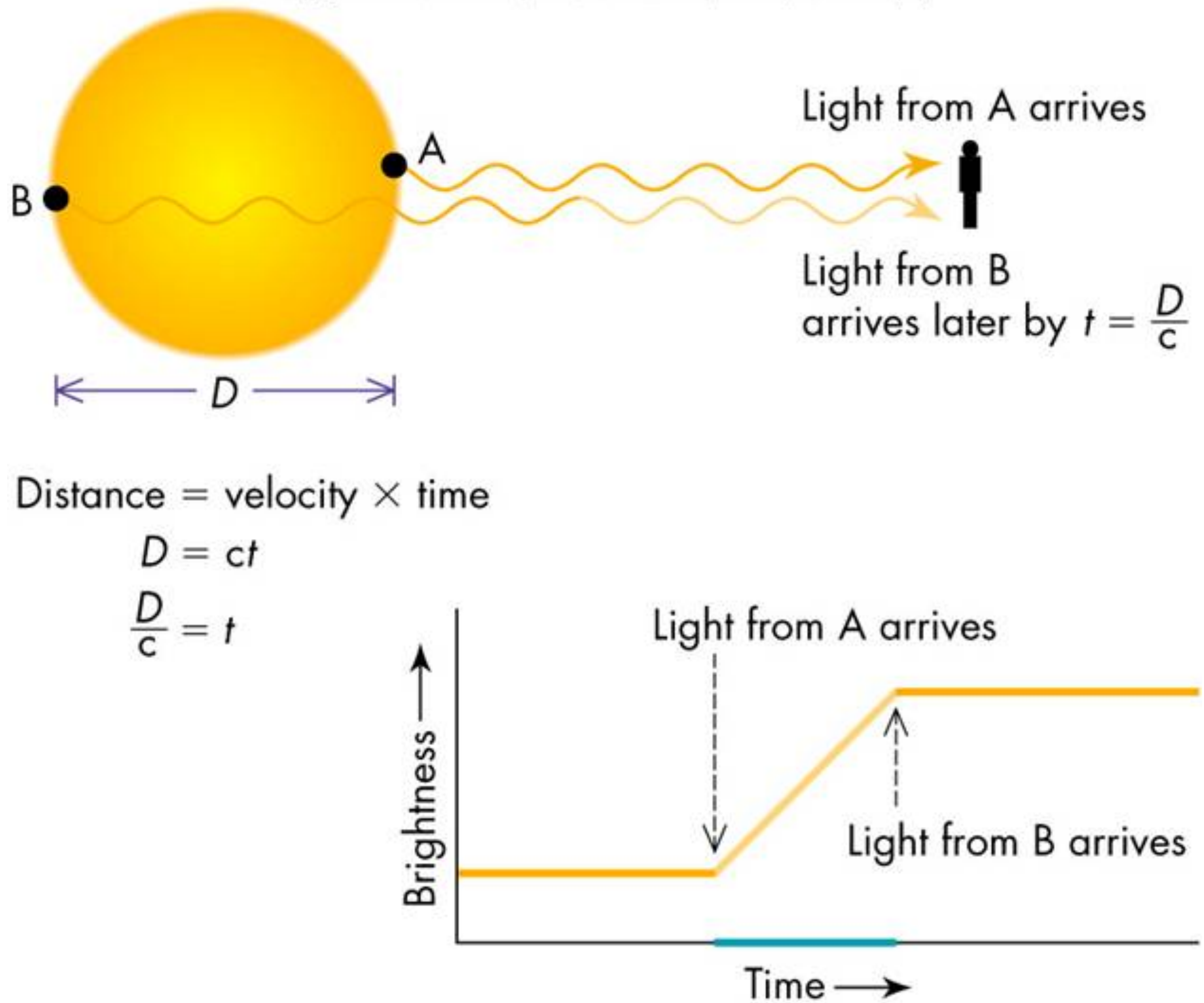


A

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

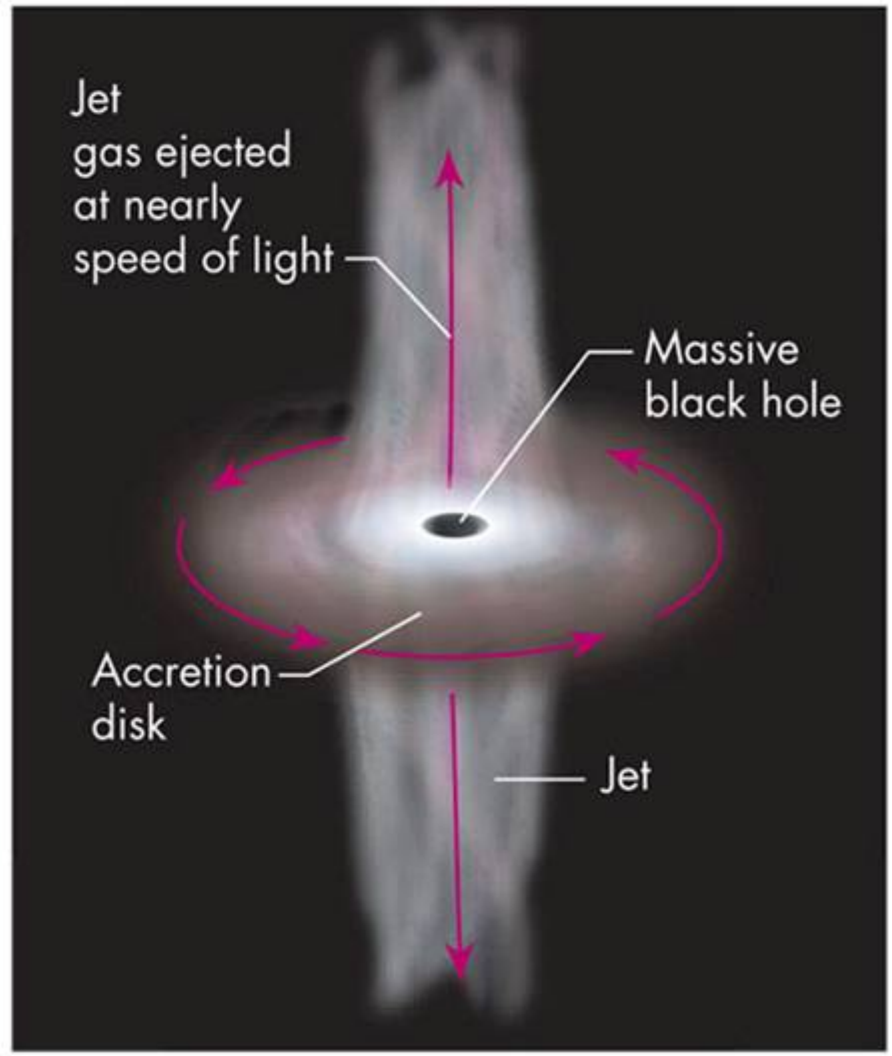


Cause of Activity in Galaxies

- 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

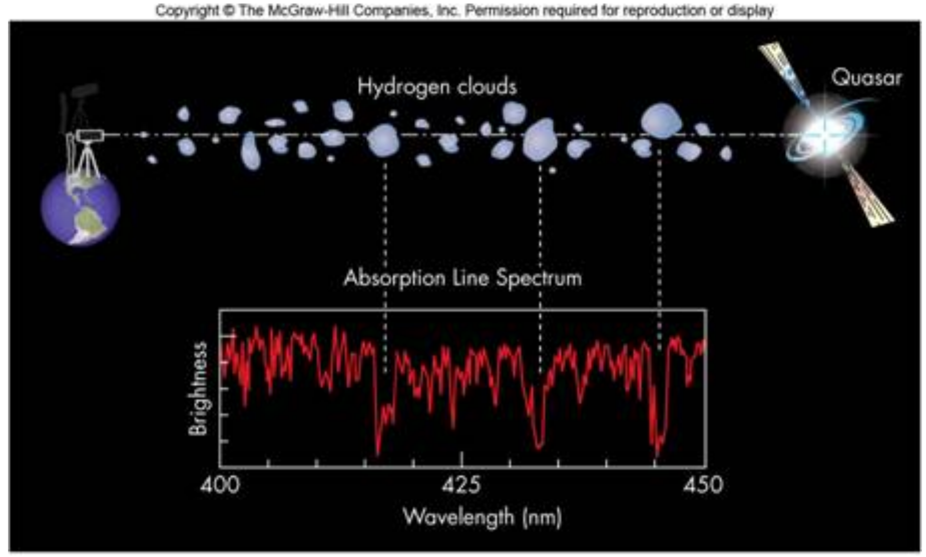
- Creation of massive black hole
  - Massive star in densely populated core of galaxy explodes forming a small black hole of ~5 $M_{\odot}$
  - Black hole grows from accretion of interstellar matter
  - Radius of black hole increases making capture of more material easier
  - Eventually black hole becomes 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

