Announcements

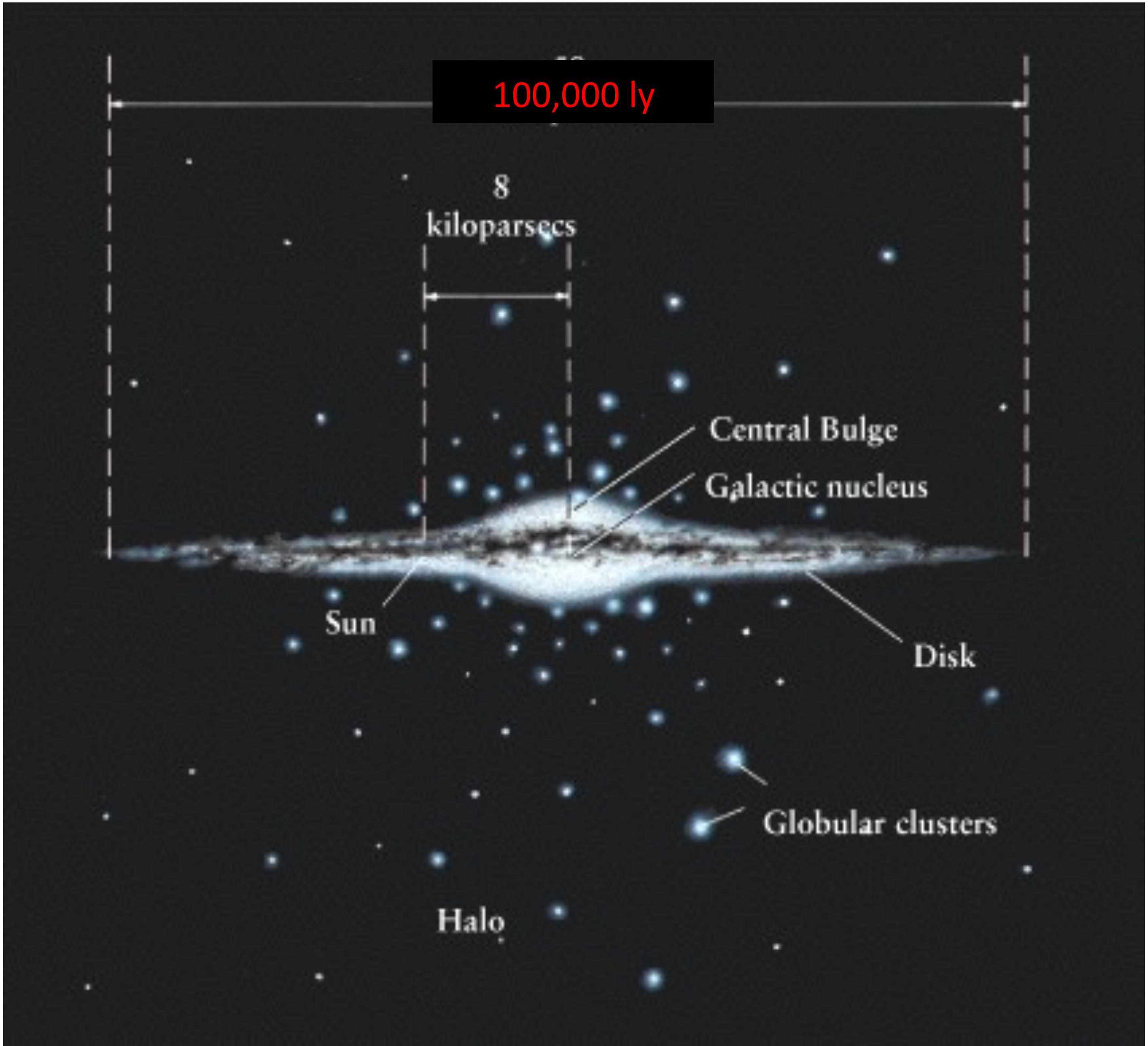
- **Quiz 10** on the solar system due Monday
  - Problem set 10 for practice
- Today: finish Chapter 14
- Please start reading Chapter 15 for Monday

Astronomy 103

Our Galaxy

Please read Chapter 14

Structure of the Milky Way



Structure of the Milky Way

- The Milky Way Galaxy consists of several parts
  - The Galactic disk
  - The Galactic bulge
  - The Galactic halo
  - And the Galactic Center

- The Galactic Disk is home to most of the young stars in the Galaxy
- The Galactic Bulge contains a mix of old and young stars
- The Galactic Halo has mainly old stars and is home to many globular clusters
- And the Galactic Center contains a supermassive black hole

The direction of the Galactic Center was identified using

A supernova remnants

B bright O and B stars in open clusters

C white dwarf stars in the spiral arms

D red giant variable stars in globular clusters

The direction of the Galactic Center was identified using

A supernova remnants

B bright O and B stars in open clusters

C white dwarf stars in the spiral arms

D red giant variable stars in globular clusters

- Structure: Halo, disk, central bulge
- Diameter of disk = 100,000 ly
- The spiral arms are in the disk, outside the bulge.
- Nearly all the gas and dust, and new stars are in the disk and bulge
- The disk rotates about the galaxy's center, at first with stars closer to the central bulge moving faster than stars farther away, and with velocity approximately constant at larger radii
- The Sun sits at 8000 pc from the Galactic Center in the disk and moves once around the Galaxy every 225 million years

Galactic Structure

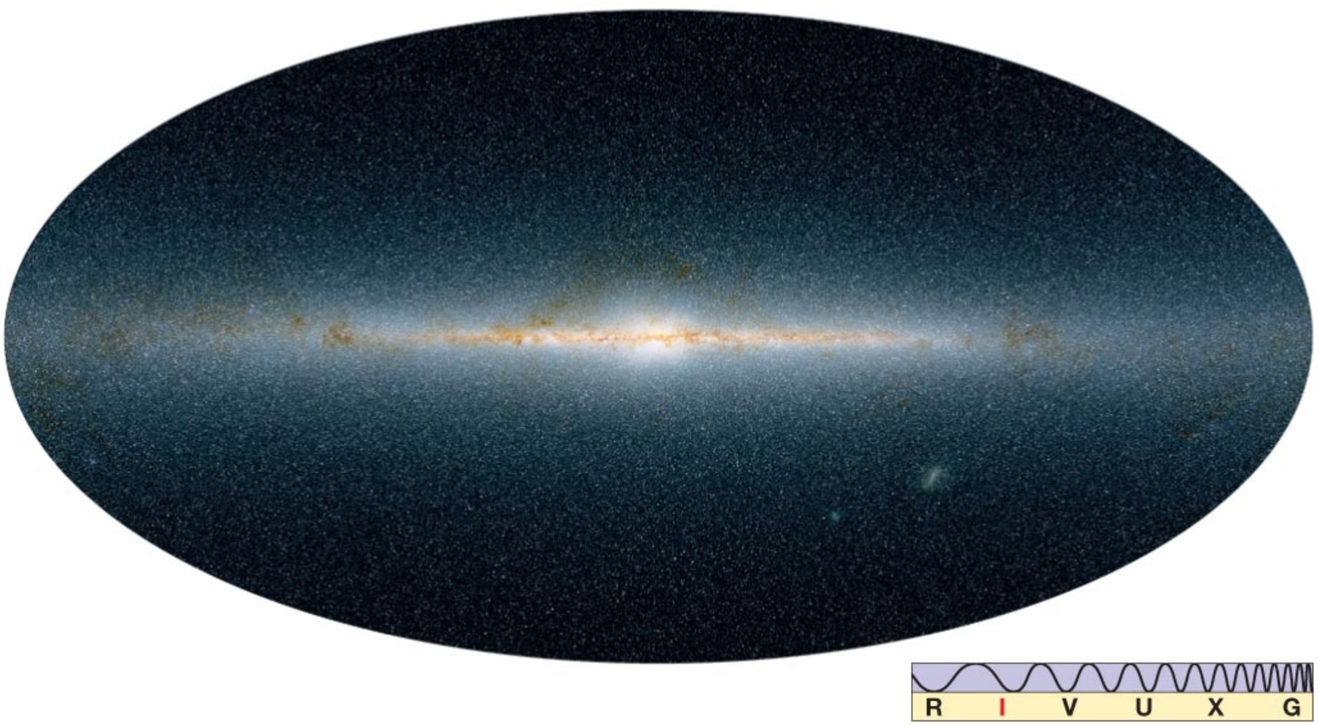
The galactic halo and globular clusters formed very early; the halo is essentially spherical. All the stars in the halo are very old, and there is no gas and dust.

The galactic disk is where the youngest stars are, as well as star formation regions – emission nebulae, large clouds of gas and dust.

Surrounding the galactic center is the galactic bulge, which contains a mix of older and younger stars.

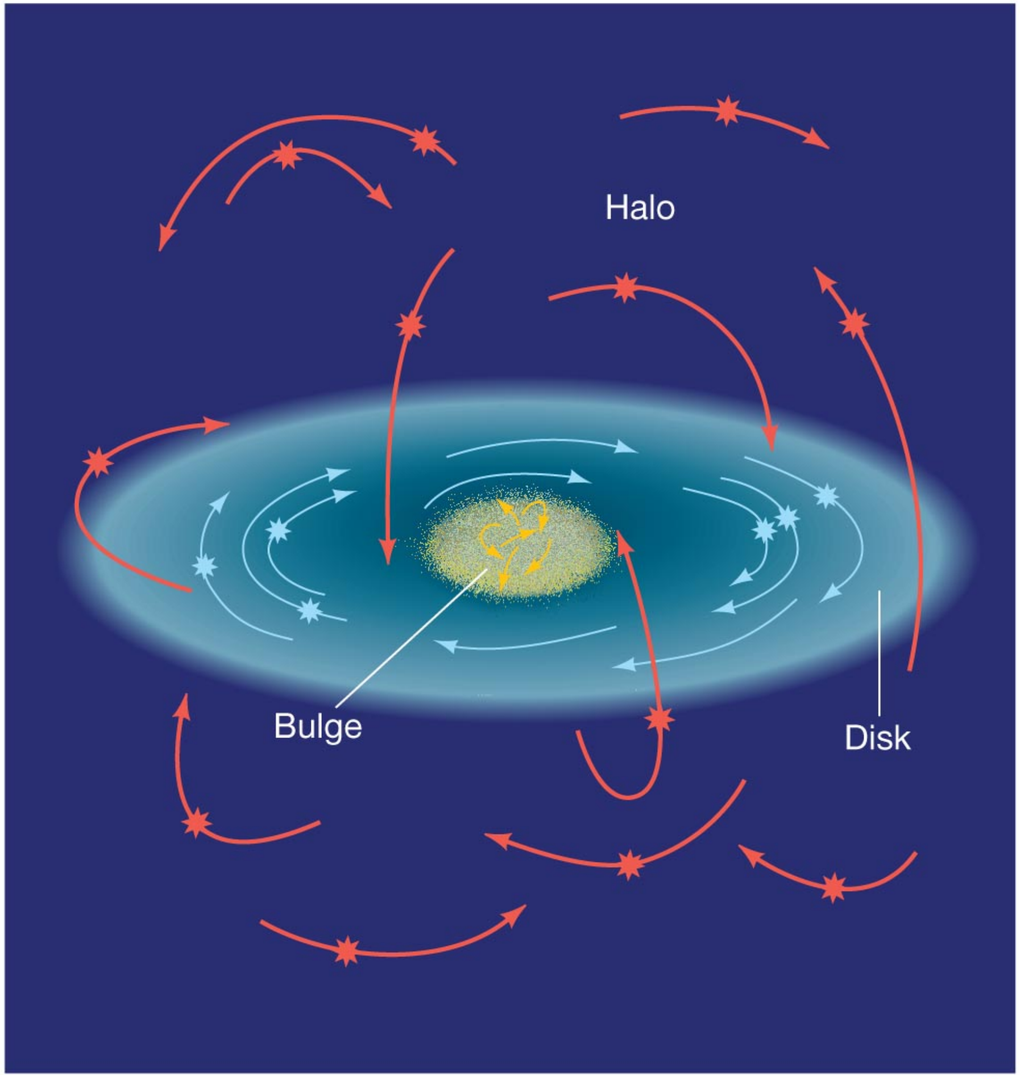
Galactic Structure

This infrared view of our Galaxy shows much more detail of the galactic center than the visible-light view does, as infrared is not as much absorbed by gas and dust.



