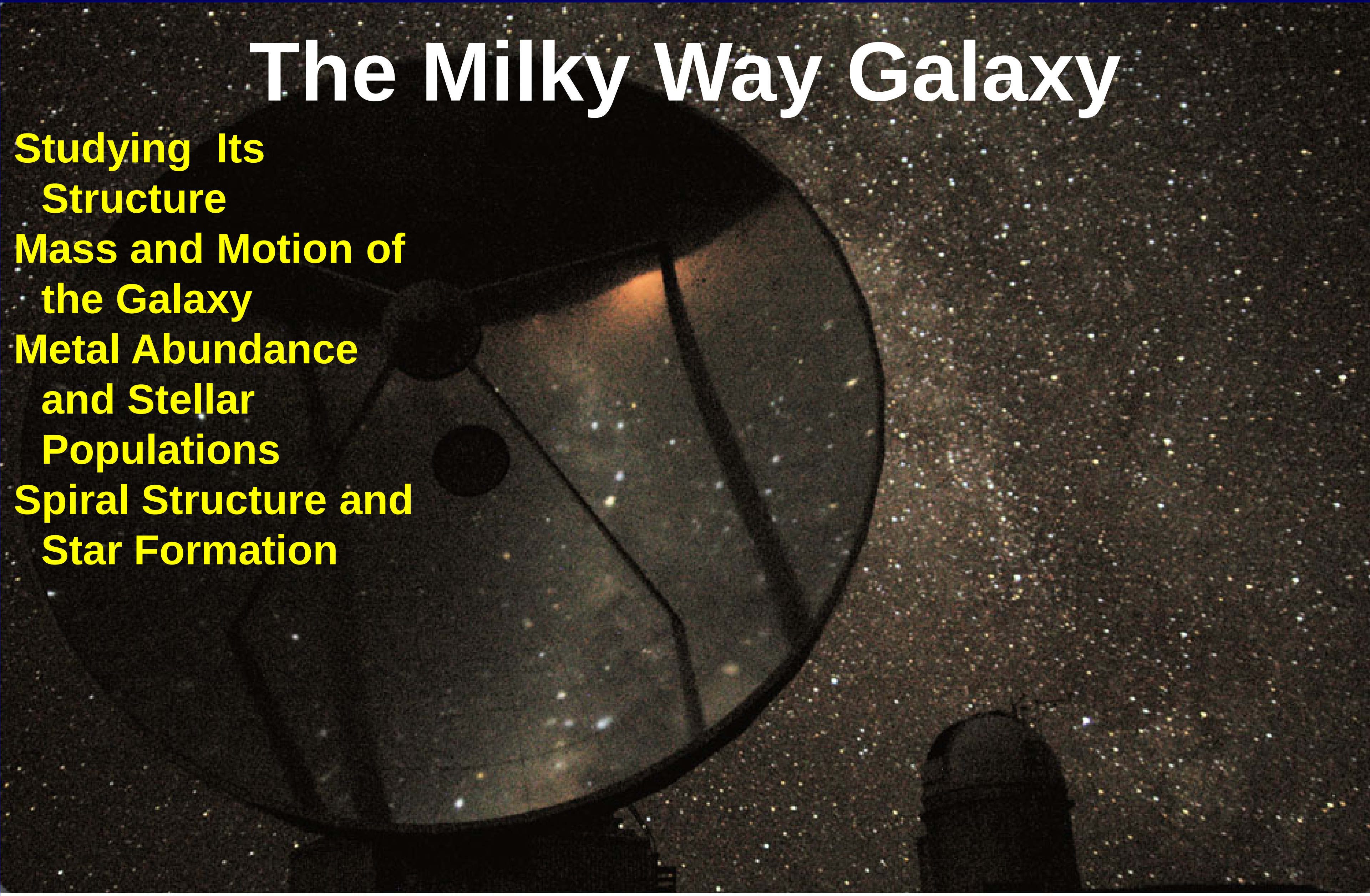
The Milky Way Galaxy

Studying Its Structure

Mass and Motion of the Galaxy

Metal Abundance and Stellar Populations

Spiral Structure and Star Formation



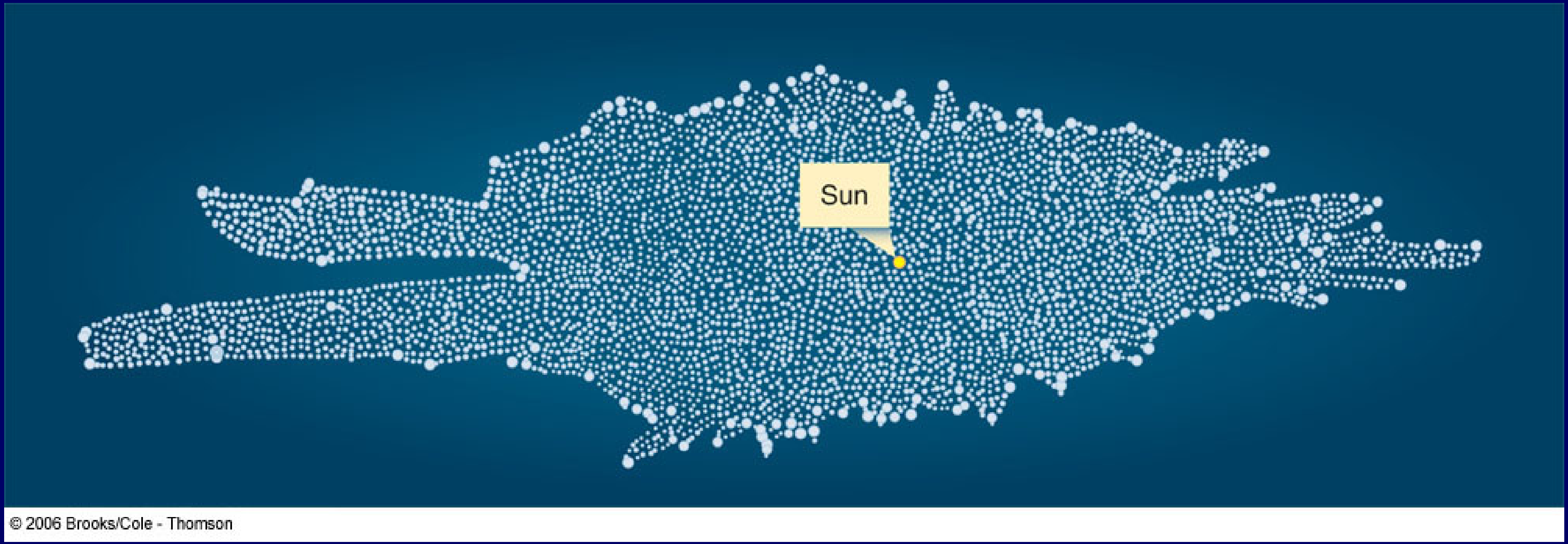
The Milky Way

Almost everything we see in the night sky belongs to the Milky Way Galaxy.

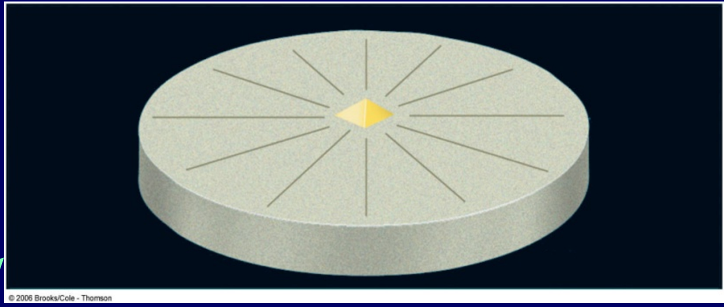
We see most of the Milky Way as a faint band of light across the sky.

From outside, our Milky Way Galaxy probably looks very much like our cosmic neighbor, the Andromeda Galaxy.

First Studies of the Galaxy

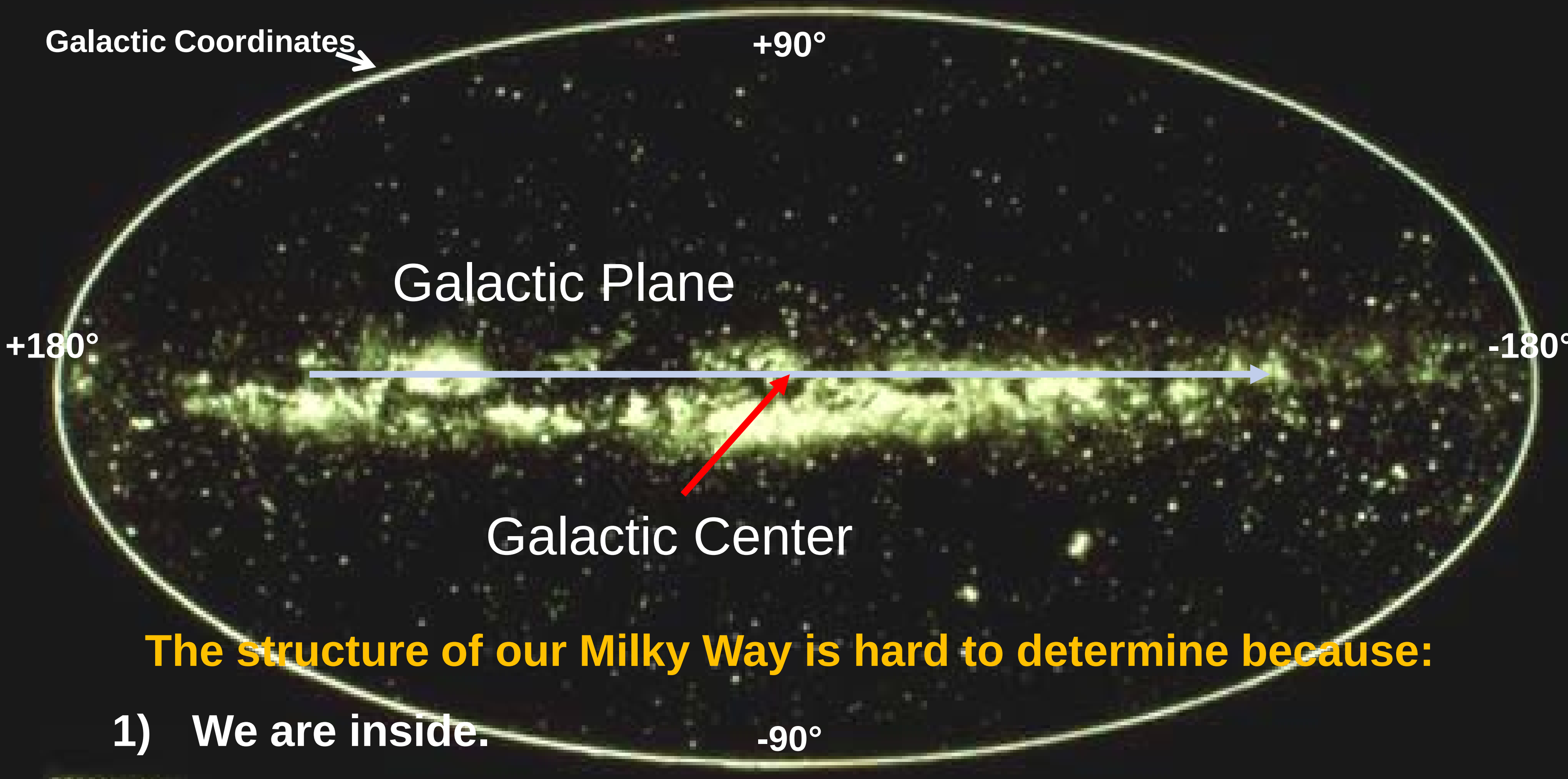


- The first attempt to unveil the structure of the galaxy by William Herschel (1785) was based on optical observations.



- He believed the shape of the Milky Way to resemble a grindstone, with the Sun close to the center
- Unfortunately, he was not aware that most of the Galaxy, particularly the center, is blocked from view by vast clouds of gas and dust.

Determining the Structure of the Milky Way



The structure of our Milky Way is hard to determine because:

1) We are inside.
2) Distance measurements are difficult.
3) Our view towards the center and the far side of the galaxy is obscured by gas and dust.

Strategies to Explore the Structure of the Milky Way

1. Select bright objects that you can see throughout the Milky Way and trace their directions and distances.
2. Observe objects at radio and infrared wavelengths to circumvent the problem of optical obscuration, and catalog their directions and distances.
3. Trace the orbital velocities of objects in different directions relative to our position.

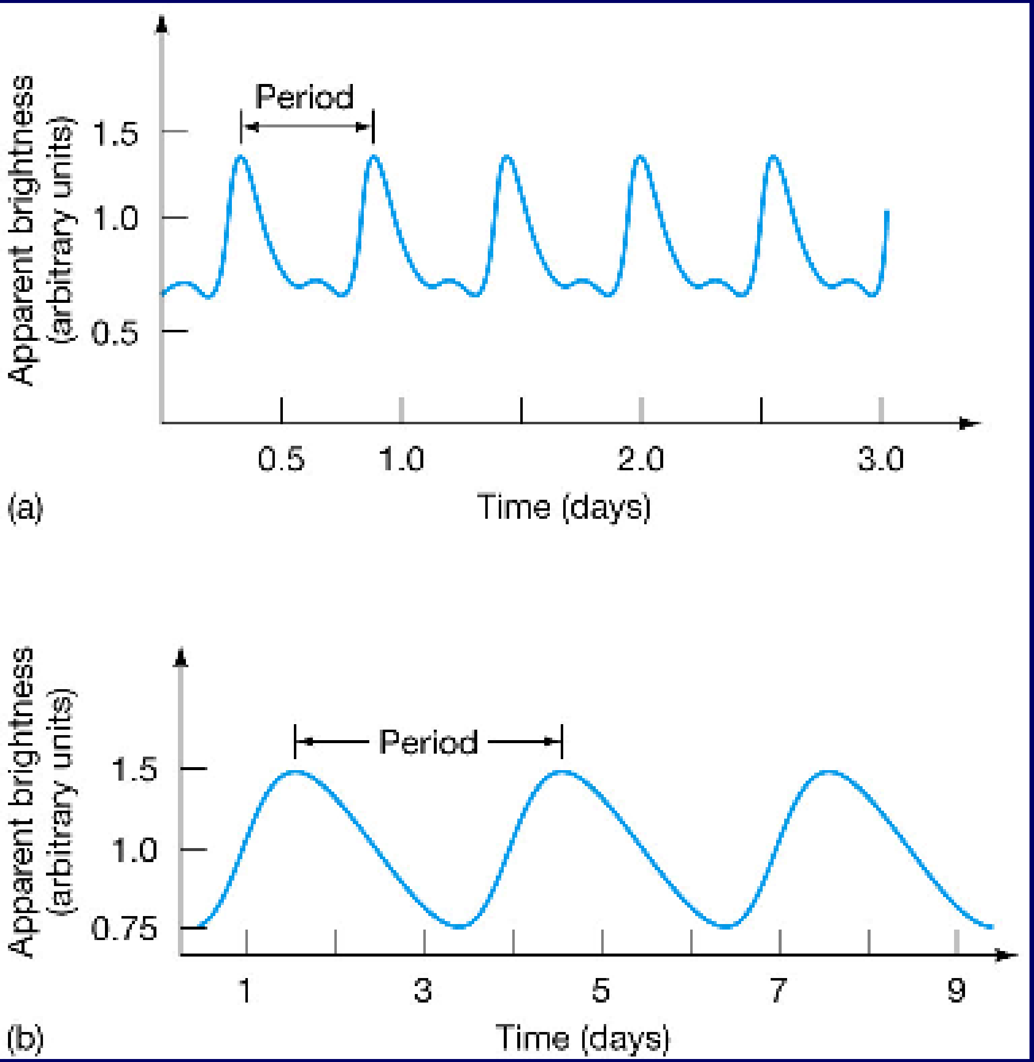
Measuring the Milky Way

- We have seen that measuring stellar parallaxes only measures the nearest stars. The spectroscopic parallax method enables us to measure far across our galaxy, but not far enough.
- However, there are bright, variable stars whose luminosity varies in a regular way depending on their size. These are called intrinsic variables.
- Three kinds of intrinsic variables have been found: RR Lyrae stars, and two types of Cepheid variables (classical and W Virginis).

Intrinsic Variables

The upper plot is an RR Lyrae star. All such stars have essentially the same luminosity curve, with periods from 0.5 to 1 day.