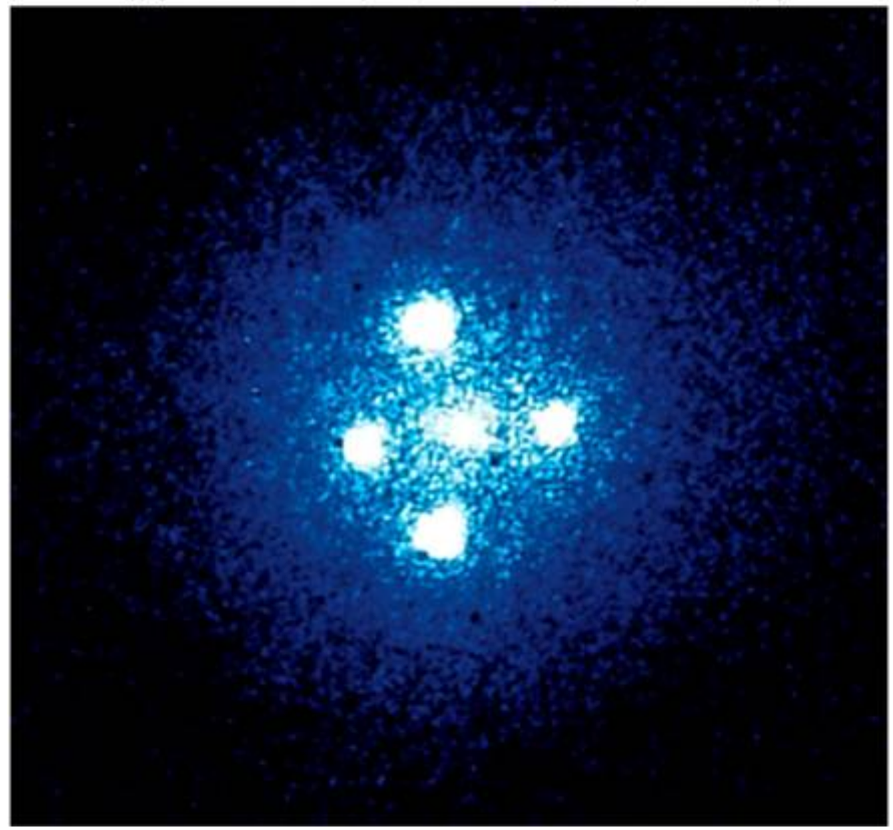
Quasars as Probes of Intergalactic Space