Galactic Structure

Stellar orbits in the disk are in a plane and in the same direction; orbits in the halo and bulge are much more random.



Stellar populations: Old and new stars

• Stars formed at the time the Galaxy formed are called Population II stars. They are almost entirely hydrogen and helium with few heavier elements, because the matter in them had not previously been in another star. They lie in all parts of the galaxy, the halo (globular clusters), disk, and bulge.

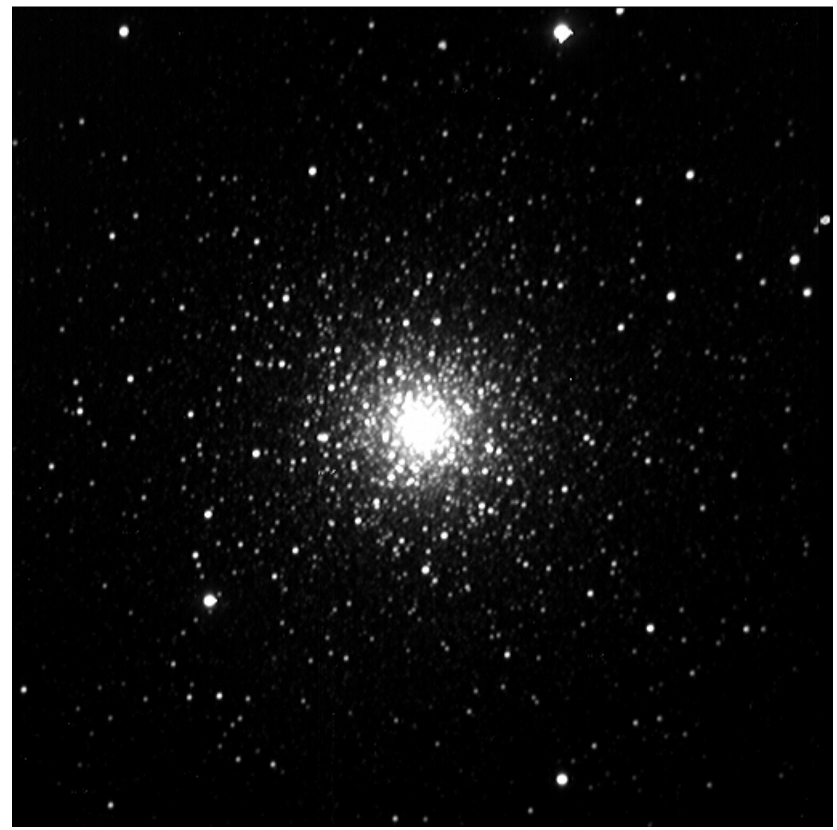
• Younger stars, formed from matter in the disk of the galaxy, are called Population I stars. They are made from reprocessed material, matter that was once in other stars and was redistributed to the galaxy when the star died.

Population I stars are thus younger and begin their lives with a larger fraction of heavier elements than Population II stars.

Both Population I and Population II stars are made mainly of hydrogen and helium. Even in Population I stars, like the Sun, heavier elements are a small fraction of the total mass.

- Globular clusters formed at the time the galaxy formed. They are dense clusters of up to 1 million stars, all Population II.

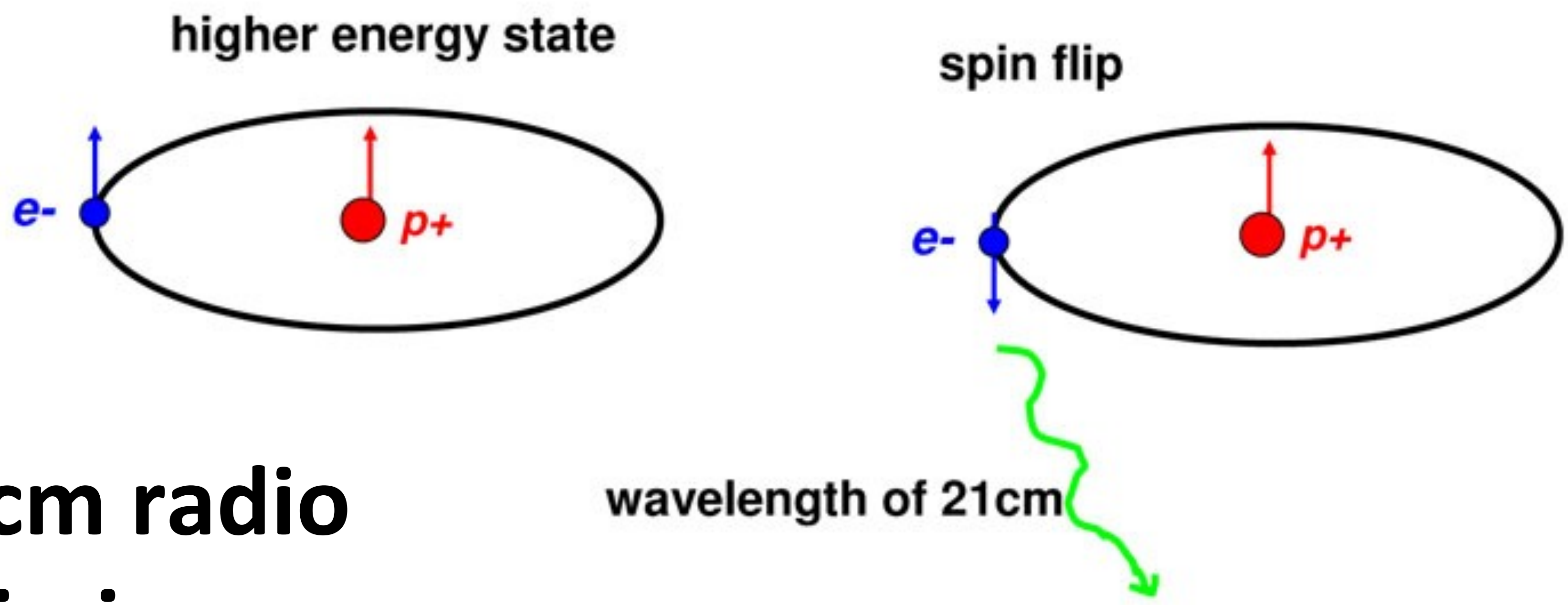
- An example of a typical globular cluster is M3



- Globular clusters are among the oldest objects in the universe.

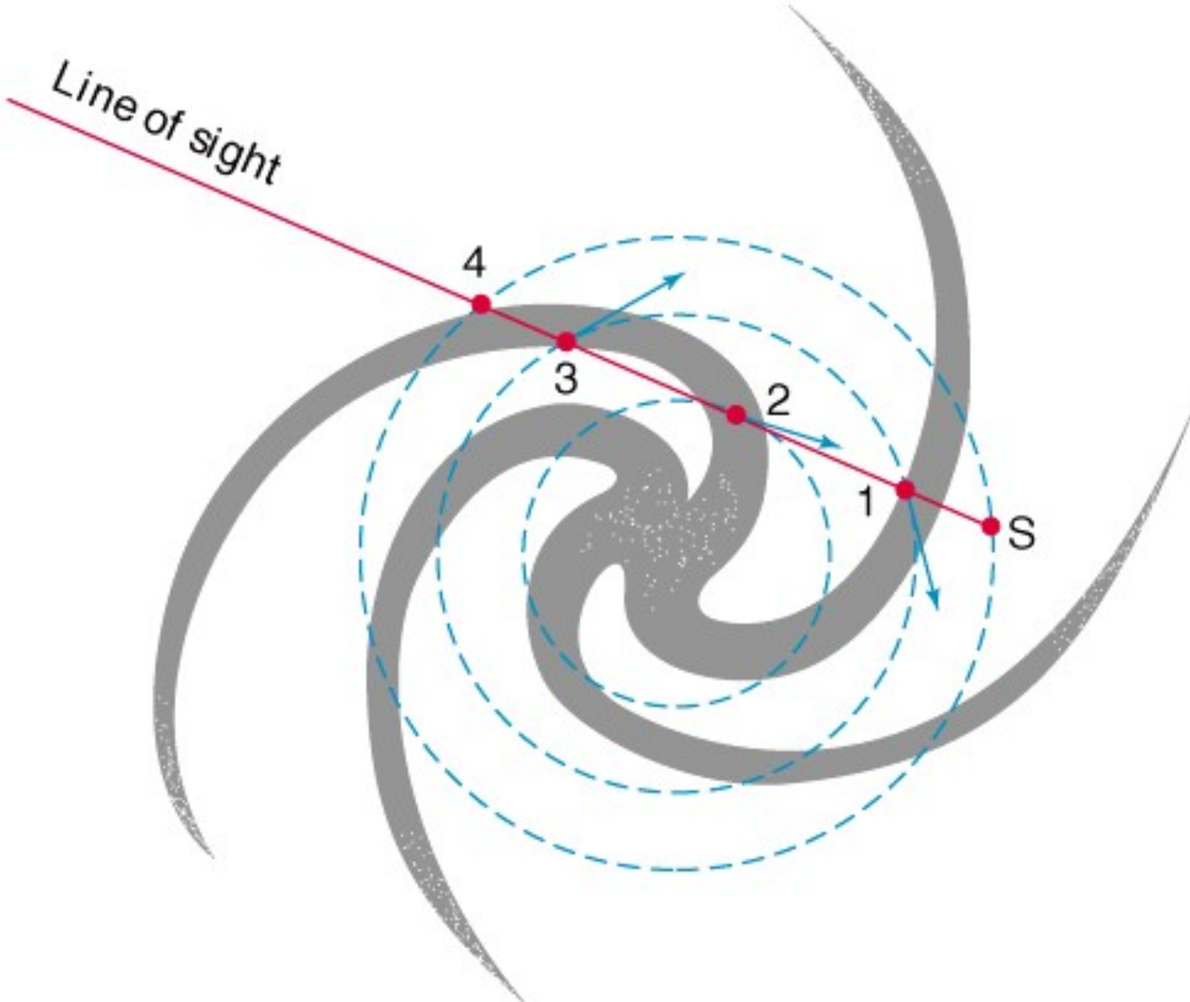
How do we know the Milky Way is a spiral galaxy?