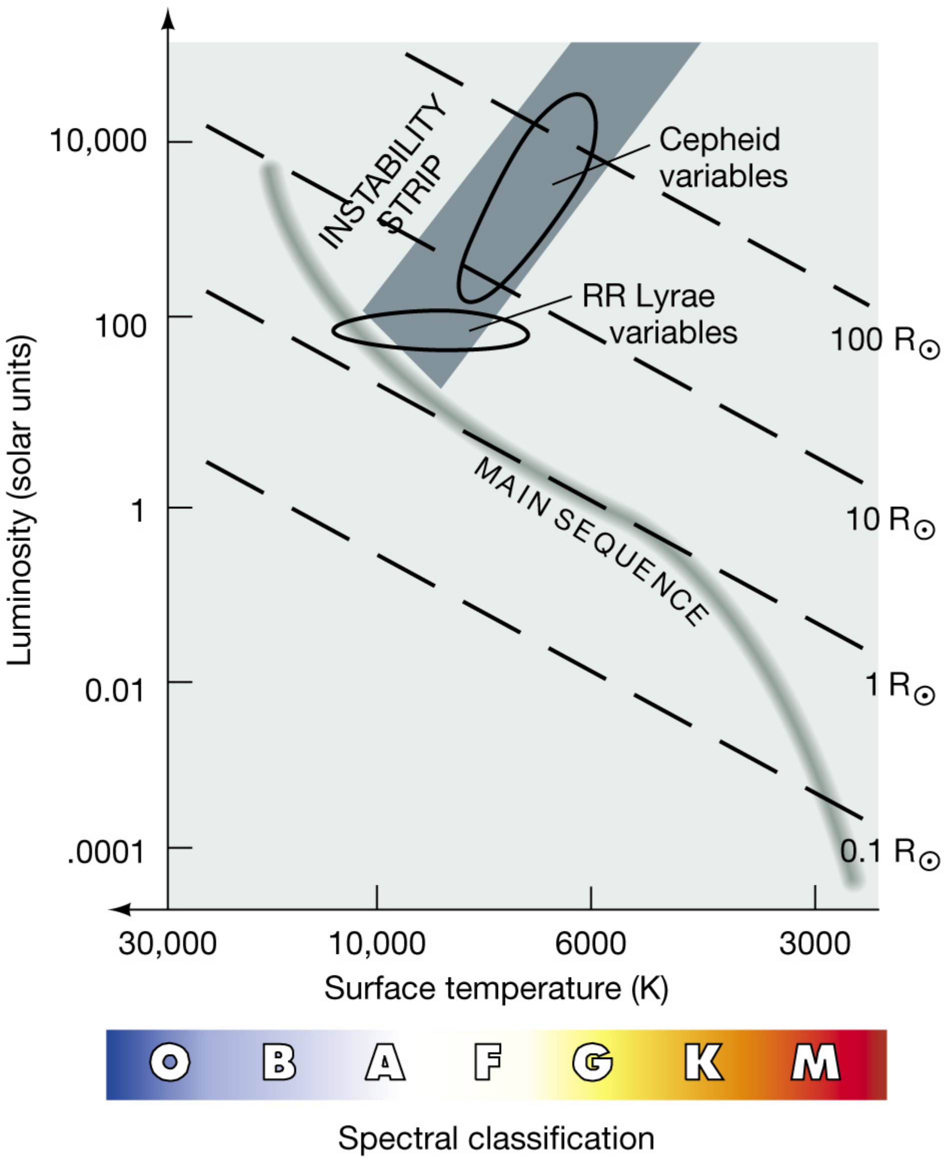
The lower plot is a classical Cepheid variable; Cepheid periods range from about 1 to 100 days.



Intrinsic Variables

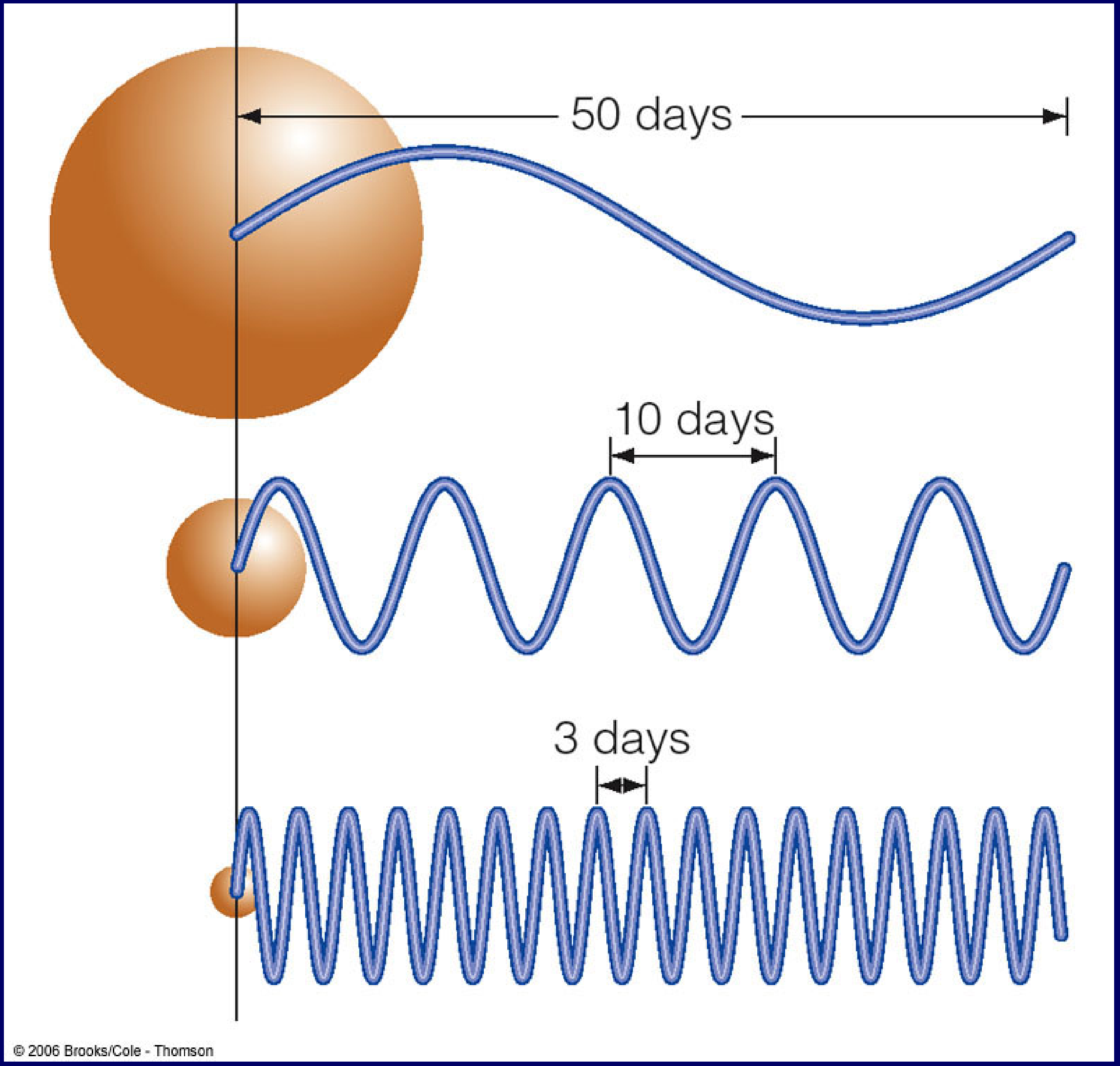
The variability of these stars comes from a dynamic balance between gravity and pressure. Their radii oscillate and therefore their luminosities oscillate:

$$L = 4\pi R^2 \sigma T^4.$$

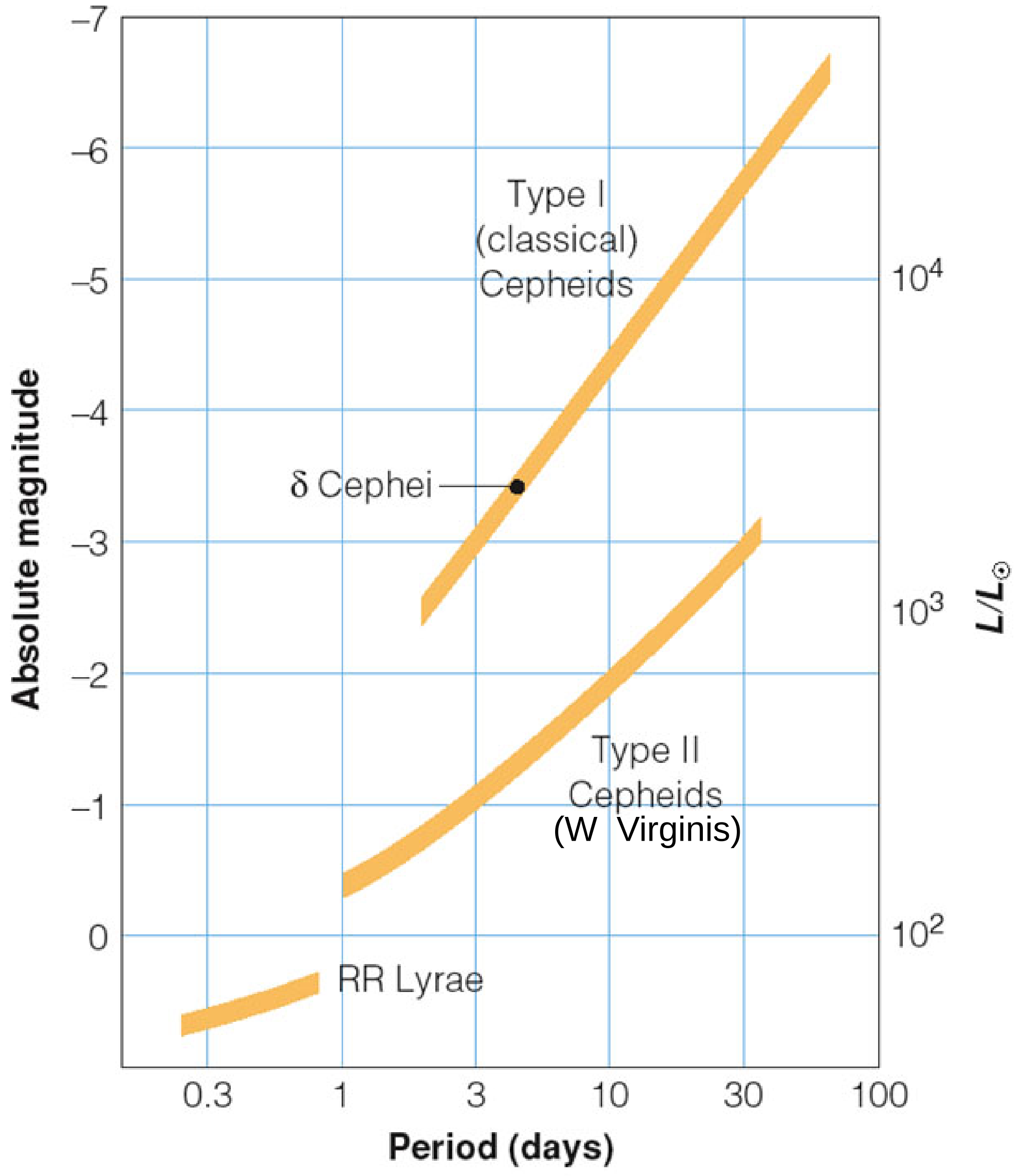


Intrinsic Variables

- **The period of oscillation depends on the mass of the star.**
- **We have already seen that the luminosity of a star is related to its mass so it follows that the oscillation period of intrinsic variables will also depend on mass.**



The Intrinsic Variable Method



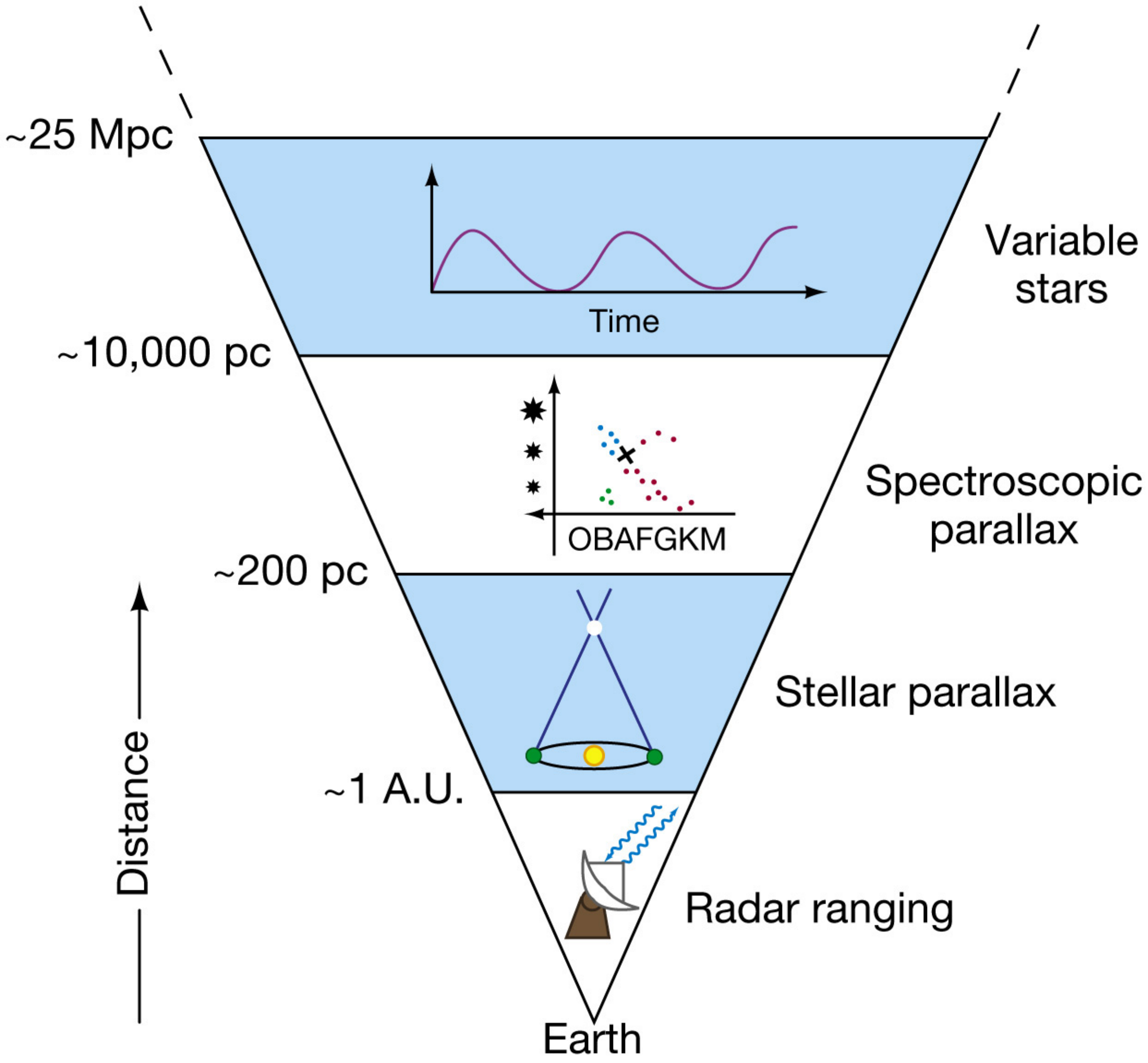
We measure the period of the variable star and look up the star's absolute magnitude M_v using these graphs. We must also measure the brightness m_v, then

$$d = 10^{(m_v - M_v + 5)/5} \text{ pc.}$$

This method allows us to measure distances to stars throughout the Milky Way.

Measuring the Milky Way

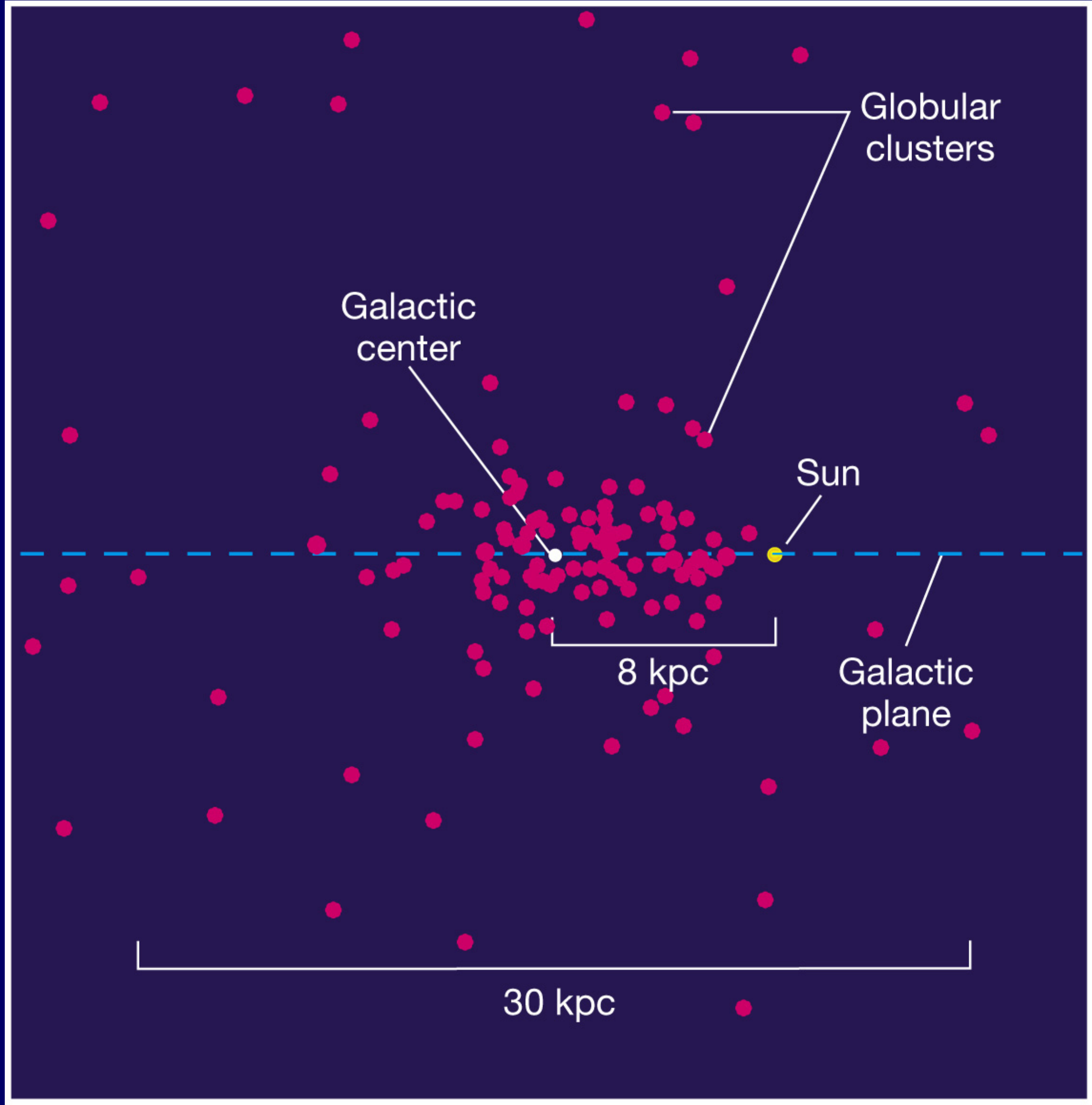
We have now **expanded** our cosmic distance ladder one more step.