- 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***

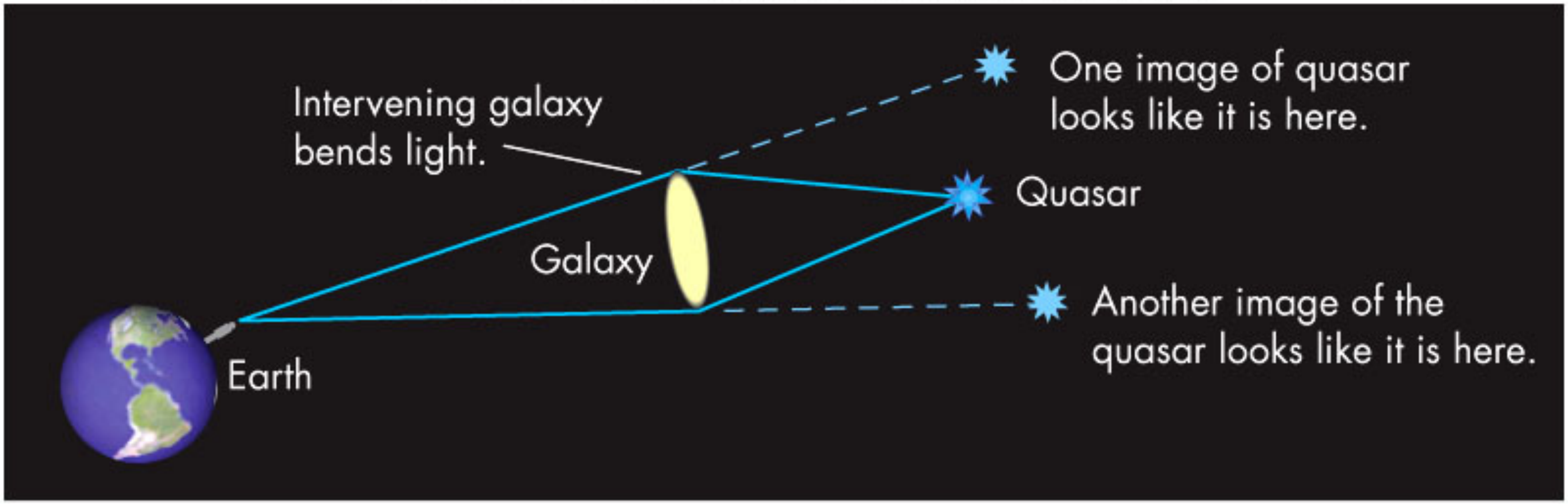


Gravitational Lenses

- 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



B

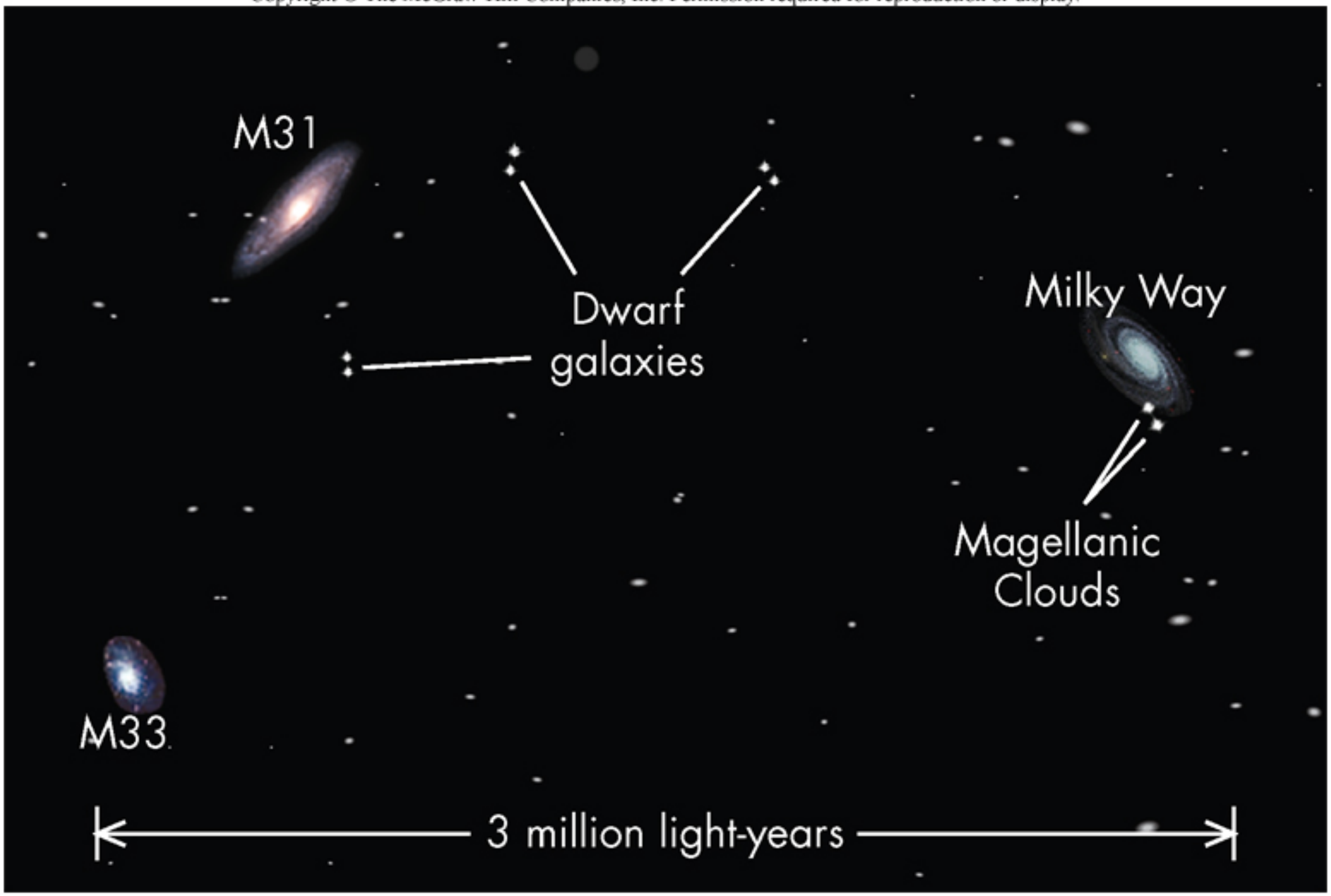