The electron and proton in an atom of neutral hydrogen have **spin**. Their spins can be aligned, or they can point in opposite directions. Sometimes the spin of the electron flips, and when this happens a photon is emitted with wavelength 21 cm. This can be observed in the radio, and is used to map neutral hydrogen gas.



21 cm radio emission

Cold hydrogen gas emits 21 cm radio waves (called 21 cm radiation), and this gas lives in the disk of the Galaxy



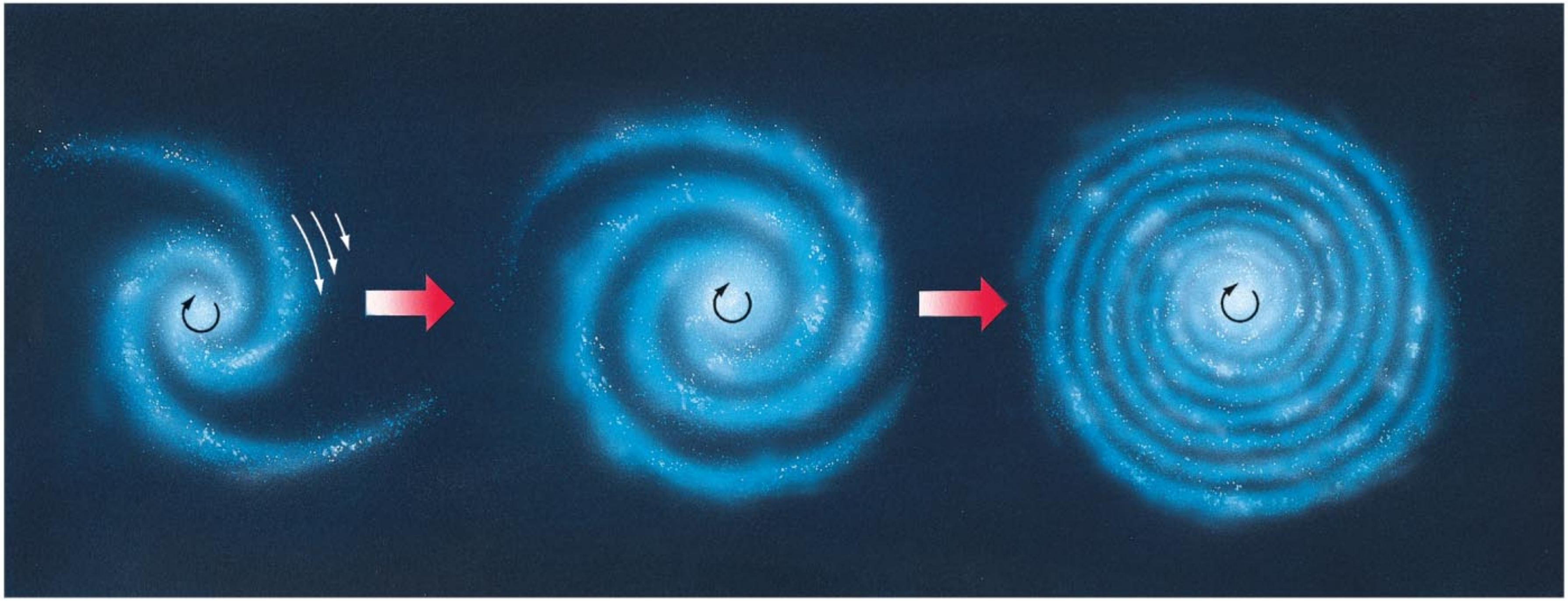
The Doppler shift is different from different parts of the arm (and different arms!)

What are the spiral arms?

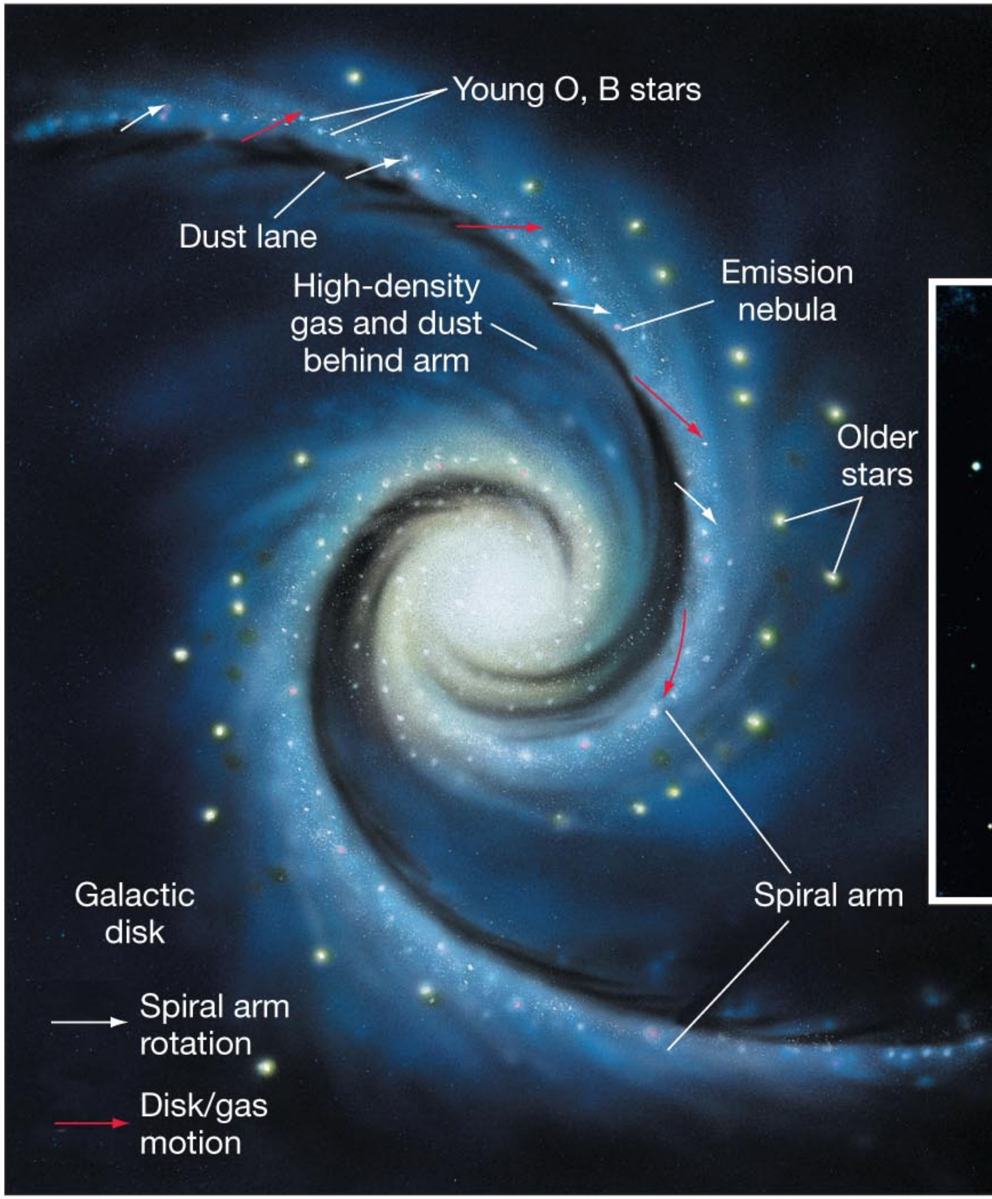
- It is still not fully understood what causes the spirals arms that we see in spiral galaxies
- We at least know that gravity plays an important role. Gravity causes things to clump up
- But how it organizes into a spiral arm is not clear

The Winding Problem

- Spiral arms are not material formed into a spiral by the rotation of the galaxy –if this were the case, the arms would wind up until they disappeared
- This is called the **winding problem**

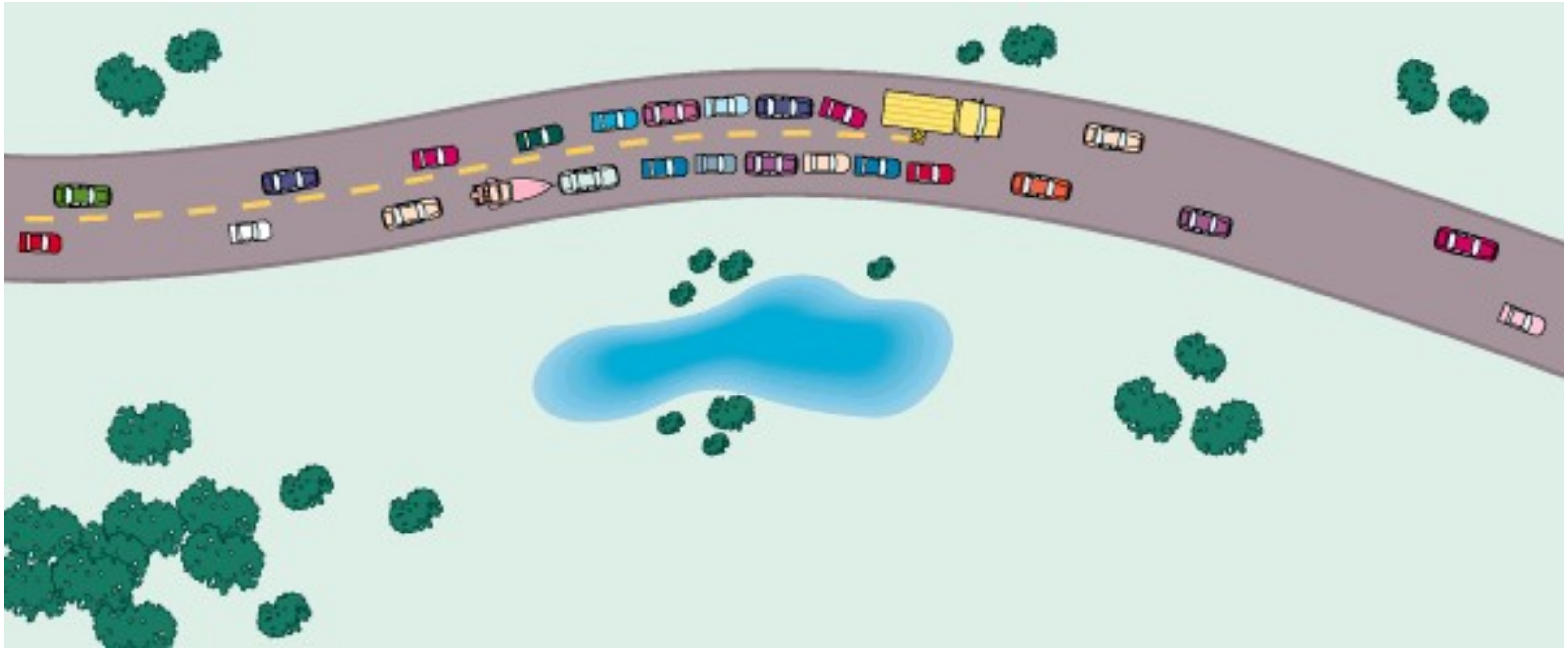


Alternatives: (1) Spiral density waves



Spiral arms are not material, but *patterns* instead. Stars and gas flow in and out of spiral arms.