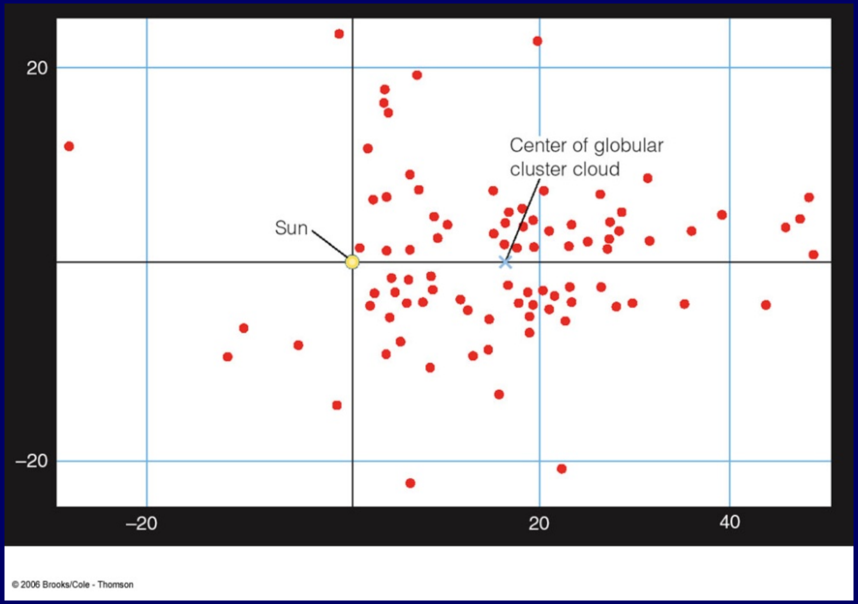
Measuring the Milky Way

Many RR Lyrae stars are found in globular clusters. These clusters are not all in the plane of the Galaxy, so they are not obscured by dust and can be seen and measured.

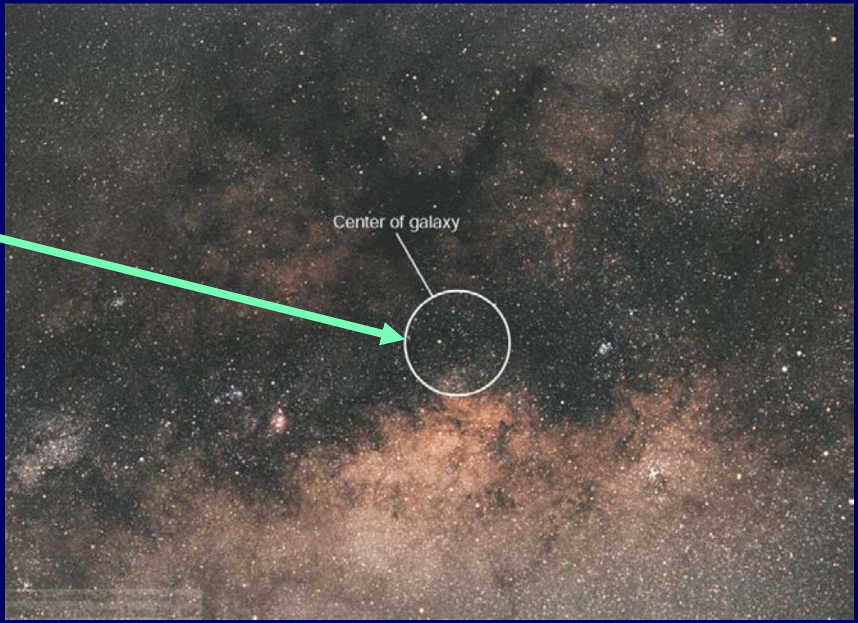
These measurements yield a much more accurate picture of the extent of our Galaxy and our place within it.



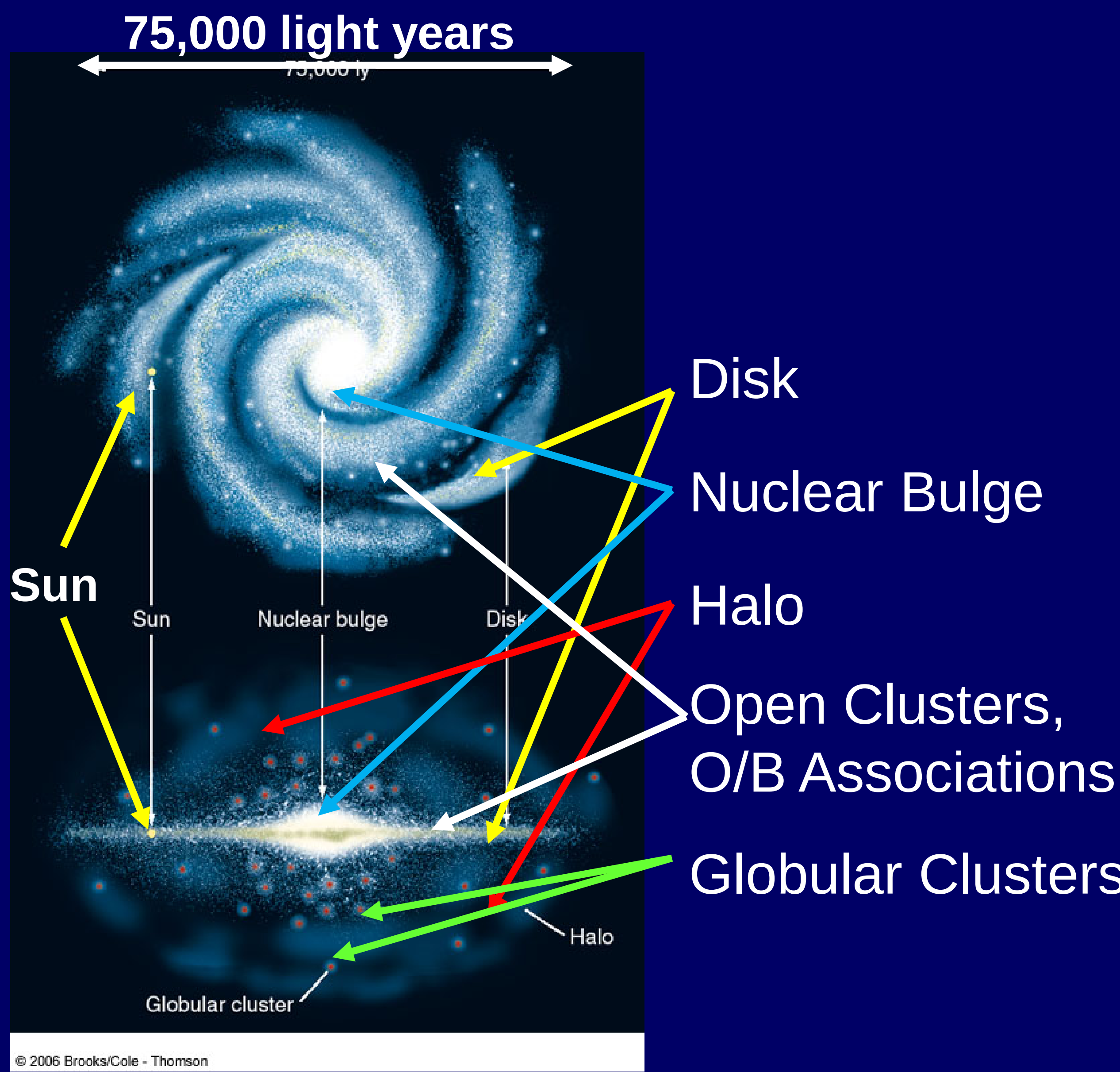
Locating the Center of the Milky Way



The distribution of globular clusters is not centered on the Sun, but on a location which is heavily obscured from direct (visual) observation. The center of the distribution is the center of the galaxy.



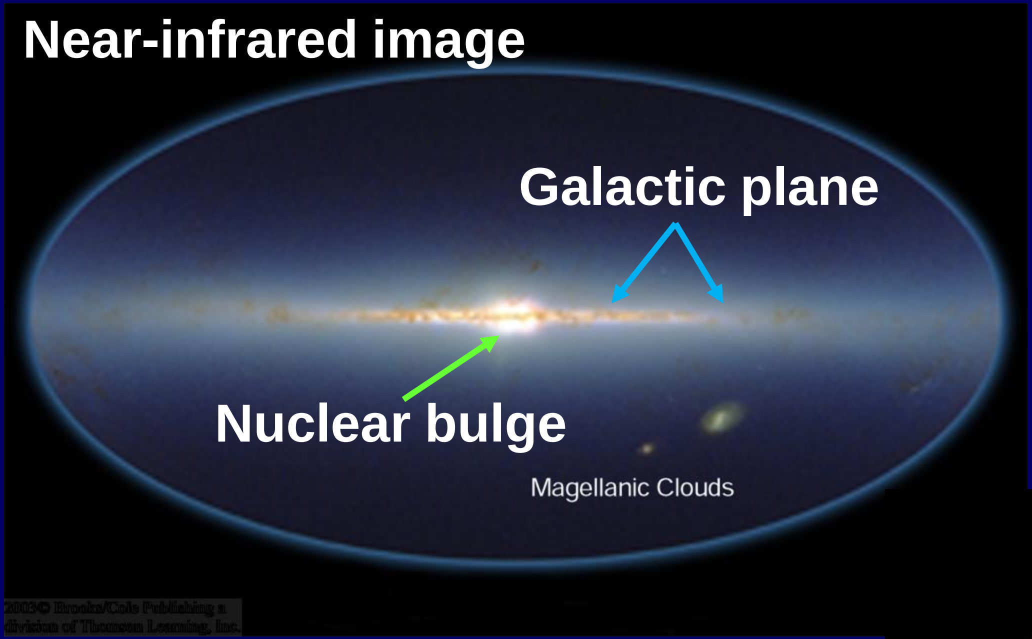
The Structure of the Milky Way



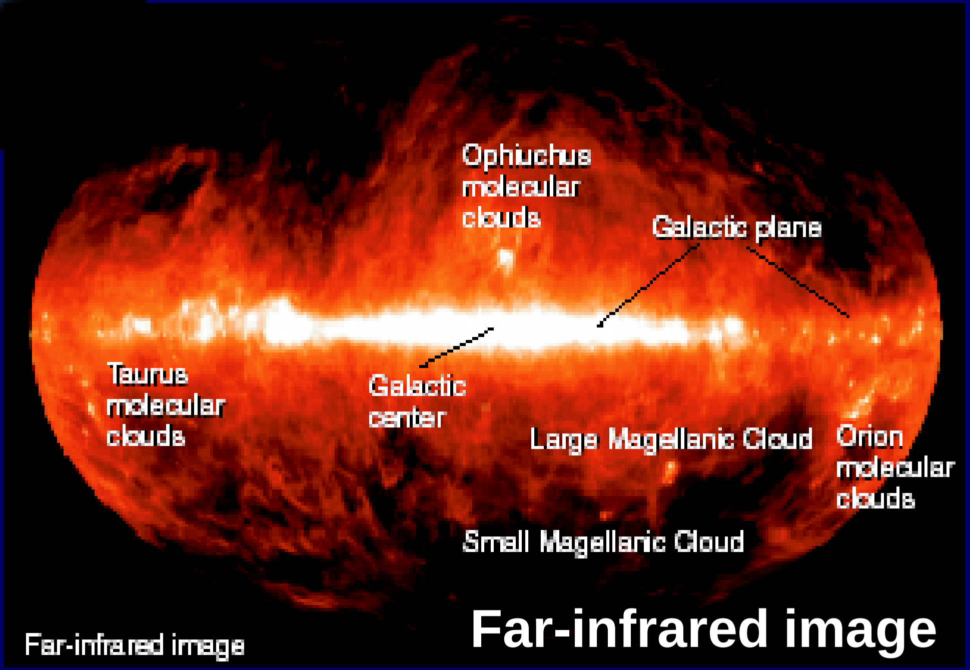
Galactic Structure

- The galactic halo and globular clusters formed very early
  - The halo is essentially spherical.
  - All the stars in the halo are very old and there is no gas or dust.
- The galactic disk is where we find:
  - The youngest stars
  - Star formation regions
  - Emission nebulae
  - Large clouds of gas and dust.
- Surrounding the galactic center is the galactic bulge which contains a mix of :
  - Old stars in globular clusters
  - Young stars

Infrared View of the Milky Way

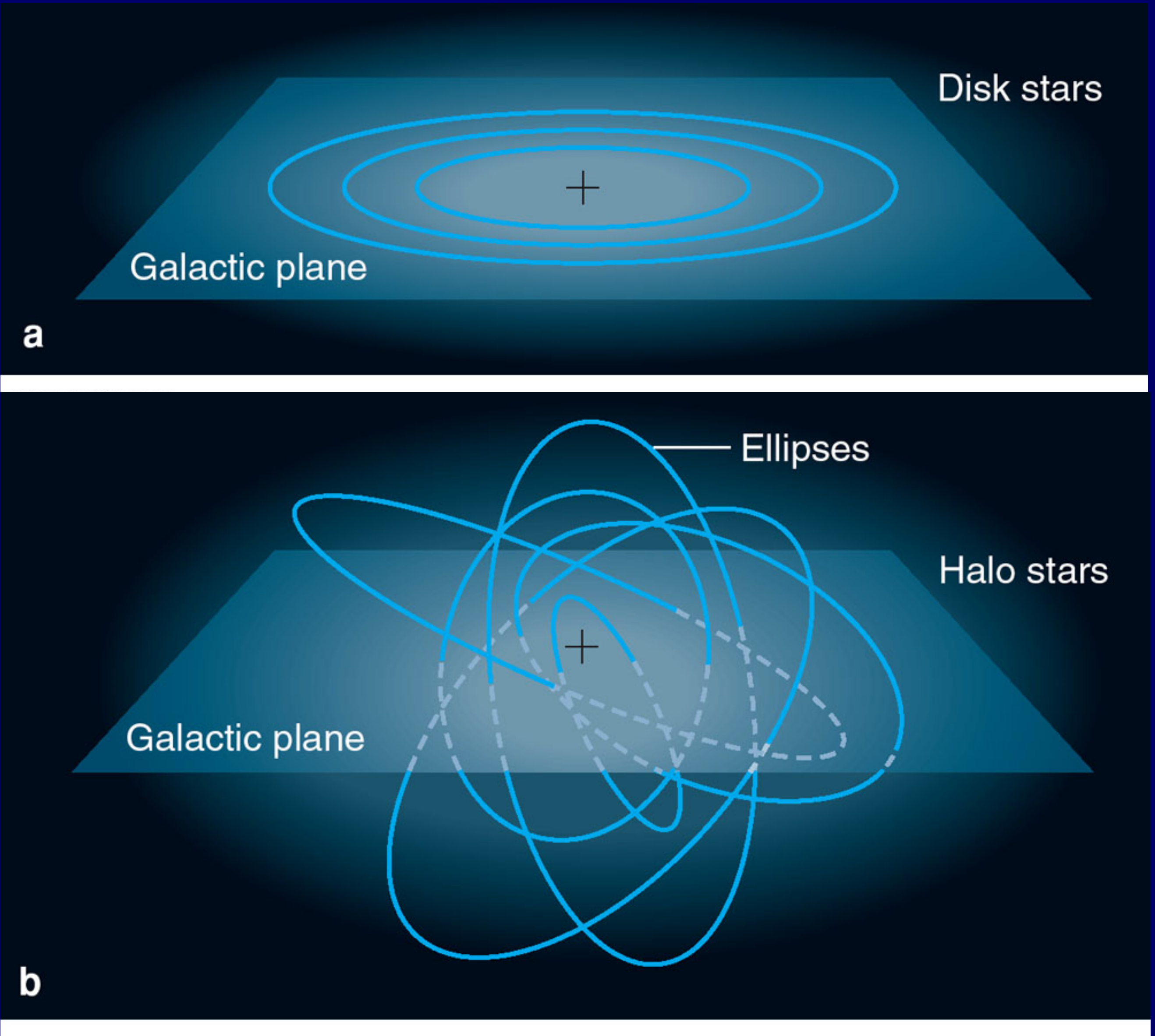


Interstellar dust (absorbing optical light) emits mostly infrared radiation.