Galaxy Clusters

- 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

The Local Group



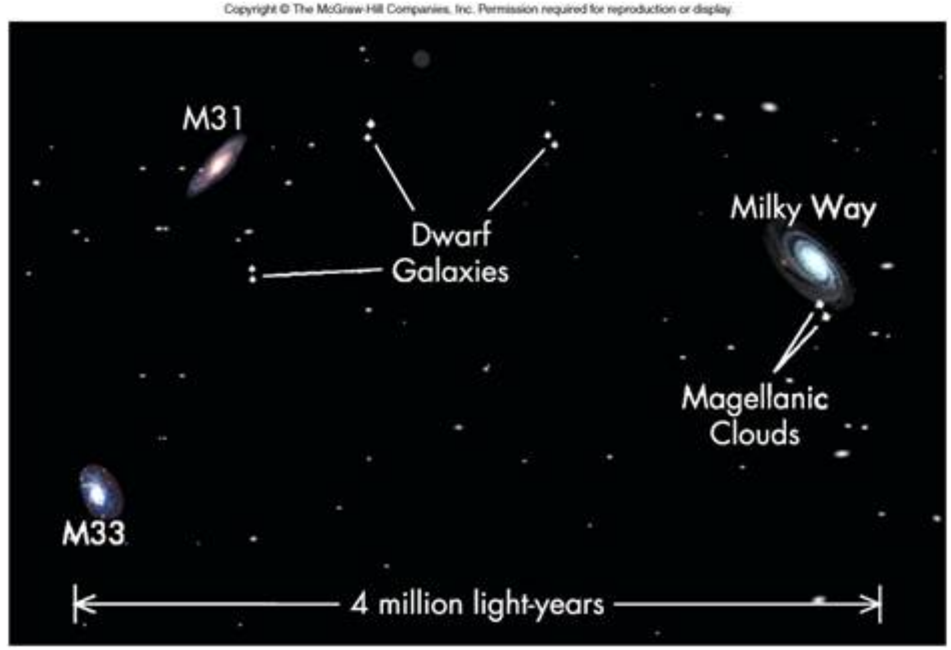
Rich Clusters

- 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