Alternatives: (1) Spiral density waves



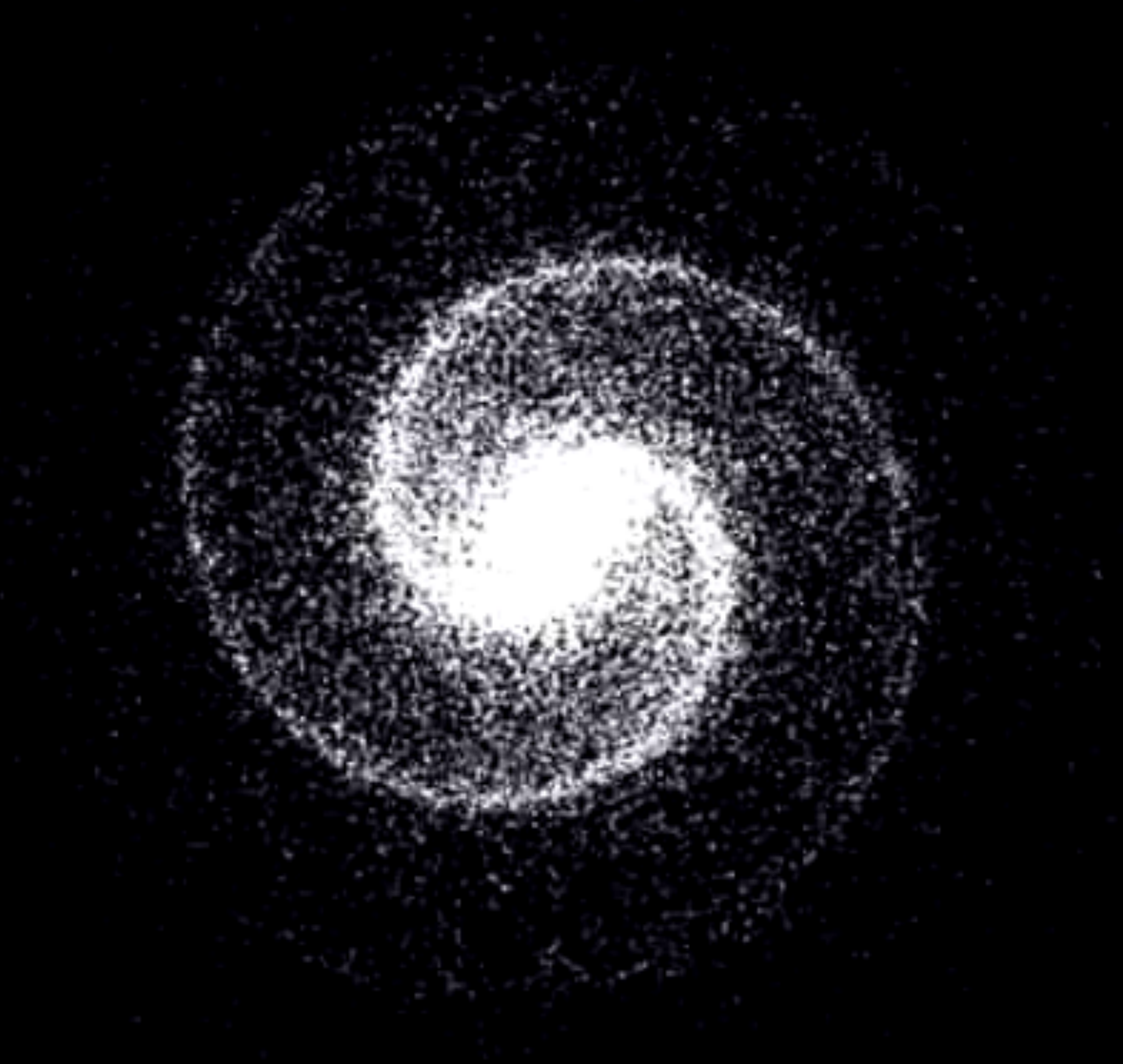
It is like a traffic jam. The traffic jam is not a physical thing, just a pattern.

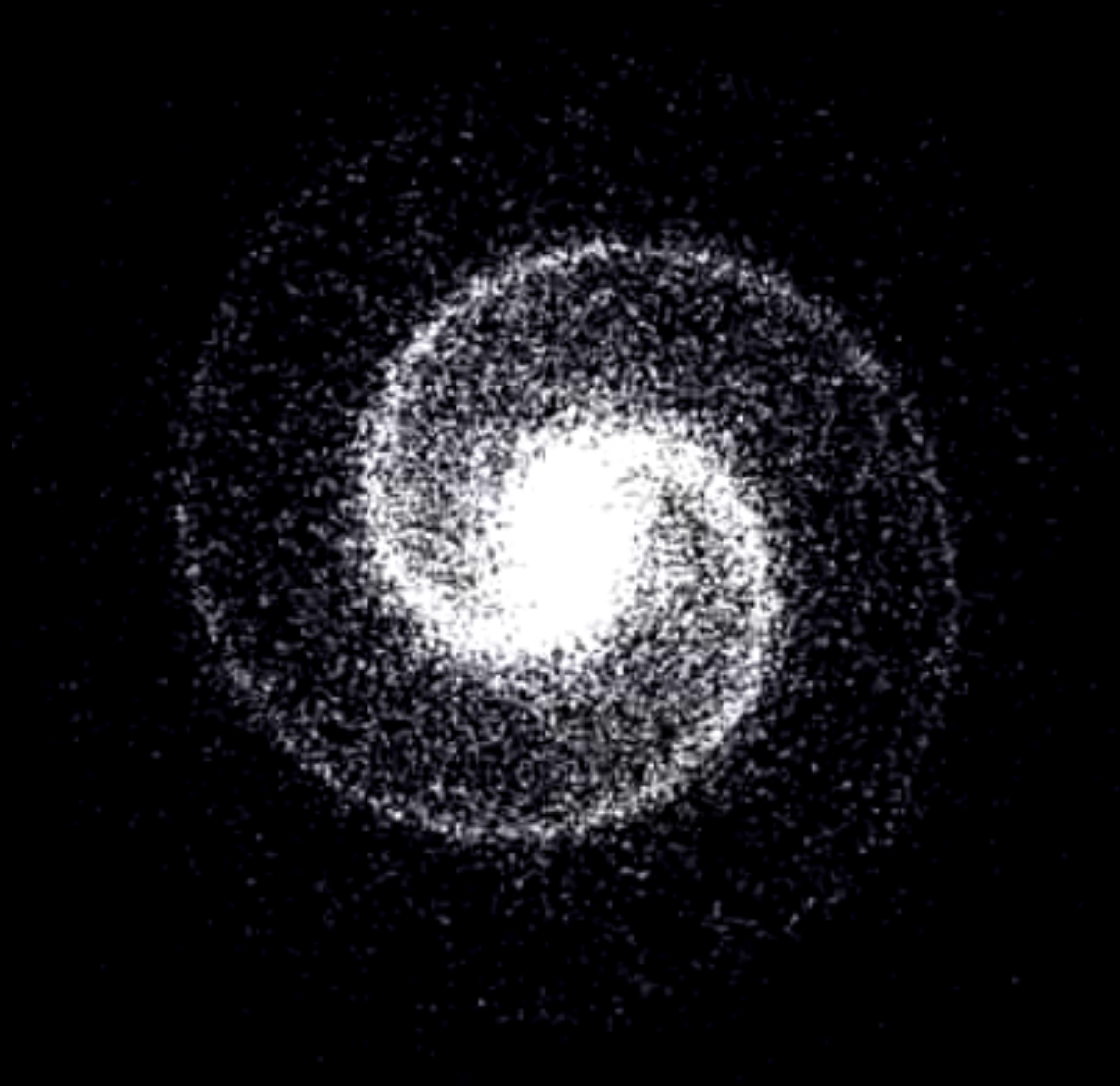
The cars that make up the traffic jam are not always the same. Cars in the jam eventually pass through it and escape, but new cars come in and the jam remains

Alternatives: (1) Spiral density waves

If we apply this traffic jam analogy to stars, we can produce a spiral like pattern.

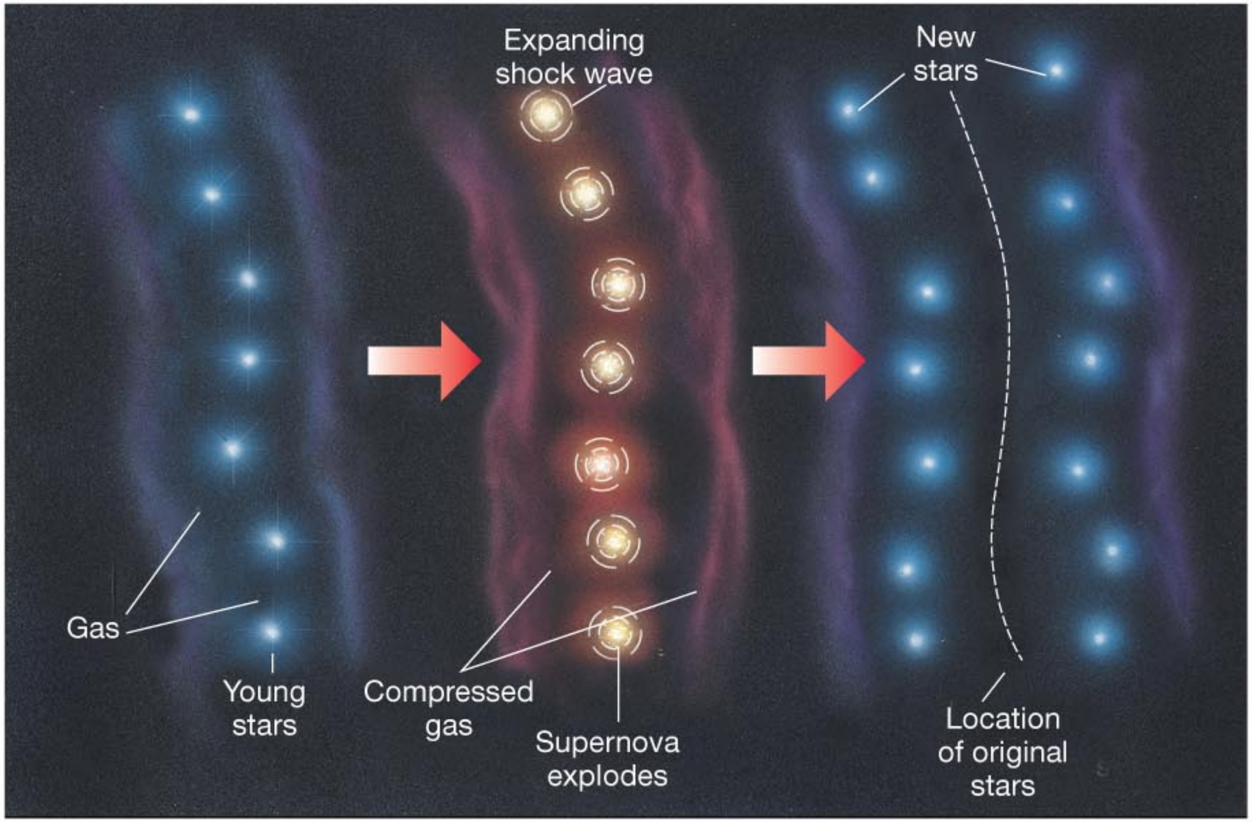
The spiral arms are just the slow regions of stellar traffic, and stars move through them



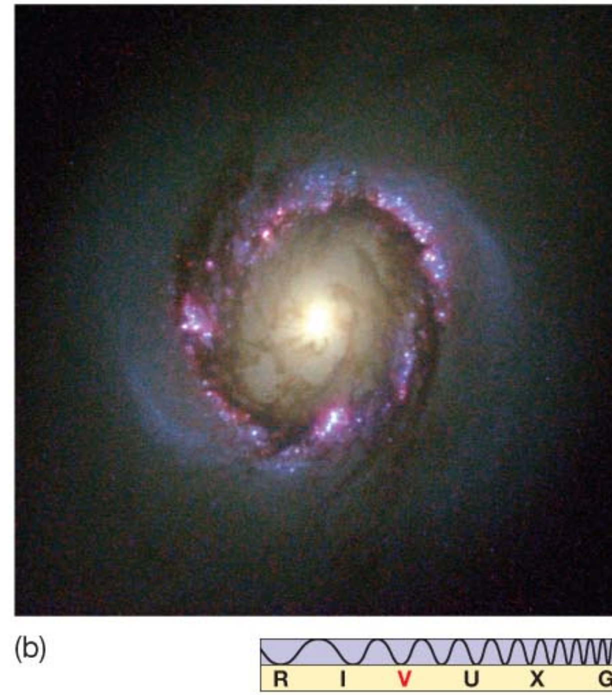


Compare the previous movie with this one, in which the stars stay fixed relative to the spiral arms. This is **not** what we think happens.