Infrared emission is not strongly absorbed and provides a clearer view throughout the Milky Way

Orbital Motions in the Milky Way



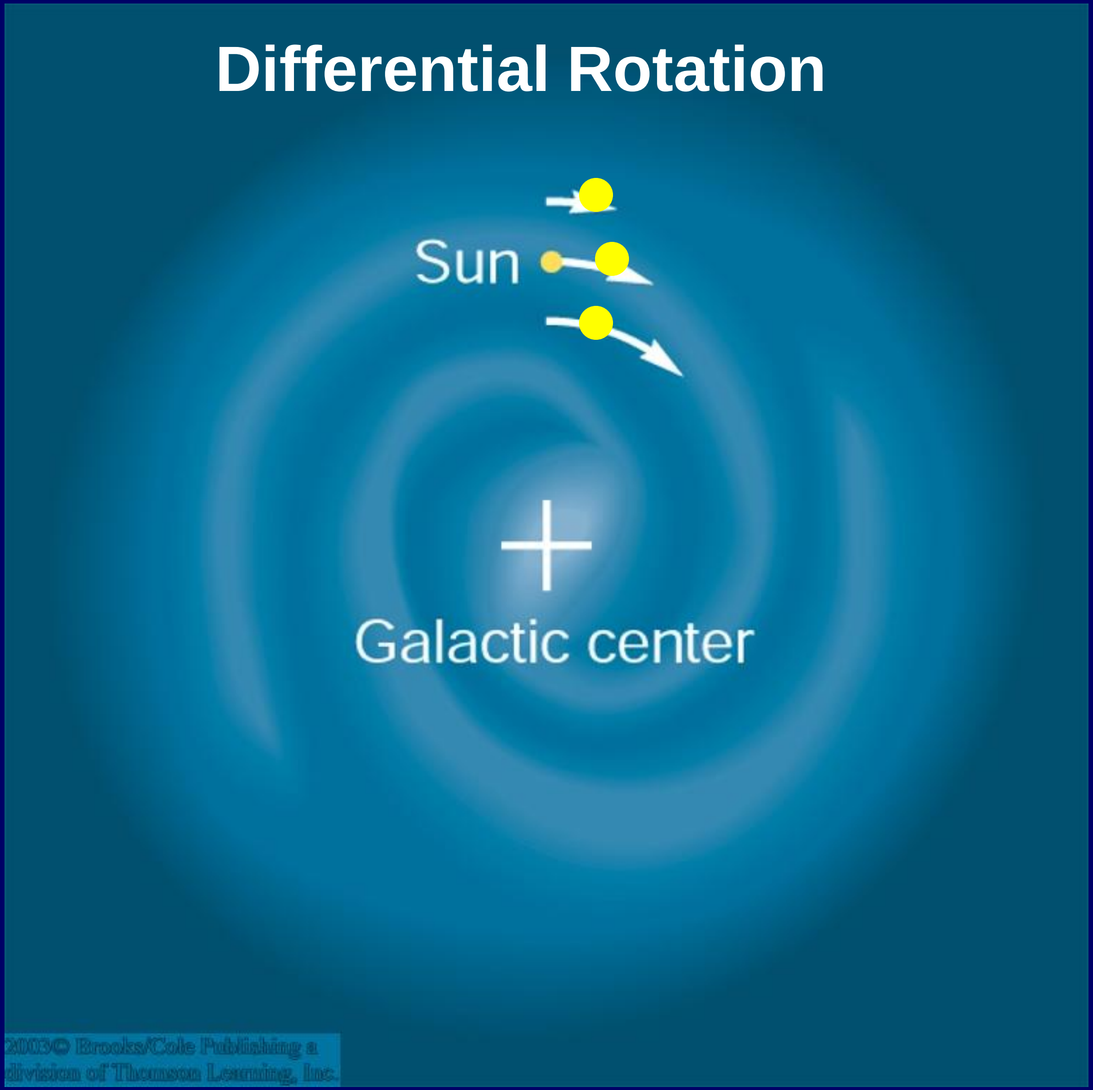
Disk stars:

Nearly circular orbits in the disk of the galaxy

Halo stars:

Highly elliptical orbits; randomly oriented

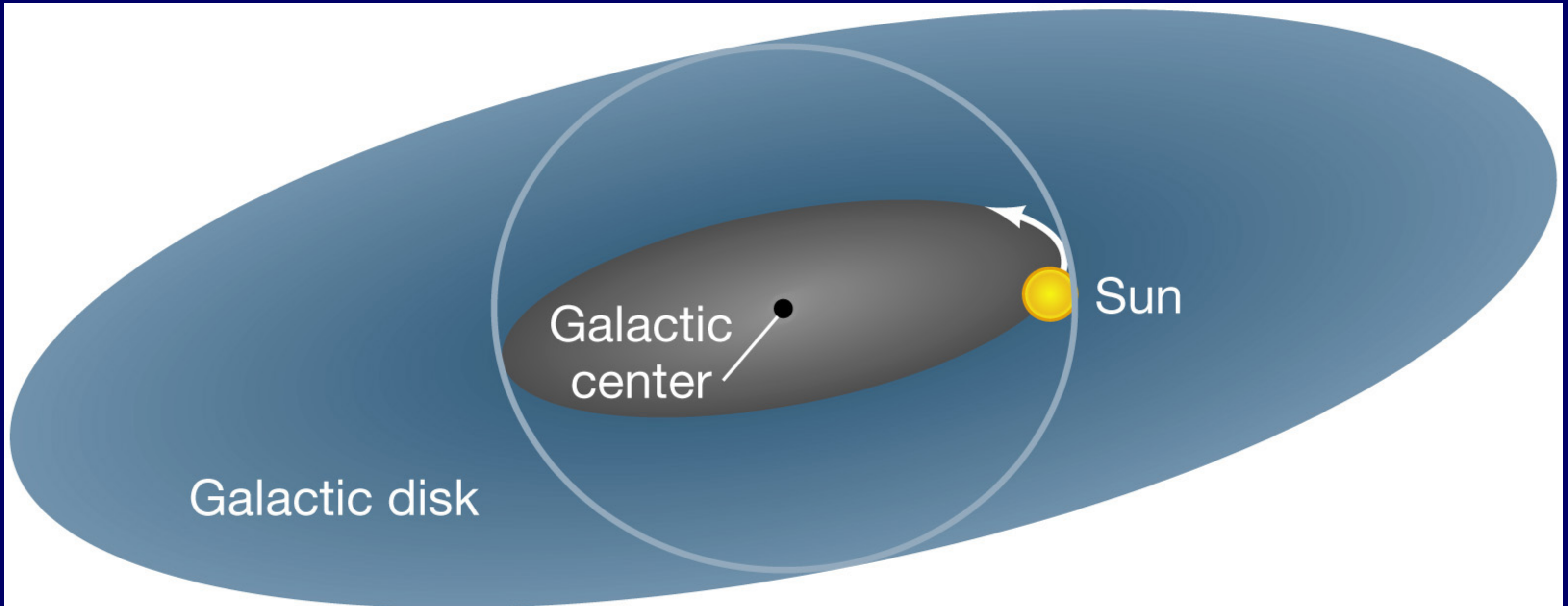
Orbital Motions in the Milky Way



- The Sun orbits around the galactic center at 220 km/s
- 1 orbit takes ~240 million years.
- Stars closer to the galactic center orbit faster.
- Stars farther out orbit more slowly (Kepler's 3rd Law).

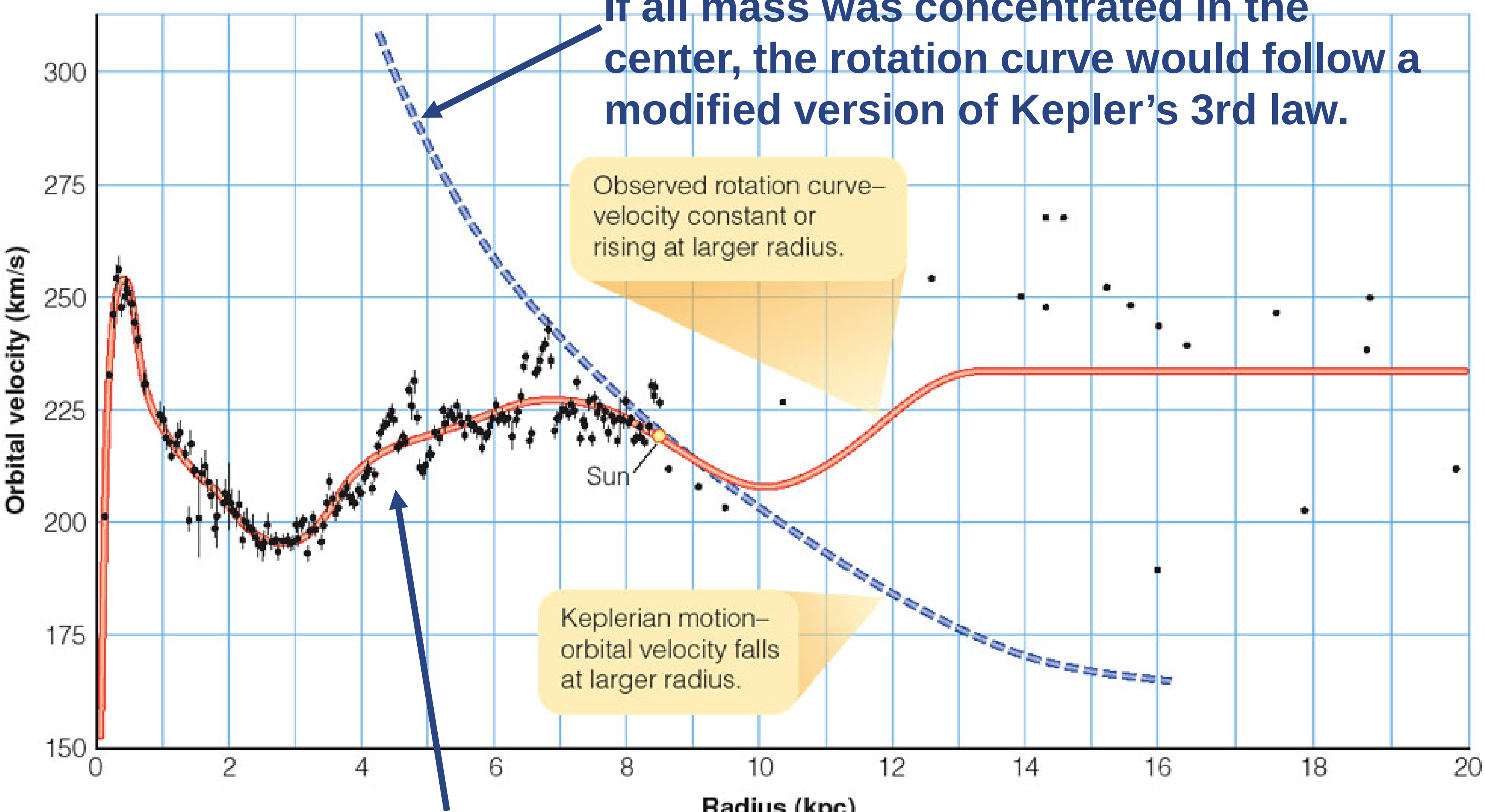
The Mass of the Milky Way Galaxy

The orbital speed of an object depends only on the amount of mass between it and the Galactic center.



The Mass of the Milky Way Galaxy

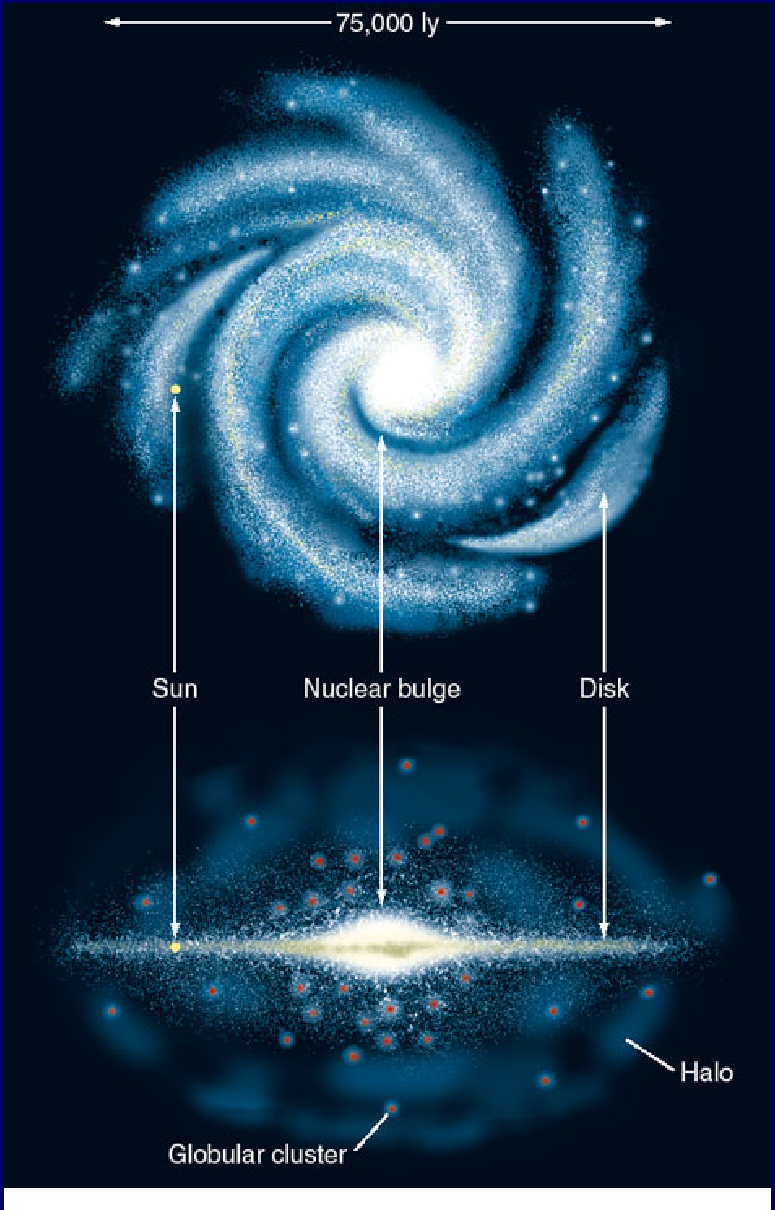
If all mass was concentrated in the center, the rotation curve would follow a modified version of Kepler's 3rd law.



Rotation Curve = orbital velocity as function of radius

The flattening of the rotation curve implies much mass near the galaxy's edge.

The Mass of the Milky Way Galaxy



Total mass of visible stars in the disk of the Milky Way:

~ 200 billion solar masses

There is additional mass in an extended halo

Total: ~1 trillion solar masses

The excess ~800 billion solar masses is not emitting any radiation:

$\Rightarrow$ dark matter!

The Mass of the Milky Way Galaxy

What could this "dark matter" be? It is dark at all wavelengths, not just the visible.

- Stellar-mass black holes?

  Probably not possible to create enough

- Brown dwarfs, faint white dwarfs, and red dwarfs?

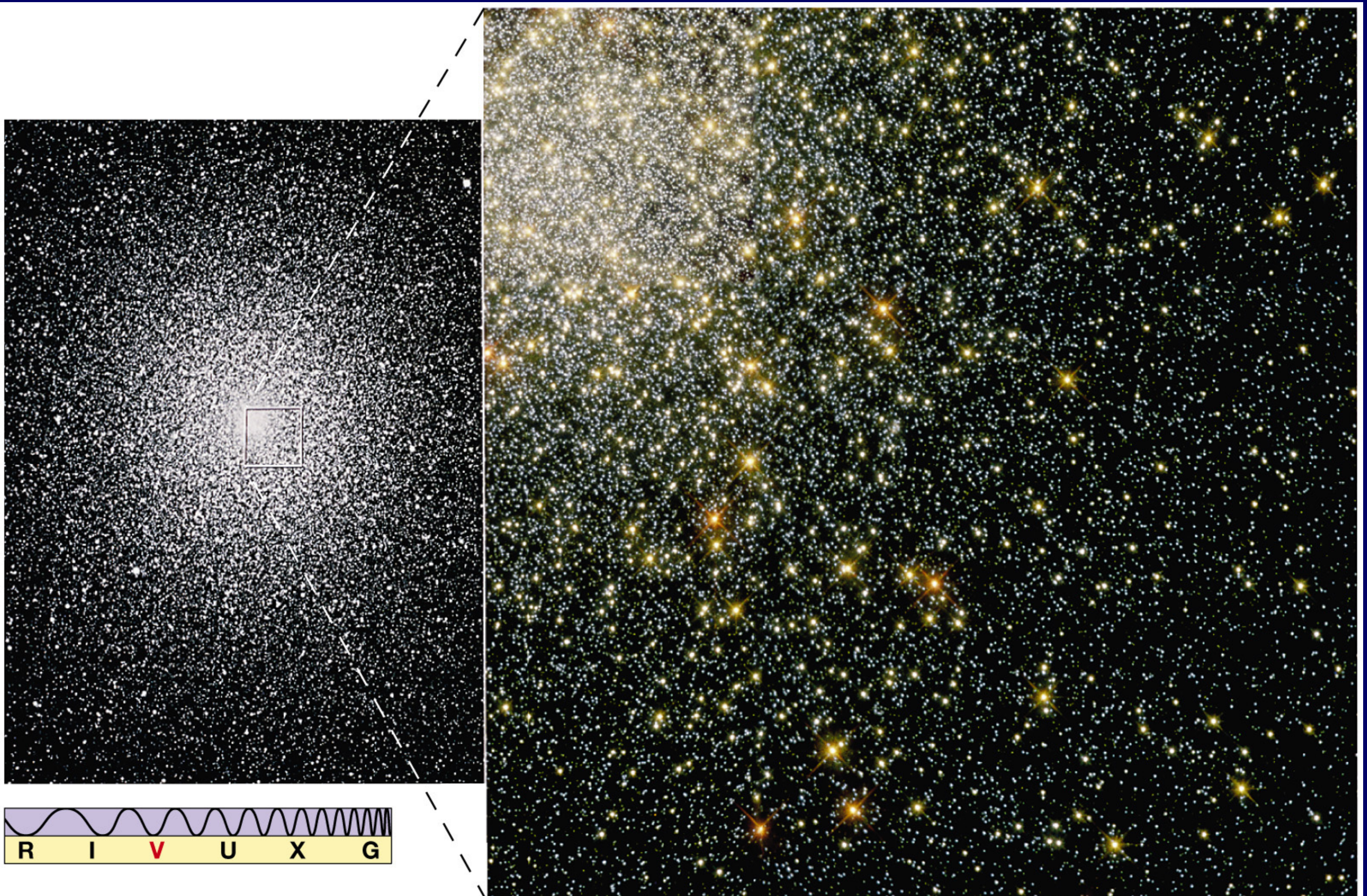
  Currently the best star-like option

- Unknown subatomic particles?