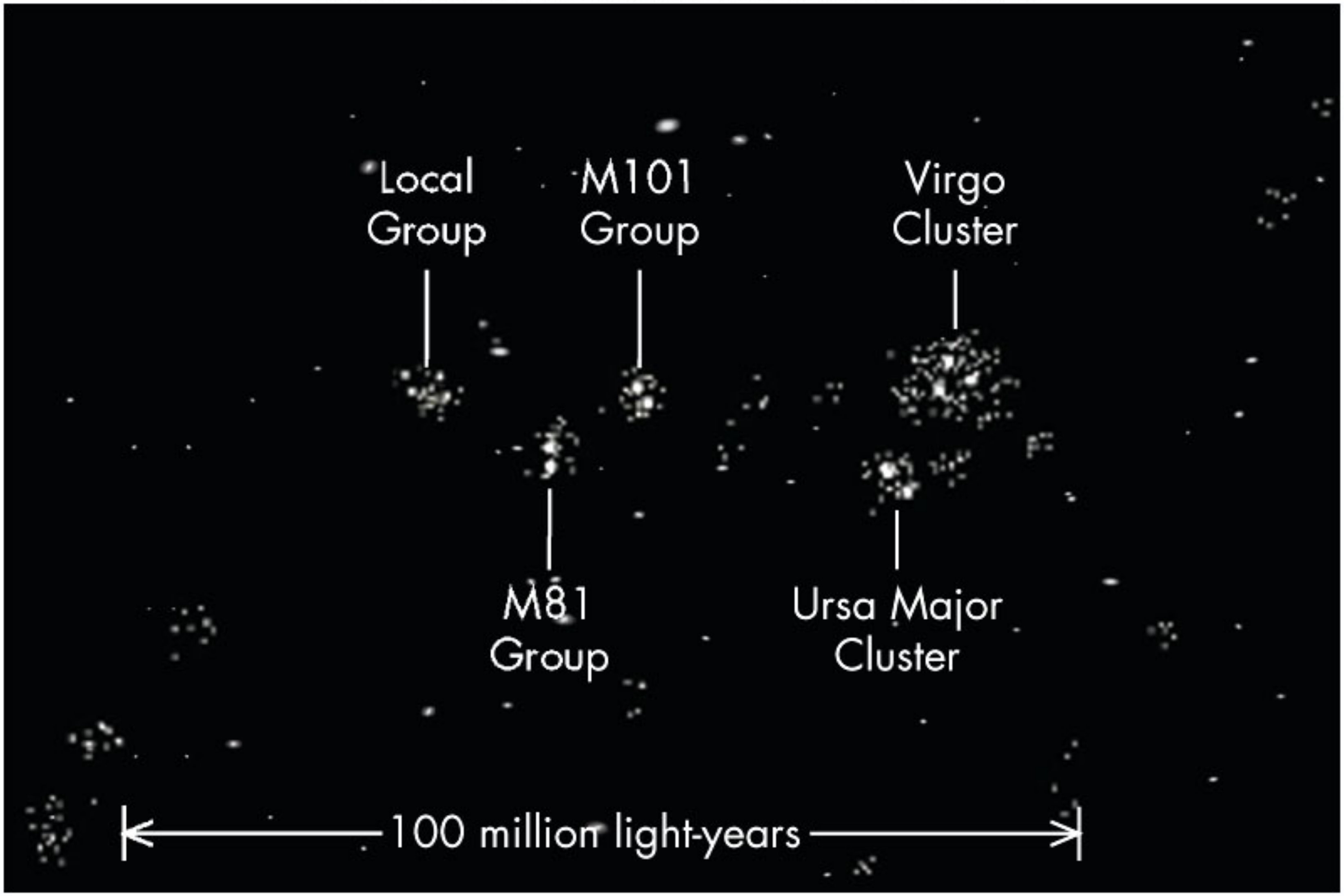
Galaxy Clusters

- 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

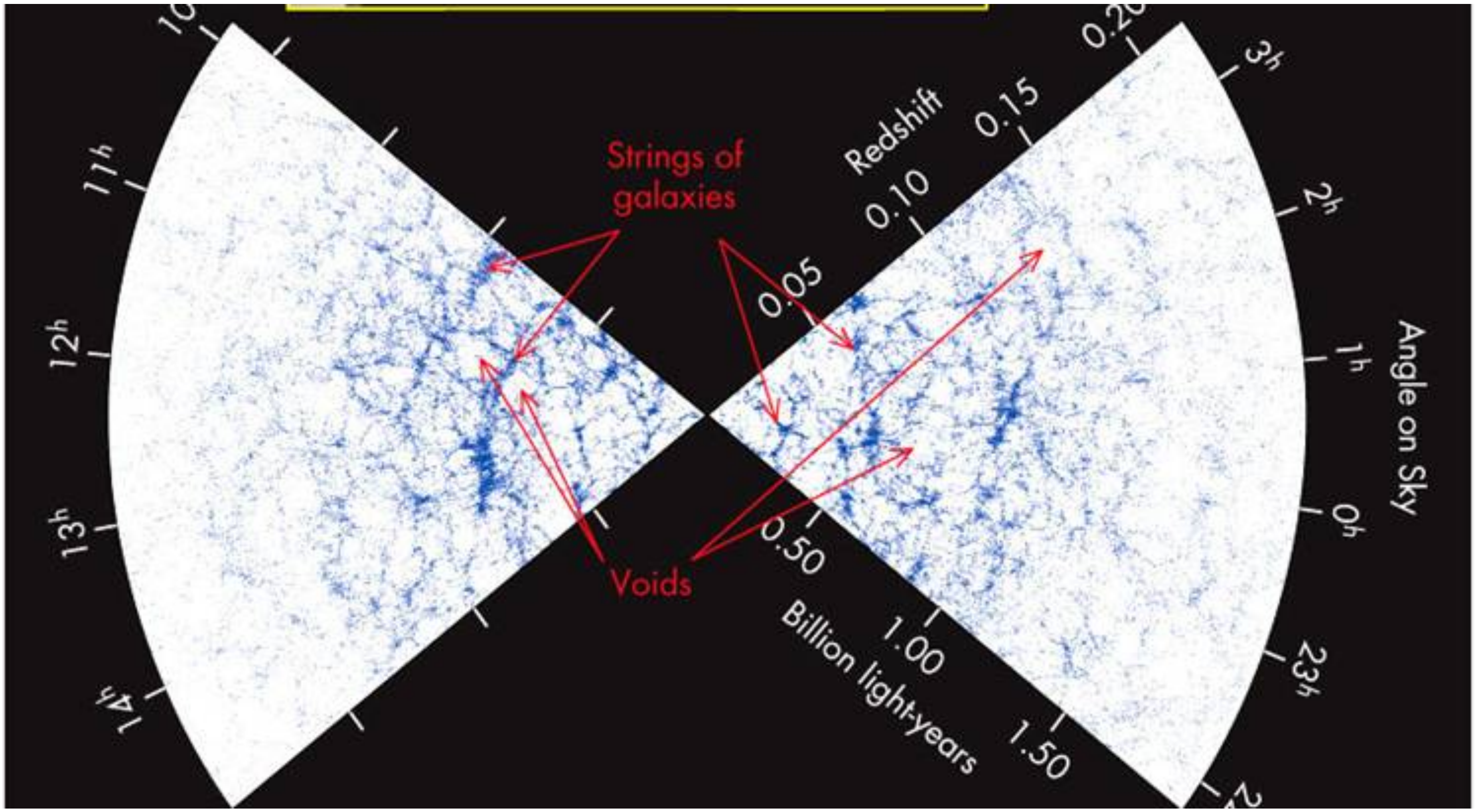
Superclusters

- 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



The Structure of the Universe



- Superclusters appear to form chains and shells surrounding regions nearly empty of galaxies – voids
- Clusters of superclusters and voids mark the end of the Universe's structure we currently see