Alternatives: (2) Self propagating star formation



(a)



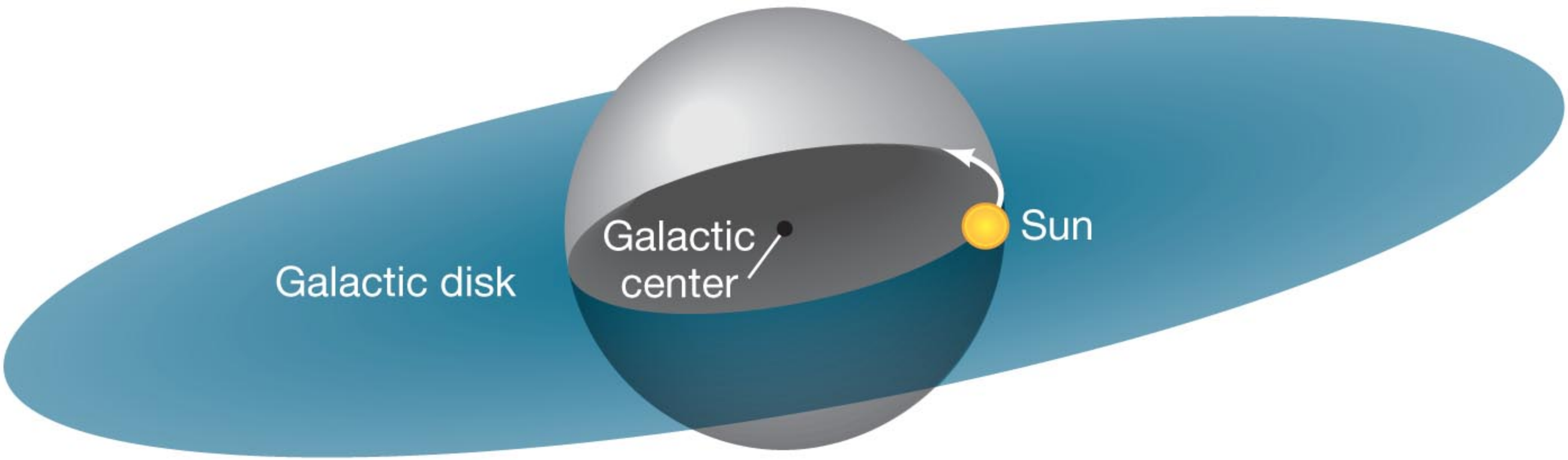
(b)

Stars form in waves and the wave of star formation makes the spiral arm – but it is not clear how whole spiral arms would appear with this mechanism.

->Spiral arm formation is still being researched!!

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.

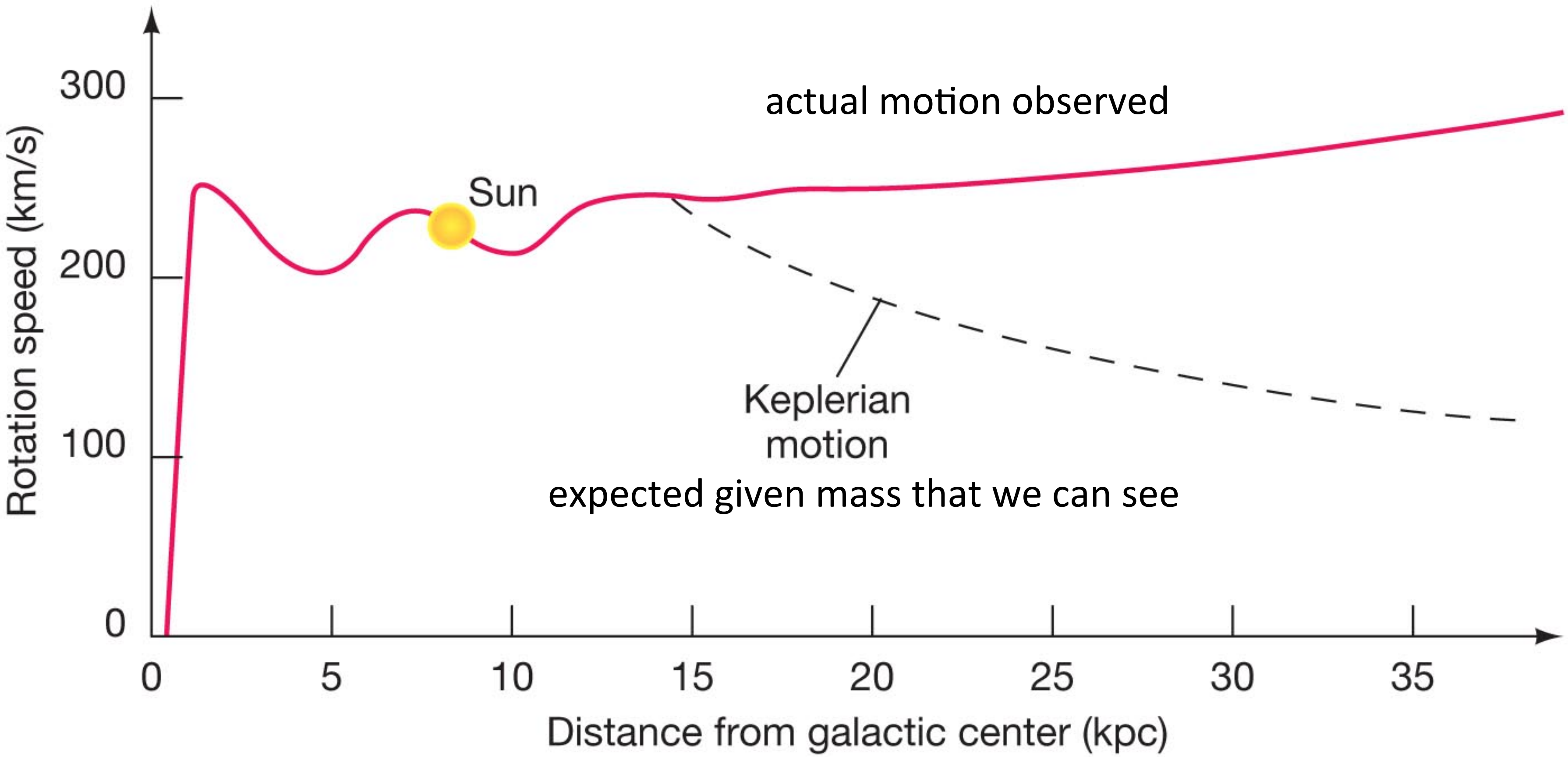


Mass of the Milky Way and Dark Matter

From Newton's law of gravity, one can, as usual, find the mass of the galaxy inside an orbiting star or globular cluster from the period of its orbit (just as one finds the mass of a star from another star in orbit about it). The mass in the Galaxy's disk is found in this way to be about 200 billion solar masses.

But as one looks at orbits of globular clusters and gas clouds that are further from the center of the Galaxy, a strange thing happens. The mass does not end with the edge of the disk, nor does it come mostly from the disk and bulge at all!

Rotation curve of the Galaxy: How fast objects move as a function of the distance to the galactic center.



Instead, the speed at which stars, globular clusters and gas clouds orbit the galaxy implies a much larger mass than is visible:

• **Most of the Galaxy's mass is dark matter, matter too dim to see at any wavelength, that lies in the halo. We do not yet know what it is.**

This is true of all other large galaxies whose mass we have measured. What constitutes most of the universe's mass is one of the most fundamental mysteries of current astronomy.

Dark Matter Summary

How fast a star orbits the galaxy tells us how much mass is inside the radius of the star's orbit

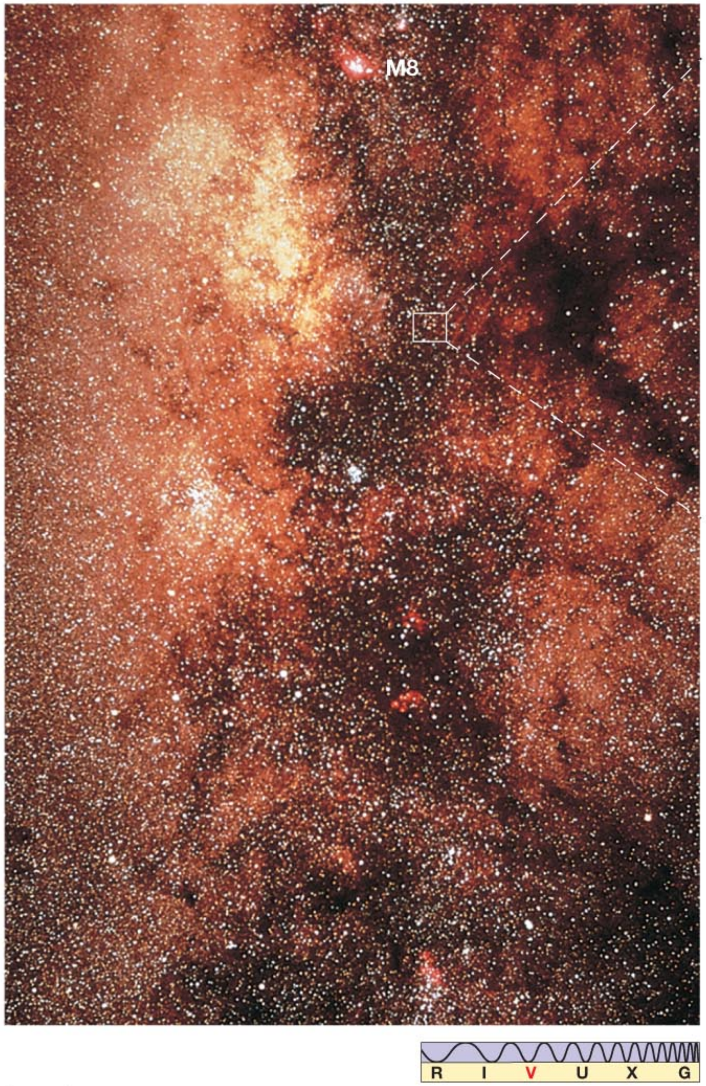
The faster the star moves, the more mass must be pulling it to keep it from flying out of the galaxy