  No evidence so far, but they are looking for them using the Large Hadron Collider

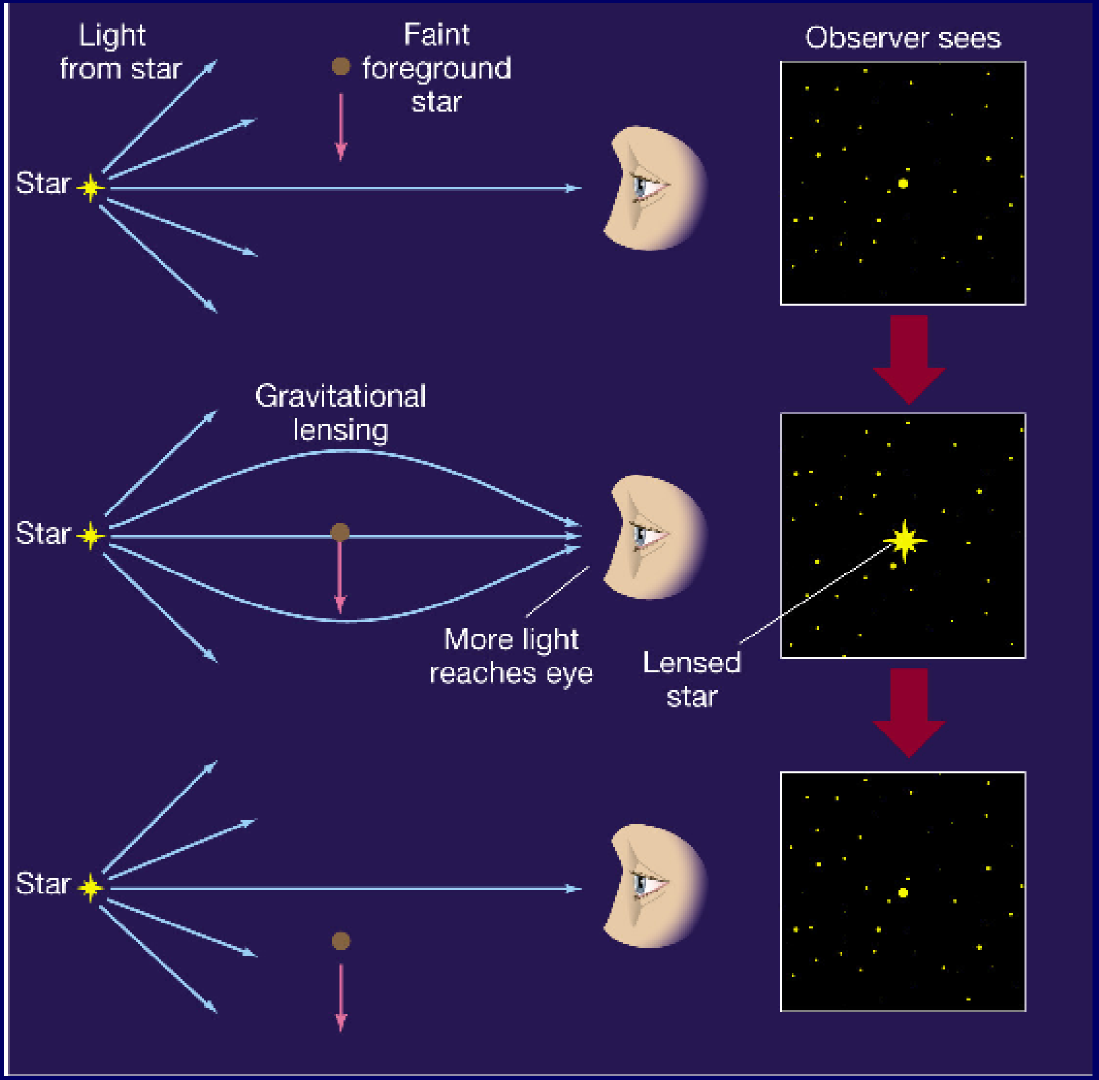
The Mass of the Milky Way Galaxy

A *Hubble* search for red dwarfs turned up very few; any that existed should have been detected.



The Mass of the Milky Way Galaxy

The bending of space-time can allow a large mass to act as a gravitational lens:



Observation of such events suggests that low-mass white dwarfs could account for about half of the mass needed.

The rest is still a mystery.

Stellar Populations

Population I: Young stars: metal rich; located in spiral arms and disk

Population II: Old stars: metal poor; located in the halo (globular clusters) and nuclear bulge

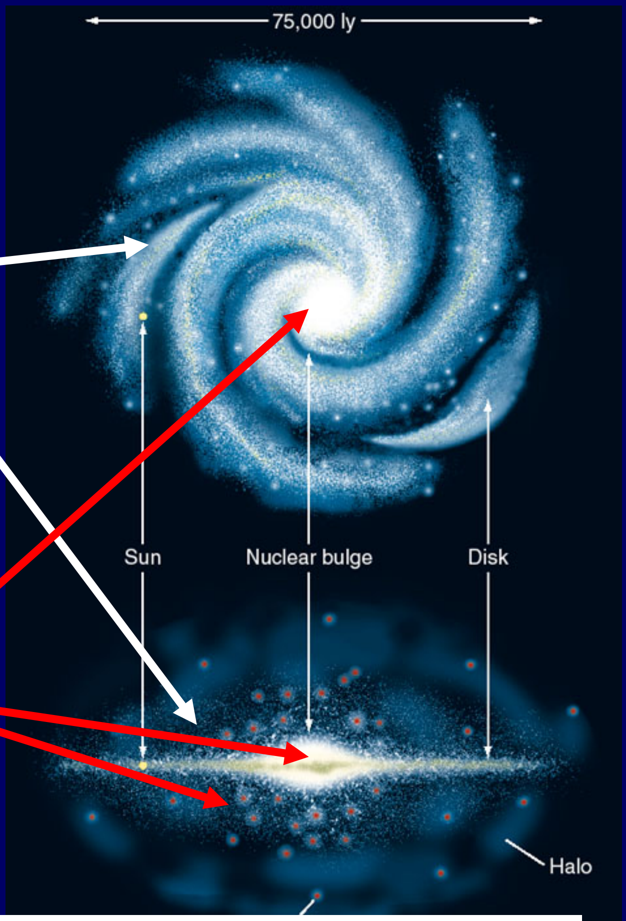
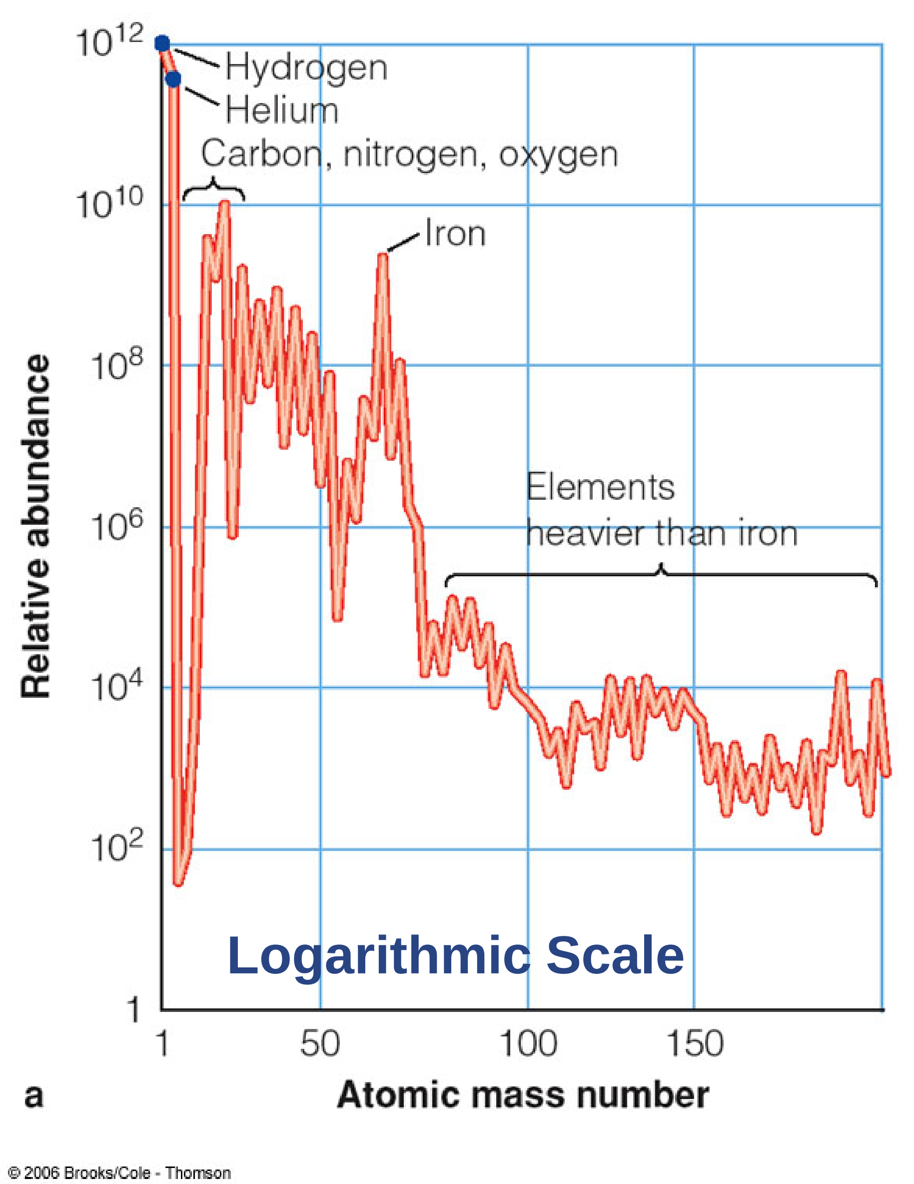
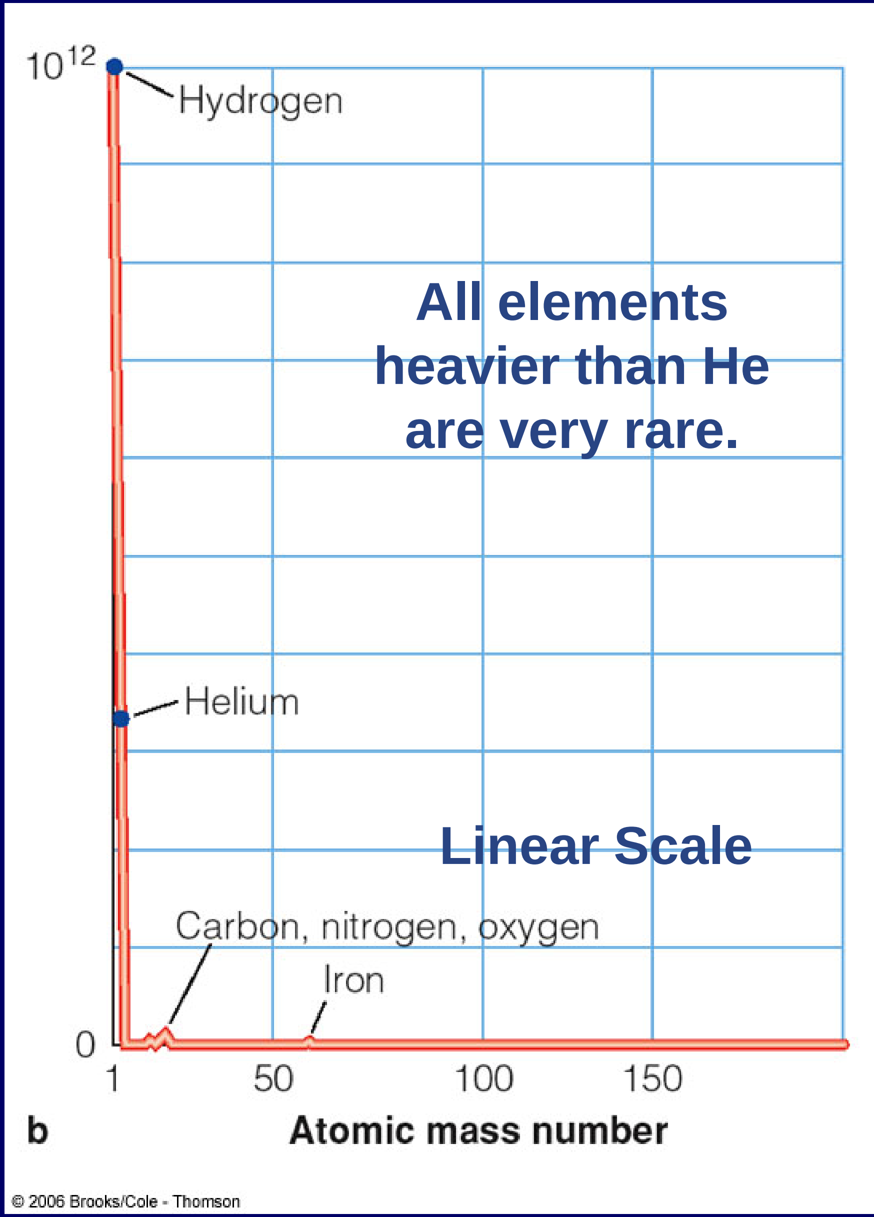


Table 12-1 | Stellar Populations

	Population I		Population II	
	Extreme	Intermediate	Intermediate	Extreme
Location	Spiral arms	Disk	Nuclear bulge	Halo
Metals (%)	3	1.6	0.8	Less than 0.8
Shape of orbit	Circular	Slightly elliptical	Moderately elliptical	Highly elliptical
Average age (yr)	100 million and younger	0.2–10 billion	2–10 billion	10–14 billion

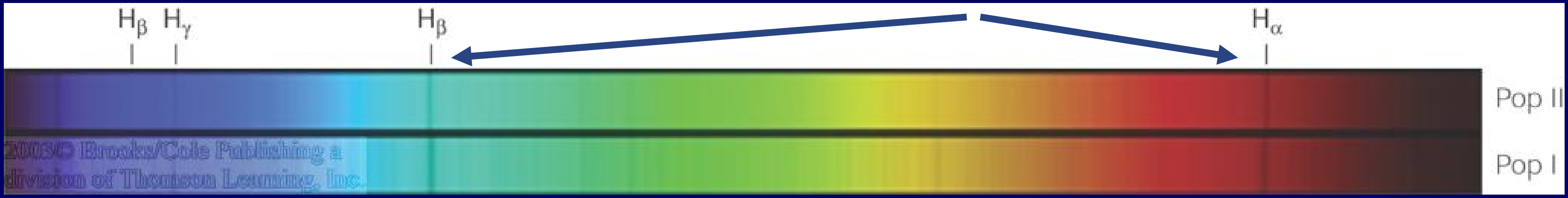
Metal Abundances in the Universe



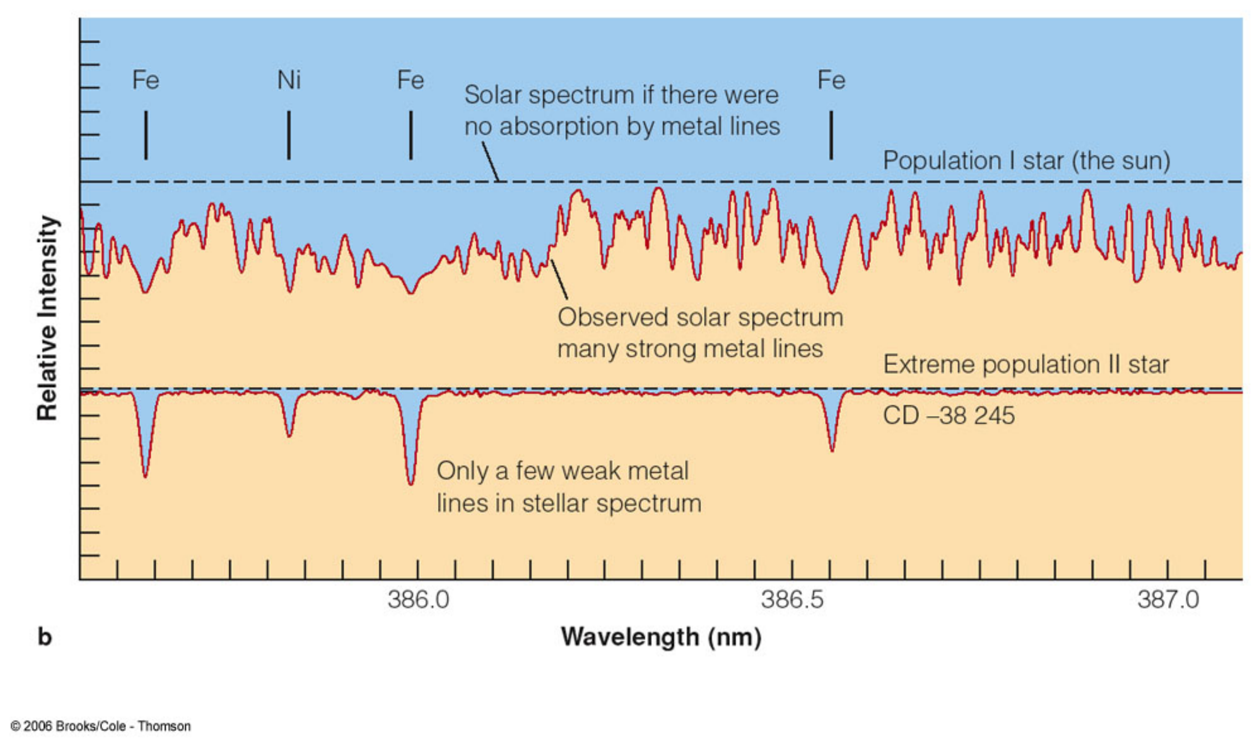


Metals in Stars

Absorption lines almost exclusively from Hydrogen: ⇒ Population II

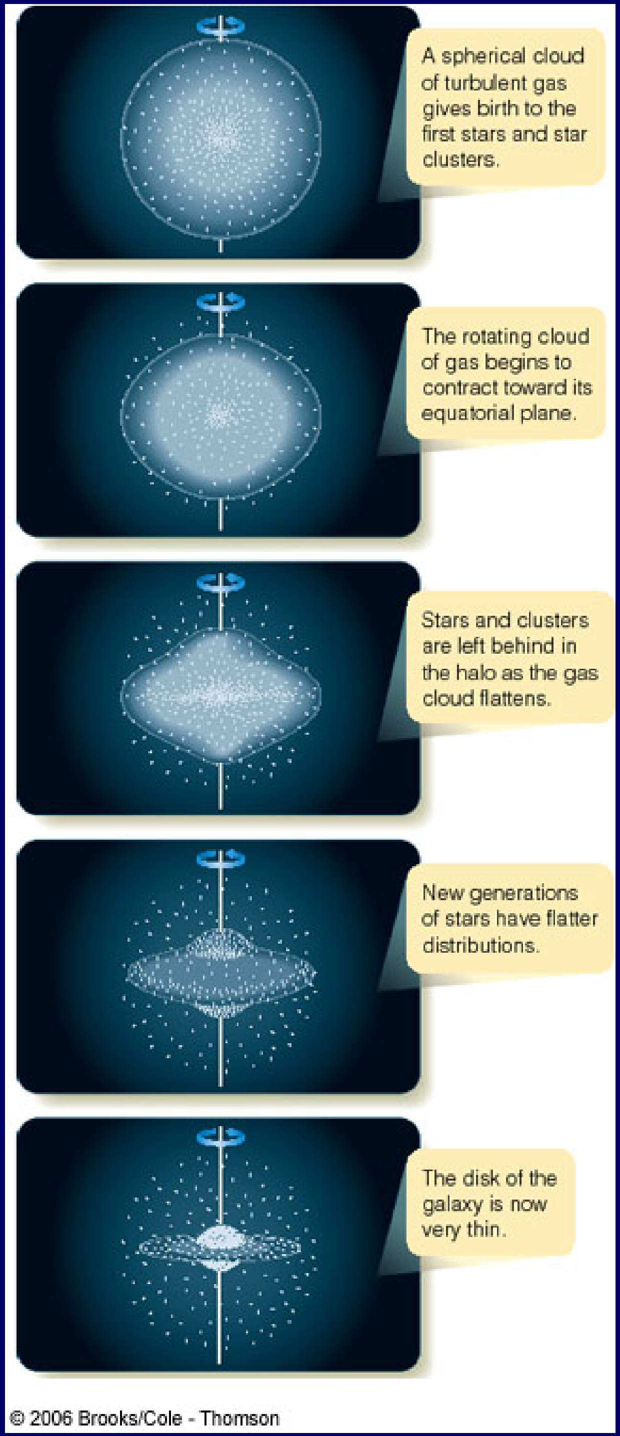


Many absorption lines also from heavier elements (metals): ⇒ Population I



At the time of formation, the gases forming the Milky Way consisted exclusively of hydrogen and helium. Heavier elements ("metals") were produced only later in stars.