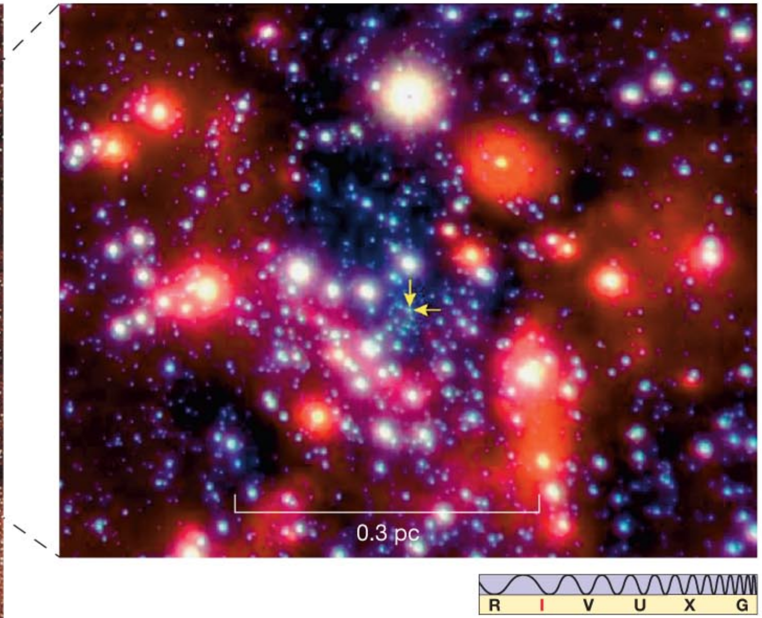
Stars far from the center of the galaxy move unexpectedly fast: **Therefore there is much more mass in the galaxy than we can see**

At least 90% of the Galaxy's mass is "dark matter," matter that we cannot see at any wavelength

We know where it is (mostly in the halo) but
we don't yet know what it is

The Galactic Center

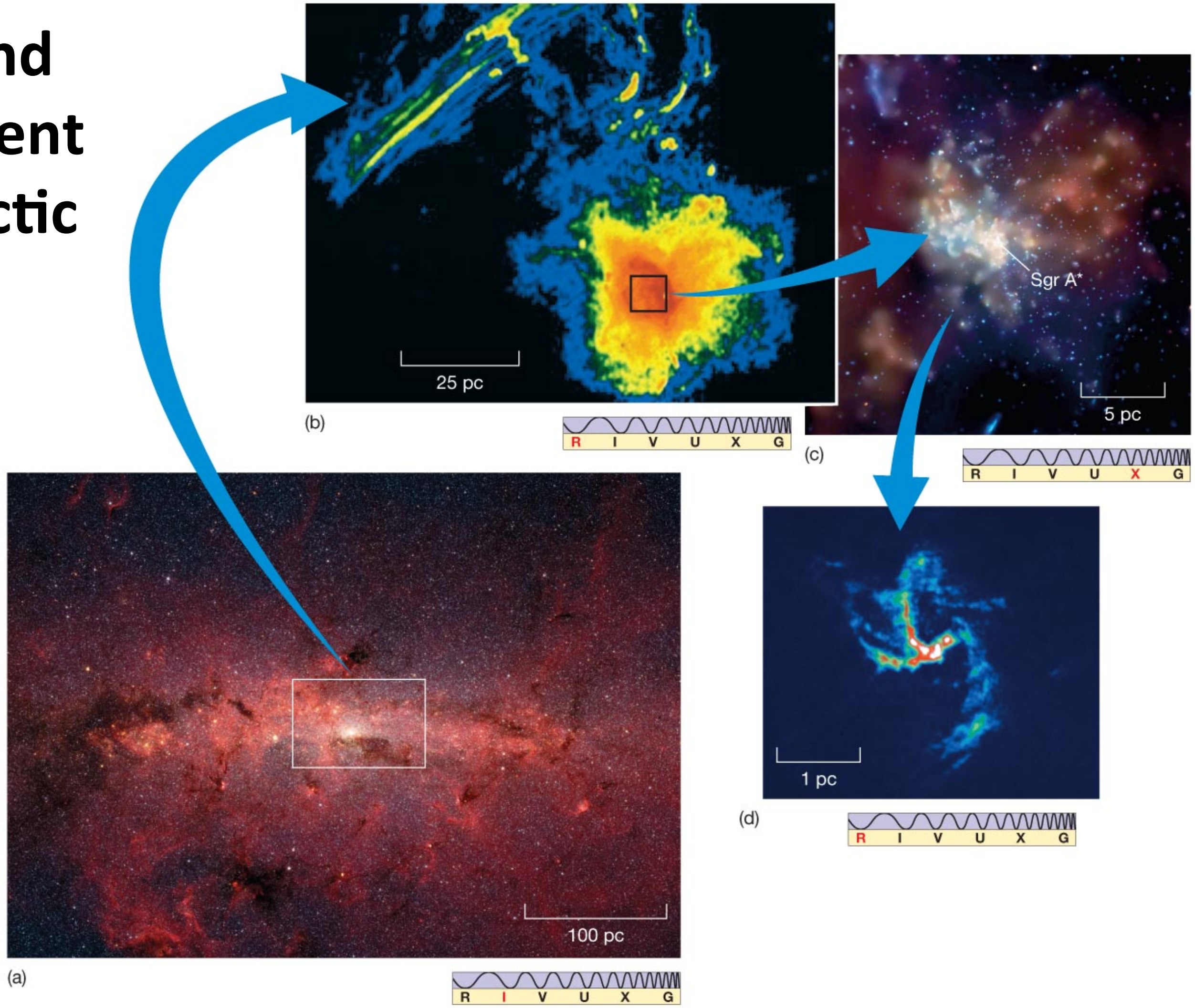




This is a view toward the galactic center, in visible light. The two arrows in the inset indicate the location of the center; it is entirely obscured by dust.

The Galactic Center

These images, in infrared, radio, and X-ray, offer different views of the galactic center



The Galactic Center

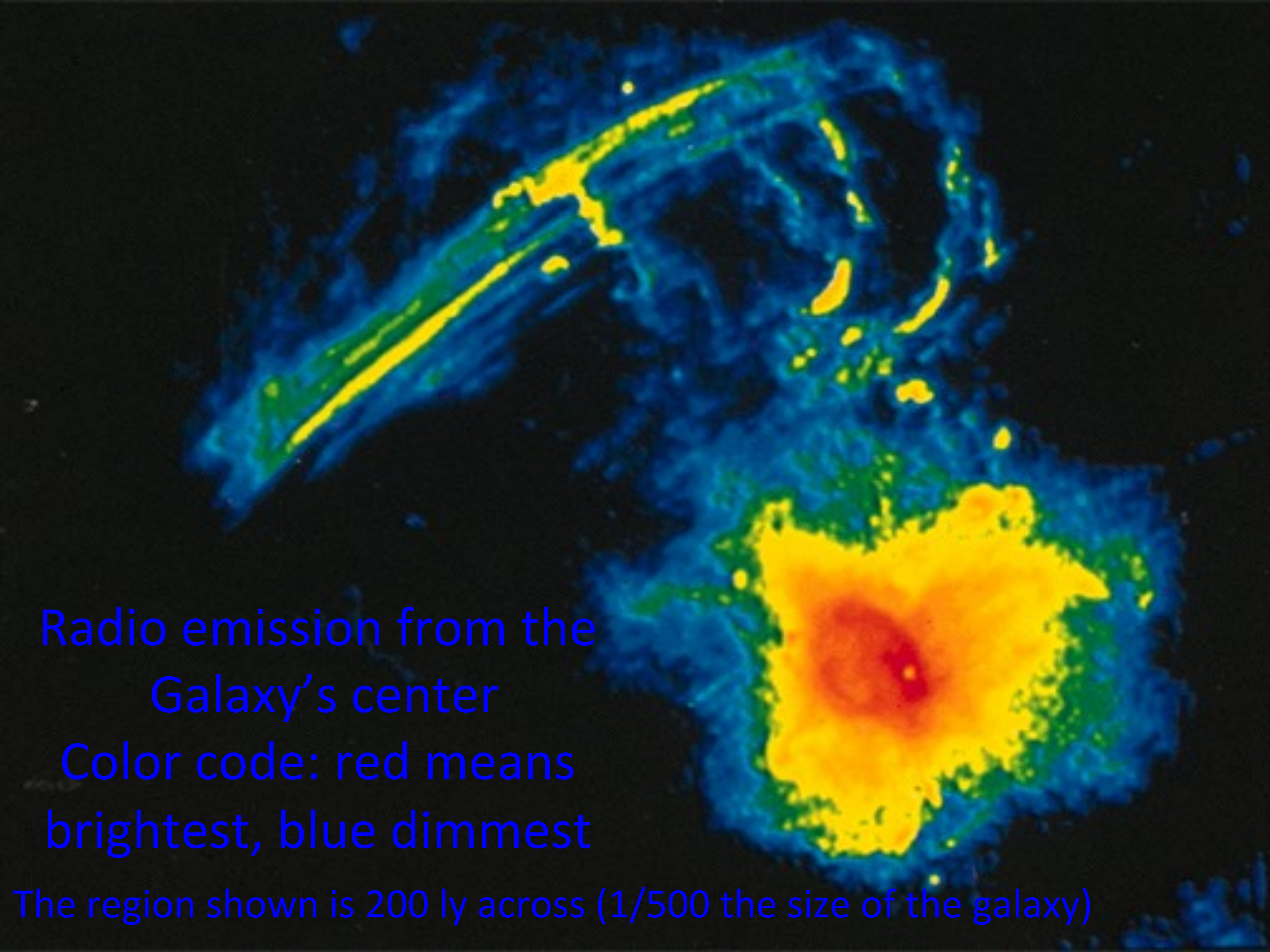
The galactic center appears to have

- **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**
- **a strong X-ray source at the center**

Evidence for a supermassive black hole at the center of the Milky Way

The center of the Milky Way is a very bright radio source. Because the center of the Galaxy is in the direction of the constellation Sagittarius and because it is the brightest radio source in Sagittarius, the source is named Sagittarius A.

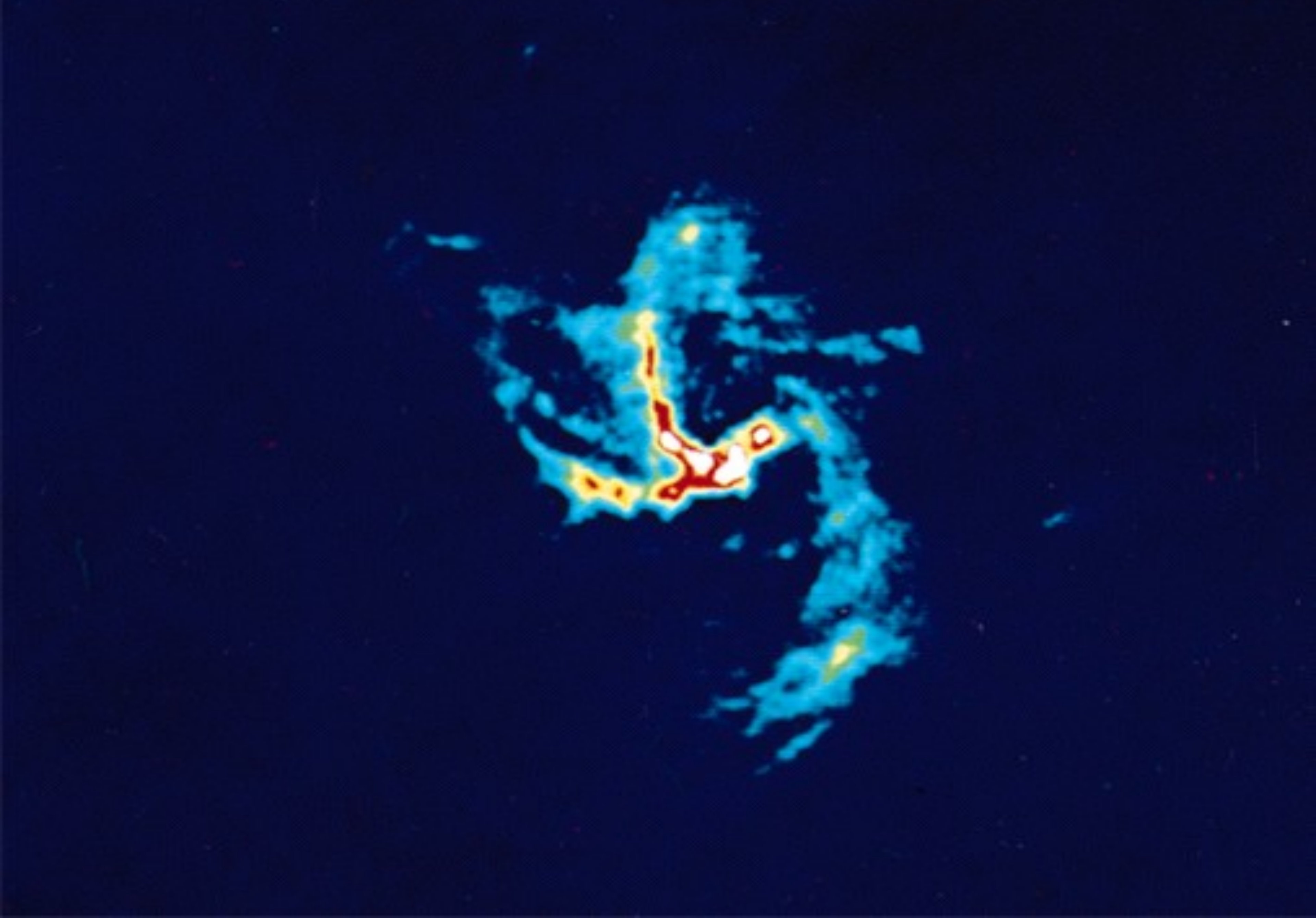
What provides the radio waves was debated for fifty years and is now answered: More than 15 years of images of the Milky Way's center have provided strong evidence for a **large black hole.**



Radio emission from the Galaxy's center
Color code: red means brightest, blue dimmest

The region shown is 200 ly across (1/500 the size of the galaxy)

Close-up of the the central 20 ly

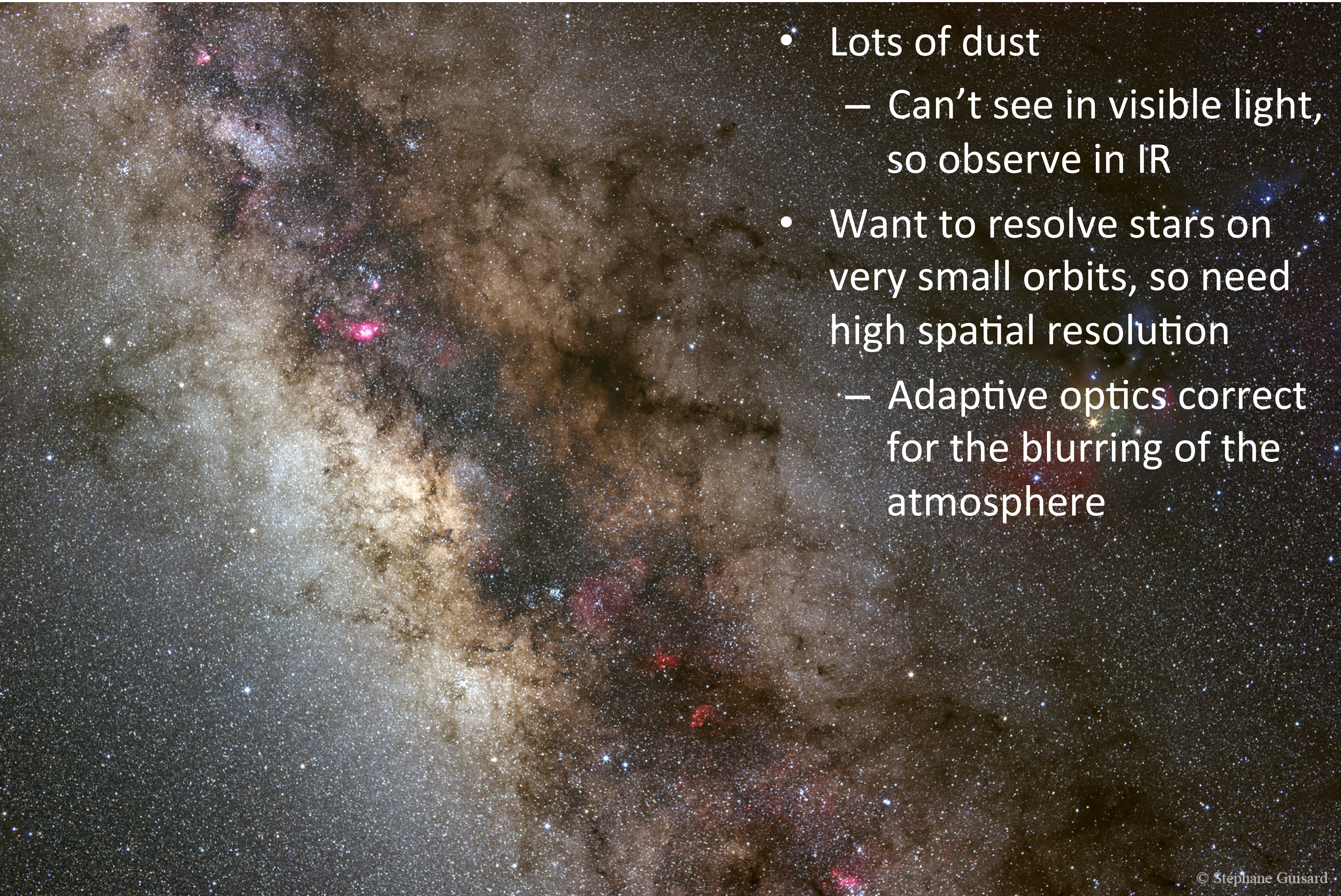


- Observations of orbiting stars near the Galaxy's center show that about 4 million solar masses lie within 6 light-hours of the center.

From the stars' distance from the center and the very short time it takes them to complete their orbits, one finds that they are orbiting something whose mass is 3.7 million times the mass of the Sun! All of that mass is squeezed into something smaller than a few light-days across – about the size of the solar system.

- This strongly suggests that there is a 4-million solar mass black hole in the center of the Galaxy.

Observing Stars in the Galactic Center



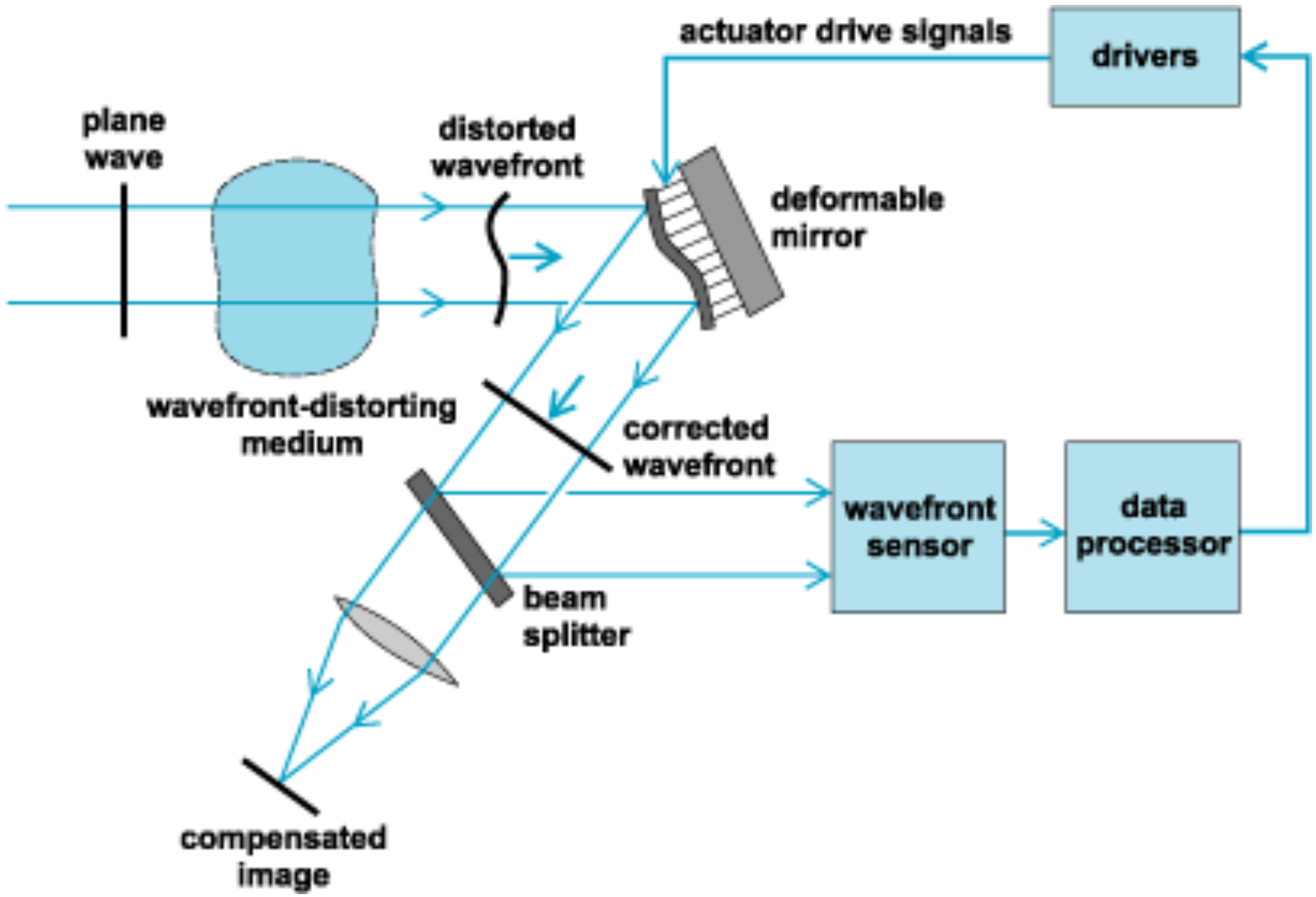
- Lots of dust
  - Can't see in visible light, so observe in IR
- Want to resolve stars on very small orbits, so need high spatial resolution
  - Adaptive optics correct for the blurring of the atmosphere