⇒ Young stars contain more metals than older stars.

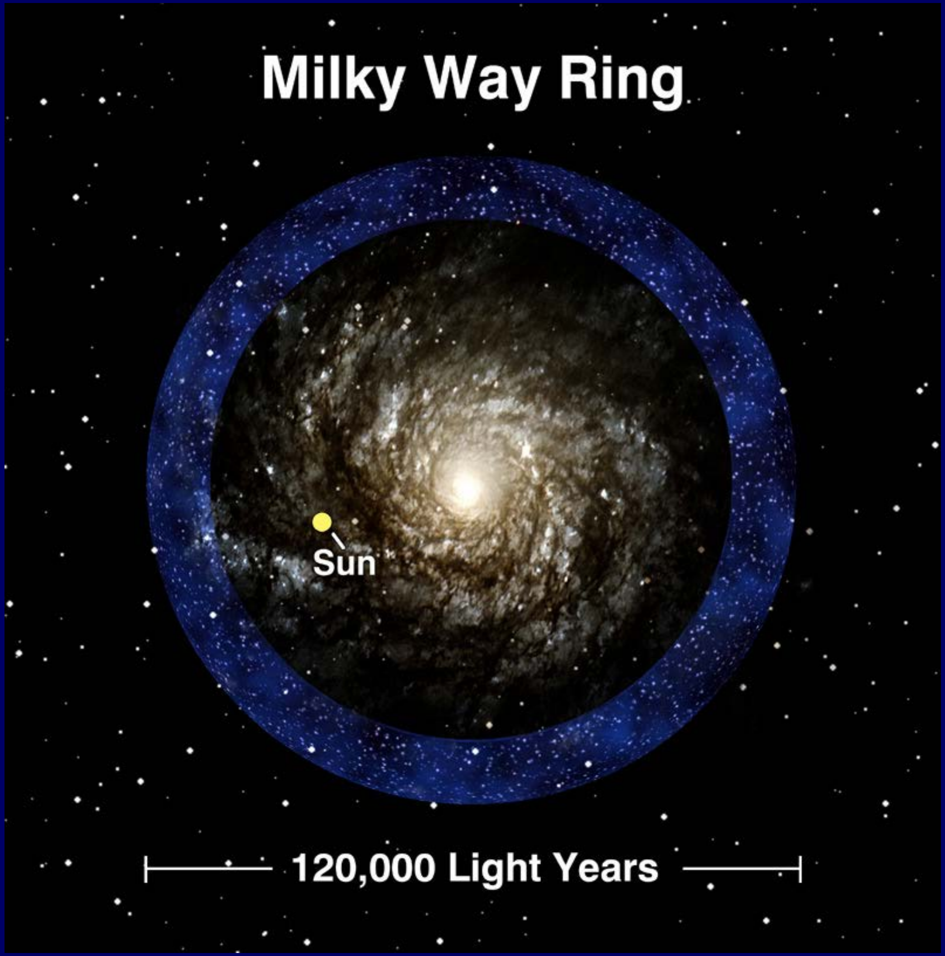


The History of the Milky Way Galaxy

The traditional theory:

- **Quasi-spherical gas cloud fragments into smaller pieces, forming the first, metal-poor stars (pop. II);**
- **Rotating cloud collapses into a disk-like structure**
- **Recently formed stars (pop. I) are restricted to the disk of the galaxy**

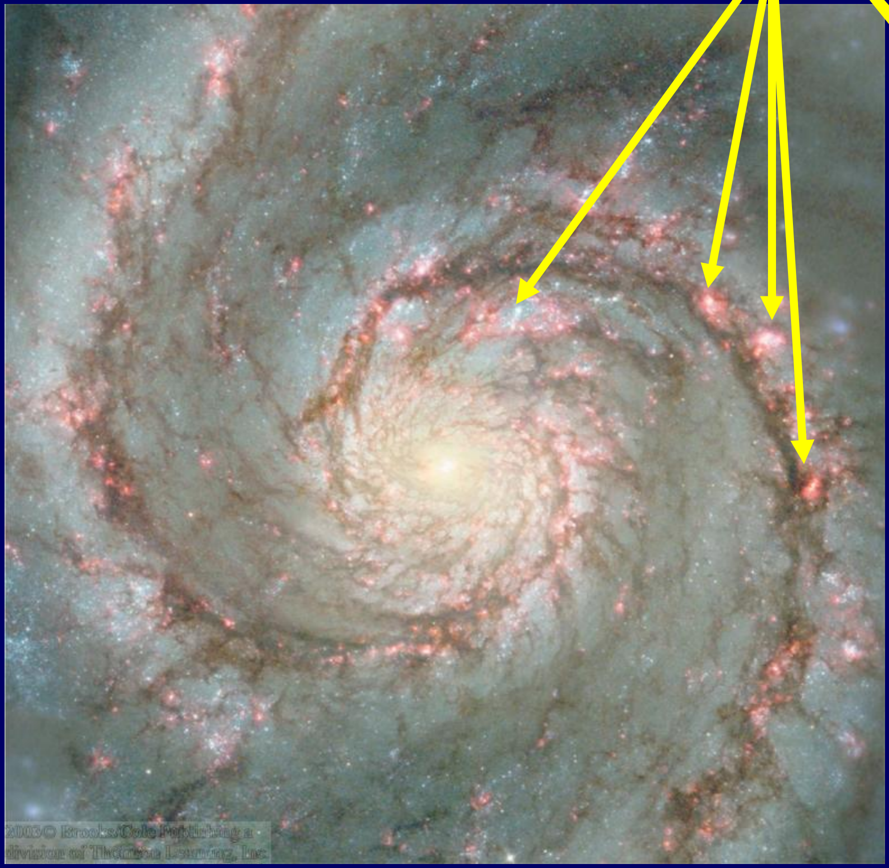
Modifications of the Traditional Theory

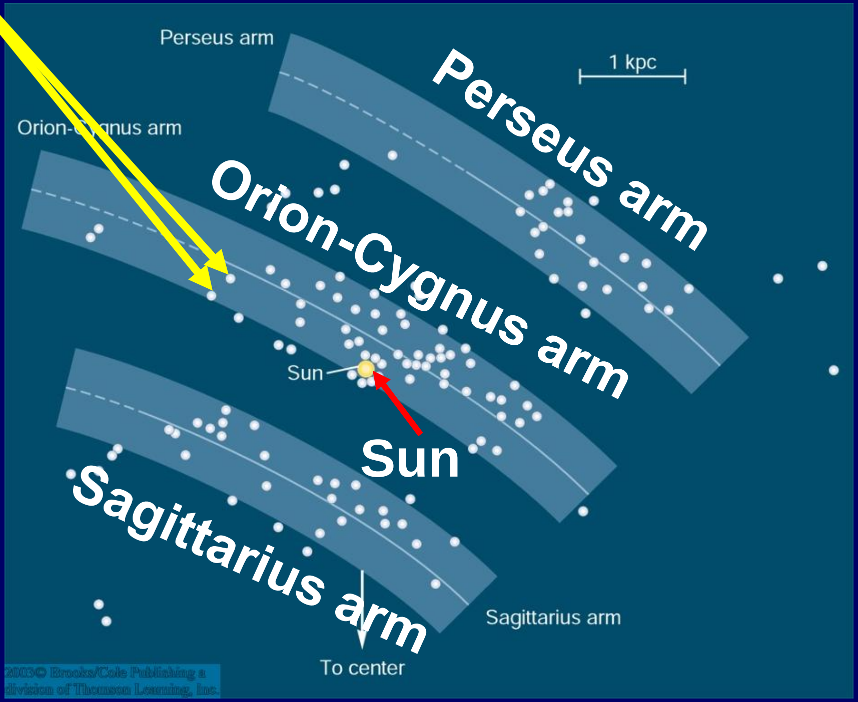


- Ages of stellar populations may pose a problem for the traditional theory of the history of the Milky Way.
- Possible solution: a later accumulation of gas, possibly from mergers with smaller galaxies.
- Recently discovered ring of stars around the Milky Way may be the remnant of such a merger.

Exploring the Structure of the Milky Way with O/B Associations

O/B Associations



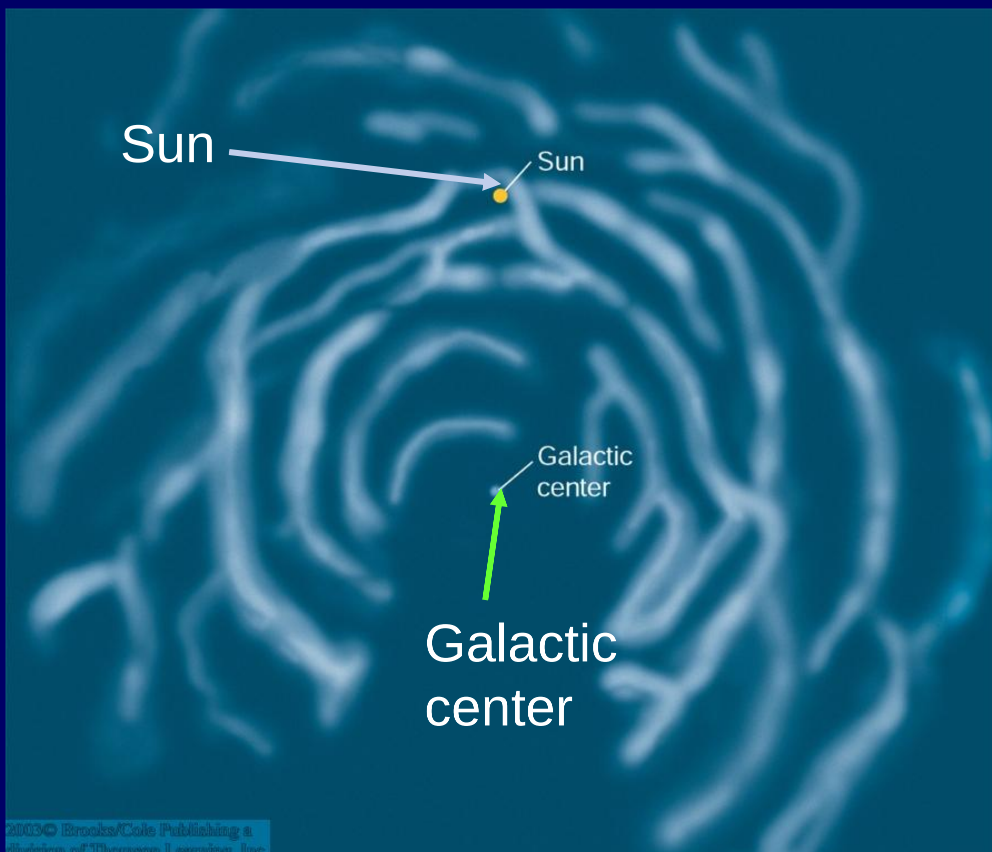


O/B Associations trace out 3 spiral arms near the Sun.

Distances to O/B Associations are determined using classical Cepheid variables

Radio Observations

21-cm radio observations reveal the distribution of neutral hydrogen throughout the galaxy.

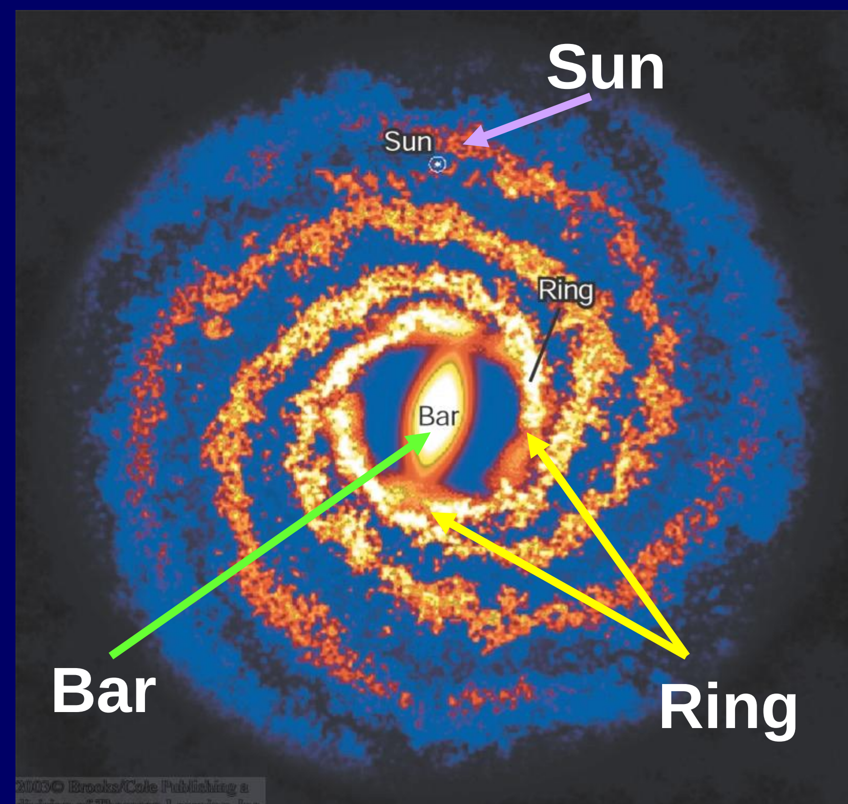


- **Distances to hydrogen clouds are determined using radial-velocity measurements (Doppler effect!)**
- **It is found that neutral hydrogen is concentrated in spiral-like arms**

The Structure of the Milky Way Revealed

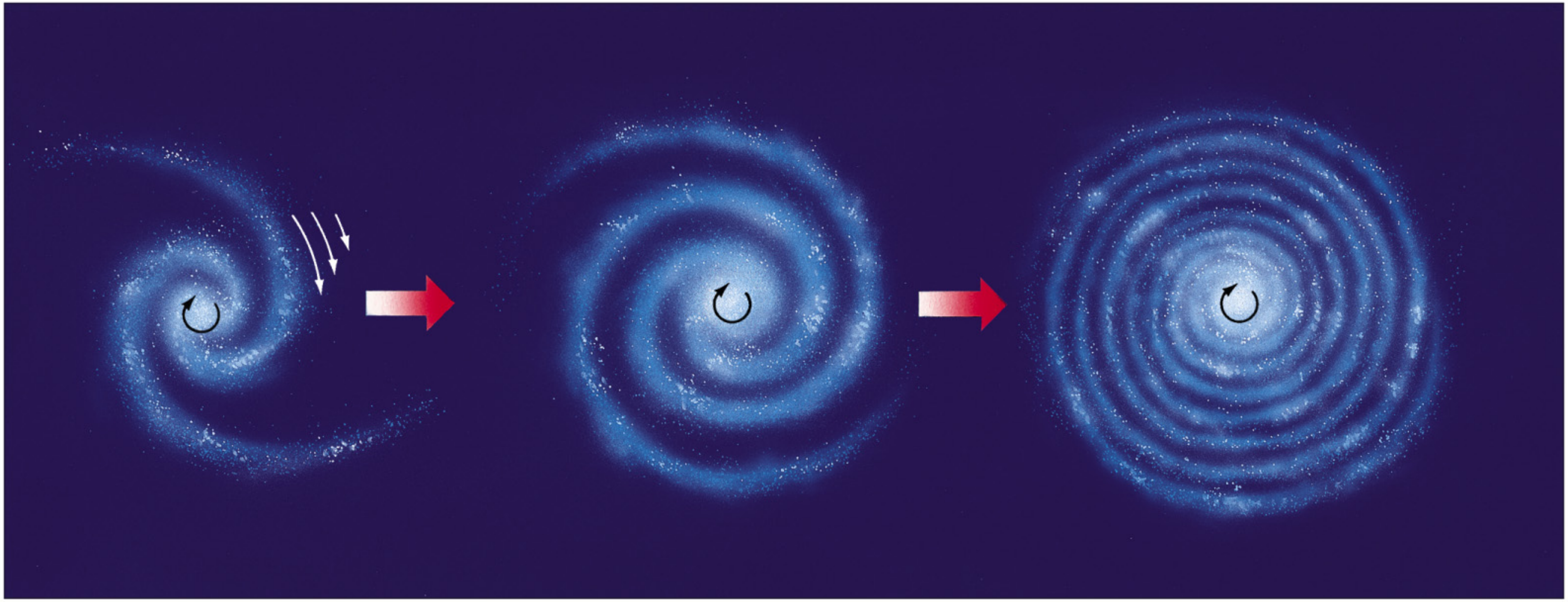
Distribution of stars and neutral hydrogen

Distribution of dust



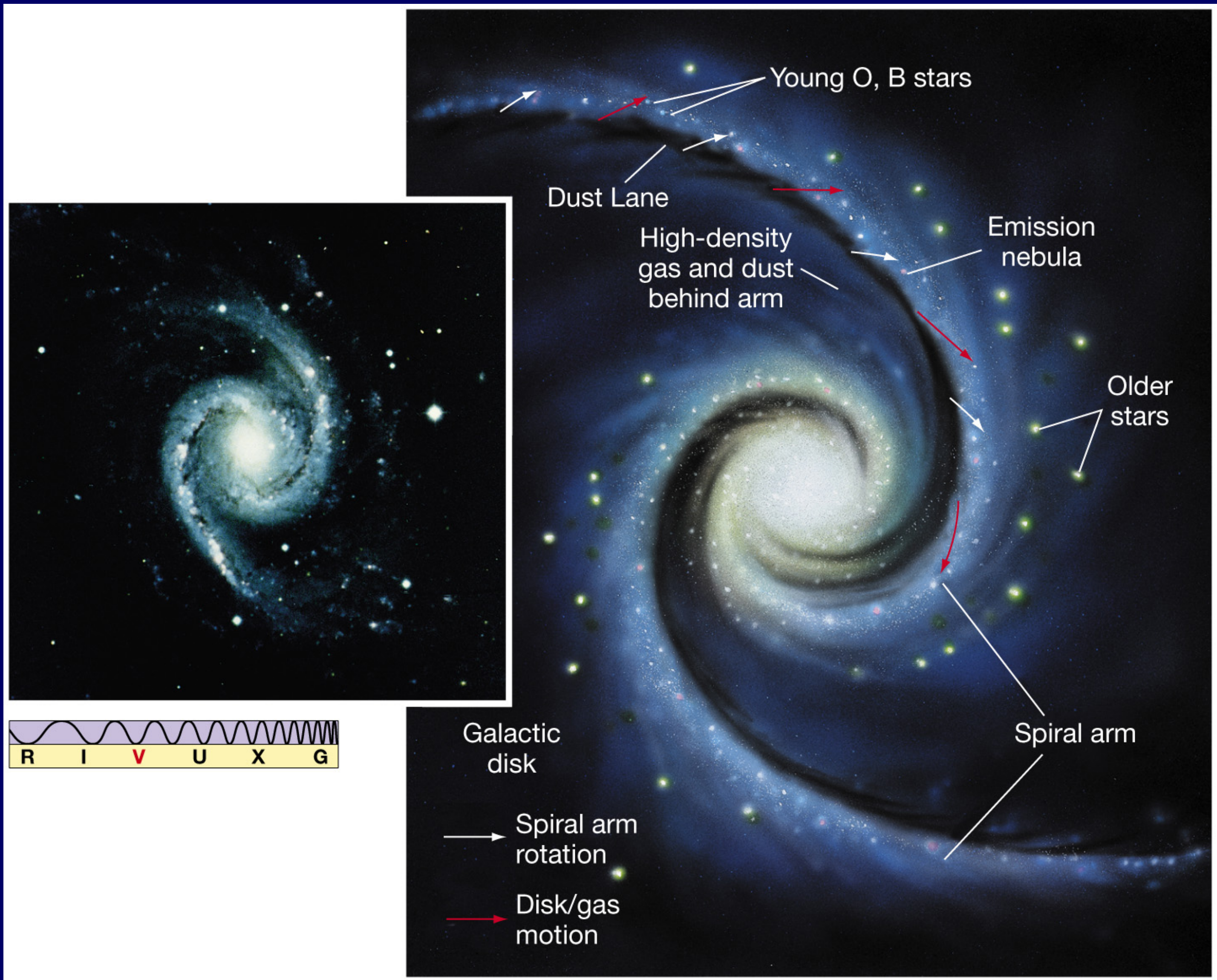
Galactic Spiral Arms

The spiral arms cannot rotate along with the Galaxy; they would "wind up".



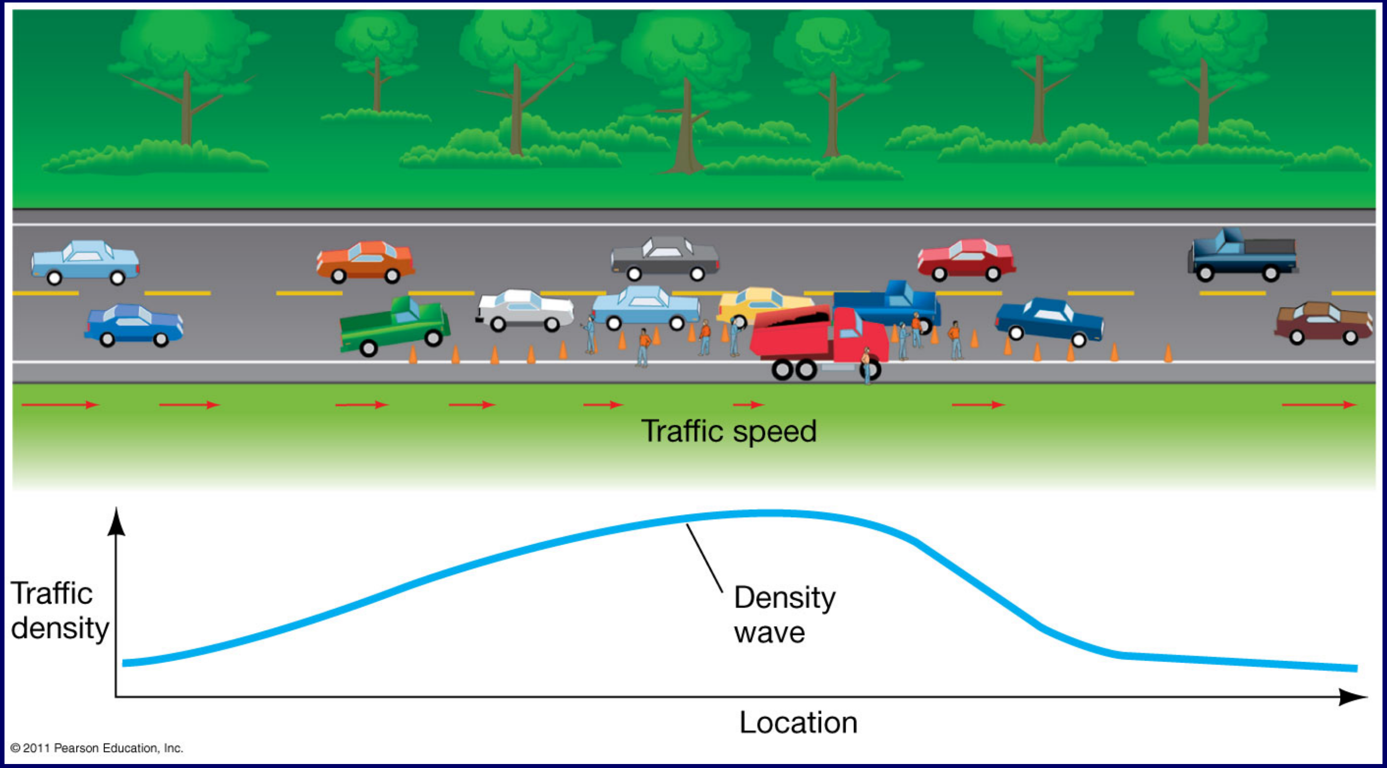
Galactic Spiral Arms

Rather, they appear to be density waves, with star densities moving outward. Stars form in the regions of high density.



Density Waves

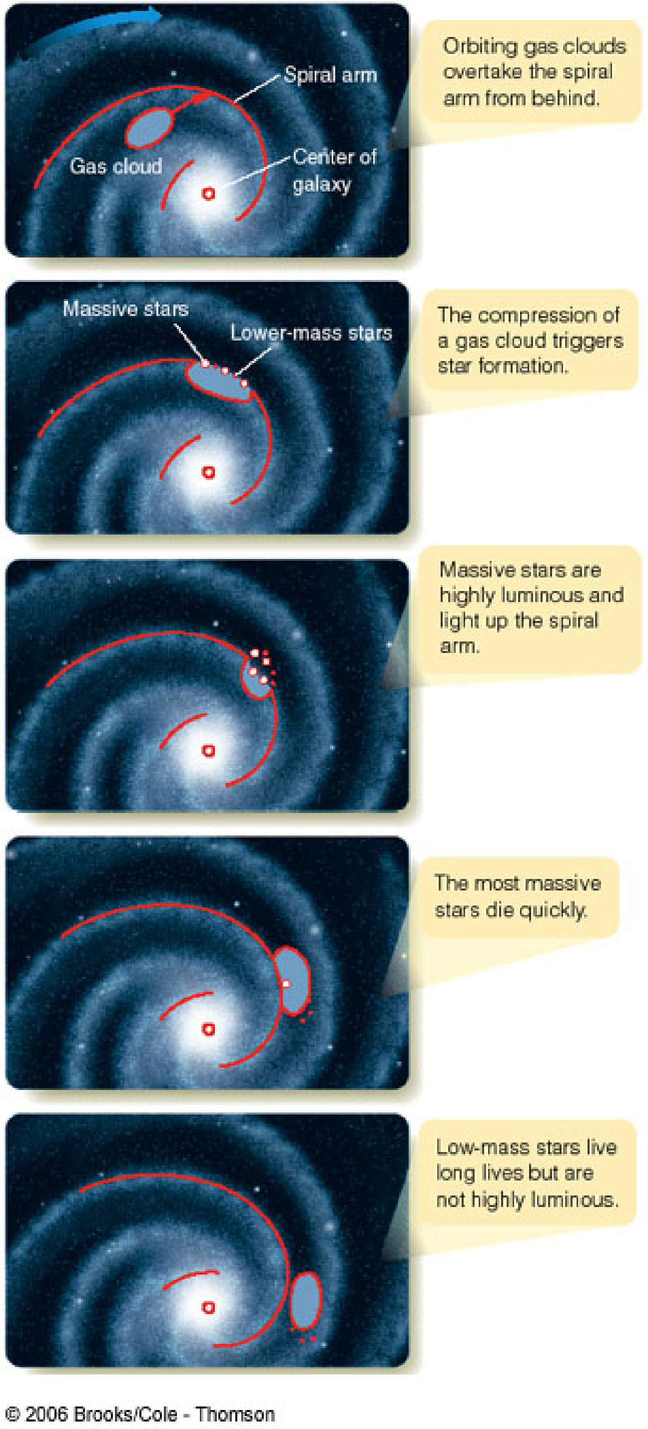
The persistence of the spiral arms as density waves, rather than as structures made up of particular stars, may be understood using a traffic jam as an analogy. The jam persists even though particular cars move in and out of it, and it can persist long after the event that triggered it is over.



Star Formation in Spiral Arms

Shock waves from supernovae, ionization fronts initiated by O and B stars, and the shock fronts forming spiral arms trigger star formation.

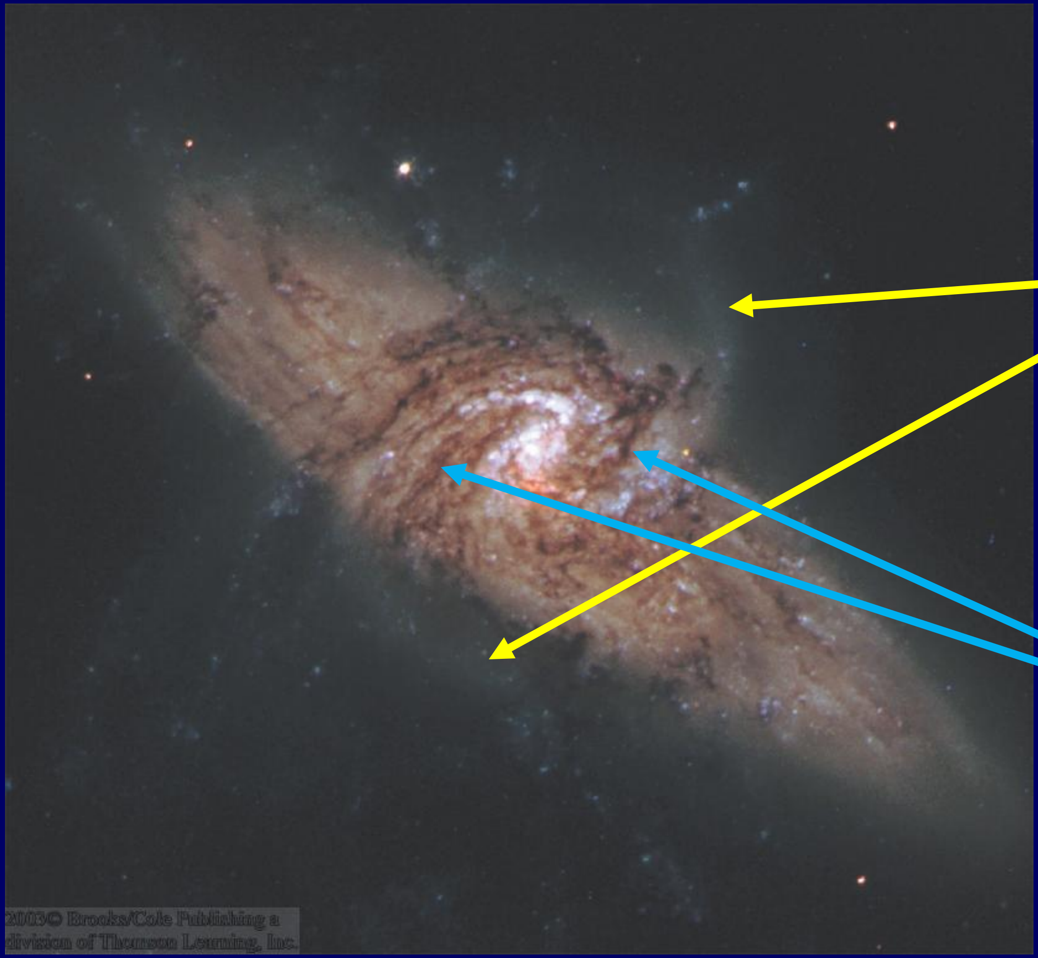
Spiral arms are stationary shock waves, initiating star formation.



Star Formation in Spiral Arms

- **Spiral arms are basically stationary shock waves.**
- **Stars and gas clouds orbit around the galactic center and cross spiral arms.**
- **Shocks initiate star formation.**
- **Star formation is self-sustaining by means of O/B ionization fronts and supernova shock waves.**

The Nature of Spiral Arms

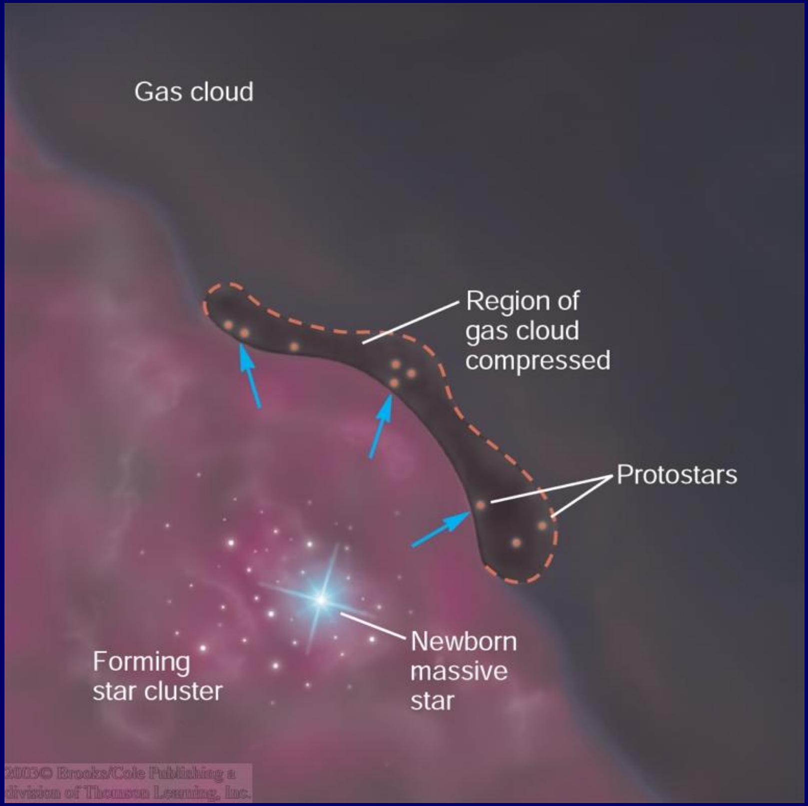


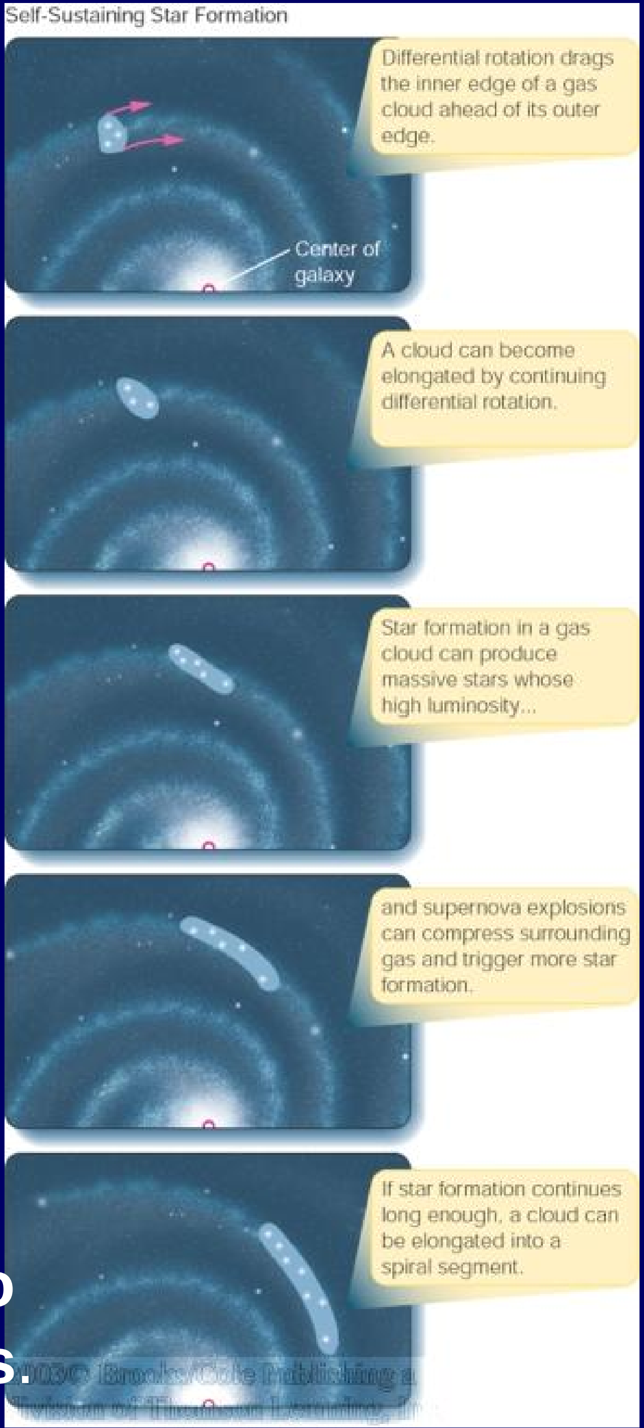
Spiral arms appear bright (newly formed, massive stars!) against the dark sky background with dark (gas and dust in dense, star-forming clouds) against the bright background of the large galaxy

Chance coincidence of small spiral galaxy in front of a large background galaxy

Self-Sustained Star Formation in Spiral Arms

Star forming regions get elongated due to differential rotation.