Remember from telescopes lecture: *Adaptive Optics*

Laser excites sodium atoms in upper atmosphere to create "artificial star"

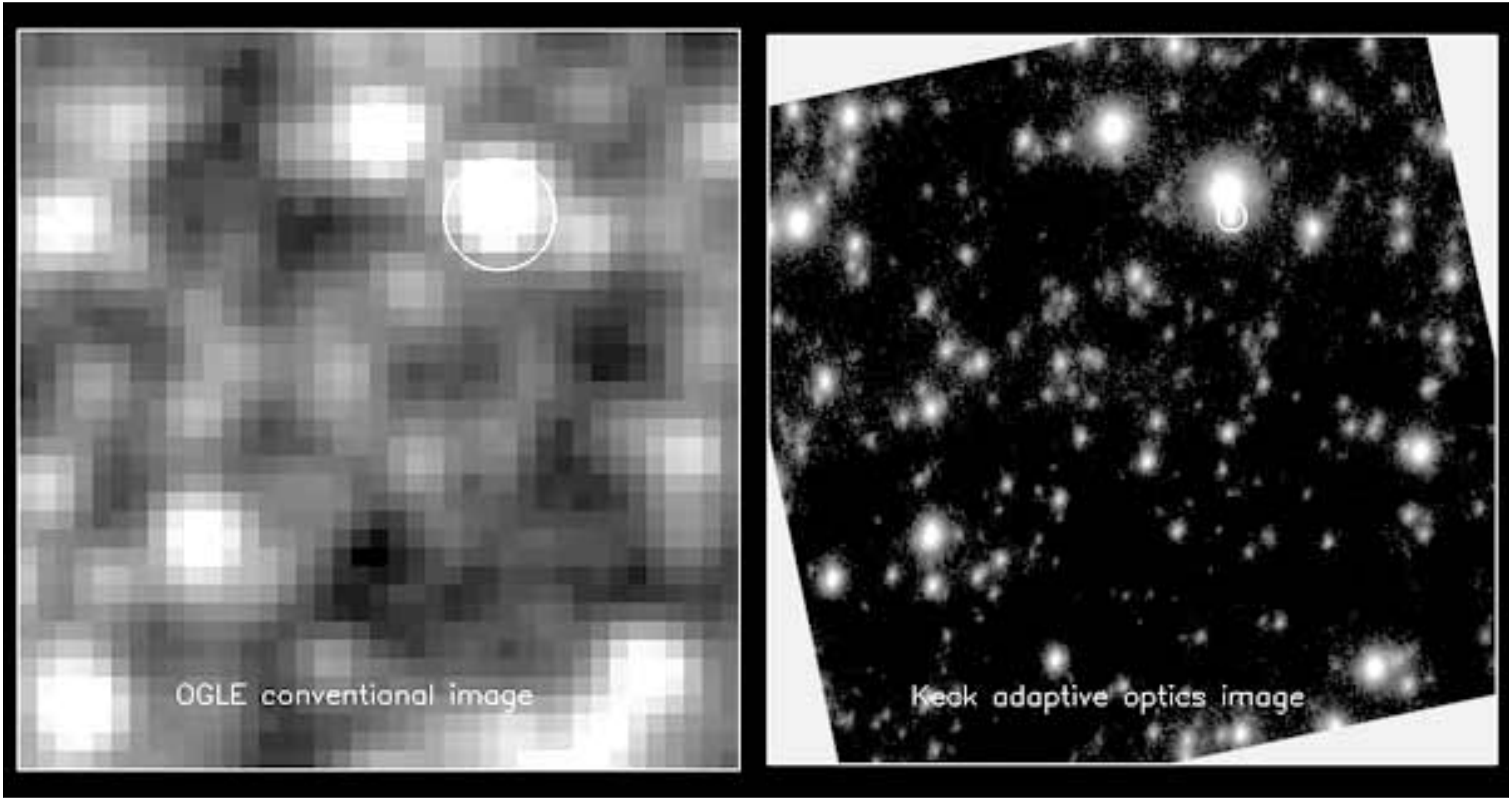
Monitor distortions of atmosphere by looking at changes in image of artificial star

Adaptive Optics



Distortions are mapped and corrected in real time (10-1000 times a second) with a deformable mirror

Adaptive Optics



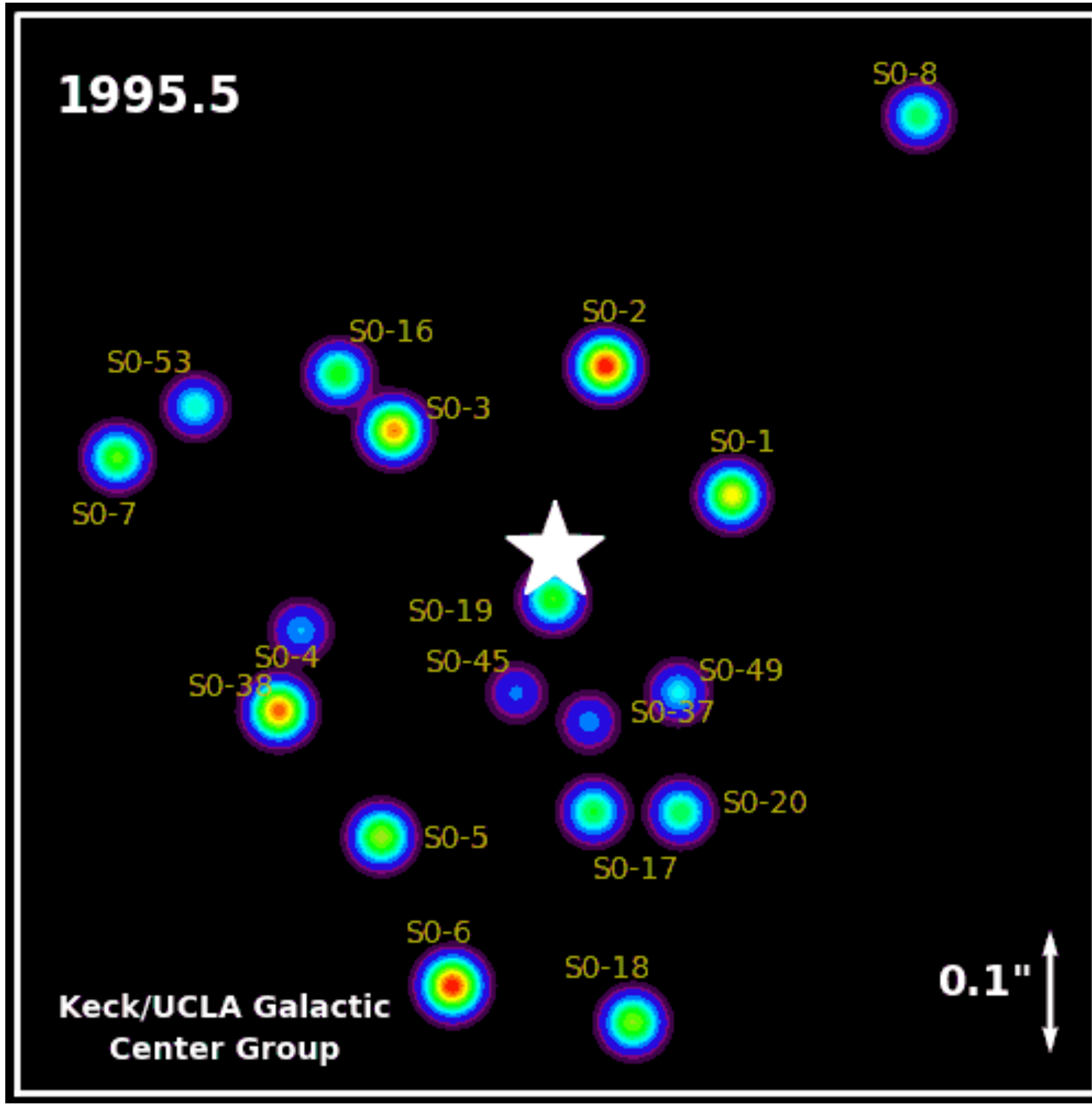
Lasers of both Keck telescopes observe Galactic Center

With 16 years of data, here's what the orbits look like

Recently the star S0-2 completed an orbit that we observed from start to finish

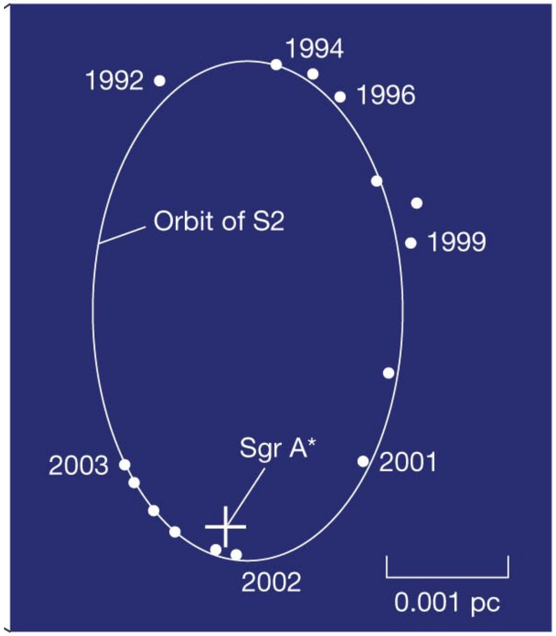
It comes very close to the center and moves very quickly

This is evidence that something very massive and dense lives in the center



A Supermassive Black Hole

- Applying Kepler's third law to the orbits of the stars gives a mass for the central black hole of 3.7 million solar masses
- This is a large black hole, but it's only about 0.0004% of the total mass of the Galaxy
- As we'll see later, most galaxies have massive black holes at their centers, and many of them are much more massive than ours



The Formation of the Milky Way

Any theory of galaxy formation should be able to account for all the properties below.

TABLE 14.1 Overall Properties of the Galactic Disk, Halo, and Bulge

Galactic Disk	Galactic Halo	Galactic Bulge
Highly flattened	roughly spherical—mildly flattened	somewhat flattened—elongated in the plane of the disk (football-shaped)
Contains both young and old stars	contains old stars only	contains both young and old stars; more old stars at greater distances from the center
Contains gas and dust	contains no gas and dust	contains gas and dust, especially in the inner regions
Site of ongoing star formation	no star formation during the last 10 billion years	ongoing star formation in the inner regions
Gas and stars move in circular orbits in the Galactic plane	stars have random orbits in three dimensions	stars have largely random orbits, but with some net rotation about the Galactic center
Spiral arms (Sec. 14.5)	little discernible substructure; globular clusters, tidal streams (Sec. 14.3)	ring of gas and dust near center; central Galactic nucleus (Sec. 14.7)
Overall white coloration, with blue spiral arms	reddish in color	yellow-white

The Formation of the Milky Way

The formation of the galaxy is believed to be similar to the formation of the solar system, but on a much larger scale