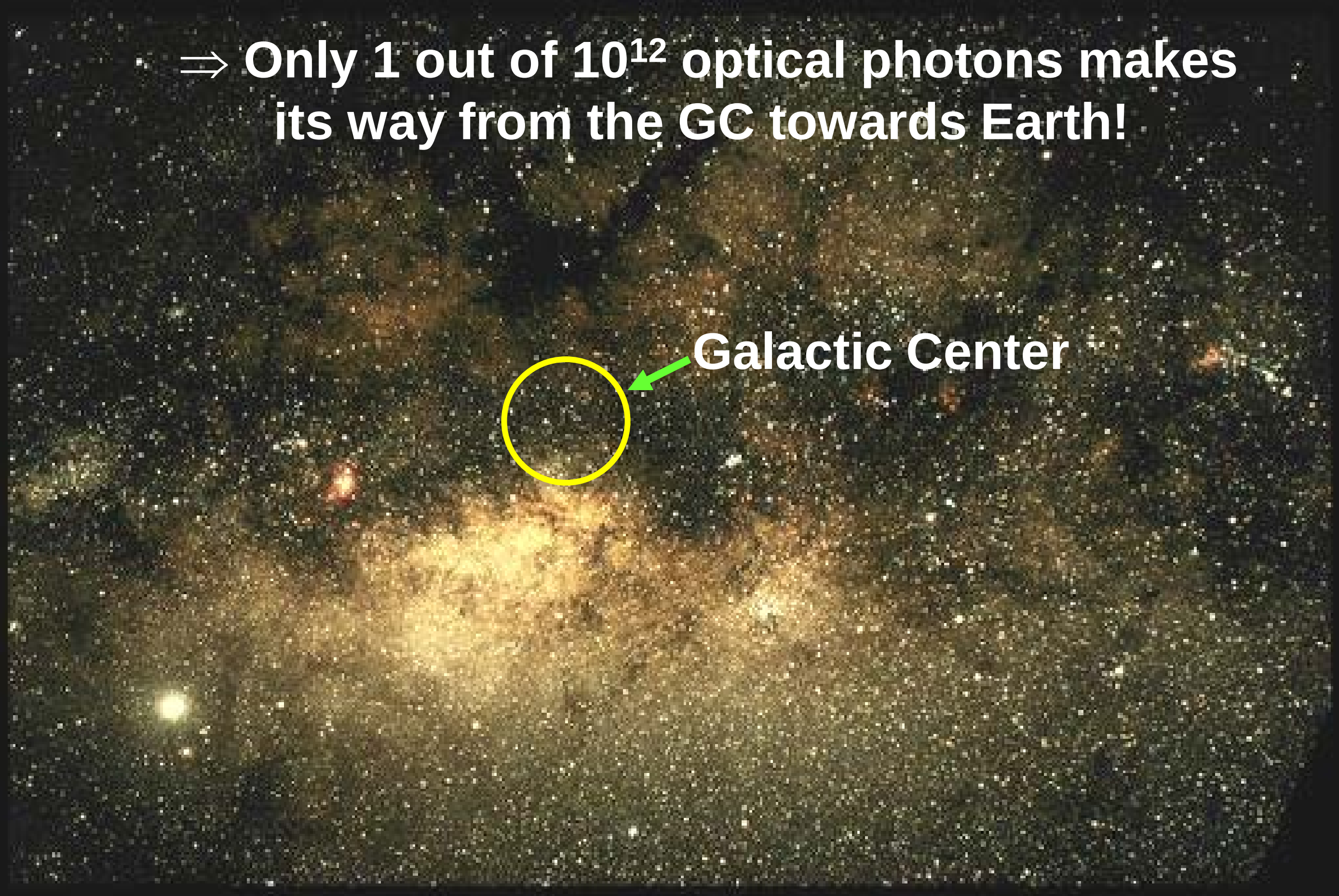
Star formation is self-sustaining due to ionization fronts and supernova shocks.

The Galactic Center

Our view (in visible light) towards the Galactic center (GC) is heavily obscured by gas and dust:

Extinction by 30 magnitudes!

⇒ Only 1 out of 10^{12} optical photons makes its way from the GC towards Earth!

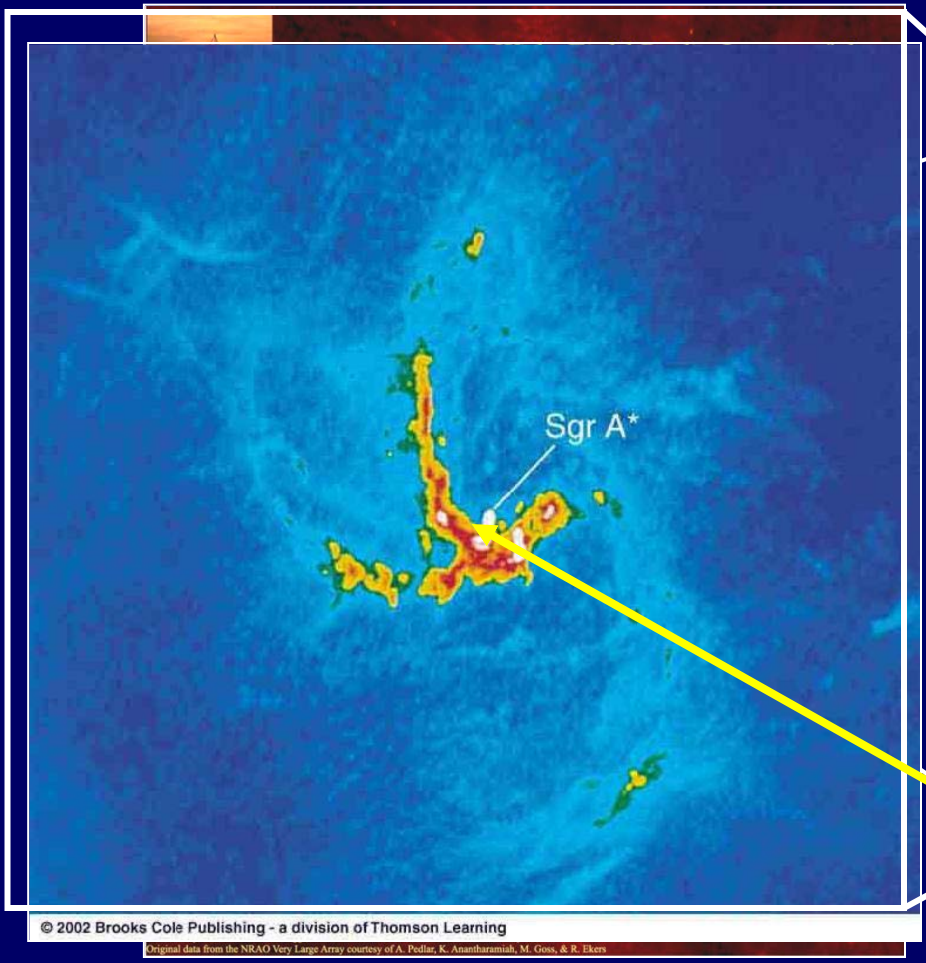


The Galactic Center

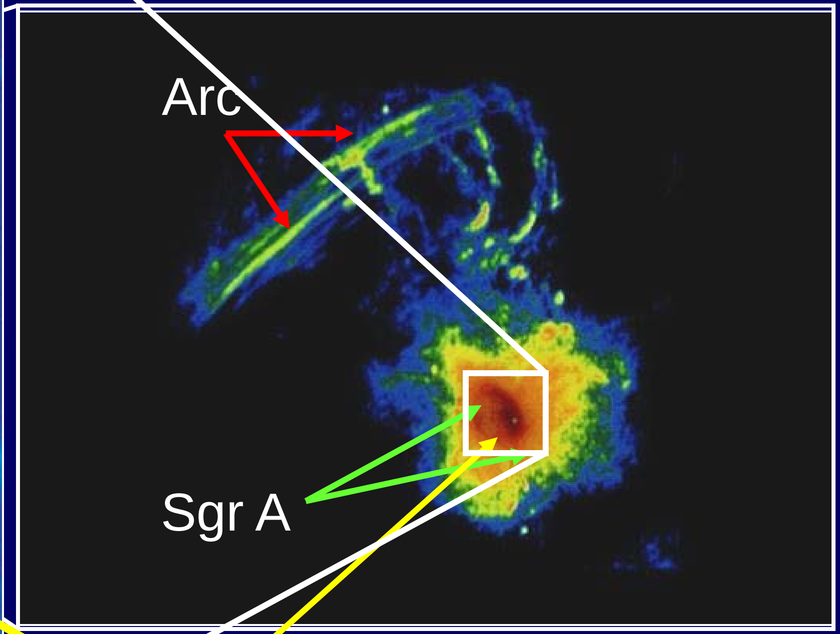
The galactic center appears to have:

- A stellar density a million times higher than near Earth.
- A ring of molecular gas 400 pc across
- Strong magnetic fields
- A rotating ring or disk of matter a few parsecs across, an accretion disk
- A strong X-ray source at the center from high velocity collisions in the accretion disk

Radio View of the Galactic Center



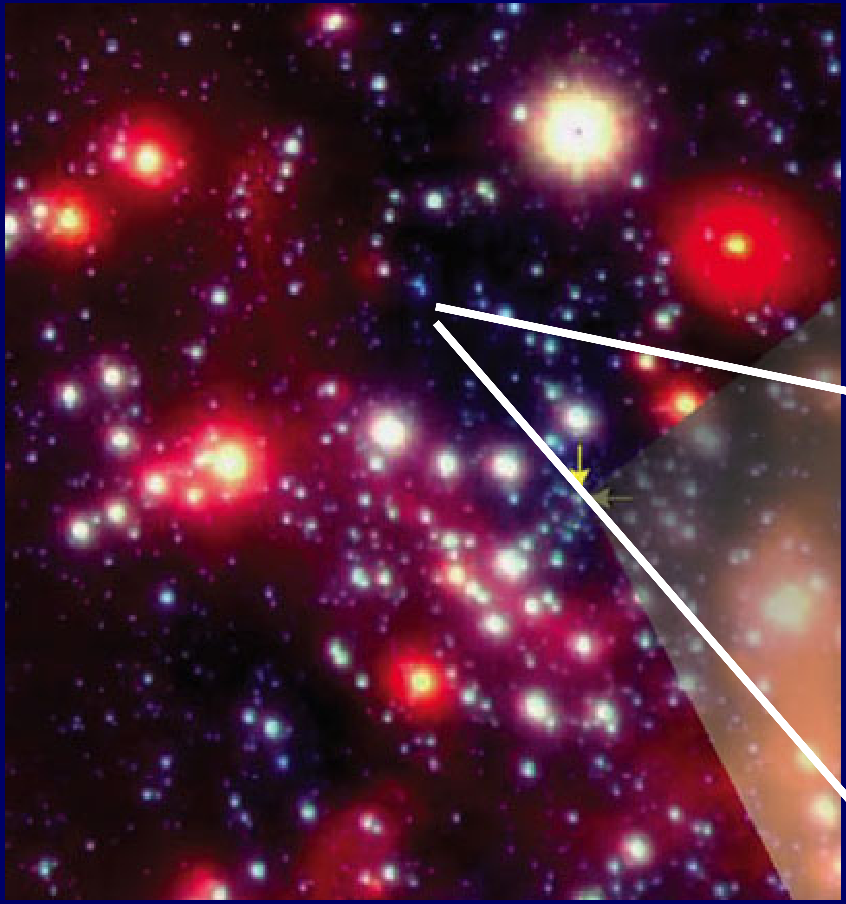
Many supernova remnants; shells and filaments



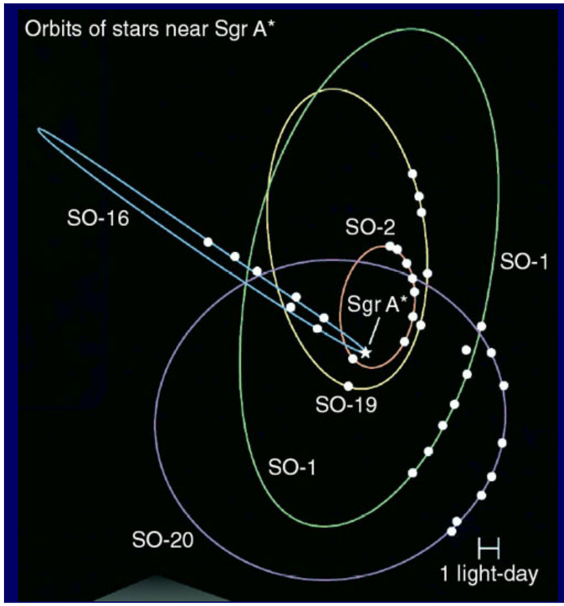
Sgr A*: The center of our galaxy

The galactic center contains a supermassive black hole of approx. 2.6 million solar masses.

Measuring the Mass of the Black Hole in the Center of the Milky Way

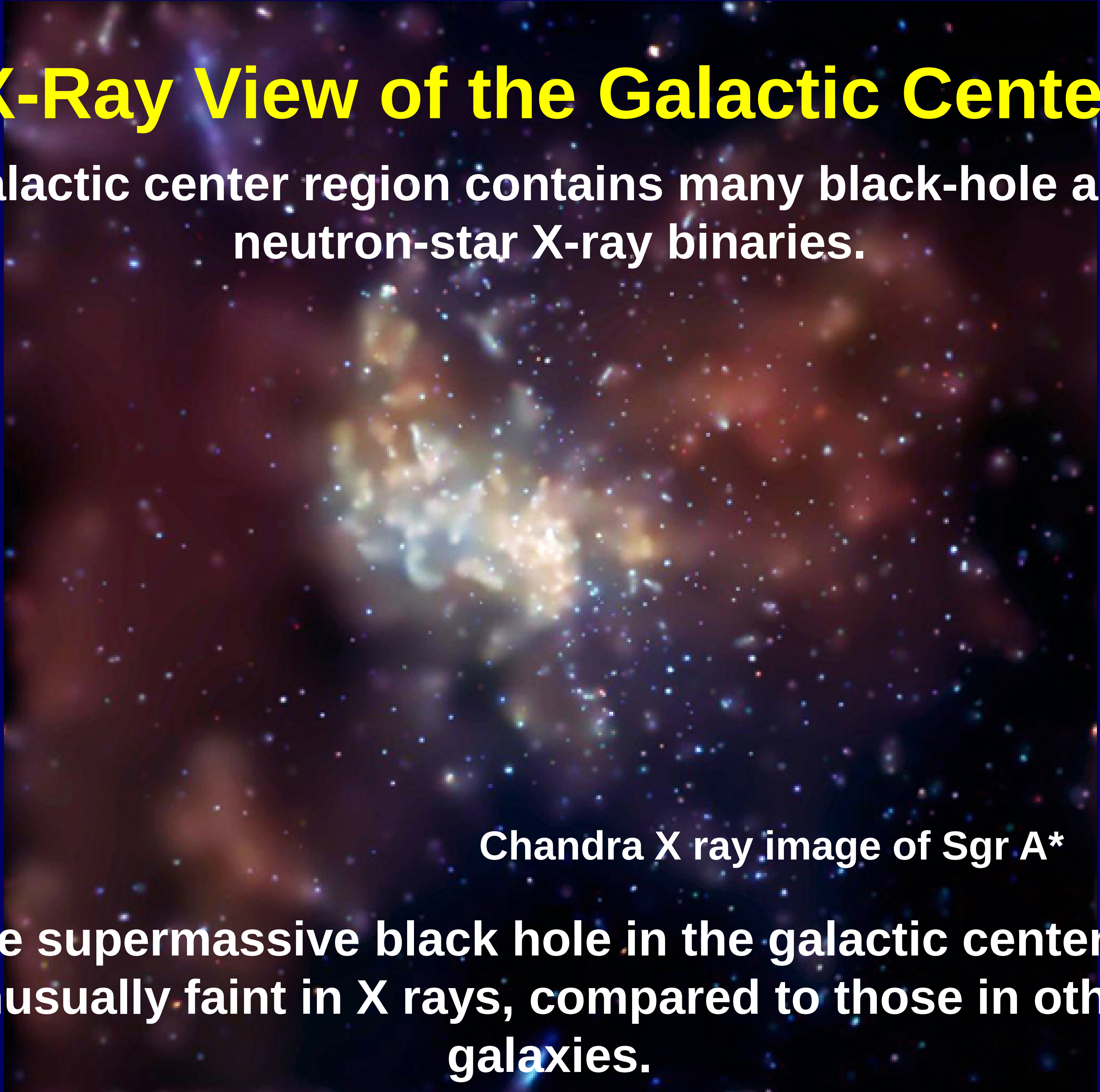


By following the orbits of individual stars near the center of the Milky Way, the mass of the central black hole is calculated to be 2.5 – 4.0 million solar masses.



X-Ray View of the Galactic Center

Galactic center region contains many black-hole and neutron-star X-ray binaries.



Chandra X ray image of Sgr A*

The supermassive black hole in the galactic center is unusually faint in X rays, compared to those in other galaxies.